Cross-validation of regional ocean model turbulence predictions and ADCP measurements

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1. INTRODUCTION

Most tidal energy converters (TECs) work on similar principles to conventional horizontal-axis wind turbines, but face their own unique environmental and technical challenges [1, 2, 3]. Among these challenges is turbulence in marine currents. Accurate modelling of turbulence would reduce the need for expensive and time-consuming measurement campaigns. In this study, we use Regional Ocean Modelling System (ROMS) and measurements from an acoustic Doppler current profiler (ADCP) to examine marine turbulence at a highly-energetic tidal site. The site in question is the West Anglesey Demonstration Zone (WADZ), a region of seabed owned by the UK Crown Estate and designated as a development zone for tidal energy technology. A more extensive discussion of the results presented in this abstract is available [4], and the reader is encouraged to refer to that paper for more detailed information.

ROMS is an open-source, three-dimensional oceanographic model based on finite-difference solution of the Reynolds-averaged Navier-Stokes equations [5]. Its ability to model mean flow properties at prospective TEC deployment sites is well-validated [6], and its turbulence modelling over timescales on the order of two days has been validated in previous studies [7], but with the current study we are able to use a much larger dataset to examine the whole spring-neap cycle. Confidence in ROMS' handling of turbulence in sites suitable for TEC deployment will mean that its predictions can be used for finer-scale array or device modelling efforts [8]. Turbulence modelling in ROMS is implemented using a generic length scale scheme, which can be tuned to a variety of different closure models such as $k - kL$ and $k - \omega$. For this study, turbulence is represented by the k-ε model. Note that wave effects are not included in the simulations whose results are presented here. Bed friction is represented by a drag coefficient $C_D = 0.003$, chosen to match the value implemented in previous studies of energetic tidal regions [6].

Figure 1 shows the modelled area. The spatial resolution is approximately 300m ($^1/_{240}$° in a longitudinal curvilinear terrain-following C-grid, with variable latitudinal spacing), and there are ten vertical ('sigma') layers. For stability, the model timestep was set to 20s, but only one data point was output per hour of model time. The time period simulated by the model was chosen to coincide with the instrument deployment times described below.

To validate the model's predictions of turbulence parameters, we use data from an RDI Sentinel V acoustic Doppler current profiler (ADCP) deployed in the WADZ between 19/09/14 and 19/11/14; concurrently, a wave buoy was taking measurements approximately 2km to the south of the ADCP's location. The ADCP measured a 15-minute burst of data every hour during its deployment; the sample rate was 2Hz, the blanking distance 1.89m and the vertical bin size 0.6m. During the deployment period, water depth varied between 41.1 and 46.2m, and peak spring currents were 2.48ms^{-1}. In this study we make use of the variance method [9, 10, 11] to calculate TKE density and the structure function method [12] to calculate turbulent dissipation rate ε.

2. RESULTS

We examine turbulence in this study by looking at turbulent kinetic energy (TKE) density and turbulent dissipation. TKE is a direct measure of the energy contained in turbulent fluctuations; it is common in industrial applications (e.g., IEC standards for wind turbines) to express the strength of turbulence by normalising the square root of TKE density by mean velocity magni-

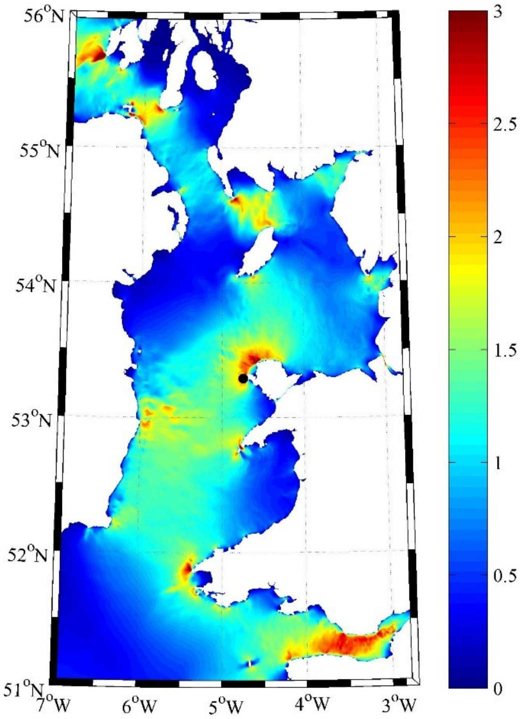

Figure 1: Map of ROMS model area. Contours show depth-averaged peak spring tidal current in ms^{-1}, as measured by the magnitude of the M2 and S2 components. Location of WADZ indicated by black circle near centre of the image.

tudes to give turbulence intensity (TI). Note that although it is convenient to characterise the strength of turbulence with a single value, as enabled by the use of TI, it is not necessarily the case that intensity is the most appropriate parameter to indicate how turbulence influences fatigue loads and lifespan for TECs.

