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Tidal resource and environmental effects of energy extraction in the Pentland Firth: sensitivity to array layouts and turbulence changes

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Abstract— **The Pentland Firth (UK) is a channel between Scotland's mainland and the Orkney Islands which has high-speed currents. This high tidal stream resource has encouraged the development of a tidal stream energy sector in Scotland, motivated to develop commercial scale tidal farms. It is important to consider how such developments may affect physical processes in the region, and how the layout of arrays could influence this.**

Tidal dynamics in the Pentland Firth and Orkney Waters (PFOW) have been reproduced by a high spatial resolution, unstructured grid, three-dimensional FVCOM model implementation [4]. The tidal stream turbines were then represented in the model as sub grid scale objects by using two different parameterizations: (1) a momentum sink approach [4]; (2) a momentum sink approach plus changes in turbulence generation and dissipation [5].

The practical resource available from the Pentland Firth, which includes feedbacks of the turbine realistic operations on the flow, has been estimated. In particular, this work explored how different tidal stream turbine arrays can interact in terms of both power resource availability and environmental effects. It has been found that different array layouts (location, number of turbines, spacing between turbines) can allow achieving very different amount of power resource, as well as degree of change to flow velocities. It has also been verified that turbulence changes can lead to an increase in bottom currents in the vicinity of the tidal turbines, which were not detectable using a simple momentum sink approach.

Keywords— **hydrodynamic modelling, Pentland Firth, tidal stream energy, tidal stream turbine arrays.**

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I. Introduction

Oceanic tides can be considered as a potential source of energy thanks to their consistent predictability and availability. With the threat of climate change, and fossil fuels becoming less readily available, tidal stream energy is receiving significant attention. It is important to consider the environmental impacts derived from extracting energy from oceanic tides. They can depend on the device design, location, animals and habitat presence and scale of development. The impacts on the ecosystem could be habitat loss or degradation and collision risk of marine mammals, fish and seabirds [3]. In terms of hydrodynamics, energy extraction induces changes in sea surface elevation and marine currents, which can then affect the associated transport of sediments, nutrients and microorganisms. Understanding these possible impacts and the mechanisms behind them might help in the exploitation of tidal energy without harming the marine environment [3].

This work is a modelling study focused on energy extraction in the Pentland Firth (UK), a channel between Scotland's mainland and the Orkney Islands with high-speed tidal currents. This high tidal stream resource has encouraged the development of a tidal stream energy industry sector in Scotland, motivated to develop commercial scale tidal farms [3]. The aim of this work is to understand how such developments may affect physical processes in the region and how the layout of arrays could influence this.

During recent years, many studies on tidal energy extraction were published. Most of them used hydrodynamic models to help understand how tidal stream turbines will change the hydrodynamic field, testing several different cases without expensive campaigns on site.

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[3] studied the environmental effects of a large theoretical array of tidal stream turbines in the Pentland Firth (UK): the ocean response to the tidal energy extraction was simulated with an unstructured grid three-dimensional FVCOM (Finite Volume Community Ocean Model, [1][2]) and near- and far-fields effects analysed on both short-term and seasonal timescales. [4] investigated the tidal stream resource and physical environmental impact in the Pentland Firth (UK) using a high spatial resolution FVCOM implementation for the Orkney Islands waters. In both [3] and [4] tidal stream turbines were represented in the model using a momentum sink approach: implementing an additional retarding force equal and opposite to the thrust in the momentum equations. [5] modified in FVCOM both the momentum and turbulent controlling equations to account not only for the additional drag induced by tidal turbines, but also for the turbulence generation and dissipation. [5] used a very high resolution mesh size at one turbine location in order to capture the details of hydrodynamics changes in the wake of the turbine due to the turbine operation.

The above-mentioned studies looked at the changes on hydrodynamics induced by tidal energy extraction and at the effects of turbulence modifications by one turbine. This work aims to study some aspects that were not explored in previous studies: how different array layouts (location, number of turbines, spacing between turbines) can (1) achieve different amount of power resource, (2) induce different changes to flow velocities and (3) the verification of the turbulence changes within an array of turbines.

II. Methodology

A. Pentland Firth and Orkney Waters (PFOW) model

Tidal dynamics in the Pentland Firth and Orkney Waters (PFOW) were reproduced by a high spatial resolution three-dimensional FVCOM model implementation outlined in [4][6]. FVCOM, is an unstructured grid, finite-volume primitive equation ocean model and developed for the study of coastal oceanic and estuarine circulation. The model domain includes a portion of the Atlantic Ocean covering Orkney and Shetland Islands waters (north of Scotland) and a portion of the North Sea; latitude and longitude are from 57°N to 62°N and 6°W to 1°E, as shown in Fig. 1. The grid is refined in the Pentland Firth and Orkney Waters region: the resolution of the unstructured grid is typically in the PFOW region between 150 and 250 m, further away from the PFOW the resolution is 1-2 km. The model has 10 vertical sigma layers which are terrain-following. The PFOW bathymetry originated from high resolution multibeam echo sounder data from the UK Hydrographic Office and Marine Scotland Science and from digitalised Admiralty Chart data. Further away from the area of interest, bathymetry data come from the European Marine Observation and Data Network (EMODnet). The data were converted to a common vertical datum and interpolated to the unstructured grid.

