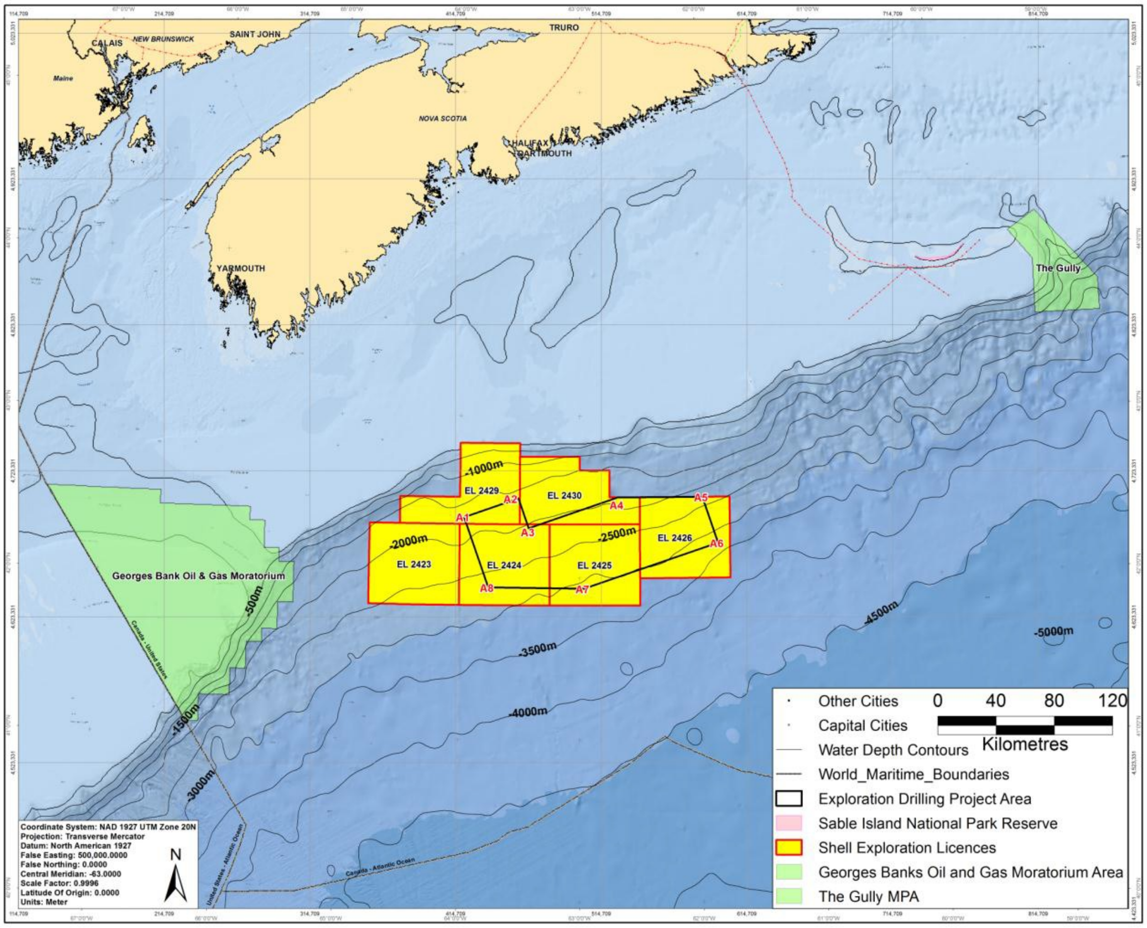
APPENDIX C

Sediment Dispersion Modelling

Sediment Dispersion Modelling in Support of the Shelburne Basin Exploration Drilling Program



Drilling Mud and Cuttings Operational Release

SBM Accidental Release

By

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EXECUTIVE SUMMARY

Shell Canada Limited contracted Applied Science Associates, Inc. (dba RPS-ASA) to perform model simulations of drilling discharges associated with the Shelburne Basin Venture Exploration Drilling Project. The sites selected for modelling (Sites 1, 2, and 3) are situated along the continental slope, approximately 250 km south of Nova Scotia within a geographical offshore area known as the Southwest Scotian Slope. Water depths at the model sites range between 1790 m and 2315 m. Numerical modelling was performed to evaluate the extent of seafloor deposition and to track suspended sediments in the water column resulting from (i) the operational discharge of mud and cuttings anticipated during offshore drilling activities, as well as from (ii) accidental releases of synthetic based mud (SBM) originating from the sea surface and the marine riser. Sites 1 and 2 were chosen as SBM release locations to represent conditions at a range of potential water depths along the continental shelf. Site 3 is situated midway between the two wells and was selected as a representative location for the dispersion modelling of operational mud and cuttings discharges.

Discharge simulations were completed using ASA's MUDMAP modelling system. The MUDMAP model predicts the transport of releases in the marine environment and the resulting seabed deposition. The model inputs include information regarding the discharge characteristics (release location, rate of discharge, etc.), the properties of the sediment (particle sizes, density), as well as environmental characteristics (bathymetry and ocean currents), to predict the transport of solids through the water column.

The general ocean circulation in the Scotian Slope region is strongly influenced by the behaviour of several major surface currents including the Gulf Stream and Labrador Current. Modelling and observational studies have highlighted seasonal variation in current speeds near the project area, particularly in the upper 400 m of the water column. Because drilling operations within the Shell's exploration licence areas could occur throughout the year, the modelling was developed to compare the results of different flow conditions that characterize a range of release periods. Specifically, operational mud and cuttings releases were simulated at Site 3 for two periods spanning the months of April-June and October-December – periods that correspond to current minima/maxima in the project area. MUDMAP simulations of accidental SBM releases at Sites 1 and 2 utilized currents from the spring period to replicate conditions that would produce higher and more sustained plume concentrations. For each scenario, vertically and time varied currents derived from the HYCOM (HYbrid Coordinate Ocean Model) global simulation were used in combination with TPXO8.0 tidal forcing to drive the advection of the discharged solids.

At Site 3, the resulting bottom deposition from individual discharge sections was analysed along with the pattern of cumulative deposits for each season. Overall, both scenarios predict a fairly concentric depositional footprint that surrounds the discharge site. The deposit is slightly elongated to the south (west) for the simulation period 1 (period 2). Contours representing very fine thickness intervals (0.1 mm) extend up to 1380 m from the release site, although most of the mass released by the model is expected to remain confined to an area within 100 m of the well head. Differences in the extent of deposition between each season are nominal and are limited to thicknesses of 10 mm and below; the extent of deposition above 20 mm is nearly indistinguishable between seasons. Considering both seasons, thicknesses at or above 1 mm extend up to 681 m from the discharge site and occupy a maximum areal extent of 71.18 ha; thicknesses greater than 10 mm extend up to 155 m with a maximum footprint of 2.51 ha.

MUDMAP was also used to assess seabed deposition and total suspended solid (TSS) concentrations associated with two accidental releases of SBM at Sites 1 and 2. Given the relatively small release volumes and fine particle sizes associated with the SBM, the sea surface releases (60 m^3) quickly disperse below levels detectible by the model. As a consequence they do not contribute to the mass accumulation on the seabed. Deposition resulting from the (573 m^3) SBM releases at the seabed is limited to thicknesses below 10 mm at both sites. 1 mm thickness contours extends up to 690 m from the release sites, and cover a maximum area of 0.27 ha of the seabed.

Sediment plumes resulting from the accidental discharges of SBM are predicted to extend between 5,080 m and 9,620 m from the release site. As with the patterns of deposition, the extent of the plume and maximum TSS concentration are larger for the releases associated with the marine riser as compared to the surface discharges. The maximum predicted concentration of suspended sediments in the water column (corresponding to the weakest current regime) is 29,401 mg/L for the marine riser discharge and 2,424 mg/L for the surface release. In all cases, the water column is predicted to return to ambient conditions (<1 mg/L) within 30 hours of the release.

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1 INTRODUCTION

Shell Canada Limited (Shell) contracted with Applied Science Associates, Inc. (dba RPS-ASA) to perform model simulations of drilling discharges associated with the Shelburne Basin Venture Exploration Drilling Project. The objective of the study was to evaluate seafloor deposition and suspended sediments in the water column resulting from (i) the operational release of mud and cuttings anticipated during offshore drilling, and (ii) accidental releases of synthetic based mud (SBM) from the sea surface and the marine riser. Two sites located within Shell's offshore exploration licences (Sites 1 and 2) were chosen as SBM release locations to represent conditions at a range of potential water depths along the continental shelf. A third site (Site 3) located midway between the two wells was selected as a representative location for the modelling study of operational mud and cuttings discharges.

Model simulations were performed for different periods (seasons) in order to evaluate the influence of variability in regional ocean currents. Simulation periods were selected based on a review of recent literature and an analysis of ocean circulation models within the drilling project area. Operational releases were simulated for two (2) discharge period to compare the impacts of drilling during the spring and late fall, when local currents are strongest. The discharge schedule for each scenario was based on a drilling plan that consists of eight well sections ranging from 36" to 9 5/8" (inches) in diameter. The accidental releases of SBM were simulated during periods of current minima (late spring) to replicate conditions that would result in higher and more sustained plume concentrations.

ASA's MUDMAP model was used to perform the mud and drill cuttings dispersion modelling. MUDMAP predicts the transport, dispersion, and seabed deposition of drilling fluids, produced water, and solid materials released into the marine environment. Inputs necessary for drilling discharge modelling typically include:

- Environmental Conditions
    - Local hydrodynamics

- Physical Characteristics of the Study Area
    - Geographic coordinates of the study area
    - Bathymetry in the vicinity of the discharge sites

- Discharge Program(s)
    - Description of the volumes and types of drilling discharges
    - Schedule of release, discharge duration and/or discharge rate
    - Approximate depth of release for each section

A description of the input data used in the modelling, including the study location and current dataset, are presented in Section 2. The drilling discharge scenarios are presented in Section 3 and model results in Section 4. Report conclusions are given in Section 5. A technical summary of the MUDMAP model is provided in Appendix A.

2 LOCATION AND ENVIRONMENTAL DATA

2.1 SHELBURNE BASIN

The Shelburne Basin Venture Exploration Drilling Project will consist of up to seven exploration wells, drilled within the area of Shell's current exploration licences in the North Atlantic (shown in Figure 1). The Exploration Drilling Project Area is located along the southwest portion of the Scotian Slope region, approximately 250 km south of Nova Scotia. Local water depths range from 500 m to >4,000 m. The Shelburne Basin is one in a series of alternating depositional basins and platforms ("lows" and "highs") that run from the southwest to the northeast along the passive North Atlantic continental margin offshore Nova Scotia and Newfoundland. As they represent approximately 250 million years of continuous sedimentation, the basins of the deep water Scotian Slope are an important hydrocarbon resource for the region.

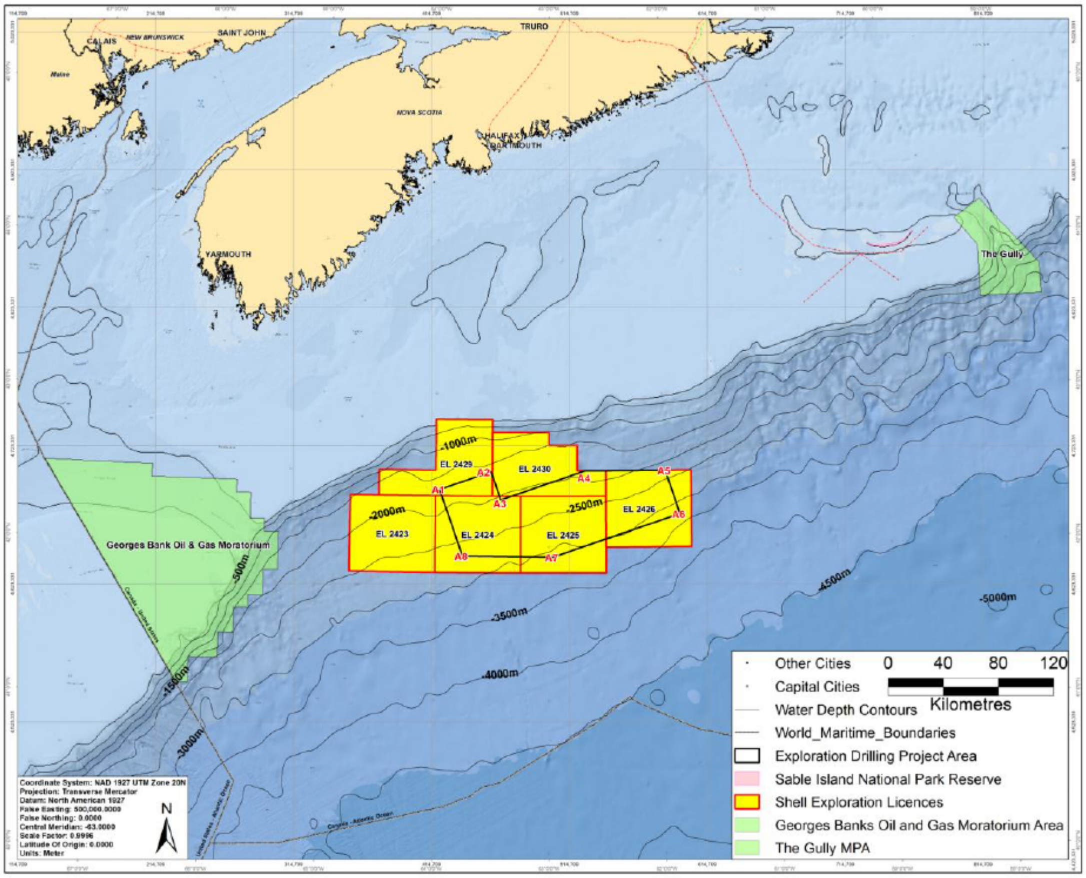


Figure 1. Shelburne Basin Venture Exploration Drilling Area (from Shell Canada Ltd, 2013).

Sites 1 and 2 are located along the continental slope directly south of Halifax, at water depths of 1790 m and 2315 m, respectively. A third site chosen for modelling (Site 3 - midway between Sites 1 and 2) falls at a water depth of 2050 m. These sites have been chosen to represent a range of water depths in addition to their proximity to sensitive features (i.e. Georges Banks). Coordinates for each site are described in Table 1. Figure 2 shows the site locations with respect to regional geography.

Table 1. Location of the discharge sites selected for modelling. Shelburne Basin, offshore Nova Scotia.

Site Name	Latitude (N)	Longitude (W)	Water Depth (m)
Site 1	42.3000	64.0000	1790
Site 2	42.1500	62.9000	2315
Site 3	42.2487	63.4776	2050

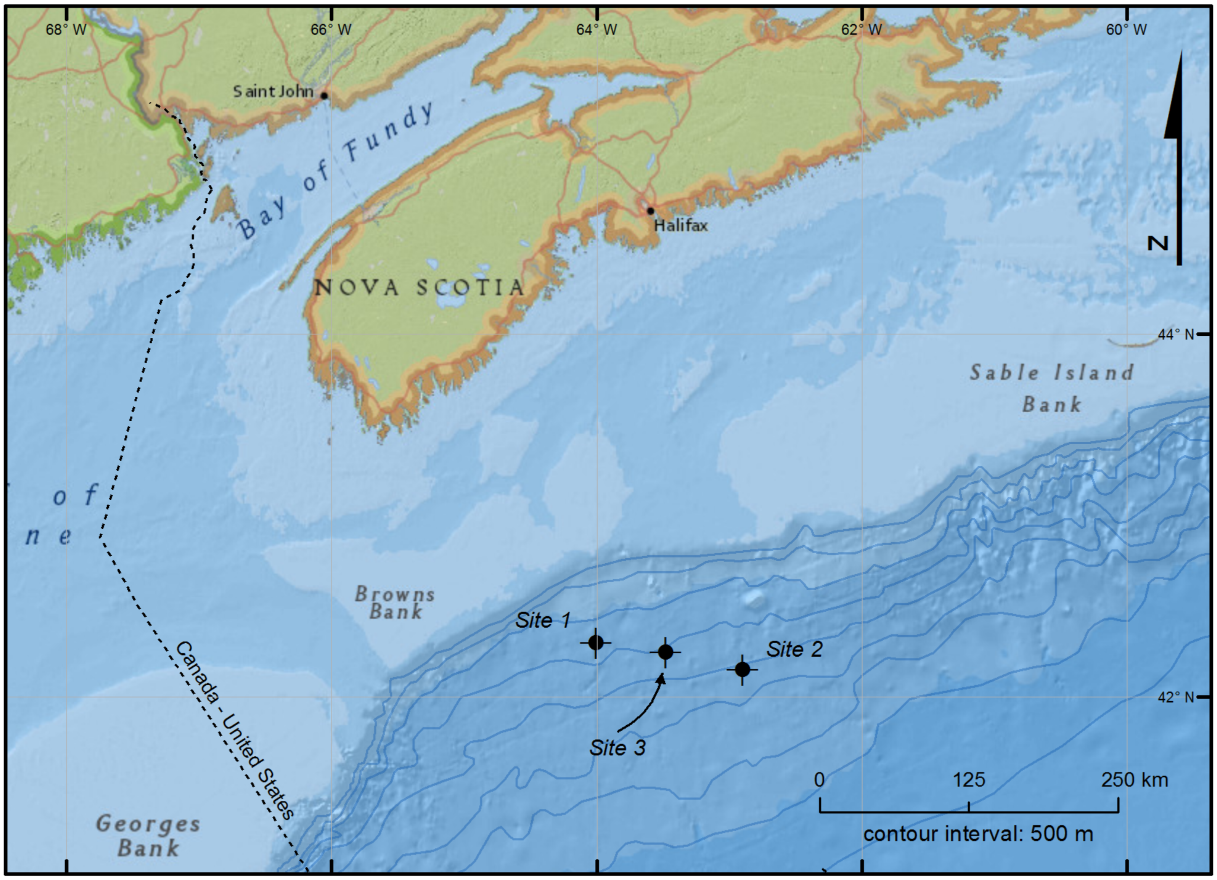


Figure 2. Map of the sites used for dispersion modelling. Dashed line shows the maritime boundary between Canada (East) and the United States (West).

2.2 REGIONAL CIRCULATION

Circulation off the coast of Nova Scotia is influenced by several major currents, including the Labrador Current and the Gulf Stream. The drilling project area is near the juncture of these features in the North Atlantic (Figure 3).

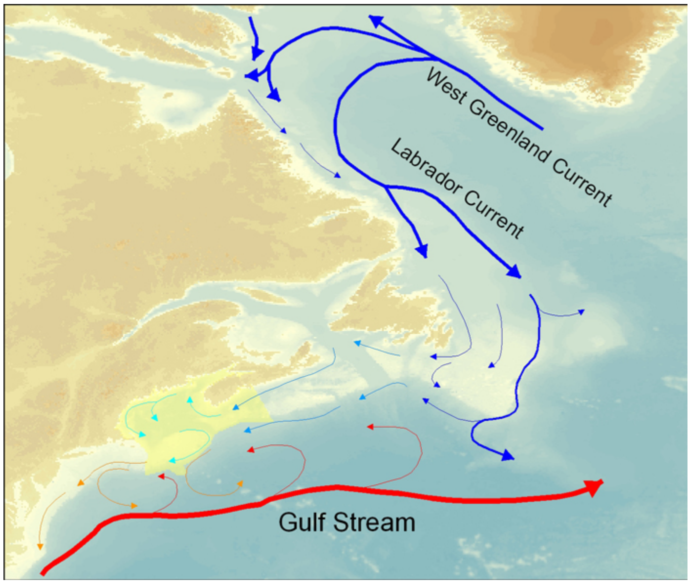


Figure 3. Schematic of of major currents in the Northeast Atlantic. Currents are colour coded for temperature, with red representing warmer currents and blue for colder currents. The Gulf of Maine region is indicated with yellow shading (Source: GoM census).

