Department for Environment Food & Rural Affairs

NERC SCIENCE OF THE ENVIRONMENT

EBAO

Optimising Array Form for Energy Extraction and Environmental Benefit

THE UNIVERSITY of EDINBURGH

SCOTTISH ASSOCIATION for MARINE SCIENCE

Loughborough University

UNIVERSITY OF EXETER

Cefas

Sea Mammal Research Unit

EBAO was funded under the NERC-Defra Marine Renewable Energy research programme, and ran for two years from September 2011. Led by the University of Edinburgh, the project consortium also included researchers from the Universities of Exeter, Loughborough and St Andrews (Sea Mammal Research Unit), plus Cefas and the Scottish Association for Marine Science (SAMS).

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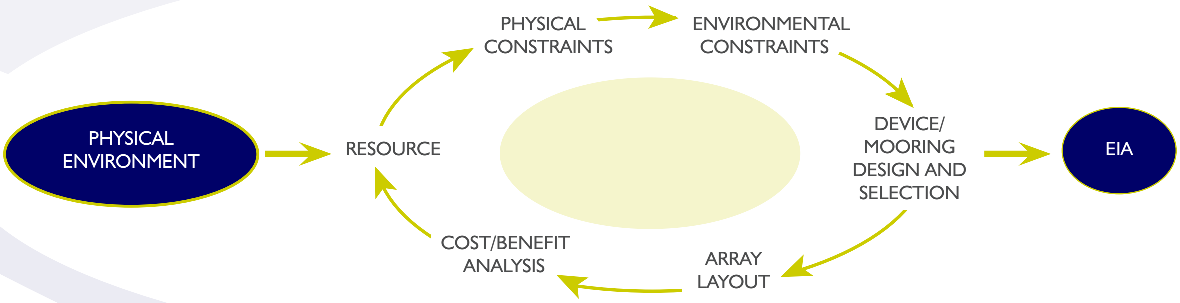
EBAO Overview

The EBAO project was developed to establish robust modelling methodologies that could be embedded into the marine energy project design cycle in order to protect, and even enhance, the natural environment while enabling array designs to maximise energy production. To achieve this, a unique consortium was assembled comprising marine environmental modellers with expertise covering the physical environment, marine ecosystems, acoustic propagation and marine mammal behaviour. The remit of the project included wave and tidal energy and, unusually for a project of this nature, offshore wind. Wind was included to enable contrasts between levels of industry maturity and scales of deployment, thus providing a wide range of potential case studies and illustrating future challenges that may be faced by the wave and tidal industry.

The aim of the project was to identify issues of environmental concern and uncertainty, develop new modelling approaches to address these issues, and demonstrate how the developed methodologies could be included in an integrated design process. Although there are variations from site to site, the usual approach to marine energy array design follows an iterative cycle similar to that shown in Figure 1. The process is based primarily on the physical site characteristics and available resource, and accounts for physical and environmental constraints in informing the design of devices, moorings and array layout for maximum financial return. Once the design process is complete, an environmental impact assessment is performed to ensure all potential impacts fall within acceptable levels, with mitigation measures established where necessary.

However, the EBAO team envisaged a process that integrates ecological acceptability throughout the design cycle (Figure 2). The local ecology would be included with the physical environment when characterising the site and a parallel environmental assessment cycle would sit within the standard design process. Information would be passed between the design and environmental assessment cycles as part of a two-way process, enabling the ongoing design process to inform environmental modelling studies, and results from the environmental work to feed back into the design cycle. An example of how this approach might work in reality is the design of channels for vessel access and maintenance within an offshore wind array. Such channels may also be highly beneficial to marine mammals attempting to swim through the site because there will be lower noise levels than in the main array. If initial plans for the channel dimensions are passed to the acoustic and mammal behaviour modellers, the likelihood of animals using the proposed channels can be assessed and any necessary changes to benefit animal movement proposed. A solution that meets the needs of both the engineering design and the local marine species can therefore be found at an early stage in the process.

