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5 **Water column organic carbon in a Pacific marginal sea (Strait of Georgia, Canada)**

6

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18 **Abstract**

19 Marginal seas provide a globally important interface between land and interior ocean
20 where organic carbon is metabolized, buried or exported. The trophic status of these seas
21 varies seasonally, depending on river flow, primary production, the proportion of
22 dissolved to particulate organic carbon and other factors. In the Strait of Georgia, about
23 80% of the organic carbon in the water column is dissolved. Organic carbon enters at the
24 surface, with river discharge and primary production, particularly during spring and
25 summer. The amount of organic carbon passing through the Strait ($\sim 16 \times 10^8$ kg C/yr) is
26 almost twice the standing inventory ($\sim 9.4 \times 10^8$ kg C). The organic carbon that is
27 oxidized within the Strait ($\sim 5.6 \times 10^8$ kg/yr) presumably supports microbial food webs or
28 participates in chemical or photochemical reactions, while that which is exported ($7.2 \times$
29 10^8 kg/yr) represents a local source of organic carbon to the open ocean.

30

31

32

33 DOC, POC, organic carbon cycling, water column, Strait of Georgia

34 **1. Introduction**

35 Organic carbon enters the coastal ocean by in situ primary production and with river
36 discharge. As emphasized by Liu et al. (2000), shelf seas are not passive receptors of this
37 organic carbon but rather provide a globally important interface between land and interior
38 ocean where organic carbon is metabolized, buried or exported. Metabolism of organic
39 carbon in coastal waters provides a globally significant source of carbon dioxide (Smith
40 and Hollibaugh, 1993), although marginal seas of the North Pacific generally export
41 organic carbon (Chen *et al.*, 2004). Whether a marginal sea is a net source or net sink of
42 CO₂ varies seasonally, depending on the strength of primary production and river inflow,
43 whose effects are particularly pronounced near shore.

44

45 A large part of the fixed carbon is suspended in water as dissolved organic carbon
46 (DOC), much of which is readily transformed back to carbon dioxide by microbial
47 respiration and photochemical oxidation. In the global ocean, the inventory of DOC (680
48 Gt) far outweighs particulate organic carbon (POC; 20 Gt) or biota (3 Gt), and a long-
49 standing puzzle is how a large component of DOC manages to persist for years and even
50 millennia in the ocean (Eglinton and Repeta, 2003). Accordingly, the fate of the reactive
51 pool of DOC helps to determine the ability of the biological pump to sequester organic
52 carbon on time scales ranging from days to thousands of years. In addition to their role in
53 the global carbon cycle, POC and DOC can affect the oceanic transport of contaminants,
54 many of which have a strong affinity for organic matter (e.g. Brannon *et al.*, 1993;
55 Chevreuil *et al.*, 1987), and can mediate their reactions (Blough and Sulzberger, 2003).

56 In some coastal areas, organic carbon can itself be the most important contaminant
57 (Turner et al., 2008).

58

59 The Strait of Georgia (Fig. 1) is a highly productive marginal sea on the west coast of
60 Canada. Its physical and biological oceanography have been studied extensively (see
61 reviews by Waldichuk, 1957; Thomson, 1981; Harrison et al., 1983; LeBlond, 1983;
62 Harrison et al., 1994; Macdonald and Crecelius, 1994; Thomson, 1994), although little
63 attention has been paid to chemical and geochemical processes, especially in the water
64 column. Estuarine circulation in the Strait of Georgia is driven largely by the discharge
65 of the Fraser River, which supplies about 65% of the fresh water to the Strait (e.g.
66 LeBlond et al., 1983). The Strait is open at both ends, exchanging with the Pacific Ocean
67 through Johnstone Strait in the north and through the much larger Juan de Fuca Strait, via
68 Haro Strait, in the south. Strong tidal currents in Haro Strait cause intense tidal mixing in
69 that area (e.g. LeBlond, 1983). The trophic status of the Strait of Georgia system remains
70 uncertain, although preliminary budgets for particulate and dissolved organic carbon
71 suggest that, unlike the other temperate Pacific marginal seas, the Strait likely provides a
72 small net source for CO₂ (Johannessen *et al.*, 2003). The data on which the seawater
73 component of these budgets was based were sparse, illustrating the need for more
74 measurements of organic carbon, particularly of DOC, which appeared to be sufficiently
75 important to control whether the system was a net sink or a net source of CO₂. Here, we
76 describe the spatial and seasonal variability of organic carbon in the water column of the
77 Strait of Georgia and discuss controls on its distribution. This overview will help to
78 focus future, hypothesis-driven research into local carbon dynamics.

79

80 **2. Methods**81 *2.1 Sample collection and in situ measurements*

82 In April, June, September and December, 2003, water samples for DOC and TOC
83 analysis were collected along a cruise track from the mouth of Juan de Fuca Strait to the
84 northern Strait of Georgia (Figs. 1 and 2) aboard the *CCGS Vector*. These samples form
85 part of a larger data set that has been collected quarterly since 1999. The full data set
86 includes conductivity / temperature / depth (CTD), fluorescence, photosynthetically
87 active radiation (PAR), and transmissivity profiles as well as nutrient and oxygen
88 measurements made on discrete water samples. The electronic measurements were made
89 at 76 stations (Fig. 1), including the 20 stations where bottle samples were collected.
90 Some of the accompanying physical and chemical data have been analyzed and published
91 elsewhere (Johannessen *et al.*, 2006; Masson, 2006).

92

93 Water samples for DOC and TOC analysis were collected at depths of 0, 20, 75 and 150
94 m (depth permitting) and at the bottom of each cast (1- 5 m off the bottom), with
95 occasional replicates, for a total of 472 samples collected during the four cruises. TOC
96 samples were collected from the Niskin bottle spigots directly into acid-washed, 40 mL
97 glass vials with EPA septa, after three rinses with the sample seawater. DOC samples
98 were gravity-filtered into the same type of vial through a 0.2 μm , Millipore, Opticap
99 cartridge filter attached to the rosette spigot with a short length (~10 cm) of acid-washed
100 Teflon tubing. Before each cruise, a new Opticap filter was flushed with 3 L of milli-Q
101 water. Preliminary experiments had shown that flushing a new filter with 2 L of milli-Q

102 water was sufficient to prevent contamination of the samples by the filter. Before
103 sampling began at each station, the filter was rinsed with 1 L of seawater from the Niskin
104 bottle collected at the greatest depth at that station. The filter and tubing were emptied
105 after each sample was filtered and then flushed with 250 mL of each sample before any
106 of the filtrate was collected. Samples were frozen immediately after collection and stored
107 frozen until analysis. Nitrile gloves were worn at all times during sample collection and
108 analysis. The concentrations of DOC and TOC were measured by high temperature
109 combustion in an Apollo 9000 TOC analyzer set to 700°C and calibrated with standard
110 additions of potassium hydrogen phthalate (KHP) to filtered open ocean seawater, with a
111 precision of 0.2 µM (average standard deviation of replicates analysed from the same
112 vial.) The concentration of POC was calculated as the difference between TOC and
113 DOC. The standard deviation of DOC and TOC samples collected in 7-12 separate vials
114 from the same Niskin bottle during each cruise was 1-4 µM and 3-7 µM, respectively.
115 By propagation of errors, the standard deviation of POC values was 4-8 µM.

