High-resolution numerical model resource assessment of Minas Passage, Bay of Fundy

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***Abstract*—Two numerical models developed by the Acadia Tidal Energy Institute are described. The models simulate the tidal flow in the Bay of Fundy, and in particular the Minas Passage. The models have different grid resolution, one suitable for site assessment and one suitable for resource assessment. The models are validated against numerous ADCP measurements. A parameterization of bottom roughness based on the RMS of high-resolution bathymetry is shown to increase the model accuracy inside the region where the parameterization is used, but decrease accuracy outside it. The model simulations are used to map the power density of the passage, illustrating a strong ebb-flood asymmetry and large variations on small spatial scales. Maps of horizontal vorticity indicate regions susceptible to turbulence from both large and small bathymetric features. Finally, idealized turbine power curves are used to illustrate how the spatial and temporal variations favour different turbine designs and deployment depths.**

***Index Terms*—Tidal energy, resource assessment, numerical modelling, Minas Passage, Bay of Fundy**

I. Introduction

Minas Passage, Bay of Fundy is one of the world's best resources for in-stream tidal energy [1], [2]. The Offshore Energy Research Association of Nova Scotia (OERA) (http://www.oera.ca/) has funded numerous research projects including ones that established the extractable energy potential of the passage of 2000-2500 MW [2] and the financial viability of 300-500 MW turbine arrays [3]. This research has allowed the Nova Scotia Department of Energy to develop a Marine Renewable Energy Strategy for the development of a 300 MW turbine array (see https://energy.novascotia.ca/renewables/marine-renewable-energy). The first part of this plan was the establishment of the Fundy Ocean Research Centre for Energy (FORCE) test site, which has built the infrastructure for grid connected arrays with a total capacity of 64 MW (see http://fundy.force/). The FORCE site is in the northern part of Minas Passage as shown in Fig. 1.

The first grid-connected turbine deployed by Cape Sharp Tidal in November 2016 (see http://capesharptidal.com/). The technologies that will be tested at the FORCE site range vary considerably from the 2 MW OpenHydro turbine or the 1.5 MW tidal turbine to be used by Atlantis/DP Energy (http://fundyforce.ca/technology/atlantis/). BlackRock is planning to deploy a semi-submerged, floating and rotating platform with 36 small turbines (see http://fundyforce.ca/technology/black-rock-tidal-power/). While the Minas Tidal Limited Partnership plans to deploy four Tocardo semi-submersible platforms, each outfitted with four 250 KW bi-directional open rotor turbine generators (see http://fundyforce.ca/technology/minas-ime-tocardo/).

The extreme tidal currents that make Minas Passage such an excellent resource also make it a challenging environment. Flow speeds can exceed 6 m/s and generate turbulent wakes downstream of bathymetric features. In such extreme conditions, in-stream turbines must be carefully designed to meet the local hydrodynamic conditions to ensure optimal power production while reducing turbine fatigue. The further development and deployment of both test and commercial arrays require detailed hydrodynamic information about the tidal resource on both site and regional scales. FORCE and its partners have gathered a large number of observations of the flow using ADCPs, radar, and new technology to measure turbulence (see http://fundyforce.ca/fast/). However, even with substantial effort, observations remain limited in their spatial and temporal scope. To fill this gap and provide the detailed hydrodynamic data required, the Acadia Tidal Energy Institute (ATEI), in collaboration with FORCE and OERA have developed two high-resolution (20 to 50 m) coastal-oceanography models of the Minas Passage region.

This paper describes the modelling research completed by Acadia for site and resource assessment in Minas Passage. We focuses on describing the numerical model, the validation of the model, the characterization of the flow in the passage and the FORCE site and use the numerical data to estimate turbine power generation. The paper is laid out as follows. In section 2, we describe the Acadia numerical models. In section 3, we summarize the validation of the two models. In section 4, we briefly describe how the models can be used to examine the spatial variation of the power density and turbulence. In sections 5, we demonstrate how turbine power generation varies with location and position in the water

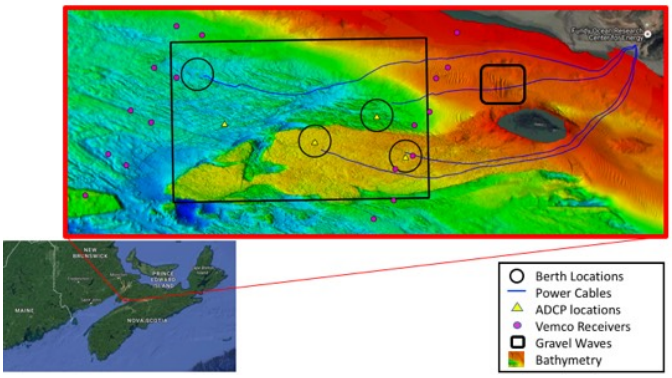


Fig. 1. The FORCE location in Minas Passage.

