Modelling the estuarine circulation of the Port of Saint John: Visualizing complex sound speed distribution.

Ian CHURCH, John HUGHES CLARKE, Susan HAIGH and Reenu TOODESH, Canada

Key words: Hydrodynamic Model, Sound Speed, Uncertainty Analysis, Estuary

SUMMARY

Hydrodynamic tidal models are currently being constructed for ports and harbours around the world to simulate the amplitude and phase of the tides and build spatially varying tidal datums. As surface fluctuations are the primary interest, these models use an isodensity assumption (barotropic), which ignores sub surface conditions of estuarine circulation. By extending the reach of the model to capture the three dimensional density distribution (baroclinic), the structure and variability of the physical properties of the water column can be monitored.

A project is currently underway in the Port of Saint John, New Brunswick, to model the estuarine dynamics that drive sediment resuspension for prediction of dredging requirements. To initialize and validate the model, temperature, salinity and current velocity data was collected simultaneously throughout the area from a survey vessel (the CSL Heron) using an MVP-30 and a pole mounted ADCP. Using these observations, and detailed bathymetry, a three dimensional baroclinic hydrodynamic model was constructed for the Port of Saint John. The temporal and spatial distribution of temperature and salinity within the water column structure can be extracted from model output to calculate sound speed structure throughout the model domain.

A three dimensional high resolution hydrodynamic model can provide more than just sea surface elevations. The fields of temperature and salinity can give insight into the temporal sound speed structure within the water column. This allows for improved survey planning and could minimize refraction errors associated with an inability to properly sample the local water mass.

1. INTRODUCTION

The Port of Saint John on Canada's east coast is an active industrial port and complex estuary. The port must contend with the massive fresh water input of the Saint John River and semi-diurnal tides with a spring range of over seven metres pushing in salt water from the Bay of Fundy. One, or both, of these inputs is also the source of massive amounts of sediment deposited in the Harbour which must be removed each year through dredging to allow access to certain areas of the port.

In an effort to discover the source of the excess sedimentation in the harbour, a multidisciplinary project has begun to estimate the sources of the sediments. One of the objectives of the project is to develop a numerical model of the harbour current velocities. The model would be used to understand the current dynamics for the fresh and salt water to aid in analysis of sediment transport. To capture the importance of mixing and evaluate differences between the salt and fresh waters of the estuary, a baroclinic model was constructed which would capture the three dimensional density distribution of the harbour along with current velocities.

To initialize and verify the baroclinic model, current velocity, acoustic and optical backscatter of the water column, temperature, salinity and seabed morphology were observed at four times of the year from the CLS Heron to simulate the extreme conditions of the estuarine environment. The initial survey occurred on April 22, 2008, at peak spring freshest; the second on November 14, 2008 at peak fall freshet; the third on March 26, 2009, close to the winter minimum before the spring freshet; and the final survey took place on June 11, 2009, after the spring freshet approaching the summer minimum. From examination of the model at these four times of year, the dynamics of the local oceanography can begin to be understood.

To monitor the dredging requirements, under keel clearances and areas of deposition and erosion in the Port of Saint John, multibeam echo sounding is done on a regular basis. The Port of Saint John has their own vessel for multibeam data acquisition, the Hawk, while other surveys have been performed throughout the years with the CSL Heron. The constantly variable stratification of the harbour throughout a tidal cycle makes sound speed errors a large concern for data processing, especially when trying to resolve sub-decimetre level changes in the harbour morphology. In an effort to understand the effects of the estuary on sound speed, the output of the baroclinic model was analyzed.

Two of the outputs of the model are high resolution temporal fields of salinity and temperature throughout the model domain; therefore these variables can be used to calculate sound speed distribution and determine its effect on the uncertainly in multibeam data acquisition. Knowledge of the temporal distribution of salinity and temperature of the entire port from the model output, instead of a single point as with a traditional CTD cast, allows the hydrographer to understand where and when a sound speed cast is required. This would aid in survey planning as a survey could be completed within specified areas without needing to frequently stop to collect a cast and potentially allows for the use of synthetic model casts to improve survey efficiency and uncertainty.

2. THE PORT OF SAINT JOHN PROJECT

The Port of Saint John is New Brunswick's largest port, bringing in over 26 million metric tonnes of cargo and hosting approximately 80 cruise ships with over 200000 passengers each year [Saint John Port Authority, 2009]. As shown in Figure 1, there are two principal channels in the harbour, the Main Harbour channel to the west and the Courtney Bay channel to the east. Sections of both channels are dredged each year to maintain minimum under keel clearances. The principal difference between the two areas is the freshwater input. The Main Harbour Channel is the entrance to the Saint John River and must cope with the entire fresh water load of the Saint John River watershed. Courtney Bay, on the other hand, has no significant input of fresh water.

Dredging takes place predominantly within Courtney Bay, with a smaller amount required in the shipping berths along the Main Harbour channel. Large amounts of sediments move into Courtney Bay and must be removed to not impede vessel traffic [Leys, 2007]. The immense annual costs of this undertaking have prompted a four year research project to examine the sources and movement of sediments within the harbour, with a focus on Courtney Bay. It is unknown whether the majority of the sediments which enter the bay are from the river or from tidal offshore re-suspension [Neu, 1960].