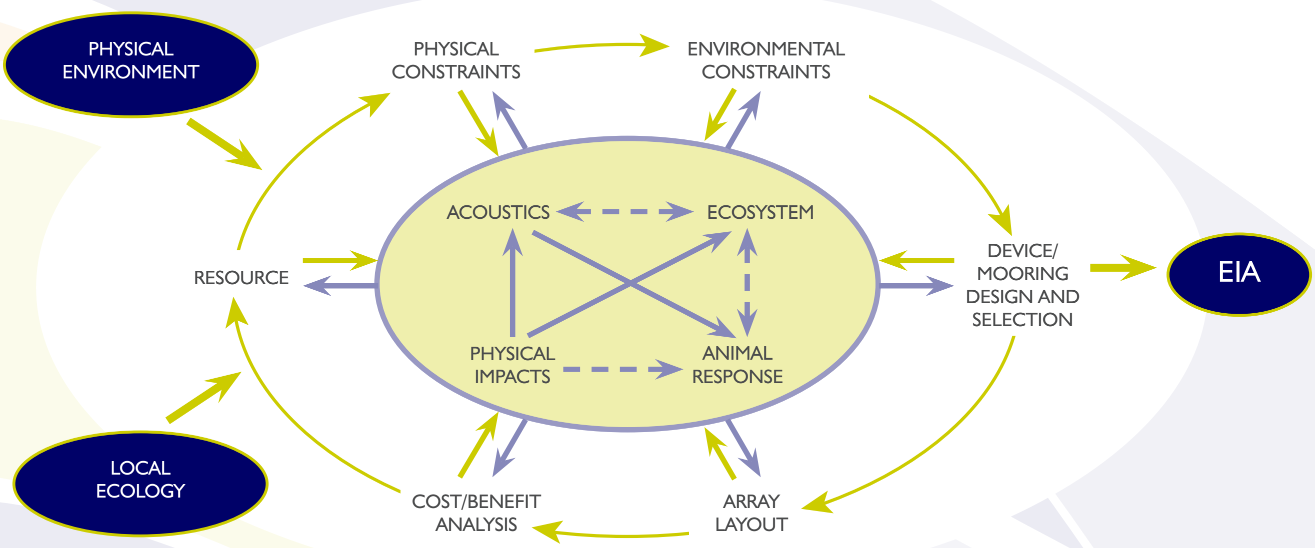
Figure 1: A typical marine energy array design process.



EBAO Overview (cont.)

What becomes clear when identifying and assessing potential impacts is that they should not be treated as stand-alone studies. In many cases, the links between the physical and ecological environment mean that a multi-disciplinary approach is needed. For example, acoustic transmission of device noise is affected by features of the physical environment such as the bathymetry, waves and currents. Changes to these parameters will therefore influence the acoustic models, and so physical impacts must be considered as part of the acoustic impact assessment process.

Figure 2: An integrated design cycle approach, incorporating the EBAO environmental modelling processes. Solid blue arrows within the environmental assessment cycle indicate co-dependencies investigated during the EBAO project, with dashed blue lines showing interactions requiring further research.



The limited duration of the project made it infeasible to assess all potential interactions. However, five key issues were identified as being of particular importance:

1. Ratio of device to ambient noise
2. Reaction of individual animals to a single device
3. Large-scale acoustic exposure
4. Large-scale physical impacts
5. Large-scale ecosystem impacts

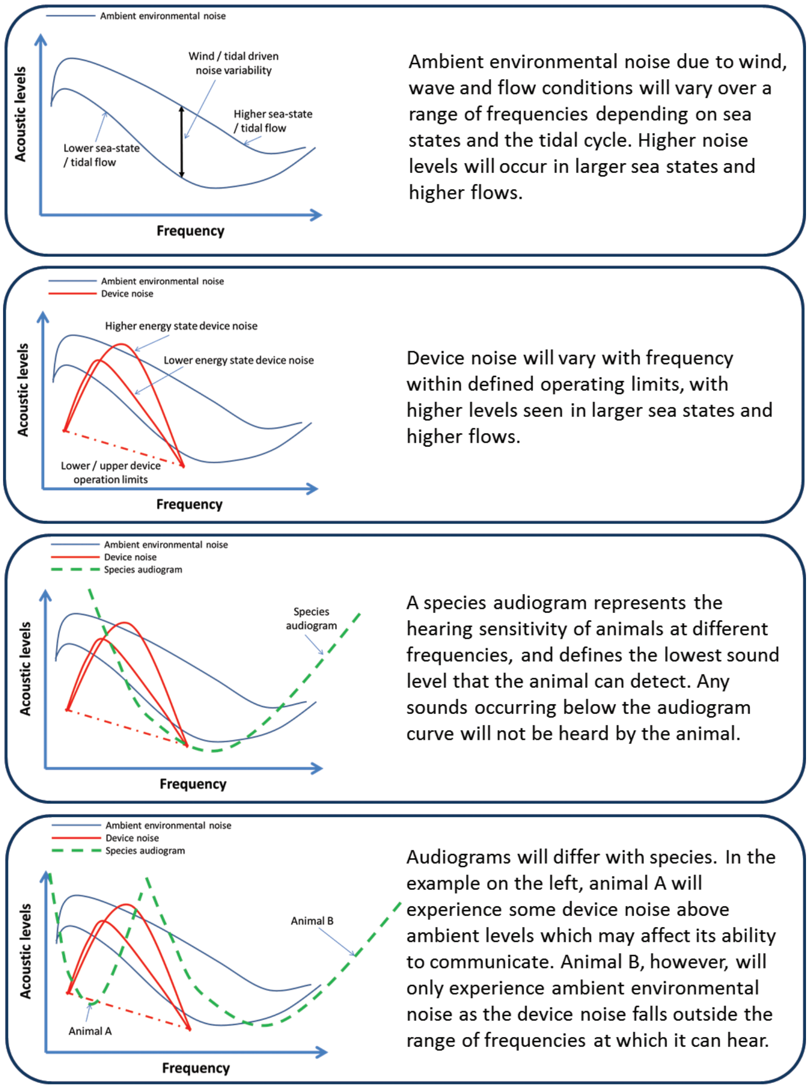
These were investigated in further detail to assess appropriate modelling approaches and the potential scale of the impacts.

