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BBLT3D, the 3D Generalized Bottom Boundary Layer Transport Model: Formulation and Preliminary Applications

by

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Abstract

Drozdowski, A. 2009. BBLT3D, the 3D Generalized Bottom Boundary Layer Transport Model: Formulation and Preliminary Applications . Can. Tech. Rep. Hydrogr. Ocean Sci. 263: vi + 32 pp.

The fate and potential environmental impacts of discharged drilling muds are ongoing issues for offshore petroleum operators, regulators, government agencies and environmentalists. The benthic boundary layer transport model, BBLT, was developed to predict the transport and dispersion of suspended particulate drill waste in the benthic boundary layer. The latest version of the code, BBLT3D, can be coupled to any arbitrary 3d currents. The limitation of horizontal uniformity in the currents and bathymetry has been removed. The new code is not limited to single point sediment discharges, as the older versions of the code, but allows user defined regions. Also new is the Runge Kutta Advection scheme. This report gives the details of the new 3d framework and presents applications in the Southern Gulf of Saint Lawrence and Sydney Bight area.

Résumé

Drozdowski, A. 2009. BBLT3D, the 3D Generalized Bottom Boundary Layer Transport Model: Formulation and Preliminary Applications . Can. Tech. Rep. Hydrogr. Ocean Sci. 263: vi + 32 pp.

L'avenir des décharges de boues de forage et leur influence potentielle sur l'environnement constituent un problème récurrent pour les opérateurs pétroliers en mer, les législateurs, les organismes gouvernementaux et les environnementalistes. Le modèle benthique de transport de couche limite, BBLT, a été développé pour prévoir le transport et la dispersion des particules en suspension issues des pertes de forage dans la couche limite benthique. La dernière version du code, BBLT3D, peut être couplée à tout champ tridimensionnel et arbitraire des courants. La limitation de l'uniformité horizontale des courants et de la bathymétrie a été supprimée. Le nouveau code n'est pas limité à des sources ponctuelles de décharge des sédiments, comme c'était le cas auparavant, mais permet à l'utilisateur de définir des aires de relâche. Comme autre nouveauté, le schéma de Runge-Kutta est maintenant utilisé pour l'advection. Ce rapport fournit les détails du nouveau cadre de travail 3d et présente des applications pour le sud du Golfe du Saint-Laurent et de la région du Sydney Bight.

1 Introduction

The benthic boundary layer model (BBLT) is a numerical modelling tool developed and used to study the fate of suspended particulate drilling waste (Hannah et al., 1995). Basic output from the model consists of drift, diffusivity, and concentration. Required inputs are time series of the current profile, estimates of bottom stress, the sediment settling velocity and the discharge scenario. Upgrades to the BBLT model over the years have included the addition of wave boundary layer, floc breakup and biological impacts (Drozdowski et al., 2004). The wave boundary layer incorporated the combined wave-current bottom stress following Grant and Madsen (1986) and Li and Amos (2001). The floc breakup capability allows the sediment to inhabit one of three settling velocity states and is bottom stress dependent. The biological impacts module is based on a growth-days-lost formulation determined from laboratory experiments on scallops (Cranford et al., 2003).

Haibo et al. (2009) has performed a case study to compare BBLT another sediment transport model, ParTrack (Rye et al., 1998). Although ParTrack and BBLT are formulated quite differently, the case study shows comparable results, especially for locations far away from the discharge. The two models predicted similar extent of spreading. The major difference between the two models is the location of peak of concentration.

Past BBLT modelling attempts focused on near field (1-20 km) and short term (5-30 day) descriptions of the suspended particulate mater (SPM) in the offshore environment (Hannah and Drozdowski, 2005; Tedford et al., 2003, 2002). Interest lay in predicting dispersion rates and sub-lethal biological impacts resulting from the sediment released during the drilling phase of oil and gas platforms such as Hibernia on the Grand Banks and North Triumph on the Scotian Shelf (Hannah et al., 2003, 2006; Tedford et al., 2003).

Some inshore work was undertaken using BBLT as well. Over the years the AMEC E&E division has used BBLT for environmental assessments of proposed discharge of drill muds. More recently they have conducted environment assessments of the discharge of effluent solid waste in Long Harbour (AMEC E&E Division, 2007). Moreover Petrie et al. (2004), have used BBLT in their study of the Sydney Harbour and found a tendency to accumulate sediment near the head of the harbour which is fairly consistent with the distribution of pollutants found in the sediment.

These past modelling efforts relied on a vertical profile of currents from one station. For practical reasons, a horizontal uniformity in the currents, ocean depth and bottom type were assumed inside the modeled domain. However, as was shown by Xu et al. (2000), using a 3D version of BBLT coupled with the currents from the hydrodynamic model covering Georges Bank (Naimie, 1995, 1996) is that horizontal shear in the currents enhance the dispersion rates, particularly near the steep topography of the bank edge.

It is clear that simulating potential environmental impacts related to SPM close to shore or near steep topographic features would benefit from the inclusion of 3D affects. In some cases this inclusion might be essential. The work described in this report deals with the development and application of BBLT3D. This is the newest version of BBLT since version 7. It can be coupled to any source of 3D currents: output of a circulation model, database of observations or an analytically prescribed flow field. The only requirement is that flow field is continuous. The physics behind BBLT3D are unchanged from older versions. In order to preserve uniformity with older versions input and output formats have undergone minimal change as well. The 3D functional version of BBLT used by Xu et al. (2000) was not used as the starting point for this work because it does not include the recent upgrades as described in Drozdowski et al. (2004). It is also restricted to the Matlab environment.

A summary of the latest development from the user perspective are described in Section 2. The methodology of transforming local BBLT into a framework compatible with horizontally variable environments is described in section 3. Section 4 gives details of coupling BBLT3D to the 3D circulation model of the Gulf of St. Lawrence. The 5th section is a demonstration of BBLT3D. Included are modelling applications in the Southern Gulf of Saint Lawrence and Sydney Bight area. The appendices provide a more detailed description of the modifications to the code, velocity interpolation scheme, and model validations.

2 What's new in BBLT

3D Functionality

Platform Independent
Of interest for future applications, is its ability to couple BBLT3D to any source of continuous 3D currents: output of a circulation model, a flow field assembled from observations or prescribed analytically. Whenever BBLT3D needs to be coupled to an new source of currents, only a new interface needs to be developed, without changing the code itself.

User Defined Horizontal Distributions
The initial particle distribution is now completely arbitrary with possibility of multiple time dependent sources. An example is the ability to distribute particles uniformly over a region. The results in a constant ubiquitous initial concentration. Possible applications for this discharge mode include, investigating the fate of fine grained sediment (i.e. mud) resuspended by storms, and subject to local tendencies to flush out or accumulate sediment. In the present version of the model, the initial particle distribution and mode of input is defined in a file named CrtPckts.f. Inside are several possible versions, each being its own subroutine. New subroutines can be added as needed. The point discharge used in older versions of the code is still available.

4th Order Runge Kutta Advection

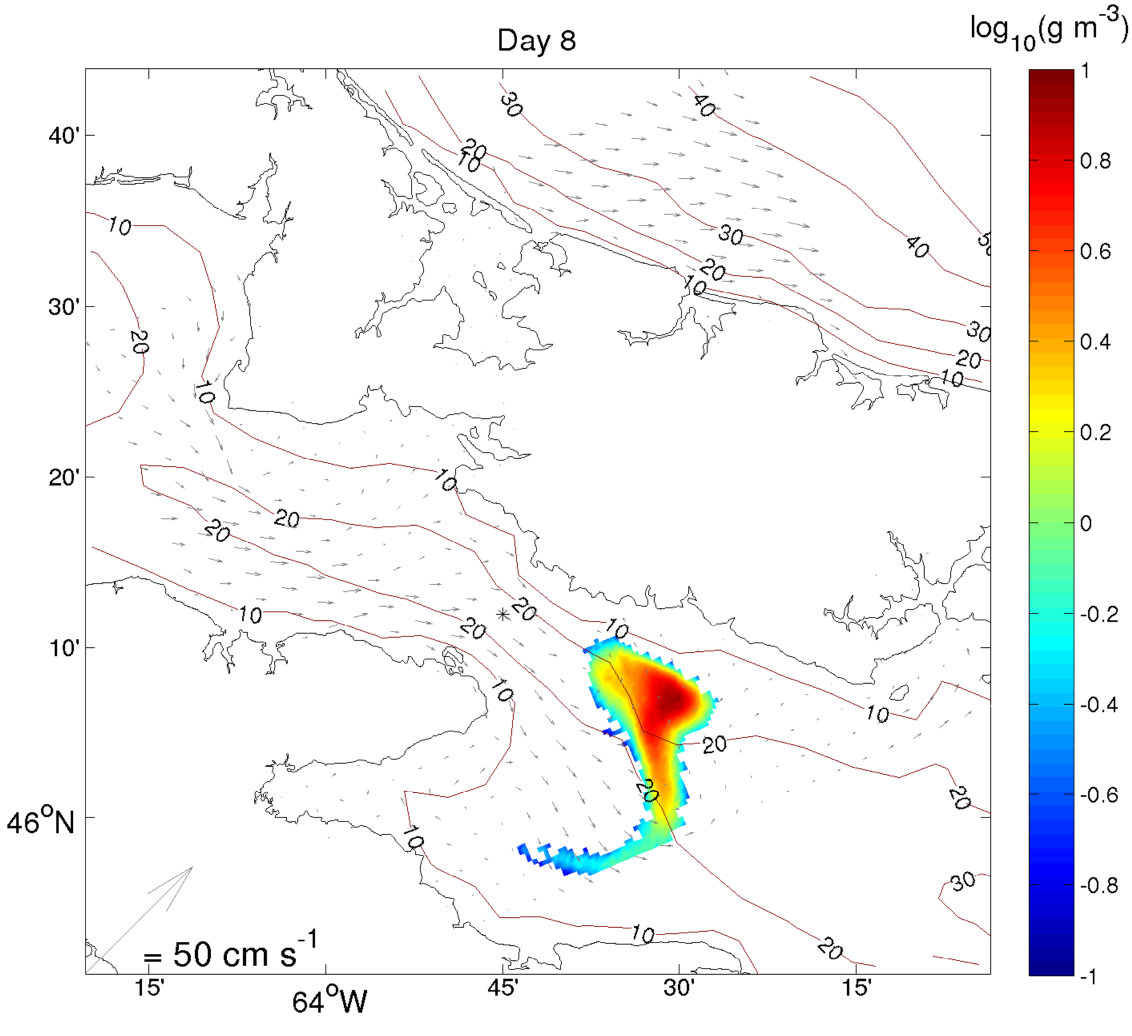

Figure 1: An example using currents from the GSS4 model (see section 4) near the Confederation Bridge in which a bulk point source discharge of sediment is greatly deformed after 8 days of simulation. The metric used is bottom 10 cm concentration averaged over the 8th day. A star marks the release site.

Particles tracking can be problematic in high gradient regions. Overshooting is common with first order advection. One way of reducing the problem is with a shorter time step. This is option is often unavailable due to limits imposed by the model time step. In this case, higher order advection schemes are an option.

BBLT3D contains the 4th order Runge Kutta advection. The method uses the starting velocity as the first guess and makes a series of improvements by using the velocity at the middle of the step and at the end. A logical switch in the main subroutine allows the user to choose the 1st or 4th order advection. A new version of MoveHoriz performs the 4th order advection. The main difficulty of the implementation lays in the fact that BBLT3D execution is tied to the ocean model which has only the velocity at the present time step. To get around this, without saving the large 3D velocity field from the previous time steps, BBLT3D builds up the calculation gradually over 2 time steps.