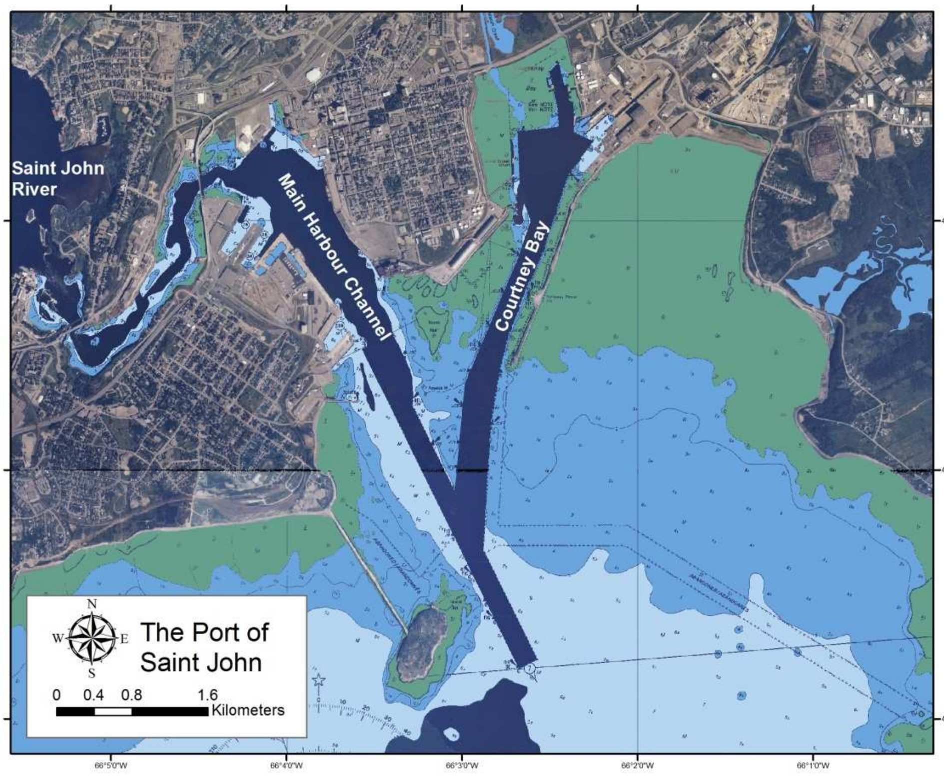

Figure 1 – The Port of Saint John Overview

One aspect of this project includes examining the estuarine circulation of the harbour through oceanographic observations and modelling. The observations were taken over a two year period at different stages of fresh water output from the Saint John River. The modelling was completed to coincide with the same time periods.

2.1 Oceanographic Sampling

Oceanographic sections of the Main Harbour Channel and Courtney Bay were observed from the CSL Heron, a 10 metre research vessel, over a 13 hour period at four times of the year [Toodesh, 2012] . These sections covered the entire Courtney Bay and Main Harbour channels over a semi-diurnal tidal cycle, as the M2 constituent is the dominant component of the tide in the area. The vessel recorded seabed bathymetry and backscatter and watercolumn backscatter from a Kongsberg EM3002 300 KHz multibeam system; watercolumn backscatter from a 200 KHz Knudsen 320 B/P single beam; current velocities and water column backscatter at 600 KHz from an RDI ADCP; and temperature, salinity and optical backscatter data from an MVP-30.

The oceanographic surveys were performed on April 22, 2008; November 14, 2008; March 26, 2009; and June 11, 2009. The surveys were designed to capture the four primary stages of the estuarine system. The March survey was completed prior to the spring freshet, when the river is in a winter stage and the freshwater output from the river is low. The April survey was completed in the middle of the spring freshet when freshwater output and river levels are high. The June survey was completed after the spring freshet and during the summer season when river levels and flow are relatively low. The November survey was completed during the fall freshet where river levels and flow are slightly elevated. See [Toodesh, 2012] for a more detailed overview of the sampling campaign.

For each of the oceanographic surveys, the MVP-30 was deployed approximately 800 times, as shown in figure 2 for the April 2008 survey. With each deployment, salinity, temperature and associated depth information was collected from near the surface to within 2 metres of the seabed. From this data, the speed of sound in water could be calculated at each cast location.

Figure 2 -- April 2008 MVP-30 Deployments

2.2 Baroclinic Hydrodynamic Model

Hydrodynamic models can be constructed for bodies of water to simulate the amplitude and phase of the tides and predict local oceanography. If surface fluctuations are the primary interest, the models can use an isodensity assumption (barotropic), which ignores sub surface conditions of estuarine circulation. If the full oceanographic properties of an area are of interest, the model can be constructed to capture the three dimensional density distribution (baroclinic). A baroclinic model allows the structure and variability of the physical properties of the water column to be examined.

With data from the four oceanographic surveys, a baroclinic hydrodynamic model was constructed of the Port of Saint John, which examined the three dimensional density distributions in the port. The model allows prediction of the current velocities and estuarine circulation at any point within the model domain and at any stage of the tide. . Temperature and salinity fields were calculated throughout the model domain for the duration of the model run.

