A 3D model of asymmetry in the Orkney tidal energy resource

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Summary: One factor that is not routinely considered in tidal energy site selection, yet which has an important role in quantifying the resource, is tidal asymmetry. Here, we present theory and develop a high-resolution 3D ROMS tidal model of Orkney to examine net power output for a range of sites along an energetic channel which exhibits varying degrees of tidal asymmetry. Since power output is related to velocity cubed, even small asymmetries in velocity lead to substantial asymmetries in power output. We also use the 3D model to assess how tidal asymmetry changes with height above the bed, i.e. representing different device hub heights, how asymmetry affects turbulence properties, and how asymmetry is influenced by wind-driven currents.

Introduction

From a resource and device perspective, it is clearly beneficial to select tidal energy sites where the tidal currents have an equal magnitude between the flood and ebb phases of the tide (tidal symmetry), and less desirable to exploit sites which have either strong flood- or ebb-dominance (tidal asymmetry). Tidal asymmetry not only affects the primary variables of the flow field such as velocity and water elevation – it is also expected to cause asymmetry in turbulence properties such as Reynolds stresses and turbulent kinetic energy, important variables in site selection [1].

Tidal waves are progressively distorted and dampened as they propagate in shallow-water coastal regions [2]. Although tidal waves in such regions still satisfy the criteria of long waves (i.e. wavelength is much greater than water depth), in shallow water the amplitudes of the waves become a significant fraction of the total water depth [3]. As a result of these non-linear shallow-water processes, tidal waves in such regions are often more complex than their linear wave counterparts, with the occurrence of double high or low water, and asymmetries observed in velocity time series due to the presence of overtones. Focussing on the principal semi-diurnal lunar constituent (M2) and its first overtide (M4), we can estimate tidal asymmetry from the phase relationship [4]

\[ 2\phi_{M2} - \phi_{M4} \]  

Methods

We apply the 3D ROMS model to simulate the barotropic currents of the northeast region of Orkney at high resolution \((1/750 \times 1/1451' \sim 75 \text{ m})\), extending from 3°13.5′W to 2°25′W, and from 58°57′N to 59°16′N, covering the Westray Firth and Stronsay Firth, which connect via the Fall of Warness (the EMEC tidal test site) (inset on Fig. 1). The model was run with 10 vertical (sigma) levels, used the Generic Length Scale (GLS) turbulence scheme, with the coefficients tuned to represent the \( k - \varepsilon \) model, and we used a drag coefficient \( C_D = 0.003 \). Since this is primarily a study of tidal asymmetry, and is not intended as a detailed resource study, we considered only the principal semi-diurnal lunar (M2) and solar (S2) constituents. We ran the model for a period of 2 weeks, and validated the M2 and S2 components of the vertical tide against data from 6 tide gauges. To validate the horizontal tide, we used ADCP data from the EMEC tidal test site at the Fall of Warness.

Results

We restrict our analysis only to sites where water depth is in the range 25-50 m, and where the peak spring (M2 and S2) currents exceed 2 m/s, i.e. locations which are suitable for the majority of first generation tidal stream devices (inset on Fig. 1). These sites are primarily located in Westray Firth and Stronsay Firth. The total area where these depth and velocity criteria are satisfied within the model domain is around 70 km\(^2\) – a substantial region for tidal energy arrays. We selected 21 sites evenly distributed along a 30 km longitudinal transect through Westray Firth and Stronsay Firth, representing a large variability in tidal asymmetry with which to examine its influence on the tidal energy resource.

If we perform tidal analysis on the simulated elevation and velocity time series at each of the 21 selected sites, we can calculate the phase relationship between the M2 and M4 constituents, and so calculate the theoretical
asymmetry based on Eq. 1. If we calculate the mean depth-averaged flood velocity over a spring-neap cycle at each location \( (v_{\text{flood}}) \) and divide by the mean depth-averaged ebb velocity \( (v_{\text{ebb}}) \), we have a metric for tidal asymmetry \( (v_{\text{flood}}/v_{\text{ebb}}) \) [5]. We plot this value in relation to Eq. 1 and numerical calculations of idealized tidal residuals presented in Neill et al. [6], demonstrating a good fit to the theory (Fig. 1), with a value of \( r^2 = 0.81 \) (based on analysis of the vertical tide), and \( r^2 = 0.69 \) (based on analysis of the horizontal tide). There is greater uncertainty when the \( M_2 \) and \( M_4 \) phase relationship is used to estimate asymmetry from the horizontal tide, since there is much larger spatial variability in the horizontal tide compared to the vertical tide.

Fig. 1 Modelled tidal asymmetry and theoretical asymmetry, based on Eq. 1 and numerical calculations of idealized tidal residuals presented in Neill et al. [6]. Black crosses=analysis based on the vertical tide; red asterisks=analysis based on the horizontal tide. Error bars indicate 95% confidence intervals estimated by the tidal analysis. Inset shows masked region (light red) and the 21 locations selected for detailed analysis.

Conclusions

At the workshop, we will present results of 3D variables output from the model, including variations of velocity, power and turbulent kinetic energy, and how these variables vary with depth. We also implement the power curve for the SeaGen S 1.2 MW device to explore how tidal asymmetry affects the practical resource, and investigate how tidal asymmetry influences the power extracted at different device hub heights.

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References: