Hydrodynamic Response to Large Scale Tidal Energy Extraction

Alice J. Goward Brown
School of Ocean Sciences, Bangor University
Menai Bridge, Isle of Anglesey, LL59 5AB UK
E-mail: a.j.gowardbrown@bangor.ac.uk.ac.uk

Simon P. Neill
School of Ocean Sciences, Bangor University
Menai Bridge, Isle of Anglesey, LL59 5AB UK
E-mail: s.p.neill@bangor.ac.uk.ac.uk

***Abstract*—Tidal energy extraction offers a highly predictable, reliable energy resource. Tidal energy devices alter the natural flow regime of the environment. Subsequently bed morphology, sensitive to changes in the tidal flow, could be affected by tidal energy extraction. This research investigates the impact of large scale tidal energy extraction by tidal stream energy devices in the form of an array on the spatial and temporal variability of seabed morphology. The research uses the 3D ROMS model (Regional Ocean Modelling System) with tidal energy extraction as a mid-water perturbation and is presented in two halves - first idealised 3D models of headland and channel scenarios are created with the purpose of investigating the sensitivity of the hydrodynamics to turbine array design and placement. The second part of this research investigates the impact of tidal arrays within the Pentland Firth, a highly dynamic and complex channel environment.**

***Index Terms*—Tidal, Energy, Extraction, Hydrodynamics, Environment**

I. Introduction

Tidal stream energy devices generate power from fast flowing tidal streams; Tidal streams are currently being investigated as a reliable source of clean energy to contribute to the energy mix [1]–[3]. The focus of this PhD research is to investigate turbine effects on realistic flows.

Tidal energy has become the focus of much research effort. The presence of turbines will alter flow fields with the potential for environmental, power prediction and power extraction implications [4]–[7]. It is widely acknowledged that a reduction of the resource by up to 10% will have little impact on the tidal current flow [7]–[10]. However, research has shown that large scale arrays could lead to a change in the non-localised natural morphodynamic processes due to a cubic relationship between velocity and total load sediment transport [11]. In this instance, changes could be seen in a 100km^2 region around the area of extraction [7]. Smaller scale tidal energy arrays are deemed unlikely to affect morphodynamics beyond the range of natural variability [10], [12]. The underlying uncertainty is a result of the complexity of these highly energetic environments [13]. In particular, device design and array size will have an impact but, with regards to sediment transport, an important mechanism to consider is the incoming wave field and and the wave-tide interaction [13], [14]. Subsequently, impacts of tidal energy devices are difficult to quantify. Therefore, adding a turbine model to a numerical ocean model is necessary for understanding the interaction between turbine arrays and hydrodynamics.

The turbine model used in this research has been developed by Roc et al., [15]. It is fundamentally based upon the actuator disk concept, where the loading of the turbine blades is uniformly distributed over a disk - acting as a discontinuity in pressure within the tidal flow (Figure 2(a)). Subsequently this method is most relevant for devices which follow the horizontal axis turbine design [16]. The method used by Roc et al., borrows techniques from high resolution computational fluid dynamics (CFD) and applies them to (comparatively) coarse resolution regional ocean models. The method has been validated against flume experiments and implemented in idealised models [17], [18].

Regions of high tidal flow are typically headland and island regions where complex bathymetry and topography lead to the augmentation of the tidal flow [1]. The Pentland Firth, a complex tidal channel between the Scottish mainland and Orkney, is a prime example of such an environment in the UK and is subsequently the focus region of this study. The Orkney region is mesotidal; tidal waves in this region, dominated by the semidiurnal lunar (M2) and solar (S2) constituents, take 2 and a half hours to propagate from the western side of the Pentland Firth, around Orkney, to the eastern side of the Pentland Firth. This phase lag is accountable for a pressure gradient accross the Pentland Firth which drives the tidal currents (Figure 1).

The Pentland Firth has been calculated to have a world leading tidal energy resource due to spring currents of up to $5\text{ms}^{-}1$ [5], [19], [20]. There are currently four sites being made available for tidal energy development by the Crown Estate. Currently, the planned developments have a total capacity of 800MW [21], [22]. This study will focus on two of these leased regions: Brough Ness (a headland region) and the Inner Sound (a strait between the Scottish mainland and the isle of Stroma).

