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**A Three-Dimensional Hydrodynamic Model to Study the Baroclinic Conditions of the Bay of Fundy**

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**Abstract:** The Bay of Fundy is home to a diverse biological environment, and to provide marine protection plans and better insight on the species communities on the seafloor, benthic habitat mapping is required. These maps are based on an integration of seabed bathymetry and backscatter, and can include physical oceanographic layers such as temperature, salinity, and currents from ocean models. For this study, the Finite-Volume Community Ocean Model (FVCOM) has been adopted to generate a baroclinic ocean model simulation, which covers the Bay and includes the Saint John River up to Evandale. The horizontal resolution ranges from 10m to 6000m in the Reversing Falls and open boundary respectively, and the model consists of 40 terrain-following layers in the vertical coordinate.

The presence of strong tidal forces, especially in the Minas Passage, the complex geometry of the Saint John River, and the river runoff at the freshet are the most important challenges in this area. The model is forced to run by the tidal elevation, temperature, and salinity at the open boundary close to the Bay entrance; river water level, salinity, and temperature at the upper part of Saint John River; and high resolution weather model data as surface forcing. The model has been initialized with the temperature and salinity from a coarser resolution regional model, the Gulf of Maine Operational Forecast System. The model results were evaluated with observational data and present good agreement with tidal elevation, gyre locations, the high tidal current locations, temperature, and salinity.

**Keywords**: Bay of Fundy, FVCOM, High-resolution model, Saint John River, Baroclinic Condition

**1 Introduction**

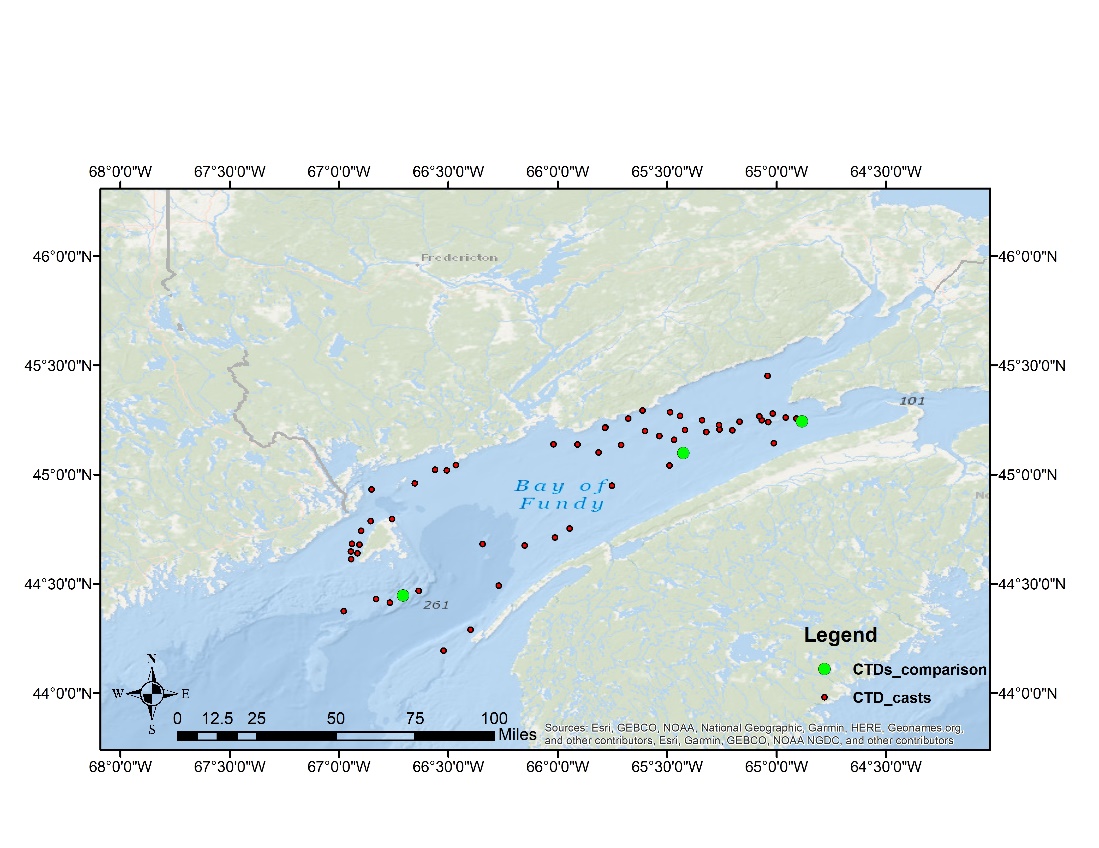
The seabed ecosystem is affected by human activities such as fishing, oil and gas pollution, and mining which reduce benthic biodiversity and without a supportive plan to manage the resources and protect the ecologically sensitive areas, the marine ecology will collapse [1]. However, benthic habitat mapping provides the location, condition, and extent of the marine ecosystem and the insight for decision-makers to apply precautionary practices [2]. The water column attributes, and the seafloor geological conditions affect benthic biology. The former can be acquired by acoustic survey methods and the later can be derived from point samples of oceanographic measurement or, for better coverage, from ocean models[2,3].

The Bay of Fundy (Fig. 1a) is located northeast of the Gulf of Maine between two Canadian Provinces, New Brunswick, and Nova Scotia. The Minas Basin and Chignecto Bay are the most important sub-basins in the northeast corner of the Bay and play an important role in sediment distribution in the Bay of Fundy [4]. The Bay is a unique area with the highest tide in the world, a diverse ecosystem, and marine recourses [5]. The tide is predominantly semidiurnal [6] with a range varying from 6.4 m in Grand Passage to 16 m in the spring tide at the Minas Basin [6–9] which makes this region experience interesting tidal-related oceanographic processes. The funnel shape, length, and gradually decreasing depth to the head of the Bay result in being in near resonance with the semidiurnal M2 [4,6,7,9,10] harmonic constituent. The resulting strong tidal currents are the dominant factors on the changes in geology from erosion and sediment transport [11,12] and affect the interaction of biological, physical and chemical conditions of Bay [9].

The main contribution of water to the Bay is from Scotian Shelf water [13] which enters the Bay along the Nova Scotia coast undertaking mixing up to the head of the Bay [14], flows out along the New Brunswick side and eastern part of Grand Manan Island [8,15–17], and combines with the Gulf of Maine circulation [16,18,19]. The main source of freshwater in the Bay is the Saint John River. The lower Saint John River includes complex bathymetry, large tides, dynamic river input, and strong currents in narrow passage. The river has a 55,000 km2 watershed (Fig. 1b) with an annual average discharge of about 1100 m3s-1  [20]( Fig. 1b) with a maximum discharge of 5000 m3s-1 at the freshet time [21]. The near-surface circulation in the Bay is affected by the river runoff, especially in the Spring season [22], and has less impact on the deeper part of water column [23,24]. The fresh water plume joins the East Maine Coastal current [24–26] with most flow coming from the west of Grand Manan Island [24,26,27] and part of it from east of the Island [28]. The influence of the Saint John River provides 30 percent of freshwater contribution to the Gulf of Maine system [24,29,30]. It is clear, therefore, that the fresh water output of the Saint John river impact the oceanographic circulation of the Bay of Fundy.

