

We would like to thank Dr Sandy Thomalla for the time she granted to this review. We acknowledge her in-depth reading and really appreciated her valuable comments and suggestions to improve the quality of our manuscript. We carefully considered the provided feedbacks and criticisms in preparing our revision. Please find below our response. We have made major efforts to improve the paper, including:

- 1. Addition of comparison to shipboard chlorophyll data from KEOPS2*
- 2. Expansion of the description and details regarding the correction for quenching (noting that no conclusions of the paper depend on this correction, because use of only the night time data yields the same outcomes).*
- 3. Addition of Lagrangian trajectory maps and analysis to relate chlorophyll inventories to water parcel histories relative to the Kerguelen plateau*
- 4. Expanded analysis of bio-profiler chlorophyll observations, using water column inventories rather than concentrations (as recommended by both reviewers).*

We believe the paper is now greatly improved and that the conclusions are well qualified.

Reviewer #1 (Dr Sandy Thomalla)

General Comments

This paper uses an extensive data set from 4 high resolution bio-profiler deployments off the Kerguelen plateau covering 6 months of the growing season (Nov to April) spread over 3 years (2011 /12 and 2014). The study investigates three primary questions each with scientific relevance to Southern Ocean research within the scope of Biogeosciences. The research is encouraging for the expanded use of autonomous platforms and is well presented and articulated. However, in my opinion, there are a number of issues with the scientific results and their interpretation (plus numerous technical corrections) that need to be addressed before this work is suitable for publication.

Specific comments

Abstract

You say that your study examines the conditions favoring phytoplankton accumulation (better to use the word growth) in particular the influences in temperature and stratification. Your results and discussion however never investigate the influence of stratification but instead correlate temp, salinity and mixed layer depth with chlorophyll. Best to correct this accordingly, but even better would be to include stratification index into the correlation section.

Authors' response:

We have kept the term “accumulation” because what was measured was the net budget as reflected by biomass, i.e = growth – loss, and thus we do not have a direct determination of growth.

The reviewer is correct that our analysis focused on the mixed layer depth, rather than a more direct measure of stratification. We have added a plot in new Figure 7 (old Figure 6) showing the maximum Brunt-Väisälä frequency squared N^2 as a function of chlorophyll inventories. We also added the temporal evolution of this variable in new Figure 10 (old Figure 8), in Section 4.3, for the 3 density layers. Conclusions are that no clear relationship emerged between chlorophyll concentrations and stratification, suggesting that it was not a strong driver of chlorophyll distributions, at least at the time and in the area of our study. In contrast, mixed layer depth was clearly an important parameter, and accordingly, we take care to use this term rather than stratification throughout the revised paper when linking upper water column structure to biological variables.

You say that your largely linear relationships suggest that dilution of chlorophyll by mixed layer variations (better to say deepening as shoaling will not result in dilution) plays a minor role in spatial distribution of chla. This is incorrect; dilution is not at play here. If the mixed layer deepens it will be expected to dilute the whole mixed layer chla signal that will be evidenced in both surface and deep chla concentrations. What researchers are concerned about and what you are trying to investigate is whether surface signals of chla (seen by satellites) are representative of water column integrated chla.

The big issue here being whether surface satellites are underestimating water column chlorophyll due to unobserved subsurface chlorophyll maxima (this has nothing to do with dilution). As such a linear relationship between surface and water column chl_a would imply that surface concentrations are representative of water column concentrations (and not that dilution is playing a minor role in distribution).

Authors' response:

We agree that this text was over-simplified. We have removed it from the abstract, and have expanded our discussion in the text on the role of subsurface chlorophyll maxima and other variations in chlorophyll water column distributions on correlations between surface chlorophyll concentrations and chlorophyll water column inventories. To do this, we replaced the mean [0-200] m chlorophyll concentrations (mg m^{-3}) by the chlorophyll inventories (mg m^{-2}) over this same depth range (integrated values). We also replaced the mean [0-50] m chlorophyll concentration by the surface (shallowest observation near 10 m depth) chlorophyll concentration. This issue is discussed further below, in our response to Dr Thomalla's comments about Section 4.1.

I would add your major result from question three of your discussion to the abstract that 40% of surface production was exported.

Authors' response:

We have done this, using our refined estimate of 35%.

I feel it is jumping to conclusion to say that a lack of correlation between regions of moderate chlorophyll and MLD suggests a diversity of sources of Fe and or its efficient dispersion across filaments of the plume.

Authors' response:

We agree and we have removed this statement.

1. Introduction

The introduction does a good job of introducing the multiple drivers of production in the Southern Ocean and the resultant complexity of chlorophyll distribution evidenced from satellite. As such it introduces the scientific relevance of question 2 well (do regions of high biomass correlate with oceanographic properties) however it does not do a satisfactory job of introducing the scientific relevance of research questions 1 and 3.

Satellite ocean colour products provide high resolution space and time data of the oceans but is limited to surface estimates which do not take into account deep chlorophyll maxima or changes in carbon to chlorophyll ratios with depth. This limits the ability to interpret these products, in particular in regions where surface measurements are not representative of the water column. Your research directly addresses this issue in the Kerguelen region of the Southern Ocean and its importance should be better introduced to support question 1 (do satellite images of chl provide an unbiased guide to spatial distribution of total water column chlorophyll).

Similarly, the percentage of primary production sequestered as organic carbon in the Southern Oceans is of great importance to better understanding the efficiency of the biological carbon pump. I think that this needs to be better articulated in the introduction to highlight the relevance of your addressing question 3 (can the fate of surface biomass be determined). I also think that a primary part of question 3 should include not only 'can it be measured' but should also include "and if so what is it"?

I think that somewhere in your introduction it would also be good to highlight the importance of measuring the system at high spatial and temporal scales (which the bioprofilers are able to do thus enhancing their appropriateness as an effective research platform to address these questions in the Southern ocean) as these fine scales are what link the physical drivers of climate change to the biogeochemistry. These include the temporal scales extending from seasonal to sub-seasonal and the spatial scale ranging from the mesoscale to the sub-mesoscale. (see Lévy et al., 2001; Le Quéré et al., 2007; Klein et al., 2008; Doney et al., 2009; Thomalla et al., 2011; Racault et al., 2012; Joubert et al., 2014; Swart et al., 2014; Carranza and Gille, in press).

Authors' response:

We thank the reviewer for encouraging us to expand on the importance of these 3 issues. We added new paragraphs dedicated to both question 1 and question 3, and included quantification of the export as an

important aspect of question 3. Our expanded text now refers to many of these suggested citations, as well as to others that illustrate the issues.

Modified text:

Assessing influences on productivity, biomass accumulation, carbon export, and carbon dioxide (CO₂) uptake in the Southern Ocean is challenging because of variations across many scales, including weather, seasonal, and interannual time-scales, and sub-mesoscale, mesoscale, and circumpolar frontal space scales (Joubert et al., 2014; Le Quéré et al., 2010; Lenton et al., 2013; Levy, 2003; Nicol et al., 2000; Shadwick et al., 2015; Sokolov and Rintoul, 2007; Swart et al., 2014; Thomalla et al., 2011; Weeding and Trull, 2014). Satellite observations offer extensive space-time coverage (Martinez et al., 2009; Moore and Abbott, 2000), but may provide a biased view if surface distributions are not representative of water column inventories. Important ways that bias could arise include correlations of surface values with their vertical extents (e.g. high surface chlorophyll values might be predominantly associated with shallow accumulations, through the promotion of production by higher light levels in shallow mixed layers; Sverdrup, 1953), the presence of unobserved subsurface chlorophyll maxima (Carranza et al., 2014; Schlitzer, 2002), or the variation of phytoplankton to chlorophyll ratios with growth conditions (Cloern et al., 1995; Fennel and Boss, 2003; Goericke and Montoya, 1998).

These difficulties of observation become even more acute for carbon export estimates, which require either flux measurements (e.g. from moored or free-drifting sediment traps or radionuclide activities; Planchon et al., 2014; Savoye et al., 2008) or the partitioning of changes in state variables across biogeochemical versus oceanographic causes (e.g. nitrate depletions in surface waters or oxygen consumption at mesopelagic depth; Mearns et al., 2000; Trull et al., 2015). Obtaining estimates of carbon export and the depth of its penetration into the ocean interior are important to determining impacts on the climate system, because variations in these two factors have similar influence to variations in total primary production in terms of the sequestration of CO₂ from the atmosphere (Boyd and Trull, 2007). Notably, export estimates expressed as 'e-ratio' fractions of primary production (Maiti et al., 2013), or as 'f-ratio' fractions of production derived from 'new' nitrate supply (Savoye et al., 2004) vary widely in the Southern Ocean, with the possibility that these efficiencies are increased by natural iron fertilisation (Jouand et al., 2011; Trull et al., 2008).

2. Methods

The bbfl2 measures total scattering in raw digital counts and not particle scattering. You need to include in your methods how raw digital counts were converted to particulate.

Authors' response:

In the method section 2.2, we added a paragraph explaining the retrieval of particulate backscattering from the raw measurements.

Modified text:

[...]the retrieval of particulate backscattering, b_{bp} (m⁻¹), at 700 nm from the backscatter raw transmitted measurement (counts) was done by applying the manufacturer-provided scaling factor after correction for dark counts (i.e. measured signal output of the backscatterometer in clean water with black tape over the detector), with the additional steps of removal of the pure seawater backscattering contribution (Zhang et al., 2009), and scaling from the limited solid angle sensor measurement to the total backscattered hemisphere based on relations estimated from observations for a wide range of marine particles (Boss and Pegau, 2001; Sullivan et al., 2012).

Whenever you use backscattering you need to be careful to say particulate backscattering (b_{bp}) or simply use b_{bp} but total scattering, backscattering and particulate backscattering are all different measurements and not interchangeable and you need to be sure to always use the right one throughout the text.

Authors' response:

We did the corrections accordingly throughout the text.

I am not familiar with uranine solutions and fluorescent and non reflective plastic covers for calibrating

fluorescence sensors. Could you please provide more information on calibrating the instrumentation and how raw fluorescence units were converted to chlorophyll concentrations (so that the methods can be reproduced by future researchers). Were no in situ chl_a samples collected at the deployment site? Was the instrument factory calibration factor applied to raw fluorescence to convert to chl. Was a dark correction applied to the fluorescence data (i.e. both the factory dark count but also a measured dark count from black plastic covers or from an average of all very deep “dark” data (see swart et al., 2014)).

Authors’ response:

Similarly to the particulate backscattering, we added a sentence to explain the retrieval of chlorophyll concentration from the raw fluorescence measurement in section 2.2. We also gave more information about the calibration of the fluorometer.

Modified text:

*The bio-optical fluorescence sensors were calibrated (by the manufacturer, Wetlabs, Inc.) against fluorescent uranine solutions as working standards, and cross-referenced to prior measurements of a laboratory culture (25 mg m⁻³ chlorophyll) of the diatom *Thalassiosira weissflogii* to yield chlorophyll estimates. These calibrations are warranted to yield linear responses with precisions among multiple sensors of better than 10%, and (after one cycle of testing and replacement with the manufacturer) we obtained reproducibility for the set of three floats deployed in 2014 of better than 4% based on measurements with fluorescent and non-reflective plastics (Earp et al., 2011). Accordingly, calculation of the chlorophyll fluorescence from the float data was done by removal of the background dark signals measured prior to deployment and scaling to chlorophyll using the manufacturer’s calibrations.*

Authors’ response:

Finally, we added Figure 2c showing that bio-profiler #1 fluorescence profiles compared well to KEOPS2 shipboard observations and associated in-situ chlorophyll data.

Modified text:

Bioprofiler #1 was deployed into a semi-permanent meander of the Polar Front, which the KEOP2 program examined as a Lagrangian time series following surface drifters. As shown in Figure 2c, the first and second stations in the meander (E1 CTD-27 on 29 October 2011 at 22:46 local time and E2 CTD-43 on 1 November 2011 at 12:00 local time) bracketed the locations of the first 11 autonomous bio-profiler #1 profiles (Figure 2c.i). The bio-profiler #1 temperature profiles are intermediate between the ship results (Figure 2c.ii), with the variations in temperature profiles mainly driven by vertical motions associated with internal waves (Park et al., 2014b). In Figure 2c.iii, the KEOPS2 shipboard fluorescence results are displayed after linear calibration to high pressure liquid chromatography (HPLC) total chlorophyll-a results from below 40 meters depth (below the depth of non-photochemical quenching). The data reveal two important features: i) good fits achieved below 40 meters do not extend to the surface – where fluorescence/chlorophyll-a ratios were higher than at depth, apparently as a result of community composition variations with depth (see also Lasbleiz et al. 2015), and ii) the bio-profiler #1 fluorescence data displayed similar characteristics and good accord with the shipboard results. In light of the limited available data, a non-linear calibration of fluorescence to chlorophyll-a was not pursued, and no adjustments were made to the laboratory bio-profiler calibration.

These variations in fluorescence/chlorophyll-a ratios within individual CTD casts in the shipboard observations serve as a strong reminder that fluorescence is an imperfect proxy for chlorophyll-a concentrations, owing to variations with phytoplankton community structure, physiology, and other effects (e.g. Babin et al., 1996; Cullen, 1982; Suggett et al., 2011). Thus, interpretation of our sensor records, as with any bio-optical sensor results, must keep this in mind and avoid over-interpreting small variations in fluorescence as necessarily resulting from variations in chlorophyll or phytoplankton biomass.

Your method states no significant temporal drift was observed in the deep values. My understanding is that you cannot use the word significant without doing actual statistically significant tests on the dataset. I think to do some statistical significance tests of variability would add to the confidence in the absence of sensor drift.

Authors' response:

We agree and we consequently added a new table, Table 2, which summarizes, for each bio-profiler, the slope of the linear trend of the mean chlorophyll concentration and b_{bp} evolutions throughout the sensor lives, for the two considered depth layers. We also compared the mean surface value of each parameter with its average drift along the whole sensor life (third column, in %), an expression that we think to be clearer and more relevant to characterize the drift significance. We discussed Table 2 results in the third paragraph of section 2.2.

Modified text:

To evaluate the possibility of temporal drifts in bio-optical sensor responses, we examined the variations of the bio-optical variables in mesopelagic (250-300 m) and deep water (950-1000 m) values, i.e. at depths where little signal was anticipated and most profiles reached steady background values (Figure 2a). The particulate backscattering and, to a lesser extent, the Chl-a fluorescence signals showed spikes which presumably reflect larger particles such as aggregates and zooplankton, motivating our examination of average values over 50 m ranges (250-300 m and 950-1000 m depth layers) for the assessment of temporal drifts. As shown in Figure 2a and quantified in Table 2, for most of their deployment periods all four bio-profilers exhibited no significant temporal drift of these deep values except for bio-profiler #1, for which high and erratic values of Chl-a and b_{bp} began to occur after profile #300 both at depth (Figure 2a) and throughout the water column (Figure 3.1c and e). We consider this to be caused by bio-fouling and do not use this data in any subsequent analysis (this loss of signal fidelity was one of the motivations for including periodic deep profiles in the subsequent three bio-profiler deployments, as a means of retarding fouling). In contrast, the high fluorescence chlorophyll values found in mesopelagic waters from profiles ~#100 to ~#170 along the bio-profiler #1 trajectory appear to be real and to reflect the deep extension of high biomass occurrence at this time, as discussed further below (see also Figure 3.1c). Consequently, this range of profile was not taken into account for the drift calculation in Table 2. Overall, except for the bio-profiler #1, most of the bio-optical sensors showed a slight loss of sensitivity with time, as indicated by the negative slopes of the trend of their responses in the two considered depth layers (Table 2). Over the time course of the bio-optical sensor observations, these sensor drifts were small in comparison to the changes observed for surface bio-optical values, contributing less than 7% to either fluorescence or particulate backscattering. The only exception was the drift for the bio-profiler #2 b_{bp} sensor in the 250-300 m layer, where drift appeared to have been larger (though of course changes at this depth range may also be oceanic) and reached up to 19 % of the low surface b_{bp} values for this bio-profiler.

I think that one sample every 10m is a really problematic bio-optical resolution of the upper water column. I realize that there is naught to be done about it now but I highly recommend that future studies using bio-profilers do not compromise the value of the data set by under sampling the vertical resolution. I think that the implications of the poor sampling resolution of the water column with regards to errors and erroneous measurements needs to be better addressed and discussed further.

On a similar note, I feel a little uncomfortable with the methods of removing bad profiles and the lack of removal of spikes. I appreciate that with such a low 10m vertical resolution data set it was not advisable to apply a box filter to each profile. I think that the method of removing profiles with high mean values in the deeper depth ranges was a really good idea. But this would potentially leave profiles in the data set that had erroneous (not real) spikes in the surface layers. I am not entirely sure what to suggest here but I wonder if one could search for profiles whose mean value in surface depth ranges was above a certain percentile and remove those profiles or at least remove the spikes in those profiles that appeared unrealistic? The problem is that I think a lot of your measured sub surface chlorophyll maxima are not real ecological maxima but merely the result of a spikey data set from instruments that have a high error associated with them (not to mention chlorophyll that is quenching corrected with an even spikier backscattering data set).

Authors' response:

We agree that higher resolution would have been desirable, but was not achievable at the time. We have made every effort to not over-interpret vertical variations owing to the low resolution of the data. Interestingly, the new Figure 2c comparing to the 2 m resolution of the shipboard data measured during KEOPS2 shows that the lower resolution bio-profiler data nonetheless captured the main features and with similar spikiness.

In order to determine if we were observing a spike or a maximum, we estimated the error of the bio-optical

sensors (“noisiness”) by calculating the standard deviation (SD) around the mean value of the bio-optical variables between 500 m and 1000 m depth –where the signal is close to its background value– and calculated the coefficient of variation $SD/MEAN_{500-1000}$ to express it in percent. As bio-profiler #1 did not extend as deep as the following ones, there are no available data at these depths so we also calculated the error of the fluorometer between 250 m and 300 m depth. We estimated the average fluorometer coefficients of variation $SD/MEAN_{Chl-a(250-300)} = 22 \pm 10 \%$ and $SD/MEAN_{Chl-a(500-1000)} = 21 \pm 7 \%$ and the average backscatterometer coefficient of variation $SD/MEAN_{bbp(500-1000)} = 14 \pm 4 \%$. Considering these results, we decided to update the threshold we defined to characterize chlorophyll concentration subsurface maxima, as mentioned below in our first response of section 4.1. We also used the b_{bp} coefficient of variation to less arbitrarily define a threshold b_{bp} surface value above which surface b_{bp} was considered potentially spiked and was not used for the quenching correction (see details just below).

Modified text

6th paragraph in Section 2.2:

Note that to avoid to correct the surface Chl-a fluorescence with a spiked surface b_{bp} value and create a “ b_{bp} spiked” interpolation, we verified before that the b_{bp} surface value did not seem to be spiked, assuming that surface value should not exceed more than $\pm 50\%$ of the b_{bp} value at the depth $d_{F/bbp}$, since within the mixed layer. This threshold was defined after assessing the backscatterometer precision (coefficient of variation of b_{bp} , equal to the standard deviation to mean ratio) between 500 and 1000 m depth of $14 \pm 4\%$ in average. If the surface b_{bp} value was considered as spiked (less than 4% of the daytime b_{bp} profiles, except for bio-profiler #4 for which it reached 9%), the test was done with the second depth value, until a “non-spiked” value was found, and the value was then extrapolated to the surface.

7th paragraph in Section 2.2:

Without the [quenching] correction, on average, more than 70% of the daytime profiles exhibited a subsurface maximum exceeding 60% of the surface value –defined after assessing the fluorometer error (coefficient of variation of standard deviation/mean ratio of the Chl-a concentration) between 250 and 300 m depth and between 500 and 1000 m depth of $22 \pm 10\%$ in average.

Your method of calculating MLD used a density criteria of 0.2 kg m^{-3} relative to the density at 10m (according to Park et al., 1998). I am more familiar with the more recent method of de Boyer Montégut et al. 2004 which uses a density criteria of 10 orders of magnitude less 0.03 kg m^{-3} (and a temperature difference of 0.2 oC). I wonder if this was simply a typo type mistake. If so then I would suggest correcting it and adding the more recent de Boyer Montégut reference. If not, then I think a discussion on why the Park method was chosen and the implications of the different (deeper) MLD it would generate.

Authors’ response:

Yes, it is a mistake that appeared in the proof stage. We corrected the typo type mistake to 0.02 kg m^{-3} . We chose to use the mixed layer depth definition of Park et al. (1998) rather than of de Boyer Montégut et al. (2004) to be more consistent with the other studies of the special issue. However, for each bio-profiler, we compared the evolution of the MLD as we defined it with the evolution of the MLD defined following de Boyer Montégut et al. (2004; depth where density increased by 0.03 kg m^{-3} relative to the density at 10 m) and we observed really similar spatial/temporal variations and amplitudes. In Section 4.1, 6th paragraph, we also compared our results with those obtained using a much larger density criterion (Levitus, 1982; seasonal mixed layer = depth where density increased by 0.125 kg m^{-3} relative to the density at 0 m) and found quite consistent results, as described and discussed.

I don’t think it is necessary to show so many examples of the quenching correction. I would suggest having just three images: without quenching, with quenching and backscattering (not four sets of three images). Then on each image have four pro-files one good example from each bio-profiler.

Authors’ response:

We agree and we revised the figure accordingly.

3. Results

3.1. Coverage of the plume: I really don't see the point of figures 1 d, e and f of the 2014 float trajectories overlaid on 2013 satellite data (the floats were not there at the time so seems odd to overlay a trajectory onto data that was not coincident. I think that it would be better to delete these images. I also think that perhaps a better way to display the coverage of the plume would be to create one composite image of November 2011 to April 2012 (covering the entire time period of the deployment of bio-profiler #1) with the float track overlaid, and one composite image from February 2014 to April 2014 (covering the time period of the deployment of bio-profiler #2, 3 and 4) with the tracks overlaid in different colours (per float) or you could do the different colour dots with time as in fig 3). I also suggest adding the position of the polar front onto the images. If you want to highlight where in the seasonal cycle the floats sampled I would perhaps average the ocean colour in each box to create an annual time series (june to june one for 2011/2012 and one for 2013/2014) with the time periods that the time series was sampled indicated on each graph (this suggestion not necessary to carry out if the authors prefer not to, but may be required if the authors wish to retain the text on seasonal coverage of the bloom).

Authors' response:

Our motivation explaining our choice to show figures d, e and f is that these figures illustrate the spring conditions and give information about the surface chlorophyll concentration distribution prior to the deployment of the bio-profiler #2, #3 and #4. We think that this is important and have kept these figures. We added a couple of sentences to better explain this aspect.

We added the location of the Polar Front as defined in Park et al. (2014), determined from a large dataset of hydrographical data.

Concerning the suggestion for construction of an annual time series, we disagree and prefer to keep showing short multiple images to illustrate synoptic features rather than seasonal ones, because we wish to not smooth away the important mesoscale patterns.

Modified text:

As shown in these images [Figure 1], the 2011 bio-profiler covered the period of highest biomass accumulation, while the 2014 deployments occurred after this seasonal peak, and thus sampled the system during its senescence (to illustrate these prior conditions, Figure 1 also includes biomass distribution images from late 2013, before the launch of the three bio-profilers in early 2014).

3.2. Overview of observed oceanographic properties: Please plot the quenching corrected chlorophyll in all sections (not the quenched chlorophyll). The whole way through this section, when you say colder, fresher, more oxygenated etc. please include the values in parenthesis next to each. E.g. colder (<30C). Also when you describe specific times in the sampling of the float e.g. when it crossed a certain longitude or the PF please always include the approximate profile numbering so one can easily locate the event on the trajectory sections. Please add the PF to all figures a)

Authors' response:

We plotted the quenching corrected chlorophyll and specified the physical values or ranges or the profile numbers to our description throughout this section.

We did not add the Polar Front on each Figure 3.1a, 3.2a, 3.3a and 3.4a because it decreased the clarity of the figures and was not necessary considering that we added the Polar Front location in Figure 1.

4. Discussion

4.1. Do satellite images of surface chlorophyll reflect total inventories?

I think that this is a really important question that needs addressing but I have some major issues with the approach chosen to do so. Firstly, I think your choice of subsurface chlorophyll that is 30% > than surface chlorophyll to define the presence of a subsurface chlorophyll maxima is within the error of the instrument and as such too small a percentage to be able to say with any certainty that there is a "real" subsurface chlorophyll maxima or not. I would increase this to at least 50% and find a reference about the high errors of chlorophyll measurements using fluorometers particularly in regions of relatively low chlorophyll concentrations.

Furthermore there needs to be some kind of investigation to determine how many of these sub surface maxima are simply the result of a noisy spikey data set. Finally, there needs to be an investigation of how any of these

incidences of sub surface chlorophyll maxima coincide with changes in physical water column characteristics. For example how many of the sub surface chlorophyll maxima relate to a changes in density, stratification, MLD etc. This I think will help you to determine the occurrence of real chlorophyll maxima that are representative of ecological phenomena (e.g.: phytoplankton living at preferred depths to promote growth through accessing limiting nutrients, mixing, subduction etc.).

Authors' response:

We initially chose this 30% threshold to be consistent with the study of Guinet et al. (2012). However, we agree with the reviewer's concern. Therefore, using the coefficient of variation of chlorophyll concentration between 250 m and 300 m depth of $22 \pm 10\%$ in average (that we detailed above), for the 4 bio-profilers, we decided to define the "real subsurface maxima" threshold as twice as large as this value and increased it to 60%.

We also added a plot in Figure 4 showing the MLD as a function of the subsurface Chl-a maxima, which revealed a more frequent occurrence of elevated subsurface maxima (for $2.5 \mu\text{g L}^{-1} \leq \text{Chl-a} \leq 5 \mu\text{g L}^{-1}$) when the mixed layer was deep, for bio-profilers #3 and #4. This would suggest that, in these cases, light limitation may not be a major driver of Chl-a vertical profiles. Contrastingly, the quasi-ubiquitous concomitance of subsurface Chl-a maxima for bio-profiler #1 with shallow mixed layer, lower than 50 m, may suggest that above a certain threshold of Chl-a content, self-shading sets up and limits the phytoplankton development in depth.

Very importantly, I think your interpretation of the occurrence of subsurface chlorophyll maxima on 46%, 14%, 45% and 41% (average 37%) of the profiles as being "rare" is very misleading. My interpretation of something occurring ~40% of the time would in fact be rather common. Hopefully taking into account my suggestions above, the occurrence of sub surface chl-a maxima will be reduced. Nonetheless this still needs to be properly addressed in the text to avoid misrepresentation.

Authors' response:

Changing the threshold from 30% to 60% reduced the occurrence of bio-profilers #1 to #4 subsurface chlorophyll maxima to 19%, 4%, 20% and 26% (average 17%), respectively. However, we changed the misleading "rare" expression to the more appropriate "occasional" one.

Secondly, you go on to show that even when there is an occurrence of a subsurface chlorophyll maxima (i.e. when satellite measurements will tend to underestimate total inventories) the effect is minor. I agree that it is important to investigate the implications of such underestimations but I do not agree with how you have gone about it. The effect of a subsurface chlorophyll maxima on measurements that only see the surface is that surface measurements will always be biased towards an underestimate of total inventories and as such will misrepresent spatial distribution of total water column chlorophyll. Your relationship of mean surface (1-50m) chlorophyll to mean water column (0-200m) will on the other hand always tend to have higher mean surface values than mean water column values (even in the presence of sub surface chlorophyll maxima). This is because your water column values are averaged over 200m when chlorophyll often only extends to the base of the mixed layer e.g. ~60m. Your water column mean chl is thus averaging over ~140 m of no chlorophyll and reducing the mean value of water column chlorophyll substantially. I don't think the relationship in figure 5 is able to tell you anything substantial about the effect of subsurface maxima on surface measurements. However, I do understand what it is that you are trying to achieve. My suggestion would be the following:

1: Instead of classifying surface measurements as a static average of the top 50 m (2 e-folding depths for satellite observations) I would suggest that you use a dynamic depth range based on the optical depth, which is relative to the surface chlorophyll concentration. Thus there will be a different optical depth for each profile and the 'surface' chlorophyll can be calculated as the mean of chlorophyll from the surface to the optical depth per profile. This way you are generating a dynamic estimate of the surface chlorophyll which equates to what the satellite would see. Now you want to compare this satellite surface chlorophyll value to a value that is representative of the water column. For reasons mentioned above, I don't believe that the mean from the surface to 200m is an accurate representative of the water column (too much inclusion of no chlorophyll depths in your averaging). Instead I would suggest 2 methods of generating a chlorophyll value representing the water column. The first would be a dynamic chlorophyll value calculated per profile averaged from the surface to the Euphotic depth (0.1% and / or 1% surface light depth) this can be calculated from surface chlorophyll concentrations based on a k_d attenuation coefficient (see also Morel, 1988 for empirical model). If the E_d is much deeper than

the MLD and much deeper than the high chlorophyll surface waters then this may result in similar issues as averaging 0 to 200m. I think you can get around this by comparing integrated values instead of surface and mean. i.e. for surface values multiply the surface chlorophyll concentration by the E_d and for water column do a trapezoid integration of the chlorophyll profile to the E_d .

The second method would be a mean calculated from the surface to the MLD. This method would however exclude any potential sub surface maxima that were below the MLD. In which case I think it would be a good idea to calculate on how many occasions and for which profiles the sub surface maxima was below the MLD. On these occasions it may be necessary to look at the individual profiles and decide on a depth based on the MLD + a threshold (e.g. 20m) to ensure that all viable chlorophyll deeper than the MLD (but still in the E_d) was included in the number representing the water column. I would also do this for surface and mean as well as MLD integrated values as described above). The comparative results between these estimates of surface and water column chlorophyll will I think do a better job of investigating the effect of sub surface maxima on satellite surface estimates off Kerguelen.

Authors' response:

We greatly acknowledge Dr Thomalla for these valuable suggestions and we have spent considerable effort refining our analysis in this section of the paper, including:

1. *Choosing to use only the shallowest measure of chlorophyll to represent a surface value as would be seen by a satellite sensor; based on the following reasoning.*

We don't have PAR measurements, but we however tried to estimate the euphotic depth z_{eu} from the model of Morel and Maritorena (2001) to estimate the first penetration depth $z_{pd} = z_{eu}/4.6$ (Gordon and McCluney, 1975). From Figure 6 of Morel and Maritorena (2001), considering that in our study, for the total data set, surface chlorophyll concentrations do not go lower than 0.4 mg m^{-3} and 0-200 m integrated chlorophyll inventories do not go lower than $40\text{-}50 \text{ mg m}^{-2}$ (Figure 5a; excluding flagged profiles), z_{eu} should not exceed much more than 50 m. Therefore, an upper estimation of z_{pd} , $\max(z_{pd})$, would be $\max(z_{eu})/4.6 \sim 10 \text{ m}$. Considering our 10 m vertical resolution for the bio-optical variables, we only have one value, the surface value, within the [0-10] m depth range, which is consequently the most accurate value than we can use as the z_{pd} value. Thus we replaced the mean 0-50 m chlorophyll concentration by the surface chlorophyll concentration in the revised Figure 5.

2. *Replacing our previous use of an average chlorophyll concentration for the top 0-200 m by the inventory over this depth range that includes all phytoplankton biomass, following the advice of the reviewer.*
3. *Exploring the correlation between these surface chlorophyll concentrations and water column chlorophyll inventories. This new analysis shows that deep chlorophyll maxima are only one source of variance in the correlation of these metrics, with another important (indeed a more dominant) source being varying depths of chlorophyll distributions (without subsurface maxima). We further advanced this discussion by adding a new Figure 6, which compares the 0-200 m inventory to what would be estimated by extending the surface chlorophyll concentration to the depth of the physical mixed layer (i.e. the product of surface chlorophyll \times mixed layer depth (MLD)). This shows that much of the chlorophyll occurs below the mixed layer (though without a subsurface maxima), and that if this is not recognized surface chlorophyll concentrations can strongly underestimate water column inventories. Accordingly, the text of this section has been almost completely rewritten.*

You discuss that your results show that satellite images tend to overestimate the dynamic range of total chlorophyll inventories (which is the opposite of what one would expect from both subsurface chl_a maxima and physiological poc:chl adjustments with decreasing light depth). You go on to say that this effect is relatively small, less than a factor of 2. Again, this may be subjective but my opinion of an error in measurement that doubles or halves your chlorophyll concentration is rather large, in particular when the seasonal range is generally between 0.1 and 3 mg m^{-3} (taken from fig 1).

Authors' response:

This analysis has been reassessed. Following the modifications we did in Figure 5 and the new Figure 6, we revised our interpretation in section 4.1 and modified our conclusions accordingly. Surface Chl-a concentrations seem to reasonably reflect the 0-200 m integrated Chl-a contents, as shown by their relatively linear

relationship, and the relative variance (expressed as newly calculated coefficients of variation) of surface Chl-a concentrations and 0-200 m Chl-a inventories are now presented. These data show that surface and inventory dynamic ranges are very similar, and are now quantified and presented. We refrain from making a judgement about whether the quantified relative variance values are large or small, since that depends on the problem under consideration.

