

# EcoWatt2050

## Project Summary 2017

**EPSRC**

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Research Council



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# INTRODUCTION TO EcoWatt2050

Marine renewable energy is an important component of the Scottish Government's vision for the future and will help the government reach its ambitious decarbonisation and climate change objectives.

The EcoWatt2050 project was created to investigate how we can ensure that the benefits of future large scale renewable energy developments can be maximised, whilst minimising the environmental impacts and ensuring that various legal requirements are met. The project considered the potential impacts of both future marine renewable energy and climate change, and quantified the changes in each case.

The EcoWatt2050 consortium was brought together under MASTS, and comprises the Universities of Heriot-Watt, Edinburgh, Strathclyde, Aberdeen, Swansea and the University of the Highlands and Islands, as well as the National Oceanography Centre (Liverpool) with Marine Scotland Science as full consortium partners. This booklet summarises the EcoWatt2050 research that has enabled a comparison of climate change impacts against those predicted from the removal of energy on a range of environmental features. EcoWatt2050 has addressed extensive array configurations, comprising very large scale arrays of horizontal axis tidal turbines, and two types of wave energy converter, deployed not only in Orkney and the Pentland Firth but also in other regions of Scottish Shelf Seas.

**Research has been specifically designed to respond to questions posed by Marine Scotland Science:**

- What criteria should be used to determine the ecological limits to marine renewable energy extraction, and what are the implications for very large scale array characteristics?
- How can we differentiate the effects of climate change from energy extraction on the marine ecosystem?
- Are there ways in which marine renewables development may improve or exacerbate the predicted effects of climate change on marine ecosystems?
- How can marine planning be used to lay the foundation for the sustainable development of very large scale arrays (developments) of marine renewable energy devices in the context of a changing climate?



# KEY FINDINGS

## Tidal Energy Extraction

- Tidal energy extraction will change the tides. Energy extraction from the Pentland Firth will alter the transport through the channel, the tidal range and the speed of the currents. The level of change will depend on the amount of power extracted and the positioning and layout of tidal turbine arrays. Far-field changes suggest an upstream increase in tidal range from energy extraction and a downstream decrease; slight far-field changes in tidal current are also observed.
- Climate change and energy extraction both increase stratification, however in the climate change scenario considered the change is an order of magnitude greater.
- Installing tidal energy arrays in the areas identified for exploitation to the west and north of Scotland will result in widespread changes in turbidity and corresponding penetration by sunlight. At turbidity levels typical of inshore waters, this change may result in a 25-30% change in light intensity at any given depth.
- Decrease in turbidity may offset the increase in stratification caused by climate change.
- Tidal energy extraction will alter circulation around seabed features, which may lead to changes in bed level. In our study of sandbanks in the Inner Sound, we have shown that wave action during storms increases the magnitude of the predicted change from tidal energy extraction.
- Our study of the effects of energy extraction on the predator prey relationships of marine mammals and seabirds suggest that energy extraction will have negligible consequences, whereas the impact of climate change could be up to ten times more severe.
- Tidal energy extraction is predicted to have only negligible effects on Priority Marine Features such as seapen and burrowing megafauna communities, whereas climate change is predicted to result in far more significant shifts and in the availability of suitable habitats for these.
- It is important that marine planners consider where tidal energy developments should be sited, and the array configurations, in order to maximise the energy extracted and minimise environmental change.

## Wave Energy Extraction

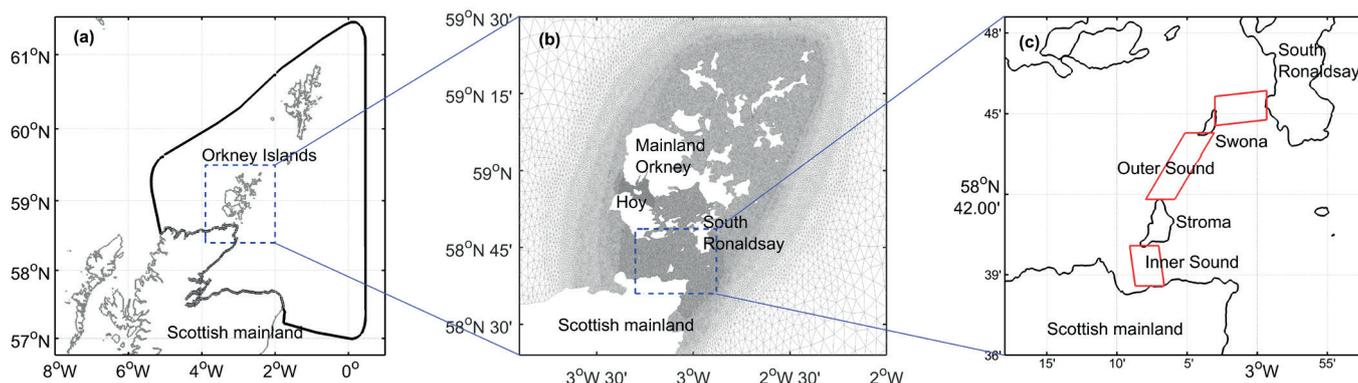
- The predicted effect of climate change on waves is small and much less than the effect of wave energy extraction. A reduction in up to 50% of mean wave height is predicted in the lee of large wave energy converter arrays. Effects, however, are limited to the envelope between the arrays and the shoreline, and in some cases a reduction in mean wave height may serve to protect coastal heritage.
- An examination of the patterns of kelp distribution suggest that climate change will have a far greater effect, with significant decreases in cold water species and increases for warm water species that are far greater than any changes predicted from wave energy extraction.

# 1: How tidal stream turbine arrays could change the tides in the Pentland Firth

Around half of Scotland's tidal stream resource is located in the Pentland Firth and Orkney Waters (PFO), with most of this resource in the Pentland Firth. On average 5.3 GW could be extracted from the Pentland Firth using tidal turbines, but doing this may cause a large change in water levels and tidal currents in the region. It is important to consider how much energy to extract from this region, with the environmental consequences in mind. This work shows that it is also important to consider **where** and **how** to extract energy, as this will influence the degree of change to the tides and the marine environment.

## APPROACH AND METHODOLOGY

The Pentland Firth is a channel separating the Scottish mainland and the Orkney Islands, and has some of the fastest tidal currents in the world. The main channel is the Outer Sound between the Islands of Stroma and Swona.



**Figure 1.**

(a) Model domain used in the study for the PFO; (b) Model grid; (c) Tidal turbine array locations in red.

We used a hydrodynamic model of the PFO to study this region (Figure 1a) <sup>1</sup>. The computational grid was made up of triangular elements which varied in size across the model domain with the smallest size in the Pentland Firth of around 150 m. The transport across the Pentland Firth (volume of water flowing per second) was calculated, in order to study how this could change with tidal energy extraction.

Tidal turbines were added to the model in three areas between the Scottish mainland and the Islands of Stroma, Swona and South Ronaldsay (Figure 1c). Two scenarios were considered in order to investigate how the array layout can influence the power extracted and the consequence of this:

- Scenario A: The tidal turbines could span the whole water column and were positioned in all water depths
- Scenario B: The tidal turbines were confined to being close to the bed and in water deeper than 27.5 m

Scenario A ensured that tidal turbines spanned the whole channel cross section. Scenario B was more realistic with the turbines being close to the bed and with clearance to the surface.

A large number of simulations were performed, with differing levels of tidal power extracted, in order to understand what effect this has on the tides and the transport through the Pentland Firth.

## FINDINGS

How might the transport change with the power extracted?

- As the total power extracted from the tide increased, the transport through the Pentland Firth decreased. This shows that tidal turbines can slow the flow of the tide.
- As the number of turbines was increased there was a peak in the extractable power. More turbines were added after this peak, but no more power was extracted even though the transport continued to fall. This shows that the channel can reach a ‘choking point’ above which no more power can be extracted.
- For 1.4 GW to be extracted, Scenario B required approx. 3.5 x more turbines than Scenario A. This is because Scenario A is much more efficient as it utilises the whole water depth.

How might the water level and current speeds change?

Figure 2 shows how the water level could change if 1.4 GW of power were extracted using scenarios A and B. In both of these scenarios the water level could increase to the west of the tidal turbines, and decrease to the east. The spatial extent of the change of Scenario A is less than that of Scenario B.

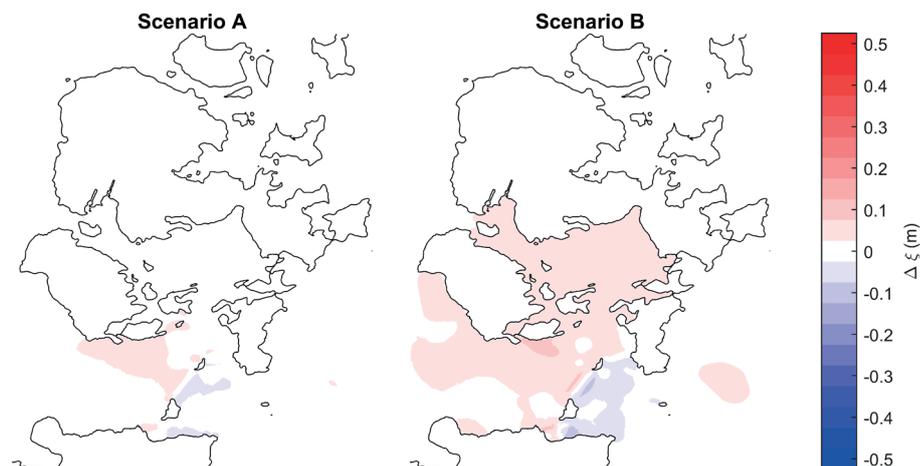
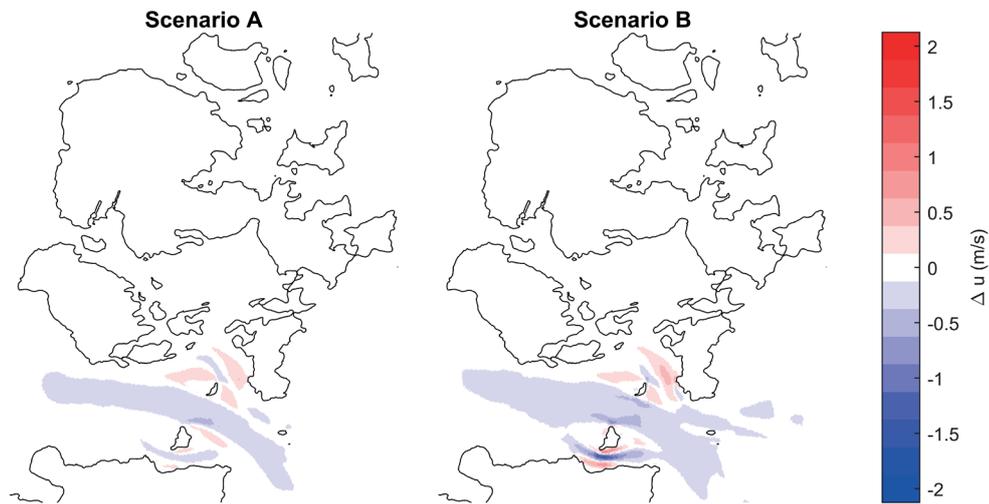


Figure 2.  
Change in tidal water elevation around Orkney for Scenarios A and B.

