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1 **Seasonal dynamics in diatom and particulate export fluxes to the deep sea in the**
2 **Australian sector of the southern Antarctic Zone**

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14

15 **Keywords:** diatom flux; particulate flux; sediment traps; Southern Ocean.

16

17 **Abstract**

18 Particle fluxes were recorded over a one-year period (2001-02) in the southern Antarctic
19 Zone in the Australian Sector of the Southern Ocean. Here, we present the results on the
20 seasonal and vertical variability of biogenic particle and diatom valve fluxes. Total mass
21 and diatom fluxes were highly seasonal, with maxima registered during the austral
22 summer and minima during winter. Biogenic opal dominated sedimentation, followed
23 by carbonate, and very low levels of organic carbon (annual average 1.4%). The strong
24 correlation between opal and organic carbon at both depth levels suggests that a
25 significant fraction of organic matter exported to the deep sea was associated with

26 diatom sedimentation events. Seasonal diatom fluxes appear driven principally by
27 changes in the flux of *Fragilariopsis kerguelensis*. The occurrence of the sea-ice
28 affiliated diatoms *Fragilariopsis cylindrus* and *Fragilariopsis curta* in both sediment
29 traps is considered to correspond to the sedimentation of a diatom bloom advected from
30 an area under the influence of sea ice. Highest fluxes of the subsurface-dwelling species
31 *Thalassiothrix antarctica* registered at the end of the summer bloom were linked to a
32 drop of the light levels during the summer-autumn transition. This study provides the
33 first annual observation on seasonal succession of diatom species in the Australian
34 sector of the Antarctic Zone, and corresponds, in terms of magnitude and seasonality of
35 diatom fluxes, to those in neighbouring sectors (Pacific and eastern Atlantic).

36

37 **1. Introduction**

38 Diatoms are unicellular algae with an absolute requirement for silicic acid to form their
39 frustules. They constitute a major component of phytoplankton communities, being
40 responsible for ~40% of all marine carbon fixation (Nelson et al., 1995). Diatoms are
41 the main contributors to the silica-rich deposits in deep-sea sediments and are thought to
42 influence the present and past global climate via their influence on the biological pump
43 of CO₂ from the atmosphere into the ocean interior (Nelson et al., 1995; Sarmiento et
44 al., 1998; Matsumoto et al., 2002). The composition of phytoplankton communities and
45 abundance of diatoms within them are related to specific ecological parameters of the
46 water masses where they live (e.g., temperature, sea-ice cover and nutrient availability),
47 and hence in the case of diatoms, their frustules can be used as biotic proxies for
48 palaeoenvironmental and palaeoceanographic reconstructions.

49 In order to evaluate the role of diatoms in the biological pump and the cycling of
50 silicon, it is essential to thoroughly understand their ecology and the processes that the
51 living biocoenoses undergo from their initial production in the euphotic zone to their
52 eventual preservation in the ocean sediments (e.g. Varela et al., 2004; Grigorov et al.,
53 2014). This knowledge is also required to validate paleoreconstructions based on the
54 diatom sedimentary record (e.g. Leventer et al., 1993; Taylor and Sjunneskog, 2002;
55 Armand and Leventer, 2010).

56 The Southern Ocean is regarded as having one of the highest diatom biomasses of the
57 global ocean. Despite its high-nutrient low chlorophyll (HNLC) regime, massive diatom
58 blooms occur every year during spring and summer associated with specific areas, such
59 as oceanographic fronts (e.g. Honjo et al., 2000; Moore and Abbott, 2002), coastal areas
60 of Antarctica (e.g. Wefer et al., 1988, Bathmann et al., 1991; Arrigo et al., 1999) and the
61 retreating sea ice edge (e.g. Smith and Nelson, 1986; Sullivan et al., 1988). As a result
62 of this relatively high diatom productivity (Pondaven et al., 2000), large amounts of
63 biogenic silica accumulate in the Southern Ocean sediments, mainly south of the
64 Antarctic Polar Front (APF), where about 30% of the global opal marine accumulation
65 occurs (Tréguer and De la Rocha, 2013).

66 Moored sediment traps are one of the few available tools for monitoring particle fluxes
67 in the open ocean over extended periods of time. They provide a means to determine the
68 magnitude and timing of phytoplankton blooms, document species succession and
69 estimate the remineralization of labile components throughout the water column. The
70 use of sediment traps has contributed significantly to our understanding of diatom
71 ecology in the Southern Ocean and coastal Antarctic systems (e.g. Leventer and
72 Dunbar, 1987; Fischer et al., 1988; Leventer and Dunbar, 1996; Abelmann and
73 Gersonde, 1991; Ishikawa et al., 2001; Suzuki et al., 2001; Pilskaln et al., 2004;

74 Ichinomiya et al., 2008; Romero and Armand, 2010). However, these studies are
75 scattered in space and time, and large regions of the Southern Ocean, including the
76 Australian Sector, remain undocumented.

77 During the Australian multidisciplinary ACE CRC SAZ Project (Trull et al., 2001a), the
78 main hydrological zones of the Australian sector of the Southern Ocean were
79 instrumented with sediment trap mooring lines. The central goal of this experiment was
80 to determine the origin, composition and fate of particulate matter transported to the
81 ocean interior. This research yielded important results, including the demonstration that
82 particulate organic carbon (POC) export in the Southern Ocean is similar to the global
83 ocean median (Bray et al., 2000; Trull et al., 2001b).

84 Here, as part of the ACE CRC SAZ project, we report on the biogenic particle fluxes
85 registered by two sediment traps deployed in the southern Antarctic Zone (60° 44.43'S;
86 139°E 53.97'S) over a year (November 2001 to September 2002) in order to (1)
87 document the magnitude, composition and seasonal distribution patterns of the settling
88 particle fluxes, with particular focus on diatoms and their specific composition; and (2)
89 assess the effects of dissolution and physical processes in the water column on the
90 diatom assemblage composition by comparing the assemblages registered by the 2000
91 and 3700 m sediment traps. An improved understanding of diatom ecology and changes
92 that the diatom assemblages undergo during their sinking through the water column
93 should lead to a better interpretation of proxy records in the Southern Ocean.

94

95 **1.1. Oceanographic setting**

96 The Antarctic Circumpolar Current (ACC) flows eastward around Antarctica driven by
97 strong westerly winds connecting the Pacific, Atlantic and Indian Oceans. Several
98 circumpolar jets or fronts divide the ACC into distinct zones (Fig. 1a), each one

99 characterized by specific hydrological and biochemical properties (Orsi et al., 1995).
100 The fronts coincide with strong current cores of the ACC defined by contours of sea
101 surface height (SSH). Each of these fronts consists of multiple branches or filaments,
102 where their position varies rapidly over time (Sokolov and Rintoul, 2002, 2007 and
103 2009a, b). From north to south, these fronts and zones are the Subtropical Front (STF),
104 the Subantarctic Zone (SAZ), the Subantarctic Front (SAF), the Polar Frontal Zone
105 (PFZ), the Polar Front (PF), the Antarctic Zone (AZ) and the Southern ACC Front
106 (SACCF) (Sokolov and Rintoul, 2009a, b).

107 The surface waters of the Australian sector of the Southern Ocean are nitrate and
108 phosphate rich and their concentrations remain fairly uniform across the ACC (Bostock
109 et al., 2013). In contrast, silicic acid (Si) content shows a marked south to north
110 gradient. Highest Si concentrations are reached south of the Polar Front Zone (up to 70
111 μM), whereas the Subantarctic Zone waters exhibits low Si values (1 to 5 μM) (Coale et
112 al., 2004; Bostock et al., 2013). Despite the relatively high macronutrient
113 concentrations, Southern Ocean surface waters are often characterized by relatively low
114 phytoplankton biomass. Light limitation related to deep mixing (Sakshaug and Holm-
115 Hansen, 1984) and extremely low concentrations of trace metals such as iron (De Baar
116 et al., 1995; Johnson et al., 1997; Fitzwater et al., 2000; Martin et al., 1990; Boyd et al.,
117 2000) seem to be the main causes for this “high-nitrate, low-chlorophyll” (HNLC)
118 regime.

119 Sea ice seasonality off East Antarctica is considered linked to patterns of oceanic
120 currents, which in turn are related to sea floor topography (Massom et al., 2013).
121 Seasonal sea-ice advance occurs from early autumn through early spring followed by
122 retreat from late spring through summer (Comiso et al., 1984; Kimura and Wakatsuchi,
123 2011; Massom et al., 2013).

124 Our study site, station 61 S ($60^{\circ} 44.43'S$; $139^{\circ}E 53.97'S$), is located within the southern
125 Antarctic Zone (AZ-S; Parslow et al., 2001), between the southern branch of the PF
126 ($59^{\circ}S$) and the southern front of the SAACF (Rintoul and Bullister, 1999; Rintoul and
127 Sokolov, 2001). The mooring site is within the same region where the first open-ocean
128 iron enrichment experiment in the Southern Ocean (Southern Ocean Iron Release
129 Experiment - SOIREE) was conducted (Boyd et al., 2000) and can be considered
130 representative of the region between the PF and the SACCF (between $54^{\circ}S$ and $62^{\circ}S$)
131 (Trull et al., 2001c). Despite surface waters rich in macronutrients (i.e. silicate,
132 phosphate and nitrate), the algal biomass accumulation is considered low ($<0.5 \mu\text{g/L}$)
133 (Parslow et al., 2001; Popp et al., 1999; Trull et al., 2001c). Copepods, mainly large
134 calanoid copepodites, dominate the zooplankton community at the study site. Grazing
135 pressure is considered low ($<1\%$ of the phytoplankton standing stock removed per day)
136 and is thought not to greatly influence the development of the annual bloom (Zeldis,
137 2001). Very low iron concentrations ($0.1\text{-}0.2 \text{ nM}$; Sohrin et al., 2000; Boyd et al., 2000)
138 appear to be responsible for the low primary production. The study area is far from the
139 influence of coastal waters and just north of the maximum winter sea-ice extent (Fig.
140 1b; Massom et al., 2013).

141

142 **2. MATERIAL AND METHODS**

143 **2.1 Field experiment**

144 Site 61 S was instrumented with a mooring line equipped with three McLane Parflux
145 time series sediment traps (Honjo and Doherty, 1988) placed at 1000, 2000 and 3700 m
146 depth in a water column of 4393m (Fig. 1c). Each trap was paired with an Aanderaa
147 current meter and temperature sensor. The trap sampling cups were filled with a
148 buffered solution of sodium tetraborate (1 g L^{-1}), sodium chloride (5 g L^{-1}), strontium

149 chloride (0.22 g L^{-1}), and mercury chloride (3 g L^{-1}). Cup rotation intervals were
150 synchronized between traps and were established based on anticipated mass fluxes. The
151 shortest sampling intervals were 8 days and correspond with the austral summer and
152 autumn, whereas the longest interval was 55 days corresponding with austral winter
153 (Table 1). No samples were recovered from the shallowest trap owing to equipment
154 malfunction. The two deeper traps completed their collection sequence as programmed
155 without any instrumental failures providing a continuous time-series for 317 days
156 (November 30, 2001 to September 29, 2002) divided into 21 collecting intervals. Owing
157 to the low particle fluxes registered at the onset and end of the experiment insufficient
158 material remained for diatom analysis of cup 1 of the 2000 m trap and cups 1, 2, 19, 20
159 and 21 of the 3700 m trap (Table 1). After recovery, sediment trap cups were removed,
160 capped on board and stored at 4°C in the dark until they were processed. The original
161 samples were sieved through a 1mm nylon mesh in order to remove the largest
162 swimmers, and only the fraction $<1 \text{ mm}$ was analyzed. Then, they were split into 10
163 equal fractions using a McLane WSD-10 wet-sample divider. One complete split was
164 used for microplankton analysis. A detailed description of the geochemical analytical
165 procedures is given by Trull et al. (2001b) and Bray et al. (2000). Component fluxes are
166 reported for individual cups along with average values over the collection or
167 deployment period for each component (Table 1). As the collection period was shorter
168 than a calendar year, annual mean estimates were determined and are presented in Table
169 1. These annual estimates take into account the fact that the unobserved days occurred
170 in winter when fluxes were low, and were obtained by using the flux for the last winter
171 cup (#21 in 2002) to represent mean daily fluxes during the unobserved period.
172 In order to investigate the correlation between time series, a correlation matrix was
173 calculated (Table 2).

174

175 **2.2 Siliceous microplankton sample preparation and analysis**

176 Each diatom fraction sample was refilled with distilled water to 40 ml, from which 10
177 ml was subsampled and buffered with a solution of sodium carbonate and sodium
178 hydrogen carbonate (pH 8) and kept refrigerated for future calcareous nannoplankton
179 analysis. The remaining 30 ml was treated with hydrogen peroxide, potassium
180 permanganate and concentrated hydrochloric acid in order to clean the sample of
181 organic matter and calcareous components following the methodology of Romero et al.
182 (1999, 2000). The resulting sediment slurry was stored in bottles filled with distilled
183 water. Microscopic slides were prepared following the decantation method outlined by
184 Flores and Sierro (1997). This method produces random settling of the diatoms for
185 quantitative microscopic purposes. The dried cover-slip was permanently mounted onto
186 a glass slide with Norland optical adhesive 61 mounting medium (Refractive index:
187 1.56).

188 Qualitative and quantitative analyses were performed using a Olympus BH-2 compound
189 light optical microscope at 1000x magnification with phase-contrast illumination. A
190 minimum of 400 specimens were counted per sample. Each diatom valve was identified
191 to the lowest taxonomic level possible. Scanning Electron Microscope observations of
192 selected samples were used to verify taxonomic identifications made with the LM. The
193 recommendations of Schrader and Gersonde (1978) were used as a basis for the
194 counting of diatom valves. We did not include the counts of the girdle bands of
195 *Dactyliosolen antarcticus* in the determination of relative abundances.

196 The microplankton counts were transformed into daily fluxes of specimens $\text{m}^{-2} \text{d}^{-1}$
197 following the formula of Sancetta and Calvert (1988) and Romero et al. (2009):

198

$$F = \frac{N \times \left(\frac{A}{a}\right) \times V \times S}{d \times T}$$

199

200 where “F” is the daily flux of specimens, “N” the number of specimens, “A” the total
 201 area of a Petri dish, “a” the analysed area, “V” the dilution volume, “S” the split of the
 202 cup, “d” the number of days of collection and “T” the aperture area of the sediment trap.

203 The diatom species diversity was estimated applying Shannon’s diversity index (H') to
 204 the relative abundance data ($H' = - \sum p_i \log_2 p_i$, where $p = n1/N$, $n1 =$ number of
 205 specimens of one taxon and N the total number of specimens). Large values of H'
 206 indicate greater diversity.

207 The annualized diatom valve flux for the 2000 m sediment trap was estimated following
 208 the same procedure as for the component fluxes (Table 1).