4.2. Do regions of high biomass correlate with oceanographic properties?

Again I think that this is a very relevant investigation that will help inform on the physical controls of enhanced primary production and biomass accumulation but I do not agree with the approach the authors have taken to examine this. The main problem I have is with the selection of the high and moderate chlorophyll boxes which are purely subjective with no concentration thresholds and an overlap of the concentration range of the majority of the data falling into both boxes (i.e. the 0-3 $\mu\text{g l}^{-1}$ chlorophyll range of the moderate box is the same range of concentration providing the majority of the data points in the rich biomass box) as such I don't see how the statistical analysis between moderate and rich biomass boxes can provide robust interpretation. I think that perhaps a better approach would be to use a threshold to characterize high (e.g. $>3 \mu\text{g l}^{-1}$), low (e.g. $<1 \mu\text{g l}^{-1}$) and moderate (e.g. $1-3 \mu\text{g l}^{-1}$) chlorophyll profiles. For this approach I think it would be better to use water column chlorophyll rather than surface chlorophyll (since you have depth profiles and don't have to rely on restricted surface measurements, as with satellites, I suggest you make the most of the data at hand).

Authors' response:

We understand your concerns and we adopted your suggested approach: 1) we replaced the surface chlorophyll concentration by the 0-200 m integrated chlorophyll inventories and 2) we used a threshold, $200 \mu\text{g L}^{-1}$, and only represented values above this threshold for the rich areas (i.e. that reach very high Chl-a concentrations) and values below this threshold for the poor to moderate areas and modified accordingly the Figure 7 (old Figure 6).

In your correlation with physical properties I would include a stratification index and date (to temp, salinity and density).

Authors' response:

We now include examination of the maximum Brunt-Väisälä frequency squared (N^2) to investigate the influence of the stratification. Based on this metric, stratification seems to play a minor role since no clear relationship was found with the 0-200 m integrated Chl-a distributions.

I would also consider an additional parameter such as bathymetry or distance from shelf in an attempt to determine the regional proximity of the float as a driver of high chlorophyll. This combination of correlations may assist in determining both regional and seasonal drivers of chlorophyll together with light (MLD) and potential Fe sources? (depending on the results you may want to only present the high and low correlations and leave out the moderate ones)

Authors' response:

We considered an additional parameter to take into account the regional proximity of the float to the bathymetry as a driver of high chlorophyll. However, instead of considering the geographical distance from the bathymetry, we used a Lagrangian approach. Following d'Ovidio et al. (2014, this volume), we computed the 'water age' and 'origin'. They represent respectively how long before the bio-profiler sampling a water parcel has left the Kerguelen Plateau (defined as the 700 m isobath) and at which latitude the parcel has left the plateau. The Kerguelen Plateau is likely to be a source of iron, because the shallow bathymetry enhances iron-rich sediments resuspension. The main advantage of this approach is that it takes into account of the different pathways water parcels can take to reach a given geographical distance. For example, with this method it is possible to discriminate between water parcels that are close to the plateau, but have spent long time recirculating away from it and the ones that have recently left the shallow bathymetry and are more likely to be iron-enriched. By comparing these diagnostics with the [0-200] m integrated chlorophyll, we found (as shown in new Figure 8) that high chlorophyll data corresponded to water masses that had recently (0-40 days) left the Kerguelen Plateau, with a preference for the Northern part of the Plateau.

When discussing the relationship between MLD and chlorophyll with respect to light limitation please refer to the paper by Joubert et al., 2014 in Biogeosciences Discussions, which presents similar results (but for NCP) and discusses the complex role of MLD in adjusting both light and Fe in driving the observed relationship between low chl when MLD is deep (light limitation) but both high and low chlorophyll when MLD's are shallow (shallow mixed layers improve light regions but can drive Fe limitation by reducing the size of the accessible reservoir).

Authors' response:

We agree and added a sentence referring to the study of Joubert et al. (2014) at the end of Section 4.2.

Modified text:

Importantly, our observations emphasize that chlorophyll distributions do not track the shoaling of mixed layer depth on seasonal or weather timescales, and thus that MLD variability is unlikely to show simple relationships to biomass accumulation. This point has also been emphasized in terms of competing effects of light and Fe limitation responses to MLD variability (Joubert et al., 2014), for waters where vertical Fe supply is dominant (rather than the horizontal dominance of supply studied here).

It is not clear to me why the chlorophyll data is correlated with oxygen saturation. Surely oxygen saturation states are driven by the biology and not the other way around, hence an existing correlation can be expected as a result of biological production and not as a driver of enhanced production. I would personally remove the correlation with oxygen saturation from this section.

Authors' response:

We prefer to keep this subplot. It is true that the oxygen supersaturation observed for the high biomass waters is biologically generated, but for the low biomass waters the presence of oxygen undersaturation could indicate the influence of mixing with subsurface waters. The revised text makes it clear that both issues are addressed by the figure.

Modified text:

This characteristic is also observed between integrated Chl-a and mean surface oxygen saturation ($O_{2\text{ sat}}$, Figure 7f), for which the high $O_{2\text{ sat}}$ states (reaching 10%) indicate oxygen production in these high biomass waters (since these values exceeding expected from processes such as warming or bubble injection; Shadwick et al., 2014). Relatively high biomass was also encountered in waters with extreme T-S properties (the warmest and freshest observed) in the vicinity of the Gallieni Spur by bio-profiler #4 (black symbols in Figure 7). Thus, there was not a unique class of waters with high biomass. This perspective is further reinforced by the lack of any clear relationships between chlorophyll inventories and local water column properties for regions of moderate biomass, including versus mixed layer depth and the intensity of stratification as represented by the Brunt-Väisälä frequency (Figure 7, right column). These low biomass waters also exhibited lower $O_{2\text{ sat}}$ states (95-103%) than those of rich biomass areas. The under-saturated oxygen levels reflect either strong local respiration or the supply of low oxygen waters from below, with these processes difficult to distinguish (except for specific portions of the bio-profiler #4 trajectory where time series within constant physical property layers were obtained, as discussed in section 4.3).

4.3. Can the fate of surface enrichments in biomass be determined.

I think this heading should be refined to include: And if so what is the percentage of biological production being exported?

Authors' response:

We modified the heading accordingly.

I really liked this section, I thought the research presented a novel use of bio-profiling data and was able to

demonstrate a robust method of determining the amount of production sequestered from the besurface layers.

One area I need to query is figure 7c. In the text it states that surface mixed layer chlorophyll concentrations declined from the start of the lagrangian study at $1.5 \mu\text{g l}^{-1}$ to $< 1 \mu\text{g l}^{-1}$. This is not clear to me from section 3.4c nor fig 7e. In fact in figure 7e, the opposite trend in chlorophyll concentration appears to exist from my analysis of figure 7e. According to figure 7a, the coloured dots mark the time trajectory of the float starting with blue and ending in red. A cursory look at figure 7e appears to me as though there are more blue profiles with lower surface mixed layer chlorophyll concentrations (at the beginning of the transect ($< 1 \mu\text{g l}^{-1}$) while there are more red profiles with higher mixed layer chlorophyll concentrations ($> 1 \mu\text{g l}^{-1}$) towards the end of the transect. This is opposite to the trend you describe.

Authors' response:

As suggested by the second reviewer, to improve the clarity of Figures 9e and 9f (old Figures 7e and 7f), we divided the 90 profiles acquired over 28 days in 4 weekly plots (~23 profiles), in an similar approach to Figure 2 of Perry et al. (2008). We detailed more precisely the evolution of the 3 variables shown in Figures 9e, 9f and 9g, as written below.

Modified text:

At the start of this period (blue lines subset in Figure 9e), chlorophyll profiles showed moderate to high surface and subsurface layer levels, well above HNLC background values, with some profiles exhibiting subsurface maxima reaching up to $1.5 \mu\text{g L}^{-1}$ between 50-70 m depth and up to $1 \mu\text{g L}^{-1}$ around 120 m depth. Both the surface constant Chl-a layer and the subsurface “chlorocline” layer (by analogy to thermocline or halocline, “chlorocline” is defined here as the depth range with the highest chlorophyll concentration gradient) were thick, equal to ~ 80 m and ~50 m, respectively. The origin of the smaller and variable subsurface maxima seen in some profiles in Figure 9e is uncertain. One possibility is that they are remnants of the high surface chlorophyll biomass observed just prior to the eddy entrainment (visible in Figure 3.4c and the “bloom 2013” animation in the supplementary material), that had been carried to depth by particle settling or by subduction of the denser, saltier, and slightly cooler water associated with that high biomass. Associated b_{bp} profiles showed similar large variations with strong local maxima correlated to local Chl-a maxima (blue lines subset in Figure 9f). The strong variability of the Chl-a/ b_{bp} profiles over the first 100 m suggests possible changes in the composition of the particulate assemblage (blue lines subset in Figure 9g).

During the Lagrangian eddy entrainment period, the surface mixed layer chlorophyll levels declined further from $1.5 \mu\text{g L}^{-1}$ to $\sim 1 \mu\text{g L}^{-1}$ (Figure 3.4c and 9e). Since the constant chlorophyll surface layer shallowed progressively with time, this Chl-a decrease did not result from the possible effect of dilution by mixed layer deepening (i.e. entrainment). Furthermore, the chlorocline content decreased briefly before re-increasing progressively in its upper part, and then its deeper part. In parallel, b_{bp} and Chl-a/ b_{bp} profiles became tighter and tighter (light blue to orange profiles in Figures 9f and 9g) before re-exhibiting larger variations (red profiles). These results suggest the possibility of some chlorophyll conversion to non-fluorescent material, or its removal by export to depth or by local respiration or both, throughout the eddy entrainment. They may also of course partly reflect small spatial variations in the structure of the biomass distributions.

Technical corrections

Figures

Figure 1: Include the following in the legend: which chlorophyll product, km resolution and period averaged. Units $\mu\text{g l}^{-1}$ not mg/m^3 . Units are sometimes touching the numbers on the legend Latitude is touching the numbers on the y axis Delete figures d, e and f. Add PF to figures Refer to text above to alternative suggestions for this figure.

Authors' response:

We modified the legend, the units and added the Polar Front location (from Park et al., 2014) as suggested. We chose to keep figures d, e and f as they illustrate the spring conditions and give information about the surface chlorophyll concentration distribution prior to the deployment of the bio-profiler #2, #3 and #4. As mentioned before, we would prefer to keep showing short composite images to show synoptic features rather than seasonal

ones and avoid to smooth the patterns. Finally, we used 3 different colors to represent the trajectory of each of the 3 bio-profilers deployed in summer 2014 to improve the clarity.

Figure 2: Refer to text above for suggested reduction of size of figure 2b.

Authors' response:

We revised this figure accordingly to both reviewers' suggestions.

Figure 3: Label figure 3.2, 3.2, 3.3, 3.4. Add PF to all figures 1a Plot quenching corrected chlorophyll (not quenched chlorophyll) I really to not think you can use your chosen colorbar for temperature, salinity and dissolved oxygen. I really don't think you cant have the same colours for low and high concentrations. It is confusing and does not justly represent your data. Please adjust to let the colours all scale in one direction only. Labels 1a) and 1b) are not aligned. I personally think that units of chlorophyll should be $\mu\text{g l}^{-1}$ with a lower case l and not an upper case L. Figure 1e in legend is particulate backscattering (bbp) not backscatter.

Authors' response:

Most of these changes have been done. We did not add the Polar Front on each Figure 3.1a, 3.2a, 3.3a and 3.4a because we believe that it was decreasing the clarity of the figure and the Polar Front location is already reported in Figure 1. We cannot label figures 3.1, 3.2 etc because it is not an allowed format in Biogeosciences. We also contoured the 700 m isobath with a red line as a support for the discussion of the water mass ages (new Figure 8). Finally, we added some important topographic features: Gallieni Spur (GS), Kerguelen Plateau (KP), Kerguelen Island (KI), and Heard Island (HI).

Figure 4: coloured dots identifying bio-profilers need to be solid circles not open circles

Authors' response:

We now distinguish the night, day and flagged day profiles (see the definition of these latter in the Method section and in the Figure 2b caption) by stars, open circles, and open squares, respectively. We increased the size of the symbols to improve the clarity of the figure.

Figure 6: Rich and moderate biomass region headers need to start with uppercase. Units kg m^{-3} not kg/m^3

Authors' response:

We did these corrections.

Text

17415 Line 6: refers to 'conditions that favor phytoplankton accumulation'. I think a better word would be favoring phytoplankton growth (accumulation in this context (to me) implies concentration of phytoplankton by hydrography rather than conditions favoring growth rates and increased phytoplankton biomass.

Authors' response:

As mentioned before, we used the term "accumulation" because what was measured was the net budget, i.e = growth - loss.

17416 Line 12: I would put (Fe) in brackets after the first time you use the word iron so that they are interchangeable.

Authors' response:

We did the modification.

Line 19: carbon (C)

Authors' response:

We defined the symbol C.

Line 20: Full stop after references. New sentence: These studies have revealed

Authors' response:

We divide the sentence in two, as suggested.

17417 Line 12: factors are also likely Line 21: high winds and strong currents do not preclude the use of alternative profilers (profiling gliders for example are deployed and retrieved in rough southern ocean seas). Maybe rather say that the currents and seas compromise the recovery such that bio-profilers were considered a suitable choice of platform?

Authors' response:

We modified the sentence

Modified text:

"Given the extent of the Kerguelen biomass plume (> 1000 km; Mongin et al., 2009), the remoteness from ports, and the generally rough sea states, the use of autonomous platforms is arguably the only affordable way to survey this region".

17418 Line 2: you do not measure stratification anywhere in your research. Better to include MLD here and even better to include stratification in your statistical correlation and then leave both stratification and MLD in the question.

Authors' response:

We agree and included stratification in our statistical correlation (old Figure 6, new Figure 7).

Line 20 (add wavelength of scattering measurement).

Authors' response:

We added it (700 nm).

17419 Line 19: full stop after variations. New sentence After several weeks Line 23: to be evaluated and corrected and thus to avoid

Authors' response:

We did the corrections accordingly.

17420 Line 13: profiling float (no s) Line 14: Temperature (T) and salinity (S) in parenthesis Line 15: suggests that Line 17: give time frame of shorter deployment in parenthesis Line 19: and require no further assessment or correction. Line 24: showing (not and showing) Line 27: To evaluate the possibility of temporal sensor drifts in bio-optical variables, we examined...

Authors' response:

We corrected as suggested.

17421 Line 2: delete second comma Line 7: don't use the word significant without a significance test Line 20: Fluorescence signals were corrected for daytime quenching Line 23: delete second comma

Authors' response:

We did the necessary corrections.

17422 Line 1: This method assumes Line 2: replace not stratified with constant. Insert the method of defining MLD here the first time you mention density defined mixed layer rather than in the next sentence. Line 5/6 what do you mean by sub surface portions? Please be more specific

Authors' response:

We did the necessary corrections. We replaced "subsurface portions" by "deeper half".

Line 17: there is no figure 6f? delete below.

Authors' response:

We did the necessary correction, considering the addition of the two new figures.

17423 Line 6: delete and

Line 13: resolution (no s)

Line 16: delete the

Authors' response:

As it concerns temporal and spatial resolutions, we think that an “s” is necessary. We did the other corrections as suggested.

17425 Line 8: replace a huge amount with a large number. (I would delete each one provides more than most oceanographic voyages) so that the sentence reads: Profilers return a large number of water column data making visualization at the scale of individual profiles only (delete is) possible for targeted issues. (full stop delete and) new sentence. The simplest first order....

Authors' response:

These sentences were modified as suggested.

Line 11: delete as

17427 Line 8: persistent high Line 19: delete Then, rather As its trajectory...

Line 22: delete the words and correlated

Authors' response:

We corrected as suggested.

17428 Line 10: delete as. After cloud cover full stop. New sentence: Instead...

Line 23: delete the last the

Authors' response:

Suggested corrections were done.

17429 Line 1: averaged from the surface down to 200m (otherwise not clear if you started at 50m)

Line 20: pick either allow or achieve not both

References cited in authors' responses

de Boyer Montégut, C., Madec, G., Fischer, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: An examination of profile data and a profile-based climatology, *Journal of Geophysical Research*, 109, C12003, doi:10.1029/2004JC002378, 2004.

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We would like to greatly thank the reviewer for the time he/she granted to this review. We gratefully acknowledge his/her in-depth reading and thoughtful comments on our manuscript. We carefully considered the provided feedback and criticism in preparing our revision. Please find below our response. We have made major efforts to improve the paper, including:

- 1. Addition of comparison to shipboard chlorophyll data from KEOPS2*
- 2. Expansion of the description and details regarding the correction for quenching (noting that no conclusions of the paper depend on this correction, because use of only the night time data yields the same outcomes).*
- 3. Addition of Lagrangian trajectory maps and analysis to relate chlorophyll inventories to water parcel histories relative to the Kerguelen plateau*
- 4. Expanded analysis of bio-profiler chlorophyll observations, using water column inventories rather than concentrations (as recommended by both reviewers).*

We believe the paper is now greatly improved and that the conclusions are well qualified.

Anonymous Referee #2

Received and published: 15 January 2015

General comments

The study by Grenier et al. presents the analysis of data collected by four bio-optical profiling floats in the Kerguelen region. The general goal of the study is to gain insights into the role of water-column physical properties in controlling the distribution and dynamics of biological properties, especially phytoplankton biomass. Three specific questions are addressed: i) Do ocean color satellites provide an accurate view of the dynamics of the water-column phytoplankton biomass? ii) Are the physical and biological properties correlated, where and why? iii) What is the fate of the organic matter produced in surface waters and can carbon export be (roughly) estimated from bio-profiler measurements? The study region and the scientific questions are sound, exciting and very relevant to BG. The authors make use of innovative, appropriate tools to address their objectives. Nevertheless, the methodology is unclear on several occasions and the interpretation of the results need to be improved and strengthened. This is especially true for questions i) and ii) (sections 4.1 and 4.2) where the methodology need to be reconsidered (see my comments below). Therefore I recommend substantial revision before the paper can be accepted for publication.

Specific comments

Method (sections 2.1 and 2.2):

- Throughout the text “backscatter” should be corrected to “particulate backscattering” or ideally “particulate backscattering coefficient”.

Authors’ response:

We corrected the term as suggested throughout the paper, and added detail on how this value was calculated from the sensor measurements.

- p. 17418: It might be desirable for readers to provide a justification of the choice of the sensors, for example O2 for biological production and respiration, chlorophyll fluorescence for chlorophyll concentration as an indicator of phytoplankton biomass, particulate backscattering as a proxy of particle load or POC, etc.

Authors’ response:

We added the justification of the choice of the sensors.

Modified text:

Chlorophyll-a fluorescence is a useful proxy for chlorophyll-a concentration and standing stocks of phytoplankton biomass (Falkowski and Kiefer, 1985; Huot et al., 2007). Particulate backscattering provides a good proxy for particulate organic carbon (Stramski et al. 2008; Cetinić et al, 2013).

- p. 17419 l. 11-12 “oxygen, phytoplankton fluorescence, and particle backscatter were sampled at 10 decibar intervals”: Why such a coarse depth resolution for the biological parameters, especially when one of your goals is to study biological subsurface maxima? As indicated in section 2.2 p. 17422 l. 15-16 “the low 10 m vertical resolution of the observations... so we have to use the unfiltered observations”. How do you determine whether you are observing a spike or a maximum?

Authors’ response:

We agree that higher resolution would have been desirable, but was not achievable at the time. We have made every effort to not over-interpret vertical variations owing to the low resolution of the data. Interestingly, as discussed in more detail in our response to Reviewer1, our new Figure 2c comparing to the 2 m resolution of the shipboard data measured during KEOPS2 shows that the lower resolution bio-profiler data nonetheless captured the main features and with similar spikiness.

In order to determine if we are observing a spike or a maximum, we estimated the error of the bio-optical sensors (“noisiness”) by calculating the standard deviation (SD) around the mean value of the bio-optical variables between 500 m and 1000 m depth –where the signal is close to its background value– and calculated the coefficient of variation $SD/MEAN_{500-1000}$ ratio to express it in percent. As bio-profiler #1 did not extend as deep as the following ones, there are no available data as these depths so we also calculated the error of the fluorometer between 250 m and 300 m depth. We estimated the average fluorometer error to $SD/MEAN_{Chl-a(250-300)} = 22 \pm 10 \%$ and $SD/MEAN_{Chl-a(500-1000)} = 21 \pm 7 \%$ and the average backscatterometer error to $SD/MEAN_{bbp(500-1000)} = 14 \pm 4 \%$. Considering these results, we decided to update the threshold we defined to characterize chlorophyll concentration subsurface maxima. We chose a threshold twice as large as the fluorometer error and increased it to 60% (instead of 30%, which was initially chosen to be consistent with Guinet et al. (2012) study).

- Fig. 2a: I recommend using a different y-axis scale for bio-profiler 1. As is, it is almost impossible to say anything about the other 3 profilers.

Authors’ response:

Accordingly to the reviewer’s suggestion, for the sake of clarity, we added a secondary y-axis in Figure 2a associated to the bio-profiler #1 chlorophyll concentration. To improve the assessment of the drift, we added a new table, Table 2, which characterizes, for each bio-profiler, the slope of the linear trend of the mean chlorophyll concentration and b_{bp} evolutions throughout the sensor lives, for the two considered depth layers ([250-300] m and [950-1000] m). We also compared the mean surface value of each parameter with its average drift along the whole sensor life (third column, in %), an expression that we think to be clearer and more relevant to characterize the drift significance. We used the revisions done for Figure 2a and the Table 2 results to strengthen our discussion about the instrument drifts.

- Fig. 2b: Too many profiles are shown. The process you are trying to illustrate will be more obvious if you select one or two examples with a night profile, day profile and quenching-corrected day profile.

Authors’ response:

We revised this figure accordingly to both reviewers’ suggestions. We now only show 3 subplots (vertical profiles of chlorophyll concentration before the quenching correction, after the correction, and the associated particulate backscattering profiles), with one profile per bio-profiler.

- The quenching correction method should be presented in a clearer (maybe more detailed) manner. This is particularly important because the paper which the method is based on has not reached the publication stage (it is cited as Sackmann et al., 2008, Biogeosciences Discussion). In the presentation of the method you say “Below the depth of daytime quenching we determined the fluorescence to backscattering ratio (over the depth range where it was constant), and multiplied this ratio by the

backscattering signal to extrapolate the fluorescence signal to the surface” (p. 17421 l. 27-29 and p. 17422 l. 1). I think the sentence is misleading as it gives the impression that the depth at which quenching starts to occur is known. It is unclear to me how the authors are able to determine whether the particulate backscattering to chlorophyll fluorescence ratio varies because of the quenching effect or because of changes in the nature of the particle assemblage. Also, does the layer of constant ratio must have a minimum thickness? I am assuming this is all based on the idea that the backscattering and chlorophyll properties should be uniformly distributed within the mixed layer. But then why not simply extrapolate the chlorophyll fluorescence value taken at the base of the mixed layer up to the surface? This would circumvent the hypothesis of a constant backscattering to chlorophyll fluorescence ratio and not introduce noise into the chlorophyll fluorescence data (as indicated by the authors p. 17422 l. 14).

Authors’ response:

First we note that none of the conclusions of our paper depend on the details of our quenching correction, because all of the conclusions hold if only the night time data is used. Nonetheless, we have made great efforts to further develop, describe, and quantify our approach to correcting for quenching. In doing this, we thought about your concern for a long time before deciding which method we thought the best to apply. We finally chose to keep the method suggested by Sackmann et al. (2008). However, we did several modifications that, we hope, give more robustness to our approach. First, for several chlorophyll results shown in the figures of the paper (Figures 4, 5 and 7), we distinguished night data from daytime data. We also flagged some of the quenching corrected daytime profiles still exhibiting decreasing surface concentrations leading to values lower than the lowest surface chlorophyll concentration of the night profiles, for which quenching might have been under-corrected (see the details in the caption of Figure 2b). Overall, we observe similar distributions for night and corrected day profiles, which converge consequently toward similar conclusions. The features and statistics that characterized the fluorescence profiles of our study are also consistent with the results of Guiney et al. (2012) and Biermann et al. (2015), who used different quenching correction method.

Furthermore, we believe that testing this method contributes to active discussion of the best way to use daylight Chl-a fluorescence data obtained from platforms which may not have as good night time coverage as our floats (such as sensors deployed on seals, on standard ARGO 10- day profile interval missions, or on float missions that target co-measurement with daytime satellite ocean colour observations). Finally, the assumption of a constant chlorophyll concentration within the mixed layer may not be less strong than the method proposed here, based on the particulate backscattering, considering the small chlorophyll concentration variations observed in night profiles within the mixed layer (see Figure 2b). Please refer to the modified text below to get the details we added about the correction method and the tests we did to avoid to use a spiked surface particulate backscattering value to correct our fluorescence profiles.

Modified text (in section 2.2):

Fluorescence signals were also corrected for daytime quenching. This effect, which derives from the photo-inhibition of phytoplankton by an excess of light (maximum at midday), decreases surface fluorescence (Falkowski and Kolber, 1995; Kiefer, 1973) and, if uncorrected, can produce a false impression of subsurface maxima in fluorescence derived chlorophyll profiles. We explain this correction and its evaluation in considerable detail in the following paragraphs, but note that none of the conclusions of the paper depend on these corrections because the same overall results are obtained if we use only Chl-a fluorescence signals collected at night. Our purpose in detailing the correction is to contribute to active discussion of the best way to use daylight Chl-a fluorescence data obtained from platforms which may not have as good night time coverage as our floats (such as sensors deployed on seals, on standard ARGO 10- day profile interval missions, or on float missions that target co-measurement with daytime satellite ocean colour observations).

We defined the daytime profiles, potentially affected by quenching, as profiles acquired between one hour after local sunrise time and one hour after local sunset time, to allow for dark acclimation since quenching effect could still persist after sunset (Sackmann et al., 2008). Daytime profiles from

the four bio-profilers are shown to illustrate this effect (continuous lines in Figure 2b, left panel). To correct this bias, we applied the method of Sackmann et al. (2008), which uses the particulate backscattering signal as a relative reference. For the sake of consistency with the other studies of this issue, we defined the mixed layer depth, MLD, as the depth where density increased by 0.02 kg m⁻³ relative to the density at 10 m (Park et al., 1998). Within the deeper half of the mixed layer (targeted to be below the depth of daytime quenching), we determined a mean value of the (relatively constant, see below) Chl-a fluorescence to b_{bp} ratio (at depth defined as $d_{F/b_{bp}}$) and multiplied this ratio by the b_{bp} signal at this depth to retrieve the Chl-a fluorescence. Then, we multiplied this same ratio by the surface b_{bp} value to estimate unquenched surface Chl-a fluorescence, and interpolated between these two depths to obtain the unquenched Chl-a fluorescence profile. This assumes that phytoplankton populations were not stratified within the density defined mixed layer. This works particularly well for deep mixed layers (>50 m) which exhibit relatively constant Chl-a fluorescence/ b_{bp} ratios (to within ~10%) in their deeper half. In less than 3% of the daytime profiles, in average, we could not identify a region of uniform Chl-a fluorescence/ b_{bp} and apply the quenching correction; consequently, these profiles were not used further.

The greater spikiness of the b_{bp} profiles in comparison to those of fluorescence (as illustrated in Figure 2b, right panels) means that this quenching correction introduces some noise into the daytime chlorophyll estimates. In principle, this could be filtered or smoothed, but the low 10 m vertical resolution of the observations made this rather uncertain and so we have used the unfiltered observations throughout this paper (except in Figure 9f below where we show median-filtered particulate backscattering profiles for the sake of visual clarity). Note that to avoid to correct the surface Chl-a fluorescence with a spiked surface b_{bp} value and create a “ b_{bp} spiked” interpolation, we verified before that the b_{bp} surface value did not seem to be spiked, assuming that surface value should not exceed more than $\pm 50\%$ of the b_{bp} value at the depth $d_{F/b_{bp}}$, since within the mixed layer. This threshold was defined after assessing the backscatterometer precision (coefficient of variation of b_{bp} , equal to the standard deviation to mean ratio) between 500 and 1000 m depth of $14 \pm 4\%$ in average. If the surface b_{bp} value was considered as spiked (less than 4% of the daytime b_{bp} profiles, except for bio-profiler #4 for which it reached 9%), the test was done with the second depth value, until a “non-spiked” value was found, and the value was then extrapolated to the surface.

Space/time evolution of the biomass plume and sampling by the profilers (section 3.1):

Based on section 3.1 and Fig. 1, I found the space/time evolution of the Kerguelen bloom quite difficult to follow. I recommend several points to be addressed to make this point clearer.

- I suggest the authors provide a general description of the bloom. When/where does the bloom typically start, propagate and decline (if, of course, a recurrent pattern can be observed)? I assume the profilers were deployed to sample specific features of the bloom. Which ones? Please specify how the date and location of profiler deployment were selected.

Authors' response:

General descriptions of the bloom have been presented elsewhere and referenced in the introduction (Blain et al., 2007, Mongin et al., 2009; Trull et al., 2014), and are available in the supplementary material as animations of satellite surface chlorophyll images. As also described in the introduction, the point of our paper is to examine the mesoscale structures, which cannot be presented in a general description of the bloom. The profilers were deployed at locations thought likely to sample a wide range of these mesoscale structures, both north and south of the Polar Front.

- I don't quite understand the authors' selection of the satellite ocean color composites in Fig. 1. Why showing images from year 2013 when there were no profiler deployed in the region? In addition it is almost impossible to distinguish the trajectory of profilers 2, 3 and 4 in panels g, h and i. You may want to show in grey scale the dates of data acquisition for each profiler. Alternatively you may have a few selected composites showing the start, end and intermediate stages of acquisition of the profilers. You may also want to use identical color scales for all panels. This will simplify the reading

of both the text and figures. Finally, adding to the maps important features you frequently refer to in the text may also help, e.g. Polar Front, Gallieni Spur...

Authors' response:

We showed images from year 2013 to illustrate the spring conditions and give information about the surface chlorophyll concentration distribution prior to the deployment of the bio-profiler #2, #3 and #4 around the end of January 2014. We improved the representation and distinction of the trajectories of the 3 bio-profilers using 3 different colours. We also used identical colour scales for all panels to more easily observe the monthly and seasonal differences of surface chlorophyll distribution. Finally, we added the Polar Front location (from Park et al., 2014). Important features such as the Gallieni Spur and the Kerguelen Plateau have been added on the maps in Figure 3 rather than in Figure 1, to not overload too much Figure 1.

- Table 1 should provide the date of the last profile acquired by each profiler. Although essential this information is only found below the x-axes of Fig. 3 (panels 1-4).

Authors' response:

We added this information in Table 1, as suggested.

Water-column chlorophyll content versus surface chlorophyll concentration (section 4.1):

I am not convinced by, or at least don't understand, the authors method for assessing whether satellite-derived surface chlorophyll values reflect the entire water-column chlorophyll content.

- How do you define a subsurface chlorophyll maximum? Fig. 4 right column shows that some of the maxima are located at a depth of 5 or 10 m. I would call these "surface maxima" and they are unlikely to be missed by ocean color satellites.

Authors' response:

The reviewer's concern helped us to clarify this issue for ourselves, and we have significantly modified our calculation and our discussion of these issues:

- 1. We estimated the noisiness of the fluorometer measurements using deep ocean data (see the details in our response to reviewer 1) and accordingly changed our criterion for subsurface maxima to 60% to ensure that the detected features were not noise.*
- 2. We note that the presence of shallow subsurface maxima are not that important to the issue of potential satellite underestimations of water column chlorophyll inventories, rather the statistics in Table 3 on their occurrence are focused on illustrating the importance of the quenching correction.*
- 3. For the issue of the potential satellite underestimations we now focus on only those subsurface maxima that occur below the mixed layer, as shown in the revised Figure 4.*

I don't understand either the criterion of more than 30 percent or 100 percent for identifying how "large" a subsurface maximum is. If your criterion is basically to compare any single chlorophyll value to the surface value (i.e. first data point) then this may be extremely sensitive to fluorometer noise.

- The interpretation that subsurface maxima are "relatively rare and localized" features (p. 17428 l. 12) is not obvious to me from Fig. 4 and Table 2: Subsurface maxima show up throughout most of the study region and their occurrence exceeds 40 percent except for profiler 2.

Authors' response:

As mentioned above, the assessment of the bio-optical sensor error allowed us to update the threshold above which subsurface chlorophyll concentrations are considered as real features. This update reduced the occurrence of bio-profilers #1 to #4 subsurface chlorophyll maxima to 19%, 4%, 20% and 26% (average 17%), respectively. However, we changed the misleading "rare" expression to the more appropriate "occasional" one. Considering the spatial distribution of these subsurface maxima

(Figure 4) and the relationship between water ages and origins and chlorophyll concentration (new Figure 8), the map of their locations in Figure 4 shows that these features are localized.

