Responses to reviewers' comments on the manuscript "Effect of tidal stream power generation on the region-wide circulation in a shallow sea", by G. I Shapiro. Submitted to Ocean Science Discussions (OS-2010-47).

REFEREE #1.

The paper discusses the efficiency of a tidal stream farm and its effect on the regional circulation of the north-eastern Celtic Sea. The paper shows that the efficiency of a farm located in the open ocean, where the circulation is fully three-dimensional, can be significantly reduced compared to the efficiency of farms placed in fjords and estuaries, where the circulation is quasi-twodimensional. The paper is well written and its science is mostly sound. I recommend that it be published after a few points have been addressed. These are as follows (ordered by page and line numbers in the manuscript).

COMMENT: 1787-10. For the physical oceanographers among the readership, it might be helpful to use the mechanical dissipation of tidal energy in the ocean as a reference. This is estimated at ~4 TW (75% on the shelves and 25% in the deep ocean; Egbert and Ray, 2000). This is 44 times larger than the 800 TWh/year (~0.1 TW) quoted in the Sorensen and Weinstein (2008) paper, but comparable to the 19,771 Twh/year (~2.25 TW) of world electricity consumption.
RESPONSE: Accepted with thanks. Additional references to Egbert and Ray (2000) and Munk and Wunsh (1998) are given to show the total rate of tidal energy dissipation (and hence production) in the World ocean (3.7 TW) as well as tidal dissipation on the World ocean shelves (2.5TW or 21,900 TWh/year).

COMMENT: 1787-12. Rogue full stop after 2008.
RESPONSE: Corrected.

COMMENT: 1791-14 & ff. As the author states, linear Rayleigh friction is one of a number of ways of parameterising friction. It is adequate for slow flow past an obstacle, but probably less so for flows fast enough to generate turbulence as they go through, or circumvent, and object. In this case, a quadratic friction law would be more appropriate. I would encourage the author to run parallel experiments with a quadratic friction law and to report on the differences between linear and quadratic friction results if these differences are found to be significant.
RESPONSE: It is correct that a quadratic (rather than linear) friction would be more appropriate for the flow past a **STATIC** object where friction would be caused due to generation of turbulence. However the dynamics of flow through the rotating turbines is very different. Here the retarding force acting on the flow is caused mainly by the transfer of momentum from the flow to the rotating blades. There is sufficient evidence both theoretical and observational, that in this case the thrust coefficient C_T (representing the drag caused by turbines) is highly dependent on the speed of the incoming flow. The C_T decreases with increasing flow speed approximately as $1/u$, this results in the retarding force being linearly proportional to the speed; this fact supports the use of linear (Rayleigh) parameterisation for turbines. I acknowledge that the fluid dynamics of turbines is a special subject which may need a more detailed explanation for oceanography readership; so I added a sub-section explaining the issue as follows:

According to Newton's third law of motion, the retarding ,or drag, force exerted on the flow by a turbine is equal and opposite to the thrust , F_T , exerted by the flow on the turbine. The thrust is related to the speed of the flow via the following equation (see e.g. Hansen, 2008):

$$F_T = \frac{1}{2} C_T \rho u^2 A;$$ (6)

where C_T is the thrust coefficient and A is the cross-sectional area of the flow passing through the turbine.

For a turbine, the thrust coefficient, $C_{T,}$ is not a constant but is highly dependent on the speed of the incoming flow, see e.g (Leishman,2000). Strong dependence of C_T on the current speed makes the dynamics of flow through turbines very different from the turbulent flow around static objects such as a disk or a plate where a similar quantity, the drag coefficient, C_d, could be reasonably assumed constant within a wide range of Reynolds numbers. The physical reason for such a difference is that in case of a turbine the retarding force is mainly caused by the transfer of momentum and energy from the flow to the rotating turbine blades. On the contrary, in the turbulent flow around a static object the frictional drag is mainly caused due to generation of turbulence by the object. As engineers aim to reduce unwanted mechanical energy losses in the turbines, the bulk of the flow energy goes into rotation of the turbine blades.