Figure 1.(a)Bay of Fundy and the location of Oak point station (in red star) and Saint John River tide gauge (in black circle), and red circles are the location for tidal analysis; ( b)The Saint John watershed(from Cunjak and Newbury 2005)

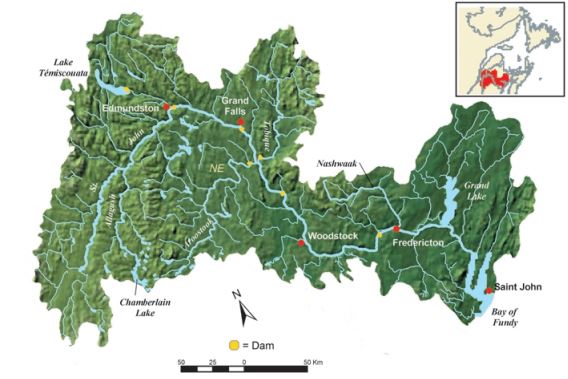
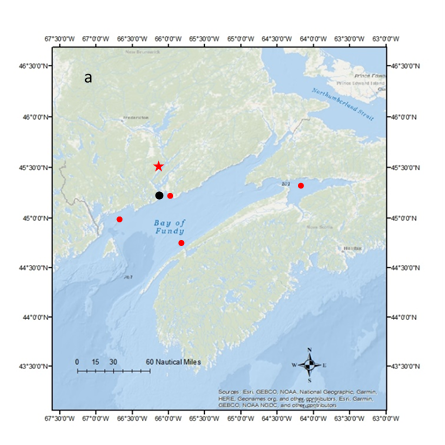
Figure 2.Location of CTD casts from field work and World Ocean Database for the model simulation period .The green spots are used as an example for the comparison with the model output



Cast 2

Cast 1

Cast 3



b

There has been previous research on the barotropic condition of Bay of Fundy using different model configuration such as the structured models [31,32] and unstructured ones, [33–36]. These models usually simulate the tidal and wind-derived variation of sea level and currents. Resolving the baroclinic condition of Bay improves the emergency response (e.g. oil spill) [21] and the transition between well-mixed and stratified zones which are important from a biological perspective [37,38]. However, few studies have focused on the baroclinic condition of Bay, with most examining the lower parts of Bay and Gulf of Maine. Watson [27], showed that the counter-clockwise gyre at the mouth of Bay is mostly driven by density effects while the tidal rectification and density-driven circulation [22] resulting from surface heating [39] and freshwater inflow [24] act as driving factors together. Also, tidal current and coastal processes may be affected by variations of temperature and salinity resulting from the surface and open boundary heat and freshwater fluxes [40]. One contributing factor which increases the model skill is how good the model can resolve the dynamic processes on the ocean domain, and this comes from the mesh resolution on which the model is running. The oceanic process properties vary on many scales which are dependent on factors such as coastline, bottom topography variation, the forcing meteorology, changing Coriolis force with latitude and the Rossby radius of deformation [41]. Coastal models usually require increased spatial and temporal resolution to provide accurate forecasts [42,43] by capturing a wider energy spectrum in the model and improving our understanding of oceanic sub-mesoscale dynamics [44] such as capturing the freshwater front from river discharge [45] or an accurate representation of sea surface temperature [21]. However, this leads to an increase in computation time, the requirement for extra computer storage space, and decreasing the model time steps to satisfy the computational fluid dynamic stability condition (Courant-Friedrichs-Lewy, CFL) [41,45].

Knowledge of the baroclinic condition of the Bay could also enhance acoustic hydrographic surveys by defining the areas of high sound speed variability for better time, cost and effort efficiency planning. Besides, by relying on the baroclinic condition of the domain, biological studies, for instance, habitat mapping, and retention of organisms such as phytoplankton [46], zooplankton [47], scallop larvae [19] which finally provide better insight for decision-makers to provide a sustainable plan for the marine environment.

In this model for the Bay of Fundy, we use a high-resolution mesh (up to 20 meters) to resolve the oceanographic condition of the Bay, specifically temperature and salinity, for two months in July and August 2018.

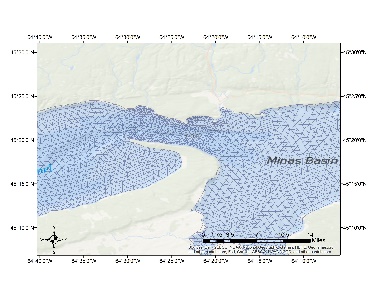
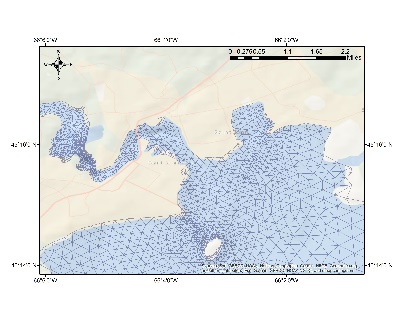
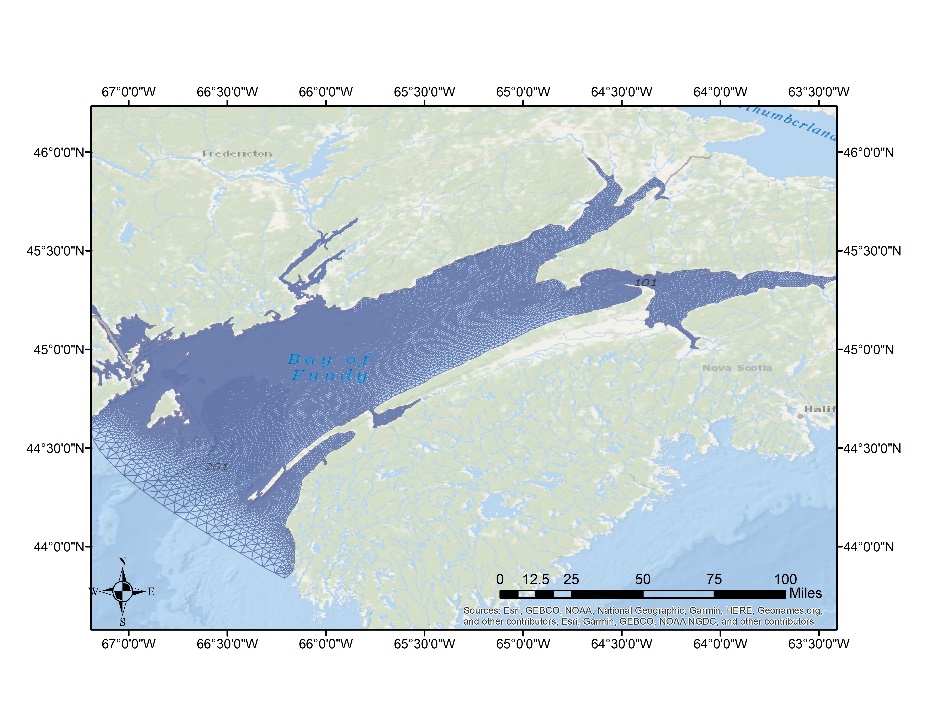
The model configuration, open boundary forcing, and initialization is reviewed in Section 2, while section 3 presents the model evaluation against Saint John River tide gauge data, Canadian Hydrographic Service (CHS) published tidal harmonic constituents for the Bay of Fundy, and CTD casts from fieldwork and the World Ocean Atlas Database. Section 4 presents the summary and conclusion.