The Gulf Stream is a western boundary current that forms the western boundary of the North Atlantic subtropical gyre. It transports a significant amount of warm water poleward, with average speeds of about 1.7 m/s, and peak values greater than 2 m/s. The current slows to around 0.4 - 0.5 m/s as it widens to the north. The width of the Gulf Stream is about 100-200 km wide as at flows along the eastern coast of the United States (Johns, 1995). The Gulf Stream is a continuation of the Florida Current, which is fed by the Loop Current and Antilles Current. The position of the Gulf Stream varies seasonally, with a more northern position in the fall and shifting south during winter and early spring (Figure 4). The range of meridional variation is relatively small (30-40 km), however, recent studies have suggested that this range may be closer to 100 km (Mariano, 2002). The Gulf Stream transport varies in phase with the seasonal north-south fluctuations. The maximum amount of water transported north occurs in the fall, with peak-to-peak amplitude in sea surface height of 10-15 cm (Gyory, 2013). These fluctuations are mostly confined to the upper 200-300 m of the water. The meandering and transport of the Gulf Stream intensifies downstream of Cape Hatteras and reaches a maximum near 65°W (Hogg, 1995). Upon reaching the Grand Banks, the structure of the Gulf Stream changes from a single front, to multiple branching fronts. One branch flows northward along the continental slope, eventually turning east and becoming the North Atlantic Current, while the other branch flows southeastward known as the Azores Current. When the Gulf Stream encounters the cold water of the Labrador Current, principally in the vicinity of the Grand Banks, there is little mixing of the waters. Instead, the juncture is marked by a sharp contrast in temperature and is called the cold wall (NIMA, 2013) (Figure 3).

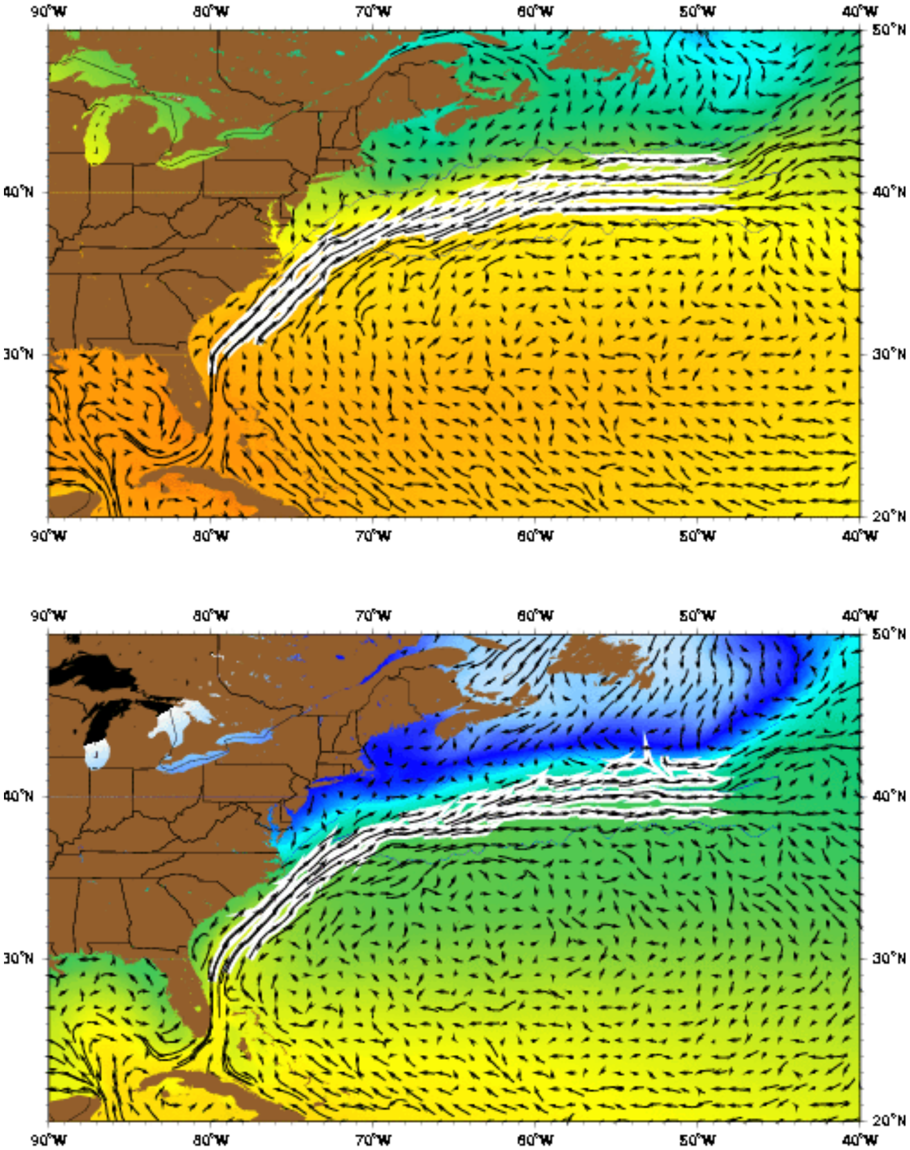


Figure 4. Gulf Stream seasonal circulation. Summer (top) and winter (bottom) (Source: Gyory, 2013).

The Labrador Current flows southeastward from Hudson Strait (60°N) along the continental slope to the Tail of the Grand Banks, around 43°N (Figure 5). The current is a continuation of the Baffin Island Current, which transports both the cold and relatively low salinity waters from Baffin Bay, and the warmer and more saline waters from a branch of the West Greenland Current (Lazier, 1993). The Labrador Current is the southward component of the North Atlantic subpolar gyre and transports cold water into the warmer Gulf Stream region. The Labrador Current has speeds of about 0.3 – 0.5 m/s along the shelf edge (Reynaud, 1995). The current exhibits some seasonal variation in speed in the upper 400 metres of the water column. The minima occur during March-April, while the maxima are typically in late fall. This is thought to be due to buoyancy forcing rather than wind forcing (Lazier, 1993). The large salinity variations induced by the additional freshwater transport from the north in spring and summer, which is largely confined to the waters over the shelf, contributes to the seasonality. Lazier (1993) revealed that there are two regimes in the Labrador Current. The first lies on the shelf and upper-slope, which is the main Labrador Current that was previously discussed. The second regime, referred to as the deep Labrador Current, is seaward of the shelf and lies over the lower continental slope around the 2500 m isobath. This is a more barotropic flow that exhibits a different annual cycle than the main current. The minimum speed appears in summer and the maximum in winter (Lazier, 1993).

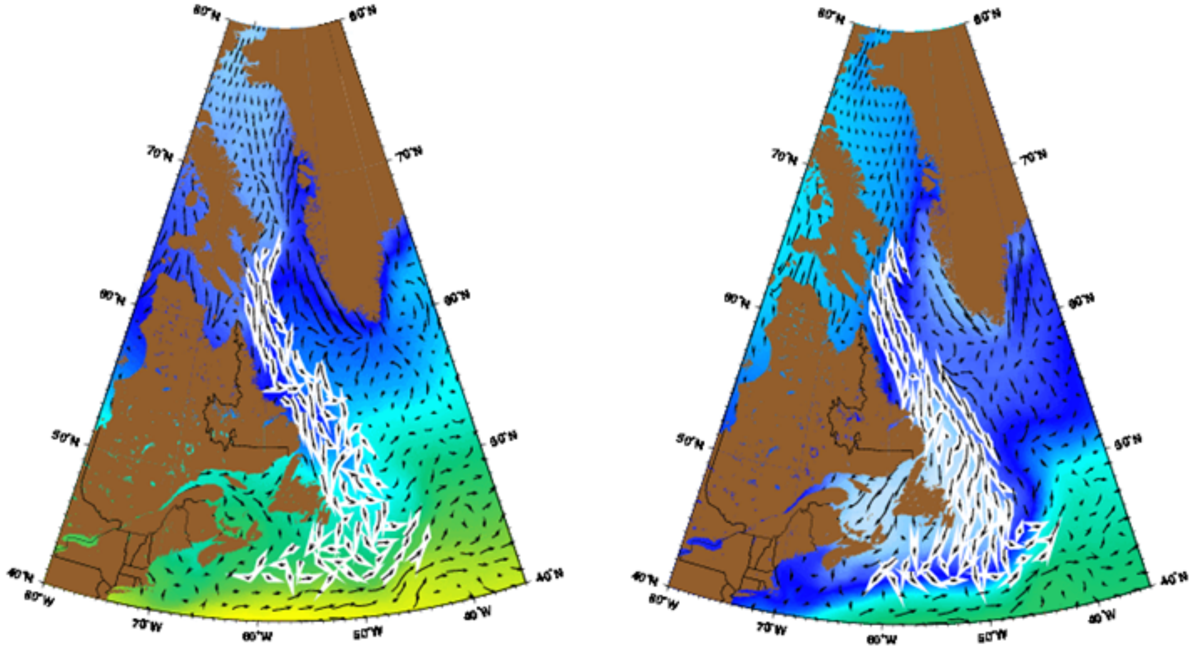


Figure 5. Labrador Current during summer (left) and winter (right) (Source: Gyory, 2013).

The surface flow into the Gulf of Maine is fed primarily by the cold, deep Labrador Current that enters along the Scotian Shelf and Northeast Channel to the south of Nova Scotia. This current helps drive the predominantly counterclockwise circulation in the Gulf of Maine. The circulation in the Gulf is characterized by several cyclonic gyres, with limbs that flow toward and around Georges Bank, although the intermediate and deep circulation generally is isolated the Bank (Figure 6) (Lynch, 1998). The Scotian Shelf's location is in a transition zone for several key forcings: it is downstream of the North Atlantic's subpolar western boundary current, has slope water intrusions that contribute to pronounced along-shelf variations in hydrographic properties, and is near the entrance to the tidal system of the Bay of Fundy and Gulf of Maine (Hannah, 2001). The southwestward flow along the Nova Scotia shelf edge and upper continental slope varies seasonally, with a stronger transport in winter and weaker transport in summer (Figure 7). Off the western Scotian Shelf, there are further fluctuations that involve a reduced westward extent of the slope water gyre in winter, spring, and summer (Hannah, 2001).

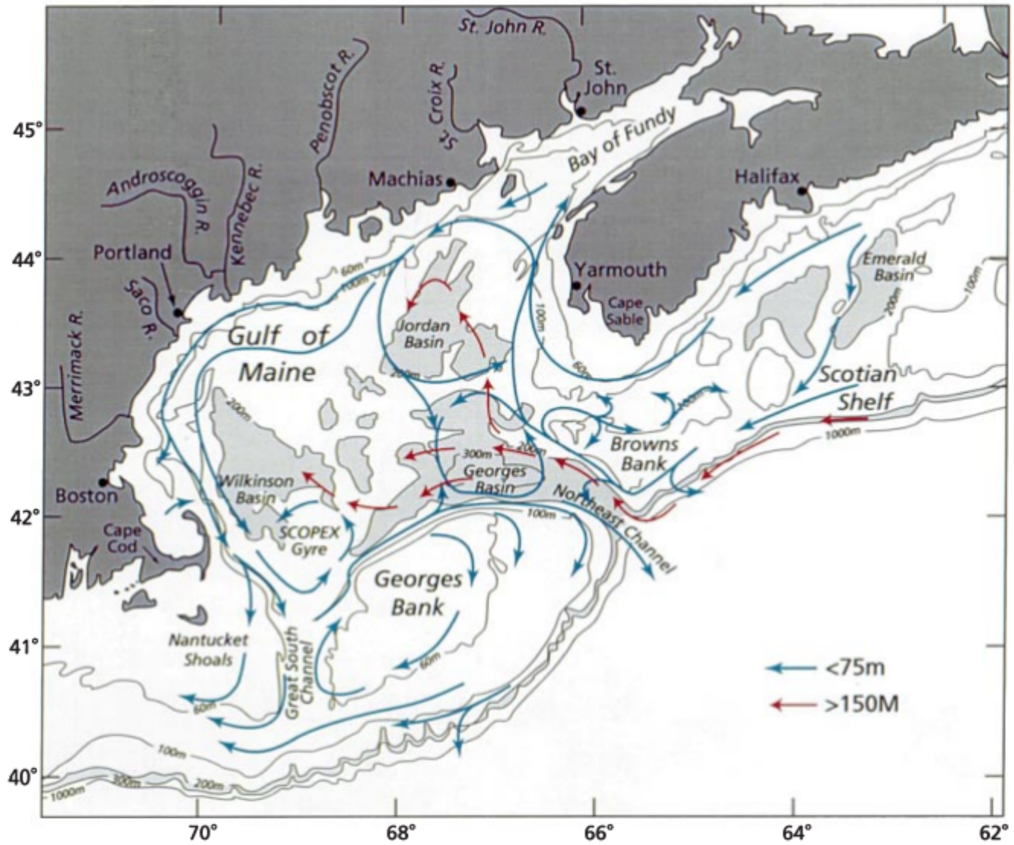


Figure 6. Typical water circulation in the spring along the Scotian Shelf and in the Gulf of Maine (Source: Miller, 1998).

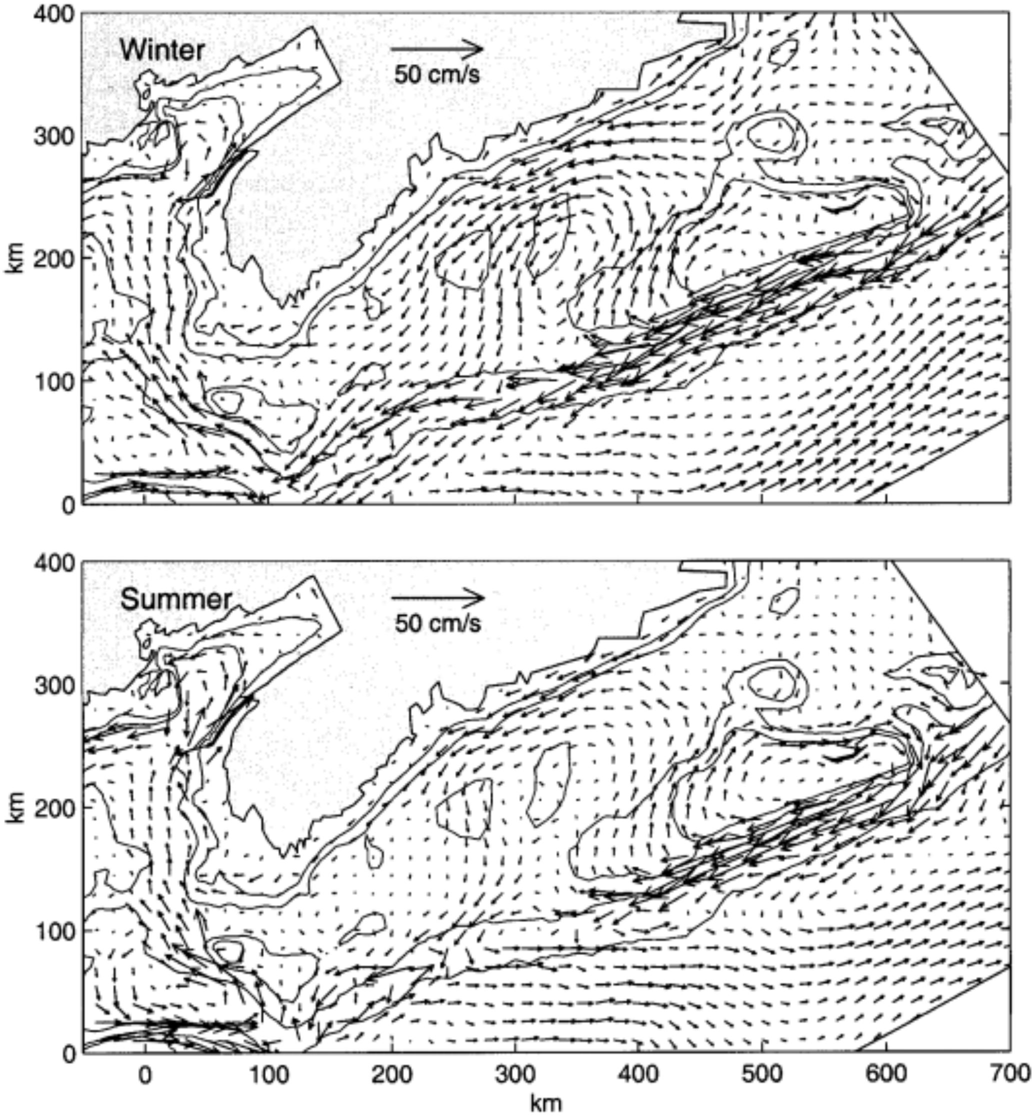


Figure 7. Seasonal-mean model velocities over the Scotian Shelf, averaged between 20-50 m below the surface for winter (top) and summer (bottom) (Source: Hannah, 2001).

The highest tides on earth occur in the Gulf of Maine, ranging as much as 16 m in the easternmost reaches of the Bay of Fundy. The currents created by these tides keep waters well mixed, thus increasing available nutrients and productivity. The currents in the Gulf of Maine are influenced by fluctuations in river outflow, which are often enhanced during spring runoff. The St. John River flows approximately 418 miles where it discharges at a rate of 990 m^3/s into the Bay of Fundy (GoMA, 2013).

2.3 OCEAN CURRENTS DATASET

Currents are one of the most significant environmental forces for the trajectory and fate of drilling discharges. To simulate oceanic circulation in the project area, vertically and time varied currents from the HYbrid Coordinate Ocean Model (HYCOM; Bleck, 2002) produced by the United States Navy were used in combination with TPXO8.0 tidal forcing. An overview of each dataset is provided below.

Tidal Currents – TOPEX/Poseidon Global Inverse Solution (TPXO)

Depth averaged tidal currents for the dispersion simulations were derived using the Oregon State University TOPEX/Poseidon Global Inverse Solution TPXO, a global model of ocean tides (Egbert and Erofeeva, 2014). The latest version (TPXO8.0) utilizes a least-squares best-fit of the Laplace Tidal Equations, as well as along track averaged data from TOPEX/Poseidon and Jason (on TOPEX/POSEIDON tracks since 2002) obtained with OSU Tidal Inversion Software (OTIS). A full description of the methods used to compute the model are described in details by Egbert, Bennett, and Foreman, 1994 and Egbert and Erofeeva, 2002. Each successive version of the TPXO model improves upon the last, based upon utilization of longer satellite time series, more data sites to integrate, improved bathymetry, and improved grid resolution of global and local grids. The tides are provided as complex amplitudes of earth-relative sea-surface elevation for eight primary (M2, S2, N2, K2, K1, O1, P1, Q1), two long period (Mf, Mm), and 3 non-linear (M4, MS4, MN4) harmonic constituents. The TPXO solution is provided on a 1440x721, ¼ degree by ¼ degree resolution full global grid. Tidal forcing is stored as a harmonic constant. Therefore, daily HYCOM files are augmented by adding the tidal forcing at the resolution of the model time step, which was 30 minutes. Therefore, hydrodynamic forcing was supplied at 30 minute intervals throughout the modeled time series.

Regional Circulation – HYCOM Global Simulation

HYCOM is a primitive equation, general circulation model. The vertical coordinates are isopycnal in the open, stratified ocean, but use the layered continuity equation to make a dynamically smooth transition to terrain-following coordinates in shallow coastal regions, and to z-level coordinates in the mixed layer and/or unstratified seas. The hybrid coordinate extends the geographic range of applicability of traditional isopycnic coordinate circulation models toward shallow coastal seas and unstratified parts of the world ocean. It maintains the significant advantages of an isopycnal model in stratified regions while allowing more vertical resolution near the surface and in shallow coastal areas, hence providing a better representation of the upper ocean physics. HYCOM is designed to provide a major advance over the existing operational global ocean prediction systems, since it overcomes design limitations of the present systems as well as limitations in vertical and horizontal resolution. The result should be a more streamlined system with improved performance and an extended range of applicability (e.g., the present systems are seriously limited in shallow water and in handling the transition from deep to shallow water).

Global HYCOM with 1/12° horizontal resolution at the equator (~7 km at mid-latitudes) is the ocean model component of an eddy-resolving operational nowcast/forecast system. The model provides nowcasts and forecasts of the three-dimensional global ocean environment. HYCOM is initially delivered with a thermodynamic “energy loan” ice model, but later will be coupled to the Polar Ice Prediction System 3.0 via the Earth System Modeling Framework (ESMF). Coupling between the ocean and ice models will more properly account for the momentum, heat and salt fluxes at the ocean/ice interface. The final component of the nowcast/forecast system is the Navy Coupled Ocean Data Assimilation (NCODA) which is a multivariate optimal interpolation scheme that will be used to assimilate surface observations from satellites, including altimeter and Multi-Channel Sea Surface Temperature (MCSST) data, sea ice concentration and profile data such as XBTs (expendable bathythermographs), CTDs (conductivity temperature depth) and ARGO floats (Cummings, 2005). By combining these observations via data assimilation and using the dynamical interpolation skill of the model, the three-dimensional ocean state can be more accurately nowcast and forecast. Data is available at daily resolution for the 5 year run between 2008 and 2013 (e.g. Figure 8).