Figure 3 shows how the tidal speed could change if 1.4 GW of power were extracted using scenarios A and B. In both of these scenarios the current speeds increase in some areas and decrease in others. Whilst the spatial extent of the change is similar in each case, Scenario B shows that the currents could speed up and slow down more in some areas.



**Figure 3.**  
Change in tidal speed for Scenarios A and B.

## SUMMARY OF FINDINGS

Tidal energy extraction from the Pentland Firth will change the tides, the transport through this channel, the tidal range and the speed of the currents. The level of change will depend on the power extracted.

The amount of change, and where the change occurs, is very dependent on the layout of the arrays. For example, this work shows how an array spanning the whole water depth requires far fewer turbines and changes the tidal flow and water levels less than an array confined to the bottom of the Pentland Firth.

## RECOMMENDATIONS

It is important for marine spatial planners to consider where tidal energy extraction should be extracted, in order to maximise the energy extracted and minimise the environmental change.

More work should be conducted in collaboration with marine spatial planners and policy makers to:

- Plan where new tidal stream lease sites should be placed.
- Determine how much energy should be extracted from this region, considering the environmental consequences.

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<sup>1</sup><http://marine.gov.scot/information/scottish-shelf-model>

## 2: Predicting changes in the physical marine environment under future scenarios: large tidal stream turbine arrays and climate change effects

### APPROACH AND METHODOLOGY

#### The Scottish Shelf Model

We used the Scottish Shelf Model (SSM). The model uses a triangular grid, which allows for accurate fitting of the complex coastline and has varying mesh size from approx 10 km at the shelf edge to approx 1 km at the coast.

It can provide water level, 3D currents, temperature and salinity predictions depending on the atmospheric and boundary forcing applied. The SSM is computationally demanding, and was therefore run for a single climatological year, representing present day conditions. At the open boundary tidal water levels and currents are specified, combined with temperature, salinity and non-tidal currents from the model of the NE Atlantic (NEMO AMM7). Atmospheric forcing was constructed as monthly-mean values of heat flux, sea-level pressure, wind-stress, atmospheric temperature, relative humidity and precipitation averaged over 25 years (1990-2014). At the coast, freshwater discharge from 577 Scottish rivers was applied.

#### Climate change scenarios

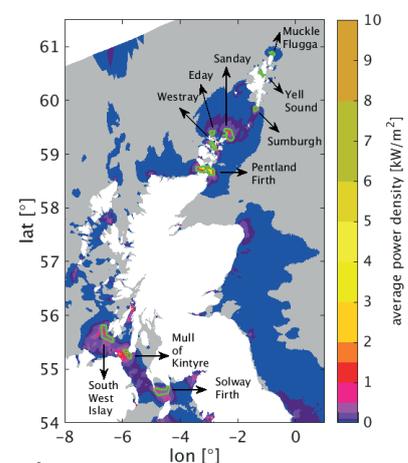
In order to examine the likely future hydrodynamics and hydrography over Scottish Waters and further afield, we used future climate forcing, constructed from an examination of the differences in the forcing between the present day and 2050. For the future climate we used the HadGEM2-ES global and regional climate model projections for the RCP8.5 emissions scenario, which represents 'business-as-usual', i.e. no reduction in emissions. The future UK climate is projected to be warmer, with an increase in sea level.

#### Tidal stream turbine array design

A generic tidal stream turbine is considered and future large tidal turbine arrays have been designed based on:

- search areas selected for potential development (Figure 1)
- tidal kinetic energy power density
- water depth

These could result in arrays of several thousand tidal turbines to maximise the energy extraction. While this is a very ambitious scenario at present, it is regarded as a potential future in 2050 if tidal energy is being fully exploited.



**Figure 1.** Areas in Scottish waters with higher tidal power resource and identified for tidal energy exploitation

## FINDINGS

### Near-field and far-field changes

Present hydrodynamic conditions and one single, physically plausible, representation of the future conditions in 2050 were reproduced by the SSM and compared with the ocean state perturbed by tidal stream energy extraction. The tide around Scotland propagates up the west coast to the north, and down the east coast to the south. Far-field changes in the tidal range ( $\pm 1-6$  cm) mainly increase “upstream” of the tidal turbine array locations (considering the direction of propagation of the tidal wave) and decrease “downstream”. Far-field changes to tidal current were also detected ( $\pm 0.02$  m/s): slowing down in some areas due to the turbines and speeding up in other areas due to flow diversion and blocking.

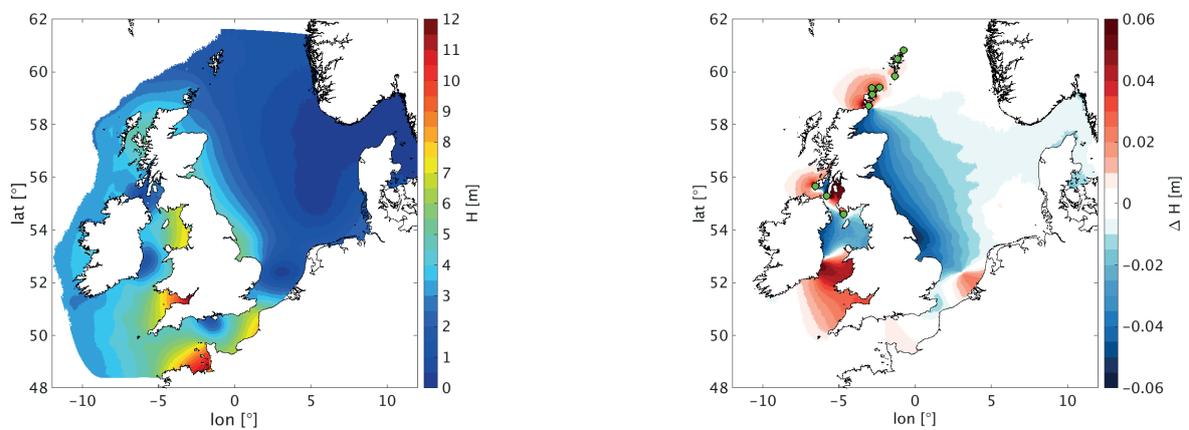


Figure 2.

(a) baseline spring peak tidal range; (b) change in spring peak tidal range.

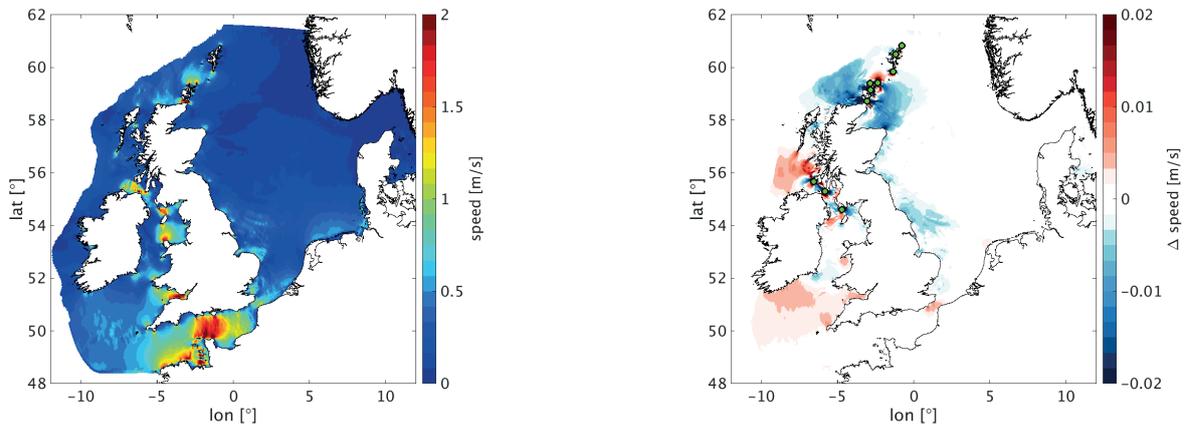
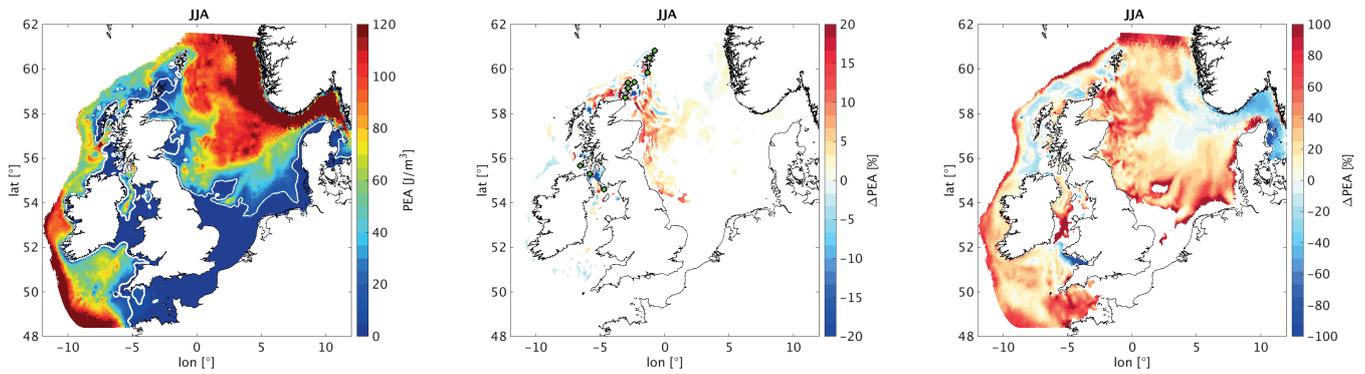


Figure 3.

(a) spring peak tidal currents; (b) change in spring peak tidal currents.



**Figure 4.**

Summer Potential Energy Anomaly (PEA) for the baseline case (no extraction) and percentage changes due to tidal energy extraction and climate change.

The strength of summer stratification, measured by the energy required to completely mix the water column Potential Energy Anomaly (PEA), was found to slightly increase (< 20%) due to tidal turbine energy extraction in present climate conditions: this is caused by the decrease of tidal mixing energy. Future hydrodynamic conditions in 2050 showed a future increase in summer water column stratification driven by the temperature increase. The change in stratification due to climate change is one order of magnitude larger and over a much wider area than the change caused by tidal energy extraction.

