State of Knowledge on Fate and Behaviour of Ship-Source Petroleum Product Spills: Volume 7, St. John's & Placentia Bay, Newfoundland & Labrador

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In response to the Expert Panel of the World Class Tanker Safety System (WCTSS) report (Houston et al., 2013), the Government of Canada commissioned pilot studies aimed to help develop and implement oil spill response plans for high risk areas in Canadian coastal waters. The Centre for Offshore Oil, Gas, and Energy Research (COOGER) published a five-volume report in 2019 focused on providing a general overview of the environmental factors that may influence oil spill fate, behaviour and response in four port areas in Canadian waters (Ryan et al., 2019). As an extension of this initiative, the Government of Canada requested volumes for three additional areas of interest: Prince Rupert and Chatham Sound, British Columbia; Placentia Bay and St. John's, Newfoundland and Labrador; and Iqaluit and Frobisher Bay, Nunavut.

This is the seventh volume of the eight-volume report. It contains information relevant to St. John's and Placentia Bay in Newfoundland and Labrador.

RÉSUMÉ

MacIsaac, B.I., King, T.L., and Ortmann, A.C. 2023. State of Knowledge of Fate and Behaviour of Ship-Source Petroleum Product spills: Volume 7, St. John's & Placentia Bay, Newfoundland & Labrador. Can. Manuscr. Rep. Fish. Aquat. Sci. 3253: vii + 32 p.

En réponse au rapport du Comité d'experts du Système de sécurité de classe mondiale pour les navires-citernes (SSCMNC) (Houston *et al.* 2013), le gouvernement du Canada a commandé des études pilotes visant à faciliter l'élaboration et la mise en œuvre des plans d'intervention en cas de déversement d'hydrocarbures dans les zones à risque élevé des eaux côtières canadiennes. En 2019, le Centre de recherche sur le pétrole, le gaz et autres sources d'énergie extracôtières a publié un rapport en cinq volumes visant à dresser un tableau général des facteurs environnementaux qui peuvent influer sur le devenir et le comportement des hydrocarbures et l'intervention en cas de déversement d'hydrocarbures dans quatre zones portuaires des eaux canadiennes (Ryan *et al.* 2019). Dans le prolongement de cette initiative, le gouvernement du Canada a demandé des volumes pour trois autres zones d'intérêt : Prince Rupert et le détroit de Chatham, en Colombie-Britannique; la baie Placentia et St. John's, à Terre-Neuve-et-Labrador; et Iqaluit et la baie Frobisher, au Nunavut.

Ce volume est le septième des huit volumes du rapport. Il contient des renseignements relatifs à St. John's et à la baie Placentia, à Terre-Neuve-et-Labrador.

1 INTRODUCTION

In response to the Expert Panel of the World Class Tanker Safety System (WCTSS) report Houston et al. (2013), the Government of Canada commissioned pilot studies aimed to help develop and implement oil spill response plans for high risk areas in Canadian coastal waters. The Centre for Offshore, Oil, Gas, and Energy Research (COOGER) published a five-volume report in 2019 focused on providing a general overview of the environmental factors that may influence oil spill fate, behaviour, and response in four port areas in Canadian waters (Ryan et al., 2019). The first Ryan et al. (2019) volume acts as an introduction to oil products handled in Canadian waters, the physical and chemical properties of these products, potential fate and behaviour in the event of a spill as well as current spill response methods and techniques. The information provided in the introductory volume is relevant to any location, and meant to accompany subsequent volumes generated for other pilot areas. The four pilot areas in the Ryan et al. (2019) report include: 1. Saint John, including the Bay of Fundy; 2. Port Hawkesbury and Canso Strait; 3. St. Lawrence Seaway from Montreal to Anticosti; and 4. the Strait of Georgia, including the Juan de Fuca Strait. As an extension of this initiative, the Government of Canada requested volumes for three additional areas of interest:

- Prince Rupert and Chatham Sound, British Columbia
- Placentia Bay and St. John's, Newfoundland and Labrador
- Iqaluit and Frobisher Bay, Nunavut

The focus of this volume is Placentia Bay and St. John's, located in southeastern Newfoundland and Labrador (Figure 1; Li et al., 2017). This region experiences high volumes of marine traffic carrying petroleum products from the Newfoundland Shelf offshore oil fields on the Grand Banks as well as crude oil imported from Europe and the Middle East (Gardner Pinfold, 2010). According to Turner (2010), most oil tanker traffic in Canadian waters is along the east coast; accounting for 17,000 of the 20,000 oil tankers navigating through Canadian waters each year. St. John's Harbour receives approximately 0.5 – 1.5M tonnes of fuel and basic chemicals yearly, a much smaller volume than Placentia Bay (SL Ross Environmental Limited, 2007).

Offshore oil extraction on the Grand Banks began in 1997. Since then, over 2.1 billion barrels of crude oil has been extracted (C-NLOPB, 2022). Offshore oil production is transported to Newfoundland refineries and holding facilities located in Placentia Bay (Figure 2; Fisheries and Oceans Canada, 2008) to be shipped elsewhere in Canada and eastern United States (C-NLOPB, 2018). Due to the increased risk of oil spill, tighter regulations have been put in place to monitor and assess ship traffic in Placentia Bay. Canadian Coast Guard (CCG) requires all oil tankers entering Placentia Bay to have AIS equipped regardless of origin or age of the ship (Turner, 2010). In St. John's, pilotage is mandatory for vessels entering the harbour, due to narrow local bathymetry (St. John's Port Authority, 2019). The information presented in this report will help inform preparedness plans in the event of an oil spill.

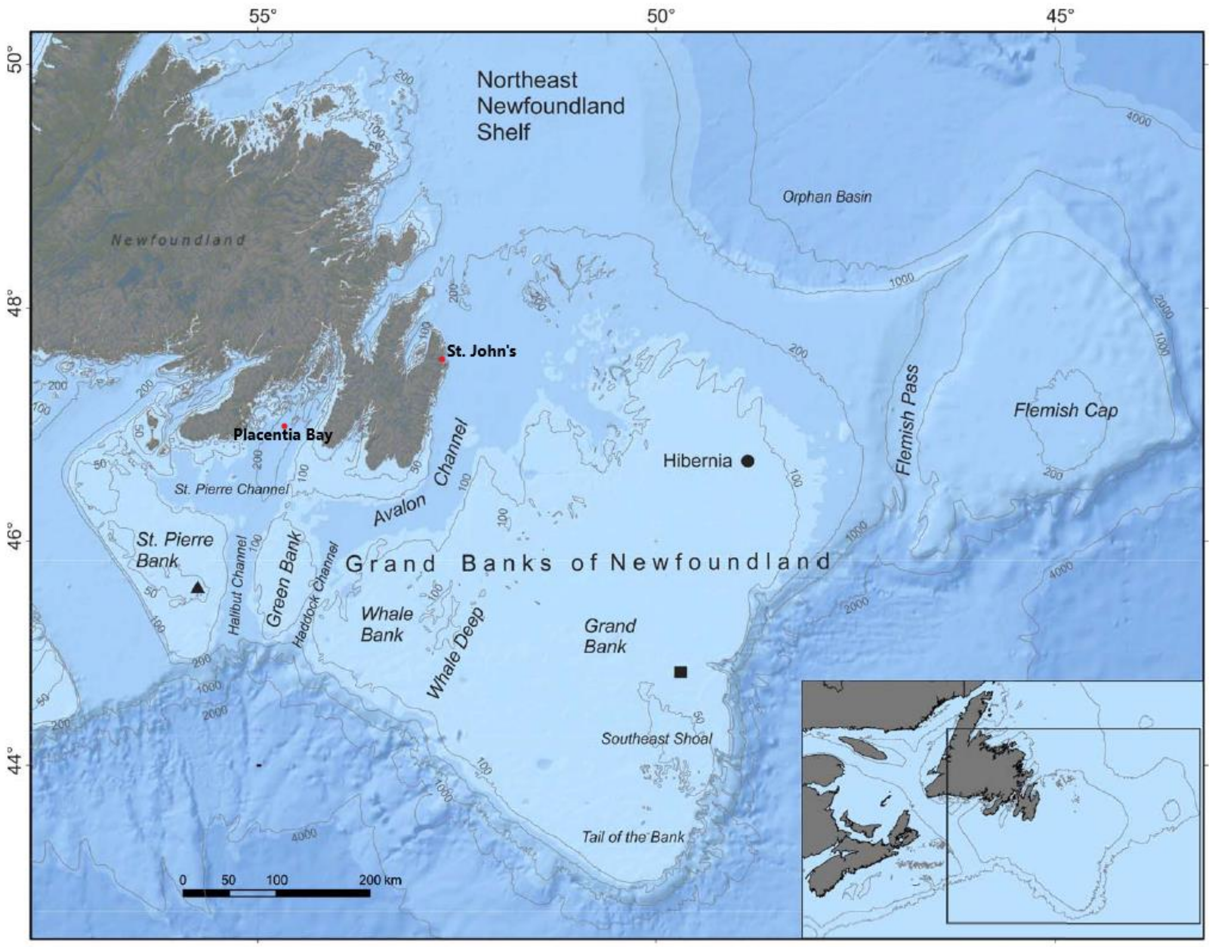

Figure 1. Southeastern region of Newfoundland and Labrador. Modified to include location of St. John's and Placentia Bay (Li et al., 2017)

2 GEOGRAPHY

2.1 LOCATION

The area of interest is located in the southeastern region of Newfoundland and Labrador (Figure 1). Placentia Bay is the largest bay in Newfoundland and its orientation, location and size has helped establish it as a shipping and transport hub in the region (Figure 2). The Bay opens up into the Atlantic Ocean from the south and is bounded by Burin Peninsula to the west and Avalon Peninsula to the east.