- I am not sure of the purpose of the comparison of the mean chlorophyll concentrations calculated over the 0-50 m layer vs. the 0-200 m layer (Fig. 5). First, the 0-50 m layer is not representative of the surface layer typically seen by ocean color satellites. I suggest using as a limit the first penetration depth (I realize you don't have PAR measurements but it may be estimated using the chlorophyll profiles) or a depth of 10 m which may be more appropriate for high chlorophyll waters.

Authors' response:

We agree with this, and have accordingly changed to using the surface chlorophyll values (10 m), because while we do not have PAR measurements, it is clear that the penetration was much shallower than 50 m. Using the model of Morel and Maritorena (2001; their Figure 6), and our surface chlorophyll concentrations which do not go lower than 0.4 mg m^{-3} with 0-200 m integrated chlorophyll inventories that do not go lower than $40\text{--}50 \text{ mg m}^{-2}$ (Figure 5a; excluding flagged profiles), the euphotic depth z_{eu} should not exceed much more than 50 m. Therefore, an upper estimation of the penetration depth z_{pd} would not exceed $\max(z_{eu})/4.6$ (Gordon and McCluney, 1975) or $\sim 10 \text{ m}$. Considering our 10 m vertical resolution for the bio-optical variables, we only have one value, the surface value, within the [0-10] m depth range, which is consequently the most accurate value than we can use as the z_{pd} value.

Second, the chlorophyll concentration averaged over the 0-200 m layer does not bring much information on the total phytoplankton biomass nor on its vertical distribution. Instead I recommend using the chlorophyll concentration integrated within the water column (using as a limit either the 200 m depth or the euphotic layer depth).

Authors' response:

We agree and we replaced our use of the 0-200 m chlorophyll average concentration by the 0-200 m integrated chlorophyll amount.

- p. 17430 l. 2-8 "As shown in Fig. 5, ... the surface estimates are consistently higher than the total ones for chlorophyll concentrations higher than $1 \mu\text{g L}^{-1}$. This suggests that variations in surface layer mixing, and the associated impact on the vertical distributions of chlorophyll, contribute insignificant bias where chlorophyll was low ($<1 \mu\text{g L}^{-1}$) but lead to over-estimation where chlorophyll was moderate to high ($>1 \mu\text{g L}^{-1}$). I think this does not show much but simply results from the averaging over the 0-200 m layer which artificially decreases your index of the water column biomass.

- p. 17430 l. 8-10 "satellite images tend to overestimate the dynamic range of total chlorophyll inventories, although this effect is relatively small, less than a factor of two even for surface chlorophyll concentrations as high as $10 \mu\text{g L}^{-1}$. Given that our bioprofilers did not sample close to the plateau during the early summer peak in biomass as seen in satellite images, it is possible that there could be greater biases under these conditions": I think that if you plot the integrated content instead of the mean concentration a different picture will emerge. Typically surface data from ocean color satellite will fail at representing the dynamics of phytoplankton biomass in relatively low chlorophyll regimes where there is a subsurface or a deep maximum. In such regimes the satellite will underestimate the water column integrated biomass.

Authors' response:

Following your suggested use of water column inventories rather than concentrations, all this paragraph has changed in the revised version, as written below.

Modified text:

Subsurface chlorophyll maxima beyond the reach of satellite imagery can be thought of as a specific class of the wide range of possible chlorophyll distributions (such as varying thicknesses of relatively constant near-surface biomass layers, or changes in the rate of decrease of biomass with depth) that could introduce bias between surface concentration and water column inventory perspectives. To gain

perspective on the overall importance of these possibilities, we compared surface chlorophyll concentrations measured by the profilers (using the shallowest ~10 m depth observation since this was reliably within both the 1/e satellite ocean colour penetration depth and the mixed layer) with their column inventories calculated from all observations in the top 200 m (since chlorophyll distributions generally reduced to background values below this depth). These comparisons, shown in Figure 5a (left column), display reasonably linear relationships over almost the entire range of both night and daytime observations. This was especially true for bio-profilers #1 and #3 (correlation coefficients $r^2 = [0.60-0.85]$), which include high chlorophyll values (greater than 2 mg m^{-3} for the surface concentration and greater than 160 mg m^{-2} for the 0-200 m inventory). Most of the flagged daytime profiles (red circles in Figure 5a) seem to be shifted slightly left of the linear regression lines, suggesting that they may well represent under-corrected quenched chlorophyll rather than true features. Overall, qualitatively, these quite linear relationship between surface Chl-a concentration and 0-200 m integrated Chl-a content suggests that satellite observations are reasonably good indicators of the spatial distributions water column chlorophyll inventories.

Concerning the particulate backscattering signal, the linear correlations between surface values and inventories were generally not as strong as for Chl-a, except for bio-profiler #3, as shown in Figure 5b (right column: $r^2 = [0.29-0.74]$). It appears that surface b_{bp} values lower than $\sim 2 \times 10^{-3} \text{ m}^{-1}$ vary similarly to the 0-200 m b_{bp} inventories, whereas higher surface values exhibit noisier correlations when compared to the 0-200 m integrated b_{bp} contents (see the slope breaks in the relationship between surface and 0-200 m integrated b_{bp} in Figure 5b). The origin of this non-linearity is not clear, and its evaluation is potentially compromised by the spikiness of the b_{bp} records and their poor vertical resolution. The particulate backscatter profiles (Figures 2b, 3e and 9e) suggest that spikes may be particularly common at the base of the mixed layer and below, and thus might reflect differential control of phytoplankton and total particle populations. Future deployments with improved firmware to yield higher resolution may be able to advance the interesting possibility that backscatter information can provide ecosystem perspectives beyond phytoplankton biomass alone.

Because our qualitative assessment indicated that surface Chl-a concentrations provide a relatively unbiased indication of the water column Chl-a inventory, we now try to go a little bit further towards a quantitative assessment of possible biases between satellite and in-situ Chl-a perspectives. First, we compared the coefficients of variation (i.e. the ratio of the standard deviation to the mean) of the surface chlorophyll concentrations and of the water column inventories. Using only the night data to avoid quenching correction uncertainties, surface distribution coefficients of variation (#1: 82%; #2: 20%; #3: 39%; #4: 43%) revealed very similar relative dispersions to the water column (0-200 m) inventory coefficients of variation (#1: 84%; #2: 20%; #3: 34%; #4: 31%). Thus, satellite images reasonably reflect the relative range of mesoscale variability in water column phytoplankton biomass accumulations. Surprisingly, surface chlorophyll values (i.e. satellite images) would tend to slightly overestimate the relative dispersion of Chl-a data for bio-profilers #3 and #4, despite those profiles exhibiting the largest numbers of night subsurface maxima (in %, Table 3). This means that the association of high surface chlorophyll concentrations with shallow chlorophyll layers was more important than the presence of subsurface chlorophyll maxima in determining the relationships between surface and water column inventories.

To further explore this issue, we calculated expected water column inventories for chlorophyll layers confined to the physical mixed layer depths at the time of observation (by multiplying each surface concentration by its associated mixed layer depth, MLD). This is akin to trying to improve satellite assessments using mixed layer depth information from, for example, standard ARGO floats that measure only temperature and salinity. These comparisons are shown in Figure 6a and reveal that this approach badly underestimates water column inventories (at least with our MLD definition) and that this underestimation is very common. Most of the “0-200 m integrated Chl-a/(surface Chl-a \times MLD)” ratios range from 1/1 to 4/1, with a few profiles of bio-profilers #1 and #3, at the time when they recorded the highest bio-optical values, reaching ratios of 20/1 (profiles ~ 70-130 for bio-profiler #1 and profiles ~ 0-70 for bio-profiler #3). Moreover, the colour coding in Figure 6a shows that this bias is strongest for shallow mixed layers in general. In other words, the presence of significant amounts of chlorophyll below the mixed layer is very common (though generally not as

local vertical chlorophyll maxima, for which our statistics confine the occurrence of those exceeding 60% of surface to 17% of the sampled locations and those exceeding 100% of surface to 11% of the sampled locations). Notably, this bias still persists strongly if we change our MLD definition to the much larger criterion of Levitus (1982; density increase of 0.125 kg m^{-3} relative to the density at 0 m). For this criterion, the (surface Chl-a \times MLD) estimation ranged between half and twice the 0-200 m integrated Chl-a content for MLD deeper than 60 m (close to half for MLD $\sim [60-90]$ m and surface Chl-a $< 2 \mu\text{g L}^{-1}$ to close to twice for MLD > 120 m and surface Chl-a $> 2 \mu\text{g L}^{-1}$). However, (surface Chl-a \times MLD) estimations are still twice to four times lower than the 0-200 m integrated Chl-a content recorded by the bio-profilers when the MLD ranges between 40 and 60 m (not shown).

The most probable explanation for these observations is that the mixed layer at the time of observation was shallower than at the time of generation of the biomass. This is of course expected as a result of seasonal shallowing of the mixed layer, but the magnitude of the effect is important to recognize (as we have shown above) it is well above what could be corrected using some other mixed layer depth criterion. Interestingly, there appears to be a relatively simple hyperbolic relationship between the ratio “0-200 m integrated Chl-a” / “surface Chl-a \times MLD” (hereafter designated as X) and MLD, as shown in Figure 6b for the MLD definition of Park et al. (1998). It also holds for the MLD definition of Levitus (1982). This X vs MLD hyperbola reaches an asymptote of $X \sim 1$ for MLD values close to the 150-200 m depths of regional winter mixed layers (visible as temperature minima remnant signatures of winter cooling in profiles south of the Polar Front in Figure 3b). Moreover, the curve is reasonably well parameterized by $X \sim \text{MLD}^t / \text{MLD}^w$, in which the superscripts t and w indicate mixed layer depths at the time of observation and the end of winter, respectively. This relationship could arise if most biomass accumulation occurred in early deep mixed layers with subsequent stratification adding little additional biomass, or if mixed layers shallowed and deepened episodically as biomass accumulation developed throughout the season.

Overall, these results emphasize the major challenges that are present for connecting surface chlorophyll distributions to total water column biomass and primary productivity, since they reveal that physical mixed layer depths are often not a reliable guide to biomass distributions. These physical and biological responses seem to be modulated differently on diel, weather, and seasonal timescales, and are also affected by the mesoscale and sub-mesoscale interleaving of water parcels. The quantification of near surface mixing (i.e. going beyond the limited mixed layer depth concept) is currently under very active exploration and debate in the context of seasonal drivers of production (Behrenfeld, 2010; Taylor and Ferrari, 2011), and these data reveal the need to extend those perspectives to shorter time and space scales. The presence of significant amounts of chlorophyll below the mixed layer is also important to its ultimate fate –if this biomass is not re-entrained then it may well contribute preferentially to export and to mesopelagic oxygen consumption (issues which we revisit in Discussion section 4.3 below).

- p. 17430 l. 13-14 “We also performed the same calculations for the backscatter signal, and found similar non-linearity”: on the same page l. 2 you say that for chlorophyll “the surface and total estimates show linear relationships”.

Authors’ response:

We corrected this inconsistency. We found a smaller correlation between surface concentrations and 0-200 m integrated contents for the particulate backscattering signal than for the chlorophyll data.

Correlation between chlorophyll biomass and oceanographic variables (section 4.2):

As stated by the authors in the introduction, factors such as mixed layer depth and upper water column stratification (p. 17418 l. 12-13) play a role in controlling phytoplankton production. This is through their effects on light availability. This is an important question and bio-profilers should bring interesting insights. Yet I am not convinced by the authors’ approach to the question nor by their interpretation of the data. What is the rationale for using surface layer (0-50 m) data instead of mixed-layer or full water-column data? This does not account for inter-site variation and exclude a large

fraction of the phytoplankton biomass. Also why splitting your dataset into two subsets of rich- and moderate-biomass regions, especially when there is such an overlap between the rich (1 to 9 $\mu\text{g L}^{-1}$) and moderate (0.5 to 3 $\mu\text{g L}^{-1}$) regimes? Instead I would analyze independently (and then also all together) the time series collected by each profiling float to determine if changes in oceanographic properties can explain changes from low to high biomass. Finally the selection of temperature, salinity, MLD etc. may not be optimal for the goal you are trying to achieve. For example, the MLD is not necessarily a good indicator of active water column mixing, mixing history and light availability to phytoplankton. I suggest trying alternative indicators, e.g. the ratio of MLD to euphotic layer depth may provide insights into the mixing/light conditions. The shape of the chlorophyll profile may also be indicative of photoacclimation processes.

Authors' response:

We understand your concerns and we adopted your suggested approach and completely revised this section of our analysis and text:

1) we replaced the surface chlorophyll concentration by the 0-200 m integrated chlorophyll inventories and

2) we used a threshold, 200 $\mu\text{g L}^{-1}$, and only represented values above this threshold for the rich areas (i.e. that reach very high Chl-a concentrations) and values below this threshold for the poor to moderate areas and modified accordingly the Figure 7 (old Figure 6).

3) we added comparison to stratification as represented by the maximum Brunt-Väisälä frequency squared (N^2). Based on this metric, stratification seems to play a minor role since no clear relationship was found with the 0-200 m integrated Chl-a distributions.

4) we expanded discussion of the relationship between the depth of the chlorophyll distributions relative to the mixed layer depth (using two different criteria for mixed layer depth).

- p. 17430 l. 3-4 “The distributions of chlorophyll with these properties showed decreases on either side of these values, suggestive of mixing with surrounding water”: I do not understand this sentence. To me two major features can be seen in Fig. 6a. One part of profiler 1 time series shows positive correlation between temperature and chlorophyll concentration. Another part of the time series, similarly to profiler 3, shows the opposite trend (i.e. increase in chlorophyll with decreasing temperature). This somewhat reflects in density data, albeit not in MLD data. Which pattern do you interpret as suggestive of “mixing with surrounding waters”? Does this imply that dissolved iron from the plateau locally leads to biomass increase, or that biomass-rich waters from the plateau mix with local waters?

Authors' response:

We believe that 3 different endmembers are characterized in Figures 7a, 7b, 7c and 7f. The first class of waters exhibits warm light waters, slightly oversaturated in oxygen ($T \sim 5.5\text{ }^{\circ}\text{C}$, $S \sim 33.81$, $\sigma \sim 26.65\text{--}26.7\text{ kg m}^{-3}$, $O_{2\text{ sat}} \sim 103\%$). The second class of waters exhibits much colder and denser waters, also slightly oversaturated in oxygen ($T \sim 3\text{ }^{\circ}\text{C}$, $S \sim 33.85$, $\sigma \sim 27\text{ kg m}^{-3}$, $O_{2\text{ sat}} \sim 103\%$). Both have moderate water column Chl-a contents ($\sim 200\text{ mg m}^{-2}$). The third class of waters exhibits intermediate physical properties but much higher oxygen saturation states ($T \sim 4.2\text{ }^{\circ}\text{C}$, $S \sim 33.83$, $\sigma \sim 26.85\text{ kg m}^{-3}$, $O_{2\text{ sat}} \sim 110\%$) and much higher 0-200 m Chl-a contents ($\sim 1000\text{ mg m}^{-2}$). The linear relationships between the Chl-a contents and the physical properties represent the mixing zones, as the linear relationship between Chl-a and $O_{2\text{ sat}}$. Thus, from these patterns, we believe that biomass-rich waters from the plateau mix with local waters poorer in Chl-a.

Modified text:

As shown in Figure 7 (a, b and c), the richest biomass regions encountered by bio-profiler #1 in 2011 and bio-profiler #3 in 2014 were associated with waters with very similar properties, specifically moderate temperatures (3.5-5 $^{\circ}\text{C}$), high salinities (33.82-33.85), and thus relatively high densities (sigma-theta values of 26.7-26.9 kg m^{-3}). The bio-profiler #1 distributions of chlorophyll with these properties showed linear decreases on either side of these values, suggestive of mixing with

surrounding waters much poorer in Chl-a. This characteristic is also observed between integrated Chl-a and mean surface oxygen saturation ($O_{2\text{ sat}}$, Figure 7f), for which the high $O_{2\text{ sat}}$ states (reaching 10%) indicate oxygen production in these high biomass waters (since these values exceeding expected from processes such as warming or bubble injection; Shadwick et al., 2014).

- p. 17430 l. 8-10 “For the moderate biomass observations, no clear relationships with mixed layer depth emerged (Fig. 6), suggesting a limited influence on production by light limitation, i.e. deep mixing was insufficient to lower light levels to limiting levels”: This cannot be concluded from the present analysis.

- p. 17430 l. 10-13 “But for the high biomass observations, there is a tendency for the highest chlorophyll concentrations to occur preferentially in shallow mixed layers, suggesting self-shading may become a limiting factor on production as biomass levels become very high (Fig. 6)”: I am not sure which observations lead to this comment. Fig. 6d does not show much trend in chlorophyll concentration vs MLD.

Authors’ response:

We agree with the reviewer and we revised our interpretation of the relationship between mixed layer depth and stratification and chlorophyll contents, as described below.

Modified text (last paragraph of Section 4.2):

[...] the bio-profiler #1 profiles with integrated Chl-a greater than 600 mg m^{-2} were mainly characterized by a shallow mixed layer, lower than 60 m (Figure 7d), and a low stratification ($-0.01\text{ s}^{-2} < \max N^2 < 0\text{ s}^{-2}$; Figure 7e). Below this Chl-a inventory threshold, no clear relationships emerged between MLD or N^2 and 0-200 m integrated chlorophyll (Figures 7d and 7e). In a steady state perspective, this lack of correlation could arise because mixed layers were shallow enough that light limitation was not sufficient to halt phytoplankton accumulation, yet not so shallow that mean mixed layer light levels allowed light promoted growth to reach accumulations that became self-shading (viewpoints that have been developed previously, based on relationships between fluorescence and mixed layer depth observations in this region using sensors on elephant seals; Blain et al., 2013). Importantly, our observations emphasize that chlorophyll distributions do not track the shoaling of mixed layer depth on seasonal or weather timescales, and thus that MLD variability is unlikely to show simple relationships to biomass accumulation. This point has also been emphasized in terms of competing effects of light and Fe limitation responses to MLD variability (Joubert et al., 2014), for waters where vertical Fe supply is dominant (rather than the horizontal dominance of supply studied here).

Fate of surface enrichment (section 4.3):

- Vertical distribution and time evolution of chlorophyll biomass (p. 17431 and Fig. 7): Fig. 7e may not be ideal to examine the temporal evolution of the vertical distribution of chlorophyll, identify subsurface maxima and characterize their origin. It is quite difficult to read the chronology of the chlorophyll profiles (despite the color code) and determine the depth of the maxima. It would be nice to have additional cross sections similar to those in Fig. 3-4a but with a zoom on profiles 150 to 250 over a shallower layer (e.g. 0-200 m). Another option would be to have a succession of chlorophyll vs. depth plots similar to, e.g., those in Perry et al. (2008) LO figure 2. It is possible that in a different graphical representation the subsurface maxima appear as relatively minor features. I also recommend plotting a cross section (or some equivalent graphic representation) of the particulate backscattering to chlorophyll fluorescence ratio. This would help to interpret possible changes in the composition of the particulate assemblage.

- p. 17431 l. 4-5 “chlorophyll profiles show elevated surface mixed layer levels, near $1.5\text{ }\mu\text{g L}^{-1}$ ”: To me most chlorophyll profiles show values of $1\text{ }\mu\text{g L}^{-1}$ with only 2 profiles reaching maxima of $1.5\text{ }\mu\text{g L}^{-1}$.

Authors’ response:

As suggested by the reviewer, following Figure 2 of Perry et al. (2008), we modified the representation of our old Figure 7e (new Figure 9e), and we added the representation of the chlorophyll fluorescence to particulate backscattering ratio. We detailed more precisely the evolution of the 3 variables shown in Figures 9e, 9f and 9g, as written below.

Modified text:

At the start of this period (blue lines subset in Figure 9e), chlorophyll profiles showed moderate to high surface and subsurface layer levels, well above HNLC background values, with some profiles exhibiting subsurface maxima reaching up to $1.5 \mu\text{g L}^{-1}$ between 50-70 m depth and up to $1 \mu\text{g L}^{-1}$ around 120 m depth. Both the surface constant Chl-a layer and the subsurface “chlorocline” layer (by analogy to thermocline or halocline, “chlorocline” is defined here as the depth range with the highest chlorophyll concentration gradient) were thick, equal to ~ 80 m and ~ 50 m, respectively. The origin of the smaller and variable subsurface maxima seen in some profiles in Figure 9e is uncertain. One possibility is that they are remnants of the high surface chlorophyll biomass observed just prior to the eddy entrainment (visible in Figure 3.4c and the “bloom 2013” animation in the supplementary material), that had been carried to depth by particle settling or by subduction of the denser, saltier, and slightly cooler water associated with that high biomass. Associated b_{bp} profiles showed similar large variations with strong local maxima correlated to local Chl-a maxima (blue lines subset in Figure 9f). The strong variability of the Chl-a/ b_{bp} profiles over the first 100 m suggests possible changes in the composition of the particulate assemblage (blue lines subset in Figure 9g).

During the Lagrangian eddy entrainment period, the surface mixed layer chlorophyll levels declined further from $1.5 \mu\text{g L}^{-1}$ to $\sim 1 \mu\text{g L}^{-1}$ (Figure 3.4c and 9e). Since the constant chlorophyll surface layer shallowed progressively with time, this Chl-a decrease did not result from the possible effect of dilution by mixed layer deepening (i.e. entrainment). Furthermore, the chlorocline content decreased briefly before re-increasing progressively in its upper part, and then its deeper part. In parallel, b_{bp} and Chl-a/ b_{bp} profiles became tighter and tighter (light blue to orange profiles in Figures 9f and 9g) before re-exhibiting larger variations (red profiles). These results suggest the possibility of some chlorophyll conversion to non-fluorescent material, or its removal by export to depth or by local respiration or both, throughout the eddy entrainment. They may also of course partly reflect small spatial variations in the structure of the biomass distributions.

- p. 17432 l. 27-29 “the rate of chlorophyll loss is too small (by factors of 2–3, assuming a moderately high C/Chl a ratio of 50) to explain all the oxygen decrease”: Please detail the reasoning (and calculation) that led you to this conclusion. I am assuming that at some point you have to use an average organic carbon to oxygen ratio or make a guess on the oxygen demand for respiration? Also note that “assuming a moderately high C/Chl a ratio of 50” should be moved, maybe at the end of the sentence, as it is currently misleading (gives the impression that the change in the chlorophyll concentration by a factor of 2-3 depends on the carbon to chlorophyll ratio).

Authors’ response:

The calculation is very simple:

“decrease in Chl-a” \times “C/Chl-a of biomass” \times “ O_2 /C ratio for respiration” = “expected decrease in O_2 ”, which yields a smaller change in O_2 than observed.

Because other readers have found this to be straightforward, we have made no modifications.

- Not being familiar with oxygen data I may have missed something. Yet it is unclear to me how identical oxygen consumption rates in layers 2 and 3 (“ $4 \mu\text{mol m}^{-3} \text{d}^{-1}$ ”, p. 17433 l. 15) lead to different percent estimates of carbon sequestration (“25 percent within layer 2 and 15 percent within layer 3” p. 17433 l. 19-20). Again please detail your reasoning here.

Authors’ response:

Identical oxygen consumption rates lead to different percent estimates of carbon sequestration because the thickness and the average density of each layer is different (see Figures 10b and 10c). We calculate the O_2 consumption of each layer by multiplying the O_2 consumption rate by the thickness and the average density of the layer, which leads to $4 \mu\text{mol kg}^{-1} \times 35 \text{ m} \times 26.70 \text{ kg m}^{-3} = 3738 \mu\text{mol}$

m^{-2} for layer 2 and $4 \mu\text{mol kg}^{-1} \times 25 \text{ m} \times 26.86 \text{ kg m}^{-3} = 2686 \mu\text{mol m}^{-2}$ for layer 3. O_2 consumption in layer 1 is equal to $5 \mu\text{mol kg}^{-1} \times 80 \text{ m} \times 26.46 \text{ kg m}^{-3} = 10584 \mu\text{mol m}^{-2}$. Among the 3 layers, the total mean consumption equals $\sim 17000 \mu\text{mol m}^{-2}$. So the oxygen consumption of layer 2 equals 22% of the total consumption of the 3 layers and layer 3 equals 16%.

Modified text:

Comparing O_2 consumption of layers 2 and 3 (by multiplying the O_2 consumption rate by the thickness and the average density of the layer) relative to the total mean consumption among the three layers, we estimate that 40% of the CO_2 produced during this autumn period of bloom decline was exported (20% within layer 2 and 15% within layer 3).

- Importantly, I don't think you can call "sequestration" a process that occurs above the mesopelagic zone. Carbon "export" would be more appropriate.

Authors' response:

We agree and did the suggested correction everywhere it was needed.

Minor corrections and typos

- p. 17416 Introduction: I recommend the authors use the term "primary production" instead of "productivity" which is not appropriate in this context.

Authors' response:

We corrected as suggested.

- p. 17416 l. 19 "C": Please define symbol on first use. Although not essential it would not hurt to define CO_2 and Fe as well (or to write "iron" in full letters).

Authors' response:

We defined the different symbols.

-p. 17417 l. 1: What do you mean exactly by "mosaic of blooms"? Patchiness?

Authors' response:

Yes, we refer to the "patchiness pattern" of the surface chlorophyll distribution. We added it in the text, to be clearer.

- p. 17417 l. 19: Regarding the deployment of floats 2, 3 and 4, please replace "in January 2014" by "between late January and early February 2014" as indicated in Table 1.

Authors' response:

We modified as suggested.

- The introduction (p. 17417-17418) provides significant background to objective 2. Yet objectives 1 and 3 are not introduced at all.

Author's response:

We thank the reviewer for encouraging us to expand on the importance of these 3 issues. We added new paragraphs dedicated to both question 1 and question 3.

Modified text:

Assessing influences on productivity, biomass accumulation, carbon export, and carbon dioxide (CO_2) uptake in the Southern Ocean is challenging because of variations across many scales, including weather, seasonal, and interannual time-scales, and sub-mesoscale, mesoscale, and circumpolar frontal space scales (Joubert et al., 2014; Le Quéré et al., 2010; Lenton et al., 2013; Levy, 2003; Nicol et al., 2000; Shadwick et al., 2015; Sokolov and Rintoul, 2007; Swart et al., 2014; Thomalla et al., 2011; Weeding and Trull, 2014). Satellite observations offer extensive space-time

coverage [Martinez et al., 2009; Moore and Abbott, 2000], but may provide a biased view if surface distributions are not representative of water column inventories. Important ways bias could arise include correlations of surface values with their vertical extents (e.g. high surface chlorophyll values might be predominantly associated with shallow accumulations, through the promotion of production by higher light levels in shallow mixed layers; Sverdrup, 1953), the presence of unobserved subsurface chlorophyll maxima (Carranza et al., 2014; Schlitzer, 2002), or the variation of phytoplankton to chlorophyll ratios with growth conditions (Cloern et al., 1995; Fennel and Boss, 2003; Goericke and Montoya, 1998).

These difficulties of observation become even more acute for carbon export estimates, which require either flux measurements (e.g. from moored or free-drifting sediment traps or radionuclide activities; Planchon et al., 2014; Savoye et al., 2008) or the partitioning of changes in state variables across biogeochemical versus oceanographic causes (e.g. nitrate depletions in surface waters or oxygen consumption at mesopelagic depth; Matear et al., 2000; Trull et al., 2014). Obtaining estimates of carbon export and the depth of its penetration into the ocean interior are important to determining impacts on the climate system, because variations in these two factors have similar influence to variations in total primary production in terms of the sequestration of CO₂ from the atmosphere (Boyd and Trull, 2007). Notably, export estimates expressed as 'e-ratio' fractions of primary production (Maiti et al., 2013), or as 'f-ratio' fractions of production derived from 'new' nitrate supply (Savoye et al., 2004) vary widely in the Southern Ocean, with the possibility that these efficiencies are increased by natural iron fertilisation (Jouandet et al., 2011; Trull et al., 2008).

- p. 17420 l. 5-7 "As discussed in the Results section below, the bio-profilers..., but what is their level of fidelity": This type of comment is very unnecessary here. Please go straight to the methodology.

Authors' response:

We removed these sentences and start directly with the methodology.

- p. 17421 l.26 "we applied the efficient method of...": Please remove "efficient". It is inappropriate unless fully supported by statistics.

Authors' response:

We removed it.

- p. 17423 l. 22-23 "the drifts of the bio-profilers provided coverage... covering territories": Awkward phrasing. Please reword.

Authors' response:

We deleted "covering territories".

- p. 17424 l. 27-28 "breadth of spatial coverage of the plume did not extend to full temporal seasonal coverage": I don't understand what you mean here.

Authors' response:

We removed it.

- p. 17424 l. 6 "biomass accumulation": Please avoid the systematic use of the word "accumulation" throughout the text. I think that "biomass" is enough in the present context.

Authors' response:

We used the term "accumulation" because we are investigating the biomass evolution along the bio-profiler trajectory and because the chlorophyll concentration we estimate is a net budget between biomass growth and biomass loss.

- p. 17426 l. 5 "as the high chlorophyll levels decreased": Delete "high" or reformulate.

Authors' response:

We deleted "high".

- p. 17428 title of section 4.1: Please be more accurate, “total inventories” does not mean much (say, e.g., “water-column integrated content” or something equivalent).

Authors’ response:

We replaced “total inventories” by “water column contents”.

- p. 17428 l. 13 “near to the plateau”: Please remove “to”.

Authors’ response:

We removed “to”.

- p. 17429 l. 6 “contribute insignificant bias”: Please reword.

Authors’ response:

This was revised.

- Table 1: Caption should be relatively self explicit. Please explain what “Hull” and “WMO” stand for.

Authors’ response:

We specified the meaning of the terms “Hull” and “WMO”.

- Table 2 could be simplified. Some information is unnecessary. There are also two rows with identical labels and different numbers: “Day time profiles with subsurface maxima before correction”?

Authors’ response:

We kept all the information because the reviewer did not detail what was considered unnecessary.

The identical labels were a mistake. We corrected the second row label by “Day time profiles with subsurface maxima after correction”.

- Fig. 1: In figure caption specify what kind of satellite image you have used (sensor, product level and temporal averaging).

Authors’ response:

We added these specifications in the caption.

- Fig. 2: Could be split into two different figures (for drifting and quenching correction). Thus you could add letter (a, b, c etc.) for convenient reference to each individual panel of the figures.

Authors’ response:

As we already have a large number of figures, we chose to not split Figure 2 into different figures. But as we lightened Figure 2b, we believe that the titles and axes of the different plots are sufficiently explicit to find easily the plot we are referring to in the text.

- Fig. 3: I recommend splitting Figs. 3a, 3b, 3c and 3d into four different figures. This would facilitate referring to the different panels (e.g., references such as Fig. 3-a1 are not so convenient). Why using a symmetric color scale for temperature, salinity and oxygen properties (i.e. max and min values have similar colors)? For Fig. 3-1 I wouldn’t show the data that are not used due to sensor drift and stop the graph at profile 300. For all panels of Fig. 3 it would be nice to focus only on the first 200 or 250 m of the water column so small features are more visible (at least for the biological variables). Please say something about salinity units, e.g. “no unit” or “psu”.

Authors’ response:

Similarly, we chose to not split this figure in 4 different figures.

We chose a more relevant and appropriate color scale for the properties.

We think that it is still interesting to show all the data acquired by the bio-profiler #1, even after profile #300, as well as to show the larger depth range documented by most of the bio-profiler profiles, because this is the only figure where the whole data set is shown, and these data may be

useful for other studies.

Until recently the recommendation of the SCOR working group on salinity is that salinity be unitless, as the measurement is now based on conductivity and is not precisely related to the mass of dissolved material. We specified that it was unitless in the text and in the captions of the figures.

- Fig. 4: The figure caption gives the impression that the titles a) and b) are for the right-column plots only. My understanding is that a) is for the top plots whereas b) is for the bottom plots.

Authors' response:

We improved the clarity between the caption, the figure and the text by labelling each subplot, from a) to f).

- Fig. 5: The figure caption indicates “water column integrated (0-200 m) biomass” but the units ($\mu\text{g L}^{-1}$) and the text (p. 17430 l. 1) suggest it is mean biomass (instead of integrated biomass). The word “distributions” is not necessary here. “Left column: fluorescence phytoplankton biomass estimates. Right column: backscatter total biomass estimates”: both expressions are incorrect and inconsistent with the yaxis labels (“Mean 0-200 m chlorophyll” and “Mean 0-200 m backscatter”).

Authors' response:

This figure has been revised as we modified the approach to answer to the question “Do the satellite images of surface chlorophyll reflect total water column contents?”. In the revised version, the caption consistently refers to the parameters represented in the figure and discussed in the text.

- Fig. 6: The caption “Chlorophyll relationships with surface water properties” sounds a bit odd. I suggest replacing by, for example, “Relationship between chlorophyll a concentration and various properties in surface waters: (a) temperature, (b) salinity etc.” Why have you labeled only the left-column profiles?

Authors' response:

We replaced the caption “Chlorophyll relationships with water properties” by “Relationship between 0-200 m integrated chlorophyll a concentration and various water properties...” and labeled all the subplots, for the sake of clarity.

