1 **Autonomous profiling float observations of the high biomass plume downstream of the**

2 **Kerguelen plateau in the Southern Ocean**

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Abstract

21 Natural iron fertilisation from Southern Ocean islands results in high primary production and

22 phytoplankton biomass accumulations readily visible in satellite ocean colour observations. These

23 images reveal great spatial complexity with highly varying concentrations of chlorophyll, presumably

24 reflecting both variations in iron supply and conditions favouring phytoplankton accumulation. To

25 examine the second aspect, in particular the influences of variations in temperature and mixed layer

26 depth, we deployed four autonomous profiling floats in the Antarctic Circumpolar Current near the

27 Kerguelen plateau in the Indian sector of the Southern Ocean. Each 'bio-profiler' measured more than

28 250 profiles of temperature (T), salinity (S), dissolved oxygen, chlorophyll-a (Chl-a) fluorescence,

29 and particulate backscattering (b_{bp}) in the top 300 meters of the water column, sampling up to 5

30 profiles per day along meandering trajectories extending up to 1000 km. Comparison of surface Chl-

31 a estimates (analogous to values from satellite images) with total water column inventories revealed

32 largely linear relationships, suggesting that these images provide credible information on total and

33 not just surface biomass accumulations. Regions of very high Chl-a accumulation (1.5-10 µg L^{-1})

34 were associated predominantly with a narrow T-S class of surface waters. In contrast, waters with

35 only moderate Chl-a enrichments (0.5-1.5 µg L^{-1}) displayed no clear correlation with specific water

36 properties, including no dependence on mixed layer depth or the intensity of stratification.

37 Geostrophic trajectory analysis suggests that both these observations can be explained if the main

38 determinant of biomass in a given water parcel is the time since leaving the Kerguelen plateau. One

39 float became trapped in a cyclonic eddy, allowing temporal evaluation of the water column in early

40 autumn. During this period, decreasing surface Chl-a inventories corresponded with decreases in

41 oxygen inventories on sub-mixed layer density surfaces, consistent with significant export of organic

42 matter (~35%) and its respiration and storage as dissolved inorganic carbon in the ocean interior.

43 These results are encouraging for the expanded use of autonomous observing platforms to study

44 biogeochemical, carbon cycle, and ecological problems, although the complex blend of Lagrangian

45 and Eulerian sampling achieved by the floats suggests that arrays rather than single floats will often

46   be required, and that frequent profiling offers important benefits in terms of resolving the role of

47   mesoscale structures on biomass accumulation.

1 Introduction

The productivity of the Southern Ocean is important for many reasons. It supports fisheries and high conservation value marine mammal and bird populations (Constable et al., 2003; Nicol et al., 2000), influences the carbon dioxide content of the atmosphere (Sarmiento and Le Quéré, 1996; Sigman and Boyle, 2000; Watson et al., 2000), and affects the magnitude of nutrient supply to large portions of the global surface ocean (Sarmiento et al., 2004). This productivity is limited by the scarce availability of iron (Fe) as an essential micro-nutrient (Boyd and Ellwood, 2010; Boyd et al., 2007; Martin, 1990). Island sources of Fe elevate productivity and produce downstream 'plumes' of elevated phytoplankton biomass that contrasts with the general HNLC (High Nutrients, Low Chlorophyll) nature of the Southern Ocean (Blain et al., 2007; de Baar et al., 1995; Mongin et al., 2009; Pollard et al., 2009; Nielsdóttir et al., 2012). Ship based studies of several of these regions, focused on the influence of Fe on carbon (C) transfer to the ocean interior (Blain et al., 2008; Salter et al., 2007), have revealed a diversity of responses in terms of intensity of enhanced productivity, biomass accumulation, and ecosystem structures. This diversity derives from interactions between the supply and bio-availability of iron with other drivers of productivity such as temperature, water column stratification and stability, light levels, and the possibility of co-limitation by other nutrients (Assmy et al., 2013; Boyd et al., 1999, 2001; Queguiner, 2013).

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 that bias could arise include lack of direct correlations of surface values with their vertical extents (e.g. high surface

74   chlorophyll values might be predominantly associated with shallow accumulations, through the

75   promotion of production by higher light levels in shallow mixed layers; Sverdrup, 1953), the presence

76   of unobserved subsurface chlorophyll maxima (Carranza et al., 2014; Schlitzer, 2002), or the variation

77   of phytoplankton to chlorophyll ratios with growth conditions (Cloern et al., 1995; Fennel and Boss,

78   2003; Goericke and Montoya, 1998).

79   These difficulties of observation become even more acute for carbon export estimates, which

80   require either flux measurements (e.g. from moored or free-drifting sediment traps or radionuclide

81   activities (Planchon et al., 2014; Savoye et al., 2008) or the partitioning of changes in state variables

82   across biogeochemical versus oceanographic causes (e.g. nitrate depletions in surface waters or

83   oxygen consumption at mesopelagic depth; Matear et al., 2000; Trull et al., 2015). Obtaining

84   estimates of carbon export and the depth of its penetration into the ocean interior are important to

85   determining impacts on the climate system, because variations in these two factors have similar

86   influence to variations in total primary production in terms of the sequestration of CO_2 from the

87   atmosphere (Boyd and Trull, 2007). Notably, export estimates expressed as 'e-ratio' fractions of

88   primary production (Maiti et al., 2013), or as 'f-ratio' fractions of production derived from 'new'

89   nitrate supply (Savoye et al., 2004) vary widely in the Southern Ocean, with the possibility that these

90   efficiencies are increased by natural iron fertilisation (Jouandet et al., 2011; Trull et al., 2008).

91   This space-time complexity is abundantly demonstrated by the 'mosaic of blooms' (i.e. patchiness

92   pattern) encountered in waters downstream from the Kerguelen plateau during the KEOPS2 field

93   program in austral spring (October-November 2011), as detailed in many papers in a special volume

94   of Biogeosciences (d'Ovidio et al., 2014; Trull et al., 2015; Lasbleiz et al., 2014; Laurenceau-Cornec

95   et al., 2015; Cavagna et al., 2014). Much of the meso-scale spatial variations in biomass accumulation,

96   as seen in satellite images and animations (Mongin et al., 2009; d'Ovidio et al., 2014; Trull et al.,

97   2015), appears to result from the interleaving of iron-enriched water parcels that have transited the

98   Kerguelen plateau with surrounding iron poor waters, as demonstrated by analysis of satellite

99   altimetry based circulation estimates and surface drifter trajectories (Park et al., 2014a; d'Ovidio et

100   al., 2014). However, shipboard studies close to the plateau (Mosseri et al., 2008; d'Ovidio et al., 2014;

101   Blain et al., 2015; Trull et al., 2015; Lasbleiz et al., 2014; Laurenceau-Cornec et al., 2015) suggest

102   that other factors are also likely to play a role, including mixed layer depth and upper water column

103   stratification.

104   To explore the influence of variations in these water column properties on bloom structure at

105   larger scale, in particular further from the plateau than could be surveyed by ship, we deployed

106   autonomous profiling drifters. The first one was successfully launched during the KEOPS2 field

107   program in late October 2011, and the other three during the MyctO-3D-MAP (referred to as

108   MYCTO, from now on in this text) interdisciplinary survey between late January and early February

109   2014. Given the extent of the Kerguelen biomass plume (> 1000 km; Mongin et al., 2009), the

110   remoteness from ports, and the generally rough sea states, the use of autonomous platforms is

111   arguably the only affordable way to survey this region. As shown in Figure 1, these deployments

112   returned data from a large proportion of the enriched biomass plume downstream of the Kerguelen

113   plateau.

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

115   1) Do satellite images of surface chlorophyll provide an unbiased guide to the spatial distribution

116   of total water column chlorophyll, or are they biased by lack of knowledge of variations in the

117   vertical extent of chlorophyll distributions or the presence of subsurface chlorophyll maxima?

118   2) Do regions of high biomass correlate with particular oceanographic properties, such as warmer

119   or fresher waters, or the intensity of stratification? If so, are these properties determined locally

120   or by the upstream origins of the different water parcels?

121   3) Can the fate of surface enrichments in biomass be determined (and eventually quantified) from

122   along-trajectory temporal variations in biogeochemical properties, for example by progressive

123   downward movement of fluorescence or particulate backscattering signals or decreases of

124   oxygen in subsurface waters?

125

126 **2   Methods**

127 *2.1* **Float sensor and mission configurations**

128   The float deployment locations are provided in Table 1, along with their identification numbers

129 which provide access to their full data sets via the Australian Integrated Marine Observing System

130 (www.imos.org.au). Float deployment was done in 2011 by manual transfer to a small boat and then

131 the sea, and in 2014 by deploying the floats from the ship deck inside cardboard boxes designed to

132 readily disintegrate after release. The autonomous profiling floats were all of the same design (Model

133 APF9I, Teledyne-Webb, Inc.). Each was equipped with pumped, poisoned, thermosalinographs

134 (Model SBE 41CP-2.0, Seabird, Inc.), end-cap mounted un-pumped oxygen optodes (Model 3830,

135 Aanderaa, Inc.), and two-channel bio-optical sensors (Model FLBBAP2, Wetlabs, Inc.) strapped onto

136 the lower third of the float hull with their optical ports facing horizontally to minimize possible

137 interferences from particle accumulation. Owing to the structure of the firmware for the floats and

138 the varying power requirements for the sensors, the sampling rates differed for the physical and

139 biogeochemical parameters. Temperature and salinity were sampled at the highest rates, yielding

140 values at 2 decibar intervals (used in this work as equivalent to 2 meter depth intervals without density

141 corrections), whereas oxygen, fluorescence and backscatter were sampled at 10 decibar intervals,

142 except for bio-profiler #1 where they were sampled at 5 decibar intervals in the first 150 m.

143   Temperature and salinity calibrations were performed by Seabird, Inc., with estimated accuracy

144 and precision of better than 0.005 °C and 0.01, respectively (Oka and Ando, 2004). These variables,

145 used as water mass proxies and to estimate mixed layer depths and stratification intensity (expressed

146 as the Brunt-Väisälä frequency), helped to determine if dissolved oxygen evolutions were mainly due

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147 to physical processes or to biological production or respiration processes. The oxygen optodes were

148 calibrated at CSIRO prior to mounting on the floats against a 20 point matrix of 4 temperatures (0.5

149 - 30) and 5 oxygen saturations (0 - 129%) using the methods detailed in Weeding and Trull (2014).

150 Similar sensors exhibited drift during a 6 month mooring deployment in the Southern Ocean of less

151 than 1.7 µmol kg^{-1} over 6 months (Weeding and Trull, 2014).

152   The bio-optical sensors measured chlorophyll-a fluorescence via stimulation/emission at 470/695

153 nm) and particulate backscattering at 700 nm. Chlorophyll-a fluorescence is a useful proxy for

154 chlorophyll-a concentration and standing stocks of phytoplankton biomass (Falkowski and Kiefer,

155 1985; Huot et al., 2007). Particulate backscattering provides a good proxy for particulate organic

156 carbon (Stramski et al. 2008; Cetinić et al, 2013). The bio-optical fluorescence sensors were calibrated

157 (by the manufacturer, Wetlabs, Inc.) against fluorescent uranine solutions as working standards, and

158 cross- referenced to prior measurements of a laboratory culture (25 mg m^{-3} chlorophyll) of the diatom

159 *Thallassiosira weissflogii* to yield chlorophyll estimates. These calibrations are warranted to yield

160 linear responses with precisions among multiple sensors of better than 10%, and (after one cycle of

161 testing and replacement with the manufacturer) we obtained reproducibility for the set of three floats

162 deployed in 2014 of better than 4% based on measurements with fluorescent and non-reflective

163 plastics (Earp et al., 2011). Accordingly, calculation of the chlorophyll fluorescence from the float

164 data was done by removal of the background dark signals measured prior to deployment and scaling

165 to chlorophyll using the manufacturer's calibrations. Similarly, the retrieval of particulate

166 backscattering, b_{bp} (m^{-1}), at 700 nm from the backscatter raw transmitted measurement (counts) was

167 done by applying the manufacturer-provided scaling factor after correction for dark counts (i.e.

