Evaluating the performance of turbulence closure models in coastal modeling for tidal stream resource characterization

Z. Yang and M. Deb

Abstract — **Turbulence in tidal energetic environment plays an important role in resource characterization and project siting. Coastal ocean models have been used to predict tidal current and turbulence characteristics in potential tidal energy sites. In this study, we evaluated two widely-used turbulence closure models implemented in a coastal hydrodynamic model – Finite Volume Community Ocean Model (FVCOM) to characterize the tidal energy resource and turbulence in the Western Passage, Maine, USA – a top ranked tidal energy site. Turbulence closure models used in this analysis are the default scheme, the Mellor–Yamada Level 2.5 model (MY2.5), and the k–eps model, which is integrated in FVCOM from the General Ocean Turbulence Model. Model simulations showed that the MY2.5 model performed better than κ-ε model in comparison with the field measurements. In particular, the simulated time series of turbulence intensity and kinetic energy matched the observed data very well in the Western Passage using MY2.5 model. Detailed analysis was conducted to characterize turbulence properties on the horizontal plane and at selective cross-sections in Western Passage. This study demonstrated that turbulence properties simulated by a coastal ocean model, along with tidal hydrodynamic properties, can be very informative for tidal energy resource characterization and project site selection.**

***Keywords*—tidal energy, resource characterization, turbulence, numerical modelling, Western Passage**

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I. INTRODUCTION

Harvesting tidal stream energy from the ocean for electricity generation has been considered as an energy resource alternative to fossil fuels for mitigating the negative impact of climate change and enhancing energy security and coastal resilience. Numerical models have been used extensively to characterize and assess tidal resources at potential tidal energy development sites. Turbulence plays an important role in site selection and should be characterized as part of tidal energy project development, as recommended by the International Electrotechnical Commission technical specifications (IEC TS 62600-201)[1]. However, most of the numerical modeling studies for tidal energy resource characterization do not include turbulence characteristics because of the limitation of Reynolds averaged Navier–Stokes coastal ocean models in resolving the inertial sub-range turbulence scales. Studies also demonstrated that turbulence properties, such as turbulence intensity and turbulence kinetic energy, simulated by the coastal ocean models based on turbulence closures can be useful in assisting tidal resource characterization at tidal energy sites [2, 3]. In this study, we applied a coastal tidal hydrodynamic model to simulate the tidal currents and turbulence characteristics in the Western Passage, ME, USA (Figure 1) [4, 5]. We evaluated the performance of two widely used turbulence models in predicting the turbulence characteristics and demonstrated that turbulence parameters can be useful in supporting tidal energy resource characterization at the project site.