II. Methods

To investigate the hydrodynamics of the Pentland Firth and the impact of tidal energy extraction the Regional Ocean Modelling System (ROMS) was used to create a 3D coarse model of the study region and two high resolution idealised modes of the extraction sites within the Pentland Firth.

A. Numerical Model and Tidal Turbine representation

The methodology behind the tidal energy extraction is described in great detail in [15] and has been shown to validate well against flume experiments which gives confidence in the method described. The turbine model is implemented through the modification of the ROMS. Within the ROMS model grid each turbine is discretized in 3D space and accounts for both momentum capture and turbulence perturbations.

ROMS is a 3D, free-surface, terrain-following, hydrostatic primitive equation oceanic model [23]. In order to solve the 3D Navier-Stokes equations ROMS simplifies them through a couple of assumptions: the hydrostatic assumption, which implies that vertical motions can be derived only from the mass-conservation equation and prevents the model from simulating vertical rotation and secondly the assumption that vertical shear is dominant and as such turbulent quantities vary predominantly in the vertical; These assumptions require the ROMS grid resolution to be split both horizontally and vertically and sub-grid mixing processes to be parameterized using both horizontal (momentum) and vertical (turbulence) closure schemes. The turbulence parameter used in the turbine model is the generic length scale (GLS) closure model. The vertical grid in ROMS is a terrain following sigma grid which adds a further level of complexity when resolving turbines.

Sensitivity experiments by Roc et al., have come up with a rule of thumb for the spatial turbine resolution (Figure 2(b)) [15]. Subsequently, the dimensions of the turbines dictate the numerical model grid dimensions. Readers are directed to consult [15] for a more detailed overview of the theoretical background behind the turbine implementation in the model. The ability to define individual turbines in *x,y,z* space will enable device scale applications and thus provide the means for array design to be examined on a regional scale.

B. Simulation Features: The Orkney Model

The initial step in this research is therefore to model the Pentland Firth and the Orkney islands. This has two purposes: it will determine the underlying regional hydrodynamics and provide boundary conditions for the idealised model runs.

The model boundaries stretch from 4° W to 1°W and from 58°N to 62°N and has the relatively coarse resolution of 500m and was run for 32 days. The first 48 hours of model run were discarded as spin-up leaving 30 days of data to analyse - appropriate for fully resolving the semi-diurnal tidal currents in the region.

The model was forced with elevations and velocities for the M2 and S2 tidal harmonics from the FES2012 tidal model, available at 1/16 degree resolution (http://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes.html). Tidal forcing was applied at all four boundaries using Chapman (free-surface) and Flather (2D velocity) boundary conditions. These boundary conditions have been examined at great length by Marchesiello et al. [25], who surmised that they are the most suitable conditions for tidal forcing. The boundaries were all free-slip and three dimensional momentum is radiated out of the model domain.

Tide Gauge	Observed Elevations				Model Elevations			
	M2		S2		M2		S2	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Wick	1.02	322	0.35	0	0.97	341	0.37	020
Gills Bay	1.12	268	0.41	300	0.95	303	0.37	335
Scrabster	1.35	247	0.51	280	1.00	282	0.40	312
Kirkwall	0.84	301	0.29	339	0.79	317	0.29	352
Loth	0.74	300	0.26	336	0.77	318	0.29	354
Tingwall	0.86	276	0.31	310	0.80	298	0.30	330
Stromness	0.89	270	0.35	305	0.76	290	0.29	321

TABLE I
ELEVATION VALIDATION FOR SEVEN TIDE GAUGE STATIONS AROUND ORKNEY

The model bathymetry was from the GEBCO$_2$014 gridded bathymetry dataset which is available from the British Oceanographic Data Centre (BODC) at a resolution of 30 arc seconds (Figure 3).

