Old Harry
Drilling Mud and Cuttings Dispersion Modelling
Final Report

Submitted to:

Corridor Resources Inc.
#301 - 5475 Spring Garden Road
Halifax, NS, B3J 3T2
Telephone: (902) 429-4511
Facsimile: (902) 429-0209

Submitted by:
AMEC Earth & Environmental
a Division of AMEC Americas Limited
Marine Services Group
50 Troop Ave, Unit 300
Dartmouth, Nova Scotia B3B 1Z1
Ph: (902) 468-2848
Fax: (902) 468-1314

20 May 2011

DATE	PROJECT NUMBER	REVISION	PREPARED BY	REVIEWED BY
20May 2011	TN11203003	Final	Patrick Roussel P. R.	Bruce Batstone

DISCLAIMER

In conducting this study and preparing this report, AMEC Earth & Environmental has applied due diligence commensurate with normal scientific undertaking of a similar nature. In no event shall the consultant, its directors, officers, employees or agents be liable for any special, indirect or consequential damages, including property damage or loss of life, arising out of the use, interpretation or implementation of the data or any information enclosed in the report by any party, including without limitation, loss of profit, loss of production, loss of use, costs of financing, and liability to others for breach of contract.

PROJECT TEAM

This study was conducted by members of the AMEC Earth & Environmental Marine Services Group:

Trajce Alcinov

Sebastien Donnet

John McClintock

Patrick Roussel

EXECUTIVE SUMMARY

Corridor Resources Inc. plans to drill one exploration well within the Old Harry Prospect offshore Newfoundland and Labrador Exploration Licence (EL) 1105. The short term drilling operation is anticipated to occur between 2013 and 2014, with the specific timing dependent upon rig availability and regulatory approvals. The drilling operation could effectively take place during any ice-free season of the year. The drilling program is expected to take place over a period of 20 to 50 days.

Drilling operations will result in:

- Sea floor discharge of 196 m^3 of cuttings;
- Surface discharge of 211 m^3 of cuttings;
- Sea floor discharge of 1210 m^3 of Water Based Mud (WBM) of various density and composition, and;
- Surface discharge of 400 m^3 of WBM combined with 50 m^3 of brine.

Sea floor discharge of cuttings is expected to result in a mound extending approximately 30 m from the well site with cuttings thicknesses greatest immediately adjacent the well site. Average thickness is about 22 cm out to approximately 20 m from the well site; maximum thickness is about 4.7 m. From 20 to 50 m out from the well site, the average thickness is less than 1 mm.

Surface release of cuttings is expected to produce a deposit with thickness greatest near the drill origin, due to the most rapid fall of the heavier pebble and sand cuttings particles, and is as thick as 15 mm directly below the point of origin. Out to approximately 100 m from the origin, thicknesses are about 2 mm on average with a maximum of around 6 mm. From 100 to 200 m, thicknesses average from about 0.5 to 1 mm with a maximum of around 6 mm.

If cuttings released from the rig are associated with Synthetic Based Mud (SBM), rather than WBM, the maximum oil concentration within 50 m from the point of discharge is predicted to be about one quarter of that of the original treated cuttings, or 17,000 mg/kg (equivalent to ppm), equal to 1.7 %. Within 100 m of the discharge point, the predicted concentration drops another factor of seven, to about 2,400 mg/kg, or 0.24 %. Outside of 200 m, the concentration is 44 mg/kg or less. Outside of 500 m, predicted concentration is 3 mg/kg or less.

The surface bulk release of WBM at the end of the well is expected to result in a plume reaching a depth of about 150 m, thereby not reaching the bottom (470 m). Dilutions of 20 to 30 times the original concentration are expected within half an hour from discharge, and dilutions of 60 to 80 times are expected within an hour of discharge. Subsequently, material in the plume is expected to sink slowly and reach the bottom boundary layer after several days.

Simulation of the long term fate of all the mud released over the entire drilling program considered the conservative scenario whereby all phases of drilling operations were conducted without interruption between phases. The modelled scenario compressed the release of all mud into a period of 15 days.

Results show that dispersion of the mud by the ambient tidal and mean currents result in an elongated plume varying from 2 to 3 km to about 40 km in length depending on settling velocity, with widths from less than one to a few kilometres, respectively. This variability is typical of the range of behaviour of drilling mud, and is consistent overall with other similar studies.

The plume concentration, averaged over one meter above the seabed, ranges from about 1 g/l initially for the high settling rate scenario a few kilometres away from the site down to about 1 mg/l for the low settling rate scenario a few tens of kilometres away from the drilling site. It was noted that the concentration varies greatly (by one order of magnitude or more) within the plumes due to the suspension/deposition cycle induced by the normal variations of current strength over the tidal cycle.

In the high settling velocity scenario, the particles are largely found very close to the seabed (less than 1 m above), but are generally not expected to fully settle to the bottom. To illustrate a worst case scenario, if all the particles were to settle to the seabed, an area on the order of 1 km^2 would be covered by a very thin layer with a thickness of 64 µm. Considering the density of barite particles, the average sediment deposition within this 1 km^2 area would amount to about 0.027 g/cm^2. This is comparable to the natural annual sediment mass accumulation rate of 0.031 g/cm^2 calculated by Smith and Schafer (1999) in their study of ocean sediments for a location between Old Harry and Anticosti Island. The model results are generally consistent with similar studies of drilling mud dispersion in the benthic boundary layer (Thomson et al., 2000; Tedford et al., 2003 and Hannah et al., 2003).

Under the low settling velocity scenario, the particles are found to travel over relatively large distances on the order of 80 km over the 30 day simulation. Considering a 40 km long plume and a residual current of 2.5 cm/s, a fixed point within the trajectory of the plume would experience maximum continuous exposure to suspended material on the order of about 20 days.

If the mud discharge was interruptions on the order of a few hours to a few days, reflecting a typical drilling program, the expected plumes would be more elongated, more patchy, and their concentrations more variable in space and time. However, mean concentrations and exposure durations would not differ significantly from the results of the conservative continuous discharge simulation considered herein.

Overall, the results of mud dispersion simulations presented in this study are found to be consistent with the results of previous generic and site-specific studies for similar discharges and receiving environment (Thomson et al., 2000; Tedford et al., 2003 and Hannah et al., 2003).

TABLE OF CONTENTS

PAGE

PAGE

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

1.0 INTRODUCTION

Corridor Resources Inc. plans to drill one exploration well within the Old Harry Prospect offshore Newfoundland and Labrador Exploration Licence (EL) 1105. The short term drilling operation is anticipated to occur between 2013 and 2014, with the specific timing dependent upon rig availability and regulatory approvals. The Old Harry prospect is located in the Gulf of St. Lawrence with the centre of the prospect approximately 80 km west-northwest of Cape Anguille, Newfoundland and Labrador. EL 1105 is located within the Laurentian Channel where the water depth is approximately 470 m.

The proposed drilling site is located at:

North Latitude 48° 03’ 05.294”
West Longitude 60° 23’ 39.385” (NAD83)

This document presents results of the modelling of the dispersion of drilling mud and cuttings released over the duration of the drilling program. Section 2.0 presents a summary of the drilling program and the volumes and composition of mud and cuttings released on the sea floor or at the sea surface for each section of the well. Section 3.0 presents the tidal and seasonal mean currents used as input for the models. Section 4.0 addresses the dispersion of cuttings released at the sea floor and from the discharge chute below the rig. Section 5.0 addresses the short term fate of drilling mud released at the sea floor and from the rig. Section 6.0 examines the long term dispersion in the bottom boundary layer of mud discharged at the sea floor and from the discharge chute 30 m below the rig.

2.0 DRILLING PROGRAM

The timing of the drilling program depends on rig availability and regulatory approvals, such that drilling operation can effectively take place during an ice free period of the year. Drilling is expected to take place over a period of 20 to 50 days. The exploration well will be drilled in four sections.

Corridor included in its Project Description an example of a possible well design. The details of the well program will be finalized closer to the start of operations. There are four phases of the drilling operations that result in discharges of mud and cuttings to the environment. The first section (conductor hole) will be drilled or jetted down to a depth of about 90 m below the sea floor. The second section (surface hole) will be drilled a further 240 m to a depth of about 330 m below the sea floor (a total distance of 800 - 470 m in Table 2.1). The depths for all sections are approximate. Sweeps of mostly seawater with bentonite will be used to drill both sections and subsequently released on the sea floor with the cuttings. The release of drill cuttings and WBM at the seafloor represent Phase I and Phase III respectively in the modelling scenarios listed below. Cementing of the casing of both sections of the exploration well will require the use of additional denser water based mud (WBM) that will also be released at the sea floor.

A riser will be installed after completion of the top two hole sections which will then keep the drilling fluids as a closed loop system and bring back the cuttings and drilling mud to the rig when drilling the lower two sections of the well (intermediate and main holes). Drilling fluid for the intermediate and main holes may be either WBM or SBM. Cuttings are processed on the rig in order to recover a large portion of the mud to be reused; however, a portion of the mud will remain attached to the cuttings and will be discharged with them, a scenario modelled as Phase II. If WBM are used the amount remaining at the end of the well is discharged through a cuttings chute out the bottom of the rig, a process modelled as Phase IV of the drilling operations. If SBM are used, cuttings are processed to meet the Offshore Waste Treatment Guidelines (NEB et al. 2010) for oil content prior to discharge and the SBM is retained on the rig or brought to shore for re-use.

Table 2.1 provides a summary of the drilling program with mud and cuttings volumes and mud composition and density involved at each step of drilling operations. Approximate duration of each step is also provided. Interruptions will occur during or between steps, so that the total duration of the program will exceed the sum of the individual durations; however, in terms of mud dispersion, an uninterrupted program is the most conservative scenario. This dispersion study therefore needs to consider the following discharges during the different phases of drilling of the well:

- Phase I: Sea floor discharge of 196 m^3 of cuttings;
- Phase II: Surface discharge of 211 m^3 of cuttings ;
- Phase III: Sea floor discharge of 1210 m^3 of WBM of various density and composition;
- Phase IV: Surface discharge of 400 m^3 of WBM combined with 50 m^3 of brine.

Dispersion of cuttings is addressed in Section 4.3 for the sea floor discharge (Phase I) and in Section 4.4 for surface discharge (Phase II). The short term fate of mud is presented in Section 5.1 for sea floor discharge (Phase III) and Section 5.2 for surface discharge (Phase IV). Finally, Section 6.0 presents results of the modelling of the long term dispersion in the bottom boundary layer of the mud discharged during the entire drilling program (Phases III and IV).

Table 2.1 Drilling Program Schedule and Combined Volumes of Mud and Cuttings

							Volumes of Cuttings		
Hole Section	Duration of Discharge (days)	From (m)	To (m)	Hole Size (mm)	Casing Size (mm)	% over Gauge	Cutting In Situ Volume (m^3)	Rock Expansion Factor	Bulk Cuttings Volume (m^3)
Conductor Hole	1.5	470	560	914.4	762.0	50	89	2.1	186
Conductor Pad Mud	1	470	560	914.4	762.0	50			
Surface Hole	1	560	800	660.4	508.0	30	107	2.1	224
Surface Pad Mud	1	560	800	660.4	508.0	30			
Intermediate Hole	3	800	1300	444.5	339.7	25	97	2.1	204
Main Hole	7.5	1300	2600	311.2	244.5	15	114	2.1	239
Total Volume							**406**		**853**

				Volumes and Masses**** of Mud					
Hole Section	Duration of Discharge (days)	From (m)	To (m)	New Volume Added (m^3)	Volume Discharged (m^3)	Density of Mud (kg/m^3)	% Low Gravity Solids (Cuttings Only)	Barite added to System (t)	Bentonite added to System (t)
Conductor Hole	1.5	470	560	340	340	1060	~0	0	20
Conductor Pad Mud	1	470	560	130	130	1440	~0	110	20
Surface Hole	1	560	800	530	530	1060	~0	0	60
Surface Pad Mud	1	560	800	210	210	1440	~0	140	40
Intermediate Hole	3	800	1300	765	0*	1100	7	15	0
Main Hole	7.5	1300	2600	250	0*	1200	7	20	0
Discharge at End of Well				0	450**	1200	7	0	0
Total Volume				**2225**	**1660*** **			**285**	**140**

Notes: *Mud on cuttings will be discharged only
**50 m^3 will be brine and 400 m^3 will be mud at a density of 1200kg/m^3
***The remaining volume (i.e., 2225-1660=565 m^3) is dilution loss, mainly mud on cuttings
**** barite and bentonite masses in tonnes

3.0 CURRENT AND STRATIFICATION INPUTS TO THE MODELS

Two publicly available sources of currents were used to serve as an input base for the Benthic Boundary Layer Transport (BBLT) model: the WebTide (DFO, 2011a) and WebDrogue (DFO, 2011b) model based velocity fields.

3.1 TIDAL CURRENT FIELDS FROM WEBTIDE

WebTide is initially a user interface designed to get the tidal predictions (elevation and velocities) at a (user selected) particular location. The tool uses the solutions of modelling studies performed over the years by Department of Fisheries and Oceans (DFO) scientists and staff. The finite element mesh used for this study was the Northwest Atlantic Mesh described in Dupond et al. 2002.

Tidal solutions (elevation and currents) from the core program of WebTide ('tidecor') were interpolated on a regular grid to provide a time-series of spatial tidal velocity fields.

To provide a representative cycle, a full lunar month (30 days) of simulation was extracted and saved hourly over a grid covering from about 46.05^{o}N to 50.05^{o}N and 62.39^{o}W to 58.39^{o}W (2 degrees around the proposed drilling location). Time-series of tidal currents and sea surface elevations are presented in Appendix A.

Tidal current speeds and directions for all the phases of the tidal cycle are summarized in Table 3.1. The currents flow toward the direction given relative to true North.

Table 3.1 Tidal Currents at Drilling Site from Webtide Model Run

	Neap-Flood	Neap-Ebb	Spring-Flood	Spring-Ebb	Slack Water
Tidal current	0.07 m/s 320° N (to)	0.08 m/s 140° N (to)	0.21 m/s 320° N (to)	0.17 m/s 140° N (to)	0 m/s

Notes: magnitudes rounded to nearest cm/s and directions rounded to nearest 10° sector

3.2 SEASONAL MEAN CURRENT FIELDS FROM WEBDROGUE

WebDrogue is another user interface developed by DFO providing access to the results of numerical modelling of the general circulation in the Eastern Canada region of the Northwest Atlantic Ocean. The domain used for this study, covering the Gulf of St. Lawrence, was the one developed for DFO's operational model to forecast currents, temperature, salinity and ice field over the Eastern Coast of Canada (DFO, 2011c).

The seasonal current fields at the surface and the bottom were extracted from the model domain mesh for winter, spring, summer and fall, and interpolated on the same grid as for tidal currents (Section 3.1). In WebDrogue, the bottom layer is defined as "the average over the bottom 10 m" (DFO, 2011c), and therefore representative of the benthic boundary layer. Seasonal bottom current fields are presented in Appendix B

Seasonal mean currents are summarized in Table 3.2.

Table 3.2 Residual Currents at Drilling Site from WebDrogue Model Run

	Winter	**Spring**	**Summer**	**Fall**
Surface	0.04 m/s 130° N (to)	0.04 m/s 110° N (to)	0.06 m/s 150° N (to)	0.08 m/s 160° N (to)
Bottom	0.025 m/s 310° N (to)	0.05 m/s 300° N (to)	0.05 m/s 310° N (to)	0.03 m/s 330° N (to)

Notes: magnitudes rounded to nearest .01 m/s and direction rounded to nearest 10° sector

3.3 STRATIFICATION

Vertical stratification of the water column was derived from DFO monthly climatology of temperature and salinity for the region of the Gulf of St. Lawrence (DFO 2011d) around Old Harry. Density stratification resulting from temperature and salinity stratification is summarized for each season in Table 3.3.

Table 3.3 Disposal Site Water Column Physical Properties

Depth (m)	**Density (kg/m^3)**			
	Winter	**Spring**	**Summer**	**Fall**
0	1025.7	1025.5	1023.6	1024.3
200	1027.9	1028.0	1028.0	1027.8
400	1029.4	1029.4	1029.4	1029.4

4.0 DISPERSION OF CUTTINGS

To estimate possible drill cuttings depositions, primarily the thicknesses and distances from the well site, a numerical model was employed which considered the proposed sequence of well sections to be drilled for the Project and an associated time history of cuttings discharges. The subsequent path of the discharged cuttings (with advection as a result of the ambient ocean current) to their ultimate fate on the seabed was predicted with a three-dimensional (3D) sedimentation computer model.

Modelling of the dispersion of cuttings predicts the initial deposition of the cuttings only, not the subsequent weathering, erosion and fate of the material accumulated on the seabed over an extended period of time.

4.1 ADVECTION DISPERSION MODEL DESCRIPTION

The analysis of the drill cuttings discharges was accomplished by making use of a numerical computer model developed by AMEC to determine cuttings depositions at the time of drilling operations. The AMEC Advection Dispersion Model (ADM) software is written in Visual Fortran and developed based on previous corporate experience and modelling algorithms including those from the Hibernia cuttings fate modelling study (Hodgins, 1993). The model has also been used as part of the Hebron Project (AMEC, 2010).

To accompany the delivery of the deposition model results, a description of the model and techniques used, and observations based on the modelling activity are presented.

In the model, a transport computation was employed to simulate the advection of the dispersed drill cuttings materials in three dimensions through the water column, following release into the sea, until the particles come to rest on the sea bottom. For the purposes of predicting their physical deposition on the seabed, the cuttings were considered as a composition of four particle types or sizes: larger cuttings pieces, pebbles, coarse sand, and fines. These particle sizes were assumed to be generally representative of the materials likely to be encountered for this exploration well.

At any given time, a particle was assumed to be subject to independent displacing forces due to the ocean current and to a fall velocity that was constant for a given particle type. A term to model turbulent diffusion was added to the displacements. Over the time-step of the available ocean current data, the displacements were calculated and added to yield a new particle position. Sequential vector additions were computed over each successive time step until the simulation terminated with deposition on the sea bottom (which may be some time after well drilling had terminated).