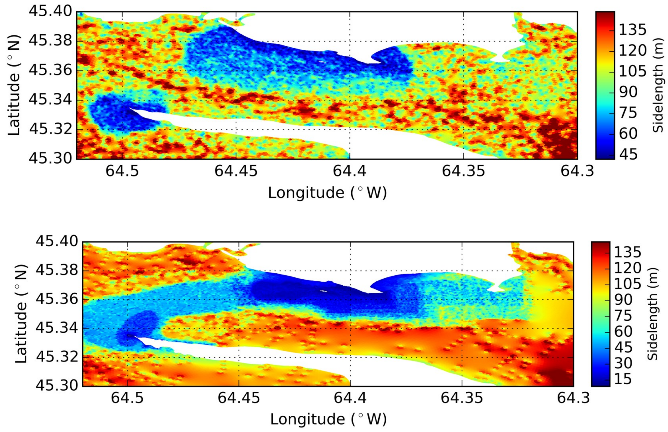


Fig. 2. Resolution of the two numerical models used to study the Minas Passage. Top: Acadia Bay of Fundy Model; Bottom: Acadia Force Model. The colours average lengths of the sides of each triangular element in metres.

column. In section 6, we provide a conclusion and description of continuing work.

II. Numerical Model Description

The ATEI has developed two numerical models to study the Bay of Fundy and, specifically, Minas Passage. The Acadia-Bay-of-Fundy (Acadia- oF) numerical model was designed for quantifying the broader tidal energy resource in the Bay of Fundy. On the other hand, the Acadia-FORCE numerical model was designed specifically to model the FORCE region and conduct site assessment/analysis for the berths locations (see Fig. 1). Both the Acadia numerical models use the Finite Volume Community Ocean Model (FVCOM) [4] as their solver. Each model consists of a set of input files for FVCOM specifying the boundary values, parameters and spatial mesh that define the region of interest and the resolution of the output.

The first and most important step in creating a model is the creation of a spatial mesh. The spatial mesh specifies the locations at which the numerical solution of the governing equation is computed. FVCOM accepts finite element, or variable resolution, meshes, consisting of triangular elements at whose nodes and vertices the solution is computed. In order to accurately model the tidal resonance that creates the extreme tides in the Bay of Fundy, Acadia's mesh includes the entire Bay of Fundy and Gulf of Maine, extending out past the continental shelf. Since our focus is the high-energy regions in the study area, we created a mesh with highest resolution in the regions of highest flow.

The Acadia-BoF model was designed for medium resolution simulations of high kinetic energy sites throughout the Bay of Fundy. In the high energy regions, the resolution is of the order of 50 m. In Minas Passage the highest resolution is in the region around the FORCE site and near the tip of Cape Split. Through the rest of the Minas Passage, the resolution is on the order of 100 m, with a smooth transition between the finer and coarser sections of the mesh, as required for numerical stability. the Acadia-BoF model also has high resolution other potential tidal energy sites in the Bay of Fundy, namely the Digby Neck passages, near Cape D'Or and near Cape Enrage. The model can be used to conduct a resource assessment of sites and to predict the interactions among sites around the Bay of Fundy. The Acadia-BoF model has been designed so that simulation data from the model can be made publicly available through the Nova Scotia Tidal Energy Atlas (http://tidalenergyatlas.acadiau.ca/)

The Acadia-FORCE model was designed to focus is the FORCE region. From experience modelling in the Digby passages, it was found that the optimal resolution for FVCOM is on the order of 20 m [5], similar to the water depth. Therefore the mesh ahas a resolution of $\sim$ 20 m throughout the FORCE region. Through the rest of the Minas Passage, the resolution is on the order of 50 m, with a smooth transition between the finer and coarser sections of the mesh, as required for numerical stability. The Acadia-FORCE model does not have high resolution in any other region of the Bay of Fundy.

The resolution of two meshes in Minas Passage are shown in Fig. 2 and Table I lists the key differences between the two models. In both models, the resolution decreases with distance from the Minas Passage, decreasing to tens of kilometres in the Gulf of Maine, see [2] for more on the meshes. Both meshes were designed by Mitchell OFlaherty-Sproul using open-source software subject to these constraints and to several technical constraints that ensure stability and accuracy of the numerical solutions.

In coastal ocean models the most expansive physical boundary is the seabed. In Minas Channel, the vigorous tidal mixing homogenizes the spatial fields of salinity and temperature, so the flow is barotropic. For simplicity, the water is considered to be of constant density with a density of 1025.27 kg/m^3.

In barotropic tidal flow, the accuracy of the model is highly dependent on the quality of the bathymetry data set. For the creation of the Acadia models, FORCE provided Acadia with a 2 m resolution bathymetry that covers the Minas Passage, the north shore of Minas Passage, and parts of Minas Channel and Basin. The FORCE bathymetry set was merged with Canadian Hydrographic Services (CHS) data and other datasets to create a bathymetry set over the full model

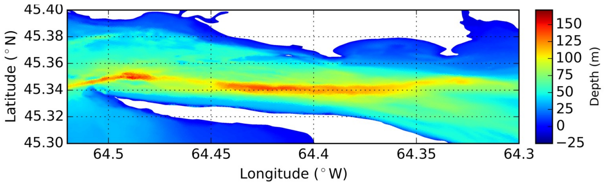


Fig. 3. Minas Passage bathymetry as represented in the two numerical models. The colours are mean water depth in metres.

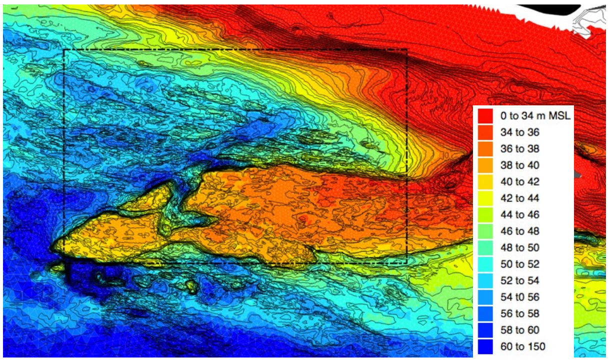


Fig. 4. The bathymetry in the FORCE region. The colours are the Acadia-FORCE model bathymetry; the black lines are contours of bathymetry from the FORCE 2 m resolution data set.)

domain. As is recommended by the developers of FVCOM, the unfiltered bathymetry data was interpolated directly onto the mesh. The model bathymetry in Minas Passage is shown in Fig. 3 and Fig.4 shows the Acadia-FORCE bathymetry in detail for the FORCE region.

For both models, no meteorological forcing was applied at the surface. Hence, there is no wave component or storm surge in the models. For both model, we defined the open boundary to extend out past the continental shelf. At the open boundary, we specified eight tidal height constituents (S2, M2, N2, K2, K1, O1, P1, Q1), derived from the Oregon State University TOPEX/Poseidon Global Inversion Solution (http://volkov.oce.orst.edu/tides/global.html), which is a data assimilation model that incorporates satellite altimetry data. The models are entirely forced by this small set of tidal constituents.

FVCOM can be run in either a 2D depth-averaged mode or a 3D layered mode. The 3D version of both models has 10 sigma layers with a parabolic distribution of the layers, concentrating the resolution at the surface and the sea bottom. Since the model data discussed in this report is 2D depth-averaged data, we will only discuss the 3D model in Section 6.

Typically for a 2-D model, the open boundary forcing, mesh resolution, and/or seabed drag is adjusted, or tuned, in order to bring the model into better agreement with observations. Here, we calibrated our model with respect to bottom friction as it had the most direct impact on the flow. Two methods of specifying the quadratic bottom friction coefficient were used. The first was to use a constant value of the bottom coefficient,

TABLE I
MODEL PARAMETERS

Parameter	**Model**	
	Acadia-FORCE	Acadia-BoF
No. of nodes, elements:	113293, 221816	109042, 212065
Time step	0.5 sec.	1.5 sec.
Bottom friction coefficient	Roughness parametrization	Constant (2.5×10^{-3})

varying it around the default value of 2.5×10^{-3}. The second is to parameterization of the seabed roughness roughness based on the variation of the high resolution bathymetry, based on similar atmospheric boundary layer models.

Many surface topologies can only be described statistically and accordingly require statistical representations of their roughness length scales. A simple and effective representation over statistically homogeneous surfaces is to let the roughness length scale be proportional to the root mean square (RMS) of surface element heights [6]. This statistical representation can be generalized by assuming that the sub-grid scale roughness length scale, z_0, is proportional to the local RMS of the unresolved part of the bathymetry fluctuations [7], that is,

$$z_0 = \alpha \sigma_h \quad \text{where} \quad \sigma_h(x, y) = \sqrt{\overline{(h - \overline{h})^2}}, \tag{1}$$

h is height of the bathymetry, α is a tuneable constant, and $\overline{*}$ is a low-pass filter of $*$.

[7] applied their roughness parameterization to a Large-Eddy Simulation (LES) of 3-D atmospheric flow, whereas we apply their parameterization to a 2-D coastal ocean model. In order to adapt their parameterization to depth-averaged flow, it is assumed that the vertical profile of velocity can be represented by the log-layer equation through the full water column. This assumption is supported by analysis of ADCPs in the FORCE region. Under this assumption we can vertically integrate the log layer equation to give:

$$C_d = \left(\frac{\kappa}{\log\left(\frac{H}{z_0 \mathrm{e}}\right)} \right) \tag{2}$$

where H is the (spatially-varying) depth and e is Eulers constant.

The RMS roughness scheme assumes that the local RMS of subgrid scale seabed heights is proportional to roughness and that the seabed type is consistent over space. This confines application of the scheme to the northwestern Minas Passage, where mesh resolution is sufficiently high and where the seabed type is dominated by exposed bedrock. Additionally, the shape of the sub-region should be generic. Given these considerations, we chose the shape of the sub-region to be an ellipse that approximately covers the region of exposed bedrock in the northwestern Minas Passage. Since the model

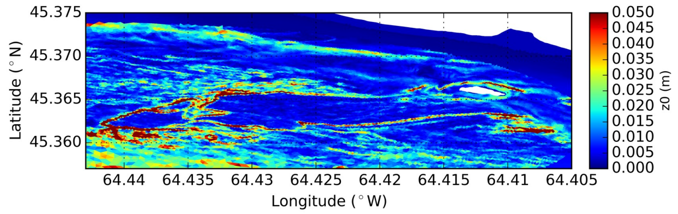


Fig. 5. Bottom roughness z_0 as calculated from the RMS of the bathymetry in the FORCE region.