For most applications only a small change in results was seen. This is because BBLT redistributes particles in the vertical at each time step. The resulting vertical shear dispersion overrides advection errors. It is useful to have the 4th order advection for future applications where accuracy of advection might be of more concern.

3 BBLT3D Framework

This section describes the restructuring of local BBLT for compatibility with a horizontally variable environment. The original BBLT v7.0 code was kept mostly intact and focus was placed on making necessary changes with minimal impact on the original code, input and output formats. The code was divided into 3 parts: core BBLT code, the control module and the interface (Figure 2). The core BBLT code is where the main calculation takes place. The control module is a subroutine which controls the time stepping of the core BBLT model. It is a simple subroutine which can be embedded in an ocean model or used as the main module to compile BBLT3D as a stand alone code. The interface is a gateway between the core and an external source of current data. The external source can be an ocean model, data archive or analytical flow field solution. Each of the 3 components is addressed below.

3.1 Core BBLT

The core of the calculation from local BBLT was preserved. Modifications fall into 4 groups.

1. The particle loop was extended to include the calculation of vertical properties which were the same for all particles but now vary.

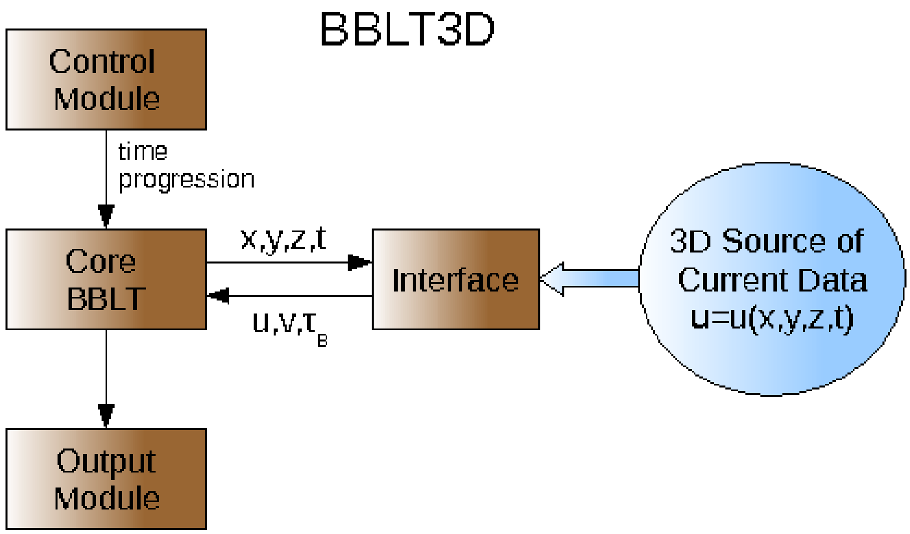

Figure 2: BBLT framework.

2. Removal of local BBLT specific code. This included calls to read velocity and bottom stress from a file and subsequent interpolation.

3. Changes to the input file

4. New features such as Runge Kutta advection and ability to change initial horizontal distribution of sediment.

Section 2 described new features and Appendix A gives details of the modifications. Modifications can often introduce errors to the code and for this reason a validation of BBLT3D was performed (Appendix B). The validation demonstrates that the core of BBLT3D was unchanged during the modification process.

3.2 Interface

The interface is a suite of subroutines and functions which provide core BBLT with the necessary external data at specified time and location. Table 1 summarizes the 5 subroutines and 1 function which are required by core BBLT. Care must be taken to ensure core BBLT and the outside world are in concert in their temporal-spacial arrangement.

3.3 Control Module

In BBLT v7 the main module of the code (bbltv7.f) contained the master time loop which carried out the sequence of operations referred to as core BBLT. In coupling the code

Table 1: Functions and subroutines required by core BBLT

---

subroutine init_get(xx,yy,timec) Called first to prepare the interface.

subroutine get_uv(uatz,vatz,xx,yy,zz,timec) Returns east and north component of velocity at specified location and time.

subroutine get_ustar1Lay(ust,xx,yy,timec) Bottom stress using 1 layer formulation

subroutine get_ustar2Lay(ust,xx,yy,timec) Bottom stress using 2 layer formulation (waves bottom layer)

subroutine get_hmax(hmax,xx,yy,timec) Returns the height of the bottom layer (hmax) at given location.

logical function is_land(xx,yy) Check to see if point is on land (currently only used by alternative discharge scenario).

---

with an external program, it was essential to remove the time loop and pass the time evolution to the external program which has it's own time progression. To accomplish this task, the main module of BBLT was converted into a subroutine which carries out one time step per call. The subroutine initializes the simulation the first time it's called and returns a logical flag to the external program telling it if the subroutine is to be called again. The time step for BBLT3D is still inside the input file. Care must be taken to ensure it matches the time step of the external model.

The external component of BBLT3D is what is refered to as the control module. This component is specific to the implementation of the code. In the stand alone case, the program is a simple main program with one loop which calls core BBLT until the simulation is completed. When embedded inside another program , the control module becomes a subroutine to be called by the program. It calls core BBLT once and performs whatever auxiliary tasks are required. In essence the control module becomes part of the interface which serves as a communication portal between the external program and BBLT3D. The distinction between the two is made in the direction the communication takes place. The control module executes the main BBLT computation, while the interface is a way for BBLT to request information from the external program.

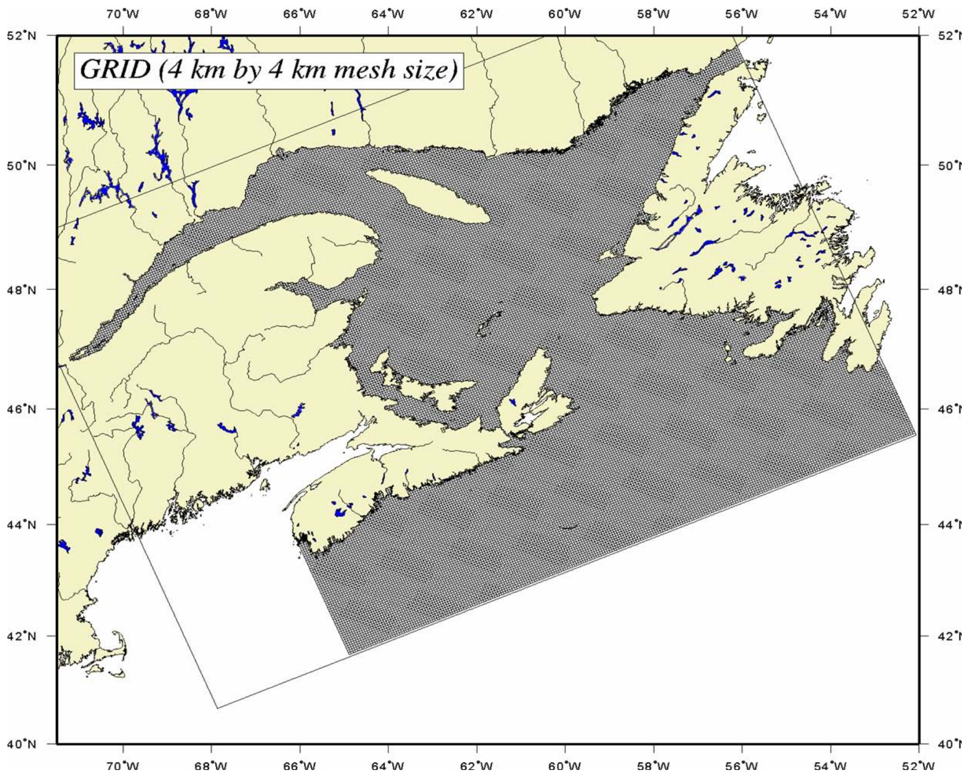

Figure 3: The domain covered by the circulation model used in the examples

4 Circulation Model Interface

For the present application, BBLT was coupled to a 3D prognostic hydrodynamic model of the Gulf of Saint Lawrence and Scotian Shelf (GSS4, Pers. Comm. J. Chassé, BIO). Figure 3 shows the domain covered by the grid. The model has a 4km nominal c-grid mesh with 32 vertical layers. It is coupled with the CICE ice model and uses NCEP atmospheric forcing. Also included are tides and fresh water runoff. Modelling is possible for 1948-Present as well as future climate scenarios.

The BBLT_Interface3D module contains subroutines specific for communication with the GSS4 model. It contains GSS4 implementations of the standard modules listed in Table 1 as well as supporting ones (Table 2).

4.1 Grid Alignment

In the present GSS4 implementation, the interface reads the location (lat,lon) of the BBLT grid origin and the calendar start date and time. From then onwards, BBLT functions relative to this location. The start time is the time index of the GSS4 model at which BBLT is to be first called. This delay allows the model to spin up before the

Table 2: Supporting functions and subroutines used in the interface with the GSS4 model

subroutine xxyy2x1y1(xx,yy,x1,y1) BBLT to GSS4 coordinate conversion.

function CalcUstar(ub,vb,friction,nfricp) Original BBLT function to compute ustar using polynomial drag law.

function get_dep(x11,y11) Gives depth at location

function valuebblt(A3d,index,xp,yp,zp,depxy) Used for c-grid velocity interpolation

sediment is released.

4.2 Bottom Stress

The bottom stress can be computed in 2 ways, with a quadratic drag law using only the bottom (1 meter off the bottom) currents in get_ustar1Lay, or using SEDTRANS96 (Li and Amos, 2001) with bottom currents and surface waves in get_ustar2Lay. To make the latter calculation possible, SEDTRANS96 was incorporated as a subroutine. The significant wave height, period and direction are passed to SEDTRANS96 along with the model current speed and direction at 1 meter off the bottom. The generic grain size of 0.25 μm was used (Hannah and Drozdowski, 2005; Li and Amos, 2001). The result is bottom stress due to waves and currents, stress due to currents only, as well as the wave layer height (Drozdowski et al., 2004).

A call to SEDTRANS96 is made at every time step and for each particle. Using SEDTRANDS96 slows down the execution time by an order of magnitude, much slower but still usable. Future implementations can speed up the execution by running SEDTRANS96 for all or part of the wet points (≈30K) rather then for all particles (100K-1000K). The result can be interpolated to particle position the same way other parameters are.

To use SEDTRANS96, set the number of friction parameters to -2 inside the BBLT input file. A time series of wave data (wave.dat), assumed to be constant in space, must be provided in the run directory. The file must have columns: year, month, day, hour, minute, seconds, significant wave height, period and direction. Nearest neighbour time interpolation is used at run time.

4.3 Velocity Interpolation

The interpolation of the velocity field proved to be the main challenge of creating an interface to a 3D velocity field. A simple bilinear interpolation of the 4 nearest neighbours can often lead to flow fields that propel particles onto land (where they can get beached) or regions were persistent near zero currents trap particles. An interpolation scheme which uses nearest neighbour extrapolation onto land was developed following (Bennet and Clites, 1987).

The code is contained in a function `valuebblt` which is called by `get_uv`, a standard interface subroutine found in Table 1). A call is made to `valuebblt` once for each of u and v. This is done for each particle at each time step. The implementation focused on speed and reliability near land and topographic features. A logarithmic bottom boundary layer was implemented for depths below bottom layer of the model. The implementation followed local BBLT (Drozdowski et al., 2004).

