Assessment of the FES2014c model for tidal currents on the shelves around the North Atlantic Ocean

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I. INTRODUCTION

Tides are natural occurrences that take place regularly and are caused by the gravitational force of the moon and the sun on the earth's rotating oceans.[1]. Tides are a relevant variable in various marine related engineering projects. They are used to inform the design of coastal structures, flood planning and management, navigation and shipping, and marine resource management. In addition, they are being investigated as a source of renewable energy through tidal energy, which is obtained by capturing hydro-kinetic energy within tidal currents. This article looks at this resource and its potential applications.

In general, understanding tides and tidal flows involves a combination of field observations, in situ measurements, data analysis, and numerical modelling [2]. It is possible to find observations in situ of tidal elevations taken at various points along the coast using tide gauges. These instruments record long-term sea-level variation. However, the availability of data on tidal currents is limited because accurate measurement requires the use of tidal current meters, such as Acoustic Doppler Current Profilers (ADCPs). These devices are expensive and require skilled personnel for operation and maintenance. In addition, the duration of the measurements could be limited, and access to the data may be restricted for privacy or security reasons. These limitations make the evaluation of this resource difficult.

To estimate the currents, different methods can be used to obtain the horizontal flow in two perpendicular directions, east-west flow, and North-South flow. These velocity vectors can be combined to calculate the magnitude and direction of the current, the choice depends on the objective of the study and the scale of the assessment [3].

These methods, can be classified into three types, hydrodynamic models that use equations of motion and consider the astronomical tidal potential, empirical models that use harmonic constants from satellite data, and data assimilative models that combine information from both [4]–[6].The empirical model analyses tides and calculates currents, but has limitations in accounting for non-linear behaviour, spatial differences, and external factors[7]–[10].Therefore, ocean modelling is an alternative approach, which has been used to simulate and predict tidal performance, including the physics of the phenomenon, coastal topography, and other factors. According to this, the hydrodynamic and data assimilative models have contributed to advances in the understanding of tides and resulting flow characteristics. Initially, only the predictions of elevations were solved, validated, and extensively assimilated [4], [11].

To verify tidal current speeds in hydrodynamical models, the depth-averaged currents generated by simulation were compared with data obtained from tidal current meters [12]. Reflecting, for example, significant errors in tidal constituents as M4, it is doubtful whether comparisons between currents computed with much finer mesh models and observations, especially in coastal areas [13], [14].

Therefore, we expanded the tidal analysis and prediction to include the tidal component to account for this effect. Allowing, a better understanding and modelling of sediment movements in large-scale studies of continental shelves [5], [15].

Although purely hydrodynamic models may perform better in certain local conditions and be more computationally efficient, they lack the capability of assimilating observational data for improving predictions.

These models may also be more susceptible to initial errors and boundary conditions. On the contrary, assimilative models can make use of data to enhance the accuracy of predictions and have a superior ability to depict intricate processes.

Therefore, global barotropic ocean tide models can be considered for this analysis. These data assimilative models have been fed from TOPEX/Poseidon satellite altimetry series since 1993 and are used to predict water levels and currents. As several studies have revealed, the accuracy of recent tidal models has improved, especially in the deep oceans, and they agree much better with each other in those areas.

Although most of these models do not solve for currents directly so much as transports, from currents, are then derived [16]. They are an effective option for investigating the basic characteristics and general patterns of tidal currents at different spatial and temporal scales.

To establish effectiveness, these methods have undertaken validation and comparison with tide current meters over considerable measurement periods. To enhance the accuracy of model predictions in both deep and shallow water ranges, it is necessary to calibrate and improve these models. [16]–[20] While this approach has benefits, the relative lack of independent empirical data makes it challenging to evaluate the latest models, to measure improvement, and identify where and how they might be further refined.

This investigation aims to enhance and assess the accuracy and performance of a data assimilation model and validating tide current meters in the northern Atlantic Ocean. For this case study, Finite Element Solution (FES), was selected which also accounts for the discharged tidal currents in version 2014c [6], [21], this model surpasses other models such as Tidal Prediction by the expertise of Oceanography (TPXO), Empirical Orthogonal Tidal (EOT), Harmonic Analysis of Tidal Model (HAMTIDE) with its exceptional ability to consider local effects, provide superior spatial and temporal resolution, and seamlessly integrate observational data [16], [22], [23]. Additionally, since in situ measurements were available from a database of ADCPs instruments deployed in the northern Atlantic Ocean, specifically in northern Scotland and Canada for further marine renewable applications, this was selected as the focus area of study.