**2 Methodology**

A high-resolution model has been developed for this study with the horizontal resolution from 20m to 6km. The domain covers the entire Bay of Fundy including Chignecto Bay and Minas Basin, and the lower part of the Saint John River to Evandale, New Brunswick. The following subsections explain the model configuration, parameters, and open boundary forcing, initialization, and surface forcing.

**2.1 Model configuration and parameters**

The Finite-Volume Community Ocean Model, FVCOM, which was originally developed by Chen, et al, 2003 [48] and upgraded by the joint effort of University of Massachusetts Dartmouth (UMAS-D) and Woods Hole Oceanographic Institution (WHOI) [49], was used for this simulation. The model uses an unstructured grid, 3D primitive equations and is embedded with optional modules such as the sediment transport, Global Ocean Turbulence Model (GOTM) [50], 3D Wet-Dry module, and nesting modules. The equations of momentum, continuity, temperature, salinity, and density in a spherical coordinate system with GOTM, k-ε, or MY-2.5 [51] turbulent mixing in the vertical and a Smagorinsky turbulent closure scheme in the horizontal [52] are used as governing equations in the model. In the horizontal, the governing equations are discretized in the flux form over the unstructured triangular mesh [48] and a generalized terrain-following coordinate is used in the vertical [53]. To integrate in time, the model benefits from mode split and semi-implicit schemes, while it uses the second-order accurate advection scheme in space. By using the unstructured grid and finite volume method the model benefits from the simple discrete computational efficiency from finite-difference and geometry flexibility from finite element methods. The accurate conservation of salt, heat, and mass is provided by the flux computational method. The domain of the mesh configuration is shown in Fig. 3.with the two fine resolution regions in the Saint John River and Minas Passage at 20 m resolution .



The coastline dataset is extracted from Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG) [54] with the full resolution. The model bathymetry in the bay of Fundy is a 100-m resolution grid derived from multibeam data collected by the CHS and Natural Recourses Canada (NRCan) , while areas which are not covered by this dataset (such as Chignecto Bay, the entrance of Passamaquoddy Bay, and close to Bear Cove) are digitized from CHS raster chart numbers 4010, 4011, 4012, 4013, 4117, and 4396. The lower Saint John River is covered partially by CHS bathymetry data and the rest is from University of New Brunswick Ocean Mapping Group dataset [55](McNeill et al., 2018).

Figure 3.Unstructured mesh generated by SMS and location of two high resolution spots.

The mesh is generated by the Surface Water Modeling System (SMS 12.1) [56], which creates the unstructured grid with different modules (Map, Mesh, and Scatter) that are necessary for FVCOM. The mesh quality recommendation for FVCOM is as follows based on the FVCOM manual: The Minimum interior angle is 30 degrees, maximum interior angle of 130 degrees, the maximum slope 0.1, the Element area change 0.5, and the connecting elements 7. The total number of nodes and elements for the coarse and fine resolution are 34871, 64765 and 35649, 66321, respectively. The horizontal resolution ranges from 6km in the open boundary attached to the Gulf of Maine to 20 m in the Reversing Falls Saint John River. In the vertical coordinate, 40 uniform sigma layers have been applied.

For time integration, the mode-split scheme is used to separate the time step between the internal (baroclinic) and external (barotropic) mode. The time steps for a barotropic run for internal and external mode is set to 0.5 seconds, and for baroclinic run 0.3 seconds is used. MY-2.5 is used as the vertical turbulence closure to parametrize the vertical eddy viscosity and the vertical thermal diffusion coefficient [49]. Spatially constant values for the minimum bottom roughness have been examined and the results are provided in section 3.1.

**2.2 Model initialization and open boundary forcing**

The model consists of two open boundaries, one in the Saint John River with 3 nodes and the other is adjacent to the Gulf of Maine with 23 nodes. The surface temperature and river water level are from Environment and Climate Change Canada. The river open boundary is close to the Oak river level station (01AP003). By using this boundary location, we can assume that we have the freshwater inflow at that point (O’Flaherty-Sproul and Haigh, pers.comm). At the Gulf of Maine open boundary, the forcing includes tidal elevation, temperature, and salinity. The tidal elevation, with five harmonic constituents for the Bay (M2, N2, S2, K1, and O1), is extracted from an unstructured barotropic tidal model, the WebTide Scotia - Fundy - Maine model, which is tuned for the Bay of Fundy [34].To facilitate the tuning process of tides in the Bay, we considered the five primary constituents which in total need 27 days of simulation data to perform the tidal analysis. 6-hourly time series of temperature and salinity for the open boundary are extracted from Gulf of Maine Operational Forecast System(GoMOFS) [57], which uses ROMs (Regional Ocean Model system) with a 700 m horizontal resolution and 30 vertical levels and is running operationally on NOAA’s High Performance Computer Systems (HPCS) predicting the water level, currents, water temperature, and salinity for 72 hours cycles. The GoMOFS is also used for the initialization of currents, temperature, and salinity for the start of the simulation. The model is set to run in ‘hot-start’ from 1st July to 1st September 2018, with 10 hours devoted to spin up. The model’s sea surface is forced with hourly atmospheric data including specific humidity, 2-m air temperature, surface incoming longwave and shortwave radiation, and 10-m wind from the High-Resolution Deterministic Prediction System (HRDPS) [58] at 2.5 km resolution, which is running operationally at the Canadian Center for Meteorological and Environment Prediction(CCMEP).

**3 Evaluation of tide and water properties**

In this section, we provide an evaluation of the model to represent the dominant features of the oceanographic conditions of the Bay. Figure 2 shows the location of CTD casts from fieldwork and the World Ocean Atlas Database during the simulation period. We evaluate the model based on the (3.1) tide, (3.2) residual currents and (3.3) variation in temperature and salinity.