The vertical velocity was not included in the interpolation. In BBLT, vertical movements are governed by the prescribed Rouse profile and random mixing. Inclusion of a vertical component of velocity would have no net affect on the dynamics. As a result of this, extra care must be taken to ensure the interpolated velocity field is continuous and reflects local horizontal transport.

For complete details of the interpolation see Appendix C.

5 Applications

5.1 Cheticamp Region

The waters off Cheticamp in the southern Gulf of Saint Lawrence is a region being considered for possible oil/gas drilling. ADCP data from the region was available (Pers. Comm. J. Chassé, BIO). The deployment took place June to September of 2005. Figure 4 shows the location of the 3 ADCP deployments.

Figure 5 shows the comparison between observed and modeled currents at the location of mooring #1579 . Shown are the velocity components (eastward and northward) of the vertically averaged flow. The model reproduces the tidal oscillations very well, but underestimates the lower frequency currents. Many of the large current events and reversals are not captured. However, the prevailing northeast flow direction is reproduced by the model. The region is difficult to model because wind is steered by topography of the Cape Breton Highlands, a feature below the resolution threshold of the NCEP forcing. Comparison with the other 2 moorings (not included here) yielded similar results.

`Description of BBLT runs`
To gauge the magnitudes and directions of dispersion and advection in the region being

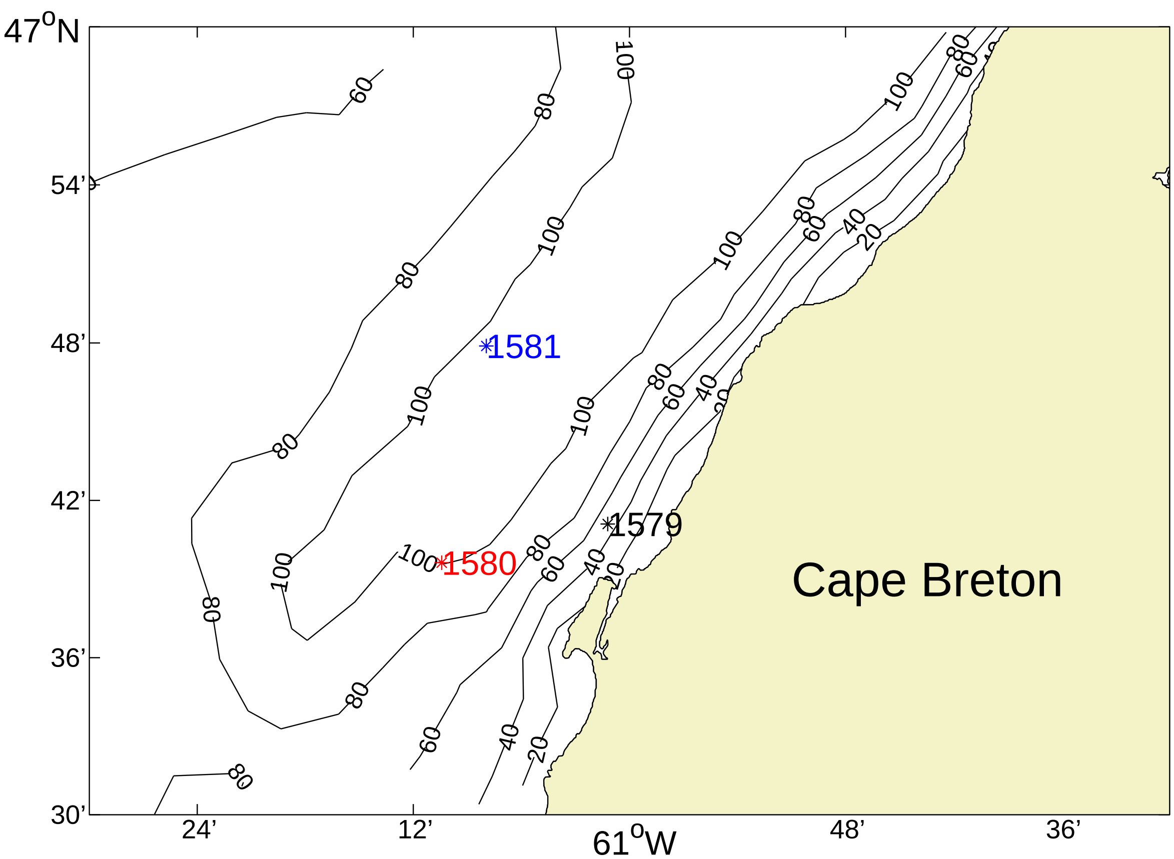

Figure 4: Location of ADCP deployments near Cheticamp, NS.

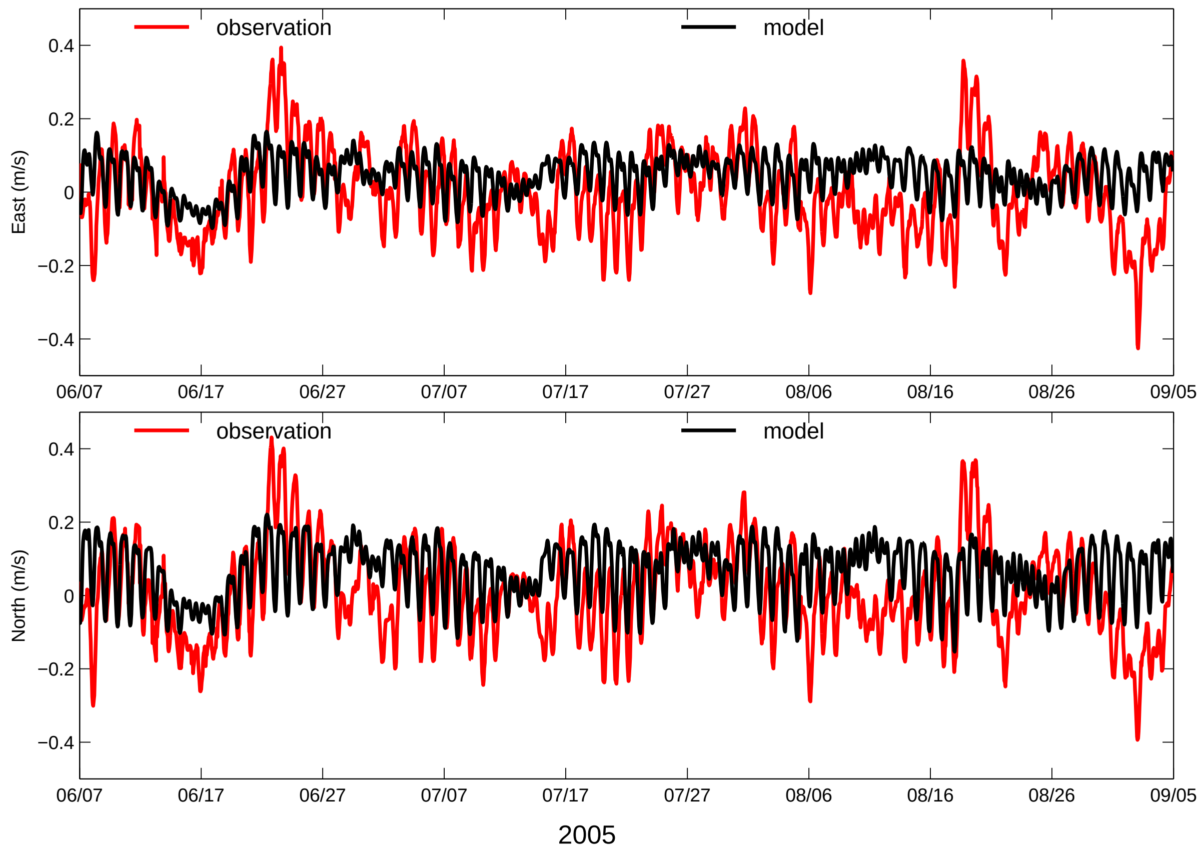

Figure 5: Comparison of the vertically integrated currents from mooring 1579 with GSS4 model.

Table 3: BBLT parameters of runs near Cheticamp.

Parameter	**Value**
Number of Packets (N)	2.5×10^5
Vertical Mixing Timescale	3.3 h
Advection Time Step	5 min
Simulation Period	10 days
Total Sediment	212 T
Reference Height (href)	0.0035 m
Settling Velocity	$0.1\ \mathrm{cm\,s^{-1}}$

considered, BBLT was set up to run several 10 day simulations covering the time period of the ADCP deployments. A total of 17, 10 day simulations were performed starting in June, 2005. The runs were staggered, so each subsequent run started 5 days before the end of the previous one. For other parameters refer to table 3.

`Discussion`
Figure 6, 7 and 8 show the results of the simulation. 3 scenarios are compared:

1. BBLT3D using full 3d currents from ocean model
2. Local BBLT results using ADCP data
3. BBLT3D pseudo1d. Using model currents from release site only.

In every scenario, with the exception of the 1580 site in local BBLT, the transport is in Northeast-Southwest axis along the shore. Local BBLT runs have much larger advection that is not seen with BBLT3D or even the pseudo1d simulation. Advection is being underestimated in the modeled currents. In addition, site 1579 modeled with local BBLT has current reversals which cause the sediment in some 10 day simulations to go in opposite directions. This feature is not seen with BBLT3D, most likely due to the limitations in wind forcing discussed above.

The size of the ellipse, which represents how much dispersion has taken place, is typically larger in the local BBLT case. The model is underestimating vertical shear in the currents.

Some local BBLT runs for mooring 1580 and 1581 wash up on shore. This is a limitation of local BBLT which does not resolve the currents steered by the deep basin and coastline.

5.2 Sydney Bight

The Sydney Bight area in the Cabot Strait is another location being considered for oil and gas exploration. Waves in this region are stronger than in the southern Gulf due to it's exposure to the North Atlantic, making this location suitable for studying wave