A model grid was selected to encompass the drilling area and possible domain for the deposition of the cuttings. The model tracked the fate and deposition of the particles. In addition to each particle's path, the weight of material was tracked. This was the primary particle attribute. After completion of a model run, when all particles were settled, or had reached the model grid boundaries (in which case, they were taken to have drifted outside the domain and tabulated as 'lost'), each particle was binned in one of the model grid cells and the total weight, W was calculated. In addition, the following other parameters were calculated for each grid cell:

$$C = W \times 1000 / A \tag{1}$$

$$T = C / \gamma \tag{2}$$

$$OC = OC_{initial} \times W / \left(A \times h \times (1 - n) \times \gamma_s \right) \tag{3}$$

where W = cuttings weight (kg)
C = cuttings density (g/m^2)
T = cuttings thickness (mm)
OC = oil concentration on cuttings (mg/kg)
A = area of one grid cell (m^2)
γ = in situ bulk density (1,850 kg/m^3)
$OC_{initial}$ = initial oil concentration
h = sediment mixing depth (0.08 m)
n = seabed porosity (0.4)
γ_s = specific weight of cuttings (2,596 kg/m^3)

Oil content OC is only applicable in the case that SBM is used for the lower two sections of the exploration well. All cuttings were assumed to be adequately treated to reclaim oil as required by present regulations. Oil content on cuttings produced during drilling with SBM, $OC_{initial}$ was set to 7.4 g / 100 g, equal to 6.9 g / 100 g oil on wet solids, as per the Offshore Waste Treatment Guidelines (NEB et al. 2010).

4.2 MODEL INPUTS

4.2.1 Cuttings Particles Characterization

No cuttings particle size distributions that would quantify the composition of different mineral materials as a function of depth are available from the anticipated well to be drilled in EL 1105.

An overall estimation of the cuttings and sediment composition for the well is 38 % sandstone, 49 % shale, and 13 % siltstone. Based on this limited knowledge, together with consideration of the cuttings sizes likely to be created from the drilling, it was assumed that most (perhaps 75 %) of the cuttings will be large on the order of 1 to 3 cm, about 20 % on the order of 0.5 to 1 cm, with the remainder less than 0.5 cm. For the two upper sections of the hole for which cuttings are discharged at the sea floor, this distribution was applied to the total in situ cuttings volume of 196 m^3 (Table 2.1). For discharge from the rig of the cuttings from the deeper two sections, a similar distribution with one refinement was applied to a total in situ cuttings volume

of 211 m^3: to consider the presence of very fine particles which could be expected during drilling of the deeper well sections, a small amount, 5 %, was moved from the larger particles to fines
(Table 4.1).

It is assumed that the cuttings will enter the sea in a disaggregated form. The model considered the large cuttings, pebble, and sand materials to remain disaggregated in their fall to the seabed. Any fines were assumed to aggregate into flocs of size on the order of about 0.1 mm and settle with a constant speed.

Table 4.1 Cuttings Particle Size Composition

	Measured Weight Percent Material			
Well Type/Section	**large cuttings**	**pebbles**	**coarse sand**	**fines**
Scenario 1: conductor and surface	75	20	5	0
Scenario 2: main and intermediate	70	20	5	5

Particle fall velocities, w, were estimated from the particle diameter using the following relationships from Sleath (1984):

$$w = 4.2\sqrt{D}, D > 0.0001m \quad (4)$$

$$w = 12x10^4 D^2, D \le 0.0001m \quad (5)$$

where w is the fall velocity in m/s and *D* is the diameter in m.

For the four particle types considered, this yields the values reported in Table 4.2.

Table 4.2 Cuttings Particle Size Characterization

	Cuttings Material			
	large cuttings	**pebbles**	**coarse sand**	**fines**
particle diameter (mm)	20	7	1	0.1
particle fall velocity (m/s)	0.594	0.351	0.133	0.0012

4.2.2 cean Currents

The seasonal bottom current fields from WebDrogue (Section 3.2) were combined with tidal current fields (Section 3.1) for use as BBLT current input. Thirty days of tidal currents were synthesized for each season. Subsequently, the corresponding residual current velocity was added to the tidal currents to yield separate composite current time-series representing each of winter, spring, summer, and fall conditions. For the near field models, currents are assumed to be uniform over the small model domain. For the mid and far field exercises with BBLT, currents vary in time and space to be representative of regional seasonal circulation patterns.

4.3 SEA FLOOR DISCHARGE OF CUTTINGS (Phase I)

4.3.1 Model Implementation

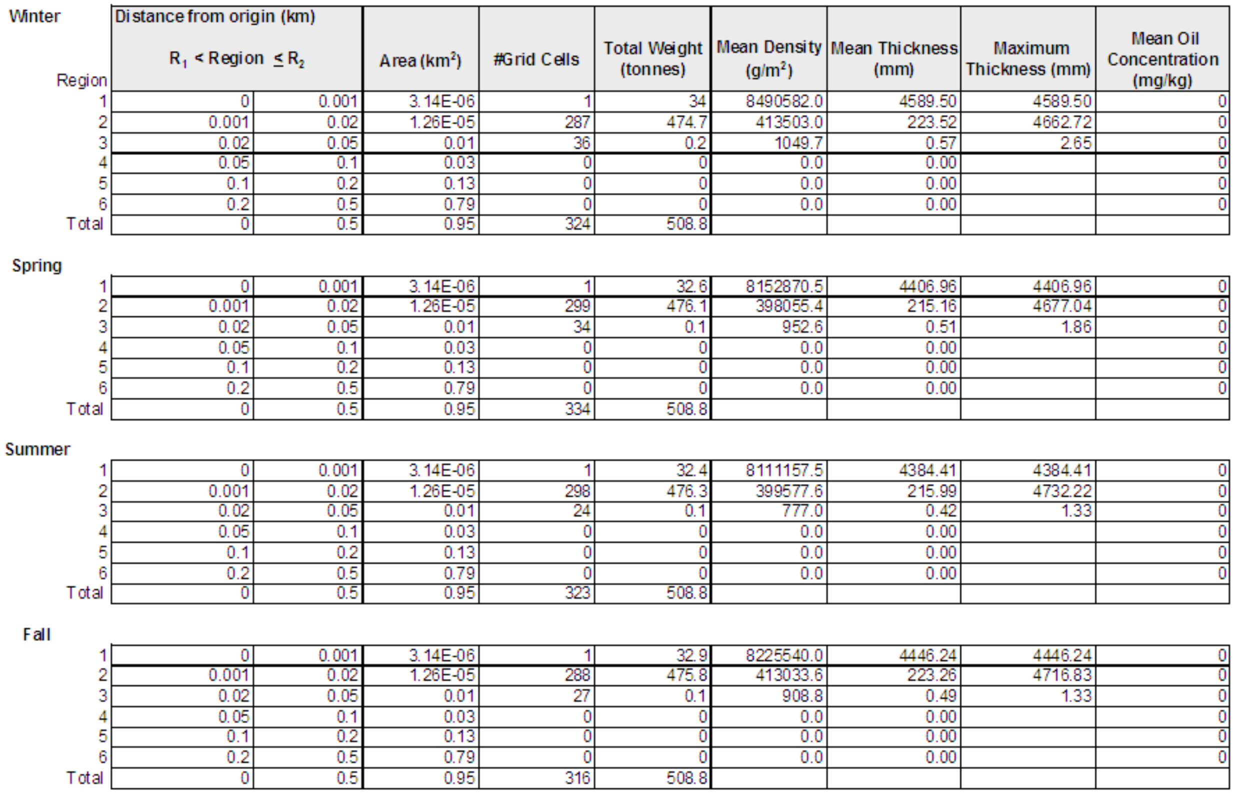
For sea floor release of cuttings, ADM was implemented on a 500x500 cells Cartesian grid centred at 48.0515° N, 060.3943° W with cell size of 2 m. This covers the drilling location ±1 km. A uniform depth of 470 m was assumed. The discharge included a total volume of 196 m^3 of drill cuttings.

4.3.2 Model results

Figure 4.1 presents the cuttings deposition predicted following completion of the conductor and surface sections for the winter season. Thicknesses of 1 mm, 1 and 2 cm, 10 and 20 cm, and 1 and 2 m are shown. There is very little difference in the pattern for spring, summer, and fall due to the discharge location being approximately 10 m above the seabed.

Table 4.3 presents summary statistics for the cuttings deposition patterns on the seabed for all four seasons. Model results indicate cuttings will be deposited up to approximately 30 m from the well site. The thickness of the deposit will be greatest immediately adjacent the well site with maximum thickness of about 4.7 m. From the well center outward to approximately 20 m, average thickness of the deposit is predicted to be about 220 mm. From 20 m outward to 50 m from the well center, the average thickness is predicted to be less than 1 mm.

Table 4.3 Drill Cuttings Deposition Pattern Summary for Sea Floor Discharge of Cuttings



Winter	Distance from origin (km)								
Region	R_1 < Region	≤ R_2	Area (km^2)	#Grid Cells	Total Weight (tonnes)	Mean Density (g/m^2)	Mean Thickness (mm)	Maximum Thickness (mm)	Mean Oil Concentration (mg/kg)
1	0	0.001	3.14E-06	1	34	8490582.0	4589.50	4589.50	0
2	0.001	0.02	1.26E-05	287	474.7	413503.0	223.52	4662.72	0
3	0.02	0.05	0.01	36	0.2	1049.7	0.57	2.65	0
4	0.05	0.1	0.03	0	0	0.0	0.00		0
5	0.1	0.2	0.13	0	0	0.0	0.00		0
6	0.2	0.5	0.79	0	0	0.0	0.00		0
Total	0	0.5	0.95	324	508.8				
Spring									
1	0	0.001	3.14E-06	1	32.6	8152870.5	4406.96	4406.96	0
2	0.001	0.02	1.26E-05	299	476.1	398055.4	215.16	4677.04	0
3	0.02	0.05	0.01	34	0.1	952.6	0.51	1.86	0
4	0.05	0.1	0.03	0	0	0.0	0.00		0
5	0.1	0.2	0.13	0	0	0.0	0.00		0
6	0.2	0.5	0.79	0	0	0.0	0.00		0
Total	0	0.5	0.95	334	508.8				
Summer									
1	0	0.001	3.14E-06	1	32.4	8111157.5	4384.41	4384.41	0
2	0.001	0.02	1.26E-05	298	476.3	399577.6	215.99	4732.22	0
3	0.02	0.05	0.01	24	0.1	777.0	0.42	1.33	0
4	0.05	0.1	0.03	0	0	0.0	0.00		0
5	0.1	0.2	0.13	0	0	0.0	0.00		0
6	0.2	0.5	0.79	0	0	0.0	0.00		0
Total	0	0.5	0.95	323	508.8				
Fall									
1	0	0.001	3.14E-06	1	32.9	8225540.0	4446.24	4446.24	0
2	0.001	0.02	1.26E-05	288	475.8	413033.6	223.26	4716.83	0
3	0.02	0.05	0.01	27	0.1	908.8	0.49	1.33	0
4	0.05	0.1	0.03	0	0	0.0	0.00		0
5	0.1	0.2	0.13	0	0	0.0	0.00		0
6	0.2	0.5	0.79	0	0	0.0	0.00		0
Total	0	0.5	0.95	316	508.8				

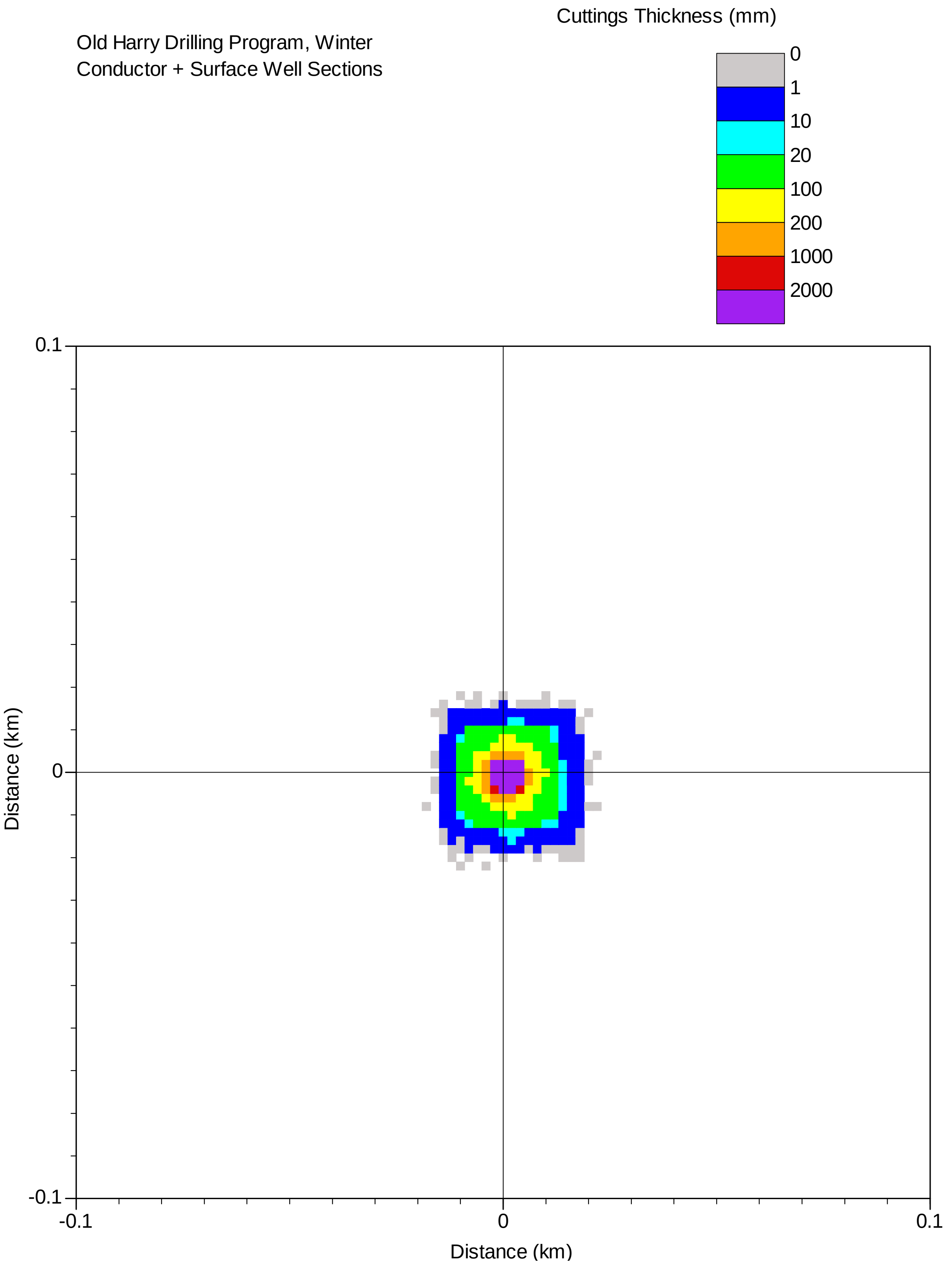


Figure 4.1 Cuttings Deposition Following Conductor and Surface Hole Section Drilling, Winter Season, 1 km view

4.4 SURFACE DISCHARGE OF DRILL CUTTINGS (Phase II)

4.4.1 Model Implementation

For surface release of cuttings, ADM was implemented on a 500 x 500 cell Cartesian grid centered at 48.0515° N, 060.3943° W with cell size of 100 m. This covers the drilling location ±25 km. A uniform water depth of 470 m was assumed over the model domain. The discharge included a total volume of 211 m^3 of drill cuttings.

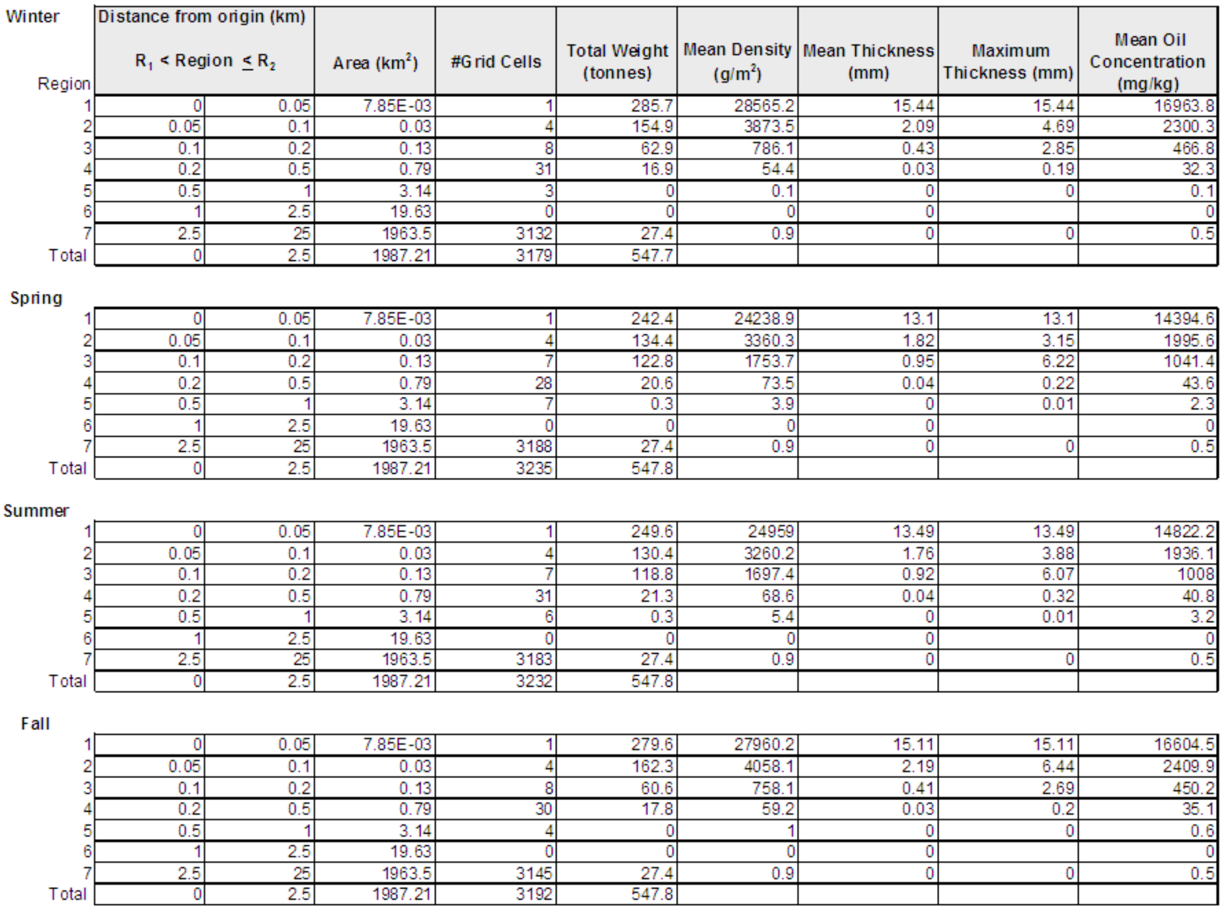
4.4.2 Model Results

Table 4.4 presents summary statistics for the cuttings deposition patterns on the seabed for all four seasons for surface discharged cuttings. Cuttings deposit thickness is greatest near the drill center, as large as 15 mm, due to the more rapid fall of the larger and heavier cuttings particles. Outward to approximately 100 m from the well center, predicted deposit thickness is as large as 6 mm but about 2 mm on average. Outward from 100 to 200 m, deposit thicknesses are as large as 6 mm but the average range is from about 0.5 to 1 mm.

