Authors response to reviewers

We would like to thank both reviewers for their constructive comments. The resulting document is clearer, and more complete. In the following, the reviewers' comments are reproduced, followed by our response and changes to the document in italics. We have also made a few minor additional changes described in the section Further Changes. A copy of the manuscript with tracked changes is included at the end.

Reviewer 1

Specific

Although the Pentland Firth has been leased by the Crown Estate for 800MW of installed capacity, I don't really believe that this number is likely any time soon. At the moment there is great talking over the potential for 8MW(ish) in the Meygen site. Is it really right to think that 800MW is realistic?

A: Time will tell. But investments in technology like this are only economically viable at sufficient scale. Analogy with the offshore wind industry, which is further advanced, suggests that it is possible. We do not think it is appropriate in this paper to speculate on how much capacity will ultimately be installed. We will add a remark to the introduction stating that for the purpose of this paper it is assumed that the 800 MW capacity will be realised.

Changes:

p. 20478, line 6: change sentence into:

Here, we assume that the licensed tidal power extraction in the Pentland Firth will be realised, and use a coupled hydrodynamics-biogeochemistry model to investigate the potential large-scale (hundreds to thousands of km) effects of on tides, currents, biogeochemistry and the planktonic and benthic ecosystem.

Pg 20484 - The 800MW is being uniformly distributed throughout the Pentland Firth and beyond. This is not what has been proposed with the main channel of the Firth actually being relatively empty and the consented sites being either near Orkney or near the main-land. Did you do this because you don't have the resolution to put them in their consented location, and what impact do you expect that this may have? I think that this would change the effective blockage ration of the channel in your model.

A: The reviewer is correct that the resolution is not sufficient. We agree that it's an omission not to state this in the paper, and will add a line to this effect, and come back to it in the discussion. Having said that the model does not show much of a response for the 800 MW case. It is not unreasonable to assume that a realisation of the hypothetical 8 GW implementation would occupy a substantial area of the Pentland Firth; we will also add a remark to this effect to the paper.

Changes:

p. 20484, line 6, add sentence:

A uniform distribution was chosen because the the shelf model does not resolve the licensed areas; moreover an 8 GW extraction would likely occupy a substantial proportion of the Pentland Firth.

p. 20490, line 16, add sentence:

It is likely that, for realistic cases, the results presented here would be modulated to some extent by the actual spatial distribution of tidal energy generation devices.

Pg 20485 - The differences in the reference runs speak about issues around water depths over several hundreds of metres, which if this refers to depth is surely outside the depth of the entire shelf. If it means horizontal length then it is not clear to me at all what you are trying to say.

A: The reviewer is correct that this refers to water depth, and applies to areas off the shelf. We will clarify the text.

Changes:

p. 20485, line 1, change sentence into:

Comparison of the reference run and the duplicate reference run indicated that results for water depths of more than several hundreds of metres (i.e. off the shelf edge, and to some extent in the Norwegian Channel) did not reproduce because of different realisations of stochastically driven eddy-type processes, and that some of these effects propagated onto the shelf, obscuring the effects of the tidal energy extraction.

Results of tide validation. The models tidal results are shown as a scatter plot which shows some issues with the model. These are explained to be issues with the Celtic Seas and thus can be safely ignores as the area around the Pentland Firth is OK. The issue though is that this paper is examining impacts at the far field extent and therefore the model must be reasonable in these far field areas. It would be helpful to see a plot of the tidal errors spatially rather than as a scatter plot only. The reader can then understand the potential tidal anomalies in the North Sea and beyond.

A: The reviewer has a point here. We did not include larger-scale versions of Figure 4, because showing such results on a single map would result in a cluttered and un-readable plot, and additional figures would add to the already large number of figures in this paper. We can, however, include an additional four-panel figure showing the difference in M2 tidal elevations and phases for the southern North Sea and for the Irish and Celtic Seas, and add some related text in the appropriate locations. The figures would show good correspondence in the southern North Sea. For the Irish and Celtic Seas, it would show over-estimation in the Bristol Channel and North Channel, and under-estimation in the Irish Sea, all in the order of up to several tens of cm.

Changes:

p. 20486, line 6: remove '(not shown)'

p. 20503, before Figure 5, insert new figure (see updated manuscript) and caption:

Figure 1. Spatial distribution of difference between model and observations of M2 tidal elevations. a) amplitude and b) phase for the southern North Sea; and c) amplitude and d) phase for the Irish and Celtic Seas. Blue circles: model smaller than observations; red circles: model larger than observations; grey circles: no data, or dry model grid cell at tide gauge location.

p. 20486, line 17, insert:

In the southern North Sea (Figure 20a) differences between modelled and observed M2 tidal elevations were typically within a few cm for offshore stations, and, with some exceptions, within 10 cm for coastal stations. M2 tidal phases (Figure 20b) were typically within 20 degrees. In the Celtic and Irish Seas (Figure 20c) differences between modelled and observed M2 tidal elevations ran up to several tens of cm, with over-estimations in the Bristol Channel and in the north around the southwestern Scottish islands, and under-estimations within the Irish Sea. M2 tidal phases (Figure 20d), with a few exceptions, were typically within 15 degrees.

Discussion on Tides - A good agreement of the hydrodynamic tidal model within the region of the Pentland Firth does not indicate suitability for examining the impacts of renewable energy across the far field scale. One might ask why the model is failing elsewhere, such as the Celtic Seas, and do these failure mechanisms come into play in the modified tidal system? Just because a model is in agreement with observation in one area does not make it suitable, necessarily, for use in other areas!

A: Agreed, we think this is a local issue limited to the Celtic Seas, see response and additions above.

Technical

Pg 20479, Line 13: "during the last decades" should be changed to either "last decade" or something like "previous few decades" depending on which you are referring to.

A: Agreed, we will make this clearer.

Changes:

p. 20479, l. 13, change sentence into:

The North Sea supports a high level of primary productivity, which has been augmented by varying and, since 1985, gradually reducing levels of anthropogenic riverine nutrient loads, and which depends on local SPM concentrations that affect the availability of light (e.g., Lenhart et al., 2010).

I assume model "confirmation" means validation?

A: This is a matter of definition, we have followed Oreskes, N., K. Shrader-Frechette, and K. Belitz (1994), Verification, validation, and confirmation of numerical models in the Earth sciences, Science, 263(5147), 641– 646, doi:10.1126/science.263.5147.641. We will add this reference.

Changes:

p. 20479, line 18, add sentence:

Note that we have followed the definitions of verification, validation and confirmation proposed by Oreskes et al. (1994).

p. 20496, line 5, add reference:

Oreskes, N., Shrader-Frechette, K., and Belitz, K.: Verification, validation, and confirmation of numerical models in the Earth sciences, Science 263(5147), 641– 646, doi:10.1126/science.263.5147.641, 1994.

Reviewer 2

The paper by J. van der Mole, P. Rurarij and N. Greenwood with the title "Potential environmental impact of tidal energy extraction in the Pentland Firth at large spatial scales: results of a biogeochemical model" is well written and provides up to date model expertise. The model study applies two scenarios in terms of marine renewable energy generation in the Pentland Firth by tidal turbines, a 800 MW and a 8 GW scenario. Of special interest are the far field implication of this local application of tidal energy extraction on the ecosystem of the North Sea and beyond. Therefore the manuscript should be published after minor revision.

Before going in any detail of the study it is necessary to define some of the terminology that is used. The expression "academic 8 GW study" might be misleading and, for my understanding, in consequence the results of the study are sold far below its practical value. The way I see it, the study should be evaluated as a kind of sensitivity study to test which response the North Sea ecosystem will show under a massive expansion of using tidal turbines. As described (noted) in the introduction a number of different forms of marine renewable energy production are under way to be implemented practically. Therefore it is highly relevant to test the system response for possible accumulation of one energy form first, before going into studies with combined forms of energy production.

A: This comment about terminology is a very good point, and something we've been to some extent struggling with. We have been looking for a balanced approach, in which we do not over-sell unrealistic results, as it is vital to keep an open dialogue with industry and regulators, while at the same time making the point that there may be effects on the system. Indeed, Reviewer 1 questions the likelyhood of achieving even the 800 MW scenario. Some of the wording that the *reviewer is suggesting is better than what we have used, so we will make appropriate changes to the document.*

Changes:

p. 20476, l. 4: change sentence:

A realistic 800 MW scenario and a high-impact scenario with massive expansion of tidal energy extraction to 8 GW scenario were considered.

p. 20476, l. 7, Change 'academic' into 'massive expansion'

p. 20478, l. 13, change sentence:

In order to put this into perspective, provide a crude estimate for extrapolation, and give an indication of a far-future scenario and/or potential cumulative effects with (as yet hypothetical) multiple other extraction schemes 'upstream' of the Pentland Firth, we also investigated an enhanced, and at the current state of technology purely academic massive-expansion scenario in which ten times the licensed amount of energy was extracted.

p. 20492, line 18, change sentence:

A broad area in the vicinity of The Wash appeared to be most sensitive to the massive-expansion 8 GW scenario.

In view of the fact that the paper deals with marine renewable energy production the sentence “As with any source of energy, energy in the atmosphere and marine environment is a finite resource, : : :” is misleading. As a matter of course the simple physical fact is correct, but if we follow the reasoning that renewable energy is beneficial in comparison with limited resources like oil or gas, then this formulation is not well worded.

A: This is indeed a statement that can be interpreted in a way which was not intended.

Changes:

p. 20476, line 21, change sentence into:

Energy in the atmospheric and marine environment is a resource that is not replenished immediately and at a local scale by solar or orbital sources, and is subject to physical conservation laws. Hence, extracting energy for human use leaves less energy remaining in the system, at least for some distance downstream of the extraction area.

The paper shows a very detailed validation for the parameters SPM, chlorophyll, silicate and nitrate for five individual Smart Buoy stations. As one can expect the selected parameters show differences compared to the measured time series. However, there is no general pattern apparent, like the model is always slightly overestimating chlorophyll or nitrate, but each site has its own local characteristics which makes it difficult to judge the overall behavior of the model on a wider scale. In addition, the results of the scenarios are only presented in horizontal maps. Concluding from these facts it would be good to see the validation also in a horizontal representation. This should at least be done for nitrate, and preferably also for chlorophyll or net primary production.

A: We agree that spatial validation is desirable and would be illustrative. Spatial validation of SPM concentrations with satellite observations is reported in Van der Molen, J., Ruardij, P., and Greenwood, N.: A 3D SPM model for biogeochemical modelling, with application to the northwest European continental shelf, J. Mar. Sci, submitted, 2016, and cannot be reproduced here; however we will add a reference. For Chlorophyll, we can include a similar comparison with remote sensing data. Nitrate concentrations cannot be observed by remote sensing, and a gridded product would rely on sparse in-situ observations. Very coarse climatologies are available from the World Ocean Atlas, but we do not think that this would provide much meaningful information here for the additional space and text that would be needed. Similarly, we are not aware of a gridded observations-based product for primary production.

Changes:

p. 20509, before Figure 11, add figure (see updated manuscript) and caption:

Figure 2. Comparison of modelled daily surface chlorophyll concentrations with daily chlorophyll composites from the MODIS satellite (Gohin et al., 2005; Gohin, 2011) for the

growing season from 1 March 2008 to 30 September 2008. a) Model growing-season average, b) satellite growing-season averaged, c) sub-sampled model growing-season average with cloudy pixels removed, d) number of clear days in the period according to the satellite, e) relative model bias compared to the satellite, f) correlation coefficient between model and satellite.

p. 20487, line 25, add:

To obtain an impression of how well the model captures temporal and spatial variations in chlorophyll concentrations, the modelled surface chlorophyll concentrations were compared with daily satellite-derived chlorophyll concentrations from the MODIS satellite (modis.gsfc.nasa.gov), obtained from the Ifremer ftp server (ftp.ifremer.fr.:/ifremer/cersat/products/gridded/ocean-color/atlantic, processed as described by Gohin et al. (2005) and Gohin (2011)) for the growing season of 2008 (Figure 27). Figure 27a presents the true model mean, and Figure 27b the satellite mean. The model results were sub-sampled to account only for clear days to obtain a less biased comparison with the satellite observations (Figure 27c); see Figure 27d for the number of clear days according to the satellite. Comparison of Figure 27a and c suggests that the satellite average may be an over-estimate of the true growing-season mean, possibly because of increased chlorophyll production during clear days and/or enhanced vertical mixing during cloudy (and most likely more windy) days. The bias in model chlorophyll as compared to the satellite (Figure 27e) suggested an over-estimate in coastal chlorophyll concentrations as well as in the area between the Dogger Bank and the continental coast, and slight under-estimates in more offshore areas. The correlation between model and satellite was generally positive (Figure 27f), with areas of poor performance in the Norwegean Trench, the Atlantic Ocean off the shelf edge, and in the area near the Dogger Bank that coincides with the over-estimates of the mean. Similar comparisons of SPM concentrations with satellite observations are available in Van der Molen et al (2016).

p. 20494, line 30, add references:

Gohin, F., Loyer, S., Lunven, M., Labry, C., Froidefond, J. M., Delmas, D., Huret, M., Herbland, A.: Satellite-derived parameters for biological modelling in coastal waters: Illustration over the eastern continental shelf of the Bay of Biscay, Rem. Sens. Env. 95, 29-46, 2005.

Gohin, F.: Annual cycles of chlorophyll-a, non-algal suspended particulate matter, and turbidity observed from space and in-situ in coastal waters, Ocean Sci. 7, 705-732, 2011.

For nitrate the additional suggestion is to show distribution of winter nitrate concentration rather than yearly averages, since it is the winter nitrate concentration that determines the spring bloom and therefore also the level of summer standing stock of chlorophyll.

A: We don't fully agree with the reviewer that 'the winter nitrate concentration [] determines the spring bloom and therefore also the level of summer standing stock of chlorophyll'. In addition to winter nitrate concentrations, the (magnitude and duration of) the spring bloom are also determined by the concentrations of other nutrients, the availability of light and grazing by zooplankton. Summer chlorophyll concentrations are determined by the summer concentrations of these factors. We agree that (changes in) seasonal dynamics are potentially interesting and important, but we don't think that going into this would add much to the main message of this paper, nor can we explore these within the space provided by this paper. Hence we think it's better to stick with the annual averages, and suggest the change below to make this clearer.