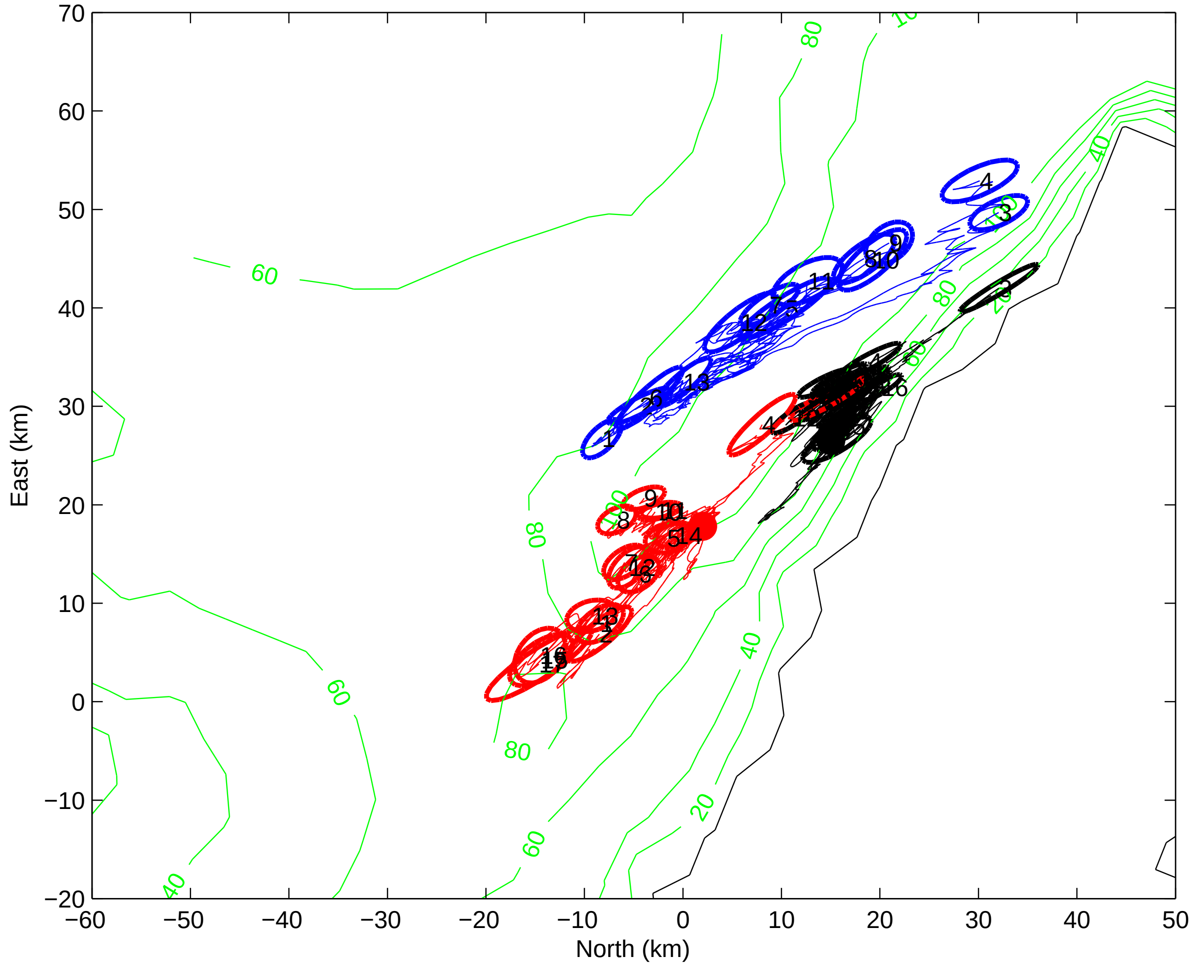

Figure 6: Tracks and final locations of sediment at the 3 Cheticamp mooring locations. For every location there were 17 BBLT3D simulations each spanning a 10 day period (comparison 1). Collectively the simulations cover the entire period the ADCP mooring was deployed. The ellipse inscribes particles within root mean square departure from center of mass.

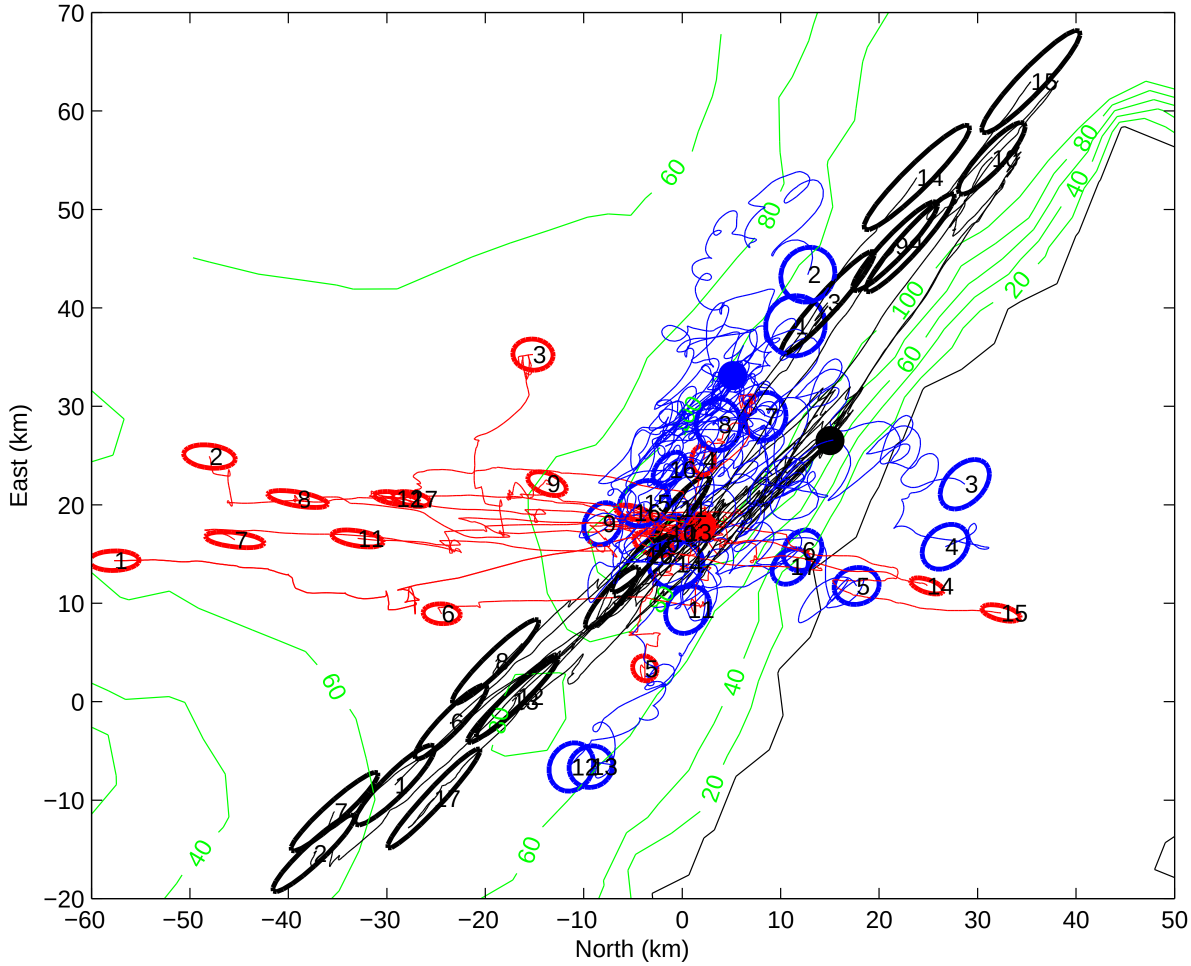

Figure 7: Tracks and final locations of sediment at the 3 Cheticamp mooring locations. For every location there were 17 local BBLT simulations each spanning a 10 day period (comparison 2). Collectively the simulations cover the entire period the ADCP mooring was deployed. The ellipse inscribes particles within root mean square departure from center of mass.

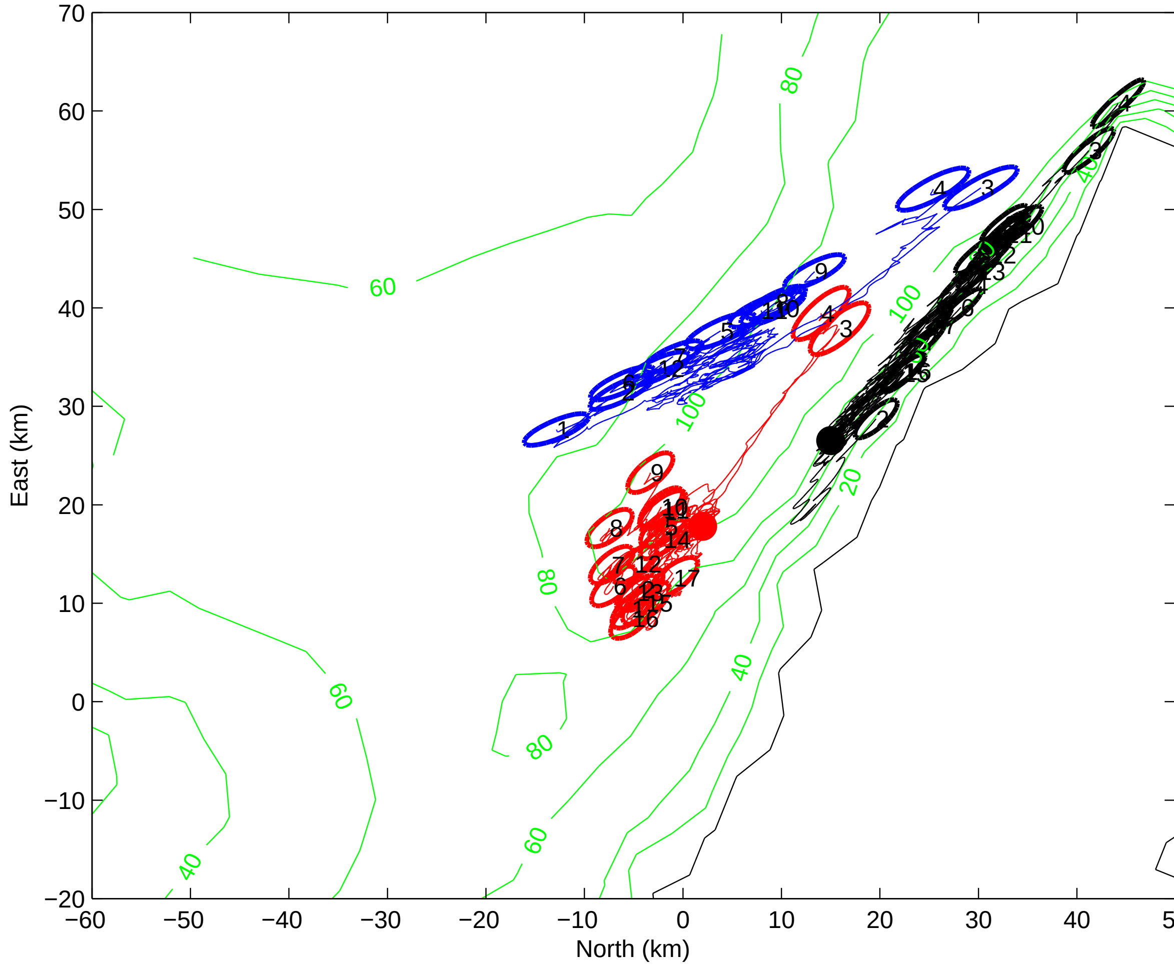

Figure 8: Tracks and final locations of sediment at the 3 Cheticamp mooring locations. For every location there were 17 pseudo1d BBLT3D simulations each spanning a 10 day period (comparison 3). Collectively the simulations cover the entire period the ADCP mooring was deployed. The ellipse inscribes particles within root mean square departure from center of mass.

ID	#runs	waves	settling	Model	Fig.
1	12	no	slow	3D	9
2	12	no	barite	3D	10
3	12	yes	barite	3D	11
4	12	yes	barite	pseudo1D	12
5	12	yes	barite	local	13

Table 4: Different scenarios considered for the Sydney Bight simulations

affects and the SEDTRANS96 functionality of BBLT3D. ADCP deployments took place in Spring 2007, allowing for an intercomparison of local forcing derived from observation, versus modelling. The focus of the BBLT simulations carried out in this region, was placed on an inter-comparison of various biological impacts resulting from different model configurations.