168 measured signal output of the backscatterometer in clean water with black tape over the detector),

169 with the additional steps of removal of the pure seawater backscattering contribution (Zhang et al.,

170 2009), and scaling from the limited solid angle sensor measurement to the total backscattered

171 hemisphere based on relations estimated from observations for a wide range of marine particles (Boss

172 and Pegau, 2001; Sullivan et al., 2012).

173   In contrast to typical Argo program float missions for climate studies (www.argo.org), which

174   consist of deep (2000 m) profiles every 10 days, the bio-profilers were programmed to focus on the

175   upper water column and carried out continuous profiling between the surface and 300 m depth,

176   achieving 4 to 6 profiles per day, depending on the stratification. This temporal resolution was

177   intended to allow examination of daily cycles related to insolation, photosynthesis, and respiration.

178   In practice, it proved difficult to extract clear cycles because of aliasing from spatial variations.

179   Consequently, after several weeks for the 2011 KEOPS2 deployment of bio-profiler #1, the frequency

180   of profiles was reduced to twice daily, to provide extended battery life while still obtaining night and

181   day observations to allow insolation quenching of the fluorescence response to be evaluated and

182   corrected, and thus to avoid inappropriate inference of subsurface chlorophyll maxima from the

183   fluorescence signal (Sackmann et al., 2008; Xing et al., 2012). For bio-profilers #2, #3, and #4

184   deployed in 2014, the missions were further refined, via automated telemetric switching of mission

185   configuration files, to carry out a deep profile to ~1500 m every 3 days to provide deep reference

186   points for temperature, salinity, and oxygen observations, and also with the intention to slow the

187   development of bio-fouling of the bio-optical sensors by exposing surface organisms to high

188   pressures.

189

190   *2.2* **Float data quality control**

191   Extensive experience by the Argo program with profiling float measurements for temperature

192   (T) and salinity (S), including recovery of floats for post deployment tests (Oka and Ando, 1994),

193   suggests that these sensors reliably deliver accurate and precise observations (to better than 0.005 °C

194   and 0.01 salinity) over multi-annual deployments. Given our much shorter bio-profiler deployments

195   (3 to 6 months) and their observed T-S relationships which fall within those of the ship-based

196   KEOPS2 observations, we assume these variables are correct and make no further assessment or

197 correction. We similarly accept the oxygen observations, given our careful attention to their pre-

198 deployment calibration, their reasonable range of surface water oxygen super-saturations (96-103%

199 for low chlorophyll waters and extending up to 108% in correlation with very high chlorophyll waters,

200 as discussed further below), and their deep ocean values (950-1000 m depths) which fall within the

201 range of nearby ship observations and showed no temporal trends and standard deviations of less than

202 4 μmol kg^{-1} over the deployment periods (ranging from 1 to 3.9 μmol kg^{-1} for the four bio-profilers).

203   To evaluate the possibility of temporal sensor drifts in bio-optical variables, we examined the

204 variations of the bio-optical variables in mesopelagic (250-300 m) and deep water (950-1000 m)

205 values, i.e. at depths where little signal was anticipated and most profiles reached steady background

206 values (Figure 2a). The particulate backscattering and, to a lesser extent, the Chl-a fluorescence

207 signals showed spikes which presumably reflect larger particles such as aggregates and zooplankton,

208 motivating our examination of average values over 50 m ranges (250-300 m and 950-1000 m depth

209 layers) for the assessment of temporal drifts. As shown in Figure 2a and quantified in Table 2, for

210 most of their deployment periods all four bio-profilers exhibited no significant temporal drift of these

211 deep values except for bio-profiler #1, for which high and erratic values of Chl-a and b_{bp} began to

212 occur after profile #300 both at depth (Figure 2a) and throughout the water column (Figure 3.1c and

213 e). We consider this to be caused by bio-fouling and do not use this data in any subsequent analysis

214 (this loss of signal fidelity was one of the motivations for including periodic deep profiles in the

215 subsequent three bio-profiler deployments, as a means of retarding fouling). In contrast, the high

216 fluorescence chlorophyll values found in mesopelagic waters from profiles ~#100 to ~#170 along the

217 bio-profiler #1 trajectory appear to be real and to reflect the deep extension of high biomass

218 occurrence at this time, as discussed further below (see also Figure 3.1c). Consequently, this range of

219 profile was not taken into account for the drift calculation in Table 2. Overall, except for the bio-

220 profiler #1, most of the bio-optical sensors showed a slight loss of sensitivity with time, as indicated

221 by the negative slopes of the trend of their responses in the two considered depth layers (Table 2).

222 Over the time course of the bio-optical sensor observations, these sensor drifts were small in

223 comparison to the changes observed for surface bio-optical values, contributing less than 7% to either

224 fluorescence or particulate backscattering. The only exception was the drift for the bio-profiler #2 b_{bp}

225 sensor in the 250-300 m layer, where drift appeared to have been larger (though of course changes at

226 this depth range may also be oceanic) and reached up to 19 % of the low surface b_{bp} values for this

227 bio-profiler.

228   Fluorescence signals were also corrected for daytime quenching. This effect, which derives from

229 the photo-inhibition of phytoplankton by an excess of light (maximum at midday), decreases surface

230 fluorescence (Falkowski and Kolber, 1995; Kiefer, 1973) and, if uncorrected, can produce a false

231 impression of subsurface maxima in fluorescence derived chlorophyll profiles. We explain this

232 correction and its evaluation in considerable detail in the following paragraphs, but note that none of

233 the conclusions of the paper depend on these corrections because the same overall results are obtained

234 if we use only Chl-a fluorescence signals collected at night. Our purpose in detailing the correction

235 is to contribute to active discussion of the best way to use daylight Chl-a fluorescence data obtained

236 from platforms which may not have as good night time coverage as our floats (such as sensors

237 deployed on seals, on standard ARGO 10- day profile interval missions, or on float missions that

238 target co-measurement with daytime satellite ocean colour observations).

239   We defined the daytime profiles, potentially affected by quenching, as profiles acquired between

240 one hour after local sunrise time and one hour after local sunset time, to allow for dark acclimation

241 since quenching effect could still persist after sunset (Sackmann et al., 2008). Daytime profiles from

242 the four bio-profilers are shown to illustrate this effect (continuous lines in Figure 2b, left panel). To

243 correct this bias, we applied the method of Sackmann et al. (2008), which uses the particulate

244 backscattering signal as a relative reference. For the sake of consistency with the other studies of this

245 issue, we defined the mixed layer depth, MLD, as the depth where density increased by 0.02 kg m^{-3}

246 relative to the density at 10 m (Park et al., 1998). Within the deeper half of the mixed layer (targeted

247 to be below the depth of daytime quenching), we determined a mean value of the (relatively constant,

248   see below) Chl-a fluorescence to b_{bp} ratio (at depth defined as $d_{F/bbp}$) and multiplied this ratio by the

249   b_{bp} signal at this depth to retrieve the Chl-a fluorescence. Then, we multiplied this same ratio by the

250   surface b_{bp} value to estimate unquenched surface Chl-a fluorescence, and interpolated between these

251   two depths to obtain the unquenched Chl-a fluorescence profile. This assumes that phytoplankton

252   populations were not stratified within the density defined mixed layer. This works particularly well

253   for deep mixed layers (>50 m) which exhibit relatively constant Chl-a fluorescence/b_{bp} ratios (to

254   within ~10%) in their deeper half. In less than 3% of the daytime profiles, in average, we could not

255   identify a region of uniform Chl-a fluorescence/b_{bp} and apply the quenching correction; consequently,

256   these profiles were not used further.

257   The greater spikiness of the b_{bp} profiles in comparison to those of fluorescence (as illustrated in

258   Figure 2b, right panels) means that this quenching correction introduces some noise into the daytime

259   chlorophyll estimates. In principle, this could be filtered or smoothed, but the low 10 m vertical

260   resolution of the observations made this rather uncertain and so we have used the unfiltered

261   observations throughout this paper (except in Figure 9f below where we show median-filtered

262   particulate backscattering profiles for the sake of visual clarity). Note that to avoid to correct the

263   surface Chl-a fluorescence with a spiked surface b_{bp} value and create a "b_{bp} spiked" interpolation, we

264   verified before that the b_{bp} surface value did not seem to be spiked, assuming that surface value should

265   not exceed more than ±50% of the b_{bp} value at the depth $d_{F/bbp,}$ since within the mixed layer. This

266   threshold was defined after assessing the backscatterometer precision (using the coefficient of

267   variation of b_{bp}, i.e. the ratio of the standard deviation to the mean) between 500 and 1000 m depth of

268   14 ± 4% in average. If the surface b_{bp} value was considered as spiked (less than 4% of the daytime

269   b_{bp} profiles, except for bio-profiler #4 for which it reached 9%), the test was done with the second

270   depth value, until a "non-spiked" value was found, and the value was then extrapolated to the surface.

271   The effects of the quenching correction on our selected chlorophyll profiles are shown in Figure

272   2b (middle panels, continuous lines), and summary statistics for all the profiles are provided in Table

273   3. Without the correction, on average, more than 70% of the daytime profiles exhibited a subsurface

274   maximum exceeding 60% of the surface value –defined after assessing the fluorometer error

275   (coefficient of variation of Chl-a concentration) between 250 and 300 m depth and between 500 and

276   1000 m depth of $22 \pm 10\%$ in average. After applying the quenching correction method, the number

277   of daytime profiles exhibiting a subsurface maximum exceeding 60% of the surface value was

278   reduced to very similar levels to those observed in the night time profiles, although slightly higher

279   (of 21% in average), indicating, with the fact that these daytime subsurface maxima occurred mostly

280   below the MLD, that the correction was largely successful. Notably, for the total data set, after

281   quenching correction, less than 11% of the profiles exhibited a deep maximum exceeding 100% of

282   the surface value (Table 3), and these profiles were primarily located in a restricted region near the

283   Gallieni Spur, as discussed further in the Results section.

284   Even after our quenching correction, 10% of the corrected daytime profiles (in average for all 4

285   bio-profilers) still exhibited significant decrease of the Chl-a fluorescence in the surface layer. We

286   were not able to conclude if these decreases were due to an incomplete quenching correction or if

287   they were true features, given that ~ 14% of the night profiles in average exhibited subsurface values

288   at least 60% higher than the surface values. Consequently, we defined a threshold surface value for

289   each bio-profiler, defined as a slightly lower value than the minimum surface value reached during

290   night profiles (see squares in Figure 2b, middle panel, and caption) and we flagged all the corrected

291   daytime profiles that had a surface value lower than this threshold as potentially arising from

292   incomplete correction of quenching. These distinctions between night, daytime and flagged profiles

293   are illustrated in Figures 4, 5 and 7, and further discussed in the Results and Discussion sections

294   below. Note that, using a different quenching correction method, Biermann et al. (2015) recently

295   observed similar features and statistics in fluorescence profiles collected by southern elephant seals

296   during austral summer in the vicinity of Kerguelen Island.

297   Finally, we emphasize that the bio-optical measures of chlorophyll and particulate backscattering

298   are based on laboratory calibrations that are not specific to Southern Ocean phytoplankton or particle

13

299   properties. This means that while interpretation of local variations is reasonably straightforward,

300   quantitative comparisons to other observations much more uncertain (except perhaps in the future for

301   other serial numbers of these sensors, calibrated in the same limited way). For the 3 bio-profilers

302   deployed in 2014, no ancillary shipboard measurements are available to evaluate this issue, but in

303   2011 some chlorophyll samples were collected by the KEOPS2 science team that allow for limited

304   evaluation of the bio-profiler #1 calibration.

