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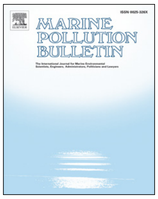

Fate of diluted bitumen spilled in the coastal waters of British Columbia, Canada

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ABSTRACT

There is public concern about the behaviour of spilled diluted bitumen (dilbit) in marine and estuarine waters. We provide a preliminary assessment of the results of laboratory experiments and models, in the context of environmental conditions in the coastal waters of British Columbia. Most dilbit spilled within this region would likely float at the surface and be transported to shore by winds and currents. Fresh dilbit is too light to sink in coastal waters. Highly weathered dilbit could sink where salinity is less than 14, typically only near river mouths and in the top 1–3 m of fjords after heavy rainfall. Subsurface plumes of weathered dilbit could re-emerge at the surface. Sinking oil-particle aggregates are unlikely to form in coastal waters. However, dilbit could be entrained below the surface by wave mixing during storms and to depths of 150 m by coherent mixing in the Haro Strait tidal convergence zone.

1. Introduction

Diluted bitumen ("dilbit") is transported through the Strait of Georgia from the Westridge Marine Terminal in Burrard Inlet (near Vancouver, Fig. 1) to the open ocean. In addition to this site, other pipelines have been proposed to bring dilbit to the tideline in Kitimat and Prince Rupert, on the central and northern coast of B.C. Proposed and existing tanker routes that service these pipeline termini (Fig. 1) pass through the southern Strait of Georgia and Juan de Fuca Strait (which form the northern part of the Salish Sea), Douglas Channel (from Kitimat) and Prince Rupert Harbour and Chatham Sound (from near Prince Rupert).

The amount of dilbit transported will increase significantly with the approval of pipeline expansion projects. About 5 tankers a month currently transport dilbit from the Westridge Marine Terminal. With the recent regulatory approval of Canada's Trans Mountain pipeline expansion project, this number will increase to 34 tankers per month (NEB, 2016; https://www.cbc.ca/news/politics/tasker-trans-mountain-trudeau-cabinet-decision-1.5180269).

There is intense public concern over the possible biological effects of a spill, particularly because it is not clear how dilbit would behave if it were spilled in B.C.'s coastal waters. Dilbit is composed of heavy bitumen mixed with a lighter oil to reduce its viscosity, allowing it to flow through pipelines. As dilbit weathers, the lighter component evaporates or is broken down, and the density of the remaining oil increases (National Academies of Sciences, Engineering, and Medicine, 2016; King et al., 2017a,b).

Dilbit spilled into fresh water has been observed to sink. In July 2010, a pipeline crossing the Kalamazoo River in Michigan State ruptured, spilling dilbit into the river during a period of high river flow. Oil-particle aggregates (OPA) formed, and some (10%) of the dilbit sank to the bottom sediments, complicating the remediation effort (Lee et al., 2015).

Although waters near urban areas like the B.C. lower mainland have elevated background levels of hydrocarbons in the water column and sediments (Yunker et al, 2015), significant oil spills are rare. To date there has only been one small spill of dilbit in coastal B.C. In 2007, 224 m^3 of dilbit was spilled in Burrard Inlet, off Vancouver. The oil

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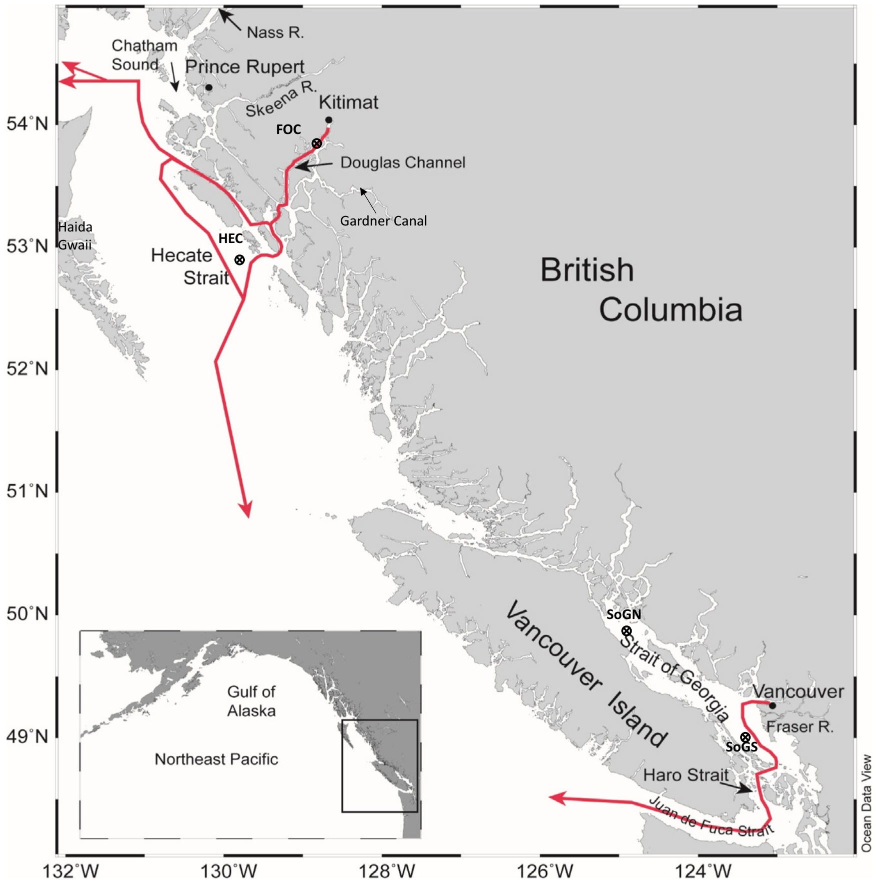

Fig. 1. Map of study area. Red arrows represent current and proposed shipping routes from Kitimat and Vancouver (Westridge Marine Terminal). Routes modified from NEB (2016) and Govt of Canada (2012). FOC, HEC, SOGN and SOGS indicate mooring locations. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

floated, and 210 m^3 of the oil (94%) was recovered (Govt of Canada, 2013). Intertidal sediments were oiled, but because the oil did not sink, the subtidal sediments were not affected. However, the environmental and logistical conditions for Burrard Inlet - calm sea-state conditions with no waves and low particle concentrations at the time of the spill, together with close proximity to an emergency response centre– are not representative of those throughout the whole coast. It would be much more difficult to contain and recover spilled dilbit effectively in the waters of British Columbia's central and north coast, which are remote from large population and oil spill response centres, and more susceptible to large storm events that would hamper clean-up operations. Response time and the availability of suitable equipment for its recovery are the primary factors controlling the success of all spill response operations (Lee et al., 2015).

Fresh dilbit can harm marine animals, including fish embryos and juvenile sockeye salmon, in a manner similar to that of other petroleum hydrocarbons including crude oils (Alderman et al., 2017). Marine mammals are also vulnerable, particularly killer whales, sea otters, sea lions and baleen whales (Jarvela Rosenberger et al., 2017). The lighter components are thought to be more acutely toxic, while the heavier components can have chronic effects (Lee et al., 2015). Because there has only been one small dilbit spill in marine waters to date (Govt of Canada, 2013), and most of the product was physically recovered, there is no comprehensive case study on the biological effects of dilbit spilled in the ocean.

Recently, the Royal Society of Canada convened an expert panel to summarize the information available on the behaviour and environmental effects of crude oils, including dilbit, and to produce recommendations for high priority research questions. The panel concluded that environmental characteristics were more important than the properties of the particular oil in the event of a spill (Lee et al., 2015).

In support of environmental risk assessments, this paper provides a preliminary assessment of the likely fate of dilbit spilled in BC coastal waters. We review results of experiments and models of the properties and behaviour of dilbit and place these in the context of new and previously-published ocean observations in this region. In particular, we address the questions of where and under what conditions spilled dilbit would sink, and where it would likely go. Since research on the behaviour of dilbit is relatively new, we also provide a brief list of data gaps.

2. Methods

We reviewed recent experimental data and model results about the properties and behaviour of dilbit, as well as published oceanographic data on water circulation, surface currents, suspended particle concentrations, sinking particle rates, and in situ oxygen concentrations. To these results, we have added new data on suspended particle concentrations, surface seawater salinity and temperature in several areas of the B.C. coast.

2.1. New suspended particle data

Suspended particles were collected in Douglas Channel, the Strait of Georgia and Chatham Sound (Fig. 2). The Douglas Channel particles were collected during survey cruises aboard the *CCGS John P. Tully* in July and October/November, 2015, and March, May and July, 2016. In May 2016, particles were also collected from rivers and streams that drained into the Kitimat/Douglas Channel fjord system. Suspended particles in the Strait of Georgia were collected during surveys aboard the *CCGS Vector* in June, September and October, 2016, and April and June, 2017. The Chatham Sound samples were collected during a survey aboard the *CCGS John P. Tully* in August, 2018.