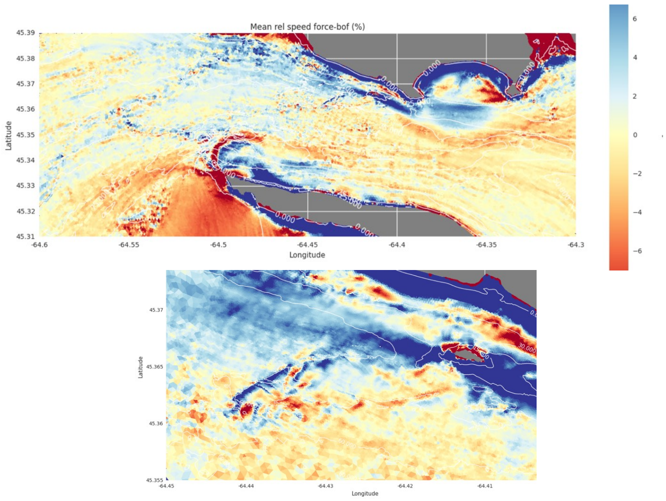


Fig. 6. The relative difference (%) in the mean speed, Acadia-FORCE minus Acadia-BoF. Top: Minas Passage; Bottom: FORCE region.

with constant bottom drag successfully simulates the large-scale hydrodynamics, we apply this spatially constant friction outside of the ellipse. The value of α was tuned through comparison to ADCP measurements, eventually determining that a best value of $\alpha = 0.0165$ The variation of the bottom roughness parameter, z_0 as calculated by (1), is shown in Fig.5. It clearly illustrates the low roughness values on the volcanic platform, with high roughness values around the boundary and to the southwest of the platform.

Before presenting the validation of these models, it is worthwhile to examine how big an effect the model resolution and different bottom friction methods have on the model results. To illustrate this, we calculate the difference in the time mean speed from the different model simulations. In Fig.6, we compare the Acadia-FORCE with constant bottom friction to the Acadia-BoF model. It illustrates that the resolution has relative small impact ($< 5\%$) over much of Minas Passage except near coasts, particularly near CapeSplit and Black Rock. In these regions, the high resolution model resolves the wakes and jets caused by the shallow water and outcroppings. Importantly, the difference around Cape Split do not cause large changes in the flow through the rest of Minas Passage.

In Fig.7, we compare the Acadia-FORCE with constant bottom drag to the model with variable bottom drag based on (2) and (1). The figure illustrates that although the bottom

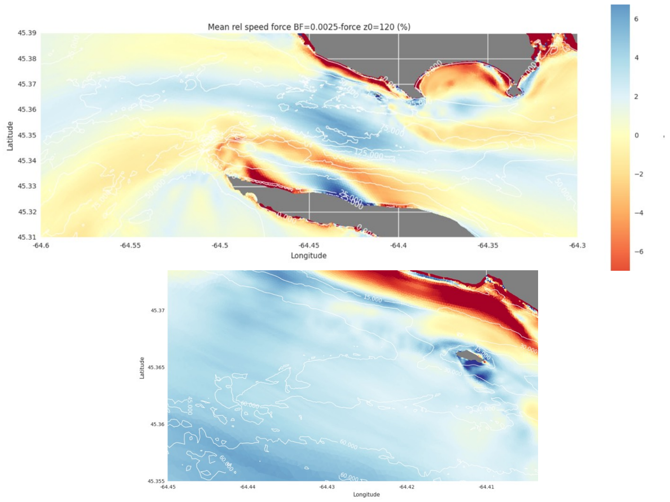


Fig. 7. The relative difference (%) in the mean speed, Acadia-FORCE with constant bottom friction minus variable bottom friction.

friction varies only in the FORCE region, it has a larger impact on the flow in the central part of Minas Passage. The higher value of the friction in the FORCE region slows the flow down throughout the central part of Minas Passage, and results in increased speeds in the southern portion of the passage. In the FORCE region, the difference is a small reduction in the speed, with little evidence of the large variations in bottom roughness, seen in Fig.(5), present in the mean speed.

III. Numerical Model Validation

In order to validate the numerical models, we compare the simulated data to observation data from Acoustic Doppler Current Profilers (ADCPs). In total, we use data comes from 26 ADCPs deployed by FORCE and its partners from 2008 through 2016 at locations near the FORCE region as shown in Fig. 8 . The ADCPs cover the shallow volcanic platform of the FORCE test area, the surrounding deeper water, and the near-shore, turbulent region around Black Rock. However, we have no ADCP data from the southern part of Minas Passage. For many of the ADCPs we chose only a week-long period corresponding to the spring tide to reduce the model integration time required for validation. Some ADCPs data sets were of low quality, for example the ADCP moved during the deployment, and therefore these results were assigned a low weight during the calibration process.

Numerical models only approximate the true hydrodynamics: firstly, the governing equations are simplified and approximated, and secondly, the simplified governing equations are discretized, that is we solve the equations on the numerical grid discussed above. For this project, we report a simple validation/calibration procedure of simply changing the level of bottom friction applied in the model. Since the high-energy, barotropic tidal flow is largely determined by the model bathymetry, the bottom friction parameter is the most obvious parameter to use for tuning. The bottom drag coefficient represents a rough representation of the complex dynamics of bottom boundary layer. There is no correct value for the coefficient, but the typical values of used oceanographic models is 2.5×10^{-3}. We varied the bottom drag coefficient over the range 2×10^{-3}. to 3×10^{-3} and compared the results to the ADCPs observations. The results of changing the bottom drag coefficient is predictable, a higher value of the bottom drag reduces the speed of the flow. But teh reduction in speed is not uniform over the entire model domain – see Fig. 7.

