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

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Abstract

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

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

1. Introduction

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

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

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

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

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

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

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

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

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

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

2.2 Calculation of inventories and fluxes

We calculated surface layer and deep layer organic carbon inventories at each station. We defined the break between upper and lower layers as the top of the deep, relatively uniform layer, as determined by visual inspection of the salinity profiles. The Strait of Georgia does not display a classical density profile with a well defined upper mixed layer and a pycnocline overlying a deep mixed layer (Masson and Peña, 2008). The upper layer comprises a series of interfingering layers of water, and in some places the density decreases all the way to the surface, without any apparently well-mixed surface layer. Consequently, choosing the top of the deep layer was the most consistent way to divide the water column throughout the study area. This depth also usually coincided with a sharp decrease in the concentrations of DOC and TOC between the upper and lower layers (shown in section 3.1 below). We assigned the organic carbon concentration measurements for each station to a small area of the surrounding basin (Fig. 1) and calculated the volume of water that that area represented, using a 1 km by 1 km depth grid (Table 1). The inventories for the upper and lower layers and for the whole water column in each area were calculated as the product of the water volume and the average

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

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

3. Results

3.1 Distribution of organic carbon

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

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

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

3.2 Inventories and fluxes

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

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 area of the Strait of Georgia considered here (7464 km², see Methods) the inventory implies an average of 130 g C m⁻², with the highest value occurring in December. However, the distribution of TOC among surface and deep layers, the northern and southern Strait, and particulate and dissolved forms, did vary considerably (Fig. 6, Table 4). The proportion of the TOC held in the surface layer varied depending both on the concentration of organic carbon and on the depth of the surface layer.

The inventory of organic carbon held in the water column of the Strait of Georgia is low, relative to the fluxes into the Strait. The annual net primary production in the Strait is estimated at 90 - 120 g C m⁻² yr⁻¹ (Mackas and Harrison, 1997).. Extrapolating that water column primary production rate to the surface area of the Strait of Georgia considered in this study (7464 km²), the annual net primary production is $6.7 \times 10^8 - 9.0 \times 10^8$ kg C (Table 1). The Fraser and other rivers add an additional 7.5×10^8 kg organic C annually, and anthropogenic sources add up to 1.2×10^8 kg C (Johannessen *et al.*, 2003). Thus, the total sources of TOC to the Strait are approximately $15 \times 10^8 - 18 \times 10^8$ kg C yr⁻¹, about twice the inventory measured year-round. The sinks are burial in the sediments (4.3×10^8 kg C yr⁻¹, Johannessen *et al.*, 2003) advection through Juan de Fuca Strait (and possibly Johnstone Strait) (7.2×10^8 kg C yr⁻¹, this study, see Methods), and oxidation. Burial and advection come to 11×10^8 kg C yr⁻¹. By difference, this leaves $4.0 \times 10^8 - 6.2 \times 10^8$ kg C yr⁻¹, about half of the inventory, to be oxidized in the Strait of Georgia and its sediments each year. The preliminary carbon budget constructed by Johannessen *et al.* (2003), indicated that about 0.9×10^8 kg C/yr was oxidized in sediments. Using this