## SUMMARY OF FINDINGS

Climate change effects and tidal energy extraction both act in the same way in terms of increasing stratification due to warming and reduced mixing. However, the climate change scenario considered is an order of magnitude larger. Tidal amplitude is reduced in most areas due to extraction of tidal energy, although locally the tidal amplitude can increase due to small displacements in areas of small tidal amplitude. Changes are small, of the order of a few cm, but in some cases may act to counter the predicted rise in sea level due to climate change by reducing extreme water levels.

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### 3: Will tidal stream turbine arrays affect the underwater light environment in the sea?

The depth to which sunlight penetrates into the sea is very important for marine life. It determines the growth of algae at the base of the food web, and is vitally important for animals that rely on vision to hunt and capture their food. In turbid coastal waters where there is a lot of fine suspended sediment the light may be reduced to very low levels within a metre, whilst in clear open ocean waters light can penetrate to several tens of metres.

Away from the mouths of large rivers and estuaries, most of the sediment suspended in the sea is picked up from the seabed by the action of waves and tidal currents. So, if we embark on industrial-scale extraction of tidal energy by large arrays of turbines there is an obvious question as to where and by how much we may affect the quantities of suspended sediment (turbidity) and light penetration. In this project we have answered this question by bringing together several strands of marine modelling.

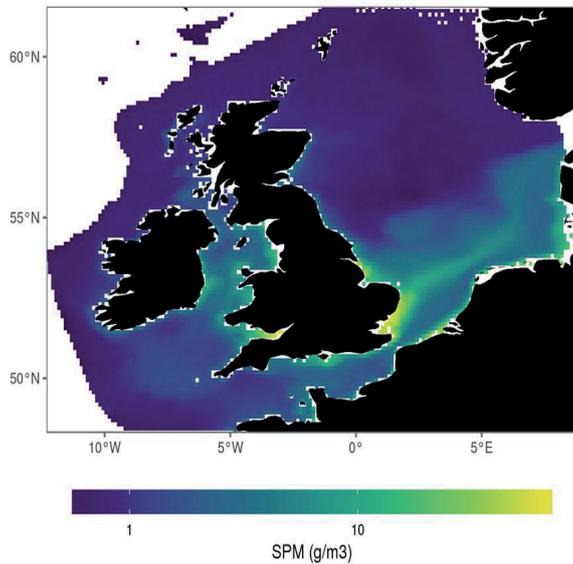
#### **APPROACH AND METHODOLOGY**

To investigate how tidal energy extraction affects light in the sea we needed to:

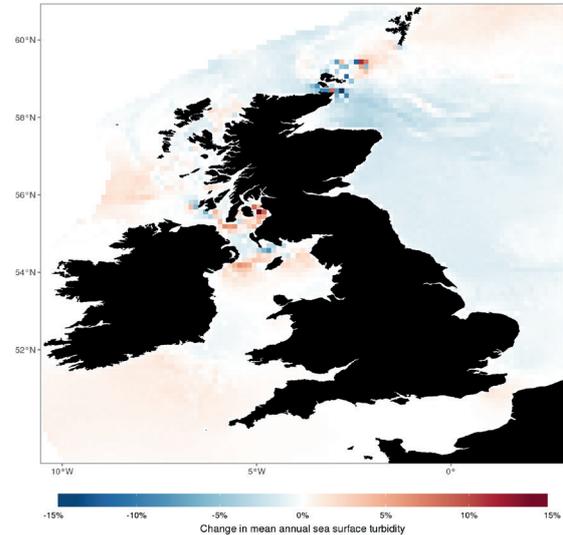
- Assemble sedimentology data from a range of international sources and use statistical modelling to produce a detailed map of the distribution of fine-grained seabed sediment material across the entire northwest European shelf.
- Assemble satellite remote sensing data on monthly average distributions of sea-surface turbidity across the region.
- Assemble outputs from the SSM on simulated current speeds on a grid covering the northwest European shelf, under present day conditions with no tidal energy extraction and a scenario of large scale tidal energy extraction (see Section 2).
- Assemble data from the European Centre for Medium Range Weather Forecasting (ECMWF) on wave conditions at the model grid points.
- Use the satellite data to calibrate a mathematical model of seawater turbidity profiles depending on seabed sediment composition, current speed and wave properties (Figure 1).
- Repeat the turbidity profile model using current speed data from the tidal energy extraction scenario.
- Compare the tidal energy extraction scenario predictions of turbidity at the sea surface with the results for contemporary conditions.

## FINDINGS

Our results show that installing tidal turbine arrays in all of the areas identified for exploitation around the west and north of Scotland would affect turbidity over a very much wider area than the immediate vicinity of the arrays due to the large scale alteration of tidal stream patterns. Changes of up to 10% in turbidity could be expected in some areas (Figure 2). However, the effects on sunlight penetration depth would be relatively small, of the order of a few metres at most.



**Figure 1.**  
1998-2016 annual averaged suspended particulate matter at the sea surface derived from satellite remote sensing data.



**Figure 2.**  
Predicted change in sea surface turbidity as a result of installing large scale tidal turbine arrays around Scotland. Red (increase in turbidity) indicates that less sunlight will penetrate below the sea surface. Blue (decrease in turbidity) indicates that the water is expected to become clearer with deeper light penetration.

## SUMMARY OF FINDINGS

Installing tidal energy extraction arrays in all of the identified areas for exploitation west and north of Scotland will result in widespread changes of up to 5% in sea surface turbidity, and up to 10% in some locations.

Light penetration is often expressed as the depth at which the intensity is 1% of that at the sea surface. A 10% change in turbidity equates to only a 1-2m change in this penetration depth. At turbidity levels typical of inshore waters around Scotland, this corresponds to a 25-30% change in underwater light intensity at any given depth.

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## 4: Assessing the importance of including waves in simulations of tidal stream turbine array impacts to sediment

This study carried out an investigation of the physical impact of tidal energy extraction on the sub-tidal sedimentary environment. The impact on morphological changes of sub-tidal offshore sandbanks located in the Inner Sound of Pentland Firth, Scotland caused by tidal turbine arrays is demonstrated, taking into account both waves and tides.

### APPROACH AND METHODOLOGY

The Inner Sound is the sub-channel in the south of the Pentland Firth, between the island of Stroma and the Scottish mainland. This area is the site of the world's first tidal array project. Wave conditions in the region are some of the most energetic in Europe. Within the Inner Sound are several sedimentary deposits. The largest is a wedge shaped sandbank located to the north of the main channel through the Inner Sound and to the east of Stroma. This sandbank is the focus of this study (marked as A in Figure 1).

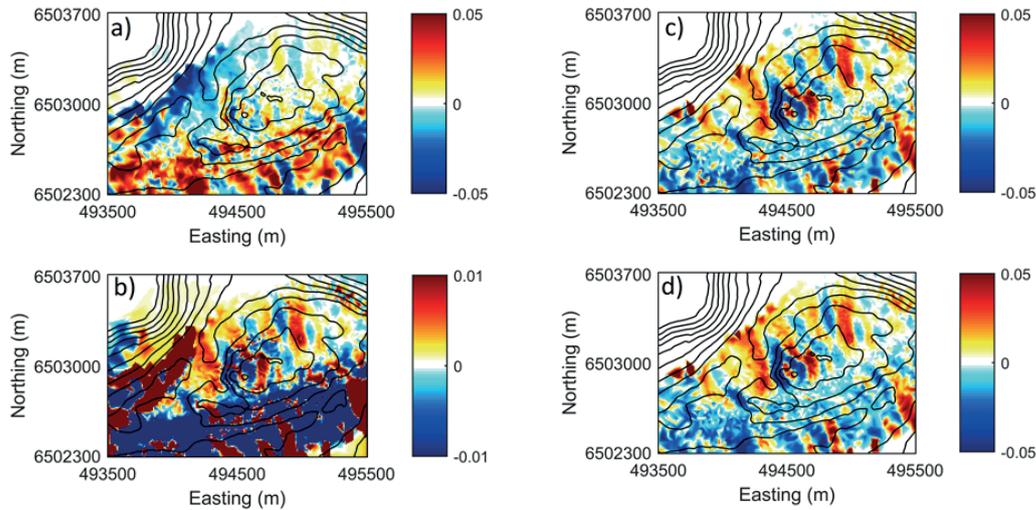


Figure 1.  
The Pentland Firth site.

A combined computational wave, hydrodynamic and morphology model of the Inner Sound was developed. Model performance was evaluated by comparing wave, current and water level measurements at numerous places in the model domain. Measured and modelled results were found to be in good agreement.

Two turbine array areas are considered in this analysis based on currently leased areas in the Pentland Firth and Orkney Waters: MeyGen Inner Sound site and Scottish Power Renewables Ness of Duncansby site (Figure 1). 400 tidal turbines are implemented at the Inner Sound site and 100 tidal turbines at the Ness of Duncansby site.

## FINDINGS



**Figure 2.**

(a) Bed level change during 12 hr period at mean spring tide for no tidal turbine case and differences in bed level change caused by tidal energy extraction for (b) the tide only case, (c) the storm from the east and (d) the storm from the west.

### SUMMARY OF FINDINGS

Tidal energy extraction in the Inner Sound of the Pentland Firth alters the residual hydrodynamic circulation around an island associated sandbank. Consideration of bed level changes shows that inclusion of wave action increases the magnitude of predicted difference over the sandbank compared to the tide only. The shape and direction of predicted difference remains similar (Figure 2). It is assumed that increased mobilisation of sediment due to the wave's orbital velocity is the cause of this increase. The short time period (24 hr) of the presented results mean that while differences are noted, longer simulations are required to better answer the question of how important wave action is to bed level change from extraction of tidal energy.

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# 5: Predicting changes in the physical and biological marine environment under climate change

## APPROACH AND METHODOLOGY

A coupled hydrodynamic-ecosystem model was used to predict changes in the future for physical and biological variables that can strongly influence mobile marine animals. The 7 km Atlantic Margin Model (AMM7) was used. The hydrodynamics are supplied by the Nucleus for European Modelling of the Ocean (NEMO) and coupled to the European Regional Seas Ecosystem Model (ERSEM). The variables studied were the potential energy anomaly (PEA) (representing the level of stratification), the sea surface and bottom temperature, depth average current speed, vertical velocity, net primary productivity and maximum chlorophyll.

The year was split into biologically relevant seasons as this work fed into Section 6. Present climate data were given as climatological means across 25 years (1989–2014). Future climate data have been produced using the future climate forcing from the RCP8.5 emissions scenario reproduced by the HadGEM2-ES climate model.

## FINDINGS

An increase in net primary productivity is observed in coastal areas, in particular during spring and summer seasons (Figure 1). There is a general decrease in the maximum chlorophyll-a at any depth, again particularly during spring and summer seasons (Figure 2).