The oil concentration on the cuttings is reported in Table 4.4 in mg/kg (equivalent to ppm) and is approximately one to two times the oil thickness in microns (e.g., if the thickness is 1,000 microns (1 mm), the oil concentration is approximately 1,000 to 2,000 mg/kg). The oil concentration within 50 m from the point of discharge, calculated for the one model grid cell immediately surrounding the well site, is predicted to be about one quarter of that on the cuttings originally released, or 17,000 mg/kg. Within the band between 50 m and 100 m of well center, the oil concentration drops to about 2,400 mg/kg, i.e., a further reduction by a factor of seven. Outside the 200 m radius, the oil concentration on cuttings is 44 mg/kg or less. The predicted concentration is 3 mg/kg or less outside of 500 m.

Figure 4.2 shows the cuttings deposition patterns on a 25 km x 25 km grid with inset showing a finer resolution 500 m view to resolve the deposition of the larger, faster settling particles. Figure 4.3 presents a regional view of the deposit in the Gulf of St. Lawrence.

Table 4.4 Drill Cuttings Deposition Pattern Summary for Surface Discharge of Cuttings



Winter	Distance from origin (km)								
Region	R_1 < Region $\le R_2$		Area (km^2)	#Grid Cells	Total Weight (tonnes)	Mean Density (g/m^2)	Mean Thickness (mm)	Maximum Thickness (mm)	Mean Oil Concentration (mg/kg)
1	0	0.05	7.85E-03	1	285.7	28565.2	15.44	15.44	16963.8
2	0.05	0.1	0.03	4	154.9	3873.5	2.09	4.69	2300.3
3	0.1	0.2	0.13	8	62.9	786.1	0.43	2.85	466.8
4	0.2	0.5	0.79	31	16.9	54.4	0.03	0.19	32.3
5	0.5	1	3.14	3	0	0.1	0	0	0.1
6	1	2.5	19.63	0	0	0	0		0
7	2.5	25	1963.5	3132	27.4	0.9	0	0	0.5
Total	0	2.5	1987.21	3179	547.7				
Spring									
1	0	0.05	7.85E-03	1	242.4	24238.9	13.1	13.1	14394.6
2	0.05	0.1	0.03	4	134.4	3360.3	1.82	3.15	1995.6
3	0.1	0.2	0.13	7	122.8	1753.7	0.95	6.22	1041.4
4	0.2	0.5	0.79	28	20.6	73.5	0.04	0.22	43.6
5	0.5	1	3.14	7	0.3	3.9	0	0.01	2.3
6	1	2.5	19.63	0	0	0	0		0
7	2.5	25	1963.5	3188	27.4	0.9	0	0	0.5
Total	0	2.5	1987.21	3235	547.8				
Summer									
1	0	0.05	7.85E-03	1	249.6	24959	13.49	13.49	14822.2
2	0.05	0.1	0.03	4	130.4	3260.2	1.76	3.88	1936.1
3	0.1	0.2	0.13	7	118.8	1697.4	0.92	6.07	1008
4	0.2	0.5	0.79	31	21.3	68.6	0.04	0.32	40.8
5	0.5	1	3.14	6	0.3	5.4	0	0.01	3.2
6	1	2.5	19.63	0	0	0	0		0
7	2.5	25	1963.5	3183	27.4	0.9	0	0	0.5
Total	0	2.5	1987.21	3232	547.8				
Fall									
1	0	0.05	7.85E-03	1	279.6	27960.2	15.11	15.11	16604.5
2	0.05	0.1	0.03	4	162.3	4058.1	2.19	6.44	2409.9
3	0.1	0.2	0.13	8	60.6	758.1	0.41	2.69	450.2
4	0.2	0.5	0.79	30	17.8	59.2	0.03	0.2	35.1
5	0.5	1	3.14	4	0	1	0	0	0.6
6	1	2.5	19.63	0	0	0	0		0
7	2.5	25	1963.5	3145	27.4	0.9	0	0	0.5
Total	0	2.5	1987.21	3192	547.8				

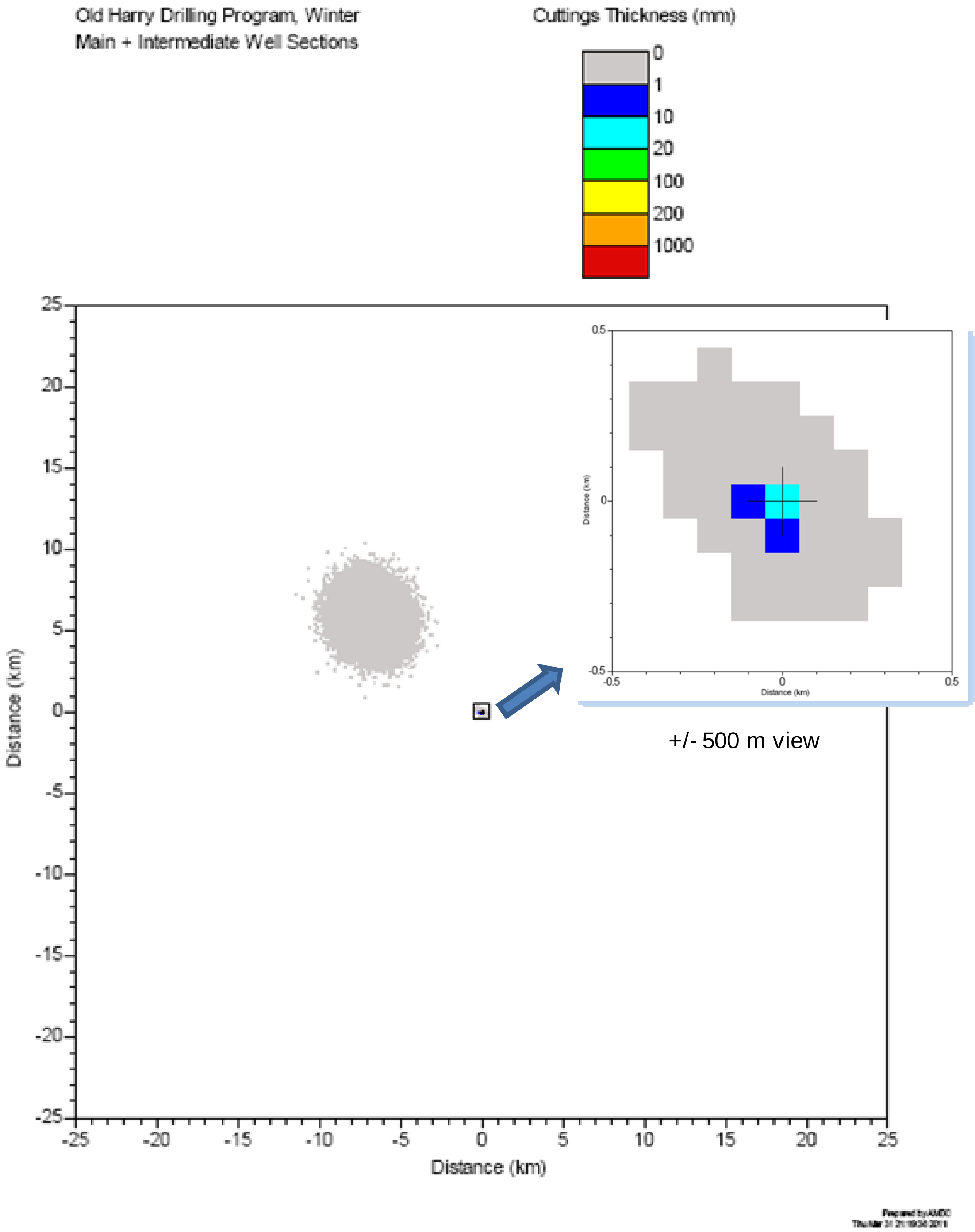


Figure 4.2 Cuttings Deposition Following Main and Intermediate Hole Section Drilling, Winter Season, 25 km view, with an inset showing a 500 m view centred on the wellsite

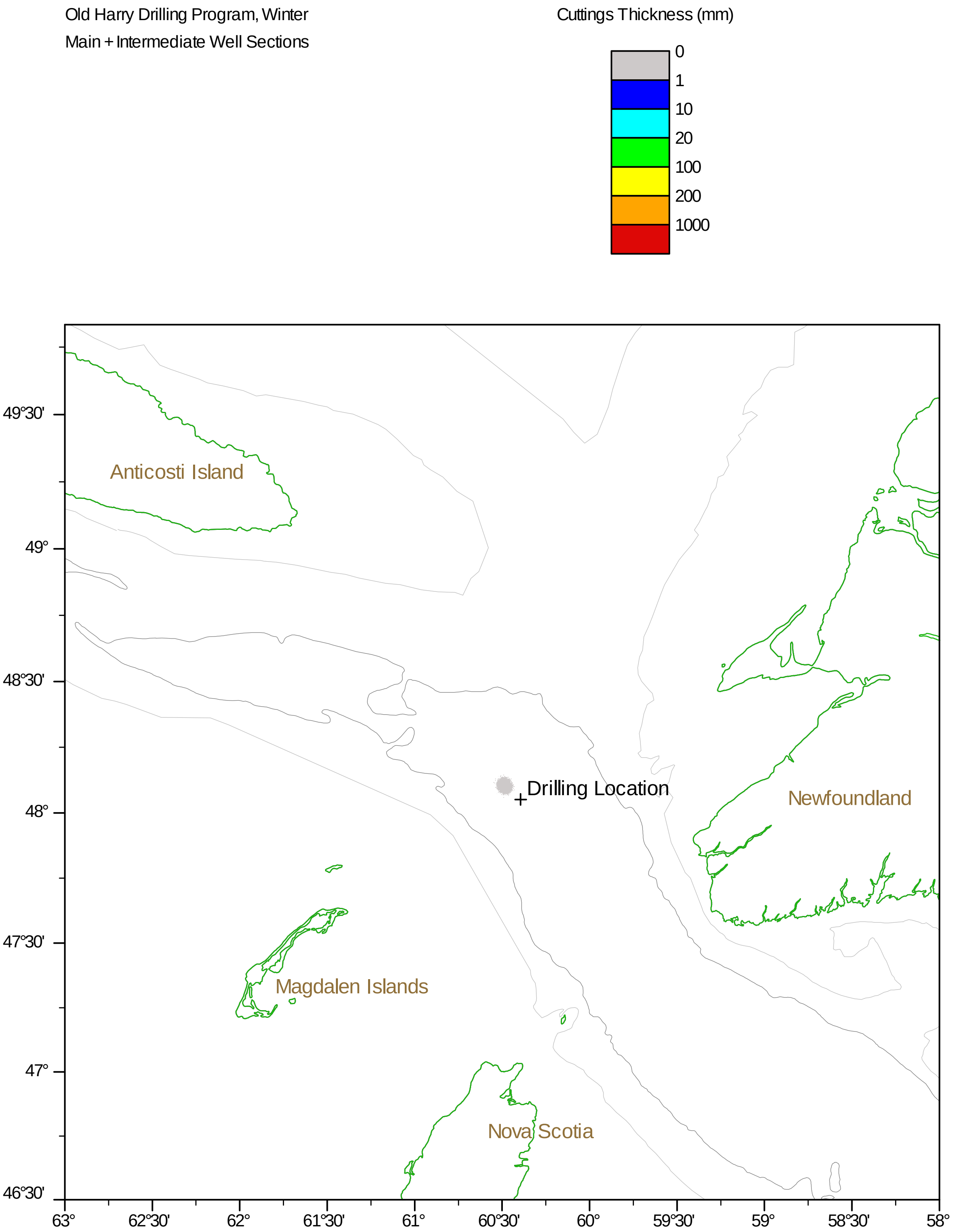


Figure 4.3 Cuttings Deposition Following Main and Intermediate Hole Section Drilling, Winter Season, Gulf of St. Lawrence view; 200 and 400 m Depth Contours Shown

5.0 SHORT TERM FATE OF DRILLING MUD DISCHARGE

5.1 SEA FLOOR DISCHARGE OF MUD (Phase III)

The mud suspension will be diluted as it rises in a turbulent eject plume. A continuous drilling operation is considered to be comprised of a series of puffs of ejected material, the total of which will amount to 1210 m^3. Each puff will experience dilution as its momentum mixes with the slower moving background currents and as a result of oceanic turbulence and shear dispersion as it is advected away from the well site by ambient currents.

It is difficult to quantify the exact dispersion path that a particular puff will experience, but the process can be described in general terms based on the expected physical processes and the ambient current. For the purposes of this assessment, it is assumed that the WBM is forced out of the hole at speeds on the order of 1 m/s, while the ambient ocean currents are between 3 to 26 cm/s (Section 5.2.1.2). Therefore, the initial dilution calculated from conservation of momentum is 4:1 to 33:1, depending on the phase of the tide. Because its density is larger than that of the ambient sea water, the diluted puff will tend to collapse into the benthic boundary layer. In the deep sea, this layer has a typical thickness on the order of 1 m (Wimbush and Munk, 1970). Due to the current shear and turbulence in the boundary layer, the puff will tend to stay in suspension above the seabed. Assuming a pill-box shape for the initial plume, a discharge volume of 15 m^3 (a typical sweep volume), and an initial dilution of 4:1, the puff will have an average diameter of about 9 m at this time. As it is advected away, the diameter of the diluted puff will continue to grow and the mud concentrations will decrease due to dispersion and mixing. Based on a typical small scale horizontal diffusivity of 0.01 m^2/s (Okubo, 1971), additional dilution by a factor of two will require on the order of two hours, at which time the cloud will have been advected by the ambient mean currents a distance between 200 and 1700 m. Other factors not taken into account here, including the effects of seabed roughness and topography, will tend to provide additional dispersion. While necessarily not rigorous, the above description provides a reasonable picture of the process by which bottom releases of mud during jetting and drilling of the upper hole sections result initially in small clouds of fine particles in the benthic boundary layer. These clouds will continue to be diluted by turbulence and will be dispersed to the northwest of the well site as they are advected by the mean current.

5.2 SURFACE DISCHARGE OF MUD (Phase IV)

The planned release of 400 m^3 of WBM at the end of the drilling program introduces suspended sediment into the water column. The bulk release of WBM is expected to occur about 30 m below the surface, and it is expected to last for a relatively short time, on the order of seconds. The material is initially expected to fall through the water column as a well-defined jet of density that is higher than the ambient. Therefore, the behavior and the short term fate of the released material can be appropriately modelled by using the ADDAMS-STFATE (Short Term FATE) model, originally developed by Brandsma and Divoky (1976) and based on the work by Koh and Chang (1973). The STFATE model can describe the short-term behavior of sediment material dumps in channels or open water sites, by capturing three phases of the sediment plume following its release:

- **Convective Descent**: the sediment cloud falls rapidly under the influence of gravity;
- **Dynamic Cloud Collapse**: the stage at which the descending cloud either impacts the bottom, or arrives at a level of neutral buoyancy, and;
- **Passive Transport-Dispersion**: the stage at which material transport and spreading are determined by ambient currents and turbulence, rather than by the dynamics of the disposal operation.

The model incorporates the equations for conservation of mass, momentum, buoyancy, solid particles and vorticity. Upon release, the material is modelled to move downward as a cloud in which the solid material concentration follows the Gaussian distribution, with maximum concentrations found in the center of the cloud. At each time step, the model also evaluates the entrainment of ambient fluid and the stripping of solid particles from the cloud. Finally, the model continuously adjusts the falling velocity of cohesive sediment fractions, with progressively diminished concentrations generally resulting in lower falling velocities.

5.2.1 Model Inputs

5.2.1.1 Water Based Mud Discharge Characteristics

The modelled scenarios include the release of 450 m^3 of material, consisting of 50 m^3 of brine at a density of 1060 kg/m^3 and 400 m^3 of WBM. The composition of the WBM includes 35.25 m^3 of clay with a density of 2700 kg/m^3, 3.45 m^3 of barite at 4200 kg/m^3, and 361.3 m^3 of seawater at 1025 kg/m^3. Therefore, the input to the STFATE model consists of the solid fractions and 411.3 m^3 of seawater with an effective density of 1029.3 kg/m^3. Both the barite and the clay fractions are considered cohesive, and they account for 0.77 % and 7.83 % of the WBM volume, respectively (Table 5.1). The initial fall velocities were based on nominal mid-range values (Niu et al., 2008), as cohesive sediments can form floccules of various sizes and their falling velocity is thus dependent on the concentration at any given time. The material is to be released from a chute with a width of approximately 0.5 m, over a period of five seconds.

Table 5.1 WBM Characteristics Input into STFATE

Description	% Total Sample (dry)	Specific Gravity	% WBM Volume	Fall Velocity (mm/s)	Character
Barite	9	4.2	0.77	5	Cohesive
Clay	91	2.7	7.83	0.6	Cohesive
Interstitial seawater density assumed: 1025 kg/m^3					

5.2.1.2 Ambient Oceanographic Characteristics

The following simplifications and assumptions were made to suit the STFATE input requirements:

- Depth at the site is assumed to be 470 m and constant for all scenarios.