305   Bioprofiler #1 was deployed into a semi-permanent meander of the Polar Front, which the

306   KEOP2 program examined as a Lagrangian time series following surface drifters. As shown in Figure

307   2c, the first and second stations in the meander (E1 CTD-27 on 29 October 2011 at 22:46 local time

308   and E2 CTD-43 on 1 November 2011 at 12:00 local time) bracketed the locations of the first 11

309   autonomous bio-profiler #1 profiles (Figure 2c.i). The bio-profiler #1 temperature profiles are

310   intermediate between the ship results (Figure 2c.ii), with the variations in temperature profiles mainly

311   driven by vertical motions associated with internal waves (Park et al., 2014b). In Figure 2c.iii, the

312   KEOPS2 shipboard fluorescence results are displayed after linear calibration to high pressure liquid

313   chromatography (HPLC) total chlorophyll-a results from below 40 meters depth (below the depth of

314   non-photochemical quenching). The data reveal two important features: i) good fits achieved below

315   40 meters do not extend to the surface – where fluorescence/chlorophyll-a ratios were higher than at

316   depth, apparently as a result of community composition variations with depth (see also Lasbleiz et al.

317   2014), and ii) the bio-profiler #1 fluorescence data displayed similar characteristics and good accord

318   with the shipboard results. In light of the limited available data, a non-linear calibration of

319   fluorescence to chlorophyll-a was not pursued, and no adjustments were made to the laboratory bio-

320   profiler calibration.

321   These variations in fluorescence/chlorophyll-a ratios within individual CTD casts in the

322   shipboard observations serve as a strong reminder that fluorescence is an imperfect proxy for

323   chlorophyll-a concentrations, owing to variations with phytoplankton community structure,

324   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.

2.3 **Satellite data sources**

We used satellite products to provide physical and biological context for the bio-profiler trajectories, including the effectiveness of their sampling of high biomass waters downstream of Kerguelen. The images of surface chlorophyll concentrations shown in Figure 1 to provide context for the plume sampling achieved by the bio-profilers are the CLS SSALTO/DUACS 4 km daily product derived from NASA MODIS-Aqua observations (Figure 1), without modification for recent suggestions that this algorithm may underestimate chlorophyll in low chlorophyll waters south of Australia (Johnson et al., 2013).

To better understand the observed bio-profiler trajectories, we calculated expected movements based on geostrophic currents estimated from satellite altimetry using the multi-satellite global product Delayed Time Maps of Absolute Dynamic Heights (DT-MADT) developed by the CNES/CLS Aviso project (www.aviso.oceanobs.com). This product has 1 week temporal and 1/3° spatial resolutions, and was used to compute Lagrangian trajectories to produce a diagnostic for eddy retention (d'Ovidio et al., 2013; Figure 9b) and water origin and age (d'Ovidio et al., 2014; Figure 8). Eddy retention is a measure of how much time a synthetic water parcel has been recirculating within an eddy core. Long-lived and coherent eddies are characterised by water parcels with high values of retention (measured in days since a water parcel has been entrained by an eddy), whereas recently formed eddies or eddies that exchange strongly with surrounding regions have low retention values. Following d'Ovidio et al. (2014) and Sanial et al. (2014), we used back-tracking of virtual water parcels (from the bio-profiler profile locations) to compute how long ago (water age) and at which latitude (water origin) the sampled parcels had been in contact with the Kerguelen Plateau (defined

349 as the 700 m isobath, as shown in red in Figure 3.1). Figure 8 a) and c), adapted from d'Ovidio et al.

350 (2014), display example maps of the calculated daily snapshots of these water ages and water origins.

351 For each pixel in these maps, virtual water parcels were back tracked for 90 days. They are shown as

352 white pixels on the maps if during that time they never touched the Kerguelen Plateau (shown in grey

353 on the map), and otherwise are coloured for the time between the contact with the plateau and the day

354 of the map computation (water age, Figure 8a) and the latitude of the last contact with the plateau

355 stored (water origin, Figure 8c). These same computations were performed for each location sampled

356 by the bio-profilers, in order to compare the water ages and origins with their measured chlorophyll

357 inventories.

358

359 3   Results

360 *3.1* Coverage of the plume

361   The drifts of the bio-profilers provided coverage of a large portion of the elevated biomass plume

362 (Figure 1), from near the Kerguelen plateau to more than 700 miles downstream (71 to 95° E) and

363 nearly 400 miles from north to south (47.5 to 54° S), thereby spanning waters of the Polar Frontal

364 and Antarctic Zones (Orsi et al., 1995; Park et al., 2008b; Sokolov and Rintoul, 2009). Unfortunately,

365 this breadth of spatial coverage of the plume did not extend to full temporal seasonal coverage, and

366 this is important to keep in mind given the strong seasonal cycle of biomass accumulation (Trull et

367 al., 2015; Blain et al., 2007; Mongin et al., 2008). As shown in these images, the 2011 bio-profiler

368 covered the period of highest biomass accumulation, while the 2014 deployments occurred after this

369 seasonal peak, and thus sampled the system during its senescence (to illustrate these prior conditions,

370 Figure 1 also includes biomass distribution images from late 2013, before the launch of the three bio-

371 profilers in early 2014). Thus, the profilers obtained some seasonal context for the central portion of

372 the plume (which was sampled well in 2011 by bio-profiler #1 in spring and summer and again by

373 bio-profilers #2 and #3 in summer and autumn). However, sampling of the north-eastern portion of

374 the downstream plume (north of the Polar Front) was achieved only in late summer and autumn (by

375 bio-profiler #4).

376 Bio-profiler #1 in spring 2011 and bio-profiler #3 in 2014 were deployed in the centre of the

377 quasi-stationary cyclonic recirculation just east of the northern Kerguelen plateau (d'Ovidio et al.,

378 2014; Park et al., 2014a). Both bio-profilers exited this region to the northeast, tracking towards the

379 Gallieni Spur, before transiting strongly southward near 74° E. This southward transport has also

380 been observed for surface drifters and appears to be associated with a persistent meander of the Polar

381 Front (d'Ovidio et al., 2014; Park et al., 2014a). Thus bio-profilers #1 and #3 provide spring and

382 summer perspectives respectively for these portions of the biomass plume (albeit in different years).

383 Bio-profiler #2 was deployed further south, close to the region where the strong north to south

384 transport portions of the bio-profilers #1 and #3 trajectories finished. Thus bio-profiler #2 provided

385 some overlap with the southern portion of the bio-profiler #1 trajectory, before being carried the

386 furthest south, where it explored cold waters close to the Williams Ridge that extends to the southeast

387 of Heard Island and terminates near the Fawn Trough (a gap in the plateau which permits the passage

388 of much of the deep water eastward transport; Park et al., 2008b; 2014a). Waters in this region tend

389 to exhibit archetypical high-nutrient, low-chlorophyll characteristics, and were used as a reference

390 station for iron non-fertilised waters during the KEOPS field program in 2005 (Blain et al., 2007;

391 2008).

392 In contrast, bio-profiler #4 was deployed at similar latitude to bio-profilers #1 and #3, but further

393 east, in particular east of the southward meander of the Polar Front which carried these others to the

394 south. Bio-profiler #4 remained in the northern portion of the plume throughout its deployment,

395 drifting to the northeast roughly parallel to the shallow Eastern Kerguelen Ridge before becoming

396 trapped in a cyclonic eddy in which it obtained a time series of ~100 profiles (as discussed in detail

397 below).

398

3.2 Overview of observed oceanographic properties

The bio-profilers return a large number of water column observations making visualisation at the scale of individual profiles only possible for targeted issues. The simplest first-order assessment is most easily done by presenting the results as along-trajectory sections. These are shown for all the observed variables for each bio-profiler in Figures 3.1, 3.2, 3.3 and 3.4, and briefly described in the following paragraphs.

Bio-profiler #1, launched in late October 2011 in the centre of the deep water recirculation just east of Kerguelen Island, initially encountered cold, well oxygenated waters with moderate biomass (T ~ 3 °C, O_2 ~ 330 μmol kg^{-1}, 0.5 μg L^{-1} < Chl-a < 2 μg L^{-1}; profiles 1-90, Nov.). It was then carried north-eastward across the Gallieni Spur where it encountered warmer waters with extremely high biomass (T ~ 5 °C, chlorophyll up to nearly 10 μg L^{-1}), which satellite ocean colour animations suggest was being swept northward as a mix of waters from the northern and central regions of the Kerguelen plateau (see the animation "bloom 2011" in supplementary material; Trull et al, 2015). During the subsequent southward transport, it crossed the Polar Front near 51.5° S, as shown by the presence of a temperature minimum near 150 m depth (T ~ 1 °C; profiles ~ 200-220, end of Jan.). The shoaling of low dissolved oxygen layers in this region provides another indication of their Antarctic Zone oceanographic classification. Surface waters above this remnant winter water were relatively warm despite deep mixed layer depths (~ 100 m, T > 6 °C; profiles ~240-330, Feb.-Mar.). Much of this warming is probably seasonal, as these waters were encountered in late summer, but the co-occurrence of somewhat elevated salinity (~ 33.8) suggests that flow of Polar Frontal Zone surface waters over the Antarctic waters was also involved. During the February bio-profiler transit, these waters exhibited only low to moderate chlorophyll biomass (~1.5 μg L^{-1}), although satellite images suggest higher concentrations (~3 μg L^{-1}) were present earlier in December and January (see Figures 1b and 1c and the animation "bloom 2011" in supplementary material; Trull et al., 2015). The

423　particulate backscattering signal reflected the chlorophyll evolution along most of the trajectory,

424　except in January when, as the chlorophyll levels decreased (from >3 µg L^{-1} to ≤ 2 µg L^{-1}), b_{bp}

425　remained high and constant (-2.5 m^{-1} ≤ log(b_{bp}) ≤ -2.0 m^{-1}), suggesting detrital particles developed

426　from the high chlorophyll biomass, or possibly a (relatively large) change in chlorophyll/particulate

427　organic carbon ratio (Chl/POC) due to phytoplankton community composition. Finally, after 300

428　shallow profiles, bio-fouling of the fluorescence and particulate backscattering sensors marked the

429　end of their utility, as shown by the occurrence of elevated and highly noisy values throughout the

430　water column (see Figure 3.1c and e).

431　　　　Bio-profiler #2, launched in late January 2014 south and east of the recirculation feature, initially

432　encountered Polar Frontal Zone waters which were present further south in this region than during

433　the 2011 year sampled by bio-profiler #1. For approximately the first 150 profiles, these waters

434　displayed relatively homogenous, moderately warm temperatures (4-5 °C) that continued to warm to

435　~6 °C through February. The bio-profiler then transited much further south, briefly encountering

436　waters with strong shoaling of subsurface salty, low oxygen characteristics around profiles 160-170

437　(S ~ 34.0-34.2, O$_2$ ~ 260 µmol kg^{-1}), and entered colder Antarctic waters where it remained through

438　profile ~220, at which time its return north brought it back into Polar Frontal Zone waters showing

439　autumn cooling. Throughout its life, in comparison to bio-profiler #1, only low-to-moderate biomass

440　waters were encountered (<1.5 µg L^{-1}), though these values were persistently above Southern Ocean

441　HNLC background values (< 0.5 µg L^{-1}). Within this range, the higher biomass values, which also

442　extended over greater vertical extents (~ 100 m), were found in the Antarctic waters (profiles 170-

443　250, Mar.-Apr.). In contrast, the higher b_{bp} values were found at the beginning of the trajectory

444　(log(b_{bp}) ~ -2.5 m^{-1}), and their deep extent and high values compared to chlorophyll levels suggest

445　the existence of higher chlorophyll concentrations prior to the bio-profiler deployment. This is in

446　agreement with satellite ocean colour animations on which high biomass development is observed in

447　December 2013 in the area of the bio-profiler deployment (see Figures 1e and 1f and the animation

448 "bloom 2013" in supplementary material). After this initial difference, the b_{bp} variations followed

449 those of chlorophyll along the rest of the trajectory.

