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Marine Renewable Energy MRE1

Annual Report

Marine Mammals and Tidal Energy

Sea Mammal Research Unit

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Executive Summary

The work presented under the Marine Renewable Energy (MRE) theme falls in to three tasks;

MRE 1.1 – Fine scale marine mammal behaviour around tidal energy devices.

MRE 1.2 – Harbour seal movement modelling.

MRE 1.3 – Estimating collision risk using available information.

This annual report only considers MRE 1.1 as MRE 1.2 and 1.3 have been completed and are available here: http://www.smru.st-andrews.ac.uk/reports/.

MRE 1.1

This task aims to monitor the behaviour of marine mammals in the vicinity of an operational tidal turbine. A monitoring system utilising a combination of Passive Acoustic Monitoring (PAM), Active Acoustic Monitoring (AAM) and video cameras was deployed on a MeyGen turbine in the Pentland Firth to identify marine mammal species using the areas around the turbine and to construct 3D tracks of their movements.

After initial deployment on 24th October 2016, power to the turbine did not become available until 18th October 2017 when initial communications tests established that the PAM system was fully functional. However, no communications could be established with the video cameras or the Gemini multibeam sonars.

The sonar platform was recovered by SIMEC Atlantis Energy on 23rd July 2018 during planned operations to recover two other turbines. Subsequent inspection and fault diagnosis was undertaken by SMRU personnel at Nigg Energy Park on 7th August 2018. A number of possible failure points were identified including minor damage to the umbilical cable from the TSS, severe corrosion of the Hydrobond connectors used to attach the umbilical cable to the junction box, and water ingress in the junction box.

Since commissioning in October 2017, the PAM system has been operating stably for 95.3% of the time. The turbine was removed for maintenance from 22nd September 2018 to 18th December 2018, with PAM data collection resuming on the 19th December 2018.

The PAM system remains operational with routine checks and data archiving continuing. As agreed in the Steering Group meeting on 19th September 2018, monthly reporting was discontinued following the September 2018 report. Data collected following 31st January 2019 will not be manually processed for detections.

From the start of data collection up to the end of 31st January 2019 (~ 13 months monitoring), a total of 27 dolphin and 571 harbour porpoise encounters ($\geq$ 30 clicks) were made. This equates to a mean of 1.6 (SD = 1.0) porpoise encounters and 0.1 (SD = 0.2) dolphin encounters per day.

A key output from the PAM data analyses will be the 3D locations of echolocation clicks in relation to the position and operational status of the turbine. Field trials to calibrate 3D localisation algorithms were conducted on 6th August 2018. This involved pinging the PAM array with a sound source from a vessel at known locations and depths. Data collected in these trials have been useful with the ongoing refinement of the PAMGuard localisation algorithms.

24 harbour seals had previously been tagged in the Inner Sound to quantify the movements of seals in a wider spatial context. A further 16 harbour seals were tagged between 16th and 24th April 2018. Of these, 12 transmitted location data and 12 transmitted high resolution dive data.

Of the tags deployed in 2018, 504 days of data were collected which included 53,484 GPS locations. Tagged seals spent ~12% of their time within the Inner Sound and ~0.001% within the MeyGen lease area. A total of 3 GPS locations were recorded within 50m of a turbine and the closest GPS location was 37m from a turbine.

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Marine Renewable Energy (MRE) Theme

Concerns about the impacts of tidal energy devices on marine mammals derive primarily from the potential for injury or mortality as a result of direct interactions (collisions) between animals and moving rotors of tidal devices. However, the true risks posed by these devices remain uncertain due to a paucity of information on a) how marine mammals behave in close proximity to operating tidal turbines, b) how marine mammals use tidally energetic areas proposed for development, and c) the individual consequences of collisions with turbines.

The MRE 1 work package comprises of three linked tasks. Together, these will be used to derive parameters required to populate improved collision risk models and to directly measure potential interactions on instrumented tidal turbines.

MRE1.1 - Fine scale marine mammal behaviour around tidal energy devices

1.1 Introduction

This task aims to monitor the behaviour of harbour seals and other marine mammals in the vicinity of an operational tidal turbine. It is based on the technology that was developed under the Scottish Government contract ‘Demonstration strategy: Trialling methods for tracking the fine scale underwater movements of marine mammals in areas of marine renewable energy development’ (Sparling *et al*., 2016). This previous work developed a combination of Active Acoustic Monitoring (AAM) and Passive Acoustic Monitoring (PAM) techniques for deployment on the turbine and on a seabed mounted platform to detect and track marine mammals at a high resolution (at a scale of metres). The work described here builds on the development phase by designing, manufacturing, and deploying a combination of an AAM sensor platform and turbine-based PAM and video at an operating tidal turbine. This aims to provide data on the movements of marine mammals around the operating turbine that will form the basis of an analysis of close range encounter rates and marine mammal behavioural responses to the turbine.