The model validation is completed using the two key characteristics of the flow: the flow speed:

$$U = \sqrt{u^2 + v^2}$$

where u and v are the eastern and northern components of the velocity, respectively, and the power density:

$$P = \frac{1}{2}\rho U^3,$$

where ρ is the water density. The power density is the key metric to the in-stream tidal turbine industry, since it is directly related to the power that turbines will generate.

In oder to compare the simulated and observed data, the time series are interpolated to the same 10-minute time steps. Before calculating the validation statistics, any shift in time between the observed time series and simulated time series is removed.

In the validation, two metrics are used to compare the simulated data to the ADCP measurements. The first is the relative bias between model data (m_i) and observations (o_i):

$$\text{bias} = \frac{\overline{o_i - m_i}}{\overline{o_i}} = 1 - \frac{\overline{m_i}}{\overline{o_i}}, \quad (3)$$

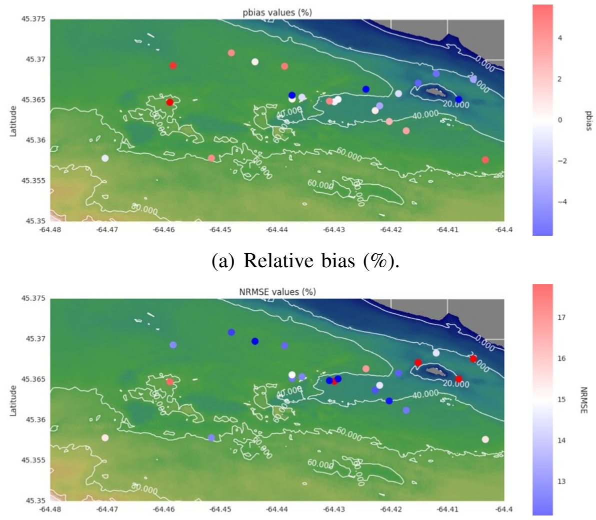
where the overbar represents a time average. The bias is presented as a percentage, so this formula is multiplied by 100, which represents the relative percentage difference in mean speed of the observations and the simulated data. A positive value indicates that the model is underestimating the flow speed–the model is too slow–and a negative value indicates that the model is overestimating the flow speed–the model is too fast. The bias gives us a basic measure that the model is getting the average dynamics of the tides correct.

In order to ensure that the model is also simulating the details of the flow correctly, we also calculate the normalized root-mean-square error (NRMSE):

$$\text{NRMSE} = \frac{\sqrt{\overline{(o_i - m_i)^2}}}{\sqrt{\overline{o_i}^2}}. \quad (4)$$

Once again, the NRMSE is presented as a percentage, so this formula is multiplied by 100. The NRMSE is an average of the instantaneous error in the simulated data and, thus, gives a specific measure of the accuracy of the model in getting the detailed tidal dynamics correct. These details include the asymmetry between the flood and ebb tide, and the macro-scale variations in the flow. The NRMSE is thus a very stringent test of the models capabilities.

The relative bias and NRMSE for the Acadia-BoF model are plotted for all the 26 ADCPs in Figs. 8. The bias shows a trend to negative bias in shallow water and positive in deeper water. The NRMSE is particularly high in the shallow, coastal waters near Black Rock.



(a) Relative bias (%).

(b) NRMSE (%).

Fig. 8. The locations of the ADCPs (dots) used to validate the numerical model. The colours are the relative bias, given by (3), and NRMSE, given by (4).

TABLE II
MODEL VALIDATION RESULTS: IN EACH COLUMN THE FIRST NUMBER IS THE RELATIVE BIAS AND THE SECOND IS THE NRMSE. THE VALUES IN BRACKETS ARE THE ACADIA-FORE MODEL WITH CONSTANT BOTTOM FRICTION.

ADCP	**Acadia-FORCE**		**Acadia-BoF**	
	speed	power	speed	power
Aug.-2014	1.83, 12.8	9.18, 23.2	5.18, 12.0	13.36, 21.1
May-2015	3.28, 13.0	10.0, 22.4	0.73, 11.6	7.05, 20.8
Oct-2016-2	6.0, 12.7	15.86, 22.7	0.13, 12.1	1.39, 18.9
Oct-2016-3	5.69, 13.2	15.16, 25.1	5.52, 12.0	13.6, 20.9
	(0.82, 14.0)	(1.08, 27.0)		
Oct-2016-4	4.48, 14.0	16.44, 26.8	-0.55, 12.7	3.77, 19.9
	(1.61, 13.9)	(9.5, 24.5)		

Table II lists the relative bias and NRMSE for both models for 5 recent ADCPs data sets. These ADCPs were used for validation as they represent a good spatial range and high quality time series for a full lunar month. The two early ADCP are within the FOCRE region, the Aug. 2014 ADCP is on the volcanic platform; the May 2015 is to the east in deeper water. The three 2016 ADCPs are located to the south of the FORCE region.