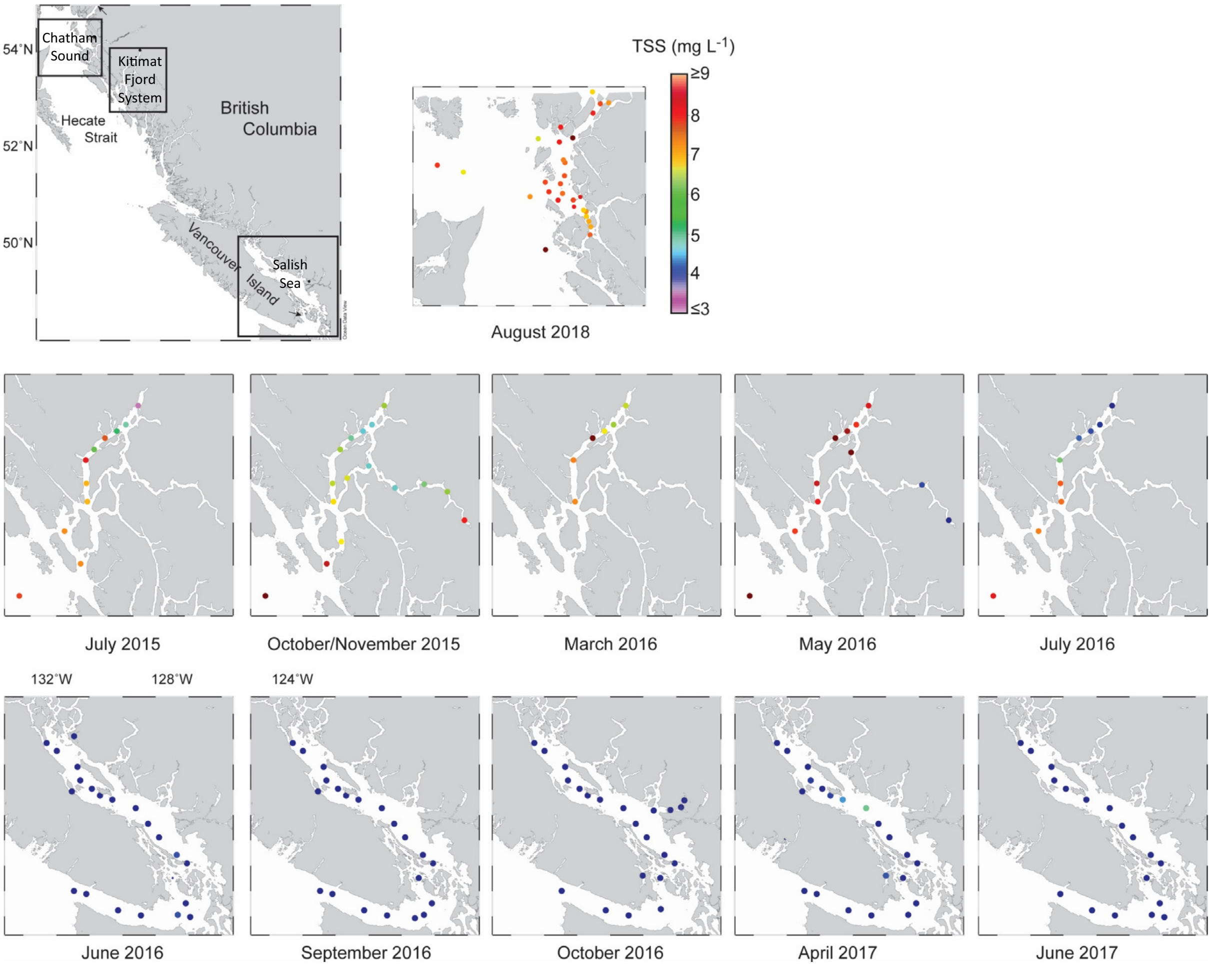

Fig. 2. Surface particle concentrations (mg/L) measured in Chatham Sound (top panel), the Kitimat/Douglas Channel fjord system (middle row), and the Salish Sea (Strait of Georgia, Haro Strait and Juan de Fuca Strait; bottom row). The range is generally 3–9 mg/L, with occasional higher and lower values. The maximum value in Chatham Sound was 11.5 mg/L in August 2018. The maximum in Douglas Channel was 17.5 mg/L in May 2016.

Surface seawater samples were collected in 10-L Niskin bottles in a standard 24-bottle rosette. Each Niskin bottle was completely emptied into a carboy and swirled to mix the particles throughout the sample, in case of settling within the Niskin bottle. The water was then subsampled into three sub-replicate 1 L polycarbonate bottles. Each 1L subsample was filtered through a 25-mm diameter, pre-baked (450 °C for 5 h) and pre-weighed GE Whatman GF/F filter (nominal pore size 0.7 µm). Samples were dried to constant mass in a desiccator and weighed on a Sartorius LE225D model balance ($\pm 1 \times 10^{-5}$ g). Particle concentration (mg/L) was determined as the quotient of the increase in dry sample mass and the volume filtered.

In case the surface Niskin bottles (usually tripped at ≤ 1.5 m depth) missed very near surface stratification of particles, we also collected some surface samples using a bucket suspended over the side of the ship during the first two cruises. No significant difference was observed between the particle concentrations measured in the bucket and those measured in the surface Niskin (data not shown), so only Niskin bottles were used subsequently, except for samples from rivers. River samples were collected from a small boat in mid-stream in three replicate 1 L polycarbonate bottles during the May 2016 cruise. The samples were filtered on return to the ship.

The proportion of inorganic matter was determined by loss-on-ignition. Dry samples on filters were weighed and then baked at 450 °C for 5 h. The baked samples were cooled and dried to constant mass in a desiccator. The proportion of inorganic matter was determined as the quotient of the final and initial masses.

2.2. Seawater density and projection of oil density onto T-S plot

Surface salinity and temperature were measured on all sampling cruises using a SeaBird SBE911 CTD attached to a sampling rosette (e.g. Wright et al., 2016; Wright et al., 2017). Seawater density was calculated from temperature and salinity, using the equation of state for seawater, through an online density calculator (https://www.mt-oceanography.info/utilities/density.htm), based on Fofonoff and Millard (1983). The same calculator was used in reverse to calculate salinity from density at a range of realistic values of temperature to project the density of weathered dilbit and tar balls onto a standard property/property plot for temperature, salinity and density (a “T/S” plot).

2.3. Sinking particles

Complete records of sinking particle flux and composition from moored sediment traps in the Strait of Georgia and Douglas Channel have been published previously (Johannessen et al., 2017, 2019). Briefly, sequential, Baker-style sediment traps were moored at sites SoGS and SoGN in the Strait of Georgia (Fig. 1) from June 2008 to October, 2012. Traps were moored at FOC1 in Douglas Channel and HEC1 in southeastern Hecate Strait from July 2013 to July 2016. Each trap contained 10 cups, which sampled at 11-to-12-day intervals.

For the current study, the dry weight flux (g m^{-2} day^{-1}) at each site was converted to a seasonal climatology. Each sample was assigned to

Table 1
Density of dilbit, tar balls and OPA formed with dilbit.

	Density (kg/L)	Reference	Notes
Dilbit in pipelines	0.920–0.931	Govt of Canada (2013)	
Fresh CLB dilbit	0.9229	King et al. (2014)	
Fresh AWB dilbit	0.9233	King et al. (2014)	
Weathered AWB dilbit	1.008	King et al. (2014)	13 days in wave tank[a] 18-20 °C
Weathered CLB dilbit	0.997/1.0014 0.998/0.995	King et al. (2014) Ross 2013[c]	13 days in wave tank[b] 18–20 °C 15 days + UV/no UV
AWB Tar balls	~1.017	King et al. (2014)	Sank in seawater with density 1.016 kg/L
OPA with kaolinite	1.057	Hua et al. (2018)	10,000 mg/L particles
OPA with kaolinite	No OPA formed	Hua et al. (2018)	100 mg/L particles
1. OPA with Douglas Channel bottom seds	1.043–1.070	Hua et al., 2018	10,000 mg/L particles
OPA with Douglas Channel bottom seds	No OPA formed	O'Laughlin et al. (2017a),b	15 mg/L particles No shaking
OPA with Douglas Channel bottom seds	Some OPA observed; density not measured	O'Laughlin et al. (2017a),b	15 mg/L particles Shaker Table 2 hours
Modelled OPA	Density not reported but up to 2% OPA sank without dispersants; up to 20% with	Wu et al. (2016)	Assumed natural particles available in excess, with density 2.2–2.4 g cm^{-3}

[a] AWB: half of total density increase within 16 h.
[b] CLB: half of total density increase within 24 h.
[c] Cited by Govt of Canada, 2013

the month in which its mid-date fell, and then all the values for each month were averaged to construct the climatology.