- The water column is considered to be stratified, with different density profiles for the four seasons given in Table 3.3 (Section 3.3).

- Five different tidal scenarios are considered in each season, making for 20 scenarios in total:
  - neap tide, flood conditions
  - neap tide, ebb conditions
  - spring tide, flood conditions
  - spring tide, ebb conditions
  - slack water

- The velocity profile within STFATE is schematized as a ‘two-point velocity profile for a constant depth grid’, and it includes both residual current components (Table 3.2) and tidal current components (Table 3.1). The seasonal residual currents for the surface and bottom levels were extracted from the WebDrogue modelling results, and the tidal current constituents were modelled using the DFO Webtide model (Section 3.0).

5.2.2 STFATE Modelling Results

The STFATE model was run for five different tidal phases in each of the four seasons, by applying the respective residual currents and density profiles for each season. The model runs simulated the short term fate of the WBM plumes within one hour from the time of release, during which the current conditions are assumed to stay relatively constant. The plume did not reach the bottom during any of the scenarios considered, as it reached a neutrally-buoyant state before reaching mid-depth in all model runs. Therefore, the model results (Table 5.2) include the plume diameter and position at the end of the convective descent phase, as well as the ellipsoid cloud horizontal width and vertical thickness at the end of the cloud collapse phase for each of the scenarios considered.

The evolution of the plume from release to end of cloud collapse is illustrated in Figure 5.1, based on the simulation run for the Spring season spring-ebb tidal scenario. In these plots, the convective descent phase and the cloud collapse phase are delineated in both the side view and the top view of the cloud progression. The release of WBM is centered at the origin of the coordinate system. It is apparent that the plume initially descends downward while expanding and entraining increasing amounts of the ambient seawater. At the end of the descent phase, the lowermost edge of the cloud reaches a depth of approximately 185 m. The sediment material then collapses into a flat generally ellipsoid cloud and levels off at a depth of about 150 m to the south-east of the point of release.

The results in Table 5.2 show that the timing of the descent and cloud collapse phases, the depth reached and the size of the cloud in each phase were similar for all tidal phases within a given season. Thus, the cloud centroid descended to the deepest level of 151 m in the winter scenarios, and to the shallowest level of 124 m in the summer scenarios, reflecting the higher ambient water stratification in the summer months. The cloud collapse ended at similar depths as the respective convective descent phases for all scenarios, indicating that once a state of neutral buoyancy was reached at a given depth, the cloud tended to stay close to that depth. The largest horizontal width at the end of the cloud collapse phase was found in the winter scenarios (210 m), and the smallest in the summer scenarios (170 m). The maximum horizontal extent of the outer edge of the collapsed cloud (425 m from origin) was reached in the winter scenarios. The different tidal scenarios showed that the clouds generally traveled to the southeast (ebb tide) and to the northwest (flood tide) of the point of release, with the excursions being larger during the spring tides than during neap tides.

At the end of the cloud collapse phase, the behaviour of the WBM sediment clouds is no longer governed by the dynamics of the release, and they are expected to be subjected to further dispersion by the ambient residual and tidal currents. The sediment concentrations at the cloud centers at the end of each phase indicate that minimum dilution factors between 20 and 30 were achieved within half an hour from release time, and minimum dilution factors between 60 and 80 were achieved within one hour from release time for all scenarios. The reduced concentration of both the barite and clay results in further reduced settling velocities. Therefore they are expected to reach the bottom boundary layer within a period on the order of days.

Table 5.2 Short Term Fate Modelling Results

STFATE model scenarios		End of Convective Descent Phase					End of Cloud Collapse Phase					
Season	**Tide Phase**	Time from release (s)	Plume centroid from caisson			Plume Diameter (m)	Time from release (s)	Cloud centroid from caisson			Cloud Width (m)	Cloud Thickness (m)
			Depth (m)	North (m)	East (m)			Depth (m)	North (m)	East (m)		
WINTER	**Neap Flood**	214	151	6	-5	81	1683	150	59	-55	210	12
	Neap Ebb			-16	15				-124	112		
	Spring Flood			30	-22				260	-188		
	Spring Ebb			-30	27				-242	212		
	Slack Tide			0	0				0	0		
SPRING	**Neap Flood**	201	146	8	-5	78	1578	145	72	-52	203	12
	Neap Ebb			-13	14				-100	105		
	Spring Flood			31	-20				260	-177		
	Spring Ebb			-26	26				-209	199		
	Slack Tide			0	0				0	0		
SUMMER	**Neap Flood**	152	124	1	-4	68	1193	123	19	-41	177	10
	Neap Ebb			-14	10				-111	44		
	Spring Flood			18	-15				160	-135		
	Spring Ebb			-24	18				-194	148		
	Slack Tide			0	0				0	0		
FALL	**Neap Flood**	170	132	1	-5	72	1340	132	23	-48	187	11
	Neap Ebb			-19	11				-149	90		
	Spring Flood			17	-17				157	-149		
	Spring Ebb			-30	21				-241	170		
	Slack Tide			0	0				0	0		

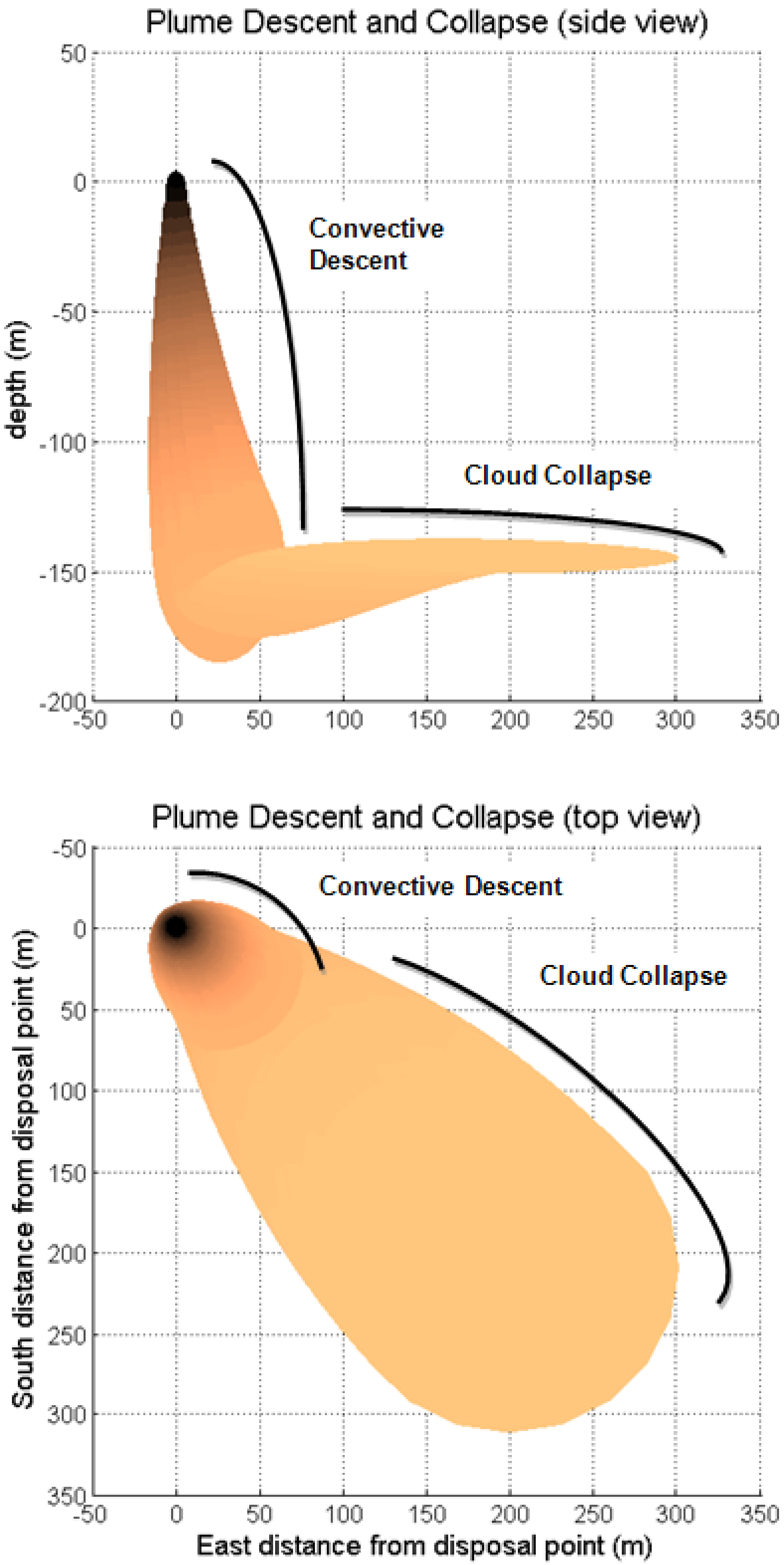


Figure 5.1 Plume Descent and Collapse Diagram for Spring Spring-Ebb Tidal Phase Scenario

6.0 LONG TERM DISPERSION OF DRILLING MUD DISCHARGE (Phases III and IV)

The fate of drilling mud was assessed using the DFO Benthic Boundary Layer Transport (BBLT) model (Drozdowski et al., 2004, Drozdowski, 2009). The model was setup using hypothetical worst case discharge scenarios of barite and bentonite based on the drilling schedule described in Section 2.0 and forced using the current fields described in Section 3.0 for a range of scenarios.

6.1 BENTHIC BOUNDARY LAYER TRANSPORT MODEL DESCRIPTION

The Benthic Boundary Layer Transport (BBLT) model was initially developed in the mid-1990s to predict the transport and dispersion of suspended particulate drilling waste (essentially the solids fraction of drilling mud) in the benthic boundary layer (Hannah et al., 1995). The focus of the model to represent the processes within the benthic boundary layer, that first few metres above the sea-bottom, was driven by the fact that the drilling mud particles have settling velocities on order of a few mm/s to a cm/s, which are high enough to allow them to settle to the bottom, yet the particles are also sufficiently small to be re-suspended by currents within this layer.

In BBLT, the material is assumed to be initially distributed on the bottom (either at a particular spatial location or within an area). Then, suspended particles are modelled in two stages: vertical distribution and horizontal transport. At each time step, the material is redistributed in the vertical dimension. Turbulent mixing in the boundary layer is modelled through vertical shuffling of discrete ‘packets’ of particles. Next, the material is advected horizontally in the flow field. As current velocity increases with height above the bottom, the patch of particles becomes dispersed.

For this study, input currents to BBLT were vertically-averaged near-bottom currents. The vertical structure of the currents in the benthic boundary layer and the associated vertical shear are parameterized in the model by a logarithmic profile as described in Drozdowski (2004).

6.2 MODEL SETUP: MUD DISCHARGE INPUT

Since barite (a weighting agent) and bentonite (a clay mineral) are the primary components of WBM and also are material of concern for the marine environment (Cranford and Gordon 1992, Cranford, 1995 and Cranford et al., 1999), only these two components were considered in this study. Barite and bentonite have significantly different densities and settling velocities so their dispersion was simulated using two separate implementations of BBLT.

The files describing the mud discharge were created using the following information and assumptions:

- The drilling program described in Section 2.0 was assumed to occur without any interruption between drilling and cementing of the sections of the hole. This represents a worst case scenario in terms of release of material into the environment. The overall discharge program was compressed and modelled to span a period of 15 days; in reality, drilling operations would span 20 to 50 days.

- Mud discharge was assumed to be continuous with material being added to the system in hourly time steps.

- Mud released from the rig with the cuttings during drilling of the two deeper sections of the well was also considered to be a continuous discharge. The volume considered is that of the loss during the recycling process (565 m^3; see Table 2.1). Only barite is assumed to be discharged here as no bentonite is used for these sections of the hole (Table 2.1). Overall, about 8.355 t and 11.14 t of barite are assumed to be discharged during the drilling of these two sections, respectively.

- The remaining amount of barite is assumed to be released instantly as a bulk discharge after completion of the last well section. The total amount of material assumed to reach the benthic boundary layer within the vicinity of the rig is estimated to be 20 % based on the fraction method of Loder el al. (1999) and the results of Section 5.2. Therefore, 3.1 t of barite are assumed to be discharged instantly at the drill site during this release.

Discharge scenarios for barite and bentonite are shown in Figure 6.1 and Figure 6.2 respectively. Each BBLT scenario was run for 720 hours (30 days).

The BBLT model setup requires individual ‘packets’, representing a certain amount of material (Hannah et al., 1995). As typically recommended, single packets were assigned a mass of 1 kg (Drozdowski, 2004). The total discharge was therefore released in the form of about 140,000 packets of bentonite and about 272,000 packets of barite.

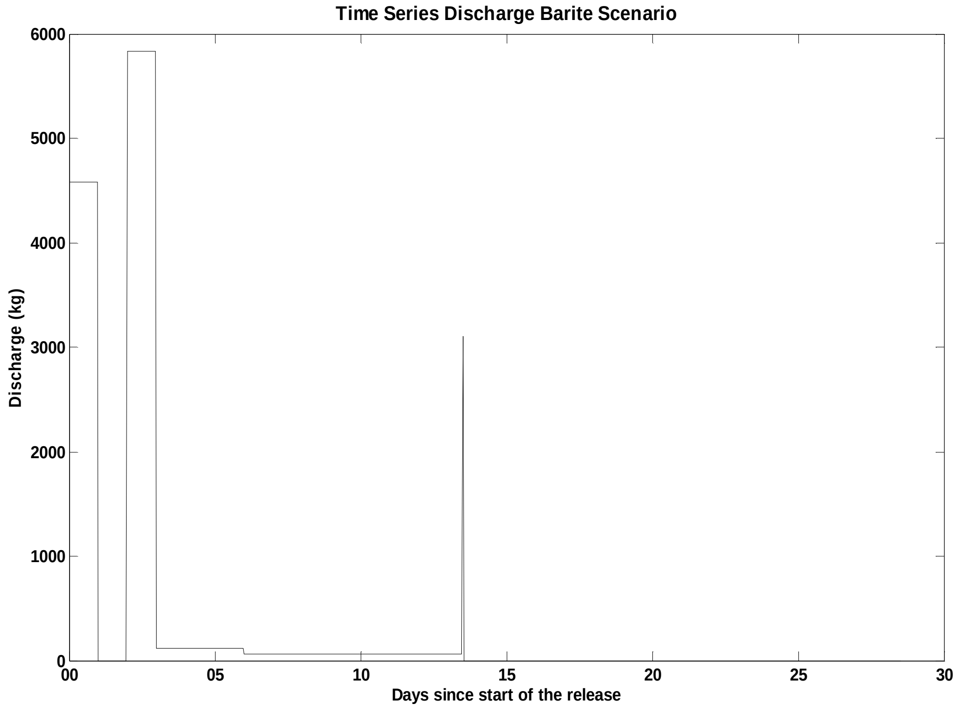


Figure 6.1 Barite Release Time-Series for BBLT

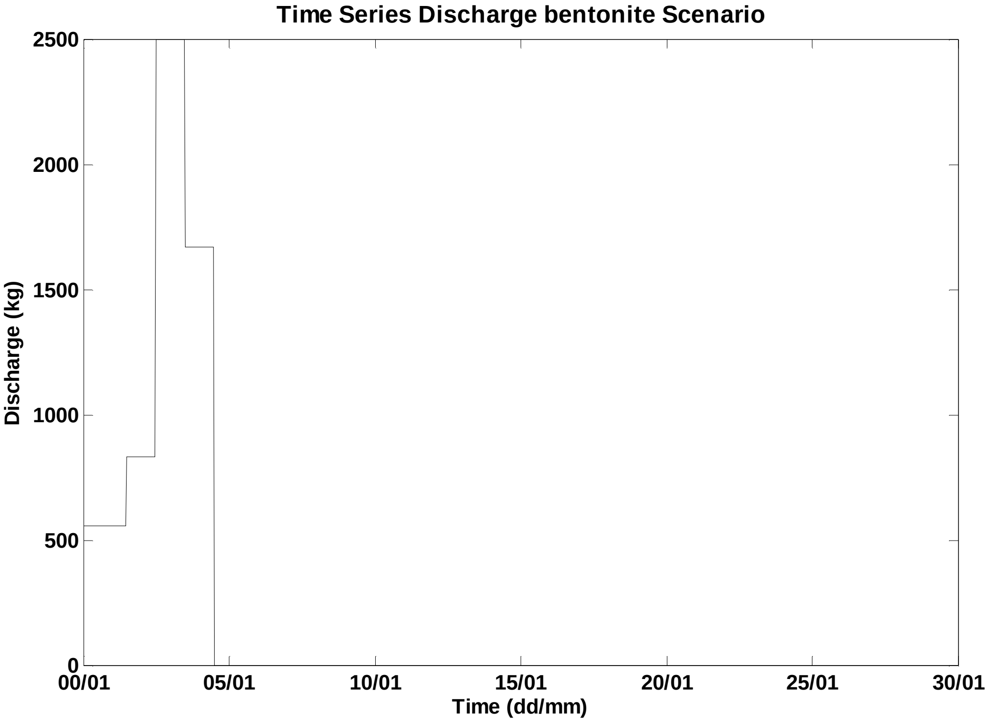


Figure 6.2 Bentonite Release Time-Series for BBLT

6.3 MODEL SETUP: VELOCITY FIELDS INPUT

The seasonal bottom current fields from WebDrogue (Section 3.2) were combined with tidal current fields (Section 3.1) for use as BBLT current input.

6.4 MODEL SETUP: PARTICLE SETTLING VELOCITY

This importance of the settling velocity parameter has been stressed in many of the previous studies (e.g., Thomson et al., 2000, Tedford et al., 2003, and Hannah et al., 2003). As stated by Drozdowski (2004): “the specification of the settling velocity will always be problematic” and “…depends strongly on what material is being modelled”.