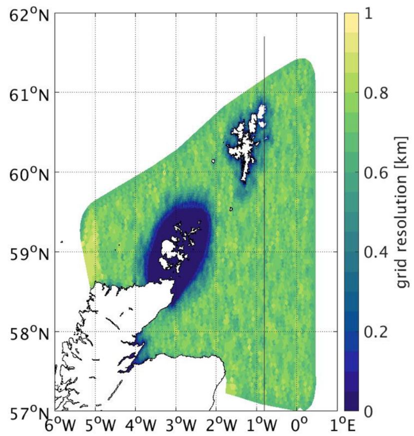

Fig. 1. Pentland Firth and Orkney Waters (PFOW) domain and grid resolution.

The model has been run and validated, as explained in [6], using full baroclinic forcing from the Atlantic Margin Model (AMM) at the open boundary including time series of temperature, salinity, water velocity and water elevation. In order to reproduce tidal dynamics, the model is forced at the boundaries by 8 tidal constituents (M_2, S_2, N_2, K_1, O_1, Q_1, P_1, K_2) computed by a tidal model based on the Oregon State University tidal inversion of TOPEX/POSEIDON altimeter data [6]. The PFOW model has been run and validated, as described in [6].

B. Turbine parameterisation

In this work, we compare two different parameterisations of tidal stream turbines represented in FVCOM as sub grid scale objects. The first parameterisation we tested is the one implemented by [4], using the sub-grid scale momentum sink method outlined in [7]. The tidal stream momentum sink terms per unit mass has been defined in [4] in the following way:

$$\overrightarrow{F^M} = \left(F_x^M, F_y^M\right) = \frac{1}{2}\frac{N C_T A}{V_c}|\vec{u}|\vec{u} \tag{1}$$

where N is the number of tidal stream turbines in one model element, V_C is the element control volume, C_T is the thrust coefficient of a turbines, A is the flow facing area of a turbines, $\vec{u}$ is the flow velocity vector and $|\vec{u}|$ is the magnitude of the velocity in a cell.

The second parameterizations tested is the approach used by [5], adding a momentum sink term outlined in [8]. The momentum sink terms per unit area has been expressed in [5] in the following way:

$$\vec{F} = (F_u, F_v) = \frac{1}{2}C_{ext}|\vec{u}|\vec{u} \tag{2}$$

where C_{ext} has been named as the energy extraction coefficient, which determines the strength of the sink term. (1) and (2) are formally equal if we assume:

$$C_{ext}(k) = C_T \frac{NA}{V_C} \quad (3)$$

This means that C_{ext}, which is given as an external input parameter, has to be scaled on the grid element volume where the turbine is located, so its value depends on the resolution of the model.

The tidal stream turbine parameterisation implemented in [5] reproduces also the turbine-induced turbulence perturbations. These perturbations are included in the TKE equations in the way suggested in [9]; in these equations the following terms were added:

- Turbine-induced turbulence generation: $P_{tp} = C_{tp} \frac{u^3}{\Delta x}$
- Turbine-induced turbulence dissipation: $P_{td} = C_{td} \frac{u*k}{\Delta x}$
- That of an interference for the turbulence length-scale (l): $P_l = C_l * P_s$

C_{tp}, C_{td}, C_l are coefficients, decided empirically and activated only at turbine locations, they are outlined in [9] in terms of C_t:

- Turbine-induced turbulence generation coefficient: $C_{tp} = C_1 (C_{pw} \frac{L_{chord} \sin\theta}{\Delta x})$
- Turbine-induced turbulence dissipation coefficient: $C_{td} = C_2 (C_{pw} \frac{L_{chord} \sin\theta}{\Delta x})$
- Interference for the turbulence length-scale coefficient: $C_l = C_3 (C_{pw} \frac{L_{chord} \sin\theta}{\Delta x})^2$

where C_1 and C_2 are given in [10] and C_3 in [11]; C_{pw} has been found to be a function of C_T: $C_{pw} = C_T \sqrt{1 - C_T}$; L_{chord} is the blade chord length, θ is the blade pitch angle and Δx is the width of the numerical control-volume.

Thus, the turbulent kinetic energy and macroscale equations are modified in the following way:

$$\frac{\partial q^2}{\partial t} + u \frac{\partial q^2}{\partial x} + v \frac{\partial q^2}{\partial y} + w \frac{\partial q^2}{\partial z} = 2(P_s + P_b + P_{tp} + P_{td} - \varepsilon) + \frac{\partial}{\partial z}\left(K_q \frac{\partial q^2}{\partial z}\right) + F_q, \quad (4)$$

$$\frac{\partial q^2 l}{\partial t} + u \frac{\partial q^2 l}{\partial x} + v \frac{\partial q^2 l}{\partial y} + w \frac{\partial q^2 l}{\partial z} = l(E_1(P_s + P_b) - P_l - \frac{\tilde{W}}{E_1}\varepsilon) + \frac{\partial}{\partial z}\left(K_q \frac{\partial q^2 l}{\partial z}\right) + F_l, \quad (5)$$

where $q^2 = (u'^2 + v'^2)/2$ is the turbulent kinetic energy; l is the turbulent macroscale; K_q is the vertical eddy diffusion coefficient of the turbulent kinetic energy; F_q and F_l are the horizontal diffusion of the turbulent kinetic energy and macroscale; $P_s = K_m(u_z^2 + v_z^2)$ and $P_b = (gK_h\rho_z)/\rho_0$ are the shear and buoyancy production terms of turbulent kinetic energy; $\varepsilon = q^3/B_1 l$ is the turbulent kinetic energy dissipation rate; $W = 1 + E_2 l^2/(\kappa L)^2$ is a wall proximity function, where $L^{-1} = (\zeta - z)^{-1} + (H + z)^{-1}$; $\kappa = 0.4$ is the von Kàrman constant; H is the mean water depth; ζ is the free surface elevation. Eqs. (4) and (5) are closed physically and mathematically using the Mellor and Yamada level-2.5 (MY-2.5) turbulent closure [12] modified by Galperin [13].