209 The temporal overlap of diatom fluxes between 2000 m and the 3700 m traps occurred
 210 between December-May (172 days) (Table 1). This overlap was used to estimate the
 211 sinking velocities of diatom valves and to track the alteration of settling diatom
 212 assemblages between traps. The sinking settling velocities for the main diatom taxa
 213 were calculated from the time lag between associated peaks in both traps and the
 214 vertical distance between traps. We used a squared-chord distance as the metric for
 215 assessing the similarity between the diatom assemblages of both traps (Ortiz and Mix,
 216 1997). Squared chord distance values can range between 0.0 and 2.0, with 0.0 indicating
 217 identical proportions of species within the assemblages being compared.

218

219 **2.3 Satellite imagery, meteorological and oceanographic data**

220 Weekly mean sea surface temperature (SST) data for the period 2001 to 2002 was
 221 extracted from the NOAA Optimum Interpolation Sea Surface Temperature Analysis
 222 database (Reynolds et al., 2002). The monthly averages of the upper 300 m thermal

223 structure for the 2001–2002 period (Fig. 2) were obtained for the sampling location
224 from the World Ocean Atlas 2009 (Locarnini et al., 2010). The maximum weekly SST
225 mean during the field experiment was 2.94 °C degrees occurring in March 2002,
226 whereas the minimum was 0.12 °C at the beginning of October 2002. Changes of the
227 weekly mean SST mirrored the seasonal changes in the vertical structure of the water
228 column temperature profile. A pattern of stratification during austral summer months
229 and vertical homogeneity in autumn and winter was noted during the field experiment
230 (Fig. 2).

231 Satellite-derived monthly chlorophyll-*a* concentration and photosynthetically active
232 radiation (PAR) estimates were obtained from NASA's Giovanni program (Acker and
233 Leptoukh, 2007) (Fig. 2). The pigment concentration record was then used as a proxy
234 for surface algal biomass accumulation. The overall chlorophyll-*a* levels were low
235 (0.07-0.30 mg/m³) and similar to previous observations in the study area (Trull et al.,
236 2001c). The increase in the algal biomass commenced in September 2001 and reached
237 its highest levels in November 2001, coinciding with a maximum in the insolation
238 levels (Fig. 2). Pigment concentration declined through summer and reached its lowest
239 levels in autumn and winter (March to August 2002).

240

241 **3. RESULTS**

242 **3.1 Bulk composition**

243 Total fluxes of particulates at both traps were highly seasonal, with maxima registered
244 during the austral summer (up to 1151 mg m⁻² d⁻¹ at 2000 m and 1157 mg m⁻² d⁻¹ at 3700
245 m) and almost negligible fluxes during winter (up to 42 mg m⁻² d⁻¹ at 2000 m and below
246 detection limits at 3700 m) (Fig. 2). The fluxes of total particulates at 2000 and 3700 m
247 depth showed similar seasonal variations and were closely correlated ($R^2 = 0.82$; Fig.

248 4). Particulate fluxes were slightly higher at 2000 m ($261 \pm \text{mg m}^{-2} \text{ d}^{-1}$ = deployment
249 average \pm standard deviation) than at 3700 m ($216 \pm 337 \text{ mg m}^{-2} \text{ d}^{-1}$). Biogenic silica
250 (SiO_2) was the dominant bulk component, regardless of the sampling period or depth
251 (deployment average = 76% at 2000 and 78% at 3700 m). The highest relative
252 contribution of opal was registered from the end of summer through early-autumn at
253 both depths (Table 1). Secondary contributors were carbonate (CaCO_3) (7% at 2000 m
254 and 9% at 3700 m) and particulate organic carbon (POC) (1.4% at 2000 m and 1.2% at
255 3700 m). The relative concentration of carbonate and POC was at its highest in austral
256 spring and summer (Table 1). The fluxes of all components were closely correlated. The
257 results of the correlation matrix are given in Table 2. Total mass flux showed a strong
258 correlation with POC at both sediment traps ($R^2 = 0.86$ at 2000 m and $R^2 = 0.87$ at 3700
259 m). BSiO_2 fluxes were also highly correlated with POC at both depths ($R^2 = 0.83$),
260 whereas CaCO_3 and POC fluxes exhibited the lowest values ($R^2 = 0.24$ at 2000 m and
261 $R^2 = 0.63$ at 3700 m).

262 The molar POC/PN ratios were relatively low (Table 1), and thus similar to surface
263 Southern Ocean particles and phytoplankton (Copin-Montegut and Copin-Montegut,
264 1983).

265 **3.2 Composition of the biogenic opal fraction**

266 The biogenic opal fraction was composed of diatoms, silicoflagellates, radiolarians and
267 the dinoflagellate *Actiniscus pentasterias*. Diatoms were, numerically, the dominant
268 siliceous plankton group registered by the traps with a mean flux between 67×10^6 and
269 76×10^6 valves $\text{m}^{-2} \text{ day}^{-1}$ at 2000 m (annualized mean and deployment average,
270 respectively). Mean diatom flux at the 3700 m trap yielded higher values (deployment
271 average = 132×10^6 valves $\text{m}^{-2} \text{ day}^{-1}$) due to the lower sampling duration (172 days)
272 over the winter season (Table 1). Silicoflagellates and radiolarians were three and four

273 orders of magnitude lower than diatoms (not shown), whereas only one specimen of *A.*
274 *pentaseries* was indentified in the lower trap. At both depth levels, total diatom fluxes
275 showed strong seasonal variations that closely followed total mass seasonality with
276 Pearson correlation coefficients of $r = 0.88$ for 2000 m and $r = 0.81$ for 3700 m (Fig. 4).
277 Diatom frustules from 61 taxa were identified over the entire experiment and are listed
278 in Table 3 together with their relative contribution for the whole sampling period. The
279 seasonal changes in the diatom flux and main species at mooring site 61°S are plotted in
280 Figure 5.

281 Diversity index values (H') followed the same seasonal trend as total diatom flux at
282 both depths, with highest values registered during austral summer and lowest during
283 winter (Fig. 5). The squared-chord distance between the sediment trap diatom
284 assemblages at 2000 and 3700 m was 0.003, indicating highly similar proportions of
285 species within depths.

286 The dominant species of the diatom assemblage was *Fragilariopsis kerguelensis* with a
287 mean flux between 53×10^6 and 60×10^6 valves $m^{-2} day^{-1}$ at 2000 m (annualized mean
288 and deployment average, respectively). This species contribution ranged from 37% to
289 96% of the total assemblage at 2000 m (average relative contribution for the
290 overlapping period between traps = 72%; Table 3) and from 31% to 82% at 3700 m
291 (average relative contribution for the overlapping period between traps = 68%) (Table
292 3). The diatom flux peaks at both depths can be attributed to an increased flux of *F.*
293 *kerguelensis*, with exception to a peak in late January at 2000 m when *Fragilariopsis*
294 *pseudonana* dominated the settling assemblage (39%). Secondary contributors to the
295 diatom assemblage at 2000 and 3700 m were *Thalassiosira lentiginosa* (average relative
296 contribution for the overlapping period between traps = 5% and 7%, respectively),
297 *Thalassiosira gracilis* var. *gracilis* (6% and 7%), *Fragilariopsis separanda* (3% and

298 2%), *Fragilariopsis pseudonana* (4% and 1%), *Fragilariopsis rhombica* (2% and 2%),
299 *Fragilariopsis curta* (1% and 1%) and *Azpeitia tabularis* (1% and 1%) (Table 3 and Fig.
300 5). It is worth noting that some large and/or entangled frustules of some diatom taxa,
301 such as *Thalassiothrix* (Hallegraeff, 1986), could have been retained in the 1 mm
302 screen mesh, and therefore, underrepresented in this study.

303 Scanning electron microscope (SEM) pictures of some of the most relevant taxa are
304 shown in Fig. 6.

305

306 **3.3 Diatom settling velocities**

307 The calculation of the sinking velocities of the main diatom taxa was only possible for
308 the “particle bloom” period, i.e. from December to March, when distinct peaks were
309 registered in both sediment traps (Fig. 5). The precision of the calculations is limited by
310 the duration of the sampling intervals during this period (8 days). The majority of the
311 taxa exhibited an offset of a single sampling interval (8 days) between the 2000 and
312 3700 m traps, suggesting an average settling speed of 210 m d⁻¹.

313

314 **4. DISCUSSION**

315 **4.1 Quality check of downward particle fluxes**

316 The use of sediment traps has greatly enhanced our understanding of particle transfer in
317 open ocean environments. However, laboratory and field experiments have shown that
318 the measurement of downward particle fluxes can be subject to several hydrodynamic
319 biases (e.g. Gardner, 1980; Baker et al., 1988, Yu et al., 2001). Therefore, an assessment
320 of the trapping efficiency is needed prior to interpreting the results of any sediment trap
321 experiment.

322 Our mooring line at site 61°S was maintained taut by the distribution of floats along the
323 line and at the mooring head. Measured mean current speeds at both trap levels were
324 always lower than 10 cm s⁻¹ that is, as a rule of thumb, considered the threshold at
325 which trapping efficiency decreases significantly (e.g. Baker et al., 1988, Honjo et al.,
326 1992, Yu et al., 2001, Heussner et al., 2006). On the basis of global comparisons, these
327 conditions suggest that fluxes registered by the traps were unlikely to be significantly
328 biased by under- or over-trapping (Honjo. 1996; Yu et al., 2001).

329 **4.2 Variability of total mass flux and composition of particles**

330 The seasonal variability of the vertical particle transfer at site 61°S appears principally
331 controlled by seasonal changes in the euphotic zone productivity. A significant increase
332 in chlorophyll-*a* concentration from October 2001, approximately two months before
333 any significant warming or stratification occurs (Fig. 2), is in line with an increase in
334 incident insolation from the beginning of spring. Taking into account that pigment
335 concentration at the sea surface reached its highest levels during November 2001 (Fig.
336 2), and that maximum total particle and diatom fluxes were registered at the beginning
337 of January 2002 (Figs 3 and 5), a time lag of about two months between peak
338 production in the surface waters and onset of particle export in the study area can be
339 assumed. This feature is in agreement with the observations of Buesseler et al. (2001) in
340 the Pacific Sector of the Southern Ocean who reported a similar delay in the delivery of
341 the surface bloom to the ocean interior. Contrastingly, algal biomass reached its annual
342 minimum during the austral winter (June-September) (Fig. 2) and very low particle and
343 diatom export fluxes were registered by the traps (Fig. 3 and 5). These low chlorophyll-
344 *a* concentration and flux values appear to be driven by two factors: (i) insufficient
345 sunlight as a result of the low solar angle and shortened day length that reduced the
346 ability to increase biomass and (ii) intense vertical mixing that transported

347 phytoplankton below their critical depth, i.e. depth at which the rate of photosynthesis
348 equals the rate of respiration (Fig. 2).

349 In terms of particle composition, silica-rich and carbonate-poor particulate fluxes
350 registered by the traps mirrored the dominance of diatoms in the waters south of the
351 Antarctic Zone, south of Tasmania. The composition of the settling material is
352 consistent with that of the surface sediments in the region. Opal content in the surface
353 sediments of the Southern Ocean increases from north to south, being the dominant
354 component south of the APF. In contrast, CaCO_3 is dominant north of the SAF and
355 decreases southward (Honjo et al., 2000).

356 Total mass and POC fluxes provided the strongest correlation at both sediment traps
357 (Table 2). As BSiO_2 dominated the mass fluxes throughout the sampling period,
358 changes in the BSiO_2 flux directly affected POC fluxes, suggesting that diatom valve
359 sedimentation plays an important role in controlling the organic carbon export to depth
360 at the AZ site. On the other hand, the small CaCO_3 fluxes and lower correlation values
361 with POC at both sediment traps suggest that CaCO_3 had a lesser influence on the POC
362 export. However, as the carrying capacity of POC per CaCO_3 unit could not be
363 quantified, the role of CaCO_3 in controlling the transfer of organic carbon to depth
364 remains unknown.

365

366 **4.3 Seasonal trend of diatom fluxes and species composition**

367 The annual diatom fluxes registered by the 2000 m sediment trap (Table 1) fall within
368 the range of those estimated by Fischer et al. (2002) in the AZ of the eastern Atlantic
369 (20×10^6 valves $\text{m}^{-2} \text{d}^{-1}$) and those reported by Grigorov et al. (2014) in the Ross Sea
370 Gyre (93×10^6 valves $\text{m}^{-2} \text{day}^{-1}$). The diatom fluxes recorded at site 61°S are therefore

371 comparable in magnitude to previously reported diatom data sets of the AZ in the
372 Southern Ocean.

373 Although several factors, such as grazing, dissolution and lateral advection, can
374 influence diatom flux (Boltovskoy et al. 1993), the similar seasonal patterns, with a two
375 month offset between primary productivity and diatom flux variations (Figs. 2 and 5a)
376 suggest that the primary signal of the phytoplankton bloom in the overlying water
377 masses is registered by the traps. About two-thirds of the annual diatom export fluxes at
378 each trap depth were registered during January and February (Fig. 5). A markedly
379 seasonal pattern is characteristic of high latitude systems (e.g. Wefer et al., 1988;
380 Dunbar et al., 1998; Honjo et al., 2000; Fischer et al., 2002; Pilskaln et al., 2004;
381 Romero and Armand, 2010) and illustrates the opportunistic character (r selection) of
382 the dominant species during the summer bloom. As a consequence of this rapid diatom
383 biomass increase, silica in the AZ-S is often stripped out the mixed layer by mid-
384 summer (Trull et al., 2001c).

385 The temporal variations in the composition of diatom assemblages mirrored the changes
386 of the hydrographic conditions in the AZ-S, south of Tasmania. Overall, the major
387 diatom taxa recorded at our mooring site are typical of living and fossil assemblages
388 representing open ocean waters of the Antarctic Zone (Romero and Armand, 2010;
389 Crosta et al., 2005, respectively).

390 The seasonal diatom flux was mainly driven by changes in the flux of the large, heavily-
391 silicified and bloom-forming *F. kerguelensis*, a prominent member of the diatom
392 assemblages in the iron-limited Southern Ocean waters (Smetacek, 1999; Abelmann et
393 al., 2006). Large abundances of *F. kerguelensis* in phytoplankton blooms have also been
394 previously reported in our study area during the SOIREE experiment (Gall et al., 2001;
395 Trull and Armand, 2001), in the AZ of the south-west Atlantic (Hart, 1934) and in the

396 vicinity of open-ocean fronts in the Atlantic and Pacific sectors (Bathmann et al., 1997;
397 Laubscher et al., 1993; Grigorov et al., 2014). The relative contribution of *F.*
398 *kerguelensis* at both 61 S traps (68-80%; Table 1) is consistent with its distribution in
399 the Southern Ocean surface sediments where its maximum abundances (70-83%) are
400 found between the Polar Front and the maximum summer sea-ice edge (Crosta et al.,
401 2005). Fischer et al. (2002) and Grigorov et al. (2014) reported lower relative
402 abundance and fluxes of this species in sediment traps in the AZ of the Atlantic sector
403 (29%; 6×10^6 valves $\text{m}^{-2} \text{d}^{-1}$) and in the Ross Sea Gyre (22%; 20×10^6 valves $\text{m}^{-2} \text{d}^{-1}$),
404 respectively. However, these sites were under the influence of seasonal ice, where sea-
405 ice affiliated taxa such as smaller *Fragilariopsis* species and *Chaetoceros* spp., are
406 known to often dominate the diatom assemblages (Armand et al., 2005).