**3.1 Tidal constituents**

The observations of water level in the Saint John Harbour is from the tide gauge located in Figure 1a (Station 65). The model run period is July and August of 2018, however, there are gaps in the tide gauge data, and we compared the data from July 19th to August 27th (Figure 4).The model water level has a good agreement in phase and amplitude with the tide gauge data with a maximum difference of less than 0.6m. The observed differences in tidal range likely result from not including all constituents in the water level forcing and non-tidal effects. The tide gauge data is vertically referenced to local chart datum while the water level in FVCOM is relative to the mean sea level (MSL)

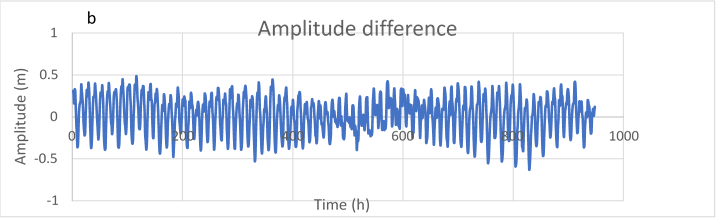
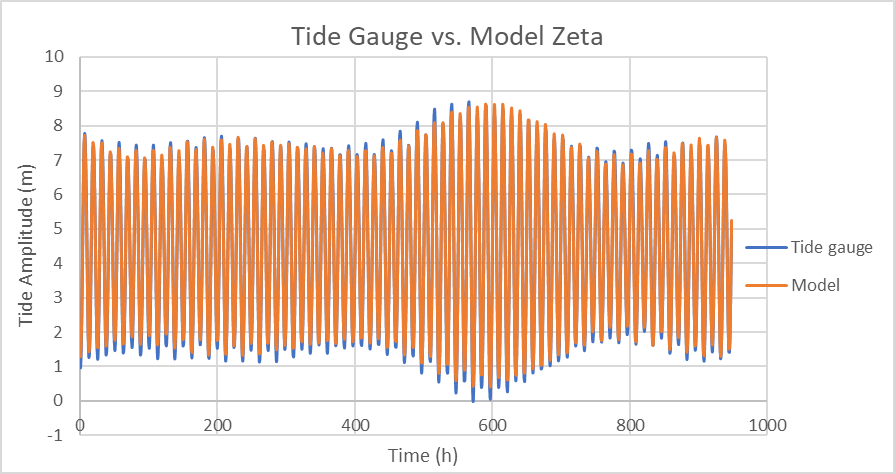


Figure 4..a) Comparison between tide gauge with simulated water level, and b) the difference between them. Time is hourly since 19th July until 27th August.



a

; therefore, the Hydrographic Vertical Separation Surfaces (HyVSEP) solution (CANEAST2015v1CL) [59] was used to relate MSL and chart datum.

The model was run with different values of the bottom roughness coefficient to evaluate which value provides a better representation of tidal propagation for the domain. A harmonic analysis [60] was performed on the simulated water level with different bottom roughness coefficients to determine the best value with the smallest error for the whole bay and the results are compared with the CHS tidal constituents in the table 1, 2, and 3 for the M2 harmonic constituent. The error metric is the distance in the complex plane between observed (CHS constituents) and modeled constituents [34] and is defined as follow:

(1)

where , are the amplitude and phase of the observed harmonic and , are the amplitude and phase of the modeled harmonic. We use this metric which combines the amplitude and phase errors in a single number for the validation.

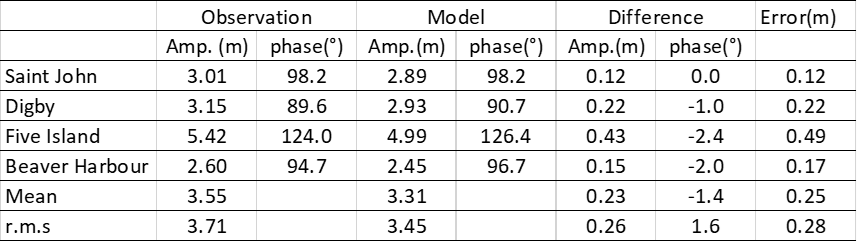
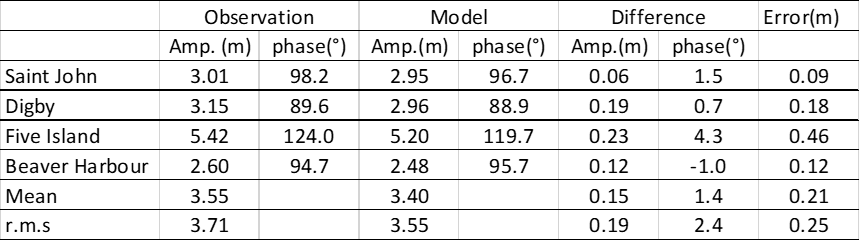


Table 1.CHS and modelled amplitude(m) and phase (degree, GMT) and discrepancies(CHS-Model) for M2 with bottom coefficient 0.015.The error is from the metric in equation 1

Table 2.CHS and modelled amplitude(m) and phase (degree, GMT) and discrepancies(CHS-Model) for M2 with bottom coefficient 0.007.The error is from the metric in equation 1



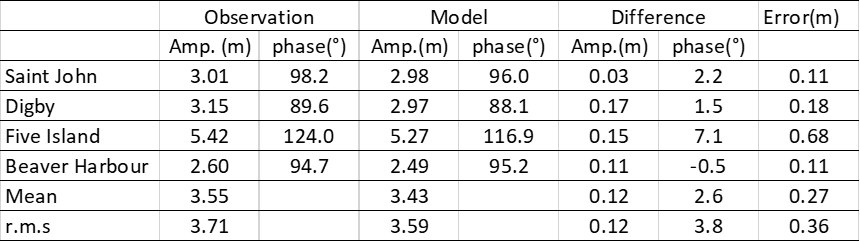
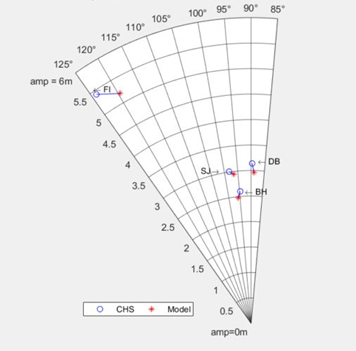


Table 3.CHS and modelled amplitude(m) and phase (degree, GMT) and discrepancies(CHS-Model) for M2 with bottom coefficient 0.005.The error is from the metric in equation 1

The r.m.s value for the M2 constituent at all four stations (Fig. 1a) with different bottom coefficient are presented in the Table 1, Table 2 and Table 3. The predicted tide by the model for Five Island and Saint John Harbour have the largest and smallest error, respectively, and the minimum mean and r.m.s error results from using a bottom roughness coefficient equal to 0.007.

The validation for all five constituents against the CHS constituents is shown in Fig. 5. In total, M2, K1, O1 and N2 phases from the model tend to be larger than the CHS ones with smaller model predicted amplitude for M2 and S2 and a larger amplitude for N2. The modelled M2 constituent is close to the CHS constituent with amplitude errors generally between 0.06 to 0.22 m and the largest error in phase at the Five Island point which lags by about 5.1 degrees. The errors in the N2 phase range from 3.3 to 14.9 degrees while the amplitude errors are less than 0.11 m.