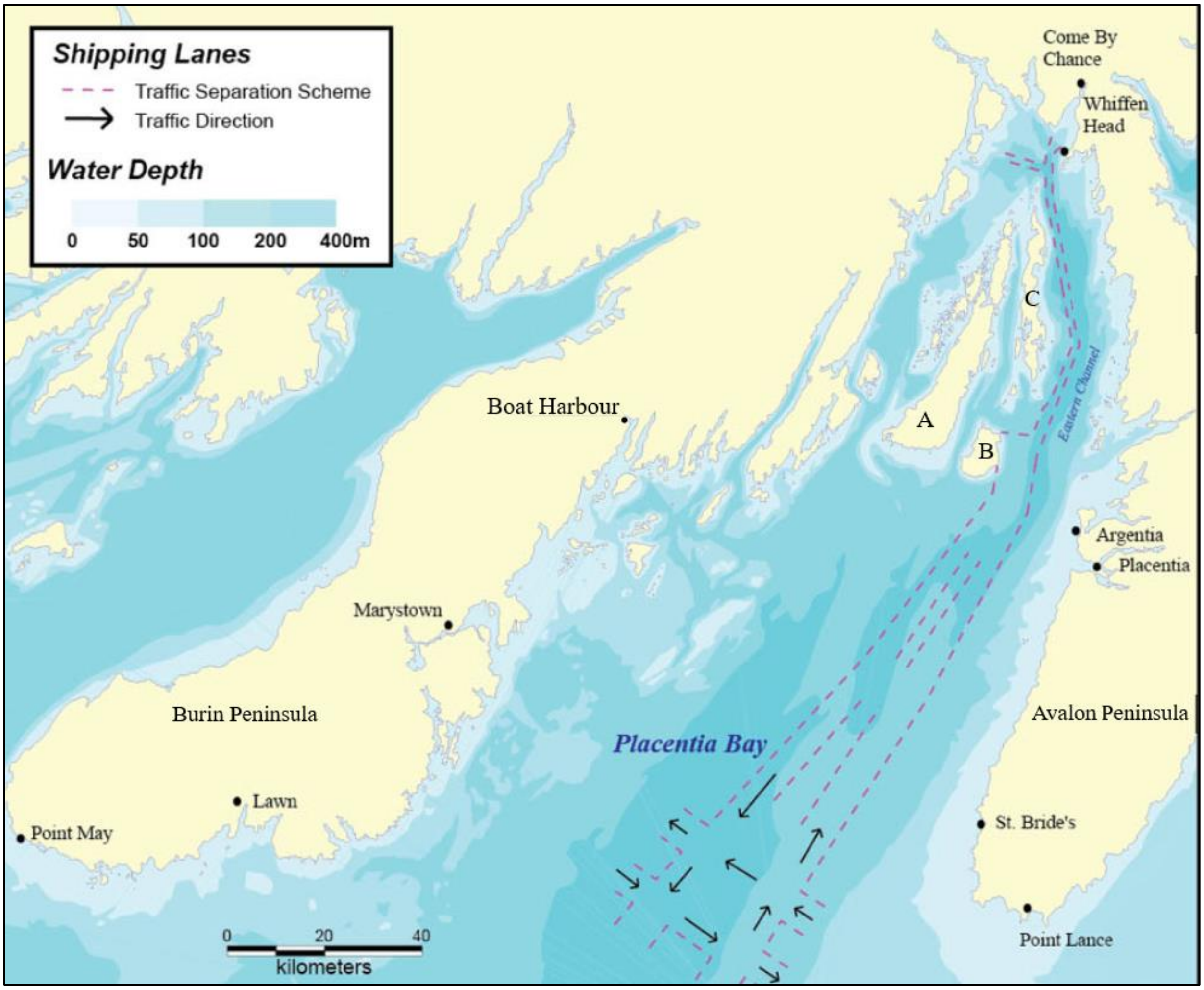

Figure 2. Closer look at Placentia Bay depicting designated shipping lanes. A) Merasheen Island, B) Red Island, and C) Long Island (Fisheries and Oceans Canada, 2008)

St. John's Harbour is situated on the northeastern Avalon Peninsula (Figure 2) and opens up to the east into the Atlantic Ocean. The inner harbour is sheltered by a curving channel, called the Narrows) as seen in Figure 3. The inner harbour is sheltered from icebergs, but they are present near the mouth of the harbour in the spring and early summer (Catto et al., 2003).

Figure 3. St. John's Harbour and the Narrows (Google Maps, 2020)

2.2 SHORELINES

2.2.1 ***St. John's Harbour***

St. John's Harbour (Figure 3) is small, approximately 2 km long with a maximum width of 0.68 km (Dewey and Palmer, 1984). St. John's Harbour shoreline has been highly modified to support the shipping and fishing industry. The backshore consists of rocky hills, sloped banks, and steep cliffs (Catto et al., 2003). The shoreline is comprised of rock and gravel material and bedrock platforms (Catto et al., 2003). There are patches of shoreline on the southeast side of the inner Harbour (Coomb's Cove) comprised of narrow gravel and sand mixed flats (Catto et al., 2003). The Harbour is narrow and difficult to enter as it is flanked by steep rock cliffs on both sides of the entrance (Lajoie, 1982; Catto et al., 2003). As the harbour is small, oil spilled in the inner Harbour may reach the shoreline quickly.

2.2.2 ***Placentia Bay***

Placentia Bay can be separated into the outer and inner bays. The outer bay is wide and open, approximately 130 km long and on average 80 km wide (Hart et al., 1999). The mouth of Placentia Bay is 100 km wide, oriented northwest to southwest, opening into the Atlantic Ocean (Hart et al., 1999; Xie, 2017). The boundary separating the inner and outer bay is just south of the collection of larger islands as seen in Figure 2. The shoreline has been primarily shaped by wind, waves, and seasonal ice cover with numerous inlets and over 300 scattered islands (Ma et al., 2012). Ice can be present in Placentia Bay between February to April but the bay is generally not completely covered by ice. Most of the ice is considered new ice; where the thickness is less than 10 cm but there are some areas that can be 15 cm or more (LGL Limited, 2007). Ice can pack along the shore in the winter if the winds stay consistent. The coastline is made up of a variety of landforms: wide and low gravel and sandy flats, steep gravel and boulder beaches, tombolos, lagoons, and estuaries backed by steep unconsolidated bluffs, bedrock platforms, and cliffs with some areas (Cape Shore) reaching over 80 m in height (Catto et al., 2003; Ma et al., 2012). Burin peninsula increases in elevation northward towards the head of the bay (Shaw and Potter, 2015). There are extensive salt marsh and eelgrass beds on the inner northwest coast (Catto et al., 1999). If an oil spill was to occur in the inner bay, it is highly likely petroleum would reach the shoreline.

3 HYDROGRAPHY

3.1 BATHYMETRY

3.1.1 ***St. John's Harbour***

St. John's Harbour is divided into two basins, the inner harbour, where the city of St. John's waterfront is located and the outer Narrows, a curved 800 m channel that links the inner harbour to the Atlantic Ocean as seen in Figure 3 and Figure 4 (Shaw and Potter, 2015). The mouth of the harbour is approximately 180 m wide (Shaw and Potter, 2015). It is difficult to navigate the Narrows because of the prominent sill and narrow boundary (Figure 4a). To enter the inner harbour, ships are confined to a shallow (14 m), narrow (91 m) channel with a sharp turn (St. John's Port Authority, 2019; Shaw and Potter, 2015). The entire basin is relatively shallow, averaging 12 – 15 m deep. The deepest section of the harbour is located in the northeast and is approximately 33 m deep (DeYoung, 2000; Shaw and Potter, 2015). The Narrows is 2 – 3 times wider at the eastern end where is connects to the Atlantic Ocean than the western end where it connects to St. John' Harbour (DeYoung et al., 2000). The bathymetry outside the harbour entrance is comprised of steep bedrock ridges (Figure 4b) covered in glacial sediment and mud (Shaw and Potter, 2015). Water depths drop quickly from 30 m to 100 m outside the entrance to the harbour. The Avalon Channel sits directly outside of the harbour.

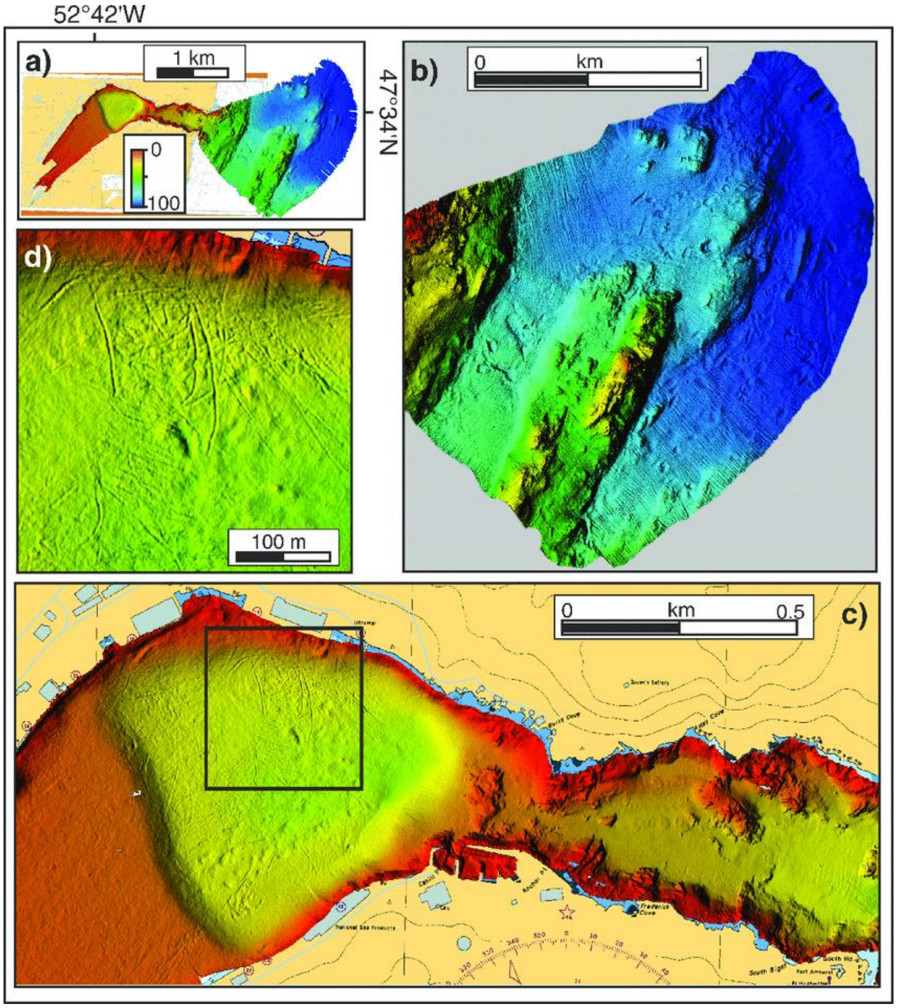

Figure 4. Multibeam bathymetry of St. John's Harbour and approaches; a) complete coverage, b) approaches to the harbour, c) part of the inner harbour including the Narrows, d) enlargement of area in the inner harbour showing anchor drag marks in (box in Fig. 4c) (Shaw and Potter, 2015)