407 At the onset of the summer particle “bloom”, H' rises significantly due to the burst of
408 reproduction and sedimentation of most of the diatom taxa (Fig. 5a). The small and
409 rapidly dividing diatoms *Chaetoceros* group, *Fragilariopsis pseudonana*, *Fragilariopsis*
410 *rhombica*, *Fragilariopsis separanda* and *Pseudo-nitzschia* spp., together with the cool
411 open ocean species *Thalassiosira gracilis*, are major contributors to the bulk of the
412 spring-summer maximum (Fig. 5). The majority of these diatoms correspond to the
413 Group 1 defined by Quéguiner (2013), consisting of slightly silicified and fast-growing
414 species that undergo rapid species succession during productive periods. The biomass
415 accumulation of such diatoms is thought to be controlled principally by nutrient
416 availability rather than grazing pressure. This concept agrees well with the observations
417 of Zeldis (2001) who reported low grazing impact over the bloom development during
418 the SOIREE experiment. At the end of their growth season, these bloom-forming
419 species are considered to undergo mass mortality resulting in the formation of
420 aggregates that rapidly sink from the euphotic zone (Assmy et al., 2013).

421 The AZ-S site is remote from the direct influence of sea-ice in summer (Massom et al.,
422 2013; Fig. 1b), which makes the occurrence of the sea-ice affiliated diatoms
423 *Fragilariopsis cylindrus* and *Fragilariopsis curta* during January (Fig. 5b) puzzling.
424 The distribution of *F. cylindrus* in the modern Southern Ocean is constrained to the
425 north by the maximum summer sea ice edge (Semina, 2003; Armand et al., 2005; Esper
426 et al. 2010), whereas *F. cylindrus* appears limited by the maximum extension of sea ice
427 during winter (Armand et al., 2005; Esper et al., 2010). Likely explanations for the
428 presence of these species at site 61°S are either (i) the occurrence of an iceberg in the
429 vicinity of our study area or (ii) the advection of a transient bloom produced in a region
430 under the influence of sea ice. Rich sea-ice affiliated diatom communities have been
431 found in association with free-drifting icebergs (e.g. Smith et al., 2011), however this
432 explanation is unlikely since our site is remote from any known iceberg pathway
433 (Gladstone et al., 2001). Taking into account a time lag of about two months between
434 peak production and particle export, a healthy and neutrally buoyant bloom could cover
435 a much larger distance than that estimated for a sinking particle (detailed in 4.5). Sea-ice
436 coverage west of ~90°E can reach latitudes well above 61°S (Massom et al., 2013; Fig.
437 1b). We hypothesize that the pulses of *F. curta* and *F. cylindrus* could correspond to the
438 sedimentation of a diatom bloom that was either advected from an area upstream the
439 ACC under the influence of seasonal sea ice or transported northward by Antarctic
440 Surface Water currents (AASW) produced by the seasonal retreat of the sea ice, south
441 of our study.

442 Enhanced fluxes of the large and thick-walled *F. kerguelensis* persisted for a longer
443 period (until April) than those of Group 1 (sensu Quéguiner, 2013) most likely
444 contributing to the progressive reduction of silicic acid concentrations in the mixed
445 layer throughout the summer. A similar pattern was reported by Assmy et al. (2013)

446 both inside and outside the iron-fertilized bloom during the European Iron Fertilization
447 Experiment (EIFEX). *Fragilariopsis kerguelensis* is considered a “sinking-silica
448 species” (Assmy et al., 2013) largely responsible for the decoupling of silicon and
449 carbon cycles in the iron-limited ACC.

450 At the end of the diatom export maximum (i.e. February-March), *Thalassiothrix*
451 *antarctica* contributed more significantly to the flux via increased abundances (Fig. 5b).
452 This species is a large, slow-growing diatom distributed within discrete layers of the
453 water column (Kemp et al., 2000). Such diatoms are considered k-strategists (Kemp and
454 Villareal, 2013) and fall within Group 2 defined by Quéguiner (2013). High abundances
455 of *Thalassiothrix antarctica* have been reported within and south of the APF (Laubscher
456 et al., 1995; Bracher et al., 1999) and associated to a subsurface chlorophyll maximum
457 in the PFZ south of Tasmania (Kopczynska et al., 2001; Parslow et al., 2001; Gomi et
458 al., 2010) and in Prydz Bay (Quilty et al., 1985). We suspect that *Thalassiothrix*
459 *antarctica* develops in parallel to Group 1 diatoms, as a result of them inhabiting the
460 pycnocline discontinuity, exploiting deep nutrients and undergoing low rates of primary
461 productivity under low-light conditions (Kemp et al., 2000, 2006; Quéguiner, 2013).
462 The abrupt drop of the photosynthetically active radiation levels to less than half their
463 peak values from February to March (Fig. 2a) and/or the occurrence of a vertical mixing
464 event may have produced both light and/or nutrient limitation leading to the rapid
465 flocculation and sinking of *T. antarctica* during the summer-autumn transition.

466 Post-March diatom export decreases significantly (Fig. 5a) due to the reduction to
467 lowest levels of light and the concomitant intensification of mixing of the water column
468 (Fig. 2a,b). The “post-bloom” diatom assemblage is characterized by low diversity
469 values (Fig. 5a) mainly due to the high relative abundance of *F. kerguelensis* (up to 96%
470 in September). The remaining assemblage is subsequently composed of large and

471 heavily silicified centrics such as *Thalassiosira lentiginosa*, *Azpeitia tabularis* and
472 *Thalassiosira oliveriana*. These are typical open ocean diatoms (Crosta et al., 2005;
473 Romero et al., 2005) with presumed lower nutrient requirements than the summer
474 bloom-forming species.

475

476 **4.4 Transfer to depth**

477 Our results suggest that a fast and relatively undisturbed downward transport of
478 particles occurred between 2000 and 3700 m (Fig. 3 and 4). The similar BSi and POC
479 content in both traps (Table 1) indicates that little silica dissolution and remineralization
480 occurred between 2000 and 3700 m. Such a result is consistent with previous sediment
481 trap studies that reported minimal alteration of the silica and organic carbon fluxes
482 below the mesopelagic-bathypelagic boundary (~2000 m) (Takahashi, 1986; Honjo et
483 al., 2009). However, the high Si/C at both depth levels also implies that organic matter
484 is recycled faster than opal before reaching the traps, and this must occur at mesopelagic
485 depths. We interpret this as the remineralization of the settling material by the microbial
486 community and by the zooplankton that preferentially feed on organic matter (Honjo,
487 2009). High Si/C ratios are characteristic of the iron-limited systems of the Southern
488 Ocean where large and highly silicified species (e.g. *Fragilariopsis kerguelensis*)
489 dominate the diatom assemblages. In this regard, the average POC content (1.4%) of
490 our samples at 2000 m is very low, and the average BSi/POC molar ratio for the entire
491 collection period was less than 0.1 for both traps, in comparison to an average of ~1 for
492 a compilation of deep Southern Ocean traps (Honjo et al., 2008) and a median of ~2 for
493 a global compilation (Lampitt and Antia, 1998). This makes it clear that the trap
494 samples have experienced very strong losses of organic carbon, consistent with previous

495 studies suggesting that Southern Ocean waters south of the Polar Front can be described
496 as low carbon export regimes (Lam and Bishop, 2007).

497 The sinking velocities of the major diatom taxa during the “particle bloom” indicate
498 rapid sedimentation of the diatom assemblages between the upper and lower traps (210
499 m d⁻¹). These settling speeds are very similar to those estimated by Honjo et al. (2000)
500 in the AZ of the Pacific Sector and are equal, or greater than, those observed in high
501 productivity areas at lower latitudes (Honjo, 1996). In contrast, based on the time delay
502 between samples with similar silicon isotopic signatures at different depths at site 61 S,
503 Closet et al. (unpublished results) estimated the settling velocities outside the
504 production period to be 120 m d⁻¹ or less. These observations suggests that sinking rates
505 of diatom valves at site 61 S are related to flux size, perhaps because higher fluxes lead
506 to the formation of fast-sinking aggregates (e.g. Alldredge and Gotschalkt, 1989). This
507 concept is consistent with the observations of Grigorov et al. (2014) on sediment trap
508 material from the Pacific Sector of the Southern Ocean who reported abundant diatom
509 aggregates at times of peak flux and mainly individual cells and small chains outside the
510 production period. Moreover, the formation of aggregates would also explain the
511 enhanced POC export (Table 1) in association with high fluxes of Group 1 diatoms
512 during the production period (Assmy et al., 2013).

513 The pulse of *Thalassiothrix antarctica* in early March at both depths coincides with an
514 upturn of the POC fluxes (Table 1). *Thalassiothrix antarctica* cells are about 60 times
515 larger (in estimated biovolume) than *F. kerguelensis* (Cornet-Barthaux et al., 2007), and
516 therefore, have the potential to contribute significantly to the annual organic carbon
517 export even at background concentrations (Goldman 1993; Goldman and McGillicuddy,
518 2003; Quéguiner et al., 2013).

519 During winter, the lower sinking rates and high area/volume ratios of single diatom
520 cells may facilitate the recycling of the valves and remineralization of organic matter in
521 the upper water column. The enrichment of dissolution-resistant diatoms (e.g.
522 *Fragilariopsis kerguelensis*, *Thalassiosira oliveriana*, *Azpeitia tabularis*) during the
523 winter months observed in our traps could, therefore, be partially related to enhanced,
524 selective dissolution of more lightly silicified species (e.g. *Pseudo-nitzschia* spp.,
525 *Fragilariopsis pseudonana*, *Chaetoceros* spp.).

526 With regard to the comparison of the annual diatom assemblage between traps, their
527 highly similar abundance proportions, as revealed by the low squared chord distance
528 score, indicate that both traps registered diatom assemblages from the same source.
529 Moreover, the latter results further support the idea that silica BSi dissolution below
530 2000 m is minimal at the AZ-S site.

531

532 **CONCLUSIONS**

533 The main objective of our study was to document the variability in the magnitude,
534 timing and composition of particle and diatom export fluxes to the deep sea in the
535 southern Antarctic Zone (AZ-S) within the Australian sector of the Southern Ocean. To
536 examine this issue, we studied the year-round dynamics of particle flux from November
537 2001 through September 2002. The overall fluxes of biogenic particles to the mid- and
538 deep water column in the AZ-S were markedly seasonal with peak fluxes occurring
539 during the austral summer and very low export during winter. This seasonal pattern is
540 mediated by algal productivity. Comparison of satellite and particle flux data suggests a
541 delay of about two months between peak production and onset of particle export. The
542 biogenic opal fraction largely dominates the export throughout the year, and is mainly
543 delivered by diatoms. Carbonate and organic carbon are secondary components.

544 Diatom seasonal fluxes followed the seasonality of the biogeochemical particle fluxes at
545 both depths and their magnitude ($67\text{-}76 \times 10^6$ valves $\text{m}^{-2} \text{day}^{-1}$) is similar to previously
546 published data recorded in the AZ of other sectors of the Southern Ocean. The diatom
547 assemblages recovered at our mooring site are typical of the open ocean waters of the
548 Antarctic Zone (Crosta et al., 2005) and their seasonal succession agrees well with the
549 conceptual scheme proposed by Quéguiner (2013) for the POOZ (Permanently Open
550 Ocean Zone) and the PFZ (Polar Frontal Zone). *Fragilariopsis kerguelensis* is, by far,
551 the most dominant diatom species in the sediment trap samples. The occurrence of the
552 sea-ice affiliated species *F. cylindrus* and *F. curta* may correspond to the sedimentation
553 of a diatom bloom advected from an area under the influence of sea ice upstream the
554 ACC. The sedimentation pulse of the deep-dwelling species *Thalassiothrix antarctica*
555 during the February-March transition appears to have been triggered by an abrupt drop
556 of the light levels and/or a vertical mixing event.

557 Finally, the good correlation between the total mass fluxes at both sediment traps and
558 their similar diatom species composition suggests fast and undisturbed settling of
559 particles through the deep water column at the AZ-S site.

560

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578

579 **FIGURE CAPTIONS**

580 **Figure 1. a.** Location of the sediment trap mooring line in the Antarctic Zone of the
581 Australian sector of the Southern Ocean. Fronts (STF - Subtropical Front, SAF -
582 Subantarctic Front, PF - Polar Front, SB - Southern Boundary), regions (STZ –
583 Subtropical Zone, SAZ – Subantarctic Zone, PFZ – Polar Front Zone, ACC – Antarctic
584 Zone and SACCZ - Zone south of the ACC) and maximum extension of winter sea ice
585 (Max WSI) are shown. Triangle represents the position of 61°S mooring during the
586 experiment (Nov. 2001 – Sep. 2002). **b.** Mean sea ice season duration map for the East
587 Antarctic sector (1979/80-2009/10), with contours for 100, 200 and 300 days marked
588 (modified from Massom et al., 2013). **c.** Schematic diagram of the Australian sector of
589 the Southern Ocean depicting the bathymetry, main water masses and mooring
590 configuration. SAMW – Subantarctic Mode Water, AAIW – Antarctic Intermediate
591 Water, UCDW – Upper Circumpolar Deep Water, LCDW – Lower Circumpolar Deep
592 Water and AABW – Antarctic Bottom Water. Figure is adapted from Bostock et al.
593 (2013).

594

595 **Figure 2:** (a) Monthly mean chlorophyll-*a* concentration (mg m^{-3}), sea surface
596 temperature (SST) ($^{\circ}\text{C}$) and photosynthetically active radiation ($\text{Einstein m}^{-2} \text{d}^{-1}$) for the
597 period November 2001 to September 2002. No data was available from April to August
598 in 2001 and 2002. (b) Seasonal variation in the vertical structure of temperature ($^{\circ}\text{C}$) at
599 the 61°S site.

600

601 **Figure 3.** Temporal variability of the total mass and major biogenic fluxes for <1 mm
602 fraction at 2000 and 3700 m water depth from November 2001 through to November
603 2002 at the 61°S site.

604

605 **Figure 4.** Correlation between (a) mass flux ($\text{mg m}^{-2} \text{day}^{-1}$) at 2000 and 3700 m, and (b)
606 mass flux ($\text{mg m}^{-2} \text{day}^{-1}$) and diatom valve flux ($10^6 \text{m}^{-2} \text{day}^{-1}$) at 2000 and 3700 m.

607

608 **Figure 5.** Seasonal variation of (a) total diatom flux and Shannon's diversity index (H')
609 and (b) flux and relative abundance of the main diatom species at 2000 and 3700 m
610 sediment traps. The arrows indicate the associated peaks of valve flux at both depths
611 used to calculate the sinking velocities.