This task uses a suite of AAM/PAM/video sensors deployed alongside an operating tidal turbine for a minimum one year period. This is being carried out at the MeyGen Inner Sound development in the Pentland Firth, which is an array of four tidal turbines (three Andritz Hydro Hammerfest HS1000 turbines and one Atlantis Resources Ltd AR1500 turbine); the sensor system has been integrated into the Atlantis AR1500 turbine. The Atlantis AR1500 turbine is a 1.5MW horizontal axis turbine with active pitch and yaw capability. It has 18 m diameter rotors that rotate at nominal maximum speeds of 14 rpm; the total height of the turbine above the seabed is 24 m. All four turbines have been deployed and are operational.

Information on the occurrence of animals and their movement tracks will be matched with rotational information from the turbine developer as well as tidal phase and speed of current information to allow analyses of close range avoidance responses of marine mammals to the tidal turbine. Overall, the analyses aim to provide the information required to reduce uncertainty in current collision risk models.

1.2 Deliverables

<u>Deliverable 1</u>: Sensor platform commissioning and deployment at turbine (complete).

<u>Deliverable 2</u>: Investigation of frequency of fine scale interactions between marine mammals and operational tidal turbine (initial findings report after one month of turbine operation).

<u>Deliverable 3</u>: Monthly reports of detections of marine mammals from AAM and PAM installed on the MeyGen tidal turbine (for 12 months from end of turbine commissioning) (complete).

<u>Deliverable 4</u>: A final report detailing the frequency and nature of the fine scale interactions between marine mammals and an operational tidal turbine, the broader scale movements of seals in relation to operating tidal turbines, and recommendations on monitoring equipment and protocols for the detection and tracking of marine mammals around tidal turbines.

<u>Deliverable 5</u>: A PhD thesis on the fine scale movements of top predators around a tidal turbine.

1.3 Progress and results

1.3.1 Deliverable 1: Sensor platform commissioning and deployment at turbine.

Following commissioning of the sensor system, no data were acquired from the Gemini multibeam sonars on the High Current Underwater Platform (HiCUP) or the video camera. A summary of the hardware, deployment and the initial fault tests were provided in an Environmental Monitoring System Commissioning Report (Gillespie *et al*., 2017). To date, the PAM system remains fully operational. The HiCUP platform was successfully recovered during operations to recover two other turbines on 23rd July 2018, approximately 22 months after its initial deployment in October 2016. Subsequent inspection and fault diagnosis was undertaken by SMRU personnel at Nigg Energy Park on 7th August 2018. Overall, the HiCUP had remained structurally intact although substantial biofouling covered the steel support frame (Figure 1), Gemini sonars (Figure 2), sonar tilt/roll mechanism, connectors (Figure 4) and cables.

Figure 1. HiCUP at Nigg Energy Park following recovery. Extensive biofouling is apparent.

Figure 2. Front-end of a Tritech Gemini sonar unit after approximately 22 months underwater. Extensive biofouling is apparent on the transducers.

A technical report detailing the diagnostic tests that were carried out and the identified faults was provided previously in the 'Report on the findings of initial inspections of the SMRU HiCUP following recovery'. This report is available upon request, however, the key findings can be summarised as follows;

1. Damage was evident to the outer sheath of the umbilical cable from the TSS to the HiCUP. However, this is unlikely to have critically damaged the integrity of the cable as the incision did not appear deep enough to pass the outer steel armour within the cable (Figure 3).
2. Hydrobond HDM205-13S/SS/CDP/L connectors between the umbilical and the HiCUP junction box were severely corroded. Alloy collars used to tighten the connectors had disintegrated. As a result, connectors had moved apart permitting water ingress to their contacts (Figure 4).
3. Water was present inside the HiCUP junction box (approx. 20% full by volume). Consequently, the internal electronics suffered water damaged. There was evidence of corrosion (indicating the presence of water) between the two O-rings used to seal the ends of the junction box and from one of the connectors. As water was present inside the junction box, it can be assumed that either both O-rings were leaking, or alternatively, that one was leaking and water entered the junction box via the corroded connector (Figure 5).

It should be noted that it is not possible to reliably determine at which point in time any of these potential failure mechanisms occurred. Therefore, it is unknown how long the system may have operated following deployment in October 2016. However, the volume of water present in the junction box is indicative of a very slow leak. Given that redox corrosion and barnacle growth acting to push apart the connectors are slow processes, it is plausible that the HiCUP would have functioned for several months had it received appropriate power from the turbine on deployment.

Figure 3. Damage to the umbilical cable connecting the HiCUP to the Turbine Support Structure (TSS).

Figure 4. Connectors on the HiCUP junction box. Alloy collars were covering the join between connector ends that are now exposed. These collars have corroded to fragments and the connectors appear to have been pushed apart by barnacles.

Figure 5. (Left) Electronics inside of the HiCUP junction box were severely corroded. A clear 'tide line' is visible allowing the approximate volume of water inside the junction box to be calculated. (Right) Corrosion between the two O-ring seals on the end cap of the junction box.

1.3.2 Deliverable 2: Investigation of frequency of fine scale interactions between marine mammals and operational tidal turbine

1.3.2.1 PAM system configuration and performance

The PAM system became operational on 19th October 2017 and has been operating stably since, except for short periods mostly attributable to power outages at the turbine or substation. The PAM system did not receive power for a period between 22nd September and 18th December 2018 due to removal of the turbine for maintenance. Excluding this period, 383 days have been available for monitoring between commissioning and 31st January 2019, of which the PAM system acquired data for 364.8 days (95.2% of the time). Of the monitoring time lost, 4 days (1%) were due to PAMGuard errors.