3.1.2 ***Placentia Bay***

There is no prominent sill at the mouth of Placentia Bay allowing for a significant exchange of water with the Atlantic Ocean from the south (Hart et al., 1999; Xie, 2017). The mouth of the bay has a maximum depth of 250 m (Ma et al., 2012). On average the bay is approximately 125 m deep with areas in channels reaching down to 400 m deep (Hart et al., 1999; Ma et al., 2012; Xie, 2017). The bay is separated into the inner and outer bay by three large islands (Figure 2). Water exchange between the inner and outer bay is restricted through three channels (Eastern, Central and Western Channel) that separates the large central islands. Merasheen Island is the largest of the three, situated between the Western and Central Channel. Red Island is the smallest of the three and is positioned in front of Long Island, both of which flank the Eastern Channel where the shipping lane transitions to one lane (Figure 2). The Central Channel is the shallowest of the three. The Eastern has an approximate depth of 200 m that extends farther headward than the Western Channel (Ma, 2010).

3.2 CIRCULATION AND CURRENTS

Circulation on the continental shelf of southeastern Newfoundland (Grand Banks) is influenced by the Labrador Current transporting cold, fresh water from the Arctic, as depicted in Figure 5 from Colbourne et al. (1997). Water generally circulates south to southwest at an average speed of 0.1 ms^{-1}, increasing in speed in the fall/winter and decreasing in the spring/summer (Petrie and Anderson, 1983; Han, 2005). The inner branch of the Labrador Current moves through the Avalon Channel (Figure 5) at a speed between 0.5 - 1 ms^{-1} (LGL Limited., 2007; Han et al., 2008). Flow through the Avalon Channel divides just east of Placentia Bay where the bathymetry shift the channel flow seaward. As a result, only a portion of the Labrador Current flows into Placentia Bay.

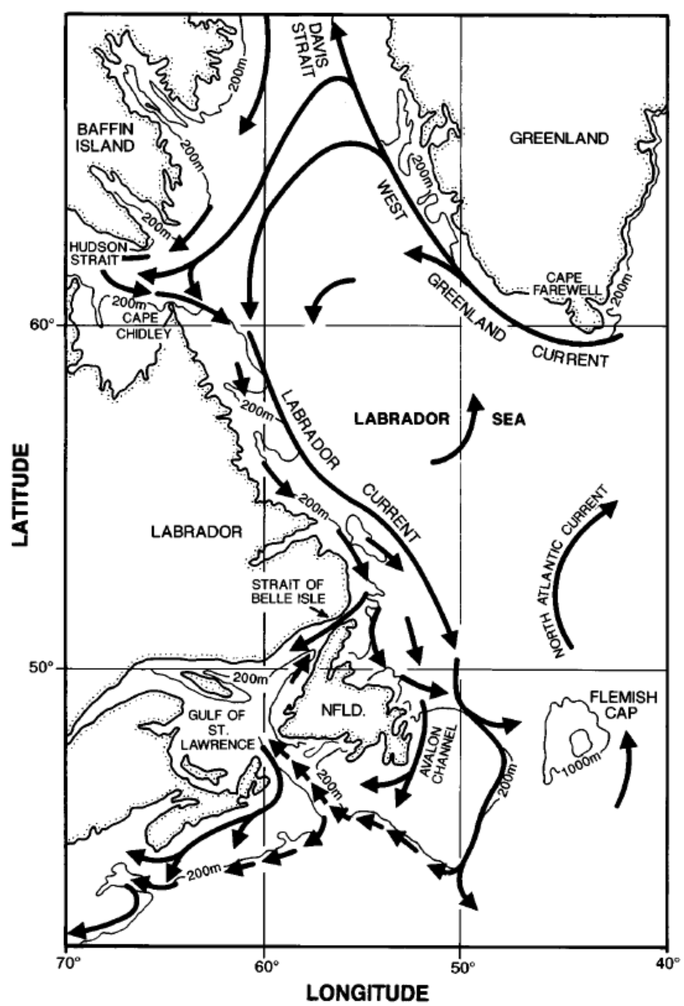

Figure 5. Circulation patterns for Northwest Atlantic from Colbourne et al., (1997)

3.2.1 ***St. John's Harbour***

Few studies have been published on the circulation in St. John's Harbour. DeYoung et al. (2000) conducted a study during the summer and fall of 1999 using Acoustic Doppler Current Profiler (ADCP) to observe circulation into and out of St. John's Harbour through the Narrows. Guo (2005) thesis further analyzed these continuous observation programs to better interpret circulation through the Narrows.

Circulation in the Narrows and St. John's Harbour is largely wind driven and directly influences surface currents. The circulation through the Narrows into the harbour is strong. The currents through the Narrows have a two layer vertical structure for most of the year, with a mean surface outflow of 0.04 m s^{-1} (4 cm s^{-1}) at 3 m and inflow occurring below 5 m with a peak flow of over 0.06 m s^{-1} (6 cm s^{-1}) at 10 m deep. When Waterford River discharge is strong, the flow through the Narrows shifts to a three layer vertical structure with an inflow current at 3-10 m (mean inflow 4 cm s^{-1}) sandwiched between two outflowing currents at the surface (0-3 m; mean outflow 4 cm s^{-1}) and below 10 m (mean outflow 6 cm s^{-1}). The stronger bottom outflow peaks in August, declines in September and is nonexistent by November (Guo, 2005).

Tides do not dominate the circulation in St. John's Harbour (DeYoung et al., 2000). The strongest tidal constituents (the portion of the tide induced by the interaction between the earth, moon and sun), are M_2 (principal lunar) and S_2 (principal solar) each with amplitudes between 2 and 4 cm s^{-1} (DeYoung, 2000). Semidiurnal tidal transport through the Narrows is approximately 50 $m^3\,s^{-1}$, accounting for less than 10% of the total volume of water flowing into the harbour during flood tides (DeYoung, 2000). DeYoung et al. (2000) observed significant baroclinic subtidal variability at a period of 2 days. A strong across channel current shear was observed, most notably during subtidal periods but more data is needed to understand across channel currents.

DeYoung (2000) estimates the average exchange rate for St. John's Harbour is between 5 – 10 days, however it is more likely shorter during strong wind conditions. Water exchange within the harbour does not appear to be uniform. Water in the northeast half of the harbour will have a shorter residency times than the southwest (DeYoung et al., 2000).

3.2.2 ***Placentia Bay***

Circulation has been monitored in Placentia Bay for various development projects and operational programs but little research is available in the public domain. Two field studies published out of Memorial University (MUN), Hart et al.(1999) and Schillinger et al.(2000), analyze current data from mooring stations deployed in 1998 (April 1 to June 18) and 1999 (April 18 – June 29). There is a lack of published research on circulation for the fall and winter conditions. The SmartBay buoy measurement and two archived Bedford Institute of Oceanography (BIO) Department of Fisheries and Oceans (DFO) Ocean Data Inventory (ODI) datasets from 1998 (February 16 to March 29) and 1998 (September 27 to October 29) have been analyzed in environmental assessment reports by LGL Limited (2007) and Stantec Consulting Ltd. (2012) to provide some general trends in Placentia Bay.

Local wind patterns play an important role in surface circulation direction and speed in Placentia Bay (Ma et al., 2012). In general there is a fairly stable near-surface counter clockwise circulation throughout Placentia Bay in April and June (Hart et al., 1999; Schillinger et al., 2000). The east side of Placentia Bay is dominated by an inward, north-easterly flowing current and the west side an outward southwesterly flowing current in both Hart et al. (1999) and Schillinger et al. (2000) observations. The existence of a near-surface counter clockwise flow was also observed in the BIO datasets collected during the winter and fall 1998, although its presence appears to be less stable (LGL Limited., 2007). Winds are predominantly from the southwest during all seasons which would account for the prevalent counter clockwise flow of near-surface currents for most of the year, waning during the fall and winter as a result of changes in wind forcing.

The flow pattern stays fairly consistent in both Hart et al.(1999) and Schillinger et al.(2000) spring observations but the speed varies throughout the bay. Mean current speeds from the surface down to 20 m were 17.9 cm s^{-1} at the mouth (47°02.79’N, 54°18.02’W) on the east side of the bay, 14.4 cm s^{-1} mid-bay by Long Island (47°24.56’N, 54°04.27’W), and 7.6 cm s^{-1} on the west side of the bay (47°11.61’N, 54° 42.80’W) (Schillinger et al., 2000). Average currents near Argentia in November range from 8 – 18 cm s^{-1} from the surface down 20 m and 3 – 7 cm s^{-1} at depths between 45 – 55 m (Stantec Consulting Ltd., 2012).

Stantec Consulting Ltd. (2012) analyzed SmartBay buoy measurements for the full year of 2011. Currents are observed to be the fastest at the mouth of Placentia Bay. Mean surface currents from SmartBay buoy (46° 58.4160' N, 54° 041.7168' W) range from 19 cm s^{-1} in June and July to 29 cm s^{-1} in November with upper limit speeds ranging from 135 cm s^{-1} in February to 178 cms^{-1} in November. Mean surface currents at the Pilot Boarding Station located near Argentia (47° 19.1026' N, 54° 007.3325' W) were approximately 22 cm s^{-1} with an upper limit speed range of 33 cm s^{-1} in December and 48 cm s^{-1} in September. Currents are generally weaker at the head of the bay but not well understood based on published observations (Lawrence et al., 1973; Schillinger et al., 2000; Ramey and Snelgrove, 2003). Mean surface currents at the now inactive Come By Chance SmartBay Buoy (47° 45.5483' N, 54° 004.4985' W) were approximately 8 cm s^{-1} for most of the year with an upper limit speed ranging from 11 cm s^{-1} in July and 23 cm s^{-1} in September.