`Description of runs`

12, 10 day runs were carried out in the Feb-May 2007 period (the time of the ADCP deployment). At the time this work was done the GSS4 model lacked the NCEP forcing for this period. The runs where carried out using the corresponding dates in 2006. In the future the runs will be updated with the correct forcing. However, no major change in the dynamics is expected. The runs were staggered as was the case in the Cheticamp simulation (See 5.1). The closest available wave data was from the Burgeo Wave Rider (Cabot Strait close to NFLD). The wave period, height and direction were assumed horizontally uniform for the modeled region. SEDTRANS96 was used to compute bottom stress due to currents and waves. Other BBLT parameters were the same as those shown in Table 3 for the Cheticamp runs. Table 4 shows the different configuration scenarios considered. The meaning of the settling parametrization will be discussed below.

BBLT uses a biological impacts module that is based on a growth-days-lost (GDL) formulation determined from laboratory experiments on scallops (Cranford et al., 2003). In these experiments, two thresholds were estimated from exposure to bentonite and barite: the no-observed-effects and no-growth concentrations. Our simulations used threshold values for barite; these were 2 $\mathrm{mg\,L^{-1}}$and 10 $\mathrm{mg\,L^{-1}}$. Impacts or concentrations between the threshold are computed with linear interpolation. Impacts outside the thresholds are truncated at the threshold values. For further details see Drozdowski et al. (2004).

`Discussion`

The first scenario gives us a basic idea of what is happening. This a slow settling (0.1 $\mathrm{cm\,s^{-1}}$) scenario which gives the widest dispersion. It can be considered as the worst case because the slow settling particles are dispersed and affect a broader area. It can also be considered least impact scenario if you are talking about near-field impacts only, in which case the particles are flushed out more quickly. A more detailed impact analysis would have to be carried out to determine which scenario is more damaging overall.

The second scenario is a more realistic portrait of barite, a waste product released during

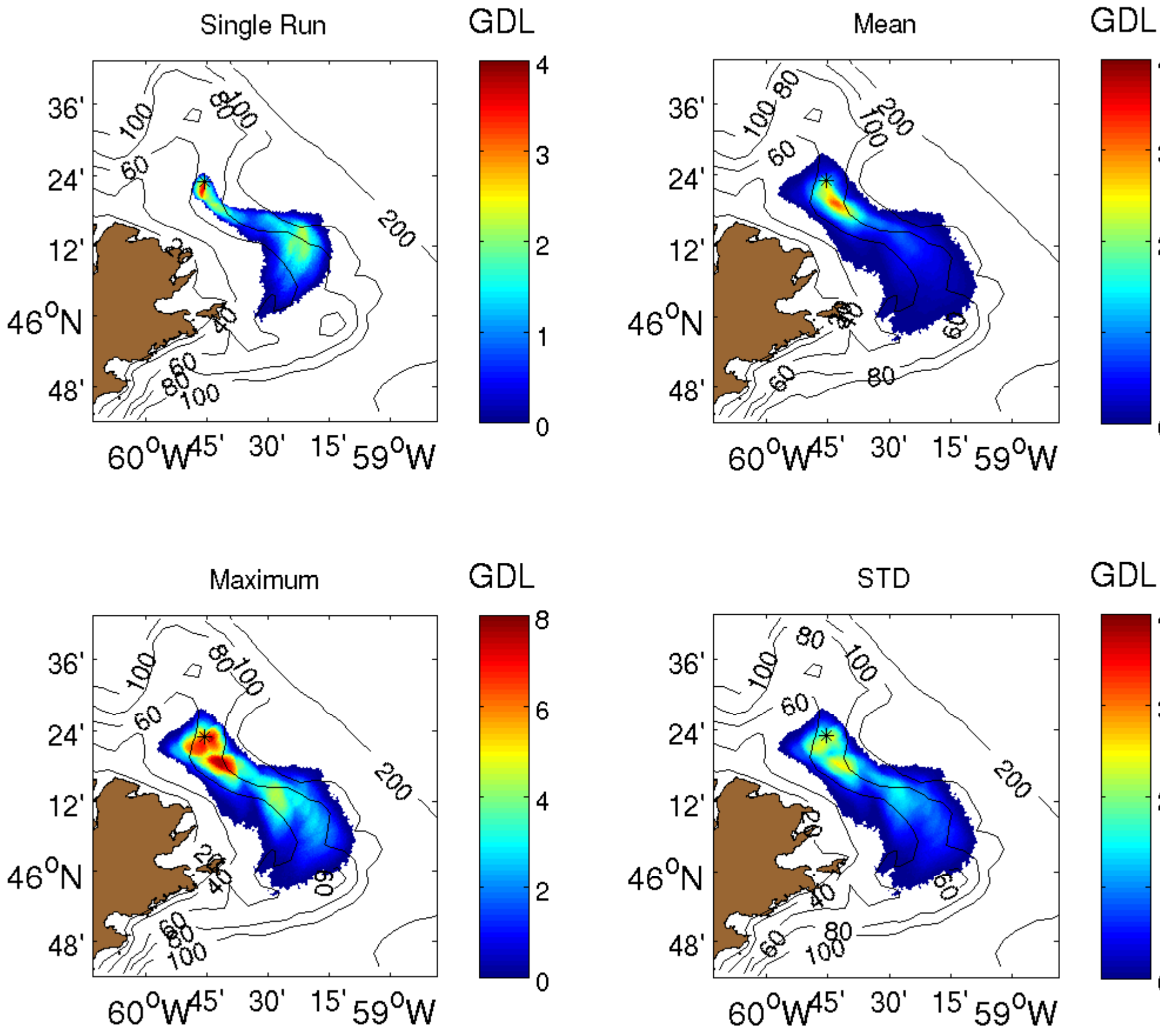

Figure 9: Statistics based on 12, 10 day Sydney Bight simulations using the slow settling scenario and no stress due to waves. The simulations used the full 3d GSS4 currents coupled with BBLT3D. Panels show the result of a single run (top left), the mean of the 12 simulations (top right), the maximum of the 12 simulations (bottom left) and the standard deviation (bottom right). Note the color scale for the maximum impact is different.

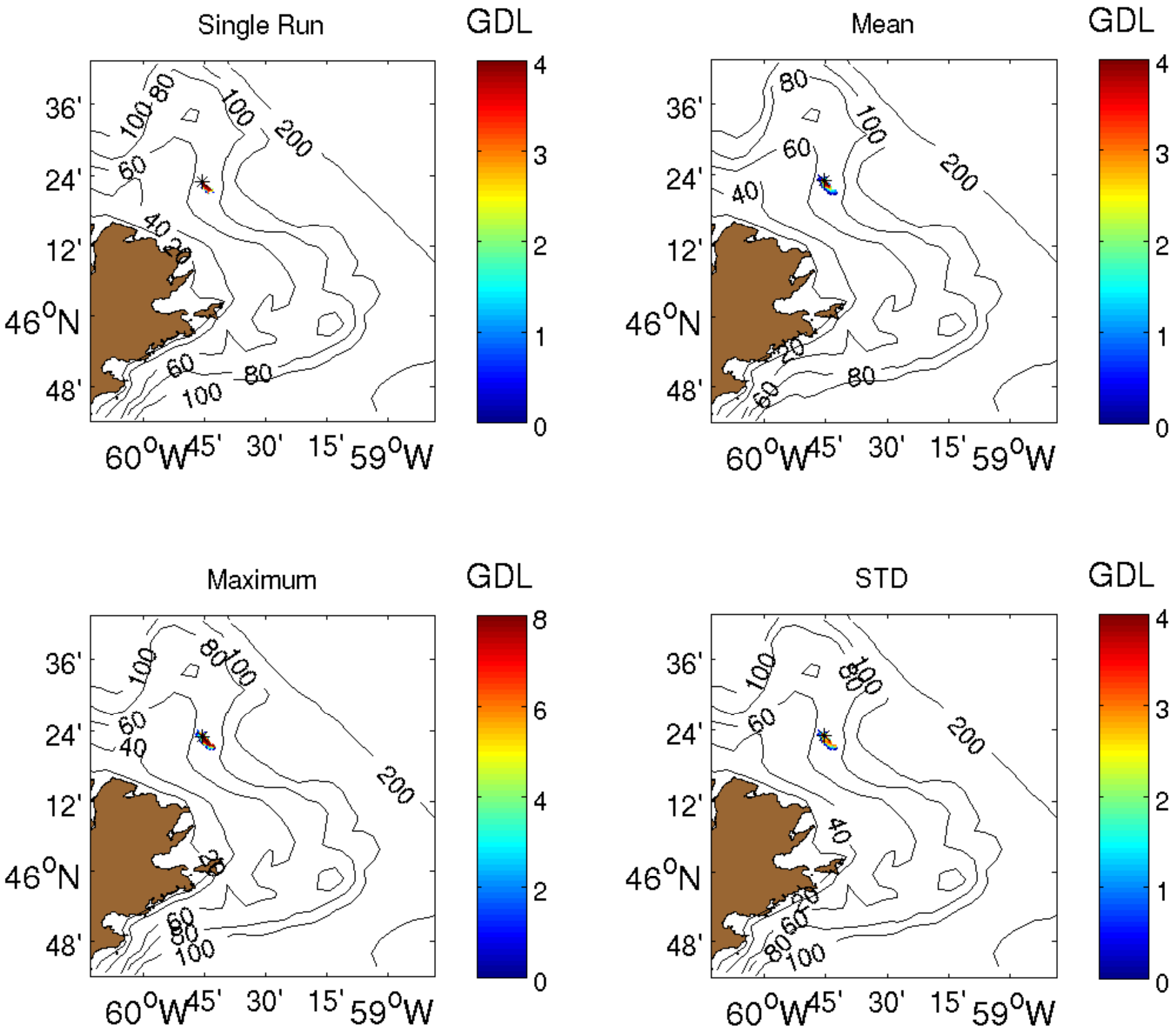

Figure 10: Statistics based on 12, 10 day Sydney Bight simulations using the barite settling scenario and no stress due to waves. The simulations used the full 3d GSS4 currents coupled with BBLT3D. Panels show the result of a single run (top left), the mean of the 12 simulations (top right), the maximum of the 12 simulations (bottom left) and the standard deviation (bottom right). Note the color scale for the maximum impact is different.