In December 2018, continuous acoustic recordings sampled at 48 kHz were terminated to minimise ongoing data storage requirements. These raw 48 kHz data were primarily to allow for reprocessing of dolphin whistles and soundscape analysis (e.g. boat noise) if more advanced detection and classification algorithms become available in the future. Full bandwidth recordings sampled at 500 kHz continue to be made for 10 seconds each hour and transient detections (which include dolphin and porpoise echolocation clicks), whistle and moan contours, noise and long-term spectral average data are still being continuously collected. Thus, apart from the removal of raw 48 kHz recordings, the PAMGuard software configuration has remained consistent with that described in the previous Annual Report and still provides highly detailed information on animal vocalisations and the surrounding soundscape. Once recovered to SMRU, data are securely backed up to the university network storage facility and to additional USB hard drives.

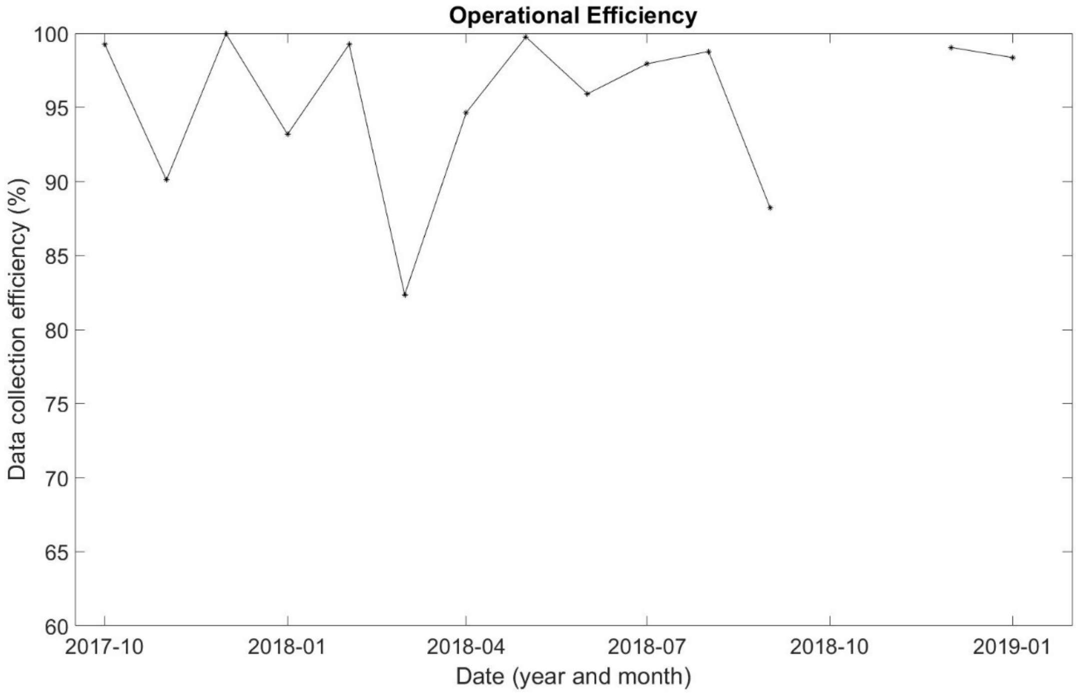


Figure 6. Percentage of time per month that PAM data was collected. Data loss was most commonly caused by power outages at the turbine or substation.

The system hardware has remained robust following over two years in the high-flow channel. A tonal noise at a frequency of 108 kHz has been present on one hydrophone channel since 7th November 2017; however, it is not affecting the ability to detect and localise animals using the other 11 hydrophones, all of which remain fully operational.

1.3.2.2 PAM data analysis

The same analytical procedure as described in the previous Annual Report has continued; click detector data are automatically processed to a) re-estimate bearings to sounds without using the noisy hydrophone and b) run an echolocation click classification algorithm for the detection of porpoise clicks. An analyst then visually scans the data to identify sequences of clicks appearing on consistent slowly varying bearings from each cluster, which are indicative of dolphin or porpoise echolocation click sequences (Figure 7). These are marked manually on the PAMGuard display and the details of each encounter are added to the PAMGuard database. Clicks from marked encounters are then localised using 3D localisation algorithms in the PAMGuard software (Macaulay *et al.,* 2017).