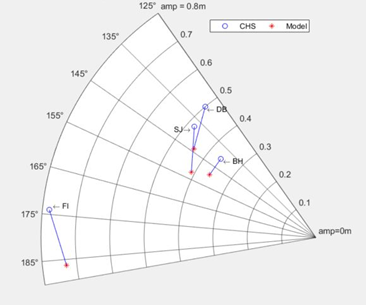
a

M2



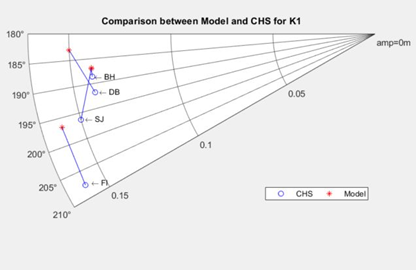
e

**O**1



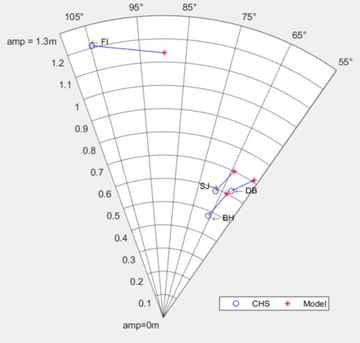
c

**S**2



d

**K**1



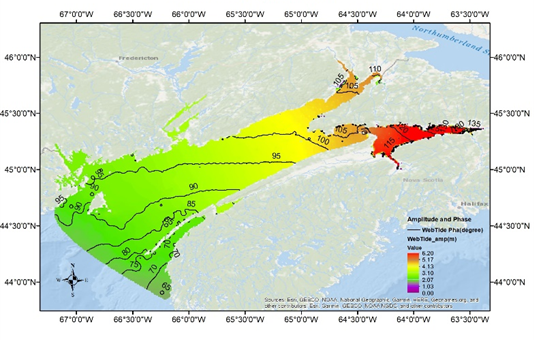
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N2

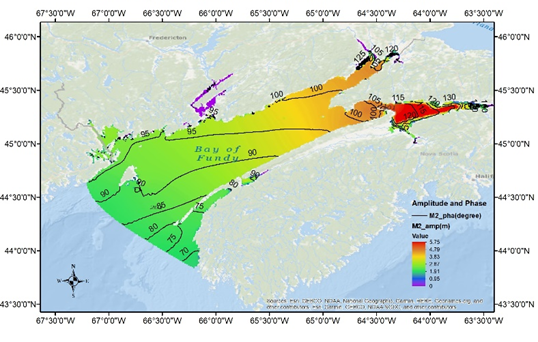
S2 is the only constituent that has a late phase between 9.1 and 20.3 degrees, and a small amplitude error of less than 0.06 m. With phase errors between 1.8 and 10 degrees and amplitude errors of less than 0.01 m, K1 is one of the model constituents which is ahead of CHS constituent. Finally, O1 , with no recognisable pattern, has an amplitude error of less than 0.02m and phase error between 0.7 and 11 degrees.

For all three bottom roughness coefficients, it seems that the phase has more impact on the error calculation than amplitude. The comparison for M2, between our model output with 0.007 as the bottom coefficient and the WebTide model, is provided in Fig.6.

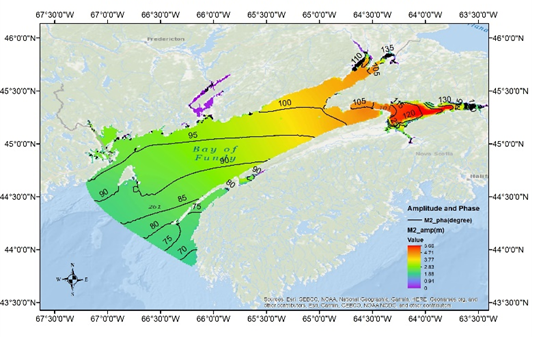
Figure 6.The Amplitude(colour shading, in m) and phase(contours, in degree, GMT) of sea level for the principal lunar semidiurnal tidal constituent(M2) a) WebTide , b)Bottom Coefficient 0.005, c) Bottom Coefficient 0.007, d) Bottom Coefficient 0.015



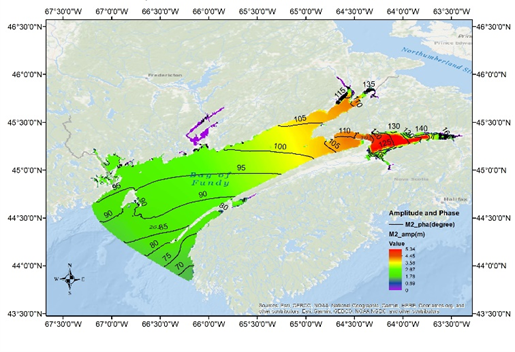
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b



c



d

The phase pattern qualitatively follows the WebTide output across the bay and there is a maximum amplitude difference of 40 cm in the Minas Passage between the two models. These discrepancies may come from unique model forcing or bottom roughness values which can impact the representation and accuracy of tidal solutions [21]. By decreasing the bottom coefficient to 0.005, the water body feels less friction from the seabed and the model phase surpasses the Webtide phase (Fig. 6b), while when we increase the coefficient to 0.015, it feels more friction and the phase lags behind the WebTide phase (Fig. 6d). With the coefficient equal to 0.007, we have the best fit for our model phase (Fig. 6c).

The finer mesh resolution of a model can potentially improve model skill, therefore the comparison with a coarse resolution (RIOPS) is shown in table 4 for the three main semi-diurnal constituents in the Saint John Harbour; M2, N2, and S2 with an amplitude of 3.01, 0.60, and 0.49 m, respectively. The M2 amplitude improves as the resolution increase from RIOPS to FVCOM with a 10% error (33cm) to 1.9% error (6cm), respectively. The tidal constituents for RIOPS is from [21].

Table 4.Comparison of tidal amplitude and phase of water level for M2 at Saint John River tide gauge, WebTide, RIOPS, and FVCOM

**3.5 Tidal Residuals**

The residual flows can result from different factors, for instance, nonlinear interaction between tides, bottom topography, the geometry of the coastline, bottom friction, winds, waves, density variations and far-field general circulation [35]. We therefore compared the residuals from each of the model runs, Barotropic and Baroclinic to examine regional circulation patterns. By analyzing current meter data, Bigelow [15] showed that there is an anticlockwise gyre near Cape split due to strong mean inward and outward flow, and further analysis of these observations by Tee [61,62] revealed three other gyres, one clockwise gyre in Minas Channel, and two gyres in the Minas Passage on the west (clockwise) and east (anticlockwise) side and last one (clockwise) off Cape Blomidon [8,35]), Fig. 7, Fig. 8, and Fig. 9 ,respectively.