Other findings predicted changes due to climate change in bottom (Figure 3) and surface (Figure 4) temperature to exceed 2°C, particularly during summer months. The strength of the seasonal stratification is predicted to increase on average about 20%, up to 50% in some areas.

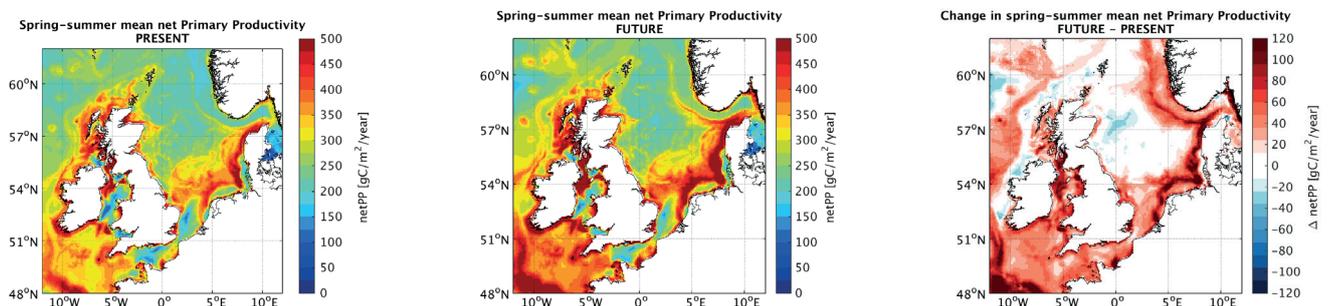
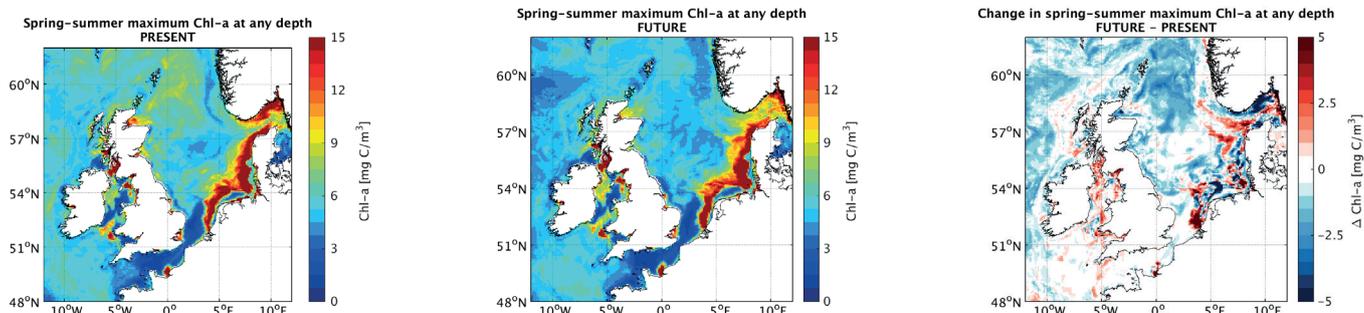


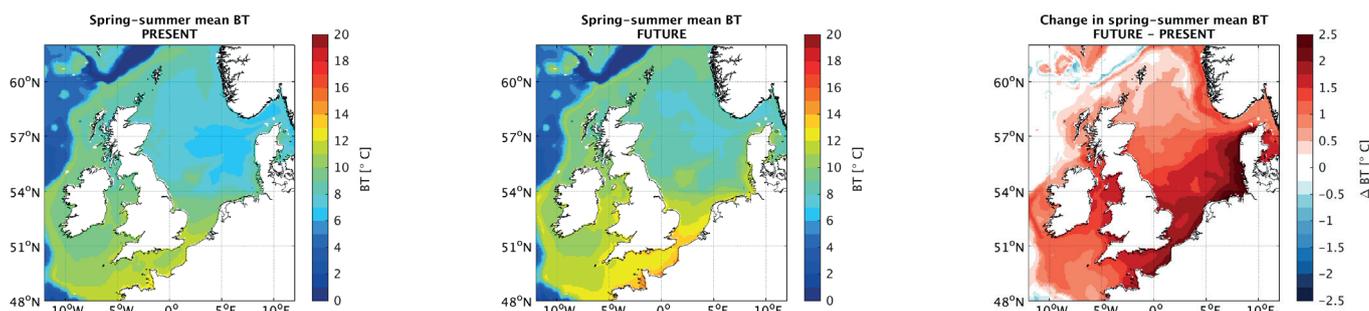
Figure 1.

Spring – summer net primary productivity for present and future conditions and the differences between present and future climate.



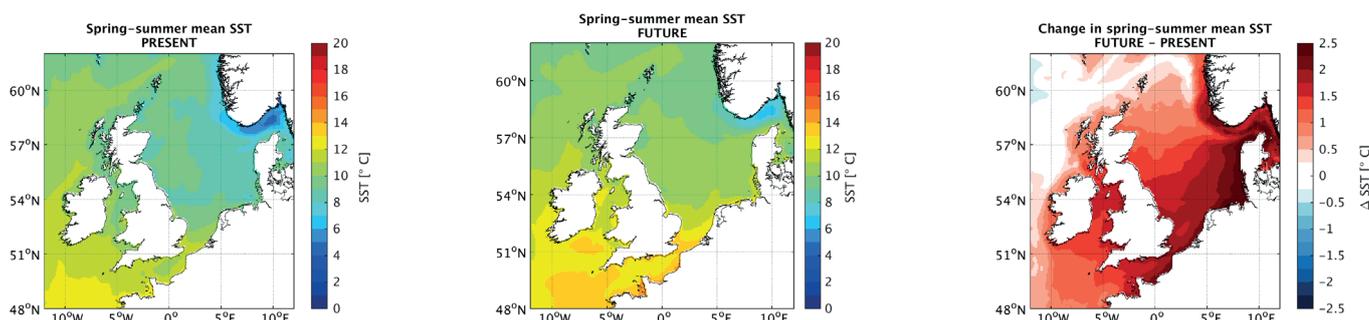
**Figure 2.**

Spring – summer maximum chlorophyll for present and future conditions and the differences between present and future climate.



**Figure 3.**

Spring – summer mean bottom temperature for present and future conditions and the differences between present and future climate.



**Figure 4.**

Spring – summer mean sea surface temperature for present and future conditions and the differences between present and future climate.

## SUMMARY OF FINDINGS

Future climate predicts increases of net primary production in coastal areas, and shifts spatially in areas of maximum chlorophyll-a. Increases in surface and bottom temperature, and also stratification were predicted.

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## 6: Assessing potential biological cost/benefit to mobile marine animals due to large scale tidal stream turbine arrays vs climate change

By estimating the changes in the overlap between mobile predators (marine mammals and seabirds) and their main prey species (herring and sandeels) distributions under tidal energy extraction and/or climate change scenarios, we can compare which has the larger effect and estimate a relative ecological level of cost or benefit to future populations.

### APPROACH AND METHODOLOGY

With almost 50+ years of fish, mammal and seabird surveys, and increasingly sophisticated tagging techniques, we have good information on the present spatio-temporal distribution of many species (Figure 1).