The results show that, in general, the model are too slow as shown by the positive bias for speed at all these locations. The validation has illustrated that the model has a low relative bias ($< 6\%$) and reasonable normalized RMSE ($< 14\%$) for most ADCP locations. Note that R^2 values always exceed 0.9. For power density, the bias is larger ($< 16\%$) and the NRMSE are in the range of 20 to 30%. Again R^2 values always exceed 0.9. These are good values for such a model that has not been highly tuned, for example see Fig. 12 to see a comparison of time series.

One other thing to note. While the Acadia-FORCE model performs equally well to the Acadia-BOF model for the two ADCPs in the FORCE region, it does not perform nearly as well for the 3 ADCPs on the boundary of the FORCE regions. This might be expected since these ADCPs lie near the boundary of the region where bottom roughness is used to calculate the bottom drag. Fig.7 showed that this region saw the biggest reduction in flow speeds in comparison to a constant bottom friction model. Indeed, the Acadia-FORCE model with constant bottom friction has speeds similar to the Acadia-BoF model in this region (see Fig. 6) and results in bias values of less than 2% for these ADCPs.

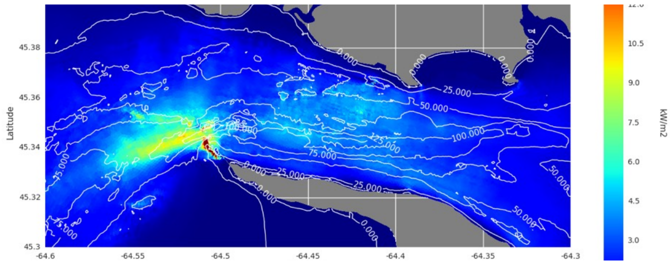
IV. Data Analysis

The numerical simulations have been analyzed using the open-source data analysis package PySeidon (https://github.com/GrumpyNounours/PySeidon) to compile a comprehensive resource database for Minas Passage. The database contains quantities related to turbine performance (mean/max speed, power density, flood/ebb asymmetry), as well as factors that affect turbine fatigue (turbulence, vorticity, directional variation). Here we comment on two features of the flow that are particularly relevant to site selection.

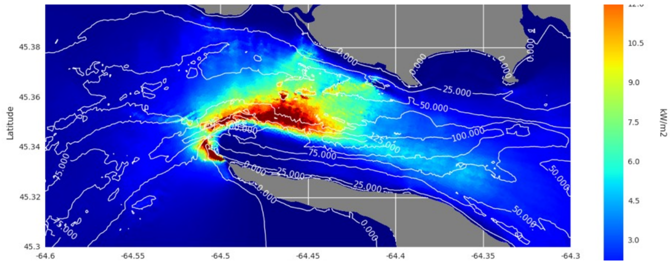
The mean power density for the ebb and flood tides, shown in Fig.9, shows considerable asymmetry between the two tides and large spatial variation over the Minas Passage region due to the effects of Cape Split. In the region of the strong flood jet in Minas Passage, the flood tide is more than 2 times, and in some locations more than 4 times, as powerful as the ebb tide. To the west of Cape Split, we see the opposite with the ebb tide 2-4 times more powerful than the flood tide. While the high power density values are obviously necessary for high power production, dealing with such a high power asymmetry is a challenge to turbine design.

A detailed image of the FORCE region in Fig.10 illustrates the large variations in the mean power density when the high resolution Acadia-FORCE model is used. First, the power density on the shallow volcanic platform is significantly higher than the surrounding deeper waters. Secondly, small scale bathymetric features create small jets of flow on both the flood and ebb tides. These result in variations of up to 25% in the time mean power density, on the a spatial scale of the grid ($\sim$ 20 m). These variations suggest that micro-site assessments at the berth locations will be required to provide accurate estimates of flows characterizations and turbine performance.

Another significant factor in turbine siting is the level of turbulence in the flow. Turbulence contributes to turbine fatigue and can make marine operations difficult. The Acadia models are hydrostatic and do not have sufficient resolution to model small scale turbulence, but they can model flow variations on a scale similar to the grid resolution. Comparison to ADCP and radar observations suggest that the $\sim$ 20 m



(a) Ebb power density.



(b) Flood power density.

Fig. 9. The mean power density for the Minas Passage region emphasizes the asymmetry ebb-flood flow.

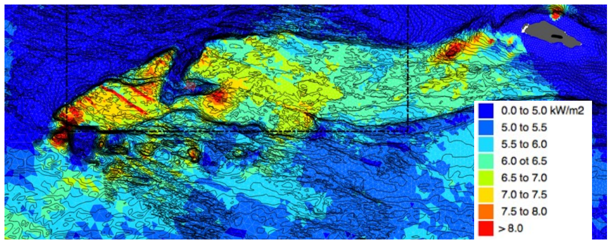


Fig. 10. The mean power density in the FORCE region. The black lines are contours of mean water depth.

