Seasonality and Physical Control of Water Properties and Sinking and Suspended Particles in Douglas Channel, British Columbia

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SEASONALITY AND PHYSICAL CONTROL OF WATER PROPERTIES AND SINKING AND SUSPENDED PARTICLES IN DOUGLAS CHANNEL, BRITISH COLUMBIA

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ABSTRACT

Johannessen, S.C., Wright, C.A., and Spear, D.J. 2015. Seasonity and physical control of water properties and sinking and suspended particles in Douglas Channel, British Columbia. Can. Tech. Report. Hydrog. Ocean. Sci. 308: iv + 26 p.

Water properties and particles in Douglas Channel were characterized during four cruises (July 2013, April, July and October 2014), and with moored sensors and sediment traps (July 2013-June 2014.) An outflowing surface layer 10-30 m thick, driven by Kitimat and Kemano River discharge, overlay a mid-depth layer that exchanged with Hecate Strait. Deep-water renewal in June increased the concentration of oxygen by 1 mL/L to 3.5 mL/L. The surface layer was turbid (beam attenuation coefficient ≤ 6 m^{-1}). The sinking particle flux at 50 m was 438 g $m^{-2}yr^{-1}$, and the organic carbon flux 37 gC $m^{-2}yr^{-1}$. Fluxes of particles and organic carbon peaked in late May, during the river freshet. The concentration of organic carbon in the sinking particles was highest in August and September (12-13%), except for a single peak in mid-November (22%).

RÉSUMÉ

Johannessen, S.C., Wright, C.A. et Spear, D.J. 2015. Saisonnalité et contrôle physique des propriétés de l'eau et des particules en suspension ou qui sombrent dans le chenal Douglas, en Colombie-Britannique. Can. Tech. Report. Hydrog. Ocean. Sci. 308: iv + 26 p.

Les propriétés de l'eau et les particules du chenal Douglas ont été caractérisées lors de quatre croisières (juillet 2013, avril, juillet et octobre 2014) à l'aide de capteurs amarrés et de pièges à sédiments (juillet 2013 – juin 2014). Une couche de surface s'écoulant vers le large d'une épaisseur de 10 à 30 m alimentée par le débit des rivières Kitimat et Kemano se superpose à une couche de mi-profondeur qui chevauche le détroit d'Hécate. Le renouvellement de l'eau profonde en juin a fait passer la concentration d'oxygène de 1 mL/L à 3,5 mL/L. La couche de surface était trouble (coefficient d'atténuation en largeur ≤ 6 m^{-1}). Le flux de particules qui sombrent à 50 m était de 438 g/m^{-2}/an^{-1}, et le flux de carbone organique, de 37 gC/m^{-2}/an^{-1}. Les flux de particules et de carbone organique ont atteint un sommet à la fin mai, au cours de la crue nivale fluviale. La concentration de carbone organique dans les particules qui sombrent était la plus élevée en août et en septembre (12-13 %), à l'exception d'un pic unique à la mi-novembre (22 %).

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INTRODUCTION

Douglas Channel, a fjord on the northwest coast of Canada, is the principal shipping route to the industrial town of Kitimat (Figure 1). The shores of the fjord are otherwise largely undeveloped except for the small communities of Hartley Bay near the mouth and Kitamaat Village near the head. Industries in Kitimat include an aluminum smelter and an international shipping port. There are plans for further industrial development along Douglas Channel, including proposed liquid natural gas plants and an oil pipeline with a terminus at Kitimat. There has been concern in the past and again currently about the effects of shipping oil through the narrow tidal passages. In the late 1970s there was a proposal to ship Alaskan oil by tanker to Kitimat, which would then have been sent by pipeline across the Rocky Mountains to Edmonton, Alberta. Currently there is a proposal to ship diluted bitumen – a heavy tar mixed with light oils – in the opposite direction. The pipeline would carry the diluted bitumen from Alberta to Kitimat, from where it would be shipped by tanker along Douglas Channel and then across the Pacific Ocean to Asia.

In order to assess the likely environmental effects of further industrialization or of oil tanker traffic, we need a clear understanding of the physical circulation, geochemistry and biology of Douglas Channel. In particular, we need to characterize the controls on the concentration of dissolved oxygen and on the flux and composition of sinking particles, both of which would interact with spilled oil.

Sinking particles, as well as carrying natural organic matter into deep water, can scavenge oil, making it sink rapidly out of the euphotic zone. This both slows the breakdown of spilled oil, by preventing photochemical oxidation, and assists with dispersion, by removing it from the zone where it will come into contact with the most marine life. Sinking also takes the oil out of reach for remediation. For the Kitimat fjord system and approaches, particulate sources include marine production (organic-rich particles associated with phytoplankton, zooplankton and grazing), coastal erosion, and riverine suspended particles from the Kitimat and Kemano Rivers, as well as from numerous small creeks along the shores.

Dissolved oxygen has declined globally since the 1970s, particularly in coastal waters (Gilbert et al., 2010). In addition, the concentration of dissolved oxygen in deep fjords is often already low, because circulation and replacement of the bottom water is restricted by one or more sills. Some coastal waters have become hypoxic, threatening benthic and deep-water marine animals (Rabalais et al., 2001). Subsurface oxygen is consumed during the remineralization of natural sinking organic matter. If heavy oil were to spill into Douglas Channel and sink, its decomposition could add to the consumption of oxygen in the deep water. Consequently, we need to understand the current cycle of oxygen consumption and replacement in Douglas Channel and its interaction with natural organic matter and sinking particles.

There has been some oceanographic work in the area in the past, notably a large study in 1976-1979 described by Macdonald (1983b). Since that time, there have been only occasional oceanographic cruises to the area. A new, national programme is under way, involving Fisheries and Oceans Canada, Environment Canada, the National Research Council, Natural Resources Canada and Transport Canada, aimed at developing a coordinated tanker traffic safety system, which includes an understanding of the oceanography of the Douglas Channel fjord system.

This report presents physical and geochemical oceanographic data from the first year of the programme (July 2013 – October 2014), in the context of the physical circulation, seasonality and connection with the open ocean through Hecate Strait and Queen Charlotte Sound. Where

possible we compare conditions in 2013-2014 with those of the late 1970s. We also identify remaining data gaps that could be filled by the new programme.

GEOLOGICAL SETTING

Douglas Channel, Squally Channel and Gardner Canal (Figure 1) are a set of fjords carved out by ice during the last glaciation. Ice began to retreat about 12000 years ago, leaving deep, flat-bottomed, straight-sided channels largely filled with unconsolidated sediment (Bornhold, 1983). Outside the fjord system, Hecate Strait is only 130 - 150 m deep, but the bottom plunges to > 600 m in Squally Channel. A wide entry sill about 200 m deep divides Caamaño Sound from Squally Channel, and another divides the outer basin of Douglas Channel from the inner one, also at about 200 m depth (Figure 1). The two basins of Douglas Channel are about 300 - 400 m deep. The sill between Caamaño Sound and Squally Channel is a moraine likely deposited during a pause in the glacial retreat, while the sill that divides the outer basin of Douglas Channel from the inner basin is made of bedrock. Since deglaciation there has been ongoing sedimentation of silt and mud through most of the system, with coarse sand deposited on the Kitimat River delta. There are many smaller fan deltas all along the sides of the channel from the rivers and streams that drain into it (Conway et al., 2013). Strong currents prevent deposition of new sediment in some areas of the channel and build it up into mounds in others, leading to an uneven seafloor (Conway et al., 2012). In addition the delta and channel sides show evidence of turbidity flows and slides, some of which were large enough to have caused significant tsunamis (Thomson, 2012).

HECATE STRAIT / QUEEN CHARLOTTE SOUND WATER PROPERTIES

Hecate Strait and Queen Charlotte Sound provide source water for the intermediate depth (75-150 m) intrusions into Douglas Channel. They are part of the Alaska Coastal Current Zone (Thomson, 1981). This zone is characterized by northwestward, alongshore surface currents in the winter, which lead to strong downwelling, and by southeastward currents in the summer, which lead to a relaxation of downwelling or light upwelling in the summer. It is also susceptible to intense storms in the autumn and winter, which mix the water column to a depth of 100-150 m (Dodimead, 1980). Consequently, the surface and intermediate water contain high concentrations of nutrients, although phytoplankton production, as estimated from satellite ocean colour imagery (Ware and Thomson, 2005), is low, probably because of the deep mixing. Upwelling-favourable winds have increased in strength since the 1970s (Foreman et al., 2011), which has likely increased the concentration of nutrients.

METHODS

WATER SAMPLING

Seawater samples were collected using a sampling rosette at 12 stations along Douglas Channel and one in Hecate Strait (Figure 1) during cruises in July 2013 and in April, July and October 2014. The July cruises were aboard the *CCGS John P. Tully*, while the April and October cruises were aboard the *CCGS Vector*. At each station a full water column profile of samples was collected for the analysis of dissolved oxygen, salinity and nutrients, with additional

sampling at the surface for dissolved organic carbon, coloured dissolved organic matter, dissolved inorganic carbon / alkalinity and stable isotopes of oxygen. At four of the stations (Doug-4, FOC1, SC-61, HEC1; Figure 1), the full suite of samples was collected at every depth. Details of the sampling stations and depths are reported by Wright et al. (2015).

SEDIMENT GRAB SAMPLING

Sediment grab samples were collected at nine of the stations (Figure 1) in July 2013 and 2014 using a 0.1 m^2 Smyth-MacIntyre grab sampler. The grab sampler was emptied into a plastic tote bin, from which subsamples were collected for analysis of organic carbon, total nitrogen, stable isotopes of carbon and nitrogen, mineralogy, microbial incubations and wave tank experiments. The microbial incubations were carried out by staff at the National Research Council in Montreal and the wave tank experiments by staff at the Centre for Offshore Oil and Gas Exploration Research at the Bedford Institute of Oceanography. Neither the microbial incubations nor the wave tank experiments will be discussed further in this report.