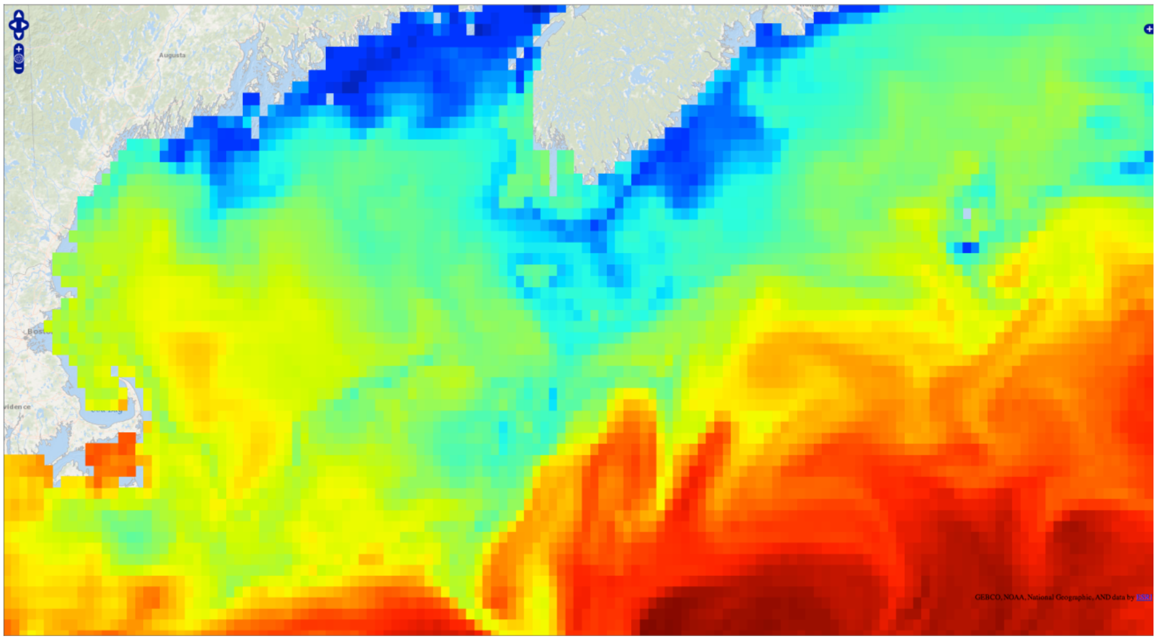


Figure 8. An example HYCOM current field in the North Atlantic for a given daily snapshot.

At each of the discharge modelling sites, daily HYCOM currents were obtained by interpolating the values from the nearest model grid points. At the model cell closest to Site 1, the water column is represented in 26 discrete vertical layers; at Sites 2 and 3, the HYCOM model contains 27 vertical layers. Summary statistics from the hydrodynamic inputs are discussed further below, although it is worth noting that the flow characteristics for each site are quite similar.

Vertical profiles derived from the nearest HYCOM grid points show the average magnitude of currents with depth at each location (Figure 9 through Figure 11). Surface currents in the region of moderate speed (20-30 cm/s) although currents greater than 60 cm/s do occur approximately 5% of the time. This range of flow speeds is comparable to measurements of the Labrador Current along the shelf edge (Reynaud, 1995). Current intensity decreases rapidly with depth in the water column and average HYCOM speeds drop to approximately 10 cm/s by 400 metres depth. Current roses showing the statistical distribution of modelled currents (by depth interval) indicate directionally variable currents at the surface, which become strongly oriented to the west and southwest at depth. At all three sites, currents near the seabed are extremely weak (average speeds between 4-5 cm/s).

When viewed as monthly averages, statistics from the HYCOM dataset also reflect seasonal variability in current speeds, particularly in the upper water column as noted above (Figure 12 through Figure 14). Surface velocities during the boreal fall (Oct—Dec) are approximately 15%-20% faster than those during spring months. The strongest surface currents (>30 cm/s, on average) occur between November and February and the slowest (~25 cm/s) between April and June. Monthly current roses (Figure 15 through Figure 17) also indicate stronger currents with more westerly distribution during the late fall and winter months. By contrast, subsurface currents below 400 m experience flow minima during the late summer (Figure 12 through Figure 14).

Figure 17 through Figure 19 present time series (stick plots) of current vectors for the complete HYCOM model period at Sites 1, 2, and 3 respectively. The highly variable currents at the surface, and interannual fluctuations in flow intensity represented in the model emphasize the complex spatial and temporal circulation patterns in the region, which are not fully captured in a regional flow schematic (e.g. Figure 3). The seasonal variability in currents are regular and repeatable features for all years in the time series and the dataset maintains these oscillations for depths above 150 m. At both locations, current directions become more consistent with depth and net westerly/south-westerly flow in the model becomes apparent at depths below 500 m. Bottom currents at all sites are characterized by generally weak, westerly oriented currents that persists year-round.

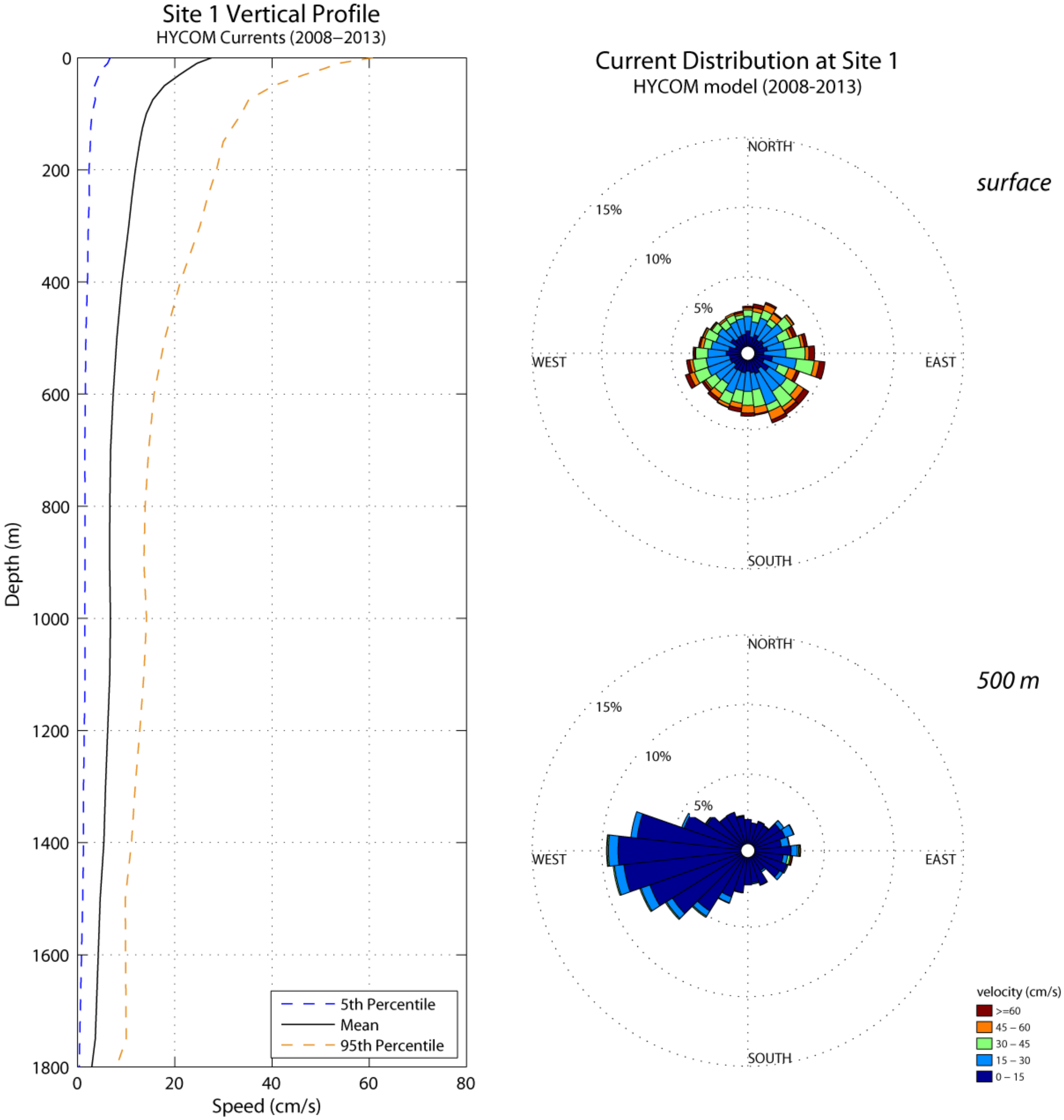


Figure 9. Vertical profile (left) and current roses showing the distribution of current speeds (right) for Site 1, derived from HYCOM model currents between 2008 and 2013.

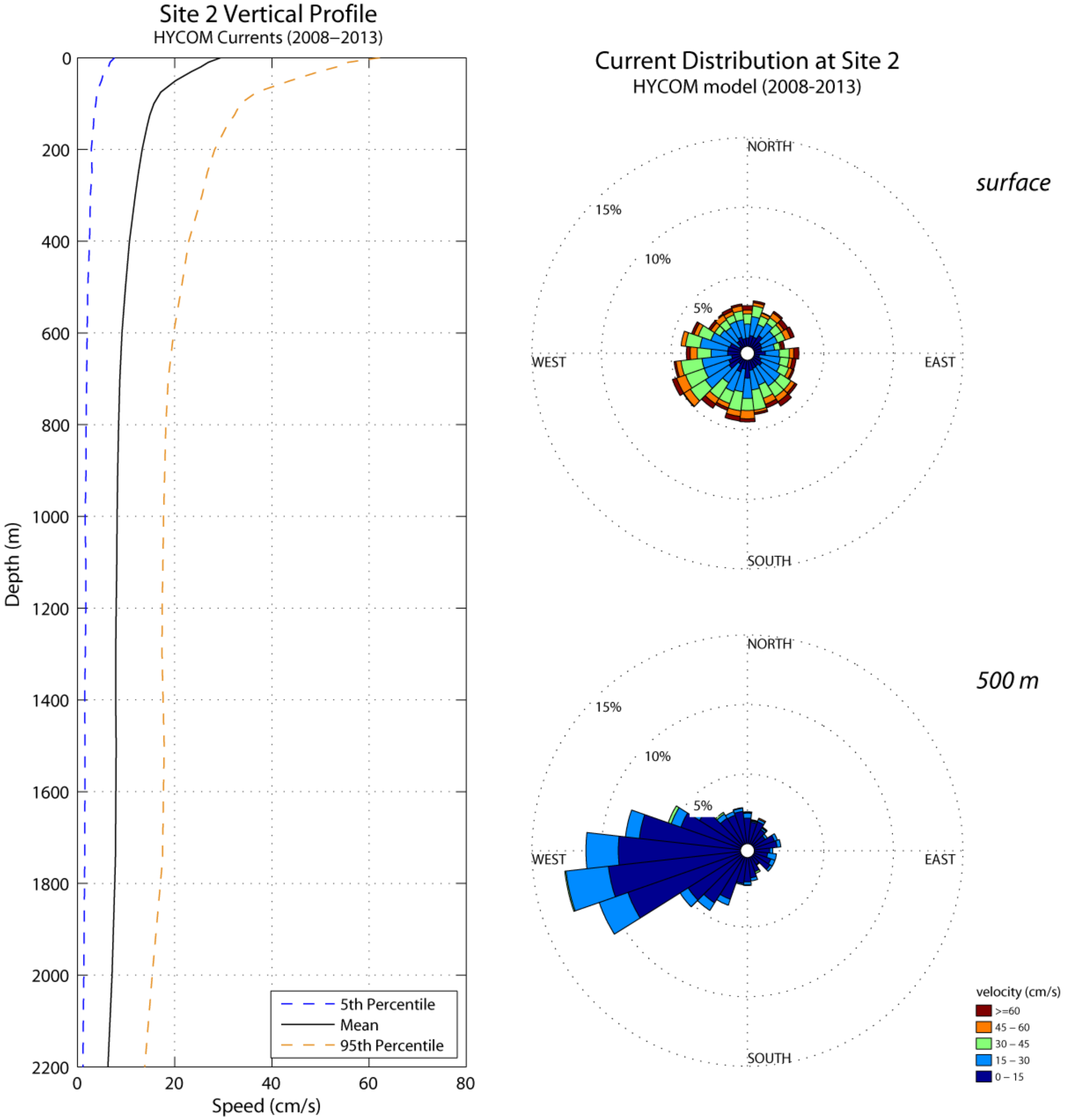


Figure 10. Vertical profile (left) and current roses showing the distribution of current speeds (right) for Site 2, derived from HYCOM model currents between 2008 and 2013.

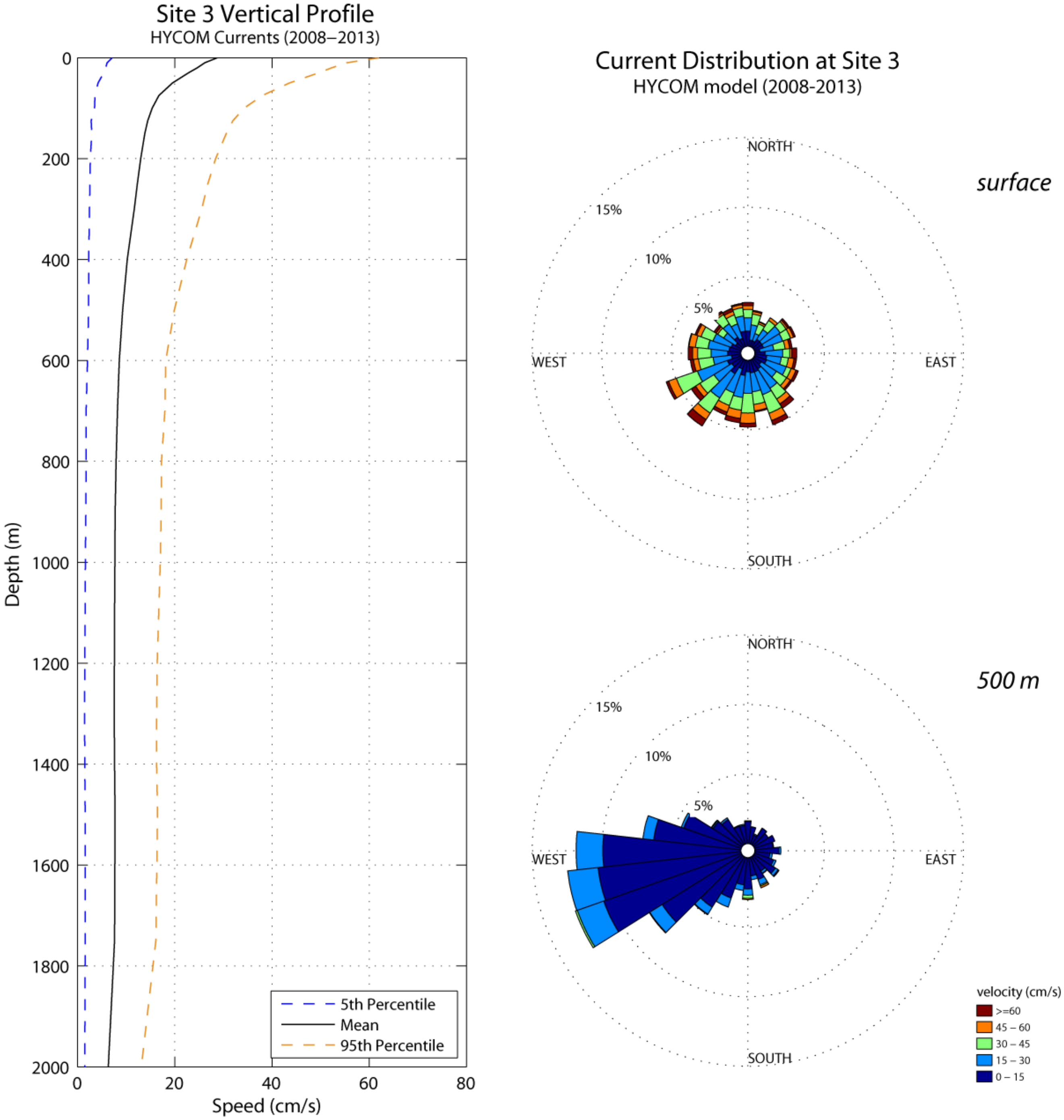
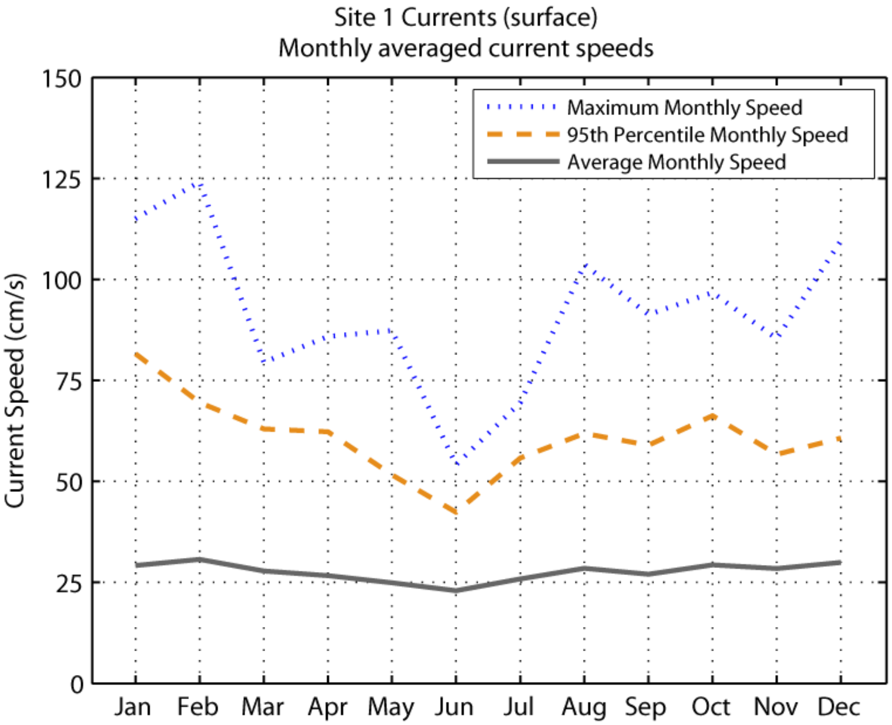


Figure 11. Vertical profile (left) and current roses showing the distribution of current speeds (right) for the Site 3, derived from HYCOM model currents between 2008 and 2013.