Experimental evidence shows (Frandsen,2007, Eq. (3.12)) that within the working range the thrust coefficient C_T can be approximated as inversely proportional to the flow speed, an approximation that is supposed to fit for most of the modern wind turbines (Frohboese and Schmuck, 2010):

$$C_T = \frac{Const}{u}$$ (7)

Fig.1(a) shows results of measurements obtained for a number of commercially available wind turbines as well as the curve computed using Eq.(7) and $Const$=7m/s (Frohboese and Schmuck, 2010). A combination of Eqs. (7) and (6) results in a linear law of 'friction' exerted by a rotating turbine

$$F = -\frac{1}{2} \alpha \rho u$$ (8)

rather than a 'quadratic law' commonly used to describe turbulent friction around static objects. The vector notation is used here to indicate the direction of the retarding force, and a new constant $\alpha = Const * A$ is introduced for brevity.

Mechanical power transferred from the flow to the turbine blades is given by the work done by the retarding force per unit time, e.g.(Hansen, 2008); using Eq.(6) one can get

$$P = \rho F u = \frac{1}{2} C_T \rho u^3 A \qquad (9)$$

The ability of a turbine to harness mechanical power of the flow is characterised by the power efficiency coefficient, C_p, defined as

$$C_p = \frac{2 P_E}{\rho u^3 A} \qquad (10)$$

where P_E is the electric output of the turbine e.g.(Hansen,2008). The generated electric power P_E is equal to the reduction of mechanical power of the flow P less small energy losses, so that from Eqs. (9) and (10) it follows that approximately $C_T \approx C_p$.

By multiplying Eq.(10) by u one can get that the linear law for the retarding force results in a quadratic law for the loss of kinetic energy of the flow and hence for electric power generation

$$P = \rho F u = \frac{dKE}{dt} = \frac{1}{2} \alpha \rho u^2 = -\alpha KE \approx P_E = \frac{1}{2} Const * \rho u^2 A \qquad (11)$$

Eq. (11) shows that energy extraction per unit volume is proportional to u^2 , and hence the power efficiency of a turbine relative to the flux of arriving kinetic energy, which is proportional to u^3 , see Eq. (2) , decreases with increasing flow.

Eq. (11) provides an alternative means for validating the linear 'friction' law Eq.(8) by using the power curve of a turbine, i.e. the graph of generated power versus the speed of the flow. An example in Fig.1(b) shows the power curve for a 1MW commercial wind turbine manufactured by LM Glasfiber A/S (Stiesdal et al, 1999). Observed values of generated power in the working range 2.5-14 m/s are accurately approximated by the quadratic dependence $P \sim u^2$ with the determination coefficient as high as $R^2 \sim 0.95$ hence confirming the linear relationship represented by Eq. (8).
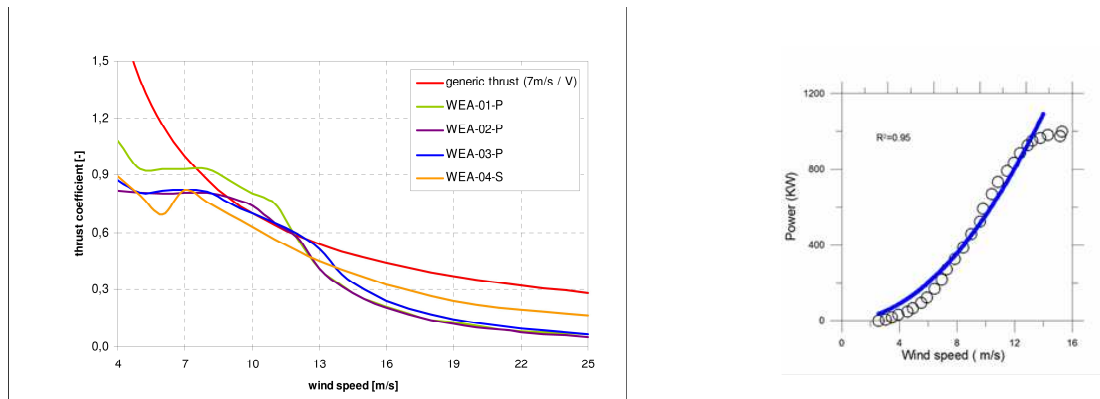
New Fig1. Thrust coefficient (left) and generated power (right) vs flow speed