The counter clockwise flow was not observed in the fall at depths below 45 m, instead oriented in the south southwest direction on the east side of the bay and east southeast at the head of the bay (LGL Limited, 2007). Bottom and near-bottom currents, those below 100 m depths, do not follow a counter clockwise pattern (LGL Limited, 2007). Observations from the 1998 mooring site (47°02.79’N, 54°18.02’W) on the east side of the bay detected weak currents at 110 m moving east to southeast direction, opposite to near-surface (10 m) currents at the same site (Hart et al., 1999). The current below 110 m at mooring site (47° 02.79’N, 54°18.02’W) were predominantly in the northeast/east direction in April before switching in May and June (Hart et al., 1999).

Mooring station (47°24.56'N, 54°04.27'W) contradicts the cyclonic pattern at 45 m deep (Schillinger et al., 2000). This mooring station was situated in the eastern channel, just outside of Long Island, indicating more complex circulation patterns are occurring around the mid-bay cluster of islands. Upwelling has been observed on the west side of the bay when shifts and surface circulation goes from west to east (Bradbury et al., 1999).

The tidal currents are considered weak and do not appear to have a major influence on circulation (Catto et a., 2003). The strongest tidal constituent is M_2 (principal lunar) with an amplitude between 3.5 – 6.1 cm s^{-1} at the near-surface and 1.7 – 4.8 cm s^{-1} in deeper waters (Hart et al., 1999; LGL Limited, 2007). Tidal currents vary throughout the bay. Mean tidal flow at depths of 20 – 32 m was stronger in the center of the bay and in the eastern channel by the Long Island from Hart et al. (1999) observations. Tide accounts for approximately 15% of the total variability in Placentia Bay and takes approximately 15 minutes to move through Placentia Bay (Catto et al., 2003; Stantec Consulting Ltd., 2012)

3.3 TIDES

3.3.1 ***St. John's Harbour***

Tides in St. John's Harbour are mixed semi-diurnal (two highs and two lows daily). Tides as reported by the Canadian Hydrographic Services (2022) tables (CHS), for Station 0905 in St. John's Harbour are summarized in Table 1. The mean tidal range is 0.9 m and large tide range is 1.6 m.

Table 1. Summary of tidal range from CHS tide tables (Canadian Hydrographic Services, 2022)

Station	Mean Water Level (m)	Range (m)	
		Mean Tide	Large Tide
0905 St. John's	0.9	0.9	1.6

3.3.2 ***Placentia Bay***

Tides are semi-diurnal in Placentia Bay, with a mean tide range of 1.6 m (Canadian Hydrographic Services, 2022). Table 2 shows the tides reported by the CHS (2022) for Station 0835 at Argentia on the central east coast of Placentia Bay, Station 0815 at the head of the bay at Come by Chance, and Station 0760 in Burin on the southwest coast of Placentia Bay.

Table 2. Summary of tidal range from CHS tide tables (Canadian Hydrographic Services, 2022)

Station	Mean Water Level (m)	Range (m)	
		Mean Tide	Large Tide
0835 Argentia	1.4	1.6	2.7
0815 Come By Chance	1.4	1.6	2.4
0760 Burin	1.2	1.5	2.3

3.4 WATERSHED

There are no large rivers draining into either St. John's Harbour or Placentia Bay (Catto et al., 2003; Ma et al., 2012). Waterford River is the only river draining into St. John's Harbour, with a mean flow of $2.2m^3s^{-1}$ (Government of Newfoundland and Labrador, 2020a). The Harbour is also subjected to anthropogenic run off from the surrounding city which can periodically cause water quality problems in the harbour (Dewey and Palmer, 1984; Catto et al., 2003).

The two peninsulas flanking Placentia Bay, Avalon and Burin, have small rivers and streams draining into the bay but there is little research published on the volume of freshwater inputs; only that freshwater input from surrounding uplands is not statistically significant (Catto et al., 2003; Ma et al., 2012). There are several real time streamflow data collection sites located in Placentia Bay that will be highlighted as examples of discharge into the bay. The Northeast River drains into the Northeast Arm near Placentia with a mean discharge of approximately 4.06 m^3s^{-1} (Government of Newfoundland and Labrador, 2020b). At the head of the bay, the Come By Chance River, mean discharge is approximately 1.95 m^3s^{-1}. Rattle Brook near Boat Harbour located on the western side of Placentia Bay has a mean discharge of 2.25 m^3s^{-1} (Government of Newfoundland and Labrador, 2020b).

3.5 SALINITY AND WATER TEMPERATURE

3.5.1 ***St. John's Harbour***

Little water profile information has been published on St. John's Harbour. Based on the information that has been published, the water column does not mix completely in the harbour and experiences seasonal stratification in the summer (July – August) and a weaker stratification in the fall (October – November) (DeYoung et al., 2000). There is a strong salinity gradient present in October from the surface down to 5m (DeYoung et al., 2000). Surface salinity in October sits between 29 – 30 psu down to 5 m. Below 5 m, salinity stabilizes at 31 psu to the bottom (DeYoung et al., 2000).

Much of the research conducted around St. John's Harbour uses Station 27 measurements due to its consistent and long term availability. Station 27 is located 7 km outside of the entrance to St. John's Harbour in the Avalon Channel and has been collecting oceanographic data at a standard depth since June 1946 (Colbourne et al., 2016; Cyr and Galbraith, 2021). Figure 6 shows the annual cycle of temperature and salinity at Station 27 between 1981 – 2010. At

Station 27, sea surface temperatures (~20 m) begins to increase starting around April and peaks in August to a maximum average temperature of ~12 °C (Cyr and Galbraith, 2020). Average sea surface temperature decrease in the fall, ~10 – 6 °C, between September and October as a result of vertical mixing (Cyr and Galbraith, 2020). The average sea surface temperature between December and March is ~0 °C and -2°C (Cyr and Galbraith, 2020). There is a prominent cold intermediate layer (CIL), water that sits below 0 °C, delineated as a thick black line in Figure 6 (Cyr and Galbraith, 2020). The CIL sits at the surface in the winter and as the surface heats up in the spring, beginning in April, the CIL is pushed down and sits below the surface for most of the year and extends down to the bottom (176 m) (Cyr and Galbraith, 2020).

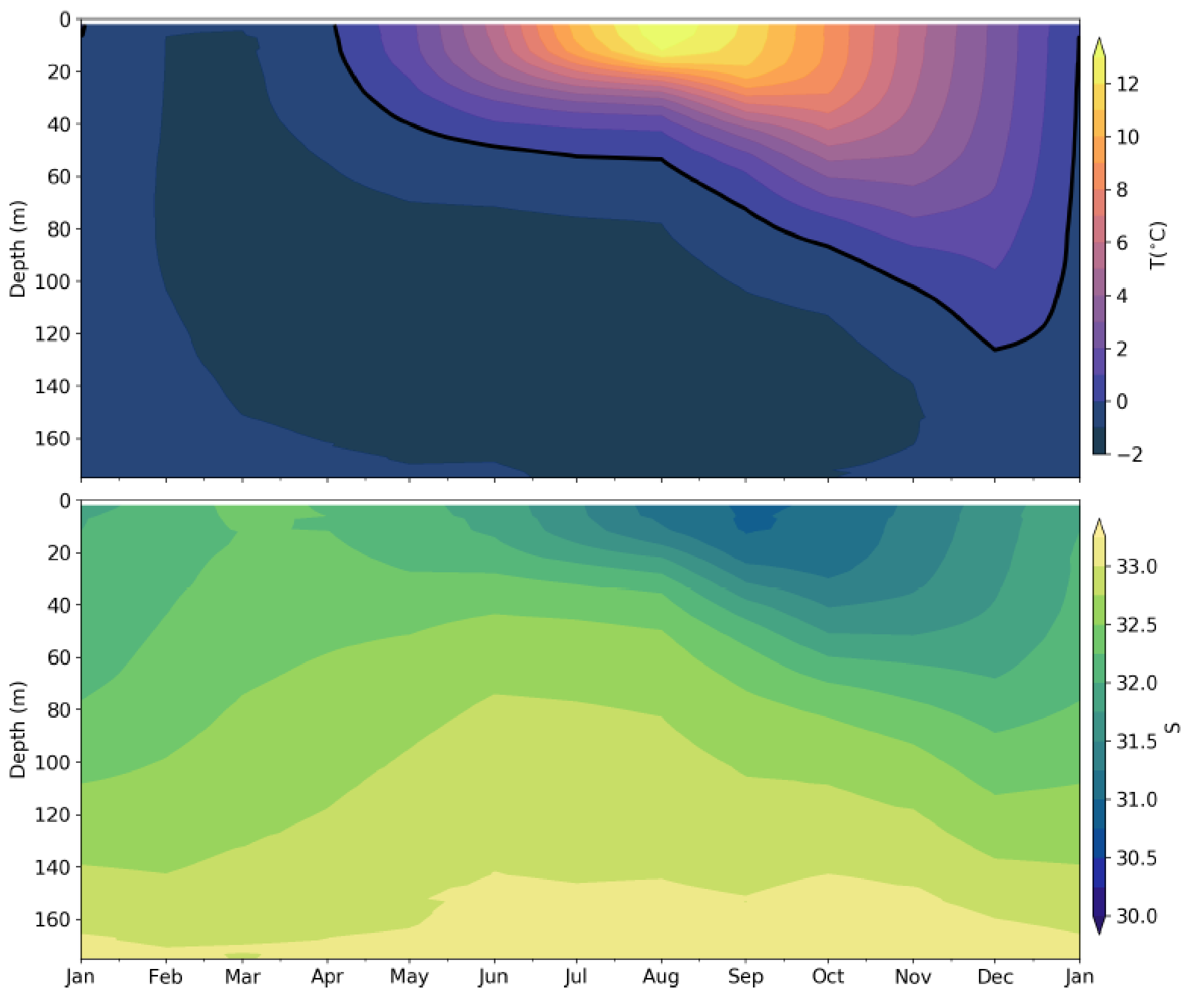

Figure 6. Annual cycle of temperature (top) and salinity (bottom) at Station 27 between 1981-2010. The black line is the isotherm showing the location of the cold intermediate layer throughout the year (Cyr and Galbraith, 2020)

In general, salinity at Station 27 and throughout most of the Newfoundland Shelf, is low (S<31 psu) at the near surface from early summer (June) to late fall (November) and highest (S>32 psu) in the winter (Figure 6) (Cyr and Galbraith, 2020). Salinity below the surface, at any depth below 20 m begins to increase in the spring, reaching it's peak in the summer before decreasing in the fall due to vertical mixing (Colbourne et al., 2016; Cyr and Galbraith, 2020). Below 150 m salinity is high, sitting between 32.75 – 33.0 psu (Cyr and Galbraith, 2020).