Considering the previous studies, the choice here was to provide a range that would bracket the possible situations. As context, large settling velocities on the order of 0.5 cm/s or more are usually found with flocculated mud, generally at the origin of a release when mud starts to mix with seawater, while lower settling velocities on the order of 0.1 cm/s or less are more representative of single grain particles of barite. Since flocculation is dependent on the concentration, the mode of discharge will determine whether or not flocs will form. The direct discharge to the sea floor for instance (representing most of the discharge here) is a process that could lead to large initial concentrations (see section 5.1) and initially large settling velocities. On the other hand, the mud that could wash off the cuttings during their descent to the seabed (a minor portion of the total discharge here) is likely to be a low-concentration process contribution to the formation of background flocs (low settling velocity). Finally, the end of well bulk discharge should be considered as a high concentration discharge but, since the water depth of the site is 470 m, the plume does not reach the bottom directly and most of the material (80 %) enters into pelagic transport (as described in Loder et al., 1998).

In order to bracket the range of possible settling velocities, two values were retained for the simulations: 0.1 cm/s and 1 cm/s.

6.5 MUD DISPERSION MODELLING RESULTS

Each of the 16 BBLT scenarios were run for a period of 720 hours. The scenarios were based on the material to be modelled and ambient conditions as follow:

Two mud components:
- Barite
- Bentonite

Two settling velocities per mud component to be modelled:
- Low settling velocity of 1 mm/s
- High settling velocity of 10 mm/s

These values correspond to the range of values used previously in similar studies (e.g., Thomson et al., 2000; Tedford et al., 2003 and Hannah et al., 2003) where a 1 mm/s value represents a single grain barite, while a value of 10 mm/s is representative of flocculated material.

Four seasonal WebDrogue current fields were constructed to represent the winter, spring, summer and fall regional circulation conditions.

A summary of the BBLT model parameter setup is presented in Table 6.1

Table 6.1 BBLT Parameter Setup Summary

Parameter	Value
Run time	720 hours
Velocity field time step	1 hour
(Internal) Advection time step	0.1 hour
Vertical Shuffling Time	3 hours
Vertical Shuffling method	2
Settling Velocities (constants)	0.001 to 0.01 m/s
Reference Height (*Href*)	0.0035 m
Boundary Layer Height (*Hmax*)	30 m
Von Karman constant	0.4

Sixteen scenarios were undertaken for preliminary simulations using the two individual releases of material (barite and bentonite), four seasons of currents (winter, spring, summer and fall) and two settling velocities (1 mm/s low settling and 10 mm/s high settling).

The analysis of these 16 preliminary simulations demonstrated an overall similar behavior for all high settling and low settling velocity scenarios, regardless of the seasons considered or the material being released. The relatively small variation in discharge amount (140 MT of bentonite versus 272.6 MT of barite) and the relatively small variation of currents (2.5 to 5 cm/s) each have limited effect on the dispersion compared to the relatively large settling velocity range considered (1 mm/s to 10 mm/s).

Two ‘extreme’ scenarios, of the total of 16 modelled, were selected and are presented here for further analysis: the high settling velocity winter scenario, and the low settling velocity summer scenario. Both consider the time-series release of barite (the largest amount of material) during the compressed drilling program. These two scenarios bracket the overall conditions expected to occur.

The depth-averaged concentration of material in the first metre of water above the sea bottom as well as at 5 m and 10 m elevations (a 1 m depth bin averaged +/-0.5 m about those values) were extracted from each set of simulation results. Final concentration maps, after the 720 h (30 day) run of BBLT, of the first depth-averaged metre above sea bottom for each scenario are shown in Figure 6.3 and Figure 6.4. Mean plume concentration time-series, extracted from the three levels at 1 m, 5 m and 10 m above sea bottom are presented in Figure 6.5 and Figure 6.6.

Overall, as seen in the figures, there is large variability within and between the two settling velocity scenario results.

For the high settling velocity scenario, the final plume size is on the order of 2 to 3 km long and less than 1 km wide. Also, because of this high settling value and low currents on the order of a few cm/s, all the material stays within the first metre of the water column (that is why Figure 6.5 only shows concentration at 1 m. Concentrations are in the range between 250 mg/l and 1 g/l. The concentration map (Figure 6.3) shows the highest concentration at the centre of the plume, two to three orders of magnitude higher than at the margins. Overall, the averaged plume concentration time-series (Figure 6.5) shows a stabilization of the concentration near about 250 mg/l after about 20 to 25 days of the 30 day modelling exercise.

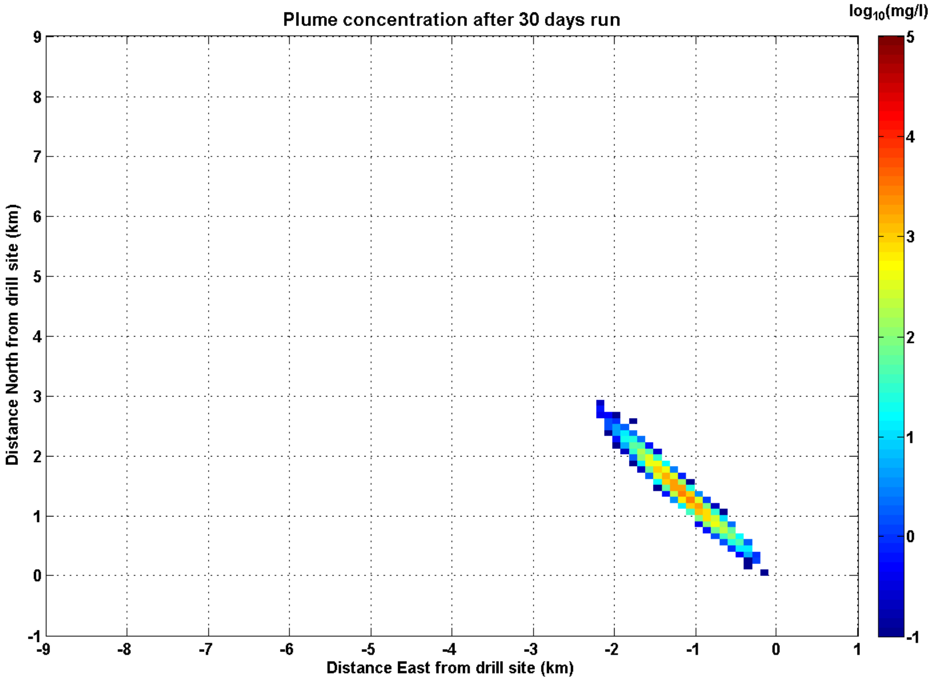


Figure 6.3 End of Run Barite Plume Concentration, High Settling Velocity, Winter Scenario

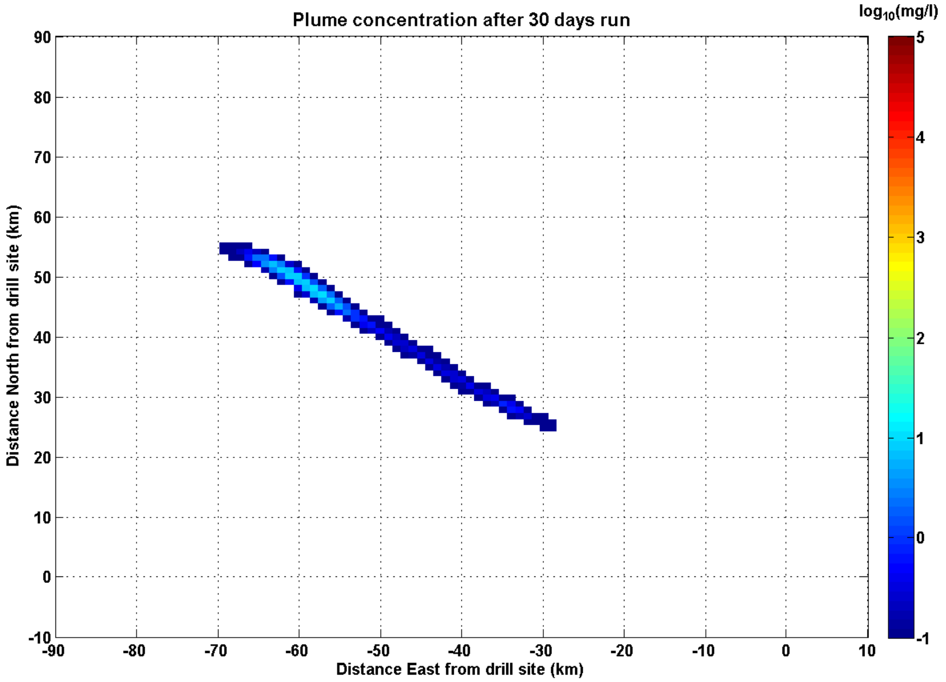


Figure 6.4 End of Run Barite Plume Concentration, Low Settling Velocity, Summer Scenario

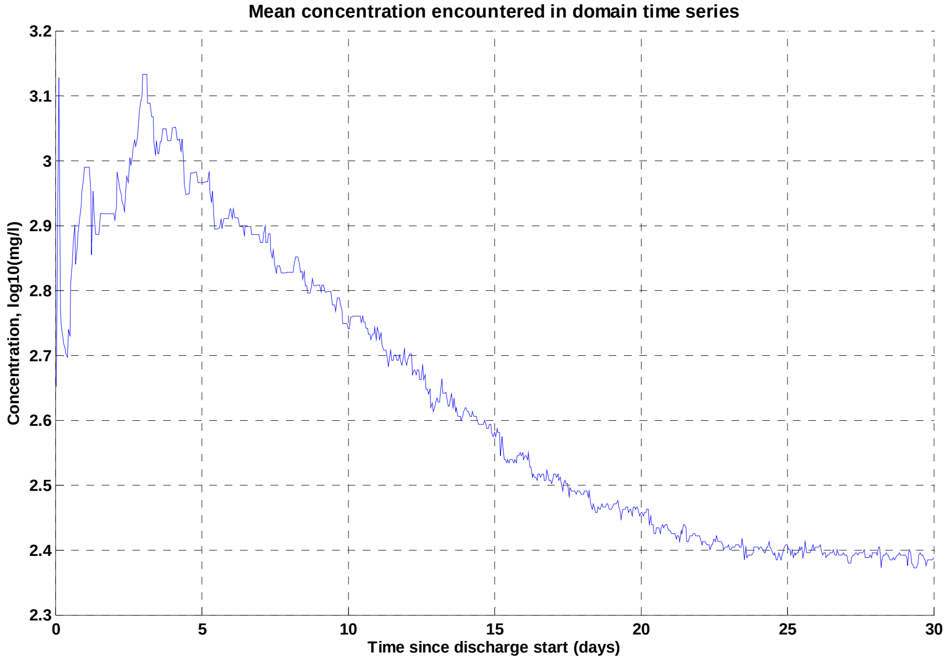


Figure 6.5 Mean Plume Concentration Time-Series, High Settling Velocity, Winter Scenario

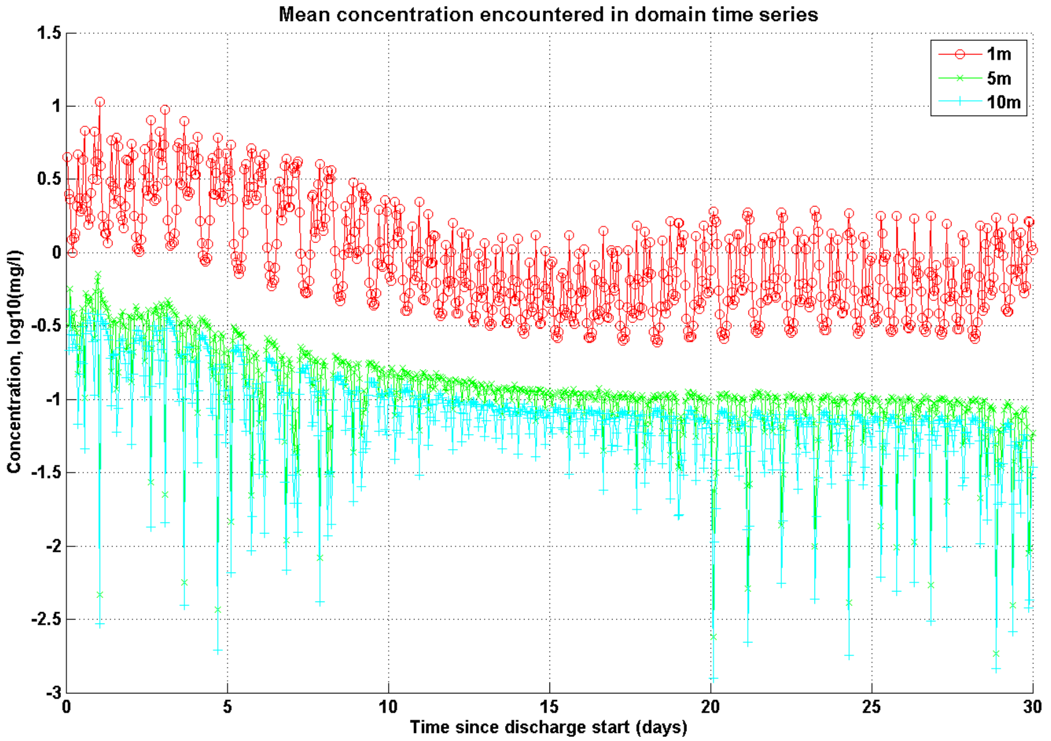


Figure 6.6 Mean Plume Concentration Time-Series, for Selected Depths, Low Settling Velocity, Summer Scenario

For the low settling velocity scenario, the final plume size is on the order of 40 km long and a few kilometres wide. Due to this low settling value, the concentration profile extends higher in the water column and material is present within zones 5 m and 10 m above the seabed (Figure 6.6). Due to the discharge scenario and subsequent dispersion, the plume exhibits a higher concentration of one or more orders of magnitude at its centre compared to its periphery (Figure 6.4), as was the case for the high settling velocity scenario. Overall, the plume is much more diluted than for the high settling rate scenario but concentrations exhibit large frequency variations of about one order of magnitude. Initially, concentrations vary between 1 mg/l and 10 mg/l, with an average value of about 3 mg/l. After about 15 days, plume concentration stabilizes around an average of 1 mg/l, with variations between about 0.3 mg/l and 2 mg/l. Concentrations within the 5 m zone are only about 20 to 50 % higher than at 10m. Concentrations at 5 m and 10 m are about one order of magnitude lower than at 1 m and stabilize after 15 days at about 0.1 mg/l. They also exhibit large variability up to more than two orders of magnitude. Looking in more detail (Figure 6.7), it can be seen that the variations of concentration at 1 m are in opposite phase to those at 5 m and 10 m: maxima at 1 m coincide with minima at 5 m and 10 m, and vice versa. In addition, variations in concentration follow the tidal cycle, with about four peaks per day.

This result demonstrates a suspension/deposition cycle due to tidal stirring. During periods of flood or ebb, when currents are strong, the particles are stirred up higher in the water column such that near bottom concentrations decrease as the plume extends vertically and material is transferred higher up from the seabed. During slack or tidal reversal periods, the material settles down again towards the seabed.

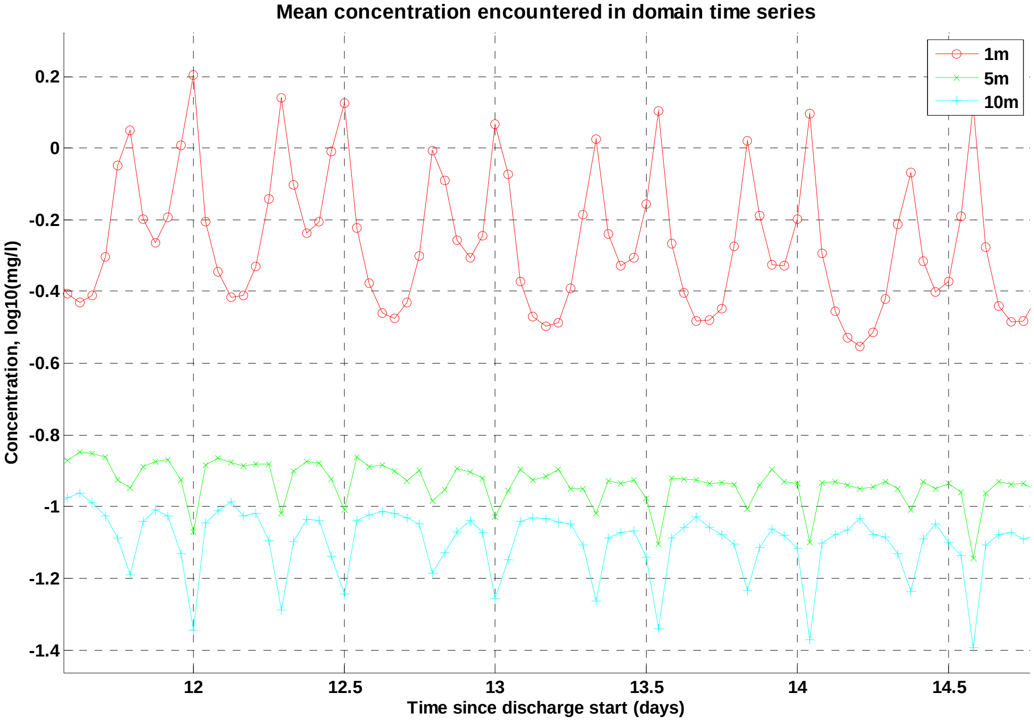


Figure 6.7 Mean Plume Concentration Time-Series, for Selected Depths, Low Settling Summer Scenario, Zoom-In

6.6 MUD DISPERSION MODELLING CONCLUSIONS

Two dispersion scenarios were selected for the modelling analysis in order to estimate the full range of expected outcomes: a high settling velocity for barite in winter conditions, and a low settling velocity for barite in summer conditions. In both scenarios the mud was dispersed in the form of an elongated plume with lengths reaching 2 to 3 km (high settling velocity, winter) to about 40 km (low settling velocity, summer) after 30 days of model simulation. Associated plume widths are less than one to a few kilometres wide, respectively. The great variability in these dimensions are reflective of mud particle behaviour and due to the large range of settling velocities taken into account by the model.

The modelled mud plumes traveled the largest distance from the source under the low settling velocity scenario. In this case, the drilling mud particles are found to travel up to 80 km over the 30 day simulation. Considering a 40 km long plume and a residual current of 2.5 cm/s, a fixed point within the trajectory of the plume would experience maximum continuous exposure to suspended material on the order of about 20 days.