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

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

4. Discussion

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

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

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

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

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

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

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

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

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

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

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

4. Conclusions

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

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

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

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

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

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

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

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

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

Table 4. Sources, sinks and inventory of organic carbon in the Strait of Georgia

	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

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

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

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

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

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

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

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

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

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

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

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

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

Fig.1



Fig.2

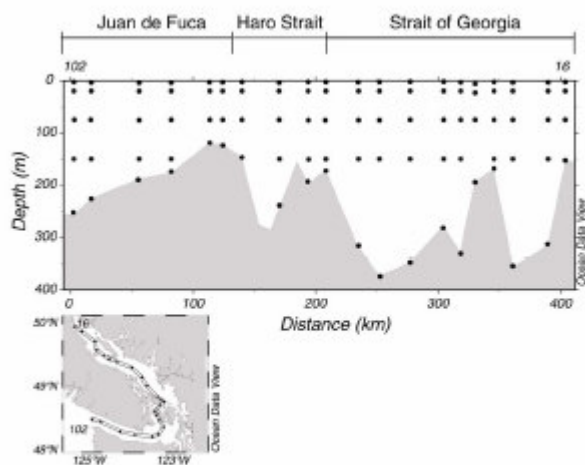


Fig.3

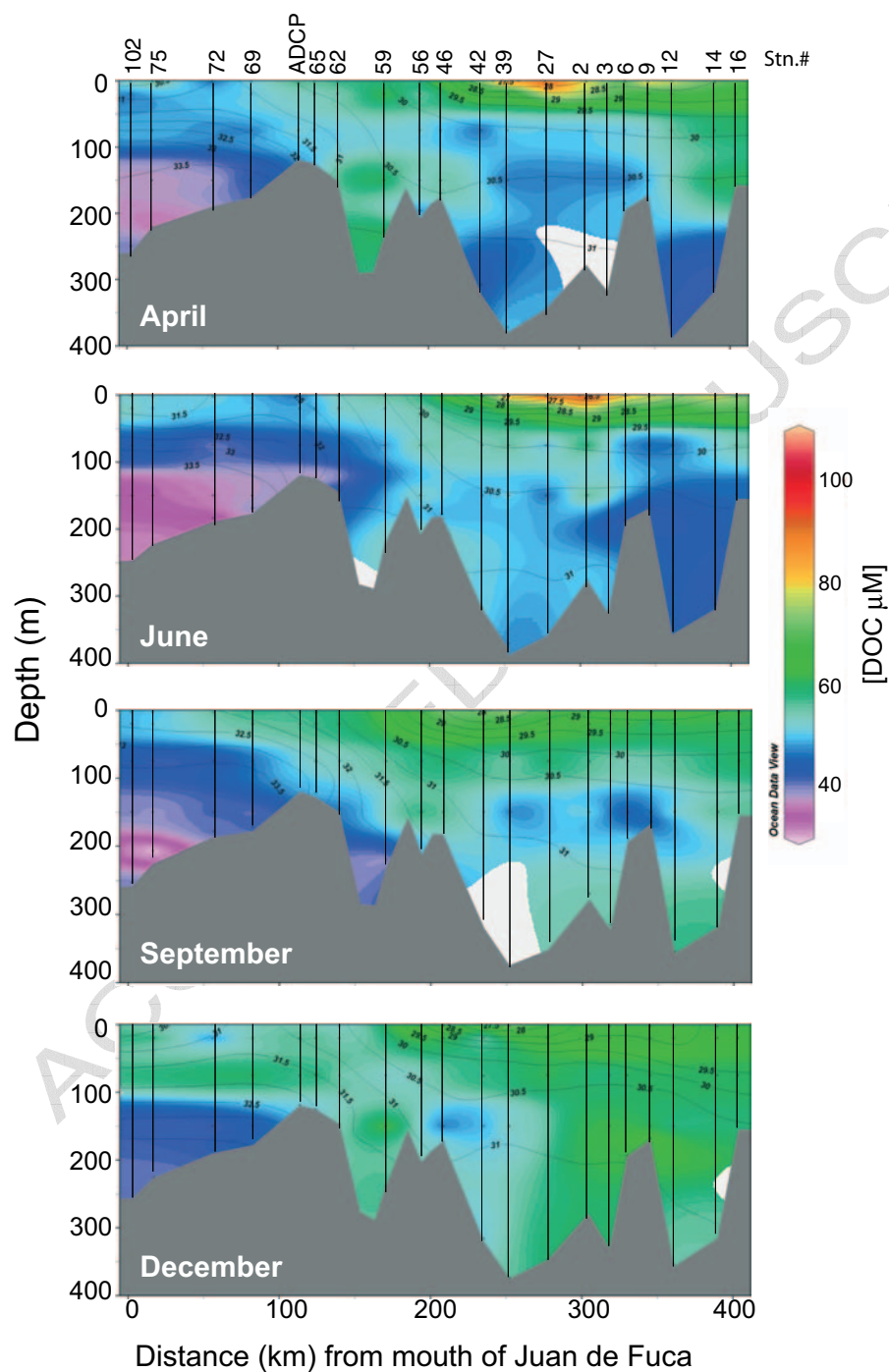


Fig.4

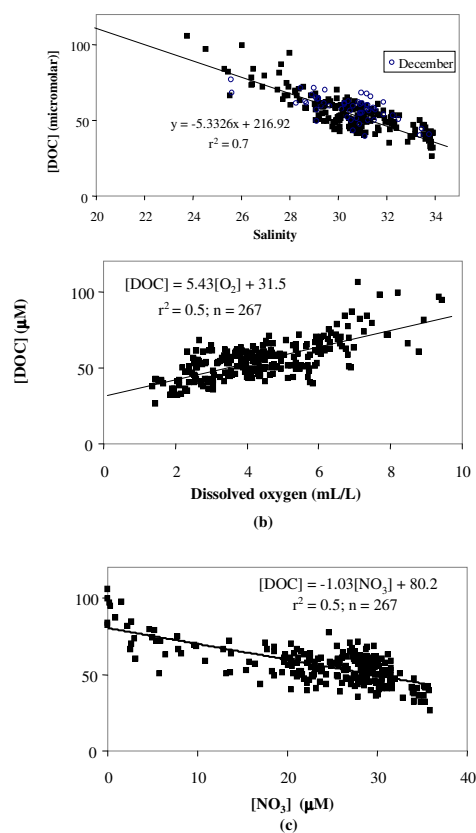


Fig.5

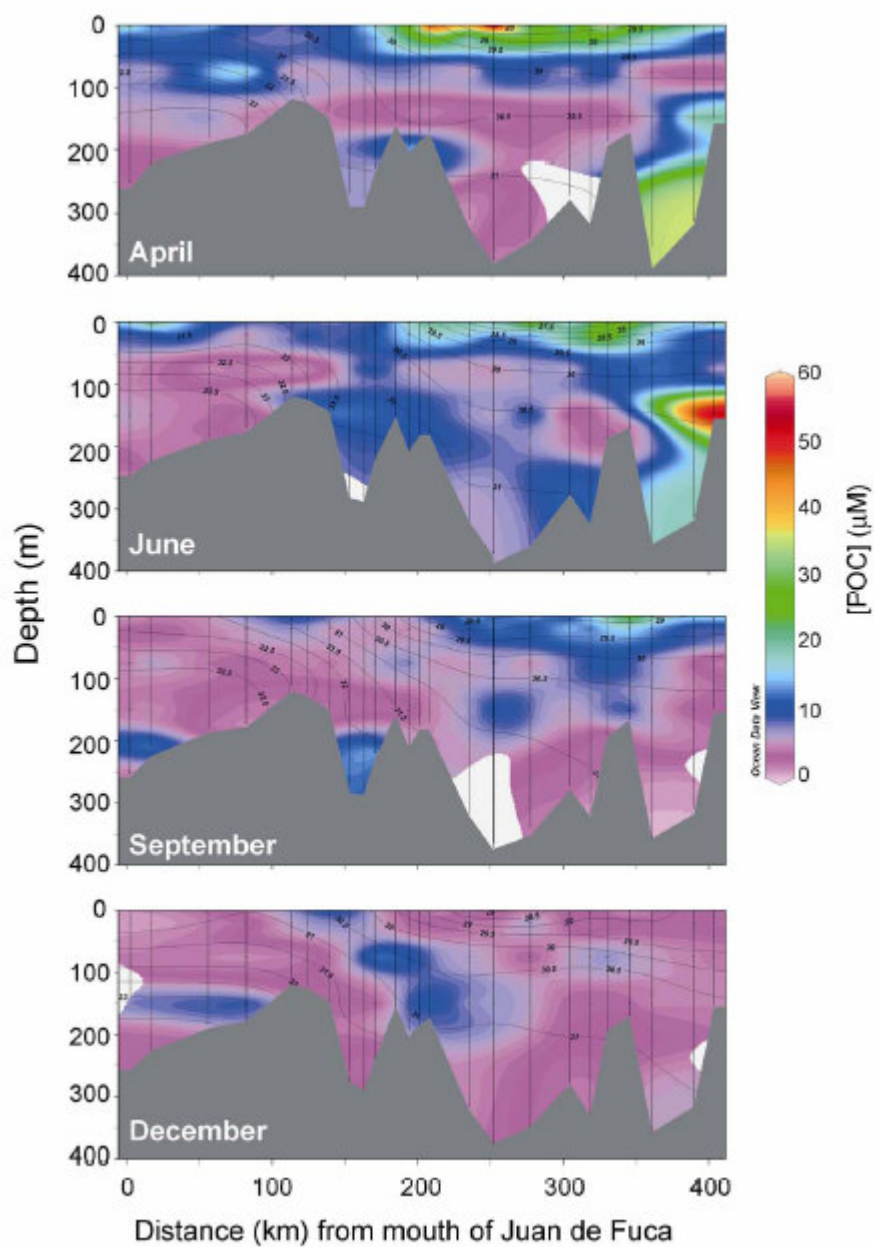


Fig.6

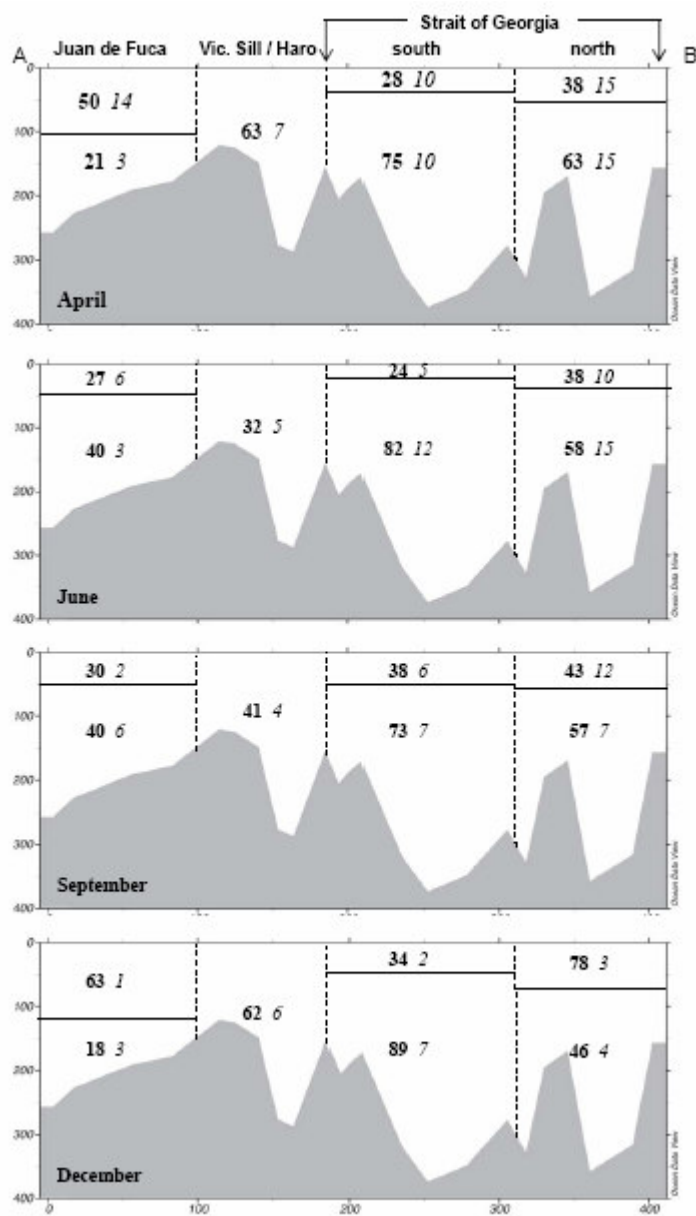


Fig.7

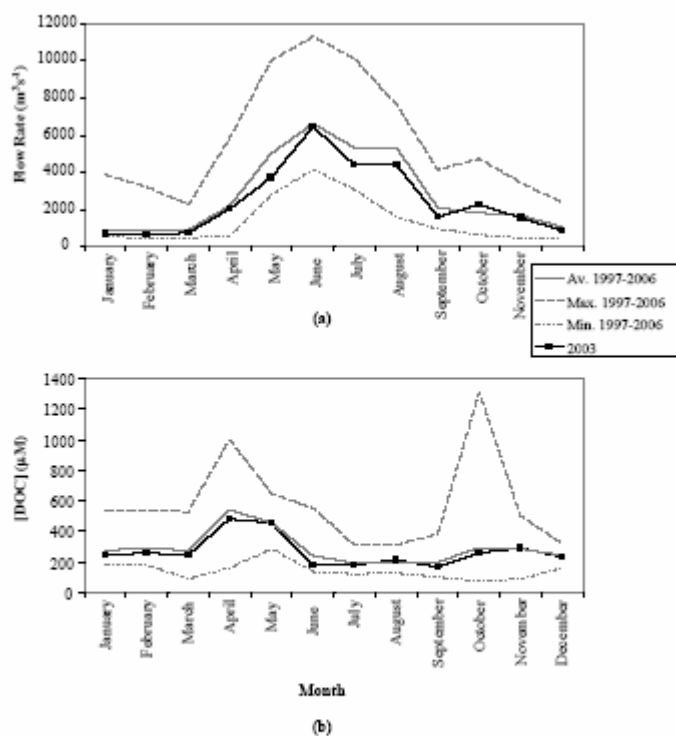


Fig.8

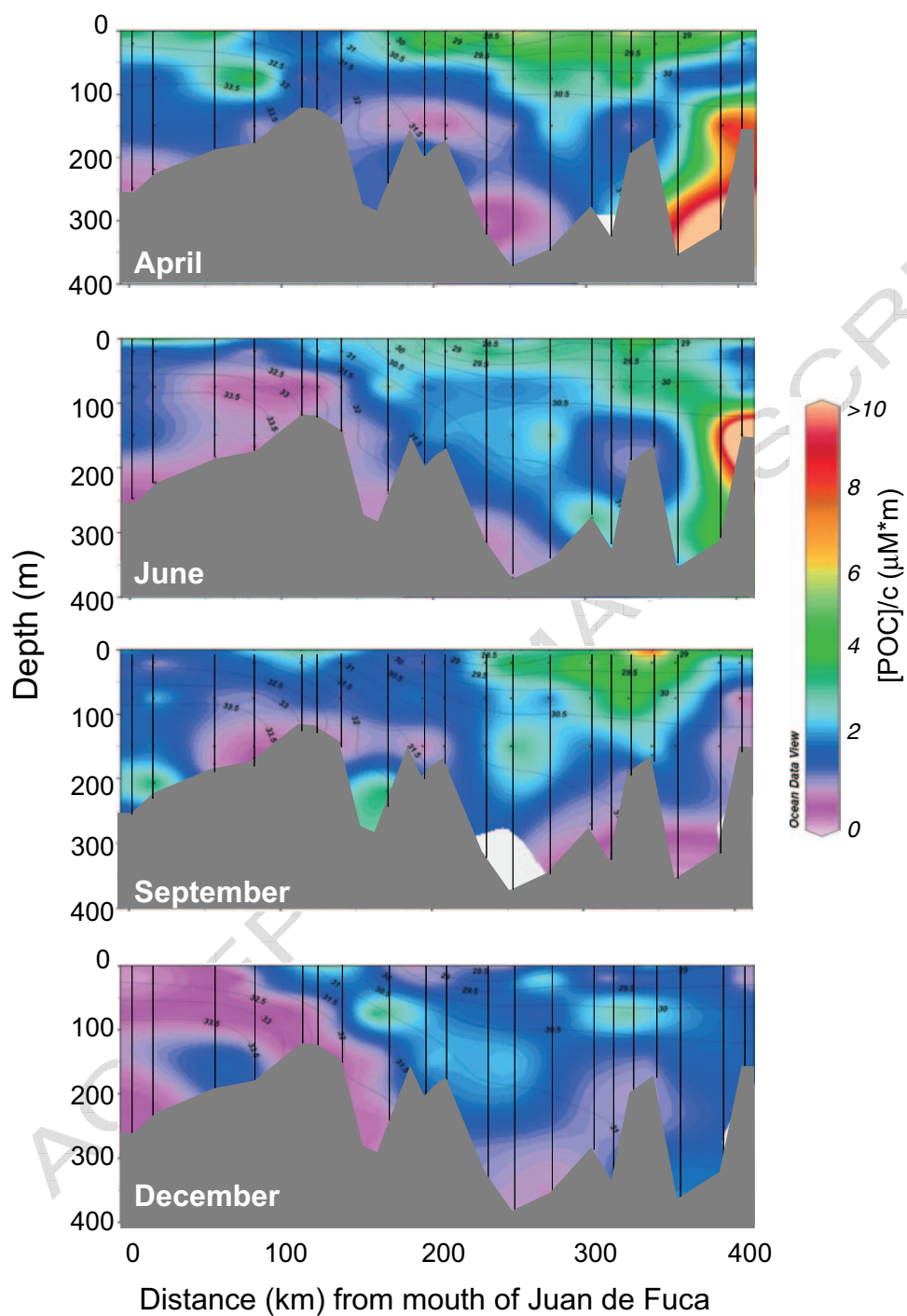


Fig.9