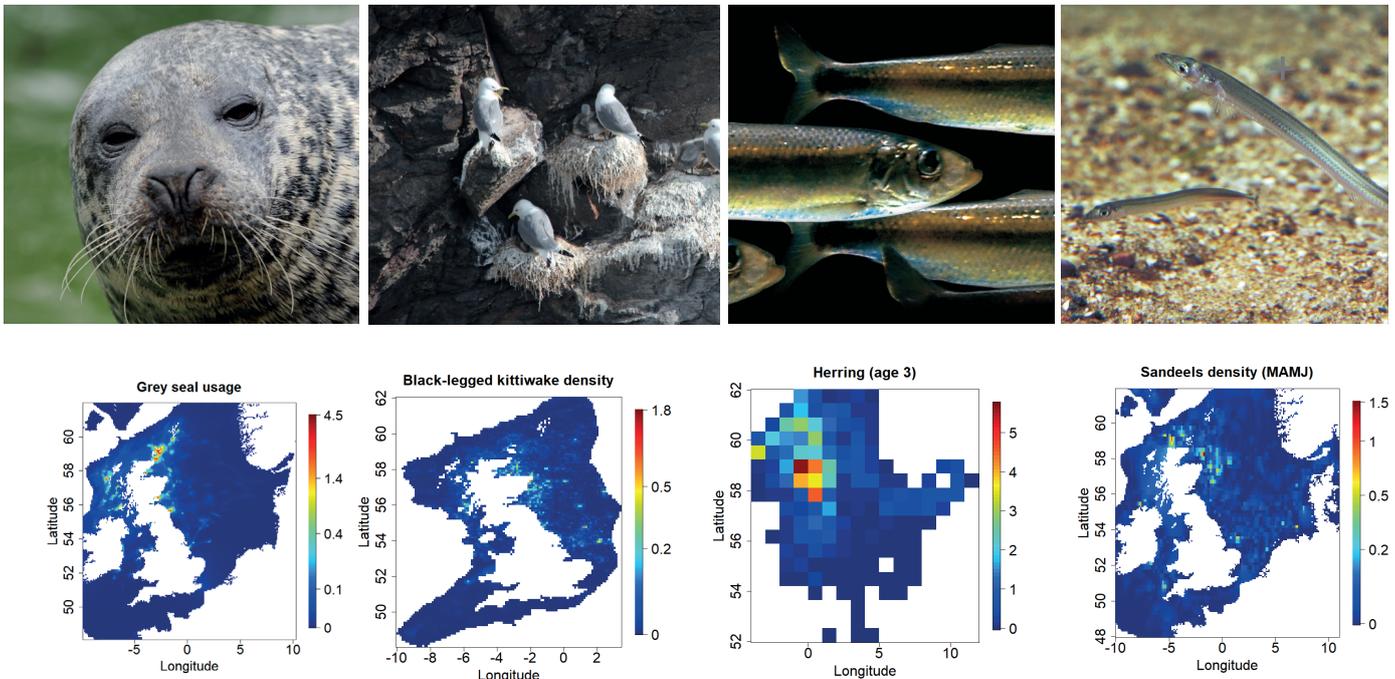


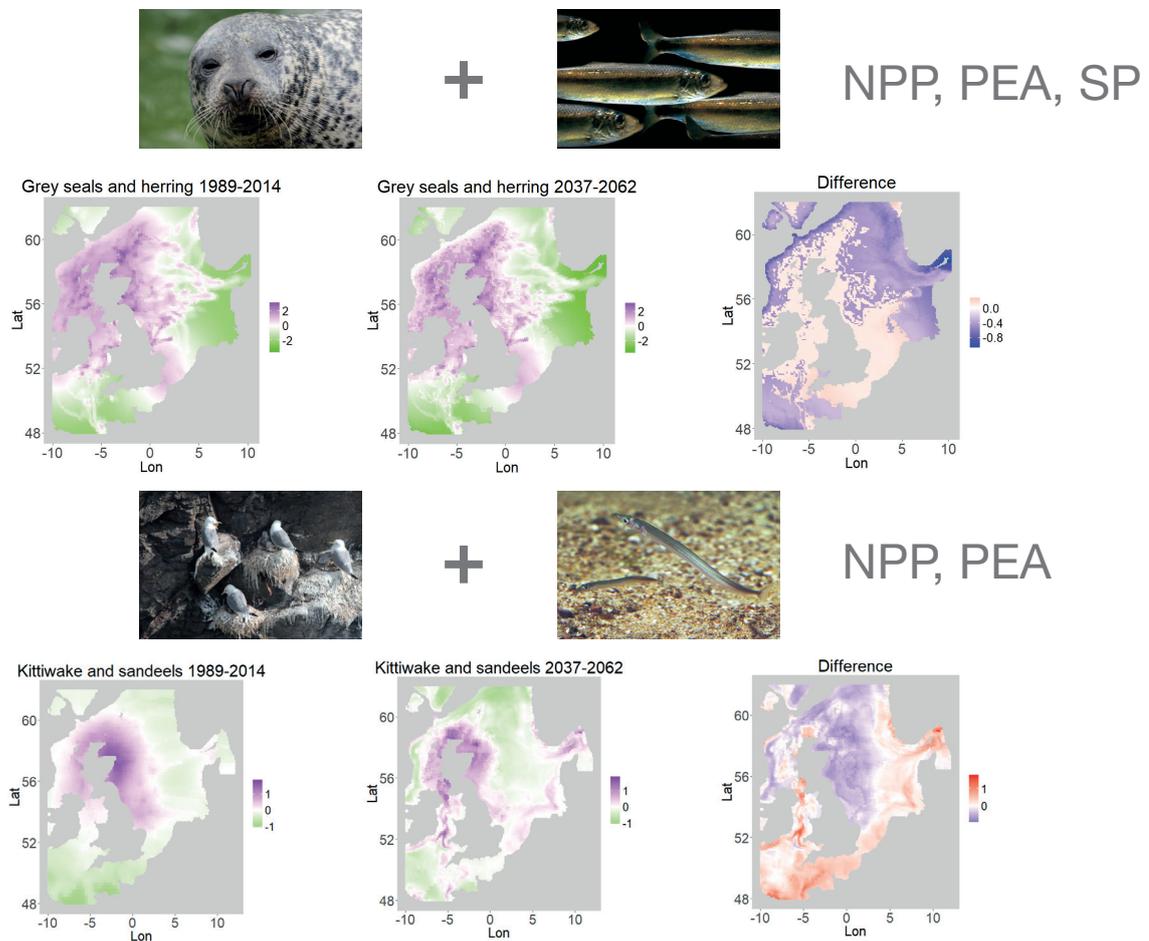
Figure 1.

Representative images of grey seals, kittiwakes, herring and sandeels and their current spatial distributions

To understand how marine habitat for mobile predator and prey species may change in the future we identified which critical habitat variables will change with large scale tidal energy extraction and climate change. Other similar studies have shown, for example, that water temperature, current speed, the level of water column mixing and plankton production influence marine mammal and seabird distributions.

We used the physical and biological models developed for EcoWatt2050 by NOC (see Section 5). This included model outputs for variables such as water column mixing (PEA), current speed (SP) and primary production (as net primary productivity, NPP) or as maximum chlorophyll levels (CHL).

To calculate the changes in overlap of predator and prey habitat we used recent advances in habitat and spatial modelling, which allow the linkage and contrasting use of the same environmental variables to both predator and prey species in the same analysis (Figure 2). This is called Joint Modelling and is a Bayesian approach. The results of the spatial modelling provide a metric of how strongly (or weakly) the pair of species overlap in any region of UK waters.



**Figure 2.**

Predator + Prey is a function of those habitat variables that are important to both species and shows their overlap in the present climate, the future climate of 2050, and the differences. Areas of purple are where they strongly overlap, green where they do not overlap. The areas of red are where there will be increases in how strongly they overlap and blue are where they are less likely to overlap in the future.

To be able to quantify the change from each scenario in terms of biological cost/benefit a common currency is needed to compare between the outputs to assess the strength and the direction of predictions. We used the distance from the location of the centre of mass for either single or joint species models and calculated how much it has moved in the different scenarios (Table 1). This allowed us to determine the effects of change in critical habitat distributions for each representative species, and assess differences in the probability of predator-prey encounters.

These differences may affect distance travelled to reach forage sites with prey present, which will increase or decrease the energetic cost of foraging. Values of under 10 km are unlikely to have an impact but values over 10 km may influence the population levels and dynamics.

**Table 1.**

The distance (km) that a single species or the location of the centre of mass for the joint species has moved in the different scenarios

Species	Distance (km)		
	Tidal turbine arrays	Climate change	Climate change + Tidal turbine arrays
Grey Seals	0.5	6.8	7.0
Herring (age 2&3)	19.8	72.7	72.5
Grey Seals + Herring	9.6	55.8	57.3
Kittiwakes	1.2	19.1	18.4
Sandeels	2.7	37.6	33.7
Kittiwakes + Sandeels	3.7	51.2	48.9

## SUMMARY OF FINDINGS

Tidal energy extractions has small to negligible changes and the effects of climate change are on average about 10 times more severe than tidal energy extraction.

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<http://onlinelibrary.wiley.com/doi/10.1002/ece3.3081/abstract>



## 7: Changes in benthic habitat owing to large scale tidal turbine arrays and climate change

Environmental conditions are the key determinant of what communities of animals and plants are found living on the seabed. The ecological niche for an individual species is defined by its response to a range of environmental parameters, which on the seabed might include temperature, salinity and flow. The composition of biological communities depends also on the interaction between species with similar ranges of environmental tolerance. Given this close relationship between ecology and the physical environment, it is relevant to ask - how are these communities likely to respond to environmental changes that may result from tidal energy extraction and climate change?

### APPROACH AND METHODOLOGY

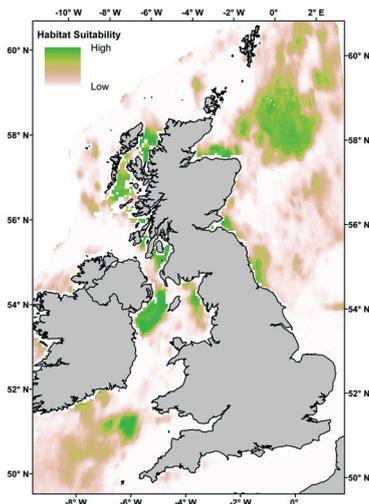
As an example, we consider ‘seapen and burrowing megafauna communities’ as defined on the OSPAR List of Threatened and/or Declining Species and Habitats. Characteristic of fine, cohesive mud seabeds, this community includes seapens, which are sessile, upright cnidarians, and a range of burrowing crustacean species including the Norway lobster, *Nephrops norvegicus*. There is a close correspondence between the distribution of this habitat and the commercially important *Nephrops* grounds on the European continental shelf. Data on the distribution of seapen and burrowing megafauna communities are available from OSPAR. By matching these georeferenced records with outputs of EcoWatt2050 tidal models constructed by NOC (see Section 2 and 5), we can make a description of the associated environmental conditions – essentially a description of the physical conditions which define the habitat.

Using gridded environmental data, we applied Maxent, a widely used species distribution modelling tool, to predict the suitability of conditions in each grid cell to support seapen and burrowing megafauna communities. Environmental parameters used in the models related to bathymetry, seabed topography, tidal flow velocity, sea bottom temperature, potential energy anomaly and chlorophyll content. Given that the existence of fine mud is a key prerequisite for the existence of this habitat, we included the percentage of mud in the sediment as a physical parameter in the model (see Section 3). Having described habitat suitability in terms of physical parameters, the Maxent model was then projected using scenarios for climate change and tidal energy extraction. These projections allow us to determine changes in the distribution and overall availability of habitat that would be expected in response to environmental alterations. The percentage of mud in the sediment was assumed to remain constant over the timescale of the projections, given that any changes in the distribution of mud in response to environmental alterations are likely to be at geological timescales. This provides an important constraint to ensure that habitat changes are not projected beyond areas that could realistically support the community in the foreseeable future.

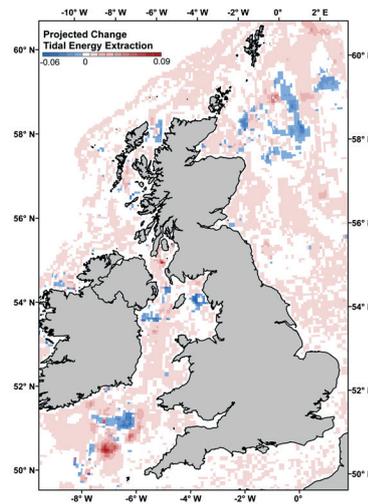
### FINDINGS

The Maxent model for seapen and burrowing megafauna communities provides a description of the distribution of suitable habitat that is consistent with its known distribution (Figure 1). Major

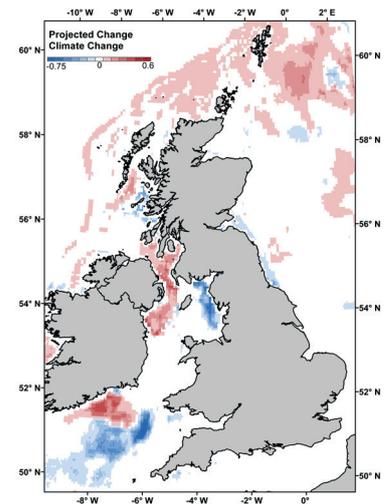
extents of habitat in the northern North Sea, Irish Sea, Celtic Sea and the west of Scotland are all well-defined by the model. Mud and bottom temperature are the dominant variables in determining the distribution. Negligible change in habitat suitability is predicted following tidal energy extraction. This amounts to a total loss of less than 0.1% over the spatial domain of the model, but some very minor shifts predicted within the northern North Sea and Celtic Sea grounds (Figure 2). A much larger response to climate change is predicted, amounting to a loss of 15% over the spatial domain of the model. Greatest losses are predicted for the Celtic Sea, partially offset by some gains in the northern North Sea and off the south-eastern coast of Ireland (Figure 3). The changes represent a northwards shift in distribution in the order of 72 km.



**Figure 1.** Predicted habitat suitability for 'seapen and burrowing megafauna communities' based on Maxent model. Green areas show areas with maximum probability of occurrence for this habitat.