The model grid was constructed using a high resolution coastline of the Port of Saint John and a combination of multibeam bathymetry and CHS chart soundings, as shown in figure 3. The mesh included 20 vertical terrain-following layers, 16471 nodes and 30679 triangles and had a horizontal resolution which varied between 3 and 128 metres. Open forcing boundaries were located above the Reversing Falls in the Saint John River and at the entrance to the harbour in the Bay of Fundy.

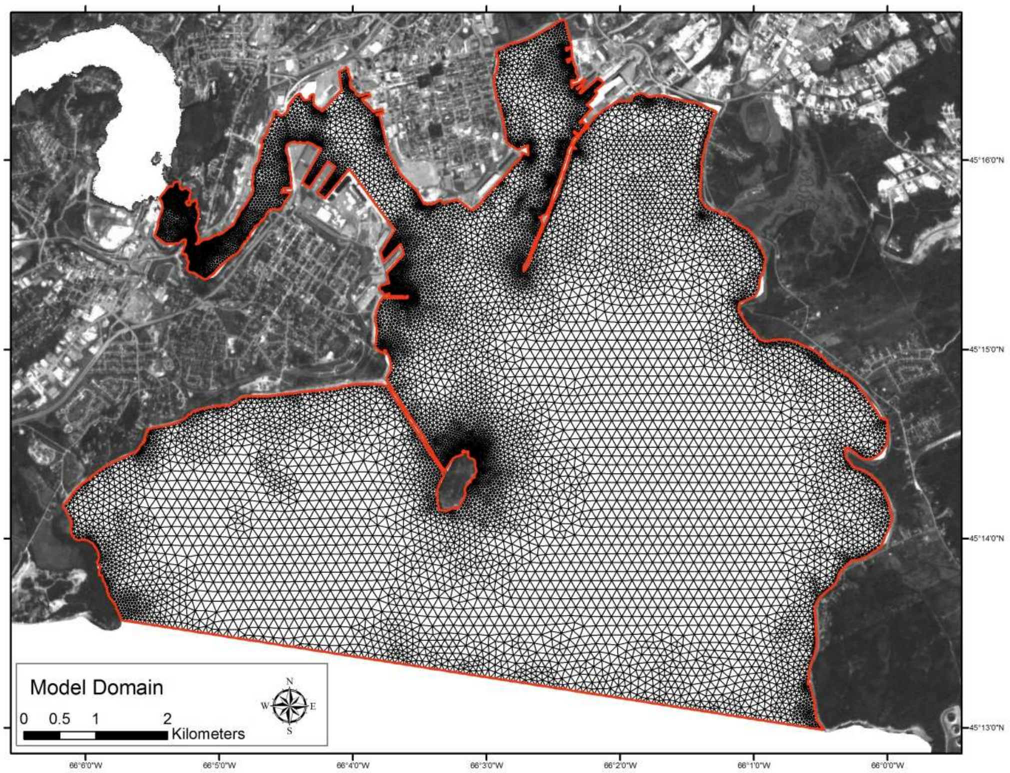

Figure 3 -- Model Mesh and Domain Overview

The grid was input to the Finite-Volume Coastal Ocean Model (FVCOM) for simulation [Chen et al., 2006]. FVCOM is capable of handling areas of complex coastlines and bathymetry, intertidal zones and vertical density distributions. The model takes as input the model grid (figure 3), an elevation time series along each of the open, non-coastal, boundaries, and initial temperature and salinity conditions at the open boundaries and throughout the domain. Temperature and salinity are initially set to a single value for the entire model domain. At each open boundary, temperature and salinity are prescribed vertically uniform, temporally constant values.. As the model runs, the differences in the open boundary conditions allow the model to stratify naturally. The model run was initiated between five and seven days prior to the specific oceanographic observation period, to allow the model to adjust to the observed temperature and salinity conditions.

FVCOM is able to take advantage of a Message Parsing Interface (MPI) parallelization to maximize efficiency [Chen et al., 2006]. Model runs were done using the Atlantic Computational Excellence Network (ACEnet) high performance computing network [ACEnet, 2011]. One seven day simulation running on 128 processors took the equivalent of 8500 CPU-hours to complete. The model outputs a series of NETCDF files which includes water surface elevations, horizontal and vertical velocities, salinity and temperature at each node and prescribed output time-step of the duration of the model run. Any of these variables can be extracted for a desired location or time period within the model domain.

Sound speed was calculated in the model post-processing for each node and time-step from the temperature and salinity fields at 20 depth layers. An example of the time varying field of sound speed throughout the model domain at one time-step is shown as a slice through both the Main Harbour channel and Courtney Bay in figure 4. The sound speed field displays the effects of the estuarine circulation on sound speed throughout the harbour at each stage of the tide.