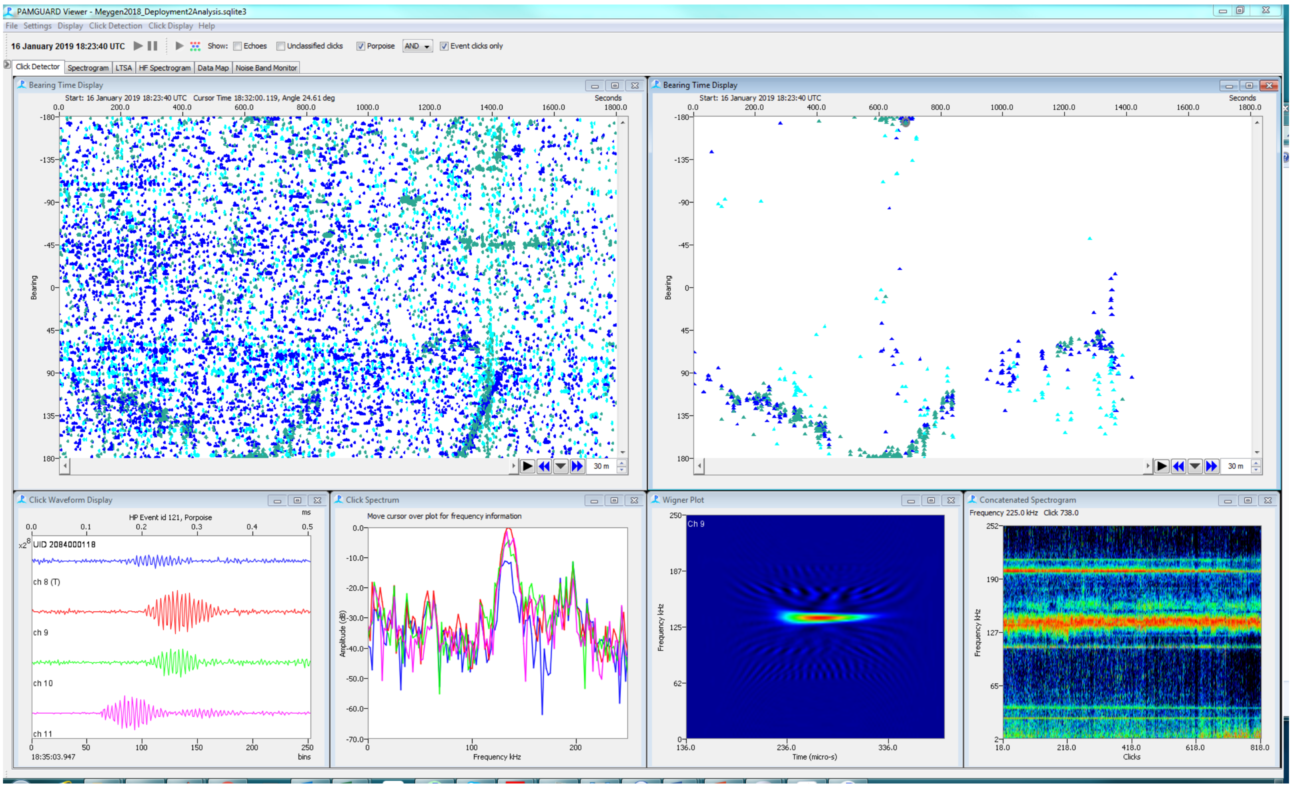


Figure 7. PAMGuard Viewer display showing a ~25 minute porpoise encounter on 16th January 2019. The top left panel of the display shows bearings to all detected clicks in a 30 minute period from each hydrophone cluster (each cluster being represented by a different colour). The top right panel has been filtered to only display clicks classified by PAMGuard as harbour porpoise clicks during the same period. The bottom panels (left to right) show the waveforms, spectrums and Wigner (time-frequency) plot for a single selected click, and the concatenated spectrogram for all harbour porpoise clicks marked as an encounter.

Currently, data have been analysed to the end of January 2019; during this period, 27 dolphin and 571 porpoise encounters (events with at least 30 echolocation clicks on a consistent bearing and close together in time, i.e. < 5 minute gap) have been detected (Table 1). The mean number of dolphin encounters per day throughout the study period was very low, peaking at 0.5/day in September 2018 (Table 1). The mean number of harbour porpoise encounters per day varied significantly throughout the study period (Figure 8); the highest encounter rate occurred in December 2017 (3.1/day) and the lowest encounter rate occurred in May and June 2018 (0.3/day; Table 1). Encounter rates subsequently increased after June 2018, indicating that the variability in encounter rate is at least partly due to seasonality rather than a progressive decrease in the ability of the PAM system to detect porpoises. However, it should be noted that the system sensitivity may have decreased as a result of biofouling on the hydrophone housing. For example, daily encounter rates were lower in December 2018 and January 2019 than the respective months of the previous year (Figure 8). Preliminary analyses of (i) octave band noise levels up to 181 kHz, (ii) noise levels in the click detector frequency band and (iii) number of click detections prior-to and post-reinstallation of the turbine in December 2018, revealed no marked changes in the noise characteristics. It is therefore likely that the decrease in porpoise encounters is mostly due to true inter-annual variability in porpoise presence.

Table 1. Summary of the numbers of detections by species and month. In total, there were 598 cetacean encounters (≥ 30 clicks) between 19 October 2017 and 31 January 2019. Note that minor discrepancies from prior reports are due to reclassifications following quality assurance checks and further changes may be made as necessary throughout the ongoing analysis (events may be further split or merged as localisations indicate how many individuals were possibly present).