**Figure 2.** Projected change in habitat suitability for 'seapen and burrowing megafauna communities' after tidal energy extraction, based on Maxent model using physical parameters output from FVCOM. Red areas indicate gains in habitat suitability, unchanged in white areas, losses in blue areas, but note very small range of change values.



**Figure 3.** Projected change in habitat suitability for 'seapen and burrowing megafauna communities' after climate change, based on Maxent model using physical parameters output from FVCOM. Red areas indicate gains in habitat suitability, blue areas indicate losses. Note difference in scale compared with Figure 2.

## SUMMARY OF FINDINGS

Habitat suitability for seapen and burrowing megafauna communities is well described by the distribution of mud and bottom temperature. Tidal energy extraction is predicted to have negligible effects on the availability and distribution of suitable conditions, but a northwards shift and overall habitat loss is predicted to occur in response to climate change.

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## 8: Effects of wave energy converters and climate change on the wave environment of the west coast of Orkney

Waves in Scotland are generated by winds in the North Atlantic and North Sea. A new computer model of the north Atlantic was developed to simulate this process, predicting waves from known wind conditions. This model was validated against measurements around the UK. The large model was used to drive a smaller, high resolution wave model of the west coast of Orkney in which wave energy converters (WECs) scenarios could be tested.

### APPROACH AND METHODOLOGY

A total of 318 wave energy devices were simulated off Orkney's west coast with a total capacity of approx. 245 MW, comprising 198 Attenuator type devices and 120 Terminator type devices, within the Round One lease zones designated by The Crown Estate (Figure 2). Recreations of individual devices in a wave-structure interaction modelling tool (WAMIT) were used to inform how they should be represented in the ocean scale model. Each device was modelled as a solid structure but representing the wave transmission, absorption and reflection by their respective coefficients obtained from the WAMIT model (Figure 1). The layouts of the arrays were based on Environmental Statements submitted by developers.

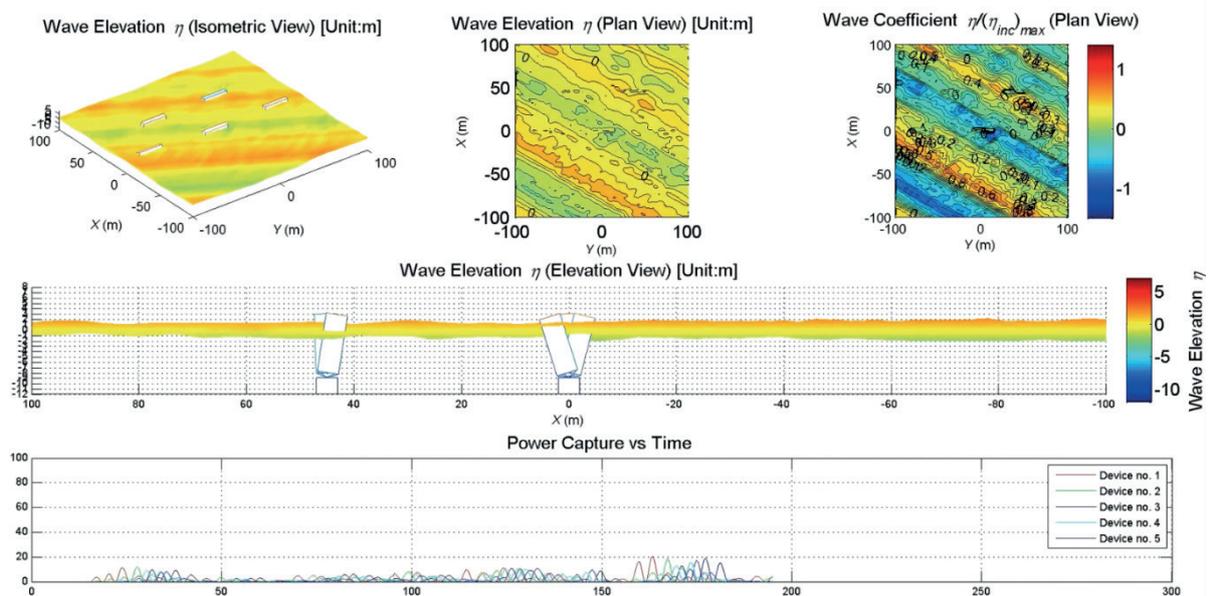
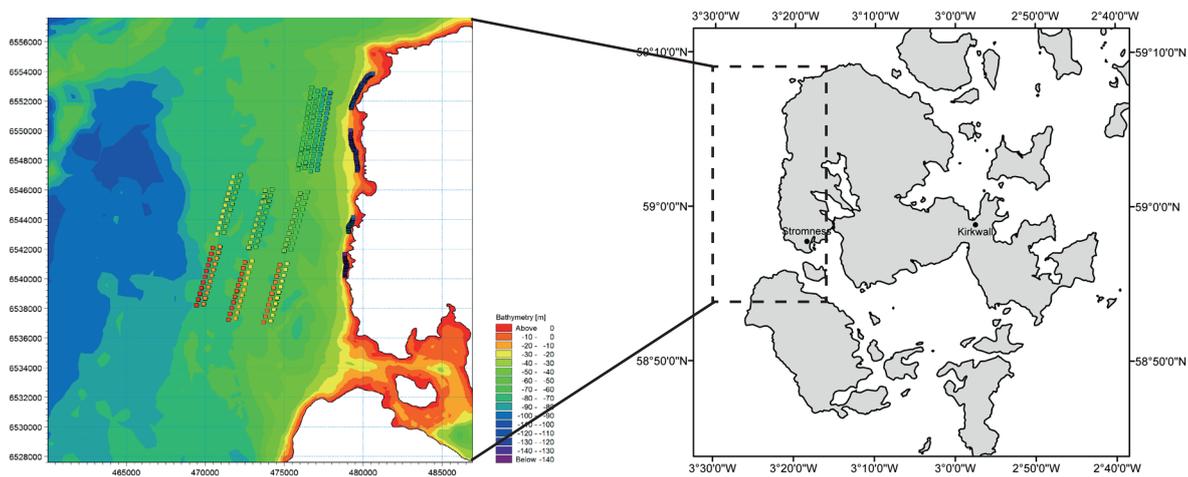


Figure 1.

Illustration of the use of WAMIT to develop input for the wave model



**Figure 2.**

Shows the layout of Terminator and Attenuator type devices in the wave model.

The waves entering the model were modified according to the predicted effects of climate change. Predictions of the changes to the North Atlantic wave climate by 2050, under the IPCC RCP8.5 emissions scenario, were obtained from a global ocean model developed by the EU RISES-AM-project. These changes were used to scale the heights of the waves entering our model. Water level was also increased by 25 cm as predicted in the IPCC AR5 report.

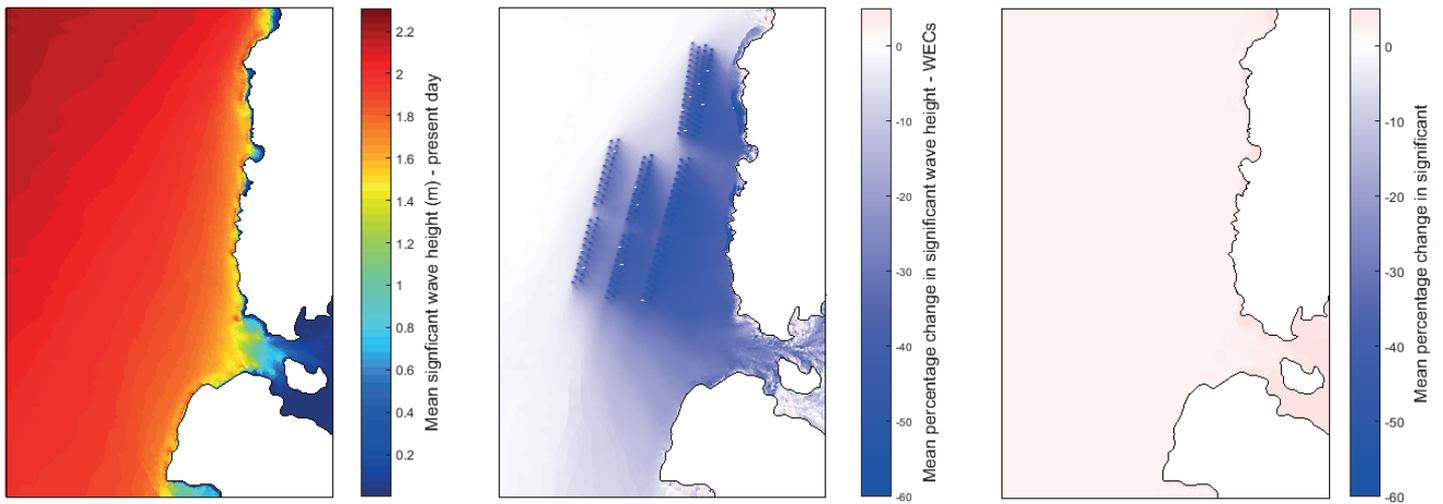
## FINDINGS

A reduction in mean wave heights of up to 50% was predicted down-sea of WEC arrays. Reductions close to the Orkney coast were predicted to exceed 50% near to inshore terminator devices, and reach up to 40% elsewhere (see Figure 3).

Potential receptors which could be impacted on the coast include:

- Benthic and intertidal species
- Coastal protection (including that for the Historic Environment Scotland site at Skara Brae) ( See Section 9).
- Surfers, and other recreational sea users

The climate change scenario did not predict any significant changes to wave conditions in the model domain.



**Figure 3.**

Map of the west coast of Orkney, showing the average effect, over six months, for (a) baseline present day conditions; (b) change due to WECs and (c) change due to climate change for significant wave height (m).



**Figure 4.**

Wave energy converters simulated in the model, Terminator on the left and Attenuator on the right.

## SUMMARY OF FINDINGS

Up to 2050, the effect of climate change on waves will be small, and much less than the potential effect of large scale WEC arrays. The expected changes to Atlantic waves affecting Scotland by 2050 are small, and so the changes to inshore waters are also small – typically <2%. This result is specific to the area modelled, and may not apply to other locations.

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## 9: Assessing effect of wave energy converters on embayed beaches

Wave energy converters (WECs) as a renewable energy resource have the potential to impact on the intertidal morphodynamics of beaches, which may have implications for coastal management. A numerical modelling study was carried out to investigate potential impacts of WECs on a coarse grained embayed beach located between two headlands.

### APPROACH AND METHODOLOGY

Bay of Skail, which is located in the west coast of Orkney, Scotland was selected as the study site. This beach is located in the vicinity of a proposed WEC lease site. The site also has national and international significance due to its close proximity to Skara Brae Neolithic Village. Bay of Skail (Figure 1) is a 1 km wide pocket beach with a predominantly bedrock subtidal seabed, a lens of sand sized sediment in the intertidal region and a cobble barrier protecting the shore face.