3.5.2 ***Placentia Bay***

As mentioned in the current and circulation section, few studies have been published that focus on hydrological conditions in Placentia Bay. While there may be a number of programs that collect temperature and salinity data for operational purposes, the results have not been peer reviewed and published. Observations in published studies are short term and focus mainly on spring, summer and early fall conditions. Little research has been focused on winter conditions in Placentia Bay. Technical and environmental reports were looked at to provide additional knowledge in the study area. Stantec Consulting Ltd. (2012) environmental report obtained archived Bedford institute of Oceanography (BIO) hydrographic data for the entire bay (47°N to 47.8°N and 54°W to 55.2°W), obtaining over 62,500 measurements to provide a general temperature and salinity profile for Placentia Bay and highlight seasonal changes.

Generally, the water column in outer Placentia Bay is relatively mixed and uniform in the winter and spring before a strong thermocline forms during the summer months when warmer, fresher water layers over top colder, saltier water (Ma, 2010). A strong thermocline can persist from June to October with a mean monthly temperature range of 10 – 14°C that generally penetrates down to 20 m before gradually decreasing to 4 – 9 °C below 20 m to approximately 50 m (Stantec Consulting Ltd., 2012). Below the layer of warmer, fresher water, the temperature is approximately 3 °C until depths of 150 m before transitioning to a colder (-1 °C) and saltier water at the near bottom. The water column starts to mix in the fall, weakening the thermocline and has a mean monthly temperature of 8 °C at the surface to approximately 60 m down. Below 60 m, the temperature steadily decreases to an average monthly temperature of 2 °C from November to December. By the end of December and persisting until May, the water column is highly mixed with a mean monthly temperature of 2 °C at the surface down to 140 m and a near zero temperatures down to 180 m (Stantec Consulting Ltd., 2012).

Salinity throughout the water column is more uniform in the winter than the summer. From the surface to the near-bottom, mean monthly salinity in the winter is 32 psu with slightly saltier water (32.5 psu) at the bottom (Stantec Consulting Ltd., 2012). The saltier (32.5 psu) near bottom layer is present year round but expands higher up in the water column in the fall, present from 60 m to near bottom. In the summer, average monthly salinity at the surface down to 30 m is 31 psu, increasing to 32 psu between 30 – 150 m deep and 32.5 psu at near-bottom, 150 – 200 m (Stantec Consulting Ltd., 2012). During the fall, the water column mixes and the surface waters down to 60 m is uniform with an average monthly salinity of 31 psu (Stantec Consulting Ltd., 2012). The water column continues to mix after December throughout the winter months and creates a somewhat uniform water column with an average monthly salinity reading of 32 psu from the surface to near-bottom (Stantec Consulting Ltd., 2012).

4 CLIMATE

The climate in southeastern Newfoundland is a cold, temperate, maritime climate (Catto et al., 2003). The spring season is the longest, stretching from March to June while the summer is short, cool and wet; except in August when it is mostly dry and hot (Catto et al., 2003). Fall begins in September and ends in mid October. Cool winter temperatures take over the region by mid to late October with snowfall events starting in late October (Catto et al., 2003; SL Ross Environmental Research Ltd., 2007). The winter months experience numerous freeze-thaw cycles between mid-December and early April (Catto et al., 2003). Areas of southeastern Newfoundland exposed to direct southwesterly winds are associated with cooler temperatures, highlighting the influence of maritime winds (Catto et al., 2003). Local topography shelters some parts of southeastern Newfoundland from the northeasterly and southwesterly winds associated with colder temperatures, creating smaller, warmer macroclimates in the region (Catto et al., 2003; Stantec Consulting Ltd., 2012). Southeastern Newfoundland is a moderately humid environment with steady precipitation falling as rain and snow over the year (Catto et al., 2003).

Climate change will continue to impact Newfoundland and Labrador in a variety of ways as air and sea surface temperatures increase, sea levels rise and weather systems shift, becoming stronger and more frequent in the region (Dietz and Arnold, 2021). Air temperatures in Newfoundland and Labrador are already 1.5°C above the historical average and the climate is expected to become warmer and wetter (Government of Newfoundland & Labrador, 2016). Warming is projected to continue across Canada, the extent of which depends on human behaviour ranging from 1 – 6 °C based on low or high emissions scenarios (Dietz and Arnold, 2021). Sea ice is present in southeastern Newfoundland from late winter and early spring, right before or during ice berg season. A change in sea ice presence in winter will shift coastal dynamics in the winter months, presenting additional challenging to navigation and oil spill response.

4.1 AIR TEMPERATURE AND PRECIPITATION

4.1.1 ***St. John's Harbour***

Figure 7 shows mean temperature and precipitation records from 1981 to 2010 at Single Hill Environment Canada weather station (Environment Canada, 2019a). The annual average temperature range is -4.2 to 16.2°C (Figure 7) in St. John's (Environment Canada, 2019a). The warmest months are July and August and the coldest are January and February. St. John's receives an average 1242mm of precipitation annually, most of which occurs in the fall and winter months while the driest month on average is July (Environment Canada, 2019a).

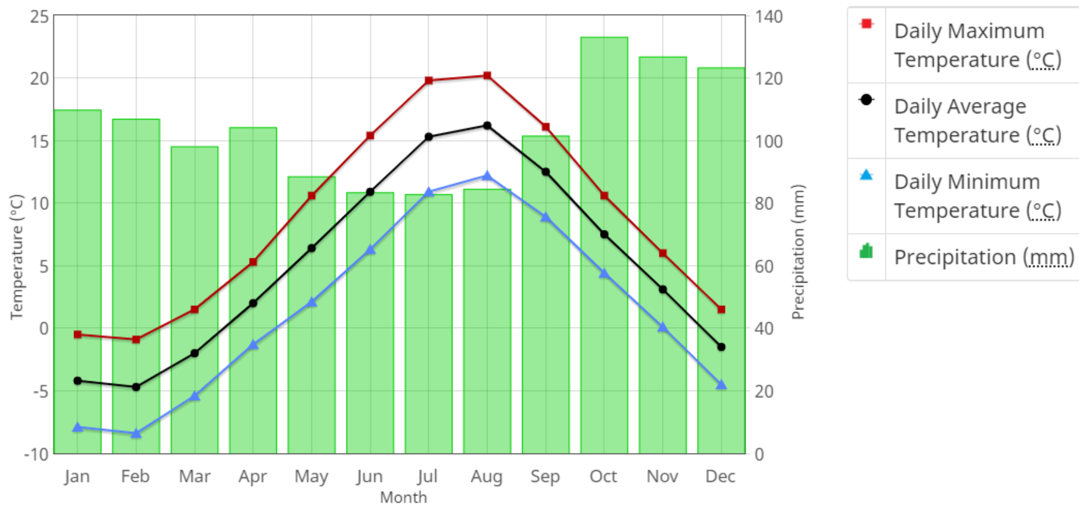

Figure 7. Average temperature and precipitation chart for 1981 to 2010 Canadian climate averages at Signal Hill in St. John's (Environment Canada, 2019a)

4.1.2 ***Placentia Bay***

Figure 8 shows the mean temperature and precipitation records from 1981 to 2010 at Boat Harbour (47.2550°N, 54.5034°W, Figure 2) Environment Canada weather station (Environment Canada, 2019b). The annual average temperature range is -4.8 to 16.2°C in Placentia Bay (Environment Canada, 2019b). The warmest months are July and August and the coldest are January and February. Air temperatures in the open waters of Placentia Bay experience less variation than the adjacent land (Stantec Consulting Ltd., 2012).

Placentia Bay receives an average 1644 mm of precipitation annually (Environment Canada, 2019b). While absolute precipitation may vary slightly around the Bay, trends in precipitation and temperature are representative of the area surrounding Placentia Bay. The driest months are July and August and the wettest months are October and November (Environment Canada, 2019b). Snow has historically occurred in every season but typically begins in October, accounting for 10 – 15% of the total annual precipitation in Placentia Bay. The heaviest snowfall occurs between late December and early April (Stantec Consulting Ltd., 2012). The western and central regions of Placentia Bay tends to experience more rainfall than the eastern side. Freezing rain events do not occur as frequently in Placentia Bay as they do in other regions of Newfoundland, occurring approximately 22 hours a year between February and March due to warm fronts moving into Placentia Bay (Stantec Consulting Ltd., 2012).

Foggy conditions are common in Placentia Bay, caused by advection, warm air moving over cooler water creating low cloud cover reducing visibility for seafaring traffic (Catto et al., 2003; LGL Limited, 2007). Fog conditions are most likely to occur in late spring and early summer, peaking in July with a 30% likelihood causing poor visibility less than 2 km (Catto et al., 2003). Poor visibility in the winter is attributed to snow conditions (Catto et al., 2003). Vessel icing during cooler months is a safety risk starting in late November and ending early April with the highest frequency of potential occurrence in February (Stantec Consulting Ltd., 2012). Placentia Bay records low iceberg numbers due to the southern location, warmer temperatures, orientation, and circulation of the bay (Colbourne et al., 2016).