3. Results

3.1. Review of the properties and behaviour of dilbit in experiments and models

3.1.1. Density

Dilbit is made up of two parts: dense bitumen is mixed with a much less dense diluent to reduce its density for transport through a pipeline (0.920–0.931 kg/L; Govt of Canada, 2013). Fresh dilbit is less dense than fresh water, which typically has a density of 0.996–1 kg/L depending on temperature (IAPWS, 2018). In comparison, Bunker C heavy fuel oil can have a wide range of densities (0.96–1.04 kg/L, Fingas, 2011). As dilbit is exposed to the environment, the lighter components evaporate or break down rapidly, causing the density of the remaining material to increase (Table 1).

Weathering increases the density of dilbit (Table 1). In wave tank experiments with two blends of dilbit - Access Western Blend (AWB) and Cold Lake Blend (CLB) (King et al., 2014; Govt of Canada, 2013), the maximum density was reached after 13 days, after which the density of the remaining material decreased, as the residual components continued to break down. The density of AWB exceeded that of fresh water after about 6 days. In treatments with ultraviolet radiation, ~15% of the oil formed tiny subsurface droplets, most of which adhered to the sides of the tank (Govt of Canada, 2013).

Tar balls were observed to form in some experiments. The density of the tar balls could not be measured directly, but based on the depth to which they sank in the wave tank, their density was estimated at 1.017 kg/L (King et al., 2014).

Short (2013) noted that weathering occurred more quickly in thinner slicks, so the time for the dilbit to reach to its maximum density could vary. Short also pointed out that at low temperatures (e.g. 0–5 °C), the density of dilbit increased more rapidly than that of seawater, so that oil that did not sink at 15 °C might sink in water of the same salinity at 0 °C.

3.1.2. Photolysis

Some of the heavier components, particularly the aromatic compounds, are subject to photolysis in the environment, which might influence the behaviour, fate and impact of spilled dilbit, as well as potential response strategies (Yang et al., 2017; Ward et al., 2018). While photolysis can cause some oils to form a dense crust at the surface, which can then sink, this phenomenon was not observed for AWB or CLB dilbit in wave tank experiments (Govt of Canada, 2013).

3.1.3. Emulsification

Fresh AWB and CLB dilbit can form emulsions with seawater, taking in up to 40% water (compared with 6–10% for highly weathered dilbit; Govt of Canada, 2013). Emulsification increases the viscosity and effective volume of spilled oil. Emulsions of some light oils can become dense enough to sink. However, emulsions with fresh dilbit are less stable than they are for light oil, and the formation of emulsions was not observed for weathered dilbit (Lee et al., 2015).

3.1.4. Dispersants

In wave tank experiments with dispersant COREXIT®EC9500A, fresh dilbit was not as readily dispersed as some other conventional crude oils, due to its high viscosity. While essentially ineffective as an operational response, and thus not a likely scenario, the addition of chemical dispersants to a spill of fresh dilbit might generate some submerged oil droplets (Govt of Canada, 2013). This dispersant formulation was ineffective on weathered dilbit due to dilbit's high viscosity (King et al., 2018).

3.1.5. Interaction with suspended particles and formation of oil-particle-aggregates (OPA)

Dilbit has been observed to form oil-particle aggregates (OPA) in laboratory and wave tank experiments. Most experiments and models investigating OPA formation with dilbit used particle concentrations of 1000 mg/L or even 10,000 mg/L (Table 1). This is two to three orders of magnitude higher than in situ concentrations in the ocean. (See Section 3.2 below). Dilbit OPA did not form when particle concentrations were low (10–100 mg/L) in calm conditions. However OPA did form with 15 mg/L of particles in one experiment in which small flasks were agitated for 2 h on shaker tables. Mixing enhances the energy of dissipation, increasing oil-particle collisions and the chance of OPA formation (Hua et al., 2018).

In the high-concentration experiments, (≥1000 mg/L) OPA formation with dilbit was dependent on the grain size of the particles; OPA formed in the presence of kaolinite fines (< 5.8 microns) and with a natural, silt-sized sediment collected from Douglas Channel (2–63 microns), but not with sand-sized grains (200–400 microns diameter)

(Hua et al., 2018).

Models have shown similar results to the experimental studies. A model by Hill et al. (2002) determined that OPA could form in minutes to hours at the energy levels typically found in coastal environments, with sediment concentrations of 100s–1000s of mg/L, but not with low sediment concentrations (~10 mg/L).

Wu et al. (2016) modelled the formation and sinking rate of OPA under excess particle concentration, which occurs when there are enough particles to coat each oil droplet completely with a single layer of particles. The particle size, degree of turbulence, and oil properties were critical to their result.

All the OPA formed in experiments with high concentrations of particles were dense enough (~1.04 kg/L) to sink to the bottom in coastal water, which has densities of at most about 1.03 kg/L, see Section 3,2, while only some of the modelled OPA were dense enough to sink. The difference is probably due to the density of the sediments used to form the OPA in each case. The experiments by Hua et al. (2018) used inorganic particles (kaolinite, density 2.65 g cm^{-3}) or bottom sediment collected from Douglas Channel, which had been dense enough to sink to the sea floor. In contrast, the Wu et al. (2016) model used a range of suspended particle concentrations (2.2–2.4 g cm^{-3}), representing a mixture of organic and inorganic material. Since there are no experimental data available for mixtures of dilbit with natural, suspended particles, we use the information determined using inorganic or bottom sediment in our discussion of the formation and density of OPA.

3.1.6. *Dilbit on the shoreline*

Oil sticks to beaches during a falling tide (Sergy et al., 2017). Dilbit behaves similarly to other oil on beaches, except that the response-time window is shorter. Dilbit becomes viscous rapidly, which decreases its penetration into the beach sediment, but increases its adhesion and retention (Laforest et al., 2017; Sergy et al., 2017). It can become a hard coating on the surface of rocks within 12–96 h (Owens et al., 2008; Sergy et al., 2017). Adhesion also increases as beach sediments dry (Harper et al., 2015).

The grain size of the substrate affects the behaviour of dilbit on the shoreline; dilbit penetrated more deeply in coarser sediments (Owens et al., 2008). Retention is greater with finer particles, while penetration is lower.

When dilbit lands on a beach, it can interact with fine sediments, forming OPA, which can be resuspended as the tide rises (Bragg and Yang, 1995) and then sink again. This can lead to longshore or offshore movement of beached oil, and particles (Lee et al., 2003).

3.1.7. *Dilbit respirometry/microbial breakdown of diluent*

Microbes capable of degrading hydrocarbons are widely distributed in the ocean (Atlas and Hazen, 2011; Lee et al., 2015). They respond rapidly to the presence of dilbit following a spill, altering the composition of the residual hydrocarbons (Ortmann et al., 2019). Light components of dilbit, such as alkanes, which are associated with acute toxicity, tend to be preferentially degraded by microbes (Lee et al., 2015; Tremblay et al., 2017; Schreiber et al., 2019). In contrast, the heavier, more persistent components are only minimally degraded (Schreiber et al., 2019). The heavier components are more likely to cause chronic effects than acute toxicity, due to their limited bioavailability (Lee et al., 2015).

After the Deepwater Horizon spill in the Gulf of Mexico in May 2010, “dirty” marine snow appeared, likely as a result of microbial activity (Passow et al., 2012; Quigg et al., 2020; National Academies of Sciences, Engineering, and Medicine. 2019). In lab experiments this occurred sometimes, but not always. It is not clear whether this could be an important mechanism for flocculation and sedimentation of residual hydrocarbons following a spill of dilbit.

3.1.8. *Synthetic bitumen (synbit)*

Synthetic bitumen (synbit) is another bitumen product that is shipped by pipeline from northern Alberta. Synbit is made by diluting bitumen with partially refined bitumen or crude oil, at a ratio of about 50:50 (Lee et al., 2015; King et al., 2017a). There are not as many experimental data available for synbit as for dilbit. However, the results to date show that, because the partially refined bitumen contains a lower proportion of condensate, synbit is more stable than dilbit in the environment. Its density and viscosity do not increase as much or as rapidly as those of dilbit when it weathers (King et al., 2017b), providing a potentially longer window of opportunity for chemical dispersant use (King et al., 2017b, 2019). In wave tank experiments, the density of synbit did not approach that of fresh water, even after 15 days of weathering (King et al., 2017b).