116

117 Transmissivity at 660 nm was measured using a Sea Tech transmissometer attached to the
118 bottom of the frame of the sampling rosette, beside the CTD. Transmissivity was
119 converted to the beam attenuation coefficient, c , according to the equation

120

$$121 \quad -c = \frac{1}{r} \ln\left(\frac{tr}{100\%}\right)$$

122

123 where r is the pathlength (m) and tr (%) is the percent transmission over that pathlength
124 (Baker and Lavelle, 1984). Chlorophyll a fluorescence was measured with a Seapoint

125 fluorometer also mounted on the frame of the rosette (excitation wavelength 470 nm,
126 emission 685 nm).

127

128 Dissolved oxygen was measured by Winkler titration aboard the ship, using an automated
129 Dosimat system, and nutrient samples were stored frozen until their analysis on return to
130 the laboratory, according the protocol established by Barwell-Clark and Whitney (1996).

131

132 *2.2 Calculation of inventories and fluxes*

133 We calculated surface layer and deep layer organic carbon inventories at each station.

134 We defined the break between upper and lower layers as the top of the deep, relatively

135 uniform layer, as determined by visual inspection of the salinity profiles. The Strait of

136 Georgia does not display a classical density profile with a well defined upper mixed layer

137 and a pycnocline overlying a deep mixed layer (Masson and Peña, 2008). The upper

138 layer comprises a series of interfingered layers of water, and in some places the density

139 decreases all the way to the surface, without any apparently well-mixed surface layer.

140 Consequently, choosing the top of the deep layer was the most consistent way to divide

141 the water column throughout the study area. This depth also usually coincided with a

142 sharp decrease in the concentrations of DOC and TOC between the upper and lower

143 layers (shown in section 3.1 below). We assigned the organic carbon concentration

144 measurements for each station to a small area of the surrounding basin (Fig. 1) and

145 calculated the volume of water that that area represented, using a 1 km by 1 km depth

146 grid (Table 1). The inventories for the upper and lower layers and for the whole water

147 column in each area were calculated as the product of the water volume and the average

148 concentration of TOC (or DOC or POC) in that section. Seasonal inventories for the
149 northern and southern Strait of Georgia, Haro Strait and Juan de Fuca Strait were
150 calculated by summing the inventories at all the stations included in the larger zones.

151

152 The fluxes of TOC, POC and DOC through Juan de Fuca Strait were calculated as the
153 product of their average surface (or deep) concentrations and the average annual outflow
154 (inflow). The inflow and outflow were taken from a salt balance calculation made by
155 Johannessen et al. (2003) and on previously published current measurements in Juan de
156 Fuca Strait (Godin et al., 1981).

157

158

159 **3. Results**

160 *3.1 Distribution of organic carbon*

161 Most of the organic carbon in the water column of the Strait of Georgia, Haro Strait and
162 Juan de Fuca Strait is dissolved. Except at the surface and in the deep, northern Strait of
163 Georgia in April and June, DOC makes up at least 80% of the total ($\text{POC}/\text{DOC} \leq 0.25$).
164 This ratio is similar to that observed in the East China Sea, where $\text{POC}/\text{DOC} = 0.1$ (Gao
165 and Song, 2006), but POC is more important in this nearshore region than in the global
166 ocean, where $\text{POC}/\text{DOC} \sim 0.03$ (Eglinton and Repeta, 2003). A similarly high
167 POC/DOC ratio was observed off the Oregon coast, to the south of the study area
168 ($\text{POC}/\text{DOC} \sim 0.3$; Hill and Wheeler, 2002). The dissolved and particulate organic carbon
169 are not significantly correlated to one another in any of the seasons ($r^2 \leq 0.2$), probably
170 indicating that different mechanisms control their distributions.

171

172 In all four seasons, the concentration of dissolved organic carbon was highest at the
173 surface, particularly in the central and southern Strait of Georgia, and lowest in the
174 subsurface seawater flowing in through Juan de Fuca Strait (Fig. 3, Table 3). The
175 concentration of DOC was inversely related to salinity (Fig. 4a), as similarly observed
176 along a transect perpendicular to the Catalan coast in the Mediterranean Sea (Doval *et al.*,
177 1999), positively related to oxygen and inversely related to nutrients (Figs. 4b, 4c).

178

179 The variation in POC through the year differs from that of DOC. Like DOC, POC was
180 highest in surface water in April and June, but in September and December it was
181 generally low throughout the study area, with only small, local maxima, possibly related
182 to particle sinking or resuspension (Fig. 5, Table 3). There was also a relatively high
183 concentration of POC in the deep water of the northern Strait of Georgia in April and
184 June. The extremely high POC concentration indicated at mid-depth in the far northern
185 Strait of Georgia in June is based on only one measurement, so we cannot be certain of
186 exactly what it represents. However, the high concentration in nearby bottom waters is
187 based on multiple measurements. While the wintertime concentration of DOC in the
188 deep, uniform layer was higher than that in the summer and spring, there was essentially
189 no POC in the study area in December.

190

191 3.2 Inventories and fluxes

192 The water column inventory of TOC in the Strait of Georgia did not vary much with
193 season (average seasonal concentrations in Table 3 multiplied by water volume in Table

194 2) and was generally about 9.5×10^8 kg C ($9.1 \times 10^8 - 9.8 \times 10^8$ kg C). Over the surface
195 area of the Strait of Georgia considered here (7464 km^2 , see Methods) the inventory
196 implies an average of 130 g C m^{-2} , with the highest value occurring in December.
197 However, the distribution of TOC among surface and deep layers, the northern and
198 southern Strait, and particulate and dissolved forms, did vary considerably (Fig. 6, Table
199 4). The proportion of the TOC held in the surface layer varied depending both on the
200 concentration of organic carbon and on the depth of the surface layer.
201
202 The inventory of organic carbon held in the water column of the Strait of Georgia is low,
203 relative to the fluxes into the Strait. The annual net primary production in the Strait is
204 estimated at $90 - 120 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Mackas and Harrison, 1997).. Extrapolating that water
205 column primary production rate to the surface area of the Strait of Georgia considered in
206 this study (7464 km^2), the annual net primary production is $6.7 \times 10^8 - 9.0 \times 10^8$ kg C
207 (Table 1). The Fraser and other rivers add an additional 7.5×10^8 kg organic C annually,
208 and anthropogenic sources add up to 1.2×10^8 kg C (Johannessen *et al.*, 2003). Thus, the
209 total sources of TOC to the Strait are approximately $15 \times 10^8 - 18 \times 10^8$ kg C yr^{-1} , about
210 twice the inventory measured year-round. The sinks are burial in the sediments ($4.3 \times$
211 10^8 kg C yr^{-1} , Johannessen *et al.*, 2003) advection through Juan de Fuca Strait (and
212 possibly Johnstone Strait) (7.2×10^8 kg C yr^{-1} , this study, see Methods), and oxidation.
213 Burial and advection come to 11×10^8 kg C yr^{-1} . By difference, this leaves $4.0 \times 10^8 -$
214 6.2×10^8 kg C yr^{-1} , about half of the inventory, to be oxidized in the Strait of Georgia and
215 its sediments each year. The preliminary carbon budget constructed by Johannessen *et al.*
216 (2003), indicated that about 0.9×10^8 kg C/yr was oxidized in sediments. Using this

217 sediment oxidation value, about $3.1 \times 10^8 - 5.3 \times 10^8$ kg of organic carbon is oxidized in
218 the water column each year. About 1.1×10^8 kg C/yr POC is exported through Juan de
219 Fuca Strait.