The sediment concentration in the plumes varied with the plume dimensions and distance from the source, with levels generally falling as the plume dispersed and was advected horizontally. The concentrations, averaged over a zone one metre above the bottom, ranged from a maximum of about 1 g/L for the high settling rate scenario a few kilometres away from the site, down to about 1 mg/L for the low settling rate scenario a few tens of kilometres away from the drilling site. It was noted as well that the concentration varies greatly (one order of magnitude or more) within the plumes due to suspension/deposition patterns induced by variations of current strength over the tidal cycle.

In the high settling velocity scenario, the particles are largely found very close to the seabed (less than 1 m above), but are generally not expected to fully settle to the bottom. To illustrate a worst case scenario, if all the particles were to settle to the seabed, an area on the order of 1 km^2 would be covered by a very thin layer with a thickness of 64 µm. Considering the density of barite particles, the average sediment deposition within this 1 km^2 area would amount to about 0.027 g/cm^2. This is comparable to the natural annual sediment mass accumulation rate of 0.031 g/cm^2 calculated by Smith and Schafer (1999) in their study of mercury uptake in ocean sediments for a location between Old Harry and Anticosti Island. The model results are generally consistent with similar studies of drilling mud dispersion in the benthic boundary layer (Thomson et al., 2000; Tedford et al., 2003 and Hannah et al., 2003).

7.0 REFERENCES

AMEC 2010. Drill Cuttings Deposition, Produced Water, and Storage Displacement Water Dispersion Modelling for the Hebron Project. Prepared for Stantec Consulting Ltd., St. John's, Prepared by AMEC Earth & Environmental, St. John's. September 2010

Brandsma M.G. and Divoky D.J. 1976. Development of models for prediction of short-term fate of dredged material discharged in the estuarine environment. Contract Report D-76-5, DAW39-74-C-0075, prepared by Tetra Tech, Inc., under contract to U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Corridor Resources Inc., 2011. Project Description for the Drilling of an Exploration Well on the Old Harry Prospect – EL 1105. February 21, 2011.

Cranford P.J., Gordon D.C., 1992. The influence of dilute clay suspensions on sea scallop (*Placopecten Magellanicus*) feeding activity and tissue growth. Netherlands J. Sea Res. Vol. 30, pp 107-120.

Cranford P.J., 1995. Relationship between food quantity and quality and absorption efficiency in sea scallops *Placopecten Magellanicus* (Gmelin). J. Exp. Mar. Bio. Ecol., Vol. 189, pp 123-142.
Cranford P.J., Gordon D.C. Jr., Lee K., Armsworthy S.L. and Tremblay G.-H., 1999. Chronic toxicity and physical disturbance effects of water and oil-based drilling fluids and some major constituents on adult sea scallops (*Placopecten magellanicus*). Marine Environmental Research, Vol. 48, Nb. 3, pp 225-256.

Department of Fisheries and Oceans (DFO), 2011a. WebTide Tidal Prediction Model. http://www2.mar.dfo-mpo.gc.ca/science/ocean/coastal_hydrodynamics/WebTide/webtide.html

Department of Fisheries and Oceans (DFO), 2011b. WebDrogue Drift Prediction Model v0.7. http://www2.mar.dfo-mpo.gc.ca/science/ocean/coastal_hydrodynamics/WebDrogue/webdrogue.html

Department of Fisheries and Oceans (DFO), 2011c. Canadian East Coast Ocean Model (CECOM). http://www2.mar.dfo-mpo.gc.ca/science/ocean/icemodel/ice_ocean_forecast.html

Department of Fisheries and Oceans (DFO), 2011d. The Gulf of St. Lawrence Climatology. http://www2.mar.dfo-mpo.gc.ca/science/ocean/gsl/gslmap.html

Drozdowski A., Hannah C., Tedford T., 2004. bblt Version 7.0 User's Manual. Canadian Technical Report of Hydrography and Ocean Sciences 240. Ocean Sciences Division Maritimes Region, Fisheries and Oceans Canada. Bedford Institute of Oceanography, P.O. Box 1006. Dartmouth, N.S., Canada B2Y 4A2.

Drozdowski A., 2009. BBLT3D, the 3D Generalized Bottom Boundary Layer Transport Model: Formulation and Preliminary Applications. Canadian Technical Report of Hydrography and Ocean Sciences 263. Ocean Sciences Division Maritimes Region, Fisheries and Oceans

Canada. Bedford Institute of Oceanography, P.O. Box 1006. Dartmouth, N.S., Canada B2Y 4A2.

Dupond F, Hannah C.G., Greenberg D.A., Cherniawsky, J.Y., Naimie C.E., 2002. Modelling System for Tides for the Northwest Atlantic Coastal Ocean. Canadian Technical Report of Hydrograph and Ocean Sciences 221, 70p.

Hannah, C.G., Y. Shen, J.W. Loder and D.K. Muschenheim. 1995. bblt: Formulation and Exploratory Applications of a Benthic Boundary Layer Transport Model. Can. Tech. Rep. Hydrogr. Ocean Sci. 166 vi +52 pp.

Hannah C.G., Drozdowski A., Muschenheim, Loder D.K., Belford S., MacNeil M., 2003. Evaluation of drilling mud dispersion models at SOEI Tier I sites: Part 1 North Triumph, Fall 1999. Canadian Technical Report of Hydrograph and Ocean Sciences 232, vi + 51p.

Hodgins, D.O.. Hibernia Effluent Fate and Effects Modelling. Report prepared for Hibernia Management and Development Company Ltd., 1993.

Koh, R.C.Y. and Y.C. Chang. 1973. Mathematical model for barged ocean disposal of waste. Environmental Protection Technology Series EPA 660/2-73-029, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

NEB, C-NLOPB and C-NSOPB (National Energy Board, Canada-Newfoundland and Labrador Offshore Petroleum Board, and Canada-Nova Scotia Offshore Petroleum Board). 15 December 2010. *Offshore Waste Treatment Guidelines*.

Niu H., Drozdowski A., Husain T., Veitch B., Bose N., and K. Lee. 1976. Modelling the dispersion of drilling muds using the bblt model: the effects of settling velocity. Environmental Model Assessment (2009) 14:585-594.

Okubo, A. 1971. Oceanic Diffusion Diagrams. Deep Sea Res. Vol. 18, pp. 789-802.

Sleath, J.F.A. 1939. Sea Bed Mechanics. Published by John Wiley & Sons.

Smith, J. N., and C. T. Schafer, 1999. Sedimentation, bioturbation, and Hg uptake in the sediments of the estuary and Gulf of St. Lawrence. *Limnol. Oceanogr.* 44(1), 1999, pp. 207-219

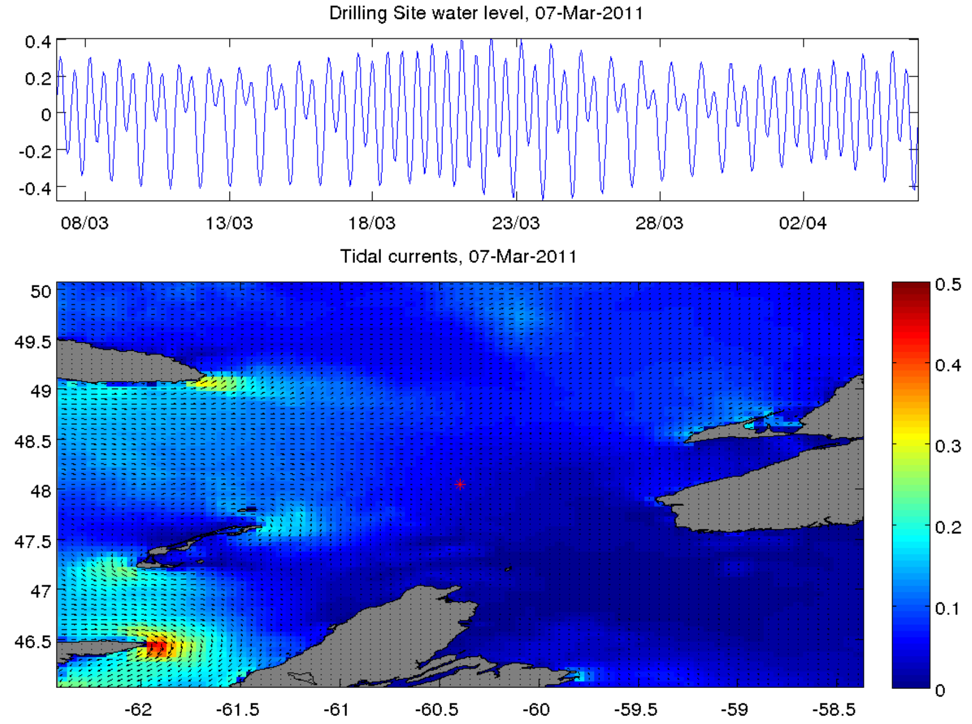
Tedford T., Drozdowski A., Hannah C.G., 2003. Suspended Sediment Drift and Dispersion at Hirbernia. Canadian Technical Report of Hydrograph and Ocean Sciences 227: vi + 57p.

Thomson D.H., Davis R.A., Belore R., Gonzalez E., Christian J., Moulton V.D. and Harris R.E., 2000. Environmental Assessment of Exploration Drilling Off Nova Scotia. Report prepared for Canada – Nova Scotia Offshore Petroleum Board and Mobil Oil Canada Properties, Shell Canada Ltd., Imperial Oil Resources Ltd, Gulf Canada Resources Ltd., Chevron Canada Resources, EnCana Petroleum Ltd., Murphy Oil Company Ltd., and Norsk Hydro Canada Oil & Gas Inc.

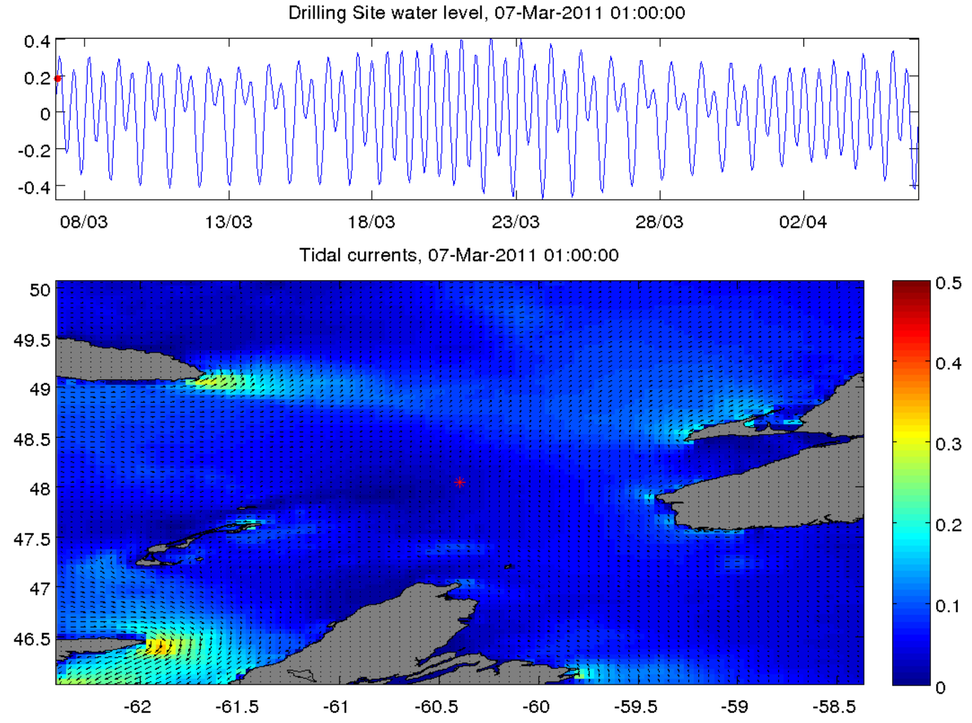
Wimbush and Munk. 1970. The Benthic Boundary Layer in the Sea, Vol. 4, Chapter 1.