612

613 **Figure 6:** SEM photos of some of the most relevant diatom taxa collected by the
614 sediment traps at site 61°S . (a) *Azpeitia tabularis*. (b) *Chaetoceros atlanticus* (resting
615 stage). (c) *Fragilariopsis curta*. (d) *Fragilariopsis cylindrus*. (e) *Fragilariopsis*
616 *kerguelensis*. (f) *Fragilariopsis pseudonana*. (g) *Fragilariopsis rhombica*. (h)
617 *Fragilariopsis separanda*. (i) *Pseudo-nitzschia* spp. (j) *Thalassiosira gracilis* var.

618 *gracilis*. (k) *Thalassiosira lentiginosa*. (l) *Thalassiothrix antarctica*. Scale bars: d, f = 1
619 μm ; h, i = 2 μm ; c, e, j = 5 μm ; a, b, g, k, l = 10 μm .

620

621 **Table 1:** Daily export fluxes of total mass flux, biogenic silica (BSiO₂), calcium
622 carbonate (CaCO₃), particulate organic carbon (POC) and diatom valves registered at
623 the 61°S site from November 2001 through October 2002. Mass fluxes listed as zero
624 were too small to measure (<1 mg). *Average diatom fluxes for the 2000 and 3700 m
625 traps have been estimated for different sampling intervals (309 and 172 days,
626 respectively).

627

628 **Table 2:** Correlation matrix (R^2) for the total mass and bulk compound fluxes at both
629 sediment traps.

630

631 **Table 3:** Integrated fractional abundances of the diatom taxa found at the 2000 and
632 3700 m sediment traps at station 61°S.

633

634 REFERENCES

635 Abelmann, A., Gersonde, R. (1991) Biosiliceous particle flux in the Southern Ocean,
636 *Mar. Chem.*, **35**, 503—536.

637

638 Abelmann, A., Gersonde, R., Cortese, G., *et al.* (2006) Extensive phytoplankton blooms
639 in the Atlantic Sector of the glacial Southern Ocean, *Paleoceanography*, **21**, PA1013

640

641 Acker, J.G. and Leptoukh, G. (2007) Online analysis enhances use of NASA Earth
642 science data. *Eos, Transactions. AGU*, **88**, 14–17.

643

644 Alldredge, A.L., Gotschalkt, C.C. (1989) Direct observations of the mass flocculation of
645 diatom blooms: characteristics, settling velocities and formation of diatom aggregates.
646 *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **36** (2), 159–17

647

648 Arrigo, K.R., Robinson, D.H., Worthen, D.L., *et al.* (1999) Phytoplankton community
649 structure and the drawdown of nutrients and CO₂ in the Southern Ocean. *Science* **283**,
650 365–367.

651

652 Armand, L.K., Crosta, X., Romero, O.E. *et al.* (2005) The biogeography of major diatom
653 taxa in Southern Ocean surface sediments: 1. Sea ice related species. *Paleogeogr.,*
654 *Palaeoclimatol., Palaeoecol.*, **223**, 93–126.

655

656 Armand, L.K., Leventer, A. (2010) Palaeo sea ice distribution and reconstruction derived from the
657 geological record. In *Sea Ice*, (Eds. D. N. Thomas & G.S. Dieckmann, G.S.), pp. 469-530,
658 Wiley-Blackwell Publishing Ltd, Oxford.

659

660 Assmy, P., Smetacek, V., Montresor, M. (2013) Thick-shelled, grazer-protected diatoms
661 decouple ocean carbon and silicon cycles in the iron-limited Antarctic Circumpolar
662 Current. *PNAS* **110** (51) 20633–20638.

663

664 Baker, E.T., Milburn, H.B., Tennant, D.A. (1988) Field assessment of sediment trap
665 efficiency under varying flow conditions. *J. Mar. Res.* **46**, 573–592.

666

667 Bathmann, U., Fischer, G., Müller, P.J. *et al.* (1991) Short-term variations in particulate
668 matter sedimentation off Kapp Norvegia, Weddell Sea, Antarctica: relation to water

669 mass advection, ice cover, plankton biomass and feeding activity. *Polar Biol.* **11**, 185–
670 195.

671

672 Boltovskoy, D., Alder, V.A., Abelmann, A. (1993) Annual flux of Radiolaria and other
673 shelled plankters in the eastern equatorial Atlantic at 853 m: seasonal variations and
674 polycystine species-specific responses. *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **40**(9),
675 1863–1895.

676

677 Bostock, H.C., Barrows, T.T., Carter, L. et al. (2013) A review of the Australian–New
678 Zealand sector of the Southern Ocean over the last 30 ka (Aus-INTIMATE project).
679 *Quat. Sci. Rev.* **74**, 35–57.

680

681 Boyd, P., Watson, J., Law, C.S. et al. (2000) Phytoplankton bloom upon mesoscale iron
682 fertilisation of polar Southern Ocean waters. *Nature* **407**, 695–702.

683

684 Bracher, A.U., Kroon, B.M.A., Lucas, M.I. (1999) Primary production, physiological
685 state and composition of phytoplankton in the Atlantic Sector of the Southern Ocean.
686 *Mar. Ecol. Prog. Ser.* **190**, 1–16.

687

688 Bray, S., Trull, T.W., Manganini, S. (2000) SAZ Project Moored Sediment Traps: Results
689 of the 1997–1998 Deployments, 128 pp, Antarct. Coop. Res. Cent., Hobart, Tasmania,
690 Australia.

691

692 Buesseler, K.O., L. Ball, J. Andrews, et al., (2001) Upper ocean export of particulate
693 organic carbon and biogenic silica in the Southern Ocean along 170°W. *Deep-Sea Res.*

694 (2 *Top. Stud. Oceanogr.*) **48** (19–20), 4275–4297.

695

696 Coale, K.H., Johnson, K.S., Chavez, F.P., *et al.* (2004) Southern Ocean iron enrichment
697 experiment: Carbon cycling in high- and low-Si waters. *Science* **304** (5669), 408–414.

698

699 Comiso, J.C., Zwally, H.J. (1984) Concentration gradients and growth/decay
700 characteristics of the seasonal sea ice cover. *J. Geophys. Res.* **89**, 8081–8103.

701

702 Copin-Montegut, C., Copin-Montegut, G. (1983) Stoichiometry of carbon, nitrogen, and
703 phosphorus in marine particulate matter. *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **30** (1),
704 31–46.

705

706 Cornet-Barthaux, V., Armand, L.K., Quéguiner, B. (2007) Biovolume and biomass
707 measurements of key Southern Ocean diatoms. *Aquat. Microb. Ecol.* **48** (3), 295–308.

708

709 Crosta, X., Romero, O., Armand, L.K., *et al.* (2005) The biogeography of major diatom
710 taxa in Southern Ocean sediments: 2. Open ocean related species. *Palaeogeogr.,*
711 *Palaeoclimatol., Palaeoecol.*, **223**, 66–92.

712

713 De Baar, H.J.W., de Jong, J.T.M., Bakker, D.C.E. *et al.* (1995) Importance of iron for
714 phytoplankton blooms and carbon dioxide drawdown in the Southern Ocean. *Nature*
715 **373**, 412–415.

716

717 Dunbar, R.B., Leventer, A.R. and Mucciarone, D.A. (1998) Water column sediment
718 fluxes in the Ross Sea, Antarctica: atmospheric and sea ice forcing. *J. Geophys. Res.*
719 **103** (30) 741–59
720

721 Esper, O., Gersonde, R., Kadagies, N. (2010). Diatom distribution in southeastern Pacific
722 surface sediments and their relationship to modern environmental variables.
723 *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 287, 1–27.
724

725 Fischer, G., Fütterer, D., Gersonde, R., *et al.* (1988) Seasonal variability of particle flux in
726 the Weddell Sea and its relation to ice cover. *Nature*, **335**, 426–8.
727

728 Fischer, G., Gersonde, R., Wefer, G. (2002) Organic carbon, biogenic silica and diatom
729 fluxes in the marginal winter sea-ice zone and in the Polar Front Region: interannual
730 variations and differences in composition. *Deep-Sea Res. (2 Top. Stud. Oceanogr.)*, **47**,
731 1721–1745.
732

733 Fitzwater, S.E. Johnson, K.S., Gordon, *et al.* (2000) Trace metal concentrations in the
734 Ross Sea and their relationship with nutrients and phytoplankton growth. *Deep-Sea Res.*
735 *(2 Top. Stud. Oceanogr.)*, **47**, 3159–3179.
736

737 Flores, J.A., Sierro, F.J. (1997) A revised technique for the calculation of calcareous
738 nannofossil accumulation rates. *Micropal.*, **43**, 321–324.
739

740 Gall, M.P., Boyd, P.W., Hall, J., *et al.* (2001) Phytoplankton processes. Part 1:
741 Community structure during the Southern Ocean Iron Release Experiment (SOIREE)

742 *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **48**, 2551–2570.

743

744 Gardner, W.D. (1980) Sediment trap dynamics and calibration: a laboratory evaluation. *J.*
745 *Mar. Res.*, **38**, 17–39.

746

747 Gardner, W.D. (1985). The effect of tilt on sediment trap efficiency. *Deep-Sea Res. (1*
748 *Oceanogr. Res. Pap.)* **32**, 349–361.

749

750 Gladstone, R.M., Bigg, G.R., Nicholls, K.W. (2001) Iceberg trajectory modelling and
751 meltwater injection in the Southern Ocean. *J. Geophys Res.*, **106** (9), 19903–19915.

752

753 Goldman, J.C. (1993) Potential role of large oceanic diatoms in new primary production.
754 *Deep-Sea Res. (1 Oceanogr. Res. Pap.)* **40** (1), 159–168.

755

756 Goldman, J.C., McGillicuddy, D.J. (2003) Effect of large marine diatoms growing at
757 low light on episodic new production. *Limnol. Oceanogr.*, **48** (3), 1176–1182.

758

759 Gomi, Y., Fukuchi, M., Taniguchi, A. (2010) Diatom assemblages at subsurface
760 chlorophyll maximum layer in the eastern Indian sector of the Southern Ocean in
761 summer. *J. Plank. Res.* **32** (7), 1039–1050.

762

763 Grigorov, I., Rigual-Hernandez, A.S., Honjo, S., *et al.* (2014) Settling fluxes of diatom
764 frustules to the interior of the Antarctic Circumpolar Current along 170°W. *Deep-Sea*
765 *Res. (1 Oceanogr. Res. Pap.)*, **93**, 1-13.

766

767 Hallegraeff, G.M. (1986) Taxonomy and morphology of the marine plankton diatoms
768 *Thalassionema* and *Thalassiothrix*. *Diatom Research*, **1**, 57-80.
769

770 Hart, T. (1934) On the phytoplankton of the South-West Atlantic and the Bellinghausen
771 Sea, 1929–31. *Discovery Reports*, **8**, 1–268.
772

773 Heussner, S., Durrieu De Madron, X., Calafat, A. *et al.* (2006) Spatial and temporal
774 variability of downward particle fluxes on a continental slope: Lessons from an 8-yr
775 experiment in the Gulf of Lions (NW Mediterranean) *Mar. Geol.*, **234**, 63–92.
776

777 Honjo, S. (1996) Fluxes of particles to the interior of the open oceans, in *Particle Flux in*
778 *the Ocean*, edited by V. Ittekkot *et al.*, pp. 91–154, John Wiley, New York.
779

780 Honjo, S. (2009) Biological pump and particulate fluxes. In: Steele, J.H., Thorpe, S.A.,
781 Turekian, K.K. (Eds.) *Encyclopaedia of ocean sciences*. Academic Press, San Diego,
782 CA, 371–375
783

784 Honjo, S., Doherty, K.W. (1988) Large aperture time-series sediment traps; design
785 objectives, construction and application. *Deep-Sea Res.* **35**(1), 133–149
786

787 Honjo, S., Francois, R., Manganini, S., *et al.* (2000) Particle fluxes to the interior of the
788 Southern Ocean in the Western Pacific sector along 170 degrees W. *Deep-Sea Res. (2*
789 *Top. Stud. Oceanogr.)*, **47** (15–16), 3521–3548.
790

791 Honjo, S., Manganini, S.J., Krishfield, R.A. *et al.* (2008) Particulate organic carbon fluxes
792 to the ocean interior and factors controlling the biological pump: A synthesis of global
793 sediment trap programs since 1983. *Progr. Ocean.*, **76** (3), 217–285.

794

795 Honjo, S., Spencer, D.W., Gardner, W.D. (1992) A sediment trap intercomparison
796 experiment in the Panama Basin, 1979. *Deep-Sea Res. (I Oceanogr. Res. Pap.)* **39**,
797 333–358.

798

799 Ichinomiya, M., Gomi, Y., Nakamachi, M., *et al.* (2008) Temporal variations in the
800 abundance and sinking flux of diatoms under fast ice in summer near Syowa Station,
801 East Antarctica. *Polar Science*, **2**, 33–40.

802

803 Ishikawa, A., Wasiyama, N., Tanimura, A., *et al.* (2001) Variation in the diatom
804 community under fast ice near Syowa Station, Antarctica, during the austral summer of
805 1997/98. *Polar Bioscience*, **14**, 10–23.

806

807 Johnson, K.S., Gordon, R.M. and Coale, K.H. (1997) What controls dissolved iron
808 concentrations in the world ocean?. *Mar. Chem.*, **57** (3–4), 137–161.

809

810 Kemp, A.E.S., Pike, J., Pearce, R.B. *et al.* (2000) The "Fall dump" a new perspective on
811 the role of a "shade flora" in the annual cycle of diatom production and export flux.
812 *Deep-Sea Res. (I Oceanogr. Res. Pap.)*, **47**, 2129–2154.

813

814 Kemp, A.E.S., Pearce, R.B., Grigorov, I. (2006) Production of giant marine diatoms and
815 their export at oceanic frontal zones: implications for Si and C flux from stratified
816 oceans. *Global Biogeochem. Cycles* **20** (4), GB4S04.

817

818 Kemp, A.E.S., Villareal, T.A. (2013) High diatom production and export in stratified
819 waters – A potential negative feedback to global warming. *Progr. Ocean.*, **119** (0), 4–
820 23.

821

822 Kimura, N., Wakatsuchi, M. (2011) Large-scale processes governing the seasonal
823 variability of Antarctic sea-ice area. *Tellus* **63A**, 828–840.

824

825 Kopczynska, E.E., Dehairs, F., Elskens, M. *et al.* (2001) Phytoplankton and
826 microzooplankton variability between the Subtropical and Polar Fronts south of
827 Australia: Thriving under regenerative and new production in late summer. *J. Geophys.*
828 *Res.*, 106, 31597–31609.

829

830 Lam, P. J., Bishop, J.K.B. (2007) High biomass low export regimes in the southern ocean.
831 *Deep-Sea Res. (2 Top. Stud. Oceanogr.)*, **54** (5–7), 601–638

832

833 Lampitt, R.S., Antia, A.N. (1997) Particle flux in deep seas: regional characteristics and
834 temporal variability. *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **44** (8): 1377–1403.