II. METHODS

The area considered is in the northern Atlantic Ocean, specifically in Fall of Warness in Orkney Islands, Scotland (C), and Dorset Island and Resolute, Baffin Bay in Nunavut, Canada (A, B). Fall of Warness was selected due to its well know tidal stream energy resource and due to the availability of data to calibrate the models. The second region was selected as a case study to understand if this type of resource could be a useful method to decarbonise remote communities in the Arctic. Dorset Island is one of the Canadian Artic islands located in Hudson Strait in Nunavut, Canada; whereas Resolute is an Inuit hamlet with a small population of 183 habitants who are heavily dependent on diesel fuel for electricity generation and diesel. The areas considered in this paper are shown in Fig. 1.

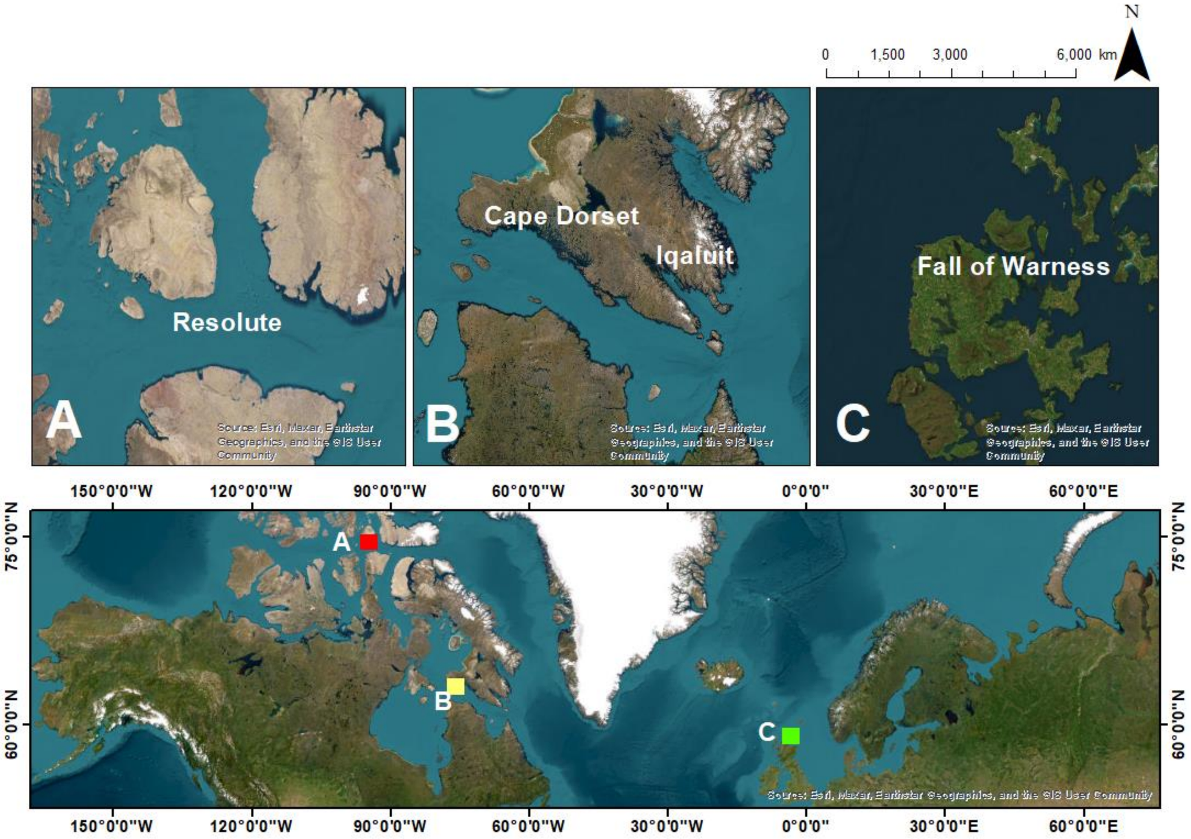


Fig. 1. Study area. A) Resolute (Nunavut, Canada), B) Dorset Island (Nunavut, Canada), C) Fall of Warness, Scotland.