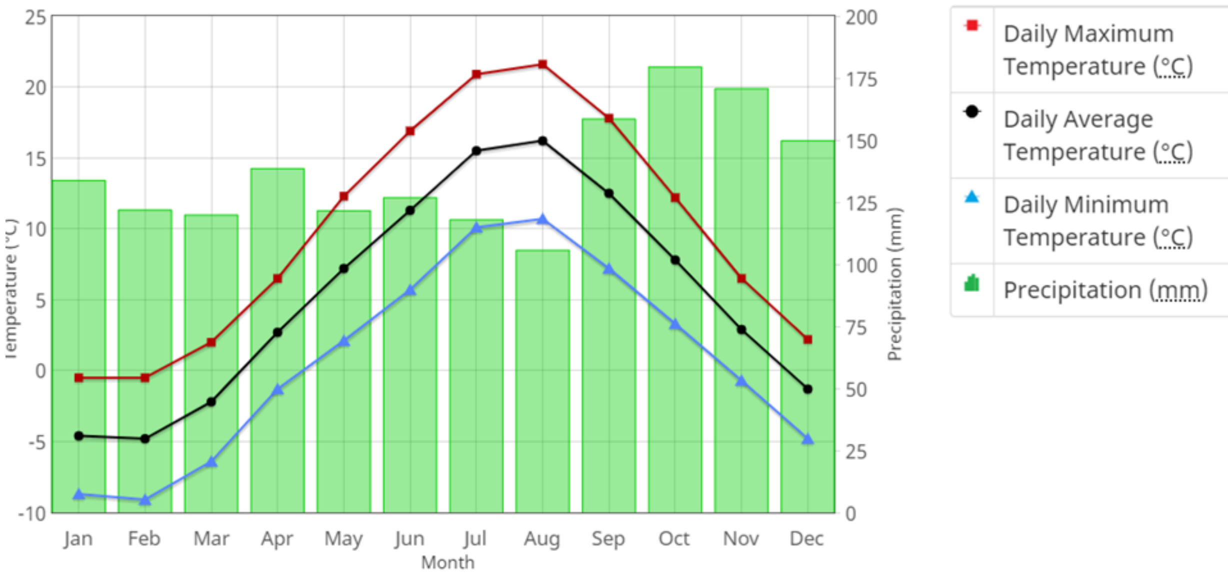

Figure 8. Average temperature and precipitation for Boat Harbour Placentia Bay between 1981 - 2010 (Environment Canada, 2019b)

4.2 WINDS AND WAVES

Southeastern Newfoundland is located along the major storm track route and can experience storm events any time of year. Hurricanes and tropical storms also bring windy, wet weather between August and October. Frequent extratropical storms occur between November and March. The most intense storms generally approach from the south, feeding off the contrasting temperatures of Labrador Current and Gulf Stream (Xie, 2017). Storm activity in southeastern Newfoundland generates storm surges and enhances vertical mixing throughout the water column.

Hurricane Igor passed over southeastern Newfoundland on September 21, 2010 and is considered one of the most intense Hurricanes in recent decades, experiencing intense storm surges and extensive damage across the region (Ma et al., 2015). A sudden drop in sea surface temperature by 6 °C was observed on the Grand Banks as a result of turbulent mixing when Hurricane Igor passed over (Han et al., 2012a).

Few published studies have examined the temporal and spatial variations of waves and wind-driven currents in southeastern Newfoundland (Li et al., 2017). In general, the wind and wave climate shows seasonal variability, lower wind speeds and wave heights are observed in the spring and summer.

4.2.1 St. John's Harbour

Wind can be from all directions any time of year but in general wind direction is mainly from the northwest and southwest. Winter wind conditions are primarily from the northwest and west and summer winds are generally from the southwest (C-CORE, 2017; St. John's Port Authority, 2019). Average wind conditions (Table 3) are weakest in the summer and strongest in the winter (C-CORE, 2017). Maximum average wind speeds are similar between seasons, ranging from 90 – 117 km h^{-1} throughout the year and tend to be strongest in the fall (C-CORE, 2017).

Table 3. Seasonal average wind speeds and maximum average wind speeds in St. John's (C-CORE, 2017)

Season	**Average Wind Speed**		**Maximum Average Wind Speed**	
	m s^{-1}	**km h^{-1}**	**m s^{-1}**	**km h^{-1}**
Spring	8 – 9	29 – 32	25 – 27.5	90 – 99
Summer	6 – 7	22 – 25	27.5 – 30	99 – 108
Fall	9 – 10	32 – 36	30 – 32.5	108 – 117
Winter	11 – 12	40 – 43	27.5 – 30	99 – 108

Sustained high speed winds (≥90 km h^{-1}) are rare in St. John's but the region experiences some of the most frequent wind gusts in the country (Cheng et al., 2014). Wind gusts are sudden increases in wind speed ≥28 km h^{-1} that last no longer than 20 seconds. Wind gusts can occur any time of year in St. John's but are less frequent in the summer months (Cheng et al., 2014).

Between May and August, St. John's harbour may experience sea breezes; a 24 hour reversal in surface wind direction that shifts between onshore and offshore (Banfield, 1991). Due in part to the influence of the Labrador Current, the air temperature change can be extreme during a sea breeze event in St. John's (Banfield, 1991). Sea breezes do not form as readily in St. John's compared to other coastal Canadian cities like Halifax and Vancouver (Banfield, 1991).

Large swells are present just outside St. John's Harbour and can reach into the Narrows but do not reach into the sheltered, inner harbour. Vessel traffic moving into and out of the harbour to the east are exposed to an unlimited fetch and subjected to high winds and large swells.

The wave climate just outside of St. John's Harbour follows a similar trend as the wind patterns, stronger conditions in the fall and winter and lighter in the spring and summer. Mean wave height is 2 – 2.5 m just outside the entrance to St. John's Harbour (C-CORE, 2017). Annual maximum significant wave heights are 11.5 – 13 m (C-CORE, 2017). Storm surges do occur outside the harbour. During Hurricane Igor, two storm surges (~1 m) were observed outside of St. John's Harbour occurring 11 hours apart (Han et al., 2012b).

4.2.2 Placentia Bay

Wind conditions in Placentia Bay are considered strong and can be from all directions, but there is a dominant wind direction shift that occurs seasonally. For most of the year (spring, summer and fall) the dominant wind direction is from the west and southwest (Catto et al., 2003). During the winter, dominant wind direction is from the west and northwest (Catto et al., 2003). The inner bay is sheltered from stronger wind conditions experienced in the outer bay due to the natural angle of the bay and large islands in the upper mid portion of the bay. Average wind conditions (Table 4) are weakest in the summer and strongest in the winter (C-CORE, 2017). Maximum average wind speeds are similar between seasons, ranging from 90 – 117 km h^{-1} throughout the year and tend to be strongest in the fall (C-CORE, 2017).

Table 4. Seasonal average wind speeds and maximum average wind speeds in Placentia Bay (C-CORE, 2017)

Season	Average Wind Speed		Maximum Average Wind Speed	
	m s^{-1}	km h^{-1}	m s^{-1}	km h^{-1}
Spring	8 – 9	29 – 32	27.5 – 30	99 – 108
Summer	6 – 7	22 – 25	25 – 27.5	90 – 99
Fall	8 – 9	29 – 32	30 – 32.5	108 – 117
Winter	10 – 11	36 – 40	25 – 27.5	90 – 99

Annual mean wave height at the mouth of Placentia Bay is 1.5 – 2 m but experiences much higher wave heights during storm events and strong persistent conditions (C-CORE, 2017). The annual maximum significant wave height is 10 – 11.5 m (C-CORE, 2017). Wave conditions tend to be strong in the winter. The head of Placentia Bay is not as well documented as the outer bay and is absent of long term wave height data. The head of the bay is protected from the south by the islands, and therefore waves would be fetch limited and locally generated by wind. Significant wave height at the head of the bay would be substantially smaller than what is experienced in the outer bay.

The shape and angle of the Placentia Bay can create seiche waves; standing waves that oscillate at a period of about 4.2 to 4.6 hours (Ma et al., 2017). During Hurricane Igor, storm surge heights observed at Argentia and Bonavista tide gauge stations were 0.8 m (Han et al., 2012b). During Hurricane Igor the Argentia tide gauge observed a short, strong oscillation with a 5 hour period, although the location of the tidal gauge may not have adequately captured the seiche (Ma et al., 2015).

5 PAST OIL SPILLS

The Transportation Safety Board of Canada (TSBC) maintains a database of air, marine, rail, and pipeline incidents and accidents, collectively called 'occurrences.' The marine occurrence database contains information on the vessels, cargo, location, summary of occurrence, reported pollution, and more, dating back to 1975. Reporting requirements have changed over the years, most recently in 2014, leading to an increase in the number of occurrences entered into the database. In this report, statistics have been compiled for marine occurrences of interest for the entire span of the database (1975-2019) and on an annual average basis for full years since the new reporting requirements (2015-2017). The database only includes marine occurrence reports up to September 4th, 2019.

Marine occurrences are compiled into four different types of events: 1) occurrences involving cargo vessels, either tankers or barges, that transport petroleum products; 2) occurrences in which pollution was reported or any type of cargo was lost overboard; 3) occurrences in which petroleum products were reported spilled on board or into the water; 4) occurrences in which vessels sunk, capsized or were otherwise seriously damaged beyond repair, and expected to release fuel into the environment. Due to the nature of the predetermined categories, some occurrences fit into several categories.

The following statistics encompass southeastern Newfoundland, including main transport routes to and from Placentia Bay and St. John's Harbour. Statistics were compiled by filtering for occurrences in Newfoundland and Labrador or in international waters within the latitudinal range 46.50^{o}N to 48.50^{o}N, and within a longitudinal range of 47.00^{o}W to 55.00^{o}W. This boundary corresponds with main vessel traffic routes to St. John's Harbour and Placentia Bay from offshore oil production platforms on the Grand Banks. Southeastern Newfoundland experiences high volumes of vessel traffic to offshore sites to service the platforms and transport oil products back to shore to be refined and shipped to their final destinations. Additionally, vessels from international markets travel through southeastern Newfoundland on route to the Gulf of St. Lawrence and Great Lakes. Their presence within the area of interest increases the risk of oil spill occurrences (SL Ross Environmental Research Ltd., 2007).