Month	Days of monitoring	Porpoise encounters (daily mean)	Dolphin encounters (daily mean)
Oct 2017	12.3	27 (2.1)	5 (0.4)
Nov 2017	27.0	71 (2.6)	4 (0.1)
Dec 2017	31.0	97 (3.1)	0 (0)
Jan 2018	28.9	85(2.9)	1 (0.03)
Feb 2018	27.8	37 (1.3)	0 (0)
Mar 2018	25.5	27 (1.1)	0 (0)
Apr 2018	28.4	23 (0.8)	0 (0)
May 2018	30.9	10 (0.3)	0 (0)
Jun 2018	28.8	9 (0.3)	0 (0)
Jul 2018	30.4	26 (0.9)	1 (0.03)
Aug 2018	30.6	37 (1.2)	4 (0.1)
Sep 2018	20.3	59 (2.9)	10 (0.5)
Dec 2018	12.5	12 (1.0)	1 (0.07)
Jan 2019	30.5	52 (1.7)	1 (0.03)
Total	364.8	571 (1.6)	27 (0.07)

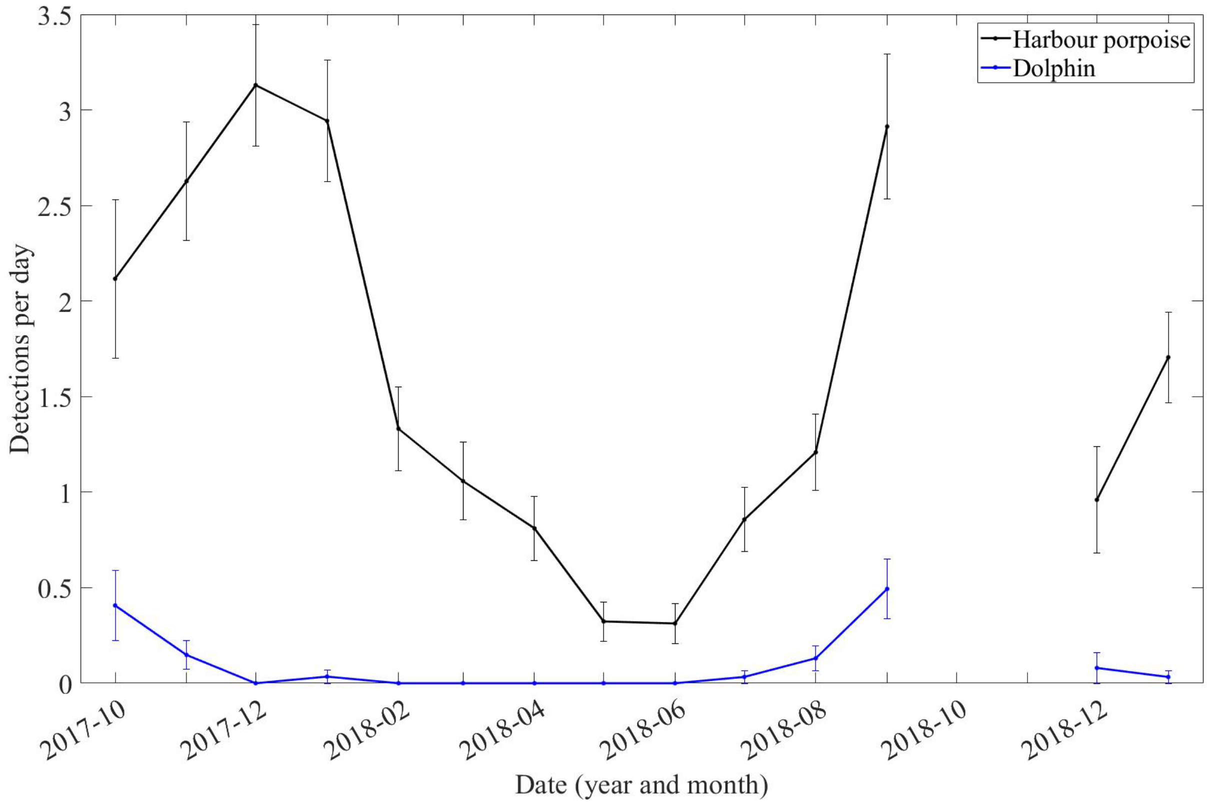


Figure 8. Mean numbers of detections per day throughout the monitoring period (October 2017 – January 2019). Error bars represent +/- one standard deviation. No data could be collected in October and November 2018 when the turbine was removed for maintenance. Please note that minor changes to these values may occur as analyses are refined.

The primary aim of this study is to measure the behaviour of animals in proximity to the operational turbine. Animal presence and behaviour at the site may also be affected by a number of other factors (co-variates) such as the state of the tide, the lunar phase, time of day and anthropogenic activities such as shipping, etc. The probability of detecting and tracking animals will also be affected by background noise. Simulations are underway to help understand how noise fluctuations over a tidal cycle and with turbine operation effect the porpoise detection range. This must be quantified prior to statistical modelling to enable the identification of biological relationships between porpoise presence/absence and physical/environmental patterns while accounting for the confounding factor of noise affecting detection probability. Subsequently, behaviour with respect to turbine operations can be quantified through multivariate statistical models, similar to the analysis described in Malinka *et al*. (2018). Due to the limited number of dolphin detections, it is likely that this modelling will only be possible for harbour porpoises.