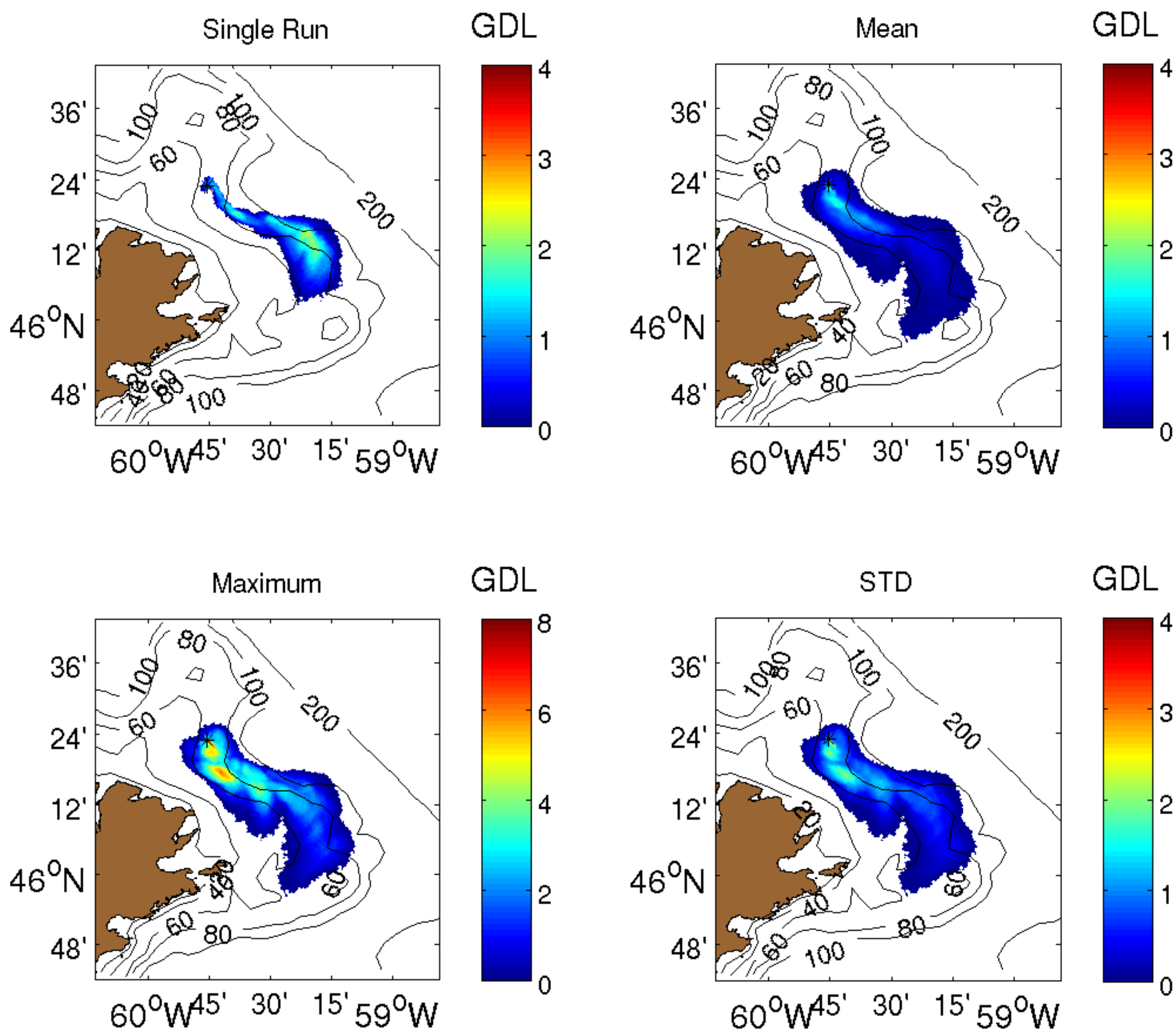

Figure 11: Statistics based on 12, 10 day Sydney Bight simulations using the barite settling scenario and stress due to waves. The simulations used the full 3d GSS4 currents coupled with BBLT3D. Panels show the result of a single run (top left), the mean of the 12 simulations (top right), the maximum of the 12 simulations (bottom left) and the standard deviation (bottom right). Note the color scale for the maximum impact is different.

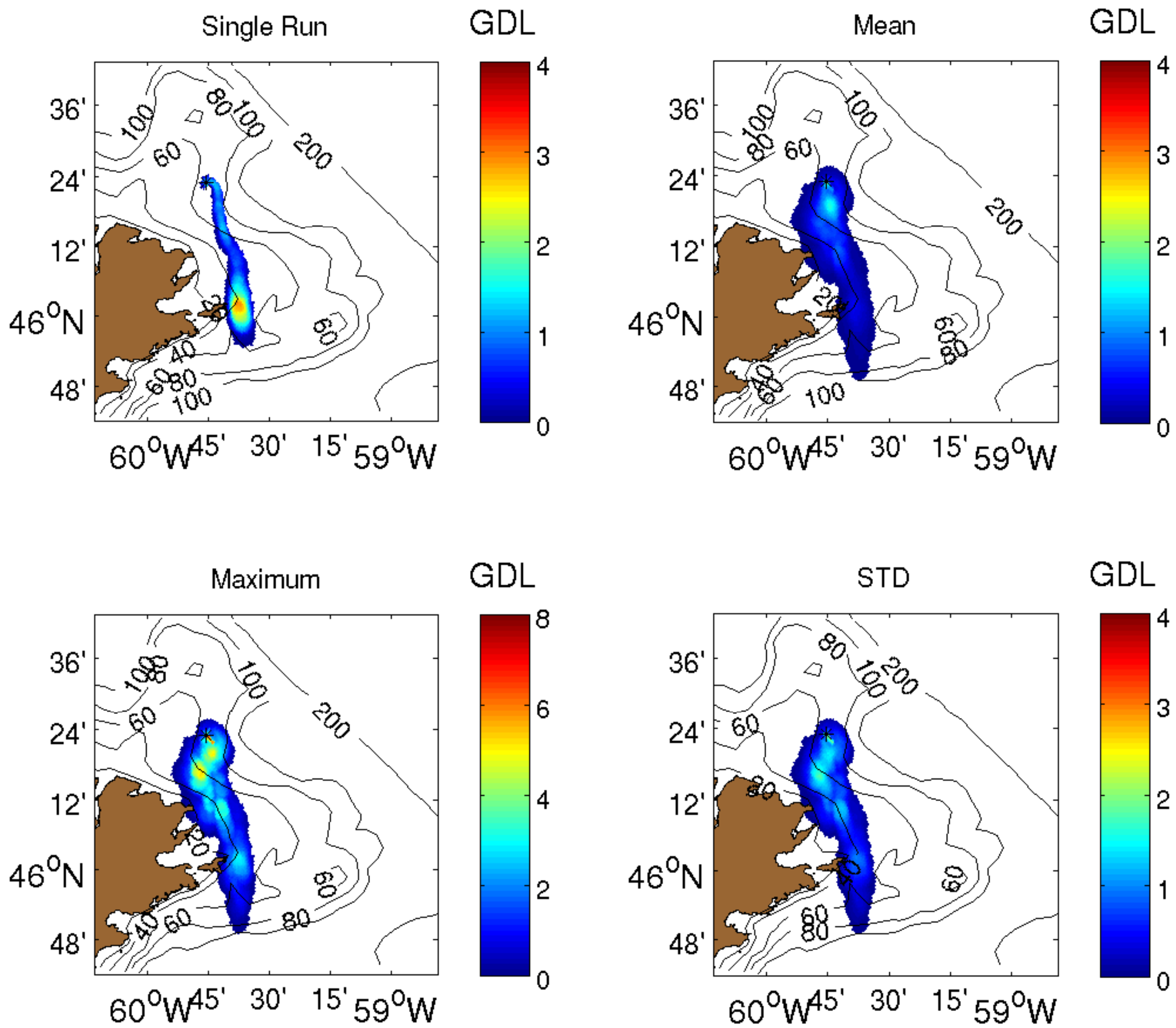

Figure 12: Statistics based on 12, 10 Day Sydney Bight Simulations using the barite settling scenario and stress due to waves. The simulations used currents only from release location coupled with BBLT3D. Panels show the result of a single run (top left), the mean of the 12 simulations (top right), the maximum of the 12 simulations (bottom left) and the standard deviation (bottom right). Note the color scale for the maximum impact is different.

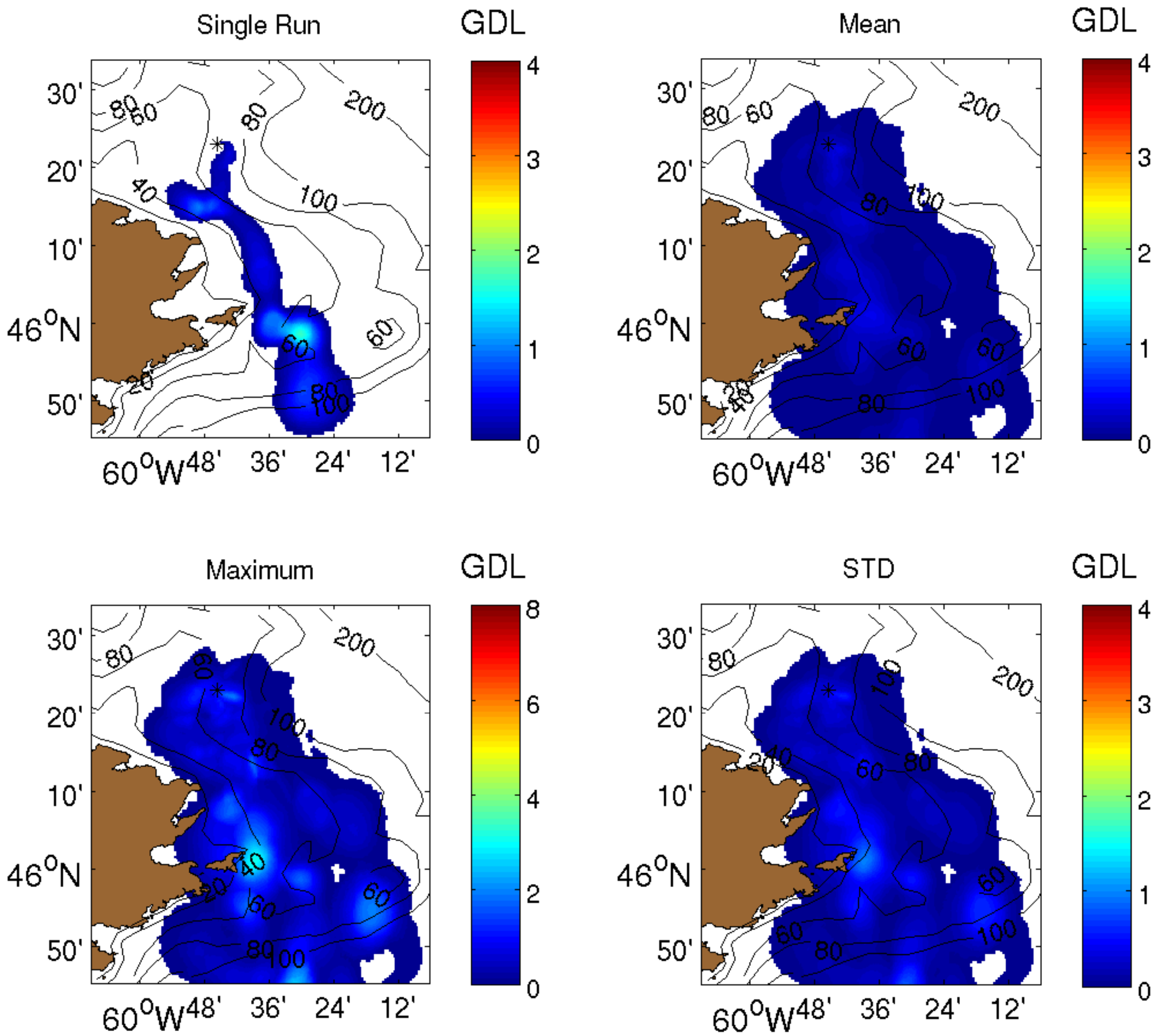

Figure 13: Statistics based on 12, 10 day Sydney Bight simulations using the barite settling scenario and stress due to waves. The simulations used BBLT ver. 7 in conjunction with the observed currents at release site. Panels show the result of a single run (top left), the mean of the 12 simulations (top right), the maximum of the 12 simulations (bottom left) and the standard deviation (bottom right). Note the color scale for the maximum impact is different.

the drilling phase of oil and gas production. The sediment is expelled in large flocs with fast (0.5 $\mathrm{cm\,s^{-1}}$) settling velocity, which leads to large near the bottom concentrations and low resuspension rates. A critical friction velocity value of 0.01 $\mathrm{m\,s^{-1}}$ (0.1 Pa) is needed to achieve breakup of flocs into fines (Hill et al., 2001). Once this slow settling state (0.1 $\mathrm{cm\,s^{-1}}$) is achieved, no further flocculation takes place. The results for this scenario show the sediment accumulating near the release site with high values of GDL (> 4). No impacts occur away from the release site. This is attribute to the bottom stress not exceeding the critical value. In this scenario, bottom stress is computed only from the near-bottom modeled velocity. The sediment sits too close to the bottom for significant transport to occur.