Changes:

p. 20484, line 27: change sentence and add sentence:

For the purpose of this paper, annual averages were calculated for all ecosystem variables for each scenario for each year, and differences with the reference run were calculated. Investigation of changes within seasons could be considered for further work.

In comparison to the detailed description of the model and the applied methods, the explanation of the results is rather sparse in its cause-effect presentation. For example, it would be interesting to explain why in the results of the current-induced bed-shear stress there is an area in both scenarios south of Ireland which still shows a reaction to the introduction of the tidal turbines. I understand that even a small implementation in the Pentland Firth which alters the current velocity and/or structure could lead to changes in the area of the English Channel as a reaction to an overall balance within the North Sea. But why this area in the south of Ireland should be effected is not clear to me. Even more, since there is no change appearing in the English Channel itself in the 800 MW scenario.

A: This is an interesting point. There are three elements to the answer: 1) a real (but small) change in the tides in the English Channel and southwestern approaches because the change in the tides in the North Sea changes the partial reflection condition that the Strait of Dover presents to that system; 2) the graphical representation: if the colour bins had been straddled around zero instead of coinciding with zero most of this area would have the same colour; 3) the filtering mechanism which has removed these small changes in the English Channel for the 800 MW scenario but let them through for the 8 GW scenario. At the extreme southwestern end the shelf edge is slightly more prominent probably because the strong spatial gradients make it a bit more senitive to changes.

Changes:

p. 20488, line 22, add sentence:

Furthermore, small changes were apparent in the English Channel up to the shelf edge, most likely due to the change in the partially reflecting boundary that the Straits of Dover present to this highly energetic tidal sub-system.

In the conclusion the sentence: " Beyond 800 MW, the current results suggest a linear far-field response of the tidal system, with associated changes to the marine ecosystem, and linear interpolation of the current results might be used as a crude first indication of potential effects" needs deeper explanation and maybe also correction. For my understanding it is extremely difficult to extract a linear relationship out of the two scenario results. I mentioned already the difference in the current-induced bed-shear stress where in the 8 GW scenario also the English Channel is affected. In contrast, for nitrate the effect in the 800 MW scenario disappears in the English Channel. So overall I do not see a simple linear increase when going from the results of the 800 MW towards the 8 GW scenario. There might be a crucial threshold value for the implementation which brings abrupt changes in the response of the presented parameters. Therefore I also commented already on the fact that the 8 GW scenario is no simple academic spinoff but provides important information on the response of the marine ecosystem.

A: We agree that this is probably an over-statement, and non-linearity is likely to show up if either this is looked into in more detail or the system is perturbed even more strongly. We will remove this element from the paper.

Changes:

p. 20488, line 22: ***remove*** *the sentence:*

Comparison of the two scenario's suggests that these changes were linear, with 10 times larger changes for the 8 GW scenario.

p. 20488, line 27: change sentence into:

For a large area centered around the Wash, where waters are shallow and shear stresses relatively large, these changes in bed-shear stress led to a reduction in annually-averaged surface SPM concentrations (Figure 30b,d,f).

p. 20492, line 15, ***remove*** *the sentence:*

Beyond 800MW, the current results suggest a linear far-field response of the tidal system, with associated changes to the marine ecosystem, and linear interpolation of the current results might be used as a crude first indication of potential effects.

One overall problem is the different simulation interval for the two models application. Since they are presented as an integral study for the two scenarios it is worthwhile to discuss in which way the two different simulation intervals can be seen as comparable in their overall representation of the North Sea. Therefore it is important to tell the reader if there are any constrains to be expected in the interpretation of the results when addressing the same scenarios for two different time intervals.

A: We are not sure what the reviewer is referring to here, there must be some confusion. Throughout the paper we consider one interval (2006-2008). Any earlier years were spin-up for the reference run and scenario runs. It is possible that the last sentences of section 3.4 have led to the confusion, these could be made clearer, see below.

Changes:

p. 20489, line 15, change sentences into:

All the results were presented for the last year of the three-year scenario runs, 2008, to allow the changes induced by introducing the turbines in January 2006 to become effective. The results were similar, however, to those found for 2006 and 2007 (not shown here for brevity), with the exception of a net air-to-sea CO_2 flux for 2006, which suggests a quick transition to a state with slightly higher carbon content.

Finally a technical

detail. For my understanding each figure should be self-explaining from its figure

caption. Therefore the description of most of the figures needs more care.

A: The reviewer does not provide much detail, but here are updated figure captions that should be clearer; note that these use the old numbering of the Discussion paper (i.e. not including the two new figures):

Figure 3. Scatter diagrams of difference of model results and observations for a) and b): M2 tidal elevation amplitudes and phases, c) and d) M2 tidal current speed ellipse semi-major axis and phase, and d) and e) M4 tidal elevation amplitudes and phases.

Figure 4. Spatial distribution of difference between model and observations of: M2 elevation amplitude (a) and phase (b); and : M4 elevation amplitude (c) and phase (d). Blue circles: model smaller than observations; red circles: model larger than observations; grey circles: no data, or dry model grid cell at tide gauge location.

Figure 5. Comparison of modelled tidal current speed in the Pentland Firth with ADCP observations (Gardline Surveys, 2001): a) ADCP 1, b) ADCP 2. Dots: observations, blue line: model results. For locations see Figure 2.

Figure 6. Comparison of model (blue line) with observations (red crosses), for the Warp Anchorage SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.

Figure 7. Comparison of model (blue line) with observations (red crosses), for the Liverpool Bay SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.

Figure 8. Comparison of model (blue line) with observations (red crosses), for the West Gabbard SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.

Figure 9. Comparison of model (blue line) with observations (red crosses), for the Oyster Grounds SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.

Figure 10. Comparison of model (blue line) with observations (red crosses), for the North Dogger SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.

Figure 11. Difference in tidal elevations between scenario run and reference run. a) M2 amplitude [m] and b) M4 amplitude [m] for the 800 MW extraction scenario. c) M2 amplitude [m] and d) M4 amplitude [m] for the 8 GW extraction scenario.

Figure 12. Difference in currents between scenario run and reference run. a) M2 tidal current ellipses and b) residual currents [cms^{-1}] for the 800 MW extraction scenario. c) M2 tidal current ellipses and d) residual currents [cms^{-1}] for the 8 GW extraction scenario.

Figure 13. a) annually averaged net primary production for 2008. b) annually averaged surface nitrate concentration for 2008. c) and d): changes in a) and b) for the 800 MW extraction scenario. e) and f): changes in a) and b) for the 8 GW extraction scenario. White areas were masked out.

Figure 14. a) annually averaged omnivorous mesozooplankton carbon biomass for 2008. b) annually averaged suspension feeder carbon biomass for 2008. c) and d): changes in a) and b) for the 800 MW extraction scenario. e) and f): changes in a) and b) for the 8 GW extraction scenario. White areas were masked out.

Figure 15. a) annually averaged benthic particulate organic carbon for 2008. b) annually averaged sea-surface CO_2 flux for 2008. c) and d): changes in a) and b) for the 800 MW extraction scenario. e) and f): changes in a) and b) for the 8 GW extraction scenario. White areas were masked out.

Further changes:

p. 20497, line 23, change into:

Van der Molen, J., Ruardij, P., and Greenwood, N.: A 3D SPM model for biogeochemical modelling, with application to the northwest European continental shelf, J. Mar. Sci, submitted, 2016.

Throughout paper: adjust figure numbers to reflect the additional two figures.

Updated references in the manuscript in line with the corrections made as part of the typesetting of the discussion paper.

p. 20481, l. 15, add sentence:

Boundary conditions for nutrients are taken from the World Ocean Atlas monthly climatology (Garcia et al., 2010).

p. 20494, l. 24, add reference:

Garcia, H. E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., Zweng, M.M., Baranova, O.K., and Johnson, D.R.: World Ocean Atlas 2009, Volume 4: Nutrients (phosphate, nitrate, silicate). S. Levitus, Ed. NOAA Atlas NESDIS 71, U.S. Government Printing Office, Washington, D.C., 398 pp., 2010.

Potential environmental impact of tidal energy extraction in the Pentland Firth at large spatial scales: results of a biogeochemical model

J. van der Molen[1], P. Ruardij[2], N. Greenwood[1,3]

[1]{The Centre for Environment, Fisheries and Aquaculture Science (Cefas), Lowestoft, UK}

[2]{Royal Netherlands Institute for Sea Research (NIOZ), Den Burg (Texel), The Netherlands}

[3]{School of Environmental Sciences, University of East Anglia, Norwich, UK}

Abstract

A model study was carried out of the potential large-scale (>100 km) effects of marine renewable tidal energy generation in the Pentland Firth, using the 3D hydrodynamics-biogeochemistry model GETM-ERSEM-BFM. A realistic 800 MW scenario and a~~n~~ ~~exaggerated academic~~high-impact scenario with massive expansion of tidal energy extraction to 8 GW scenario were considered. The realistic 800 MW scenario suggested minor effects on the tides, and undetectable effects on the biogeochemistry. The ~~academic~~ massive-expansion 8 GW scenario suggested effects would be observed over hundreds of kilometres away with changes of up to 10% in tidal and ecosystem variables, in particular in a broad area in the vicinity of The Wash. There, waters became less turbid, and primary production increased with associated increases in faunal ecosystem variables. Moreover, a one-off increase in carbon storage in the sea bed was detected. Although these first results suggest positive environmental effects, further investigation is recommended of: i) the residual circulation in the vicinity of the Pentland Firth and effects on larval dispersal using a higher resolution model; ii) ecosystem effects with (future) state-of-the-art models if energy extraction substantially beyond 1 GW is planned.

1 Introduction

1.1 Background

Techniques to generate marine renewable energy are maturing, with wind turbines currently being installed in hundreds to thousands, first commercial models of tidal energy generators becoming available, with wave-energy generators not far behind and macro-algae farming at field-testing research stage. ~~As with any source of energy, e~~Energy in the atmospheric and marine environment is a ~~finite~~ resource that is not replenished immediately and at a local scale by solar or orbital sources, and is subject to physical conservation laws. Hence, extracting energy for human use ~~by definition~~ leaves less energy remaining in the system, at least for some distance downstream of the extraction area. As a result, if applied in large farms with hundreds of devices, marine renewable energy extraction has the potential to noticeably alter the local and regional hydrography, and through that influence the marine ecosystem. Potential effects on the physical marine environment include changes in tidal currents, residual circulation, wave climate, bed-shear stress and associated transport of materials, turbulence, turbidity, water temperature, salinity and stratification, and noise levels. Knock-on effects on the biological marine environment could include changes in nutrient and plankton transport (including larval stages), changes in primary production, changes in food availability and feeding and migration behavior, and resulting changes in species composition and distribution. All of these potential effects, including many others, have been identified in a series of review studies (Gill, 2005; Cada et al., 2007; Boehlert and Gill, 2010; Frid et al., 2012; Kadiri et al., 2012; Hooper and Austen, 2013). Whereas effects on the local hydrodynamics are often investigated as part of the design procedure, potential larger scale effects on the hydrodynamics and in particular the ecosystem are largely unknown, although the first studies are starting to emerge (see Neil et al., 2009 for tidal turbine effects on sediment dynamics in the Bristol Channel; Wolf et al., 2009 for effects of multiple tidal barrages in the Irish sea; Defne et al, 2011 for tidal energy extraction on estuarine hydrodynamics in Georgia, USA; Shapiro, 2011 for a hypothetical tidal farm in the Celtic Sea; Ahmadian and Falconer, 2012 for effects of tidal turbines on the hydrodynamics in the Bristol Channel; Aldridge et al., 2012 for a hypothetical macro-algae farm in the north-western North Sea; and van der Molen et al., 2014 for a hypothetical wind farm in the North Sea). These studies found a varying degree of potential impacts, depending on the location, the extraction technique and (subset of) processes under investigation and the models and assumptions used. These first results, combined with increasing (inter)national legislation to regulate the anthropogenic use of the marine environment (eg., the Marine Strategy Framework Directive (European Commission, 2008) to promote healthy and productive seas), indicate that more should be done to investigate the effects of marine renewable energy extraction on the environment, including combined effects of large-scale extractions and interactions with other economic activities such as fishing, and climate change to ensure that marine renewable energy extraction can be carried out in a sustainable way. As the scales of extraction increase, and various farms/extraction schemes start to interact with one-another, more knowledge will become increasingly necessary.

Recently, the Crown Estate has licensed areas in the Pentland Firth and around the Orkney Islands for tidal and wave energy generation (The Crown Estate, 2013). Shields et al. (2009) outlined gaps in the knowledge on ecological impacts of tidal energy extraction in the Pentland Firth. Here, we assume that the licensed tidal power extraction in the Pentland Firth will be realised, and use a coupled hydrodynamics-biogeochemistry model to investigate the potential large-scale (hundreds to thousands of km) effects of ~~the licensed tidal power extraction in the Pentland Firth~~ on tides, currents, biogeochemistry and the planktonic and benthic ecosystem. In order to put this into perspective, provide a crude estimate for extrapolation, and give an indication of a far-future scenario and/or potential cumulative effects with (as yet hypothetical) multiple other extraction schemes 'upstream' of the Pentland Firth, we also investigated an enhanced, and at the current state of technology purely academic~~,~~ massive-expansion scenario in which ten times the licensed amount of energy was extracted. More detailed, local effects, including array optimization for combinations of criteria including power yield, cost and environmental effects, were investigated as part of the same project by Funke et al. (2014) and Martin-Short et al. (2015).

1.2 Study area

The shelf to the west and north of the UK (Figure 16) is typically one to several hundreds of km wide, and has a depth of 100-200 m. The Celtic and Irish Seas separate Ireland from the mainland of the UK, and the English Channel separates the UK from the continent in the south. The North Sea to the east of the UK has typical depths of over 100 m in the north, and less than 50 m in the south. The North-west European shelf, and in particular the North Sea, support a high biological production, but are at the same time used heavily for a range of economic activities including shipping, fishing, oil and gas extraction, pipe lines, and aggregate extraction, while also containing a large number of marine protected areas of various types (see, e.g., Paramor et al., 2009, OSPAR, 2010).