For the selected areas, tidal currents were downloaded using the tidal prediction software FES2014, which is distributed in C or Python API and describes the functions to calculate the elevations and currents using this language. According to the above features, the FES tidal model was developed between 2014 and 2016. A 20-year time series of altimeters was used to solve the barotropic tidal equations, allowing for improved bathymetry and a higher level of resolution in shallow water regions. The model assimilates all the exact variables that repeat the mission's altimeter data into a hydrodynamic model based on Laplace's tidal equations and assimilates most of the available coastal and deep ocean data from tide gauges. The native finite element resolution of FES2014c ranges from 5 to 80 km; however, the area of departures is distributed at a uniform resolution of 1/16th of a degree. In comparison with other models, this model includes all tidal frequencies, including several long-period tides, minor diurnal, and semi-diurnal tides, and nonlinear overrides; therefore, it is the one selected in this research (See Table 1).

TABLE I
BAROTROPIC TIDE MODEL SUMMARY

Model	Tides	Resolution
FES2014c	Q_1, O_1, P_1, K_1, S_1, N_2, M_2, S_2, K_2, M_4, ($2N_2$, MN_4, MS_4) [S_a, M_m, M_f, MS_f, M_{tm}, M_{Sqm}, J_1, ἐ_2, μ_2, $\breve{\upsilon}_2$, MKS_2, λ_2, L_2, T_2, R_2, M_3, N_4, S_4, M_6, M_8	1/16 degrees

To assess the accuracy and performance of the model, different comparisons embedded in this study are frequency and time domain comparisons for tidal currents. In contrast, with elevations, the validation of currents requires accurate time series of tide current meters (several months or years) to extract the harmonic constants from the tidal harmonic analysis, in that case according to EMEC Manual for tidal resource assessment, data should be collected for one year minimum, being enough for tidal stream energy applications as a future work [21], [24].

The frequency analysis consists of the harmonic analysis of the tidal currents in each direction separately (eastward and northward). These in situ tidal harmonic components were compared with the tidal currents of the FES2014c model in terms of the vector and characteristic differences in the tidal ellipses. The ellipse parameters (orientation and lengths of the minor and major axes) were calculated from the estimated tidal harmonic velocity components in both directions (eastward and northward).

On the other hand, in the time domain, a comparison of the time series is performed, in which the obtained directly from the FES2014c model are compared with the data were taken in situ in terms of the vectors (eastward and northward components) and magnitude of the velocity. The quality of the modelled and predicted data must be evaluated under cross-correlation. Statistics will be derived to quantify the differences between predicted and modelled by comparing the sample mean values of the predicted and observed time series with the four statistical metrics used for tidal stream validation [13], [14]: Root Mean Square Error (RMSE), Coefficient of Determination (R-squared), Normalized Root Mean Square Error (N RMSE) as is defined as follows as Table 2,

TABLE II
DATA SUMMARY STATISTICS

Statistics	Position
Mean Absolute Error (MAE)	$MAE = \frac{\sum_{i=1}^{n} \lvert y_i - \hat{y}_i \rvert}{n}$
Root Mean Square Error (RSME)	$RSME = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}}$
Coefficient of Determination (R-squared)	$R^2 = 1 - \frac{\sigma_r^2}{\sigma^2}$
Normalized Root Mean Square Error (NRMSE)	$NRSME = \frac{\sum (S_i - O_i)^2}{\sum O_i^2}$

With this standard error, it is intended to measure the variability or dispersion of a sample. By comparing tidal models with field data over time, they have been shown to be a useful measure for comparing accuracy and performance in terms of variable selection, fit measures, predictive capacity [4], [16], [19], [25], [26].

III. PRELIMINARY RESULTS

Comparison of model with the static field data

The Fall of Warness case in Scotland utilized the ReDAPT project, a Reliable Data Acquisition Platform for Tidal Energy [27].