MOORINGS

In July 2013 we deployed one mooring in Hecate Strait and two in Douglas Channel (Figure 1). All three moorings included current meters and temperature and salinity (conductivity) sensors (Figure 2). The moorings in Hecate Strait (HEC1) and in the inner basin of Douglas Channel (FOC1) also each included an oxygen sensor 10 m above the bottom, and a set of three cylindrical Baker sequential sediment traps (Baker and Milburn, 1983) at 50 m depth, with a Wetlabs Eco-FLNTU fluorometer just below the traps. Each sediment trap comprised 10 sample cups, which rotated into position at 11.5-day intervals, and the three traps were set to collect consecutively, to recover a complete, year-long record of sinking particles, although there were several malfunctions. The last two intervals of the second trap at FOC1 (Jan. 21 – Feb. 18, 2014) were lost, as were all the samples from the second trap at HEC1 (Oct. 25, 2013 – Feb. 17, 2014). In addition, one of the traps at FOC1 functioned well and collected a full record but then seized up during the eight months following the completion of its cycle, likely because the drive shaft corroded during prolonged exposure to salt water.

ANALYTICAL METHODS

The analytical methods for this project are described in detail by Wright et al. (2015). Briefly, dissolved oxygen was measured onboard by modified Winkler titration (Carpenter, 1965, ± 0.01 mL/L or 0.446 μmol/L), following the standard international procedure established for the World Ocean Circulation Experiment (Culberson et al., 1991). Nutrients were frozen immediately on collection and stored frozen until they were measured at the Institute of Ocean Sciences, using a Technicon Autoanalyzer II (Barwell-Clarke and Whitney, 1996, ± 2%). Organic carbon, nitrogen and biogenic silica were measured in the sediment grab and trap samples at the University of British Columbia by CHN analysis, following Calvert and Pedersen (1995, ± 3%). Stable isotopes were measured in sediment grab and trap samples (where sample volumes permitted) at the Deltaplus Laboratory at the University of British Columbia, using a VG PRISM

IRMS with Carlo-Erba CHN analyzer (± 0.3 ‰). Mineralogy was measured at the University of British Columbia by X-ray diffraction.

SUSPENDED PARTICLES

Seawater turbidity was assessed both by filtration, which yielded absolute concentrations of suspended particles in small samples, and by transmissivity, which measured the relative concentrations of particles over a large area. Transmissivity was measured at all rosette stations (Figure 1), using a Wetlabs C-Star transmissometer (pathlength, *r*, 25 cm) attached to the rosette frame. Transmissivity, *Tr* (% transmission over the light path), was converted to beam attenuation coefficient, *c* (m^{-1}), according to equation 1 (Baker, 1984).

$$c = -\frac{1}{r} ln(\frac{Tr}{100\%}) \qquad (1)$$

Water samples for particle filtration were collected at 0.5 m depth at four stations along the transect (Table 1) in April, July and October 2014. Each sample was filtered sequentially through 47-mm diameter Whatman GF/C (nominal pore size 1.2 μm) and GF/F (nominal pore size 0.7 μm) glass-fibre filters, followed by a 47-mm diameter Millipore 0.2-mm Durapore membrane filter. Total suspended solids were measured on each filter, and the particle concentration was calculated as the mass of retained particles divided by the filtered volume (3 L). The glass-fibre filters were sent for analysis of organic C and N (data not yet available). At two stations (Doug-4, SC-61) in July 2014, large volume pumps were used to collect suspended particles on a 142-mm GF/F glass-fibre filter at 2 m depth and on 142-mm diameter, 0.8μm Supor membrane filters at 4 and 6 m depth. Total suspended solids were measured on each filter, and the glass-fibre filters were analyzed for organic C and total N. The 4-m and 6-m samples were sent to the Bedford Institute of Oceanography to characterize the interaction between oil and suspended particles.

DATA

Tables and plots of the data have been compiled by Wright et al. (2015). The data are archived in the Data Archive at the Institute of Ocean Sciences and are available electronically on request (www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/index-eng.html).

RESULTS AND DISCUSSION

PHYSICAL CIRCULATION IN DOUGLAS CHANNEL

The physical circulation of Douglas Channel is best described as a three-layer flow.

Surface outflow

Fresh water discharged from the Kitimat River (July 2013-July 2014 average 133 m^3s^{-1}) and the Kemano River (52 m^3s^{-1}; Water Survey of Canada, preliminary data), as well as from smaller streams and rivers distributed along the channel sides, drives a year-round estuarine circulation. The Kitimat and Kemano Rivers have a freshet in mid- to late May fed by snowmelt, and frequent, smaller peaks in the autumn and winter, following heavy rainfall (Figure 3). The

distributed freshwater sources likely exceed the combined input from the Kitimat and Kemano Rivers (Macdonald et al., 1983a), and since these are short rivers, they are mainly rainfed. The upper part of the water column is strongly stratified, with a sharp pycnocline beneath the outflowing, brackish surface water at about 20 m depth (Figure 4) in Douglas Channel.

Mid-depth exchange

The water that flows into Douglas Channel from Queen Charlotte Sound and Hecate Strait is restricted by the depth of the seafloor in eastern Hecate Strait (130-150 m). Exchange and inflow into the deep basins inside the Channel is further restricted by the entry sill and the sill south of Doug-31 (Figure 1), which are both about 200 m deep. Above this depth, entrainment of subsurface water by estuarine outflow results in a mid-depth inflow and exchange with Queen Charlotte Sound / Hecate Strait. The strong connection between Douglas Channel and Hecate Strait at mid-depth is apparent year-round in the salinity and temperature records from moored sensors. Changes in water properties in Hecate Strait (HEC1, 53 m) often occur at the same time, though with lower variability in Douglas Channel (FOC1, 53 m). For example, on about September 20, 2013, the temperature began to rise (and the salinity to fall) simultaneously at the two sites, peaking about 10 days later, before falling again (Figure 5). From December to March some of the variations occur out of phase at the two sites, with each site sometimes leading, although the main patterns in variability are similar. It is not clear why variations at the Douglas Channel site occasionally appeared to lead those in Hecate Strait. This question will be the subject of further research. The covariation inside and outside the Channel is consistent with the interpretation of Macdonald et al. (1983b), based on limited observations in 1977 and 1978. These authors suggested that the connection was strong enough that surface temperature at Cape St. James, at the southern tip of Haida Gwaii, might be used to predict water temperature in the 75-150 m intrusions into Douglas Channel.

Previous authors have noted that in the winter, water in Queen Charlotte Sound / Hecate Strait is well-mixed to a depth of 100-150 m (Dodimead, 1980). The moored records show that this mixing occurs in a series of discrete events (Figure 6). September- October windstorms (reflected in high northwestward current driven by strong southeasterly winds) mix the surface water, increasing the temperature and decreasing the salinity measured at 53 m depth, without affecting water properties at 128 m. By December the water properties in the upper layer have reached their winter values, so January - February windstorms do not have much further effect on the temperature or salinity at 53 m. In contrast, storms in January-February cause dramatic changes at 128 m (rapid decline in salinity and temperature; Figure 6).

Deep-water renewal

The bottom water in Douglas Channel is replaced in June by dense, upwelled water that flows over the sills into the deep basins, lifting up the existing bottom water. Relaxation of downwelling in Hecate Strait, when the southeasterly winds relax, permits the depressed isopycnals to rebound (which is indistinguishable, in a single point measurement, from upwelling). The upwelled deep water does not always reach the surface. The current meter at 103 m at HEC1 recorded a sustained change to strong southeastward flow in mid-May, 2014, that lasted for about a month (Figure 7a). The relaxation of downwelling caused a rapid increase

in salinity and decrease in temperature at 127 m (Figure 7b), which was not observed in the 53 m record (not shown). However, even though the upwelled water did not reach the surface, it was sufficiently dense to flow down over the 200 m sills into Douglas Channel and renew the deep water a week later at station KSK1 (324 m) and then, after another week, at station FOC1 (358 m; Figure 7). Macdonald et al. (1983b) observed a summer renewal in progress in June, 1978, and reported that it proceeded along the fjord system over the course of several weeks, with Gardner Canal being the last to receive the inflowing water.

WATER PROPERTIES AND PARTICLES

Oxygen

The concentration of dissolved oxygen in seawater is controlled by primary production and remineralization, together with atmospheric exchange and the physical circulation. In Douglas Channel, the largest seasonal range in oxygen occurred within the top 50 m (Figure 8). Oxygen was high year-round in the surface water (uppermost 20 – 100 m, depending on location and season), ranging from 6 mL/L in July to a maximum of 12 mL/L in April that was likely due to high primary productivity. (1 mL/L = 44.6 μmol/L.) In July and October, the elevated oxygen was restricted to the uppermost ~ 20 m, associated with the brackish, outflowing surface water. Macdonald et al. (1983b) observed a subsurface oxygen maximum just below the outflowing surface layer in 1978, associated with a subsurface chlorophyll maximum, but this was not observed during 2013-2014.

Oxygen in the intermediate layer (50-200 m) is consumed by respiration and replenished by downward mixing and diffusion from the surface during storms, as well as by intrusion from Hecate Strait. The concentration of dissolved oxygen in the intermediate layer (50-200 m) was highest in April (4-7 mL/L), lowest in July (2.5 – 4 mL/L), and intermediate in October (3.5 – 4 mL/L). It is possible that at certain times of the year, the intrusions from Hecate Strait might decrease the concentration of oxygen in the intermediate layer, but at the times of measurement (July, April and October), this was not the case. We lack a continuous record of oxygen concentration at mid-depths, but the temperature and salinity records indicate a tight coupling with water properties in Hecate Strait at mid-depth (Figure 5), which might also include oxygen. New mid-depth oxygen sensors deployed in July 2014 should help to determine the controls on oxygen in this layer.

In the deep water (336 m sensor at station FOC1) the concentration of dissolved oxygen varied seasonally by about 1 mL/L, from a low of 2.5 mL/L in February - May to a high of 3.5 mL/L in mid-June (Figure 7e). After the mid-June peak, there was a rapid decline of 0.7 mL/L by mid-August, followed by a slower decline of 0.3 mL/L over the subsequent six months. The slow, six-month decline likely represented remineralization of organic matter in the bottom water, while the initial, rapid decline might have resulted either from rapid remineralization of a summertime pulse of organic matter, or from diffusive mixing of more oxygen-depleted water from above, or both.