The remainder of this report provides an overview of these issues, before presenting two case studies arising from them in greater detail and outlining how combinations of physical and ecological modelling techniques can be used to investigate these interactions. The report concludes with a series of recommendations for the incorporation of modelling methodologies into the marine energy array design cycle.

1. Ratio of device to ambient noise

Marine mammals such as dolphins and porpoises use sound for communication, navigation and locating food. This leads to particular challenges in areas of significant human activity, such as marine energy developments, where changes to the ambient noise environment through device noise or increased vessel traffic can mask their communication whistles. Ambient noise in the water column occurs due to wave motion and tidal flows and can be recorded at potential development sites across a range of conditions. Using knowledge of the acoustic signals emitted by devices, the ratio of ambient to device noise in the audio frequencies used by marine mammals can be investigated to identify the extent to which different species might be affected. This is described in more detail in Figure 3. It should be noted that operational noise is not the only device-related noise source. Studies should also be performed for the construction and decommissioning stages of a project, where pile driving, for example, will be far more intrusive in acoustic terms than ongoing operational noise. An increased knowledge and understanding of the acoustic signals relating to installation and operation of different devices in a range of conditions is therefore essential in order to fully understand the potential impacts.

Figure 3: Importance of the ratio of device to ambient noise for marine mammal communication.

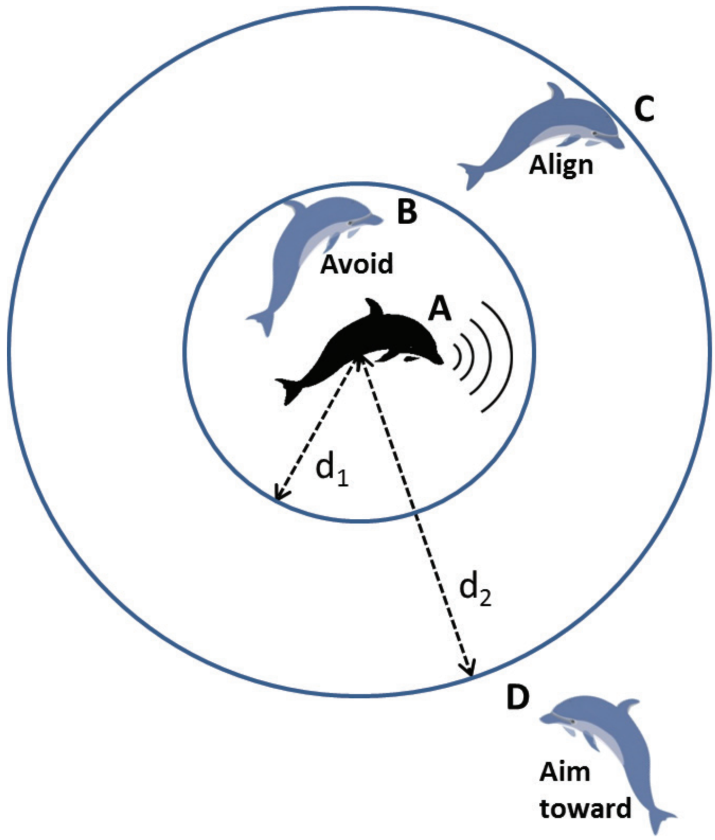


2. Reaction of individual animals to a single device

In situations where underwater noise sources such as tidal turbines mask the whistles used by marine mammals, a particular area of concern is how communication within a group, or even between a mother and calf, might be affected. Marine mammals use sound to maintain their group dynamic, with individuals emitting and responding to whistles at a particular frequency and sound level. In the example shown in Figure 4, animals B, C and D will respond to signals from animal A depending on their proximity. Animal B, at a distance less than d_1 (~4m), will use the loud short-range signal for collision avoidance. Animal C, at a distance between d_1 and d_2 (~4-10m), will use the mid-range signal to align itself with A, and animal D, at a distance greater than d_2 (~10m), will use the quieter long-range signal to move back towards the group.

Models were developed to investigate the behaviour of pairs and groups of animals in response to acoustic signals from tidal devices and predict scenarios in which animals would become separated from the group. Further details are provided in Case study 1 on page10.

Figure 4: Effect of distance on marine mammal response to whistles emitted by a member of the group.