The velocities obtained from the model FES2014c were compared to the actual data from the static field. Depth-averaged velocities can be compared to the measured tide models using velocity components in each direction to avoid uncertainties[22], [28] (see Fig. 2).

To evaluate the model's performance, we have extracted statistics indices for tidal currents from FES2014c for east velocity, and shows them in Table 3 and Fig. 2, respectively. It is evident that the FES14c results offer a more accurate tidal prediction for this specific ADCP dataset. Reliable estimations are deemed to have an NRMSE of less than 0.50, which is the case for both developments, indicating a good agreement with the model. However, an NRMSE of 0.50 or higher suggests unreliable estimates for the corresponding region and season, which cannot be ignored. It is crucial to conduct additional research for the progress of other developments and selected areas. The latter will be done by using additional ADCP data from the Fall of Warness and using the Polar Data Catalogue from Canada [29].

TABLE III
DATA SUMMARY STATISTICS

Statistics	Dep0	Dep 2
RSME	0.40	0.59
R2	0.88	0.84
NRMSE	0.33	0.39

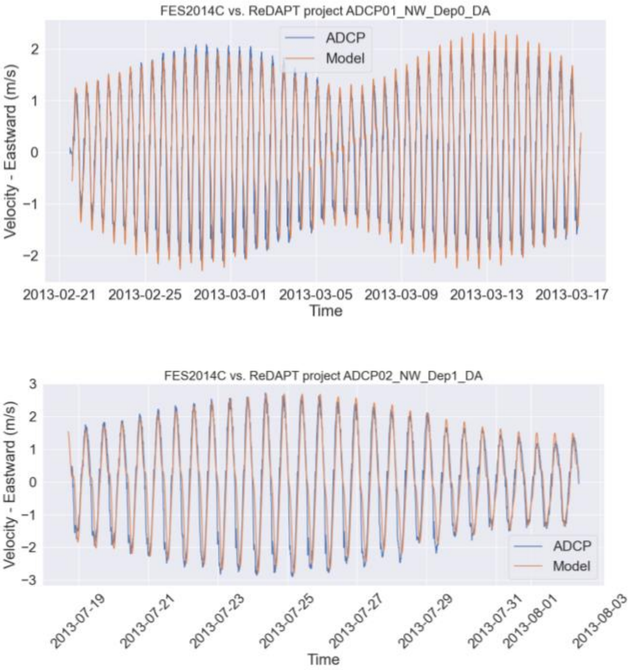


Fig. 2. Comparison of the u-component between FES2014c – ReDAPT

Data analysis

Using the methodology mentioned previously, tidal currents were downloaded into the FES2014c model prediction software in Python language for the API, for the following areas described in Table 4, for a one (1) year in the selected areas according to EMEC Manual mentioned in the methodology,

TABLE IV
DATA SUMMARY

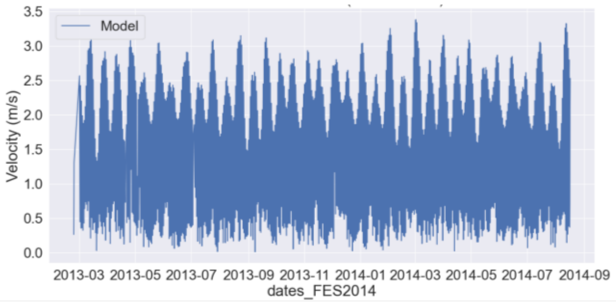
Name	Country	Area	Temporal resolution
Fall of Warness	Scotland	Lat: 59.14; Lon: -2.81	2013 - 2014
Dorset Island	Canada	Lat: 64.19; Lon: -76.55	2010-2011
Resolut	Canada	Lat: 74.47; Lon: -94.70	2000-2001

In order to describe what is most suitable conditions in the areas, a histogram analysis for the tidal current speed shall be carried out using the results from the tidal barotropic model. The percentage of time, that the velocity falls within each bin was computed and are shown in the following plot as velocity distribution or exceedance curve, at the site location.