Deep-water renewal is not instantaneous throughout the fjord system but progresses along Douglas Channel over a period of several weeks, as illustrated by the temperature and salinity records described above. This results in temporary pockets of low-oxygen water, such as those observed at the Kitimat end of the inlet in April and July 2014 (Figure 8). In June 2014, about

one week after relaxation of downwelling was observed at the Hecate Strait mooring, we observed a deep-water renewal by colder, saltier water at the bottom of Douglas Channel at the KSK1 site. (There was no oxygen sensor at KSK1.) About a week after that, the renewal in temperature and salinity reached the FOC1 site, where it was coincident with an increase in dissolved oxygen (Figure 7d,e). The concentration of dissolved oxygen at FOC1 increased from 2.5 mL/L to 3.5 mL/L over a period of 7 days.

In contrast, in 1978 Macdonald et al. (1983b) observed that the June renewal reduced the concentration of oxygen in the deep water of the Channel from 4.5 mL/L to 3.5 mL/L. With only two data points, it is impossible to determine whether the pre-renewal concentration of oxygen in the deep water of Douglas Channel has really declined by 2 mL/L since 1978, or whether one or both of these years was anomalous. It is surprising that the concentration of oxygen in the replacement water was the same in both years, given the global decline in subsurface oxygen over the last few decades. Possibly, while the background concentration has changed since 1978, the 2014 renewal water came from a shallower depth. The temperature and salinity data give some support to that interpretation: the salinity after replacement appears to have been about the same in the two years, while the temperature was higher in the 2014 water, making it less dense. Additional oxygen sensors deployed in July 2014 at the entrance to Douglas Channel and further sensors scheduled to be deployed in July 2015 should help to determine the inter-annual variability of deep-water oxygen renewal.

The rapid change in deep-water oxygen over the two months following the 2014 renewal was also observed in 1978, but like that of the renewal itself, the direction of change was opposite in the two cases. The opposite changes at these two times support the hypothesis that the late summer decline in deep-water oxygen in 2014 was driven by mixing, not by rapid remineralization of organic matter from above, because if remineralization had been the key process, then the direction of the change should have been the same in 1978.

Nutrients and primary production

Nutrient concentrations are low at the surface and increase with depth as the nutrients are regenerated (Figure 9). In April 2014 the concentration of nitrate + nitrite in surface water was lower (~ 7.5 μmol/L) at the Kitimat end of the channel than at the seaward end (~ 20 μmol/L), suggesting that, as in many estuarine systems, the main supply of nutrients into the channel was entrainment of subsurface water, not direct discharge from the rivers. By July, however, nutrients had been drawn down all along the channel, but much more so at the seaward end (~ 0 μmol/L) than at the Kitimat end (~ 5 μmol/L). The stronger stratification in July would have restricted the resupply of nutrients to the surface from below. Since the rivers are poor in nitrogen, relative to phosphate (Macdonald et al., 1983b), the surface nitrate at the landward end was likely sustained by entrainment caused by the outflow of brackish water across the surface, rather than by direct discharge from the Kitimat River.

The inflowing water that replaces the bottom water in the summer is nutrient rich, so the summer replacement further increases the concentration of nutrients at the bottom of the Channel. The autumn windstorms likely mix nutrients from the intermediate layer into the surface water.

Phytoplankton in Douglas Channel appear to be nutrient-limited in the summer, as evidenced by a reduction in silicate and depletion to zero of N in the surface layer in the summer.

Suspended and sinking particles

The outflowing surface water (uppermost 5 - 20 m) in Douglas Channel is turbid, while the subsurface water is relatively clear (Figures 10 and 11). The surface turbidity is particularly high in May-June, during the freshet of the snowfed rivers, and episodically during the autumn and winter following heavy rain. During the October 2014 cruise, strong rainfed runoff was observed in numerous rushing creeks and waterfalls along the steep sides of the channel. The surface water was even more turbid than that near the Kitimat River in July. However, it appeared that the turbidity in October was confined to a very thin surface layer < 50 cm thick, while it extended to 10 m in the summer. We lack measurements of transmissivity / beam attenuation coefficient within the uppermost 2 m of the water column, but we do have some particle concentration data collected by filtration of seawater from the uppermost 50 cm and 2 m (Table 1).

Particle concentrations in the uppermost 50 cm varied over a range of 14.0 – 20.7 mg/L in April, July and October of 2014 at the mid-channel and seaward stations (Table 1). The seasonal variation was much wider at station Doug-4, near the Kitimat River, ranging from 6.3 mg/L in July to 47.8 in October. The largest increase between July and October was in the concentration and proportion of the largest size fraction of particles (those retained on the filter with a nominal pore size of 1.2 μm).

Table 1. Suspended particle concentrations in Douglas Channel surface water (top 0.5 m) in April, July and October, 2014. Station locations are shown in Figure 1. The mid-channel station (Doug-40 / KSK1 / Doug-45) varied among cruises, as noted above, and in October the Squally Channel station SC-61 replaced SC-69.

	Doug-4	FOC1	Doug-40	SC-69
April				
>1.2μm	6.2	5.6	6.8	6.6
0.7-1.2 μm	7.5	6.1	8.1	7.6
0.2-0.7 μm	2.3	3.1	3.3	3.2
April Total	**16.0**	**14.8**	**18.3**	**17.4**
July			KSK1	
>1.2 μm	2.6	-	7.5	8.1
0.7-1.2 μm	2.0	-	6.4	8.6
0.2-0.7 μm	1.7	-	2.7	3.9
July Total	**6.3**	**-**	**16.7**	**20.7**
October			Doug-45	SC-61
>1.2 μm	32.8	6.2	7.0	6.4
0.7-1.2 μm	9.5	5.5	8.0	8.4
0.2-0.7 μm	5.6	2.3	2.8	3.3
October Total	**47.8**	**14.0**	**17.8**	**18.1**

Despite the very high concentration of particles measured in surface water in October near the mouth of the Kitimat River, the sinking particle flux at 50 m at station FOC 1 (Figure 12) peaked in mid- to late May of 2014, with the onset of freshet in the Kitimat and Kemano Rivers. There were also smaller peaks observed at the beginning of several short river discharge spikes in October and January, associated with heavy rainfall (Figure 3). The rain-related particle flux peaks (1 - 1.5 g $m^{-2}day^{-1}$) were considerably smaller than the peak associated with the onset of the May freshet (5 g $m^{-2}day^{-1}$). The total annual particle flux at 50 m over July 2013 – June 2014 was 438 g $m^{-2}day^{-1}$. This falls within the range estimated by Macdonald (1983a) of 200 – 3700 g m^{-2} yr^{-1}.

Macdonald (1983a) reported that the concentration of particles in the water column was more important than the size distribution for determining sinking rate: fine particles do not sink at all until they flocculate. (The particles observed in Douglas Channel in 1978 were larger below the surface, indicating flocculation.) Flocculation reaches a secular equilibrium, in which new floccs form at about the same rate as the existing ones sink. Consequently, sinking rate is controlled by the concentration of particles, since floccs can form faster at higher particle concentration. Zooplankton ingest some inorganic and organic particles, and their fecal pellets sink, but Macdonald suggested that in Douglas Channel flocculation far exceeded fecal pellet formation as a mechanism for particle sinking. To test the hypothesis that particle concentration is the deciding factor in the rate of particle flux in this system, we will require further data from the time of maximum particle flux: late May. We plan to sample water and particles in Douglas Channel and in the Kitimat and Kemano Rivers during late May of 2016.

The sinking particles in Douglas Channel are primarily inorganic. Organic carbon made up 5 -13 % by weight of the total particulate flux (Figure 13) at 50 m at station FOC1. The maximum organic carbon flux coincided with the peak particle flux in late May, while the concentration of organic carbon was lowest at that time. The concentration of organic carbon was highest in August-September and during one episode of high organic carbon flux in November, 2013. The average organic C flux into the traps was 0.1 gC m^{-2} day^{-1}, which amounts to 37 gC m^{-2} yr^{-1}. Depending on how much of that carbon was remineralized in the water column, this flux could have been sufficient to support the observed consumption of oxygen in the deep water.

The residence time of surface water is about 7 days in Gardner Canal and 5 – 30 days in Douglas Channel (Macdonald et al., 1983a). Whether particles will sink or be advected out of the system depends on whether the particles fall out of the surface layer before the surface water reaches the outer ocean.

SUMMARY

Water properties in Douglas Channel are controlled by physical circulation, primary production and remineralization of organic matter. Dissolved oxygen was high at the surface year-round (6 mL/L in October to 12 mL/L in April) and declined with depth. Deep-water oxygen was low (≥ 2.5 mL/L) in spring 2014, but not hypoxic (< 1.4 mL/L). Deep-water renewal in June 2014 increased the concentration of oxygen by ~ 1 mL/L, followed by a rapid decline likely caused by mixing of more oxygen-depleted water from above. In contrast, the deep-water renewal observed in June 1978 decreased the concentration of oxygen in the deep water. It is unclear whether one or both of those years was anomalous or whether conditions have changed

substantially since 1978. We have redeployed the mooring and added more oxygen sensors at other depths and at other locations to continue to investigate this question.

Nutrient profiles were opposite to those of oxygen in surface and intermediate waters: low at the surface, where they had been consumed by phytoplankton, and increasing with depth, as nutrients were remineralized. By July, nitrate was depleted at the seaward end of the transect, while it was low but not entirely depleted at the landward end, likely because of the continuing supply of nitrate due to entrainment of subsurface water by the outflowing river plumes. Deep-water renewal likely increases the concentration of nutrients in the deep water of Douglas Channel at the same time as it increases the concentration of oxygen, but we lack data at that time of year.