Table 5 displays the incident and accident occurrences in southeastern Newfoundland that are reported in the four predetermined categories. The total number of occurrences within the boundary is 1574. Out of the total, 1419 occurrences did not fall within the parameters analyzed in this report. The occurrence was either out of scope or lacked information necessary to properly categorize. Only 155 out of the total 1574 occurrences fit into the predetermined categories. Petroleum cargo vessels were involved in 47 of the occurrences. Of those 47 occurrences, 16 involved oil field platforms or rigs engaged in offshore oil production.

Table 5. Transportation Safety Board incident and accident occurrences in Southeastern Newfoundland Coast, including St. John's, Placentia Bay, and extending to the Grand Banks oil field production sites

Occurrences involving..	All Years (1975 – 2019)	Annual Averages (2015 – 2018)
All occurrences	1574	47.5
Petroleum cargo vessels	47	2
Pollution or cargo lost overboard	39	1
Petroleum spills onboard or overboard	21	0.47
Vessels sunk, capsized or destroyed	63	0.5

Pollution or cargo lost overboard was noted in 39 of the incident reports and 21 of the incidents mentioned petroleum spilling onboard or overboard during the occurrence. It is important to note that 956 of the total occurrences within the boundary state that pollution was 'unknown'. Despite the unknown pollution designation, pollution would have likely occurred during a number of incidents based on information written in the occurrence summary. Due to limited information provided in the occurrence report, it is unclear how to determine which incidents out of 956 designated as 'unknown' did experience pollution and the quantity.

A large number of occurrences filed had no reference to the type of vessel involved. The incidents that did include vessel type involved barges (7), tankers (16), bulk carriers (3), container vessels (23), and fishing boats (418). Winter conditions involving ice damage played a factor in 67 of the incidents that occurred in the study area. Icebergs were involved in four of the incidents.

The following section provide additional information on two occurrences within the area of interest (Come by Chance and *SeaRose* FPSO) and three occurrences (*Katsheshuk*, *Manolis L*, and Baie Verte) that occurred outside of the boundary of interest on the north coast of Newfoundland and are considered major incidents in the region.

Come By Chance

In March 1988, 500 barrels of light crude oil spilled in the Come By Chance harbour while unloading a tanker (McKnight, 1996; Williams et al., 1988). The occurrence was the result of human error, spilling approximately 22,500 gallons of oil alongside the wharf. Responders were able to recover about half of the oil using containment booms and suctioning equipment (McKnight, 1996). The remaining oil either reached the shoreline or moved into the outer reaches of Placentia Bay (McKnight, 1996).

SeaRose FPSO

On November 16 2018, over 1571 barrels (250,000 litres) of crude oil spilled 350 km east off the coast of Newfoundland at Husky Energy White Rose oilfield on the Grand Banks (National Post, 2018). While connected to *SeaRose* FPSO, the vessel experienced a loss in pressure causing a leak between the flow line (Transportation Safety Board of Canada, 2019). Weather conditions at the time of the occurrence deterred safe deployment of oil spill response and recovery equipment. Gale force wind warnings were in effect in the area with south winds reaching 35 knots and waves were 3 – 5 m, dispersing oil throughout the water column (Transportation Safety Board of Canada, 2019).

After the incident the Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) reviewed all operators' adverse weather plans and procedures which resulted in changes to procedures and new requirements that were put in place based on the lessons learned from this event (C-NLOPB, 2022).

Katsheshuk

A fire broke out on March 17, 2002 in a large fishing vessel *Katsheshuk* near Belle Isle located between Newfoundland and Labrador (Transportation Safety Board of Canada, 2002). Unable to contain the fire, the ship had to be abandoned. After several days the tug *Atlantic Maple* towed the vessel towards St. John's but had to seek refuge in Trinity Bay (NL) to wait out a storm. On March 30, 2002 approximately six nautical miles north-west of Cape St. Francis (NL) the *Katsheshuk* listed and sank (Transportation Safety Board of Canada, 2002). The environmental impact of oil released and when the vessel sank was considered minimal. Winds were from the north-northwest at 50 knots with swells of 4 m during the time of the occurrence and northwest 15 – 20 knots and swells of 1.5m when the vessel sank (Transportation Safety Board of Canada, 2002).

Manolis L

In January 1985, *Manolis L* ran aground on Blow Hard Rock and sank in 70 m of water in Notre Dame Bay located on the north coast of Newfoundland. At the time of the incident the *Manolis L* had approximately 462 tonnes of heavy fuel and 60 tonnes or diesel on board (Canadian Coast Guard, 2018). For 28 years the wreck had no reports of oil pollution until intense storm in 2013 caused additional damage to the ship and oil sheens were observed close to the wreck. Two cracks had developed in the hull, leaking small quantities of oil (Canadian Coast Guard, 2018). The Canadian Coast Guard contained the oil using weighted neoprene sealants and a cofferdam to catch small amounts of oil escaping. Over the next several years, technical assessments were completed to determine recovery methods and amount of oil remaining. Canadian Coast Guard and its partners removed bulk oil from the Manolis L. wreck in September 2018.

Baie Verte

In March 1982, 500 barrels of diesel spilled in Baie Verte (49°56'N, 56°10'W) on the north coast of Newfoundland. The spill occurred in a relatively low energy shoreline and was trapped under the ice until spring. Kicenuik and Williams (1987) conducted a four year study to help understand the effects of weathering on spilled oil and assess the feasibility of recovery in contaminated sediments. Samples were collected in June over a four year period (1982 – 1985) at the contamination site and a nearby control site. The concentration of polycyclic aromatic hydrocarbons (PAHs) were consistently higher in the samples taken at the spill site than samples from the control site. Aromatic concentrations decreased over the four year sampling period but still had high concentrations relative to control sites after 27 months. After 39 months, PAHs levels were similar to the control site. If a small marine diesel spill occurs in the marine environment, it typically spreads out as a thin film on the surface and will evaporate or naturally disperse into the water column in a couple of hours to days, depending on sea state (waves and currents) and environmental conditions. The marine spill in Baie Verte occurred in the winter in a low wave energy environment, contaminating the shoreline. The low energy sea state increased the longevity of contaminates and prolonged the weathering process.

5.1 The Canada-Newfoundland and Labrador Offshore Petroleum Board: Oil Production and Spill History

The Canada-Newfoundland and Labrador Offshore Petroleum Board (C-NLOPB) regulates petroleum-related activities in the Canada – Newfoundland and Labrador Offshore Area. The C-NLOPB[1] website is a central information and reporting hub for offshore oil and gas exploration, development, extraction activities. Since offshore oil production started in 1997, over 2.1 billion barrels of oil and 97 million 10^3 m^3 of gas has been extracted from the Grand Banks (C-NLOPB, 2022). Cumulative production result from 2018 – 2021 and total production from 1997 – 2022 (cumulative up to March 31st, 2022) are found in Table 6.

Table 6. Canada-Newfoundland and Labrador Offshore Petroleum Board Production totals for years 2018 – 2021 and total cumulative production from 1997 – 2022 (C-NLOPB, 2022)

Year	Production			
	Oil		Gas	
	m^3	bbls	10^3 m^3	MMscf**
2018	13 355 790	84 005 388	5 649 166	200 510
2019	15 185 011	95 510 840	5 101 411	181 068
2020	16 535 628	104 005 970	4 791 241	170 059
2021	14 948 285	94 021 880	4 459 076	158 269
Total 1997 – 2022*	340 575 317	2,142,154,236	97 895 262	3 474 668

*Cumulative to March 31,2022
**MMscf = Million standard cubic feet per day

[1] Canada – Newfoundland & Labrador (C-NLOPB) Offshore Petroleum Board

Operators working in the C – NLOPB offshore oil fields must report all pollution incidents including: petroleum spills, unauthorized and/or unplanned discharges, and releases and issues with effluent quality (C-NLOPB, 2021). The C-NLOPB publishes oil spill incident reports, providing information on the spill frequency, volume, and type of petroleum released between 1997 to present day (last reporting period March 31st, 2022). Table 7 shows the total spill frequency and volume released during exploration and production between 1997 – 2021.

Table 7. Canada-Newfoundland and Labrador Offshore Petroleum Board total spill frequency and volume from exploration and production between 1997 – 2022 (C-NLOPB, 2022)

Total Spill frequency and volume: Exploration and Production 1997 - 2021		
	Number	**Volume (L)**
Synthetic Based Drilling Fluid	64	332346.30
All Other Hydrocarbons	505	454389.45
Total	569	786735.75

Oil spill incidents from exploration drilling activities were compiled to look at spill frequency and volume by type of oil released (Table 8). Hydraulic/lubricating and crude oil were tied for spill frequency by type, each making up 28.6% of the incidents, followed by synthetic oils/fluids (19%), diesel and jet fuel (15.9%). Other hydrocarbons accounted for 7.9% of the spill frequency by type. When comparing spill volume by type, synthetic oils/fluids account for a significant 95.7% of oil released during exploration drilling. Diesel and jet fuel account for 2.7% followed by crude (1.4%), hydraulic/lubricating oil (0.1%) and other hydrocarbons (0.1%). Although hydraulic/lubricating oil and crude accounted for the highest total frequency of incidents by type, they accounted for a small percentage of the total volume of oil released during exploration drilling between 1997 to 2021.

Table 8. Oil spill incidences from exploration drilling activities based on spill frequency and volume by type of oil released (C-NLOPB, 2022)

Exploration Drilling 1997 - 2021		
Oil Type	**Spill Frequency By Type (Percentage of Incidents)**	**Spill Volume by Type (Percent of Volume)**
Hydraulic and Lubricating Oil	28.6	0.1
Synthetic Oils/Fluids	19.0	95.7
Diesel and Jet	15.9	2.7
Crude	28.6	1.4
Other Hydrocarbons	7.9	0.1

To reflect current day operations, Table 9 summarizes oil spills that occurred within the C-NLOPB operational boundary between 2018 – 2021. The majority of oil released between 2018 – 2021 occurred during one incident at White Rose field, releasing approximately 250,000 litres of crude oil into the environment, as discussed in the previous section. Another incident, involving the MODU *Transocean Barents* reported a discharge of over 28,000 litres of synthetic based mud on April 27, 2018.