220

221 The area-weighted inventory of organic carbon was lower in Haro and Juan de Fuca
222 Straits than in the Strait of Georgia and was relatively stable year-round in Juan de Fuca
223 Strait, ranging from 76 ± 3 kg C m⁻² in June to 88 ± 2 kg C m⁻² in April (Fig. 6). The
224 seasonal variation in the carbon that was held in the surface layer was due principally to
225 changes in the depth of that layer throughout the year (Fig. 6). In Haro Strait the water
226 column inventory of TOC varied from 37 g C m⁻² in June to about double that in April.

227

228

229 **4. Discussion**

230 The correlations shown in Figure 4 are consistent with both algal and terrigenous sources
231 of DOC to the Strait of Georgia. Phytoplankton release DOC in the daytime as they grow
232 (e.g. Maranon et al., 2004; 2005). During an estuarine phytoplankton bloom, Gobler and
233 Sanudo-Wilhelmy (2003) measured production rates of POC and DOC that were nearly
234 equivalent to one another. In the Strait of Georgia the growth rate of *Chaetoceros* and
235 other algae is greatest during the late spring bloom (e.g. Harrison *et al.*, 1991). However,
236 we cannot use timing alone to apportion sources of organic carbon as either terrigenous
237 or marine.

238

239 Terrigenous DOC discharged by the Fraser and other rivers also enters the Strait of
240 Georgia at the surface, where the concentration of oxygen is high and those of the
241 nutrients are low. Of course, some of the DOC carried by the river is undoubtedly
242 produced by algae in the river. Unlike the situation in some Arctic rivers, where the
243 DOC is highest during the spring freshet (Rember and Trefry, 2004), DOC in the Fraser
244 River usually peaks in the late spring, about two months before the peak water discharge
245 (Fig. 7). It is not possible from the data collected for this study to discriminate among the
246 three sources of DOC (terrigenous, riverine algal, marine algal). Future work could use
247 stable isotopes of carbon and nitrogen, ^{14}C radiodating, degree of aromaticity or
248 biomarkers to investigate the distribution and fate of DOC from the three sources. For
249 example, in the Mississippi River estuary, $\delta^{13}\text{C}$ measurements indicated that most of the
250 terrigenous DOC was removed from the water column in the salt – fresh water mixing
251 zone (salinity ~ 25 , Wang *et al.*, 2004). Also, in the Mid-Atlantic Bight, rivers have been
252 shown to export new, high- ^{14}C DOC to the coastal ocean (Mortazavi and Chanton, 2004).
253

254 The distribution of POC was not tied directly to that of total suspended particles. Using
255 data collected during 2000–2003, Johannessen *et al.* (2006) showed that the beam
256 attenuation coefficient (c), a proxy for suspended particle concentration, was relatively
257 high throughout Haro and Juan de Fuca Straits in the winter, while the POC was low
258 there at that time (Fig.5). There was no significant relationship between POC and c for
259 most of the year and only a weak one ($r^2=0.5$) in April, indicating that the organic content
260 of particles varies in time and space. The distinction between particulate and dissolved
261 organic carbon is operational - for this project organic carbon that passed through a 0.2

262 μm filter was considered dissolved – so the lack of a correlation between POC and c is
263 not surprising. However, the ratio of POC to c describes in a relative way how much of
264 the particulate matter is organic. The ratio is low throughout the year in Juan de Fuca and
265 Haro Straits (Fig. 8), implying that most of the suspended particles in that area are
266 inorganic. This could reflect their source or that all the available organic matter had been
267 consumed or broken down into DOC by the time the particles had reached that area. In
268 the Strait of Georgia POC/ c is high at the surface in April, June and September (Fig. 8),
269 indicating a high proportion of organic particles near the surface. This is consistent with
270 primary production in the surface layer. Near-surface particulate organic matter is likely
271 largely consumed, oxidized or broken down into DOC within the Strait, consistent with
272 previous observations of the rapid consumption of organic carbon after a phytoplankton
273 bloom (Gobler and Sanudo-Wilhelmy, 2003).

274
275 Because of the estuarine nature of its circulation and the presence of several sills, the
276 Strait of Georgia does not export POC to the open ocean along the bottom, as occurs in
277 some other Pacific marginal seas (e.g. Chen *et al.*, 2004). Rather, POC in bottom waters
278 is predominantly buried in the Strait itself (Johannessen *et al.*, 2003), although some may
279 be broken down to DOC and then consumed by bacteria, as occurs in the deep Pacific
280 Ocean (Hansell and Ducklow, 2006). The observation in this study that POC is exported
281 in surface water through Juan de Fuca Strait contrasts with Johannessen *et al.*'s (2003)
282 conclusion that it was not. The discrepancy probably results in part from the in situ
283 production of POC in the surface waters of Juan de Fuca Strait that is of necessity
284 included in the exchange estimate made in this paper but which was excluded from the

285 2003 work. However, in situ production is unlikely to account for the whole calculated
286 export. There is no estimate of net primary productivity available for Juan de Fuca Strait,
287 but the Strait of Georgia rate (90- 120 g C m⁻² yr⁻¹; Harrison et al., 1983) applied to Juan
288 de Fuca implies a net annual production of $2.0 \times 10^8 - 2.6 \times 10^8$ kg C, or about a third of
289 the estimated export. Possibly much of the export occurs on very small particles that did
290 not contribute much to the total sediment budget. Some of the POC also sinks to the
291 bottom in the northern Strait, particularly in April. This seasonal pulse of organic-rich
292 particles in late spring / early summer may explain the high concentration of organic
293 carbon observed in the bottom sediments of the northern Strait (3.5-5% Johannessen,
294 2003; $\leq 3.5\%$ Bornhold, 1978) relative to that measured in the southern Strait and Fraser
295 River ($\sim 1\%$ Johannessen, 2003). The isotopic composition ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$) of the organic
296 matter measured in a northern Strait sediment core implies the organic carbon to be
297 predominantly recycled material of algal origin (Macdonald et al., 2008), which is
298 consistent with the pulse of high-POC particles to the bottom observed in April, at the
299 end of the spring bloom season.

300

301 The correlation between DOC and salinity (Fig. 4a) suggests that about 70% of the
302 variation in DOC is related to conservative mixing. This does not imply that all of the
303 DOC is terrigenous; rather, both algally-derived and terrigenous DOC enter the system at
304 the surface and are associated with the fresher water. However, the scatter about the
305 regression line is not randomly distributed. DOC residuals calculated as the vertical
306 distance to the regression line in Figure 4a represent non-conservative variations in the
307 concentration of DOC, with higher values implying production of DOC in situ. The