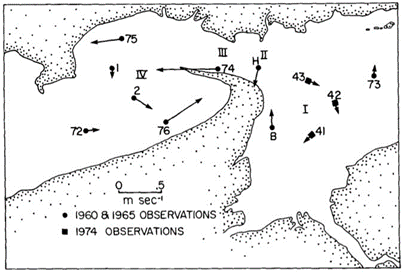
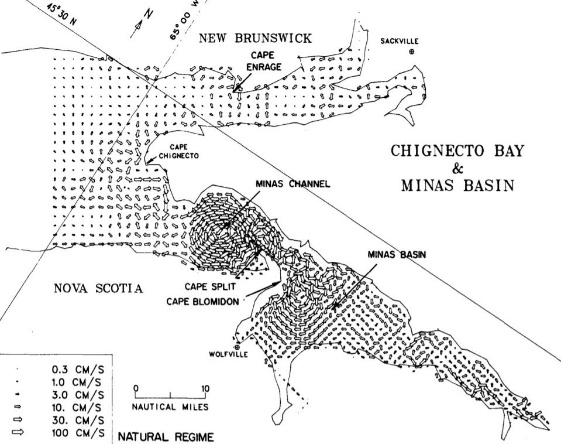


Figure 7. The observed residual currents in the Minas area (from Tee, 1977)

Figure 8. The residual currents in the Minas Basin and channel (from Greenberg, 1982)

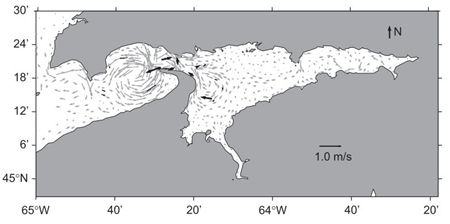
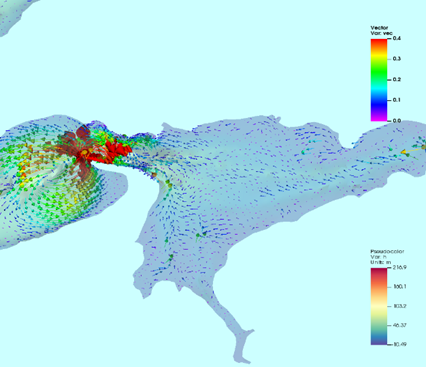
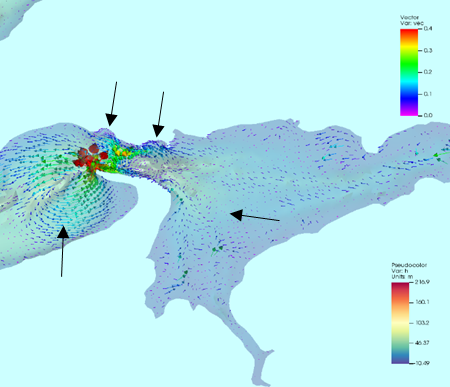


Figure 9. The depth-averaged residual flow (from Wu et al, 2011)





a

b

Figure 10.Tidal residual currents in the Minas Basin area and location of four gyres in (a)Barotropic run and (b) Baroclinic run

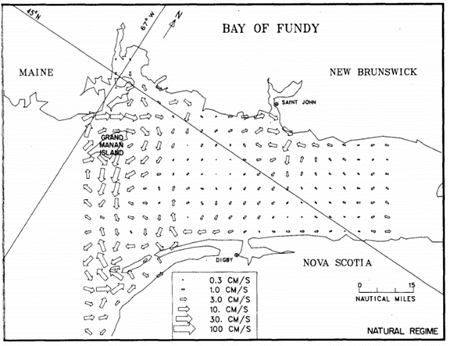
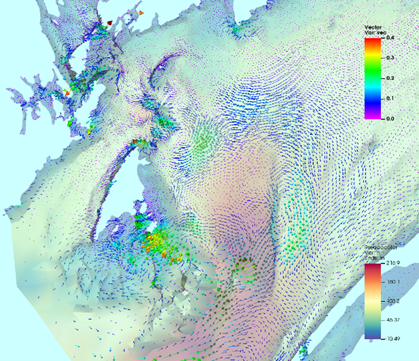
The residual flow for the barotropic run is presented in Fig. 10a at the end of the simulation period, August 31st. The high-resolution grid in the model, especially in the Minas Passage and Channel, can resolve the gyre features. It appears that the tide and complex geometry at the entrance of Minas Passage are responsible for the generation of the gyres. There is an improvement for the residual currents in the Baroclinic run (Fig. 10b) and it shows that in the Minas Basin area, the shape of the gyre persists but the residual currents speed increase due to baroclinic effects.

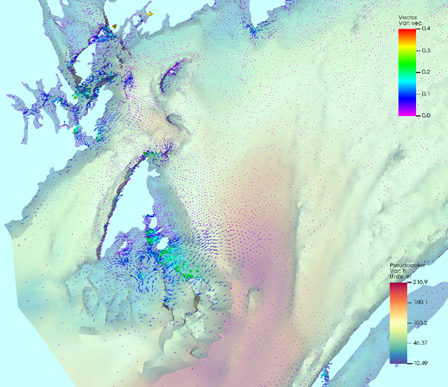
Figure 11.Residual currents at the Bay entrance and Grand Manan Island (from Greenberg, 1982).

In the lower part of Bay, northeast of Grand Manan Island, the baroclinic effect has generated a clockwise gyre around the high gradient depth area (Fig. 12b), which is missing in the barotropic run (Fig. 12a),. ~~In the lower part of Bay, northeast of Grand Manan Island, the baroclinic effect has generated a clockwise gyre around the high gradient depth area.~~ The same residual current (Fig.11) in known to exist at the entrance of the Bay [63,64], which demonstrates the importance of density driven flow in the Bay of Fundy.

Figure 12.The tidal residual currents at entrance of the Bay for(a)Barotropic and (b) Baroclinic run



b

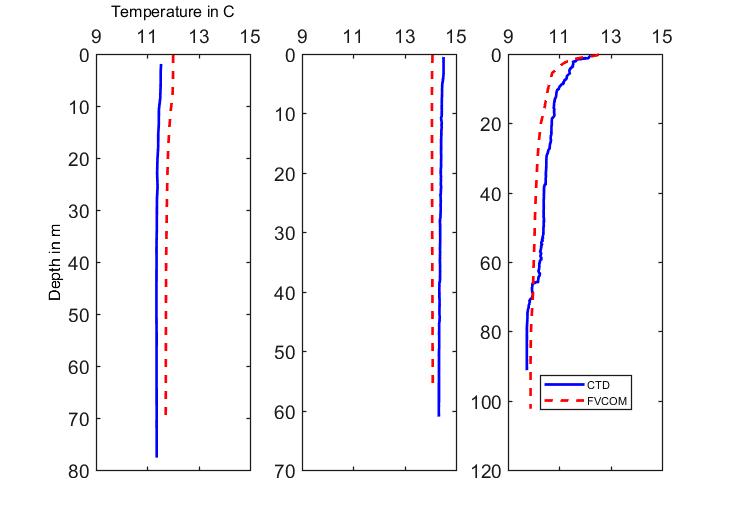


a

**3.4 Temperature and salinity variability**

**3.4.1 Temperature and salinity profile**

The temperature and salinity output from the baroclinic run are evaluated against a set of 58 CTD casts from field observations and the World Ocean Database [65] in July and August 2018 (Fig. 2). A comparison between CTD casts and model output are demonstrated in the Figure 13 for three locations in the bay of Fundy, one at the entrance, the other in the middle, and the last one at the head (Casts are numbered in the Fig.2). The model generated profiles in b A statistical analysis on the model output is provided in the model skill assessment section.