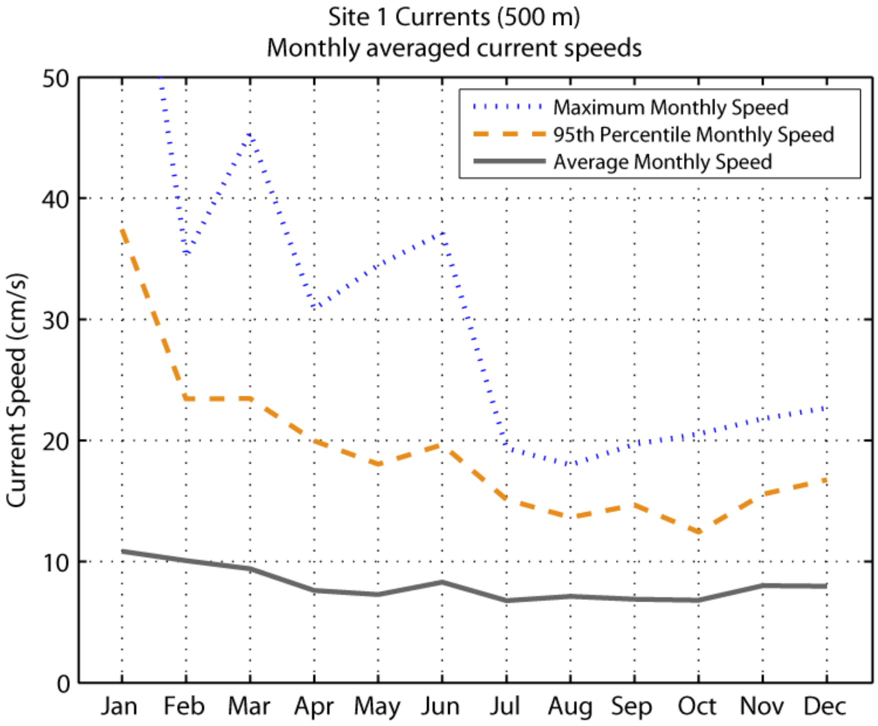
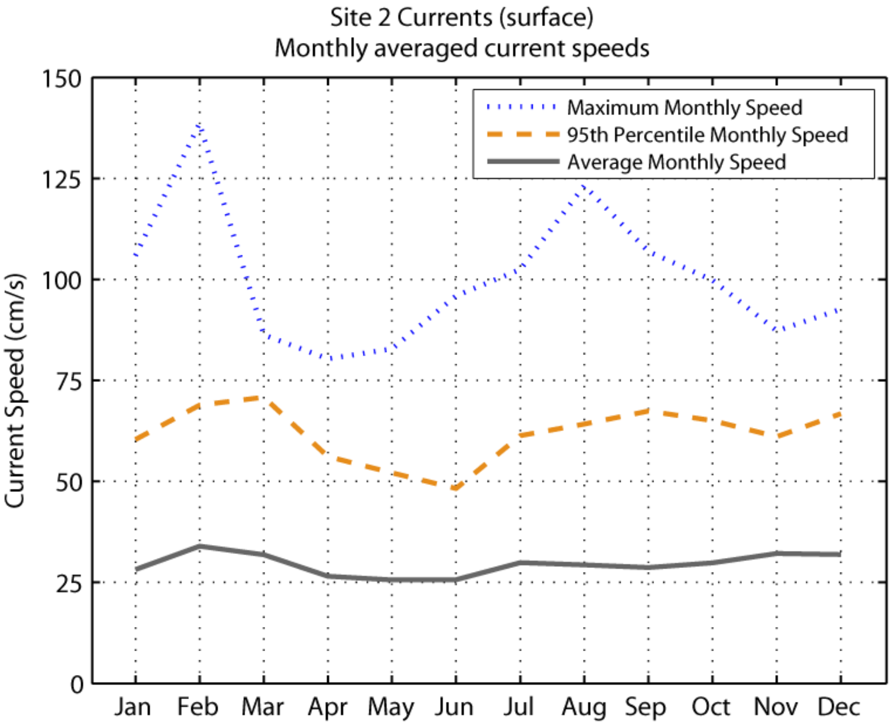


Figure 12. Monthly averaged current speeds at Site 1 derived from the HYCOM global dataset. Average current speeds are shown for the surface (top figure) and 500 m (bottom figure) water depths.



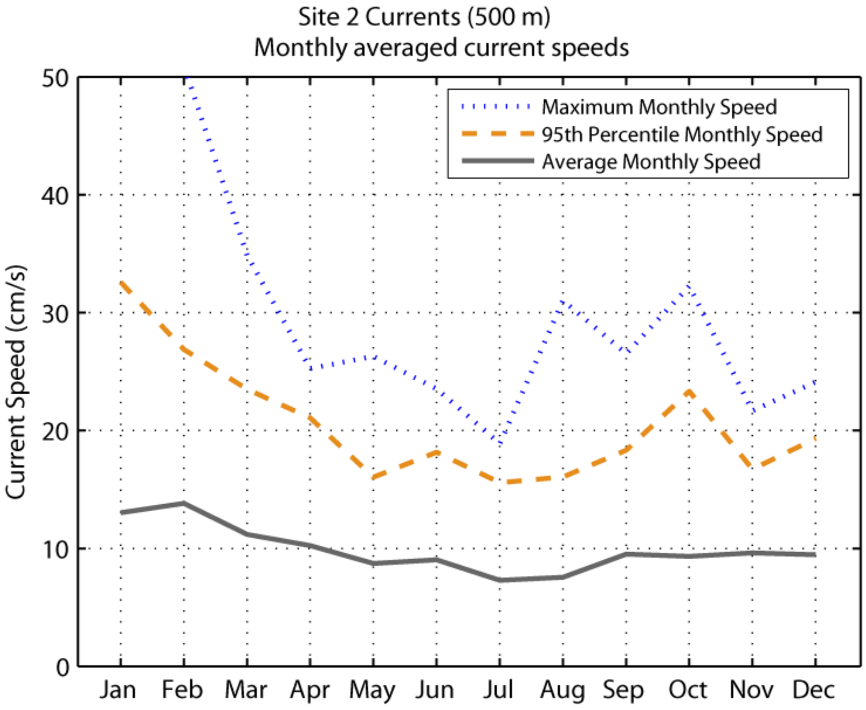
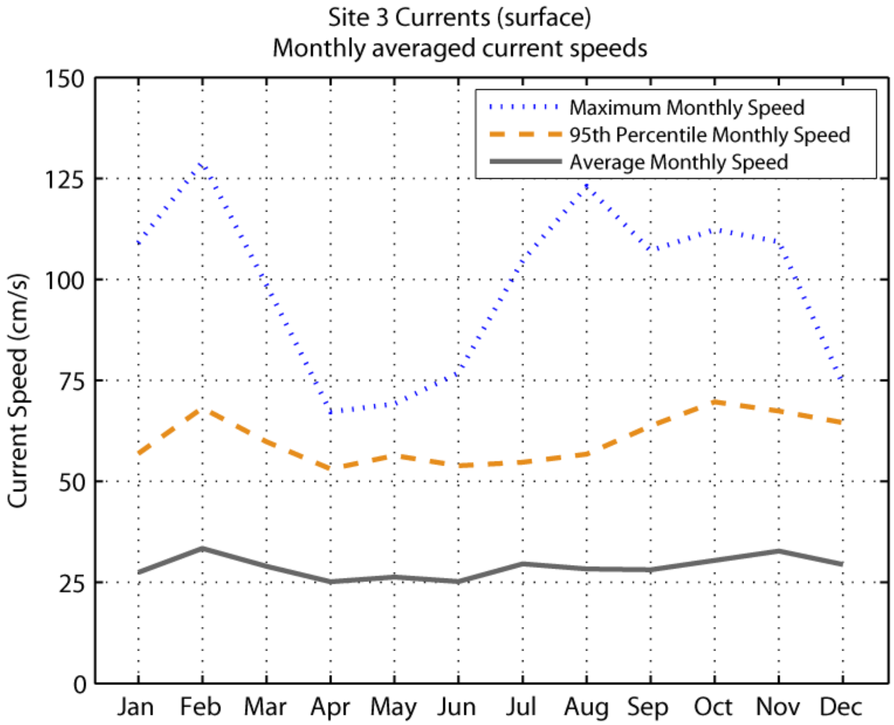


Figure 13. Monthly averaged current speeds at Site 2 derived from the HYCOM global dataset. Average current speeds are shown for the surface (top figure) and 500 m (bottom figure) water depths.



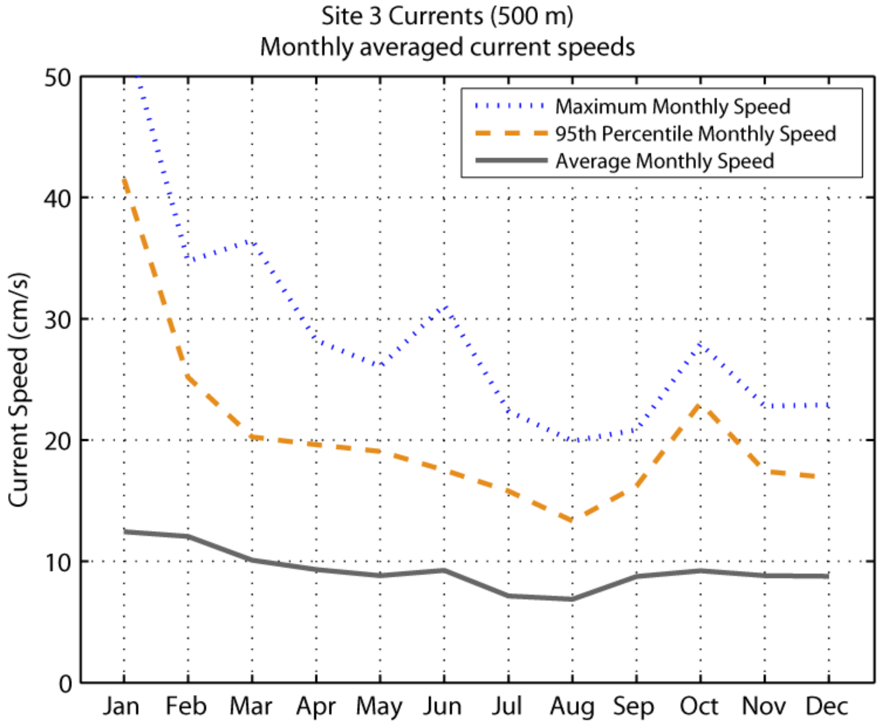


Figure 14. Monthly averaged current speeds at Site 3 derived from the HYCOM global dataset. Average current speeds are shown for the surface (top figure) and 500 m (bottom figure) water depths.

Figure 15. Current roses showing the distribution of surface currents (speed and direction) by month at Site 1, derived from HYCOM model currents between 2008 and 2013.

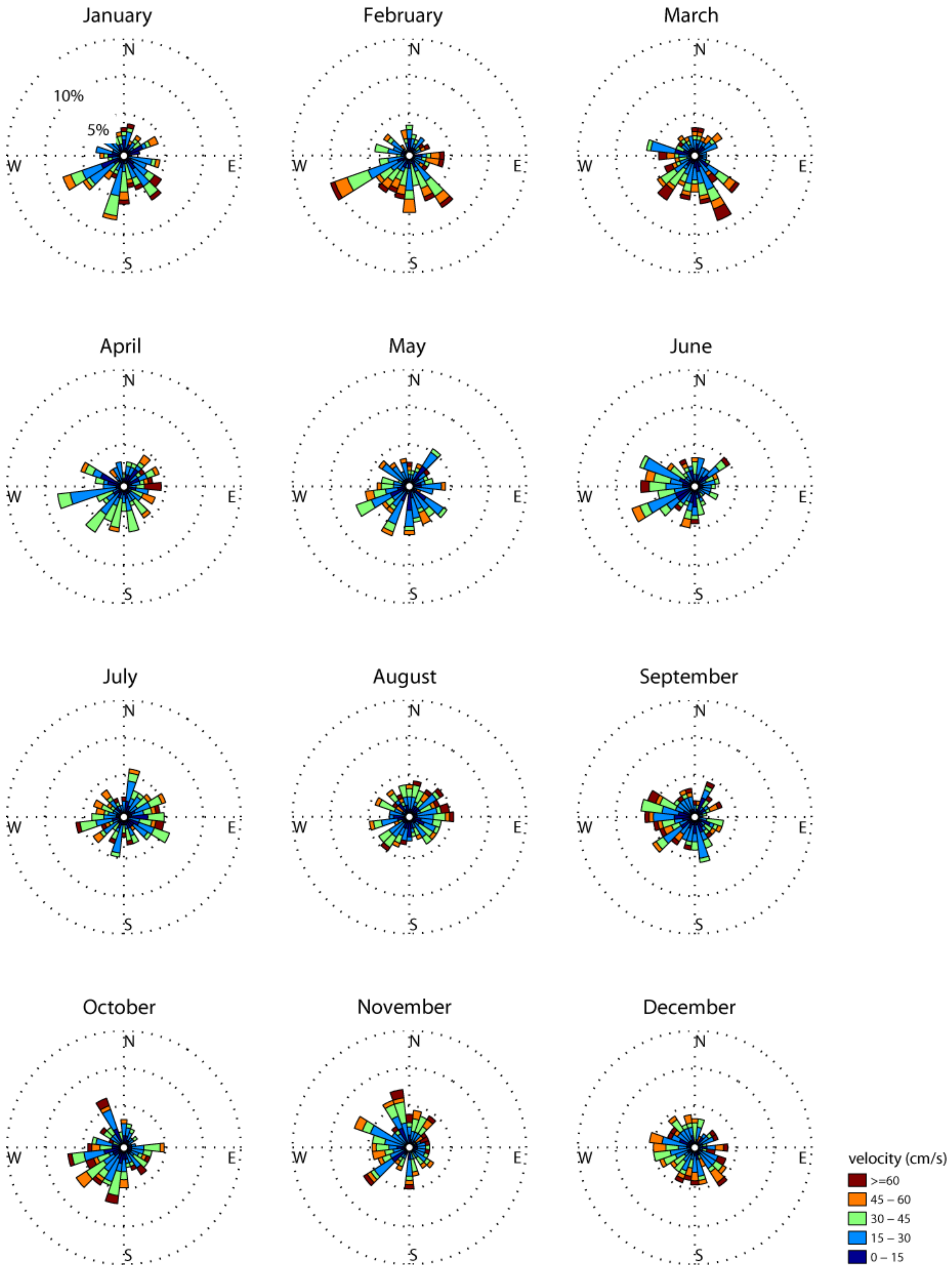


Figure 16. Current roses showing the distribution of surface currents (speed and direction) by month at Site 2, derived from HYCOM model currents between 2008 and 2013.

Figure 17. Current roses showing the distribution of surface currents (speed and direction) by month at Site 3, derived from HYCOM model currents between 2008 and 2013.

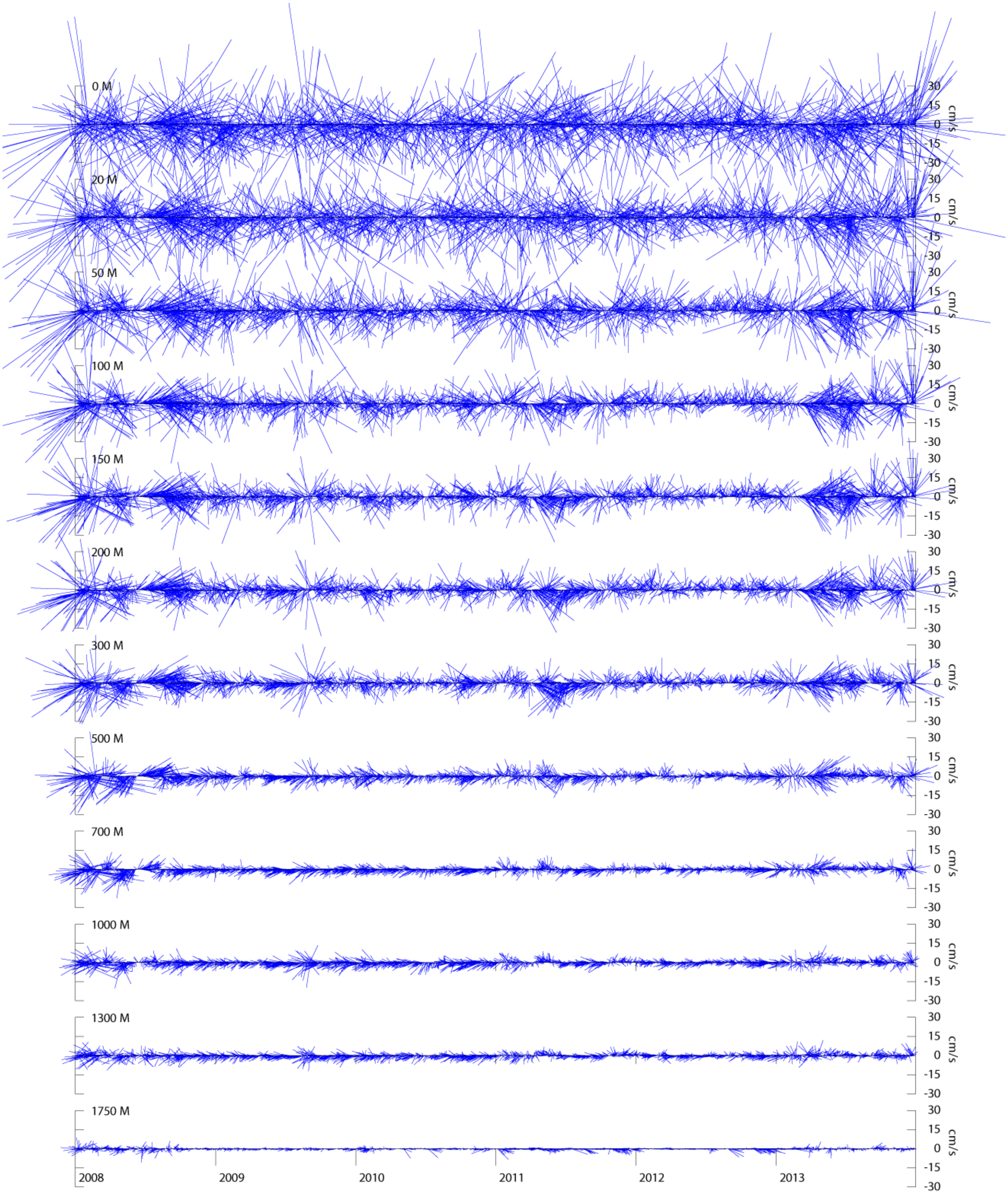


Figure 18. Time series of HYCOM model currents with depth at Site 1.

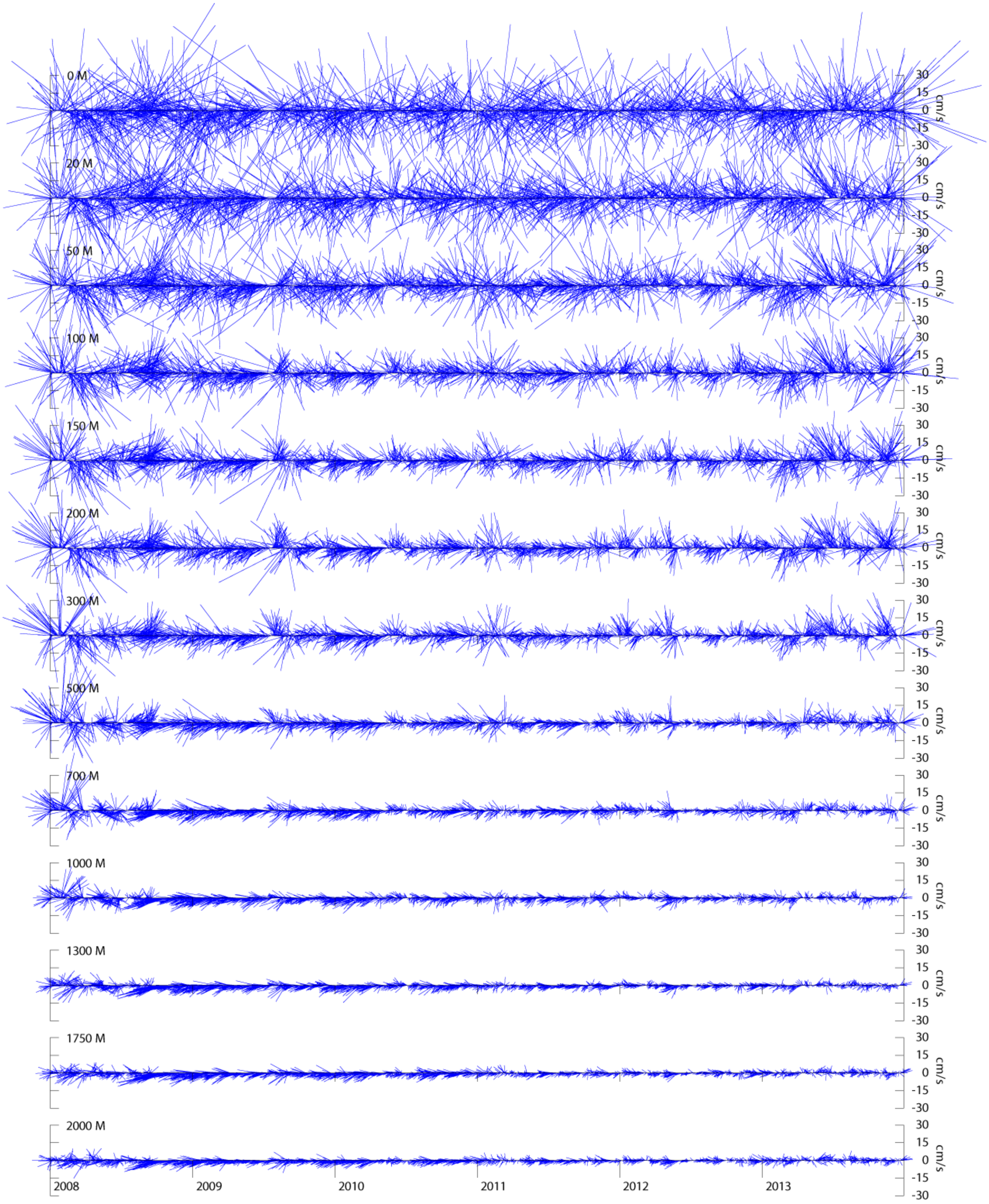


Figure 19. Time series of HYCOM model currents with depth at Site 2.