308 residuals are generally lower in April and June (study area average -5.1 and -6.8 μM ,
309 respectively) than in September and December (average $+3.1$ and $+2.9$ μM). In the Strait
310 of Georgia, the residual DOC is high in the surface water in April and June and low in the
311 deep water at that time, while in September, it is closer to the value expected from mixing
312 alone (Fig. 9). By December, a pool of high-DOC water appears in the deep Strait of
313 Georgia. Overall in the study area, DOC is positively correlated with dissolved O_2 ,
314 because most of the time the two are produced or consumed together. However, in the
315 deep Strait of Georgia in the winter, the increase in DOC in the winter is accompanied by
316 a decrease in O_2 . Since the deep water of the Strait is renewed only a few times a year, in
317 the late spring and late summer (Masson, 2002; Pawlowicz *et al.*, 2007), it becomes
318 stagnant in the winter, and oxidation of organic matter uses up oxygen. For DOC to be
319 produced at the same time, it must be derived from the breakdown of POC. Since the
320 residuals represent the non-conservative portion of the variation in DOC, the winter
321 increase is not from the advection of DOC from outside the Strait. Indeed, the deep
322 ocean water that intrudes periodically into the Strait has a lower concentration of DOC
323 than that already in the Strait (Fig. 3). The POC that is broken down could derive from
324 algal material that sinks into the deep northern Strait in late spring, or from resuspended
325 bottom material. Similarly, the high DOC residual observed in Haro Strait / Victoria Sill
326 and extending into Juan de Fuca Strait in September and December might result from the
327 breakdown of POC resuspended from the bottom sediments during storms. The exact
328 source of the winter DOC cannot be determined from these data.
329

330 Summing the DOC residuals in the deep Strait of Georgia using the same procedure as
331 for the inventory calculation described in Section 3.2 and dividing the inventory by the
332 sea level surface area of the Strait as calculated for this work (7464 km²), gives a change
333 in the DOC residual inventory between June and December of about 15 g C m⁻² (Table
334 5). This represents about 5 % of the total annual primary production (Harrison *et al.*,
335 1983), so there is easily enough carbon entering the system annually to support this
336 ingrowth. The residual is also smaller than, but a significant portion of, the flux of
337 sinking organic carbon measured using sediment traps moored in the southern and central
338 Strait in 1996-1999 (31 – 365 g C m⁻² yr⁻¹, Johannessen *et al.*, 2005). If the observed
339 seasonal pattern is repeated annually, then there must be a mechanism to remove the
340 winter DOC from the Strait by the spring. Likely processes include oxidation,
341 flocculation and settling to the sediments, or advection as part of the annual replacement
342 of Strait of Georgia water, which occurs with a time scale of about 65 days, according to
343 a recent model (Pawlowicz *et al.*, 2007).

344

345 Quarterly measurements such as these cannot capture variability on daily, weekly or
346 monthly time scales, so the difference between the June and December measurements
347 represents a minimum change in residual inventory over that time period. The spatial
348 scale of sampling also misses patchiness on the scale of hundreds of meters or smaller,
349 but this is the first study to provide the requisite data to quantify the spatial and seasonal
350 variability of water column organic carbon in the Strait of Georgia, and to provide a
351 general depiction of the seasonal and spatial patterns.

352

353 Unfortunately, since we have organic carbon data for 2003 only, we cannot judge the
354 range of interannual variability in the observed patterns. A useful extension of this work
355 would be to characterize the source and age of the DOM in the Strait. Davis and Benner
356 (2007), for example, used carbon-normalized yields of amino acids to assign proportions
357 of labile, semi-labile and refractory organic matter to the DOC pool in the western Arctic
358 Ocean. They were able to discriminate terrigenous from marine-derived organic matter,
359 which would be helpful in understanding the observed seasonal variations in the
360 distribution of organic carbon in the Strait of Georgia.

361

362

363 **4. Conclusions**

364 Organic carbon enters the Strait of Georgia mainly at the surface, from a combination of
365 in situ primary production and river discharge. The seawater that flows in below the
366 surface of Juan de Fuca Strait and through Haro Strait into the Strait of Georgia brings
367 with it very little organic carbon. In the spring and summer, there is a relatively high
368 concentration of particulate organic carbon at the surface and throughout the water
369 column of the northern Strait, with a pulse of probably marine-derived organic particles
370 to the bottom associated with the spring bloom. However, most of the organic carbon in
371 the study area is dissolved, particularly in the autumn and winter, when more than 80% of
372 the TOC is dissolved.

373

374 The Strait of Georgia is dynamic with respect to organic carbon. About twice as much
375 organic carbon passes through the Strait each year as is present in the year-round water

376 column inventory, which implies sub-annual residence times for the carbon. Much of this
377 carbon is advected out of the Strait or buried in the bottom sediments, but an amount
378 equivalent to about half of the standing inventory is oxidized in the water column or
379 sediments. This carbon may sustain microbial ecosystems or undergo photochemical
380 reactions, producing carbon dioxide, nutrients, free radicals and other photoproducts.
381 Conservative mixing explains about 70% of the observed variability in the concentration
382 of DOC, but there are also non-conservative seasonal variations, probably related to the
383 transport and breakdown of POC. In the deep Strait of Georgia, this non-conservative
384 variation amounts to a difference of about 15 g C m^{-2} between December and June, when
385 the concentration is low.

386

387 To understand fully the effects of organic carbon cycling in this environment, future
388 studies should examine the sources and fluxes of organic matter to the Strait and their
389 variability on time scales of days to seasons.

390

391 **Acknowledgements**

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393 dissolved organic carbon and to Dr. Lisa Miller for the use of her TOC analyzer. We
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398 and Oceans Canada and by Metro Vancouver (formerly the Greater Vancouver Regional
399 District).

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522 particulate organic carbon in the Mississippi River estuary and adjacent coastal
523 waters of the northern Gulf of Mexico. *Marine Chemistry*, 89, 241-256.
- 524

525 **Table 1.** Volume and seasonal pycnocline depth for each “box” of the study area. The
 526 area represented by each box is shown in Fig.1. The pycnocline depth is the depth of
 527 separation between the upper and lower layers, as described in Section 2.2.

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Station number inside box	Volume of box (10^9 m^3)	April pycnocline depth (m)	June pycnocline depth (m)	September pycnocline depth (m)	December pycnocline depth (m)
16	47.8	54	49	62	97
14	67.9	54	49	63	92
12	82.4	50	46	65	76
9	53.5	50	44	66	70
6	69.3	49	44	66	63
3	54.0	48	43	64	62
Malaspina	76.1	48	44	64	68
2	137	46	42	62	60
27	175	43	34	59	58
39	213	39	32	63	52
42	71.2	38	30	58	47
46	33.5	10	19	41	41
56	71.4	10	6	35	35
59	65.1	0	0	175	0
62	52.9	0	50	0	0
65	40.5	0	50	0	0
ADCP	45.3	0	50	0	0
69	65.6	119	50	58	120
72	90.7	104	43	54	116
75	105	96	50	45	114
102	28.4	96	48	50	115

530
 531

532 **Table 2.** Areas and volumes of large zones used in Table 3. The station locations
 533 are shown in Figure 1.

534
 535

Zone	Stations / boxes included	Area (km²)	Volume (10⁹ m³)
N. Strait of Georgia	16, 14, 12, 9, 6, Malaspina	3058	451
S. Strait of Georgia	2, 27, 39, 42, 46, 56	4408	701
Haro Strait / Victoria Sill	59, 62, 65, ADCP	2239	204
Juan de Fuca Strait	69, 72, 75, 102	2185	290

536
 537

538 **Table 3.** Seasonal and annual average concentrations of DOC, POC and TOC in each
 539 zone. The seasonal values are the averages of all the station boxes included in each zone.
 540 (See Table 2.) The annual averages were calculated as the average of the four seasonal
 541 values, all given equal weight. N. SoG = northern Strait of Georgia, S. SoG = southern
 542 Strait of Georgia, Haro = Haro Strait / Victoria Sill, JdeF = Juan de Fuca Strait. Values in
 543 brackets following concentrations represent 1 standard deviation, calculated by
 544 propagation of error formulae from the standard deviation of replicates described in
 545 Section 2.2 of the text.