Turbine rotational data for the Atlantis AR1500 turbine have now been provided by SIMEC Atlantis Energy up to October 2018. SIMEC Atlantis Energy also provided modelled tidal flow metrics for the site at ten minute intervals including flow velocity, flow bearing and water depth. From these, phase in the tidal cycle as a percentage of the maximum flow for that flood/ebb window can be derived. Further covariates that will be included in modelling have also been acquired, such as lunar (timeanddate.com) and diel phases. MATLAB (R2018b) and RStudio (Version 1.0.136) are being used for preliminary analysis on data acquired up to 22nd September 2018 when the turbine was removed for maintenance.

Data exploration is underway to investigate the distribution of detections with environmental and/or physical covariates throughout the monitoring period up to 22nd September 2018 (Figures 9-14). However, no further inferences should be made from these data until the modelling work has been completed and noise-related variability in detection ability are accounted for.

Figure 9 shows noise in the click detector frequency band over a two-month period. Changes by up to 20 dB occur over a tidal cycle and between spring-neap tides. Such variability in noise significantly impacts the range at which harbour porpoises and dolphins can be detected and thus must be factored into any model that seeks to resolve spatial and/or temporal patterns in animal behaviour. There is also an apparent difference in noise levels between hydrophone clusters between the flood and ebb tide (Figure 10). Channel 1 (northeast cluster) and channel 5 (southeast cluster) are relatively noisier on the flood than the ebb, whereas channel 9 (west cluster) is relatively noisier on the ebb tide. This could be due the respective orientation of each cluster relative to the flow direction at these times. Evaluation of the number of clicks detected and localised on each channel during the flood and ebb tides do not indicate that noise differences between channels have led to systematic bias against any particular clusters. Therefore, detection and localisation ability is not believed to be affected. Further, noise in the click detector frequency band generally increases with flow speed during the flood and ebb tides (Figure 11).

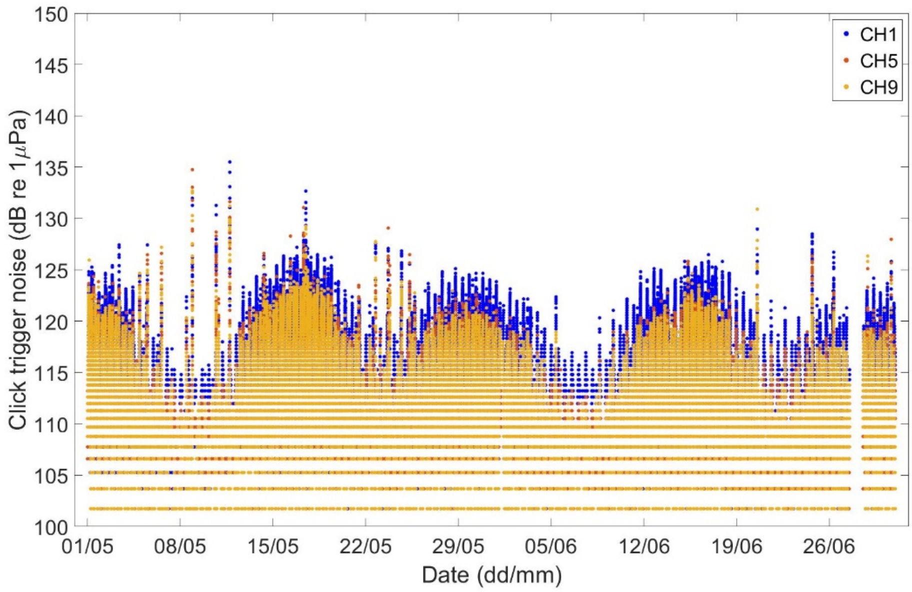


Figure 9. Data showing noise in the click detector frequency band from a single hydrophone in each cluster. There are changes by up to 20 dB over a tidal cycle and between neap-spring tides. Such changes significantly impact the range at which harbour porpoises and dolphins can be detected. Banding at low noise levels is caused by rounding of raw sound levels during data acquisition, which when converted to a dB scale, results in a larger error at lower noise levels.