For both parameterization turbines were modelled with some simplifications: a yaw mechanism allows the turbine to be always in the flow direction. The operating window is often turbine-specific, i. e. usually a turbine has cut-in and cut-out velocity, in [5] this has not been implemented, while it is accounted in [4]. In this study the generic tidal turbine design developed in [14] was used. It is a 20 m diameter rotor turbine anchored to the seabed with a nominal capacity of 2.5 MW, a rated speed of 2.5 m/s and cut-in and cut-out speed of 1 m/s and 4 m/s. So, the turbine thrust coefficient C_T can be considered constant or varied as a function of the flow speed. Below 1 m/s, the turbine doesn't work because the flow is too weak to rotate the blades; between 1 m/s and 2.5 m/s, power extraction grows until it gets the maximum at the rated speed; between 2.5 m/s and 4 m/s, the power output reaches the limit that the electrical generator is capable of, the thrust force on the rotor is reduced because the turbine is regulated to limiting the power output above 4 m/s, the turbine is blocked in order to avoid structural damages and it doesn't extract power.

C. *Turbine arrays*

Three different arrays of turbines in the Pentland Firth were simulated; in fact, diverse location, number of turbines and spacing between turbines can achieve a very different amount of power resource and can cause different changes in current speed and surface elevation. Turbines were not placed in shallow elements, thus, considering that the hub height was fixed at 15 m above sea-bed and the blade diameter is about 20 m, turbines were not located in water depth less than 27.5 m. This allowed the turbines to remain submerged at all tidal states.

1) *Array B 12*

It is composed by 5636 turbines, they are located in the Pentland Firth between Scottish mainland and the island of Stroma, between Stroma and Swona and between Swona and South Ronaldsay (Fig. 2a). This array has been designed in [4] to maximize the tidal energy extraction, so turbines are distributed across the three channels to limit the deviation of the flow around groups of turbines.

2) *Array TeraWatt Pentland Firth*

Turbines are located in the PFOW Round One Development Sites, those are the sites for commercial renewable energy development with lease agreements granted by The Crown Estate in 2010. The array is composed by 800 turbines, they are located in 4 different locations: 200 turbines are south of the island of Hoy, 400 turbines are between the Scottish mainland and Swona,

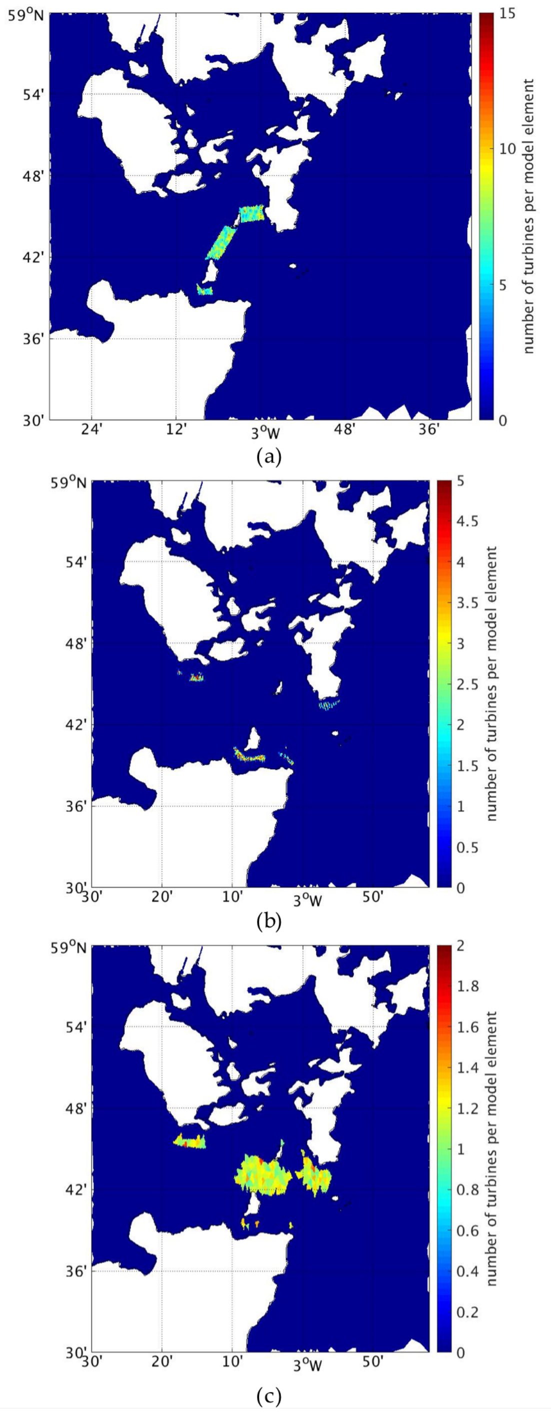

Fig. 2. Turbines location: B 12 array (a), TeraWatt Pentland Firth array (b) and EcoWatt Pentland Firth array (c).

100 are between South Ronaldsay and the island of Muckle Sherry and 100 turbines are at the western end of Pentland Firth channel (Fig. 2b).