	Average Surface [DOC] (μM)	Average Deep [DOC] (μM)	Average Surface [POC] (μM)	Average Deep [POC] (μM)	Average Surface [TOC] (μM)	Average Deep [TOC] (μM)
April						
N. SoG	70(2)	52(2)	25(3)	16(3)	94(3)	68(3)
S. SoG	74(2)	49(2)	30(3)	6.1(3)	100(3)	55(3)
Haro		57(2)		6.6(4)		64(3)
JdeF	48(2)	40(2)	14(4)	5.3(4)	62(3)	45(3)
June						
N. SoG	76(1)	47(1)	19(2)	13(2)	95(2)	60(2)
S. SoG	74(1)	51(1)	18(2)	8(2)	92(2)	59(2)
Haro	49(1)	44(1)	10(2)	6(2)	59(2)	49(2)
JdeF	52(1)	37(1)	10(2)	3(2)	62(2)	40(2)
September						
N. SoG	62(1)	53(1)	17(2)	6(2)	79(1)	59(1)
S. SoG	69(1)	55(1)	10(2)	4(2)	79(1)	60(1)
Haro	57(1)	49(1)	2(2)	78(2)	59(2)	57(2)
JdeF	52(1)	40(1)	4(2)	4(2)	57(2)	45(2)
December						
N. SoG	64(2)	59(2)	3(3)	5(3)	68(3)	65(3)
S. SoG	63(2)	53(2)	4(4)	6(4)	67(3)	59(3)
Haro		57(2)		5(4)		62(3)
JdeF	56(2)	40(2)	1(5)	8(5)	57(4)	47(4)
Annual average						
N. SoG	68(1)	53(1)	16(3)	10(3)	84(2)	63(2)
S. SoG	70(1)	52(1)	16(3)	6(3)	85(2)	58(2)
Haro	53(2)	52(1)	6(3)	6(3)	59(3)	58(3)
JdeF	52(2)	39(1)	7(3)	5(3)	59(3)	44(3)

548
549

550 **Table 4.** Sources, sinks and inventory of organic carbon in the Strait of Georgia
 551
 552

	DOC	POC	TOC	Reference
<i>Sources</i>				
Fraser and other river flux into Strait (10^8 kg C yr ⁻¹)	5.3	2.2	7.5	Johannessen et al., 2003
Net primary production (10^8 kg C yr ⁻¹)	4.9	2.4	7.3	Total production from Mackas and Harrison, 1997 (See Johannessen et al., 2003, for calculation of new production; multiplied by surface area used for this study)
Anthropogenic fluxes into Strait (10^8 kg C yr ⁻¹)	< 0.83	< 0.37	< 1.2	Johannessen et al., 2003
Total sources of organic C (10^8 kg C yr ⁻¹)	11	5.0	16	Sum of above
<i>Sinks</i>				
Burial in sediments of Strait (10^8 kg C yr ⁻¹)	0	4.3	4.3	Johannessen et al., 2003
Net outflow through Juan de Fuca Strait (10^8 kg C yr ⁻¹)	6.1	1.1*	7.2*	this study
Sinks: burial + outflow (10^8 kg C yr ⁻¹)	6.1	4.3 (5.4*)	10 (12*)	Sum of above
Sink: oxidation, by difference (10^8 kg C yr ⁻¹)	4.9	0.7	5.6	Sum of above
Strait of Georgia water column inventory (10^8 kg C): averaged over four seasons	8.1	1.3	9.4	this study

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* Apparent outflow of particulate organic carbon may reflect in situ production in Juan de Fuca Strait, and not outflow from the Strait of Georgia

558 **Table 5.** Inventory of DOC residuals (10^7 kg C) calculated, as described in Section 4,
 559 from the vertical distance to the mixing line in Fig. 4a: [DOC] vs. salinity. “SoG” = Strait
 560 of Georgia; “HS” = Haro Strait/ Victoria Sill; “JdF” = Juan de Fuca Strait.
 561

Area	April surface	April deep	June surface	June deep	Sept. surface	Sept. deep	Dec. surface	Dec. deep
N. SoG	0.30	-1.4	0.70	-3.8	-0.29	-0.39	0.99	1.0
S. SoG	1.1	-4.6	-0.35	-3.8	0.52	0.12	-0.81	3.2
SoG Total	1.4	-6.0	0.35	-7.6	0.23	-0.27	0.18	4.2
HS	0	0.76	-0.09	-0.56	0.24	1.0	0	1.3
JdF	-1.0	-0.06	0.10	-0.05	0.83	0.06	0.04	0.18

562

563 **List of Figures**

564

565 **Fig. 1.** The study area. Numbered, circled dots show locations of rosette and CTD casts,
566 where water samples were collected for DOC and TOC analysis. The dots without
567 numbers represent additional CTD casts. The small polygons marked around the rosette
568 stations are those used in the carbon inventory calculations (see section 2.2 and Tables 1
569 and 2).

570

571 **Fig. 2.** Distribution of sampling stations and depths along a vertical transect from the
572 mouth of Juan de Fuca Strait (station 102) to the northern end of the Strait of Georgia
573 (station 16). The bottom shape (grey) actually shows the cast depth (usually < 5 m off
574 the bottom); all the samples were taken in the water column. The inset map shows the
575 transect route in plan view. Plot generated in Ocean Data View, Schlitzer (2006).

576

577 **Fig. 3.** Vertical profile of DOC concentration in April, June, September and December
578 along the transect shown in Figure 1, overlain with salinity contour lines. The vertical
579 lines represent rosette cast locations. Plot generated in Ocean Data View with VG-
580 gridding, Schlitzer (2006).

581

582 **Fig. 4.** Relationships between [DOC] and (a) salinity, (b) the concentration of dissolved
583 oxygen, (c) the concentration of nitrate for all cruises (n=267). All three fits were
584 somewhat improved by omitting the December data (see section 3.1), but for
585 completeness all data are shown and included.

586

587 **Fig. 5.** Vertical profile of POC concentration in April, June, September and December
588 along the transect shown in Figure 1, overlain with salinity contour lines. The vertical
589 lines represent rosette cast locations. Plot generated in Ocean Data View with VG
590 gridding, Schlitzer (2006).

591

592 **Fig. 6.** Inventories of DOC (**bold**) and POC (*italic*) in the upper and lower layers of the
593 northern and southern Strait of Georgia, Haro Strait / Victoria Sill and Juan de Fuca Strait
594 (gC m^{-2} ; calculated as inventory divided by total surface area for comparison with
595 average rates of primary production). Horizontal lines represent the average depth of
596 separation of the upper and lower layers at the stations included in each zone in each
597 season (see Tables 1 and 2). The water column is relatively well-mixed in the Haro Strait
598 / Victoria sill zone, and there was no clear separation of layers at most stations in that
599 zone. By propagation of errors from the zone average concentrations shown in Table 3,
600 and assuming no error in the defined volume of each zone, the standard deviation in these
601 inventories is 1- 5 gC m^{-2} .

602

603 **Fig. 7.** (a) Monthly average discharge of the Fraser River and (b) monthly average
604 [DOC] in the river, measured at Hope. Environment Canada, unpublished data, 2007.
605 The discharge and concentration measured in 2003 were comparable to the average
606 observed over the past 10 years.