3.2. *Oceanography/environment*

3.2.1. *Strait of Georgia, Juan de Fuca and Haro Straits (collectively the Salish Sea)*

The Salish Sea functions like a large estuary. Fresh water, largely from the snow-fed Fraser River (Fig. 1), drives a seaward surface outflow in the upper part of the water column (Thomson, 1981). The outflow passes through a strong tidal mixing zone in Haro Strait, and then continues through Juan de Fuca Strait to the Pacific Ocean. Subsurface seawater is entrained into the surface layer. The residence time of fresh water in the Strait of Georgia ranges from an average of ~10 days during the summer to ~40 days in winter, reaching the open ocean in 20–50 days (Pawlowicz et al., 2007, 2019).

Drifters released at the surface of the Strait of Georgia in a recent research project moved in all directions for about the first week, driven by wind, tide and freshwater discharge (Pawlowicz et al., 2019). In Haro Strait and Juan de Fuca Strait, they moved more consistently seaward. If they remained afloat, drifters released near the mouth of the Fraser River reached the Pacific Ocean in about 16 ± 4 days in summer (a little faster than the average for the outflowing surface water layer). However, nearly all drifters released in the Salish Sea grounded on the shoreline without reaching the open ocean. The mean time to first grounding was only about 3 days in the Strait of Georgia, and 1.5 and 1.8 days, respectively, in Haro Strait and Juan de Fuca Strait. The probability that a drifter released near the Fraser River would reach the open ocean without touching land was ≤ 0.005 (effectively zero).

Temperature, salinity and particle concentration vary seasonally in the surface water of the Strait of Georgia. The surface water is typically warmest in July–August and freshest in late May – early June (Thomson, 1981; Masson, 2006), with a seasonal temperature range of 6–20 °C, and salinity of 17–30 (Practical Salinity Scale[1]). Consequently, the density of the surface seawater (1.01–1.02 kg/L) is lowest in summer. The greatest seasonal variability occurs near the mouth of the Fraser River. Nearshore in the Fraser plume, surface salinity in the uppermost 2–3 m in the summer can be as low as 4–10 (density ≥ 1.002 kg/L), but such conditions occur for less than 5% of the year (Halverson and Pawlowicz, 2008). Seawater density may also be low over the extensive and partially tidally-exposed mudflats of Sturgeon and Roberts Banks, on either side of the Fraser's main outflow.

Below 20 m depth, water in the Strait of Georgia has a much narrower range of temperature (9 ± 1 °C), salinity (30 ± 2), and density (1.022–1.025 kg/L).

The Fraser River carries a high load of particles (19×10^9 kg/yr, Thomas and Bendell-Young, 1999), with particle concentrations in the

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[1] Since 2010 the salinity of seawater has been officially described using Absolute Salinities on the Reference Composition Salinity Scale (IOC et al., 2010); a Practical Salinity of 20 is roughly equivalent to an Absolute Salinity of 20.1 g/kg. In the context of this paper the two scales are numerically indistinguishable.

Table 2
Particle concentrations in BC coastal surface seawater and rivers.

Location	Concentration (mg/L)	Reference	Notes
Lower Fraser River	1–600	Milliman (1980)	Highest at low tide
Lower Fraser River	20–70	Stecko and Bendell-Young (2000)	
Lower Fraser River	5 - 18, 224	Hospital et al. (2016)	Low in February, high in May
Salish Sea[a] (inorganic fraction)	6 - 9, 16 (5–6, 11)	This study	High in April
Salish Sea[a]	2-5, 21	Phillips and Costa (2017)	High in spring
Salish Sea[a]	< 1 - 2	Pawlowicz et al. (2017)	From satellite ocean colour
Fraser River plume	59.6	Hospital et al. (2016)	
Fraser River plume	2–30	Pawlowicz et al. (2017)	From satellite ocean colour
Kitimat fjord system	3–9, 16, 17.5	This study	Highs spring bloom, May freshet
Kitimat fjord system Rivers	0.4–5	This study	May, 2016 only
Kitimat fjord system	< 5 - 20	Lazin et al. (2017)	From satellite ocean colour High near Kitimat
Kitimat fjord system	≤60	Lazin et al. (2017)	From satellite ocean colour High after rainstorms and after rain-on-snow event
Chatham Sound	6.5–11.3	This study	August 2018 only
Dixon Entrance (north of Haida Gwaii)	≤8	This study	August 2018 only
Hecate Strait	< 4	Lazin et al. (2017)	From satellite ocean colour

[a] Strait of Georgia, Haro Strait, Juan de Fuca Strait; excluding the Fraser River plume.

lower river of 1–600 mg/L (Table 2). The river plume, which floats in the upper 10 m of the water column, is visibly turbid, at times covering most of the southern Strait (Pawlowicz et al., 2017). Although the Fraser River carries sand during the peak annual freshet, most of the sand settles to the bottom in the upper or mid-reaches of the river (Hill et al., 2008; Milliman, 1980). At the river mouth, suspended particles are predominantly silt and clay (Milliman, 1980; Stecko and Bendell-Young 2000).

Surface particle concentrations are lower in the Strait of Georgia (~1–21 mg/L, except in the Fraser River plume; Table 2). Concentrations are highest in May–June, because of the Fraser River freshet, which is driven by snowmelt in the high-altitude areas of the B.C. interior. The highest particle concentrations in the Salish Sea are observed in the Fraser River plume (Table 2). Inside the plume, satellite-derived suspended particulate matter concentrations (SPM) are generally 2–3 mg/L, with an average seasonal peak of about 10 mg/L in the heart of the plume (Pawlowicz et al., 2017, Fig. 3), although maxima in individual satellite images can reach three times that value.

Satellite imagery also shows relatively high values in the shallow regions of Roberts and Sturgeon Banks, just north and south of Sand Heads. About half of this area is made up of mudflats exposed at low water; the high particle concentrations are presumably the result of surface-wave-driven resuspension. SPM values are also high near the mouths of other rivers, e.g., at the head of Howe Sound.

Sinking particle fluxes follow similar patterns to the surface particle concentration (e.g. Pawlowicz et al., 2017). Sediment trap studies show that in the Strait of Georgia, natural particles sink year-round, with a much higher flux (~20 x higher) in the southern than the northern Strait (Johannessen et al., 2017). In the southern Strait, particle flux is strongly driven by the Fraser River discharge and is highest during the May/June freshet. In the north, the peak particle flux sometimes occurs during freshet too, but in other years, it occurs after heavy autumn rainstorms or after a strong spring phytoplankton bloom (Johannessen et al., 2017, Fig. 4).

3.2.2. *Burrard Inlet*

Burrard Inlet contains the Westridge Marine Terminal and the anchorage for ships waiting to access the terminal (origin of the southern, red tanker track in Fig. 1). Surface salinity in Burrard Inlet is usually > 18, but lower-salinity water (≥9) sometimes intrudes into the mouth of the inlet during times of high Fraser River flow (Thomson, 1981). There are strong tidal currents at the surface, and the predominant direction of winds is east-west (landward – seaward through the entrance). Surface particle concentration in Burrard Inlet is ≤ 10 mg/L (Pawlowicz et al., 2017). The highest concentration of particles occurs near the entrance to the inlet, when the Fraser River plume intrudes from the Strait of Georgia. Intermediate fuel oil spilled in Burrard Inlet in April 2015 moved in and out of the inlet with the tide and washed up along the shoreline, consistent with modelled surface currents in the area (Zhong et al., 2018).

3.2.3. *Douglas Channel/Kitimat fjord system*

Circulation in the upper layers of Douglas Channel is mainly estuarine (Wan et al., 2017), with a brackish, outflowing surface layer (0–32 m depth) overlying an inflowing layer (33–131 m). Sometimes in the summer, wind pushes the top 1–3 m of water up-channel, against the outflow (Wan et al., 2017).

Surface salinity is usually 20–30 (Fig. 5), except near Kitimat and in Gardner Canal, where it is often < 14 in the summer and during autumn rainstorms. On occasion surface waters can be much fresher than these typical values. During a heavy, multi-day rainstorm in October 2015, the salinity was as low as 1.8 in surface water at one station in Kitimat Arm and one in Gardner channel. The density of this very fresh seawater can be lower than that of the most highly weathered AWB dilbit (1.008 kg/L, King et al., 2014). The low-density water is confined to the uppermost 5 m, usually the uppermost 3 m. Water at this depth flows seaward on average, mixing with saltier water and becoming denser as it goes. When present at the head of Douglas Channel, the 1.008 kg/L isopycnal reaches the surface at or before station Doug-11, located 11 nautical miles (20 km) seaward of Kitimat (Fig. 6).

Surface drifters released in the Kitimat fjord system travelled in every direction from the point of release (Page et al., 2019). Eventually, most of the drifters washed up on the shoreline, although some escaped the fjord system and moved westward and northward toward Haida Gwaii and Alaska.