The Pentland Firth is a narrow strait situated between main-land Scotland and the Orkney Islands. It has a maximum water depth of 80 m in the main channel, and tidal current speeds in excess of 3 ms^{-1} (see Easton et al., 2012 for details on the tides in Pentland Firth). It serves as a conduit for some of the tidal energy propagating as Kelvin waves in a clockwise direction on the North-west European continental shelf along the Atlantic coasts of the UK, around the north of Scotland, into the North Sea, down the east coast of the UK and across to the coasts of the Netherlands, Germany, Denmark and Norway (see, eg., Holt et al., 2001). Also, some of the residual flows into the North Sea enter through the Pentland Firth. Within the North Sea, the tides interact with the topography, wave climate and river runoff to create a range of stratification and mixing conditions (Pingree et al., 1978; van Leeuwen et al., 2015), and sea bed disturbance and transport mechanisms (van der Molen, 2002; Aldridge et al., 2015). The North Sea supports a high level of primary productivity, which~~, during the last decades, ~~ has been augmented by varying and, since 1985, gradually reducing levels of anthropogenic riverine nutrient loads, and which depends on local SPM concentrations that affect the availability of light (e.g., Lenhart et al., 2010).

For five sites (Figure 16), time-series observations of biogeochemical variables from SmartBuoy (Greenwood et al., 2010) were used for model confirmation (Section 3.2). Note that we have followed the definitions of verification, validation and confirmation proposed by Oreskes et al. (1994). Site 1, Warp Anchorage, is situated in well-mixed conditions at 15 m water depth in a channel in the Thames Estuary. Site 2, Liverpool Bay, is situated in intermittently stratified, river-influenced conditions (e.g., Verspecht et al., 2009) at 23 m water depth in the eastern Irish Sea, and forms part of the Liverpool Bay Coastal Observatory (http://cobs.pol.ac.uk/cobs). Site 3, West Gabbard, is situated in well-mixed conditions in 32 m water depth in the southern bight of the North Sea. Site 4, Oyster Grounds, was situated in mostly seasonally stratified waters in 45 m water depth. Site 5, North Dogger, was situated in seasonally stratified waters in 80 m water depth. Sites 4 and 5 were studied extensively as part of the Marine Ecosystem Connections programme (see Painting and Foster, 2013 and references therein).

2 Methods

2.1 SmartBuoy

SmartBuoys are instrumented moorings deployed to make high frequency measurements of physical, chemical and biological variables (Mills et al. 2005) which are published online (https://www.cefas.co.uk/publications-data/smartbuoys/). SmartBuoys have been deployed in UK and Dutch waters as components of monitoring programmes designed to meet the needs of international legislation such as the Marine Strategy Framework Directive and within specific research projects. SmartBuoys were configured to determine turbidity, chlorophyll fluorescence, salinity, temperature and dissolved oxygen and data processed according to Greenwood et al. (2010). Concentrations of suspended particulate matter and chlorophyll were derived from measurements of turbidity and chlorophyll fluorescence respectively (Greenwood et al. 2010).

Discrete samples were collected on all SmartBuoys using an automated Aquamonitor and subsequently analysed for TOxN (total oxidisable nitrogen) and silicate according to Gowen et al (2008). In addition on Warp, West Gabbard, Liverpool Bay and North Dogger, TOxN was determined using an automated in situ NAS-2E or NAS-3X nutrient analyser. Daily mean values were calculated from all data which passed the quality assurance process. All SmartBuoys in this study were operational for the whole period apart from North Dogger which was deployed between February 2007 and September 2008.

2.2 North-west European Shelf setup for GETM-ERSEM

The 3D hydrodynamic model GETM (General Estuarine Transport Model, www.getm.eu; Burchard & Bolding, 2002) solves the shallow-water, heat balance and density equations. It uses GOTM to solve the vertical dimension. For the current work, GETM was run on a spherical grid covering the area 46.4°N-63°N, 17.25°W-13°E with a resolution of 0.02° longitude and 0.05° latitude (approximately 5 km), and 25 non-equidistant layers in the vertical. The model bathymetry was based on the NOOS bathymetry (www.noos.cc/index.php?id=173). At this resolution, the Pentland Firth is resolved by several model grid cells, which cannot reproduce local detail, but should be sufficient to study the potential far-field effects of tidal energy extraction. The model was forced with tidal constituents derived from TOPEX-POSEIDON satellite altimetry (LeProvost et al., 1998), atmospheric forcing from the ECMWF ERA-40 and Operational Reanalysis (ECMWF, 2006a,b), interpolated river runoff from a range of observational data sets (the National River Flow Archive (www.ceh.ac.uk/data/nrfa/index.html) for UK rivers, the Agence de l'eau Loire-Bretagne, Agence de l'eau Seine-Normandie and IFREMER for French rivers, the DONAR database for Netherlands rivers, ARGE Elbe, the Niedersächsisches Landesamt für Ökologie and the Bundesanstalt für Gewässerkunde for German rivers, and the Institute for Marine Research, Bergen, for Norwegian rivers; see also Lenhart et al., 2010), and depth-resolved temperature- and salinity boundary conditions from ECMW-ORAS4 (Balmaseda et al., 2013; Mogensen et al., 2012; http://www.ecmwf.int/products/forecasts/d/charts/oras4/reanalysis/). Boundary conditions for nutrients are taken from the World Ocean Atlas monthly climatology (Garcia et al., 2010).

The ERSEM-BFM (European Regional Seas Ecosystem Model - Biogeochemical Flux Model) version used here (19-02-2015) is a development of the model ERSEM III (see Baretta et al., 1995; Ruardij and Van Raaphorst, 1995; Ruardij et al., 1997; Vichi et al., 2003; Vichi et al., 2004; Ruardij et al., 2005; Vichi et al., 2007; Van der Molen et al., 2013; van der Molen et al., 2014; www.nioz.nl/northsea_model), and describes the dynamics of the biogeochemical fluxes within the pelagic and benthic environment. The ERSEM-BFM model simulates the cycles of carbon, nitrogen, phosphorus, silicate and oxygen and allows for variable internal nutrient ratios inside organisms, based on external availability and physiological status. The model applies a functional group approach and contains five pelagic phytoplankton groups, four main zooplankton groups and five benthic faunal groups, the latter comprising four macrofauna and one meiofauna groups. Pelagic and benthic aerobic and anaerobic bacteria are also included. The pelagic module includes a number of processes in addition to those included in the oceanic version presented by Vichi et al. (2007) to make it suitable for temperate shelf seas: (i) a parameterisation for diatoms allowing growth in spring, (ii) enhanced transparent exopolymer particles (TEP) excretion by diatoms under nutrient stress, (iii) the associated formation of macro-aggregates consisting of TEP and diatoms, leading to enhanced sinking rates and a sufficient food supply to the benthic system especially in the deeper offshore areas (Engel, 2000), (iv) a *Phaeocystis* functional group for improved simulation of primary production in coastal areas (Peperzak et al., 1998), (v) a pelagic filter-feeder larvae stage, and (vi) benthic diatoms, including resuspension, transport and pelagic growth. The suspended particulate matter (SPM) module, containing contributions by waves and currents, and included for improved simulation of the under-water light climate, has been developed further compared to the version used by van der Molen et al. (2014). It now includes full 3D transport, according to formulations similar to the method of van der Molen et al. (2009), but uses only one SPM fraction subject to a concentration-dependent settling velocity to parameterise the effects of multiple grain sizes for computational efficiency (van der Molen et al., ~~in prep.~~2016). An experimental method to include resuspension of particulate organic matter as a proportion of the SPM resuspension is also included.

2.3 Model implementation of tidal turbines

For each grid cell in the model that contained tidal turbines, an additional frictional sink term S_f was applied to the u- and v-momentum equations, respectively, throughout the water column, using the mechanisms introduced in GETM by Rennau et al. (2012):

$$S_{f,u} = C_{d,t} u \sqrt{\left(u^2 + v^2\right)}, \quad S_{f,v} = C_{d,t} v \sqrt{\left(u^2 + v^2\right)} \qquad (1)$$

where u and v are the depth-averaged horizontal velocity components in the longitudinal and latitudinal directions, respectively. The coefficient for the additional friction induced by the tidal turbines $C_{d,t}$ was calculated as (Stefan Kramer, pers. comm., 2014):

$$C_{d,t} = \tfrac{1}{2} N C_{thr} \frac{\frac{\pi}{4} D_{rotor}^2}{dxdyH} \qquad (2)$$

where dx and dy the local grid spacing in the longitudinal and latitudinal direction, respectively, in m, H the local instantaneous water depth, N the number of rotors (note that, depending on the make and type, a tidal energy generation device can consist of multiple rotors) in the grid cell, C_{thr} the non-dimensional thrust coefficient of each rotor, and D_{rotor} the rotor diameter. For this work, we have assumed Triton 3 Tidal Stream Generators (3 rotors of 1MW each per device, D_{rotor}=20 m), and have assumed a typical value C_{thr}=0.6 (note that in reality, thrust coefficients tend to vary depending on operating conditions).

2.4 Model experiments

Because of differences in response times, and different requirements for model output, separate sets of model runs were carried out to study the effects on tidal propagation and biogeochemistry, respectively.

2.4.1 Tidal propagation

The hydrodynamics model was run from 1 January 1997 to 30 June 2001 from initial conditions consisting of a cold start for tides, and 3D temperature and salinity fields derived from ECMW-ORAS4. Subsequently, it was run for 6 months storing hourly fields, which were subjected to tidal harmonic analysis, resolving a residual, 5 diurnal, 11 semi-diurnal, and 5 shallow-water constituents for elevations and depth-averaged velocity components in the longitudinal and latitudinal directions.

The M_2 tidal constituents were compared with data from tide gauges and current meters from Jones (1983), Gjevik and Straume (1989), Smithson (1992), MARIS (pers. comm., 1998), FRV (pers. comm., 1998), Young et al. (2000), Jones and Davies (2007), and Easton et al. (2012) (see Figure 16 for locations). In addition, time series of flow velocities within the Pentland Firth were compared with ADCP observations (Gardline Surveys, 2001), supplied originally from the Maritime and Coastguard Agency through the Environmental Research Institute and Heriot Watt University (see also Dillon, 2007), see Figure 17 for locations.

Subsequently, two model scenarios with tidal energy extraction were run: one scenario using a uniform distribution of the planned energy extraction within the Pentland Firth (800 MW as currently proposed, The Crown Estate, 2013), see Figure 17, and a similar scenario extracting 8 GW. A uniform distribution was chosen because the the shelf model does not resolve the licensed areas; moreover an 8 GW extraction would likely occupy a substantial proportion of the Pentland Firth. Harmonic analysis was carried out on these results, and the difference with the reference scenario was mapped for i) the M_2 constituent to assess the main impact on overall tidal propagation, ii) the M_4 constituent to assess the main impact on tidal asymmetry and potential effects on the transport of particulate material with a non-zero settling velocity, and iii) on the residual velocity to assess the potential effects on the transport of particulate and dissolved material.

2.4.2 Biogeochemistry

The coupled hydrodynamics-biogeochemical model was run for three years: 2006-2008 (reference run). These years were chosen because of the availability of validation data, and to assess the potential of longer-term accumulation of the potential effects of tidal energy extraction. Longer runs would have been desirable, but were not possible with the financial and computational resource available. The spin-up period covered 2000-2005, with minor fixes to improve model stability applied in January 2004. The biogeochemistry state at the start of the spin-up period was taken from the end results of a run with an earlier, very similar model version covering 1995-2008. Model confirmation of this reference run consisted of a time-series comparison with SmartBuoy observations at 5 sites representing different hydrographic conditions, involving nutrient concentrations, SPM concentrations and chlorophyll concentrations (Greenwood et al., 2010). As nitrite concentrations are usually small, we compared modelled nitrate with observed TOxN. Subsequently, three scenario runs were carried out for 2006-2008: a duplicate reference run, and the 800 MW and 8 GW tidal energy extraction scenarios. For the purpose of this paper, ~~A~~annual averages were calculated for all ecosystem variables for each scenario for each year, and differences with the reference run were calculated. Investigation of changes within seasons could be considered for further work. Comparison of the reference run and the duplicate reference run indicated that results for water depths ~~over~~ of more than several hundreds of metres (i.e. off the shelf edge, and to some extent in the Norwegian Channel) did not reproduce because of different realisations of stochastically driven eddy-type processes, and that some of these effects propagated onto the shelf, obscuring the effects of the tidal energy extraction. To remove these, the 800 MW and 8 GW scenarios were filtered by, for each ecosystem variable, applying the following mask to each of the wet points in the model:

$$M = \left[\frac{|D_s|}{|D_R|} > T_1 \right] \& \left[\left| \nabla \frac{D_R}{|R|} \right| < T_2 \right] \qquad (3)$$

Here, the mask M gets a value of 0 or 1, D_S is the difference of the scenario and the reference run, D_R the difference of the reference runs, R the value of the reference run, T_1=2.0 and T_2=1.0 empirical thresholds (the values of which were determined by trial and error), and ∇ a gradient operator taking the magnitude of the local spatial gradient scaled by the horizontal grid-averaged value of the wet points. Essentially, this filter removes cells with a small scenario difference compared with the difference between the reference runs, and cells where the spatial variability of the difference of the reference runs is high. We acknowledge that this filtering method is relatively crude, and that it could be improved either by taking (multi-)decadal averages, or by using means and standard deviations derived from a sufficiently large number of realisations of the reference run. However, these methods would involve a computational effort far beyond the resources available for this project. We are confident that the cheap method applied here is effective enough to support the results presented in this paper.

As renewable energy generation is, among others, done to reduce CO_2 emissions, and carbon cycling is an important element of the marine ecosystem, we also looked at effects on CO_2 uptake from the atmosphere, and particulate carbon storage in the sea bed.