3) Array Ecowatt Pentland Firth

The EcoWatt Pentland Firth is an array composed by 2777 turbines, they are located mostly in the middle of the channel (Fig. 2c). This array has lower density of turbines than TeraWatt arrays. This array is an adaptation of the one designed in [3]. It has been designed following three criteria: (i) turbines are placed in elements where water depths is > 27.5 m, (ii) the capacity factor, a measure of device utilization, is between 30% and 40%, and (iii) the spatial density has a minimum lateral turbine spacing of 3 device widths and a minimum downstream spacing of 15 device widths to eliminate wake effects.

III. Results

D. Baseline case

This paragraph describes the hydrodynamic features of the Pentland Firth in terms of current speeds and surface elevation. The average power density [kW/m²] in the Pentland Firth was estimated from a 30 days PFOW model run forced by the aforementioned tidal constituents without including any feedbacks of tidal array on the flow (undisturbed resource). The link between power density and currents speed is:

$$APD(i) = \langle \frac{1}{2}\rho\left|\overline{u(\iota,t)}\right|^3\rangle_t \quad (6)$$

where *APD(i)* [kW/m²] is the power density in the vertical plane perpendicular to the tidal current direction, $\left|\overline{u(\iota,t)}\right|$ is the depth-averaged tidal current speed, $\langle\ \rangle_t$ represent a time mean average over 30 days. Fig. 3a shows that the maximum average power density is in the

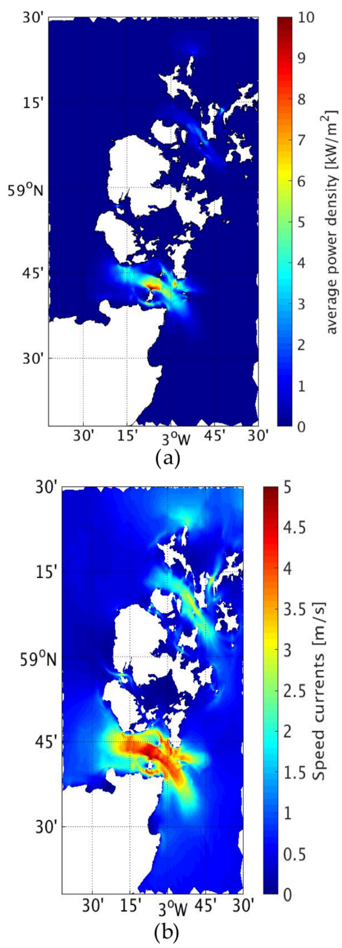

Fig. 3. Baseline case (undisturbed resource): average power density [kW/m2] (a) and maximum currents speed [m/s] (b).

middle of the channel between Scotland and Orkney Islands and it could reach 10 kW/m² north of Stroma. Moreover, Fig. 3b shows that in the channel the maximum value of *APD* is related to the maximum currents speed.

E. *Tidal resource*

This paragraph examines how much power could be extracted from the tidal flow with different arrays. For each array, the instantaneous tidal stream power extracted at any instant of time, using the three-dimensional velocities from the sigma layers spanned by the turbine, has been calculated as:

$$P(t) = \frac{1}{2}\rho A_b C_T |\overrightarrow{u_T}|^3 \qquad (7)$$

where $\overrightarrow{u_T} = \sum_{\sigma=1}^{\sigma=k} K_\sigma \overrightarrow{u_\sigma}$ is the weighted average velocity vector over the diameter of the tidal turbine, where $\overrightarrow{u_\sigma}$ is the flow velocity vector at the σ layer and k is the number of sigma layers.

A monthly time series of the tidal stream power available for electricity generation for the three arrays is presented in this section. The time series follow the