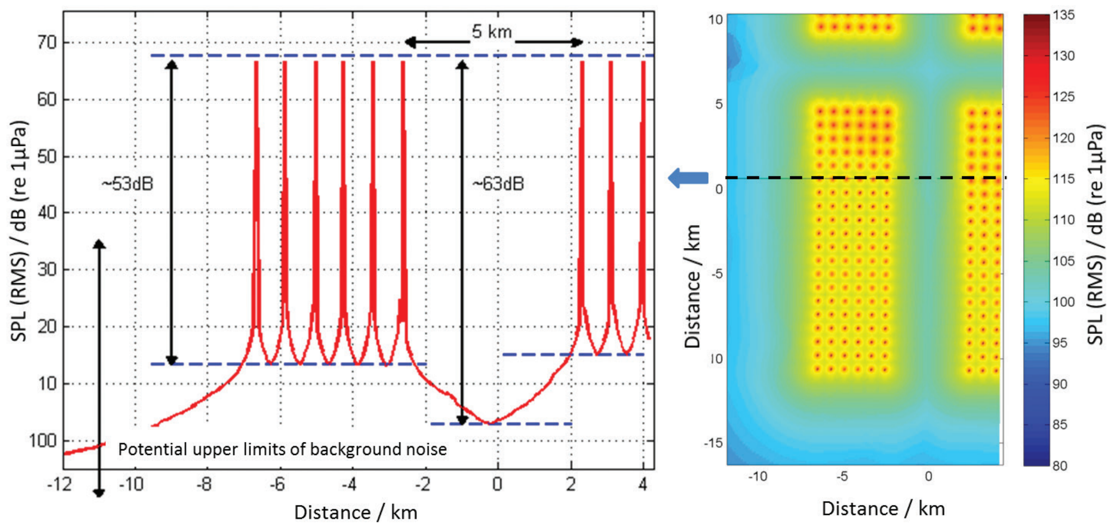


3. Large-scale acoustic exposure

Although the issues associated with individual devices or small arrays are important to understand at a local level, they are unlikely to lead to significant wider impacts. However, the scale of developments currently being proposed for offshore wind, and the potential wave and tidal arrays of the future, mean acoustic exposure over much wider areas must be considered. The cumulative noise arising from multiple devices within an array may mean that animals swimming toward the array may choose to avoid the array completely or swim around it. For smaller arrays, this may not lead to significant impacts. However, for a very large array measuring tens of kilometres in each direction, if noise levels mean that animals are avoiding the area completely the result could be the exclusion of particular species from a large area of sea. The food chain in the region could be altered, leading to fundamental changes in the ecosystem.

However, these issues can be mitigated through careful array design. EBAO modelling studies have shown how cumulative acoustic exposure within an offshore wind array might vary along a transect which passes from open water through a farm of turbines, across an access channel, and then into a second farm (Figure 5). Acoustic intensity peaks in the immediate vicinity of the turbines, potentially masking marine mammal communications, then drops away to within the normal background noise limits between turbines. However, in the channels between farms, noise levels drop significantly lower, potentially providing a quieter route for animals through the large array.

Figure 5: Variation in acoustic intensity along a transect through a section of a large offshore wind array.



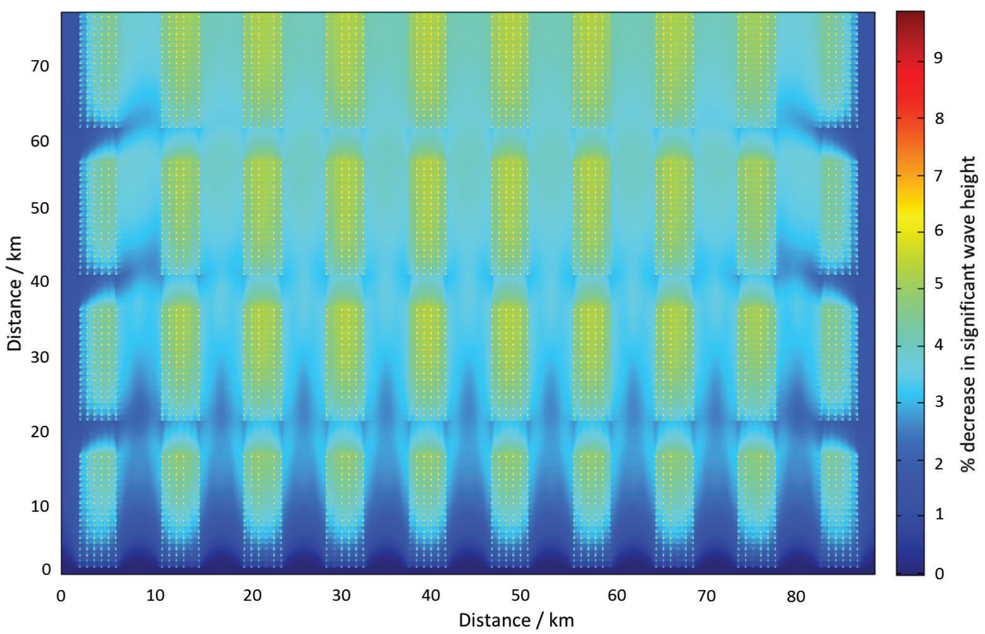
4. Large-scale physical impacts

Extracting energy from the wind, waves or tidal flow will reduce the level of resource in the wake of devices, and for tidal flows will affect the overall flow regime. Modelling methods for assessing effects of single devices or small arrays are becoming increasingly established, but the computational power required to apply these tools to arrays of several thousand devices makes it challenging to scale up high resolution studies to assess impacts of these very large arrays.

During the EBAO project, wave and tidal modellers investigated both tidal and large-scale wave and wind array modelling techniques. Tidal modellers used the flow modelling software TELEMAC-2D to investigate appropriate methods of representing tidal turbines in the model, and then applied these to different array scenarios in a realistically-shaped tidal channel with highly variable flow speeds across the channel. Results from the simulations were then passed to the marine mammal modellers investigating animal response to turbine noise in such channels.