3 Results

3.1 Tidal model confirmation

Scatter plots of the difference between model and observations at the tide gauge and current-meter locations (Figure 16, Figure 18) showed reasonable agreement for many stations. A substantial number of stations showed substantial differences; these are located mostly within the Irish Sea ~~(not shown)~~. M_2 elevation amplitudes typically agreed within 20 cm, but with high scatter for amplitudes over 2 m. M_2 phases typically agreed within 30 degrees. M_2 current meter amplitudes (magnitude of the semi-major axis of the current ellipse; exclusively from the Irish and Celtic seas, Figure 16) mostly agreed within 15 cms^{-1}, with phases within 30 degrees. M_4 tidal elevation amplitudes were mostly within 5 cms^{-1} of the observations, with high scatter and a suggestion of under-prediction for amplitudes above 5 cms^{-1}. M_4 phases were mostly within 50 degrees.

Considering the spatial distribution of the differences between model and observations in the area of interest around northern Scotland (Figure 19), M_2 elevation amplitudes were mostly within a few cm, and M_2 phases were within a few degrees. M_4 elevation amplitudes were also within a few cm, but M_4 phase differences were substantial, and negative in the west, and positive in the east. In the southern North Sea (Figure 20a) differences between modelled and observed M2 tidal elevations were typically within a few cm for offshore stations, and, with some exceptions, within 10 cm for coastal stations. M2 tidal phases (Figure 20b) were typically within 20 degrees. In the Celtic and Irish Seas (Figure 20c) differences between modelled and observed M2 tidal elevations ran up to several tens of cm, with over-estimations in the Bristol Channel and in the north around the southwestern Scottish islands, and under-estimations within the Irish Sea. M2 tidal phases (Figure 20d), with a few exceptions, were typically within 15 degrees.

Modelled current speeds at the ADCP locations (Figure 21) were more or less in phase with the observations. At ADCP site 1, the modelled difference between peak flood and ebb currents was substantially smaller than observed, with the model more or less reproducing the ebb currents, and underestimating flood currents. At ADCP site 2, the observed asymmetry between flood and ebb currents was much smaller than at site 1, and the model reproduced the currents very well.

3.2 Biogeochemical model confirmation

For SmartBuoy site 1 (Warp Anchorage, Figure 16), the seasonal cycle in SPM concentrations (Figure 22a) was reproduced by the model, but peak concentrations were over-estimated, probably because the buoy is in a sheltered position behind a sand bank that the model cannot resolve. Chlorophyll concentrations (Figure 22b) were represented well with good low winter concentrations, a slight early onset of the spring bloom, good representation of peak concentrations, and under-estimated autumn bloom values. Nutrient concentrations (Figure

22c,d) were overestimated substantially by the model, in particular in winter. This is an artifact of the newly introduced organic matter resuspension mechanism, which buries too much material in the coastal zone. This will be addressed in a subsequent model version.

At SmartBuoy site 2 (Liverpool Bay, Figure 16), SPM concentrations (Figure 23a) were slightly under-predicted. Chlorophyll concentrations (Figure 23b) were represented well. In similarity to Smartbuoy site 1, (winter) nutrient concentrations (Figure 23c,d) were substantially over-predicted.

At SmartBuoy site 3 (West Gabbard, Figure 16), peak concentrations of SPM (Figure 24a) were over-predicted, but with good representation of the seasonal cycle. Chlorophyll concentrations (Figure 24b) were represented well, but with under-estimation of the maximum spring bloom in two out of the three years. Nutrient concentrations (Figure 24c,d) were represented reasonably well.

Smartbuoy site 4 (Oyster Grounds, Figure 16) showed good seasonality but an over-estimate in peak SPM concentrations (Figure 25a), good representation of chlorophyll except for an over-estimate of spring-bloom values (Figure 25b), and good representation of nutrient concentrations (Figure 25c,d).

Winter SPM concentrations (Figure 26a) at Smartbuoy site 5 (North Dogger, Figure 16) were over-estimated, while chlorophyll concentrations (Figure 26b) were reasonable. Winter nutrient concentrations (Figure 26c,d) were approximately half the observed values.

To obtain an impression of how well the model captures temporal and spatial variations in chlorophyll concentrations, the modelled surface chlorophyll concentrations were compared with daily satellite-derived chlorophyll concentrations from the MODIS satellite (modis.gsfc.nasa.gov), obtained from the Ifremer ftp server (ftp.ifremer.fr.:/ifremer/cersat/products/gridded/ocean-color/atlantic, processed as described by Gohin et al. (2005) and Gohin (2011)) for the growing season of 2008 (Figure 27). Figure 27a presents the true model mean, and Figure 27b the satellite mean. The model results were sub-sampled to account only for clear days to obtain a less biased comparison with the satellite observations (Figure 27c); see Figure 27d for the number of clear days according to the satellite. Comparison of Figure 27a and c suggests that the satellite average may be an over-estimate of the true growing-season mean, possibly because of increased chlorophyll production during clear days and/or enhanced vertical mixing during cloudy (and most likely more windy) days. The bias in model chlorophyll as compared to the satellite (Figure 27e) suggested an over-estimate in coastal chlorophyll concentrations as well as in the area between the Dogger Bank and the continental coast, and slight under-estimates in more offshore areas. The correlation between model and satellite was generally positive (Figure 27f), with areas of poor performance in the Norwegean Trench, the Atlantic Ocean off the shelf edge, and in the area near the Dogger Bank that coincides with the over-estimates of the mean. Similar comparisons of SPM concentrations with satellite observations are available in Van der Molen et al (2016).

3.3 Effects on tides

For the 800 MW scenario, differences in tidal elevations with the reference scenario were very small (Figure 28). M_2 elevation amplitudes (Figure 28a) were up to 1 cm higher to the west of the Pentland Firth, and a few mm smaller along the east coast of the UK down to East Anglia. M_4 elevation amplitudes (Figure 28b) were a few mm smaller within the Pentland Firth, and up to 1 mm higher in Moray Firth. For the 8 GW scenario, M_2 elevation amplitudes (Figure 28c) were up to 8 cm higher to the west of the Pentland Firth, and up to 4 cm lower along the east coast of the UK. M_4 elevation amplitudes (Figure 28d) were up to 3 cm smaller within the Pentland Firth, and up to 1 cm higher in the Moray Firth.

Considering currents (Figure 29), for the 800 GW scenario, M_2 currents (Figure 29a) changed by up to 2 cms^{-1} within the Pentland Firth, and by only a few mms^{-1} elsewhere. Changes in residual velocities (Figure 29b) were up to 3 cms^{-1} in the Pentland Firth, and very small elsewhere. For the 8 GW scenario, M_2 currents (Figure 29c) were similar within the Pentland Firth, and up to 10 cms^{-1} different on either side of the Pentland Firth. Changes in residual velocities (Figure 29d) were up to 10 cms^{-1} in the immediate vicinity of the Pentland Firth, and up to 5 cms^{-1} at considerable distance away from the Pentland Firth.

3.4 Effects on biogeochemistry and ecosystem

The model detected increases in annually-averaged current-induced bed-shear stress around the Orkney's for both the 800 MW scenario (Figure 30c) and the 8 GW scenario (Figure 30e) (see Figure 30a for the results of the reference run). Moreover, reductions in shear stress were detected all along the UK east coast, with largest reductions in the vicinity of the Wash. For the 8 GW scenario, an increase was detected in the Straits of Dover. Furthermore, small changes were apparent in the English Channel up to the shelf edge, most likely due to the change in the partially reflecting boundary that the Straits of Dover present to this highly energetic tidal sub-system. ~~Comparison of the two scenario's suggests that these changes were linear, with 10 times larger changes for the 8 GW scenario.~~ For this scenario, depending on the location, the changes ran up to 10% of the reference scenario. For a large area centered around the Wash, where waters are shallow and shear stresses relatively large, these changes in bed-shear stress led to a reduction in annually-averaged surface SPM concentrations ~~with similar linear characteristics~~ (Figure 30b,d,f). For the 8 GW scenario, this reduction in SPM concentration led to higher primary production in the light-limited area around the Wash as shown in Figure 31a,e. This was caused mainly by an increase in diatoms and phaeocystis colonies (not shown). Associated with this increase was a decrease in annually averaged nutrient concentrations, shown here for nitrate (Figure 31b,f). Similar changes were not detected for the 800 MW scenario (Figure 31c,d). Pelagic and benthic fauna profited from the increase in production in the 8 GW scenario, as shown here for omnivorous mesozooplankton and suspension feeders (Figure 32a,b,e,f). The zooplankton also showed increase biomass further north along the UK coast. This was also evident in the 800 MW scenario (Figure 32c), whereas suspension feeders did not show a response (Figure 32d). The reduced bed-shear stress also induced an increase in annually averaged particulate organic carbon in the sea bed in a wide area centered around the Wash for the 8 GW scenario (Figure 33a,e). Again, nothing was detected for the 800 MW scenario (Figure 33c). For the sea-surface CO_2 flux, some spatial changes were suggested for both scenario's (Figure 33b,d,f), but no clear net change. All the~~se~~ results were presented for the last year of the three-year scenario runs, 2008, to allow the changes induced by introducing the turbines in January 2006 to become effective. The results were ~~S~~similar, however, to those ~~results were~~ found for 2006 and 2007 (not shown here for brevity), with the exception of a net air-to-sea~~award~~ CO_2 flux for 2006, which suggests a quick transition to a state with slightly higher carbon content. In addition to the results presented here, numerous other model variables were investigated, but none showed significant changes not related to the mechanisms presented here.

4 Discussion and conclusions

4.1 Tides

The good agreement of the model with observed tidal characteristics in the area around Scotland, and in particular with the ADCP observations within the Pentland Firth, indicated that the model is suitable to study the large-scale effects of tidal energy extraction in the Pentland Firth. The difference in tidal asymmetry between the two adcp's suggests that local bathymetry plays an important role in these observations. Such differences cannot be expected to be picked up by a model of the resolution used. However, increasing the resolution would make the model too costly if run with a biogeochemistry model. For a very high-resolution study of tidal turbines in part of the Pentland Firth, see Martin-Short et al. (2015).

The model results for the 800 MW scenario suggested that far-field effects on tidal elevations, currents and residual circulation would be negligible, and would most likely not be measurable. The model results for the 8 GW scenario suggested measurable changes in the Pentland Firth and Orkneys area, and along most of east coast of the UK. This change in the tidal system is equivalent with more radical results reported by Wolf et al. (2009) for power generation with multiple barrage systems in the Irish Sea. Changes in transport pathways should be expected within the Pentland Firth and its approaches for suspended and dissolved materials due to the changes in residual flows, and in the Morray Firth for bed-load materials due to the increase in tidal asymmetry; similar effects of tidal stream generators on a smaller, local scale were suggested by Neil et al. (2009) and Ahmadian and Falconer (2012). It is likely that, for realistic cases, the results presented here would be modulated to some extent by the actual spatial distribution of tidal energy generation devices. The difference in the response of the M_2 tidal currents within the Pentland Firth between the two scenarios suggests a change to complete friction-dominated conditions in the 8 GW scenario, resulting in only small changes in tidal velocities within the Pentland Firth as the energy extracted is compensated for by increased tidal surface elevation differences between the two ends of the channel. This result suggests that, as far as the response of the local tidal system within the Pentland Firth is concerned, large amounts of tidal energy can potentially be harvested without reducing the effectiveness of individual turbines by a reduction in overall current speeds. This result contrasts with that found by Shapiro (2011) for a farm at open sea, where the tidal flow progressively evaded the farm area with increasing power extraction.

The changes in tidal amplitude along the east coast of the UK suggest that local, high-resolution model studies of the impact of tidal energy devices should include sufficiently large spatial scales (in this case up to a few thousands of km) to prevent boundary conditions from affecting the results, either by i) using large-scale models with local grid refinement, ii) two-way nested models, or iii) one-way nested models with inclusion of the energy extraction at all nest levels.

4.2 Biogeochemistry

The model results for SPM, chlorophyll, nitrate and silicate corresponded well with time-series observations from 5 stations situated in very different hydrographic conditions. The exception was winter-nutrient concentrations in the near-shore locations, which were over-estimated. As the most dominant effects of the tidal energy extraction scenarios were in a very turbid area where phytoplankton growth is light-limited, this artifact is not expected to affect the main results of this study.

For the 800 MW scenario, as was to be expected from the minor changes in tidal conditions, and apart from coherent minor changes in bed-shear stress and SPM concentrations along the (central and southern parts of) the UK east coast, the biogeochemical model did not demonstrate clear differences with the reference scenario.

For the 8 GW scenario, changes in ecosystem variables of up to 10% were simulated in a substantial area in the vicinity of The Wash. The mechanism was through reduced bed-shear stress, reduced SPM concentrations and increased light availability, leading to increased primary production, secondary production and benthic biomass. This mechanism has also been identified in earlier studies on potential and observed effects of tidal barrages (Radford and Ruardij, 1987; Kadiri et al., 2012; Hooper and Austen, 2013). These studies focused on the local scale, however, making direct comparison and contrasting of barrage and tidal stream methods difficult because the present study does not resolve the local scales in detail. For some ecosystem variables, changes also occurred further north along the coast. In terms of carbon cycling, we found a minor increase in particulate carbon content in the sea bed in the area associated with the increase in productivity. This increase was most likely caused primarily by a combination of increased production of detrital material, improved hydrodynamic conditions for settling of particulates, and a reduction in current-induced resuspension relative to the amount of detritus in the sediments (the absolute resuspension and settling rates increased, but to a smaller proportion than the content of detritus in the sediments). Aerobic benthic bacterial biomass also increased in the model, so the increase in particulate carbon in the sea bed was probably reduced by an increase in bacterial decomposition. It is possible that changes in bioturbation associated with the increase in benthic biomass also influenced the balance, but information on this activity was not stored. This increase in benthic particulate organic carbon content appeared to be a one-off, acquired as the system adjusted in the first year of the scenario simulation, and did not change substantially in the subsequent two years.