607

608 **Fig. 8.** Vertical profile of the ratio of POC concentration to beam attenuation coefficient
609 ($[\text{POC}]/c$) in April, June, September and December along the transect shown in Figure 1,
610 overlain with salinity contour lines. The vertical lines represent rosette cast locations.
611 Plot generated in Ocean Data View with VG gridding, Schlitzer (2006).

612
613 **Fig. 9.** Vertical profile of DOC residual (see text section 41) in April, June, September
614 and December along the transect shown in Figure 1. The residuals represent the vertical
615 distance of each DOC point from the regression line of $[\text{DOC}]$ on salinity in Figure 4a. A
616 high value indicates that there is a high concentration of DOC relative to the conservative
617 mixing line.

618 Fig.1

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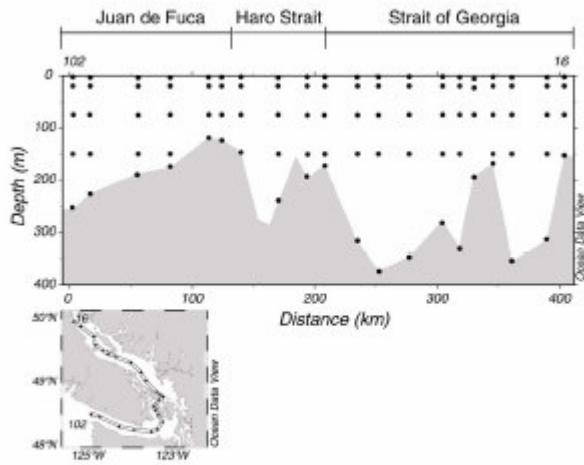
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623 Fig.2

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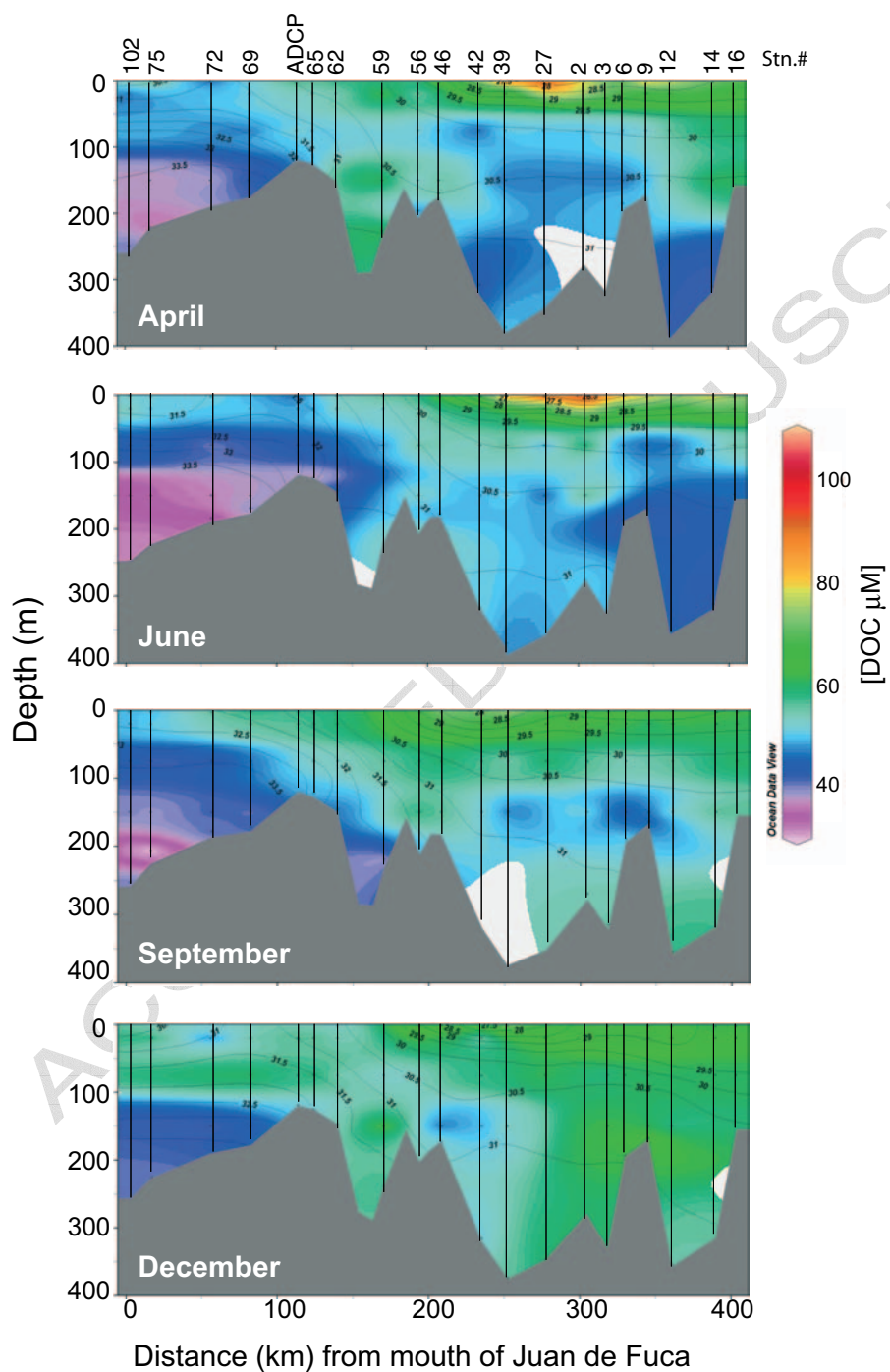
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629 Fig.3

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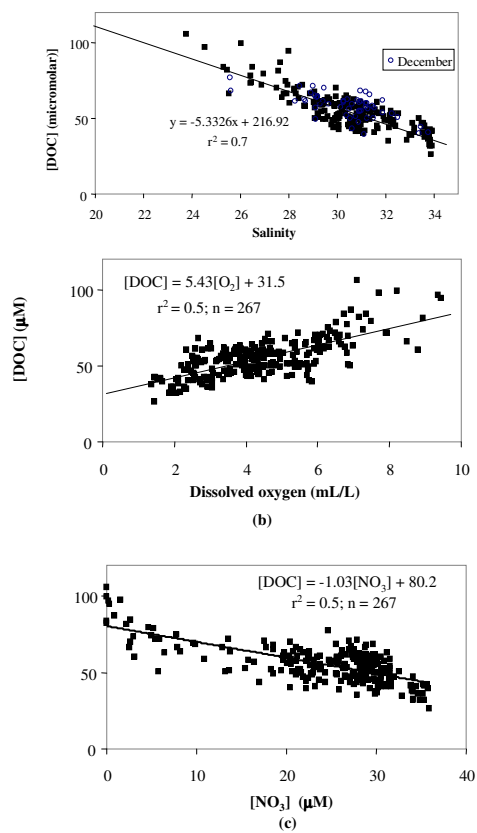