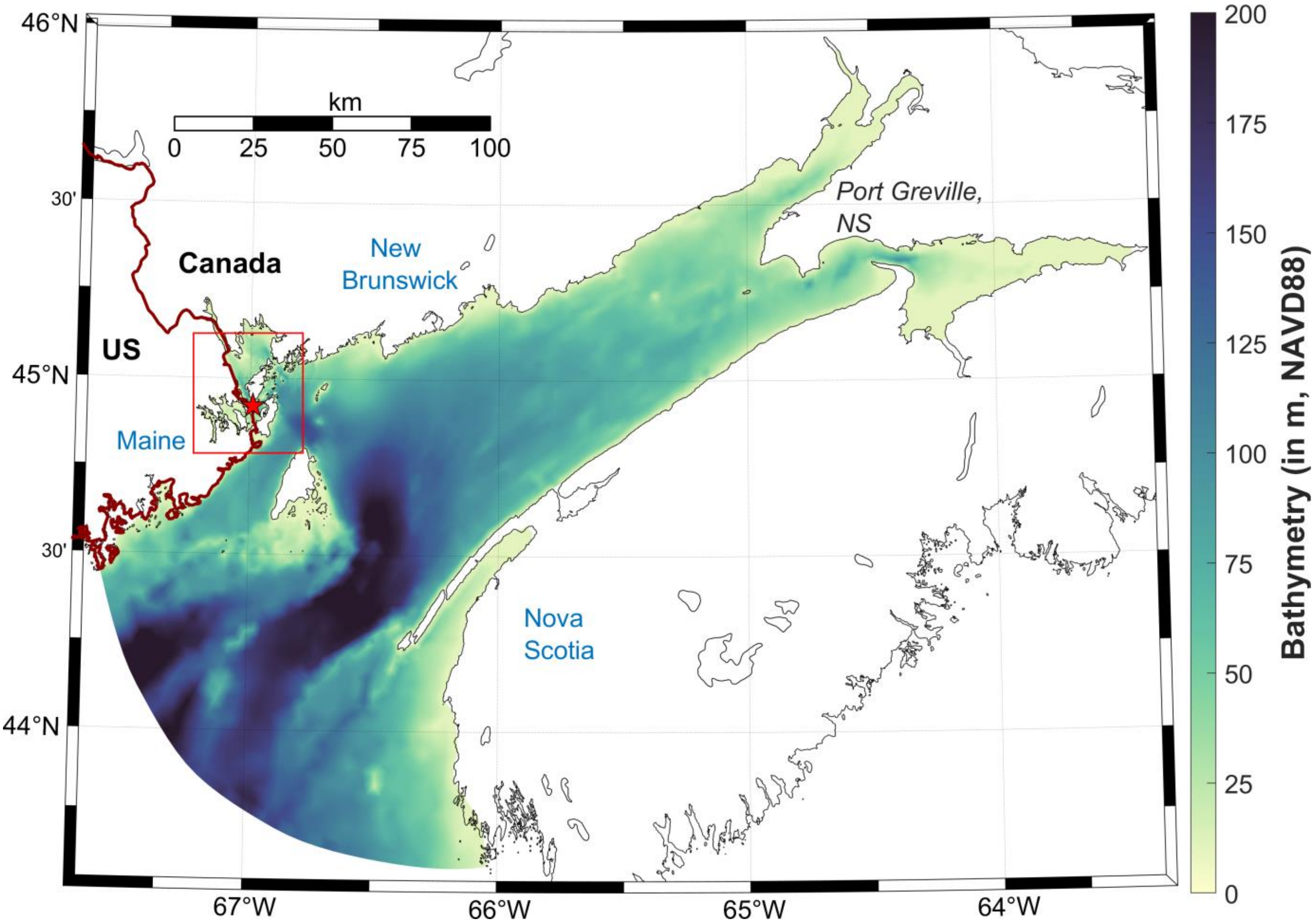

Fig. 1 Unstructured grid model domain and bathymetry (in meters) used in this study. The red polygon shows the location of the focus area Western Passage, ME, USA, and the red star represent the ADV location used for turbulence measurement.

II. Methods

In this study, A high-resolution tidal hydrodynamic model was developed by Yang et al. [4] for the Western Passage using the Finite Volume Community Ocean Model (FVCOM), and subsequently, the model was applied to simulate turbulence intensity and kinetic energy using Mellor-Yamada 2.5 scheme (MY2.5) [5]. In this study, we compared the performance of MY2.5 with another popular turbulence model (κ-ε) for predicting the turbulence characteristics in the Western Passage. We compared the simulated mean tidal velocity and turbulent kinetic energy for two purposes: 1) hydrodynamic model validation and 2) evaluating how the errors in model results can affect resource assessment for tidal energy farm deployment. We used multiple current profiler data sets from the Western Passage to validate predictions of three-dimensional tidal currents. Field datasets of turbulent kinetic energy and intensity from the study site were collected following IEC TS 62600-201 guidelines [6], and this publicly available data was used to validate model-generated turbulence statistics. Then, we used the model results of macro-scale turbulence with two different schemes to see which is more accurate for an energetic tidal system like the Western Passage, ME, and how the difference in model estimates can change tidal energy conversion (TEC) site ranking.

A. Field data

We used the only available tide gauge data maintained by National Oceanic and Atmospheric Administration (NOAA) in the study area: Eastport, ME, and two XTide stations: Cutler, ME, and Port Greville, NS (https://flaterco.com/xtide/) to validate the model-predicted water surface elevation. We also used three historical acoustic Doppler current profiler (ADCP) current data sets from locations close to the Western Passage for further model validation. These stations consist of historical data sets from different periods, and more information about them can be found in [4, 5].

As part of a tidal resource assessment study, Kilcher et al [6] collected various flow and turbulence data sets using vessel and bottom-mounted ADCPs and an acoustic Doppler velocimeter (ADV) from the Western Passage. The field campaign in April - July 2017 used different instruments to measure flow properties at various locations and periods. For example, the ADV mounted on a stable tidal turbulence mooring (STTM) was deployed at 10 meters above the bottom (mab) and collected turbulence data from 24 - 31 May 2017, while the ADCPs collected data for a much longer period (~3 months). In this study, we used the tidal turbulence statistics and current data collected in 2017 at the Western Passage, shown in Fig. 1, for model validation.