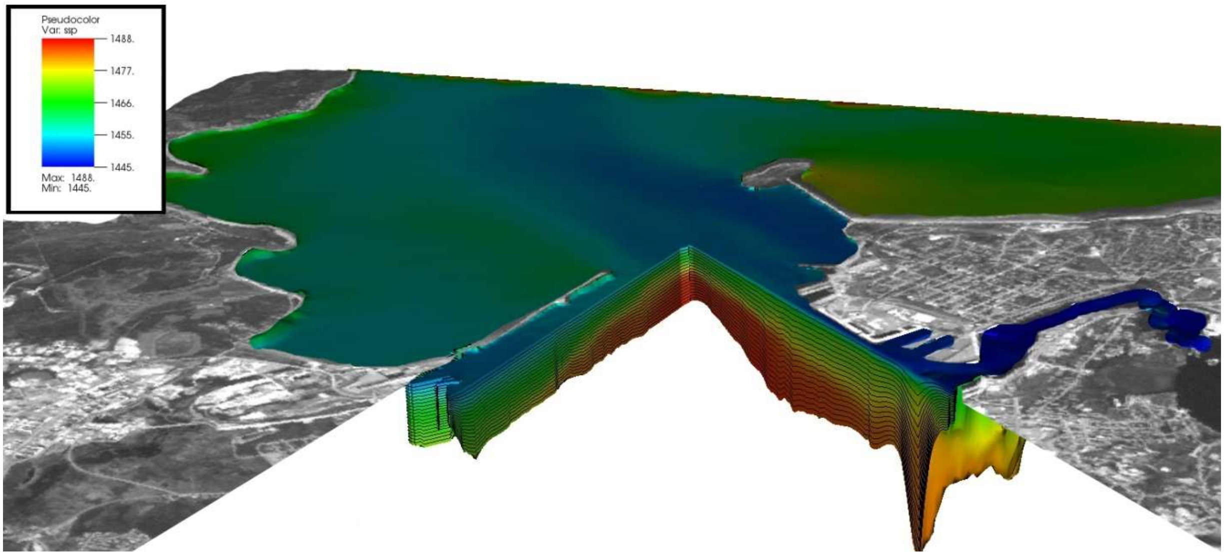

Figure 4 – Sound Speed Field slice through the Main Harbour channel and Courtney Bay

2.3 Model Surface Elevations

The model calculates surface elevations throughout the model domain. Using the location of a permanent tide gauge at the Bay Ferry Terminal Dock (45.251º N, 66.063ºW) in the Port of Saint John as a reference, the effects of the changing tide on the potential vertical elevation uncertainty can be determined by examining the amplitude and phase of the M2 component of the tide throughout the model domain. The M2 constituent values were extracted from the model output for the April 2008 period using the T_TIDE harmonic tidal analysis software [Pawlowicz et al., 2002].

The maximum difference in tidal amplitude between the tide gauge and the upper limits of Courtney Bay as predicted by the model is only 0.01m, and between the gauge and the Harbour Bridge is 0.06m. Beyond the Harbour Bridge to the Reversing Falls, the amplitude of the tide changes by up to 0.4m, but due to extreme currents, that area is only surveyed at slack water, when there is little difference in the tidal amplitude throughout the area.

The maximum tidal phase difference between the tide gauge and the upper limits of Courtney Bay as described by the model is 0.3 degrees (37 seconds for M2), and between the gauge and the Harbour bridge is 1 degree (124 seconds for M2). Beyond the Harbour Bridge to the Reversing Falls, the phase changes by an additional 0.8 degrees (99 seconds for M2).

The total potential tidal error is calculated using Fermat's Theorem which states that the local maximum, or minimum, of the difference function, as shown in equation 1, is found when the differential of that function is set to zero [Stewart, J., 1999]. The difference function shown in equation 1 describes the vertical difference between two tidal waves where A_1 is the tidal amplitude at the tide gauge location, A_2 is the tidal amplitude at another point in the model domain, ω is the M2 constituent speed, φ_1 is the tidal phase at the tide gauge location and φ_2 is the tidal phase at another point in the model domain.

$$\Delta_{Elev}(t) = A_1 cos(\omega t - \varphi_1) - A_2 cos(\omega t - \varphi_2) \quad \mathbf{(1)}$$

For a survey constrained by the limits of the Harbour Bridge, the maximum error would equate to 0.08 m, while a survey constrained by the Reversing Falls could see a maximum tidal error of 0.41 m. Harbour dredging is constrained exclusively to below the harbour bridge, therefore the maximum tidal uncertainty should be below 0.08m, which is below the decimeter level dredging accuracy limit, but could still prove important in the overall error budget. These results are only relevant to those surveys using the Saint John tide gauge for vertical reference. Ellipsoidally referenced surveys, which are not related to local chart datum, would be independent of these error sources, although they are susceptible to their own vertical referencing errors.

2.4 Comparison of Oceanographic Survey to Baroclinic Model Output

While the oceanographic survey was completed only along a transect through the centre of the Main Harbour channel and Courtney Bay, as shown in figure 2, it can be compared to the model output along the same section. Variables of temperature, salinity and derived sound speed can be compared directly to the model output at the same times and locations as each profile of the oceanographic survey. The effects on sound speed and the consequences of the differences are examined in section 3.2.

As an example, a profile for a single stage of the tidal cycle from the November transect can be examined along a transect shown in figure 5. Figure 6 shows the original salinity, temperature and derived sound speed data from the observations. Figure 7 shows the output from the model for the same location and time period while figure 8 illustrates the differences between the two.

