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THE ROLE OF TIDAL ASYMMETRY IN CHARACTERIZING THE TIDAL ENERGY RESOURCE OF ORKNEY

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ABSTRACT

When selecting sites for marine renewable energy projects, there are a wide range of economical and practical constraints to be considered, from the magnitude of the resource through to proximity of grid connections. 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, i.e. variations between the flood and ebb phases of the tidal cycle. Here, we present theory and develop a high-resolution three-dimensional ROMS tidal model of Orkney to examine net power output for a range of sites along an energetic channel with 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. Finally, although there is minimal potential for tidal phasing over our study site, we demonstrate that regions of opposing flood- versus ebb-dominant asymmetry occurring over short spatial scales can be aggregated to provide balanced power generation over the tidal cycle.

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 overtides. Focussing on the principal semi-diurnal lunar constituent (M_2) and its first overtide (M_4), we can estimate tidal asymmetry from the phase relationship [4]

$$2\phi_{M2} - \phi_{M4}$$

METHODS

We apply the ROMS model to simulate the 3D barotropic currents of the northeast region of Orkney at high resolution ($1/750 \times 1/1451° \sim 75$ 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) (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 (M_2) and solar (S_2) constituents. We ran the model for a period of 2 weeks, and validated the M_2 and S_2 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 (M_2 and S_2) currents exceed 2 m/s, i.e. locations which are suitable for the majority of first generation tidal stream devices (Fig. 2). 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.

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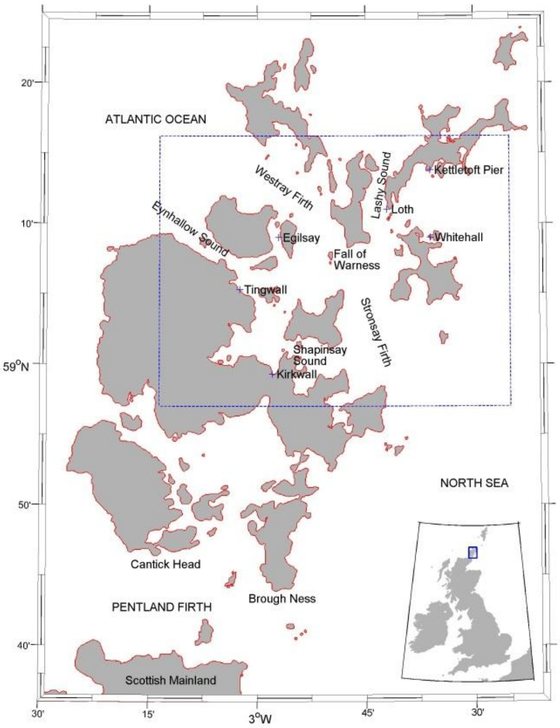

Figure 1. Principal locations in Orkney and surrounding waters. The dashed box shows the boundaries of the high resolution nested model, and tide gauge stations used for model validation (labelled) are shown as blue crosses. Inset shows the location of Orkney in relation to the British Isles.

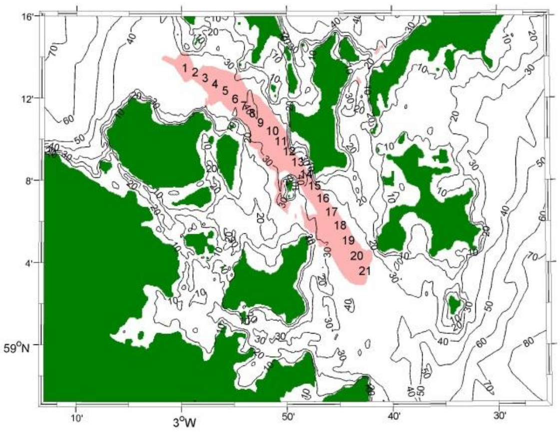

Figure 2 Masked region showing the 21 locations selected for detailed analysis. Green = land; light red = region where water depth is between 25 and 50 m, and where the peak spring current exceeds 2 m s−1. The EMEC tidal test site (Fall of Warness) spans locations 12−14.

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 M_2 and M_4 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_{flood}) and divide by the mean depth-averaged ebb velocity (v_{ebb}), we have a metric for tidal asymmetry (v_{flood}/v_{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. 3), 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). Provided we can simulate and quantify the phase relationship between the M_2 tidal constituent and its first overtide, M_4, for proposed sites, it is possible to understand the nature of tidal asymmetry.