835

836 Laubscher, R.K., Perissinotto, R. and McQuaid, C.D. (1993) Phytoplankton production
837 and biomass at frontal zones in the Atlantic Sector of the Southern Ocean. *Polar Biol.*,
838 **13**, 471–481.

839

840 Leventer, A., Dunbar, R.B. (1987) Diatom flux in McMurdo Sound, Antarctica. *Mar.*
841 *Micropaleontol.*, **12**, 49–64.

842

843 Leventer, A., Dunbar, R.B., DeMaster, D.J. (1993) Diatom Evidence for Late Holocene
844 Climatic Events in Granite Harbor, Antarctica. *Paleoceanography* **8**, 373-386.

845

846 Leventer, A., Dunbar, R.B., (1996) Factors influencing the distribution of diatoms and
847 other algae in the Ross Sea. *J. Geophys. Res.*, **101**, 18489–500.

848

849 Locarnini, R.A., Mishonov, A.V. and Antonov, J.I. (2010) *World Ocean Atlas 2009*,
850 Volume 1: Temperature. Vol. 1, U.S. Government Printing Office, Washington, D.C.

851

852 Massom, R., Reid, P., Stammerjohn, S., *et al.* (2013) Change and Variability in East
853 Antarctic Sea Ice Seasonality, 1979/80–2009/10. *Plos one* **8** (5), e64756.

854

855 Martin, J.H., Fitzwater, S.E., Gordon, R. M. (1990) Iron deficiency limits phytoplankton
856 growth in Antarctic waters. *Global Biogeochem. Cycles* **4**, 5-12.

857

858 Matsumoto K., Sarmiento J.L. and Brzezinski M.A. (2002) Silicic acid leakage from the
859 Southern Ocean: A possible explanation for glacial atmospheric pCO₂. *Global*
860 *Biogeochem. Cycles*, **16**, 1031.

861

862 Moore, J.K., Abbott, M.R. (2000) Phytoplankton chlorophyll distributions and primary
863 production in the Southern Ocean. *J. Geophys. Res.*, **105**, 28709–28722.

864

865 Nelson, D.M., Tréguer, P., Brzezinski, M.A., *et al.* (1995) Production and dissolution of
866 biogenic silica in the ocean: Revised global estimates, comparison with regional data
867 and relationship to biogenic sedimentation. *Global Biogeochem. Cycles*, 9, 359–372.

868

869 Orsi, A.H., Whitworth III, T., Nowlin Jr., W.D. (1995) On the meridional extent and
870 fronts of the Antarctic Circumpolar Current. *Deep-Sea Res. (I Oceanogr. Res. Pap.)*,
871 **42**, 641–673.

872

873 Ortiz, J.D., Mix, A.C. (1997) Comparison of Imbrie-Kipp transfer function and modern
874 analog temperature estimates using sediment trap and core top foraminiferal faunas.
875 *Paleoceanography*, **12**, 175–190.

876

877 Parslow, J., Boyd, P., Rintoul, S.R. *et al.* (2001) A sub-surface chlorophyll maximum in
878 the Polar Frontal Zone south of Australia: seasonal evolution and implications for
879 phytoplankton-light-nutrient interactions. *J. Geophys. Res.*, **106**, 31543–31550.

880

881 Pilskaln, C.H., Manganini, S.J., Trull, T., *et al.* (2004) Geochemical particle fluxes in the
882 Southern Indian Ocean seasonal ice zone: Prydz Bay region, east Antarctica. *Deep-Sea*
883 *Res. (I Oceanogr. Res. Pap.)*, **50**, 307–32.

884

885 Pondaven, P., Ragueneau, O., Tréguer, P., *et al.* (2000) Resolving the 'opal paradox' in
886 the Southern Ocean. *Nature*, **405**, 168–172.

887

888 Popp, B.N., Trull, T., Kenig, F. *et al.* (1999) Controls on the carbon isotopic composition
889 of Southern Ocean phytoplankton. *Global Biogeochem. Cycles* **13** (4), 827–843.
890

891 Quéguiner, B. (2013) Iron fertilization and the structure of planktonic communities in
892 high nutrient regions of the Southern Ocean. *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*,
893 **90**, 43-54.
894

895 Quilty, P., Kerry, K.R., Marchant, H.J. (1985) A seasonally recurrent patch of Antarctic
896 planktonic diatoms. *Search (ANZAAS)*, **16**, 48.
897

898 Reynolds, R.W., Rayner, N.A., Smith, T.M. *et al.* (2002) An improved in situ and satellite
899 SST analysis for climate. *J. Climate*, **15**, 1609–1625.
900

901 Rintoul, S.R., Bullister, J.L. (1999) A late winter Hydrographic section from Tasmania to
902 Antarctica. *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **46**, 1417–1454.
903

904 Rintoul, S.R., Sokolov, S. (2001) Baroclinic transport variability of the Antarctic
905 Circumpolar Current south of Australia (WOCE repeat section SR3). *J. Geophys. Res.*
906 **106**, 2795–2814.
907

908 Romero, O., Armand, L.K., Crosta, X. *et al.* (2005) The biogeography of major diatom
909 taxa in Southern Ocean sediments: 3. Tropical/Subtropical species. *Palaeogeogr.,*
910 *Palaeoclimatol., Palaeoecol.*, **223**, 49–65.
911

912 Romero, O.E., Fischer, G., Lange, C.B. *et al.*(2000) Siliceous phytoplankton of the
913 western equatorial Atlantic: sediment traps and surface sediments. *Deep-Sea Res. (2*
914 *Top. Stud. Oceanogr.)* **47**, 1939–1959.

915

916 Romero, O.E., Lange, C.B., Fischer, *et al.* (1999). Variability in export production
917 documented by downward fluxes and species composition of marine planktonic
918 diatoms: observations from the tropical and equatorial Atlantic. In: Fischer, G., Wefer,
919 G. (Eds.), *The Use of Proxies in Paleoceanography, Examples from the South Atlantic*.
920 Springer, Berlin, Heidelberg, pp. 365–392.

921

922 Romero, O., Thunell, R.C., Astor, Y., *et al.* (2009) Seasonal and interannual dynamics in
923 diatom production in the Cariaco Basin, Venezuela. *Deep-Sea Res. (1 Oceanogr. Res.*
924 *Pap.)*, **56**, 571–581.

925

926 Sakshaug, E., Holm-Hansen, O. (1984) Factors governing pelagic production in polar
927 oceans. In: Holm-Hansen, O., Bolis, L., Gilles, R. (Eds.), *Marine Phytoplankton and*
928 *Productivity. Lecture Notes on Coastal and Estuarine Studies*, vol. 8. Springer, Berlin,
929 pp. 1–18.

930

931 Sancetta, C., Calvert, S.E. (1988) The annual cycle of sedimentation in Saanich Inlet,
932 British Columbia: implications for the interpretation of diatom fossil assemblages. *Deep*
933 *Sea Res.* **35** (1), 71–90

934

935 Sarmiento, J.L., T.M.C. Hughes, R.J. Stouffer *et al.* (1998) Simulated response of the
936 ocean carbon cycle to anthropogenic climate warming, *Nature*, **393**, 245–249.

937

938 Schrader, H. J., Gersonde, R. (1978) Diatoms and silicofagellates. Micropaleontological
939 counting methods and techniques: an exercise on an eight metres section of the Lower
940 Pliocene of Capo Rosello, Sicily. *Utrecht Bull. Micropaleontol.* **17**, 129–176.

941

942 Semina, H.J. (2003) SEM-studied diatoms of different regions of the World Ocean.
943 *Iconographia Diatomologica* **10**, 1– 362.

944

945 Smetacek, V. (1985) Role of sinking in diatom life-history cycles: ecological,
946 evolutionary and geological significance. *Mar. Biol.* **84**, 239-251.

947

948 Smetacek, V. (1999). Diatoms and the ocean carbon cycle. *Protist*, **250**, 25– 32

949

950 Smetacek, V., Assmy, P., Henjes, J. (2004) The role of grazing in structuring Southern
951 Ocean pelagic ecosystems and biogeochemical cycles. *Antarctic Science*, **16**: 541–558.

952

953 Smith Jr., W.O., Nelson, D.M. (1986) Importance of ice edge phytoplankton production
954 in the Southern Ocean. *Bioscience* **36** (4), 251–257.

955

956 Smith Jr., K.L., Sherman, A.D., Shaw, T.J. *et al.* (2011) Carbon export associated with
957 free-drifting icebergs in the Southern Ocean. *Deep-Sea Res. (2 Top. Stud. Oceanogr.)*
958 **58**, (11–12), 1485–1496.

959

960 Sohrin, Y., Iwamoto, S., Matsui, M. *et al.* (2000) The distribution of Fe in the Australian
961 sector of the Southern Ocean. *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **47**, 55–84.

962

963 Sokolov, S., Rintoul, S.R. (2002) Structure of southern ocean fronts at 140 E. *J. Mar.*
964 *Syst.* **37**, 151–184.

965

966 Sokolov, S., Rintoul, S.R. (2007) Multiple Jets of the Antarctic Circumpolar Current
967 South of Australia. *J. Physical Oceanogr.*, **37**, 1394–1412

968

969 Sokolov, S., Rintoul, S.R. (2009a) Circulation structure and distribution of the Antarctic
970 Circumpolar Current fronts: 1. Mean circumpolar paths. *J. Geophys. Res.* **114**, C11018.

971

972 Sokolov, S., Rintoul, S.R. (2009b) Circulation structure and distribution of the Antarctic
973 Circumpolar Current fronts: 2. Variability and relationship to sea surface height. *J.*
974 *Geophys. Res.* **114**, C11019.

975

976 Sullivan, C.W., McClain, C.R., Comiso, J.C., Smith, W.O. (1988) Phytoplankton standing
977 crops within an Antarctic ice edge assessed by satellite remote sensing. *J. Geophys. Res.*
978 **93**, 12487–12498.

979

980 Suzuki, H., Sasaki, H., Fukuchi, M. (2001) Short-term variability in the flux of rapidly
981 sinking particles in the Antarctic Marginal Ice Zone. *Polar Biol.* **24**, 697–705.

982

983 Takahashi, K. (1986) Seasonal fluxes of pelagic diatoms in the subarctic Pacific, 1982–
984 1983. *Deep-Sea Res.* **33**, 1225–51.

985

986 Taylor, F., Sjunneskog, C. (2002) Postglacial marine diatom record of the Palmer Deep,
987 Antarctic Peninsula (ODP Leg 178, Site 1098) 2. Diatom assemblages.
988 *Paleoceanography* **17**, PAL 2-1-PAL 2-12.

989

990 Tréguer, P. J., De La Rocha, C. L. (2013) The world ocean silica cycle. *Annual review of*
991 *marine science*, **5**, 477-501.

992

993 Trull, T., Armand, L. (2001) Insights into Southern Ocean Carbon export from the $\delta^{13}\text{C}$
994 of particles and dissolved inorganic carbon during the SOIREE iron release experiment.
995 *Deep-Sea Res. (2 Top. Stud. Oceanogr.)*, **48**, 2655–2680.

996

997 Trull, T., Sedwick, F. P.N., Griffiths, F.B. et al. (2001a) Introduction to special section:
998 SAZ Project. *J. Geophys. Res.*, **106**, 31425–31429.

999

1000 Trull, T., Bray, S., Manganini, S., et al. (2001b) Moored sediment trap measurements of
1001 carbon export in the Subantarctic and Polar Frontal Zones of the Southern Ocean, south
1002 of Australia, *J. Geophys. Res.*, **106**, 31489–31510.

1003

1004 Trull, T., Rintoul, S. R., Hadfield, M., et al. (2001) Circulation and seasonal evolution of
1005 polar waters south of Australia: Implications for iron fertilization of the Southern
1006 Ocean, *Deep-Sea Res. (1 Oceanogr. Res. Pap.)*, **48**, 2439–2466

1007

1008 Varela, D.E., Pride, C.J., Brzezinski, M.A. (2004) Biological fractionation of silicon
1009 isotopes in Southern Ocean surface waters. *Global Biogeochem. Cy.*, **18**, GB1047.

1010

1011 Wefer, G., Fischer, G., F. Utterer, D. *et al.* (1988) Seasonal particle flux in the Bransfield
1012 Strait, Antarctica. *Deep-Sea Res. (I Oceanogr. Res. Pap.)* **35** (6), 891–898.

1013

1014 Yu, E.F., Francois, R., Bacon, M.P. *et al.* (2001) Trapping efficiency of bottom-tethered
1015 sediment traps estimated from the intercepted fluxes of ^{230}Th and ^{231}Pa *Deep-Sea Res.*
1016 *(I Oceanogr. Res. Pap.)*, **48** (3) 865–889.

1017

1018 Zeldis, J. (2001) Mesozooplankton community composition, feeding, and export
1019 production during SOIREE. *Deep-Sea Res. (2 Top. Stud. Oceanogr.)*, 48, 2615–2634.