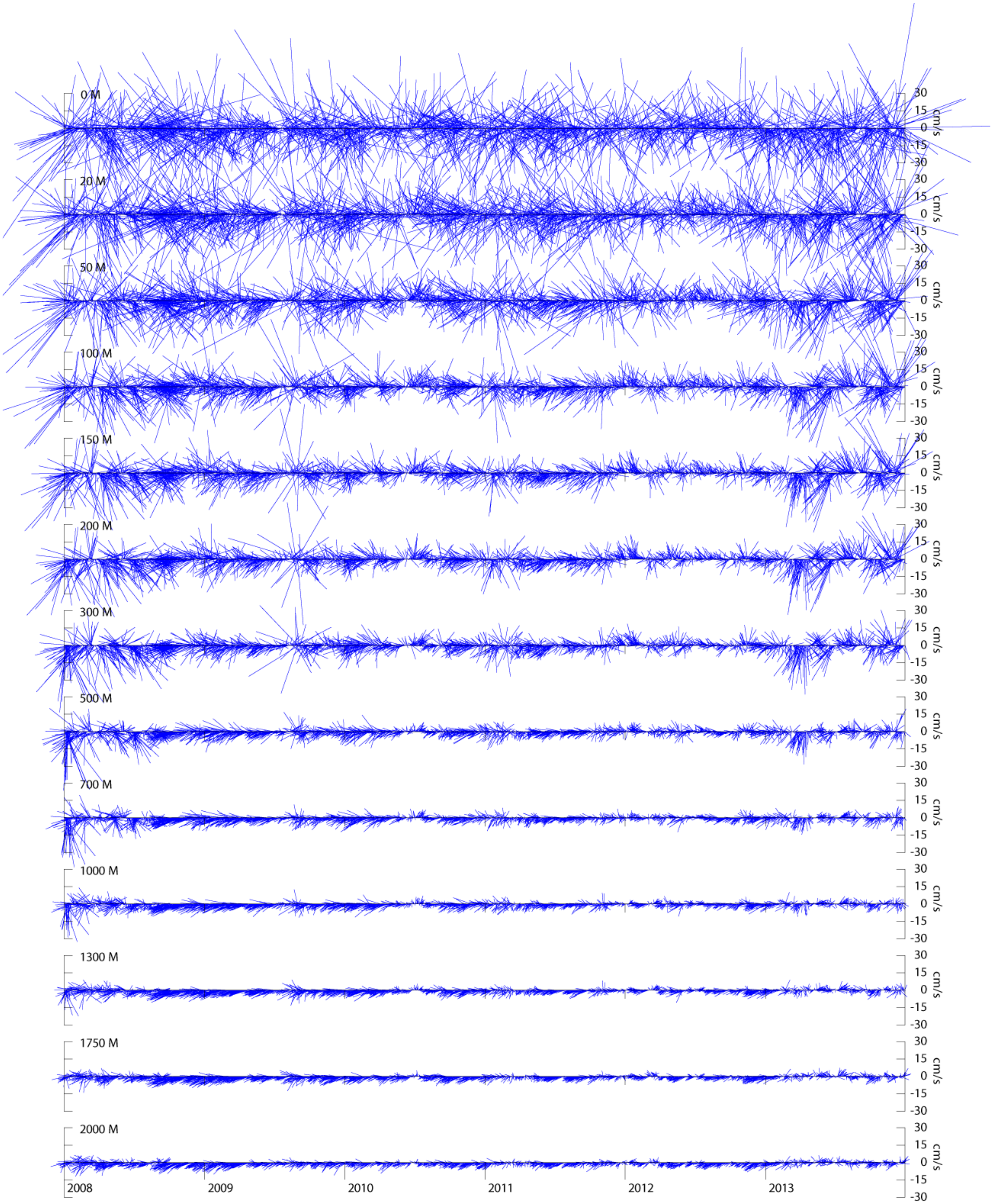


Figure 20. Time series of HYCOM model currents with depth at Site 3.

3 DRILLING DISCHARGES AND ACCIDENTAL RELEASE SIMULATIONS

The following section describes the model used for simulating operational drilling discharges and accidental releases of drilling fluids. Operational drilling discharges refers to waste materials and by-products of drilling that are often released directly to the marine environment, including drill cuttings and spent drilling muds. Because drilling is typically performed in different intervals (sections) reflecting differences in operational parameters (drilling diameters), the discharge schedule may vary as a function of drilling rate, cuttings and mud volumes, or depth of release in the water column (near-surface or near-seabed typically). The analysis presented evaluates variations in seabed deposition for a single discharge program released over two different time periods (a total of two deterministic model scenarios). Additionally the model is used to simulate the two accidental release scenarios of synthetic based mud (SBM) at two locations (four deterministic model scenarios) and predict impacts associated with these scenarios. .

3.1 MUDMAP DISPERSION MODEL

Drilling discharges simulations were completed using ASA's MUDMAP modelling system (Spaulding et al., 1994). MUDMAP is a numerical model developed by ASA to predict the near and far field transport, dispersion, and bottom deposition of drilling mud and cuttings. In MUDMAP, the equations governing conservation of mass, momentum, buoyancy, and solid particle flux are formulated using integral plume theory and then solved using a Runge Kutta numerical integration technique. The model includes three stages: convective descent/ascent, dynamic collapse, and far field dispersion. It allows the transport and dispersion of the release to be modelled through all stages of its movement. The initial dilution and vertical spreading of the release is predicted in the convective descent/ascent process. The far field process predicts the transport and dispersion of the release caused by the ambient current and turbulence fields. In the dynamic collapse process, the release impacts the surface or bottom, or becomes trapped by vertical density gradients in the water column.

The model output consists of definition of the movement and shape of the discharge plume, the concentrations of insoluble (i.e., cuttings and mud) discharge components in the water column, and the accumulation of discharged solids on the seabed. The model predicts the transport of discharged solids from the time of discharge or release to initial settling on the seabed. MUDMAP does not account for resuspension and transport of previously discharged solids; therefore it provides a conservative estimate of the potential seafloor depositions. The far field and passive diffusion stage is based on a particle based random walk model. More details about MUDMAP are included in Appendix A.

3.2 MODEL INPUTS – OPERATIONAL DISCHARGE SCHEDULE

Dispersion modelling was completed to evaluate seabed deposition resulting from operational discharges at a representative site (Site 3) within the Exploration Drilling Project Area. Based on volumes of cuttings and mud provided by Shell, the drilling program is expected to consist of eight sections. The first three sections (riserless) will be drilled using seawater (section1) and water-based mud (WBM; sections 2-3), while the intermediate and main well hole (riser in place) will require the use of SBM. The discharge schedule provided by Shell is shown in Table 2 and consists of the release of 1,469 m^3 of cuttings and 21,031 m^3 of drilling fluids over the duration of the drilling campaign (88 days).

During the riserless phase of drilling (sections 1-3), all cuttings and WBM are expected to be released directly at the seabed (5 m above the wellhead on the seafloor). Subsequent sections will be drilled using 13.0 ppg Rheliant SBM, and returned to the surface for treatment. Treated cuttings will be discharged near the surface from the drilling unit. The direct release of bulk SBM is not expected to occur during exploratory drilling although for modelling it was presumed that a small fraction of the drilling fluid would remain adhered to cuttings drilled with SBM (approximately 6.9% of the discharged cuttings volume). The release of these combined surface returns (cutting and adhered SBM) was simulated from a depth of 2 metres below the sea surface at a continuous discharge rate. The release of the remaining drilling fluids from sections 4 through 8 was not simulated as part of the operational discharge schedule as it is expected that SBM used for drilling will be recycled and eventually transported onshore for disposal.

Table 2. Drilling discharges program used for model simulations at Site 3.

Section	**Diameter (in)**	**Cuttings Volume (m^3)**	**Mud Volume (m^3)**	**Mud Type**	**Drilling Start Date**		**Drilling Duration (days)**	**Release Rate**	**Release Depth[1]**
1	36	68	–	Seawater	1-Apr	1-Oct	2	continuous	seabed
2	32	487	8745	WBM	3-Apr	3-Oct	3	continuous	seabed
3	26	292	12243	WBM	6-Apr	6-Oct	3	continuous	seabed
4	22	164	11	SBM	9-Apr	9-Oct	16	continuous	sea surface
5	20	82	6	SBM	25-Apr	25-Oct	16	continuous	sea surface
6	17.5	166	11	SBM	11-May	10-Nov	16	continuous	sea surface
7	13.5	84	6	SBM	27-May	26-Nov	16	continuous	sea surface
8	11.7	126	9	SBM	12-Jun	12-Dec	16	continuous	sea surface
Total Discharges		**1,469**	**21,031**						

[1] releases simulated at 5 m above the seabed and 2 m below the sea surface

Because currents are the main driving force for the transport and dispersion of discharged drilling muds and cuttings in the water column, seasonal, annual, or interannual variability in ocean currents will influence the fate and trajectory of discharged material. Analysis of hydrodynamic model data (Section 2.3) suggests that currents in the region are complex, and exhibits seasonal flow patterns. Because the drilling schedule is currently unknown and will depend on the rig availability and regulatory approvals, a modelling strategy was developed to compare the results of different flow conditions that characterize the potential range of release periods at Site 3. Seasonal differences in the current field were represented by simulating releases during the late spring, and again in the late fall -- periods that correspond to current minima/maxima in both modelling and observational studies. Operational drilling releases were simulated to begin on April 1, a period characterized by relatively weak and directionally variable surface currents. An additional model of the same duration was then run with discharges beginning on October 1, a period characterized by slightly stronger currents in the upper water column. For both periods, subsurface currents (below 500 m) are consistently weak and directed west of the release site.

In total, two (2) deterministic drilling discharge scenarios were performed using the MUDMAP dispersion model to represent the discharge program shown in Table 2, simulated at different times of the year. For both scenarios, vertically and time varied currents derived from HYCOM for a representative period (2012-2013) were used as the primary environmental forcing.

3.3 MODEL INPUTS – ACCIDENTAL SBM RELEASES

In addition to the operational discharges of mud and cuttings, the MUDMAP model was used to simulate accidental releases of synthetic based drilling fluids at both Sites 1 and 2. For each site, two deterministic scenarios were performed (4 total) representing (i) a subsea full riser release of 573 m^3 of SBM associated with the disconnection of the riser at the Blow Out Preventer (BOP), and (ii) a surface release of 60 m^3 of SBM associated with the accidental discharge of a full mud tank from the drilling platform. In all cases, the release of SBM was assumed to occur near-instantaneously (over the course of several minutes).

The formulation for 13.0ppg Rheliant SBM was provided by Shell and is shown in Table 3. To achieve the expected mud density (1558 kg/m^3) and maintain a synthetic/water ratio of 75/25 for the base fluid requires the addition of 4.1 SG barite (M-I Wate) at a concentration of approximately 290 lb/bbl. This formulation equates to approximately 474 Metric Tonnes (MT) of barite for the marine riser release and 50 MT of barite for the sea surface discharge. These approximate masses were used as input to MUDMAP.

Table 3. Composition of SBM used for modelling (data provided by Shell).

Product	Function	Concentration
S/W Ratio		75/25
VG-Plus	Viscosifier	1.5 ppb
VG-Supreme	Viscosifier	0.8 ppb
Lime	Alkalinity Control	3 ppb
Suremul	Emulsifier	7 ppb
Surewet	Wetting Agent	2 ppb
Ecotrol RD	Fluid Loss Control Agent	0.5 ppb
Calcium Chloride (% by wt)		20-25
Rheflat	Rheological Modifier	0.5-2 ppb
Rhethik	Rheological Modifier	0.5 ppb
M-I Wate (4.1SG Barite)	Weighting Agent	As required

3.4 MODEL INPUTS – DISCHARGED SEDIMENT CHARACTERISTICS

To assess the fate of drilling discharges in the marine environment it is critical to characterize the components of the released materials. The composition of the drilling mud applied will depend on the characteristics of the formation and this composition determines the density and weight of the discharged fluid, its toxicity, and the settling velocities of the material released in the water column.

In addition to the composition and density of SBM (described above), the modelling of mud discharges from the riserless phase of drilling also requires the use of a representative WBM fluid composition. The composition (in weight percent) for the various components of a typical WBM is presented below in Table 4. The bulk density of the drilling fluids used for simulations is 1,192.1 kg/m^3. Solid particles occupy 22% of the total mud weight.

Table 4. Composition of WBM used for modelling (NRC, 1983; OGP, 2003; Neff, 2005; Neff, 2010).

Discharged material	Component	Weight %	Specific gravity	Mud bulk density (kg/m^3)	Percent solid by weight
WBM	water	76	1.026	1192.1	22.0
	barite	15	4.48		
	bentonite clay	7	2.5		
	other (salt/additives)	2	0.53		

Particle size data, along with material density, is typically used to calculate settling velocities for MUDMAP simulations. The size distribution of discharged solids varies as a function of the geology, the type of drilling fluid, and the treatment of cuttings. For this study, a representative size distribution (based on published values) was used to characterize the drill cuttings releases from sections 1 and 2 (Table 5). Settling velocities of the WBM used to drill sections 1 and 2 were also based on published values and are described in Table 6. The particle sizes used to represent SBM solids (M-I Wate barite) were obtained from a drilling mud supplier (Table 7). The data were measured by laser diffraction of the actual weighting element. The conversion of particle sizes to settling velocities assumed a specific gravity 4.1 for the solid fraction of SBM.

Table 5. Drill cuttings settling velocities used for simulations (adapted from Southwest Research Institute, 2003).

Size Class	Percent Volume	Settling Velocity	
		(cm/s)	(m/day)
1	0.88	0.03	25.9
2	0.75	0.23	198.7
3	1.54	0.65	561.6
4	1.20	2.01	1736.6
5	0.52	4.03	3481.9
6	1.17	7.57	6540.5
7	5.39	13.07	11292.5
8	14.47	18.34	15845.8
9	27.04	23.04	19906.6
10	37.99	28.17	24338.9
11	8.62	51.24	44271.4
12	0.43	106.29	91834.6

Table 6. WBM settling velocities used for simulations; drill sections 1 and 2 (Brandsma and Smith, 1999).

Size Class	Percent Volume	Settling Velocity	
		(cm/s)	(m/day)
1	7.00	0.0027	2.4
2	8.00	0.0061	5.3
3	5.00	0.0148	12.8
4	10.00	0.0300	25.9
5	13.26	0.0436	37.7
6	13.26	0.0512	44.2
7	19.24	0.0640	55.3
8	19.24	0.0823	71.1
9	4.00	0.4267	368.7
10	1.00	1.1217	969.1

Table 7. SBM settling velocities used for simulations (data provided by client).

Size Class	Percent Volume	Settling Velocity	
		(cm/s)	(m/day)
1	0.1800	0.000006	0.004929
2	0.5300	0.000009	0.008007
3	0.8000	0.000015	0.013056
4	1.0200	0.000025	0.021214
5	1.1500	0.00004	0.034642
6	1.2900	0.000065	0.056459
7	1.4800	0.000106	0.091893
8	1.7600	0.000173	0.149858
9	2.1200	0.000282	0.243979
10	2.5200	0.00046	0.397539
11	2.8800	0.00075	0.647688
12	3.1900	0.001221	1.055258
13	3.4800	0.00199	1.719767
14	3.8000	0.003243	2.802305
15	4.2200	0.005283	4.564905
16	4.8200	0.00861	7.438836
17	5.7500	0.01403	12.12121
18	6.9600	0.02286	19.7501
19	8.2500	0.03725	32.18188
20	9.1300	0.06069	52.43882
21	9.3400	0.0989	85.44795
22	8.8300	0.1611	139.2328
23	7.6200	0.2626	226.8706
24	5.6000	0.4279	369.6726
25	2.9400	0.6972	602.3632
26	0.3400	1.136	981.525

The extent to which discharged sediments accumulate on the seabed is largely controlled by the particle settling velocities (a function of size and density) and the prevailing currents in the water column. The fine particle sizes associated with the bulk SBM are illustrated in Figure 21, which compares settling characteristics for each of the materials (cuttings and muds) used as model input. The data emphasize how any bulk SBM released near the sea surface (either accidentally, or adhered to drill cuttings) is not likely to contribute to any measureable deposition on the seabed. For example, without accounting for advective processes, over 90% of the SBM solids would require at least 10 days to settle from the surface to the seabed at Site 2. As a result, any SBM that is accidentally released from the sea surface or that remains adhered to cuttings discharged from the sea surface is expected to disperse widely throughout in the water column and thus accumulate at very low concentrations on the seabed.

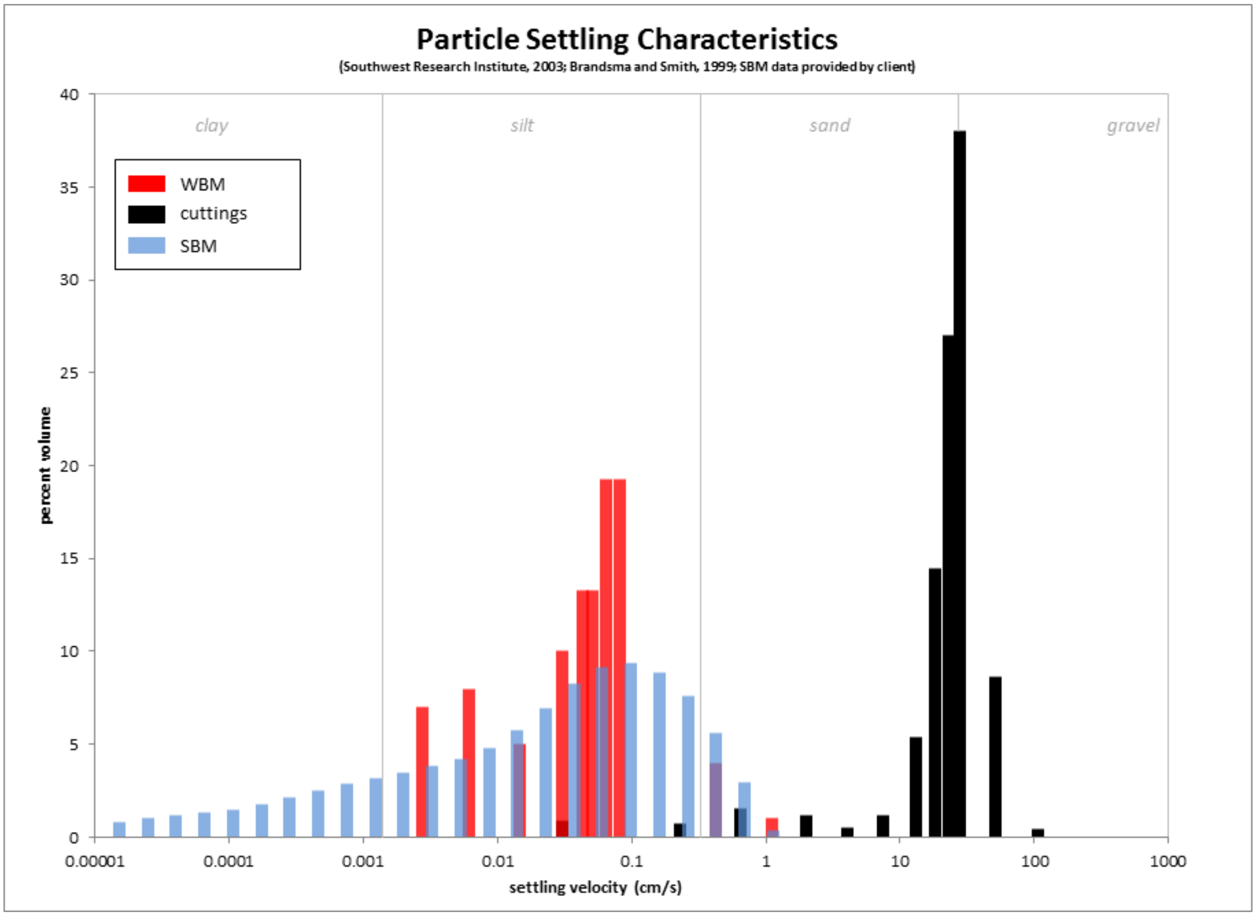


Figure 21. Comparison of settling velocities for solid discharges used in the modelling study. Size class divisions are from Gibbs et al. (1971).