Our initial analysis showed that waves had a strong influence on the ADCP measurements, and in fact dominated the turbulent fluctuations in the upper half of the water column. Except where noted, therefore, we restrict our comparison to the lower half of the water column; in any case, it is here that TECs are most likely to be operated. Figure 2 compares mean flow velocities and mean TKE densities between ADCP measurements and ROMS predictions for a representative subset of the deployment period; significant wave height from the wave buoy is also shown.

We see that there is very strong agreement in both magnitude and phase for the current, as is expected. Agreement in TKE density is also satisfactory; in particular, we observe that TKE peaks higher on ebb than on flood in the ADCP data, and this asymmetry is captured by ROMS. There are some times during which the ADCP measurements of TKE density significantly exceed the predictions of ROMS; in the date range shown, this behaviour is seen towards the end of October 26th and November 1st. Cross-referencing these times with the wave buoy data shows that they coincide with very strong wave activity. We therefore conclude that at such times the effect of wave-induced velocities exceeds that of the turbulent fluctuations even into the lower half of the water column.

The probability distribution of TKE over the whole record is visualised in figure 3. These distributions are created from populations of data points from ADCP measurements and ROMS estimates. Since each data point from either model or measurement represents an hour of data, the comparison is like-to-like. To reduce the effect of the anomalous strong wave conditions, as seen in figure 2, we have employed an exclusion criterion: all times for which the significant wave height exceeded its 95th percentile value were discarded.

Model-measurement agreement can be seen to be very good when we examine these distributions. Ebb distributions are shifted to higher energies compared to flood distributions, reflecting the asymmetry observed in Figure 2. This shift is seen across springs and neaps in both ROMS and ADCP. These probability distributions demonstrate that the ROMS model does a good job of representing the range of turbulent conditions encountered at the measurement site throughout the entire spring-neap cycle.

Comparing dissipation shows less agreement between model and measurements. Figure 4 compares dissipation time series at four different depths in the lower half of the water column. Note that the sigma layers of ROMS and the ADCP bin heights do not correspond exactly; we show the closest available matches. Phase agreement is good, but there is a significant difference in magnitude, particularly close to the bed. Excluding times of slack water, the ROMS estimate of dissipation exceeds the measured value by a factor of at least 1.5 on average (at the highest location shown), and this factor rises to 4.8 at the location nearest the seabed.

3. DISCUSSION AND CONCLUSIONS

A previous study comparing turbulence from ROMS and field measurements [7] had found relatively good agreement on turbulent dissipation values; TKE, however, did not match as well. The differences in TKE were attributed to the the modelled turbulence in ROMS corresponding to a smaller range of wavenumbers than that measured by the ADCP. Applying a correction based on this assumption significantly improved agreement.

In our study, however, we find that the ROMS estimates of TKE density are very well corroborated by the measured values, without any need for a similar correction. In the lower half of the water column, where wave influence is reduced, the mean flood and ebb profiles predicted by ROMS match the measured values to within 2% on floods and within 13% on ebbs. On the other hand, the dissipation values differ significantly between ROMS and ADCP. This could mean that the structure function calculation of ε used for the ADCP is underestimating the true dissipation; however, examining the values of the structure functions themselves does not show any suggestion that the method is being applied in an