1020

Table(s)

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61_2000	Sampling period	Length	Total Mass Flux			BSiO ₂		CaCO ₃		POC		POC/PN	Diatoms
Cup	mid point	days	mg m ⁻² d ⁻¹	mg m ⁻² d ⁻¹	%	mg m ⁻² d ⁻¹	%	mg m ⁻² d ⁻¹	%	molar ratio	10 ⁶ valves m ⁻² d ⁻¹		
1	Nov. 30, 2001	8	48	26	54	14	30	0.7	1.5	6.6	-		
2	Dec. 08, 2001	8	78	47	61	17	22	1.7	2.2	6.1	9		
3	Dec. 16, 2001	8	326	198	61	62	19	6.9	2.1	5.4	82		
4	Dec. 24, 2001	8	509	326	64	140	28	6.4	1.3	3.5	85		
5	Jan. 01, 2002	8	1151	856	74	44	4	26.9	2.3	7.4	408		
6	Jan. 09, 2002	8	1069	796	75	170	16	14.8	1.4	4.9	200		
7	Jan. 17, 2002	8	656	478	73	60	9	11.3	1.7	6.1	159		
8	Jan. 25, 2002	8	702	541	77	38	5	11.0	1.6	6.1	296		
9	Feb. 02, 2002	8	666	520	78	39	6	12.0	1.8	6.5	184		
10	Feb. 10, 2002	8	595	469	79	24	4	8.2	1.4	6.2	295		
11	Feb. 18, 2002	8	534	425	80	20	4	6.2	1.2	6.5	149		
12	Feb. 26, 2002	8	524	418	80	19	4	4.7	0.9	6.5	152		
13	Mar. 06, 2002	8	586	471	80	15	3	6.9	1.2	7.2	120		
14	Mar. 14, 2002	8	285	230	81	11	4	3.2	1.1	6.6	71		
15	Mar. 22, 2002	8	290	253	87	7	3	3.2	1.1	6.8	66		
16	Mar. 30, 2002	8	263	218	83	8	3	2.6	1.0	6.1	87		
17	Apr. 08, 2002	10	264	220	83	7	3	2.2	0.8	6.4	97		
18	May. 08, 2002	50	130	102	78	5	4	1.2	1.0	5.9	47		
19	Jun. 29, 2002	54	65	52	79	2	4	0.7	1.0	6.6	10		
20	Aug. 22, 2002	55	56	44	78	2	4	0.8	1.5	6.6	19		
21	Sep. 29, 2002	20	42	34	81	2	4	0.5	1.3	7.2	6		
Annualised values			232	178	76	17	7.4	3.3	1.4	6.1	67		
Annual flux			85 g m⁻² y⁻¹	65 g m⁻² y⁻¹		6 g m⁻² y⁻¹		1.2 g m⁻² y⁻¹			24 10⁹ valves m⁻² y⁻¹		

61_3700	Sampling period	Length	Total Mass Flux			BSiO ₂		CaCO ₃		POC		POC/PN	Diatoms
Cup	mid point	days	mg m ⁻² d ⁻¹	mg m ⁻² d ⁻¹	%	mg m ⁻² d ⁻¹	%	mg m ⁻² d ⁻¹	%	molar ratio	10 ⁶ valves m ⁻² d ⁻¹		
1	Nov. 30, 2001	8	38	25	64	9	23	0.4	1.1	7.4	-		
2	Dec. 08, 2001	8	31	17	54	9	28	0.4	1.2	6.4	-		
3	Dec. 16, 2001	8	99	51	52	29	30	1.4	1.4	6.7	4		
4	Dec. 24, 2001	8	231	148	64	59	26	1.4	0.6	2.6	12		
5	Jan. 01, 2002	8	873	656	75	87	10	17.3	2.0	6.8	118		
6	Jan. 09, 2002	8	1157	886	77	154	13	19.8	1.7	6.9	479		
7	Jan. 17, 2002	8	828	611	74	166	20	9.4	1.1	4.6	354		
8	Jan. 25, 2002	8	490	376	77	34	7	6.4	1.3	6.4	169		
9	Feb. 02, 2002	8	491	384	78	32	6	6.5	1.3	6.1	385		
10	Feb. 10, 2002	8	419	335	80	19	4	6.0	1.4	7.0	281		
11	Feb. 18, 2002	8	584	475	81	36	6	6.2	1.1	6.2	254		
12	Feb. 26, 2002	8	581	473	81	31	5	5.2	0.9	5.5	238		
13	Mar. 06, 2002	8	849	737	87	23	3	7.6	0.9	6.5	326		
14	Mar. 14, 2002	8	369	233	63	18	5	3.3	0.9	6.5	44		
15	Mar. 22, 2002	8	218	174	80	8	4	2.6	1.2	7.3	32		
16	Mar. 30, 2002	8	258	198	77	10	4	2.5	1.0	7.2	43		
17	Apr. 08, 2002	10	257	202	79	9	3	2.3	0.9	6.9	32		
18	May. 08, 2002	50	118	98	83	5	4	1.2	1.0	6.3	8		
19	Jun. 29, 2002	54	0	0	83	0	4	0.0	1.0	6.3	-		
20	Aug. 22, 2002	55	0	0	83	0	4	0.0	1.0	6.3	-		
21	Sep. 29, 2002	20	0	0	83	0	4	0.0	1.0	6.3	-		
Annualised values			188	146	78	17	9	2.3	1.2	6.2	62		
Annual flux			69 g m⁻² y⁻¹	53 g m⁻² y⁻¹		6 g m⁻² y⁻¹		0.9 g m⁻² y⁻¹			23 10⁹ valves m⁻² y⁻¹		

Table 1

2000 m	Total Mass Flux	BSiO ₂	CaCO ₃	POC
Total Mass Flux	-			
BSiO ₂	0.99	-		
CaCO ₃	0.37	0.30	-	
POC	0.86	0.83	0.24	-

3700 m	Total Mass Flux	BSiO ₂	CaCO ₃	POC
Total Mass Flux	-			
BSiO ₂	0.99	-		
CaCO ₃	0.61	0.54	-	
POC	0.87	0.83	0.63	-

Table 2

Table(s) Click here to download Table(s): Table 3.eps	2000m		3700 m
	Average 309 days	Average 172 days	Average 172 days
<i>Actinocyclus</i> spp.	0.01	0.01	0.03
<i>Actinocyclus actinochilus</i> (Ehrenberg) Simonsen	0.02	0.01	0.00
<i>Asteromphalus hookeri</i> Ehrenberg	0.17	0.20	0.48
<i>A. hyalinus</i> Karsten	0.16	0.26	0.29
<i>A. parvulus</i> Karsten	0.19	0.32	0.35
<i>Asteromphalus</i> spp.	0.01	0.01	0.01
<i>Azpeitia tabularis</i> (Grunow) Fryxell et Sims	0.68	0.57	0.74
<i>Chaetoceros aequatorialis</i> var. <i>antarcticus</i> Manguin	0.02	0.03	0.06
<i>Ch. atlanticus</i> Cleve	0.16	0.29	0.37
<i>Ch. dichchaeta</i> Ehrenberg	0.11	0.19	0.16
<i>Ch. peruvianus</i> Brightwell	0.00	0.00	0.01
<i>Chaetoceros</i> sp. A	0.08	0.14	0.11
<i>Chaetoceros</i> sp. B	0.07	0.13	0.19
<i>Chaetoceros</i> spp.	0.15	0.27	0.32
<i>Chaetoceros</i> Hyalochaete resting spores	0.14	0.25	0.14
<i>Corethron</i> spp.	0.01	0.01	0.00
<i>Dactyliosolen antarcticus</i> Castracane			
<i>Eucampia antarctica</i> (Castracane) Mangin	0.13	0.14	0.20
<i>Fragilariopsis curta</i> (Van Heurck) Hustedt	0.57	1.00	1.11
<i>F. cylindrus</i> (Grunow) Krieger	0.16	0.29	0.10
<i>F. kerguelensis</i> (O'Meara) Hustedt	79.91	72.41	68.34
<i>F. obliquecostata</i> (van Heurck) Heiden	0.02	0.03	0.05
<i>F. pseudonana</i> (Hasle) Hasle	2.03	3.64	1.43
<i>F. rhombica</i> (O'Meara) Hustedt	0.93	1.58	2.13
<i>F. ritscheri</i> Hustedt	0.07	0.13	0.11
<i>F. separanda</i> Hustedt	2.10	2.85	2.03
<i>F. cf. sublineata</i> (Van Heurck) Heiden	0.03	0.04	0.03
<i>Haslea trompii</i> (Cleve) Simonsen	0.01	0.01	0.02
<i>Navicula directa</i> (Smith) Ralfs in Pritchard	0.33	0.58	1.06
<i>N. sicula</i> var. <i>bicuneata</i> (Castracane) Grunow	0.06	0.10	0.14
<i>Pleurosigma directum</i> Grunow in Van Heurck	0.02	0.03	0.03
<i>Pseudo-nitzschia</i> < 3 µm transapical axis	0.40	0.72	1.41
<i>P-n. heimii</i> Manguin	0.01	0.02	0.02
<i>Pseudo-nitzschia</i> spp.	0.11	0.19	0.08
<i>Porosira pseudodenticulata</i> (Hustedt) Jousé	0.02	0.03	0.03
<i>Proboscia</i> spp.	0.00	0.00	0.01
<i>Rhizosolenia antennata</i> (Ehrenberg) Brown f. <i>semispina</i> Sundström	0.00	0.00	0.02
<i>Rhizosolenia bergonii</i> Peragallo	0.00	0.00	0.02
<i>Rhizosolenia</i> sp. f. 1A (Armand et Zielinski)	0.01	0.01	0.02
<i>Rhizosolenia</i> spp.	0.09	0.07	0.02
<i>Thalassionema nitzschioides</i> f. <i>capitulata</i> (Castracane) Moreno-Ruiz	0.06	0.09	0.11
<i>T. nitzschioides</i> f. <i>lanceolata</i> (Grunow) Pergallo et Pergallo	0.05	0.02	0.02
<i>Stellarima stellaris</i> (Roper) Hasle et Sims	0.00	0.00	0.02
<i>Thalassiosira gravida</i> Cleve	0.03	0.05	0.11
<i>T. gracilis</i> var. <i>gracilis</i> (Karsten) Hustedt	3.65	6.08	7.41
<i>T. gracilis</i> var. <i>expecta</i> (Van Landingham) Fryxell et Hasle	0.42	0.65	1.30
<i>T. lentiginosa</i> (Janisch) Fryxell	4.97	4.63	6.77
<i>T. maculata</i> Fryxell et Johansen	0.05	0.02	0.02
<i>T. oestrupii</i> (Ostenfeld) Hasle	0.01	0.02	0.01
<i>T. oliveriana</i> (O'Meara) Makarova et Nikolaev	0.67	0.37	0.42
<i>T. tumida</i> (Janisch) Hasle	0.12	0.07	0.10
<i>T. leptopus</i> (Grunow ex Van Heurck) Hasle et G.Fryxell	0.01	0.01	0.54
<i>T. lineata</i> Jousé	0.11	0.14	0.36
<i>Thalassiosira</i> spp. < 20 µm	0.37	0.62	0.29
<i>Thalassiosira</i> spp. > 20 µm	0.04	0.05	0.00
<i>Thalassiosira</i> sp. A	0.18	0.22	0.01
<i>Thalassiosira</i> sp. B	0.02	0.03	0.08
<i>Thalassiothrix antarctica</i> Schimper ex Karsten	0.20	0.18	0.58
<i>Tropidoneis</i> group	0.04	0.05	0.12
Other centrics	0.07	0.07	0.02
Other pennates	0.01	0.01	0.01