Acadia-FORCE grid does a reasonable job of resolving eddies and wakes formed by resolved bathymetric features. A good measure of this large-scale turbulence is the time mean of the magnitude of the horizontal vorticity, shown in Fig. 11. To put these values in context, a value of 1×10^{-2} (the maximum on the figure) corresponds to a change in flow speed of 10 cm/s over a distance of 10 m. As expected, the mean vorticity is high downstream of Cape Split, Cape Sharp, Partridge Island, Black Rock and other bathymetric features. These wakes of high vorticity extend 100s of metres downstream. In the FORCE region, we see that high values of vorticity are generated by Black Rock and rapid change in depth around the volcanic platform. The FORCE region sees both eddies from the upstream coastal features and the volcanic platform, that can results in significant variations in the flow. For example, Fig. 12 shows a time series of the signed speed at such a location. The speed shows both high and lower frequency variations. The time series in the figure illustrate 4 realizations of the flow, with almost identical tidal flow but different turbulent characteristics.

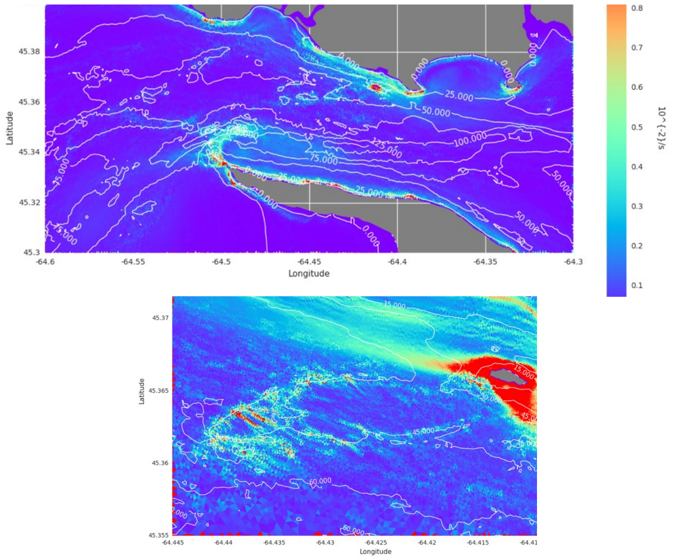


Fig. 11. The mean magnitude of the horizontal vorticity for the Minas Passage (top) and FORCE (bottom) regions. A value of 1×10^{-2} corresponds to a change in flow speed of 10 cm/s over a distance of 10 m. (The white lines are contours of mean water depth.)

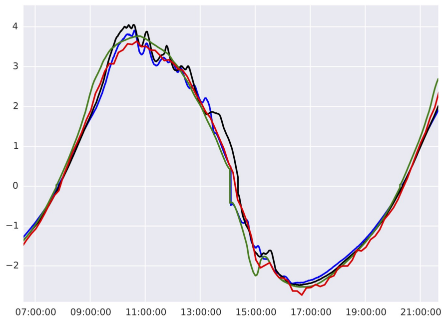


Fig. 12. Time series of the flow for a site in the FORCE region west of the volcanic platform. The red line is 5-minute averaged ADCP data. The blue and black curves are from Acadia-FORCE simulations with bottom-roughness and constant bottom drags. The green curve is from a 3D Acadia-FORCE simulation. The model simulations are sampled at a 10s rate.

V. Turbine Power

The numerical simulations allow for the calculation of turbine power given a turbine power curve. Using such calculations, the Acadia-FORCE model has been used to conduct specific site assessments, while the Acadia-BoF model has been used to estimate the technical resource for the passage, see for example [8], [9]. Here we use models of a typical turbine to illustrate how the spatially varying flow will result into spatially varying estimates of power generation.

We present the results of two possible power curves of a typical turbines with varying cut-out speeds, rated speeds and rated powers are shown in Figure 13. The two curves are chosen to have a equal area under the rated power section of the curve, so that if the speeds were equally probable, the turbines would generate equal power. The mean power output

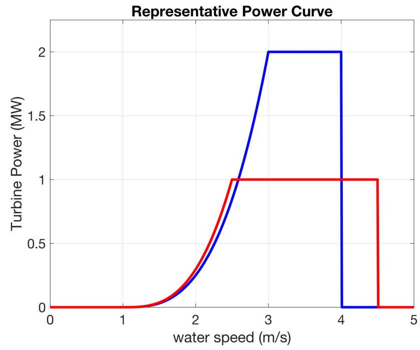


Fig. 13. Three power curves for a high (blue) and low (red) power turbines.

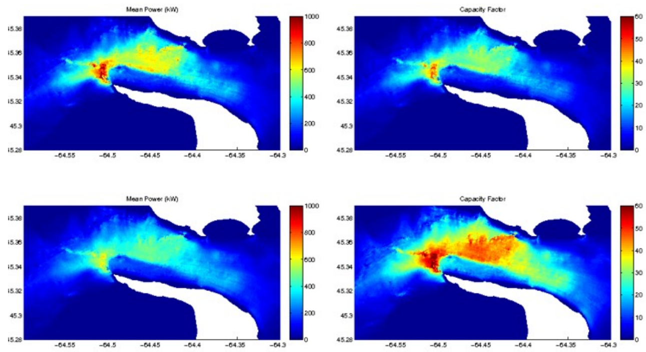


Fig. 14. Mean power (left) and capacity factor (right) output for a high (top) and low (bottom) power turbines.

and capacity factor for each of these turbines is plotted versus location in Fig. 14. In general, the high-power turbine produces more power, roughy 50% more, but at a much lower capacity factor $\sim 30\%$ versus $\sim 40\%$. The plots show that by increasing the cut-out speed, as the low-power turbine does, the capacity factor can be increased in the central part of Minas Passage where the flood speeds exceed 4 m/s. And while the low power turbine cannot take advantage of the high speed flow in the central passage, it works at high capacity factors and generates more power in the lower energy areas of the passage.