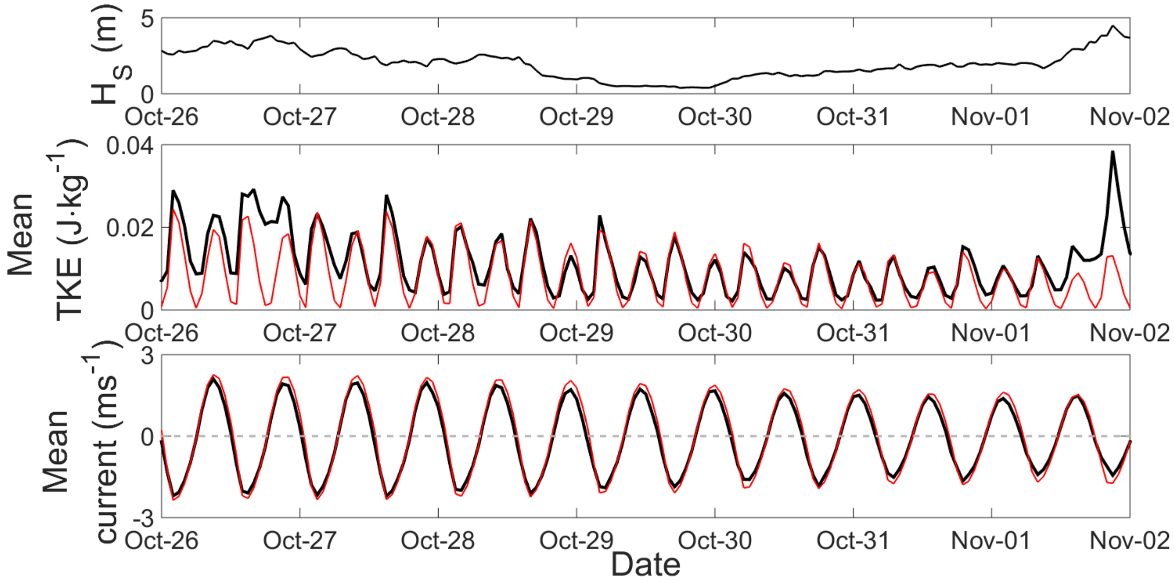

Figure 2: Comparison of ADCP and ROMS results for a representative week during the ADCP deployment. Top panel shows significant wave height (H_S) taken from buoy, middle panel shows time series of vertical-mean TKE from the lower half of the water column and bottom panel shows mean current velocities; flood velocities are shown as positive and ebb velocities as negative.

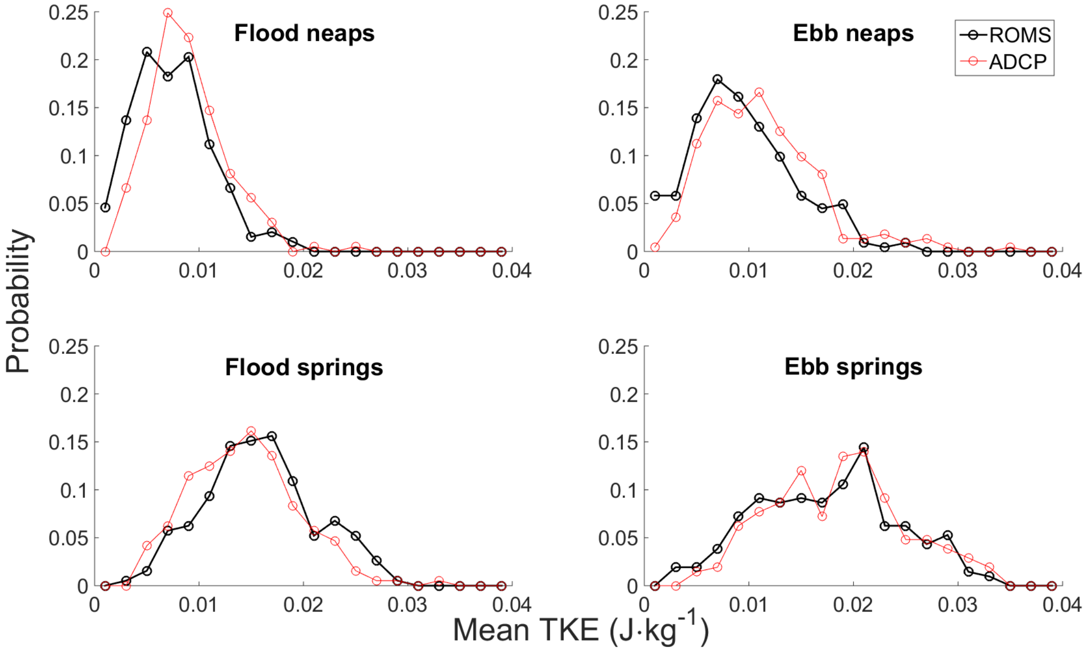

Figure 3: Probability distributions of mean TKE density.