Table 3

Figure(s)
Click here to download Figure(s): Fig. 1. Black and white.eps

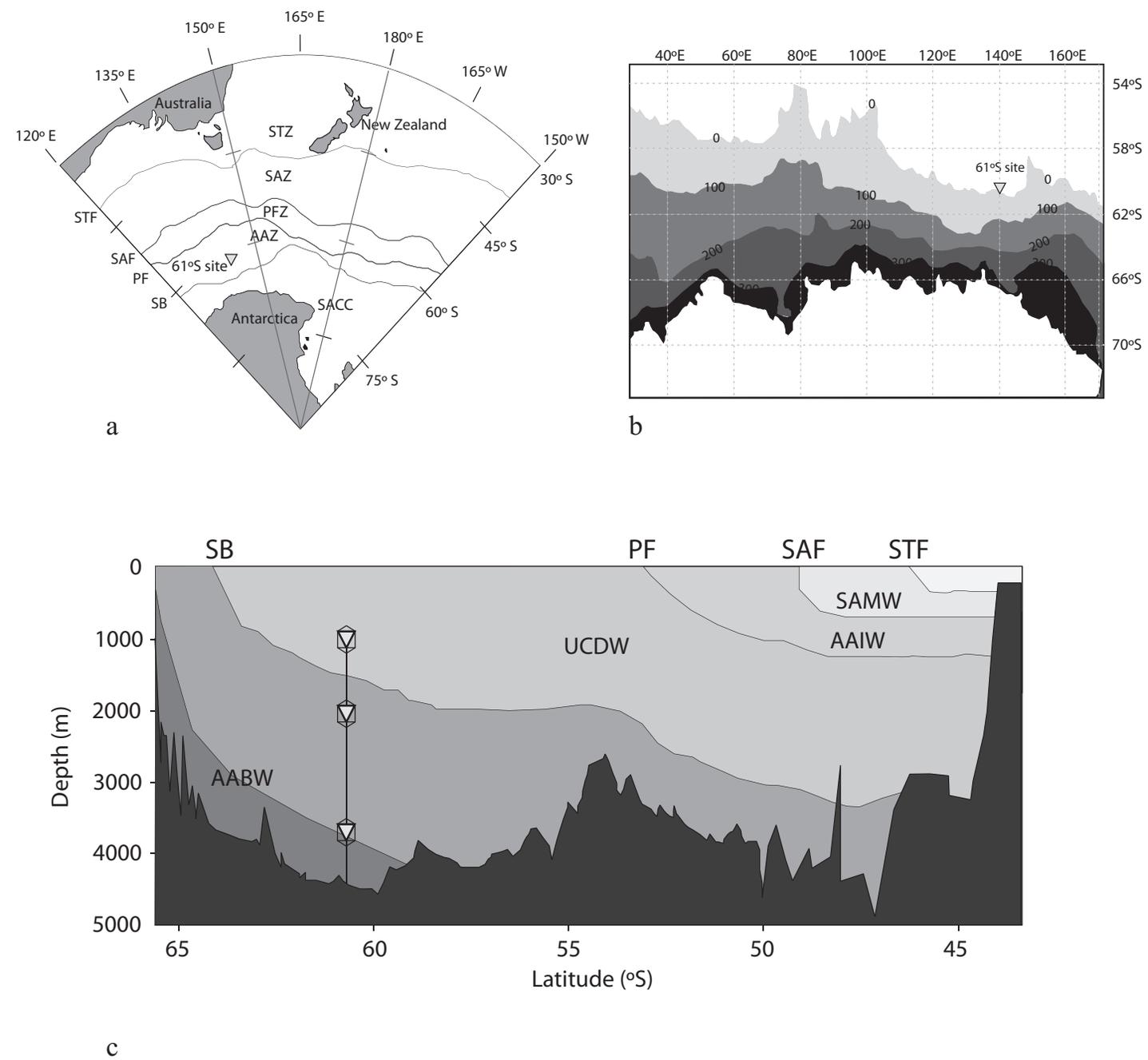


Figure 1

Figure(s)
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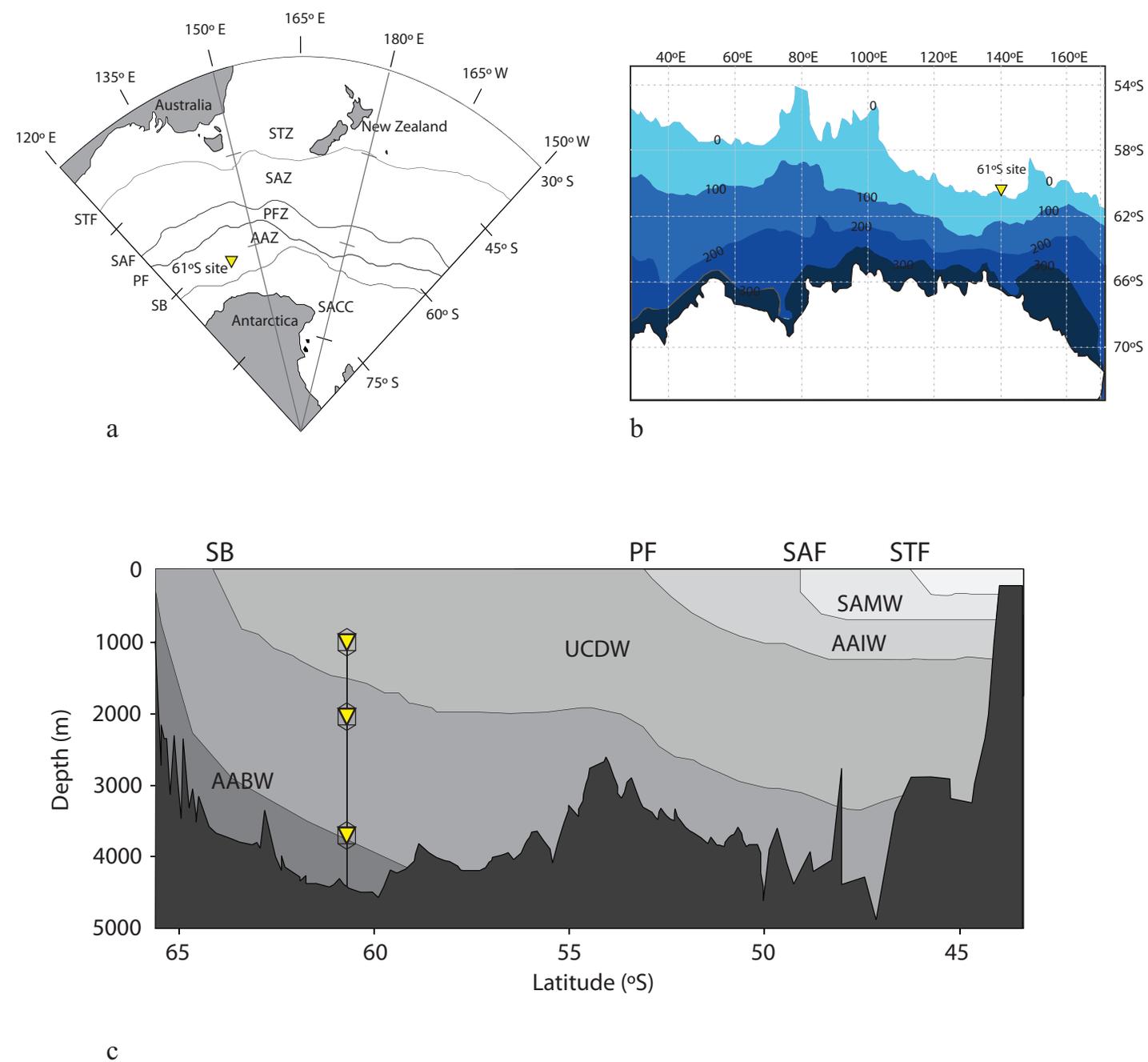


Figure 1

Figure(s)

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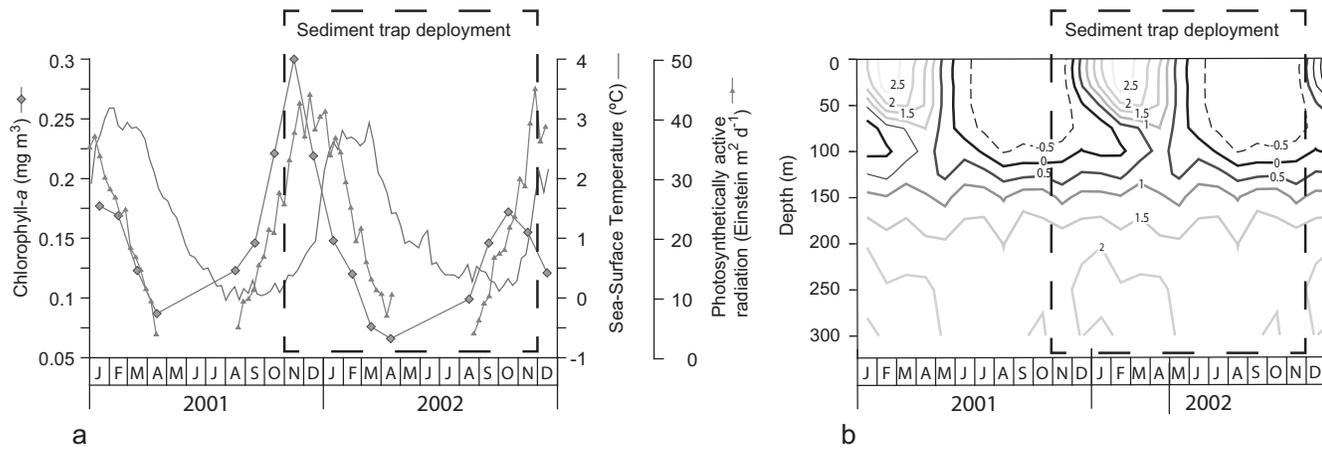


Figure 2

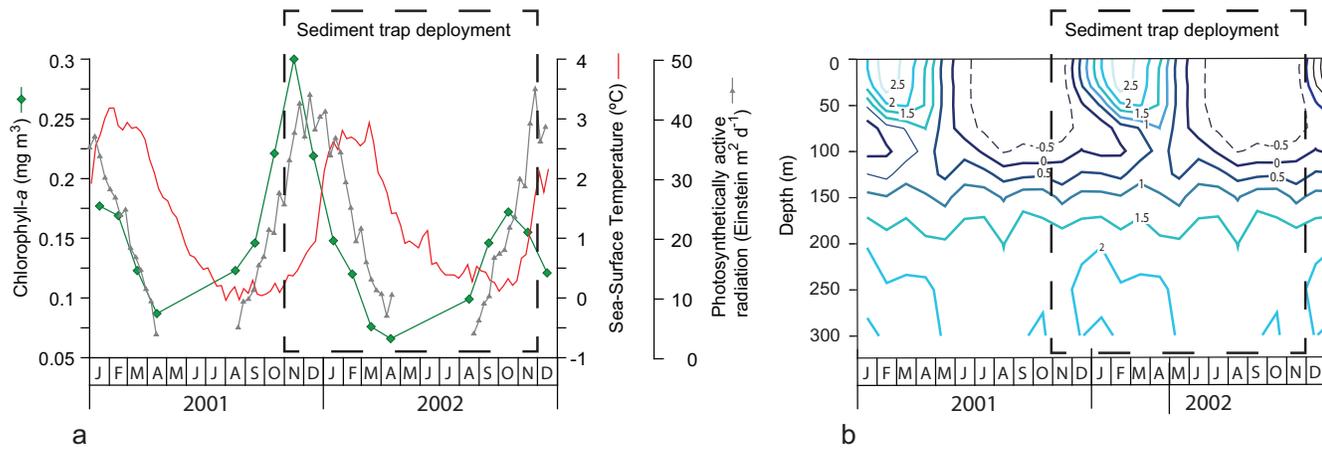


Figure 2

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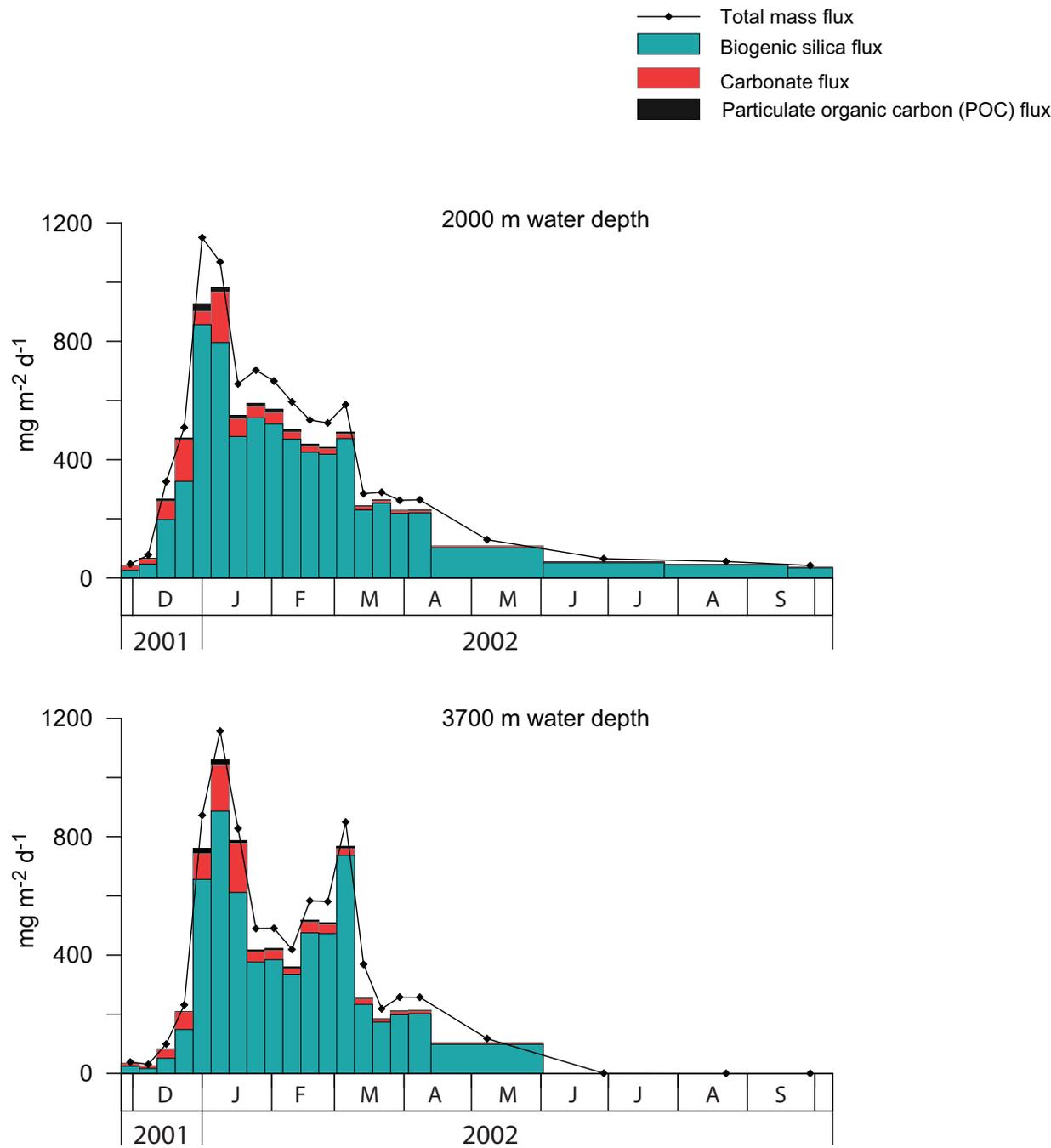