COMMENT: 1793-16. The geometry of the farm seems rather awkward. The highest friction coefficients occur at the centre of the farm. Assuming that all turbines have equal efficiency, the friction coefficient reflects the density of turbines. It seems strange to put the higher density of turbines in the centre of the farm, where screening, as demonstrated in the numerical experiments, is quite strong. In my opinion, this work would greatly benefit from a more thorough study of how the farm geometry influences efficiency. The numerical simulations with POLCOMS demonstrate that the distribution of Rayleigh coefficients in the numerical experiments is probably far from optimal to achieve efficiency. Maybe the author could be persuaded to carry out a few additional experiments in which the impact of the spatial distribution of turbines (Rayleigh friction) on energy extraction is investigated. It is tempting to anticipate that a line of turbines oriented in a direction perpendicular to the tidal flow would often be the optimal arrangement.

RESPONSE: This paper shows the basic effects of the in-stream tidal farm on the shelf sea circulation, and it the does not aim at suggesting the best shape of the farm or other technical parameters as this a special topic and solution depends on a number of factors including those outside physical oceanography, such the cost of cabling, location of marine conservation zones, potential conflicts with other stakeholders etc. , which are well outside the scope of this paper. However, for the sake of comparison I have added a new figure, showing the disturbance of the residual flow and energy extraction by an elongated farm with the same rated power (i.e. same number of turbines) as the main farm. A short explanation is added to DISCUSSION. I agree that in the future the issue of optimisation of the layout of the tidal farm would attract as much attention as it does for the wind farms, see e.g. (A.Kusiak and Z. Song, Design of wind farm layout for maximum wind energy capture. Renewable Energy 35 (2010) 685–694, 2010.)
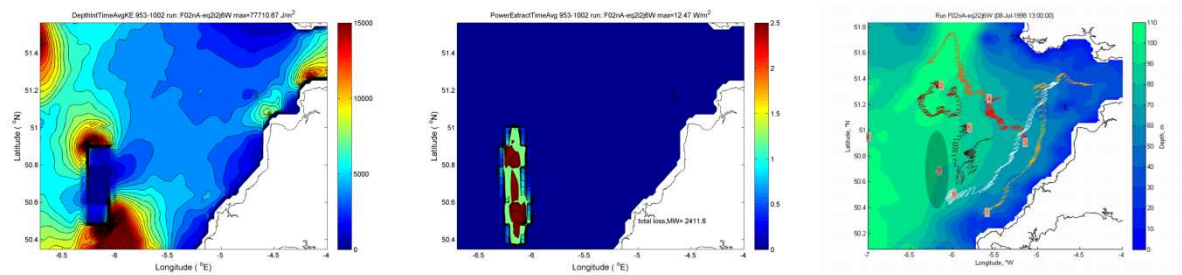
Fig.8. Effect of the farm shape on the main parameters of the flow. Left panel- kinetic energy per unit area (J/m^2); middle panel- mean extracted power in W/m^2; right panel - simulated trajectories of Lagrangean drifters drogued at 22.5 m depth, for a farm extended along the meridian. The rated capacity of the farm (i.e. the number of turbines) is the same as for high-rated circular farm shown in Figs (5)-(7).The shape of the farm is shown by a shaded oval on the right panel.

COMMENT: 1794-24. "...some springs are stronger than the other."?
RESPONSE: The ambiguous phrase removed.

COMMENT: 1794-25. Figure 3a. I would be more interested in seeing the kinetic energy integrated over the area where the tidal stream farm is going to be located.
RESPONSE: Spatial distribution of kinetic energy is shown in Fig.6a, from which the area averaged values can be derived. Time series of kinetic energy are very similar at various locations, differing mainly in the amplitude, which again can be derived from Fig.6a.

COMMENT: 1805. Figure 2. Please, indicate the location of the farm in this figure.
RESPONSE: Done as advised.

COMMENT: Figures 3, 5, 6 and 7. Text and numbers are tiny and not easy to read. Please, increase the size of the figures and the fonts.
RESPONSE: High quality figures will be uploaded at the production phase.