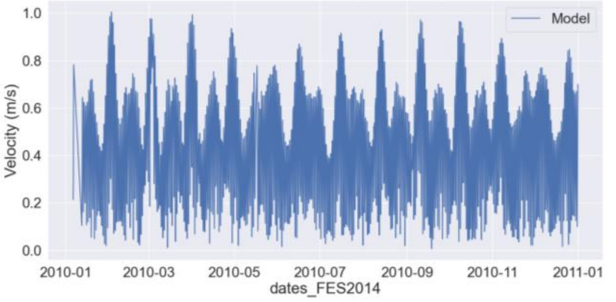
The probability of exceedance for the tidal stream at the selected points is determined, to obtain immediately the probability that a tidal current does not exceed a certain value in an average year. According to the results obtained it is possible to estimate that in a cycle of time, associated speeds between 1 to 1.5m / s with a probability of 80% were found for the Fall of Warness. However, these estimates were not as favourable in the studied Canadian regions where probabilities of 80-85% were found for speeds between 0.4 -0.6 m / s and 0.15 – 0.2m / s, respectively.

On another hand, the average tidal velocities vary between 0.021 to 3.33 m/s at Fall of Warness, 0.0011 m/s and 1.0 m/s at Dorset Islands and between 0.000558 m/s and 0.5 m/s at Resolute, that shows the Fig. 3. Correspondingly, the maximum average speeds found are 3.33 m/s for Fall of Warness, 1.0 m/s and 0.5 m/s for Dorset Island and Resolute, in that order.

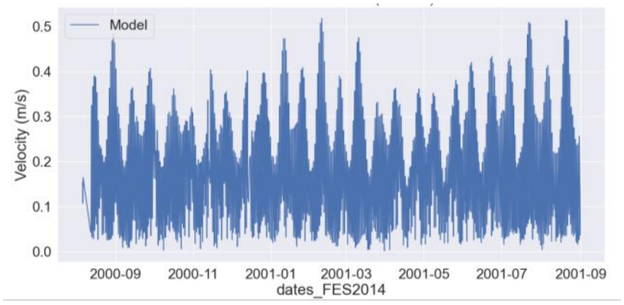
Future work will consider the further validation of the FES model as well as the investigation of other sites of interest in remote locations in Canada and the UK.



A. Fall of Warness, Scotland

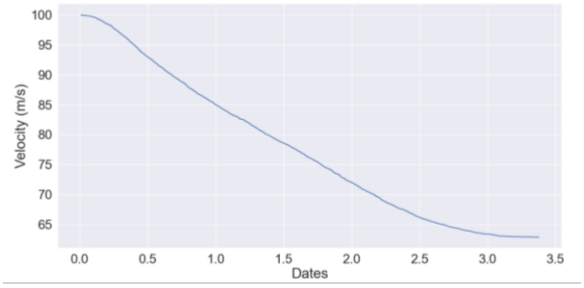


B. Dorset Island, Canada

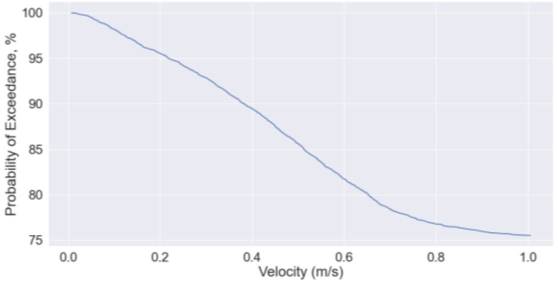


C. Resolute, Canada

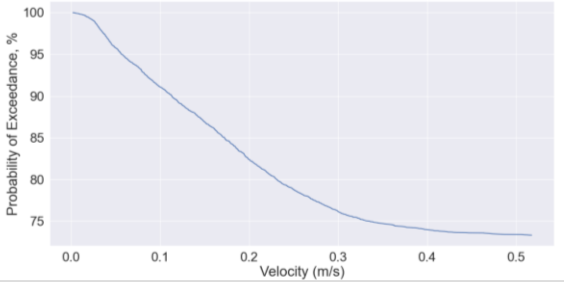
Fig. 3. Average velocities in the selected points – One year time series.



A. Fall of Warness, Scotland



B. Dorset Island, Canada



C. Resolute, Canada

Fig. 4. Exceedance curve – distribution velocity curve in the selected points.

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