450   Bio-profiler #3, launched in late January 2014 in the northern portion of the recirculation feature,

451 followed a similar trajectory to that of bio-profiler #1 launched in October 2011 and encountered

452 much warmer waters with similar mixed layer depths, between 40 and 70 m (Figure 3.3). Presumably

453 this represents seasonal warming as salinities were similar to those encountered in spring (~ 33.85),

454 and the warming from ~3 °C to nearly 6 °C is consistent with seasonal warming amplitudes observed

455 in satellite surface temperature records for unfertilized open ocean Polar Frontal Zone waters (Trull

456 et al., 2001). Persistent high chlorophyll levels were also observed initially in the recirculation region

457 (up to ~4 versus ~1 µg L^{-1}), but the float did not cross the Gallieni Spur (GS in maps of Figure 3)

458 where bio-profiler #1 encountered values up to nearly 10 µg L^{-1}. During its transit south near 75° E,

459 only Polar Frontal Zone waters were encountered, and chlorophyll levels remained moderately high

460 (between 1 and 2 µg L^{-1}). At the beginning of the trajectory, the particulate backscattering b_{bp} signal

461 evolved in concert with the chlorophyll signal, but with a ~ 7-10 day delay. Another difference

462 between the two biomass parameter evolutions was the large increase of b_{bp} compared to chlorophyll

463 between the surface and 100 m, right after the profiler turned southward in the vicinity of the Gallieni

464 Spur (~ profiles 190-205, end of March).

465   Bio-profiler #4, deployed well east of the recirculation feature in early February, was initially in

466 warm, quite salty and well oxygenated waters, characterized by moderate biomass (first 80 profiles:

467 T ~ 5.5 °C, S ~ 33.8, O$_2$ ~ 310 µmol kg^{-1}, Chl-a < 1.5 µg L^{-1}, log(b_{bp}) ~ 3.35 m^{-1}). As its trajectory

468 approached the Gallieni Spur, surface waters became progressively warmer, fresher and less

469 oxygenated (profiles 80-250: T ~ 7 °C, S ~ 33.7, O$_2$ ~ 290 µmol kg^{-1}). During this time, the bio-

470 profiler recorded high chlorophyll and particle concentrations (chlorophyll values reaching up to 3

471 µg L^{-1} for profiles 80-130). This high biomass could be a remnant of the rich filament that transited

472 in this area a month prior to the visit of the bio-profiler (see the animation "bloom 2013" in

473 supplementary material). As the bio-profiler drifted further east, it was entrained in a relatively

474   stationary cyclonic eddy where it performed several loops before exiting to the south (profiles ~ 130-

475   240, mid-March – mid-April). This eddy can be identified from altimetry as retentive – i.e. capable

476   of entraining Lagrangian particles for, in this case, a few weeks to one month (d'Ovidio et al., 2013;

477   Figure 8b). While retained by this mesoscale eddy, the bio-profiler measured a relatively constant

478   profile of temperature and salinity, with slowly decreasing Chl-a concentrations and b_{bp} (Figure 8).

479   Relatively constant hydrological properties throughout this period and the repeated looping suggest

480   a largely Lagrangian trajectory within a single water parcel at this time. Of all the observations, this

481   region displayed surface waters with the highest temperatures and lowest salinities (T ~ 8.0 °C, S ~

482   33.6).

483

484   **4   Discussion**

485   With this overview of the spatial and temporal characteristics of our observations in hand, we

486   proceed to evaluate our research questions.

487   *4.1* **Do the satellite images of surface chlorophyll reflect water column contents?**

488   As discussed in the Introduction, it is important to determine whether the water column

489   information provided by the bio-profilers changes perspectives on the mesoscale distributions of

490   chlorophyll as seen in satellite images (Figure 1) This is a larger issue than whether our in-situ

491   measurements of surface values differ from satellite values. We did not evaluate that question owing

492   to extensive cloud cover greatly limiting match-ups between bio-profiler and satellite observations,

493   and because we know that both our sensor calibrations and the satellite algorithms have large

494   uncertainties (see the Methods sections 2.2 and 2.3). Instead, we examined the bio-profiler water

495   column observations to determine what biases might be expected from observing only their upper

496   portions, i.e. as a satellite would. There are two aspects of this issue that we could readily address: i)

497   were subsurface chlorophyll maxima commonly present below the depth of satellite observation, and

21

498   did they vary spatially or temporally? ii) were surface chlorophyll values linearly and tightly

499   correlated with water column inventories with similar dynamic ranges, or were surface values poor

500   guides to water column inventories? We address these issues in this order in the following paragraphs.

501   Our statistics on the occurrence of subsurface chlorophyll maxima (Table 3) show that these

502   features were present in a significant fraction of the profiles (up to 14% of the night profiles and up

503   to 21% of the quenching-corrected day profiles). They mostly occurred at depths greater than the

504   MLD (Table 3) and, thus, too deep to be taken into account in the satellite observations. Without

505   radiation sensors on the bio-profilers, the first penetration depth (z_{pd}, light attenuation by 1/e) that

506   characterizes satellite observations could not be directly estimated, but based on the model of Morel

507   and Maritorena (2001; their figure 6), and using the relationship $z_{pd} = z_{eu}/4.6$ for the euphotic zone

508   definition of the 1% photosynthetically active radiation level (Gordon and McCluney, 1975), it was

509   at most 10-15 meters, and thus always within the mixed layer. Thus, we focused on these subsurface

510   maxima occurring below the MLD (hereafter SubMax$_{>MLD}$) and we examined the location of the

511   profiles exhibiting these features as well as their associated depth (see Figures 4a, 4b, 4d and 4e).

512   These SubMax$_{>MLD}$ were quite localized. They occurred primarily near the plateau or close to the

513   location of the Polar Front. Specifically, most of the profiles exhibiting this feature were found in the

514   vicinity of the steep slope between the Northern Kerguelen Plateau and the Gallieni Spur, between

515   40 and 80 m depth (Figures 4a, 4b, 4d and 4e). Occurrences of SubMax$_{>MLD}$ were much more sporadic

516   south of 50° S, on the south-eastward trajectories of bio-profilers #1 and #2. These conclusions about

517   the locations of subsurface chlorophyll maxima are similar for both night and day occurrences (stars

518   and open circles in Figure 4, respectively), although SubMax$_{>MLD}$ of day flagged profiles occurred

519   mostly at shallow depths (< 50 m, Figures 4b and 4d) and may result from an under-correction of the

520   surface quenched Chl-a concentrations (see Methods section 2.2). It seems that light limitation may

521   not be a major driver of subsurface Chl-a maxima via the mechanism of increased Chl-a production

522   per cell, at least under a certain threshold of Chl-a content, since SubMax$_{>MLD}$ observed by bio-

523   profilers #3 and #4 occurred more frequently when the mixed layer was deep (for 2.5 μg L^{-1} $\leq$ Chl-a

524 ≤ 5 μg L^{-1}; Figures 4c and 4f). However, the quasi-ubiquitous concomitance of SubMax$_{>MLD}$ for bio-

525 profiler #1 with shallow mixed layers, less than 50 m, suggests that above a certain threshold of Chl-

526 a content, self-shading may promote pigment production by phytoplankton at depth.

527   Subsurface chlorophyll maxima beyond the reach of satellite imagery can be thought of as a

528 specific class of the wide range of possible chlorophyll distributions (such as varying thicknesses of

529 relatively constant near-surface biomass layers, or changes in the rate of decrease of biomass with

530 depth) that could introduce bias between surface concentration and water column inventory

531 perspectives. To gain perspective on the overall importance of these possibilities, we compared

532 surface chlorophyll concentrations measured by the profilers (using the shallowest ~10 m depth

533 observation since this was reliably within both the 1/e satellite ocean colour penetration depth and

534 the mixed layer) with their column inventories calculated from all observations in the top 200 m

535 (since chlorophyll distributions generally reduced to background values below this depth). These

536 comparisons, shown in Figure 5a (left column), display reasonably linear relationships over almost

537 the entire range of both night and daytime observations. This was especially true for bio-profilers #1

538 and #3 (correlation coefficients r^2=[0.60-0.85]), which include high chlorophyll values (greater than

539 2 mg m^{-3} for the surface concentration and greater than 160 mg m^{-2} for the 0-200 m inventory). Most

540 of the flagged daytime profiles (red circles in Figure 5a) seem to be shifted slightly left of the linear

541 regression lines, suggesting that they may well represent under-corrected quenched chlorophyll rather

542 than true features. Overall, qualitatively, these quite linear relationship between surface Chl-a

543 concentration and 0-200 m integrated Chl-a content suggests that satellite observations are reasonably

544 good indicators of the spatial distributions water column chlorophyll inventories.

545   Concerning the particulate backscattering signal, the linear correlations between surface values

546 and inventories were generally not as strong as for Chl-a, except for bio-profiler #3, as shown in

547 Figure 5b (right column: r^2 = [0.29-0.74]. It appears that surface b_{bp} values lower than ~2 x 10^{-3} m^{-1}

548 vary similarly to the 0-200 m b_{bp} inventories, whereas higher surface values exhibit noisier

549   correlations when compared to the 0-200 m integrated b_{bp} contents (see the slope breaks in the

550   relationship between surface and 0-200 m integrated b_{bp} in Figure 5b). The origin of this non-linearity

551   is not clear, and its evaluation is potentially compromised by the spikiness of the b_{bp} records and their

552   poor vertical resolution. The particulate backscatter profiles (Figures 2b, 3e and 9e) suggest that

553   spikes may be particularly common at the base of the mixed layer and below, and thus might reflect

554   differential control of phytoplankton and total particle populations. Future deployments with

555   improved firmware to yield higher resolution may be able to advance the interesting possibility that

556   backscatter information can provide ecosystem perspectives beyond phytoplankton biomass alone.

557   Because our qualitative assessment indicated that surface Chl-a concentrations provide a

558   relatively unbiased indication of the water column Chl-a inventory, we now try to go a little bit further

559   towards a quantitative assessment of possible biases between satellite and in-situ Chl-a perspectives.

560   First, we compared the coefficients of variation (i.e. the ratio of the standard deviation to the mean)

561   of the surface chlorophyll concentrations and of the water column inventories. Using only the night

562   data to avoid quenching correction uncertainties, surface distribution coefficients of variation (#1:

563   82%; #2: 20%; #3: 39%; #4: 43%) revealed very similar relative dispersions to the water column (0-

564   200 m) inventory coefficients of variation (#1: 84%; #2: 20%; #3: 34%; #4: 31%). Thus, satellite

565   images reasonably reflect the relative range of mesoscale variability in water column phytoplankton

566   biomass accumulations. Surprisingly, surface chlorophyll values (i.e. satellite images) would tend to

567   slightly overestimate the relative dispersion of Chl-a data for bio-profilers #3 and #4, despite those

568   profiles exhibiting the largest numbers of night subsurface maxima (in %, Table 3). This means that

569   the association of high surface chlorophyll concentrations with shallow chlorophyll layers was more

570   important than the presence of subsurface chlorophyll maxima in determining the relationships

571   between surface and water column inventories.

572   To further explore this issue, we calculated expected water column inventories for chlorophyll

573   layers confined to the physical mixed layer depths at the time of observation (by multiplying each

574   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 × 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 µg L^{-1} to close to twice for MLD > 120 m and surface Chl-a > 2 µg L^{-1}). However, (surface Chl-a × 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 × 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

600   MLD definition of [Levitus](#) ([1982](#)). This X vs MLD hyperbola reaches an asymptote of X ~ 1 for MLD

601   values close to the 150-200 m depths of regional winter mixed layers (visible as temperature minima

602   remnant signatures of winter cooling in profiles south of the Polar Front in Figure 3b). Moreover, the

603   curve is reasonably well parameterized by $X \sim MLD^{t}/MLD^{w}$, in which the superscripts t and w

604   indicate mixed layer depths at the time of observation and the end of winter, respectively. This

605   relationship could arise if most biomass accumulation occurred in early deep mixed layers with

606   subsequent stratification adding little additional biomass, or if mixed layers shallowed and deepened

607   episodically as biomass accumulation developed throughout the season.