B. Numerical model

The incompressible, u-momentum equation in FVCOM is given as

$$\frac{\partial u}{\partial t} + U \cdot \nabla u - fv = -\frac{1}{\rho_0}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}\left(K_m \frac{\partial u}{\partial z}\right) + F_u \quad (1)$$

where $U = (u, v, w)$ is the Cartesian mean velocity vector corresponding to the spatial coordinate vector (x, y, z); f is the Coriolis parameter; ρ_0 is the density; P is the hydrostatic pressure; K_m is the vertical eddy viscosity; and F_u represents the horizontal momentum diffusion term. The horizontal diffusion term F_u is closed using the Smagorinsky eddy parameterization method, as described in more detail in Chen et al. [7].

FVCOM has different options for ocean turbulence closure models to parameterize the vertical eddy viscosity K_m. As a default, it uses the Mellor and Yamada (1982) [8] level 2.5 (MY 2.5) turbulent closure model ($q^2 - q^2 l$), the standard and most widely used scheme in coastal fluid dynamics. In this two-equation framework, the first equation solves the transport of the turbulent kinetic energy (q^2) and the second equation is for the turbulence length scale (l). MY 2.5 specifically resolves the turbulence macro-scale (wavelength containing peak turbulent energy). The other option available in FVCOM for parametrizing K_m is the General Ocean Turbulent Model (GOTM; [9]) that has explicit formulations for four closures: k–kl (same as $q^2 - q^2 l$), k–eps, k–w, and gen. All these closures are different from each other, primarily for the second equation, where the length scale parameters and set of coefficients have different values. For this study, we chose the k–eps (eps representing ε, the turbulent dissipation rate) closure from GOTM for evaluating the model performance along with the model default scheme MY 2.5. Between these two turbulence closure schemes, the essential differences are in turbulent kinetic energy estimates; the MY 2.5 solves the macro-scale energy (anisotropic eddies) and requires a wall proximity function, while k–eps approximates roughly isotropic turbulence [10].

The unstructured model grid used for model simulation was initially developed by Rao et al. [11] as part of a tidal energy resource assessment study and further modified by Yang et al. [4] for including both the Bay of Fundy and the northern Gulf of Maine, shown in Fig. 1. We assigned a model grid resolution of 20 m in the Western Passage, approximately 1 km near the Bay of Fundy and 2 km along the open boundary. Sea surface wind and baroclinicity effects were neglected in model configuration, and simulations were carried out in a 3D barotropic mode, where 15 uniform sigma layers were specified for the vertical resolution. Finally, to force the model from the lateral open boundary, we selected a time series of tidal surface elevation using TPXO 7.2 global ocean tide database [12].

III. RESULTS

A. Model performance comparison

Initial validation of the Western Passage model was conducted using variables such as water surface elevation, amplitude and phase lag of the tidal constituents and current velocity, and a good agreement between the model and field data was obtained in [4]. In the present study, we focused on the ADCP and ADV gauges in the Western Passage (Fig. 1) to compare the turbulence properties. We ran the tidal hydrodynamic model for a week (May 24, 2017 - June 01, 2017) covering the STTM (ADV) deployment period and validated the modeled velocity and turbulence kinetic energy (TKE), shown in Fig. 2. Fig. 2 compares two turbulence closure schemes and observation, where we can see good model agreement for tidal velocity for both of them. However, if we look at Fig. 2 bottom panel, we can see a significantly different TKE estimate by the two turbulence models. While the MY 2.5 model shows a good agreement with the observed data, k–eps underpredicted the TKE magnitude by ~4-5 times for the entire simulation period. In Fig. 2 top panel, we can also see a slight overprediction of the mean flow velocity during flood tide by the k–eps scheme, indicating less turbulence production, which is reflected in the TKE magnitude.

A similar TKE underprediction by the k–eps scheme was also observed by Thyng and Riley [10] in Admiralty Inlet, WA, USA. They have shown that if the total TKE observed in the field data is split into anisotropic lower frequency and roughly isotropic higher frequency motions (classical TKE), then the modeled TKE by the k–eps scheme matches well with the classical TKE. To compensate for this model underprediction, they proposed an alternative TKE post-processing by increasing the classical range of frequencies in the model turbulence spectra based on the field data. This procedure can improve the model (k-eps) TKE estimates at point locations; however, it is not feasible when we select an entire channel for site ranking and resource assessment. And if we do not make this correction, the error can propagate into other subsequent estimates, such as the turbulence intensity, which TEC designers use for extraction efficiency and device fatigue calculations. Ultimately, it will change the site ranking for TEC siting and lead to an erroneous resource assessment.