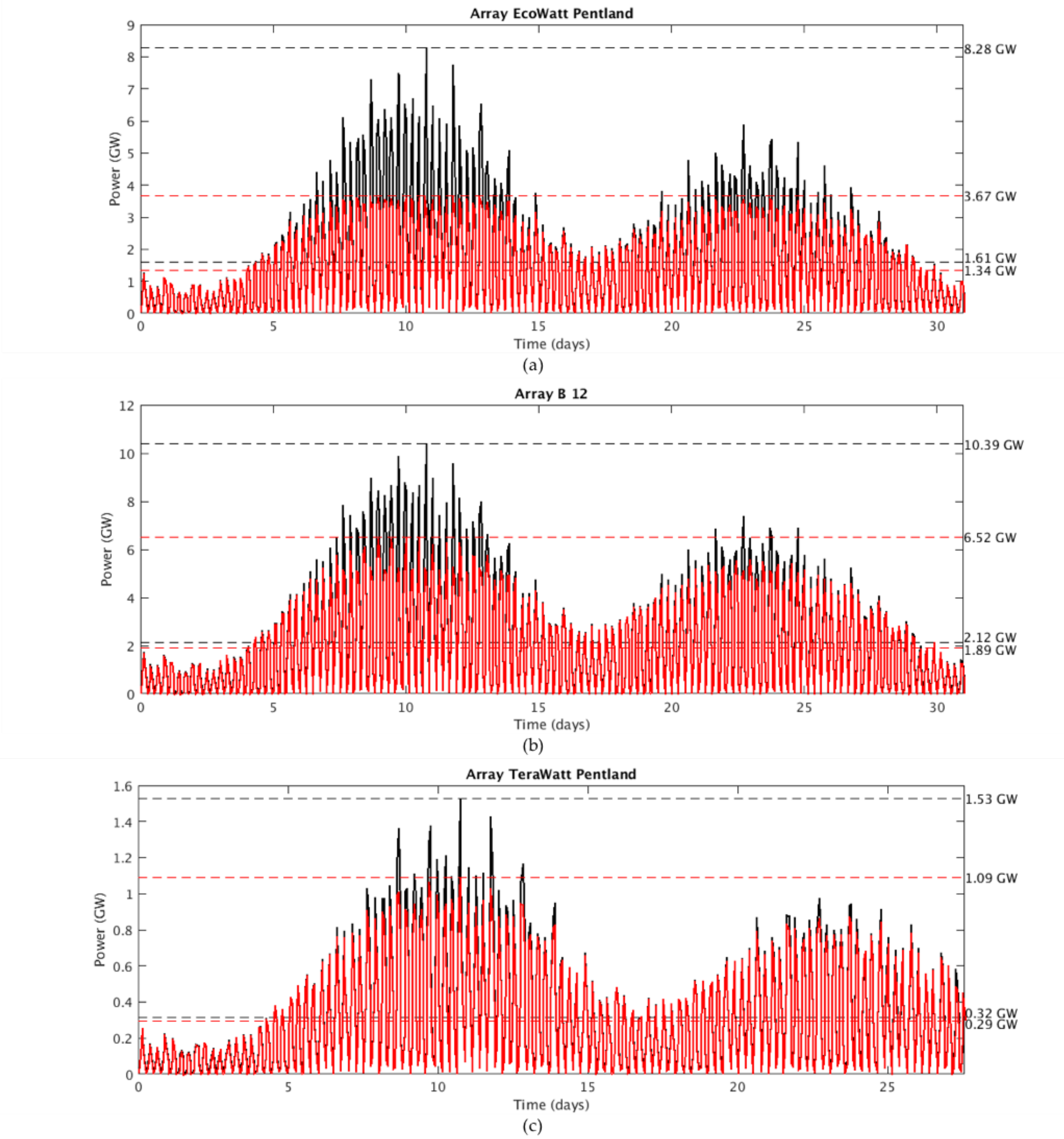

Fig. 4. Time series of the tidal stream power extractable by EcoWatt Pentland Firth array (a), B 12 array (b) and TeraWatt Pentalnd Firth array (c). Turbines can work at every speed of currents (C_T constant) (black line), turbines have a cut-in and cut-out velocity (C_T variable) (red line).

TABLE I
TABLE OF EXPERIMENTS

Array	Number of turbines	C_T	Maximum extractable power [GW]	Mean extractable power [GW]	Turbine parameterisation
B 12	5636	0.85	10.39	2.12	O'Hara Murray et al. (2017)
		variable	6.09	1.85	
TeraWatt Penltland Firth	800	0.85	1.53	0.32	O'Hara Murray et al. (2017)
		variable	1.09	0.29	
EcoWatt Pentland Firth	2777	0.85	8.28	1.61	O'Hara Murray et al. (2017)
		variable	3.67	1.34	
EcoWatt Pentland Firth	2440	0.85	7.63	1.56	Li et al. (2017)

sinusoidal tidal behaviour and show two peaks and two lows corresponding on the tidal peaks and lows.

Fig. 4a shows extractable power time series by the EcoWatt Pentland Firth array**.** If the turbines can work at any current speed (C_T constant, black line), the EcoWatt Pentland Firth array (2777 turbines) could extract a maximum of 8.28 GW, with 1.61 GW on average over 30 days. On the other hand, if the turbines have a cut-in and cut-out velocity (C_T variable, red line), the extractable power peaks at 3.67 GW and 1.34 GW on average.

Comparing with the results of [3], the results in this work are more correct, and this is due to an overestimation of the power in [3], due to the low resolution of the hydrodynamic model which implies having many turbines in one cell without any reduction of the velocity in the wake of each single turbine.

For the B 12 array (5636 turbines), if the turbines can work at every speed of currents (C_T constant), a maximum of 10.39 GW could be extracted, and the array can provide 2.12 GW on average over 30 days; on the other hand, if turbines have a cut-in and cut-out velocity (C_T variable), the power available is 10% less (see Fig. 4b).

Comparing with the results of [4], the results in this work are more correct, in [4] only an M_2 tide was investigated, rather than a full spring-neaps tidal cycle.

The TeraWatt Pentland Firth array (800 turbines distributed in four different locations in Pentland Firth) can provide 1.53 GW as maximum power and 0.32 GW on average with a constant C_T. With a variable C_T the maximum power and mean power are 1.09 GW and 0.29 GW, respectively (see Fig. 4bc).

The EcoWatt PFOW array was the most efficient, because it extracted a greater amount of power with the half of turbines of the B 12 array. Table I summarizes the different array layouts considered in the work together with the turbine parametrization and extractable power available for electricity generation.