608   Overall, these results emphasize the major challenges that are present for connecting surface

609   chlorophyll distributions to total water column biomass and primary productivity, since they reveal

610   that physical mixed layer depths are often not a reliable guide to biomass distributions. These physical

611   and biological responses seem to be modulated differently on diel, weather, and seasonal timescales,

612   and are also affected by the mesoscale and sub-mesoscale interleaving of water parcels. The

613   quantification of near surface mixing (i.e. going beyond the limited mixed layer depth concept) is

614   currently under very active exploration and debate in the context of seasonal drivers of production

615   ([Behrenfeld, 2010](#); [Taylor and Ferrari, 2011](#)), and these data reveal the need to extend those

616   perspectives to shorter time and space scales. The presence of significant amounts of chlorophyll

617   below the mixed layer is also important to its ultimate fate –if this biomass is not re-entrained then it

618   may well contribute preferentially to export and to mesopelagic oxygen consumption (issues which

619   we revisit in Discussion section 4.3 below).

620   *4.2* **Do regions of high biomass correlate with (local) oceanographic properties?**

621   To evaluate this issue, we examined bivariate regressions of Chl-a inventories (0-200 m) with

622   physical water column characteristics, after having separated the observations into two groups: 1)

623   Chl-a inventories > 200 mg m^{-2} in rich biomass regions close to the plateau, and 2) Chl-a inventories

624   ≤ 200 mg m^{-2} in moderate biomass regions far from the plateau (the rich and moderate biomass

625 regions considered here are identified by red and yellow rectangles in Figures 3.1c, 3.2c, 3.3c and

626 3.4c). As shown in Figure 7 (a, b and c), the richest biomass regions encountered by bio-profiler #1

627 in 2011 and bio-profiler #3 in 2014 were associated with waters with very similar properties,

628 specifically moderate temperatures (3.5-5 °C), high salinities (33.82-33.85), and thus relatively high

629 densities (sigma-theta values of 26.7-26.9 kg m^{-3}). The bio-profiler #1 distributions of chlorophyll

630 with these properties showed linear decreases on either side of these values, suggestive of mixing

631 with surrounding waters much poorer in Chl-a. This characteristic is also observed between integrated

632 Chl-a and mean surface oxygen saturation (O$_{2\ sat}$, Figure 7f), for which the high O$_{2\ sat}$ states (reaching

633 10%) indicate oxygen production in these high biomass waters (since these values exceeding expected

634 from processes such as warming or bubble injection; Shadwick et al., 2014). Relatively high biomass

635 was also encountered in waters with extreme T-S properties (the warmest and freshest observed) in

636 the vicinity of the Gallieni Spur by bio-profiler #4 (black symbols in Figure 7). Thus, there was not a

637 unique class of waters with high biomass. This perspective is further reinforced by the lack of any

638 clear relationships between chlorophyll inventories and local water column properties for regions of

639 moderate biomass, including versus mixed layer depth and the intensity of stratification as

640 represented by the Brunt-Väisälä frequency (Figure 7, right column). These low biomass waters also

641 exhibited lower O$_{2\ sat}$ states (95-103%) than those of rich biomass areas. The under-saturated oxygen

642 levels reflect either strong local respiration or the supply of low oxygen waters from below, with

643 these processes difficult to distinguish (except for specific portions of the bio-profiler #4 trajectory

644 where time series within constant physical property layers were obtained, as discussed in section 4.3).

645   Linking local water parcel properties to past water trajectories with respect to the Kerguelen

646 Plateau, as a known natural source of iron fertilization, provides an additional view of the role of

647 water mass properties in the control of chlorophyll inventories. For the richest Chl-a waters (T ~ 4

648 °C, S ~ 33.83, σ ~ 26.8 kg m^{-3}) encountered by bio-profiler#1, surface drifters released during the

649 KEOPS2 voyage (d'Ovidio et al., 2014) suggest these waters derive from the northern Kerguelen

650   plateau. The computation of trajectories based on satellite altimetry (see Methods section 2.3) for all

651   the bio-profilers confirms this perspective and also indicates that the time since a water mass left the

652   plateau (Figure 8b) is another important determinant of chlorophyll levels (presumably as a result

653   loss of Fe over time after its addition from the plateau; d'Ovidio et al., 2014). These results are shown

654   in Figure 8. Figure 8 b) and d) compares water age and origin with the 0-200 m Chl-a inventories for

655   spring (bio-profiler #1, in blue in the plots) and summer (bio-profilers #2, #3, #4, in black in the

656   plots). Beside a strong seasonal difference –spring values range from up to 1000 mg m^{-2}, whereas in

657   the summer few measurements exceed 300 mg m^{-2}– water parcels corresponding to high Chl-a

658   inventories appear to be waters that have recently left the Kerguelen Plateau (20-40 days of water

659   age; Figure 8a) and come generally from its northern part ([-49; -47] °S; Figure 8c). Bio-profilers

660   locations that correspond to water parcels that have not touched the Plateau in the last 100 days (points

661   shown in white for water age = 100 in Figure 8b) do not present any high integrated Chl-a values,

662   suggesting that the main source of iron fertilization for the explored water masses is horizontal

663   advection from the Kerguelen Plateau. This correlation of high Chl-a inventories with age since

664   leaving the plateau is unlikely to be biased by the lower frequency of sampling (shown in the Figure

665   8b inset) of older waters, given that a statistical test based a 10^4 samplings of a uniform distribution

666   of integrated Chl-a at the sampling frequency of each water age yielded a probability (p) of not-

667   sampling integrated Chl-a value greater than 200 mg m^{-2} for water parcels with water ages greater

668   than 40 days of $p < 10^{-4}$.

669   These results suggest that the northern Kerguelen Plateau is an important target region for future

670   studies of iron delivery mechanisms into the plume downstream. In terms of the secondary influences

671   of mixed layer depth and stratification, the bio-profiler #1 profiles with integrated Chl-a greater than

672   600 mg m^{-2} were mainly characterized by a shallow mixed layer, lower than 60 m (Figure 7d), and a

673   low stratification (-0.01 s^{-2} < max N^2 < 0 s^{-2}; Figure 7e). Below this Chla-a inventory threshold, no

674   clear relationships emerged between MLD or N^2 and 0-200 m integrated chlorophyll (Figures 7d and

675   7e). In a steady state perspective, this lack of correlation could arise because mixed layers were

676 shallow enough that light limitation was not sufficient to halt phytoplankton accumulation, yet not so

677 shallow that mean mixed layer light levels allowed light promoted growth to reach accumulations

678 that became self-shading (viewpoints that have been developed previously, based on relationships

679 between fluorescence and mixed layer depth observations in this region using sensors on elephant

680 seals; Blain et al., 2013). Importantly, our observations emphasize that chlorophyll distributions do

681 not track the shoaling of mixed layer depth on seasonal or weather timescales, and thus that MLD

682 variability is unlikely to show simple relationships to biomass accumulation. This point has also been

683 emphasized in terms of competing effects of light and Fe limitation responses to MLD variability

684 (Joubert et al., 2014), for waters where vertical Fe supply is dominant (rather than the horizontal

685 dominance of supply studied here).

686

687 *4.3* **Can the fate of surface enrichments in biomass be determined, and if so, what is the**

688   **percentage of biological production exported?**

689   Evaluating this question requires the extraction of a temporal perspective from the bio-profiler

690 records, and is thus only possible for portions of their trajectories which appear to be essentially

691 Lagrangian. The best record for this approach is for bio-profiler #4 during the period when it carried

692 out several clockwise loops in late autumn, i.e. for profiles 150-240 (Figure 3.4a). During this time,

693 its trajectory was very similar to that expected based on surface currents estimated from satellite

694 altimetry, the density stratification of the water column was relatively steady, and the T-S profiles

695 were tightly grouped (Figures 9b, 9c and 9d). These observations suggest that the profiler remained

696 within a single water parcel, that was entrained by a retentive eddy and underwent only small

697 exchanges with surrounding waters, as shown by slightly warmer (profiles 165-170 and 200-220) and

698 cooler (profiles 175-195) conditions along the trajectory (these are discussed further below).

699 At the start of this period (blue lines subset in Figure 9e), chlorophyll profiles showed moderate

700 to high surface and subsurface layer levels, well above HNLC background values, with some profiles

701 exhibiting subsurface maxima reaching up to 1.5 µg L^{-1} between 50-70 m depth and up to 1 µg L^{-1}

702 around 120 m depth. Both the surface constant Chl-a layer and the subsurface "chlorocline" layer (by

703 analogy to thermocline or halocline, "chlorocline" is defined here as the depth range with the highest

704 chlorophyll concentration gradient) were thick, equal to ~ 80 m and ~50 m, respectively. The origin

705 of the smaller and variable subsurface maxima seen in some profiles in Figure 9e is uncertain. One

706 possibility is that they are remnants of the high surface chlorophyll biomass observed just prior to the

707 eddy entrapment (visible in Figure 3.4c and the "bloom 2013" animation in the supplementary

708 material), that had been carried to depth by particle settling or by subduction of the denser, saltier,

709 and slightly cooler water associated with that high biomass. Associated b_{bp} profiles showed similar

710 large variations with strong local maxima correlated to local Chl-a maxima (blue lines subset in

711 Figure 9f). The strong variability of the Chl-a/b_{bp} profiles over the first 100 m suggests possible

712 changes in the composition of the particulate assemblage (blue lines subset in Figure 9g).

713 During the Lagrangian eddy entrapment period, the surface mixed layer chlorophyll levels

714 declined further from 1.5 µg L^{-1} to ~1 µg L^{-1} (Figure 3.4c and 9e). Since the constant chlorophyll

715 surface layer shallowed progressively with time, this Chl-a decrease did not result from the possible

716 effect of dilution by mixed layer deepening (i.e. entrainment). Furthermore, the chlorocline content

717 decreased briefly before re-increasing progressively in its upper part, and then its deeper part. In

718 parallel, b_{bp} and Chl-a/b_{bp} profiles became tighter and tighter (light blue to orange profiles in Figures

719 9f and 9g) before re-exhibiting larger variations (red profiles). These results suggest the possibility

720 of some chlorophyll conversion to non-fluorescent material, or its removal by export to depth or by

721 local respiration or both, throughout the eddy entrapment. They may also of course partly reflect

722 small spatial variations in the structure of the biomass distributions.

723 To evaluate these possibilities we examined changes in three layers, the surface layer (labelled

724 layer 1 and defined as the surface down to the 26.6 isopycnal surface), and two density layers

725   immediately below it (layers 2 and 3, respectively for density ranges 26.6-26.8 and 26.8-26.9). In

726   order to characterize the existence of vertical or horizontal mixing during the eddy entrapment, mean

727   temperature, salinity, depth of the density layers, as well as their thickness and their stratification

728   state, are shown in Figure 10 (a, b, and c). The thickness and mean depth of the surface density layer

729   were relatively constant in the first half of the eddy entrapment, then slightly increased as some

730   warmer and fresher - thus lighter - water entered into the eddy structure (profiles 200-220).

731   Contrastingly, the physical properties of the two deeper underlying density layers showed

732   insignificant temporal trends and smaller variability over the period of interest, and thus changes in

733   their biogeochemical properties can be attributed to local processes rather than exchanges.

734   The evolution of chlorophyll, particulate backscattering and dissolved oxygen inventories also

735   exhibited different trends and variability for each layer (as shown in Figure 10d, e and f). In surface

736   layer 1, mean chlorophyll and b_{bp} showed no overall temporal trend (green and grey curves in Figure

737   10d, respectively), although characterized by two maxima, one at the beginning of the eddy and one

738   coinciding with the fresher warmer water occurrence described above. The oxygen content

739   continuously decreased steadily until after profile 200, when larger variations were observed, with a

740   minimum content coinciding with the fresher warmer waters. Within the underlying layer 2,

741   chlorophyll, b_{bp} and oxygen inventories showed similar evolutions: all had maximums at the

742   beginning of the eddy and then decreased with time until the bio-profiler exited the eddy (Figure 10e).