The particle concentration in surface seawater in the Kitimat fjord system is generally 3–9 mg/L (Table 2). Higher values (≤60 mg/L) occur episodically with the spring bloom, river freshet, and intense, multi-day rainstorms (Table 2). Suspended particle concentrations in May, 2016, were lower in the rivers and streams (0.4–5 mg/L), suggesting a marine origin for many of the particles measured in the seawater of the fjord system.

During the 2013–2016 sediment trap deployment, sinking particle fluxes were highest in May and October–November (Fig. 4), coinciding, respectively, with the freshet of the snowfed Kitimat, Kildala and Kemano Rivers, and with heavy rainstorms in October–November (Johannessen et al., 2019). On average, the highest particle fluxes occurred in October–November (Fig. 4).

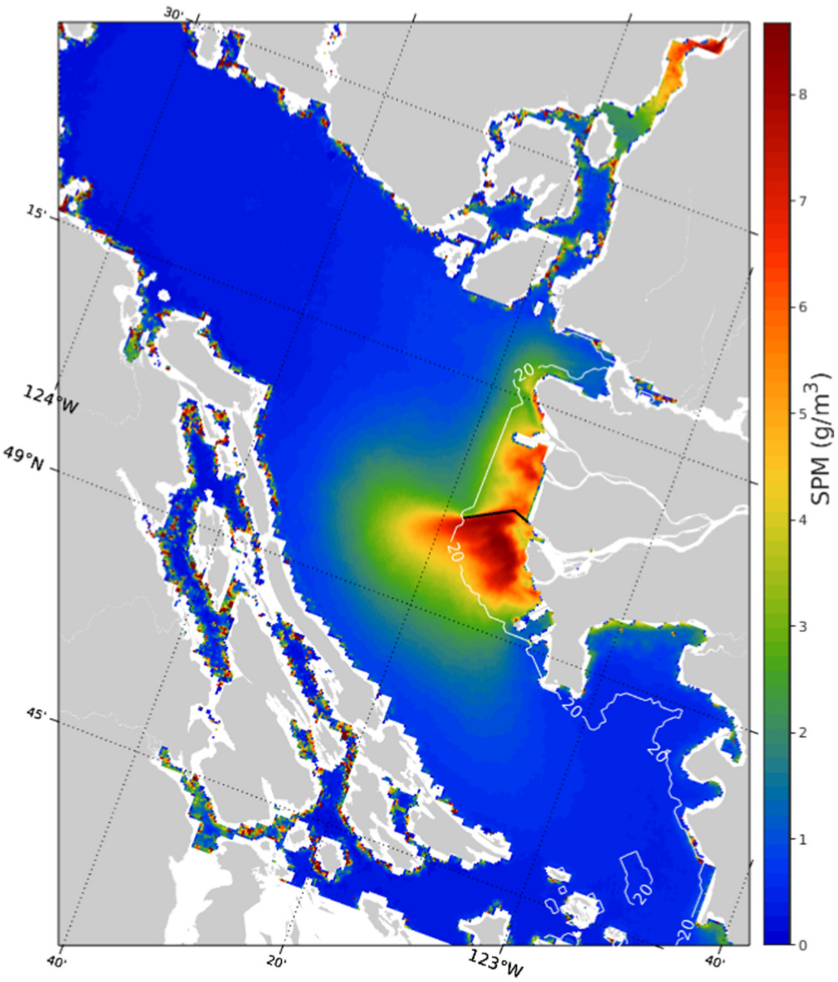

Fig. 3. Annual mean surface suspended particulate matter (SPM) concentration (mg/L) in the Fraser River plume and Strait of Georgia, estimated from ocean colour imagery over the years 2003–2015. The 20 m depth contour, indicated in white on eastern shore, marks the seaward boundary of shallow mudflats. Modified from Pawlowicz et al. (2017). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2.4. Prince Rupert Harbour/Chatham Sound

There are limited data available for Chatham Sound. In August 2018 surface temperature ranged from 7 to 16 °C, surface salinity 19–31. Trites (1956) reported that salinity in Chatham Sound did not fall below 20‰, even during the May freshet of the Skeena and Nass Rivers. Surface salinity is lower along the eastern side of Chatham Sound, and the low-salinity water moves generally northwards (Lin and Fissel, 2018). The surface particle concentration in August 2018 (Fig. 2) was 6.5–11.3 mg/L (Table 2). Measurement of sinking particle fluxes is in progress, with sediment traps deployed in Chatham Sound. Fissel et al. (2017) reported high turbidity near the mouth of the Nass River. Crawford and Thomson (1991) commented that the water in Dixon Entrance, outside of Chatham Sound, was sometimes turbid, due to sand eroded off the north island of Haida Gwaii.

3.2.5. Other areas of the BC coast

Outside of the fjords and inlets, surface seawater in coastal B.C. is relatively dense. These waters also have low particle concentrations (Table 2), because they are far from river mouths and other sources of terrigenous particles. For example, ocean colour data (Lazin et al., 2017) show that in Hecate Strait, particle concentrations are always < 4 mg/L. Concentrations as high as 8 mg/L were measured in situ in Dixon Entrance in August 2018 (Fig. 2), associated with a lens of fresher water and high chlorophyll. Phytoplankton blooms increase particle concentrations episodically. The central and north coast are subject to intense wind and rainstorms, particularly in the winter. Queen Charlotte Sound and Hecate Strait are thoroughly mixed by wind storms in winter (Crawford and Thomson, 1991). For example, oxygen concentrations at the bottom (150 m) of southeastern Hecate Strait remained at ~ 6 mL/L throughout the winter of 2015 (Wright et al., 2017), showing that surface water can be mixed to the bottom in the winter in that area.

4. Discussion

Knowing whether spilled dilbit would float or sink is of high importance for environmental risk assessments and preparedness. Containment of surface oil and its subsequent recovery with skimmers remains the major oil spill response method, and the only legally-approved option in Canada (Fingas, 2012; King et al., 2017a,b). The spill of diluted bitumen in the Kalamazoo River in 2010 illustrated that despite advances in technology, the tracking and recovery of sunken and submerged oil is logistically challenging, time consuming and expensive (Dollhopf et al., 2014).

4.1. Density comparisons

Without weathering, vertical mixing or high concentrations of particles, fresh dilbit is not dense enough to sink in seawater (Fig. 5). Highly-weathered dilbit, in contrast, might reach a density greater than that of seawater in places where salinity is < 14 (Fig. 5). Such low-salinity conditions occur along the BC coast near the mouths of rivers

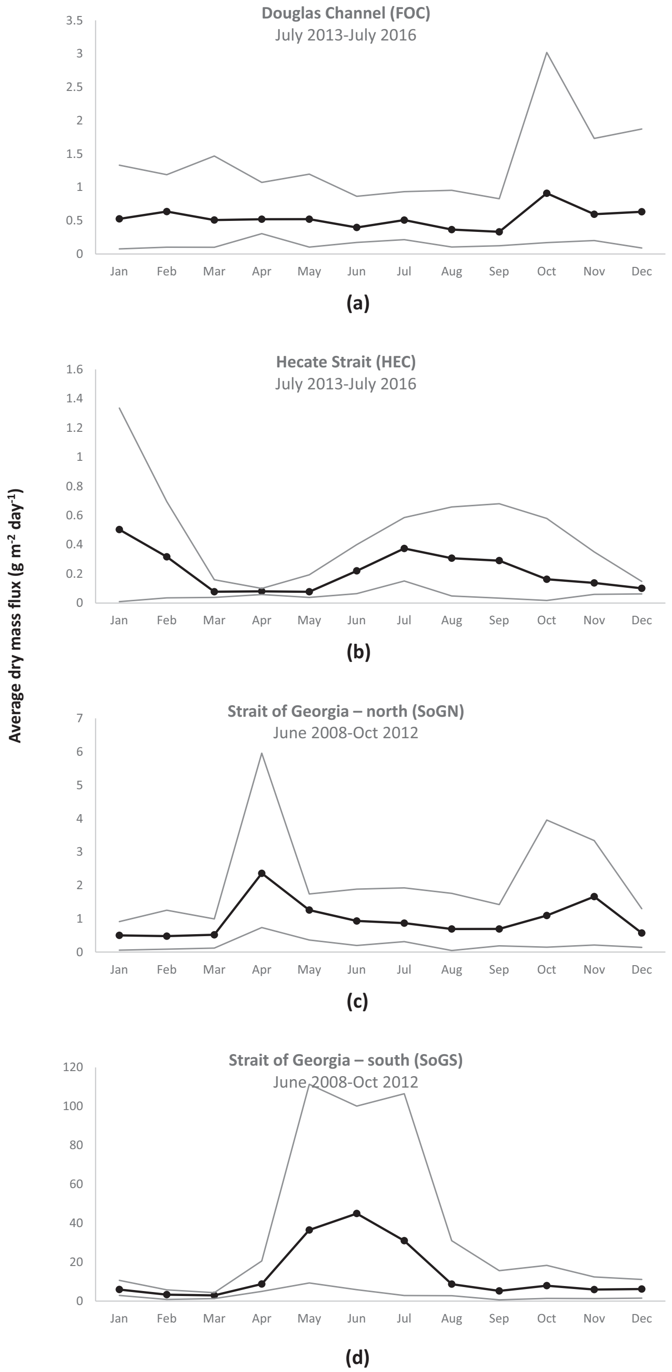

Fig. 4. Sinking particle climatology determined from sediment trap deployments in (a) Douglas Channel, July 2013–July 2016; (b) Southeastern Hecate Strait, July 2013–July 2016; (c) northern Strait of Georgia (June 2008–October 2012); (d) southern/central Strait of Georgia June 2008–October 2012. Black lines represent the average climatology; grey lines represent the maximum and minimum fluxes observed for each month. Note changes in vertical scale.