- Fig. 7: In caption “coloured by time” is probably not what you mean. Maybe “with color code indicating the date of acquisition” would be more appropriate. “relative to profile 177 (red square)”: Please recall what the red square is/where it is.

Authors' response:

We clarified “coloured by time” by “with the colour of the points changing, from blue to red over time, from profile 150 to profile 240”. We added some details to better explain the signification of the red square.

Modified text:

b) Overlay of bio-profiler trajectory (white line) and eddy retention indices, showing the portion of the trajectory within a long-lasting (more than 30 days) retentive structure. The red square marks the temporal reference (profile 177) from which the Lagrangian trajectories were computed for the retention statistic, as described in Methods section 2.3.

- Fig. 8: The figure caption says “Temporal evolution during eddy entrainment for bio- profiles 4”: Temporal evolution of what?

Authors' response:

We clarified the caption: “Temporal evolution of physical and biological properties during the eddy entrainment”.

- I haven't found any reference to the online supplementary material in the text...

Authors' response:

We added references, mainly in Section 3.2 (Overview of observed oceanographic properties), to the animations constituting the supplementary material.

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**Autonomous profiling float observations of the high biomass plume downstream of the
Kerguelen plateau in the Southern Ocean**

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Abstract

Natural iron fertilisation from Southern Ocean islands results in high primary production and phytoplankton biomass accumulations readily visible in satellite ocean colour observations. These images reveal great spatial complexity with highly varying concentrations of chlorophyll, presumably reflecting both variations in iron supply and conditions favouring phytoplankton accumulation. To examine the second aspect, in particular the influences of variations in temperature and ~~stratification~~mixed layer depth, we deployed four autonomous profiling floats in the Antarctic Circumpolar Current near the Kerguelen plateau in the Indian sector of the Southern Ocean. Each 'bio-profiler' measured more than 250 profiles of temperature (T), salinity (S), dissolved oxygen, chlorophyll-a (Chl-a) fluorescence (~~Chla~~), and ~~particle backscatter~~particulate backscattering (b_{bp}) in the top 300 meters of the water column, sampling up to 5 profiles per day along meandering trajectories extending up to 1000 km. Comparison of surface ~~Chla~~Chl-a estimates (~~top 50 meters depth~~, analogous to values from satellite images) with total water column inventories revealed largely linear relationships, suggesting that ~~dilution of chlorophyll by mixed layer depth variations plays only a minor role in the spatial distributions observed by satellite, and correspondingly that these images~~ provide credible information on total and not just surface biomass accumulations. Regions of very high ~~Chla~~Chl-a accumulation ($1.5\text{-}10\ \mu\text{g L}^{-1}$) were associated predominantly with a narrow T-S class of surface waters, ~~which appears to derive from the northern Kerguelen plateau.~~ In contrast, waters with only moderate ~~Chla~~Chl-a enrichments ($0.5\text{-}1.5\ \mu\text{g L}^{-1}$) displayed no clear correlation with specific water properties, including no dependence on mixed layer depth, ~~suggesting a diversity or the intensity of sources of iron and/or its efficient dispersion across filaments of stratification.~~ Geostrophic trajectory analysis suggests that both these observations can be explained if the plume. ~~The lack of dependence on mixed layer depth also indicates~~main determinant of biomass in a limited influence on production by light limitation given water parcel is the time since leaving the Kerguelen plateau. One float became trapped in a cyclonic eddy, allowing temporal evaluation of the water column in early autumn. During this period, decreasing surface ~~Chla~~Chl-a inventories corresponded

46 with decreases in oxygen inventories on sub-mixed layer density surfaces, consistent with significant
47 export of organic matter (~35%) and its respiration and storage as dissolved inorganic carbon in the
48 ocean interior. These results are encouraging for the expanded use of autonomous observing
49 platforms to study biogeochemical, carbon cycle, and ecological problems, although the complex
50 blend of Lagrangian and Eulerian sampling achieved by the floats suggests that arrays rather than
51 single floats will often be required, and that frequent profiling offers important benefits in terms of
52 resolving the role of mesoscale structures on biomass accumulation.

53

54 **1 Introduction**

55 The productivity of the Southern Ocean is important for many reasons. It supports fisheries and
56 high conservation value marine mammal and bird populations (~~Constable et al., 2003; Nicol et al.,~~
57 ~~2000~~), (~~Constable et al., 2003; Nicol et al., 2000~~), influences the carbon dioxide content of the
58 atmosphere (~~Sarmiento and Le Quéré, 1996; Sigman and Boyle, 2000; Watson et al.,~~
59 ~~2000~~), (~~Sarmiento and Le Quéré, 1996; Sigman and Boyle, 2000; Watson et al., 2000~~), and affects the
60 magnitude of nutrient supply to large portions of the global surface ocean ([Sarmiento et al., 2004](#)).
61 This productivity is limited by the scarce availability of iron (Fe) as an essential micro-nutrient (~~Boyd~~
62 ~~and Ellwood, 2010; Boyd et al., 2007; Martin, 1990~~), (~~Boyd and Ellwood, 2010; Boyd et al., 2007;~~
63 ~~Martin, 1990~~). Island sources of Fe elevate productivity and produce downstream 'plumes' of elevated
64 phytoplankton biomass that contrasts with the general HNLC (High Nutrients, Low Chlorophyll)
65 nature of the Southern Ocean (~~Blain et al., 2007; de Baar et al., 1995; Mongin et al., 2009; Pollard et~~
66 ~~al., 2009; Nielsdóttir et al., 2012~~). Ship based studies of several of these regions have mainly focused
67 ~~on determining the influence of Fe on C transfer to the ocean interior as part of understanding the role~~
68 ~~of these blooms' CO₂ absorption in the climate system (Blain et al., 2008; Salter et al., 2007), but in~~
69 ~~the process have revealed a complexity~~ (~~Blain et al., 2007; de Baar et al., 1995; Mongin et al., 2009;~~
70 ~~Pollard et al., 2009; Nielsdóttir et al., 2012~~). Ship based studies of several of these regions, focused
71 ~~on the influence of Fe on carbon (C) transfer to the ocean interior (Blain et al., 2008; Salter et al.,~~
72 ~~2007), have revealed a diversity~~ of responses in terms of intensity of enhanced productivity, biomass
73 accumulation, and ecosystem structures. This diversity ~~is the result of the~~ derives from interactions
74 between the ~~nature of the supply and bio-availability of iron, as well as variations in~~ with other drivers
75 of productivity such as temperature, water column stratification and stability, light levels, and the
76 possibility of co-limitation by other nutrients (~~Assmy et al., 2013; Boyd et al., 1999, 2001; Queguiner,~~
77 ~~2013~~), (~~Assmy et al., 2013; Boyd et al., 1999, 2001; Queguiner, 2013~~).

78 Assessing influences on productivity, biomass accumulation, carbon export, and carbon dioxide
79 (CO₂) uptake in the Southern Ocean is challenging because of variations across many scales,

80 including weather, seasonal, and interannual time-scales, and sub-mesoscale, mesoscale, and
81 circumpolar frontal space scales (Joubert et al., 2014; Le Quéré et al., 2010; Lenton et al., 2013; Levy,
82 2003; Nicol et al., 2000; Shadwick et al., 2015; Sokolov and Rintoul, 2007; Swart et al., 2014;
83 Thomalla et al., 2011; Weeding and Trull, 2014). Satellite observations offer extensive space-time
84 coverage (Martinez et al., 2009; Moore and Abbott, 2000), but may provide a biased view if surface
85 distributions are not representative of water column inventories. Important ways that bias could arise
86 include lack of direct correlations of surface values with their vertical extents (e.g. high surface
87 chlorophyll values might be predominantly associated with shallow accumulations, through the
88 promotion of production by higher light levels in shallow mixed layers; Sverdrup, 1953), the presence
89 of unobserved subsurface chlorophyll maxima (Carranza et al., 2014; Schlitzer, 2002), or the variation
90 of phytoplankton to chlorophyll ratios with growth conditions (Cloern et al., 1995; Fennel and Boss,
91 2003; Goericke and Montoya, 1998).

92 These difficulties of observation become even more acute for carbon export estimates, which
93 require either flux measurements (e.g. from moored or free-drifting sediment traps or radionuclide
94 activities (Planchon et al., 2014; Savoye et al., 2008) or the partitioning of changes in state variables
95 across biogeochemical versus oceanographic causes (e.g. nitrate depletions in surface waters or
96 oxygen consumption at mesopelagic depth; Matear et al., 2000; Trull et al., 2015). Obtaining
97 estimates of carbon export and the depth of its penetration into the ocean interior are important to
98 determining impacts on the climate system, because variations in these two factors have similar
99 influence to variations in total primary production in terms of the sequestration of CO₂ from the
100 atmosphere (Boyd and Trull, 2007). Notably, export estimates expressed as ‘e-ratio’ fractions of
101 primary production (Maiti et al., 2013), or as ‘f-ratio’ fractions of production derived from ‘new’
102 nitrate supply (Savoye et al., 2004) vary widely in the Southern Ocean, with the possibility that these
103 efficiencies are increased by natural iron fertilisation (Jouandet et al., 2011; Trull et al., 2008).

104 This space-time complexity is abundantly demonstrated by the 'mosaic of blooms' (i.e. patchiness
105 pattern) encountered in waters downstream from the Kerguelen plateau during the KEOPS2 field
106 program in austral spring (October-November 2011), as detailed in many papers in 2014a special
107 volume of Biogeosciences (d'Ovidio et al., 2014; Trull et al., 20142015; Lasbleiz, et al., 2014;
108 Laurenceau-Cornec et al., 20142015; Cavagna et al., 2014). Much of the meso-scale spatial variations
109 in biomass accumulation, as seen in satellite images and animations (Mongin et al., 2009;
110 ~~D'Ovidio~~d'Ovidio et al., 2014; Trull et al., 20142015), appears to result from the interleaving of iron-
111 enriched water parcels that have transited the Kerguelen plateau with surrounding iron poor waters,
112 as demonstrated by analysis of satellite altimetry based circulation estimates and surface drifter
113 trajectories (Park et al., 20142014a; d'Ovidio et al., 2014). However, shipboard studies close to the
114 plateau (Mosseri et al., 2008; ~~D'Ovidio~~d'Ovidio et al., 2014; Blain et al., 20142015; Trull et al.,
115 20142015; Lasbleiz, et al., 2014; Laurenceau-Cornec et al., 20142015) suggest that other factors are
116 ~~also-are~~ likely to play a role, including mixed layer depth and upper water column stratification.

117 To explore the influence of variations in these water column properties on bloom structure at
118 larger scale, in particular further from the plateau than could be surveyed by ship, we deployed
119 autonomous profiling drifters. The first one was successfully launched during the KEOPS2 field
120 program in late October 2011, and the other three during the MyctO-3D-MAP (referred to as
121 MYCTO, from now on in this text) interdisciplinary survey ~~in~~between late January and early February
122 2014. Given the extent of the Kerguelen biomass plume (> 1000 km; Mongin et al., 2009), the
123 remoteness from ports, and the ~~presence of high waves and strong currents which preclude~~generally
124 rough sea states, the ~~navigation and recovery~~use of ~~other~~ autonomous platforms, ~~autonomous~~
125 ~~profilers were indeed~~ is arguably the only affordable way to ~~obtain~~survey this ~~information~~region. As
126 shown in Figure 1, these deployments returned data from a large proportion of the enriched biomass
127 plume downstream of the Kerguelen plateau.

128 In this paper, we use the bio-profiler observations to address three questions:

- 129 1) Do satellite images of surface chlorophyll provide an unbiased guide to the spatial distribution
130 of total water column chlorophyll, or are they biased by lack of knowledge of variations in the
131 vertical extent of ~~deep-mixing~~chlorophyll distributions or the presence of subsurface chlorophyll
132 maxima?
- 133 2) Do regions of high biomass correlate with particular oceanographic properties, such as warmer
134 or fresher waters, or the intensity of stratification? If so, are these properties determined locally
135 or by the upstream origins of the different water parcels?
- 136 3) Can the fate of surface enrichments in biomass be determined (and eventually quantified) from
137 along-trajectory temporal variations in biogeochemical properties, for example by progressive
138 downward movement of fluorescence or ~~backscatter~~particulate backscattering signals or
139 decreases of oxygen in subsurface waters?

140

141 **2 Methods**

142 **2.1 Float sensor and mission configurations**

143 The float deployment locations are provided in Table 1, along with their identification numbers
144 which provide access to their full data sets via the Australian Integrated Marine Observing System
145 (~~www.imos.org.au~~), are provided in Table 1: www.imos.org.au). Float deployment was done in 2011
146 by manual transfer to a small boat and then the sea, and in 2014 by deploying the floats from the ship
147 deck inside cardboard boxes designed to readily disintegrate after release. The autonomous profiling
148 floats were all of the same design (Model APF9I, Teledyne-Webb, Inc.). Each was equipped with
149 pumped, poisoned, thermosalinographs (Model SBE 41CP-2.0, Seabird, Inc.), end-cap mounted
150 ~~unpumped~~un-pumped oxygen optodes (Model 3830, Aanderaa, Inc.), and two-channel bio-optical

151 sensors (Model FLBBAP2, Wetlabs, Inc.) strapped onto the lower third of the float hull with their
152 optical ports facing horizontally to minimize possible interferences from particle accumulation.
153 Owing to the structure of the firmware for the floats and the varying power requirements for the
154 sensors, the sampling rates differed for the physical and biogeochemical parameters. Temperature
155 and salinity were sampled at the highest rates, yielding values at 2 decibar intervals (used in this work
156 as equivalent to 2 meter depth intervals without density corrections~~These sensors measure chlorophyll~~
157 ~~fluorescence by blue light stimulation and particle backscatter by red light scattering.~~), whereas
158 oxygen, fluorescence and backscatter were sampled at 10 decibar intervals, except for bio-profiler #1
159 where they were sampled at 5 decibar intervals in the first 150 m.

160 Temperature and salinity calibrations were performed by Seabird, Inc., with estimated accuracy
161 and precision of better than 0.005 °C and 0.01, respectively ~~(Oka and Ando, 2004).~~ °C and 0.01,
162 respectively (Oka and Ando, 2004). These variables, used as water mass proxies and to estimate
163 mixed layer depths and stratification intensity (expressed as the Brunt-Väisälä frequency), helped to
164 determine if dissolved oxygen evolutions were mainly due to physical processes or to biological
165 production or respiration processes. The oxygen optodes were calibrated at CSIRO prior to mounting
166 on the floats against a 20 point matrix of 4 temperatures (0.5 - 30) and 5 oxygen saturations (0 -
167 129%) using the methods detailed in [Weeding and Trull \(2014\)](#). Similar sensors exhibited drift during
168 a 6 month mooring deployment in the Southern Ocean of less than 1.7 $\mu\text{mol kg}^{-1}$ over 6 months
169 ~~(Weeding and Trull, 2014).~~ The bio-optical sensors were measured against uranine solutions (with
170 secondary sealing to a phytoplankton culture to roughly estimate chlorophyll concentrations;
171 ~~Wetlabs, Inc.) to calibrate linear responses with precisions of better than 10%, and reproducibility for~~
172 ~~the set of three floats deployed in 2014 was found to be better than 4% for values obtained by exposure~~
173 ~~to plastic covers made of fluorescent and non-reflective plastics (Earp et al., 2011).~~ (Weeding and
174 Trull, 2014).

175 The bio-optical sensors measured chlorophyll-a fluorescence via stimulation/emission at 470/695
176 nm) and particulate backscattering at 700 nm. Chlorophyll-a fluorescence is a useful proxy for

177 chlorophyll-a concentration and standing stocks of phytoplankton biomass (Falkowski and Kiefer,
178 1985; Huot et al., 2007). Particulate backscattering provides a good proxy for particulate organic
179 carbon (Stramski et al. 2008; Cetinić et al, 2013). The bio-optical fluorescence sensors were calibrated
180 (by the manufacturer, Wetlabs, Inc.) against fluorescent uranine solutions as working standards, and
181 cross-referenced to prior measurements of a laboratory culture (25 mg m^{-3} chlorophyll) of the diatom
182 *Thalassiosira weissflogii* to yield chlorophyll estimates. These calibrations are warranted to yield
183 linear responses with precisions among multiple sensors of better than 10%, and (after one cycle of
184 testing and replacement with the manufacturer) we obtained reproducibility for the set of three floats
185 deployed in 2014 of better than 4% based on measurements with fluorescent and non-reflective
186 plastics (Earp et al., 2011). Accordingly, calculation of the chlorophyll fluorescence from the float
187 data was done by removal of the background dark signals measured prior to deployment and scaling
188 to chlorophyll using the manufacturer's calibrations. Similarly, the retrieval of particulate
189 backscattering, $b_{bp} (\text{m}^{-1})$, at 700 nm from the backscatter raw transmitted measurement (counts) was
190 done by applying the manufacturer-provided scaling factor after correction for dark counts (i.e.
191 measured signal output of the backscatterometer in clean water with black tape over the detector),
192 with the additional steps of removal of the pure seawater backscattering contribution (Zhang et al.,
193 2009), and scaling from the limited solid angle sensor measurement to the total backscattered
194 hemisphere based on relations estimated from observations for a wide range of marine particles (Boss
195 and Pegau, 2001; Sullivan et al., 2012). ~~Owing to the structure of the firmware for the floats and the~~
196 ~~varying power requirements for the sensors, the sampling rates differed for the physical and~~
197 ~~biogeochemical parameters. Temperature and salinity were sampled at the highest rates, yielding~~
198 ~~values at 2 decibar intervals (used in this work as equivalent to 2 meter depth intervals without density~~
199 ~~corrections); whereas oxygen, phytoplankton fluorescence, and particle backscatter were sampled at~~
200 ~~10 decibar intervals.~~

201 In contrast to typical Argo program float missions for climate studies (www.argo.org), which
202 consist of deep (2000 m) profiles every 10 days, the bio-profilers were programmed to focus on the
203 upper water column and carried out continuous profiling between the surface and 300 m depth,
204 achieving 4 to 6 profiles per day, depending on the stratification. This temporal resolution was
205 intended to allow examination of daily cycles related to insolation, photosynthesis, and respiration.
206 In practice, it proved difficult to extract clear cycles because of aliasing from spatial variations, ~~and~~
207 Consequently, after several weeks for the 2011 KEOPS2 deployment of bio-profiler #1, the frequency
208 of profiles was reduced to twice daily, to provide extended battery life while still obtaining night and
209 day observations to allow insolation quenching of the fluorescence response to be evaluated and
210 corrected, and thus to avoid inappropriate inference of subsurface chlorophyll maxima from the
211 fluorescence signal (~~Sackmann et al., 2008; Xing et al., 2012~~). (Sackmann et al., 2008; Xing et al.,
212 2012). For bio-profilers #2, #3, and #4 deployed in 2014, the missions were further refined, via
213 automated telemetric switching of mission configuration files, to carry out a deep profile to ~1500 m
214 every 3 days to provide deep reference points for temperature, salinity, and oxygen observations, and
215 also with the intention to slow the development of bio-fouling of the bio-optical sensors by exposing
216 surface organisms to high pressures. ~~Float deployment was done in 2011 by manual transfer to a small~~
217 ~~boat and then the sea while the ship was on station, and in 2014 by lowering the floats from the ship~~
218 ~~deck inside cardboard boxes designed to readily disintegrate.~~

219

220 **2.2 Float data quality control**

221 ~~As discussed in detail in the Results section below, the bio-profilers clearly provide an interesting~~
222 ~~and abundant source of measurements with which to examine correlations between biogeochemical~~
223 ~~and physical characteristics in the Kerguelen plume, but what is their level of fidelity? Are the values~~
224 ~~accurate, comparable, and free of temporal drifts? These are difficult questions to evaluate precisely,~~
225 ~~but some simple tests as summarized here, suggest that the data are reliable for our biogeochemical~~

226 ~~purposes, though more careful assessment against historical observations would be required for use~~
227 ~~in climate studies.~~

228 Extensive experience by the Argo program with profiling ~~floats~~float measurements for
229 temperature (T) and salinity, (S), including recovery of floats for post deployment tests ([Oka and](#)
230 [Ando, 1994](#)), suggests that these sensors reliably deliver accurate and precise observations (to better
231 than 0.005 °C and 0.01 salinity) over multi-annual deployments. Given our much shorter bio-profiler
232 deployments (3 to 6 months) and their observed T-S relationships which fall within those of the ship-
233 based KEOPS2 observations, we assume these variables are correct and make no further
234 ~~assessments~~assessment or ~~corrections~~correction. We similarly accept the oxygen observations, given
235 our careful attention to their pre-deployment calibration, their reasonable range of surface water
236 oxygen super-saturations (96-103% for low chlorophyll waters and extending up to 108% in
237 correlation with very high chlorophyll waters, as discussed further below), and their deep ocean
238 values (950-1000 m depths) which fall within the range of nearby ship observations and showed no
239 temporal trends and standard deviations of less than 4 ~~μmol~~ μmol kg^{-1} over the deployment periods
240 (ranging from 1 to 3.9 ~~μmol~~ μmol kg^{-1} for the four bio-profilers).

241 ~~For the bio-optical variables, to~~To evaluate the possibility of temporal sensor drifts in ~~sensor~~
242 ~~responses, bio-optical variables, we examined the variations of the bio-optical variables~~ in
243 mesopelagic (250-300 m) and deep water (950-1000 m) values, i.e. at depths where little signal was
244 anticipated and most profiles reached steady background values (Figure 2a). The
245 ~~backscatter~~particulate backscattering and, to a lesser extent, the Chl-a fluorescence signals showed
246 spikes which presumably reflect larger particles such as aggregates and zooplankton, motivating our
247 examination of average values over 50 m ranges (250-300 m and 950-1000 m depth layers) for the
248 assessment of temporal drifts. As shown in Figure 2a and quantified in Table 2, for most of their
249 deployment periods all four bio-profilers exhibited no significant temporal drift of these deep values,

250 but with a few important exceptions. The most important exception was except for bio-profiler #1,
251 for which high and erratic values of fluorescenceChl-a and backscatterb_{bp} began to occur after profile
252 #300 both at depth (Figure 2a) and throughout the water column (Figure 3.1c and e). We consider
253 this to be caused by bio-fouling and do not use this data in any subsequent analysis (this loss of signal
254 fidelity was one of the motivations for including periodic deep profiles in the subsequent three bio-
255 profiler deployments, as a means of retarding fouling). ~~In addition, a few discrete values (indicated~~
256 ~~by black arrows in Figure 2a), were considered unrealistic and these profiles were also not used~~
257 ~~further.~~ In contrast, the high fluorescence chlorophyll values found in mesopelagic waters from
258 profiles ~#110100 to ~#160170 along the bio-profiler #1 trajectory appear to be real and to reflect
259 the deep extension of high biomass occurrence at this time, as discussed further below (see also Figure
260 3.1c). Consequently, this range of profile was not taken into account for the drift calculation in Table
261 2. Overall, except for the bio-profiler #1, most of the bio-optical sensors showed a slight loss of
262 sensitivity with time, as indicated by the negative slopes of the trend of their responses in the two
263 considered depth layers (Table 2). Over the time course of the bio-optical sensor observations, these
264 sensor drifts were small in comparison to the changes observed for surface bio-optical values,
265 contributing less than 7% to either fluorescence or particulate backscattering. The only exception was
266 the drift for the bio-profiler #2 b_{bp} sensor in the 250-300 m layer, where drift appeared to have been
267 larger (though of course changes at this depth range may also be oceanic) and reached up to 19 % of
268 the low surface b_{bp} values for this bio-profiler.

269 We~~Fluorescence signals were also corrected our fluorescence signals~~ for daytime quenching.
270 This effect, which derives from the photo-inhibition of phytoplankton by an excess of light (maximum
271 at midday), decreases surface fluorescence (~~Falkowski and Kolber, 1995; Kiefer, 1973~~), (Falkowski
272 and Kolber, 1995; Kiefer, 1973) and, if uncorrected, can produce a false impression of subsurface
273 maxima in fluorescence derived chlorophyll profiles. ~~A selection~~We explain this correction and its
274 evaluation in considerable detail in the following paragraphs, but note that none of the conclusions
275 of the paper depend on these corrections because the same overall results are obtained if we use only

276 Chl-a fluorescence signals collected at night. Our purpose in detailing the correction is to contribute
277 to active discussion of the best way to use daylight Chl-a fluorescence data obtained from platforms
278 which may not have as good night time coverage as our floats (such as sensors deployed on seals, on
279 standard ARGO 10- day profile interval missions, or on float missions that target co-measurement
280 with daytime satellite ocean colour observations).

281 We defined the daytime profiles, potentially affected by quenching, as profiles acquired between
282 one hour after local sunrise time and one hour after local sunset time, to allow for dark acclimation
283 since quenching effect could still persist after sunset (Sackmann et al., 2008). Daytime profiles from
284 the four bio-profilers are shown to illustrate this effect (continuous lines in Figure 2b, left
285 panelspanel). To correct this bias, we applied the efficient method of Sackmann et al. (2008), which
286 uses the particulate backscattering signal as a relative reference. Below the depth of daytime
287 quenching we determined the fluorescence to backscattering ratio (over the depth range where it was
288 constant), and multiplied this ratio by the backscattering signal to extrapolate the fluorescence signal
289 to the surface. This assumes that phytoplankton populations are not stratified within the density
290 defined mixed layer. This works particularly well for deep mixed layers (For the sake of consistency
291 with the other studies of this issue, we defined the mixed layer depth, MLD, as the depth where
292 density increased by 0.02 kg m^{-3} relative to the density at 10 m; Park et al., 1998) (Park et al., 1998).
293 Within the deeper half of the mixed layer (targeted to be below the depth of daytime quenching), we
294 determined a mean value of the (relatively constant, see below) Chl-a fluorescence to b_{bp} ratio (at
295 depth defined as d_F/b_{bp}) and multiplied this ratio by the b_{bp} signal at this depth to retrieve the Chl-a
296 fluorescence. Then, we multiplied this same ratio by the surface b_{bp} value to estimate unquenched
297 surface Chl-a fluorescence, and interpolated between these two depths to obtain the unquenched Chl-
298 a fluorescence profile. This assumes that phytoplankton populations were not stratified within the
299 density defined mixed layer. This works particularly well for deep mixed layers ($>50 \text{ m}$) which

300 exhibit relatively constant Chl-a fluorescence/backscatter_{bbp} ratios (to within ~10%) in their
301 subsurface portions. We also identified profiles where daytime fluorescence quenching penetrated
302 below the MLD, but a region of uniform fluorescence/backscatter ratios could still be identified below
303 the MLD and this value was used for the extrapolation (for deeper half. In less than 15% of the total
304 quenching-corrected profiles). Finally, in less than 53% of the daytime profiles, in average, we could
305 not identify a region of uniform Chl-a fluorescence/backscatter_{bbp} and apply the quenching
306 correction; consequently, these profiles were not used further.

307 The greater spikiness of the backscatter_{bbp} profiles in comparison to those of fluorescence (as
308 illustrated in Figure 2b, right panels) means that this quenching correction introduces some noise into
309 the daytime chlorophyll estimates. In principle, this could be filtered or smoothed, but the low 10 m
310 vertical resolution of the observations made this rather uncertain and so we have used the unfiltered
311 observations throughout this paper (except in Figure 6f below where we show median-filtered
312 backscatter profiles for the sake of visual clarity). 9f below where we show median-filtered particulate
313 backscattering profiles for the sake of visual clarity). Note that to avoid to correct the surface Chl-a
314 fluorescence with a spiked surface b_{bp} value and create a “ b_{bp} spiked” interpolation, we verified before
315 that the b_{bp} surface value did not seem to be spiked, assuming that surface value should not exceed
316 more than $\pm 50\%$ of the b_{bp} value at the depth $d_{F/bbp}$, since within the mixed layer. This threshold was
317 defined after assessing the backscatterometer precision (using the coefficient of variation of b_{bp} , i.e.
318 the ratio of the standard deviation to the mean) between 500 and 1000 m depth of $14 \pm 4\%$ in average.
319 If the surface b_{bp} value was considered as spiked (less than 4% of the daytime b_{bp} profiles, except for
320 bio-profiler #4 for which it reached 9%), the test was done with the second depth value, until a “non-
321 spiked” value was found, and the value was then extrapolated to the surface.

322 The effects of the quenching correction on our selected chlorophyll profiles are shown in Figure
323 2b (middle panels, continuous lines), and summary statistics for all the profiles are provided in Table
324 23. Without the correction, on average, more than 9070% of the daytime profiles exhibited a
325 subsurface maximum exceeding 3060% of the surface value: defined after assessing the fluorometer

error (coefficient of variation of Chl-a concentration) between 250 and 300 m depth and between 500 and 1000 m depth of $22 \pm 10\%$ in average. After applying the quenching correction this method, the number of daytime profiles exhibiting a subsurface maximum exceeding 60% of the surface value was reduced to very similar levels to those observed in the night time profiles (of less than 50%), although slightly higher (of 21% in average), indicating, with the fact that these daytime subsurface maxima occurred mostly below the MLD, that the correction was largely successful. Notably, for the total data set, after quenching correction, less than 11% of the profiles exhibited a deep maximum exceeding 100% of the surface value (Table 23), and these profiles were primarily located in a restricted region near the Gallieni Spur, as discussed further in the Results section.

Even after our quenching correction, 10% of the corrected daytime profiles (in average for all 4 bio-profilers) still exhibited significant decrease of the Chl-a fluorescence in the surface layer. We were not able to conclude if these decreases were due to an incomplete quenching correction or if they were true features, given that ~ 14% of the night profiles in average exhibited subsurface values at least 60% higher than the surface values. Consequently, we defined a threshold surface value for each bio-profiler, defined as a slightly lower value than the minimum surface value reached during night profiles (see squares in Figure 2b, middle panel, and caption) and we flagged all the corrected daytime profiles that had a surface value lower than this threshold as potentially arising from incomplete correction of quenching. These distinctions between night, daytime and flagged profiles are illustrated in Figures 4, 5 and 7, and further discussed in the Results and Discussion sections below. Note that, using a different quenching correction method, Biermann et al. (2015) recently observed similar features and statistics in fluorescence profiles collected by southern elephant seals during austral summer in the vicinity of Kerguelen Island.

349 Finally, we emphasize that the bio-optical measures of chlorophyll and particulate backscattering
350 are based on laboratory calibrations that are not specific to Southern Ocean phytoplankton or particle
351 properties. This means that while interpretation of local variations is reasonably straightforward,
352 quantitative comparisons to other observations much more uncertain (except perhaps in the future for
353 other serial numbers of these sensors, calibrated in the same limited way). For the 3 bio-profilers
354 deployed in 2014, no ancillary shipboard measurements are available to evaluate this issue, but in
355 2011 some chlorophyll samples were collected by the KEOPS2 science team that allow for limited
356 evaluation of the bio-profiler #1 calibration.

357 Bioprofiler #1 was deployed into a semi-permanent meander of the Polar Front, which the
358 KEOP2 program examined as a Lagrangian time series following surface drifters. As shown in Figure
359 2c, the first and second stations in the meander (E1 CTD-27 on 29 October 2011 at 22:46 local time
360 and E2 CTD-43 on 1 November 2011 at 12:00 local time) bracketed the locations of the first 11
361 autonomous bio-profiler #1 profiles (Figure 2c.i). The bio-profiler #1 temperature profiles are
362 intermediate between the ship results (Figure 2c.ii), with the variations in temperature profiles mainly
363 driven by vertical motions associated with internal waves (Park et al., 2014b). In Figure 2c.iii, the
364 KEOPS2 shipboard fluorescence results are displayed after linear calibration to high pressure liquid
365 chromatography (HPLC) total chlorophyll-a results from below 40 meters depth (below the depth of
366 non-photochemical quenching). The data reveal two important features: i) good fits achieved below
367 40 meters do not extend to the surface – where fluorescence/chlorophyll-a ratios were higher than at
368 depth, apparently as a result of community composition variations with depth (see also Lasbleiz et al.
369 2014), and ii) the bio-profiler #1 fluorescence data displayed similar characteristics and good accord
370 with the shipboard results. In light of the limited available data, a non-linear calibration of
371 fluorescence to chlorophyll-a was not pursued, and no adjustments were made to the laboratory bio-
372 profiler calibration.

373 These variations in fluorescence/chlorophyll-a ratios within individual CTD casts in the
374 shipboard observations serve as a strong reminder that fluorescence is an imperfect proxy for

375 chlorophyll-a concentrations, owing to variations with phytoplankton community structure,
376 physiology, and other effects (e.g. Babin et al., 1996; Cullen, 1982; Suggett et al., 2011). Thus,
377 interpretation of our sensor records, as with any bio-optical sensor results, must keep this in mind and
378 avoid over-interpreting small variations in fluorescence as necessarily resulting from variations in
379 chlorophyll or phytoplankton biomass.