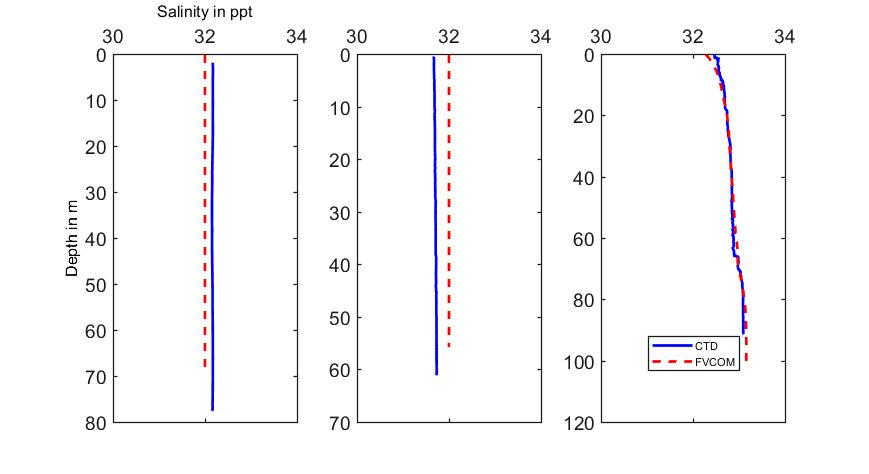
Temperature in C

Cast 1

Cast 2

Cast 3

**a**



Salinity in ppt

**b**

Cast 1

Cast 2

Cast 3

Figure 13.Comparison between CTD cast and Model output for a) temperature and b) salinity for three locations in green circles in Fig.2, cast 1,2,3

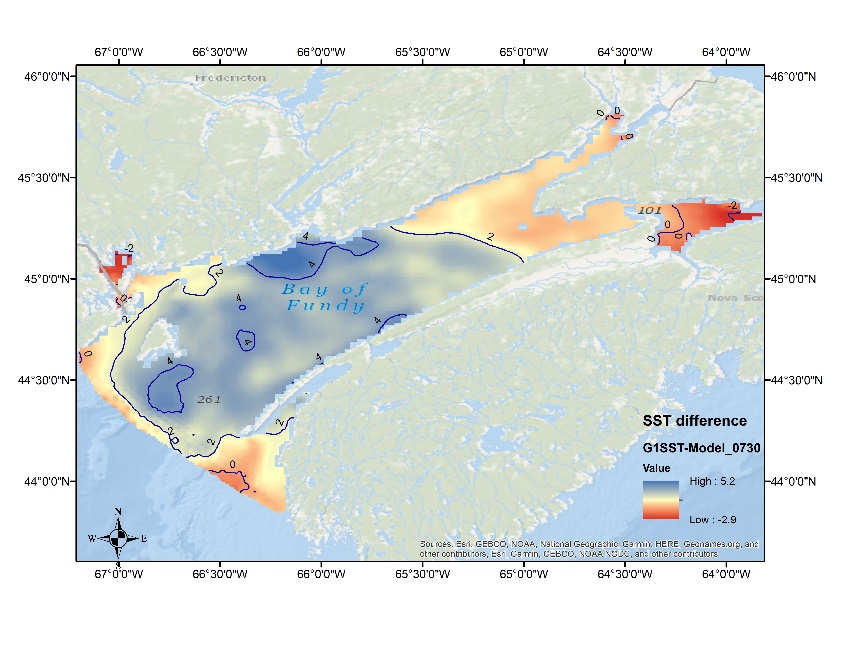
**3.4.2 Sea Surface Temperature**

The model output was also validated through comparison to Sea Surface Temperature (SST) from satellite derived SST. The level 4 SST analysis here is provided by the Group of High-Resolution Sea Surface Temperature (GHRSST) , produced by the JPL OurOcean group which use different satellite and in situ data from drifting and moored buoys to form the sea surface foundation temperature with daily temporal variation and 0.01 degree spatial resolution (G1SST,Global 1km Sea Surface Temperature). The surface temperature in GHRSS is called the foundation temperature, which is a value free of diurnal temperature variability. The result of the difference between G1SST and the daily mean SST from model are illustrated in the Fig. 14 for three days on 15 Jul., 30 Jul., and 30 Aug. 2018. For mid July, the model tends to be a little warm with cold spots in the middle of the Bay and close to the Grand Manan Island. The cold spot in front of the Saint John River may result from not having the temperature profile of the river to use for the open boundary. At the end of July, the cold area increases, specifically in front of Saint John River and at the end of August the difference decreases, with the exception of the area north-east of Grand Manan Island.

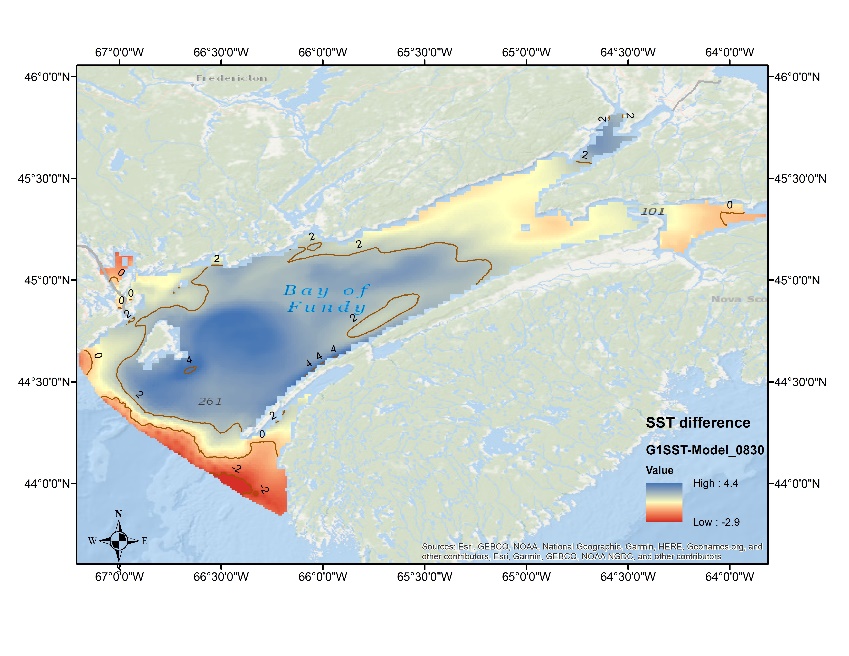
Figure 14.Results of daily SST difference from G1SST minus Model output for a)20180715, b)20180730, and c)20180830



a



b



c

Going back to the model open boundary conditions, the temperature from the GoMOFS is slightly higher than G1SST data showing a warm front in that area. In total, by keeping the definition of foundation temperature in mind, the model SST dose not show a significant difference with the satellite derived one.