The third scenario has the same settling scenario as the previous. But this time the additional stress due to waves provides the trigger for breakup. This changes the impact dramatically. It bears much more resemblance to scenario 1 than 2. The mean distribution pattern is very similar for both. However scenario 1 reaches higher values in the center of the impact plume. Both reach the same maximum value $\approx$8 GDL but for scenario 1 it has a broader extent. The larger impact values of scenario 1 can be attributed to the higher suspension rates caused by the additional wave contribution to bottom stress in scenario 3.

The parameters of the 4th scenario are identical to the 3rd in all respects but one. The entire simulation is carried using only currents from the release site. This creates a horizontally uniform environment which mimics local BBLT. The goal of this scenario is to gauge the affects of removing 3d currents. The most striking feature of the pseudo1d scenario is that all impacts occur directly south of release site. The sediment moves across bathymetry contours and even onto land (with the pseudo1d modification to the code, land boundaries are ignored since interpolation always takes place at release site). The impact pattern of scenario 3 follows contour lines, something we would expect the mean flow to do. If we examine the top left panels of scenario 3 and 4, which give results of a single simulation, we can see the impact of scenario 4 is narrower but slightly stronger at the highest impact location (3.0 GDL, compared with 2.5 GDL for scenario 3). With this we are seeing the direct affect of horizontal shear in the currents which the pseudo1d scenario is lacking. This 0.5 GDL difference is visible in the single run only. It is likely to be lost in statistics due to horizontal differences in 12 runs. A better analysis would be an inter-comparison of the GDL difference between each of the 12 runs and statistics based on that difference.

The parameters of the 5th scenario once again are identical to the 3rd in all respect but one. This time the entire simulation was carried out using local BBLT with currents taken from observation at release site. The goal of this simulation was to examine the limitations of using modeled ocean currents. This can be done by examining the differences between this scenario and scenario 4. The most striking feature of this simulation is how low and how broadly spread out the impact is (about double the impacted area for the single run and 4-5 times the area for the statistics). The highest impact location values are much smaller with 1 GDL for the mean and 3 for the maximum compared to 2 and 5 GDL for scenario 4. What we are seeing here is the large amount of vertical shear present in the observation which the model lacks.

6 Conclusion

BBLT3D was designed to overcome the limitations of local BBLT. Local BBLT applications in dynamic environments can run into difficulties such as violation of topographic constraints. The BBLT3D implementation is based based on BBLT version 7. Minimum changes where made so that the core of the code as well as input and output are very similar to older versions. The design focused on compatibility with arbitrary sources of 3d currents. Presently, only an interface to the GSS4 Gulf of Saint Lawrence model was developed. Efforts are being made to couple BBLT3D with the NEMO shelf circulation model which covers the Gulf of Maine, Scotian Shelf and Gulf of Saint Lawrence. The aim of this report was a description of the development of BBLT3D, future work will focus more closely on applications.

Validation of the new code was done by comparing runs done with the circulation model using only currents from the release site to runs done with local BBLTusing currents exported from the ocean model. Another validation was done by coupling the code with a horizontally uniform rotary and linear flow fields. The dispersion from these runs was very similar to previous local BBLT fits to analytic solutions (Drozdowski et al., 2004).

Demonstrations of the new code were made in waters off Cheticamp and in the Sydney Bight area. In most cases the ocean model underestimates the vertical in the currents. However comparison of model runs using horizontally uniform currents versus the fully modeled 3d currents shows importance of horizontal shear in the dispersion and drift dynamics. The results are reasonable and show the wide range of application for this new version of BBLT. The demonstration also shows the limitations of local BBLT. This can be seen in both the Cheticamp and Sydney Bight applications when currents only from the release site are used. The results of these applications are only reliable in the near field region. In the far field the results are questionable due to drift onto land and across bethymetric contours.

From a modelling stand point BBLT3D has the following advantages. It can be used with relative confidence in near shore locations where horizontal shears are known to dominate the dispersion dynamics. BBLT3D can also be used to model arbitrary sediment distributions. This was possible in local BBLT, but there it yielded little new informations due to the assumption of horizontal uniformity.

From a pragmatic stand point, the use of 3d circulation models can reduce the need of costly current meter deployments. BBLT3D can be used to obtain quick estimates of sediment transport for any location and time within the circulation model's domain.

With local BBLT extracting currents from the circulation model and converting them to the correct format was a slow process. The task is greatly simplified with a direct interface as was developed here. The greater efficiency allows for greater utilization of the modelled currents. By performing an exhaustive sensitivity analysis for a region of interest we can gage the relative magnitudes of diffusivity at different spots. This process can aid in determining optimal location current meter deployments or benthic sampling.

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A Details of Modifications to the BBLT code

A.1 Modifications to Vertical Calculation

The vertical position of each particle is calculated from the bottom stress using the modified Rouse profile (Rouse, 1937). In local BBLT, this involves computing the cumulative mass distribution table (ComputePDF), which gives the fraction of the total mass below a given vertical position. The table contains ≈ 60 log distributed entries (i.e. more entries near bottom). The vertical position of each particle is then determined inside the main particle loop by matching rank with mass fraction. The rank is a number between 0 and 1 assigned during initialization and retained until vertical mixing occurs (Drozdowski 2004). In the local BBLT formulation, particles share the same bottom stress and hence only one calculation of the mass distribution table is needed per time step. In the 3D compliant formulation, the table must be computed for each particle.

The straight forward inclusion of the call to the computePDF subroutine inside the main particle loop increased the total computational time by 2 orders of magnitude. The reason for this time increase is the overhead cost in creating the lookup table for each particle as well as the large number of math operations (logs and exponentials) involved. The calculation time was reduced to previous levels by avoiding the computation of the lookup table altogether. The tasks of ComputePDF and AbRVertPos2 were combined into one iterative search algorithm (H_AtRank). The basic idea is to make a guess and then lower the search domain until the desired tolerance is reached. The size of the search domain decreases by powers of 2 and the solution is generally found within 2-4 iterations.

A.2 Removal of local BBLT specific code

The time progression of older versions of BBLT was dependent on the velocity time step (dtvel) and the advection (dta). The former defined the time between velocity updates while the latter was the actual desired resolution to which the velocities where to be interpolated. In the new 3D arrangement only the advection time step plays a role. The velocity time step is still retained as part of the input. Its value can be set to equal dta or any multiple of dta with out any impact on the calculation.

A.3 Changes to input file

Some changes were made to the BBLT input file. Since the lines specifying the current-meter and bottom stress files are no longer needed, they have been excluded. The discharge type parameter includes 2 new features in addition to 2 old ones: 0=time series,1=bulk discharge, 3 = uniform distribution over grid, 4= user defined patch (for features 3 and 4, the user might need to modify details in CrtPckts.f). The rest of the input file remains intact. Some parameters like the number of friction parameters have been retained for backward compatibility even though they are unused. For the same reason, two empty lines are read where there was once input in the old version. Older BBLT input files should be compatible with BBLT3D provided the velocity file lines have been stripped out. An example of an input file is shown below.

```
/home4/tmp/BBLTout/echo.out     # echo file
379481019       831796018       # random seed
120.08333333    0.              # total hours of simulation, start day
0.08333333                      # velocity update step
0.08333333      3.3             # advection time step, mixing timescale
2                               # vert. mix. method
-1                              # num. fric. peram.
******************              # empty
0.001   0.001   0.0001  -1.0    # settling velocities
0.4     0.0035                  # kappa, href
******************              # empty
1                               # discharge type (0=series,1=bulk,etc)
212000000.   250000    1.0      24.0  # discharge scenario
1.0                                   # Output params :
/home4/tmp/BBLTout/sedparams.out
1.0
/home4/tmp/BBLTout/vel.out
1.0
/home4/tmp/BBLTout/stats.out
0.0035 0.1035 250
10000000.0
/home4/tmp/BBLTout/pack.out
1.0
/home4/tmp/BBLTout/cnstr.out
1
0. 0. 250 0.0035 0.1035
1.0
/home4/tmp/BBLTout/cnstrmp.out
151 -30000 45000 151 -30000 45000 0.0035 0.1035
1.0
```

```
/home4/tmp/BBLTout/biology.out
0.1 0.5
1.0
/home4/tmp/BBLTout/biologymap.out
0.1 0.5
```

B Validation

The purpose of this validation was to determine if the core of BBLT3D still works fundamentally the same as it's predecessor, BBLT v7.0. A version of the interface called `pseudo1d` was created for this purpose. It overrides the 3d behaviour of the ocean model and returns velocities at the sediment release location. A time series of these velocities was written to file at 1 meter vertical resolution above 1 meter. Below 1 meter, velocities were saved at 0.02, 0.05, 0.1, 0.2 and 0.5 meters off the bottom. A bottom stress file was also saved for the simulation. The stress was computed using quadratic stress law computed with the speed 1 meter off the bottom. Stress due waves was not considered. The aim was to establish basic validation. The saved files were used to create BBLT v7.0 input.

A 10 day simulation at Syndey Bight was done with BBLTv7.0 and the `pseudo1d` version of BBLT3D. The comparison is shown in Figure 14 and Figure 15. The agreement is almost perfect. Slight deviation are expected since sampling resolution in the vertical was finite.

A comparison more theoretical in nature was made using BBLT3Din stand alone mode. The interface in this example supplied flow fields based on the steady and rotary flow examples of Drozdowski et al. (2004). Figure 16 reproduces Figure 19 of that document. The plot shows how dispersion relates to the vertical mixing time scale,a parameter that controls the amount of random vertical movement. Dispersion was computed from the slope of the variances. Refer to table 4 of that report for a complete explanation of the simulations. Vertical mixing method 2 was used in this simulation.