1) Model Validation: The model velocities and elevations are validated against 9 tide gauge harmonic data sets provided by the UK Tide Gauge Network and tidal ellipses processed from three ADCP devices which were deployed for the duration if one month by the Navigation Safety Branch of the Maritime and Coastguard Agency in the main tidal channel (Table I and Figures 4(b),-4(d)).

Tidal elevations have a root-mean-square-error (rmse) for amplitude of 15cm and 5cm for M2 and S2 respectively. Both M2 and S2 phase rmse are within 20 degrees. There is high positive correlation between observed and modelled U and V values for all cases with the exception of the V correlation plot for ADCP 1 which shows weak negative correlation (Figure 4(a)). It can thus be deduced that the model is missing some of the variability within the flow, but is able to capture the correct phase and overall range of magnitude, allowing a bigger picture to be built up of the flow dynamics within the Pentland Firth.

The outputs from this parent model are used to force the boundaries of the finer resolution (child) models which have a resolution in *x* relative to the diameter of the turbines and in *y* the resolution is relative to 1/3 of the turbine diameter.

This initial study is not intended to be a detailed resource study but rather a study which examines the flow dynamics of the region which would act as a useful tool for tidal energy site developers.

C. Simulation Features: Idealised models

An idealised model was created of the Inner Sound site. The model domains had a width of 1km and a length of 4km. has a flat bed with a depth of 60m.

The model has two no-slip closed (North and South) and two open (East and West) boundaries. A semi-diurnal M2 tide is applied at the open boundaries with Chapman and Flather boundary conditions. Three dimensional momentum is radiated out of the channel. The turbulence closure scheme chosen was the $k - \epsilon$ scheme since it gave the lowest error values in a comparison study performed by [18] and the bottom roughness is parameterized using the ROMS quadratic friction expression representative of a turbulent channel flow regime with a value of 3×10^{-3} [18], [26].

Initially the model ran for two tidal cycles without tidal energy extraction, which will hereby be referred to as the control case, the first tidal cycle was discarded as spin-up. For the turbine model, the turbines were defined with a diameter of 20m and were positioned mid-way in the water column. Only 9 turbines were deployed in these tests to investigate the effect of array design and (Figures 5(a) and 5(b)). This idealised experiment can thus be used as a tool to determine appropriate array design and locations before implementing into a full-scale regional model which has a much greater computational cost. The purpose for this study is to investigate the impact of turbines on channel hydrodynamics and to test a new method of tidal energy extraction modelling.

III. Results

A. Tidal Currents in the Pentland Firth Region

The mean depth-averaged tidal currents and the corresponding peak velocity vectors are shown in Figure 6(a). It is clear that tidal flow is strongest at the constrictions of the channels. The peak velocity vectors provide an overview of the tidal symmetry/assymetry in the region. Tidal flow in the Inner Sound region appears to be flood dominated whereas in the Brough Ness site looks to be somewhat more varied with currents close to the headland appearing to be ebb dominated but further into the main channel clear flood dominance can be observed. Regions where there is a divergence of velocity vectors or a convergence of velocity vectors are likely to be bed-load parting or accumulation zones respectively [27]. Investigating how these peak velocity vectors change with tidal energy extraction may be an important consideration when determining potential change to bed-load transport. Figure 6(b) shows the result of restricting our investigation of the tidal currents to locations where water depth is in the region of 25-50m and where the mean current is greater than 1ms^-1. The contour lines show the percentage of the time that the tidal currents are greater than the threshold value of 1ms^-1 and the colours show the mean velocity in these regions of interest. The black stars on the plot indicate the two sites to be examined in more detail later on: Brough Ness and the Inner Sound. Figure 6(b) indicates that short of positioning the tidal energy sites in the main channel - impossible for many reasons [28] - the two starred sites have the next best availability of extractable tidal currents. Here the tidal currents are greater than 1ms^-1 over 50% of the time.