**4. Model skill Assessment**

Depending on the different specific factors, such as goals of the modeling exercise or spatial and temporal importance of the output variables, the model skill criteria is subject to change. Generally, the skill means how well the model represents the truth over a specific range of conditions, however, we compare the model output against the observations (having a range of uncertainty in both) since we cannot measure the truth[66]. A visual comparison for the temperature and salinity was completed in the previous sections. A quantitative technique is provided to determine the reliability of the model simulation. These are the quantitative metrics to assess the model skill based on the pairs of model-observations [67]:

1. r: The correlation coefficient of the model predictions and observations:
2. RMSE: the root mean squared error:
3. RI: the reliability index:
4. AE: the average error(bias)
5. AAE: the average absolute error:
6. MEF: the modeling efficiency

Where n = the number of observations, Oi = the ith of n observations, Pi = the ith of n prediction, and and are the observation and prediction averages, respectively.

The tendency of the observed and predicted values to vary together is measured by r, the correlation coefficient which ranges from -1 to 1. The r value will ideally be close to one, however, the values could differ by a consistent value while still having the r close to one, as it does not account for biases.

The magnitude of discrepancies between the observation and prediction are measured by the root mean squared (RMSE), average error (AE), and average absolute error (AAE), with ideal values close to zero. The AE is a measure of aggregate model bias and AAE and RMSE consider the magnitude of each discrepancy rather than the direction.

The average factor by which the model predictions differ from observation is calculated by the RI [68] which ideally should be close to one.

Finally, The MEF measures the model efficiency on how well it predicts relative to the average of the observations [69,70] where an ideal value of one represents a close match between model prediction and observation. An MEF value close to zeros indicate that the model cannot predict each observation better than the average of observations, and for values less than zero it is better to use the average of the observation than the model prediction.

Three levels for CTD profile are defined, including surface, middle layer, and bottom layer. The model skill is calculated for each level to show how well the model can predict the values in each of these layers in comparison to the observations. The results are provided in the table 5.

Table 5.The result of Model skill assessment using the CTD casts for temperature and salinity

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | layer | r | RMSE | | RI | AE | AEE | Variance (CTD) | Std(CTD) | MEF |
| Temperature | Surface | 0.90 | 0.59 | 1.02 | | -0.29 | 0.47 | 1.43 | 1.19 | 0.75 |
| Middle | 0.96 | 0.42 | 1.01 | | -0.11 | 0.35 | 2.23 | 1.49 | 0.92 |
| Bottom | 0.96 | 0.44 | 1.01 | | -1.01 | 0.36 | 2.59 | 1.61 | 0.92 |
|  |  |  |  |  | |  |  |  |  |  |
| Salinity | Surface | 0.66 | 0.19 | 1.00 | | -0.01 | 0.15 | 0.06 | 0.26 | 0.44 |
| Middle | 0.88 | 0.21 | 1.00 | | -0.02 | 0.18 | 0.17 | 0.41 | 0.74 |
| Bottom | 0.91 | 0.22 | 1.00 | | -0.05 | 0.19 | 0.24 | 0.49 | 0.79 |

There is a high correlation between model prediction and observation values for temperature in all three layers, while the RMSE, AE, and AEE are all small in comparison to the variability of observations. The RI is close to one, which show a good model reliability and a fairly close MEF, especially for the middle layer and bottom. The model shows significantly better skill in temperature prediction for the middle and bottom layer than surface. For Salinity, the correlation values are lower than for temperature, especially at the surface, but the RMSE, AE, and AEE are relatively small. However, the salinity variability is not as large as temperature which lead to the lower values of MEF while the model prediction provides better skill for salinity at the bottom and middle layer than the surface. The MEF is function of RMSE and the variance of observations according to which S2 represents the variance of observations. In the case of salinity, all layers have almost the same RMSE (close to 0.20) while there is a larger range of variances at 0.06, 0.17, and 0.24 at the surface, middle, and bottom layer, respectively. The lower values of variance at the surface in comparison to the middle and bottom layer indicate that the surface layer is more homogeneous. Also, the lower variance values in salinity will reduce the MEF.

**4 Summary**

In this work, a three-dimensional coastal ocean model is developed based on the FVCOM. The model is configured to run in baroclinic mode by including the temperature and salinity, tidal level, and Saint John River water level. A high-resolution mesh was generated to resolve the complex geometry of the lower Saint John River to capture the freshwater plume discharge [45] to the Bay. The tidal level was extracted from the tidal model, WebTide Scotia - Fundy - Maine, and temperature and salinity from an operational model in the area, GoMOFS. The model is assessed using observational data, including temperature and salinity from CTD casts, and the published tidal constituents for sea level. The model was able to predict the tide with good accuracy in Saint John Harbour, underestimating the amplitude and phase by no more than 6 cm and 1.5° for M2, 10cm and 2° for N2, and 6cm and 15° for S2. The average error throughout the Bay is about 21cm and 2.1°. In the Minas Basin area, the model had the largest M2 error of 45cm which may result from using a constant bottom roughness for the whole Bay. It may be useful to increase the bottom roughness coefficient in the Minas Passage and in the Reversing Falls to improve the tidal level representation. By increasing the resolution in the Minas Passage and channel, the model resolved all four gyres in that area. Also, the result of the baroclinic run showed an increase in the magnitude of residual currents while conserving the gyre shapes, as compared to the barotropic run. A clear clockwise residual current was generated to the northeast of Grand Manan Island on the bottom, however, the barotropic run did not generate any clockwise residual flow in that area. In the Bay of Fundy, salinity is a dominant factor in the variation of density structure and by increasing the resolution in the Saint John River area, which is the main source of freshwater discharge in the Bay, the Model could capture the outflow of the river which flows on the surface close to the New Brunswick side, and extends to Grand Manan Island. A comparison of the model data against the CTD data showed that the model could provide better skills at the middle and bottom layers for both temperature and salinity while the skills are in favour of temperature which may resulted from the lack of temperature and salinity profile for the Saint John River which is the main contribution of fresh water to the Bay and also the resolution of surface forcing and whether it is reanalysis or not, and the specification of the river discharge to the Bay affect the temperature and salinity in the water column. This assumption needs more analysis to find out the effect of different spaciotemporal surface forcing resolution on the predicted tracer values.

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