The wave modelling was performed using the SWAN spectral wave model. Although unable to model wave radiation and inter-device interactions, SWAN provides a facility to represent wave energy devices as partially transmitting barriers that absorb a user-defined proportion of the incident wave energy. The model was set up to model both large wave arrays (up to 50 devices) and very large offshore wind arrays (up to 4800 turbines). The wind farm case is particularly interesting because the turbine towers themselves do not absorb wave energy, they merely block it. However, with sufficient turbine numbers, the cumulative effect of such blockage was found to be significant (almost 10% maximum wave height reduction), and variable across the array (Figure 6). This information is therefore important for other modelling studies including acoustic transmission and ecosystem impacts which use parameters such as wave height as model input.

Figure 6: Modelled reduction in significant wave height across a 4800 turbine array, with 2m waves and a 10ms^{-1} wind from the south.



5. Large-scale ecosystem impacts

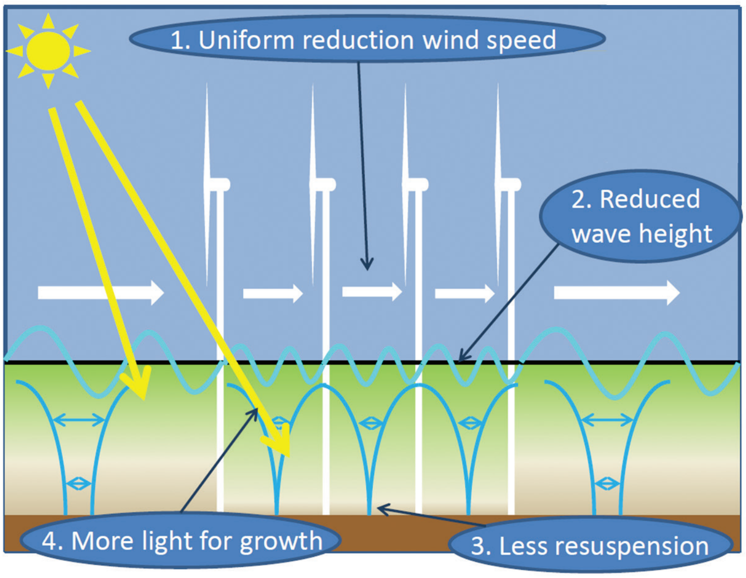
One of the least addressed areas of environmental impact from marine energy is the potential effect on the wider ecosystem, mainly due to the relatively small scale of existing developments which makes these types of impacts unlikely.

Although changes in the food chain and species populations may occur due to increased acoustic exposure, changes in the physical resource due to large-scale developments may have significant impacts on the bio-chemical composition of the water column, leading to wide-scale ecological impacts on microorganism levels. Figure 7 summarises the subset of processes investigated here, which can be described as follows:

- Energy extraction by large arrays of wind turbines will lead to a reduction in wind speed both within the array and in its lee.
- Reduced wind speed, plus interactions with turbine towers, will lead to a reduction in wave heights within the array and in its lee.
- Lower wave heights mean wave motion does not propagate as far down into the water column, leading to less interaction between the waves and the seabed.
- Less wave motion at the seabed means less resuspension of sediment and lower levels of turbidity in the water column.
- With lower turbidity, sunlight can penetrate further into the water column, leading to enhanced primary production and plankton growth.
- Enhanced production leads to a growth in the numbers of smaller organisms, and this in turn attracts larger predators, thus affecting the food-chain and the overall ecology of the region.

A large-scale marine energy development, or the cumulative effects of many smaller developments, could therefore lead to impacts beyond the immediate vicinity of the array. Case study 2 on page 12 presents the results of a study to investigate these impacts in the North Sea.

Figure 7: Ecosystem impacts due to changes in the physical resource.



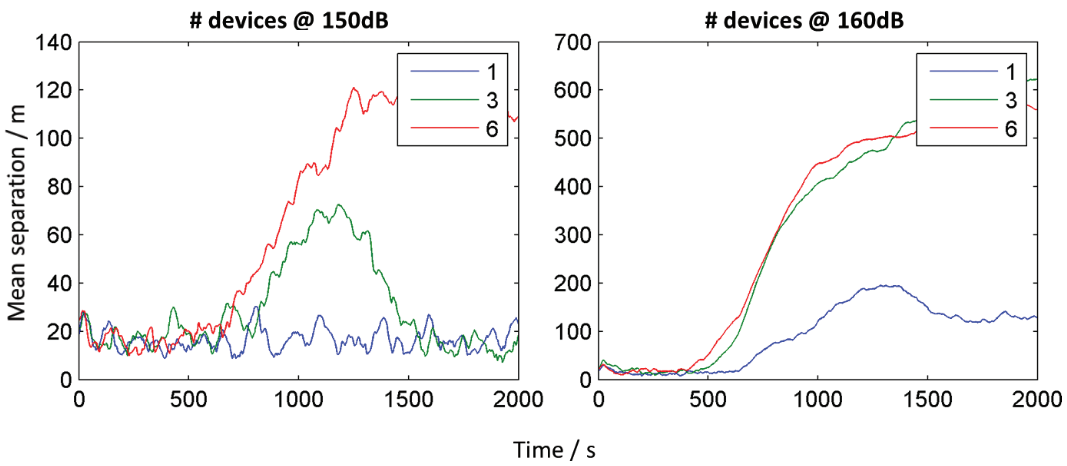
Marine mammal response to underwater noise