B. Current analysis at the individual sites

To examine the hydrodynamics of each site we present a detailed time series of tidal elevation and velocity (Figure 7). The tidal elevation at both locations is broadly similar but there appears to be a greater tidal range at the Inner Sound site. Both sites appear to be in phase with each other - tidal phase becomes important to tidal energy developers when tidal energy sites begin to be thought of as an interconnected grid. Sites with the same phase will provide peaks and troughs of power at similar times throughout the day. The optimum location is the site which has a tidal phase similar to the energy demands of country [29]. The bottom plot shows a time-series of tidal current variability. The Brough Ness site has larger values of peak velocity than the Inner Sound site. However, the Inner Sound site appears to have a greater symmetry than the Brough Ness site. The assymetry of tidal regions must be considered for any resource estimates and device designs. A tidal flow which has a very strong flood velocity but very weak ebb velocity may produce more power than a site which produces a small amount of power at each stage of the tide. However the symmetric site will produce a more consistent amount of energy. Different designs of tidal energy device may also be required for each location [26].

The directionality of currents is another important consideration for tidal developers and one which we examine in Figure 8. Directional asymmetry is caused by re-circulating eddies around headlands [30]. Both sites are somewhat rectilinear. As expected there is less variation in flow directionality at the Inner Sound site whereas our headland site, Brough Ness, does show a greater tendency to lean away from the rectilinear plane. Interestingly, our flood dominated Inner Sound site shows less directional variability in the peak flood values than in its ebb values and vice versa for the Brough Ness site. This suggests that faster flows are less likely to be affected by the topography in the region.

Finally we examine the vertical velocity structure at each site in relation to tidal asymmetry (Figure 9). The asymmetry is evident at all depths in the water column and is more pronounced during spring tides. We can clearly see that the Brough Ness site is more asymmetric than the Inner Sound site and the ebb dominance is pronounced whereas the flood dominance at the Inner Sound site is much more subtle.

C. Tidal energy extraction: idealised model

From Figure 10, we get an idea of how an idealised tidal wave propagating through the channel will interact with the local topography - remember that for this test the bathymetry is flat.

From the control case we can build up a picture of where to site the turbines for optimum energy extraction if we were only to worry about flow velocity as a factor in turbine deployment. Other factors we consider are proximity to land and water column position: in an attempt to prevent blockage affects the turbines were placed more than 5 rotor diameters away from the coast and mid-depth in the water column - (30m for the idealised case).

The impact of tidal energy devices with regard to turbine design is shown in Figures 11(a) and 11(b). Both cases show that for a relatively small scale turbine array, the effects of tidal energy extraction on the far-field resource can change by up to 30%. However, what is clear too from a comparison of these figures is that the array design has a big difference on the far field impact.

IV. Conclusion

There is much complexity in the flow around the coastline, particularly around headland regions which create eddy shedding. The Pentland Firth itself is highly complex, many of the regions within the Pentland Firth which have been allocated for tidal energy development have an element of tidal asymmetry. This further complicates the impact of tidal energy extraction as well as complicating resource assessments for tidal energy developers. The wake of the turbines persists to the edges of the domain in the idealised models which implies far-field change to morphodynamics. What we can see from the idealised results is that changes to the array design will have a large impact on the far-field flow and thus must be considered carefully.