Finally, the impact of a change in the location of the turbines in the water column is estimated. The change in water speed with depth was estimated using a logarithmic profile of water speed and the local bottom roughness, as follows:

$$\frac{U_s}{U} = \frac{\log\left((D - D_T)/z_0\right)}{\log(D/(z_0 e))} \quad \text{and} \quad \frac{U_b}{U} = \frac{\log(H_T/z_0)}{\log(D/(z_0 e))}$$

where U is the depth-averaged water speed; U_s is the calculated water speed for the turbine at a depth D_T below the surface; U_b is the calculated water speed for the turbine at a height H_T above the bottom; z_0 is a parameter proportional to the bottom roughness, here taken as 1/50 the bottom roughness.

For the following power calculations, the high power turbine was used, surface turbines used flow speeds 10 m below the surface and bottom turbines used flow at 15 m above the

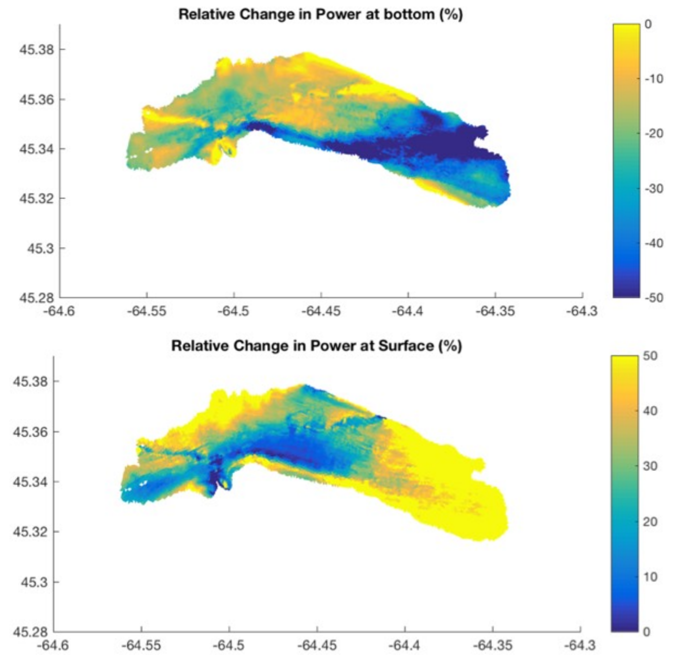


Fig. 15. Change in power if turbine is near bottom (top) or near surface (bottom).

bottom. In general, the results indicate that surface turbines have a power that is 10 to 20% higher than the depth average and bottom turbines have a power that is 10 to 20% lower than the depth average. However there is considerable variation with location depending on the water depth and bottom roughness, as shown in Fig. 15. In locations with lower speed, and deeper waters, surface turbines can see up to a 50% gain in power, while bottom mounted turbines can see 50% less power. In locations, where the turbine is already operating at higher capacity factors, the change with depth is smaller.

VI. Conclusion and Future Work

The paper has presented a description of the Acadia numerical models for tidal flow in Minas Passage. The models have two different resolutions and use different formulations for bottom drag, a constant value and one parameterized on bottom roughness. These differences results in relatively small differences in the mean characteristics of the flow, but do result in significant differences in the variation of the flow at small scales. The models have been validated against a large number of ADCP observations. When compared to recently gathered ADCP data, the model bias and NRMSE errors are reasonable but vary considerably with ADCP location. The bottom roughness formulation for bottom drag demonstrated some advantages but also some disadvantages since it did not extend over the entire passage. The model simulations were used to demonstrate the high asymmetry in the ebb and flood tides, and the high level of spatial variation in the flow. As well, regions of high levels of large-scale turbulence were illustrated by plotting the mean vorticity. Most of the turbulent regions were connected to large bathymetric or coastal features, but smaller changes in water depth also resulted in significant vorticity. Power generation calculations using idealized power curves again emphasized the spatial variation of the flow and the need to design a turbine to the flow characteristics to obtain a high capacity factor. In conclusion, the models are capable of providing significant data required for flow characterization both on the scale of the entire Minas Passage and the FORCE berth sites.

There are several main areas of future work. First, the models have been run in 3D mode, usually with 10 sigma layers. These simulations are in the final stage of validation, with results similar to the 2D model for the depth averaged flow (for example see Fig. 12). The 3D models capture the vertical variation of the flow well, but initial analysis is showing that they are more viscous than the 2D model and result in less flow variation. Second, all the models need to be validated against measurements in the central and southern regions of Minas Passage. Two measurement programs, one using drifters and one using X-band radar, will provide the spatial coverage to allow the validation of the model throughout Minas Passage. The X-band radar has already shown broad agreement over the majority of the passage, and in particularly has validated the existence of streaks of turbulent flow generated by small scale bathymetric features.

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