during periods of high discharge; in sheltered inlets during and shortly after heavy rainstorms; and over shallow mudflats, such as Sturgeon and Roberts Banks. Since the density of dilbit increases with declining temperature more rapidly than that of seawater, weathered dilbit might become denser than seawater over a wider area at very low temperatures (Short, 2013). However, the differential density conclusion was based on experiments conducted at 0–1 °C, well below the typical temperature range of coastal waters.

The maximum density of weathered AWB dilbit (1.008 kg/L, King et al., 2014) is greater than that measured in surface water in July 2006 in the Fraser River plume, at the two stations closest to the mouth of the river (Loos et al., 2017). If AWB dilbit were spilled in the Fraser River plume at that time of year and had 13 days to weather to its maximum density, it would sink to a depth of about 3–4 m. However, in the summer, the residence time of water in the Fraser River plume is only about 1–2 days (Pawlowicz et al., 2007, 2017), so it is unlikely that the dilbit would have time to become dense enough to sink. As the plume water moves away from the mouth of the river, it mixes with subsurface seawater, and its density increases. Consequently, even if dilbit did sink in the Fraser River plume, it would likely resurface some distance seaward. Sharp density fronts at the edge of the plume, which, when they occur, trap foam and floating objects, could also concentrate this resurfacing dilbit. Even at its maximum weathered density, CLB dilbit would not be dense enough to sink at all, even in the Fraser River plume, as measured in July 2006.

In the Kitimat fjord system, fresh dilbit would float. However, at the head of Douglas Channel and in Gardner Canal, the density of surface water is low enough in the summer and autumn for highly weathered AWB dilbit to sink to a depth of 2–4 m (Fig. 6). Seawater at that depth moves seaward on average, mixing with more dense water on the way, so – as in the Fraser River plume – the submerged dilbit could re-emerge at the surface some distance seaward of where it sank. On one occasion (after a heavy rainstorm in October, 2015), the density of the surface water at one Kitimat Arm station became so low that even CLB dilbit (highly weathered) could have sunk to about 3 m depth. A spill might not have enough time to weather to maximum density, however, since the residence time of surface water in Kitimat Arm is only a few days.

In Chatham Sound, near Prince Rupert, the minimum observed surface salinity is about 20 (Trites, 1956; Lin and Fissel, 2018). This implies that, even during the May freshet of the Skeena and Nass Rivers, the surface water is too dense to permit dilbit to sink in Chatham Sound.

The density of synbit did not reach that of fresh or salt water during weathering experiments in a wave tank (King et al., 2017a,b), so it would likely float anywhere in British Columbia's coastal waters. In contrast, it is worth noting that Bunker C fuel oil, a conventional heavy oil product, has a wide range of densities (0.96–1.04 kg/L, Fingas, 2011), and would sink to the bottom in BC coastal waters at the higher end of its density range (Fig. 5).

4.2. Formation of sinking oil-particle aggregates in BC waters

Based on the data currently available, there is a low probability that OPA could form in BC coastal waters. Oil-particle aggregates formed with either kaolinite or natural sediment in wave tank experiments would be dense enough (~1.04 kg/L) to sink to the bottom of the coastal ocean. However, OPA formed at particle concentrations (1000 or 10,000 mg/L) that were much higher than those observed in the surface seawater of the BC coast (usually < 8 mg/L, with a range of < 1–60 mg/L; Figs. 2 and 3). OPA only formed at lower concentrations (~15 mg/L) in some laboratory experiments in small flasks that were shaken vigorously.

At low suspended particle concentration, high energy dissipation rates are required for OPA formation (Gong et al., 2014; Hospital et al., 2016), on the order of ~10 $m^2 s^{-3}$ for conventional oil (Hospital et al., 2016). (Since dilbit is more viscous, it would probably require higher energy for OPA formation.) This could explain why OPA formed with dilbit at low particle concentration in the shaken-flask experiments, but not in the wave tank experiments.

Hospital et al. (2016) pointed out that in the Strait of Georgia such high rates were seldom reached, with energy dissipation rates rather in the range of 10^{-8} – 10^{-3} $m^2 s^{-3}$, with a maximum, in the presence of breaking waves, of 10 $m^2 s^{-3}$. One area where OPA might form is over the intertidal and shallow subtidal banks on either side of the Fraser River mouth. Under northwesterly winds there is high energy from

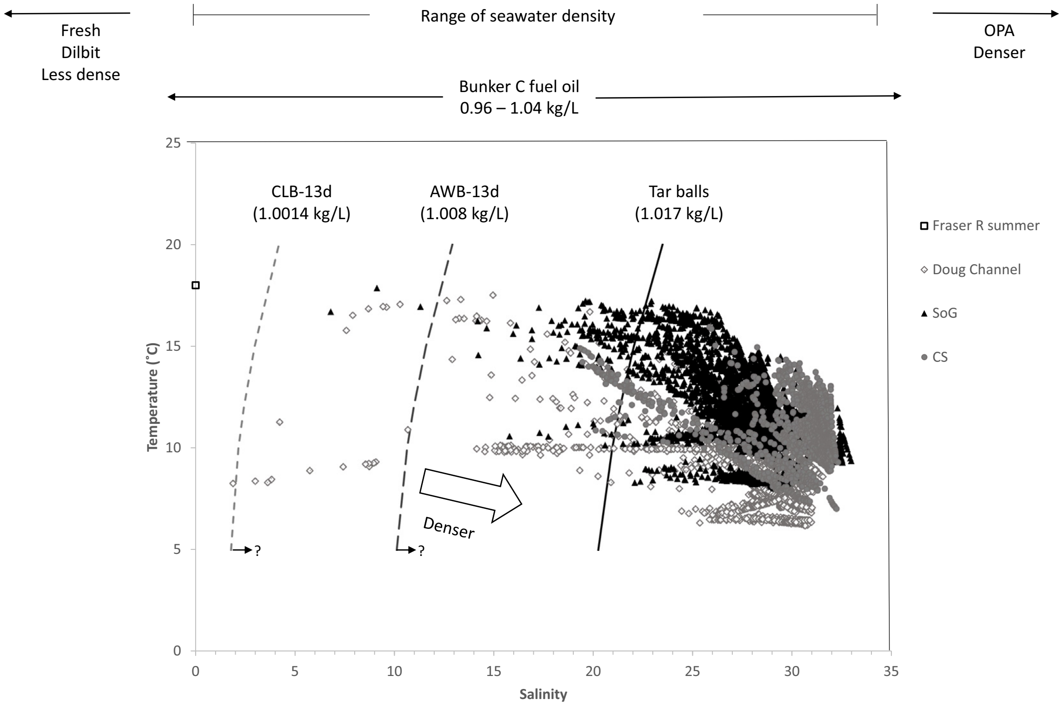

Fig. 5. Temperature-salinity plot over the range of T and S observed in coastal seawater. The maximum weathered densities of CLB (Cold Lake Blend), AWB (Access Western Blend) dilbit and tar balls (King et al., 2014) are projected onto the plot as lines of constant density. Symbols represent measurements in seawater in the top 20 m from: Douglas Channel, 2013–2016 (open diamonds); the Strait of Georgia, 2015–2016 (solid triangles); and Chatham Sound, August 2018 (solid circles), n ~ 12,400. Fewer than 0.5% of the samples from the top 20 m had densities lower than that of the most highly weathered dilbit. Symbols to the left of the AWB line show stations where the most highly weathered dilbit could sink to a depth of 2–5 m. The density of fresh dilbit is too low to be represented within the range of seawater S and T; the density of OPA, too high. The arrows at the bottom of the AWB and CLB lines represent uncertainty over the density of these compounds at low temperature.