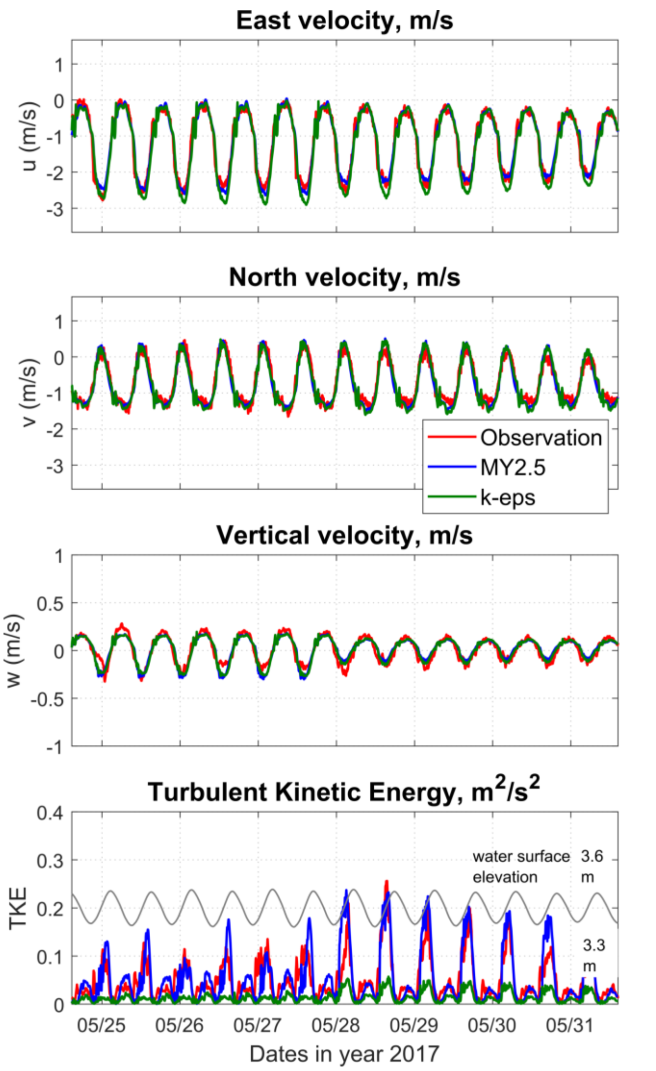

Fig. 2 Model performance comparison for the two turbulence closure models in FVCOM against the ADV dataset collected during 24 - 31 May 2017

B. Effects on the channel flow structures

In this study, to compare the differences in vertical structure of the current magnitude, TKE, and turbulence intensity (I_u) distribution simulated by the two turbulence models, we picked three transects at the entrance of Western Passage that demonstrated the highest across-channel TKE, as identified by Deb et al. [5] based on mean tidal power density. Fig. 3 shows the distribution of depth- averaged TKE during peak flood tide on May 28 03:00Z for the different closures, where we can see the underestimation of the TKE by k-eps model at the entrance of Western Passage. Deb et al. [5] have demonstrated the role of channel confluence zone attributes, such as the momentum ratio between the tributary and main channel, and underwater sills near headlands in enhancing the sheared flow and macro-scale turbulent eddies at the entrance of the Western Passage. In this study, the approximation of roughly isotropic turbulence by the k-eps model seems to underestimate the production of TKE (Fig. 3b) at the confluence zone. To investigate it further, we also compared the across-channel and vertical distribution of TKE during the same peak flood tide, shown in Fig. 4. In all three transects, we can see the significantly different TKE distribution, where at XS-1, the turbulence production is much lower for k-eps and it subsequently affecting the downstream distribution at XS-2 and XS-3. If we had selected only the k-eps model for this study and improved the TKE estimate during the post-processing following [10], the model validation at the gauge location would have improved for the k-eps model; however, this is a non-trivial task when we consider improving the distribution for a larger portion of an energetic channel.