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633 Fig.4

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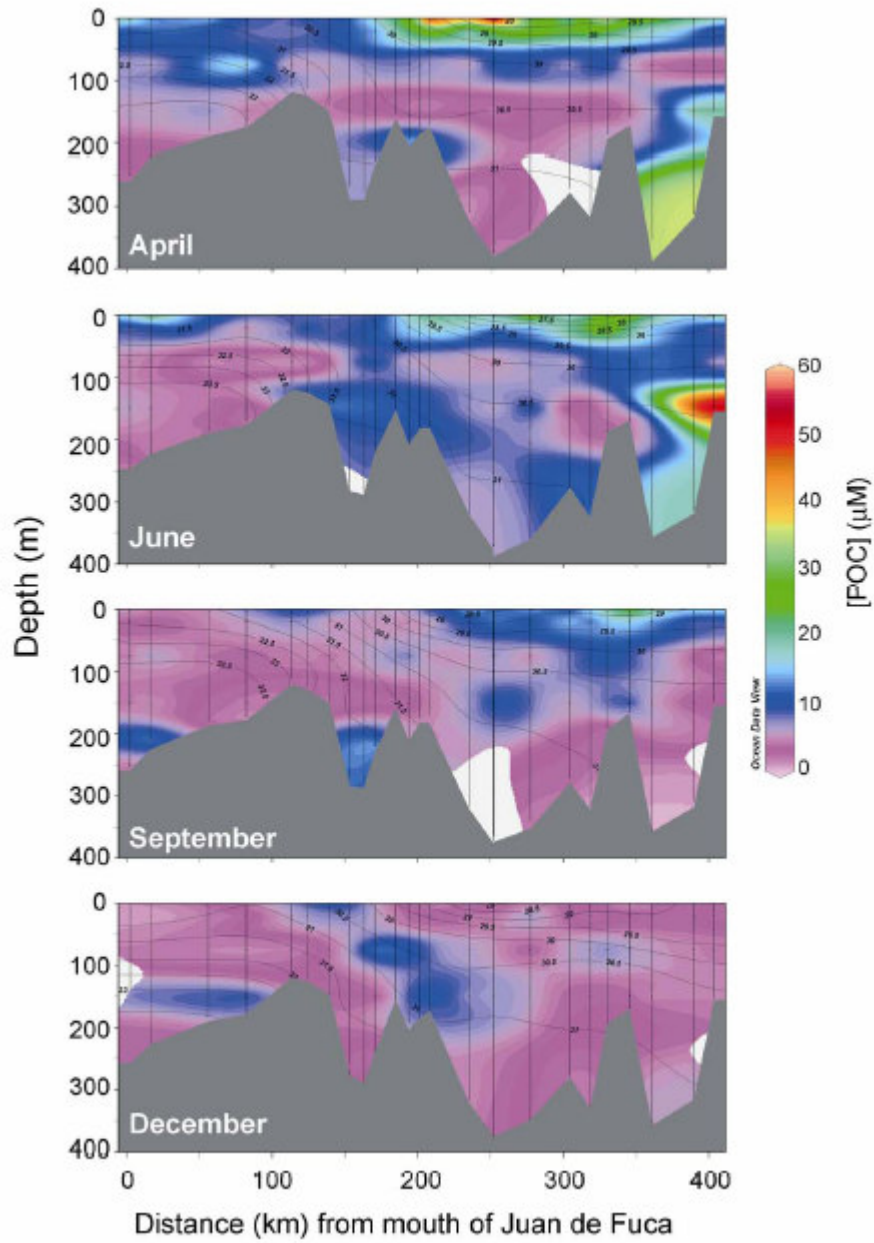


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637 Fig.5

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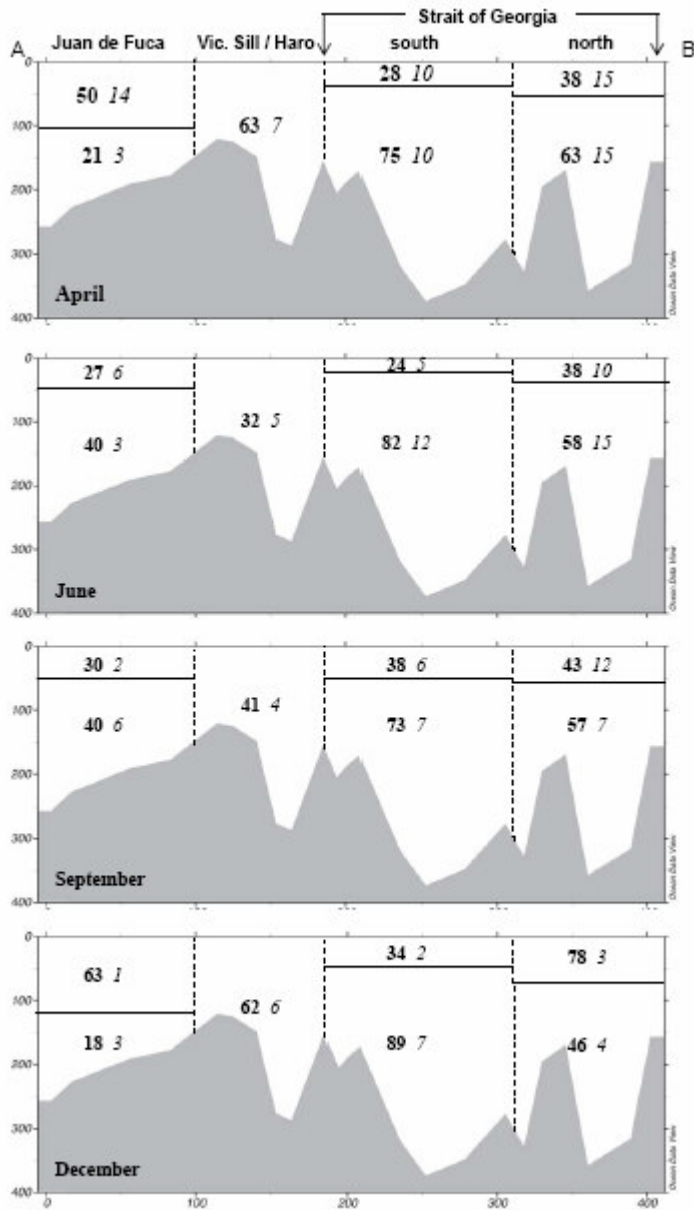


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641 Fig.6

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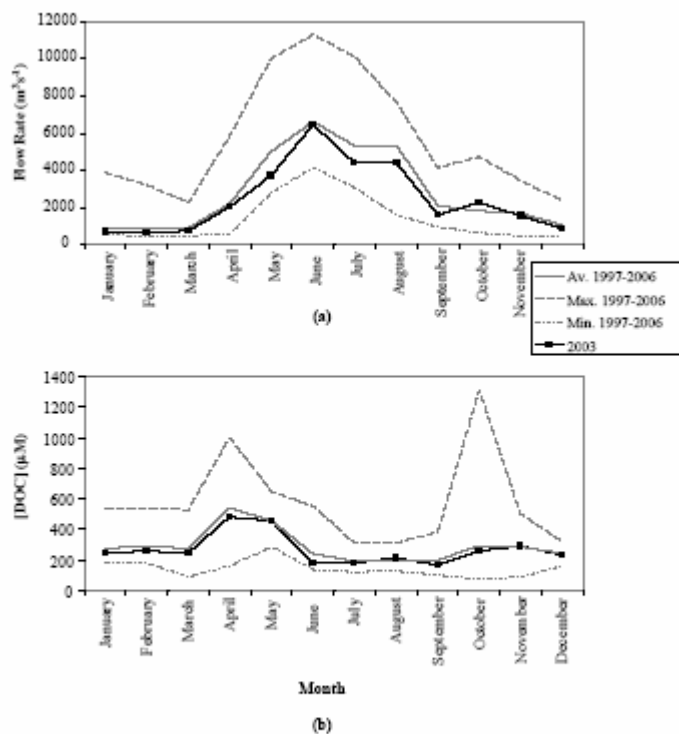