The outflowing surface water was more turbid than the subsurface water year-round. Of the three months surveyed (April, July and October), turbidity was especially high and tightly constrained to the near-surface in October, when the surface water was very strongly stratified as a result of intense runoff of rainwater from the channel sides and via the rivers. Suspended particles have not yet been measured at freshet (late May), but the sediment trap record shows that the flux of sinking particles is highest at that time. We will endeavour to measure particle concentrations and distributions during freshet in 2016.

Samples have been also collected for analysis of dissolved organic carbon, coloured dissolved organic matter, stable isotopes of oxygen, dissolved inorganic carbon, alkalinity and chlorophyll. Analysis of those samples and interpretation of the data are in progress.

Remaining research questions

The geochemical parameters most critical to the fate and effects of spilled oil in the Douglas Channel and approaches to Kitimat are subsurface oxygen and suspended and sinking particles. Work to date has yielded a general view of the cycling of oxygen and particles, but the effects of spilled oil will likely depend on details. The following questions remain to be addressed over the next two years:

1. What is the natural range of subsurface oxygen in this environment, including the concentration of oxygen in the upwelled water that replaces the deep water annually in June?

2. How much of the O_2 drawdown in deep water is driven by deep-water renewal / mixing, and how much by in situ consumption during the remineralization of organic matter?

3. How does intruding water from Hecate Strait affect the concentration of oxygen at intermediate depth at different times of the year?

4. Could a large oil spill cause subsurface waters to become hypoxic, and, if so, for how long?

5. What is the seasonal and spatial distribution of suspended particle concentration and composition?

6. Does the seasonal variation in particle flux at 50 m reflect that in particle concentration at the surface?

7. Is the seasonal timing of sinking particle flux the same every year?

8. Can we determine the distribution and concentration of particles from satellite imagery?

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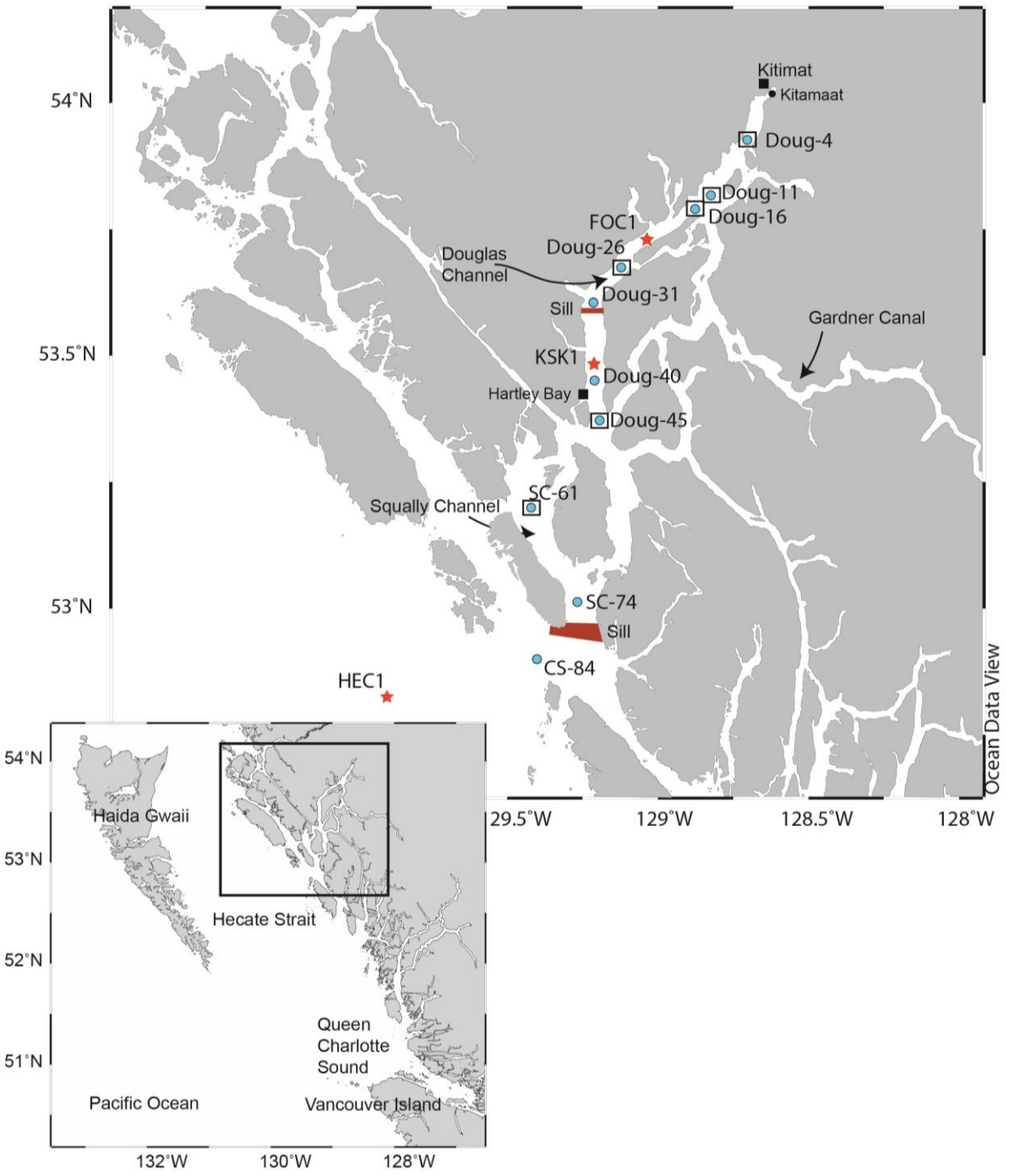
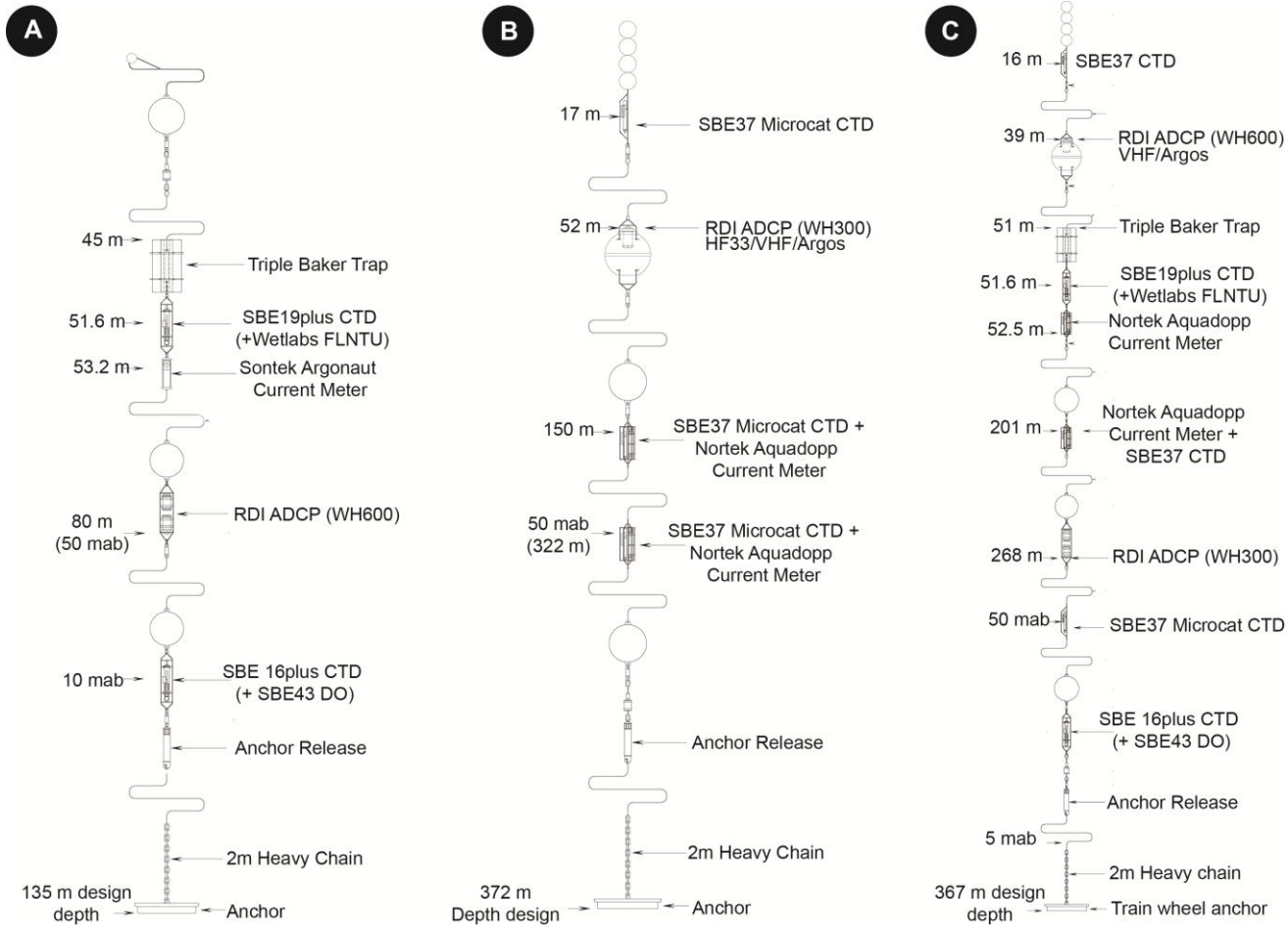


Figure 1. Map of station locations in Douglas Channel and Hecate Strait. Blue dots represent rosette water sampling stations; squares are sediment grab sample stations. The red stars represent the positions of the three moorings. Rosette and grab samples were also collected at the mooring sites.



HEC1 **KSK1** **FOC1**

Figure 2. Diagrams of the three moorings, showing design depth and instrumentation. The moorings were deployed at the three sites indicated in Figure 1.