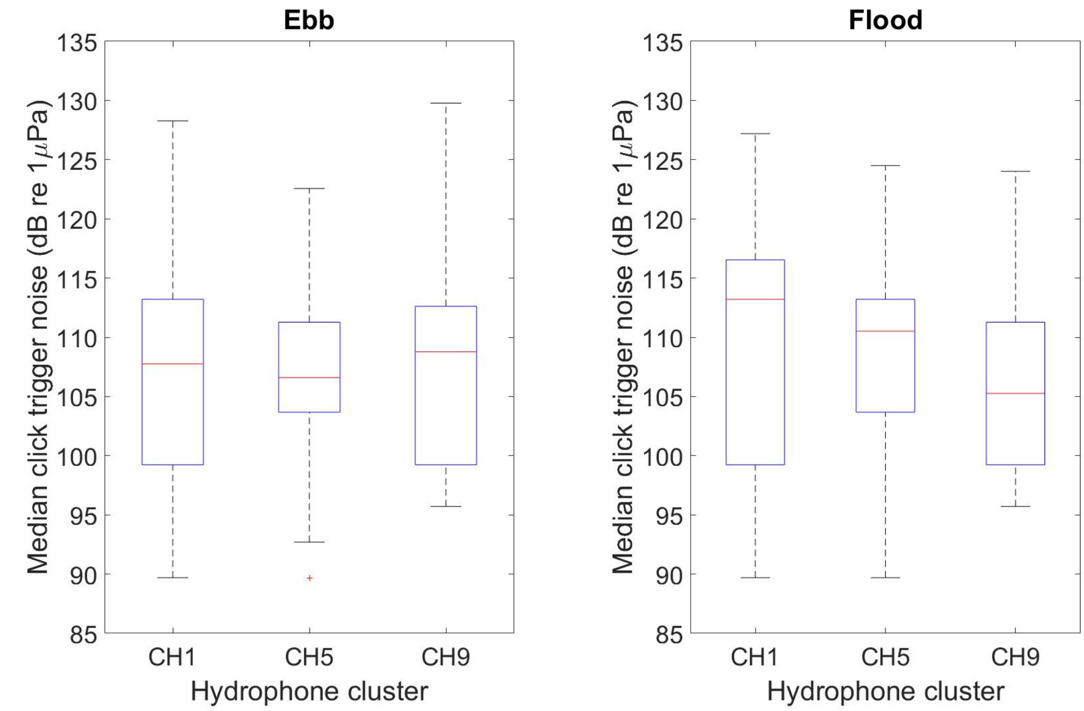


Figure 10. Distribution of noise levels in the click detector frequencies for each hydrophone cluster on the ebb (left) and flood (right) tide. CH1 represents the northeast cluster, CH5 represents the southeast cluster and CH9 represents the west cluster. Noise on CH1 and CH5 is greater on the flood than the respective channels on the ebb tide. Noise is greater on CH9 on the ebb tide than the flood tide. On each box, the red line is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the 99th percentiles and outliers are represented as red crosses.

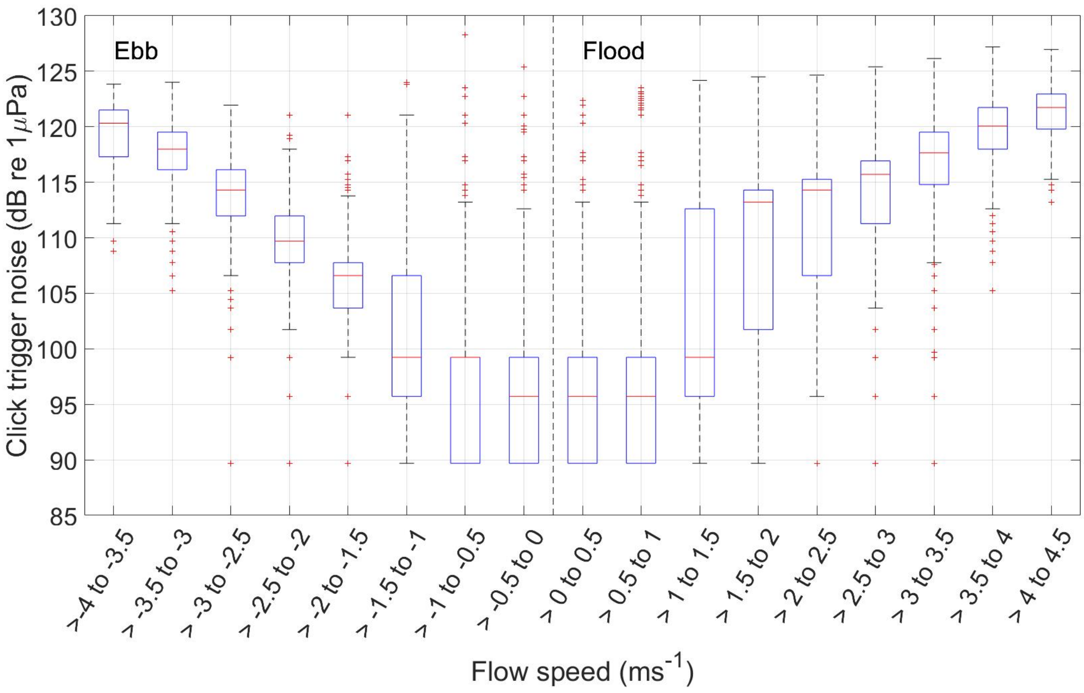


Figure 11. Relationship between flow speed and noise levels in the click detector frequency band for channel 1 from the northeast hydrophone cluster, which is generally the noisiest cluster. On each box, the red line is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the 99th percentiles and outliers are represented as red crosses.

Previous studies have reported diel variation in harbour porpoise detections in Scottish waters (Carlstrom, 2005; Williamson *et al.,* 2017). During the period from October 2017 to September 2018 in the current study, there were more porpoise encounters between the hours of 19:00 and 05:00 UTC than the intervening hours (Figure 12). To explore whether day length is a potential driver behind this observed pattern, the mean number of harbour porpoise encounters per day and mean hours of sunlight were calculated for each month. There appears to be a strong negative relationship between the hours of daylight and the daily rate of porpoise detection (Figure 13). This could be due to fewer porpoises, although there is some evidence to suggest vocalisation rates may be lower in daylight hours (Linnenschmidt *et al.,* 2013; Thomas & Burt, 2016).