4 DRILLING DISCHARGES MODEL RESULTS

4.1 OPERATIONAL DISCHARGES AT SITE 3

The fate of mud and cuttings released from operational drilling were assessed through two discharge model scenarios corresponding to the drilling schedule and release volumes described in Section 3.2. MUDMAP was used to predict the resulting bottom deposition from each discharged section at Site 3 along with the pattern of cumulative deposits. Following the release of each section in MUDMAP, the model continued to track the far field dispersion for several days, to account for the settling of fine material suspended in the water column. Figure 22 and Figure 23 show the plan view extents of the model-predicted seabed deposition during the late spring and late fall periods, respectively; Table 8 and Table 9 summarize the areal impact of each scenario. For both scenarios, deposit thicknesses were calculated based on mass accumulation on the seabed and assume a sediment bulk density of 2,500 kg/m^3 and no void ratio (zero porosity).

As shown in Figure 22 and Figure 23, the extent of deposition between seasons is similar, particularly for deposits greater than 10 mm in thickness. Simulations performed during the spring period produce a cumulative deposit that is slightly elongated along its southern axis, while during the fall similar elongation is predicted toward the west. Overall however, both scenarios result in a fairly concentric depositional footprint that surrounds Site 3. Contours representing very fine thickness intervals (0.1 mm) extend up to 1380 m from the release site, although the majority of mass released remains confined to an area within 100 m of the well. Differences in the extent of deposition between each season are nominal and limited to thicknesses of 10 mm and below (Figure 24). For both periods, the overall shape is indicative of the flow characteristics during the period of surface releases, although it is important to note that months typified by weaker surface currents (spring period) result in a greater extent of deposition at the 0.5-2 mm levels. Under a stronger current regime (fall period), the extent of deposition is slightly expanded for both the very fine (0.1 mm) and thicker (10 mm) intervals. For all scenarios, the gradient of contours at or above 20 mm is uniform and concentric around the well, which indicates that dispersion processes are nearly as influential as advection from currents due to the settling characteristics of material being released and the release depths.

When drilling occurs in deep water (> 1000 m), which is the case for all modelled sites, any mud discharges that occur from the sea surface are not likely to contribute substantially to the observed deposition at the seafloor. For this study, the small volumes and fine particle sizes associated with SBM that is adhered to drill cuttings also contribute to this outcome. In both scenarios, discharged drill cuttings settle rapidly to the seabed, while the mud fraction of the discharge remains mostly suspended in the upper water column until eventually dispersing below levels detectible by the model. By contrast, both the cuttings and WBM discharged directly at the seabed (sections 1 through 3) settle relatively quickly owing to (i) the release depth, (ii) the size distribution of the WBM, and (iii) the relatively weak currents near the seabed.

For Scenario 1 (spring), the discharge program results in deposition of 100 mm up to 30 m from the well and an aerial extent of 0.26 ha; deposition at 10 mm extends a maximum of 155 m and covers an area of 1.89 ha; and deposition at thickness of 1 mm extends a maximum of 681 m and covers 71.18 ha of the seabed. For Scenario 2 (fall) thicknesses of 100 mm or greater are confined to a distance of 30 m from the discharge site and an aerial extent of 0.25 ha; deposition at 10 mm extends a maximum of 122 m and covers an area of 2.51 ha; and deposition at thickness of 1 mm extends 584 m and covers up to 68.24 ha of the seabed.

Table 8. Areal extent of seabed deposition (by thickness interval) at Site 3.

Deposition Thickness (mm)	**Cumulative Area Exceeding (ha)**	
	Scenario 1 (Spring)	Scenario 2 (Fall)
0.1	**284.703**	**302.676**
0.2	203.21	204.423
0.5	117.332	114.406
1	**71.178**	**68.244**
2	39.334	36.997
5	11.683	11.97
10	**1.887**	**2.506**
20	0.549	0.569
50	0.359	0.359
100	**0.26**	**0.25**
200	0.16	0.16
500	0.06	0.06

Table 9. Maximum extent of thickness contours (distance from release site) at Site 3.

Deposition Thickness (mm)	**Maximum extent from discharge point (m)**	
	Scenario 1 (Spring)	Scenario 2 (Fall)
0.1	1360	1380
1	681	584
10	155	122
100	30	30
500	14	14

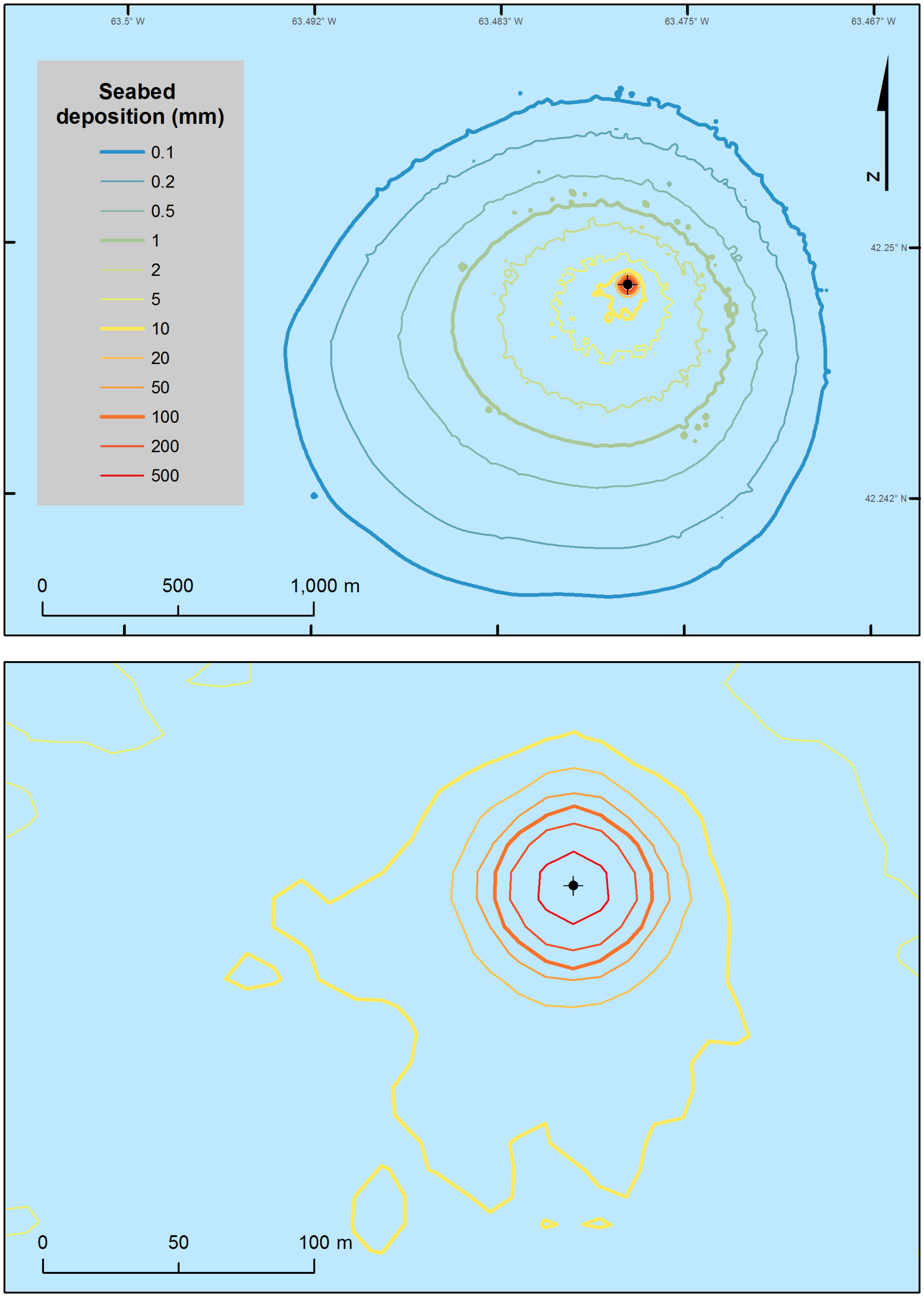


Figure 22. Predicted thickness of drilling discharges at Site 3 (spring period). Top: composite deposition resulting from all drilling intervals. Bottom: contours above 10 mm (bold yellow) shown at an expanded scale.

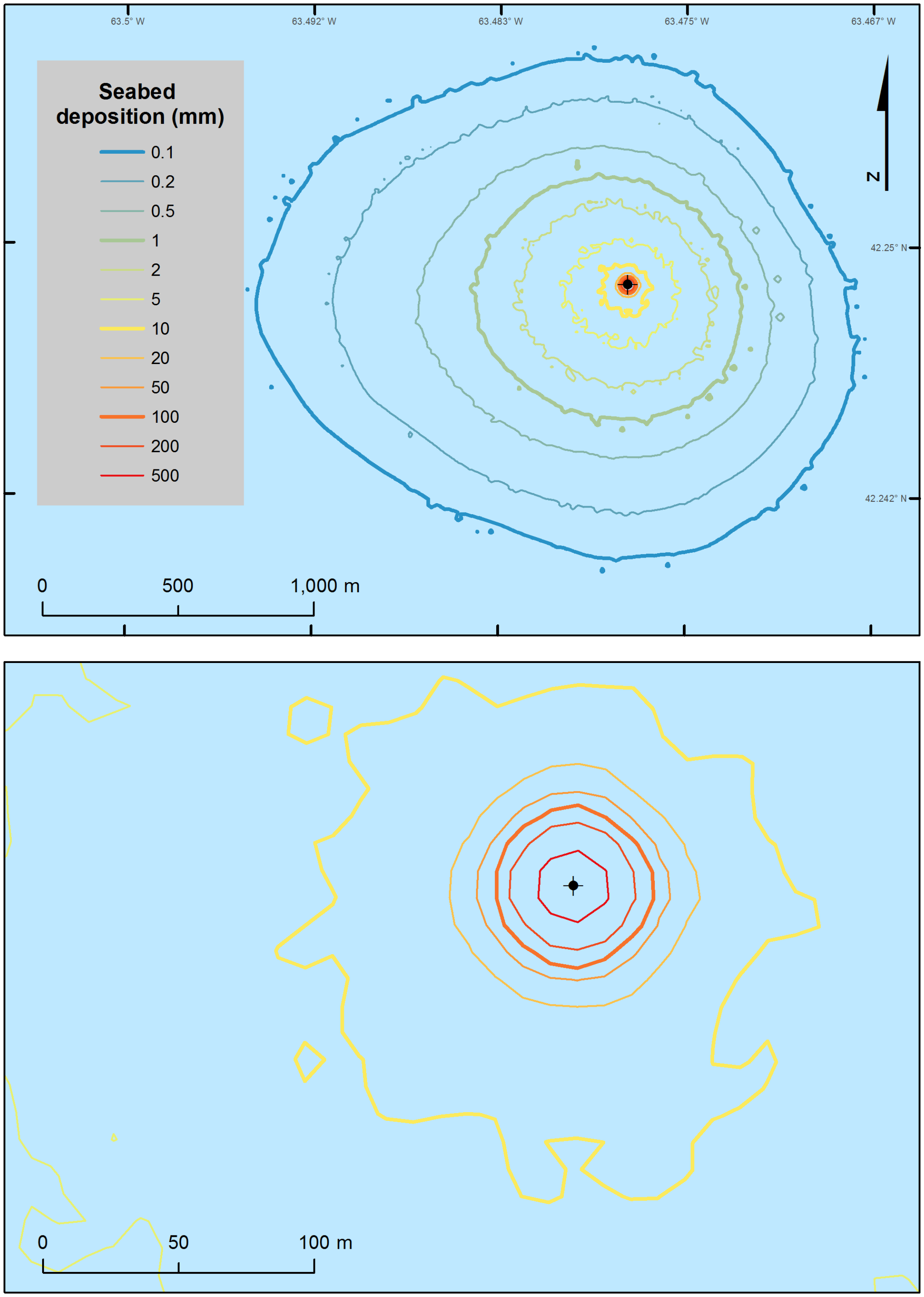


Figure 23. Predicted thickness of drilling discharges at Site 3 (fall period). Top: composite deposition resulting from all drilling intervals. Bottom: contours above 10 mm (bold yellow) shown at an expanded scale.

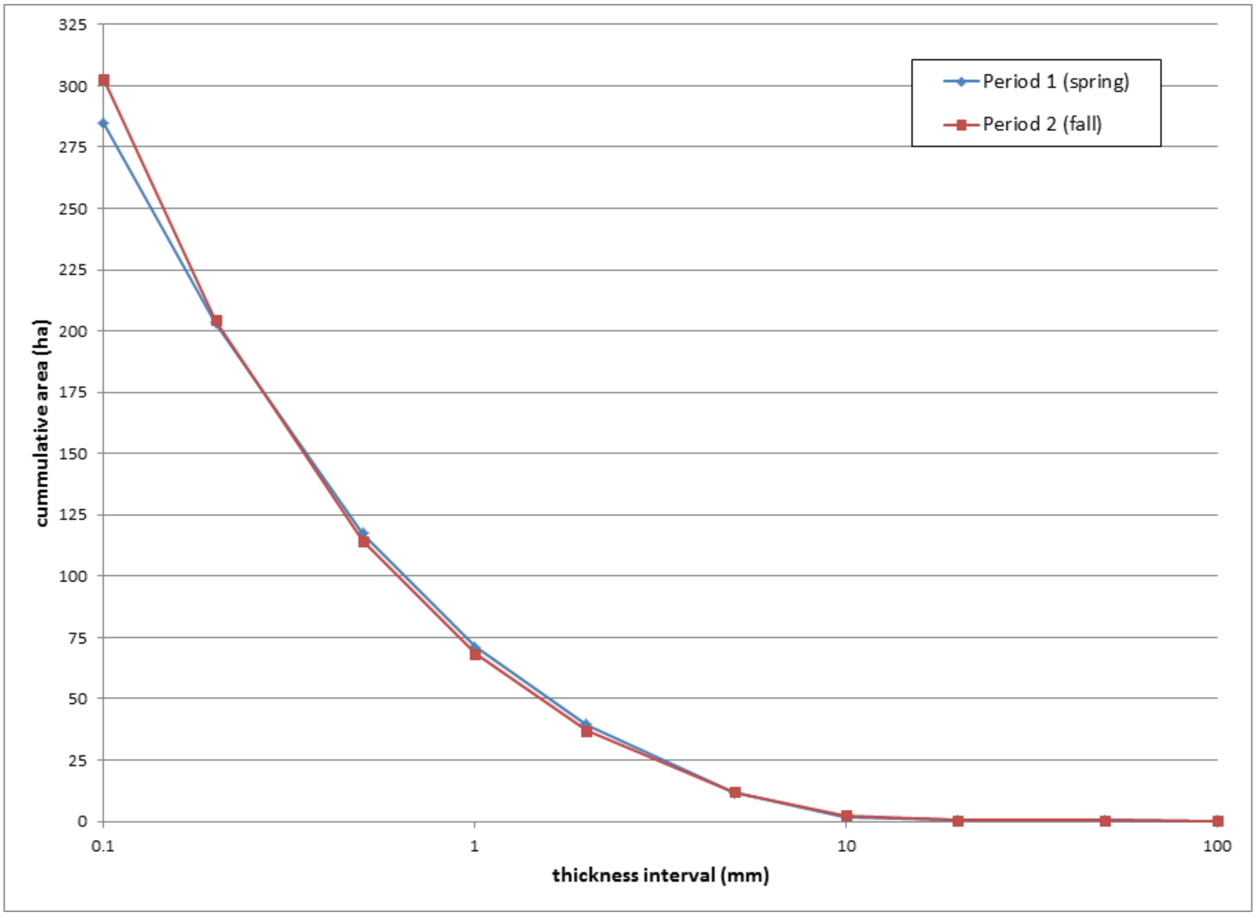


Figure 24. Comparison of seabed deposition (by thickness interval) for cumulative discharges at Site 3. Blue – spring discharge schedule, Red – fall discharge schedule.

4.2 ACCIDENTAL SBM RELEASES

MUDMAP was also used to predict seabed deposition and concentrations of total suspended solids (TSS) in the water column at drilling Sites 1 and 2 as a result of the accidental releases of SBM. As described above, two deterministic scenarios were performed at each site (4 total) representing different release depths and corresponding SBM volumes. The mode of release and associated model parameters are summarized in Table 10. For each scenario the release of SBM was assumed to occur near-instantaneously (over the course of several minutes). Releases were simulated during periods of current minima (late spring) to replicate conditions that would result in higher and more sustained plume concentrations. Following each release, the model continued to track the transport and dispersion of the plume until the maximum concentrations declined below 1 mg/L (~1 ppm).

Table 10. Summary of model parameters used to characterize the accidental release of SBM at Sites 1 and 2.

Model Scenario	Discharge Period	Mode of Release	Mud Volume (m^3)	Mud Type	Release Location
Drill Site 1					
SBM-1	1-Jun 2012	Marine Riser	573	Rheliant SBM	5 m above seafloor
SBM-2	1-Jun 2012	Mud Tank	60	Rheliant SBM	2 m below platform
Drill Site 2					
SBM-3	1-Jun 2012	Marine Riser	573	Rheliant SBM	5 m above seafloor
SBM-4	1-Jun 2012	Mud Tank	60	Rheliant SBM	2 m below platform

Figure 25 and Figure 26 present seabed deposition associated with the release of each of the SBM scenarios described above. At both sites deposition is limited to thicknesses of 10 mm. Sea surface discharges of SBM (Scenario SBM-2 and SBM-4) remain suspended in the upper water column until eventually dispersing below levels detectible by the model (1 mg/L). As a consequence, the surface releases of SBM at both sites do not contribute to mass accumulation on the seabed at a level that is measureable by the model (bottom panels of Figure 25 and Figure 26). Table 11 and Table 12 summarize the extent of deposition associated with each SBM release scenario.

Figure 27 through Figure 30 show the aggregation of TSS values that occur over the duration each SBM release simulation. These figures do not represent any instantaneous snapshot of water column concentrations, but instead show the maximum, time-integrated TSS within the study domain for each modelled release. The maximum predicted concentration of suspended sediments in the water column ranges from a maximum of 29,401 mg/L as a result of releases from the marine riser at Site 1 (Scenario SBM-1), to 2,411 mg/L for surface releases (mud tank spill) at the Site 2 well (Scenario SBM-4). As mentioned above, the slow settling velocities of the SBM and the current speeds at the sea surface cause most of the suspended sediment released from the drilling platform to remain within the uppermost 10-20 metres of the water column as can be seen in the corresponding cross-sections.

Table 13 summarizes the maximum distance of observed excess water column concentrations for each of the four scenarios. The trends observed in the model-predicted TSS plume are similar to those of the seabed deposition simulations; namely, that the plume trajectories vary as a result of the flow regime occurring on the day of the release. For that reason the results should be considered within the context of all possible current conditions within the lease block that are under consideration for drilling. Both the extent of the plume and maximum TSS concentration are notably larger for the releases associated with the rupture of the marine riser (Scenarios SBM-1 and SBM-3) as compared to the surface discharge (Scenarios SBM-2 and SBM-4). This is presumably due to the total volume of mud released and the very weak currents at depths near the seabed. Because the release is a near-instantaneous event in all cases, the total volume of discharged material influences the overall extent of TSS contours, particularly for concentrations > 1,000 mg/L. At this level, SBM releases associated with the marine riser (573 m^3 release volume) extend approximately 4 times the distance of the releases at the sea surface (60 m^3 release volume).