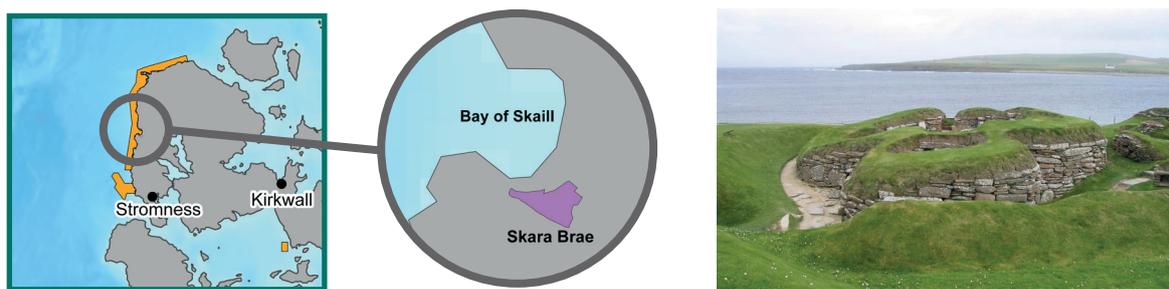


Figure 1.

Bay of Skail and its location in Orkney. The orange areas in the figures show sites leased for wave energy extraction.

The state-of-the-art MIKE3 model is applied to the study area to simulate waves hydrodynamics and non-cohesive sediment transport in Bay of Skail (Figure 2). The model simultaneously simulates waves, tidal flows, sediment transport and seabed change, taking into account interactions of waves, tides and sediment transport. Wave boundary conditions were taken from a regional scale model developed by The Crown Estate. Tidal boundary conditions were taken from the Danish Hydraulics Institute global tidal atlas. Sediment details of the mobile seabed were determined from sidescan sonar. The model was used to investigate morphodynamic change of the beach with and without WECs. Wave energy extraction areas are based on leased sites in the Pentland Firth and Orkney Waters (Figure 1). Given the uncertainties in deployment strategy, a worst case scenario of total absorption of wave energy is applied at the leading edge of the leased areas. The model was validated against measured cross shore profiles at 5 locations along the bay and good agreement found. Simulations were done over a 9 day period using characteristic average wave conditions.

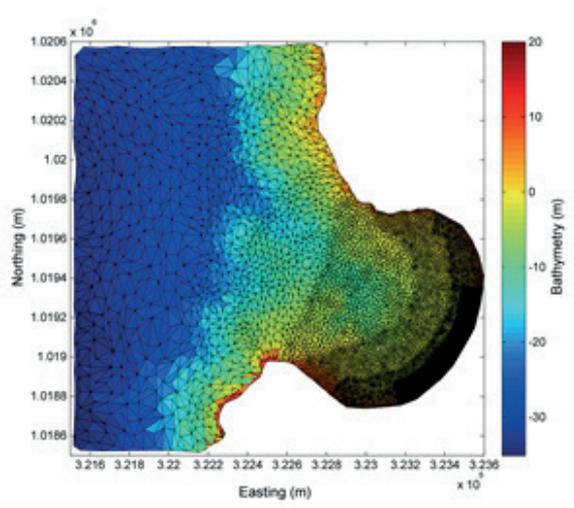


Figure 2.  
Bay of Skail model domain and computational grid in MIKE3.

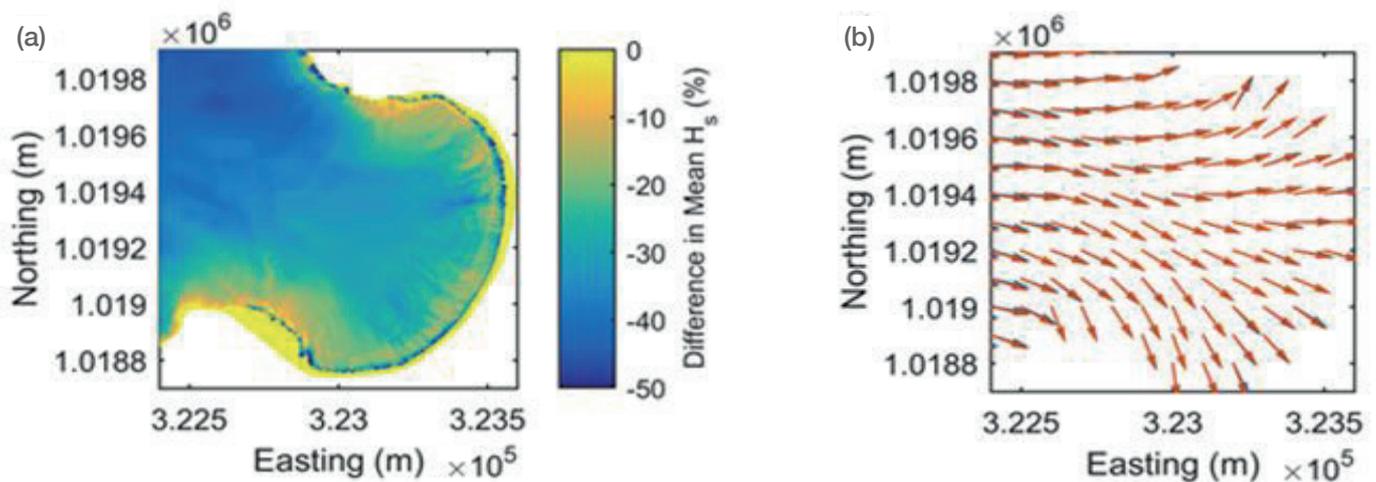


Figure 3.  
(a) Difference in significant wave height; (b) Change in wave direction (red arrows- with WECs, black arrows- without WECs).

## SUMMARY OF FINDINGS

The greatest reduction in wave energy due to WECs was found offshore of Bay of Skail.

Reduction in wave energy in the intertidal zone of the bay was between 5-30% for the WECs scenario used in this study. Impact of wave energy extraction on incident wave direction was insignificant (Figure 3).

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## 10: Effects of wave energy converters and climate change on kelp habitats: near-field effects inferred from large scale patterns

Large brown seaweeds, mostly kelp, are the most conspicuous feature of shallow subtidal rock on cold temperate latitudes. Kelp provide a habitat for many other species and act as shelter and feeding areas. Kelp also shed dead material, contributing large quantities of detritus to coastal ecosystems. Some will be directly consumed by suspension feeders, and much is potentially added to long-term carbon stores mitigating atmospheric CO<sub>2</sub> emissions.

Wave exposure is the dominant influence on patterns of local distribution of kelp species. In the absence of explicit physical models of wave climate, ecologists have used geographical indices based on the openness of coastal sites to incoming ocean waves and the distance to the nearest land ('wave fetch'). Wave-modelling is a better option, offering the possibility of linking distribution patterns in seabed species to real measurements such as bed stress and involving quantifiable mechanisms such as the effect of flow of dislodgement of organisms. However, computational demands prevent the application of wave models at the scales needed to characterise the habitats (sub-km scale), while encompassing the broadscale coverage of coastal surveys at scales designed to capture geographical variations in abundance (100's km).

For EcoWatt2050, we used large-scale patterns of the distribution of the five dominant UK kelp species in relation to temperature, waves and water clarity (derived from ocean colour satellites) to make predictive models for kelp habitat suitability. When coupled with predicted changes in wave climate around wave energy converters (WECs) and forecasts of temperature change, these habitat suitability models can predict likely changes due to wave energy extraction in a changing climate.

### APPROACH AND METHODOLOGY

We used kelp abundance data from the UK Marine Nature Conservation Review dataset of dive surveys (from JNCC), combined with summer sea surface temperature data (Section 5) for the present day, average surface chlorophyll concentrations from NASA ocean colour sensing satellites, and summed wave fetch (Figure 1a-c). Statistical models that characterise the patterns (Figure 1d) allow prediction of the likely presence and biomass of kelp for any combination of these environmental influences.

Models of the wave climate with and without WECs along the west coast of Orkney (see Section 8) were used to force statistical models.

### Kelp habitat suitability: changes with WECs

With the statistical models of kelp habitat suitability driven by patterns of temperature, water clarity and wave fetch, it was possible to map the predicted biomass of kelp of different species across the WEC site. For the wave-exposed kelp species, *Laminaria hyperborea* known as 'tangle', the model

predicted suitable habitat in shallow areas next to the shoreline on the outer coast, and in Hoy Sound, the western entrance to Scapa Flow (Figure 4b). For the wave-sheltered species, *Saccharina latissima* or ‘sugar kelp’, most biomass was predicted in the more protected conditions of the channels leading into Scapa Flow (Figure 4c).

In present day temperatures, the addition of WECs reduced the predicted total biomass of tangle across the WEC area by 1.0%, and increased the biomass of sugar kelp by 3%. Similar changes were predicted for the less-abundant species, a 2.0% decline for wave-exposed *Alaria esculenta* (dabberlocks), and small increases for *Laminaria digitata* (‘oarweed’, +1.1%) and *Saccorhiza polyschides* (‘furbellows’, +0.8%).