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645 Fig.7

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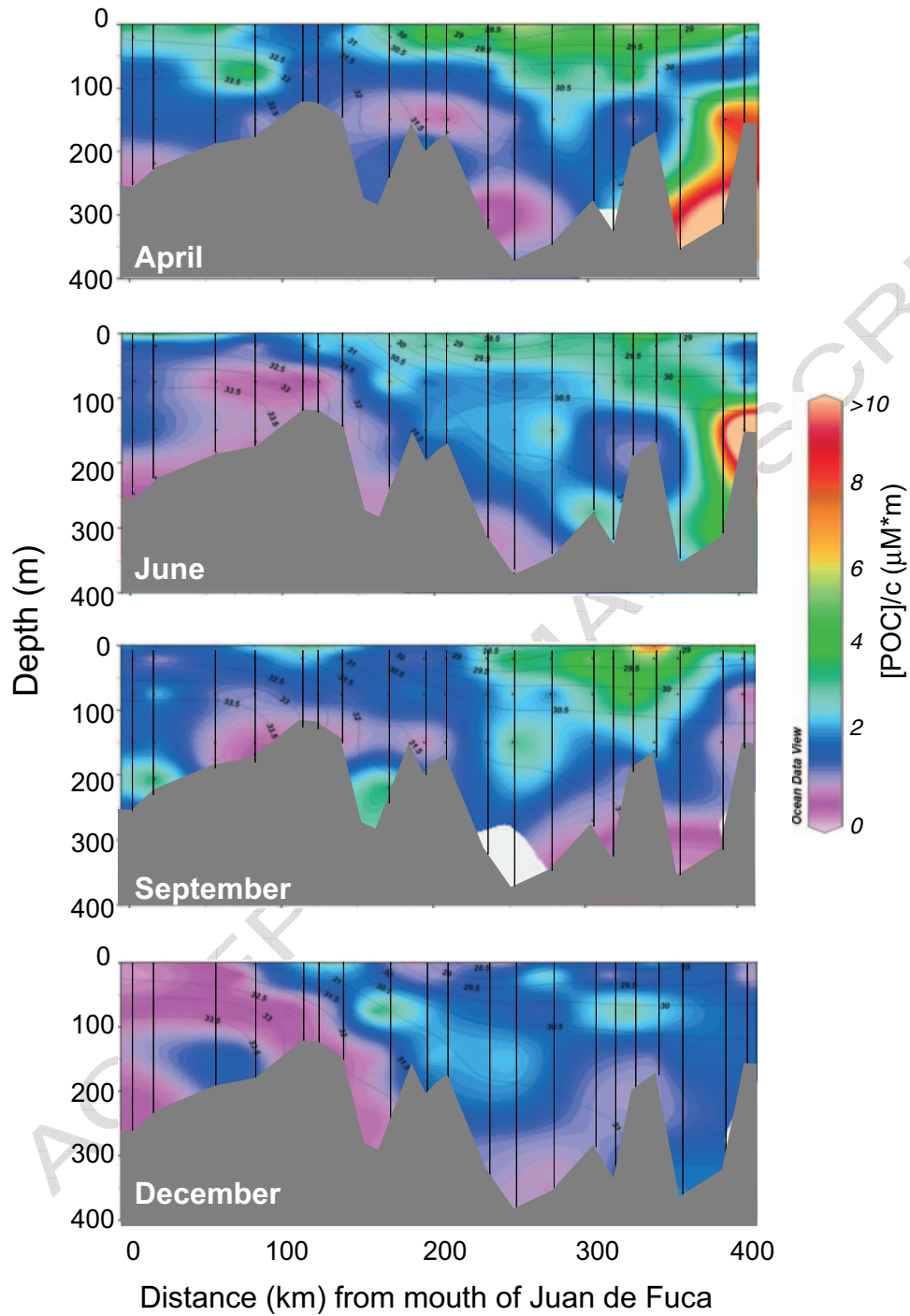
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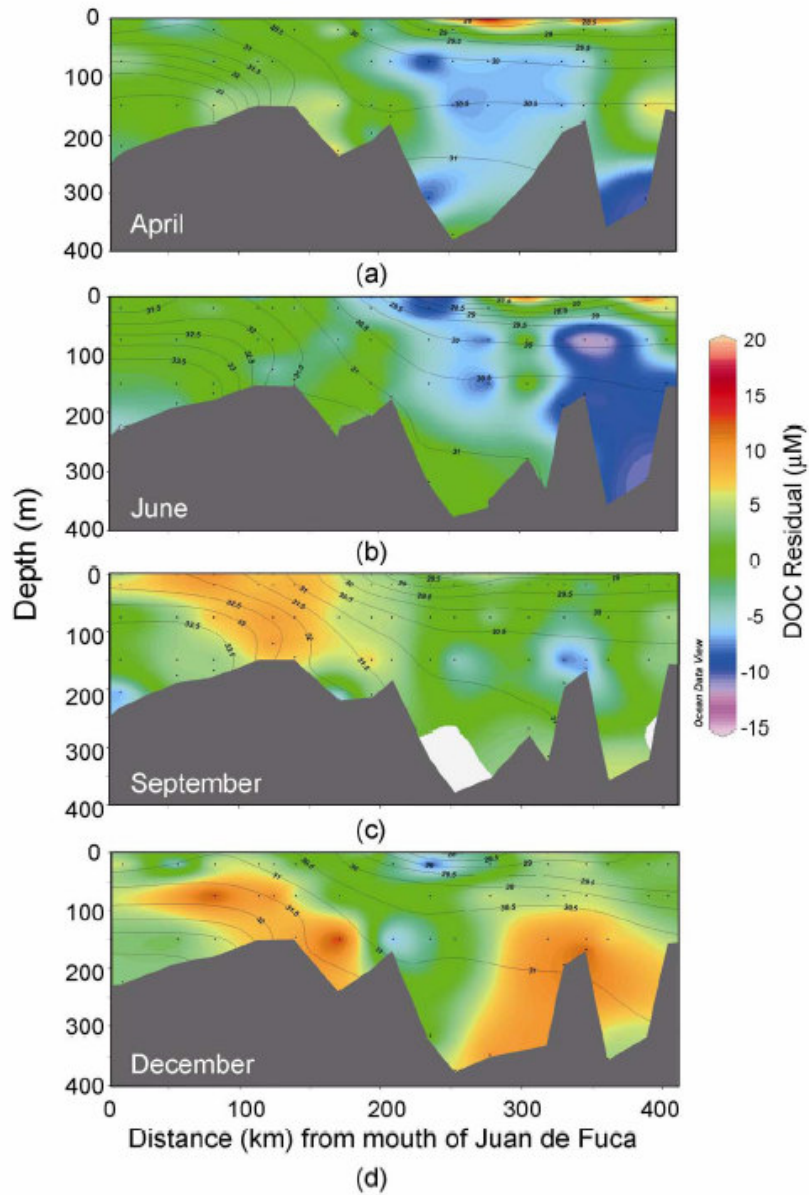
649 Fig.8

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652 Fig.9

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