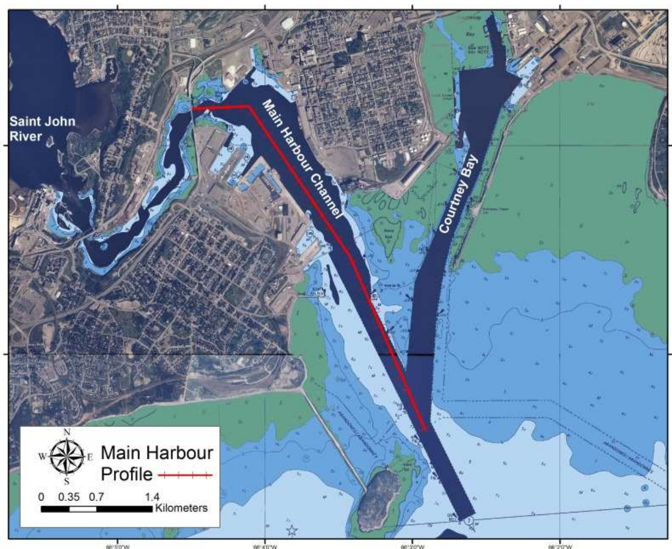

Figure 5 – Sample Profile Location

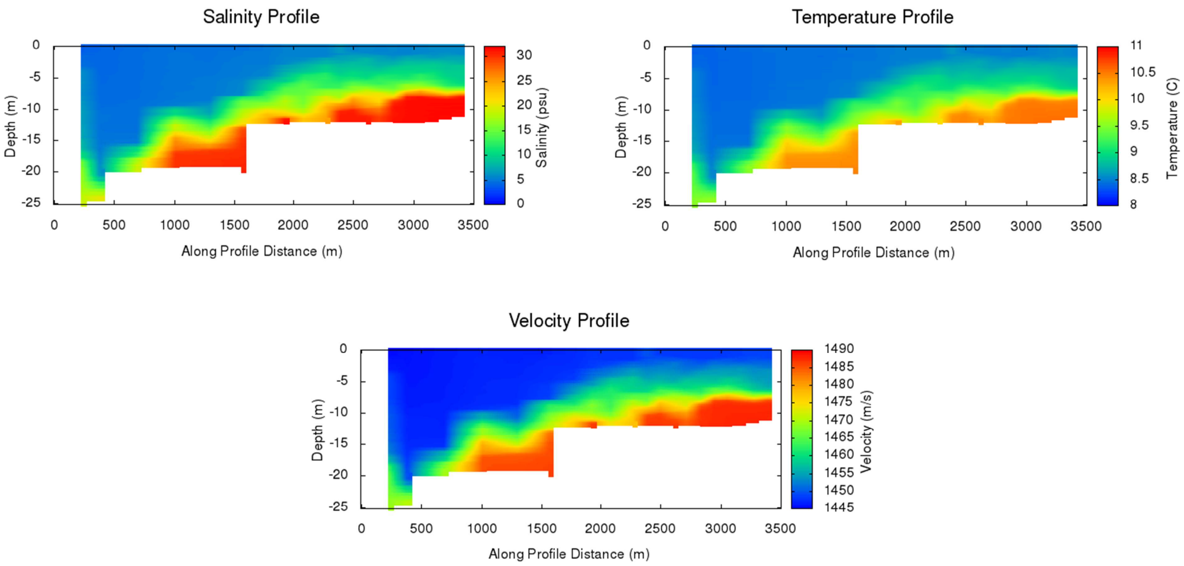

Figure 6 – Observed Salinity, Temperature and Sound Speed Profile along Main Harbour Transect

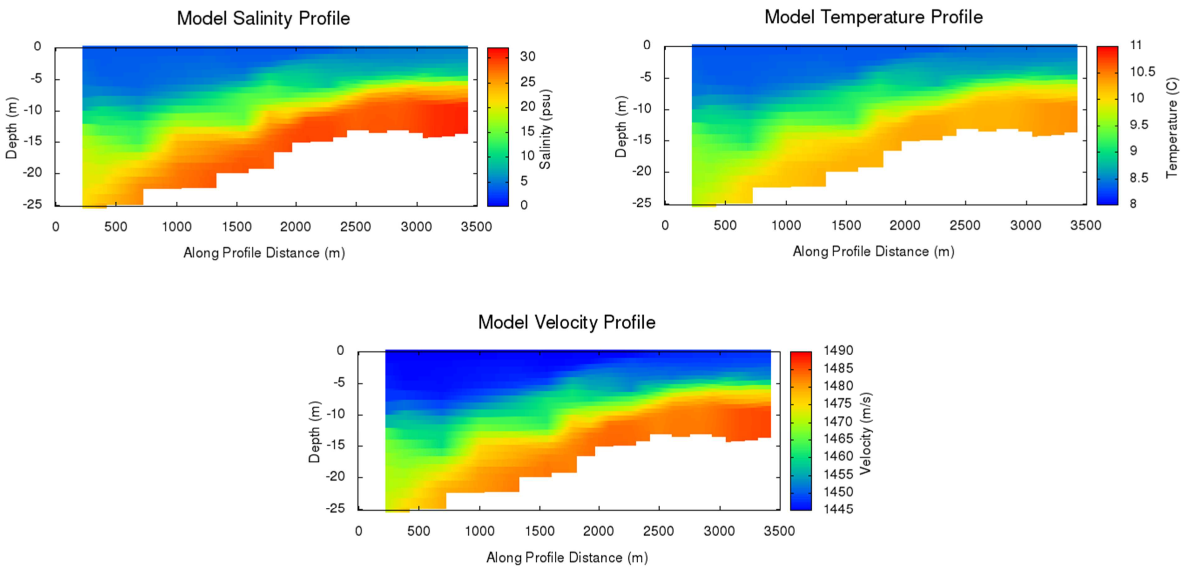

Figure 7 – Modeled Salinity, Temperature and Sound Speed Profile along Main Harbour Transect