380 **2.3 Satellite data ~~comparisons~~sources**

381 ~~To~~We used satellite products to provide physical and biological context for the bio-profiler
382 trajectories ~~and, including~~ the effectiveness of their sampling of high biomass waters downstream of
383 Kerguelen, ~~we compared them to satellite products. For estimates. The images~~ of surface chlorophyll
384 concentrations ~~we used~~shown in Figure 1 to provide context for the plume sampling achieved by the
385 bio-profilers are the CLS SSALTO/DUACS 4 km daily product derived from NASA MODIS-Aqua
386 ~~and~~ observations (Figure 1), without modification for recent suggestions that this algorithm may
387 underestimate chlorophyll ~~based on observations in low chlorophyll waters south of Australia~~
388 ~~(Johnson et al., 2013). Bio-profiler trajectory comparisons to eddy circulations were based on~~
389 expectations for in low chlorophyll waters south of Australia (Johnson et al., 2013).

390 To better understand the observed bio-profiler trajectories, we calculated expected movements
391 based on geostrophic currents estimated from satellite altimetry using the multi-satellite global
392 product Delayed Time Maps of Absolute Dynamic Heights (DT-MADT) developed by the
393 CNES/CLS Aviso project (~~www.aviso.oceanobs.com~~); www.aviso.oceanobs.com). This product has
394 1 week temporal and 1/3° spatial resolutions, and was used to compute Lagrangian trajectories to
395 produce a diagnostic for eddy retention (d'Ovidio et al., 2013; Figure 7b). ~~This diagnostic~~9b and
396 water origin and age (d'Ovidio et al., 2014; Figure 8). Eddy retention is a measure of how much time
397 a synthetic water parcel has been recirculating within an eddy core. Long-lived and coherent eddies
398 are characterised by ~~the~~ water parcels with high values of retention (measured in days ~~passed since~~

399 thea water parcel has been entrained by thean eddy), whereas recently formed eddies or eddies that
400 exchange strongly with surrounding regions have low retention values. Following d'Ovidio et al.
401 (2014) and Sanial et al. (2014), we used back-tracking of virtual water parcels (from the bio-profiler
402 profile locations) to compute how long ago (water age) and at which latitude (water origin) the
403 sampled parcels had been in contact with the Kerguelen Plateau (defined as the 700 m isobath, as
404 shown in red in Figure 3.1). Figure 8 a) and c), adapted from d'Ovidio et al. (2014), display example
405 maps of the calculated daily snapshots of these water ages and water origins. For each pixel in these
406 maps, virtual water parcels were back tracked for 90 days. They are shown as white pixels on the
407 maps if during that time they never touched the Kerguelen Plateau (shown in grey on the map), and
408 otherwise are coloured for the time between the contact with the plateau and the day of the map
409 computation (water age, Figure 8a) and the latitude of the last contact with the plateau stored (water
410 origin, Figure 8c). These same computations were performed for each location sampled by the bio-
411 profilers, in order to compare the water ages and origins with their measured chlorophyll inventories.

412

413 **3 Results**

414 **3.1 Coverage of the plume**

415 The drifts of the bio-profilers provided coverage of a large portion of the elevated biomass plume
416 (Figure 1), covering territory from near the Kerguelen plateau to more than 700 miles downstream
417 (71 to 95° E) and nearly 400 miles from north to south (47.5 to 54° S), thereby spanning waters of
418 the Polar Frontal and Antarctic Zones (Orsi et al., 1995; Park et al., 2008b; Sokolov and Rintoul,
419 2009). (Orsi et al., 1995; Park et al., 2008b; Sokolov and Rintoul, 2009). Unfortunately, this breadth
420 of spatial coverage of the plume did not extend to full temporal seasonal coverage, and this is
421 important to keep in mind given the strong seasonal cycle of biomass accumulation (Trull et al., this
422 issue; Blain et al., 2007; Mongin et al., 2008). (Trull et al., 2015; Blain et al., 2007; Mongin et al.,
423 2008). As shown in these images, the 2011 bio-profiler covered the period of highest biomass

424 accumulation, while the 2014 deployments occurred after this seasonal peak, and thus sampled the
425 system during its senescence. ~~This provides~~ (to illustrate these prior conditions, Figure 1 also includes
426 biomass distribution images from late 2013, before the launch of the three bio-profilers in early 2014).
427 Thus, the profilers obtained some seasonal context for the central portion of the plume (which was
428 sampled well in 2011 by bio-profiler #1 in spring and summer and again by bio-profilers #2 and #3
429 in summer and autumn). However, sampling of the north-eastern portion of the downstream plume
430 (north of the Polar Front) was achieved only in late summer and autumn (by bio-profiler #4).

431 Bio-profiler #1 in spring 2011 and bio-profiler #3 in 2014 were deployed in the centre of the
432 quasi-stationary cyclonic recirculation just east of the northern Kerguelen plateau ~~(d'Ovidio,~~
433 ~~2014; Park et al., 2014).~~ (d'Ovidio et al., 2014; Park et al., 2014a). Both bio-profilers exited this region
434 to the northeast, tracking towards the Gallieni Spur, before transiting strongly southward near 74°
435 E. This southward transport has also been observed for surface drifters and appears to be associated
436 with a persistent meander of the Polar Front ~~(d'Ovidio, 2014; Park et al., 2014).~~ (d'Ovidio et al., 2014;
437 Park et al., 2014a). Thus bio-profilers #1 and #3 provide spring and summer perspectives respectively
438 for these portions of the biomass plume (albeit in different years).

439 Bio-profiler #2 was deployed further south, close to the region where the strong north to south
440 transport portions of the bio-profilers #1 and #3 trajectories finished. Thus bio-profiler #2 provided
441 some overlap with the southern portion of the bio-profiler #1 trajectory, before being carried the
442 furthest south, where it explored cold waters close to the Williams Ridge that extends to the southeast
443 of Heard Island and terminates near the Fawn Trough (a gap in the plateau which permits the passage
444 of much of the deep water eastward transport; Park et al., 2008b; 2014~~2014a~~). Waters in this region
445 tend to exhibit archetypical high-nutrient, low-chlorophyll characteristics, and were used as a
446 reference station for iron non-fertilised waters during the KEOPS field program in 2005 (Blain et al.,
447 2007; 2008).

448 In contrast, bio-profiler #4 was deployed at similar latitude to bio-profilers #1 and #3, but further
449 east, in particular east of the southward meander of the Polar Front which carried these others to the
450 south. Bio-profiler #4 remained in the northern portion of the plume throughout its deployment,
451 drifting to the northeast roughly parallel to the shallow Eastern Kerguelen Ridge before becoming
452 trapped in a cyclonic eddy in which it obtained a time series of ~100 profiles (as discussed in detail
453 below).

454

455 3.2 Overview of observed oceanographic properties

456 The bio-profilers return a ~~huge amount~~large number of water column data; ~~each one provides~~
457 ~~more than most oceanographic voyages. Thus~~observations making visualisation at the scale of
458 individual profiles ~~is only possible for targeted issues, and the~~. The simplest first-order assessment is
459 most easily done by presenting the results as along-trajectory sections. These are shown for all the
460 observed variables for each bio-profiler in Figures 3.1, 3.2, 3.3 and 3.4, and briefly described in the
461 following paragraphs.

462 Bio-profiler #1, launched in late October 2011 in the centre of the deep water recirculation just
463 east of Kerguelen Island, initially encountered cold, ~~fresh~~, well oxygenated waters with moderate
464 biomass ($T \sim 3\text{ }^{\circ}\text{C}$, $\text{O}_2 \sim 330\text{ }\mu\text{mol kg}^{-1}$, $0.5\text{ }\mu\text{g L}^{-1} < \text{Chl-a} < 2\text{ }\mu\text{g L}^{-1}$; profiles 1-90, Nov.). It was
465 then carried north-eastward across the Gallieni Spur where it encountered warmer waters with
466 extremely high biomass ($T \sim 5\text{ }^{\circ}\text{C}$, chlorophyll up to nearly $10\text{ }\mu\text{g L}^{-1}$), which satellite ocean colour
467 animations suggest was being swept northward as a mix of waters from the northern and central
468 regions of the Kerguelen plateau (see the animation “bloom 2011” in supplementary material; [Trull](#)
469 [et al., 2014](#)[2015](#)). During the subsequent southward transport, it crossed the Polar Front near 51.5°
470 S, as shown by the presence of a temperature minimum near 150 m depth: ($T \sim 1\text{ }^{\circ}\text{C}$; profiles ~ 200 -
471 220, end of Jan.). The shoaling of low dissolved oxygen layers in this region provides another
472 indication of their Antarctic Zone oceanographic classification. Surface waters above this remnant

473 winter water were relatively warm (~~$\geq 6^{\circ}\text{C}$~~) despite deep mixed layer depths ($\sim 100\text{ m}$), $T > 6^{\circ}\text{C}$
 474 profiles $\sim 240\text{--}330$, Feb.-Mar.). Much of this warming is probably seasonal, as these waters were
 475 encountered in late summer, but the co-occurrence of somewhat elevated salinity (~ 33.8) suggests
 476 that flow of Polar Frontal Zone surface waters over the Antarctic waters was also involved. During
 477 the February bio-profiler transit, these waters exhibited only low to moderate chlorophyll biomass
 478 ($\sim 1.5\text{ }\mu\text{g L}^{-1}$), although satellite images suggest higher concentrations ($\sim 3\text{ }\mu\text{g L}^{-1}$) were present earlier
 479 in December and January (see Figures 1b and 1c and the animation “bloom 2011” in supplementary
 480 material; Trull et al., 20142015). The particulate backscattering signal reflected the chlorophyll
 481 evolution along most of the trajectory, except in January when, as the ~~high~~-chlorophyll levels
 482 decreased, ~~backscattering~~ (from $>3\text{ }\mu\text{g L}^{-1}$ to $\leq 2\text{ }\mu\text{g L}^{-1}$), b_{bp} remained high and constant, ($-2.5\text{ m}^{-1} \leq$
 483 $\log(b_{\text{bp}}) \leq -2.0\text{ m}^{-1}$), suggesting detrital particles developed from the high chlorophyll biomass, - or
 484 possibly a (relatively large) change in chlorophyll/particulate organic carbon ratio (Chl/POC) due to
 485 phytoplankton community composition. Finally, after 300 shallow profiles, bio-fouling of the
 486 fluorescence and ~~backscatter~~particulate backscattering sensors ~~marks~~marked the end of their utility,
 487 as shown by the occurrence of elevated and highly noisy values throughout the water column (see
 488 Figure 3.1c and e).

489 Bio-profiler #2, launched in late January 2014 south and east of the recirculation feature, initially
 490 encountered Polar Frontal Zone waters which were present further south in this region than during
 491 the 2011 year sampled by bio-profiler #1. For approximately the first 150 profiles, these waters
 492 displayed relatively homogenous, moderately warm temperatures ($4\text{--}5^{\circ}\text{C}$) that continued to warm
 493 to $\sim 6^{\circ}\text{C}$ through February. The bio-profiler then transited much further south, briefly encountering
 494 waters with strong shoaling of subsurface cold, salty, low oxygen characteristics ~~near profile~~around
 495 profiles 160,–170 ($S \sim 34.0\text{--}34.2$, $\text{O}_2 \sim 260\text{ }\mu\text{mol kg}^{-1}$), and entered colder Antarctic waters where it
 496 remained through profile ~ 220 , at which time its return north brought it back into Polar Frontal Zone

507 waters showing autumn cooling. Throughout its life, in comparison to bio-profiler #1, only low-to-
508 moderate biomass waters were encountered ($< 1.5 \mu\text{g L}^{-1}$), though these values were persistently well
509 above Southern Ocean HNLC background values ($< 0.65 \mu\text{g L}^{-1}$). Within this range, the higher
500 biomass values, which also extended over greater vertical extents, ($\sim 100 \text{ m}$), were found in the
501 Antarctic waters: (profiles 170-250, Mar.-Apr.). In contrast, the higher backscattering b_{bp} values were
502 found at the beginning of the trajectory, ($\log(b_{bp}) \sim -2.5 \text{ m}^{-1}$), and their deep extent and high values
503 compared to chlorophyll levels suggest the existence of higher chlorophyll concentrations prior to the
504 bio-profiler deployment. ~~After this initial difference, the backscattering~~ This is in agreement with
505 satellite ocean colour animations on which high biomass development is observed in December 2013
506 in the area of the bio-profiler deployment (see Figures 1e and 1f and the animation “bloom 2013” in
507 supplementary material). After this initial difference, the b_{bp} variations followed those of chlorophyll
508 along the rest of the trajectory.

509 Bio-profiler #3, launched in late January 2014 in the northern portion of the recirculation feature,
510 followed a similar trajectory to that of bio-profiler #1 launched in October 2011, and encountered
511 much warmer waters with similar mixed layer depths, between ~~5040~~ and ~~10070~~ m. (Figure 3.3).
512 Presumably this represents seasonal warming as salinities were similar to those encountered in spring,
513 (~ 33.85), and the warming from $\sim 3^\circ\text{C}$ to nearly 6°C is consistent with seasonal warming
514 amplitudes observed in satellite surface temperature records for unfertilized open ocean Polar Frontal
515 Zone waters ([Trull et al., 2001](#)). ~~Persistently higher~~ Persistent high chlorophyll levels were also
516 observed initially in the recirculation region (up to ~ 4 versus $\sim 1 \mu\text{g L}^{-1}$), but the float did not cross
517 the Gallieni Spur (GS in maps of Figure 3) where bio-profiler #1 encountered values up to nearly 10
518 $\mu\text{g L}^{-1}$. During its transit south near ~~74°~~75° E, only Polar Frontal Zone waters were encountered, and
519 chlorophyll levels remained moderately high: (between 1 and 2 $\mu\text{g L}^{-1}$). At the beginning of the
520 trajectory, the particulate backscattering b_{bp} signal evolved in concert with the chlorophyll signal, but
521 with a ~ 7 -10 day delay. Another difference between the two biomass parameter evolutions was the
522 large increase of ~~particle backscatter~~ b_{bp} compared to chlorophyll between the surface and 100 m, right

523 after the profiler turned southward in the vicinity of the Gallieni Spur- (~ profiles 190-205, end of
524 March).

525 Bio-profiler #4, deployed well east of the recirculation feature in early February, was initially in
526 warm, ~~fresh~~quite salty and ~~highly~~well oxygenated waters, characterized by moderate biomass (first
527 80 profiles: ~~chlorophyll~~T ~ 5.5 °C, S ~ 33.8, O₂ ~ 310 μmol kg⁻¹, Chl-a < 1.5 μg L⁻¹, log(b_{bp}) ~ 3.35
528 m⁻¹). ~~Then, as~~As its trajectory approached the Gallieni Spur, surface waters became progressively
529 warmer, fresher and less oxygenated- (profiles 80-250: T ~ 7 °C, S ~ 33.7, O₂ ~ 290 μmol kg⁻¹).
530 During this time, the bio-profiler ~~encountered a biomass rich filament, characterized by~~recorded high
531 ~~and correlated~~ chlorophyll and particle concentrations (chlorophyll values reaching up to 3 μg L⁻¹ for
532 profiles 80-130). ~~As it drifted further east~~This high biomass could be a remnant of the rich filament
533 that transited in this area a month prior to the visit of the bio-profiler (see the animation “bloom 2013”
534 in supplementary material). As the bio-profiler drifted further east, it was entrained in a relatively
535 stationary cyclonic eddy where it performed several loops before exiting to the south- (profiles ~ 130-
536 240, mid-March – mid-April). This eddy can be identified from altimetry as retentive – i.e. capable
537 of entraining Lagrangian particles for, in this case, a few weeks to one month (~~d’Ovidio et al.,~~
538 2013; (d’Ovidio et al., 2013; Figure 7b8b)). While retained by this mesoscale eddy, the bio-profiler
539 measured a relatively constant profile of temperature and salinity, with slowly decreasing ~~chlorophyll~~
540 ~~and backscatter~~Chl-a concentrations and b_{bp} (Figure 78). Relatively constant hydrological properties
541 throughout this period and the repeated looping suggest a largely Lagrangian trajectory within a single
542 water parcel at this time. Of all the observations, this region displayed surface waters with the highest
543 temperatures and lowest salinities- (T ~ 8.0 °C, S ~ 33.6).

544

545 4 Discussion

546 With this overview of the spatial and temporal characteristics of our observations in hand, we
547 can proceed to evaluate our research questions.

548 549 4.1 Do the satellite images of surface chlorophyll reflect ~~total inventories~~ water column 550 contents?

551 ~~To~~ As discussed in the Introduction, it is important to determine whether the water column
552 information provided by the bio-profilers changes perspectives on the mesoscale distributions of
553 chlorophyll as seen in satellite images (Figure 1) This is a larger issue than whether our in-situ
554 measurements of surface values differ from satellite values. We did not evaluate this issue we did not
555 compare our limited results to those from satellites (that question owing to only a small number of
556 match-ups as limited by extensive cloud cover), instead we considered our greatly limiting match-
557 ups between bio-profiler and satellite observations, and because we know that both our sensor
558 calibrations and the satellite algorithms have large uncertainties (see the Methods sections 2.2 and
559 2.3). Instead, we examined the bio-profiler water column observations to determine what biases might
560 be expected from observing only their upper portions, i.e. as a satellite would. There are two aspects
561 of this issue that we could readily address: i) were subsurface chlorophyll maxima commonly present
562 below the depth of satellite observation, and did they vary spatially or temporally? ii) were surface
563 chlorophyll values linearly and tightly correlated with water column inventories with similar dynamic
564 ranges, or were surface values poor guides to water column inventories? We address these issues in
565 this order in the following paragraphs.

566 Our statistics on the occurrence of subsurface chlorophyll maxima (Table 2), which
567 these features are relatively rare and were present in a significant fraction of the profiles (up to 14%
568 of the night profiles and up to 21% of the quenching-corrected day profiles). They mostly occurred
569 at depths greater than the MLD (Table 3) and, thus, too deep to be taken into account in the satellite

570 observations. Without radiation sensors on the bio-profilers, the first penetration depth (z_{pd} , light
571 attenuation by $1/e$) that characterizes satellite observations could not be directly estimated, but based
572 on the model of Morel and Maritorena (2001; their figure 6), and using the relationship $z_{pd} = z_{eu}/4.6$
573 for the euphotic zone definition of the 1% photosynthetically active radiation level (Gordon and
574 McCluney, 1975), it was at most 10-15 meters, and thus always within the mixed layer. Thus, we
575 focused on these subsurface maxima occurring below the MLD (hereafter SubMax_{>MLD}) and we
576 examined the location of the profiles exhibiting these features as well as their associated depth (see
577 Figures 4a, 4b, 4d and 4e).

578 These SubMax_{>MLD} were quite localized. They occurred primarily near to the plateau and/or close
579 to the location of the Polar Front (Figure 4). Specifically, most of the profiles exhibiting this feature
580 were found in the vicinity of the steep slope between the Northern Kerguelen Plateau and the Gallieni
581 Spur, between 40 and 600 m depth. (Figures 4a, 4b, 4d and 4e). Occurrences of subsurface
582 maxima SubMax_{>MLD} were much more sporadic south of 50° S, on the south-eastward trajectories of
583 bio-profilers #1 and #2. From this These conclusions about the locations of subsurface chlorophyll
584 maxima are similar for both night and day occurrences (stars and open circles in Figure 4,
585 respectively), although SubMax_{>MLD} of day flagged profiles occurred mostly at shallow depths (< 50
586 m, Figures 4b and 4d) and may result from an under-correction of the surface quenched Chl-a
587 concentrations (see Methods section 2.2). It seems that light limitation may not be a major driver of
588 subsurface Chl-a maxima via the mechanism of increased Chl-a production per cell, at least under a
589 certain threshold of Chl-a content, since SubMax_{>MLD} observed by bio-profilers #3 and #4 occurred
590 more frequently when the mixed layer was deep (for $2.5 \mu\text{g L}^{-1} \leq \text{Chl-a} \leq 5 \mu\text{g L}^{-1}$; Figures 4c and
591 4f). However, the quasi-ubiquitous concomitance of SubMax_{>MLD} for bio-profiler #1 with shallow
592 mixed layers, less than 50 m, suggests that above a certain threshold of Chl-a content, self-shading
593 may promote pigment production by phytoplankton at depth.

594 Subsurface chlorophyll maxima beyond the reach of satellite imagery can be thought of as a
595 specific class of the wide range of possible chlorophyll distributions (such as varying thicknesses of
596 relatively constant near-surface biomass layers, or changes in the rate of decrease of biomass with
597 depth) that could introduce bias between surface concentration and water column inventory
598 perspectives. To gain perspective, their presence is likely to lead to underestimation from satellite
599 images of total chlorophyll inventories in this region. However, this effect is actually rather minor.
600 To evaluate it on the overall importance of these possibilities, we compared surface chlorophyll
601 estimates from the bio-profilers with their total concentrations measured by the profilers (using the
602 shallowest ~10 m depth observation since this was reliably within both the 1/e satellite ocean colour
603 penetration depth and the mixed layer) with their column inventories. For the surface estimates we
604 used the average of the top 50 meters in each profile (a depth which was within the mixed layer for
605 the majority of the bio-profiler profiles and which represents ~2 e folding depths for the satellite
606 observations under conditions of low chlorophyll; we also calculated results for just the top 25 m,
607 and found indistinguishable results). For the total column inventories we averaged down to from all
608 observations in the top 200 m (a depth below which negligible chlorophyll was observed). As since
609 chlorophyll distributions generally reduced to background values below this depth). These
610 comparisons, shown in Figure 5, the surface and total estimates show 5a (left column), display
611 reasonably linear relationships over almost the entire range of observations, although the surface
612 estimates are consistently higher than the total ones for chlorophyll concentrations higher than $1 \mu\text{g L}^{-1}$. This suggests that variations in surface layer mixing, and the associated impact on the vertical
613 distributions of chlorophyll, contribute insignificant bias where chlorophyll was low ($< 1 \mu\text{g L}^{-1}$) but
614 lead to over-estimation where chlorophyll was moderate to high ($> 1 \mu\text{g L}^{-1}$). As such, satellite images
615 tend to overestimate the dynamic range of total chlorophyll both night and daytime observations. This
616 was especially true for bio-profilers #1 and #3 (correlation coefficients $r^2=[0.60-0.85]$), which include
617 high chlorophyll values (greater than 2 mg m^{-3} for the surface concentration and greater than 160 mg
618 m^{-2} for the 0-200 m inventory). Most of the flagged daytime profiles (red circles in Figure 5a) seem

620 to be shifted slightly left of the linear regression lines, suggesting that they may well represent under-
621 corrected quenched chlorophyll rather than true features. Overall, qualitatively, these quite linear
622 relationship between surface Chl-a concentration and 0-200 m integrated Chl-a content suggests that
623 satellite observations are reasonably good indicators of the spatial distributions water column
624 chlorophyll inventories.

625 Concerning the particulate backscattering signal, the linear correlations between surface values
626 and inventories, although this effect is relatively small, less than a factor of two even for surface
627 chlorophyll concentrations as high as $10\text{ }\mu\text{g L}^{-1}$. Given that our bio-profilers did not sample close to
628 the plateau during the early summer peak in biomass as seen in satellite images, it is possible that
629 there could be greater biases under these conditions. We also performed the same calculations for the
630 backscatter signal, and found similar non-linearity, with negligible bias for surface backscatter were
631 generally not as strong as for Chl-a, except for bio-profiler #3, as shown in Figure 5b (right column:
632 $r^2 = [0.29-0.74]$. It appears that surface b_{bp} values lower than $\sim 3.52 \times 10^{-43}\text{ m}^{-1}$, and a significant bias
633 towards vary similarly to the 0-200 m b_{bp} inventories, whereas higher estimates for surface values
634 higher than this threshold value (where exhibit noisier correlations when compared to the 0-200 m
635 integrated b_{bp} contents (see the slope breaks in the relationship between surface and total column
636 backscatter, see 0-200 m integrated b_{bp} in Figure 65b). The origin of this non-linearity is not clear, and
637 its evaluation is potentially compromised by the spikiness of the backscatter records and their poor
638 vertical resolution, motivating refinement of bio-profiler firmware to allow achieve more frequent
639 observations, potentially for subsets of profiles to retain reasonable mission duration. b_{bp} records and
640 their poor vertical resolution. The particulate backscatter profiles (Figures 2b, 3e and 9e) suggest that
641 spikes may be particularly common at the base of the mixed layer and below, and thus might reflect
642 differential control of phytoplankton and total particle populations. Future deployments with

improved firmware to yield higher resolution may be able to advance the interesting possibility that backscatter information can provide ecosystem perspectives beyond phytoplankton biomass alone.

Because our qualitative assessment indicated that surface Chl-a concentrations provide a relatively unbiased indication of the water column Chl-a inventory, we now try to go a little bit further towards a quantitative assessment of possible biases between satellite and in-situ Chl-a perspectives. First, we compared the coefficients of variation (i.e. the ratio of the standard deviation to the mean) of the surface chlorophyll concentrations and of the water column inventories. Using only the night data to avoid quenching correction uncertainties, surface distribution coefficients of variation (#1: 82%; #2: 20%; #3: 39%; #4: 43%) revealed very similar relative dispersions to the water column (0-200 m) inventory coefficients of variation (#1: 84%; #2: 20%; #3: 34%; #4: 31%). Thus, satellite images reasonably reflect the relative range of mesoscale variability in water column phytoplankton biomass accumulations. Surprisingly, surface chlorophyll values (i.e. satellite images) would tend to slightly overestimate the relative dispersion of Chl-a data for bio-profilers #3 and #4, despite those profiles exhibiting the largest numbers of night subsurface maxima (in %, Table 3). This means that the association of high surface chlorophyll concentrations with shallow chlorophyll layers was more important than the presence of subsurface chlorophyll maxima in determining the relationships between surface and water column inventories.

To further explore this issue, we calculated expected water column inventories for chlorophyll layers confined to the physical mixed layer depths at the time of observation (by multiplying each surface concentration by its associated mixed layer depth, MLD). This is akin to trying to improve satellite assessments using mixed layer depth information from, for example, standard ARGO floats that measure only temperature and salinity. These comparisons are shown in Figure 6a and reveal that this approach badly underestimates water column inventories (at least with our MLD definition) and that this underestimation is very common. Most of the “0-200 m integrated Chl-a/(surface Chl-a × MLD)” ratios range from 1/1 to 4/1, with a few profiles of bio-profilers #1 and #3, at the time when

they recorded the highest bio-optical values, reaching ratios of 20/1 (profiles ~ 70-130 for bio-profiler #1 and profiles ~ 0-70 for bio-profiler #3). Moreover, the colour coding in Figure 6a shows that this bias is strongest for shallow mixed layers in general. In other words, the presence of significant amounts of chlorophyll below the mixed layer is very common (though generally not as local vertical chlorophyll maxima, for which our statistics confine the occurrence of those exceeding 60% of surface to 17% of the sampled locations and those exceeding 100% of surface to 11% of the sampled locations). Notably, this bias still persists strongly if we change our MLD definition to the much larger criterion of Levitus (1982; density increase of 0.125 kg m^{-3} relative to the density at 0 m). For this criterion, the (surface Chl-a \times MLD) estimation ranged between half and twice the 0-200 m integrated Chl-a content for MLD deeper than 60 m (close to half for MLD ~ [60-90] m and surface Chl-a $< 2 \mu\text{g L}^{-1}$ to close to twice for MLD > 120 m and surface Chl-a $> 2 \mu\text{g L}^{-1}$). However, (surface Chl-a \times MLD) estimations were still twice to four times lower than the 0-200 m integrated Chl-a content recorded by the bio-profilers when the MLD ranges between 40 and 60 m (not shown).

The most probable explanation for these observations is that the mixed layer at the time of observation was shallower than at the time of generation of the biomass. This is of course expected as a result of seasonal shallowing of the mixed layer, but the magnitude of the effect is important to recognize (as we have shown above) it is well above what could be corrected using some other mixed layer depth criterion. Interestingly, there appears to be a relatively simple hyperbolic relationship between the ratio “0-200 m integrated Chl-a” / “surface Chl-a \times MLD” (hereafter designated as X) and MLD, as shown in Figure 6b for the MLD definition of Park et al. (1998). It also holds for the MLD definition of Levitus (1982). This X vs MLD hyperbola reaches an asymptote of $X \sim 1$ for MLD values close to the 150-200 m depths of regional winter mixed layers (visible as temperature minima remnant signatures of winter cooling in profiles south of the Polar Front in Figure 3b). Moreover, the curve is reasonably well parameterized by $X \sim \text{MLD}^t / \text{MLD}^w$, in which the superscripts t and w

693 indicate mixed layer depths at the time of observation and the end of winter, respectively. This
694 relationship could arise if most biomass accumulation occurred in early deep mixed layers with
695 subsequent stratification adding little additional biomass, or if mixed layers shallowed and deepened
696 episodically as biomass accumulation developed throughout the season.

697 Overall, these results emphasize the major challenges that are present for connecting surface
698 chlorophyll distributions to total water column biomass and primary productivity, since they reveal
699 that physical mixed layer depths are often not a reliable guide to biomass distributions. These physical
700 and biological responses seem to be modulated differently on diel, weather, and seasonal timescales,
701 and are also affected by the mesoscale and sub-mesoscale interleaving of water parcels. The
702 quantification of near surface mixing (i.e. going beyond the limited mixed layer depth concept) is
703 currently under very active exploration and debate in the context of seasonal drivers of production
704 (Behrenfeld, 2010; Taylor and Ferrari, 2011), and these data reveal the need to extend those
705 perspectives to shorter time and space scales. The presence of significant amounts of chlorophyll
706 below the mixed layer is also important to its ultimate fate –if this biomass is not re-entrained then it
707 may well contribute preferentially to export and to mesopelagic oxygen consumption (issues which
708 we revisit in Discussion section 4.3 below).

709 **4.2 Do regions of high biomass correlate with (local) oceanographic properties?**

710 To evaluate this issue, we examined bivariate regressions of surface chlorophyll (top 50 Chl-a
711 inventories (0-200 m) with physical water column characteristics, after separation of having separated
712 the observations into two groups: 1) $\text{Chl-a inventories} > 200 \text{ mg m}^{-2}$ in rich biomass regions close to
713 the plateau, and 2) $\text{Chl-a inventories} \leq 200 \text{ mg m}^{-2}$ in moderate biomass regions far from the plateau
714 (see the rich and moderate biomass regions considered here are identified by red and yellow rectangles
715 in Figures 3.1c, 3.2c, 3.3c and 3.4c). As shown in Figure 6.7 (a, b and c), the richest biomass
716 regions encountered by bio-profiler #1 in 2011 and bio-profiler #3 in 2014 were associated with
717 waters with very similar properties, specifically moderate temperatures ($3.5\text{-}4.75^\circ\text{C}$), high salinities

718 (33.82-33.8685), and thus relatively high densities (sigma-theta values of 26.8-27). The 7-26.9 kg m⁻³). The bio-profiler #1 distributions of chlorophyll with these properties showed linear decreases on
 719 either side of these values, suggestive of mixing with surrounding waters. The origins of this
 720 particular class of waters is difficult to discern from our data, but based on surface drifter maps much
 721 poorer in Chl-a. This characteristic is also observed between integrated Chl-a and mean surface
 722 oxygen saturation (O_{2 sat}, Figure 7f), for which the high O_{2 sat} states (reaching 10%) indicate oxygen
 723 production in these high biomass waters (since these values exceeding expected from processes such
 724 as warming or bubble injection; Shadwick et al., 2014). Relatively high biomass was also encountered
 725 in waters with extreme T-S properties (the warmest and freshest observed) in the vicinity of the
 726 Gallieni Spur by bio-profiler #4 (black symbols in Figure 7). Thus, there was not a unique class of
 727 waters with high biomass. This perspective is further reinforced by the lack of any clear relationships
 728 between chlorophyll inventories and local water column properties for regions of moderate biomass,
 729 including versus mixed layer depth and the intensity of stratification as represented by the Brunt-
 730 Väisälä frequency (Figure 7, right column). These low biomass waters also exhibited lower O_{2 sat}
 731 states (95-103%) than those of rich biomass areas. The under-saturated oxygen levels reflect either
 732 strong local respiration or the supply of low oxygen waters from below, with these processes difficult
 733 to distinguish (except for specific portions of the bio-profiler #4 trajectory where time series within
 734 constant physical property layers were obtained, as discussed in section 4.3).