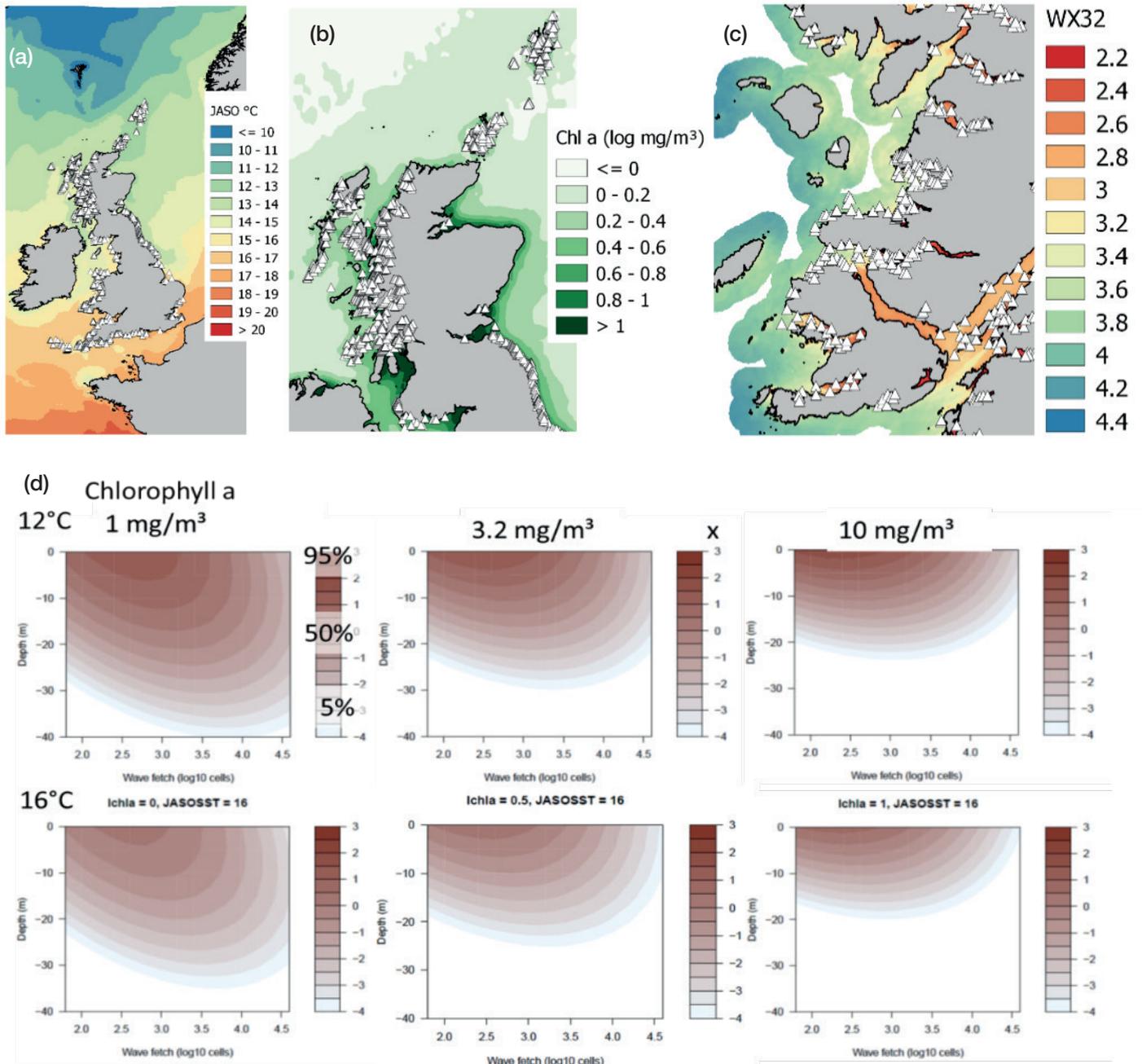


Figure 1. Patterns of kelp occurrence in historical surveys (triangles) around the UK in relation to (a) present day summer temperatures, (b) chlorophyll-a concentrations, and (c) wave exposure allowed the construction of (d) models of the likelihood of finding kelp as a combination of these factors. The model shown here is for sugar kelp (*Saccharina latissima*).

## Kelp habitat suitability: impacts of 2°C climate warming

Installation of WECs is likely to happen during a period of rapid climate change, and the changes likely to result from adding these devices should be compared with the effects of the changing climate over the same period. We used average summer temperatures for 2050 (Section 5). Globally, kelp is abundant only on cold-temperate coastlines, and most species in the UK show a decline in abundance across the gradient of average summer temperatures from 12 to 17°C. This geographical trend suggests that the 2°C warming by 2050 will result in declines. When the habitat suitability models were reapplied using 2050 temperatures for the area, overall declines were predicted for *Laminaria hyperborea* (-21%), *Alaria esculenta* (-53%) and *Saccharina latissima* (-25%), with increases only for the warm-water species *Saccorhiza polyschides* (+19%) and much-less-abundant *Laminaria digitata* (+57%). Climate change impacts therefore are likely to far outstrip those from the changing wave climate of adding WECs.

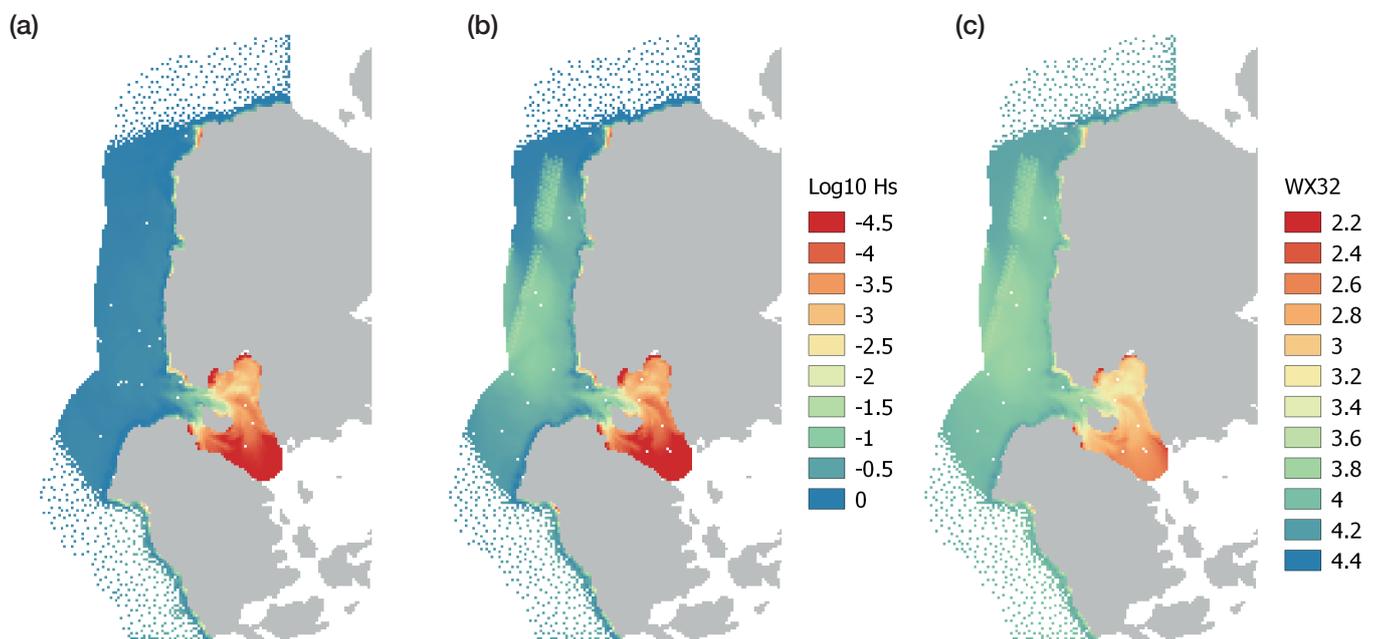
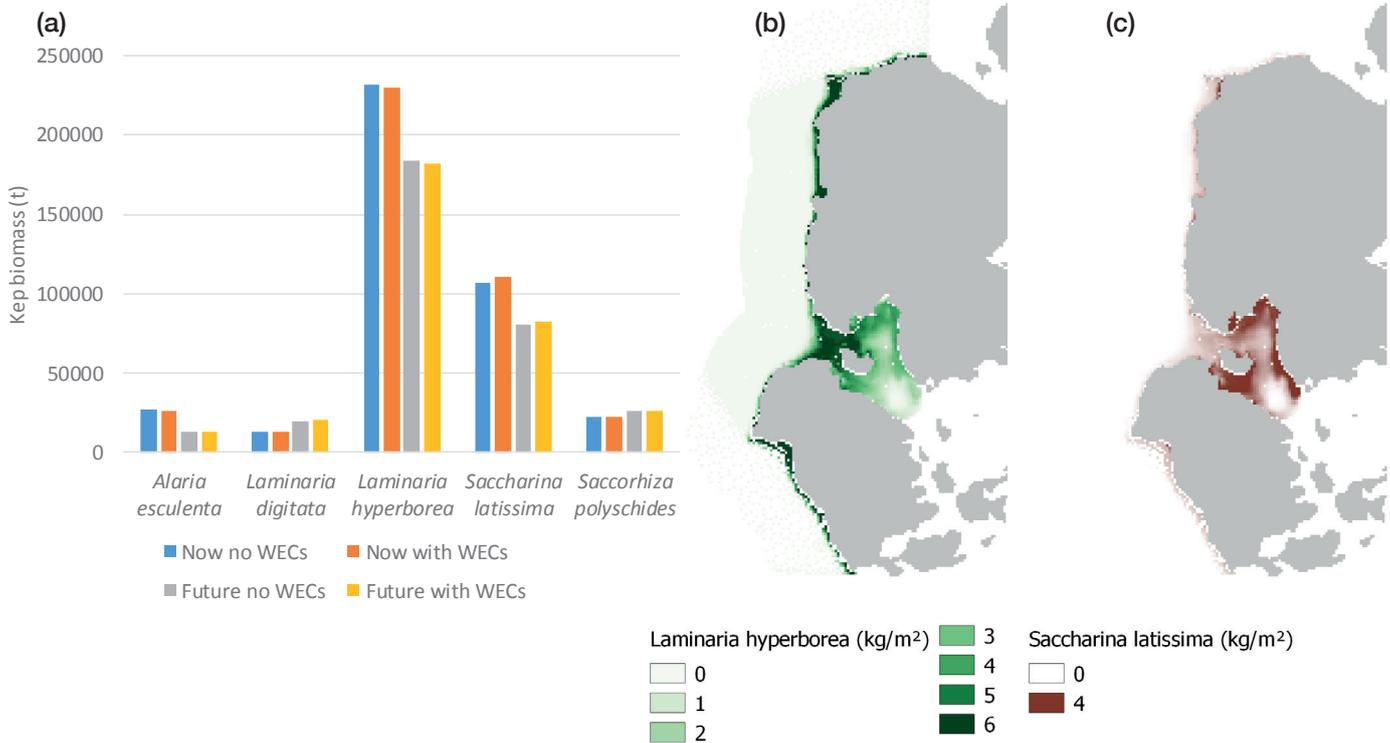


Figure 3.

(a) Without WECs, present day models show large wave heights all across the area, (b) but considerable reductions after adding a large array of WECs, and (c) the equivalent pattern in wave fetch units.



**Figure 4.**

(a) Changes in predicted kelp biomass across the WEC site, based on (b & c) changing maps of habitat suitability between present day conditions, without WECs (“Now no WECs”), future conditions (approximately a 2°C temperature rise, “Future no WECs”), and the same conditions after the installation of a large array of WECs (“Now with WECs”, “Future with WECs”).

## SUMMARY OF FINDINGS

Models that describe patterns in kelp populations across UK-scale gradients of wave exposure and temperature have been combined with physical wave climate models to forecast the effects of WECs on kelp abundance and biomass along the west coast of Orkney; both now and in a changed future climate.

The projected effects of WECs on kelp are small and species-specific, with kelp species characteristic of wave-exposed habitats declining in biomass by 1-2% and those from wave-sheltered habitats increasing by 1-3%.

Climate change has a much bigger effect on kelp: a 2°C increase in temperature by 2050 is likely to result in decreases in cold water species between 20 and 50% and increases of 20% for warm-water

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