Acknowledgement

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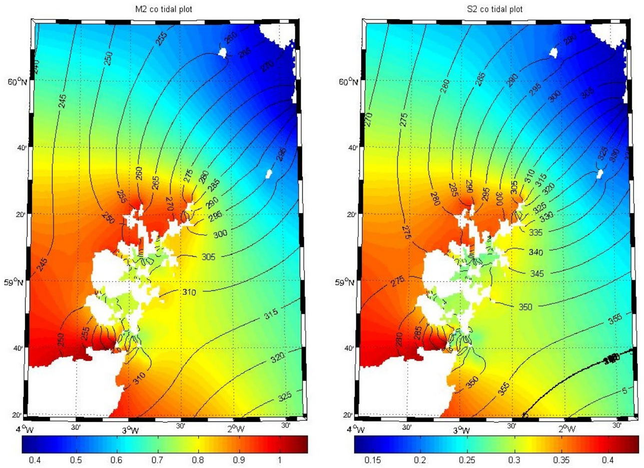
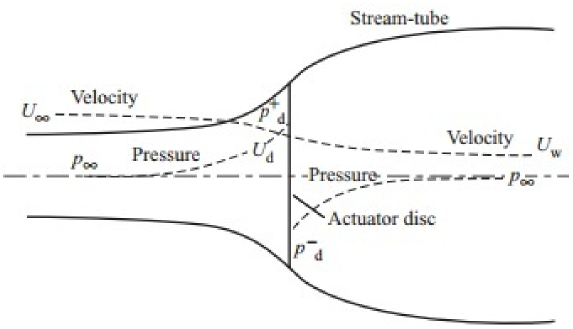
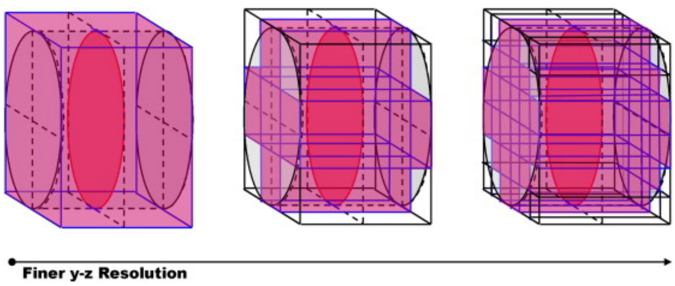


Fig. 1. Co-tidal plot of Pentland Firth model domain



(a) Actuator disk theory [24]



(b) Numerical control-volume approximation with the exact smeared control volume (blue cylinder). The red disc represents the actuator disc. [15]

Fig. 2.

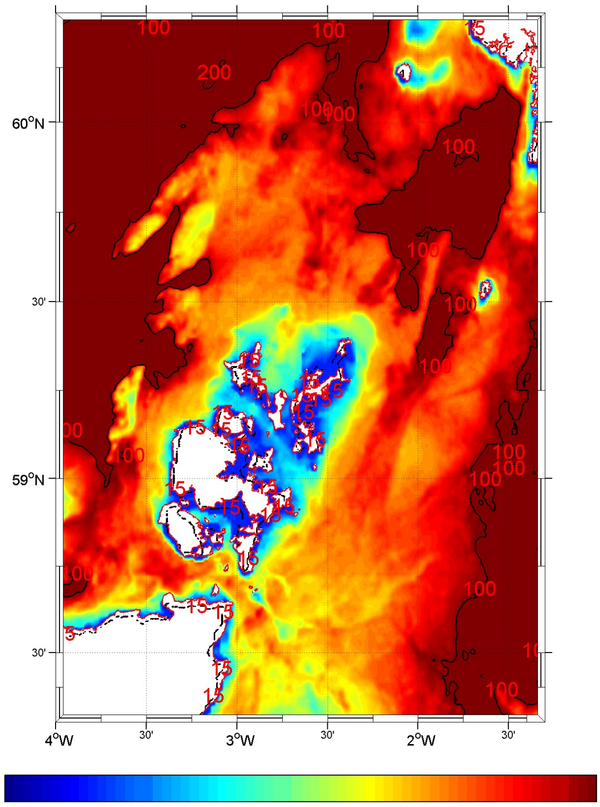
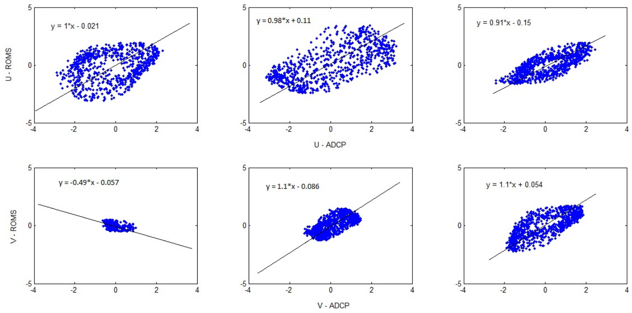
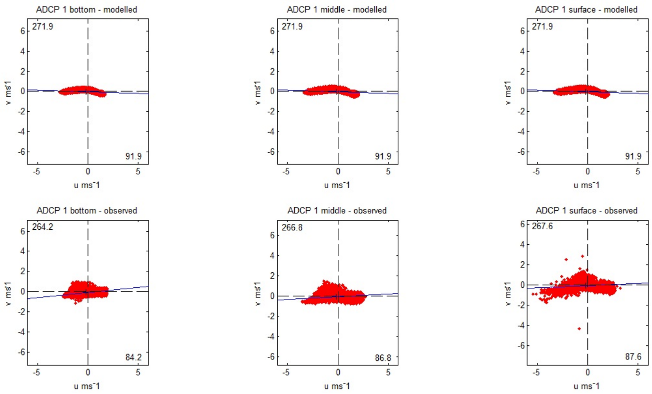