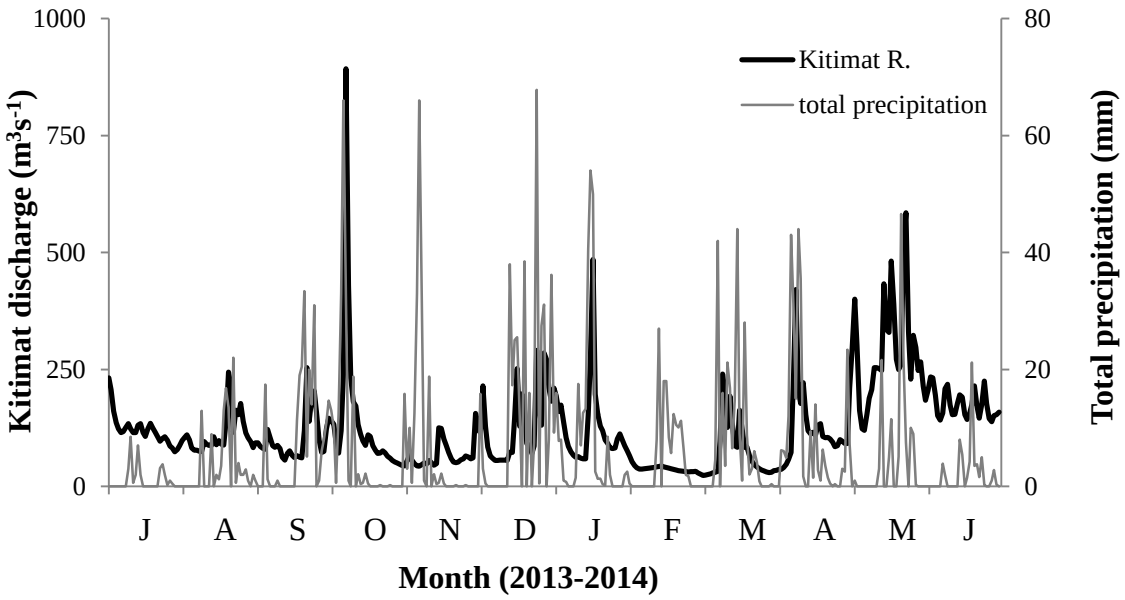


Figure 3. Discharge of the Kitimat River at station 08FF001 for July 2013 – June 2014, and total rainfall at Kitimat for the same period. Environment Canada, Water Survey of Canada and Climate Services data. Available online at: http://wateroffice.ec.gc.ca/search/search_e.html?sType=h2oArc and http://climate.weather.gc.ca/, respectively.

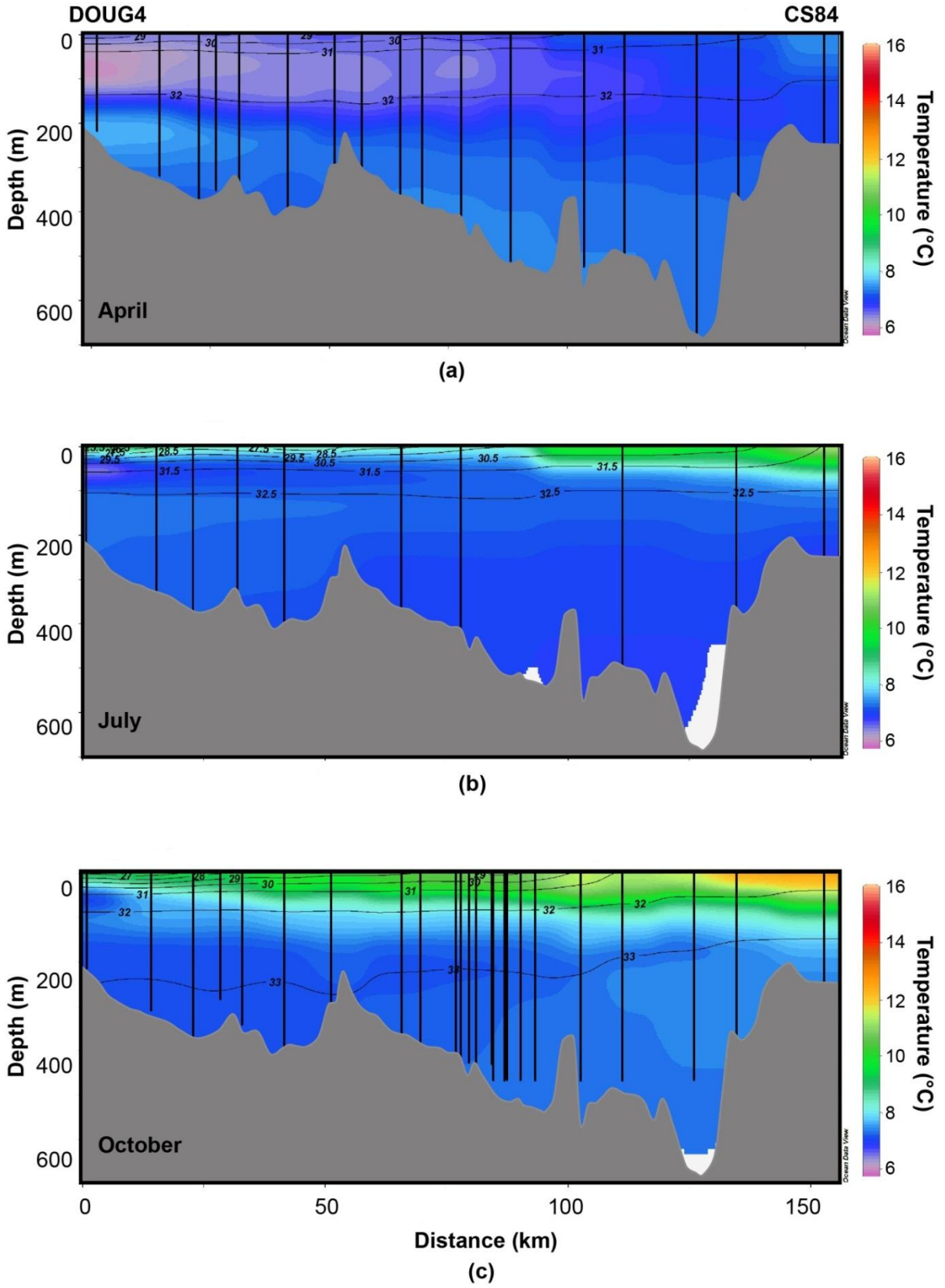


Figure 4. Seawater temperature (ºC), shown in colour, overlain with salinity contours for a transect down the centre of the channel from station Doug-4 to station CS-84 (Figure 1) for (a) April, (b) July and (c) October, 2014.

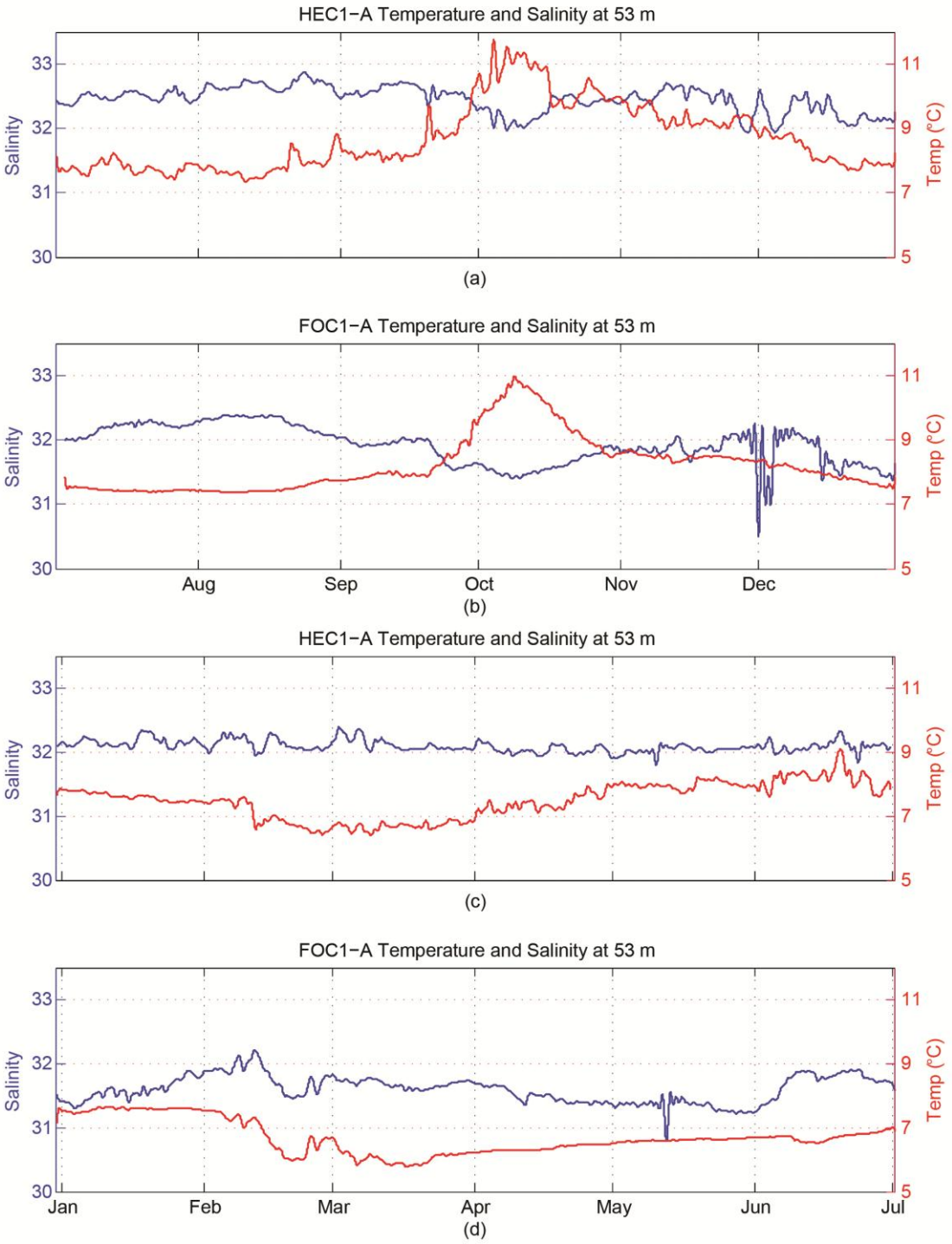


Figure 5. Mid-depth temperature and salinity records for July 2013 – January 2014 (plots a, b) and January – June 2014 (plots c,d) at stations HEC1 and FOC1 at 53 m. Axis tick marks show the first day of the month indicated. Data were collected hourly and have had a 30-hour filter applied for display.