Table 9. Canada-Newfoundland and Labrador Offshore Petroleum Board annual review spill summary from 2018 – 2021 based on oil type (C-NLOPB, 2022)

Component	Litres	Percentage of Total	Number of Incidents
Crude Oil	250,380.783	89.80	9
Hydraulic and Lubricating Oil	420	0.151	2
Other Petroleum	0.002	7.2×10^{-7}	1
Synthetic Base Mud	28,004	10.044	2

6 MODELLING

6.1 CIRCULATION MODELLING

The Global Ice Ocean Prediction System (GIOPS) was the first operational global ocean forecasting system implemented at the Canada Centre for Meteorological and Environmental Predictions (CCMEP). This system supports medium-range deterministic weather predictions, seasonal predictions and sonar range predictions for marine operations. As an extension to the GIOPS, a higher-grid-resolution Regional Ice Ocean Prediction System (RIOPS) was created to provide 48 hour ice and ocean forecasting systems to support marine operations and environmental incident response in Canadian ice-covered waters (Government of Canada, 2021). Geographically the RIOPS domain covers 26° N in the Atlantic Ocean through the Arctic Ocean to 44° N in the Pacific Ocean and has a resolution grid of 3 – 8 km. The ice and ocean forecast and analysis products from RIOPS include: sea surface heights (m), water temperature (°C), salinity (psu), currents (m/s), sea ice fraction (%), snow depth on sea ice (m), ice thickness (m), ice drift velocity (m/s), and ice pressure (N/m). The RIOPS higher resolution grid improves on GIOPS, modifying atmospheric pressure forcing fields and spatial filtering to better represent mesoscale features. RIOPS has limitations, particularly close to the coast due to its coarser resolution ~3 – 6 km grid (Smith et al., 2021). To rectify this, two sub-domains are in development, Coastal Ice Ocean Prediction System for the east (CIOPS-E) and west (CIOPS-W) as an extension to the RIOPS on a 2 km resolution grid to improve near-coast forecasting. The CIOPS-E geographically covers 34.88°N to 54.46°N in the North Atlantic and from the coast out to 323°E with a higher resolution grid (2 – 2.5 km). Compared to current operational systems, CIOPS-E improves tides relative to current and provides more accurate storm surge predictions when compared to RIOPS. Research and development continues to support and improve each of these ocean modeling systems.

Most working operational models have a 3 – 10 km resolution. This is insufficient to simulate circulation in near-shore environments like Placentia Bay and St. John's Harbour. The lack of reliable high resolution ocean circulation models for the near coast make it challenging to force a reliable oil spill model for Placentia Bay and St. John's Harbour. Attempts to develop higher resolution ocean currents models for Placentia Bay use short term data and/or focus on understanding circulation in the bay during hurricane events. While Han et al., (2011), Ma et al. (2012) and Ma (2015) 3D finite-volume coastal ocean model (FVCOM) models were able to reproduce general circulation patterns well for parts of Placentia Bay, short term simulations may not provide much insight into seasonal variations or yearly fluctuations. In an attempt to understand inter-annual variability in Placentia Bay, Xie (2017) developed a 3D FVCOM model simulation between September 2010 and August 2014. The model was able to reproduce monthly mean water levels, surface currents and sea surface temperature well. Xie's (2017) results noted a positive correlation between observed air temperature, sea surface temperature flow into the bay and annual shifts in the inshore branch of the Labrador Current; notably in August 2010 and August 2014 model runs. The inner bay was still not as well represented in the model and does not capture the details needed to accurately simulate near-coastal waters in Placentia Bay.

6.2 OIL BEHAVIOUR AND TRANSPORT

The waters off southeastern Newfoundland's coast experience a high volume of tanker traffic carrying petroleum products and operational models and scenario exercises are an important part of environmental response preparedness and planning in the region. Although spill risk scenario planning is an important part of operations in southeastern Newfoundland, little oil spill modelling research is available in the public domain. Oil spill fate and behaviour research in the region has a strong focus around the Grand Banks offshore oil field. Most of the publicly available spill risk modelling is found in environmental assessment reports for development or extension projects. Spill risk models presented in environmental assessments for offshore development projects often omit shoreline interaction. As noted previously, the offshore oil fields are situated 200 – 350 km off the coast of Newfoundland, indicating oil released in that vicinity will have undergone extensive weathering before reaching the shoreline.

6.2.1 Characteristics of Oil in Placentia Bay

Most of the oil bearing reservoirs in the Grand Banks are classified as light crude oil (≥ 31.1° API) or medium crude oil (22.3° - 31.1° API). Heavy crude oil (API gravity below 22.3°) has been located at the Hebron - Ben Nevis and Mara oil field test sites, with oil as heavy as 19 - 21° API. Some of the crude oil extracted from the Grand Banks has a moderate to high wax content that may increase the potential to emulsify under strong wave conditions instead of spreading into a thin sheen (SL Ross Environmental Research Ltd., 2007). Most crude oils will initially float on water because of their density and only heavier crude oils will likely sink.

In addition to offshore crude oil production, large volumes of imported oil travels into Placentia Bay to Holyrood generating station and Come By Chance refinery. Over 50% of the crude oil imported to Come By Chance refinery are categories as medium crude oils (SL Ross Environmental Research Ltd., 2007), which have an API range of 22.3 - 31.1°.

Lighter refined oil-base products, gasoline, diesel and jet fuel have APIs > 10°, low densities and viscosities, meaning they will float if spilled in fresh of salt water and much of the lighter components will evaporate rapidly when released. Heavier refined products (Bunker C), have a higher density and viscosity, with APIs < 10°, indicating they would likely sink if released in a marine environment. High density products like bitumen from the oil sands in northern Alberta travel just outside the area of interest from other Canadian ports. Bitumen has a API gravity ~8° and due to its high viscosity is often diluted for transport, concentration depending on the season, transport type and producer.

6.2.2 Oil Spill Behaviour in Placentia Bay

As noted above, little oil spill modelling research is found in the public domain for southeastern Newfoundland, including Placentia Bay, although operational models exist and are used in scenario planning for emergency response.

Water movement in Placentia Bay is influenced mainly by wind and wave conditions, indicating that an oil spill would move in a similar direction as prevailing wind and waves. As oil weathers in marine environments, evaporation can account for up to 75% of volume losses in lighter oils, 40% for medium crudes and <5% for heavy and residual oils (Fingas, 1999). Depending on the location and volume of oil released and response time, it is likely oil would quickly reach the shoreline, particularly along the eastern channel and at the head of the Placentia Bay. Large vessel traffic is designated to the eastern channel so larger spills events would likely occur around the designated shipping zone (Figure 2). Smaller spills from smaller vessels could occur anywhere in the bay. The shoreline consists of a variety of consolidated and unconsolidated material. Depending on the location of the spill, stranded oil may sit on the surface if the shoreline is comprised of consolidated rock or mix into the sediment if stranded on shorelines made up of loose material like gravel, sand and soils. A summer spill may result in a longer slick survival rate due in part to the calmer wave conditions during the summer months but the rate of evaporation would be faster in the summer because of the higher atmospheric and sea surface temperatures. Winter ice is not consistently present in Placentia Bay but if a spill occurred when ice is present the oil would mainly stay on the surface under the ice, limiting rate of evaporation and natural dispersion from wave activity. Without ice, the wind would expanding the spill impact zone. Without ice, evaporation rates would increase and winter wave activity would also entrain and naturally disperse into the upper water column.

7 CONCLUSION

Southeastern Newfoundland, surrounding Placentia Bay and St. John's Harbour experience a cold, temperate, maritime climate with an annual average temperature range of -4.2 to 16.2°C (Environment Canada, 2019a; Environment Canada, 2019b). Precipitation falls as rain in the spring and summer, and a mix of snow/rain in the fall and winter. The nearshore bathymetry and rugged coastline creates many hazards for vessel traffic as vessels converge into narrow traffic lanes in both St. John's Harbour and Placentia Bay. Vessels moving along the southeastern coast of Newfoundland navigate through rough seas and large swells, particularly off the eastern coast near St. John's (SL Ross Environmental Research Ltd., 2007). The shoreline is comprised of bedrock, gravel/sand beaches, estuaries and steep banks.

Southeastern Newfoundland experiences high volumes of marine traffic carrying petroleum products and Placentia Bay in particular is one of the busiest ports for tanker traffic in the Atlantic Provinces. Offshore oil production activity on the Grand Banks increases the area's risk to an oil spill. Since production started in 1997, over 2.1 billion barrels of crude oil has been extracted and transported into Placentia Bay (C-NLOPB, 2022). Placentia Bay is wide and open at the mouth subjecting the outer bay to high wave activity while the inner bay is sheltered by islands situated mid-bay. Surface circulation in the outer bay is heavily influenced by the local wind patterns. Winds are predominately from the southwest during all seasons, with more variability in the fall and winter due to heavy storm activity. The predominant winds from the southwest would account for a prevalent counter clockwise near-surface flow that is present for most of the year, even though it weakens in the fall and winter. This counter clockwise surface flow creates an inward dominant flow on the east side of the bay and outward dominant flow on the west side of the bay. Currents can be strong and somewhat variable, making safe navigating a challenge during weather events. Fog conditions are common in Placentia Bay adding to the navigation risk. Ice can be present in Placentia Bay during in the winter months but it is generally not covered compared to areas around St. John's. Icebergs are a navigation hazard in spring and early summer around St. John's Harbour (SL Ross Environmental Research Ltd., 2007).

Few studies are available in the public domain that look at temporal and spatial hydrological trends in Placentia Bay and St. John's Harbour. Literature found in the public domain are based on short term studies or out of date and may not be an accurate reflection of current conditions. Seasonal inter-annual variations may not be accurately reflected based on available information in the public domain.

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