4.3 Concluding remarks

The model did not detect significant changes for the currently licensed energy extraction of 800 MW, with potential exception of residual currents in the vicinity of the Pentland Firth. These need to be investigated further, at higher resolution, and in conjunction with particle tracking to assess potential effects on larval dispersal and recruitment. ~~Beyond 800 MW, the current results suggest a linear far-field response of the tidal system, with associated changes to the marine ecosystem, and linear interpolation of the current results might be used as a crude first indication of potential effects.~~ A broad area in the vicinity of The Wash appeared to be most sensitive to the massive-expansion 8 GW scenario. The model results indicated an increase in productivity. Local fisheries could benefit, in particular of shell fish and crustaceans. A limited, one-off increase in carbon storage in the sea bed was simulated, which could be regarded as an additional positive contribution to mitigating CO_2-induced climate change. However, the authors are of the opinion that further investigations of far-field effects would be advisable if tidal energy extraction was planned beyond the currently licensed 800 MW, or if substantial additional tidal energy extraction were planned at other sites along the coast, as the effects of multiple sites are likely to interact (Wolf et al., 2009). Moreover, interactions with climate change and potential effects of other marine renewable energy generation schemes should be investigated.

Acknowledgements

This research was financially supported by EPSRC grant EP/J010065/1. The model development was funded by Cefas Seedcorn projects DP261 and DP315. Claire Coughlan, while at JRC (Ispra), created the open-boundary forcing for temperature, salinity and nutrients. The SmartBuoy data were collected in projects A1228, AE004 and SLA25 funded by Defra as part of the National Eutrophication Monitoring Programme. The SmartBuoy in Liverpool Bay forms part of the Liverpool Bay Coastal Observatory (www.cobs.pol.ac.uk) coordinated by the Proudman Oceanographic Laboratory. ECMWF and BADC are thanked for making the atmospheric forcing available.

References

Ahmadian, R., and Falconer, R.A.: Assessment of array shape of tidal stream turbines on hydro-environmental impacts and power output, Ren. Energy. 44, 318-327, 2012.

Aldridge, J., van der Molen, J. and Forster, R.: Wider ecological implications of Macroalgae cultivation, The Crown Estate, Edinburgh, London, 95 pp. ISBN: 978-1-906410-38-4, 2012.

Balmaseda M.A., Mogensen, K., and Weaver, A.: Evaluation of the ECMWF Ocean Reanalysis ORAS4, Q. J. R. Meteorol. Soc. 139, 1132-1161, DOI:10.1002/qj.2063, 2013.

Baretta, J.W., Ebenhöh, W., and Ruardij, P.: The European Regional Seas Ecosystem Model, a complex marine ecosystem model, Neth. J. Sea Res. 33, 233-246, 1995.

Boehlert, G. and Gill, A.: Environmental and ecological effects of ocean renewable energy development: A current synthesis, Oceanography 23, 68-81, 2010.

Burchard, H., and Bolding, K.: GETM – a general estuarine transport model, Scientific documentation, Tech. Rep. EUR 20253 EN, European Commission, Ispra, Italy, 2002.

Cada, G., Ahlgrimm, J., Bahleda, M., Bigford, T., Stavrakas, S., Hall, D., Moursund, R. and Sale, M.: Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments, Fisheries 32(4), 174-180, 2007.

Defne, Z., Haas, K.A., and Fritz, H.M.: Numerical modelling of tidal currents and the effect of power extraction on estuarine hydrodynamics along the Georgia coast, USA, Ren. Energy 36, 3461-3471, 2011.

Dillon, L. J.: Tidal energy in the Pentland Firth, Scotland: High Resolution Mapping using GIS techniques, MSc Thesis, University of Aberdeen, Aberdeen, 2007.

Easton, M.C., Woolf, D.K., and Bowyer, P.A.: The dynamics of an energetic tidal channel, the Pentland Firth, Scotland, Cont. Shelf Res. 48, 50-60, 2012.

Engel, A.: The role of transparent exopolymer particles (TEP) in the increase in apparent particle stickiness (α) during the decline of a diatom bloom, J. Plankton Res. 22, 485-497, 2000.

European Centre for Medium-Range Weather Forecasts: Assimilated Data from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis program, NCAS British Atmospheric Data Centre, http://catalogue.ceda.ac.uk/uuidf6ce34fc/c462480467660a36d9b10a71 (last access: January 2012), 2006b.

European Centre for Medium-Range Weather Forecasts: European Centre for Medium-Range Weather Forecasts (ECMWF) 40-year Re-Analysis (ERA-40) model data, NCAS British Atmospheric Data Centre, http://catalogue.ceda.ac.uk/uuid/775634f7e339b5262067e28a5d7b679d (Last access: July 2007), 2006a.

European Commission: Establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive), Directive 2008/56/EC, Strassbourg, 2008.

Frid, C., Andonegi, E., Depestele, J., Judd, A., Rihan, D., Rogers, S.I., and Kenchington, E.: The environmental interactions of tidal and wave energy generation devices, Environ. Impact Assess. ~~Rev.~~ 32, 133-139, 2012.

Funke, S.W., Farrell, P.E., and Piggot, M.D.: Tidal turbine array optimisation using the adjoint approach, Ren. Energy 63, 658-673, 2014.

Gardline Surveys: Pentland Firth – Tidal Stream Observations, Report Produced for the Navigation Safety Branch of the Maritime and Coastguard Agency, Contract NBSA5B/2959, Gardline, Great Yarmouth, UK, 57pp, 2001.

Garcia, H. E., Locarnini, R.A., Boyer, T.P., Antonov, J.I., Zweng, M.M., Baranova, O.K., and Johnson, D.R.: World Ocean Atlas 2009, Volume 4: Nutrients (phosphate, nitrate, silicate). S. Levitus, Ed. NOAA Atlas NESDIS 71, U.S. Government Printing Office, Washington, D.C., 398 pp., 2010.

Gill, A.: Offshore renewable energy: Ecological implications of generating electricity in the coastal zone, J. Appl. Ecol. 42, 605-615, 2005.

Gjevik, B., and Straume, T.: Model simulations of the M2 and the K1 tide in the Nordic Seas and the Arctic Ocean, Tellus 41A, 73-96, 1989.

Gohin, F., Loyer, S., Lunven, M., Labry, C., Froidefond, J. M., Delmas, D., Huret, M., Herbland, A.: Satellite-derived parameters for biological modelling in coastal waters: Illustration over the eastern continental shelf of the Bay of Biscay, Rem. Sens. Env. 95, 29-46, 2005.

Formatted: Indent: Left: 0 cm, First line: 0 cm

Gohin, F.: Annual cycles of chlorophyll-a, non-algal suspended particulate matter, and turbidity observed from space and in-situ in coastal waters, Ocean Sci. 7, 705-732, 2011.

Formatted: German (Germany)

Gowen, R.J., Tett, P., Kennington, K., Mills, D.K., Shammon, T.M., Stewart, B.M., Greenwood, N., Flanagan, C., Devlin, M., and Wither, A.: The Irish Sea: Is it eutrophic? Estuarine, Coastal and Shelf Science 76(2) 239-254, 2008.

Greenwood N., Parker E.R., Fernand L., Sivyer D.B., Weston K., Painting S.J., Kröger S., Forster R.M., Lees H.E., Mills D.K., and Laane R.W.P.M.: Detection of low bottom water oxygen concentrations in the North Sea; implications for monitoring and assessment of ecosystem health, Biogeosci 7, 1357-1373, 2010.

Holt, J.T., James, I.D., and Jones, J.E.: An s coordinate density evolving model of the northwest European continental shelf, part 2, Seasonal currents and tides, J. Geophys. Res. 106, 14035-14053, 2001.

Hooper, T., and Austen, M.: Tidal barrages in the UK: ecological and social impacts, potential mitigation, and tools to support barrage planning, Ren. sust. energy rev. 23 289-298, 2013.

Jones, J.E., and Davies, A.M.: On the sensitivity of computed higher tidal harmonics to mesh size in a finite element model, Cont. Shelf Res. 27, 1908-1927, 2007.

Jones, J.E.: Charts of the O1, K1, N2, M2, and S2 tides in the Celtic Sea including M2 and S2 tidal currents, Institute of Oceanographic Sciences, NERC, Report 169, Wormley, UK, 59pp, 1983.

Kadiri, M., Ahmadian, R., Bockelmann-Evans, B., Rauen, W., and Falconer, R.: A review of the potential water quality impacts of tidal renewable energy systems. Ren. sust. energy rev. 16, 329-341, 2012.

Le Provost C., Lyard F., Genco M.L., and Rabilloud F.: A hydrodynamic ocean tide model improved by assimilation of a satellite altimeter-derived data set, J. Geophys. Res, 103, C3, 5513-5529, 1998.

Lenhart, H.J., Mills, D.K., Baretta-Bekker, H., van Leeuwen, S.M., van der Molen, J., Baretta, J.W., Blaas, M., Desmit, X., Kühn, W., Lacroix, G., Los, H.J., Ménesguen, A., Neves, R., Proctor, R., Ruardij, P., Skogen, M.D., Vanhoutte-Grunier, A., Villars, M.T., and Wakelin, S.L.: Predicting the consequences of nutrient reduction on the eutrophication status of the North Sea, J. Mar. Syst., 81, 148-170, 2010.

Martin-Short, R., Hill, J., Kramer, S.C., Advis, A., Allison, P.A., and Piggott, M.D.: Tidal resource extraction in the Pentland Firth, UK: Potential impacts on the flow regime and sediment transport in the Inner Sound of Stroma, Ren. Energy 76, 596-607, 2015.

Mills, D.K., Greenwood, N., Kröger, S., Devlin, M., Sivyer, D.B., Pearce, D., Cutchey, S., and Malcolm, S.J.: New Approaches to Improve the Detection of Eutrophication in UK Coastal Waters, Env. Res., Eng. and Management, 2(32), 36-42, 2005.

Mogensen, K., Alonso Balmaseda, M., and Weaver, A.: The NEMOVAR ocean data assimilation system as implemented in the ECMWF ocean analysis for System4, ECMWF Thechnical Memorandum 668, Toulouse, France, 59 pp., 2012.

Neill, S.P., Litt, E.J., Couch, S.J., and Davies, A.G.: The impact of tidal stream turbines on large-scale sediment dynamics, Ren. Energy 34, 2803-2812, 2009.

Oreskes, N., Shrader-Frechette, K., and Belitz, K.: Verification, validation, and confirmation of numerical models in the Earth sciences, Science 263(5147), 641– 646, doi:10.1126/science.263.5147.641, 1994.

OSPAR: Quality status report 2010, Ospar Commision, London, 176 pp., ISBN 978-1-907390-38-8, http://qsr2010.ospar.org (last access: December 2015), 2010.

Painting, S.J., and Forster, R.M.: Marine Ecosystem Connections: essential indicators of healthy, productive and biologically divers seas, Biogeochem. 113, 1-7. DOI: 10.1007/s10533-013-9838-0, 2013.

Paramor, O.A.L., Allen, K.A., Aanesen, M., Armstrong, C., Hegland, T., Le Quesne, W., Piet, G.J., Raakær, J., Rogers, S., van Hal, R., van Hoof, L.J.W., van Overzee, H.M.J., and Frid C.L.J.: (2009) MEFEPO North Sea Atlas, University of Liverpool, Liverpool, ISBN 0 906370 60 4, 2009.

Peperzak, L., Colijn, F., Gieskes, W.W.C. and Peeters, J.C.H.: Development of the diatom-Phaeocystis spring bloom in the Dutch coastal zone of the North Sea: the silicon depletion versus the daily irradiance threshold hypothesis, J. Plankt. Res. 20, 517-537, 1998.

Pingree, R.D., Holligan, P.M., and Mardell, G.T.: The effects of vertical stability on phytoplankton distributions in the summer on the northwest European Shelf, Deep Sea Res. 25, 1011-1028, 1978.

Radford, P.J., and Ruardij, P.: The validation of ecosystem models of turbid estuaries, Cont. Shelf Res. 7, 1483-7, 1987.

Rennau, H., Schimmels, S., and Burchard, H.: On the effect of structure-induced resistance and mixing on inflows into the Baltic Sea: a numerical model study, Coast. Eng. 60, 53-68, 2012.

Ruardij, P., and van Raaphorst, W.: Benthic nutrient regeneration in the ERSEM-BFM ecosystem model of the North Sea, Neth. J. Sea Res. 33, 453-483, 1995.

Ruardij, P., van Haren, H., and Ridderinkhof, H.: The impact of thermal stratification on phytoplankton and nutrient dynamics in shelf seas: a model study, J. Sea Res. 38, 311-331, 1997.

Ruardij, P., Veldhuis, M.J.W., and Brussaard, C.P.D.: Modeling the bloom dynamics of the polymorphic phytoplankter *Phaeocystis globosa:* impact of grazers and viruses, Harmf. Alg. 4, 941-963, 2005.

Shapiro, G.I.: Effect of tidal stream power generation on the region-wide circulation in a shallow sea, Ocean Sci. 7, 165-174. DOI 10.5194/os-7-165-2011, 2011.

Shields, M.A., Dillon, L.J., Wolff, D.K. and Ford, A.T.: Strategic priorities for assessing ecological impacts of marine renewable energy devices in the Pentland Firth (Scotland, UK), Mar. Policy 33(4)L, 635-642, 2009.

Smithson, M.J.: Pelagic tidal constants - 3. IAPSO Publication Scientifique No.35, Published by the International Association for the Physical Sciences of the Ocean (IAPSO) of the International Union of Geodesy and Geophysics, 191pp, 1992.

The Crown Estate: Pentland Firth and Orkney Waters Strategic Area Review Project, 8pp., www.thecrownestate.co.uk/media/5446/pfow-strategic-area-review-project-2012.pdf (last access: December 2015), 2013.

Van der Molen, J., Aldridge, J.N., Coughlan, C., Parker, E.R., Stephens, D., and Ruardij, P.: Modelling marine ecosystem response to climate change and trawling in the North Sea, Biogeochem. 113, 213-236, DOI 10.1007/s10533-012-9763-7, 2013.

Van der Molen, J., Bolding, K., Greenwood, N., and Mills, D.K.: A 1-D vertical multiple grain size model of suspended particulate matter in combined currents and waves in shelf seas, J. Geophys. Res. 114, F01030, doi:10.1029/2008JF001150, 2009.

Van der Molen, J., Ruardij, P., and Greenwood, N.: A 3D SPM model for biogeochemical modelling, with application to the northwest European continental shelf, J. Mar. Sci, submitted, 2016.