CONCLUSIONS

Our 3D tidal model of an energetic tidal channel in Orkney has demonstrated that the phase relationship between the principal semi-diurnal lunar constituent, M_2, and its first harmonic, M_4, can be used to predict the degree of asymmetry in velocity, and hence power, at potential tidal energy sites. In accordance with previous modelling studies, we have demonstrated that relatively modest asymmetries in velocity can result in large asymmetries in power density, since the latter is a function of velocity cubed. Our model simulations indicate that a 30% asymmetry in velocity translates into a 100% asymmetry in power density. At the conference, 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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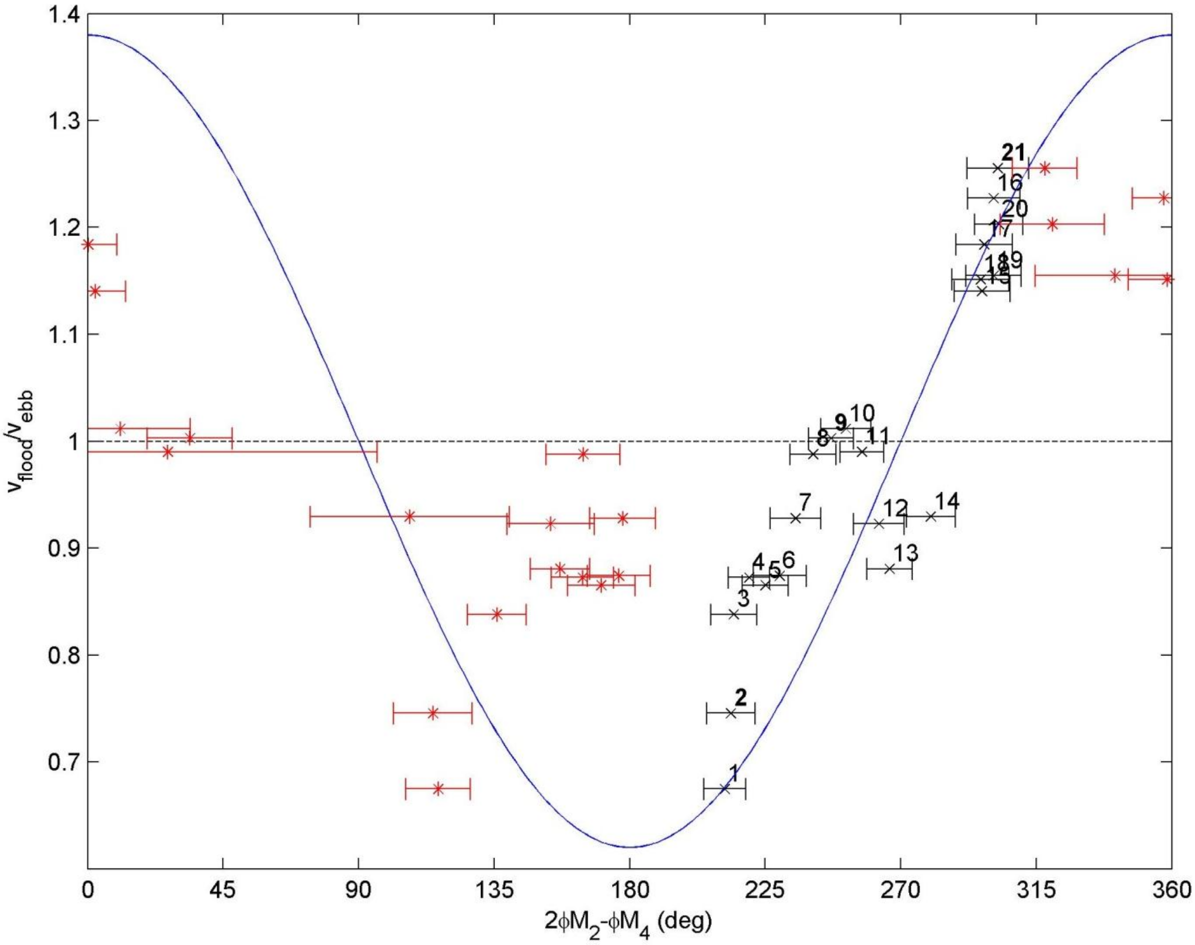

Figure 3. Modelled tidal asymmetry and theoretical asymmetry, based on Eq. 1 and numerical calculations of idealized tidal residuals presented in Neill et al. [6]. Black crosses=analysis based on the vertical tide; red asterisks=analysis based on the horizontal tide. Error bars indicate 95% confidence intervals estimated by the tidal analysis.