For all scenarios, the SBM plume migrates from the release site immediately after the discharge event terminates. The plume travels with ambient currents until dispersion and turbulence cause the TSS concentrations to fall below the 1 mg/L threshold. Table 14 lists the distance travelled by the plume at instantaneous time steps, until water column concentrations are no longer detected. To this end, the stronger current regime at the surface has the effect of clearing the water column more quickly than weaker and more variable flow at depth. For Scenario SBM-4, the model domain returns to background water column concentrations after 12 hours and 10 minutes, while Scenario SBM-1 requires over 30 hours to return to ambient conditions. While it is possible that TSS values below 1 mg/L are maintained for a longer duration, water column concentrations below this threshold were not quantified by the model.

Table 11. Areal extent of seabed deposition (by thickness interval) for SBM release scenarios.

Deposition Thickness (mm)	**Cumulative Area Exceeding (ha)**			
	SBM-1 (Site 1, 573 m^3)	**SBM-2 (Site 1, 60 m^3)**	**SBM-3 (Site 2, 573 m^3)**	**SBM-4 (Site 2, 60 m^3)**
0.1	**21.001**	**0**	**19.145**	**0**
0.2	7.875	0	7.057	0
0.5	0.639	0	0.569	0
1	**0.269**	**0**	**0.25**	**0**
2	0.13	0	0.13	0
5	0.03	0	0.03	0
10	**0**	**0**	**0**	**0**
20	0	0	0	0
50	0	0	0	0
100	**0**	**0**	**0**	**0**
200	0	0	0	0
500	0	0	0	0

Table 12. Maximum extent of thickness contours (distance from release site) for SBM release scenarios.

Deposition Thickness (mm)	**Maximum extent from discharge point (m)**			
	SBM-1 (Site 1, 573 m^3)	**SBM-2 (Site 1, 60 m^3)**	**SBM-3 (Site 2, 573 m^3)**	**SBM-4 (Site 2, 60 m^3)**
0.1	657	0	690	0
1	40	0	41	0
10	0	0	0	0
100	0	0	0	0
500	0	0	0	0

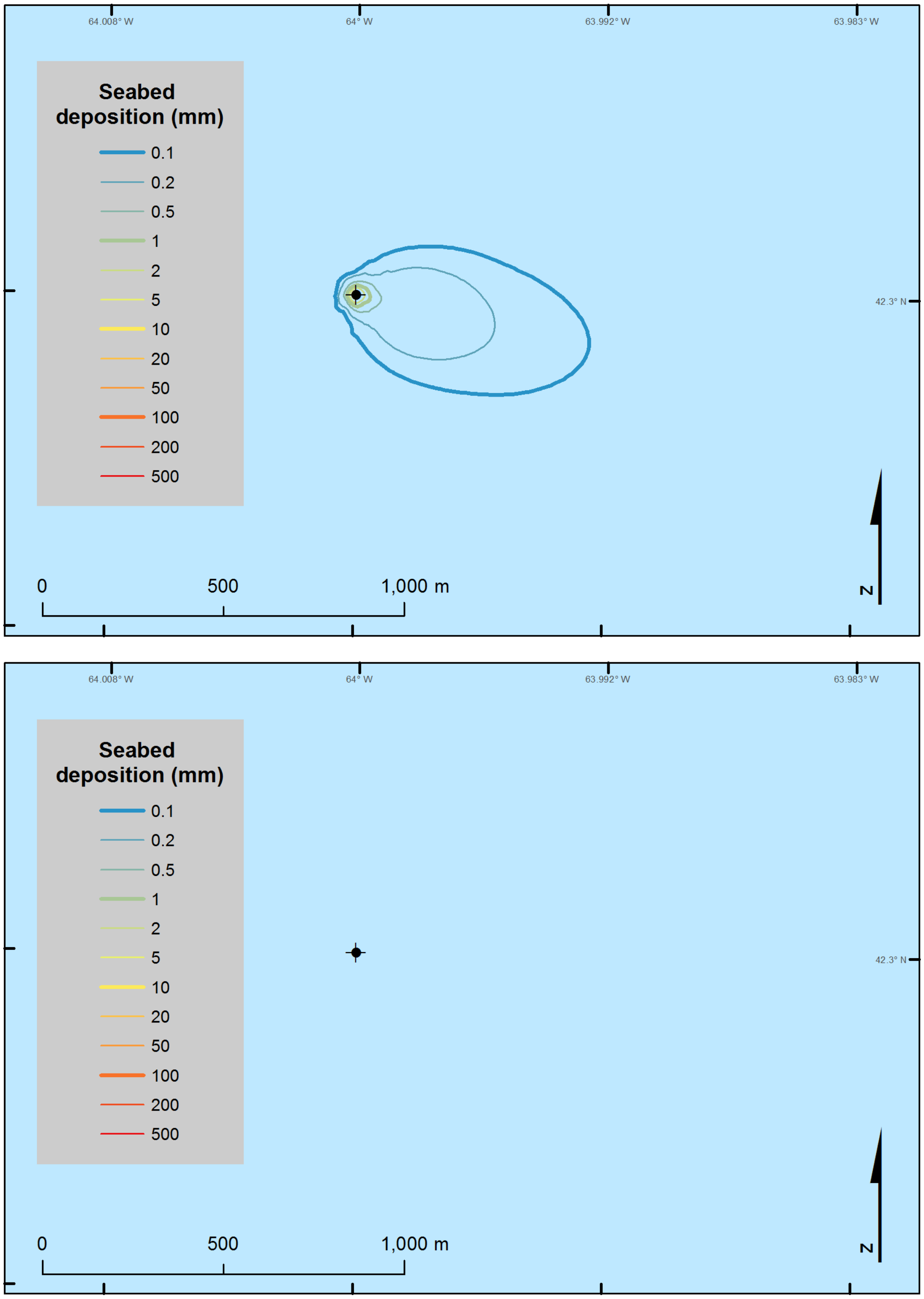


Figure 25. Predicted thickness resulting from simulated SBM releases at Site 1. Top: Scenario SBM-1, release of the full marine riser (573 m^3 SBM) at the seabed. Bottom: Scenario SBM-2, sea surface release (60 m^3 SBM). Note that measurable thicknesses (greater than 0.01 mm) are not predicted for scenario SBM-2.

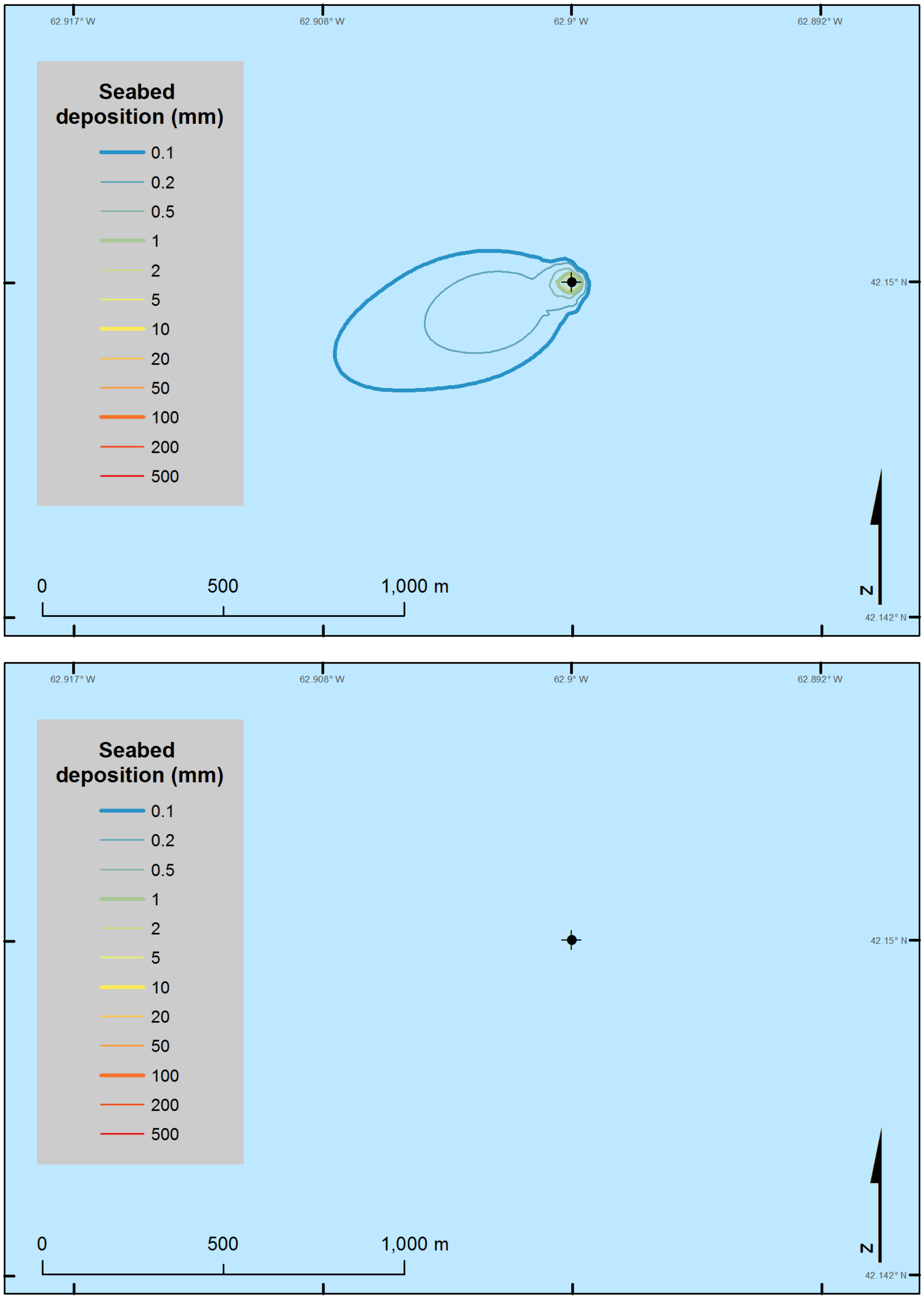


Figure 26. Predicted thickness resulting from simulated SBM releases at Site 2. Top: Scenario SBM-3, release of the full marine riser (573 m^3 SBM) at the seabed. Bottom: Scenario SBM-4, sea surface release (60 m^3 SBM). Note that measurable thicknesses (greater than 0.01 mm) are not predicted for scenario SBM-4.

Table 13. Maximum distance of excess water column concentrations for each SBM discharge scenario.

Water Column Concentration (mg/L)	Distance from discharge point (m)			
	SBM-1	SBM-2	SBM-3	SBM-4
1	5,450	5,080	9,620	5,310
10	1,680	1,550	3,230	1,590
100	616	284	749	320
1000	153	39	177	41
10000	32	–	33	–

Table 14. Instantaneous distance traveled by the plume for each SBM discharge scenario

Time from start of discharge	Distance from discharge point (m)			
	SBM-1	SBM-2	SBM-3	SBM-4
1 h	704	868	776	915
2 h	1,100	1,500	1,250	1,500
4 h	1,690	2,540	2,070	2,550
8 h	2,310	3,770	3,810	4,400
12 h	2,850	4,720	5,270	5,220
16 h	3,770	–	6,430	–
20 h	4,070	–	7,900	–
24 h	4,410	–	9,200	–
max distance*	5,450	5,080	9,620	5,310

*represents the maximum distance of water column concentrations observed above 1 mg/L; corresponds to the following time steps: Scenario SBM-1 (30 h 4 min), SBM-2 (15 h 24 min), SBM-3 (27 h 30 min), SBM-4 (12 h 10 min).

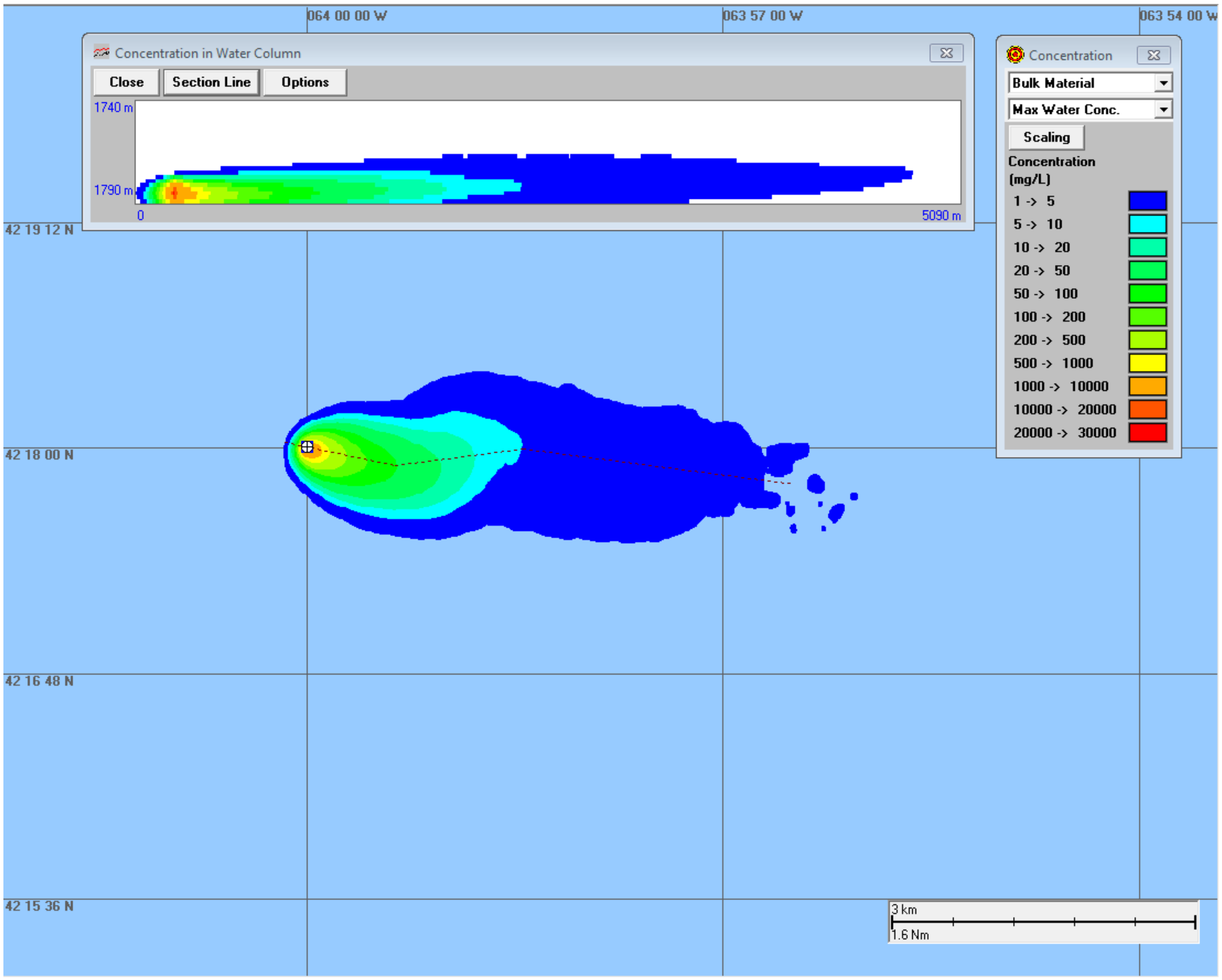


Figure 27. Maximum water column concentrations (mg/L) resulting from the near instantaneous discharge of 573 m^3 of synthetic based mud from the base of the marine riser at Site 1 during June 2012 (Scenario SBM-1); dashed line corresponds to cross-section transect (bottom figure), plotted above as a vertical profile of maximum water column concentrations.

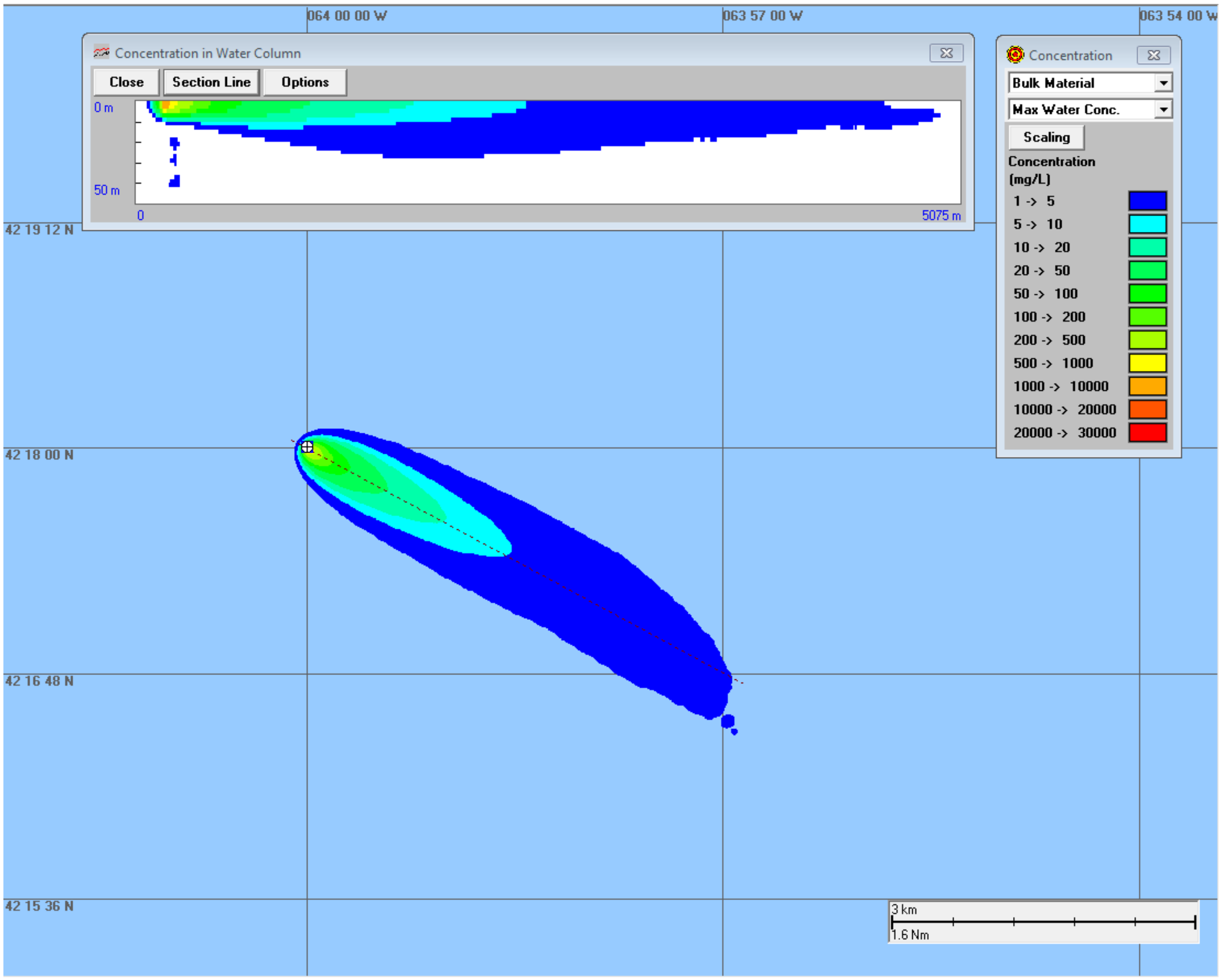


Figure 28. Maximum water column concentrations (mg/L) resulting from the near instantaneous discharge of 60 m3 of synthetic based mud from the sea surface at Site 1 during June 2012 (Scenario SBM-2); dashed line corresponds to cross-section transect (bottom figure), plotted above as a vertical profile of maximum water column concentrations

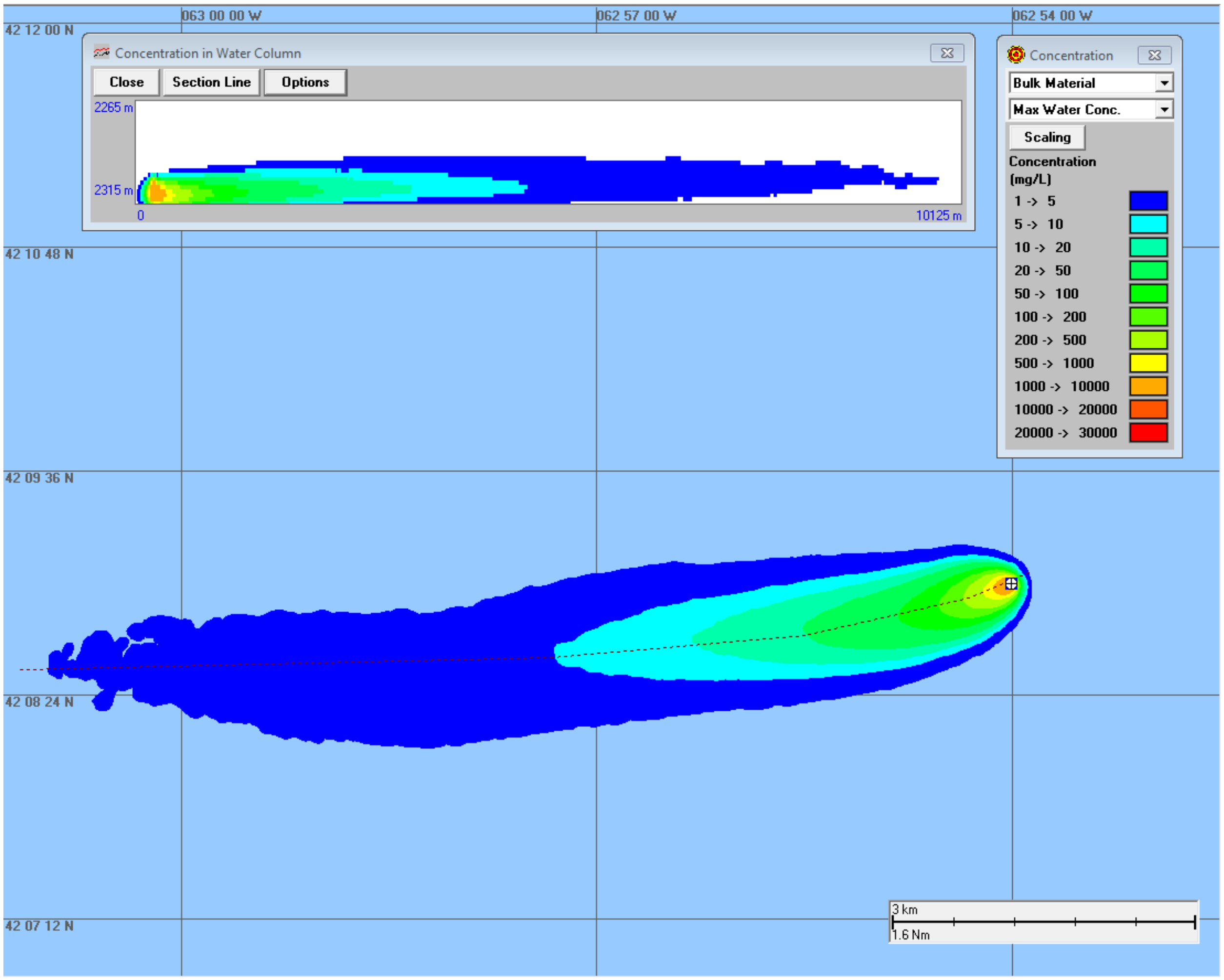


Figure 29. Maximum water column concentrations (mg/L) resulting from the near instantaneous discharge of 573 m3 of synthetic based mud from the base of the marine riser at Site 2 during June 2012 (Scenario SBM-3); dashed line corresponds to cross-section transect (bottom figure), plotted above as a vertical profile of maximum water column concentrations

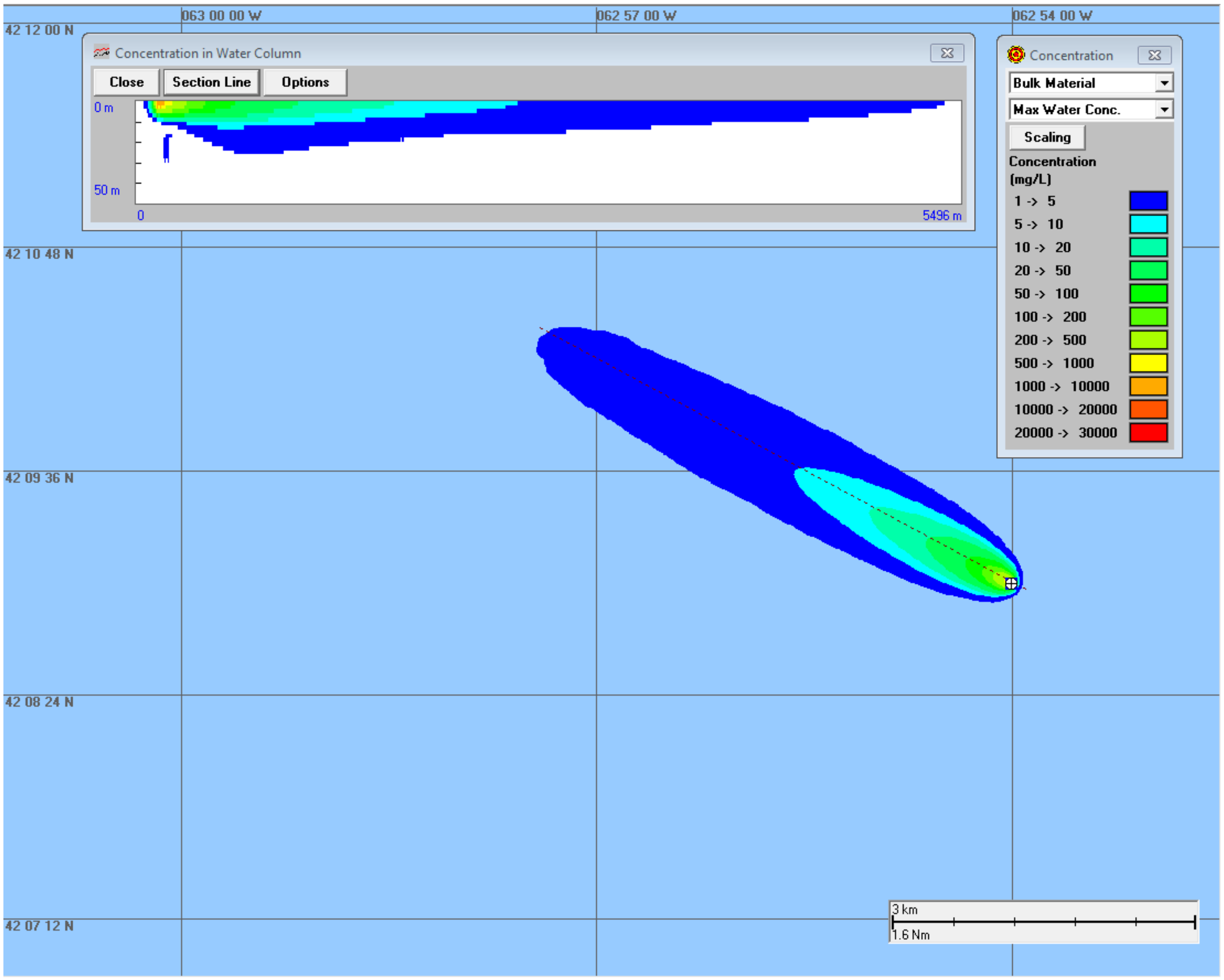


Figure 30. Maximum water column concentrations (mg/L) resulting from the near instantaneous discharge of 60 m3 of synthetic based mud from the sea surface at Site 2 during June 2012 (Scenario SBM-4); dashed line corresponds to cross-section transect (bottom figure), plotted above as a vertical profile of maximum water column concentrations

5 CONCLUSIONS

This report presents the results of drill cuttings and mud discharge simulations conducted at three locations associated with the Shelburne Basin Venture Exploration Drilling Project. The sites chosen for simulations (Sites 1, 2, and 3) are located approximately 250 km south of Nova Scotia within a geographical offshore area known as the Southwest Scotian Slope. Dispersion modelling was completed at Site 3 in order to evaluate seabed deposition from the operational releases of drilling mud and cuttings anticipated during offshore drilling. Additional simulations were conducted at Sites 1 and 2 to model the extent of sediment plumes and seabed deposition from accidental releases of synthetic based mud.

Simulations of drilling releases were completed using ASA's MUDMAP modelling software. Because drilling operations within Shell's exploration licence areas could occur throughout the year, a modelling strategy was developed to compare the results of different flow conditions that characterize the potential range of release periods. Specifically, mud and cuttings releases were simulated for two periods spanning the months of April-June and October-December – periods that correspond to current minima/maxima in both modelling and observational studies of the Scotian Shelf. MUDMAP simulations of accidental SBM releases utilized currents during the late spring period to replicate conditions that would produce higher and more sustained plume concentrations. In total, two (2) deterministic drilling discharge scenarios and four (4) deterministic SBM release scenarios were performed using the MUDMAP dispersion model:

- Scenario 1: Operational drilling discharges at Site 3; Spring period (Apr-Jun)
- Scenario 2: Operational drilling discharges at Site 3; Fall period (Oct-Dec)
- Scenario SBM-1: Accidental SBM release (573 m^3) at Site 1; seabed; Spring period
- Scenario SBM-2: Accidental SBM release (60 m^3) at Site 1; sea surface; Spring period
- Scenario SBM-3: Accidental SBM release (573 m^3) at Site 2; seabed; Spring period
- Scenario SBM-4: Accidental SBM release (60 m^3) at Site 2; sea surface; Spring period

For each scenario, vertically and time varied currents from a representative period (2012-2013) were derived from the HYCOM model and were used in combination with TPXO8.0 tidal forcing to drive the advection of the discharged solids.

The cumulative seabed deposition resulting from each discharge scenario was analysed along with predictions of suspended sediment plumes resulting from the accidental releases of SBM. In summary:

Operational Discharges

- At Site 3, both operational discharge scenarios result in a slightly elongated and westerly oriented, depositional footprint. Contours representing very fine thickness intervals (0.1 mm) extend up to 1380 m from the release site. The majority of mass released by the model remains confined to an area within 100 m of the wellhead.
- Differences in the deposition footprint arising from the seasonal variability of currents are limited to thicknesses of 10 mm and below. The extent of deposition above 20 mm is nearly indistinguishable between seasons.
- Thicknesses at or above 1 mm extend 681 m from the release site for Scenario 1 (spring) and 584 m for Scenario 2 (fall). Thickness greater than 10 mm extends 155 m and 122 m for the two periods (respectively) and thickness at or above 100 mm is confined to a distance of 30 m from the well head.

Accidental Releases

- At both the Sites 1 and 2, the sea surface releases of SBM do not accumulate on the seabed at a level that is measureable by the model. Deposition resulting from the accidental SBM discharges at the seabed is limited to thicknesses < 10 mm.
- Sediment plumes resulting from discharges of SBM are predicted to extend between 5,080 m and 9,620 m from the release site; the trajectory varies as a result of the flow regime occurring on the day of the release.
- In general, the extent of the plume and maximum TSS concentration are larger for the releases associated with the marine riser rupture (Scenarios SBM-1 and SBM-3) as compared to the surface discharges (Scenarios SBM-2 and SBM-4). The maximum predicted concentration of suspended sediments in the water column (corresponding to the weakest current regime) is 29,401 mg/L.
- TSS concentrations above 1 mg/L may persist for up to 30 hours following SBM releases at the Site 2 well.

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APPENDIX A: MUDMAP MODEL DESCRIPTION

MUDMAP is a personal computer-based model developed by ASA to predict the near and far-field transport, dispersion, and bottom deposition of drill muds and cuttings and produced water (Spaulding et al; 1994). In MUDMAP, the equations governing conservation of mass, momentum, buoyancy, and solid particle flux are formulated using integral plume theory and then solved using a Runge Kutta numerical integration technique. The model includes three stages:

> Stage 1: **Convective decent/jet stage** – The first stage determines the initial dilution and spreading of the material in the immediate vicinity of the release location. This is calculated from the discharge velocity, momentum, entrainment and drag forces.
>
> Stage 2: **Dynamic collapse stage** – The second stage determines the spread and dilution of the released material as it either hits the sea surface or sea bottom or becomes trapped by a strong density gradient in the water column. Advection, density differences and density gradients drive the transport of the plume.
>
> Stage 3: **Dispersion stage –** In the final stage the model predicts the transport and dispersion of the discharged material by the local currents. Dispersion of the discharged material will be enhanced with increased current speeds and water depth and with greater variation in current direction over time and depth.

MUDMAP is based on the theoretical approach initially developed by Koh and Chang (1973) and refined and extended by Brandsma and Sauer (1983) and Khondaker (2000) for the convective descent/ascent and dynamic collapse stages. The far-field, passive diffusion stage is based on a particle based random walk model. This is the same random walk model used in ASA's OILMAP spill modelling system (ASA, 1999).

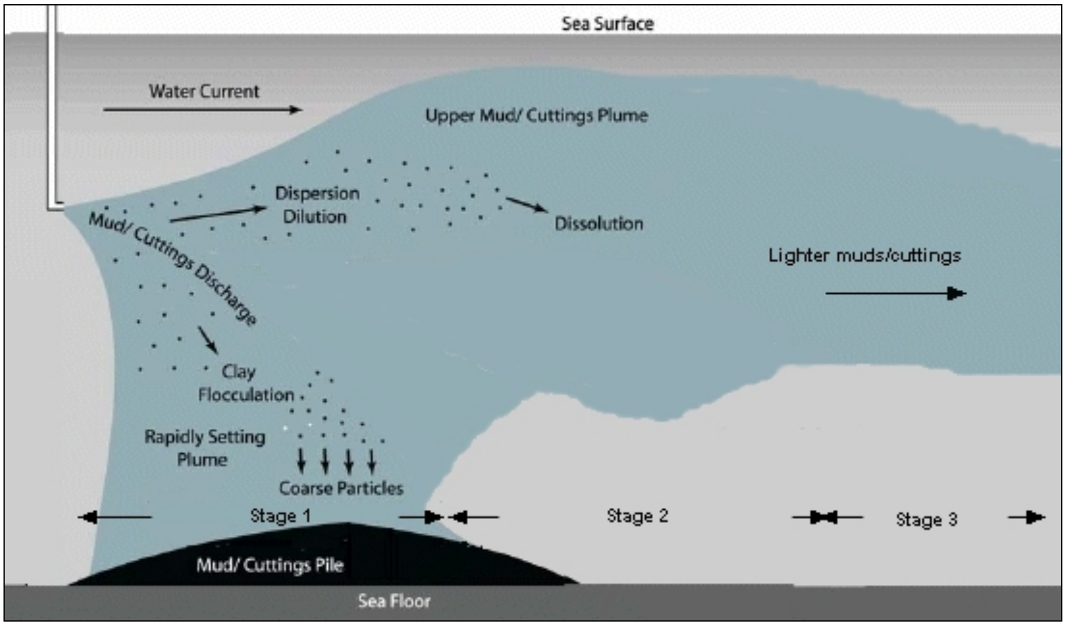

Figure A1. Conceptual diagram showing the general behaviour of cuttings and muds following discharge to the ocean and the three distinct discharge phases (after Neff 2005).

The model's output consists of calculations of the movement and shape of the discharge plume, the concentrations of soluble (i.e. oil in produced water) and insoluble (i.e. cuttings and muds) discharge components in the water column, and the accumulation of discharged solids on the seabed. The model predicts the initial fate of discharged solids, from the time of discharge to initial settling on the seabed As MUDMAP does not account for resuspension and transport of previously discharged solids, it provides a conservative estimate of the potential seafloor concentrations (Neff 2005).

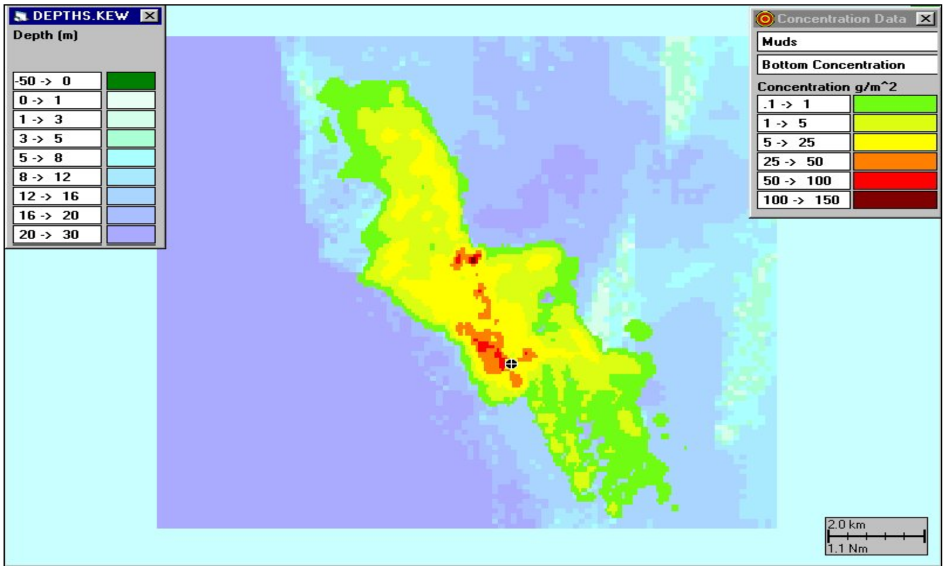

Figure A2 Example MUDMAP bottom concentration output for drilling fluid discharge.

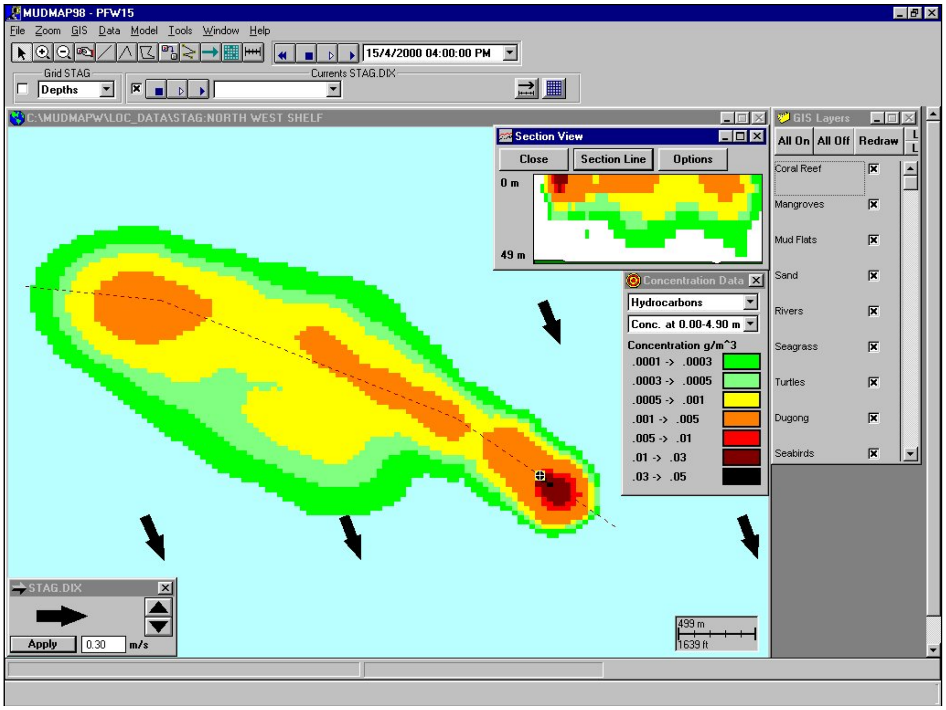

Figure A3. Example MUDMAP water column concentration output for drilling fluid discharge.

MUDMAP uses a colour graphics-based user interface and provides an embedded geographic information system, environmental data management tools, and procedures to input data and to animate model output. The system can be readily applied to any location in the world. Application of MUDMAP to predict the transport and deposition of heavy and light drill fluids off Pt. Conception, California and the near-field plume dynamics of a laboratory experiment for a multi-component mud discharged into a uniform flowing, stratified water column are presented in Spaulding et al. (1994). King and McAllister (1997, 1998) present the application and extensive verification of the model for a produced water discharge on Australia's northwest shelf. GEMS (1998) applied the model to assess the dispersion and deposition of drilling cuttings released off the northwest coast of Australia.

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