~~Van der Molen, J., Ruardij, P., and Greenwood, N.: A 3D SPM model for biogeochemical modelling. Manuscript in preparation.~~

Van der Molen, J., Smith, H.C.M., Lepper, P., Limpenny, S., and Rees, J.: Predicting the large-scale consequences of offshore wind array development on a North Sea ecosystem, Cont. Shelf Res. 85, 60-72I 10.1016/j.csr.2014.05.018, 2014.

Van der Molen, J.:, The influence of tides, wind and waves on the sand transport in the southern North Sea, Cont. Shelf Res., 22, 2739-2762, 2002.

van Leeuwen, S.M., Tett, P., Mills, D.K., and van der Molen, J.: Stratified and nonstratified areas in the North Sea: long-term variability and biological and policy implications, J. Geophys. Res. Oceans 120, 4670-4686, DOI: 10.1002/2014JC010485, 2015.

Verspecht, F., Rippeth, T.P., Howarth, M.J., Souza, A.J., Simpson, J.H., and Burchard, H.: Processes impacting on stratification in a region of freshwater influence: application to Liverpool Bay, J. Geophys. Res. Oceans 114 C11022, DOI: 10.1029/2009JC005475, 2009.

Vichi M., Oddo, P., Zavatarelli, M., Coluccelli, A., Coppini, G., Celio, M., Fonda Umani, S., and N. Pinardi: Calibration and validation of a one-dimensional complex marine biogeochemical flux model in different areas of the northern Adriatic Sea, Annales Geophysicae, 21, 413-436, 2003.

Vichi, M., Pinardi, N., and Masina, S.: A generalized model of pelagic biogeochemistry for the global ocean ecosystem. Part I: Theory, J. Mar. Syst. 64, 89-109, 2007.

Vichi, M., Ruardij, P., and Baretta, J.W.: , Link or sink: a modelling interpretation of the open Baltic biogeochemistry, Biogeosci. 1, 79-100. SRef-ID: 1726-4189/bg/2004-1-79, 2004.

Wolf, J., Walkington, I.A., Holt J., and Burrows R.: Environmental impacts of tidal power schemes, Proc. Inst. Civil Eng-Marit Eng. 162, 165–77, 2009.

Young, E.F., Aldridge, J.N., and Brown, J.: Development and validation of a three-dimensional curvilinear model for the study of fluxes through the North Channel of the Irish Sea, Cont. Shelf Res. 20, 997-1035, 2000.

Formatted: Indent: Left: 0 cm, First line: 0 cm

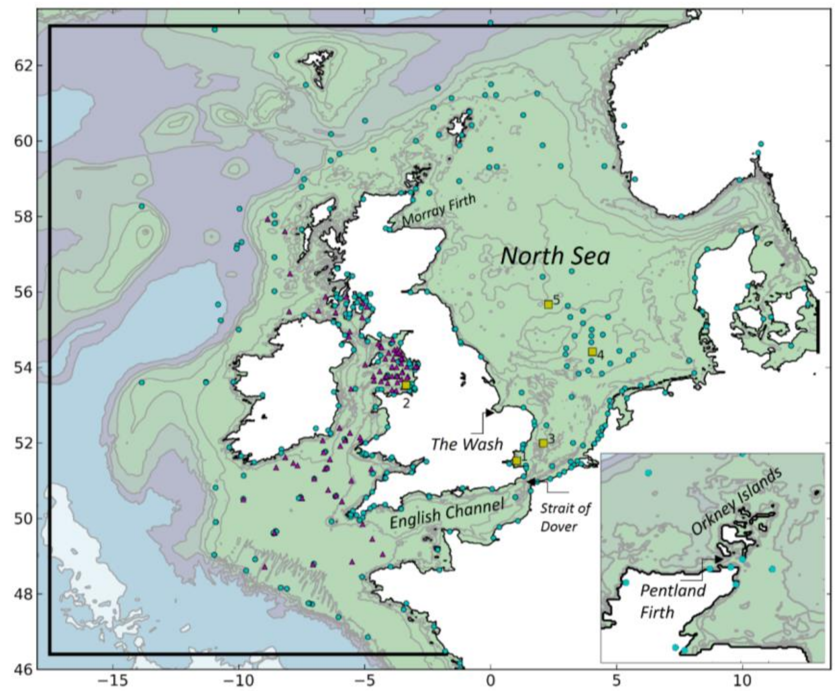

Figure 16. Model area (thick line) with tide gauge (green circles), current meter (purple triangles) stations and SmartBuoy stations (yellow squares; 1: Warp Anchorage, 2: Liverpool Bay, 3: West Gabbard, 4: Oyster Grounds, 5: North Dogger). Depth contours: 25, 40, 80, 150, 300, 600, 1200, 2400, 4800 m. Inset: Pentland Firth area.

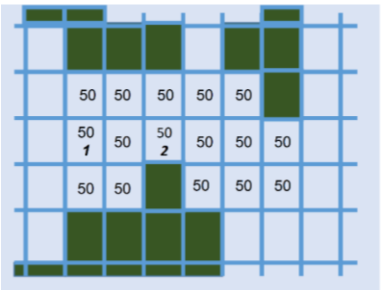

Figure 17. Model grid in the Pentland Firth, with uniform distribution of 800 MW tidal power extraction (numbers in MW). Bold, italic numbers indicate the grid cells coinciding with the ADCP locations. Green coloured cells are land.

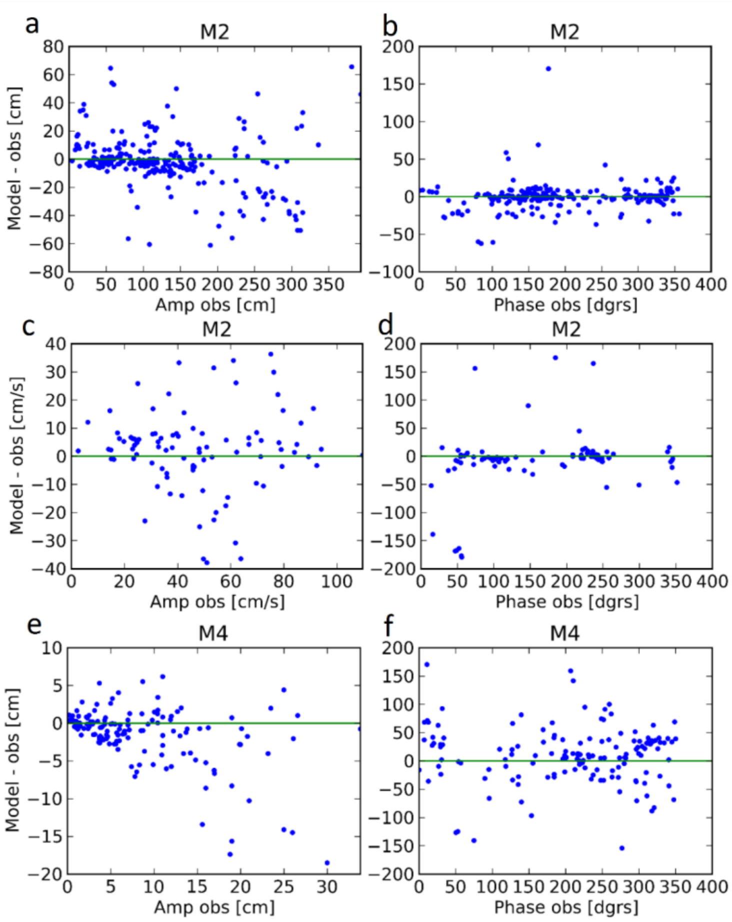

Figure 18. Scatter diagrams of difference of model results and observations for ~~Comparison of~~ a) and b): ~~modelled~~ M2 tidal elevation ~~constituent with tide gauge data~~amplitudes and phases, c~~b~~) and d) ~~modelled~~ M2 tidal current speed ellipse semi-major axis and phase~~with current meter data~~, and d~~e~~) and e) ~~modelled~~ M4~~4~~ ~~with tide gauge data~~tidal elevation amplitudes and phases.

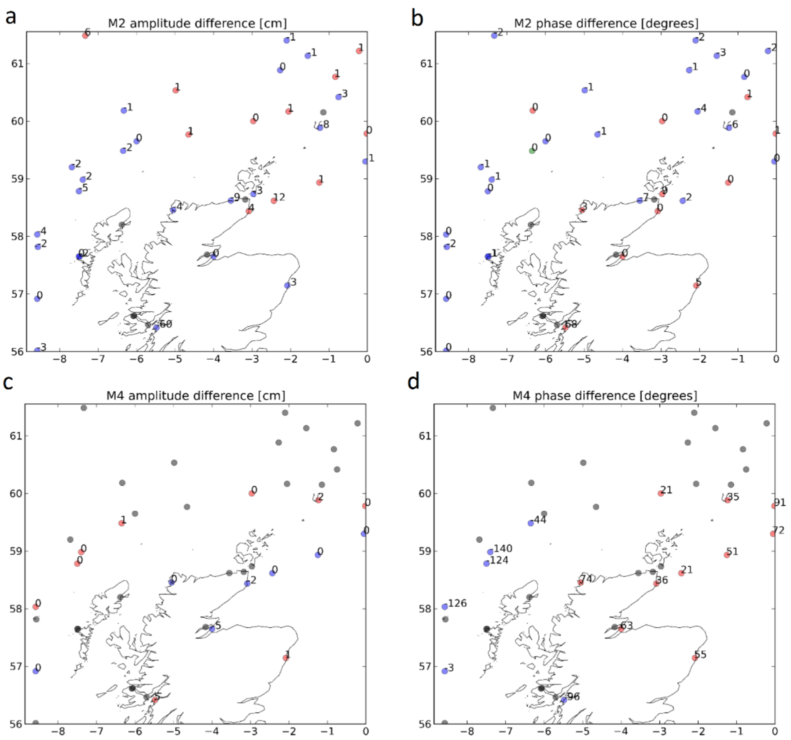

Figure 19. Spatial distribution of difference between model and observations of ~~top~~: M2 elevation amplitude (a) and phase (b); and ~~bottom~~: M4 elevation amplitude (c) and phase (d). Blue circles: model smaller than observations; red circles: model larger than observations; grey circles: no data, or dry model grid cell at tide gauge location.

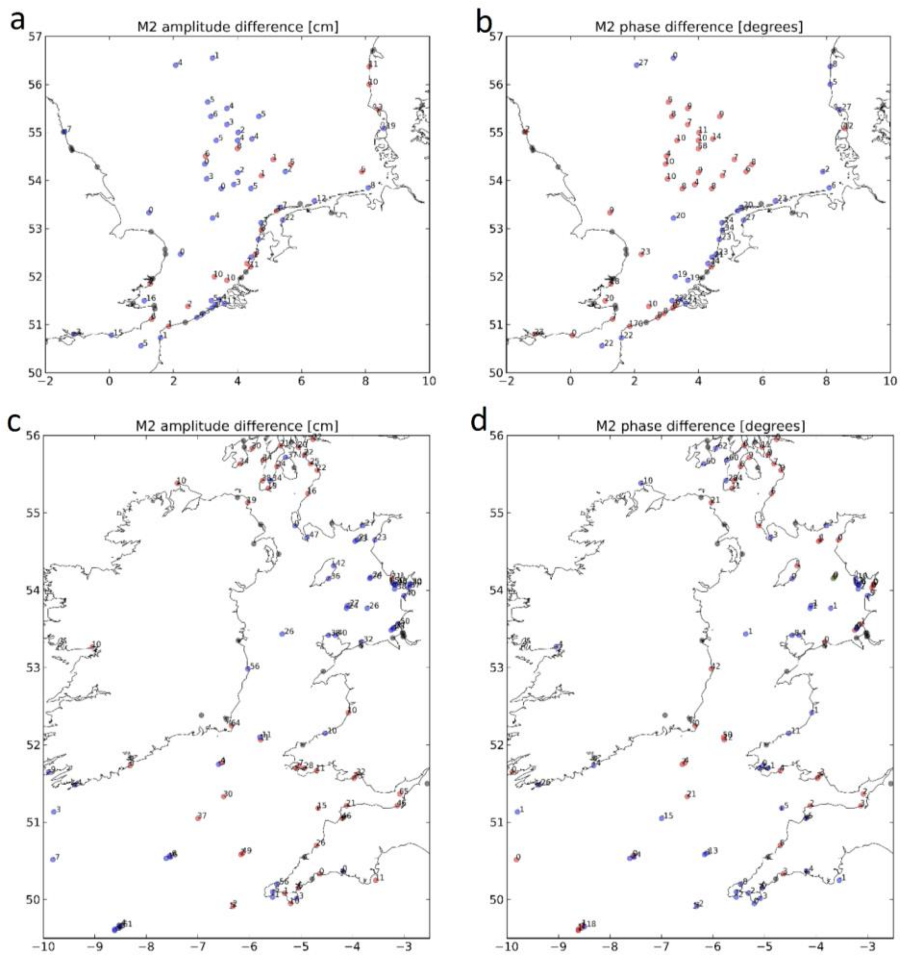

Figure 20. Spatial distribution of difference between model and observations of M2 tidal elevations. a) amplitude and b) phase for the southern North Sea; and c) amplitude and d) phase for the Irish and Celtic Seas. Blue circles: model smaller than observations; red circles: model larger than observations; grey circles: no data, or dry model grid cell at tide gauge location.

Formatted: Keep with next

Formatted: English (United Kingdom)

Formatted: Caption, Justified

Formatted: English (United Kingdom)

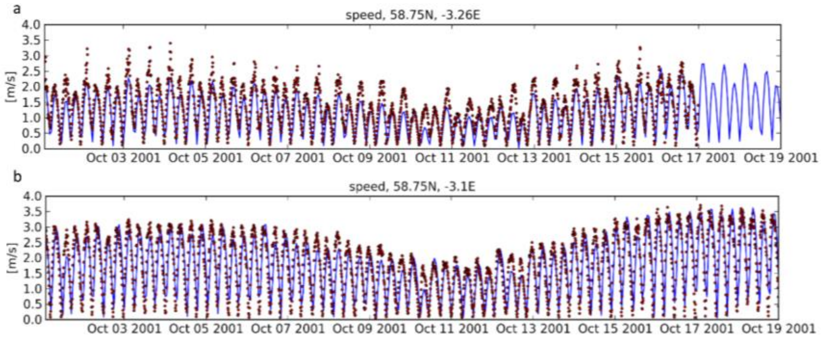

Figure 21. Comparison of modelled tidal current speed~~s~~ in the Pentland Firth with ADCP observations (Gardline Surveys, 2001): a) ADCP 1, b) ADCP 2. Dots: observations, blue line: model results. For locations see Figure 17.