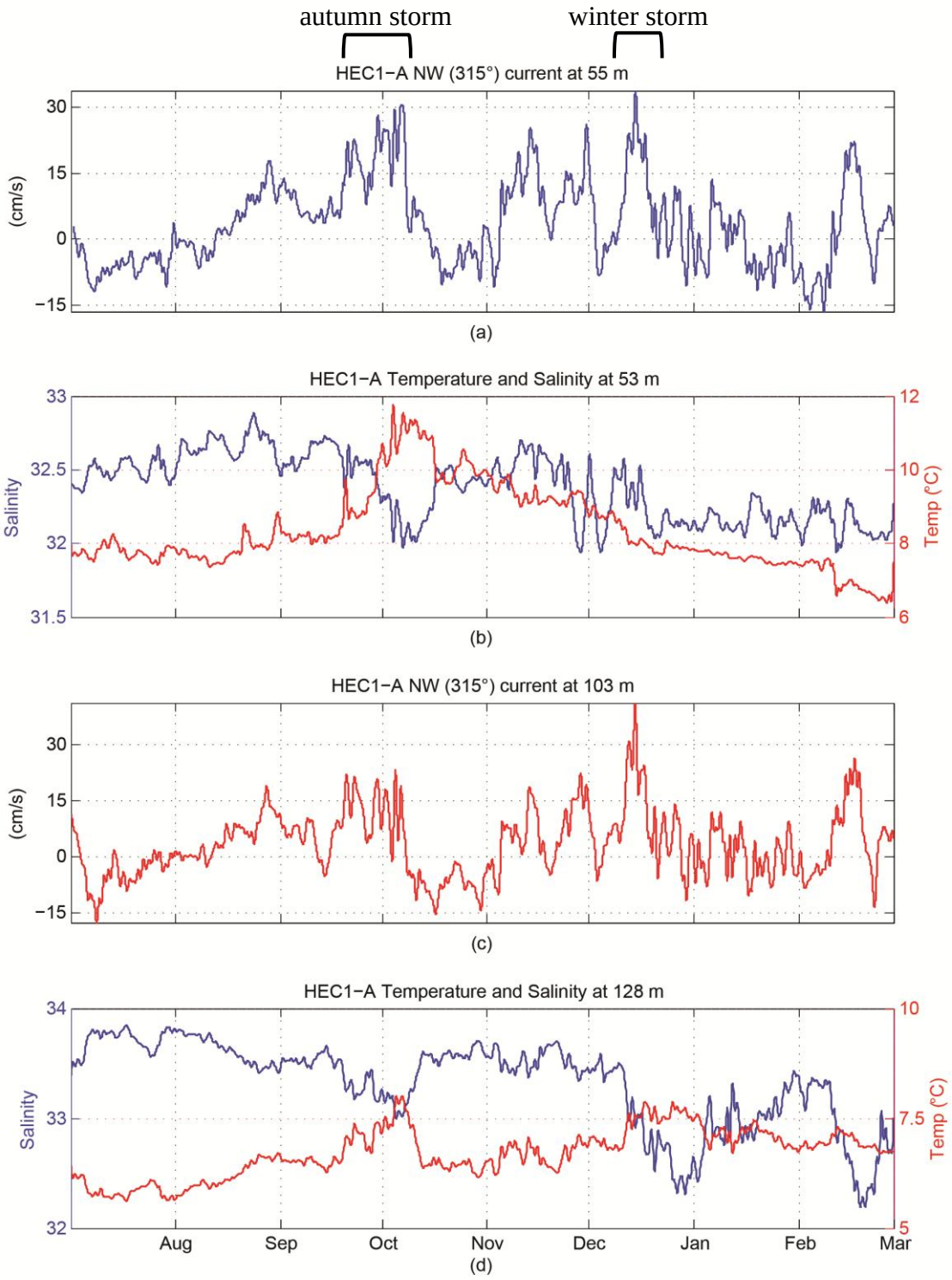


Figure 6. Current, temperature and salinity over the water column at station HEC1, July 2013 – February, 2014. (a) northwestward current at 55 m, (b) temperature and salinity at 53 m, (c) northwestward current at 103 m, (d) temperature and salinity at 128 m. Data were collected hourly and have had a 30-hour filter applied for display.

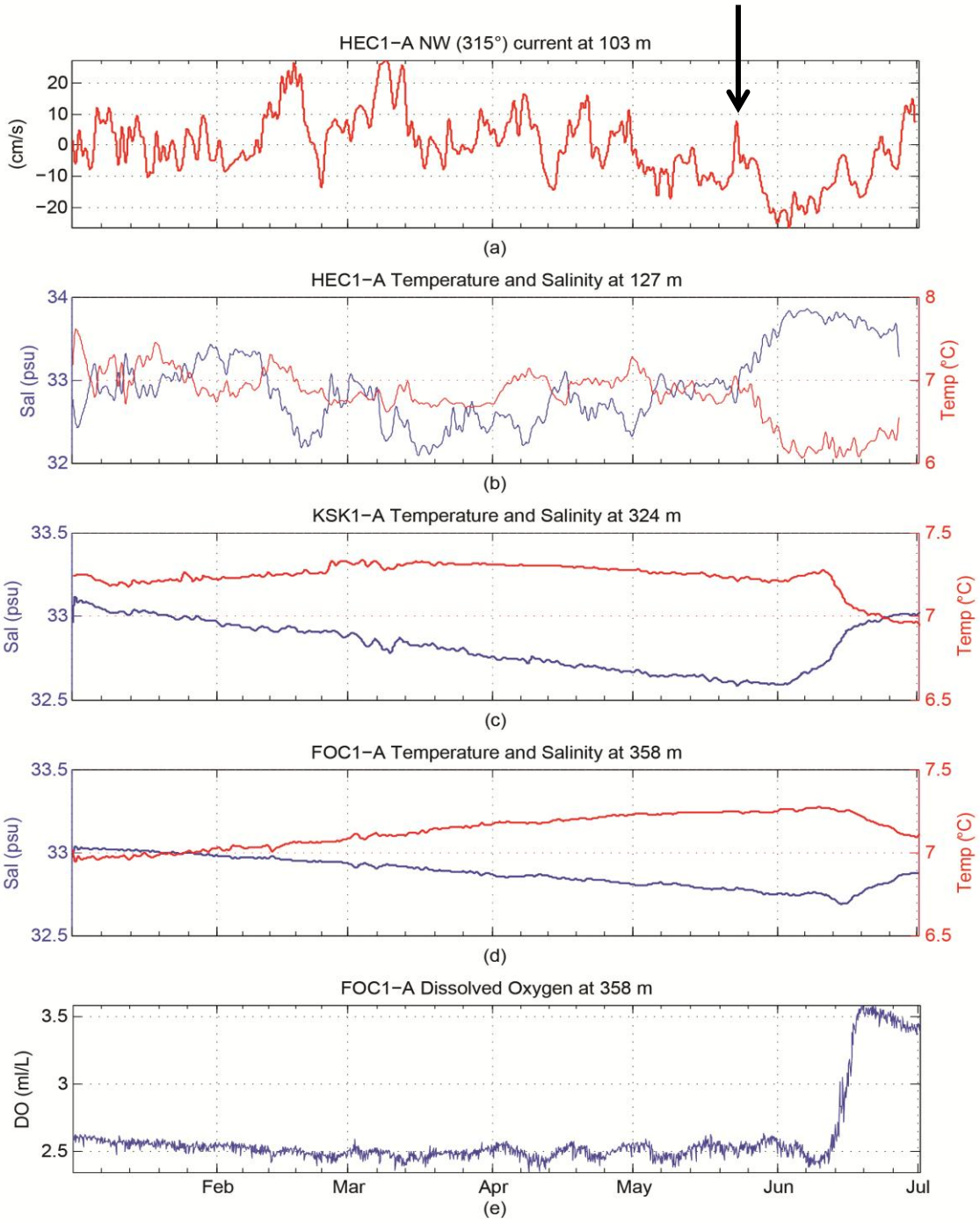


Figure 7. Deep-water renewal in Douglas Channel. (a) northwestward current at 103 m at HEC1 indicates relaxation of downwelling (black arrow), causing (b) increase in salinity and increased in temperature near bottom at HEC1; (c) replacement bottom water with increased S and decreased T arrive at station KSK1 about a week later; (d) replacement water arrives another week later at station FOC1, bringing (e) a pulse of oxygen-rich water. Data were collected hourly and have had a 30-hour filter applied for display.