736 Linking local water parcel properties to past water trajectories with respect to the Kerguelen
 737 Plateau, as a known natural source of iron fertilization, provides an additional view of the role of
 738 water mass properties in the control of chlorophyll inventories. For the richest Chl-a waters (T ~ 4
 739 °C, S ~ 33.83, σ ~ 26.8 kg m⁻³) encountered by bio-profiler#1, surface drifters released during the
 740 KEOPS2 voyage (d'Ovidio et al., 2014) appears to suggest these waters derive from the northern
 741 Kerguelen plateau. Thus this The computation of trajectories based on satellite altimetry (see Methods

742 section 2.3) for all the bio-profilers confirms this perspective and also indicates that the time since a
743 water mass left the plateau (Figure 8b) is another important determinant of chlorophyll levels
744 (presumably as a result loss of Fe over time after its addition from the plateau; d'Ovidio et al., 2014).
745 These results are shown in Figure 8. Figure 8 b) and d) compares water age and origin with the 0-200
746 m Chl-a inventories for spring (bio-profiler #1, in blue in the plots) and summer (bio-profilers #2, #3,
747 #4, in black in the plots). Beside a strong seasonal difference –spring values range from up to 1000
748 mg m^{-2} , whereas in the summer few measurements exceed 300 mg m^{-2} – water parcels corresponding
749 to high Chl-a inventories appear to be waters that have recently left the Kerguelen Plateau (20-40
750 days of water age; Figure 8a) and come generally from its northern part ($[-49; -47]$ °S; Figure 8c).
751 Bio-profilers locations that correspond to water parcels that have not touched the Plateau in the last
752 100 days (points shown in white for water age = 100 in Figure 8b) do not present any high integrated
753 Chl-a values, suggesting that the main source of iron fertilization for the explored water masses is
754 horizontal advection from the Kerguelen Plateau. This correlation of high Chl-a inventories with age
755 since leaving the plateau is unlikely to be biased by the lower frequency of sampling (shown in the
756 Figure 8b inset) of older waters, given that a statistical test based a 10^4 samplings of a uniform
757 distribution of integrated Chl-a at the sampling frequency of each water age yielded a probability (p)
758 of not-sampling integrated Chl-a value greater than 200 mg m^{-2} for water parcels with water ages
759 greater than 40 days of $p < 10^{-4}$.

760 These results suggest that the northern Kerguelen Plateau is an important target region for future
761 studies of iron delivery mechanisms. ~~For the moderate biomass observations into the plume~~
762 ~~downstream. In terms of the secondary influences of mixed layer depth and stratification, the bio-~~
763 ~~profiler #1 profiles with integrated Chl-a greater than 600 mg m^{-2} were mainly characterized by a~~
764 ~~shallow mixed layer, lower than 60 m (Figure 7d), and a low stratification ($-0.01 \text{ s}^{-2} < \max N^2 < 0 \text{ s}^{-2}$;~~
765 ~~Figure 7e). Below this Chla-a inventory threshold, no clear relationships with mixed layer depth~~
766 ~~emerged (Figure 6), suggesting a limited influence on production by light limitation, i.e. deep mixing~~
767 ~~was insufficient to lower light levels to limiting levels. But for the high biomass observations, there~~

768 is a tendency for the highest chlorophyll concentrations to occur preferentially in shallow mixed
769 layers, suggesting self shading may become a limiting factor on production as biomass between MLD
770 or N² and 0-200 m integrated chlorophyll (Figures 7d and 7e). In a steady state perspective, this lack
771 of correlation could arise because mixed layers were shallow enough that light limitation was not
772 sufficient to halt phytoplankton accumulation, yet not so shallow that mean mixed layer light levels
773 become very high (Figure 6). This inference has allowed light promoted growth to reach
774 accumulations that became self-shading (viewpoints that have been made developed previously from,
775 based on relationships between fluorescence and mixed layer depth observations in this region using
776 sensors on elephant seals (Blain et al., 2013). Finally, for the highest chlorophyll profiles, mixed
777 layer oxygen saturation states were as high as 8%, exceeding levels expected from processes such as
778 warming or bubble injection (Shadwick et al., 2014), and thus representing biological production;
779 Blain et al., 2013). Importantly, our observations emphasize that chlorophyll distributions do not track
780 the shoaling of mixed layer depth on seasonal or weather timescales, and thus that MLD variability
781 is unlikely to show simple relationships to biomass accumulation. This point has also been
782 emphasized in terms of competing effects of light and Fe limitation responses to MLD variability
783 (Joubert et al., 2014), for waters where vertical Fe supply is dominant (rather than the horizontal
784 dominance of supply studied here).

785

786 **4.3 Can the fate of surface enrichments in biomass be determined, and if so, what is the** 787 **percentage of biological production exported?**

788 Evaluating this question requires the extraction of a temporal perspective from the bio-profiler
789 records, and is thus only possible for portions of their trajectories which appear to be essentially
790 Lagrangian. The best record for this approach is for bio-profiler #4 during the period when it carried
791 out several clockwise loops in late autumn, i.e. for profiles 150-240 (Figure 3.4a). During this time,

21

792 its trajectory was very similar to that expected based on surface currents estimated from satellite
793 altimetry, the density stratification of the water column was relatively steady, and the T-S profiles
794 were tightly grouped (~~Figure 7~~-Figures 9b, 9c and 9d). These observations suggest that the profiler
795 remained within a single water parcel, that was entrained by a retentive eddy and underwent only
796 small exchanges with surrounding waters, as shown by slightly warmer (profiles 165-170 and 200-
797 220) and cooler (profiles 175-195) conditions along the trajectory (these are discussed further below).

798 At the start of this period, (blue lines subset in Figure 9e), chlorophyll profiles showed
799 ~~elevated~~moderate to high surface mixed and subsurface layer levels, near $1.5 \mu\text{g L}^{-1}$, ~~and thus well~~
800 ~~above HNLC background values, with some profiles exhibiting subsurface maxima (Figure~~
801 ~~7e)-reaching up to $1.5 \mu\text{g L}^{-1}$ between 50-70 m depth and up to $1 \mu\text{g L}^{-1}$ around 120 m depth. Both~~
802 the surface constant Chl-a layer and the subsurface “chlorocline” layer (by analogy to thermocline or
803 halocline, “chlorocline” is defined here as the depth range with the highest chlorophyll concentration
804 gradient) were thick, equal to ~ 80 m and ~ 50 m, respectively. The origin of these the smaller and
805 variable subsurface features~~maxima seen in some profiles in Figure 9e~~ is uncertain. One possibility
806 is that they are remnants of the high surface chlorophyll biomass observed just prior to the eddy
807 entrapment (~~Figure 3.4e~~visible in Figure 3.4c and the “bloom 2013” animation in the supplementary
808 material), that had been carried to depth by particle settling or by subduction of the denser, saltier,
809 and slightly cooler water associated with that high biomass. ~~After the start of~~Associated b_{bp} profiles
810 showed similar large variations with strong local maxima correlated to local Chl-a maxima (blue lines
811 subset in Figure 9f). The strong variability of the Chl-a/b_{bp} profiles over the first 100 m suggests
812 possible changes in the composition of the particulate assemblage (blue lines subset in Figure 9g).

813 During the Lagrangian eddy entrapment period, the surface mixed layer chlorophyll levels
814 declined further from $1.5 \mu\text{g L}^{-1}$ to $\leq 1 \mu\text{g L}^{-1}$ (Figure 3.4c and 7e). ~~This~~9e). Since the constant
815 chlorophyll surface layer shallowed progressively with time, this Chl-a decrease much exceeds~~did~~
816 not result from the possible effect of dilution by mixed layer deepening ~~of less than 10%, (i.e.~~
817 entrainment). Furthermore, the chlorocline content decreased briefly before re-increasing

818 progressively in its upper part, and thus indicates then its deeper part. In parallel, b_{bp} and Chl-a/ b_{bp}
819 profiles became tighter and tighter (light blue to orange profiles in Figures 9f and 9g) before re-
820 exhibiting larger variations (red profiles). These results suggest the possibility of some chlorophyll
821 conversion to non-fluorescent material, or its removal by export to depth or by local respiration or
822 both, throughout the eddy entrainment. They may also of course partly reflect small spatial variations
823 in the structure of the biomass distributions.

824 To evaluate these possibilities we examined changes in three layers, the surface layer (labelled
825 layer 1 and defined as the surface down to the 26.6 isopycnal surface), and two density layers
826 immediately below it (layers 2 and 3, respectively for density ranges 26.6-26.8 and 26.8-26.9). In
827 order to characterize the existence of vertical or horizontal mixing during the eddy entrainment, mean
828 temperature, salinity, depth of the density layers, as well as their thickness and their stratification
829 state, are shown in Figure 810 (a, b, and c). The thickness and mean depth of the surface density layer
830 were relatively constant in the first half of the eddy entrainment, then slightly increased as some
831 warmer and fresher - thus lighter - water entered into the eddy structure (profiles 200-220).
832 Contrastingly, the physical properties of the two deeper underlying density layers showed
833 insignificant temporal trends and smaller variability over the period of interest, and thus changes in
834 their biogeochemical properties can be attributed to local processes rather than exchanges.

835 The evolution of chlorophyll, ~~backscatter~~particulate backscattering and dissolved oxygen
836 inventories also exhibited different trends and variability for each layer (as shown in Figure 810d, e
837 and f). In surface layer 1, mean chlorophyll and ~~backscatter~~ b_{bp} showed no overall temporal trend
838 (green and grey curves in Figure 810d, respectively), although characterized by two maxima, one at
839 the beginning of the eddy and one coinciding with the fresher warmer water occurrence described
840 above. The oxygen content continuously decreased steadily until after profile 200, when larger
841 variations were observed, with a minimum content coinciding with the fresher warmer waters. Within

842 the underlying layer 2, chlorophyll, backscatter_{bbp} and oxygen inventories showed similar evolutions:
843 all had maximums at the beginning of the eddy and then decreased with time until the bio-profiler
844 exited the eddy (Figure 8e10e). These characteristics were also present in the deepest layer 3, although
845 with significant differences in the magnitudes of change, specifically the oxygen decrease was similar
846 to that of layer 2, but the chlorophyll level and its absolute magnitude of decrease were much smaller,
847 and the backscatter_{bbp} levels remained relatively high for a longer portion of the record.

848 ~~These variations suggest the following overall interpretation.~~ To verify that these changes were
849 oceanographic, we again evaluated fluorometer and oxygen sensor drifts, but this time only over the
850 range of profiles considered for the eddy entrapment investigation (following the approach used in
851 Table 2, of examining the evolution of the mean values within the depth layer 950-1000 m). Chl-a
852 and O₂ drifts were respectively estimated to be +0.017 $\mu\text{g L}^{-1}$ and +1.05 $\mu\text{mol kg}^{-1}$. Thus, the temporal
853 drifts probably lead to underestimations of the observed decrease of Chl-a (of ~7% in layer 2 and of
854 ~ 20% in layer 3) and of O₂ (~30% in layers 2 and 3). Knowing that excluding the contribution of the
855 drifts would only reinforce the trends described above, we can now suggest the following overall
856 interpretation to explain these variations of Chl-a, b_{bp} and O₂ in these 3 density layers during the eddy
857 entrapment of bio-profiler #4. In the surface layer 1, the chlorophyll inventory seems to result from
858 the combination of local biological processes with weak horizontal resupply from warmer, fresher,
859 and less oxygenated water (Figures 7a9a and 49d). In the middle density layer 2, where mixing is
860 considered insignificant because of the tightly grouped T-S properties, the chlorophyll decrease does
861 not seem to be due to local transformation to non-fluorescent detritus since no corresponding increase
862 in the backscatter_{bbp} signal was observed (Figure 8e10e). This leaves loss by settling or respiration
863 as possible explanations. Loss by settling is certainly possible on this timeframe (rates of only a few
864 meters per day are required), and the high backscatter_{bbp} values found in the lower density layer 3
865 around profiles 160-180 could reflect transfer from the overlying layer 2. Biomass loss by respiration
866 and remineralization to dissolved inorganic carbon is almost certainly also occurring given the
867 decreasing oxygen inventories of the middle layer 2 and deep layer 3. For both these layers the rate

868 of chlorophyll loss is too small (by factors of 2-3, assuming a moderately high phytoplankton
869 C/~~Chl-a~~Chl-a ratio of 50) to explain all the oxygen decrease, implying that degradation of detritus
870 (represented by the decreasing ~~backscatter~~particulate backscattering signal) and dissolved organic
871 matter probably also contributes (this remains true even if we use a very high phytoplankton C/~~Chl-a~~
872 ~~ratio of 100; (Cloern et al., 1995))~~Chl-a ratio of 100; Cloern et al., 1995). For the deepest layer 3,
873 remineralization of settling particles coming from above with a minor remineralization of local
874 chlorophyll may best explain the slower decrease of chlorophyll in comparison to that of oxygen.

875 In combination, these results suggest that not all of the accumulated biomass was respired in the
876 surface layer, with the CO₂ then returned to the atmosphere, and thus that there was some
877 ~~sequestration~~export. Quantifying ~~the sequestration~~this export amount is difficult and merits a
878 modelling and sensitivity assessment that is beyond the scope of this paper. Here we simply provide
879 an indication of its possible magnitude by comparison of the rates of mean oxygen loss in the surface
880 layer 1 (representing carbon likely to be returned to the atmosphere) versus the subsurface layers 2
881 and 3 (representing carbon which may be ~~sequestered~~exported in the ocean interior). The linear fits
882 to the oxygen decreases for layers 1, 2, and 3 (as shown in Figure 810) imply oxygen consumption
883 rates of approximately 5, 4, and 4 $\mu\text{mol m}^{-3} \text{ d}^{-1}$, respectively. These values lie towards the lower end
884 of estimates for annual rates at mesopelagic depths (~~Sarmiento et al., 1990~~)(Sarmiento et al., 1990).
885 Comparing O₂ consumption of layers 2 and 3 (by multiplying the O₂ consumption rate by the
886 thickness and the average density of the layer) relative to the total mean consumption among the three
887 layers, we estimate ~~40~~that 35% of the CO₂ produced during this autumn period of bloom decline was
888 ~~sequestered (25%~~exported from the surface layer (with 20% respired within layer 2 and 15% within
889 layer 3). An analogous area of low-to-moderate production and relatively high export was observed
890 during the KEOPS2 field cruise just south of Polar Front, in a meander area around 72.5° E – 49°
891 S where the flow – considered as Lagrangian – was sampled in few stations as a time series

([Laurenceau-Cornec et al., this issue 2015](#); [Planchon et al., this issue 2014](#)). This area coincides with the location of the anti-cyclonic trajectory of bio-profiler #3, around profile #110, where moderate biomass production was observed (Figure 3.3c), although spatial variations in this region unfortunately precluded estimation of biologically driven oxygen consumption from the bio-profiler.

896

897 **5 Conclusions**

898 The bio-profilers revealed several interesting aspects of the enriched biomass plume downstream from the Kerguelen plateau, by providing observations of its vertical dimension. First of all, the observations show that surface and total water column chlorophyll inventories are generally well correlated, which suggests that satellite perspectives on bloom spatial dynamics (e.g. [Mongin et al., 2008](#); [2009](#)) are unlikely to be strongly biased. This result holds true despite the presence of ~~weak~~ (30% moderate (60% above surface values) subsurface chlorophyll maxima in ~36 up to ~20% of all the profiles, and strong (100% above surface values) in ~~~12~~ 10% of all the profiles (Table ~~23~~ and Figure 4). Furthermore, satellite surface observations seem to well reflect the water column relative range of mesoscale variability in biomass accumulations. However, half of these subsurface maxima were within the first 50 m depth, which corresponds to the depth range over which retrieval of water column Chl-a inventory from satellite surface observations is not simple. The bio-profilers often recorded significant quantities of biomass below the surface data were integrated. That could partly explain why the mixed layer, potentially correlated to the magnitude of total degree of shallowing of the mixed layer from deep winter values. The mixed layer at the time of the observations may not be the best parameter to quantify the chlorophyll still correlates well with surface inventories, especially when stratification by advection of lighter water mass or by seasonal warming creates strong density variations in the upper layer and, thus, shallow mixed layers, and considering that chlorophyll even when subsurface maxima are present (Figure 5). Our inference of lack of bias in satellite evaluations of the bloom spatial patterns production may have occurred much earlier than at the time of the

917 observations. And of course, our work does not ~~mean~~imply that satellite chlorophyll estimates are
918 necessarily accurate. That is an issue which our data cannot address owing to the imprecision of the
919 bio-optical sensors and the absence of calibration against local chlorophyll observations, an approach
920 which recent work has shown to be necessary (~~Johnson et al., 2013~~).for satellite estimates as well
921 (Johnson et al., 2013).

922 ~~The occurrence of weak subsurface chlorophyll maxima in our data (~36% of all profiles) was~~
923 ~~higher than for results obtained with fluorescence sensors deployed on elephant seals around the~~
924 ~~Kerguelen plateau (<9%; Guinet et al., 2012) but lower than observed with other sets of autonomous~~
925 ~~floats elsewhere in the Southern Ocean (Carranza et al., 2014). This difference~~The occurrence of
926 moderate subsurface chlorophyll maxima in our data (17%) was higher than for results obtained with
927 fluorescence sensors deployed on elephant seals around the Kerguelen plateau (~9% using a criterion
928 of 30% excess over surface values to define the maxima; Guinet et al., 2012). This may reflect the
929 greater proportion of observations in the southern portion of the plume in the Guinet et al. (2012)
930 study, a region where we also found that subsurface maxima were ~~uncommon (14%~~less common (~4%
931 of profiles for bio-profiler #2; for our moderate criterion of 60% excess, Table 23, and ~6% using
932 their 30% criterion, data not shown). Subsurface maxima were also uncommon well downstream to
933 the east of the Kerguelen plateau. This is interesting in that it suggests that subsurface iron levels
934 supplied by upwelling or vertical mixing were insufficient to drive biomass accumulations at the base
935 of the mixed layer, or at least were less important than horizontal supply of Fe in surface waters. This
936 is in contrast to Polar Frontal Zone waters much further to the east south of Australia where persistent
937 subsurface maxima have been observed (~~Parslow et al., 2001~~),(Parslow et al., 2001), and with
938 observations from other autonomous profiling floats elsewhere in the Southern Ocean in which small
939 subsurface maxima were found to be common in summer below the mixed layer (~~Carranza et al.,~~
940 ~~2014~~).(Carranza et al., 2014). Variations in the relative intensities of surface and deep iron supplies

941 is a possible cause of these variations, but other processes may also be involved. As an example, the
942 origin of the relatively more common and stronger subsurface chlorophyll maxima near the Gallieni
943 Spur is not clear. Settling of surface biomass generated earlier in the season (Figure 1) and/or seasonal
944 depletion of iron in surface waters which reduces phytoplankton ~~abundances~~growth rates are
945 possibilities, but they cannot be assessed given our lack of early seasonal observations. A third
946 possibility of the overlaying of low density waters southward across the Polar Front appears less
947 likely, given that shipboard observations during ~~KEOP2~~KEOPS2 found that this process generated
948 shallow high biomass layers (at the Polar Frontal stations F-L, TEW-7, and TEW-8; ~~(Lasbleiz et al.,~~
949 ~~2014; Trull et al., 2014).~~(Lasbleiz et al., 2014; Trull et al., 2015).

950
951 Our initial research goals included looking for oxygen ~~production~~supersaturations in deep
952 chlorophyll maxima ~~(Spitzer and Jenkins, 1989),~~to estimate net community production (Spitzer and
953 Jenkins, 1989), but this could not be achieved owing to confounding effects on super-saturations from
954 strong mixing with higher productivity overlying waters, and on ~~apparent~~aliasing of daily cycles
955 ~~from~~by internal waves ~~(Park et al., 2008a).~~(Park et al., 2008a). Thus our results cannot address the
956 issues of whether productivity in subsurface layers may partly explain offsets between satellite and
957 in-situ estimates of the Southern Ocean biological pump ~~(Schlitzer, 2002)~~(Schlitzer, 2002) or whether
958 the phytoplankton that grow in deep chlorophyll maxima are preferential contributors to carbon
959 export ~~(Kemp et al., 2000; Queguiner, 2013).~~(Kemp et al., 2000; Queguiner, 2013). We were able to
960 make a first simple assessment of subsurface autumn oxygen consumption during the portion of the
961 bio-profiler #4 trajectory that delivered a quasi-Lagrangian time series, and this provided the very
962 useful result that approximately ~~40~~35% of the biomass respiration in that period occurred beneath the
963 mixed layer, and thus ~~under conditions at depths~~ favouring CO₂ ~~sequestration in~~export toward the
964 ocean interior. This ~~40~~35% can be approximately equated to an export/production “e-ratio” of 0.4-,
965 which is relatively high by global standards, but in the middle of the large range of values observed
966 in cold Southern Ocean waters ~~(Maiti et al., 2013).~~(Maiti et al., 2013), and similar to f-ratios estimated

967 for high biomass waters over the central Kerguelen plateau in autumn during the KEOPS1 campaign
968 ~~(Trull et al., 2008).~~(Trull et al., 2008). Of course the subsequent fate of the ~~sequestered~~exported CO₂
969 inferred from the bio-profiler #4 observations is uncertain, in that these waters were still within the
970 depth range of possible exposure to the atmosphere during later deeper winter mixing, although the
971 larger scale circulation in this region suggests it is a region dominated by subduction ~~(Sallée et al.,~~
972 ~~2010).~~(Sallée et al., 2010).

973

974 Our simple correlative evaluation of the bio-profiler observations of biomass variations revealed
975 that the highest chlorophyll levels were observed in surface waters with a narrow range of densities
976 and moderate temperatures (~~(σ_t ~26.9 ± 0.05, ρ ~1025.5 kg m⁻³, T ~4 ± 0.5°C; Figure 67).~~ This occurrence of
977 maximum biomass at moderate temperatures, along with the lack of correlation with mixed layer
978 depth (Figure 67) suggests that local controls on growth rates were less important than the history of
979 the levels of iron supplied in this water type. Notably, water with these properties was found
980 preferentially near the northern Kerguelen plateau and Gallieni Spur suggesting iron supply from this
981 region. This is consistent with geostrophic circulation estimates and a favourable wind regime for
982 upwelling in this region during the 2011 KEOPS2 period when bio-profiler #1 was deployed
983 ~~(d'Ovidio, 2014; Gille et al., 2014).~~(d'Ovidio et al., 2014; Gille et al., 2014) and with Lagrangian
984 analyses that backtrack water parcels to identify their origin. Further observations and
985 ~~analysis~~analyses are of course necessary to determine the generality of this inference that the northern
986 Kerguelen plateau provides the major source of iron to the downstream biomass plume. This is
987 especially true given the limited seasonal and inter-annual scope of our bio-profiler observations.

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Acknowledgements

This work was supported by the Australian Commonwealth Cooperative Research Program via the ACE CRC. M. Grenier was supported by a conjoint LEGOS and ACE CRC postdoctoral appointment- and a [CAMPUS FRANCE grant \(FASIC award # 30418QG; campusfrance.org\)](#). A. Della Penna was supported by a conjoint Frontières du Vivant (Paris 7) and CSIRO-UTAS Quantitative Marine Science PhD scholarship. We thank Ann Thresher (CSIRO) for the harvesting and processing of the data from the bio-profilers, as supported by the Australian Integrated Marine Observing Argo and Southern Ocean Time Series facilities. We thank Cedric Cotté and Francesco d'Ovidio (LOCEAN, Université de Paris VI) and the crew of the *RV Marion Dufresne* for bio-profiler deployments, and Stephane Blain and Bernard ~~Queguiner~~[Quéguiner](#) for KEOPS2 voyage leadership.- Thanks to Vito Dirita, Alan Poole, and Craig Hanstein (CSIRO) for bio-profiler preparation, and Craig Neill and Kelly Brown (CSIRO) for oxygen optode calibrations. Thanks to Helen Phillips (IMAS) for fruitful discussions and advice concerning physical analyses of the hydrological variables, and Francesco d'Ovidio (~~University of Paris~~[LOCEAN, CNRS](#)) for insights into Lagrangian perspectives on water parcel trajectories and their evolution. Finally, we gratefully acknowledge Dr S. Thomalla and an anonymous reviewer for their valuable comments on an earlier version of the paper that allowed us to improve it significantly.

1009 **List of Tables**

1010 Table 1. Bio-profiler deployments.

1011 Table 2. Drift assessment of the bio-profilers over their life time within the [250-300] m and [950-
1012 1000] m depth layers.

1013 Table 3. Fluorescence quenching corrections and subsurface chlorophyll maxima statistics.

Figure Captions

Figure 1. ~~Bi~~Maps of bio-profiler trajectories (white and grey lines) in comparison to satellite over
remotely sensed chlorophyll-a distributions: (a-h: daily, 4 km CLS/CNES product; i: weekly
composite from GlobColour 4 km product). Top row: 2011 ~~year~~bloom season for bio-profiler #1.
Middle and bottom rows: 2013-14 ~~year~~2014 bloom and beginning of post-bloom season for bio-
profilers #2- (light grey trajectory), #3-4- (dark grey trajectory) and #4 (white trajectory). Red
squares ~~show~~indicate the bio-profiler locations on ~~corresponding to the day of the image dates.~~ The
black thick line refers to the position of the Polar Front measured from hydrographic samples by
Park et al. (2014a).

Figure 2. a) Assessment of bio-optical sensor stability from temporal evolution of ~~the mean~~
chlorophyll and ~~backscatter~~particulate backscattering values ~~within~~averaged over two depth ranges,
250-300 m (lines) and 950-1000 m (stars), ~~for the 4 bio-profilers.~~ Arrows indicate discrete profiles
~~or ranges of profiles considered to be affected by bio-fouling, and~~which were not used in further
analysis. b) Illustration of quenching corrections, showing pairs of successive ~~day/night or night/day~~
profiles (day: continuous lines; night: dashed lines). For each bio-profiler, the ~~panels show~~panel
shows: chlorophyll profiles without quenching correction (left), chlorophyll profiles with quenching
correction (middle), and associated backscatterparticulate backscattering profiles (right). Squares in
the middle panel represent threshold values of the lowest surface chlorophyll concentration for the
night profiles of each bio-profiler (#1: 0.7 $\mu\text{g L}^{-1}$; #2: 0.4 $\mu\text{g L}^{-1}$; #3: 0.65 $\mu\text{g L}^{-1}$; #4: 0.7 $\mu\text{g L}^{-1}$).
These threshold were used to flag day profiles having surface chlorophyll concentration still below
this threshold after the quenching correction (see Table 3, Figures 4 (squares), 5 (red circles) and 7
(squares)), for which quenching might have been under-corrected. c) Comparison of bio-profiler #1
fluorescence Chl-a estimates to shipboard results obtained by the KEOPS2 project., c.i. Location of
KEOPS2 stations E1 (blue symbols) and E2 (black symbols) along a quasi-Lagrangian track

1039 followed by bio-profiler#1 (red symbols); c.ii Temperature profiles showing similar structures of
1040 the ship and bio-profiler sampled water columns; c.iii Fluorescence profiles (lines) showing that the
1041 bio-profiler provided similar fluorescence results to the ship CTD mounted sensor, and that both
1042 exhibited complex relationships to Niskin bottle total chlorophyll-a sample values (dots; see text for
1043 further discussion).

1044

1045 Figure 3.1. Bio-profiler #1 observations

1046 a) ~~Bio~~bio-profiler #1 trajectory over the bathymetry, with each point representing a depth profile
1047 and the colour of the points changing from blue to red over time (dates are shown below the bottom
1048 plots). The 700 m isobath is represented by the red line contour. KI = Kerguelen Island; KP =
1049 Kerguelen Plateau; HI = Heard Island; GS = Gallieni Spur. b-f) Evolution of hydrological
1050 parameters along the float trajectory: b) temperature (°C), c) chlorophyll ($\mu\text{g L}^{-1}$), d) salinity;
1051 (unitless), e) backscatter (particulate backscattering (b_{bp} ; log scale; m^{-1}), and f) dissolved oxygen
1052 ($\mu\text{mol kg}^{-1}$). ~~White~~The white line represents the mixed layer depth. Red and yellow rectangles refer
1053 to rich and moderate chlorophyll areas used in Figure 67 and discussed in Section 4.2.

1054

1055 Figure 3.2. ~~As~~Bio-profiler #2 observations (see Figure 3.1, but caption for bio-profiler #2 details).

1056

1057 Figure 3.3. ~~As Figure 3.1, but for bio~~Bio-profiler #3: observations (see Figure 3.1 caption for
1058 details).

1059

1060 Figure 3.4. ~~As~~Bio-profiler #4 observations (see Figure 3.1, but caption for bio-profiler #4 details).

1061

1062 Figure 4. Locations of subsurface chlorophyll maxima. Left: areas with subsurface chlorophyll
1063 maxima exceed the surface content by more than a) 30% and b) 100%. Right: associated depths of
1064 the chlorophyll maxima.

1065

1066 Figure 5. Comparison of surface (0-50 m) and water column integrated (0-200 m) biomass
1067 distributions for each bio-profiler. Left column: fluorescence phytoplankton biomass estimates.
1068 Right column: backscatter total biomass estimates (note that scales are slightly larger for bio-
1069 profiler #1 than for the others).

1070

1071 Figure 6. Chlorophyll relationships with surface water properties for a) temperature; b) salinity; c)
1072 density; d) mixed layer depth (MLD); e) oxygen saturation state. The left column shows results for

1073 Figure 4. Characteristics of subsurface chlorophyll maxima occurring at depths greater than the
1074 mixed layer depth and exceeding the surface content by more than 60% (top) and 100% (bottom). a)
1075 and d): geographical areas where these subsurface Chl-a maxima occur with an expanded view for
1076 the Gallieni Spur region; b) and e): associated depths of these subsurface Chl-a maxima along the
1077 bio-profiler trajectories (i.e. versus profile numbers); c) and f): relationship between the amplitude
1078 of these Chl-a maxima (in $\mu\text{g L}^{-1}$) and the mixed layer depth (MLD, in m). Symbols: stars refer to
1079 night profiles, circles to day profiles and squares to flagged day profiles (i.e. which still exhibit, in
1080 the surface layer, a large concentration decrease toward low surface values that indicates the
1081 possibility of incomplete quenching correction; see definition in the caption of Figure 2b).

1082

1083 Figure 5. a) Surface chlorophyll concentrations (in mg m^{-3}) compared to chlorophyll inventories (0-
1084 200 m; in mg m^{-2}), for each bio-profiler. b) Surface particulate backscattering (m^{-1}) compared to
1085 particulate backscattering inventories (0-200 m), for each bio-profiler. Note that scales are slightly

1086 larger for bio-profiler #1 than for the others; the dashed rectangles in upper plots indicate the scales
1087 used for the other bio-profilers. Night profiles (black circles), day profiles (green circles) and
1088 potentially quenching under-corrected day profiles (red circles, flagged as defined in the caption of
1089 Figure 2b) are distinguished. Correspondingly, the green and black lines refer to the linear
1090 regression of day and night profiles, and their associated correlation coefficients, r^2 .

1091

1092 Figure 6: a) Chlorophyll water column inventories (in mg m^{-2}), estimated by multiplying surface
1093 chlorophyll concentrations by the mixed layer depth, compared to chlorophyll inventories (0-200 m;
1094 in mg m^{-2}) recorded by the bio-profilers. Only night and unflagged day profiles are represented. The
1095 colour code shows the associated depth of the mixed layer (in m). The 5 lines $y = x$, $y = 2x$, $y = 4x$,
1096 $y = 8x$ and $y = 20x$ are given as indicators to quantify the ratio between the “surface Chl-a \times MLD”
1097 product and the 0-200 m integrated Chl-a.

1098 b) Representation of the X factor ($X = (0\text{-}200 \text{ m integrated Chl-a}) / (\text{surface Chl-a} \times \text{MLD})$) as a
1099 function of the mixed layer depth (in m), for the total data set. Symbols and colours are defined in
1100 the legend.

1101

1102 Figure 7. Relationship between 0-200 m integrated chlorophyll a concentration and various water
1103 properties for a-f) high biomass regions close to the plateau (bio-profilers #1 and #3) or entrapped
1104 in eddies (bio-profilers #2 and #4; red rectangles in Figures 3.1, 3.2, 3.3 and 3.4). The right column
1105 shows results for) and g-l) moderate biomass regions far from the plateau (yellow rectangles in
1106 Figures 3.1, 3.2, 3.3 and 3.4). a) and g): surface temperature (in $^{\circ}\text{C}$); b) and h): surface salinity
1107 (unitless); c) and i): surface density (in kg m^{-3}); d) and j) mixed layer depth (MLD; in m); e) and k)

1108 maximum Brunt-Väisälä frequency squared (N^2 ; in s^{-2}) f) and l) oxygen saturation state (in %).

1109 Symbols and colours are defined in the legend.

1110

1111 Figure 7. Eddy entrainment of bio-profiler #4

1112 Figure 8: Lagrangian diagnostics computed from altimetry. Maps of age and origins of the water
1113 parcels shown in plots (a) and (c) are from Figure 4 of d'Ovidio et al. (2014). White pixels represent
1114 water parcels that have not touched in the past 100 days the Kerguelen Plateau (defined by the 700
1115 m isobath and shown in grey). Comparison of these age and origin metrics with the bio-profiler
1116 total integrated Chlorophyll-a values are shown in plots (b) and (d). Blue dots correspond to data
1117 collected during spring (bio-profiler #1, mean values in red) and black dots to data collected during
1118 summer (bio-profilers #2, #3, #4, mean values in magenta). White dots correspond to water parcels
1119 that have not touched the Kerguelen Plateau. The inset in plot b) shows the number of
1120 measurements for each water age. The black arrow highlights the fact that low Chl-a levels
1121 associated with water parcels that have not touched the Kerguelen Plateau within the last 100 days
1122 is supported by a large number of samples and, thus, seems to be a robust feature.