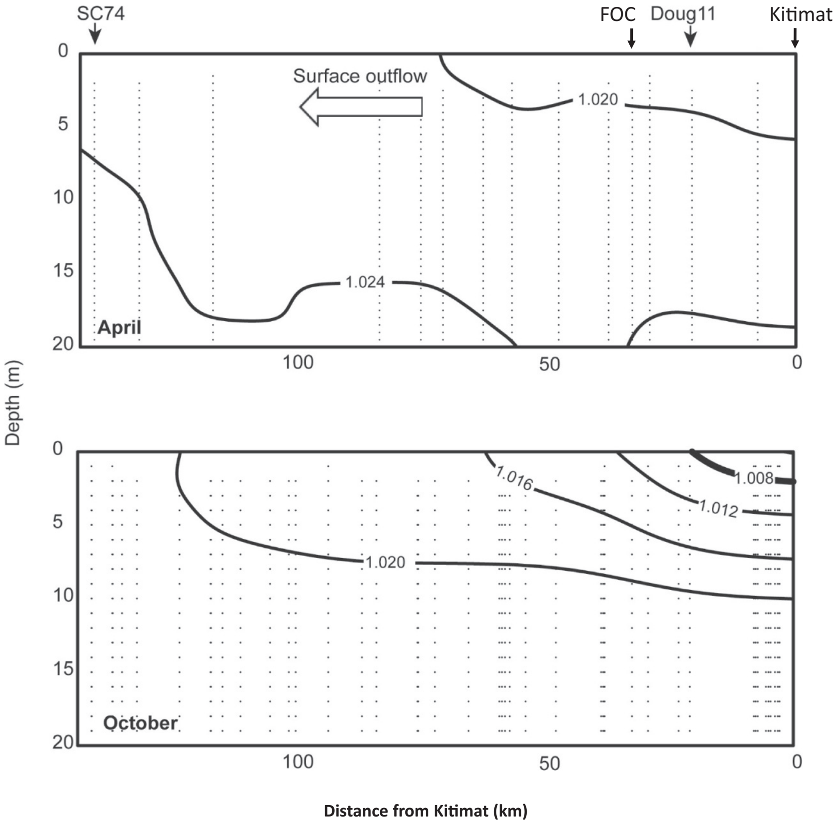

Fig. 6. Density contours (kg/L) in the uppermost 20 m of Douglas Channel, from Kitimat to Squally Channel (Fig. 1) in April 2014 (upper panel) and October, 2015 (lower panel). The 1.008 kg/L contour line matches the maximum weathered density of AWB dilbit. The large arrow shows the direction of surface outflow. Dotted vertical lines represent sampling stations.

breaking waves, the water is likely brackish, and there could be high particle concentrations due to resuspension of bottom sediment.

If dilbit were spilled in an area with relatively high particle concentrations (for marine waters), such as in a river plume during freshet, and there was a storm at the same time, it is possible that OPA could form.

4.3. Submergence of dilbit in areas of strong mixing

Turbulence or strong, coherent mixing might draw dilbit below the sea surface, even if the oil is lighter than the ambient seawater. For example, wave-induced turbulence can break up oil droplets and diffuse them within the top few meters of seawater, especially during storms (Farmer and Li, 1994). The subducted oil re-surfaces once the turbulence has subsided. Storms are common in coastal B. C., especially on the north coast in the winter, so submergence by waves, at least temporarily, is likely.

If there is coherent vertical circulation, oil forced below the surface by waves might remain there. Langmuir cells, a type of circulation in which downwelling occurs in long downwind lines, driven by combined surface wave and wind forcing, is one such type of vertical circulation. A model by Farmer and Li (1994) showed that oil droplets in the size range of 10s–1000s of μm in diameter mix evenly throughout Langmuir cells on a time scale of minutes to hours, so long as there is some surface turbulence to entrain the oil droplets below the surface in the first place. Larger oil droplets are likely to be trapped in a zone ranging from the surface to the depth at which the magnitude of their rise velocity caused by buoyancy equals that of the downward velocity of the flow (the Stommel Retention Zone) (Farmer and Li, 1994). The circulation cells and trapping depth can be on the order of tens of meters deep in the open ocean, but would likely be shallower in more sheltered areas. The droplets of dilbit observed by O'Laughlin et al. (2017a) were in the range of 10s–1000s of microns, and so would likely be mixed evenly if spilled in an area with this kind of vertical circulation.

Strong vertical circulation can also arise from tidal convergences. Such convergences exist within the Salish Sea, in Haro Strait and Boundary Pass, among the Gulf Islands (Fig. 1). One area studied in Haro Strait contained a 100-m-wide region of average downwelling, as well as an upwelling boil 175 m wide, surrounded by a ring of strong downwelling (Farmer et al., 1995). In this area, suspended particles are mixed throughout the 100–200 m water column (Johannessen et al., 2006, Fig. 7), and clouds of bubbles (much less dense than oil) are dragged down to a depth of 50–100 m. Bubbles have been observed as deep as 140 m (Farmer et al., 2002). It is likely that spilled dilbit would be subducted well below the surface in this area. Similar conditions with deep entrained bubbles exist at other locations among the Gulf Islands (Baschek et al., 2006; Baschek and Farmer, 2010) and could also result in the subduction of dilbit.

There are several other areas of large-scale coherent mixing along the coast, including Johnstone Strait, at the northern end of the Strait of Georgia (Thomson, 1981) and the entrance to Puget Sound, south of the Strait of Georgia (Geyer and Cannon, 1982), although there are no plans to ship dilbit through Johnstone Strait or into Puget Sound. Perry et al. (1983) and Jardine et al. (1993) also inferred areas of persistent, strong tidal mixing near Cape Scott, at the northern tip of Vancouver Island, and near Cape St. James, at the southern tip of Haida Gwaii (Fig. 8).

Whenever there is a sudden bathymetric drop, such as over an entrance sill at the mouth of a fjord, strong advective mixing, modulated by tidal flow, can occur (e.g. Janzen et al., 2005; Klymak and Gregg, 2004). Many BC inlets are fjords, with sills either at the mouth or partway along the channel (Pickard, 1961). However, salinity and transmissivity data collected during our recent sampling programs did not indicate any areas in inlets along proposed tanker routes with such strong coherent mixing as in Haro Strait/Boundary Pass.

4.4. Stranding of dilbit onshore

Like the surface drifters described by Pawlowicz et al. (2019), spilled dilbit released in the Kitimat fjord system and the Strait of Georgia (including Burrard Inlet) would likely spread, with no particular direction, and hit the shoreline within hours to days. Dilbit spilled in Haro Strait or Juan de Fuca Strait would move mainly seaward, but likely wash up on shore even more quickly.

Once dilbit was landfast, its fate would depend on the details of shoreline sediments. Information about shoreline substrate type is collated by the BC Ministry of Environment and Climate Change in its Marine Oil Spill Information System (OSRIS) and classified by Zachiarias et al. (1998). Most of the BC coastline is rocky, with some areas of sand and pebbles among the Gulf Islands, around Haida Gwaii, in Burrard Inlet, and at river mouths. Fine sediments occur on mudflats near the Fraser River, and in some bays and inlets.

In coastline regions with fine sediment, dilbit could form OPA and be subject to resuspension and longshore drift. Most beaches are relatively narrow, so that their surface area is small. However, notable exceptions in the Salish Sea include parts of the east coast of Vancouver Island between Parksville and Comox, where the intertidal region on sandy beaches can extend up to 1 km offshore. There are even more extensive mudflats at the mouth of the Fraser River (Sturgeon and Roberts Banks) and just to the south of Vancouver ((Boundary Bay), where the intertidal extent is up to 5 km. These mudflats provide important habitat for seabirds and juvenile fish. Salinity can be very low in these areas, which could permit sinking and resettling of OPA (e.g. salinity as low as 2 on Roberts Bank; Port of Vancouver, 2018).

4.5. Oxygen consumption by microbial degradation of dilbit

Microbial breakdown of dilbit is unlikely to have a measurable

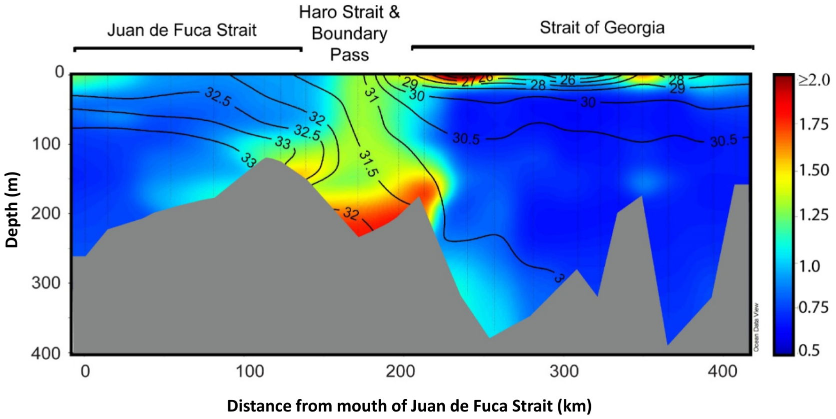

Fig. 7. Beam attenuation coefficient along the deepest channel from the mouth of Juan de Fuca Strait (Fig. 1) at left to the northern end of the Strait of Georgia at right (in June 2001; modified from Johannessen et al., 2006). Salinity contours show very strong tidal mixing in Haro Strait. The strong mixing re-suspends and mixes particles throughout the water column, as shown by the high beam attenuation coefficient.