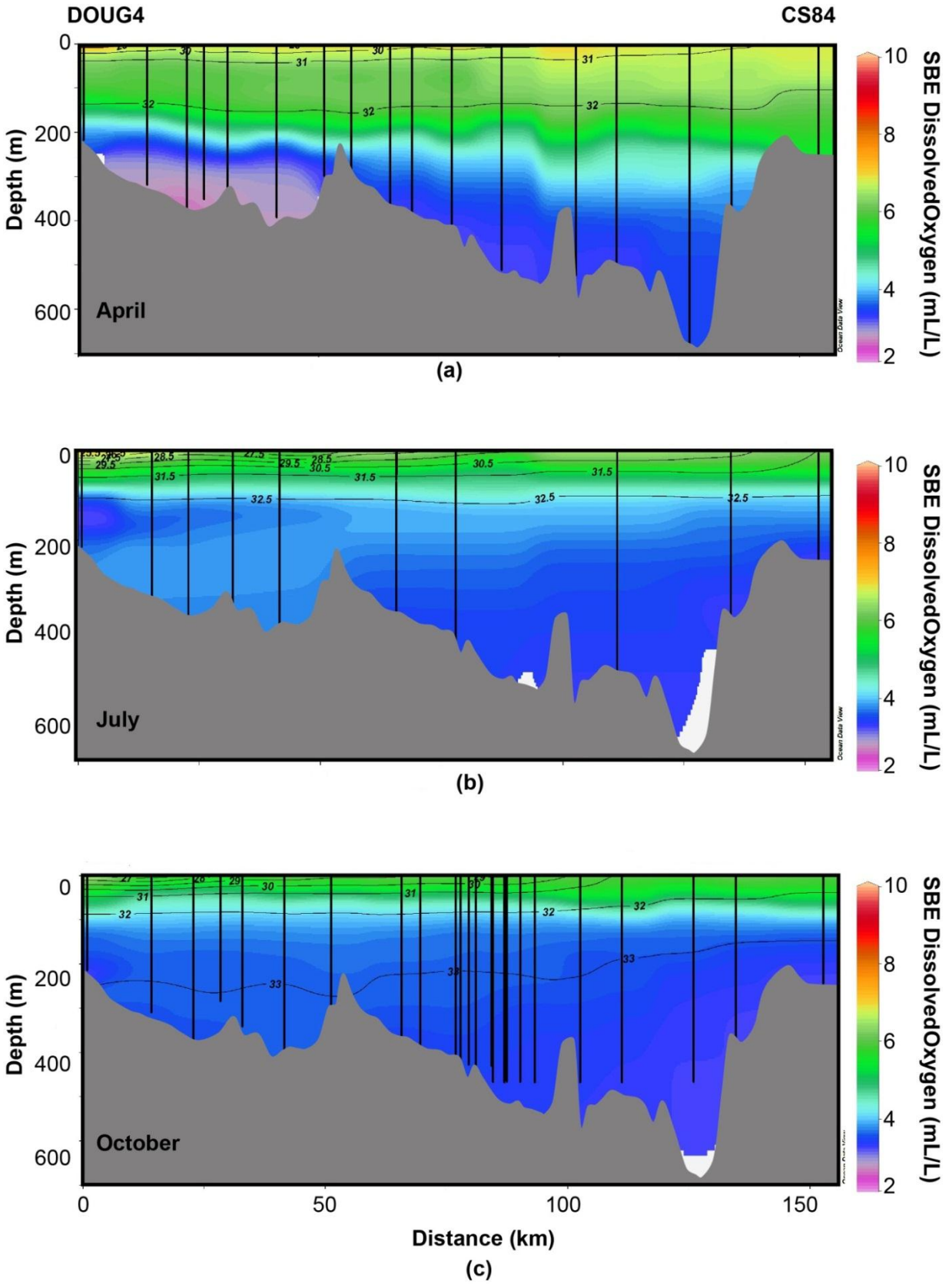


Figure 8. Dissolved oxygen concentration (mL/L), shown in colour, overlain with salinity contours for a transect down the centre of the channel from station Doug-4 to station CS-84 (Figure 1) for (a) April, (b) July and (c) October, 2014.

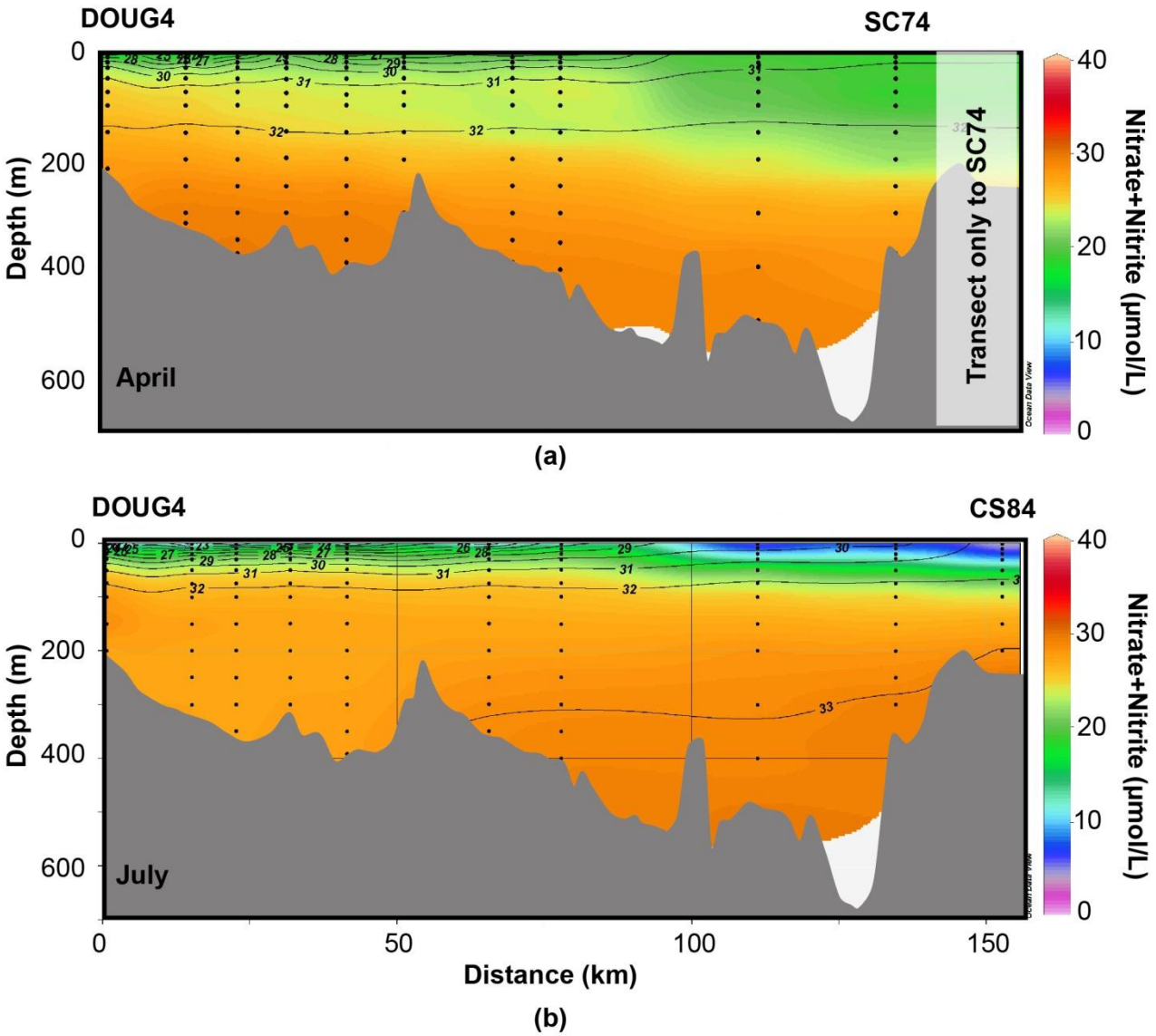


Figure 9. Nitrate + nitrite concentration (mmol/L), shown in colour, overlain with salinity contours for a transect down the centre of the channel from station Doug-4 to station CS-84 (Figure 1) for (a) April and (b) July, 2014.

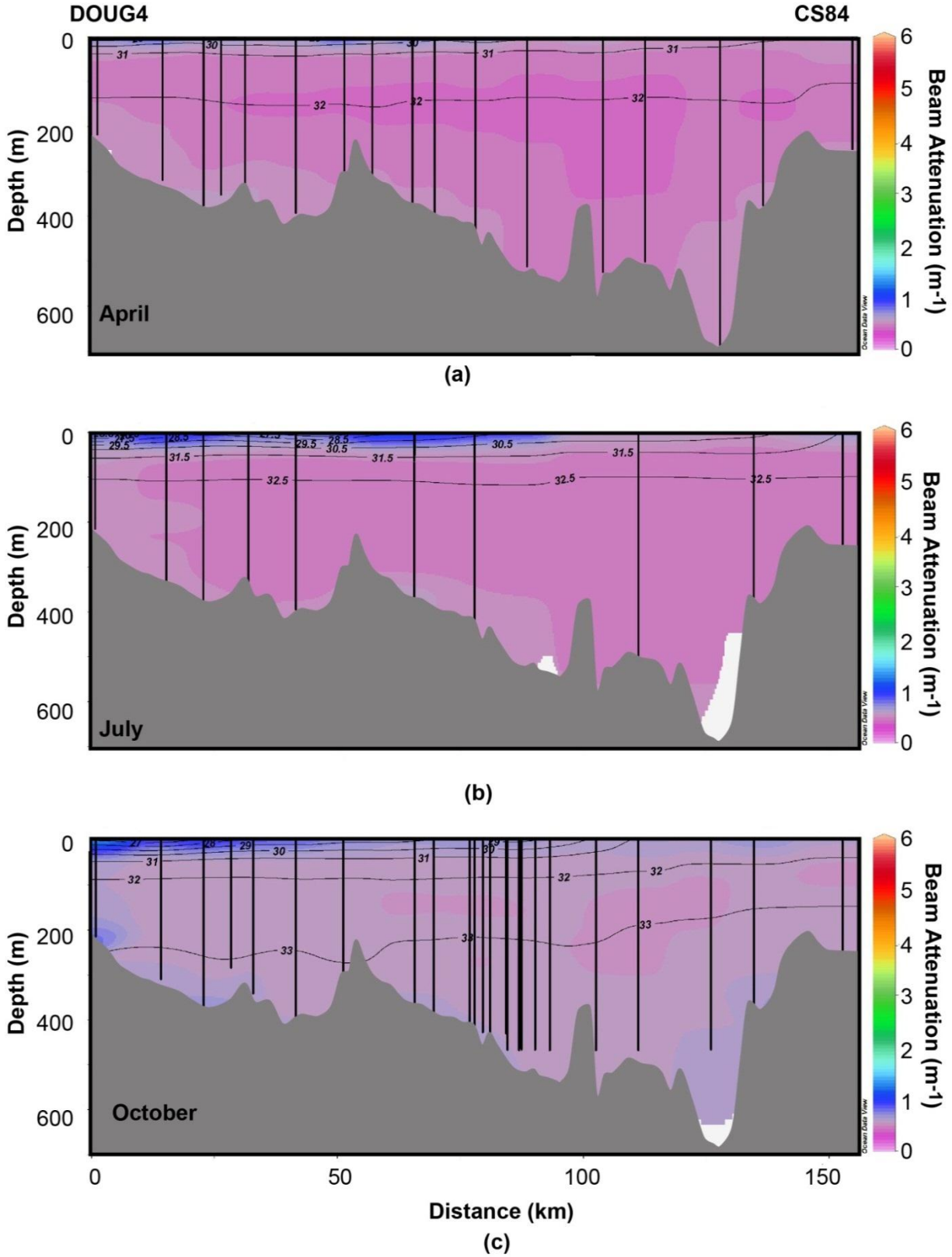


Figure 10. Beam attenuation coefficient (m^{-1}), calculated from transmissivity, shown in colour, overlain with salinity contours, for a transect down the centre of the channel from station Doug-4 to station CS-84 (Figure 1) for (a) April, (b) July and (c) October, 2014.