1123

1124 Figure 9. Eddy entrainment of bio-profiler #4.

1125 a) Identification of entrainment along the bio-profiler trajectory, coloured by with the colour of the
1126 points changing, from blue to red over time, from blueprofile 150 to redprofile 240.

1127 b) Overlay of bio-profiler trajectory with map of (white line) and eddy retention (see Methods for
1128 details of the retention calculation), relative to profile 177 (red square). A consistent sector indices,
1129 showing the portion of the trajectory is located within a long-lasting (more than 30 days) retentive
1130 structure (more than 30 days of retention). The red square marks the temporal reference (profile

1131 177) from which the Lagrangian trajectories were computed for the retention statistic, as described
1132 in Methods section 2.3.

1133 ec) Temperature-salinity diagram. Colours correspond to location on the map in a).

1134 d) Temperature versus depth section with mixed layer depth (black line) and isopycnals indicated
1135 (white lines).

1136 ~~d) Temperature-salinity diagram, coloured as on the map.~~

1137 e) Chlorophyll profiles, coloured as on the map.

1138 ~~f) Backscatter and separated, for the sake of clarity, in 4 subsets of ~23 profiles, coloured as on the~~
1139 ~~map. (equivalent to ~2 weeks of data acquisition).~~

1140 f) As e), but for particulate backscattering (b_{bp}) profiles.

1141 g) As e), but for the chlorophyll/ b_{bp} ratio.

1142 Note that chlorophyll and ~~backscatter~~ b_{bp} signals were filtered for visual clarity, using a 3 point
1143 running median.

1144

1145 Figure 810: Temporal evolution of physical and biological properties during the eddy entrainment
1146 ~~for~~of bio-profiler #4, for three density layers: with sigma-theta ranges of surface-26.6; 26.6-26.8;
1147 26.8-26.9. Left: Mean column plots a-c) show physical properties: mean depth (in m; black line and
1148 scale), thickness (in m, dashed black line and black scale), temperature (θ , in $^{\circ}\text{C}$; red line and scale),
1149 salinity (S , unitless; blue line and scale) and), density (σ , in kg m^{-3} ; purple line and scale) as a
1150 function of profile numbers (i.e. along the eddy trajectory), for three density layers: d) surface-26.6;
1151 e) 26.6-26.8; f) 26.8-26.9 and Brunt-Väisälä frequency squared (N^2 , in s^{-2} ; gray line and scale).
1152 Right: As left side panels, but with column plots d-f) show biogeochemical properties: mean

1153 chlorophyll (Chl-a, in $\mu\text{g L}^{-1}$; green line and scale), ~~backscatter~~particulate backscattering (b_{bp} , in m^{-1} ;
1154 1 ; gray line and scale), and oxygen concentrations (O_2 , in $\mu\text{mol kg}^{-1}$; orange line and scale)
1155 ~~inventories~~).

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1545

1546 Table 1. Bio-profiler deployments

1547

1548	#	Hull#*	WMO#**	UTC Date	Lat. (° N)	Long. (° E)	Campaign	Last profile (UTC Date)
1549	1	5122	1901329	29 Oct 2011	-48.5	72.2	KEOPS2	22 Apr 2012
1550	2	6684	5904882	26 Jan 2014	-49.9	76.2	MYCTO	14 Apr 2014
1551	3	6682	1901338	28 Jan 2014	-48.4	71.5	MYCTO	14 Apr 2014
1552	4	6683	1901339	4 Feb 2014	-48.6	74.0	MYCTO	14 Apr 2014

1553

1554 * Hull#: serial number for the bio-profiler body

1555 ** WMO#: World Meteorological Organization identification number for the bio-profiler data stream

Table 2. Drift assessment of the bio-profilers over their life time within the [250-300] m and [950-1000] m depth layers

Chlorophyll concentration drift within the [250-300] m depth layer

#	Mean slope ($\mu\text{g L}^{-1} \text{ profile}^{-1}$)	Mean absolute drift ^a ($\mu\text{g L}^{-1}$)	Mean drift relative to the mean surface Chl-a concentration ^b
1 ^c	8.4050 E-5	0.0252	+1 %
2	-1.7832 E-4	-0.0531	-5 %
3	-2.8722 E-4	-0.0798	-6 %
4	-1.1976 E-4	-0.0304	-3 %

Chlorophyll concentration drift within the [950-1000] m depth layer

#	Mean slope ($\mu\text{g L}^{-1} \text{ profile}^{-1}$)	Mean absolute drift ^a ($\mu\text{g L}^{-1}$)	Mean drift relative to the mean surface Chl-a concentration ^b
1	–	–	–
2	-2.1917 E-6	-0.0007	< -1 %
3	-9.0120 E-5	-0.0251	-2 %
4	1.2438 E-5	0.0032	< +1 %

Particulate backscattering drift within the [250-300] m depth layer

#	Mean slope (m^{-1})	Mean absolute drift ^a (m^{-1})	Mean drift relative to the mean surface b_{bp} ^d
1 ^c	1.1625 E-6	3.4876 E-04	+11 %
2	-1.1613 E-6	-3.4608 E-04	-19 %
3	-1.9682 E-7	-5.4716 E-05	-2 %
4	-6.7301 E-7	-1.7094 E-04	-10 %

Particulate backscattering drift within the [950-1000] m depth layer

#	Mean slope (m^{-1})	Mean absolute drift ^a (m^{-1})	Mean drift relative to the mean surface b_{bp} ^d
1	–	–	–
2	-2.2931 E-7	-6.8335 E-05	-4 %
3	-4.4734 E-7	-1.2436 E-04	-6 %
4	-2.0227 E-7	-5.1378 E-05	-3 %

^a = mean slope * nb of profiles

^b = mean slope * nb of profiles / mean chlorophyll concentration

^c Calculated between profiles #1 and profile #300, and excluding the deep biomass production profiles (range #[100-171])

^d = mean slope * nb of profiles / mean particulate backscattering

1596 Table 3. Fluorescence quenching corrections and subsurface chlorophyll maxima statistics

1597

Individual bio-profiler statistics	#1	#2	#3	#4
Fluorescence profiles collected	384	298	278	254
Fluorescence profiles usable	300	298	277	254
Day <u>Night</u> time profiles	150 <u>129</u>	122 <u>143</u>	111 <u>133</u>	107 <u>119</u>
Night <u>Day</u> time profiles	150 <u>171</u>	176 <u>155</u>	166 <u>144</u>	147 <u>135</u>
Night time profiles with subsurface maxima* <u>maxima^a</u> (percent <u>total</u> /within the ML/below the ML (% of night time profiles))	68 (45%) <u>17/5/12/</u> (13/4/9)%	16 (9%) <u>3/1/2</u> (2/1/1)%	74 (45%) <u>24/9/15</u> (18/7/11)%	54 (37%) <u>25/14/11</u> (21/12/9)%
Day time profiles with subsurface maxima* <u>maxima^a</u> before correction (percent <u>total</u> /within the ML/below the ML (% of daytime profiles))	138 (99%) <u>142/62/80</u> (83/36/47)%	96 (96%) <u>93/55/38</u> (60/35/25)%	106 (95%) <u>105/48/57</u> (73/33/40)%	98 (92%) <u>95/40/55</u> (70/30/40)%
Quenching corrected profiles (and among them, number of corrected profiles which still exhibit low surface values ^c)	148 <u>170</u> (22)	117 <u>155</u> (6)	106 <u>139</u> (12)	104 <u>127</u> (18)
Day time profiles with subsurface maxima* before correction (percent of daytime profiles)		70 (47%)	26 (22%)	49 (46%)
Day time profiles with correction <u>total</u> /within the ML/below the ML (% of all corrected daytime profiles)	14 (9%) <u>40/0/40</u> (24/0/24)%	3 (3%) <u>10/1/9</u> (6/0/6)%	15 (14%) <u>32/3/29</u> (23/2/21)%	14 (13%) <u>40/9/31</u> (31/7/24)%
Total night and corrected day profiles with <u>moderate</u> subsurface maxima* <u>maxima^a</u> <u>total</u> /within the ML/below the ML (% of night and corrected day profiles)	138 (46%) <u>57/5/52</u> (19/2/17)%	42 (14%) <u>13/2/11</u> (4/1/3)%	123 (45%) <u>56/12/44</u> (20/4/16)%	104 (41%) <u>65/23/42</u> (26/9/17)%

Total night and corrected day
profiles with **large** subsurface
maxima**maxima^b

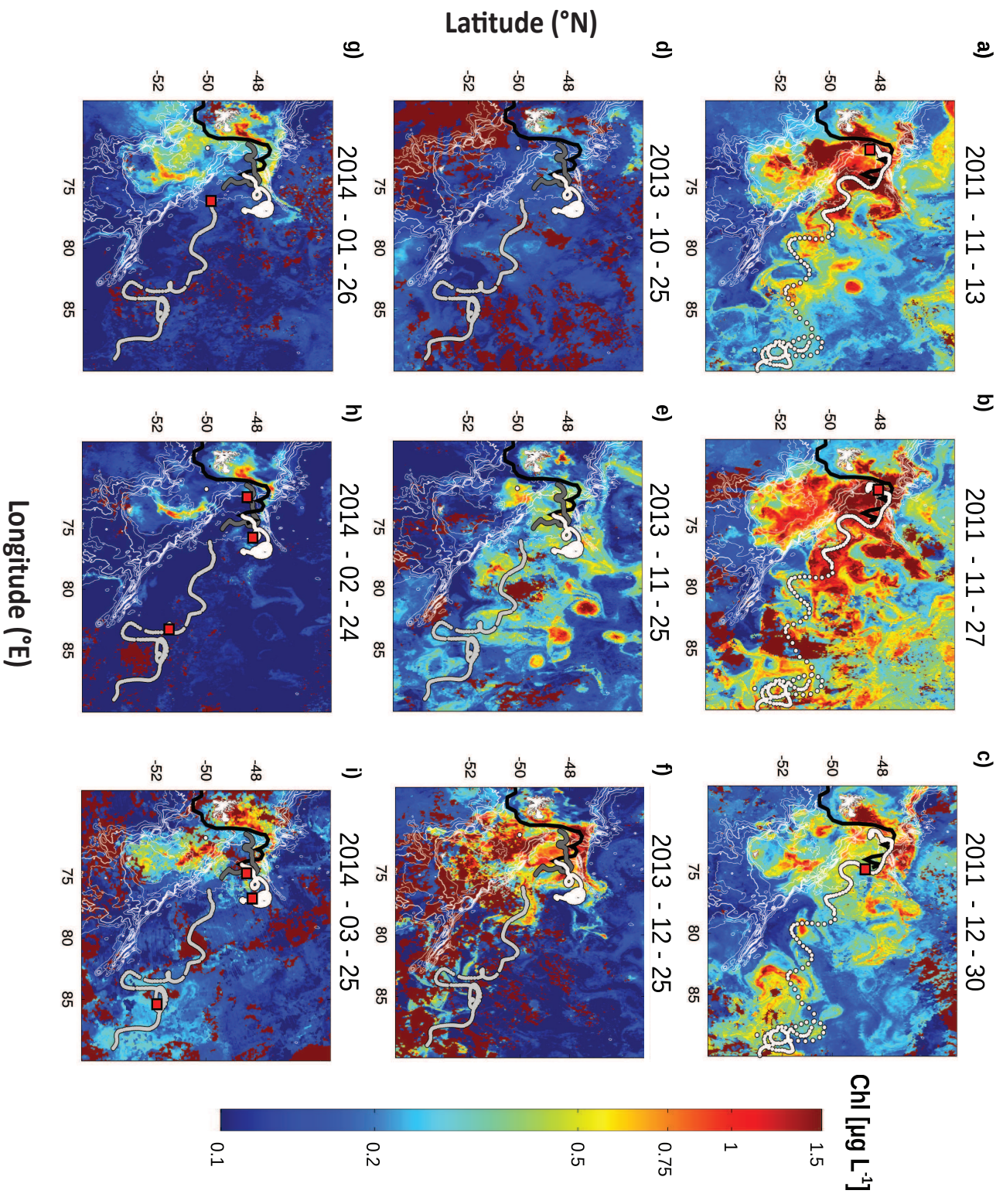
	39	6/0/6	28	51
	(13%)32/1/31	(2%)0/2/0%	(10%)36/5/31	(20%)45/15/30
	(10/0/10)%		(13/2/11)%	(18/6/12)%
<u>total/within the ML/below</u> <u>the ML</u> (% of night and corrected day profiles)				

1598 *^a Subsurface values exceeding surface values by more than ~~30%~~^{**}60%

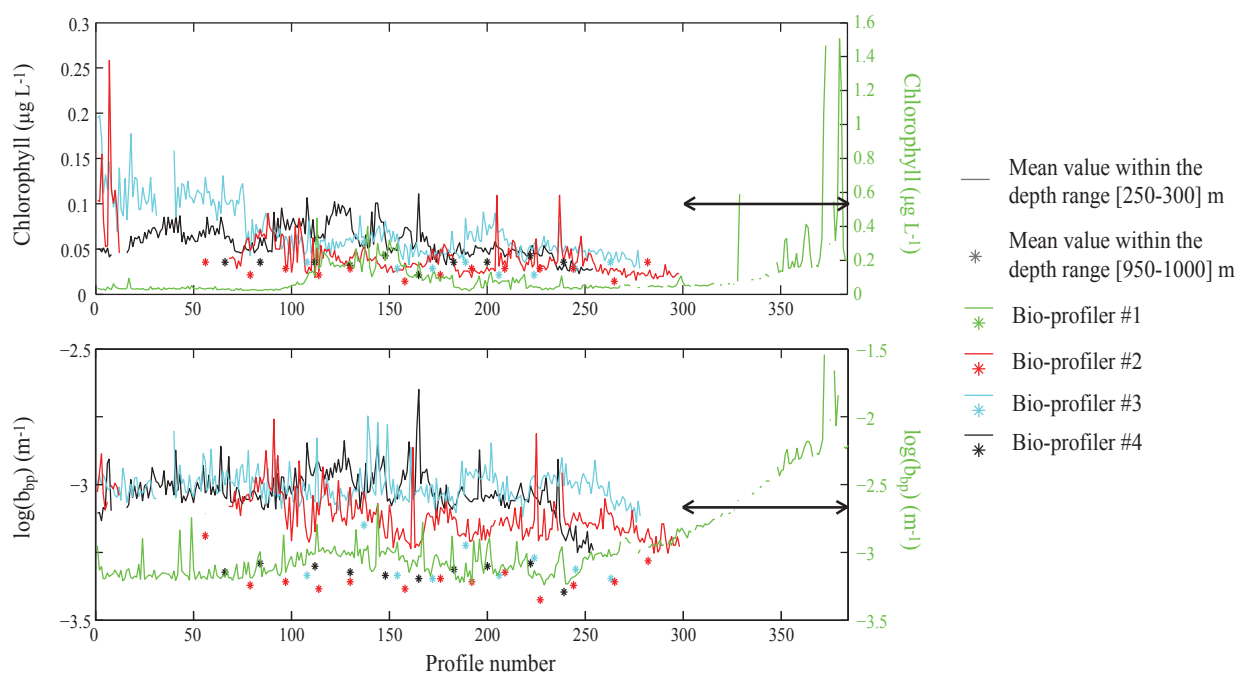
1599 ^b Subsurface values exceeding surface values by more than 100%

1600 ^c For some corrected profiles, a large decrease of the chlorophyll concentration still occurred in the
1601 surface layer. These profiles were flagged in Figures 2b (squares), 4 (squares) and 5 (red circles).

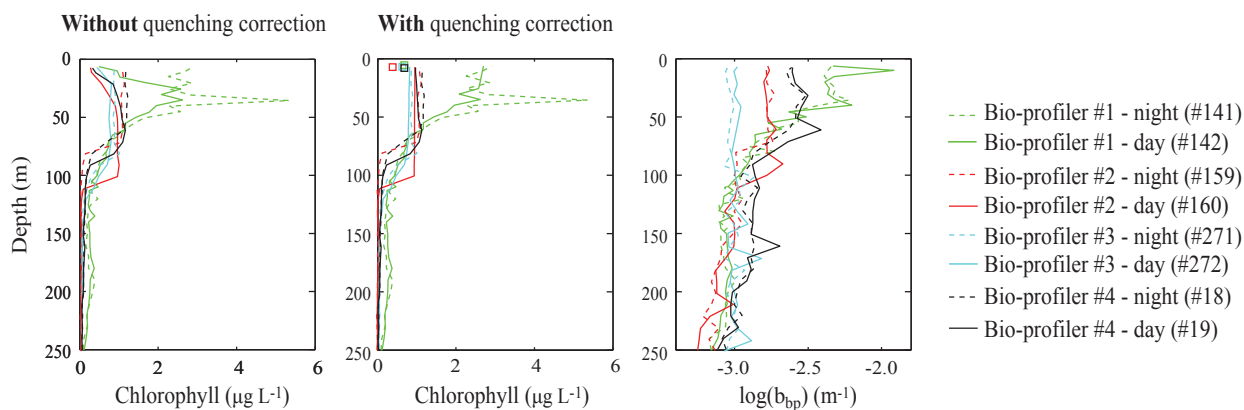
1602 See the method section and the caption of Figure 2b for more details.



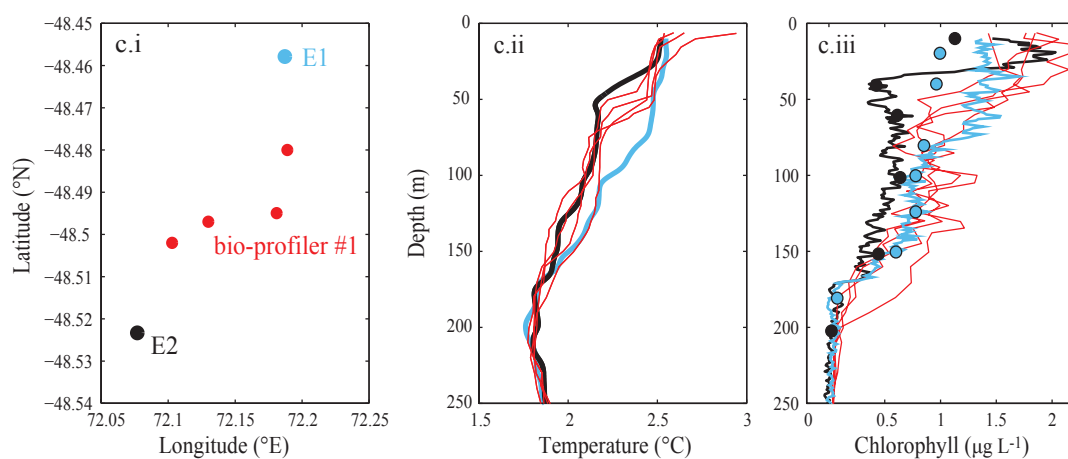
a) Drifting assessment

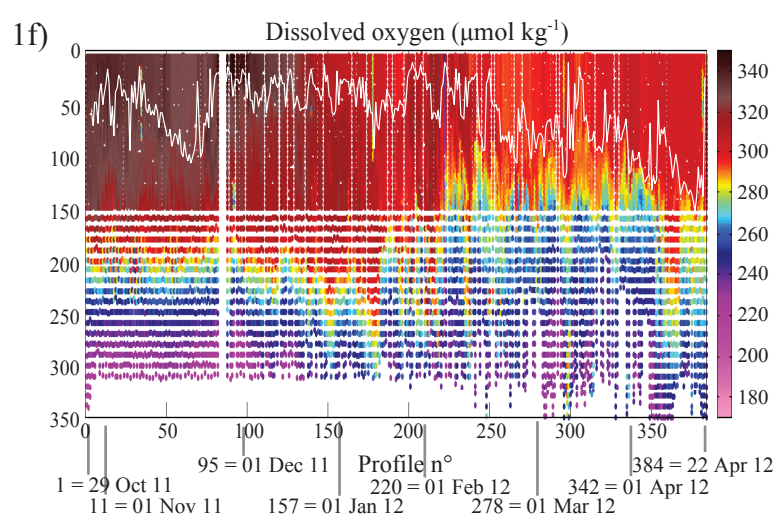
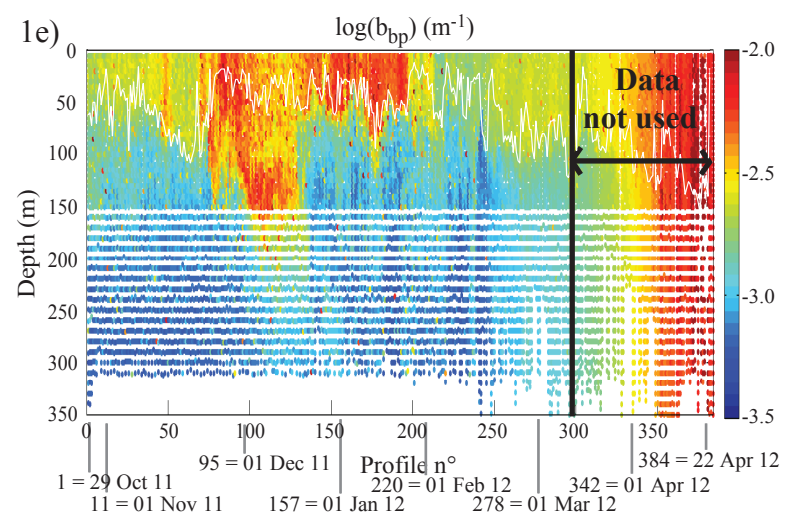
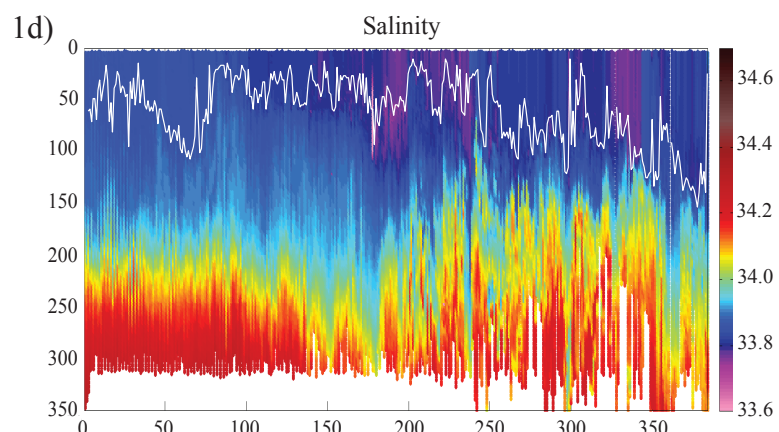
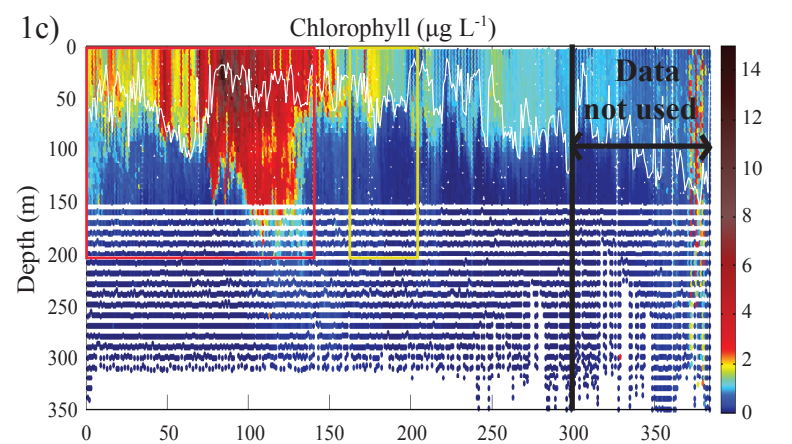
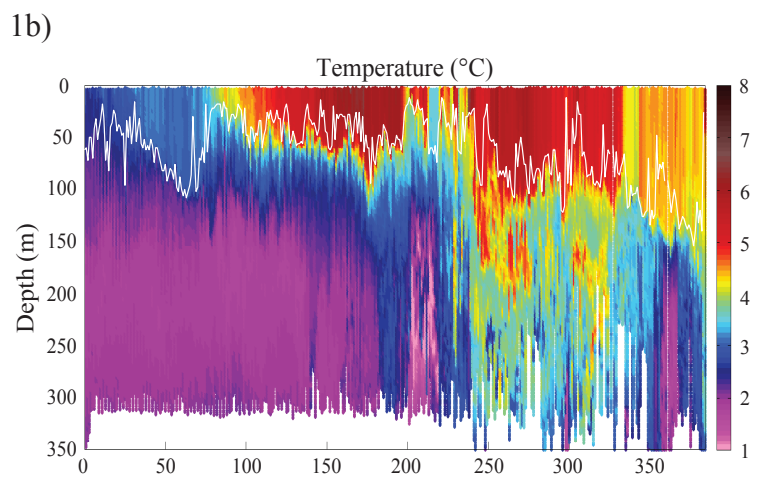
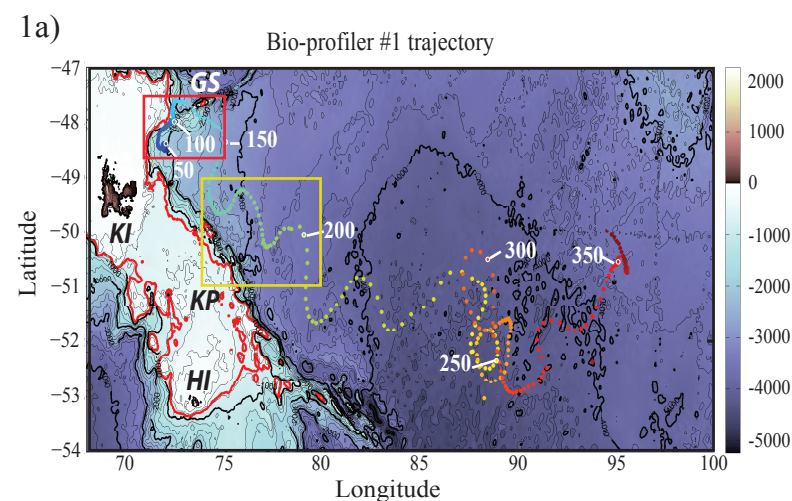


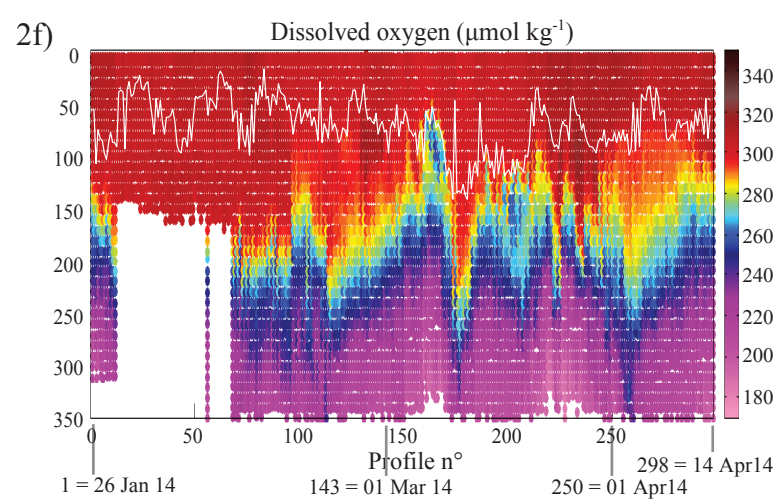
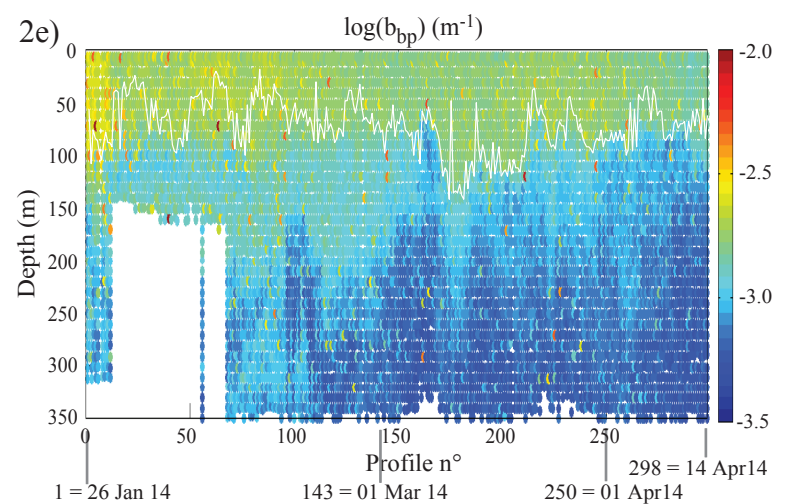
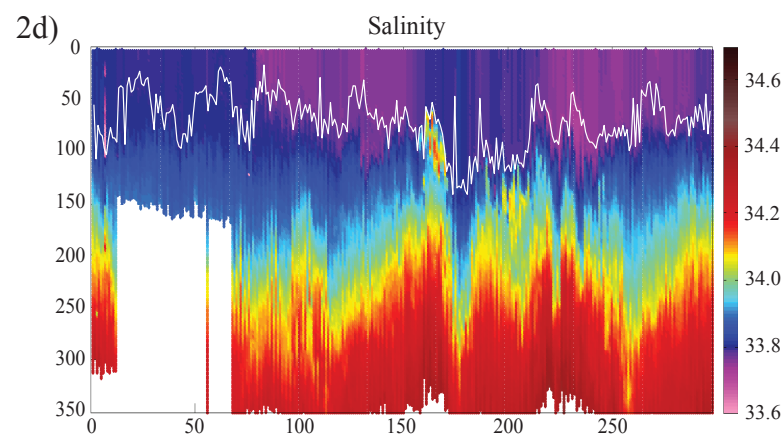
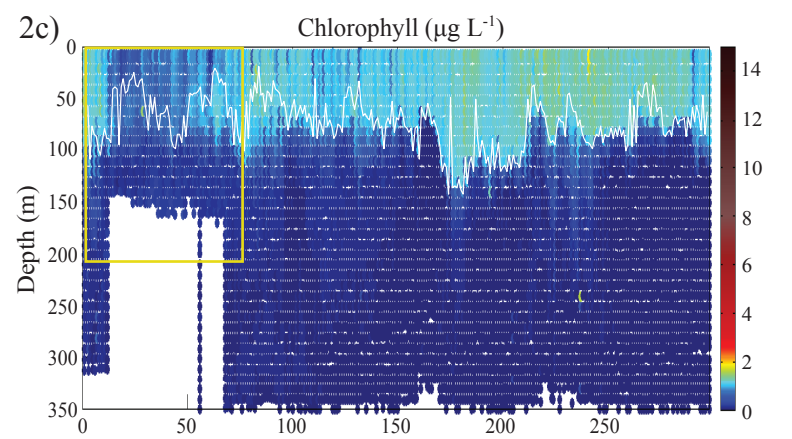
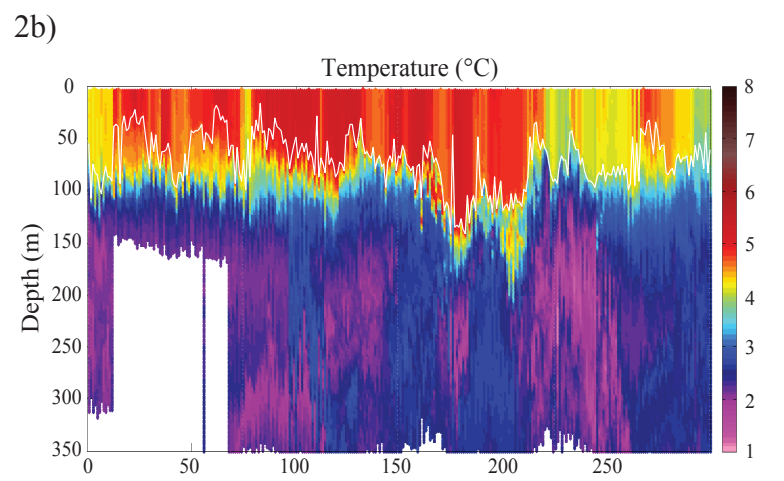
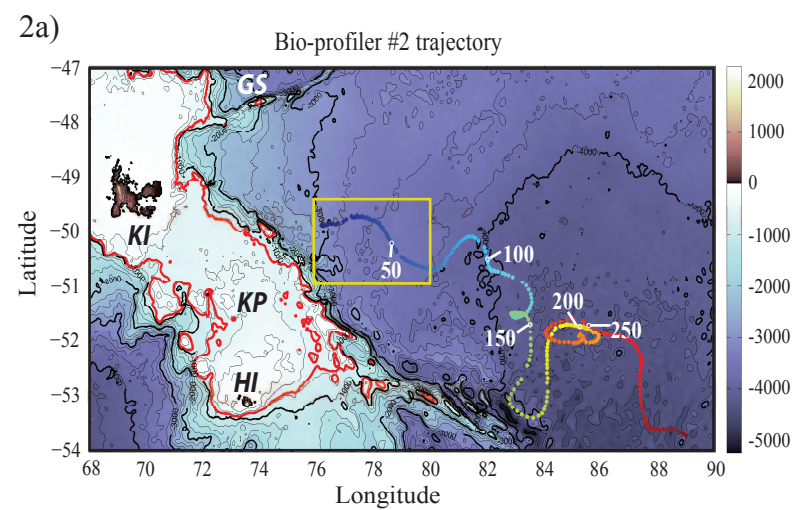
b) Quenching assessment