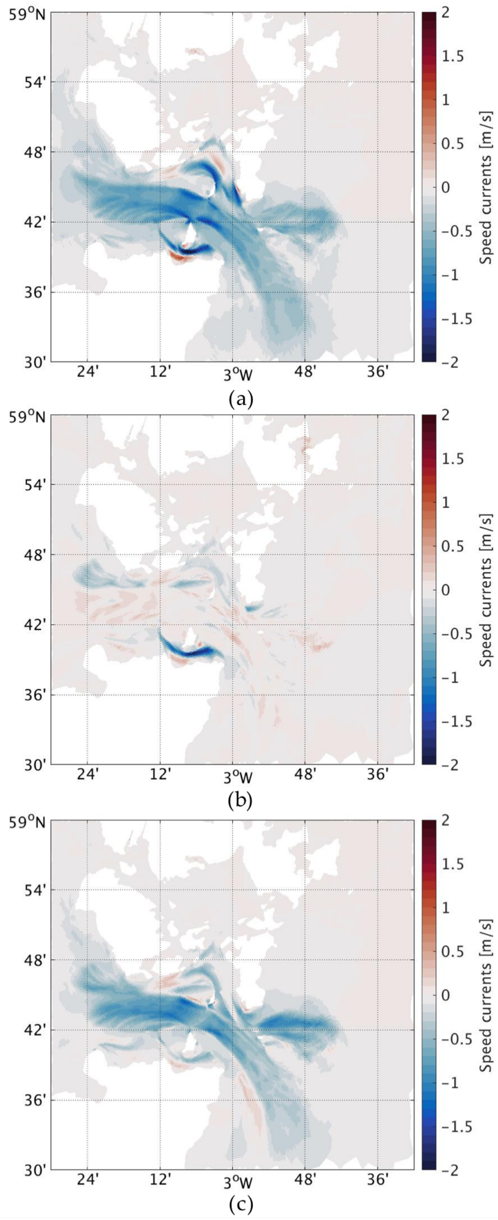

Fig. 5. Maximum changes in speed currents due to tidal stream energy extraction in the Pentland Firth: B 12 array (a), TeraWatt Pentland Firth array (b) and EcoWatt Pentland Firth array (c).

F. *Environmental effects of energy extraction*

Installing an array of turbines leads to a perturbation of the currents in the Pentland Firth. Fig. 5 shows the maximum differences in current speed due to the different tidal arrays. Common to all arrays is a deceleration where the turbines are located and in the wake of them and an acceleration at both sides of the array. However as shown in Fig. 5 each array could change currents differently. For example, B 12 is the largest array simulated, so it has the larger impact on the

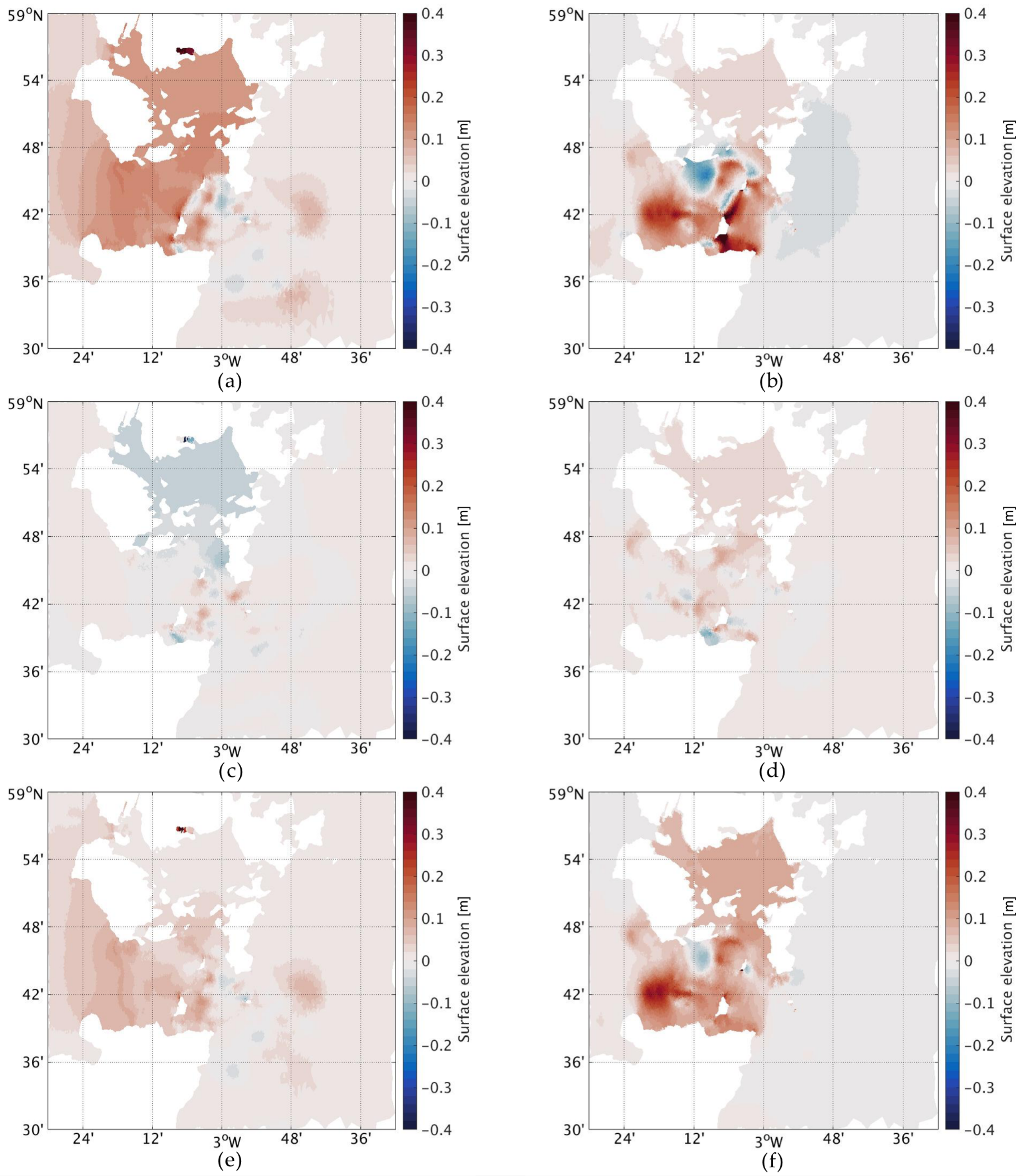

Fig. 6. Changes in maximum (high tide) and minimum surface elevation (low tides) due to tidal stream energy extraction in the Pentland Firth: B 12 array (a) and (b), TeraWatt Pentland Firth array (c) and (d) and EcoWatt Pentland Firth array (e) and (f).