743   These characteristics were also present in the deepest layer 3, although with significant differences in

744   the magnitudes of change, specifically the oxygen decrease was similar to that of layer 2, but the

745   chlorophyll level and its absolute magnitude of decrease were much smaller, and the b_{bp} levels

746   remained relatively high for a longer portion of the record.

747   To verify that these changes were oceanographic, we again evaluated fluorometer and oxygen

748   sensor drifts, but this time only over the range of profiles considered for the eddy entrapment

749   investigation (following the approach used in Table 2, of examining the evolution of the mean values

750   within the depth layer 950-1000 m). Chl-a and O_2 drifts were respectively estimated to be +0.017 μg

751   L^{-1} and +1.05 μmol kg^{-1}.Thus, the temporal drifts probably lead to underestimations of the observed

752   decrease of Chl-a (of ~7% in layer 2 and of ~ 20% in layer 3) and of O_2 (~30% in layers 2 and 3).

753   Knowing that excluding the contribution of the drifts would only reinforce the trends described above,

754   we can now suggest the following overall interpretation to explain these variations of Chl-a, b_{bp} and

755   O_2 in these 3 density layers during the eddy entrapment of bio-profiler #4. In the surface layer 1, the

756   chlorophyll inventory seems to result from the combination of local biological processes with weak

757   horizontal resupply from warmer, fresher, and less oxygenated water (Figures 9a and 9d). In the

758   middle density layer 2, where mixing is considered insignificant because of the tightly grouped T-S

759   properties, the chlorophyll decrease does not seem to be due to local transformation to non-fluorescent

760   detritus since no corresponding increase in the b_{bp} signal was observed (Figure 10e). This leaves loss

761   by settling or respiration as possible explanations. Loss by settling is certainly possible on this

762   timeframe (rates of only a few meters per day are required), and the high b_{bp} values found in the lower

763   density layer 3 around profiles 160-180 could reflect transfer from the overlying layer 2. Biomass

764   loss by respiration and remineralization to dissolved inorganic carbon is almost certainly also

765   occurring given the decreasing oxygen inventories of the middle layer 2 and deep layer 3. For both

766   these layers the rate of chlorophyll loss is too small (by factors of 2-3, assuming a moderately high

767   phytoplankton C/Chl-a ratio of 50) to explain all the oxygen decrease, implying that degradation of

768   detritus (represented by the decreasing particulate backscattering signal) and dissolved organic matter

769   probably also contributes (this remains true even if we use a very high phytoplankton C/Chl-a ratio

770   of 100; Cloern et al., 1995). For the deepest layer 3, remineralization of settling particles coming from

771   above with a minor remineralization of local chlorophyll may best explain the slower decrease of

772   chlorophyll in comparison to that of oxygen.

773   In combination, these results suggest that not all of the accumulated biomass was respired in the

774   surface layer, with the CO_2 then returned to the atmosphere, and thus that there was some export.

775   Quantifying this export amount is difficult and merits a modelling and sensitivity assessment that is

776 beyond the scope of this paper. Here we simply provide an indication of its possible magnitude by

777 comparison of the rates of mean oxygen loss in the surface layer 1 (representing carbon likely to be

778 returned to the atmosphere) versus the subsurface layers 2 and 3 (representing carbon which may be

779 exported in the ocean interior). The linear fits to the oxygen decreases for layers 1, 2, and 3 (as shown

780 in Figure 10) imply oxygen consumption rates of approximately 5, 4, and 4 μmol m^{-3} d^{-1}, respectively.

781 These values lie towards the lower end of estimates for annual rates at mesopelagic depths (Sarmiento

782 et al., 1990). Comparing O_2 consumption of layers 2 and 3 (by multiplying the O_2 consumption rate

783 by the thickness and the average density of the layer) relative to the total mean consumption among

784 the three layers, we estimate that 35% of the CO_2 produced during this autumn period of bloom

785 decline was exported from the surface layer (with 20% respired within layer 2 and 15% within layer

786 3). An analogous area of low-to-moderate production and relatively high export was observed during

787 the KEOPS2 field cruise just south of Polar Front, in a meander area around 72.5° E – 49° S where

788 the flow – considered as Lagrangian – was sampled in few stations as a time series (Laurenceau-

789 Cornec et al., 2015; Planchon et al., 2014). This area coincides with the location of the anti-cyclonic

790 trajectory of bio-profiler #3, around profile #110, where moderate biomass production was observed

791 (Figure 3.3c), although spatial variations in this region unfortunately precluded estimation of

792 biologically driven oxygen consumption from the bio-profiler.

793

794 **5 Conclusions**

795 The bio-profilers revealed several interesting aspects of the enriched biomass plume downstream

796 from the Kerguelen plateau, by providing observations of its vertical dimension. First of all, the

797 observations show that surface and total water column chlorophyll inventories are generally well

798 correlated, which suggests that satellite perspectives on bloom spatial dynamics (e.g. Mongin et al.,

799 2008; 2009) are unlikely to be strongly biased. This result holds true despite the presence of moderate

800   (60% above surface values) subsurface chlorophyll maxima in up to ~20% of all the profiles, and

801   strong (100% above surface values) in ~10% of all the profiles (Table 3 and Figure 4). Furthermore,

802   satellite surface observations seem to well reflect the water column relative range of mesoscale

803   variability in biomass accumulations. However, the retrieval of water column Chl-a inventory from

804   satellite surface observations is not simple. The bio-profilers often recorded significant quantities of

805   biomass below the diel mixed layer, potentially correlated to the degree of shallowing of the mixed

806   layer from deep winter values. The mixed layer at the time of the observations may not be the best

807   parameter to quantify the chlorophyll inventories, especially when stratification by advection of

808   lighter water mass or by seasonal warming creates strong density variations in the upper layer and,

809   thus, shallow mixed layers, and considering that chlorophyll production may have occurred much

810   earlier than at the time of the observations. And of course, our work does not imply that satellite

811   chlorophyll estimates are necessarily accurate. That is an issue which our data cannot address owing

812   to the imprecision of the bio-optical sensors and the absence of calibration against local chlorophyll

813   observations, an approach which recent work has shown to be necessary for satellite estimates as well

814   (Johnson et al., 2013).

815   The occurrence of moderate subsurface chlorophyll maxima in our data (17%) was higher than

816   for results obtained with fluorescence sensors deployed on elephant seals around the Kerguelen

817   plateau (~9% using a criterion of 30% excess over surface values to define the maxima; Guinet et al.,

818   2012). This may reflect the greater proportion of observations in the southern portion of the plume in

819   the Guinet et al. (2012) study, a region where we also found that subsurface maxima were less

820   common (~4% of profiles for bio-profiler #2 for our moderate criterion of 60% excess, Table 3, and

821   ~6% using their 30% criterion, data not shown). Subsurface maxima were also uncommon well

822   downstream to the east of the Kerguelen plateau. This is interesting in that it suggests that subsurface

823   iron levels supplied by upwelling or vertical mixing were insufficient to drive biomass accumulations

824   at the base of the mixed layer, or at least were less important than horizontal supply of Fe in surface

825   waters. This is in contrast to Polar Frontal Zone waters much further to the east south of Australia

826   where persistent subsurface maxima have been observed (Parslow et al., 2001), and with observations

827   from other autonomous profiling floats elsewhere in the Southern Ocean in which small subsurface

828   maxima were found to be common in summer below the mixed layer (Carranza et al., 2014).

829   Variations in the relative intensities of surface and deep iron supplies is a possible cause of these

830   variations, but other processes may also be involved. As an example, the origin of the relatively more

831   common and stronger subsurface chlorophyll maxima near the Gallieni Spur is not clear. Settling of

832   surface biomass generated earlier in the season (Figure 1) and/or seasonal depletion of iron in surface

833   waters which reduces phytoplankton growth rates are possibilities, but they cannot be assessed given

834   our lack of early seasonal observations. A third possibility of the overlaying of low density waters

835   southward across the Polar Front appears less likely, given that shipboard observations during

836   KEOPS2 found that this process generated shallow high biomass layers (at the Polar Frontal stations

837   F-L, TEW-7, and TEW-8; (Lasbleiz et al., 2014; Trull et al., 2015).

838   Our initial research goals included looking for oxygen supersaturations in deep chlorophyll

839   maxima to estimate net community production (Spitzer and Jenkins, 1989), but this could not be

840   achieved owing to confounding effects on super-saturations from strong mixing with higher

841   productivity overlying waters, and on aliasing of daily cycles by internal waves (Park et al., 2008a).

842   Thus our results cannot address the issues of whether productivity in subsurface layers may partly

843   explain offsets between satellite and in-situ estimates of the Southern Ocean biological pump

844   (Schlitzer, 2002) or whether the phytoplankton that grow in deep chlorophyll maxima are preferential

845   contributors to carbon export (Kemp et al., 2000; Queguiner, 2013). We were able to make a first

846   simple assessment of subsurface autumn oxygen consumption during the portion of the bio-profiler

847   #4 trajectory that delivered a quasi-Lagrangian time series, and this provided the very useful result

848   that approximately 35% of the biomass respiration in that period occurred beneath the mixed layer,

849   and thus at depths favouring CO_2 export toward the ocean interior. This 35% can be approximately

850   equated to an export/production "e-ratio" of 0.4, which is relatively high by global standards, but in

851 the middle of the large range of values observed in cold Southern Ocean waters (Maiti et al., 2013),

852 and similar to f-ratios estimated for high biomass waters over the central Kerguelen plateau in autumn

853 during the KEOPS1 campaign (Trull et al., 2008). Of course the subsequent fate of the exported CO_2

854 inferred from the bio-profiler #4 observations is uncertain, in that these waters were still within the

855 depth range of possible exposure to the atmosphere during later deeper winter mixing, although the

856 larger scale circulation in this region suggests it is a region dominated by subduction (Sallée et al.,

857 2010).

858   Our simple correlative evaluation of the bio-profiler observations of biomass variations

859 revealed that the highest chlorophyll levels were observed in surface waters with a narrow range of

860 densities and moderate temperatures (σ~26.9 ±.05 kg m^{-3}, T ~4 ±.5°C; Figure 7). This occurrence of

861 maximum biomass at moderate temperatures, along with the lack of correlation with mixed layer

862 depth (Figure 7) suggests that local controls on growth rates were less important than the history of

863 the levels of iron supplied in this water type. Notably, water with these properties was found

864 preferentially near the northern Kerguelen plateau and Gallieni Spur suggesting iron supply from this

865 region. This is consistent with geostrophic circulation estimates and a favourable wind regime for

866 upwelling in this region during the 2011 KEOPS2 period when bio-profiler #1 was deployed

867 (d'Ovidio et al., 2014; Gille et al., 2014) and with Lagrangian analyses that backtrack water parcels

868 to identify their origin. Further observations and analyses are of course necessary to determine the

869 generality of this inference that the northern Kerguelen plateau provides the major source of iron to

870 the downstream biomass plume. This is especially true given the limited seasonal and inter-annual

871 scope of our bio-profiler observations.

872

889

890   **List of Tables**

891   Table 1. Bio-profiler deployments.

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

893   1000] m depth layers.

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

Figure Captions

896 Figure 1. Maps of bio-profiler trajectories (white and grey lines) over remotely sensed chlorophyll-a

897 distributions (a-h: daily, 4 km CLS/CNES product; i: weekly composite from GlobColour 4 km

898 product). Top row: 2011 bloom season for bio-profiler #1. Middle and bottom rows: 2013/2014

899 bloom and beginning of post-bloom season for bio-profilers #2 (light grey trajectory), #3 (dark grey

900 trajectory) and #4 (white trajectory). Red squares indicate the bio-profiler locations corresponding

901 to the day of the image. The black thick line refers to the position of the Polar Front measured from

902 hydrographic samples by Park et al. (2014a).