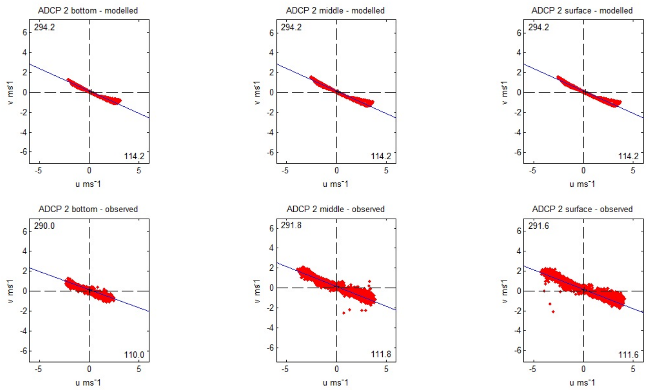
Fig. 3. Bathymetry plot of Pentland Firth model domain



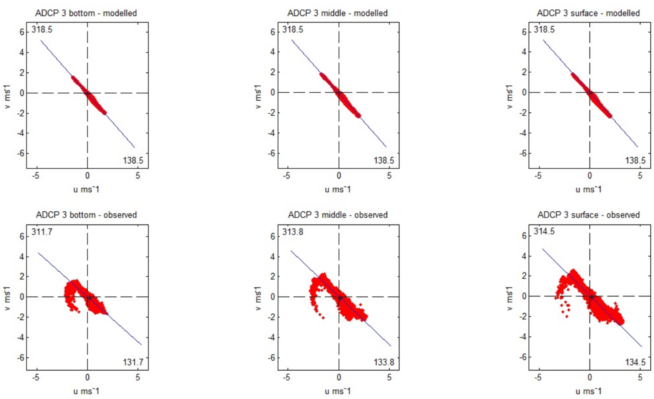
(a) Depth averaged tidal ellipse comparison: left to right show modelled and observed U and V values for ADCP1, ADCP2 and ADCP3 plotted against each other. Also given is the gradient of the line of best fit



(b) Tidal ellipse validation at ADCP site 1

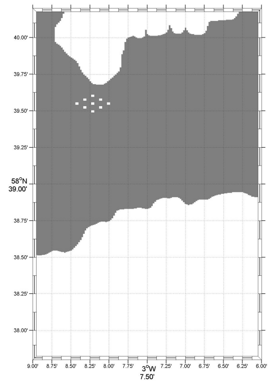


(c) Tidal ellipse validation at ADCP site 2

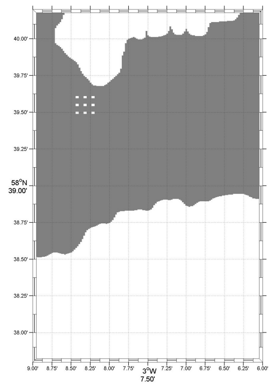


(d) Tidal ellipse validation at ADCP site 3

Fig. 4.