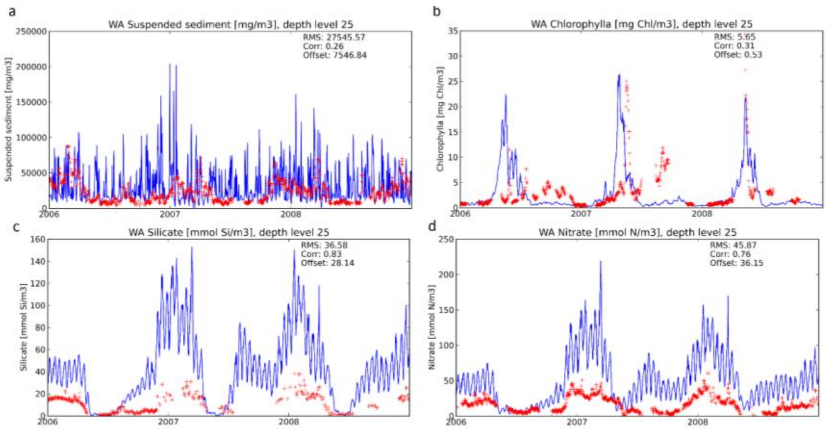

Figure 22. Comparison of model (blue line) with observations (red crosses), for the Warp Anchorage SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.

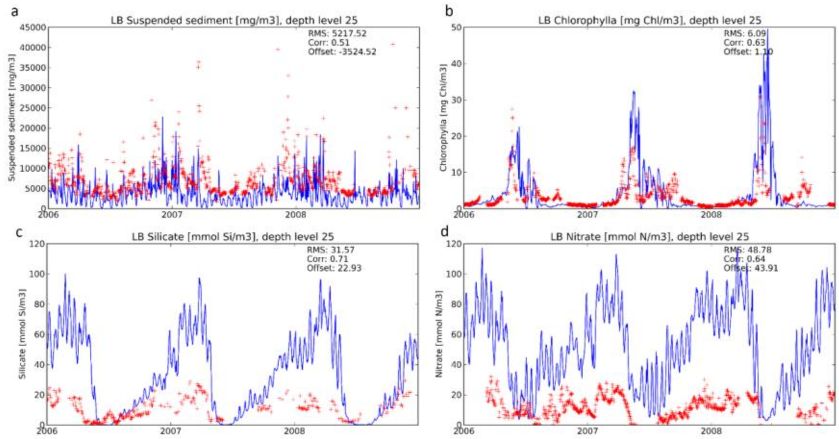

Figure 23. Comparison of model (blue line) with observations (red crosses), for the Liverpool Bay SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.~~As Figure 6, but for Liverpool Bay SmartBuoy.~~

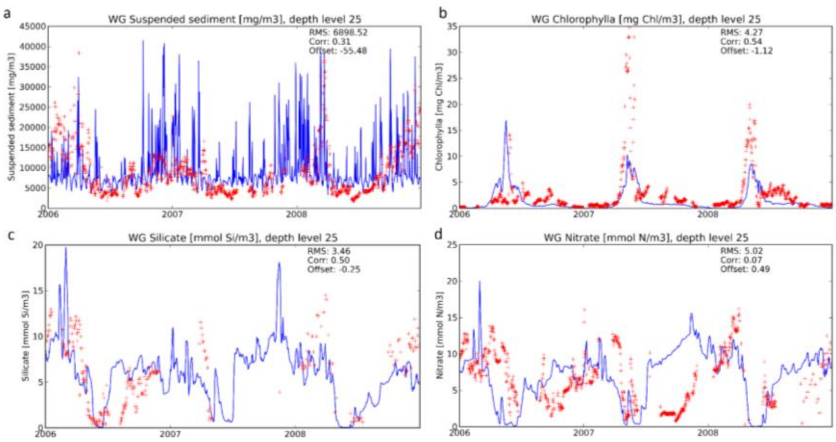

Figure 24. Comparison of model (blue line) with observations (red crosses), for the West Gabbard SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.~~As Figure 6, but for West Gabbard SmartBuoy~~

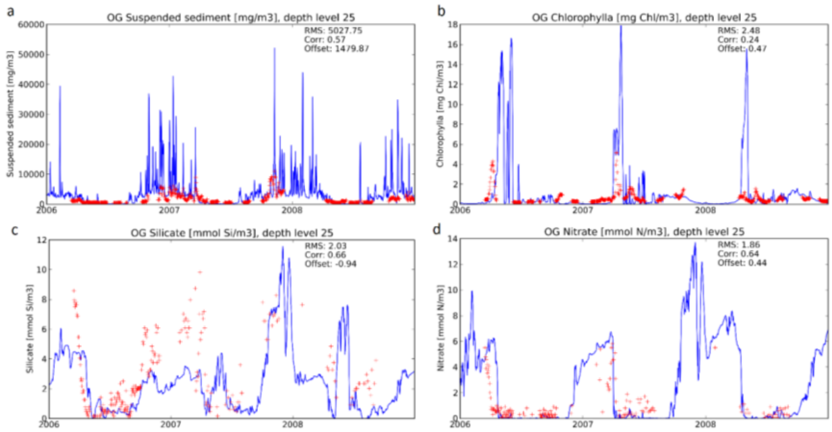

Figure 25. Comparison of model (blue line) with observations (red crosses), for the Oyster Grounds SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.~~As Figure 6, but for Oyster Grounds SmartBuoy.~~

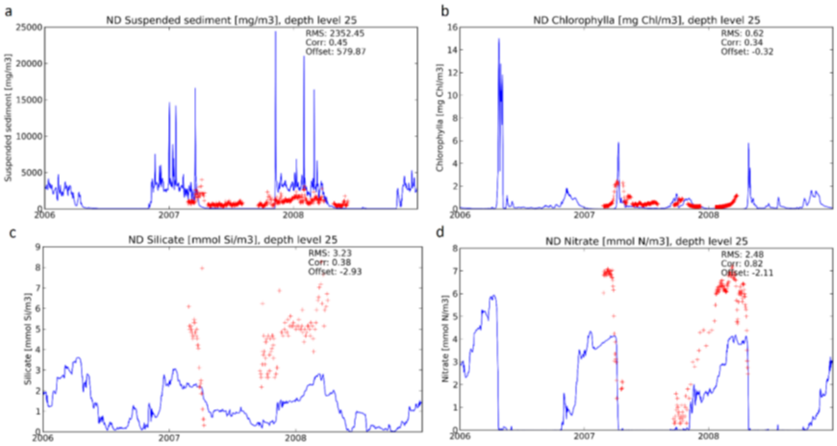

Figure 26. Comparison of model (blue line) with observations (red crosses), for the North Dogger SmartBuoy. a) SPM, b) chlorophyll, c) silicate, d) nitrate.~~As Figure 6, but for North Dogger SmartBuoy.~~

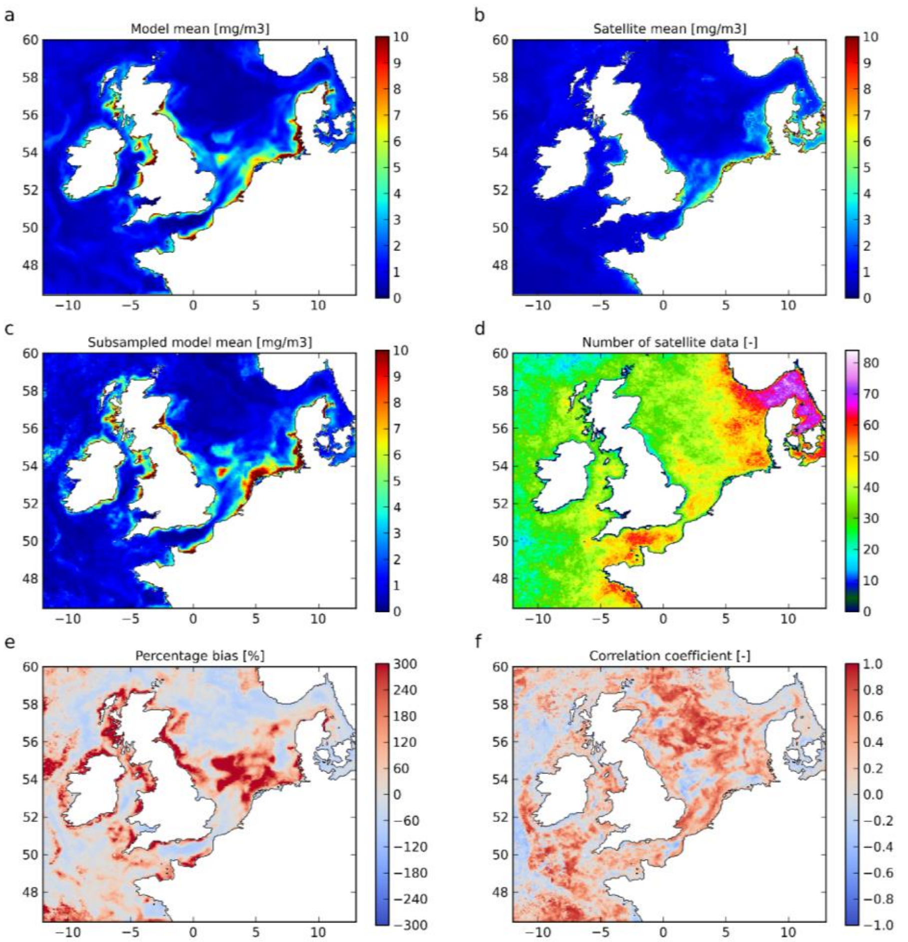

Figure 27. Comparison of modelled daily surface chlorophyll concentrations with daily chlorophyll composites from the MODIS satellite (Gohin et al., 2005; Gohin, 2011) for the growing season from 1 March 2008 to 30 September 2008. a) Model growing-season average, b) satellite growing-season averaged, c) sub-sampled model growing-season average with cloudy pixels removed, d) number of clear days in the period according to the satellite, e) relative model bias compared to the satellite, f) correlation coefficient between model and satellite.

Formatted: Caption

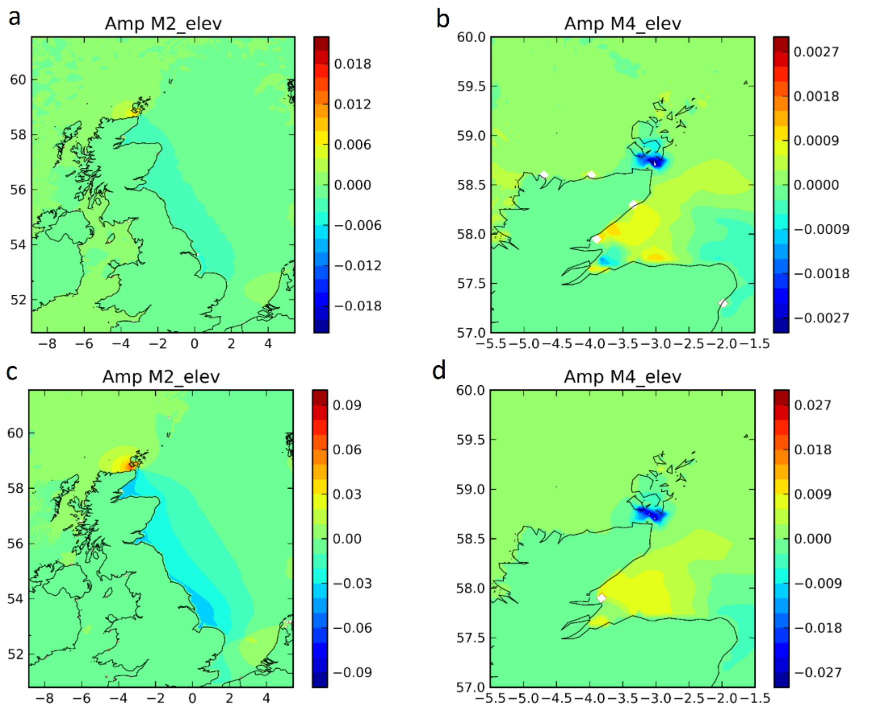

Figure 28. Difference in tidal elevations between scenario run ~~with~~ and reference run ~~of tidal elevations~~. a) M2 amplitude [m] and b) M4 amplitude [m]~~, both~~ for the 800 MW extraction scenario. c) M2 amplitude [m] and d) M4 amplitude [m]~~:~~ ~~similar~~ for the 8 GW extraction scenario.