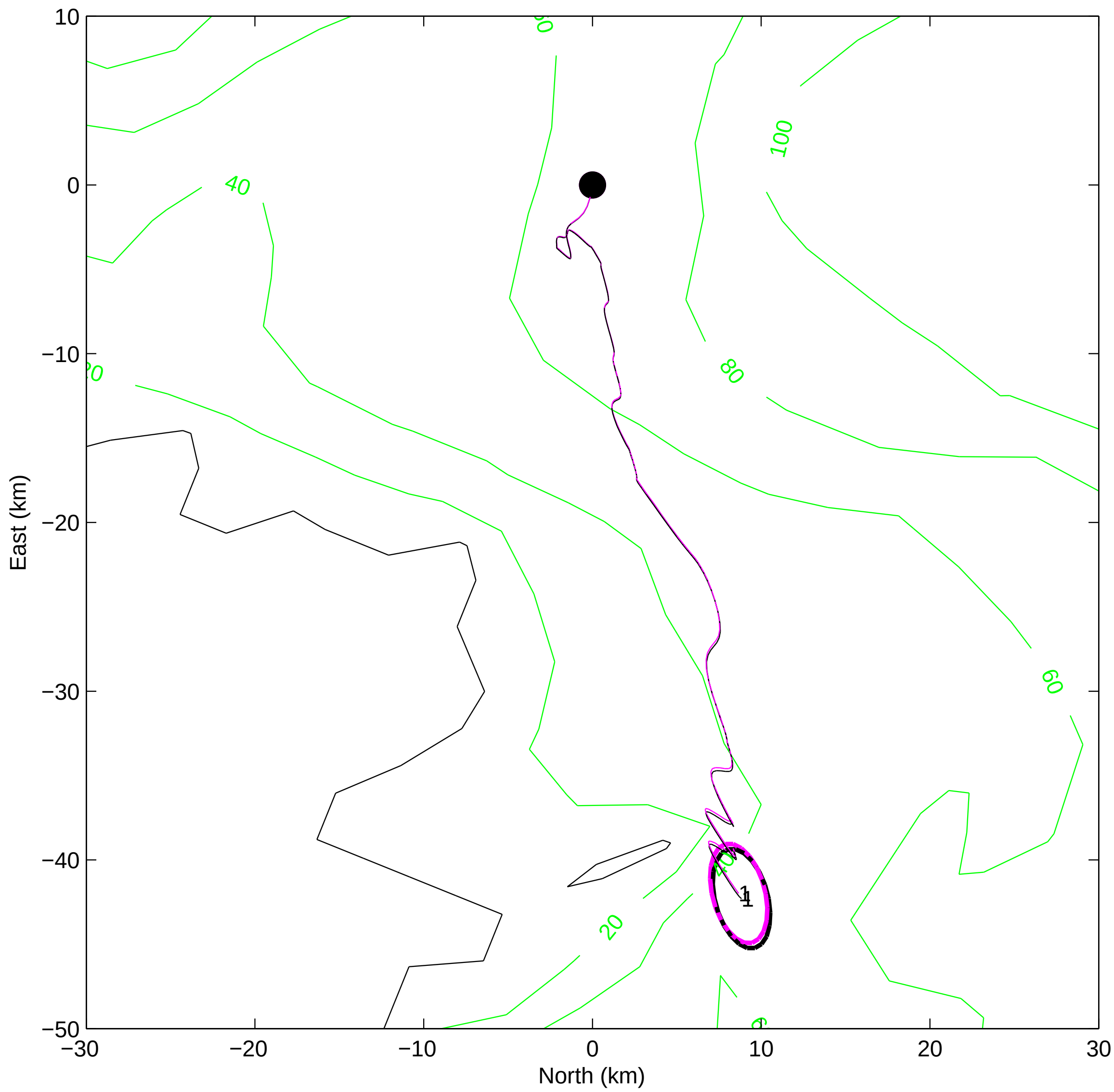

Figure 14: The comparison of `pseudo1d` (red) with BBLT v7.0 (black). Shown are track and size of center of mass of sediment. The ellipse inscribes particles within rms departure from center of mass.

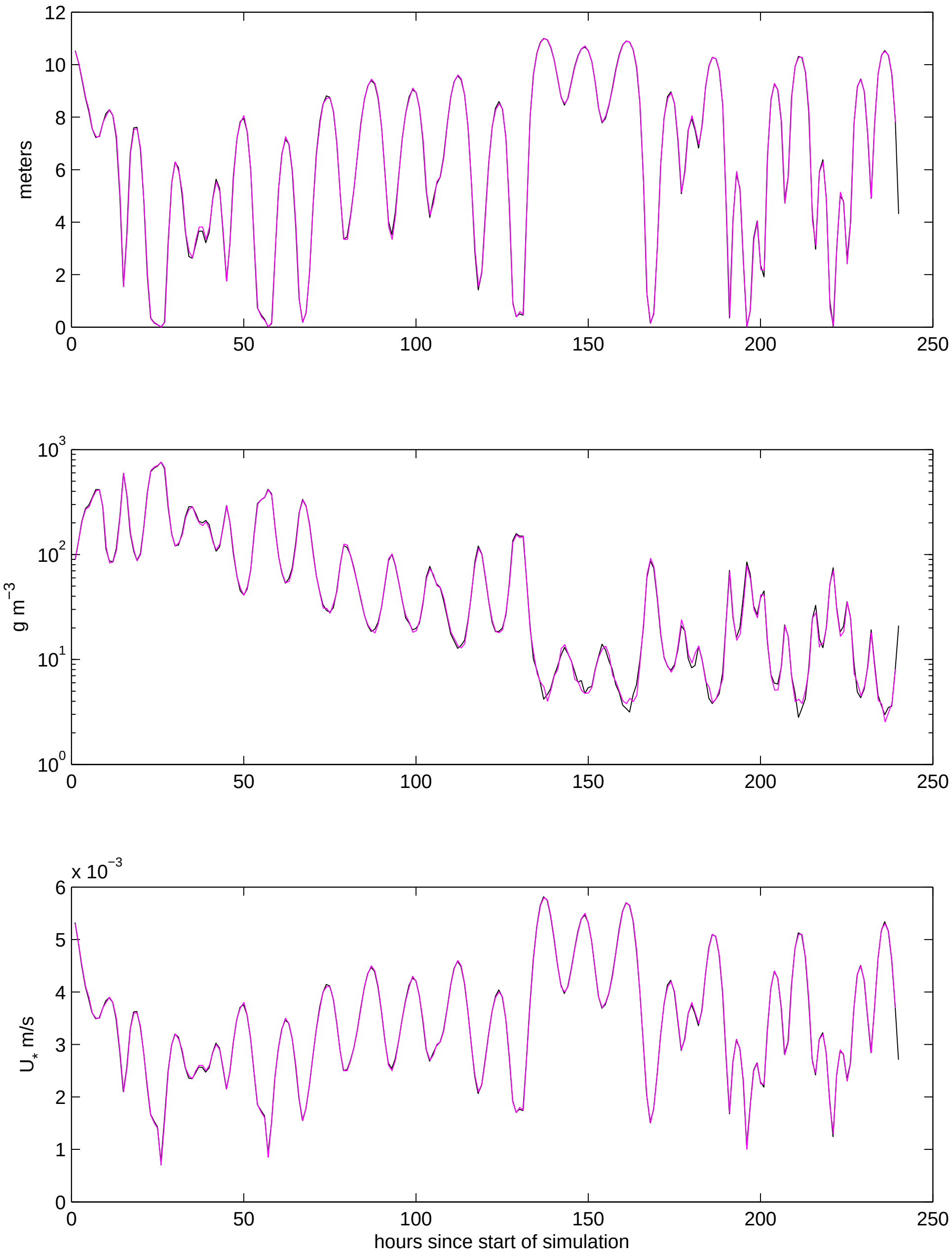

Figure 15: The comparison of `pseudo1d` (red) with bblt v7.0 (black). Shown (down from the top) are the mean vertical position of center of mass, near-bottom concentration at center of mass and bottom stress.

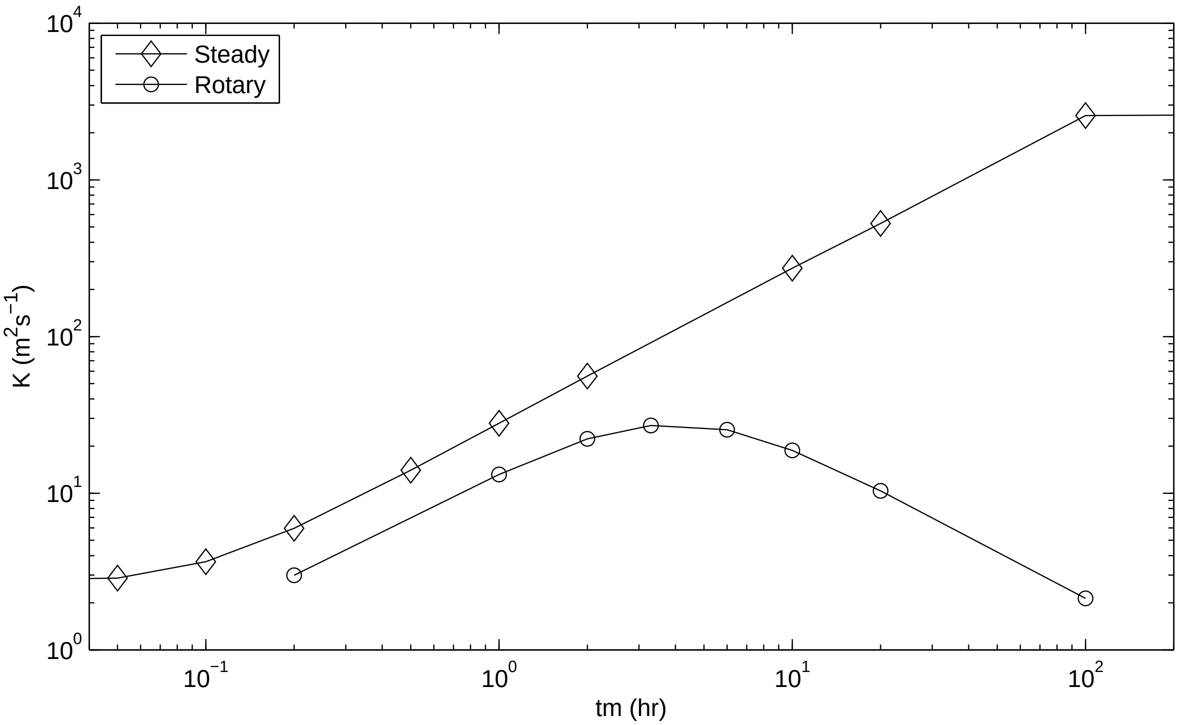

Figure 16: Impact of vertical mixing time scale parameter on dispersion. Test cases are for the Steady and Rotary flow of Drozdowski et al. (2004)

C Velocity Interpolation

At its core, `valuebblt` uses 4 neighbour bilinear interpolation. Interpolating velocity near topographic features required some fine tuning. The goal was for particles to move near land-water with as little artificial drag as possible and to reflect local transport while respecting land-water boundaries. The implementation below is for the GSS4 model but can be used with any c-grid model. The basic method is to bring the u and v values which are located on the midpoint of the sides (c-grid), to a common place at the corners of the cell, the b-grid (Bennet and Clites, 1987). The following steps were taken:

1. Find the cell in which the point of interest falls.
2. Identify 4 corners and 2 neighbour cells. This yields 6 velocity components.
3. for each of the 6 velocity components, Interpolate vertically by finding 2 bounding layers. For depths above middle of top layer and below middle of bottom layer, use nearest layer (i.e top or bottom). Care must be taken in wet cells adjoining topographic features (not coast). In these places use the nearest vertical layer that does not adjoin land.
4. Check to see if velocity point in local cell or the one directly above it adjoin the coast. Replace zero coast values by non zero values from opposite side of cell. This ensures correct transport for particles across the entire cell.
5. For each corner average the velocity component from the 2 neighbour cells. If one of the 2 is on the coast, use only the other.
6. Check to see if particle is washed up on land. If this is the case reverse the velocity toward nearest wet cell. Apply minimum of 10 $\mathrm{cm\,s^{-1}}$ in this direction. The goal hear is to nudge particles toward water. This is somewhat artificial but is the best way to ensure particles stay where they are supposed to.
7. If particle is below the middle of bottom cell, apply a logarithmic bottom boundary layer correction to the velocity. This ensures the velocity profile transitions to zero following the methodology derived and used by older versions of BBLT. This step particularly important, as most of the vertical shear which is crucial for dispersion in BBLT, occurs in this region.