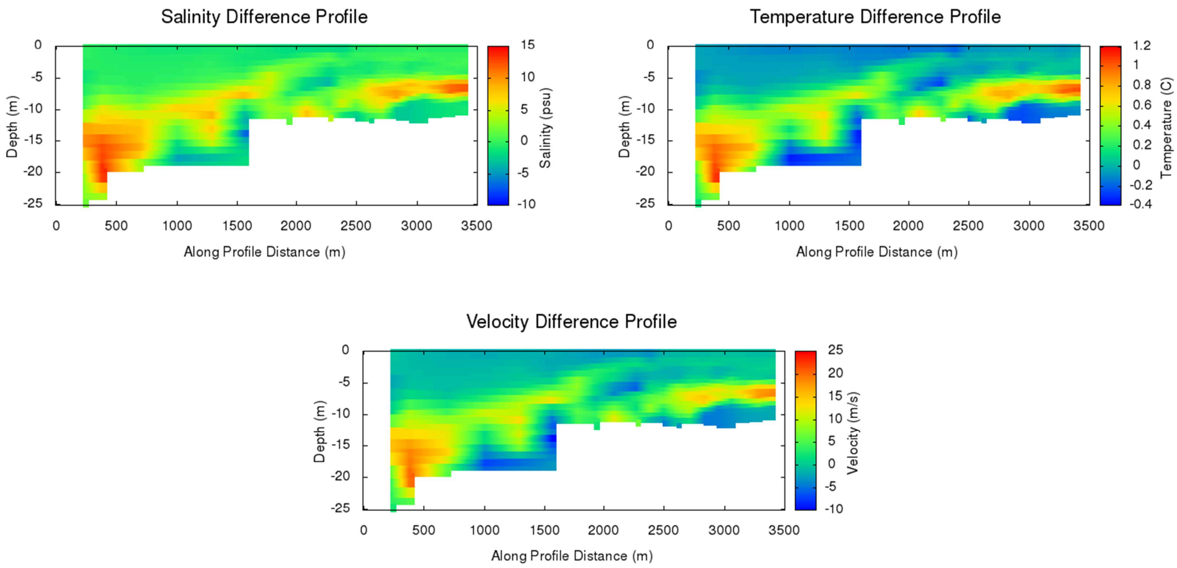

Figure 8 – Difference between Observed and Modeled Salinity, Temperature and Sound Speed Profile along Main Harbour Transect

For the salinity, temperature and sound speed difference profiles in figure 8, it can be noted that there exists a discrepancy mid watercolumn. This anomaly is caused by incorrect mixing between the salt and fresh water layers in the model. The interface in the observed data is sharper, as shown in figure 6, while the model is much more diffuse, as shown in figure 7. This implies that the turbulence at the density interface is improperly modeled and should be re-examined. Once the interface is properly tuned for a single tidal cycle it should provide better results for all other times of the year.

While the magnitude of the differences can be noted for each variable, it is difficult to determine the significance of the differences. Section 3 examines the differences noted for each profile and describes their impact on hydrographic data acquisition. Perceived anomalies between the model output and the observations may appear significant, but could have little bearing on acoustic raytracing.

3. RESULTS AND ANALYSIS

The baroclinic model described above can provide an estimate of the distribution of sound speed within the bounds of the port of Saint John. It extends observational capabilities and gives insight into the dynamics of the sound speed field. Using this information the extent of similar water masses can be determined and the consequences of not sufficiently capturing the variability can be resolved. The model is simply a representation of the actual oceanographic conditions of an area; therefore the model will not perfectly replicate the observations. What's important is determining the consequences of this mismatch on hydrographic data acquisition and using the mismatch in the observations to improve the model.

3.1 Model vs. Observations

To determine the differences between the model output and the oceanographic observations, data from the oceanographic sections can be compared to the model results at the same time period. For each MVP-30 cast, corresponding temperature, salinity and sound speed can be compared to the model output at the same time and location for each depth layer. To evaluate the consequence of the observed difference, the absolute depth error associated with raytracing the outer beams of multibeam sonar at 60 degrees at that point in the harbour is examined. This method of evaluation emphasizes the significance of the differences for a standard hydrographic survey.

Table 1 shows the mean difference and standard deviation between the ray-tracing result from the MVP-30 data and the model data for each of the four survey periods. The number of MVP-30 casts used in the calculation and the percentage of the differences which fall within the 10 cm dredging accuracy limits are also presented in table 1.