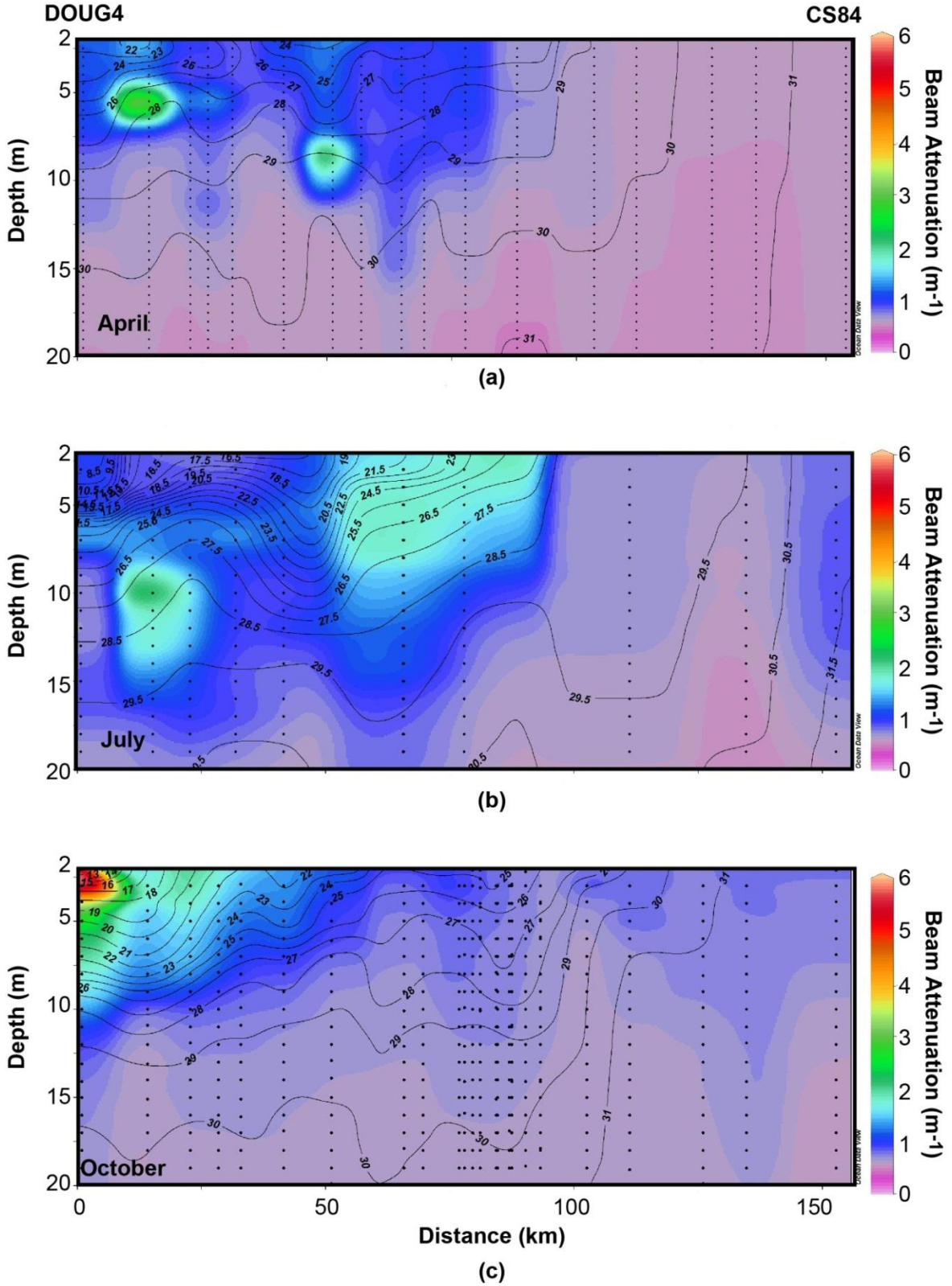


Figure 11. Uppermost 20 m only. Beam attenuation coefficient (m^{-1}), calculated from transmissivity, shown in colour, overlain with salinity contours, for a transect down the centre of the channel from station Doug-4 to station CS-84 (Figure 1) for (a) April, (b) July and (c) October, 2014.

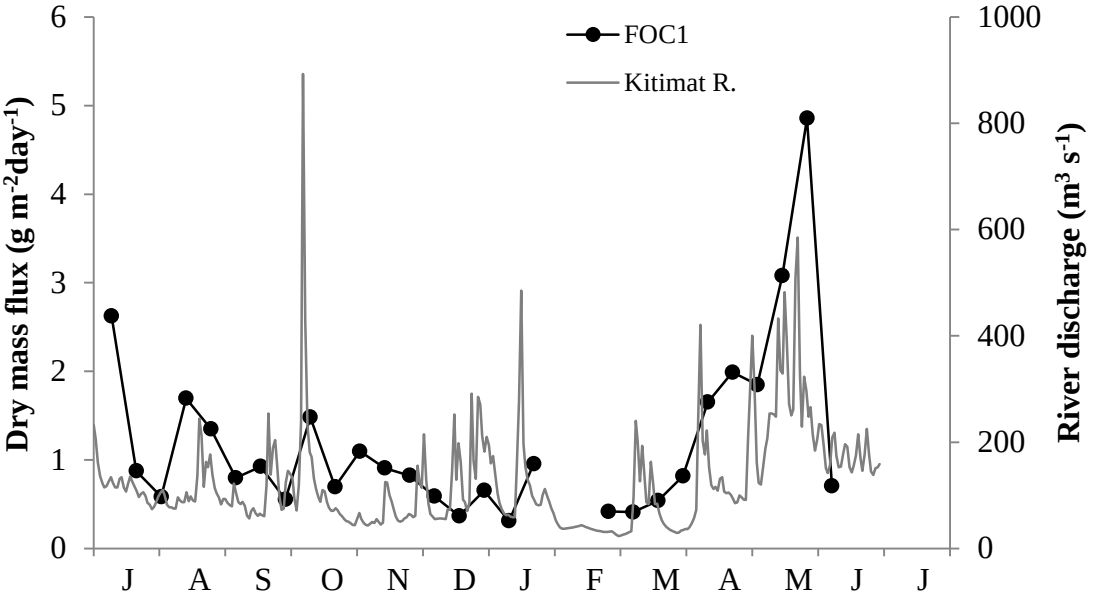


Figure 12. Sinking particle dry mass flux into sediment trap at 50 m depth at station FOC1, and Kitimat River discharge, July 2013 – June 2014.

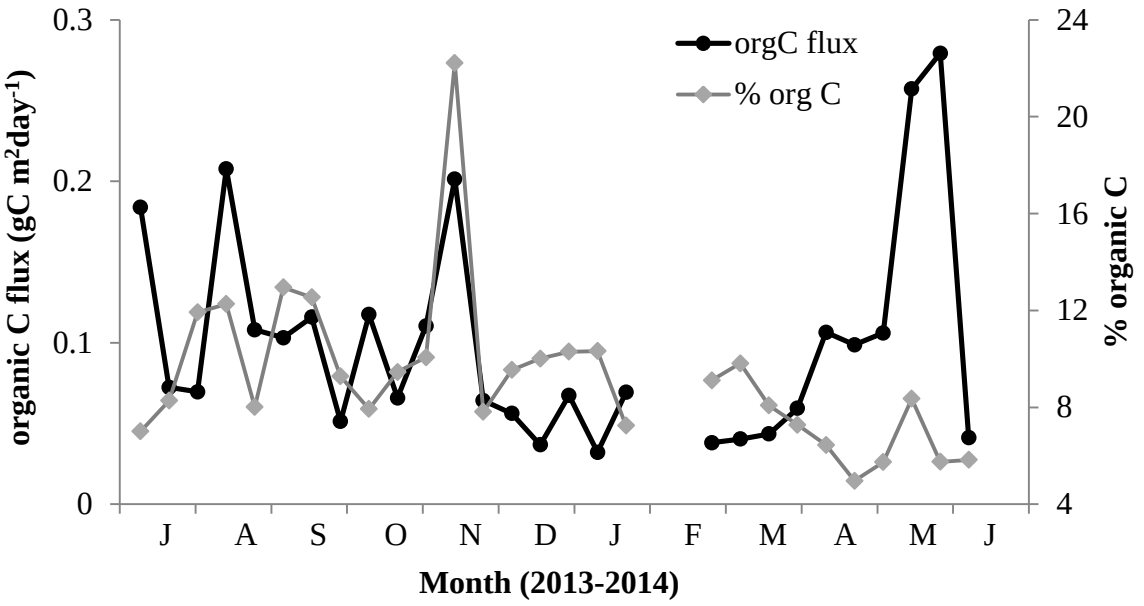


Figure 13. Organic carbon flux and concentration in sediment trap at 50 m depth at station FOC1, July 2013 – June 2014.