hydrodynamics in the Pentland Firth. Fig. 5a shows a strong deceleration, induced by the 5636 turbines located in the middle of the Pentland Firth, with velocities 2 m/s slower than the undisturbed ones. Fig. 5b refers to to the TeraWatt Pentland Firth array. In this case, we observed a 1 m/s deceleration in four different areas corresponding to the turbine locations. Furthermore, due to the multiple turbine locations realized in this array, currents are forced to flow in the middle of the channel where velocities slightly increase. Fig. 5c, referring to the EcoWatt Pentland Firth array shows results similar to the ones obtained for the B 12 array, as a deceleration in the middle of the channel is observed. In this case, due the EcoWatt Pentland Firth lower turbine density the deceleration is almost 1 m/s, instead of 2 m/s as for the B 12 array.

Moreover, the surface elevation changes due to the turbine presence were analysed. Fig. 6 shows the differences in the maximum (high tide) and minimum surface elevation (low tide) induced by the turbines of the B 12, TeraWatt Pentland Firth and EcoWatt Pentland Firth arrays. Fig. 6a shows the change in high tide level induced by array B 12. In this case, the presence of the turbines (located between Scottish mainland and the island of Stroma, between Stroma and Swona and between Swona and South Ronaldsay) forces the rise of the water level in the western waters of the channel and in the area of Scapa Flow. This increase is between 0.1 and 0.2 m. Fig. 6c shows the effect of the TeraWatt

Pentland Firth array. Here, we observed a decrease in high tide of the water level of 0.1 m in the Scapa Flow and a slight increase in the middle of the channel. The EcoWatt array (Fig. 6e) induces an increase in water level during high tide of 0.1 m, mostly located in the western Pentland Firth.

In general, tidal elevation increases upstream of the tidal array location (considering the direction of propagation of the tidal wave coming from the Atlantic) in the Pentland Firth. This effect is possibly generated by the blockage of the flow and by a consequent decrease of kinetic energy, which is transformed into potential energy upstream of the tidal array. Differently, low tide levels show larger changes than high tide levels for the B12 and the EcoWatt Pentland Firth arrays. The B 12 array produces a strong increase of the low tide level between the Scottish mainland and the island of Stroma and between Stroma and Swona, as shown in fig. 6b. Furthermore, in the western Pentland Firth is visible an increase of 0.2 m and a decrease of the same amount south of the island of Hoy (Fig. 6b). The TeraWatt Pentland Firth array produces a slight increase of the low tide Fig. 6d. As shown in Fig. 6f the low tide level in the Pentland Firth and in Scapa Flow increases and this is more significant in the area where the waters from the Atlantic Ocean enter in the channel.

G. *Turbulence effects*

The turbine parameterization used in [5] allows to study the changes in turbulence induced by the tidal arrays. First, we studied a simple idealized case considering the changes induced by only one turbine. Fig. 7 shows the difference in currents speed at the bottom layer without (Fig. 7a) and with (Fig. 7b) the changes in turbulence. As shown in Fig. 7b the changes in turbulence generate an acceleration of 0.1 m/s both at the turbine location and at the side of the deceleration area, in the wake of the turbine. On the contrary, current speed is only decelerated by the presence of the turbine, Fig. 7a, when changes in turbulence are not considered. Physically, the turbine work enhances the turbulence in its wake. In detail, as verified by the computed cross-section velocity profile, not shown here for the sake of brevity, turbulence produces a mixing of momentum on the water depth; so there is a transfer of momentum from the upper layers to the bottom layer. That means water at bottom layers gain more energy and it is accelerated. The phenomenon is represented mathematically in the modifications of the turbulence coefficients introduced in

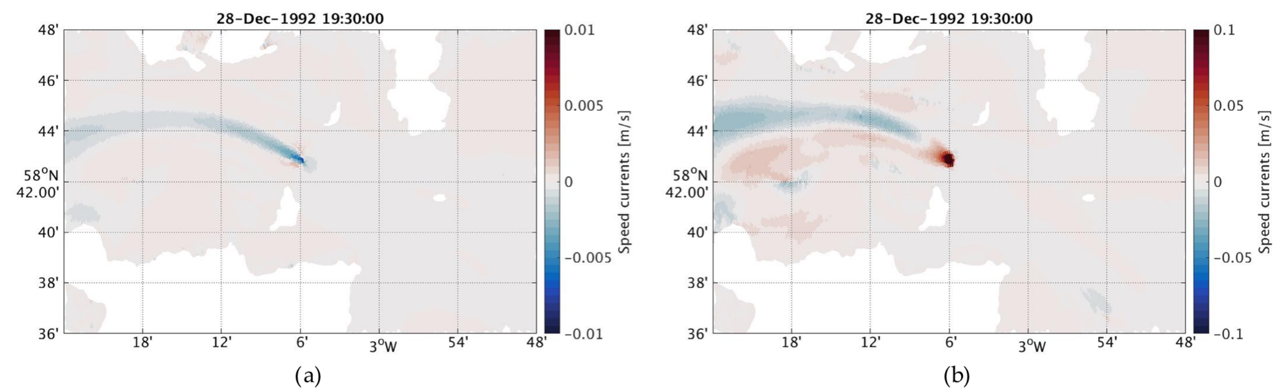

Fig. 7. Li et al. (2017) turbine parameterization: changes on currents speed at bottom layer induced by 1 turbine (a) considering the effects of turbulence on current speed in the wake of turbine (b).