Figure 9 demonstrates a 30 bin histogram of the differences in the ray tracing results based on an absolute depth difference and a percentage of water depth difference for the November 2008 survey. The mean and the 10 cm dredging accuracy limits are shown in the figure.

Table 1 -- Mean and Standard Deviation of MVP-30 casts vs. Model Output

Survey Period	Value	Mean Difference	Standard Deviation	Count	Percent within 10cm dredging limit
April 2008	Absolute Depth Error (m)	0.002	0.269	750	52%
	Percentage of Water Depth Error (%)	0.277	1.292	750	
November 2008	Absolute Depth Error (m)	0.054	0.093	906	78%
	Percentage of Water Depth Error (%)	0.497	0.615	906	
March 2009	Absolute Depth Error (m)	-0.036	0.130	685	77%
	Percentage of Water Depth Error (%)	-0.128	0.605	685	
June 2009	Absolute Depth Error (m)	0.050	0.027	667	93%
	Percentage of Water Depth Error (%)	0.403	0.166	667	

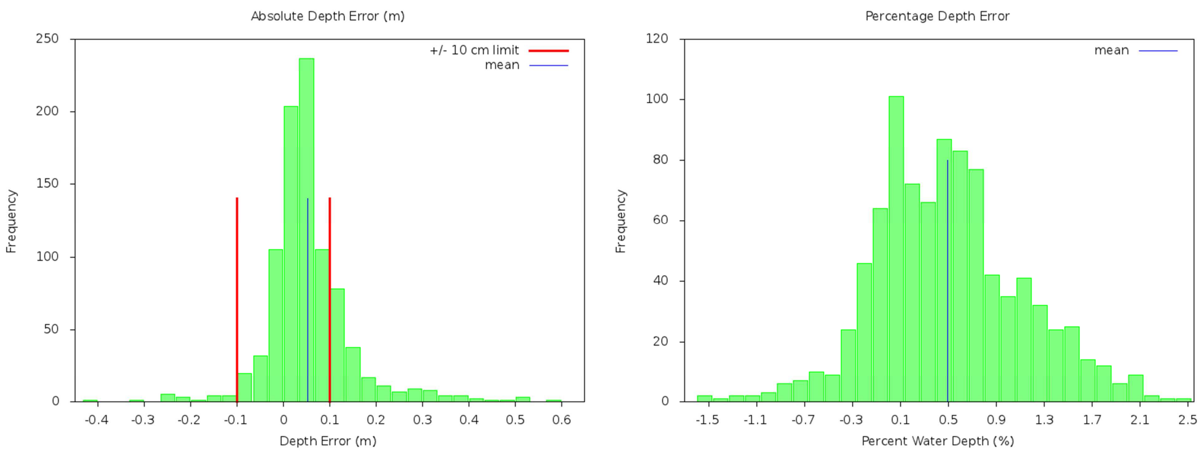

Figure 9 – November 2008 Absolute and Percentage Depth Error Histograms

3.2 Estimating Potential Error Distributions

Another method to examine the variability of the sound speed field over time is to analyze the consequences of using a single sound speed profile over a certain area and time period instead of constantly varying the profile based on the model output data. By assuming that a single profile is input to a multibeam system at a specified time, the effects of using that profile over the survey area (the entire model domain) can be evaluated as the difference between the raytracing results using the input profile and a modeled profile at the actual real-time location of the vessel. It is assumed that the vessel has a surface sound speed sensor; therefore the calculation of the difference uses a varying surface sound speed which corresponds to the model result at the depth of the transducer. This gives a depth error which is caused by the differences in the water masses. The depth error is converted to a percentage of water depth error and an associated level of IHO S-44 order [International Hydrographic Organization, 2008]. It is assumed that 50% of the uncertainty error budget is allocated for sound speed errors.

Examining the potential error field not only provides an estimate of sounding uncertainty throughout the domain, it also adds a planning capability to the model output. Regions can now be determined where if a single sound speed profile is used then depth errors will be below a certain threshold. Polygons can be created for certain stages of the tide which show zones of minimum and maximum errors based on an initial sound speed cast location. Figures 13 through 24 examine the error field for each tidal cycle and illustrate the maximum potential error.

As an example, figure 10 shows the associated IHO acceptance levels with contours indicating vertical errors within Special Order, within Order 1, within Order 2 and larger than the limits of Order 2. This clearly shows that a sound speed profile collected at the “Reference Cast Location” at the intersection of the Courtney Bay and Main Harbour Channels is only representative of a portion of the Port of Saint John area. Special order is maintained around the location of the cast and up into Courtney Bay. Uncertainties beyond the limits of Order 2 result in the Main Harbour channel.