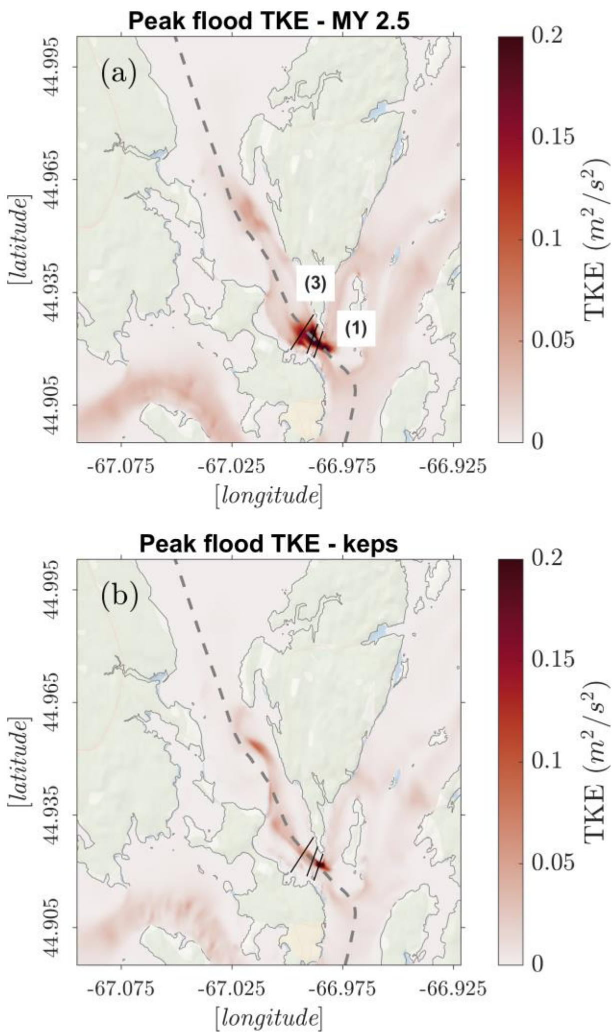

Fig. 3 Difference in the spatial distribution of the depth-integrated TKE (in m²/s²) during a peak flood tide. Three transects are placed at the entrance of Western Passage to assess the along- and across-channel distribution of the TKE. Here (a) represents model results using MY 2.5, and (b) represents results from k-eps.

In tidal energy resource assessment, more specifically, for TEC site ranking, device designers and project developers seek channel locations with lower I_u, which affects the TEC structural performance and energy extraction efficiency.

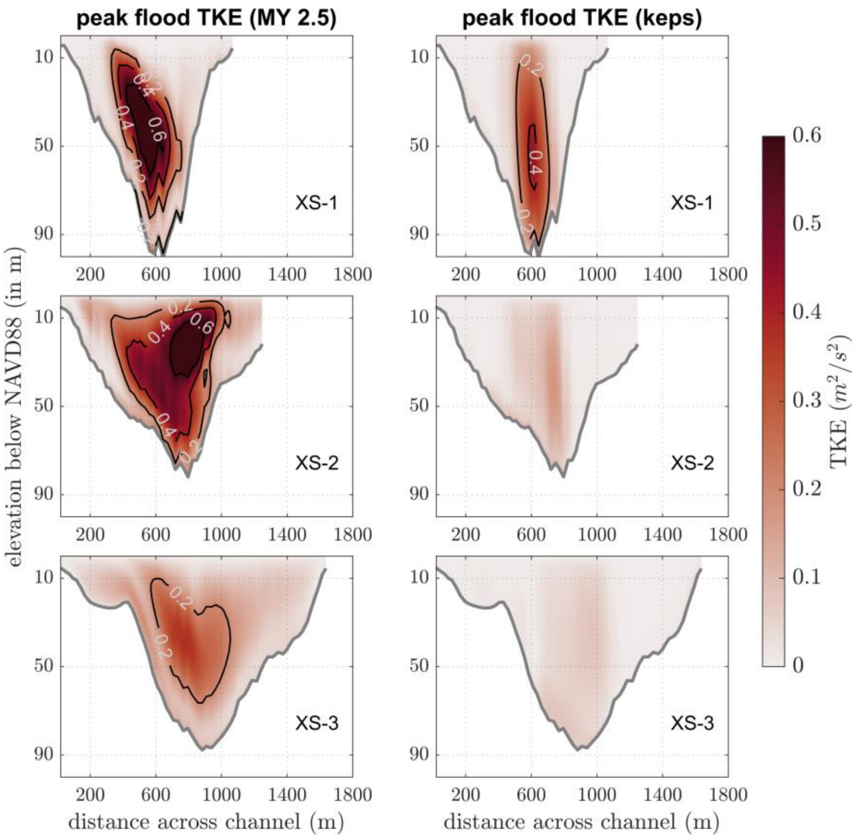

Fig. 4 Peak flood turbulent kinetic energy, TKE (in m^2/s^2) at different channel transect locations shown in Fig. 3.