APPENDIX A

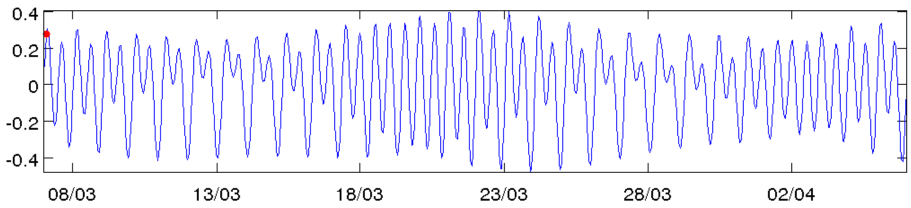
Regional Tidal Streams Over One Cycle

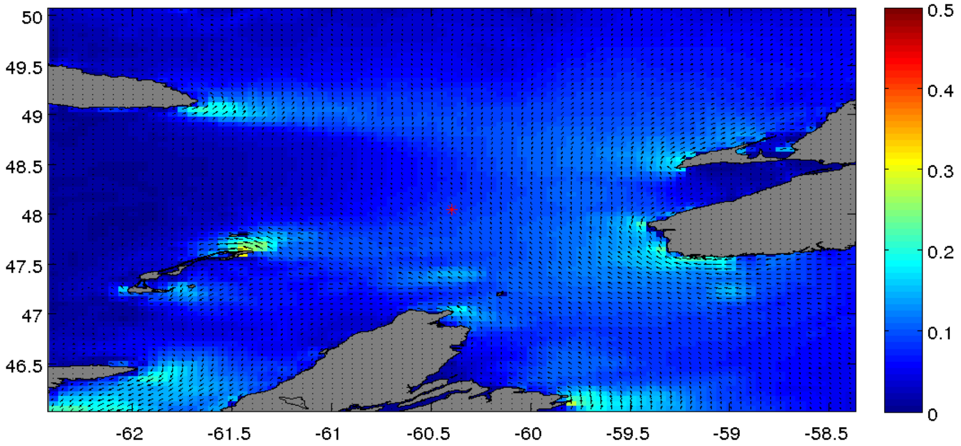

Drilling Site water level, 07-Mar-2011

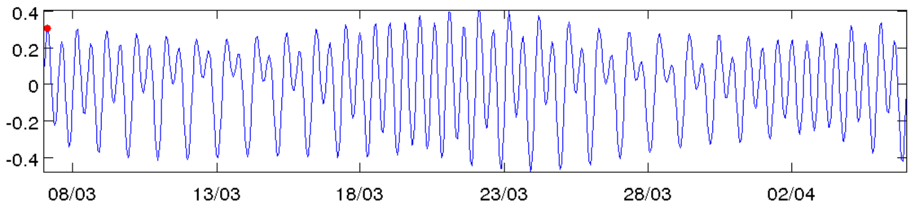
Tidal currents, 07-Mar-2011

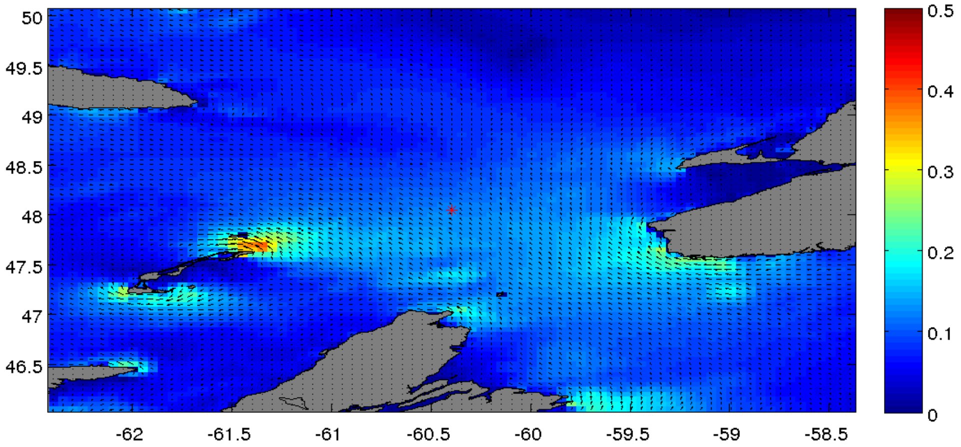

Drilling Site water level, 07-Mar-2011 01:00:00

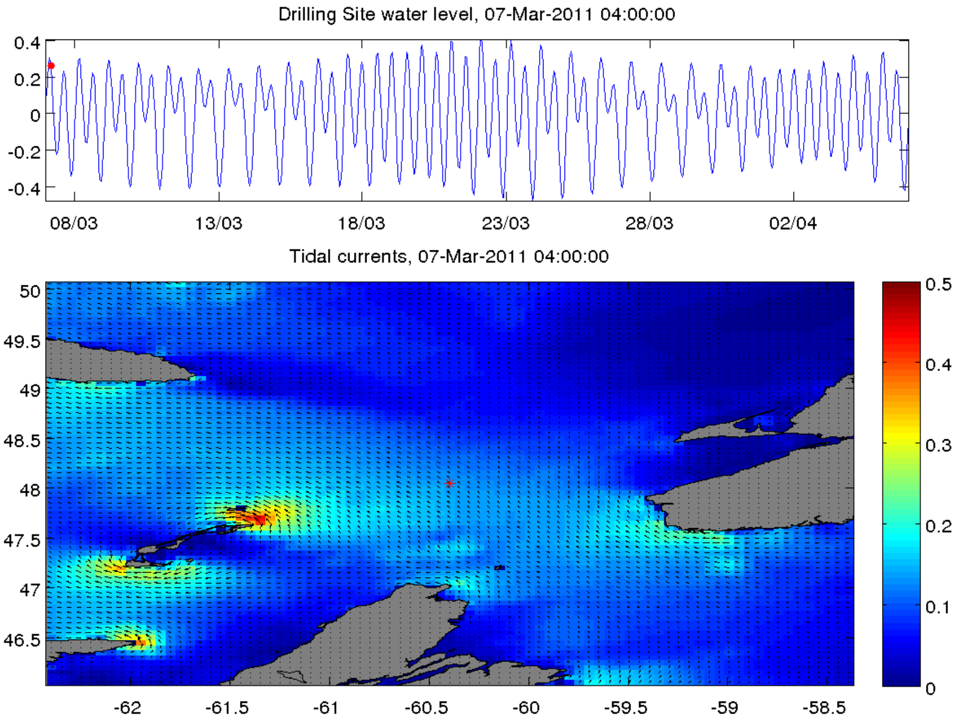
Tidal currents, 07-Mar-2011 01:00:00


Drilling Site water level, 07-Mar-2011 02:00:00


Tidal currents, 07-Mar-2011 02:00:00

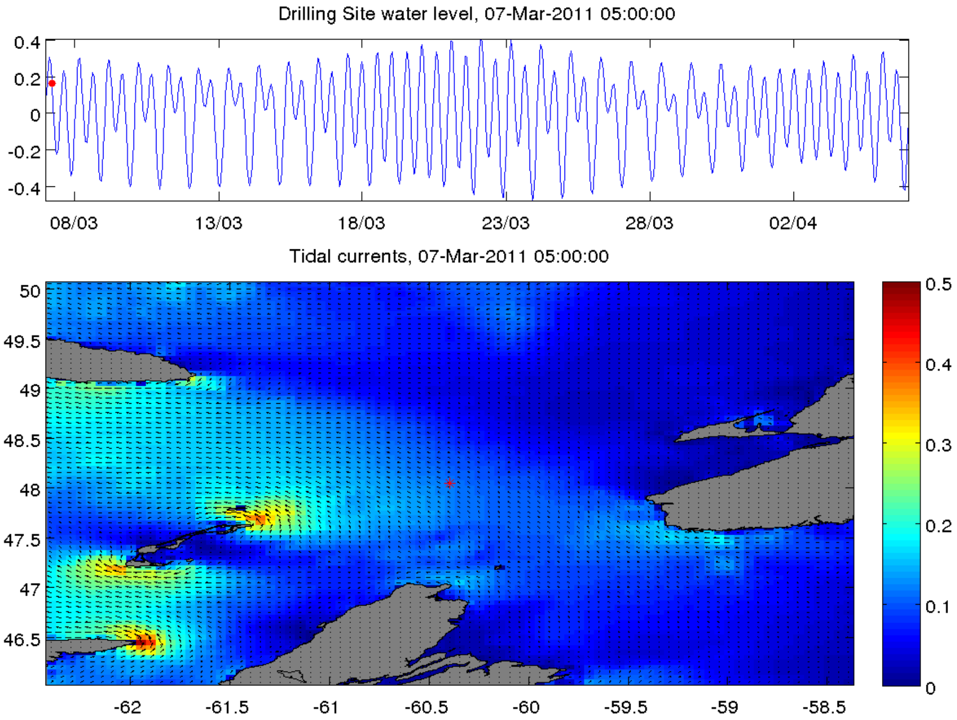

Drilling Site water level, 07-Mar-2011 03:00:00


Tidal currents, 07-Mar-2011 03:00:00



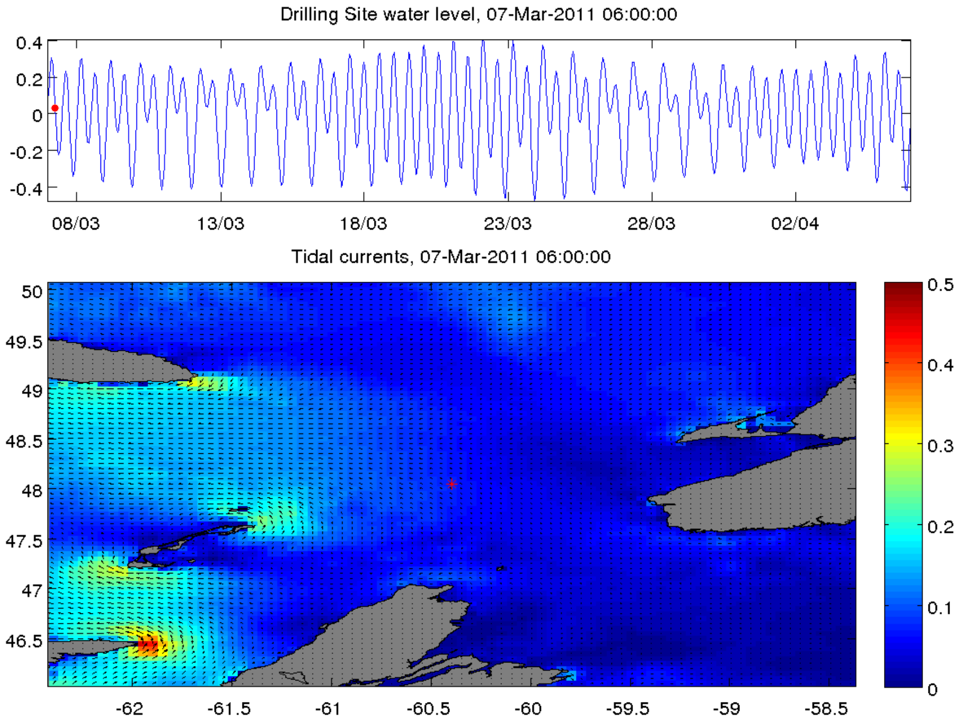
Drilling Site water level, 07-Mar-2011 04:00:00

Tidal currents, 07-Mar-2011 04:00:00



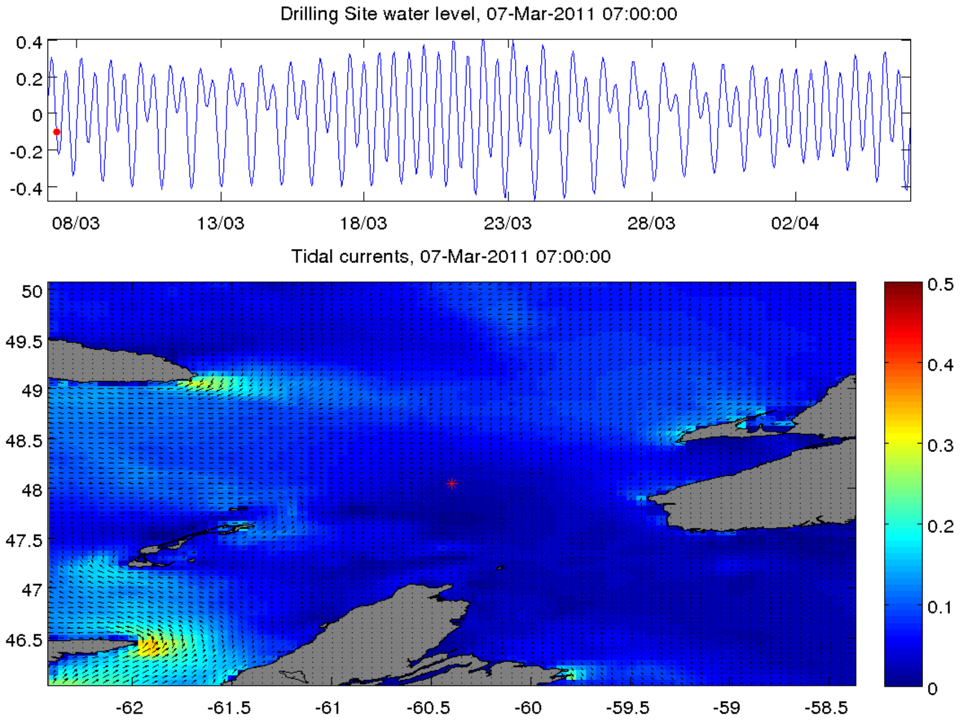
Drilling Site water level, 07-Mar-2011 05:00:00

Tidal currents, 07-Mar-2011 05:00:00



Drilling Site water level, 07-Mar-2011 06:00:00

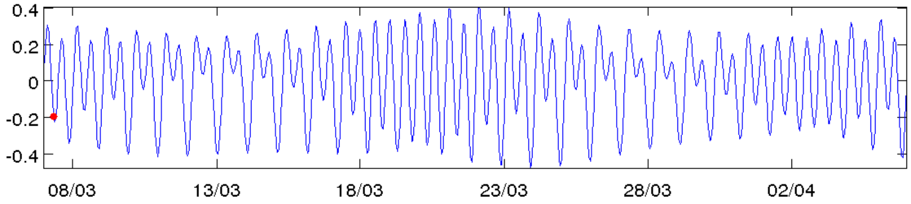
Tidal currents, 07-Mar-2011 06:00:00



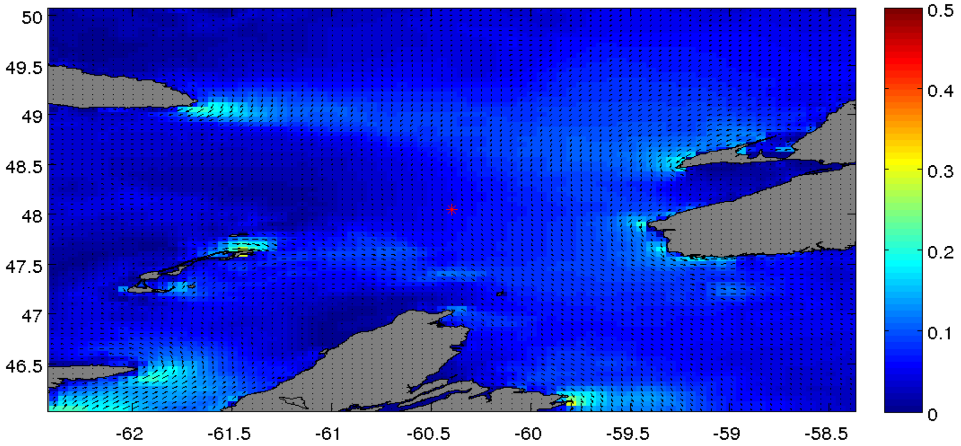
Drilling Site water level, 07-Mar-2011 07:00:00

Tidal currents, 07-Mar-2011 07:00:00

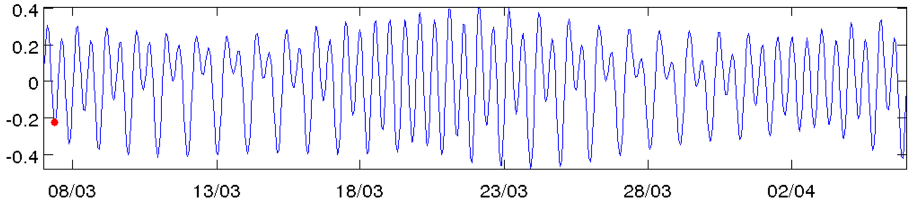
Drilling Site water level, 07-Mar-2011 08:00:00