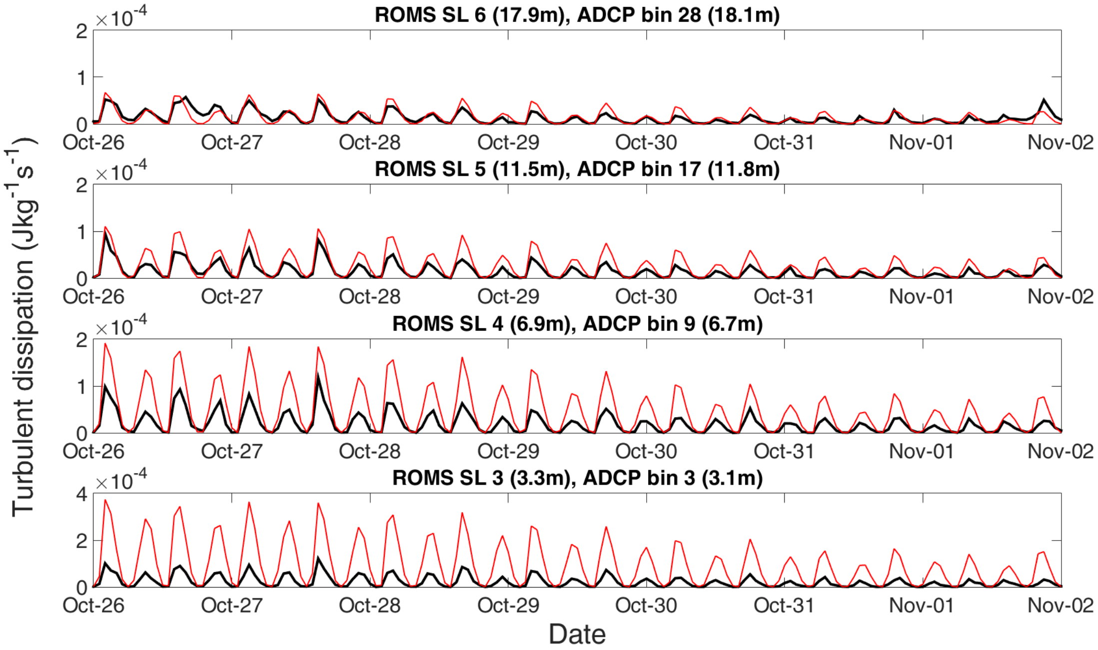

Figure 4: Comparison of time series of dissipation at four locations in water column from ROMS (red) and ADCP (black) for representative time period. SL denotes the sigma layer number from the ROMS simulation. Note the vertical scale differs for the lowest panel.

inappropriate flow regime. Alternatively, ROMS may be overestimating dissipation; if this were true, though, it must also be overestimating TKE production.

One difficulty with this interpretation of differences between the findings of the current study and that of Thyng *et al* [7] is that the same problem of TKE corresponding to different wavenumber ranges in ADCP observations and ROMS predictions is still, presumably, present. Furthermore, there is no such discrepancy between observations and model in what is represented by ε. Given these differences, why should it be the case that there is such strong agreement for TKE, but poorer agreement for dissipation? It is possible that we are seeing a situation where ROMS is predicting more energetic turbulence in the range of wavenumbers represented by the modelled k-value than is present in the observed data, but the extended range of wavenumbers captured by the ADCP measurements is enough to make up any deficit relative to ROMS predictions. The fit between ROMS and ADCP TKE values is very strong, however - with the times of strongest waves excluded as described above, a linear fit of TKE values for corresponding ROMS and ADCP data points has an R^2 of 0.84, and almost all systematic difference is explained (in a statistical sense) by wave action. Further investigation is required to unpick the reasons for these differences.

The importance of wave effects in the ADCP data is remarkable. The variance method cannot distinguish between the quasi-random fluctuations of turbulence and regular oscillations due to wave action. It may be possible to apply a bandpass filter to the velocity signals to mitigate the effects of waves; the wave period appears in the spectra of velocity as a very clear peak. However, bearing in mind that the fundamental motivation of this study is to predict turbulence's effects on TECs, it is worth considering that this may not be particularly fruitful: the fatigue life of a structure is largely agnostic to the source of fluctuating loads applied to it, but instead depends only on the loads themselves.

4. ACKNOWLEDGEMENTS

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