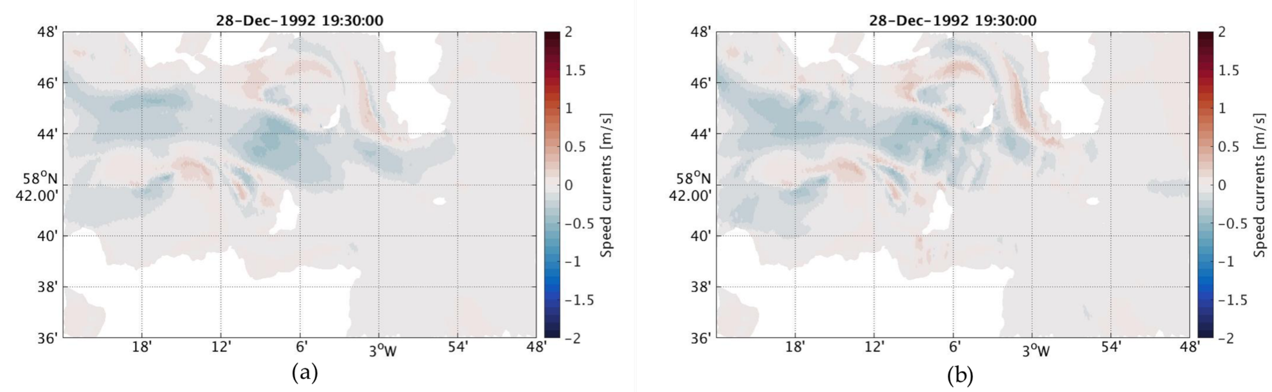

Fig. 8. Li et al. (2017) turbine parameterization: changes on currents speed at bottom layer induced by the EcoWatt Pentland Firth array (a) and considering the effects of turbulence on current speed in the wake of turbine (b).

the TKE equations (4) and (5). The increase in velocity at the turbine location is due to the fact that the turbine-induced turbulence generation coefficient exceeds the turbine-induced turbulence dissipation coefficient. The changes in turbulence within an array were studied for the EcoWatt Pentland Firth array only. Fig. 8b shows the changes in current speed at the bottom layer. It is visible a modification of the deceleration induced by the turbines. As for the case of the single turbine (Fig. 7b), the turbulence modifications produce an acceleration of the current speed which is opposite to the decrease in velocity due to the drag force of the turbines (momentum sink). These two effects generate a patchy deceleration in the middle of the Pentland Firth reaching 0.2 m/s.

IV. Conclusion

In this study a high spatial resolution, unstructured grid, three-dimensional FVCOM hydrodynamic model was used to estimate the available tidal stream resource in the Pentland Firth and to simulate the far-field impacts of tidal turbines, in terms of modification of currents speed, water elevations and turbulence. The tidal stream turbines were represented as sub grid scale objects by using a momentum sink approach. Three different tidal stream arrays were simulated to estimate tidal resource available in the Pentland Firth and to understand how the layout of the arrays of turbines could influence the physical processes in the region.

The most realistic array analysed has 800 turbines, distributed in four different locations in the Pentland Firth and they could extract a maximum power and mean power of 1.09 GW and 0.29 GW, respectively. While the tidal resource of a theoretical very large array of 5636 turbines, located in the three main channels of the Pentland Firth, could potentially extract 1.85 GW on average over 30 days with a maximum peak of 6.09 GW. This estimate is the "practical resource" available, it takes into account the tidal stream energy extraction feedbacks on the flow (i.e. flow deceleration) and it considers the realistic operation of a generic tidal stream turbine, which is limited to operate in a range of flow velocities due to technological constraints. It was found that the geometry and turbine density of the array lead to different power available for electricity generation. In fact, an array with a lower turbine density and a total of 2777 turbines could extract 1.34 GW on average, and 3.67 GW as maximum peak. This means that 2777 turbines can be more efficient than 5636 turbines if located in the same areas, but with more space in between turbines.

The tidal stream turbine arrays induced changes in the current speeds. For all the arrays considered we observed a deceleration where the turbines are located and in their wake and an acceleration on both sides of the array. The common pattern for the maximum change in currents is a deceleration of 0.5 m/s, but each array changes the currents differently. For example, 5636 turbines, located in the middle of the Pentland Firth, lead to velocities 2 m/s slower than the undisturbed velocities. The modification of currents velocity could alter the transport of sediments, nutrients and microorganisms, with consequent sea-bed changes and a possible removal of the benthic layer. Hence it is necessary to consider this phenomenon.

Changes in water elevation are also induced by tidal stream turbine arrays. The increase of the water levels during both high and low tide could reach 0.1 m and is mostly located in the western waters of the channel. This has to be considered for the coastal protection. In general, tidal elevation increases upstream of the tidal array location (considering the direction of propagation of the tidal wave coming from the Atlantic) in the Pentland Firth, which is possibly generated by the blockage of the flow and by a consequent decrease of kinetic energy.

Changes in turbulence are also induced by the turbines. We modelled an acceleration in the bottom layer currents of 0.1 m/s where a turbine is located. The turbine enhances the turbulence in its wake. Within an array the turbulence changes combined with the flow deceleration induced by the drag of the turbines produces a patchy deceleration in the Pentland Firth.

In the future, higher resolution hydrodynamic model at the turbine location, for example with a grid resolution of the scale of the turbine, will enable studies of the turbulent wake of a tidal turbine. Moreover, new and different arrays can be tested in order to maximize the available power for electricity generation, while minimizing the environmental effects.

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