Figure 3

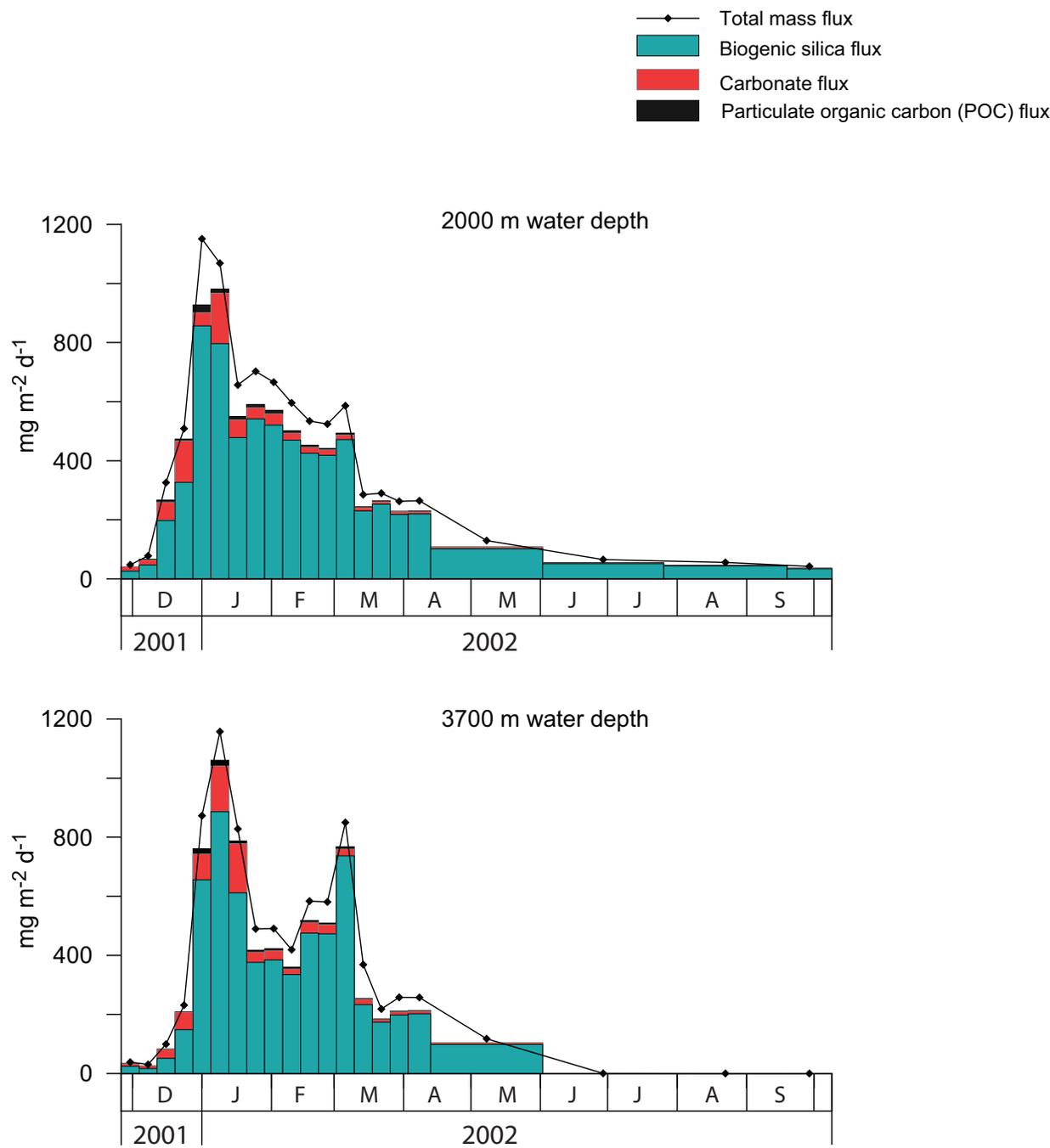


Figure 3

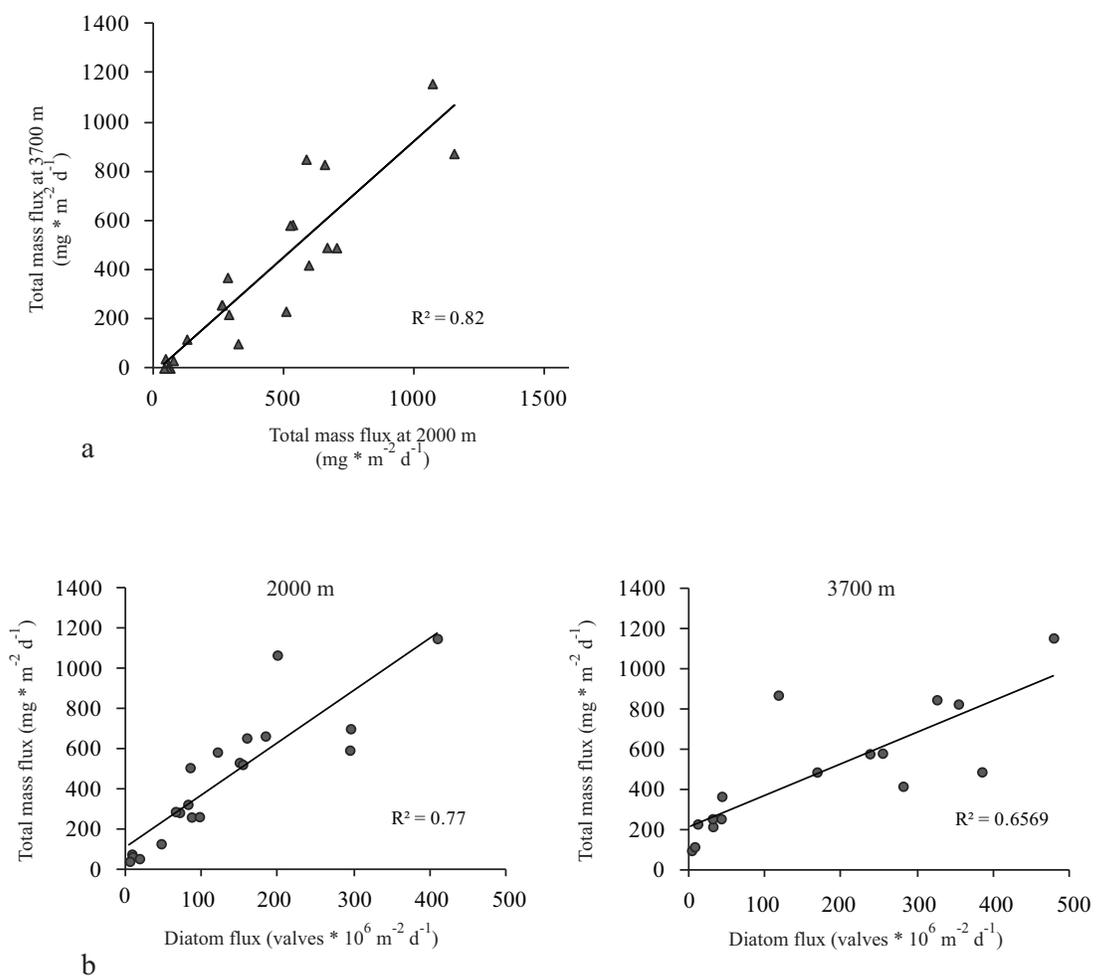
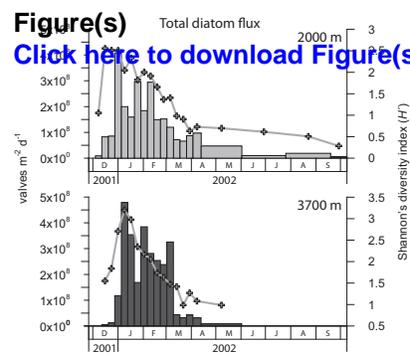
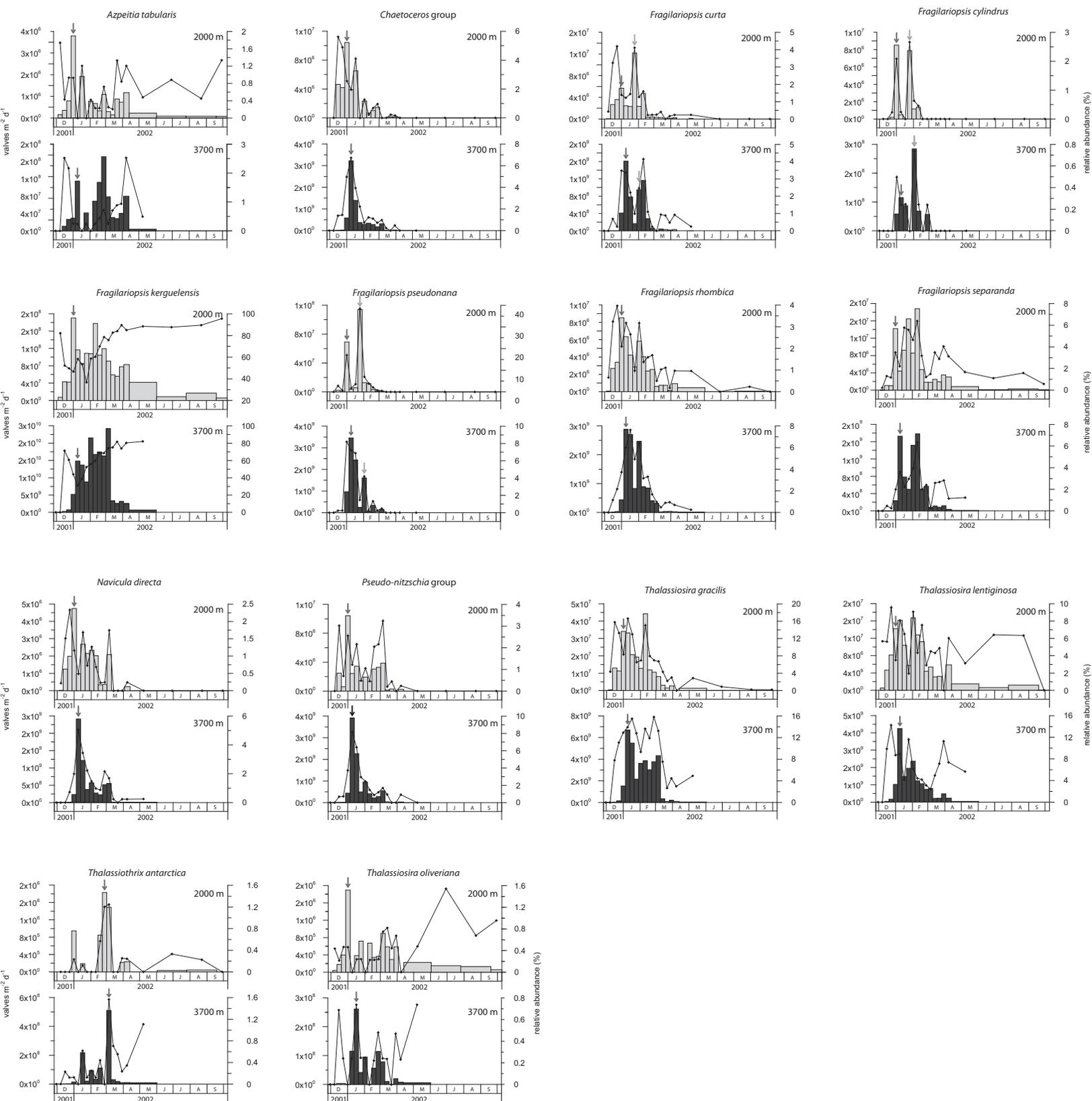


Figure 4

Figure(s)
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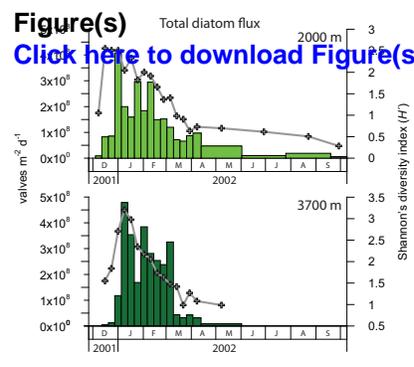


a

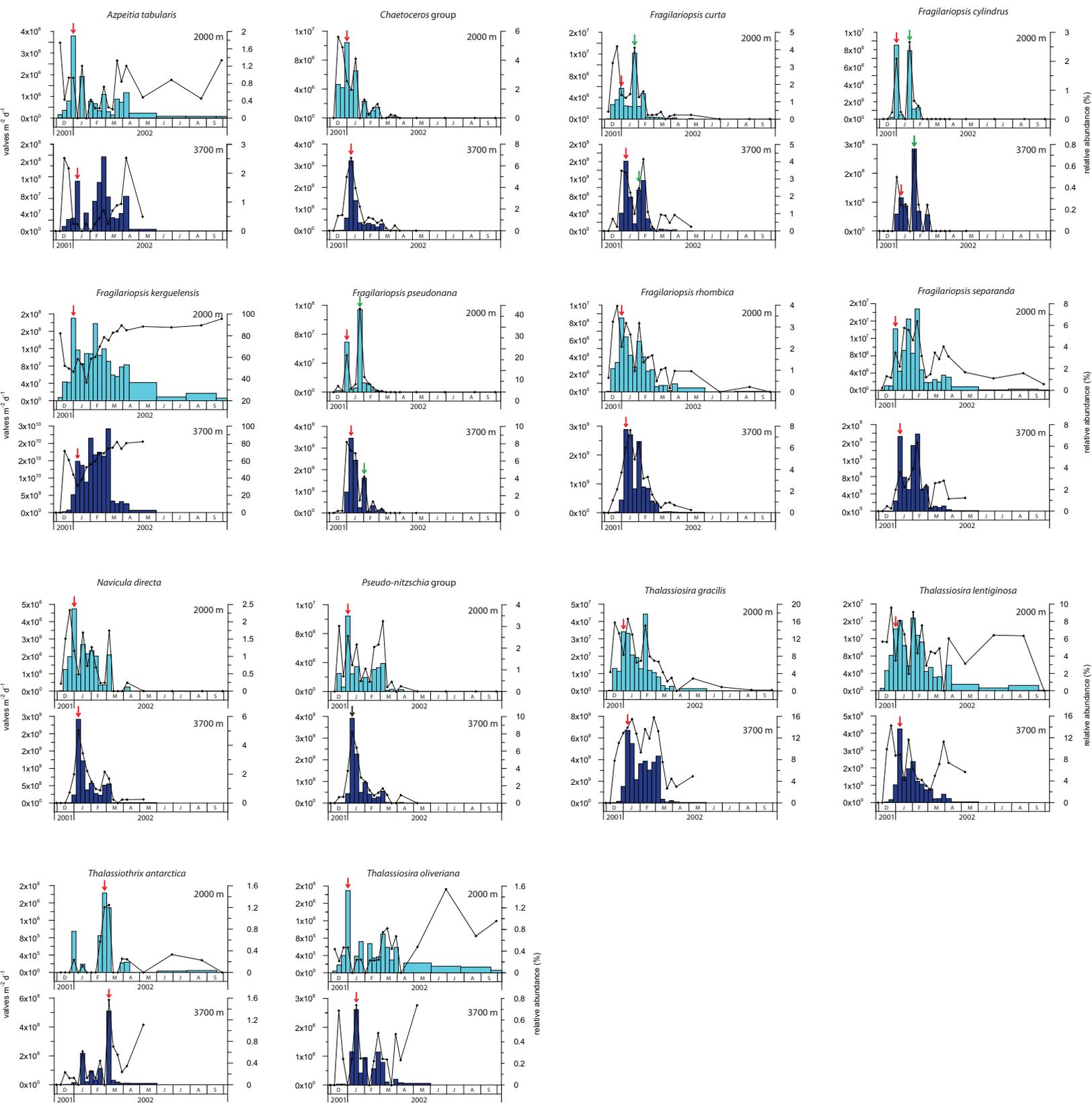


b

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a



b

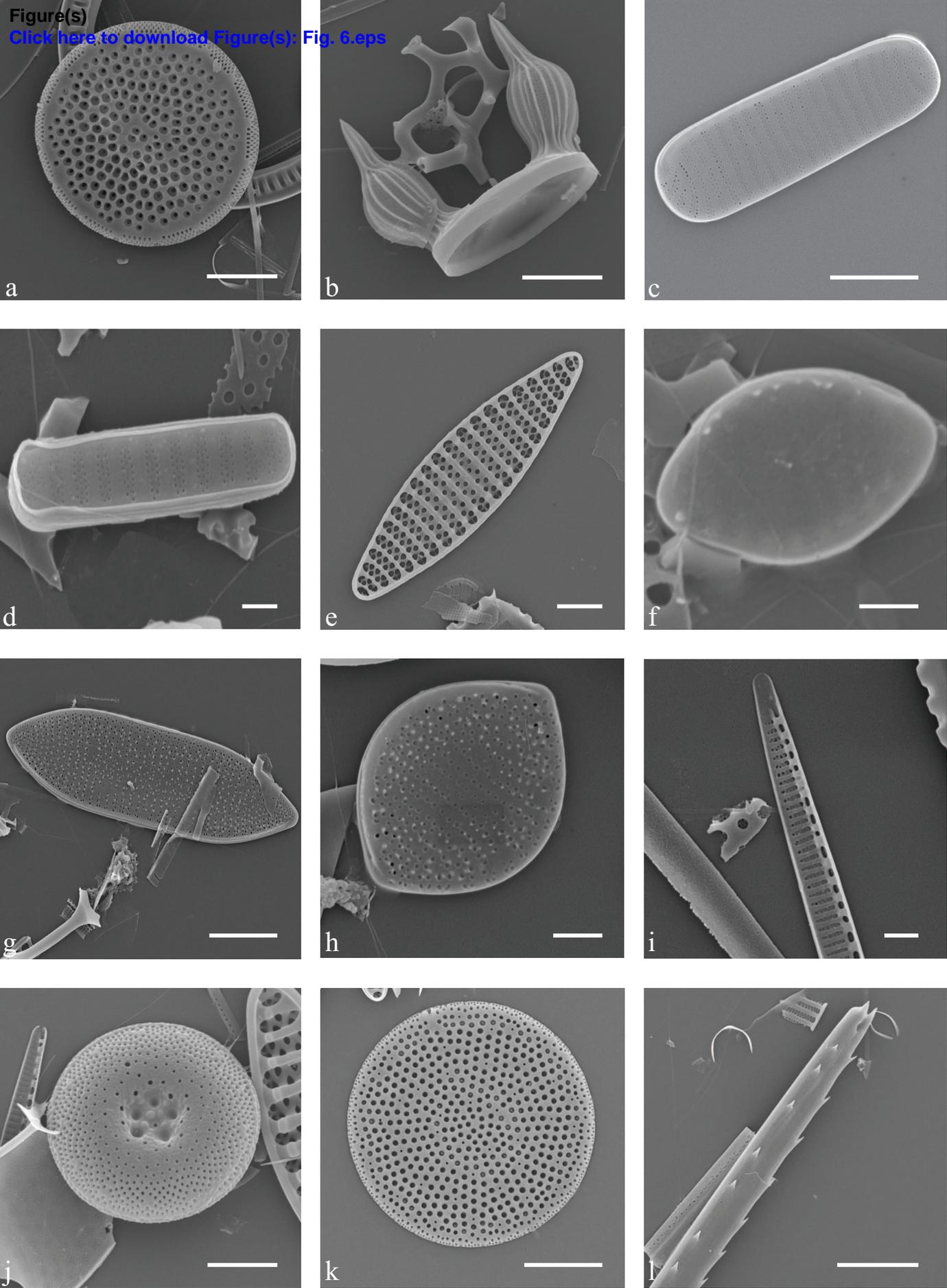


Figure 6