EBAO researchers developed a model to predict the impact of device noise on groups of marine mammals swimming in the vicinity of an array of tidal energy devices. The model is based on particular characteristics of animal movement and group behaviour, with three fundamental behaviours identified: the swimming speed, the random whistles emitted (including sound level, length of whistle and frequency of whistle), and the probability of a listening animal responding to the whistle. The response of the listening animal will be one of the actions described in Figure 4, i.e. avoidance, alignment or swimming towards the vocalising animal, depending on their separation. A standard formula for the transmission loss of the acoustic signal with distance and frequency was applied. A random element was also added to the model to represent small changes in an animal's direction of travel in the absence of hearing any whistles.

Two contrasting scenarios were investigated: a channel containing up to six tidal turbines and an area of open water containing up to 400 devices. In each scenario, two different animal group sizes were considered: two animals (for example a mother and calf), and a group of 10 animals. Different numbers of devices with individual device noise levels in the range of 130 – 170dB (with animal vocalisations of 150dB) were assessed.

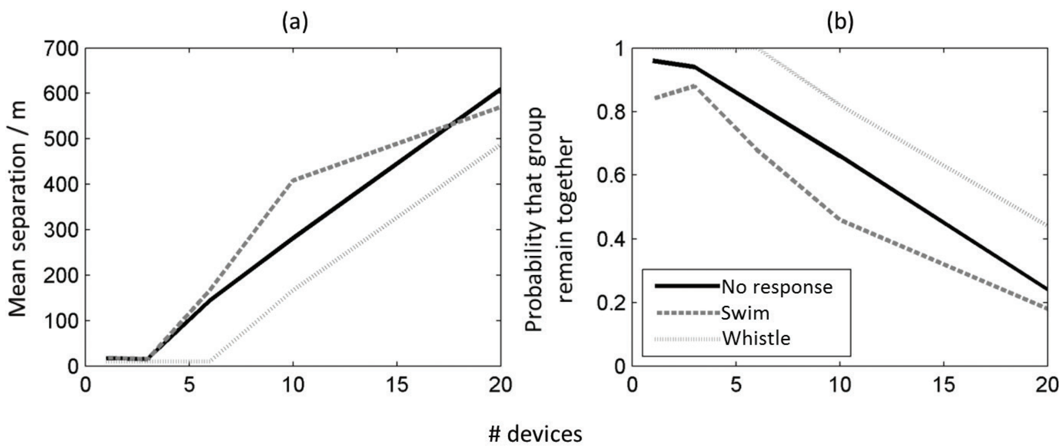
A subset of the results for the mother-calf channel scenario is shown in Figure 8. These show how the mean separation between the two animals is affected over time by both the number of devices and the noise level emitted by the devices. For example, for a single device at 150dB, separation stays relatively constant, up to around 30m, indicating that the animals' communication has not been adversely affected. In contrast, three devices leads to a much larger temporary separation, although the animals move back together once out of the vicinity of the devices. An array of six devices, however, leads to a larger and possibly more permanent separation. The contrast between devices emitting noise at 150dB and 160dB is notable, with the increased noise leading to significantly larger separations and increased impacts with fewer turbines.

Figure 8: Mean separation between a mother and calf over time due to device noise from up to six turbines in a tidal channel.



However, animals have methods which enable them to mitigate these impacts in some cases. These include increasing their whistle rate, increasing their rate of response to whistles, or moving in larger groups (groups of 10 were more 'robust' than groups of two). Figure 9 shows how the mean separation increases with the number of devices, and the impact of increased panic swim speeds, or increased whistle rate. The risk of separation reduces due to both an increased rate of whistles and an increased response rate. However, faster 'panic swimming' in the presence of loud sounds does not help animals stay together.

Figure 9: Impact of altering behaviour for two animals swimming past devices in a channel. (a) Mean separation of pairs of animals after 50 simulation runs. (b) Proportion of runs in which animals remain together in a tight group. The dashed line indicates the effect of swimming faster in response to loud sounds, and the pale line indicates the impact of whistling more frequently.



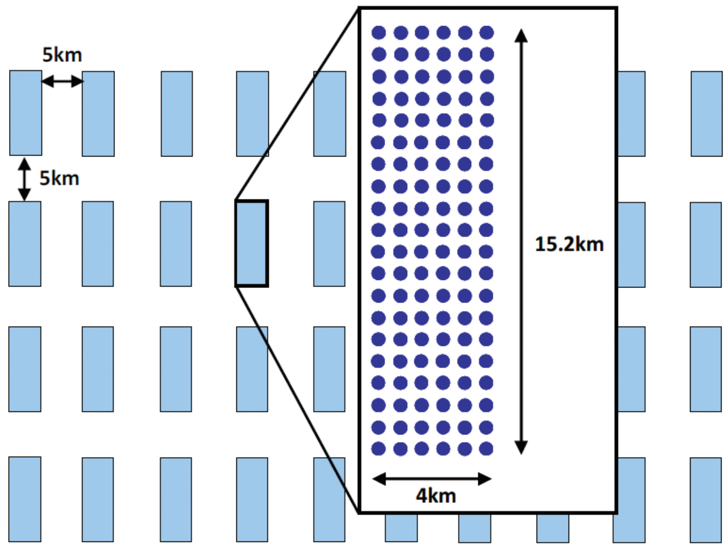
IN SUMMARY:

- Arrays of devices acting as sources of sufficiently loud underwater noise in the frequencies used for communication by marine mammals have the potential to impact on the movement and group cohesion of the animals.
- The impact of multiple devices is not simply additive, e.g. an array of six turbines does not lead to double the separation caused by three turbines.
- Impact occurs across a wider area than the immediate region where the animal vocalisation is masked by device noise.
- Device noise has the potential, in extreme cases, to lead to permanent separation between animals. This could have serious implications for the survival of young animals or for the coordination of group feeding activities.
- A range of animal behaviours may mediate the impact, potentially enabling animals to adapt to future developments.
- Regrouping downstream may be possible after separation, particularly in high current speeds or if whistle levels are elevated.

A multi-layered modelling approach to assess large-scale impacts

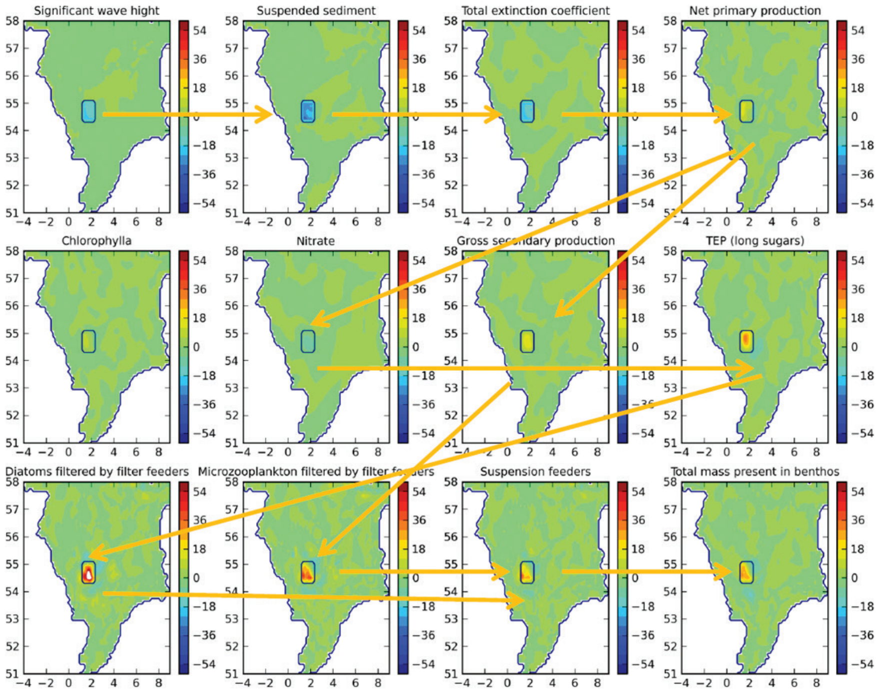
Physical, acoustic and ecological modellers from the EBAO team combined their expertise to develop a multi-layered modelling approach to assess wide-scale consequences of large array deployment. For this study, a 'large' array was taken to measure tens of kilometres by tens of kilometres, i.e. significantly larger than any currently planned wave and tidal developments. The study was based on a hypothetical offshore wind development in the North Sea, of a scale that might realistically be seen in the next 50 years. The study envisaged an array of up to 4800 turbines, with a key feature of the array design being a recognition that for reasons relating to construction, operational access and cabling, the array would need to be divided into smaller 'farms' separated by wide access channels. The basic array design investigated therefore comprised 40 farms of 120 turbines, separated by 5km channels (Figure 10). Variations on this layout, including wider channels and larger and smaller farms were also investigated.

Figure 10: Basic layout of a large hypothetical offshore wind array of 4800 turbines, constructed as forty individual farms of 120 turbines with 800m spacing (van der Molen et al., 2014).



The first stage of the process was the setup of a coupled physical-biogeochemical model (using a combination of two different models, GETM and ERSEM-BFM) to explore the potential effects of wind energy extraction across the array. The complexity of the model meant it was run at a spatial resolution of 11km, covering the whole of the North Sea. The primary driver of ecosystem change is the reduction in wind speed in the array as described on page 9. A 10% reduction was applied based on reported observations from other sites, leading to a reduction in wave height of 17% and a reduction in suspended sediment concentration of 25%, and resulting in an increase in primary production of 8%. These results, and impacts on a range of other nutrient and microorganism concentrations, are shown in Figure 11.

Figure 11: Relative changes between a reference run with no turbines and a model run based on an array of 4800 turbines. The wind farm array location is shown by the black rectangle.