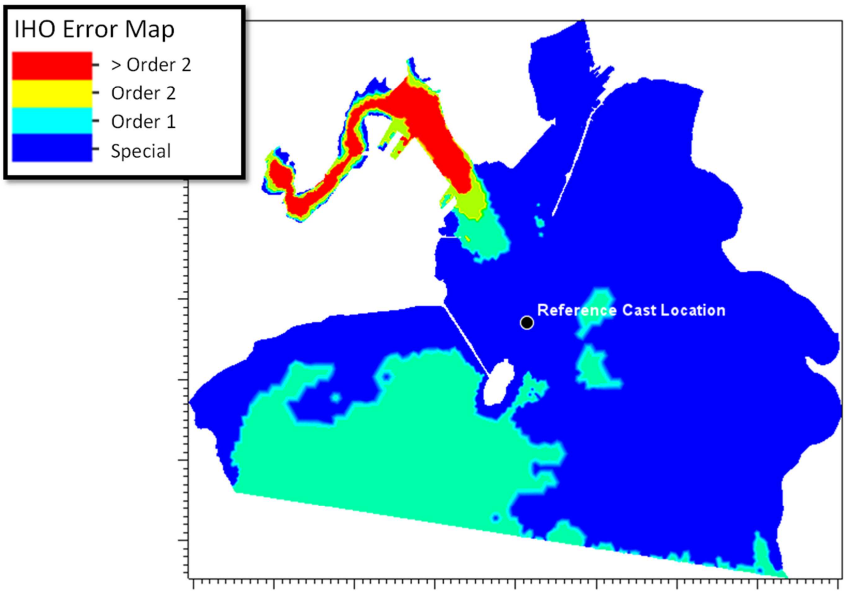

Figure 10 – November 2008 IHO Order Distribution

4. CONCLUSION

Baroclinic hydrodynamic models provide a three dimensional temporal overview of the temperature and salinity conditions for a specified area. Sound speed fields can be calculated from these variables which provide a method for analyzing potential sound speed uncertainty. The optimal frequency and locations of sound speed casts, the consequences of using specified casts and the creation of synthesized casts can be determined from the model output. A case study is undertaken in the estuary of the Port of Saint John, New Brunswick, Canada at four times of the year: winter minimum, spring freshet, summer minimum and fall freshet. The simulations for the four periods illustrate the influence of the estuarine conditions on the potential sound speed uncertainty.

For an area of complex oceanography, such as the Saint John Harbour, the model provides an alternative to high density collection of sound speed profiles. As the model results will never perfectly match the observations, the significance of the difference must be determined. The model provides a raytracing solution which matches the observed profile within a maximum standard deviation of 27 cm at 60 degrees for the April survey, while the fit is much better for other times of the year. While not discussed here, the maximum differences shown in section 3.1 are spatially correlated; therefore depending on the desired survey area, the differences and associated standard deviations will vary.

The next step is to tune the model to better correspond to the actual conditions of the Port of Saint John. This may include modifying the bottom roughness and mixing coefficients. As noted in section 2.4, the single largest improvement in the results will likely come from using an improved turbulence model to deal with the intense density differences between the fresh and salt water layers. Once the turbulence is modelled to fit the actual conditions, the density interface will improve and the differences between the model results and the observations will improve for all times of the year.

The initial testing of this baroclinic hydrodynamic model for the Port of Saint John shows promising results. The majority of the time, the model could substitute actual observations with little effect on ray-tracing uncertainty. Areas of acceptable uncertainty resulting from CTD cast locations can be determined through examination of the error fields in terms of IHO uncertainty levels at each time of year.

REFERENCES

ACEnet(2011). "About ACEnet - ACEnet " [On-line] 3/26/2012, 2012. http://www.ace-net.ca/wiki/About_ACEnet .

Chen, C., R. C. Beardsley, and G. W. Cowles (2006). " An unstructured grid, finite-volume coastal ocean model (FVCOM) system." *Oceanography,* 19(1), pp. 78.

International Hydrographic Organization. (2008). "IHO Standard for Hydrographic Survey." *Rep. No. Special publication No. 44, 5th edition,* International Hydrographic Bureau, Monaco.

Leys, V. (2007). "3D Flow and Sediment Transport Modelling at the Reversing Falls - Saint John Harbour, New Brunswick." *Proceedings of OCEANS 2007,* pp. 1-16.

Neu, H. (1960). "Hydrographic Survey of Saint John Harbour, N. B."

Pawlowicz, R., B. Beardsley, and S. Lentz (2002). "Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE." *Computers & Geosciences,* 28 pp. 929.

Saint John Port Authority(2009). "Saint John Port Authority - Media Center - Quick Facts " [On-line] 2/27/2012, 2012. http://www.sjport.com/english/media_center/quick_facts.html .

Stewart, J. (1999). *Calculus : early transcendentals.* 4th ed., Thomson/Brooks/Cole, Belmont, CA.

Toodesh, R. (2012). *The Oceanographic Circulation of the Port of Saint John over Seasonal and Tidal Time Scales.* University of New Brunswick, Fredericton, New Brunswick,.

BIOGRAPHICAL NOTES

Ian Church has been working with the Ocean Mapping Group at UNB for the past 7 years. During that time he's been involved in various survey operations, including annual surveys aboard the CCGS Amundsen throughout the Canadian Arctic. He is currently working part-time towards his PhD in Geomatics and Geodesy Engineering.

CONTACT

Ian Church
Ocean Mapping Group, University of New Brunswick
15 Dineen Drive
Fredericton, N.B.
Canada
Tel. +1-506-453-5146
Fax +1-506-453-4943
Email: ichurch@unb.ca
http://www.omg.unb.ca/