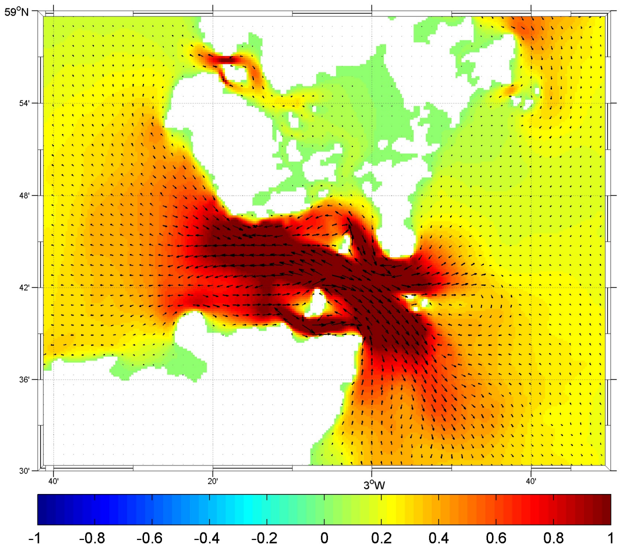


(a) Array design 1 for the Inner Sound region - individual turbines represented by white squares.

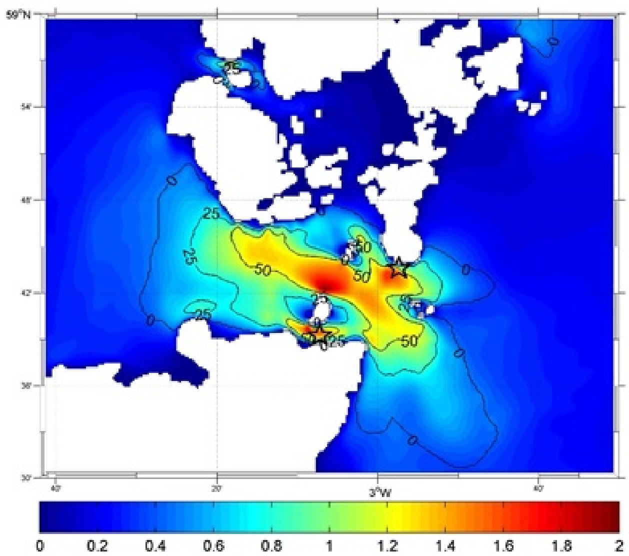


(b) Array design 2 for the Inner Sound region - individual turbines represented by white squares.

Fig. 5.



(a) Mean current speed (colour scale) and the respective peak velocity vectors



(b) Plot of Pentland Firth Region. Colours show mean tidal velocity. Contours represent % of tidal currents greater than $1\mathrm{ms}-1$. The locations which the idealised model grids are based on are shown by the star symbol

Fig. 6.

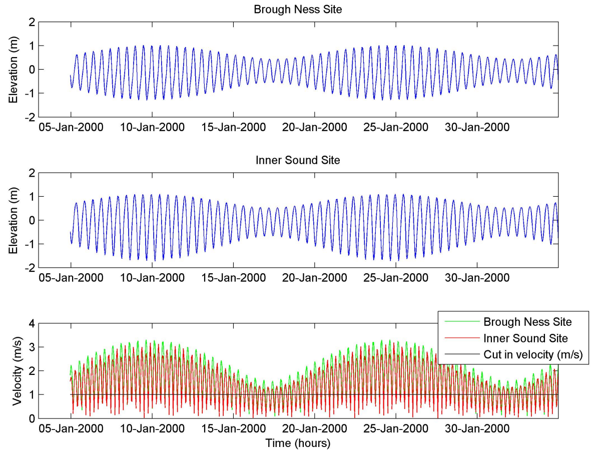


Fig. 7. The top two plots show tidal elevation for both sites. The bottom plot shows a time-series of tidal current variability.