903

904 Figure 2. a) Assessment of bio-optical sensor stability from temporal evolution of chlorophyll and

905 particulate backscattering values averaged over two depth ranges, 250-300 m (lines) and 950-1000

906 m (stars). Arrows indicate profiles considered to be affected by bio-fouling, which were not used in

907 further analysis. b) Illustration of quenching corrections, showing pairs of successive night/day

908 profiles (day: continuous lines; night: dashed lines). For each bio-profiler, the panel shows:

909 chlorophyll profiles without quenching correction (left), chlorophyll profiles with quenching

910 correction (middle), and associated particulate backscattering profiles (right). Squares in the middle

911 panel represent threshold values of the lowest surface chlorophyll concentration for the night

912 profiles of each bio-profiler (#1: 0.7 μg L^{-1}; #2: 0.4 μg L^{-1}; #3: 0.65 μg L^{-1}; #4: 0.7 μg L^{-1}). These

913 threshold were used to flag day profiles having surface chlorophyll concentration still below this

914 threshold after the quenching correction (see Table 3, Figures 4 (squares), 5 (red circles) and 7

915 (squares)), for which quenching might have been under-corrected. c) Comparison of bio-profiler #1

916 fluorescence Chl-a estimates to shipboard results obtained by the KEOPS2 project:, c.i. Location of

917 KEOPS2 stations E1 (blue symbols) and E2 (black symbols) along a quasi-Lagrangian track

918 followed by bio-profiler#1 (red symbols); c.ii Temperature profiles showing similar structures of

919 the ship and bio-profiler sampled water columns; c.iii Fluorescence profiles (lines) showing that the

920 bio-profiler provided similar fluorescence results to the ship CTD mounted sensor, and that both

921 exhibited complex relationships to Niskin bottle total chlorophyll-a sample values (dots; see text for

922 further discussion).

923

924 Figure 3.1. Bio-profiler #1 observations

925 a) bio-profiler #1 trajectory over the bathymetry, with each point representing a depth profile and

926 the colour of the points changing from blue to red over time (dates are shown below the bottom

927 plots). The 700 m isobath is represented by the red line contour. KI = Kerguelen Island; KP =

928 Kerguelen Plateau; HI = Heard Island; GS = Gallieni Spur. b-f) Evolution of hydrological

929 parameters along the float trajectory: b) temperature (°C), c) chlorophyll (μg L^{-1}), d) salinity

930 (unitless), e) particulate backscattering (b_{bp}; log scale; m^{-1}), and f) dissolved oxygen (μmol kg^{-1}).

931 The white line represents the mixed layer depth. Red and yellow rectangles refer to rich and

932 moderate chlorophyll areas used in Figure 7 and discussed in Section 4.2.

933

934 Figure 3.2. Bio-profiler #2 observations (see Figure 3.1 caption for details).

935

936 Figure 3.3. Bio-profiler #3 observations (see Figure 3.1 caption for details).

937

938 Figure 3.4. Bio-profiler #4 observations (see Figure 3.1 caption for details).

939

940 Figure 4. Characteristics of subsurface chlorophyll maxima occurring at depths greater than the

941 mixed layer depth and exceeding the surface content by more than 60% (top) and 100% (bottom). a)

942 and d): geographical areas where these subsurface Chl-a maxima occur with an expanded view for

943   the Gallieni Spur region; b) and e): associated depths of these subsurface Chl-a maxima along the

944   bio-profiler trajectories (i.e. versus profile numbers); c) and f): relationship between the amplitude

945   of these Chl-a maxima (in $\mu g\ L^{-1}$) and the mixed layer depth (MLD, in m). Symbols: stars refer to

946   night profiles, circles to day profiles and squares to flagged day profiles (i.e. which still exhibit, in

947   the surface layer, a large concentration decrease toward low surface values that indicates the

948   possibility of incomplete quenching correction; see definition in the caption of Figure 2b).

949

950   Figure 5. a) Surface chlorophyll concentrations (in mg m^{-3}) compared to chlorophyll inventories (0-

951   200 m; in mg m^{-2}), for each bio-profiler. b) Surface particulate backscattering (m^{-1}) compared to

952   particulate backscattering inventories (0-200 m), for each bio-profiler. Note that scales are slightly

953   larger for bio-profiler #1 than for the others; the dashed rectangles in upper plots indicate the scales

954   used for the other bio-profilers. Night profiles (black circles), day profiles (green circles) and

955   potentially quenching under-corrected day profiles (red circles, flagged as defined in the caption of

956   Figure 2b) are distinguished. Correspondingly, the green and black lines refer to the linear

957   regression of day and night profiles, and their associated correlation coefficients, r^2.

958

959   Figure 6: a) Chlorophyll water column inventories (in mg m^{-2}), estimated by multiplying surface

960   chlorophyll concentrations by the mixed layer depth, compared to chlorophyll inventories (0-200 m;

961   in mg m^{-2}) recorded by the bio-profilers. Only night and unflagged day profiles are represented. The

962   colour code shows the associated depth of the mixed layer (in m). The 5 lines y = x, y = 2x, y = 4x,

963   y = 8x and y = 20x are given as indicators to quantify the ratio between the "surface Chl-a × MLD"

964   product and the 0-200 m integrated Chl-a.

965   b) Representation of the X factor (X = (0-200 m integrated Chl-a)/(surface Chl-a × MLD)) as a

966 function of the mixed layer depth (in m), for the total data set. Symbols and colours are defined in

967 the legend.

968

969 Figure 7. Relationship between 0-200 m integrated chlorophyll a concentration and various water

970 properties for a-f) high biomass regions close to the plateau (bio-profilers #1 and #3) or entrapped

971 in eddies (bio-profilers #2 and #4; red rectangles in Figures 3.1, 3.2, 3.3 and 3.4) and g-l) moderate

972 biomass regions far from the plateau (yellow rectangles in Figures 3.1, 3.2, 3.3 and 3.4). a) and g):

973 surface temperature (in °C); b) and h): surface salinity (unitless); c) and i): surface density (in kg m$^-$

974 ^{3}); d) and j) mixed layer depth (MLD; in m); e) and k) maximum Brunt-Väisälä frequency squared

975 (N^2; in s^{-2}) f) and l) oxygen saturation state (in %). Symbols and colours are defined in the legend.

976

977 Figure 8: Lagrangian diagnostics computed from altimetry. Maps of age and origins of the water

978 parcels shown in plots (a) and (c) are from Figure 4 of d'Ovidio et al. (2014). White pixels represent

979 water parcels that have not touched in the past 100 days the Kerguelen Plateau (defined by the 700

980 m isobath and shown in grey). Comparison of these age and origin metrics with the bio-profiler

981 total integrated Chlorophyll-a values are shown in plots (b) and (d). Blue dots correspond to data

982 collected during spring (bio-profiler #1, mean values in red) and black dots to data collected during

983 summer (bio-profilers #2, #3, #4, mean values in magenta). White dots correspond to water parcels

984 that have not touched the Kerguelen Plateau. The inset in plot b) shows the number of

985 measurements for each water age. The black arrow highlights the fact that low Chl-a levels

986 associated with water parcels that have not touched the Kerguelen Plateau within the last 100 days

987 is supported by a large number of samples and, thus, seems to be a robust feature.

988

989 Figure 9. Eddy entrapment of bio-profiler #4.

990   a) Identification of entrapment along the bio-profiler trajectory, with the colour of the points

991   changing, from blue to red over time, from profile 150 to profile 240.

992   b) Overlay of bio-profiler trajectory (white line) and eddy retention indices, showing the portion of

993   the trajectory within a long-lasting (more than 30 days) retentive structure. The red square marks

994   the temporal reference (profile 177) from which the Lagrangian trajectories were computed for the

995   retention statistic, as described in Methods section 2.3.

996   c) Temperature-salinity diagram. Colours correspond to location on the map in a).

997   d) Temperature versus depth section with mixed layer depth (black line) and isopycnals indicated

998   (white lines).

999   e) Chlorophyll profiles, coloured as on the map and separated, for the sake of clarity, in 4 subsets of

1000   ~23 profiles (equivalent to ~2 weeks of data acquisition).

1001   f) As e), but for particulate backscattering (b_{bp}) profiles.

1002   g) As e), but for the chlorophyll/b_{bp} ratio.

1003   Note that chlorophyll and b_{bp} signals were filtered for visual clarity, using a 3 point running median.

1004

1005   Figure 10: Temporal evolution of physical and biological properties during the eddy entrapment of

1006   bio-profiler #4 for three density layers: with sigma-theta ranges of surface-26.6; 26.6-26.8; 26.8-

1007   26.9. Left column plots a-c) show physical properties: mean depth (in m; black line and scale),

1008   thickness (in m, dashed black line and black scale), temperature (θ, in °C; red line and scale),

1009   salinity (S, unitless; blue line and scale), density (σ, in kg m^{-3}; purple line and scale) and Brunt-

1010   Väisälä frequency squared (N^2, in s^{-2}; gray line and scale). Right column plots d-f) show

1011   biogeochemical properties: mean chlorophyll (Chl-a, in µg L^{-1}; green line and scale), particulate

1012   backscattering (b_{bp}, in m^{-1}; gray line and scale), and oxygen concentrations (O_2, in µmol kg^{-1};

1013   orange line and scale).

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1400

1401 Table 1. Bio-profiler deployments

1402

1403
#	Hull#*	WMO#**	UTC Date	Lat. (° N)	Long. (° E)	Campaign	Last profile (UTC Date)
1	5122	1901329	29 Oct 2011	-48.5	72.2	KEOPS2	22 Apr 2012
2	6684	5904882	26 Jan 2014	-49.9	76.2	MYCTO	14 Apr 2014
3	6682	1901338	28 Jan 2014	-48.4	71.5	MYCTO	14 Apr 2014
4	6683	1901339	4 Feb 2014	-48.6	74.0	MYCTO	14 Apr 2014

1408

1409 * Hull#: serial number for the bio-profiler body

1410 ** WMO#: World Meteorological Organization identification number for the bio-profiler data stream

1411 Table 2. Drift assessment of the bio-profilers over their life time within the [250-300] m and [950-
1412 1000] m depth layers

1413

1414 ***Chlorophyll concentration*** *drift within the [250-300] m depth layer*

#	Mean slope ($\mu g\ L^{-1}\ profile^{-1}$)	Mean absolute drift[a] ($\mu g\ L^{-1}$)	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 %

1422 ***Chlorophyll concentration*** *drift within the [950-1000] m depth layer*

#	Mean slope ($\mu g\ L^{-1}\ profile^{-1}$)	Mean absolute drift[a] ($\mu g\ L^{-1}$)	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 %

1430 ***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 %

1438 ***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 %

1446 [a] = mean slope * nb of profiles
1447 [b] = mean slope * nb of profiles / mean chlorophyll concentration
1448 [c] Calculated between profiles #1 and profile #300, and excluding the deep biomass production
1449 profiles (range #[100-171])
1450 [d] = mean slope * nb of profiles / mean particulate backscattering