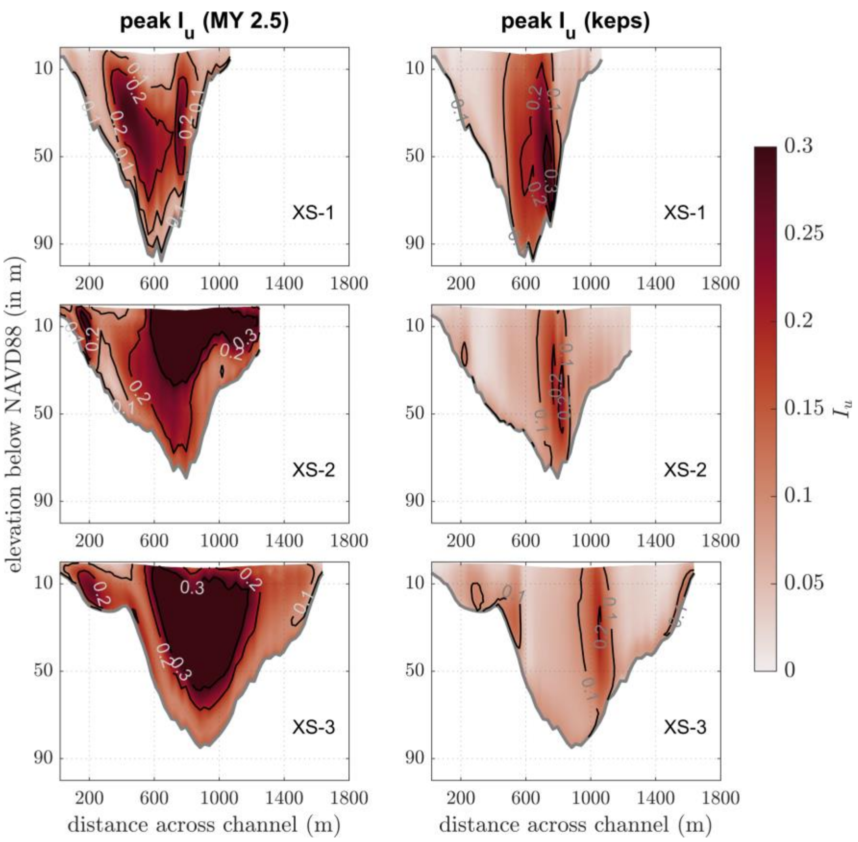

Fig. 5 Peak flood turbulence intensity at different channel transect locations shown in Fig. 3.

This metric I_u can be estimated using the turbulent kinetic energy and mean flow velocity as

$$I_u = \frac{\sqrt{q^2}}{\sqrt{u^2 + v^2}} \quad (2)$$

Fig. 5 represents I_u for the same instantaneous peak flood tide, where both turbulence models show dramatically different intensity estimates. The intensity for MY 2.5 is much higher (around 20-30%), and indicates that all of these transect locations are not suitable sites if priorities are given to device fatigue cycles caused by the unsteady loading. In contrast, results with k-eps display a different intensity where XS-2 and XS-3 have a gentle across-channel variation and are ideal for TEC siting. Ultimately, these results show that underestimating TKE and overestimating the mean velocity by the k-eps model can decrease turbulence intensity and lead to a wrong system and resource assessment interpretation.

IV. Conclusion

This study assessed two widely-used turbulence closure models implemented in a tidal hydrodynamic model – FVCOM – to assist tidal energy resource characterization and ranking TEC siting locations in the Western Passage, Maine, USA. A comparison between turbulence closure models, Mellor–Yamada Level 2.5 (MY 2.5) and k-epsilon (k-eps), showed that the MY 2.5 model better predicted TKE against the field measurements. While the k-eps model underestimates TKE due to the roughly isotropic turbulence assumption, the model-generated turbulence spectrum can be modified to take care of the macro-scale energy during the post-processing. However, this approach is not feasible when a large portion of an energetic channel is under assessment, and a turbulence closure scheme that directly provides a higher fidelity of macro-scale turbulence statistics is needed for ranking the TEC sites and resource assessment. We used both schemes' default settings and parameterization for the present work. We need to conduct a future sensitivity study to see if we can better tune the k-eps model (e.g., using different stability functions) to improve the existing performance. Overall, the work demonstrated why we must compare different turbulence closure models within the 3D hydrodynamic modeling frameworks before implementing one for TEC site ranking and resource characterization.

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