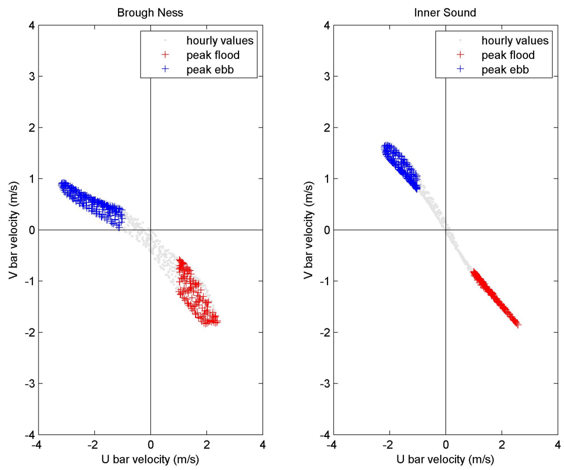


Fig. 8. Tidal directionality for both flood and ebb tides

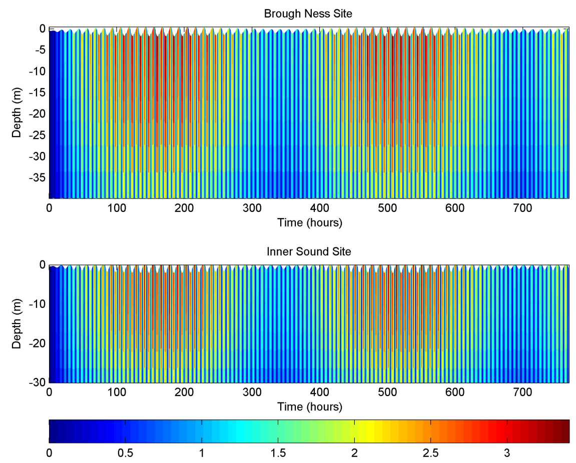


Fig. 9. Time series of simulated current speed at the Brough Ness site (Top) and the Inner Sound site (Bottom).

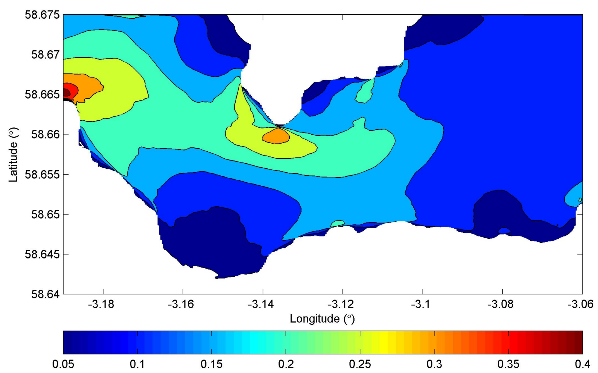
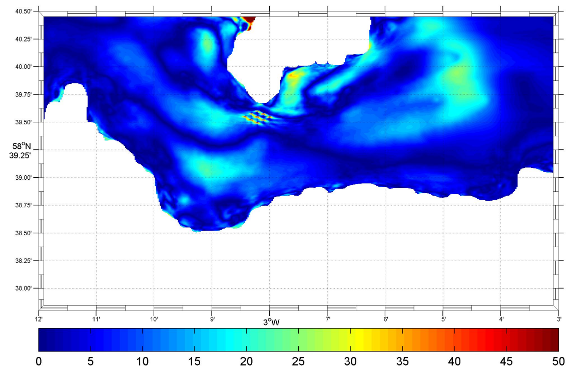
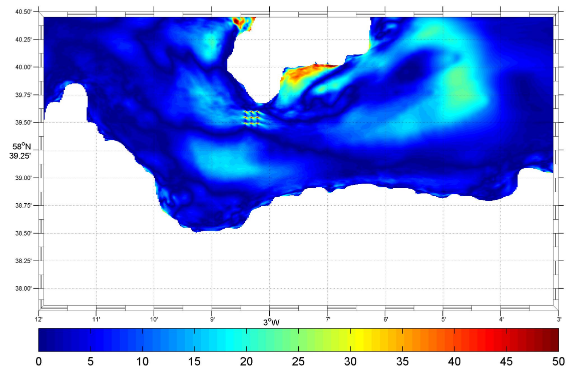


Fig. 10. Idealised plot of the Inner Sound region of the Pentland Firth. Colours show mean tidal velocity for the control case.



(a) Idealised plot of the Inner Sound region of the Pentland Firth. Colours show % change in mean tidal velocity between the control case and array layout 1.



(b) Idealised plot of the Inner Sound region of the Pentland Firth. Colours show % change in mean tidal velocity between the control case and array layout 2.

Fig. 11.