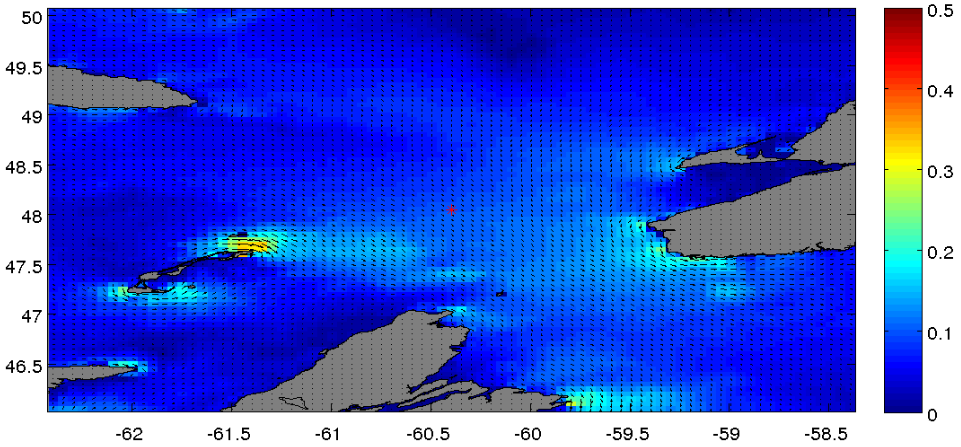
Tidal currents, 07-Mar-2011 08:00:00

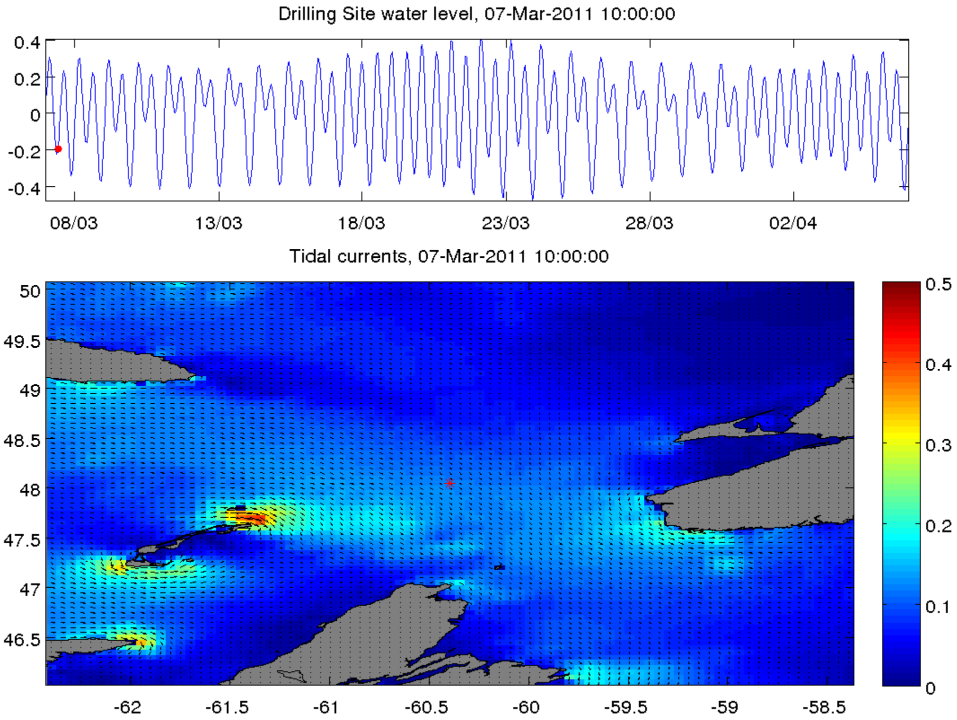


Drilling Site water level, 07-Mar-2011 09:00:00



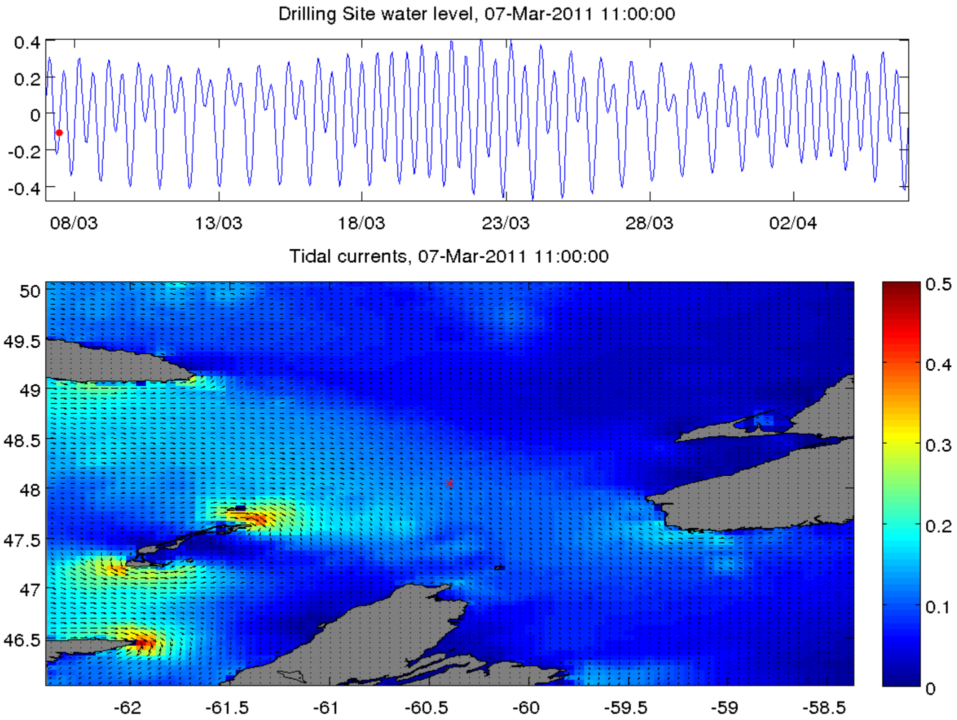
Tidal currents, 07-Mar-2011 09:00:00





Drilling Site water level, 07-Mar-2011 10:00:00

Tidal currents, 07-Mar-2011 10:00:00

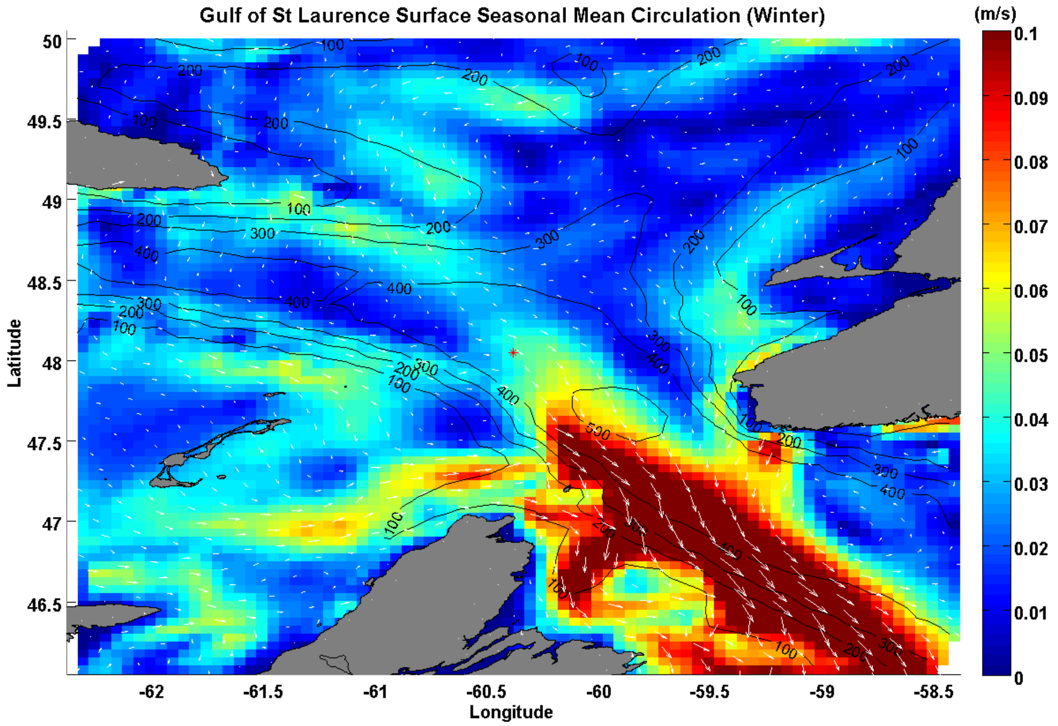


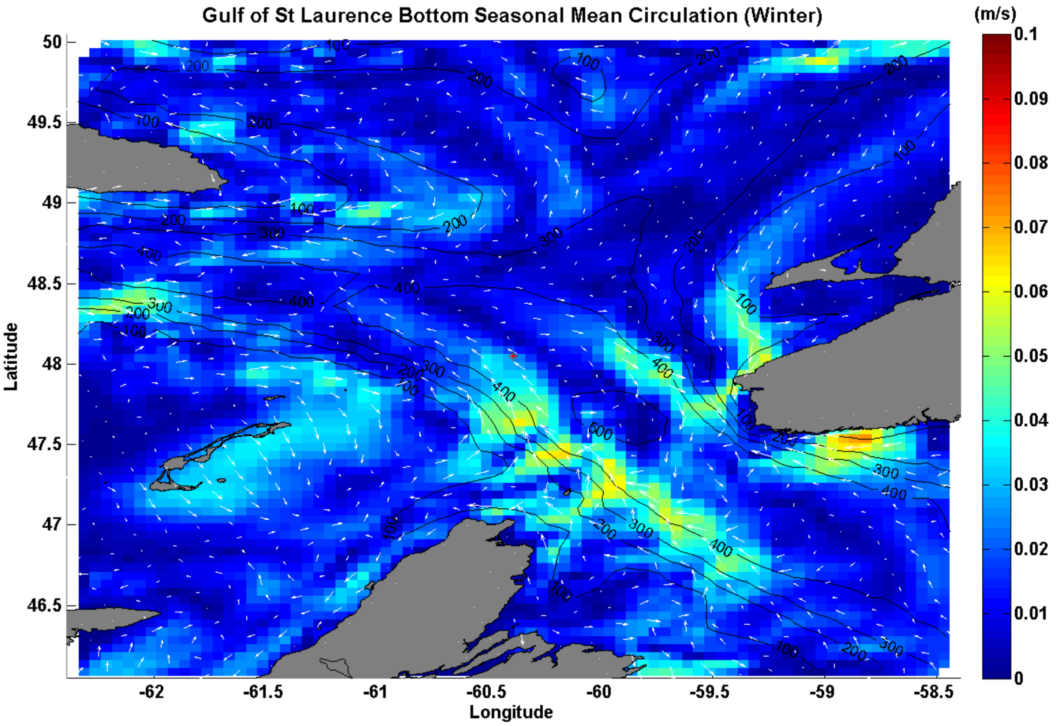
Drilling Site water level, 07-Mar-2011 11:00:00

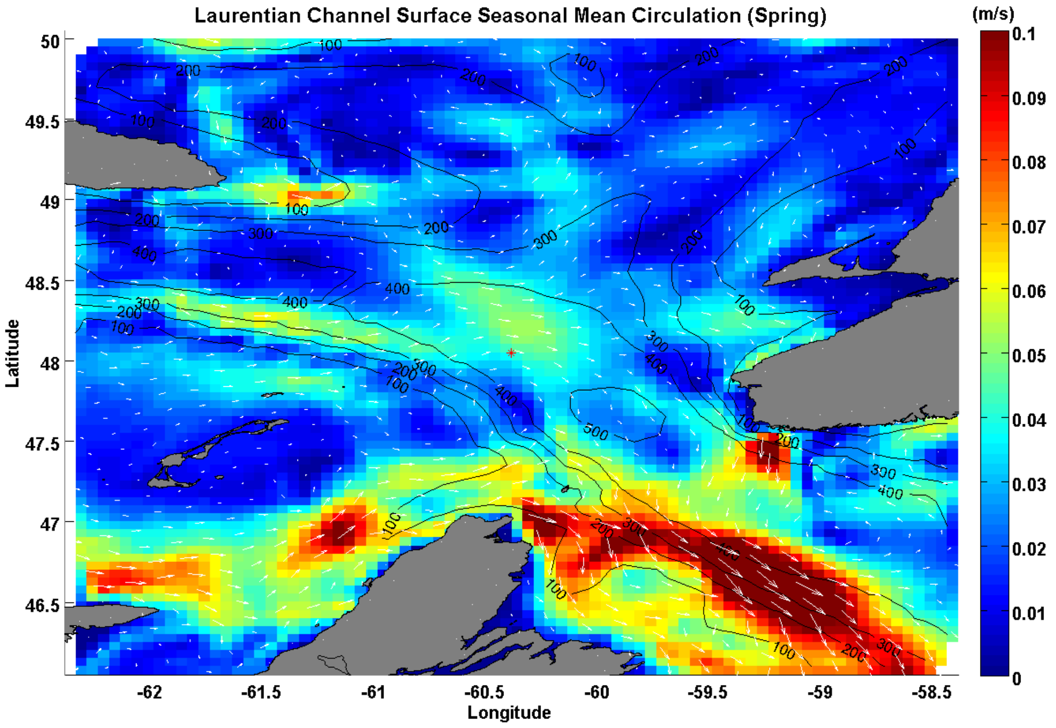
Tidal currents, 07-Mar-2011 11:00:00

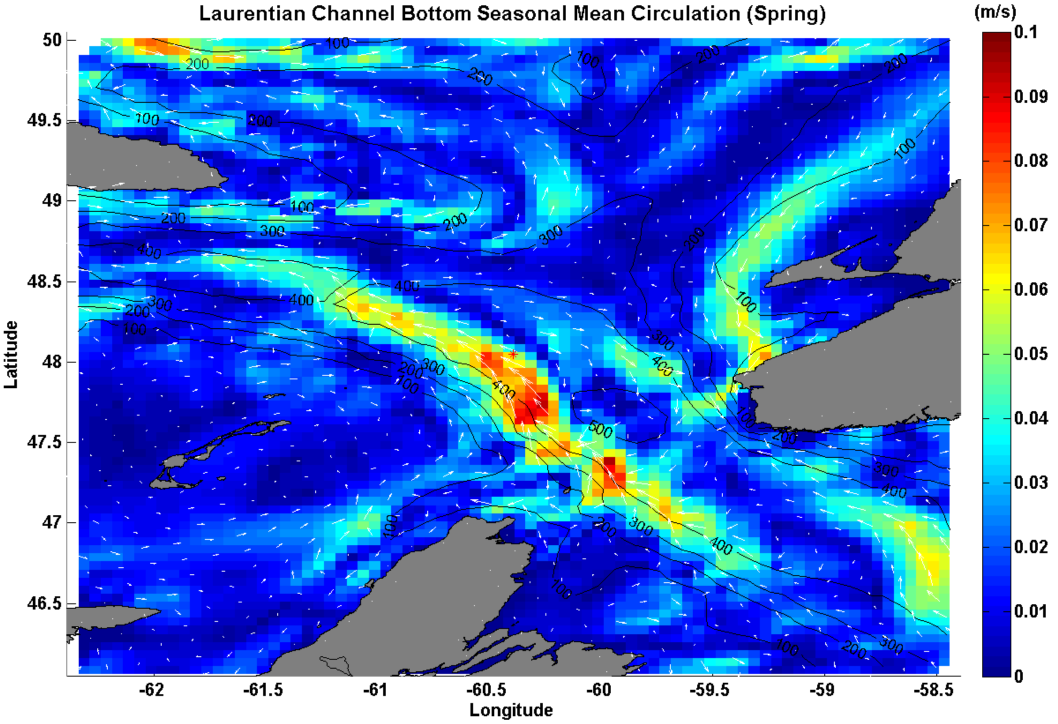
APPENDIX B

Seasonal Mean Circulation

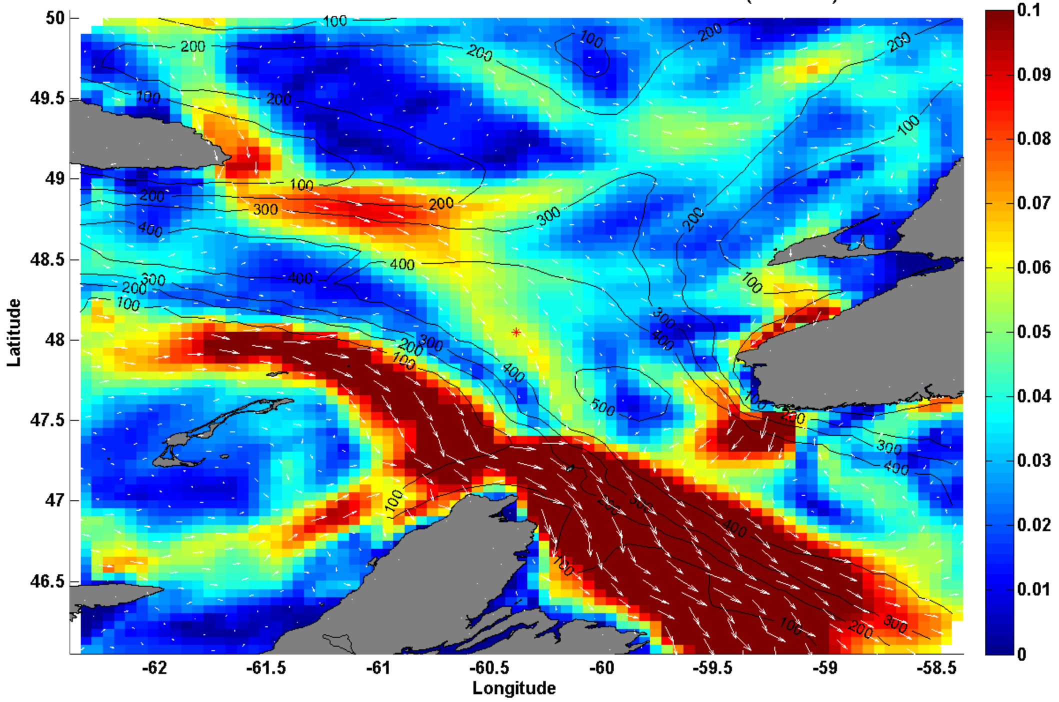

Gulf of St Laurence Surface Seasonal Mean Circulation (Winter)


Gulf of St Laurence Bottom Seasonal Mean Circulation (Winter)

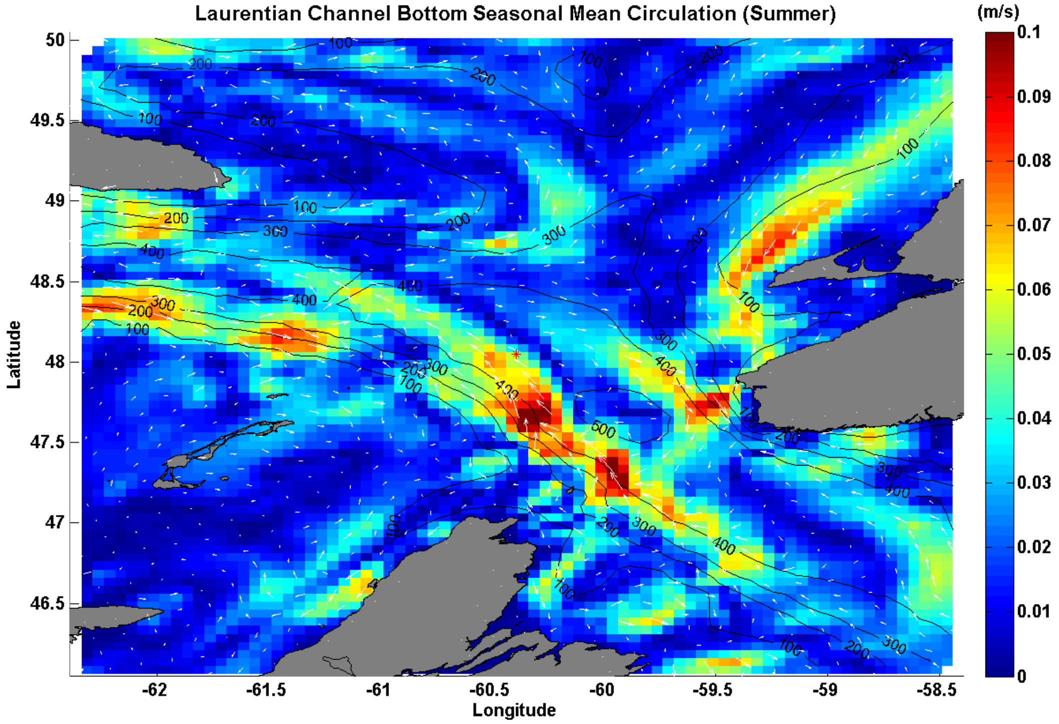

Laurentian Channel Surface Seasonal Mean Circulation (Spring)

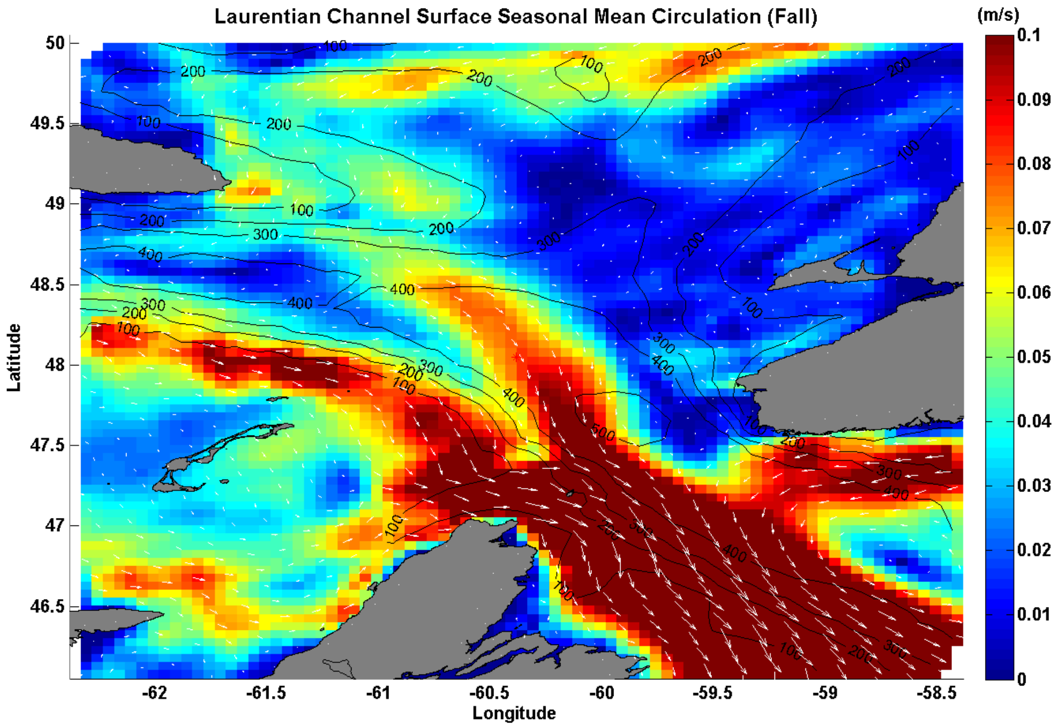

Laurentian Channel Bottom Seasonal Mean Circulation (Spring)

Laurentian Channel Surface Seasonal Mean Circulation (Summer)

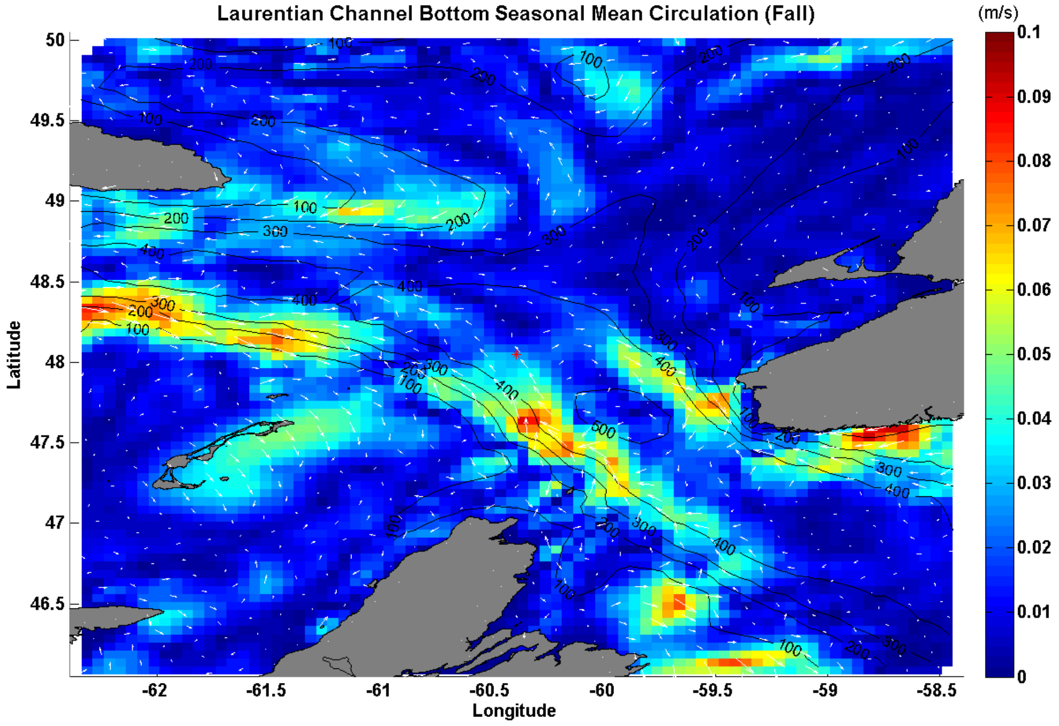


Laurentian Channel Bottom Seasonal Mean Circulation (Summer)





Laurentian Channel Surface Seasonal Mean Circulation (Fall)



Laurentian Channel Bottom Seasonal Mean Circulation (Fall)