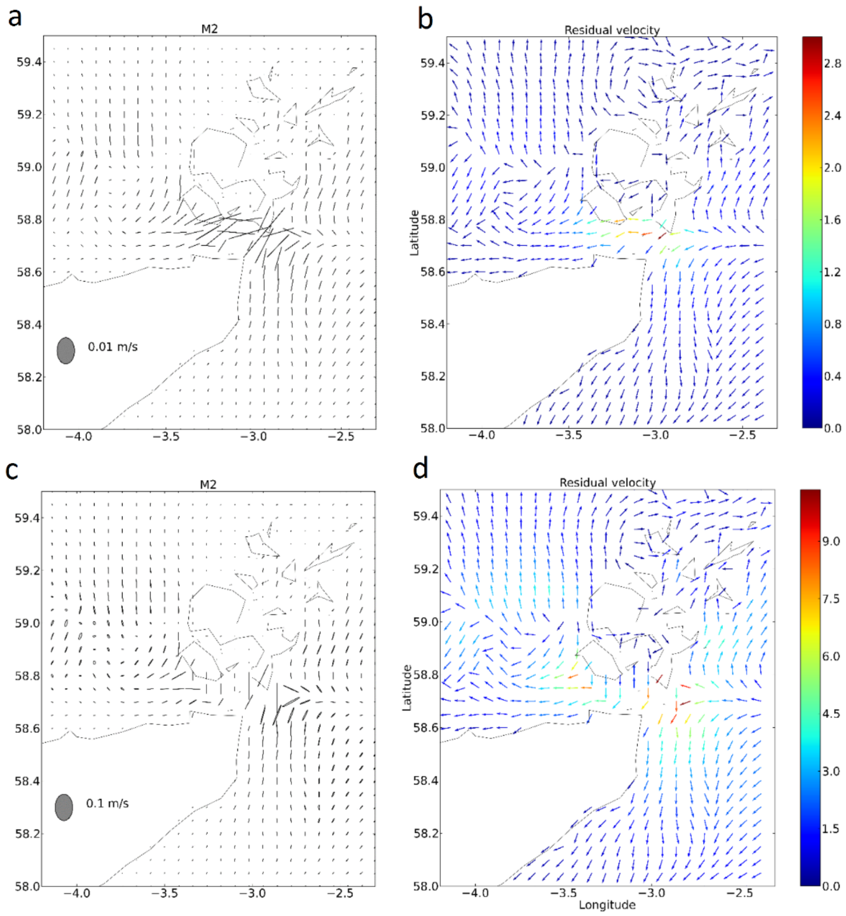

Figure 29. Difference in currents between scenario run and ~~with~~ reference run ~~of currents~~. a) M2 tidal current ellipses and b) residual currents [cms^{-1}]~~, both~~ for the 800 MW extraction scenario. c) M2 tidal current ellipses and d) residual currents [cms^{-1}]~~:~~ ~~similar~~ for the 8 GW extraction scenario.

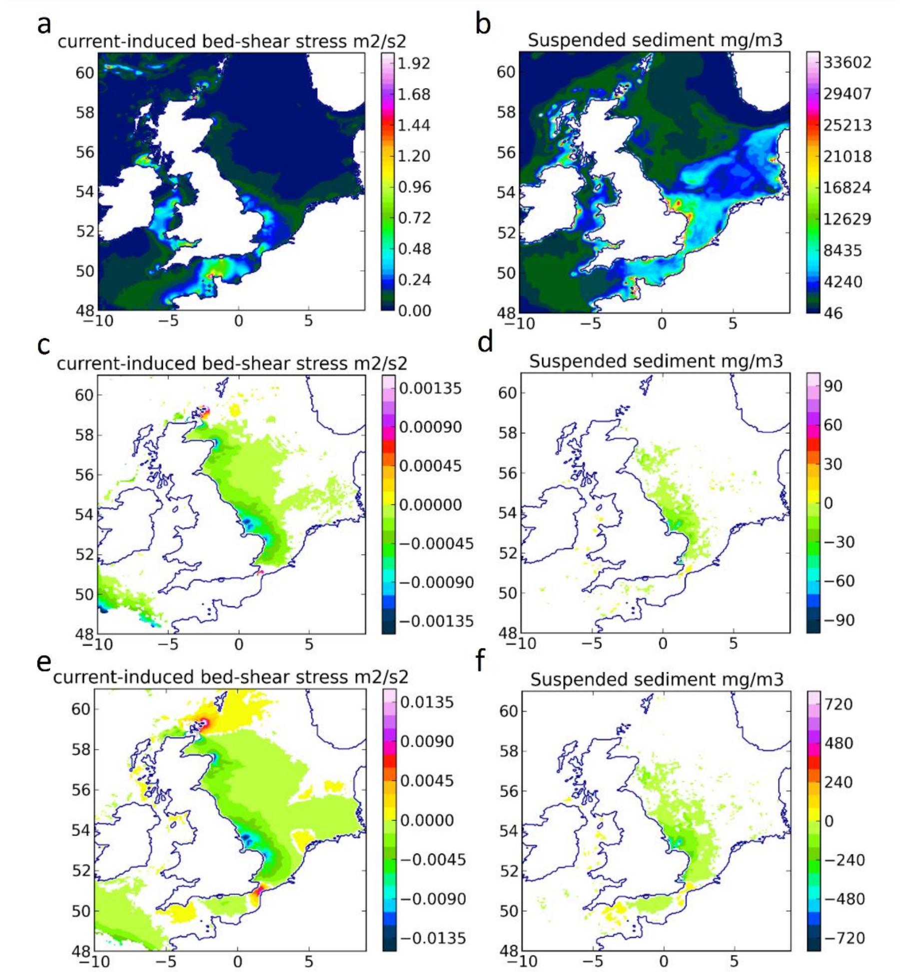

Figure 30. a) annually averaged current-induced bed-shear stress for 2008. b) annually averaged surface SPM concentration for 2008. c) and d): changes in a) and b) for the 800 MW extraction scenario. e) and f): changes in a) and b) for the 8 GW extraction scenario. White areas were masked out.

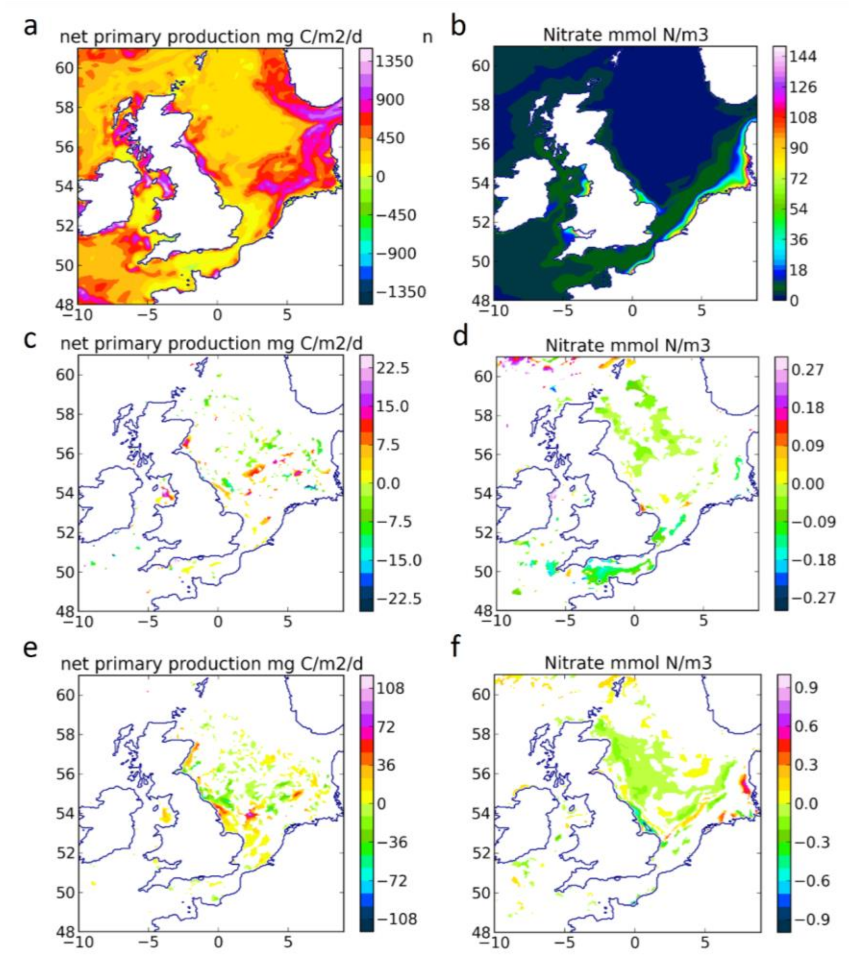

Figure 31. a) annually averaged net primary production for 2008. b) annually averaged surface nitrate concentration for 2008. c) and d): changes in a) and b) for the 800 MW extraction scenario. e) and f): changes in a) and b) for the 8 GW extraction scenario. White areas were masked out.~~As Figure 13, but for net primary production and surface nitrate concentrations.~~

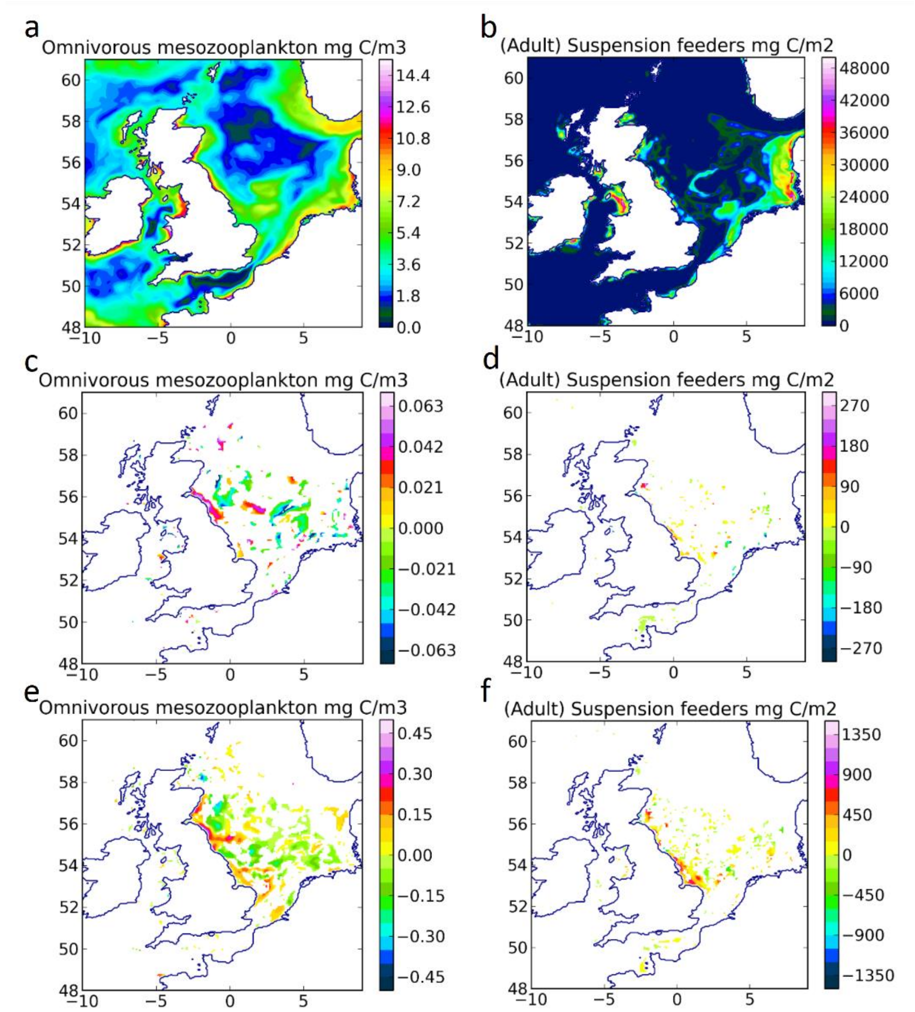

Figure 32. a) annually averaged omnivorous mesozooplankton carbon biomass for 2008. b) annually averaged suspension feeder carbon biomass for 2008. c) and d): changes in a) and b) for the 800 MW extraction scenario. e) and f): changes in a) and b) for the 8 GW extraction scenario. White areas were masked out.~~As Figure 13, but for omnivorous mesozooplankton and suspension feeders.~~

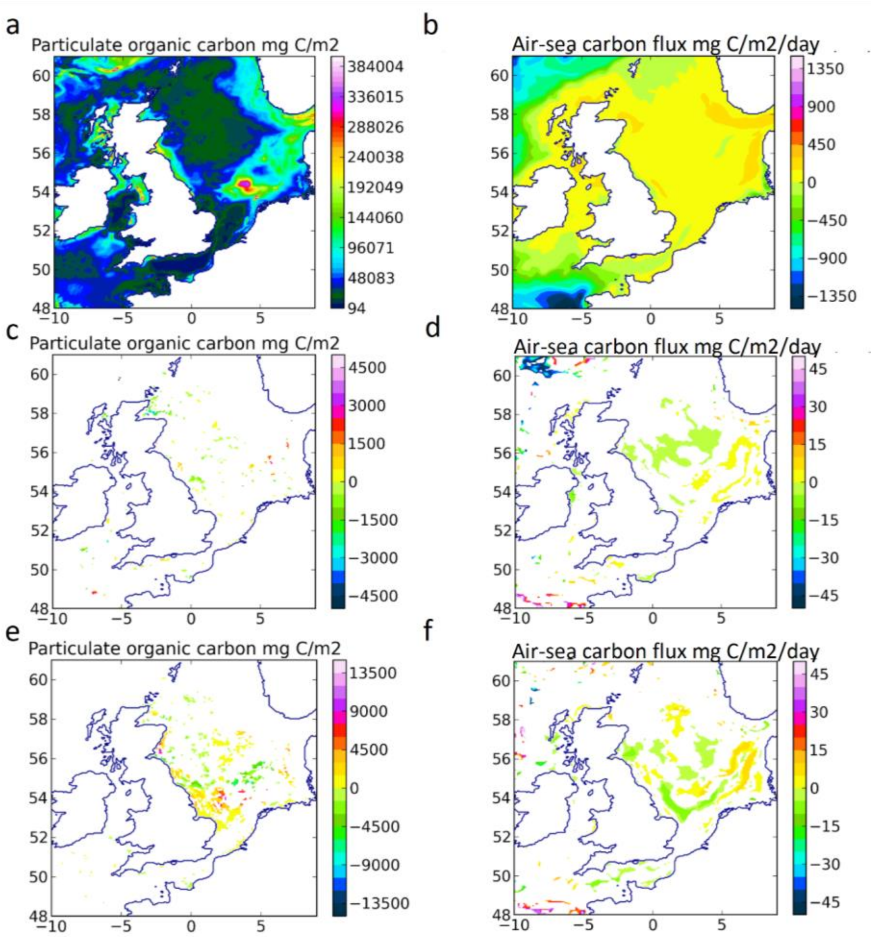

Figure 33. a) annually averaged benthic particulate organic carbon for 2008. b) annually averaged sea-surface CO_2 flux for 2008. c) and d): changes in a) and b) for the 800 MW extraction scenario. e) and f): changes in a) and b) for the 8 GW extraction scenario. White areas were masked out.~~As Figure 13, but for particulate organic carbon in the sea bed and sea-surface CO_2 flux.~~