1451 Table 3. Fluorescence quenching corrections and subsurface chlorophyll maxima statistics

1452

Individual bio-profiler statistics	#1	#2	#3	#4
Fluorescence profiles collected	384	298	278	254
Fluorescence profiles usable	300	298	277	254
Night time profiles	129	143	133	119
Day time profiles	171	155	144	135
Night time profiles with subsurface maxima[a] **total**/within the ML/below the ML (% of night time profiles)	**17**/5/12/ (13/4/9)%	**3**/1/2 (2/1/1)%	**24**/9/15 (18/7/11)%	**25**/14/11 (21/12/9)%
Day time profiles with subsurface maxima[a] before correction **total**/within the ML/below the ML (% of daytime profiles)	**142**/62/80 (83/36/47)%	**93**/55/38 (60/35/25)%	**105**/48/57 (73/33/40)%	**95**/40/55 (70/30/40)%
Quenching corrected profiles (and among them, number of corrected profiles which still exhibit low surface values[c])	170 (22)	155 (6)	139 (12)	127 (18)
Day time profiles with subsurface maxima[a] after correction **total**/within the ML/below the ML (% of corrected day profiles)	**40**/0/40 (24/0/24)%	**10**/1/9 (6/0/6)%	**32**/3/29 (23/2/21)%	**40**/9/31 (31/7/24)%
Total night and corrected day profiles with **moderate** subsurface maxima[a] **total**/within the ML/below the ML (% of night and corrected day profiles)	**57**/5/52 (19/2/17)%	**13**/2/11 (4/1/3)%	**56**/12/44 (20/4/16)%	**65**/23/42 (26/9/17)%
Total night and corrected day profiles with **large** subsurface maxima[b] **total**/within the ML/below the ML (% of night and corrected day profiles)	**32**/1/31 (10/0/10)%	**6**/0/6 (2/0/2)%	**36**/5/31 (13/2/11)%	**45**/15/30 (18/6/12)%

1453 [a] Subsurface values exceeding surface values by more than 60%

1454 [b] Subsurface values exceeding surface values by more than 100%

1455 [c] For some corrected profiles, a large decrease of the chlorophyll concentration still occurred in the
1456 surface layer. These profiles were flagged in Figures 2b (squares), 4 (squares) and 5 (red circles).
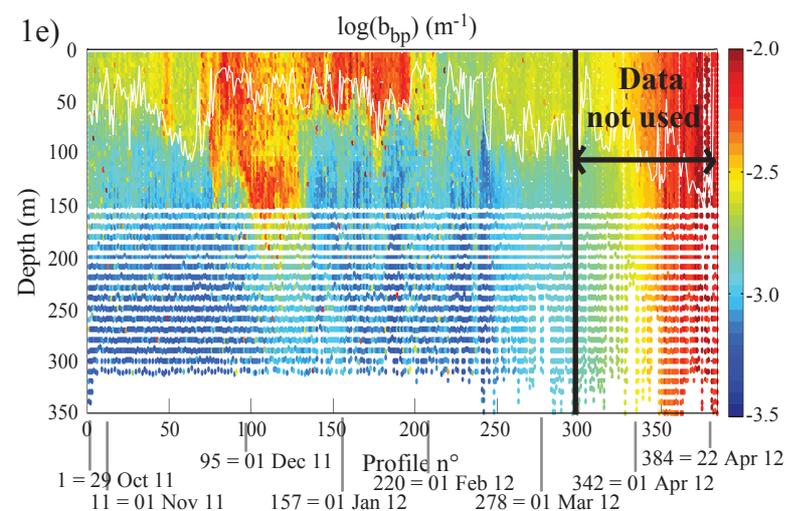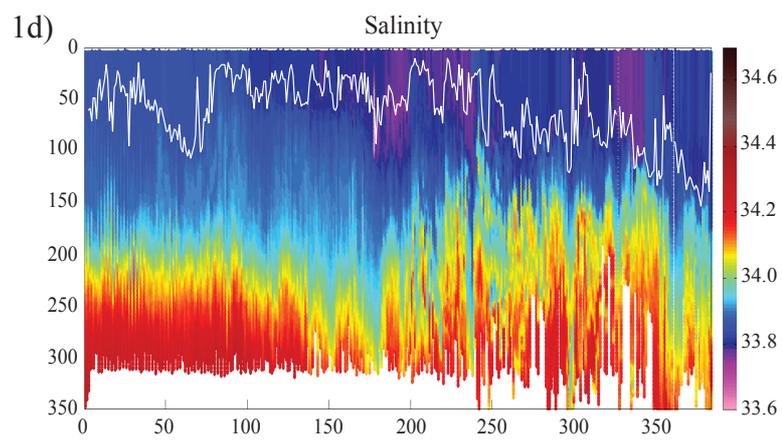1457 See the method section and the caption of Figure 2b for more details.

Latitude (°N)

Longitude (°E)

a) 2011 - 11 - 13
b) 2011 - 11 - 27
c) 2011 - 12 - 30
d) 2013 - 10 - 25
e) 2013 - 11 - 25
f) 2013 - 12 - 25
g) 2014 - 01 - 26
h) 2014 - 02 - 24
i) 2014 - 03 - 25

Chl [µg L⁻¹]

0.1   0.2   0.5   0.75   1   1.5

a) Drifting assessment

Mean value within the depth range [250-300] m

Mean value within the depth range [950-1000] m

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

b) Quenching assessment

Without quenching correction   **With** quenching correction

Bio-profiler #1 - night (#141)
Bio-profiler #1 - day (#142)
Bio-profiler #2 - night (#159)
Bio-profiler #2 - day (#160)
Bio-profiler #3 - night (#271)
Bio-profiler #3 - day (#272)
Bio-profiler #4 - night (#18)
Bio-profiler #4 - day (#19)

c) Comparison to KEOPS2 shipboard observations

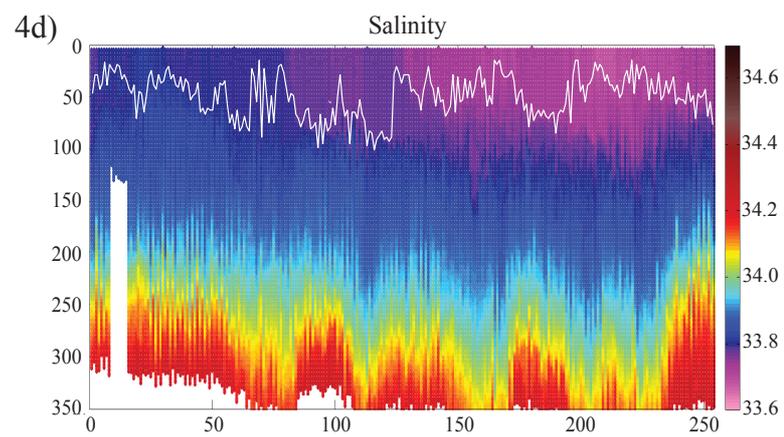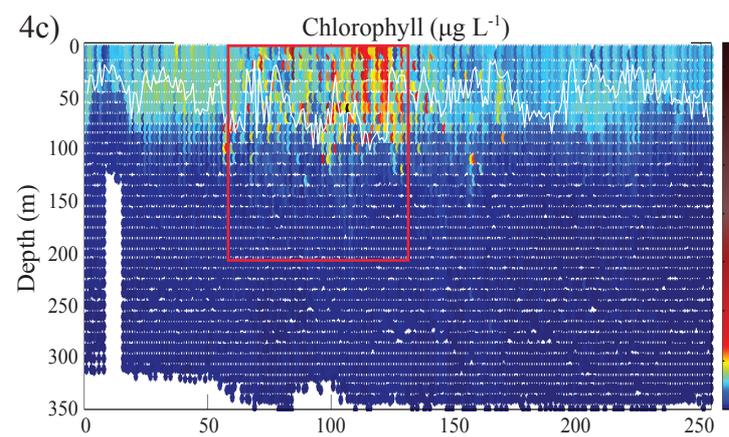**1a)** Bio-profiler #1 trajectory

1b) Temperature (°C)

1c) Chlorophyll (µg L⁻¹)

Data not used

1d) Salinity

1e) $\log(b_{bp})$ (m⁻¹)

Data not used

1 = 29 Oct 11
11 = 01 Nov 11
95 = 01 Dec 11
157 = 01 Jan 12
Profile n°
220 = 01 Feb 12
278 = 01 Mar 12
342 = 01 Apr 12
384 = 22 Apr 12

1f) Dissolved oxygen (µmol kg⁻¹)

1 = 29 Oct 11
11 = 01 Nov 11
95 = 01 Dec 11
157 = 01 Jan 12
Profile n°
220 = 01 Feb 12
278 = 01 Mar 12
342 = 01 Apr 12
384 = 22 Apr 12

2a) Bio-profiler #2 trajectory

2b) Temperature (°C)

2c) Chlorophyll (µg L⁻¹)

2d) Salinity

2e) log(b$_{bp}$) (m⁻¹)

2f) Dissolved oxygen (µmol kg⁻¹)

Profile n°

1 = 26 Jan 14   143 = 01 Mar 14   250 = 01 Apr14   298 = 14 Apr14

3a) Bio-profiler #3 trajectory

3b) Temperature (°C)

3c) Chlorophyll (µg L^{-1})

3d) Salinity

3e) log(b$_{bp}$) (m^{-1})

3f) Dissolved oxygen (µmol kg^{-1})

Profile n°

1 = 28 Jan 14   121 = 01 Mar 14   230 = 01 Apr 14   278 = 14 Apr 14

4a) Bio-profiler #4 trajectory

4b) Temperature (°C)

4c) Chlorophyll (µg L⁻¹)

4d) Salinity

4e) log(b_bp) (m⁻¹)

4f) Dissolved oxygen (µmol kg⁻¹)

1 = 04 Feb 14   96 = 01 Mar 14   206 = 01 Apr14   254 = 14 Apr14

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

a)

b) Associated depths

c) Chlorophyll maximum vs. MLD

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

d)

e) Associated depths

f) Chlorophyll maximum vs. MLD

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

✳ Night profiles   ◯ Corrected day profiles   ▢ Corrected day profiles which still exibit, in the surface layer, a large concentration decrease toward low surface values

a)

Bio-profiler #1

$r^2 = 0.85$
$r^2 = 0.69$

Bio-prof. #3 & #4 scale

Bio-prof. #2 scale

Bio-profiler #2

$r^2 = 0.38$
$r^2 = 0.27$
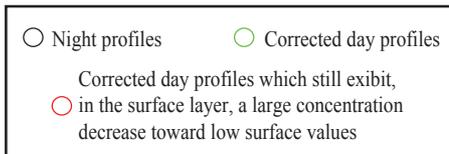
Bio-profiler #3

$r^2 = 0.67$
$r^2 = 0.60$

Bio-profiler #4

$r^2 = 0.71$
$r^2 = 0.34$

0−200 m integrated chlorophyll (mg m^{-2})

Surface chlorophyll (mg m^{-3})

b)

Bio-profiler #1

$r^2 = 0.43$
$r^2 = 0.40$

Bio-prof. #2, #3 & #4 scale

Bio-profiler #2

$r^2 = 0.43$
$r^2 = 0.29$

Bio-profiler #3

$r^2 = 0.74$
$r^2 = 0.64$

Bio-profiler #4

$r^2 = 0.44$
$r^2 = 0.40$

0−200 m integrated backscatter

Surface backscatter (m^{-1})

○ Night profiles   ○ Corrected day profiles

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

○ Night profiles   ○ Corrected day profiles

Rich biomass regions

Moderate biomass regions

a) Mean surface temperature (°C)
g)

b) Mean surface salinity
h)

c) Mean surface densiy (kg m^{-3})
i)

d) Mixed layer depth (m)
j)

e) Maximum N^2 (s^{-2})
k)

f) Mean surface oxygen saturation (%)
l)

0-200 m integrated chlorophyll (mg m^{-2})

0-200 m integrated chlorophyll (mg m^{-2})

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

* Night profiles   ○ Corrected day profiles   □ Corrected day profiles which still exibit, in the surface layer, a large concentration decrease toward low surface values

a) Bio-profiler #4 trajectory

b)

c)

d) Temperature (°C)

e) Chlorophyll (ug L⁻¹)

#150-173   #174-196   #197-219   #220-240

f) Particulate backscattering b_{bp} (x 10⁻³ m⁻¹)

g) Chl-a / b_{bp} (mg m⁻⁴)

a) Density layer surface−26.6
b) Density layer 26.6−26.8
c) Density layer 26.8−26.9
d) Density layer surface−26.6
e) Density layer 26.6−26.8
f) Density layer 26.8−26.9