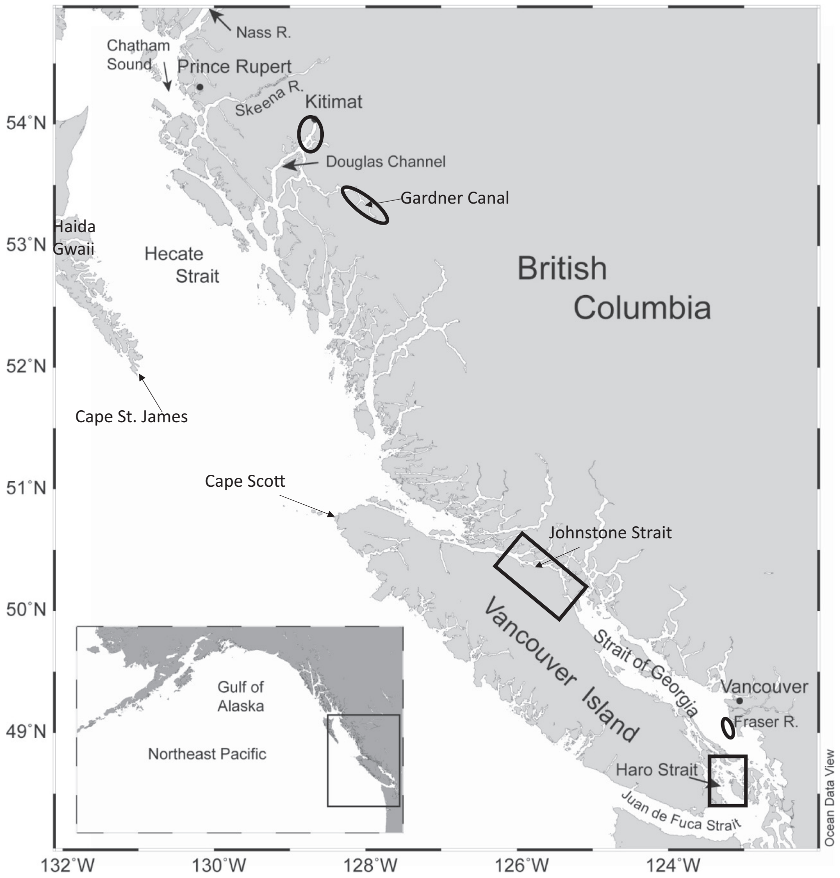

Fig. 8. Map of the BC coast, showing areas of low density seawater (circled), where highly weathered AWB dilbit could sink (to a maximum depth of 5 m). These areas coincide with areas of highest particle concentration. The square boxes indicate areas where strong, coherent mixing could entrain dilbit, or other oil, below the surface (to a maximum depth of 100–150 m).

effect on subsurface oxygen in most cases. At the surface, seawater is well supplied with oxygen from the atmosphere and from phytoplankton. In general, the lighter, more microbially-available components are consumed or weathered away before dilbit becomes dense enough to sink. If the dilbit were submerged by deep mixing (e.g. in Haro Strait), the breakdown of the more biologically-available components could consume oxygen at mid-depths.

5. Conclusions

Although important data gaps remain, the available data support the following conclusions. Most dilbit spilled in the coastal waters of British Columbia would remain at the surface of the ocean, until it was transported to shore by wind and currents. Once landfast, it would adhere to rocks and boulders where, within days, it could form a hard coating on rocks, become trapped below a surface layer of coarse particles, and/or form oil-particle aggregates (OPA) with fine beach sediments that might become resuspended or move along- or off-shore.

Fresh dilbit is not dense enough to sink anywhere in seawater, as a result of its density alone. Once weathered, AWB dilbit could be dense enough to sink in areas where the surface salinity is less than 14. These conditions mainly occur near river mouths during times of high discharge, as well as in fjords or narrow inlets after heavy rain. In the Fraser River plume during freshet, highly weathered dilbit could sink to a depth of 2–3 m before reaching more dense seawater. In the Kitimat fjord system, highly weathered dilbit could sink to 2–5 m near Kitimat and in Gardner Canal in the summer and fall, particularly after a heavy rainfall. Fig. 8 shows areas of the BC coast where low-density surface water could permit weathered dilbit to sink under these conditions.

However, given the short residence time of surface waters in these areas (1–2 days in summer in the Fraser River plume and a few days at the head of Douglas Channel or Gardner Canal), there would probably not be enough time for the dilbit to weather to a density that would allow it to sink. If it did sink initially, it would probably re-emerge at the surface as the outflowing layer of water mixed with denser seawater, increasing the density of the surface water.

Tar balls of the density observed by King et al. (2014, 1.017 kg/L) could sink below the surface in low-density seawater (similar conditions as for highly weathered dilbit). Based on the CTD data set collected for this project, submerged tar balls would not sink to the bottom, but would rather be suspended within the uppermost 10 m of the water column.

Synbit would not sink in coastal seawater, due to density alone, unlike Bunker C (heavy fuel oil), which, at the higher end of its density range, could sink anywhere in seawater.

The areas where salinities are low enough to permit the sinking of dilbit (Fig. 8) also coincide with areas of high particle concentration. However, oil-particle aggregates are unlikely to form in seawater. Experimental results show that OPA can be much denser than seawater, dense enough to sink all the way to the bottom in BC's coastal water. However, such OPA have nearly all been observed in experiments with dense, inorganic sediment, at suspended particle concentrations of 1000 or 10,000 mg/L, orders of magnitude higher than the 1–15 mg/L generally observed in surface seawater. It is possible that OPA could form in areas with high particle concentration during a storm.

Dilbit (and other types of oil) could be drawn below the surface by turbulent processes. Wave mixing during storms could submerge dilbit temporarily to depths of a few meters. More significantly, large coherent mixing cells, such as those observed in Haro Strait/Boundary Pass and Johnstone Strait (Fig. 8) due to tidal convergence and downwelling, could bring dilbit or any other oil down to a depth of 150 m or more.

Although there is a possibility that dilbit can be brought into deeper waters by turbulent processes, in general we would expect that the lighter, more readily degradable components of dilbit will largely evaporate or be consumed near the surface. Thus microbial degradation of dilbit is unlikely to affect the concentration of subsurface oxygen.

The Westridge Terminal in Burrard Inlet remains the only dilbit shipping port in BC. It is expected to be expanded to serve up to seven times as many tankers in the future. Based on the experience of the 2007 spill in Burrard Inlet, together with the analysis of density and particle concentration patterns presented here, it is likely that dilbit spilled near the terminal would float. It would then be dispersed by surface currents, and wash up on the shoreline inside or outside of Burrard Inlet.

5.1. Data gaps

This paper presents an initial assessment of the likely behaviour of dilbit spilled in B.C.'s coastal waters, based on the best information currently available. More detailed environmental assessments will require additional information. This could include more detailed mapping of areas of fine sediment on shoreline, vertically-mixed or downwelling areas among the Gulf Islands, and areas with strong vertical mixing over sills, where recovery of spilled dilbit might be more difficult.

A better understanding of the cross-channel density structure in Kitimat Arm and Gardner Canal would allow for more detailed maps of potential shoreline contamination. Detailed measurements of seawater density and particle concentration over the mudflats of Sturgeon and Roberts Banks, near the mouth of the Fraser River, would help to determine whether floating dilbit would leave the area, or sink and stick to the bottom.

Weathering experiments conducted at intermediate temperatures relevant to B.C. waters (e.g. 6–15 °C) would be useful, as the physical characteristics of weathered dilbit may not vary linearly with temperature. In addition, investigation of the interaction of spilled dilbit with phytoplankton blooms and its role in the formation of oiled marine snow is needed to understand how these other processes may remove oil from the surface waters.

For the fraction of a total dilbit spill that ends up below the surface, microbial consumption will require the consumption of dissolved oxygen. Rates of oxygen consumption should also be determined. Finally, the development of numerical models of the ocean circulation, validated by comparison with drifter experiments, are required to create detailed maps of the specific areas which could be affected by spilled dilbit.

Declaration of competing interest

None.

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