In order to validate the estimated reduction in wind speed and thus wave height, a high resolution model of the entire array including individual turbine towers was established using the spectral wave model SWAN. For the basic array layout in Figure 10, the spatially varying reductions in wave height shown in Figure 6 were obtained. For this scenario, an average reduction in wave height of 5.9% was obtained across the array, with a maximum reduction of 9.6%. The average reduction is less than half that predicted by the ecosystem model, suggesting the ecological impacts may be less severe than the model predicted.

The third stage of the process was a high resolution acoustic modelling study, with each turbine location represented in the model as an individual sound source. This enabled the overall levels of acoustic disturbance to be modelled, and noise levels with increasing distance from turbines to be established as illustrated in Figure 5. These data can then be used to assess the behaviour of groups of marine mammals, building on the work presented in Case study 1.

IN SUMMARY:

- Large marine energy arrays have the potential to cause a small increase in food levels within the array.
- The array area will also experience reduced wave conditions but increased levels of noise.
- These factors combine to provide an attraction to marine species (increased food, calmer seas) offset by the deterrent of noise and obstacles.
- The combined impact will be experienced to varying degrees across the array, depending on array layout and distance from turbines.
- Effects decrease with increasing distance between individual turbines and farms, suggesting that a smaller number of more powerful turbines may cause less impact than larger numbers of smaller ones.

This case study has been published as 'van der Molen et al., 2014'.

Conclusions and recommendations

EBAO has successfully demonstrated the value of a multi-disciplinary modelling approach to assessing potential environmental impacts due to marine energy arrays. For the wave and tidal energy industry in particular, the lack of deployed arrays means very few data points are available to inform impact assessment studies. Modelling studies are therefore crucial for predicting the impacts of early arrays and de-risking projects. However, the early wave and tidal arrays will be small and therefore impacts are also likely to be limited. By including offshore wind in the project scope, EBAO researchers were able to extend the studies to very large scales and address questions of what the most significant impacts might be many years in the future. The multi-disciplinary approach is vital to this work; the physical marine environment influences the marine ecology, and impacts to one will affect the other. Research in the areas covered in this report is ongoing, and there are a number of interactions between the different modelling disciplines still to explore. These include linking the mammal response studies with the large-scale acoustic modelling, and further investigating how impacts on the physical environment will affect both the acoustic modelling results and mammal behaviour.

Incorporating these types of modelling studies into the array design cycle rather than applying them at the end of the process has potential benefits for project developers and environmental stakeholders alike. Integrating small changes into array designs may lead to significant environmental benefits, reassure stakeholders and facilitate the consenting process. Communication between environmental scientists and project developers and engineers is key to making this happen.

EBAO has also demonstrated that the need for data sharing is increasingly important. Although individual companies are collecting large quantities of environmental and acoustic data from their testing and deployment activities, the proprietary nature of these datasets means they are rarely shared outside the project, necessitating duplication of effort and expense.

A controlled database of records from these early projects, accessible to all engineers and scientists working in marine energy, would speed up the development of appropriate modelling tools and facilitate the de-risking of projects.

As a final point, part of the process of producing this report involved interviews with a number of marine energy developers, regulators and consultants. One of the clear messages received was the need for better engagement between the industry and academia, both to raise awareness in the academic community of what the industry really needs and to disseminate research outputs that may have tangible benefits for the industry in an accessible way. This report is intended to be a stepping stone in that direction for the EBAO research. The project partners welcome any feedback or questions on the work presented here.

If you would like to discuss any aspects of the work further, please contact Helen Smith at h.c.m.smith@exeter.ac.uk.

EBAO references

Further details on the studies performed and results obtained through EBAO can be found in the following publications and conference papers:

Adams, T., Wilson, B., Hastie, G. & Lepper, P., 2014. Sticking together: movement of marine mammals and response to underwater noise. Proc. 2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR 2014), 28 April – 02 May 2014, Stornoway, UK.

Adams, T., Wilson, B., Hastie, G. & Lepper, P., 2014. Sticking together: simulating movement of marine mammals and response to underwater noise. *Journal paper in preparation.*

Perez-Ortiz, A., Pescatore, J. & Bryden, I., 2013. A systematic approach to undertake tidal energy resource assessment with Telemac-2d. *Proc. 10th European Wave and Tidal Energy Conference*, 02 – 05 September 2013, Aalborg, Denmark.

Smith, H.C.M, 2014. Modelling changes to physical environmental impacts due to wave energy array layouts. *Proc. 2nd International Conference on Environmental Interactions of Marine Renewable Energy Technologies (EIMR 2014)*, 28 April – 02 May 2014, Stornoway.

van der Molen, J., Rees, J. & Limpenny, S., 2013. Modelling potential changes in marine biogeochemistry due to large-scale offshore wind farms. *Geophysical Research Abstracts*, vol. 15, EGU2013-7233.

van der Molen, J., Smith, H.C.M., Lepper, P., Limpenny, S. & Rees, J., 2014. Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem. *Continental Shelf Research,* 85, p.60-72.

van der Molen, J., van Leeuwen, S., Farcas, A., Limpenny, S. & Rees, J., 2014. Modelling hydro-biogeochemical effects of an offshore wind array. *AMEMR IV*, 30 June - 04 July 2014, Plymouth, UK.

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