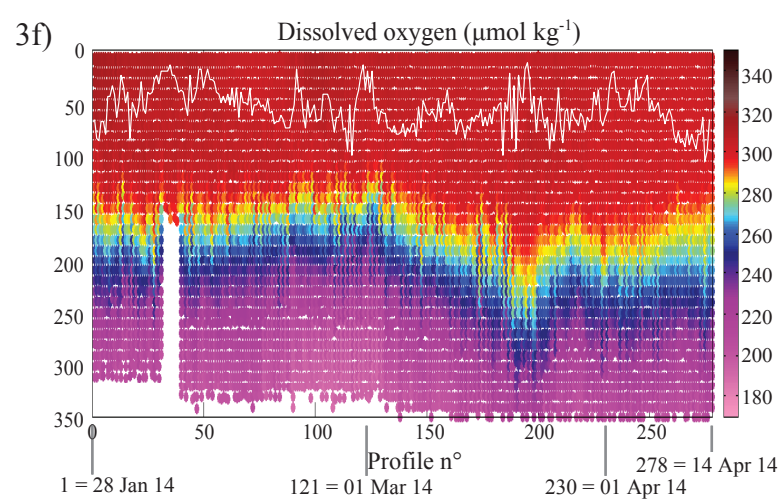
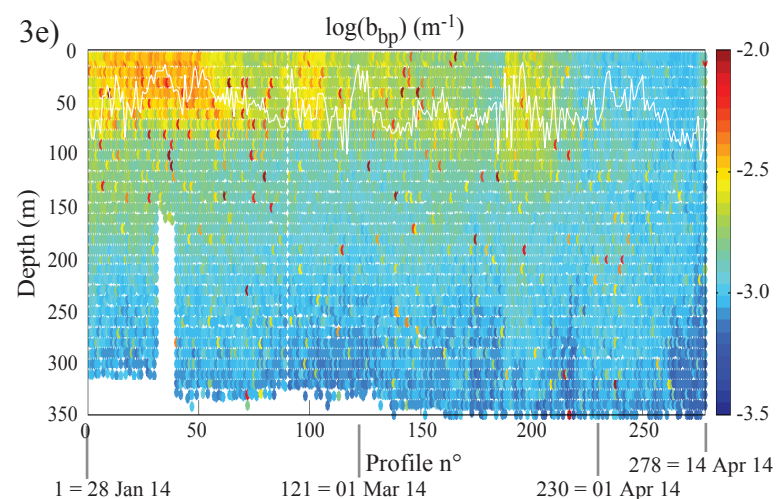
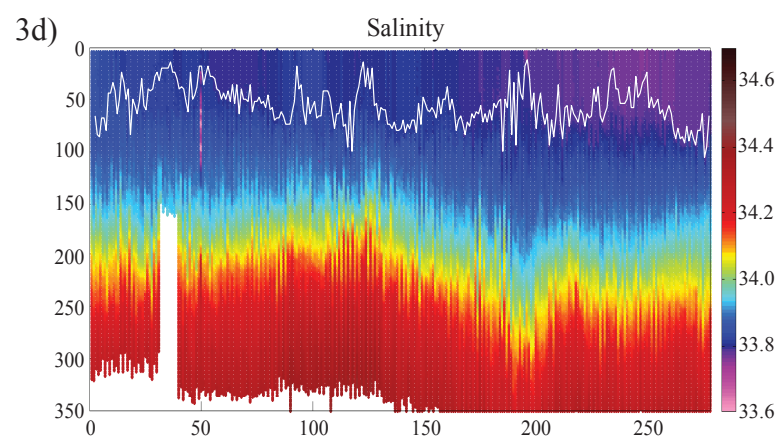
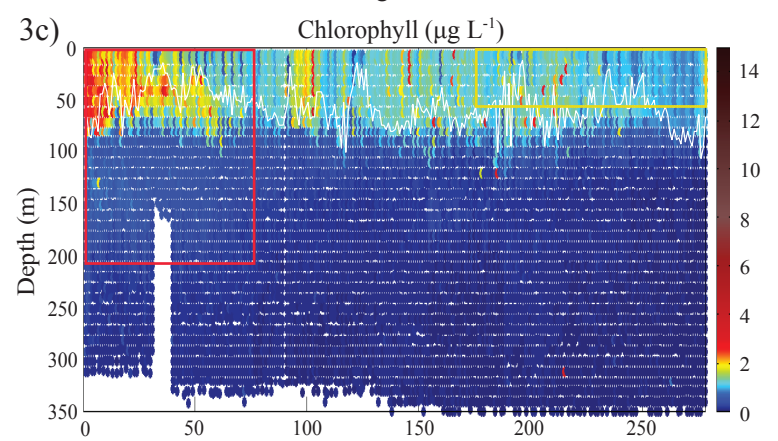
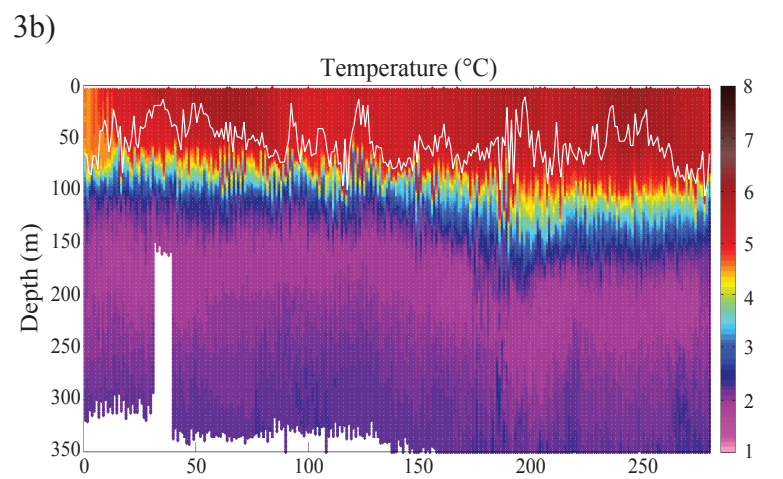
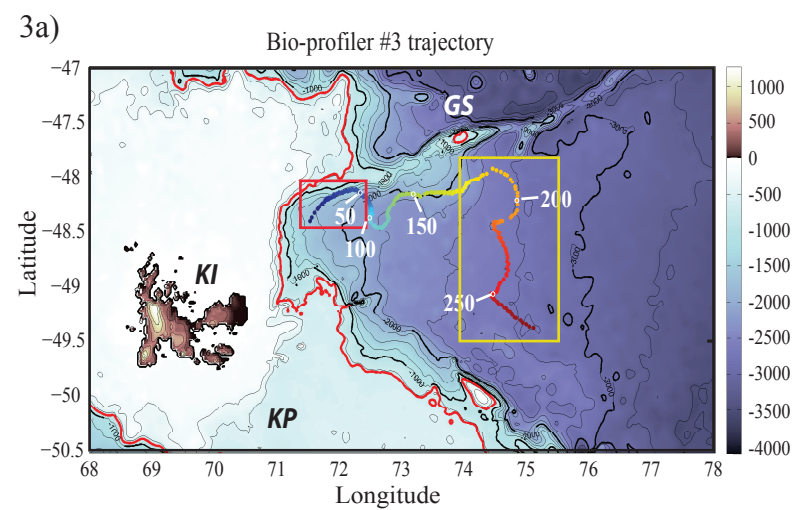


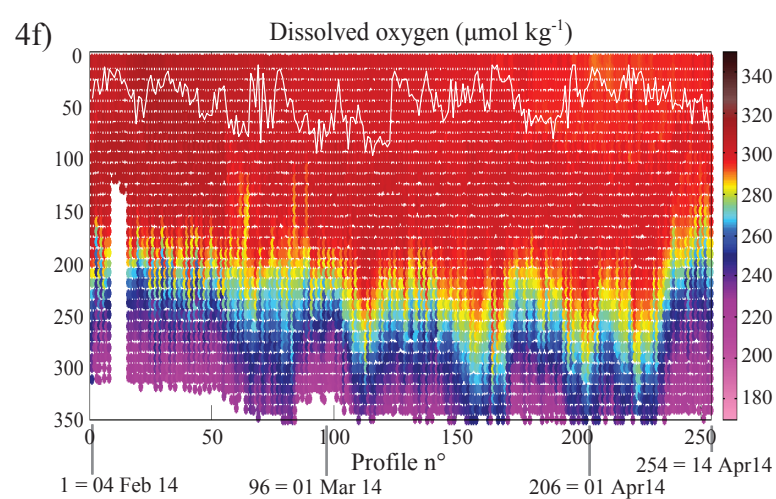
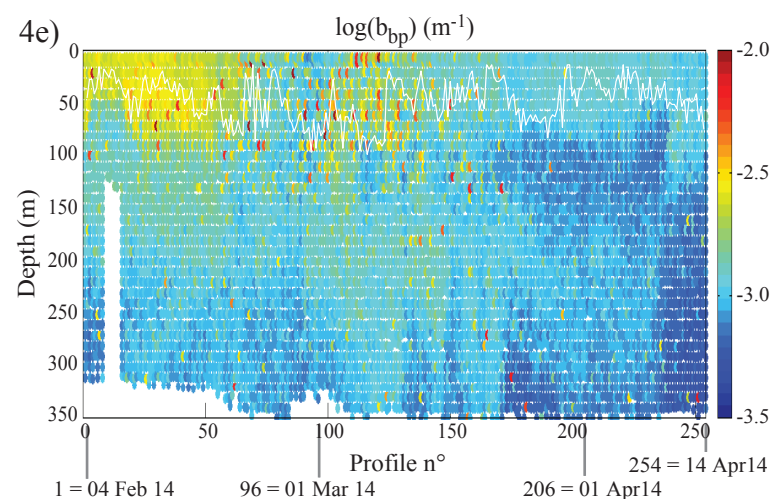
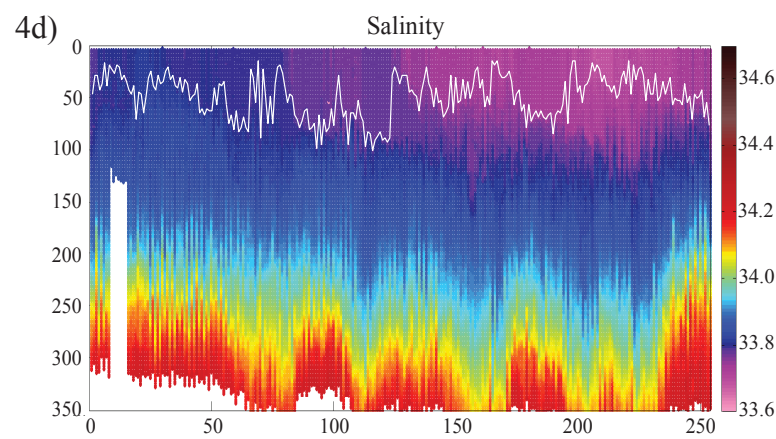
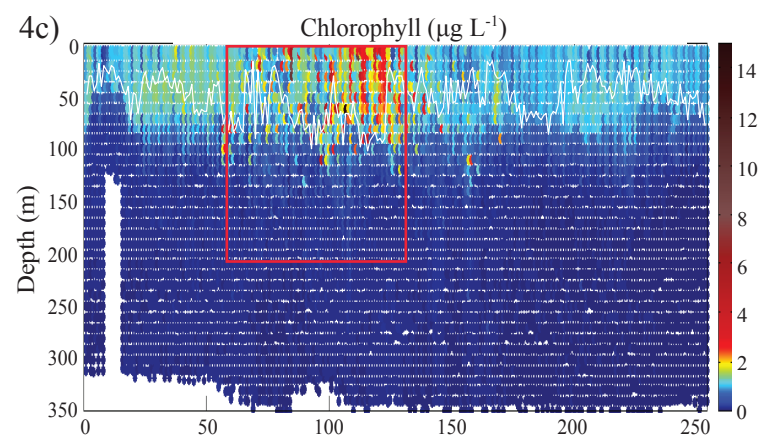
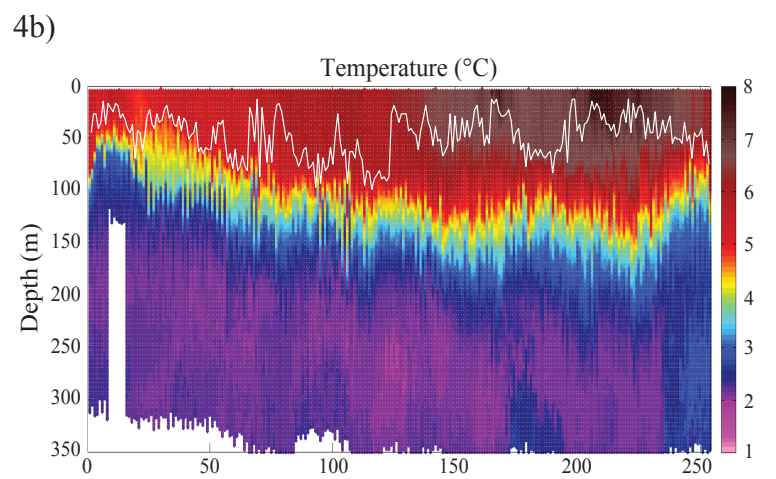
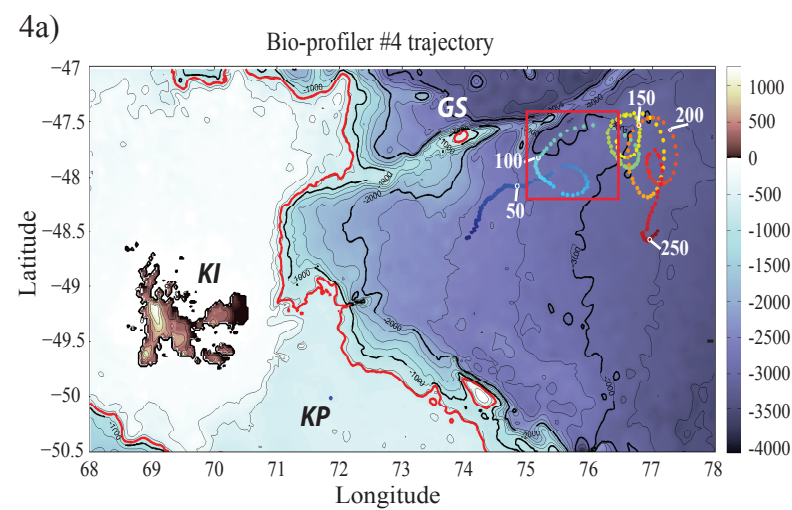
c) Comparison to KEOPS2 shipboard observations



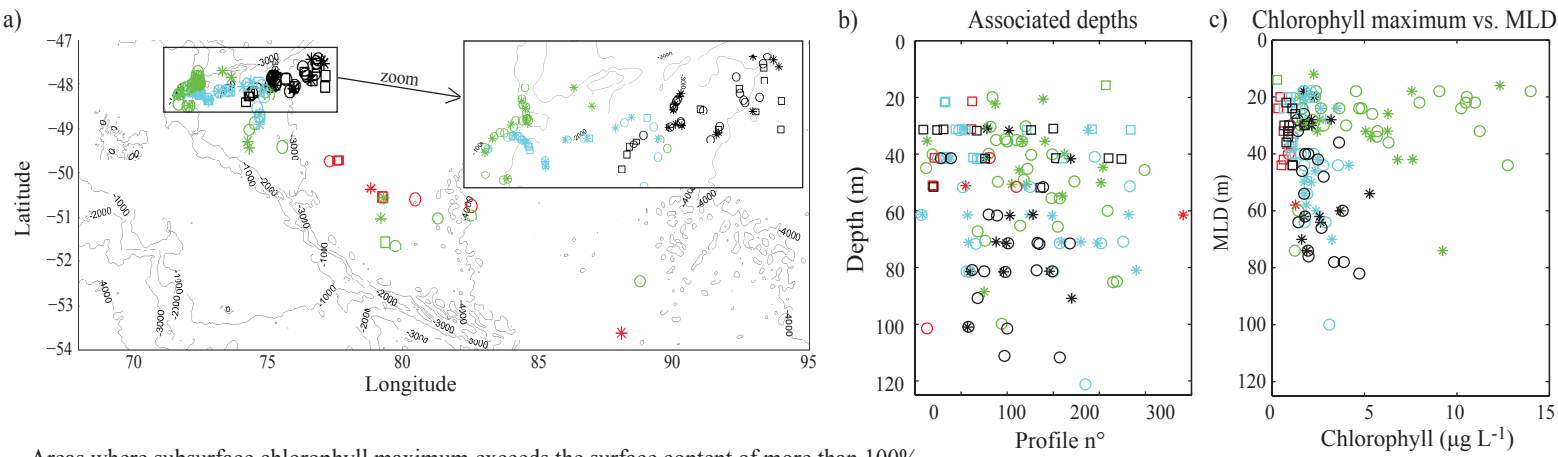




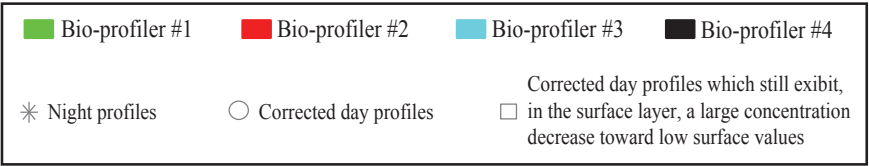
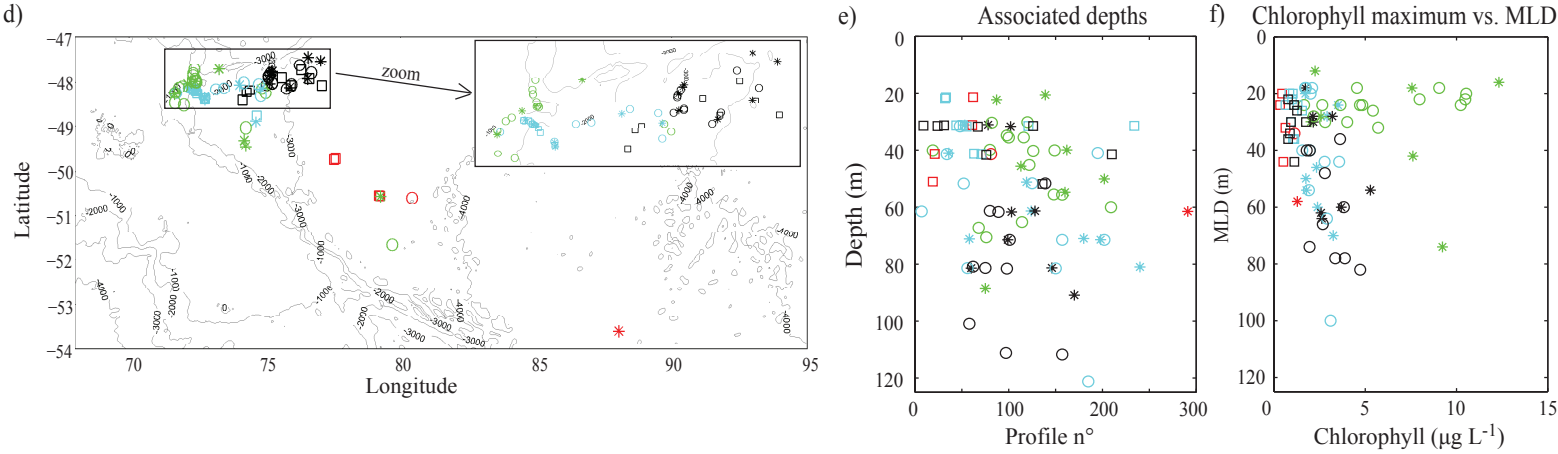


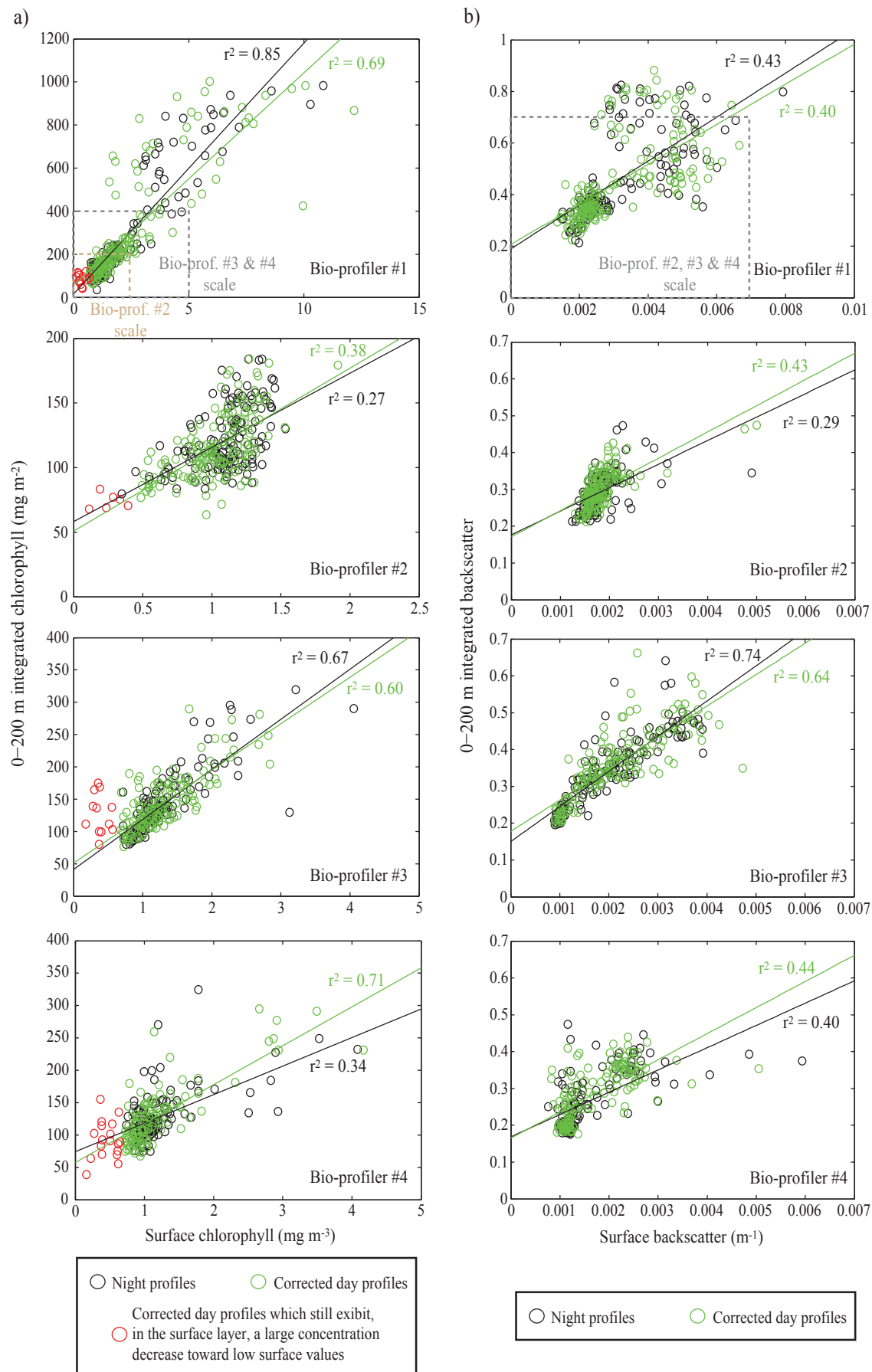


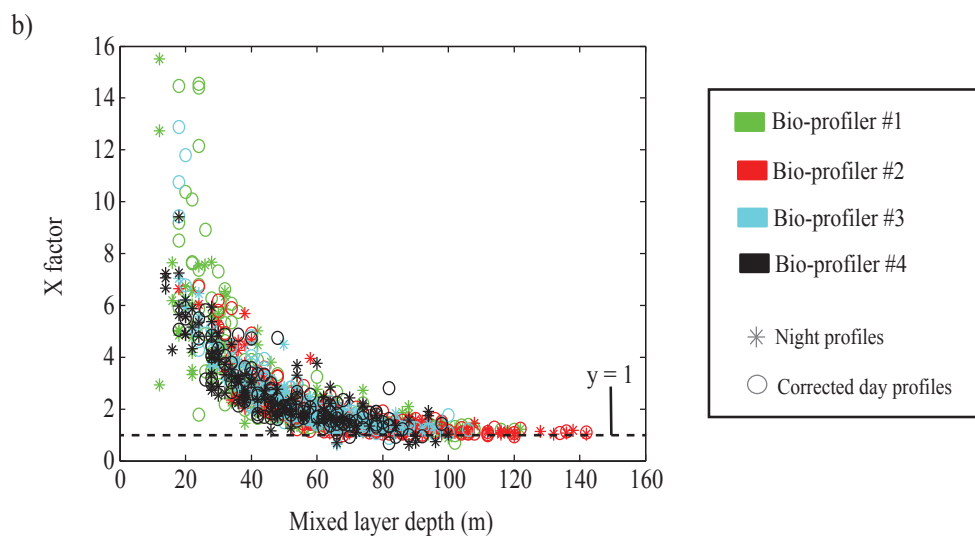
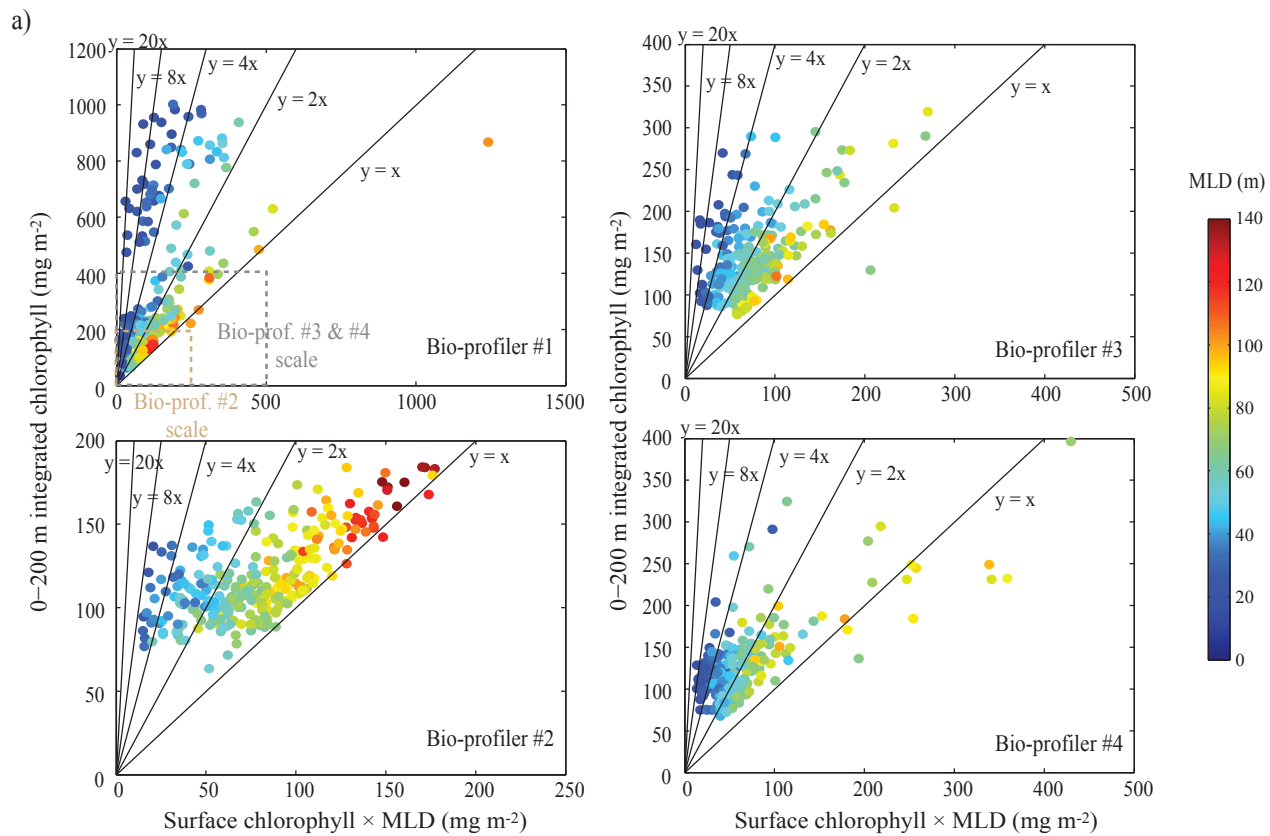
Areas where subsurface chlorophyll maximum exceeds the surface content of more than 60%



Areas where subsurface chlorophyll maximum exceeds the surface content of more than 100%

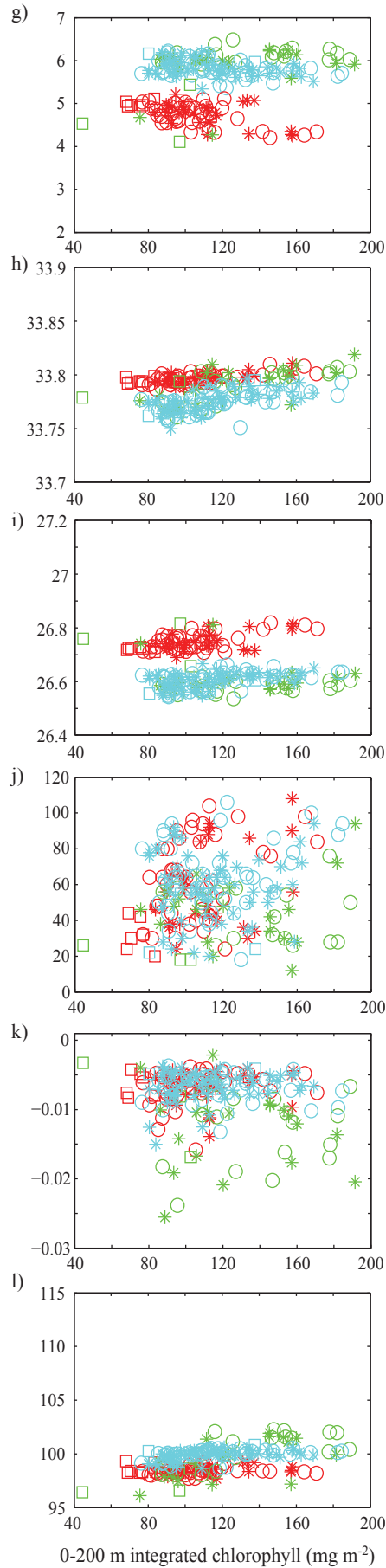
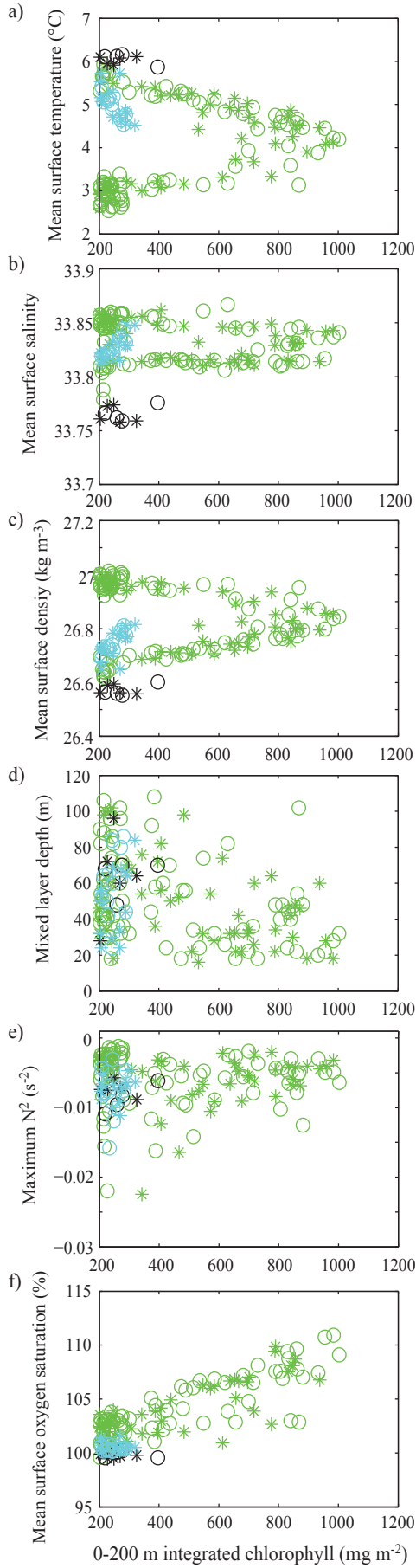






Rich biomass regions

Moderate biomass regions



■ Bio-profiler #1 ■ Bio-profiler #2 ■ Bio-profiler #3 ■ Bio-profiler #4

* Night profiles

○ Corrected day profiles

□ Corrected day profiles which still exhibit,
in the surface layer, a large concentration
decrease toward low surface values