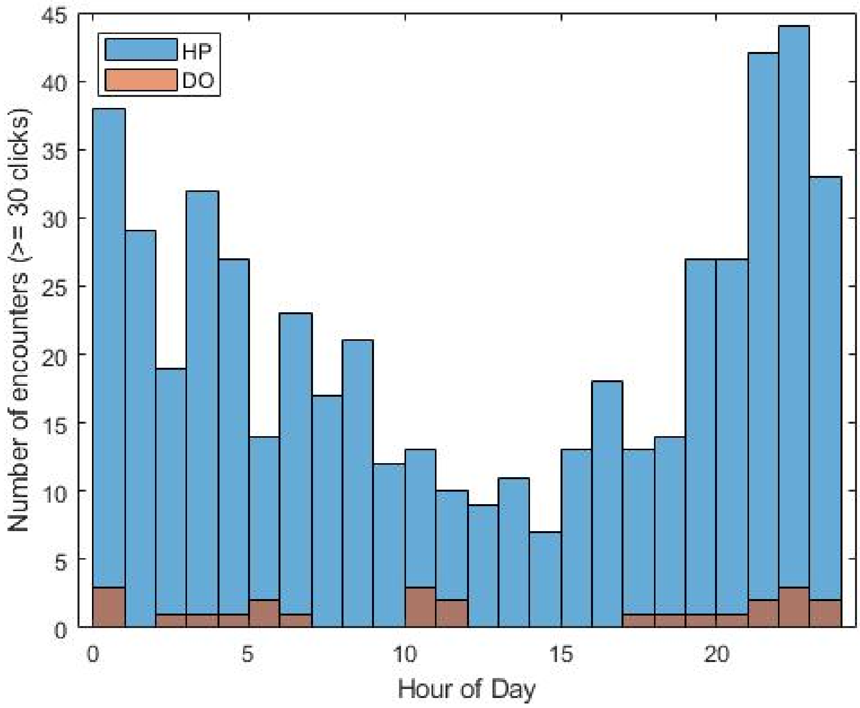


Figure 12. Summary of all cetacean encounters by hour of day (00:00-23:59) between October 2017 and September 2018. More encounters occurred between the hours of 19:00 and 05:00.

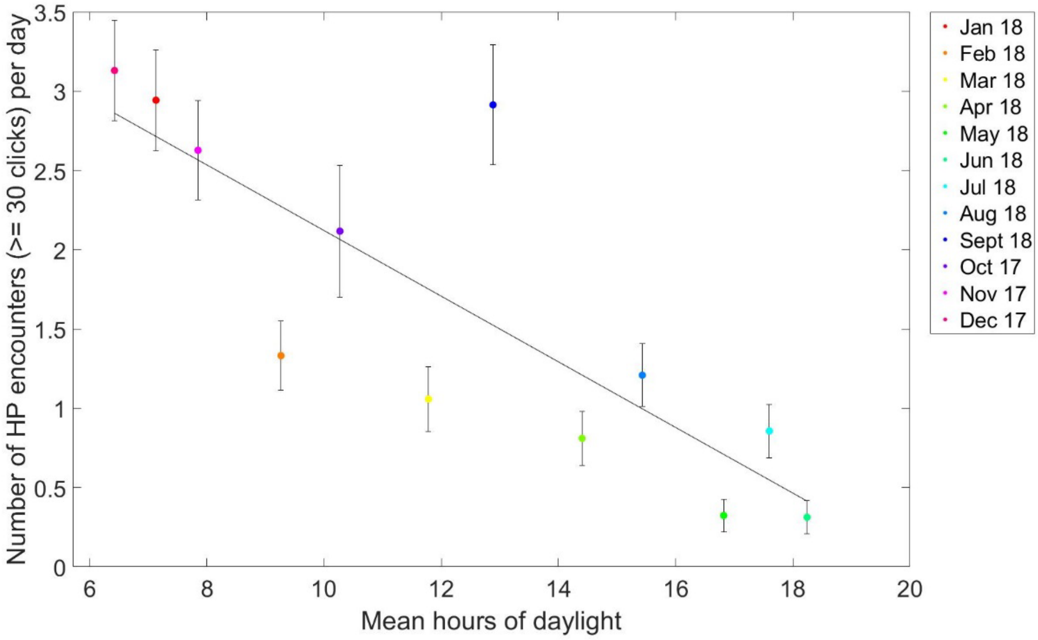


Figure 13. Relationship between mean day length (hours of daylight) per month and the mean number of harbour porpoise encounters per day. Day length was calculated as the number of hours between sunrise and sunset. Error bars represent +/- one standard deviation and the line of best fit is shown in black.

The distribution of cetacean encounters as a function of flow speed is presented in Figure 14. Harbour porpoise detections were made during most flow speeds throughout the study period, despite the increased noise levels at high flow (Figure 11). Due to the correlation between noise and flow speed, fewer detections at high flows must not be interpreted as there being fewer animals present during times of high flow. Dolphin detections also occurred over a range of flow speeds, including during high flow speeds on the flood tide (Figure 14).

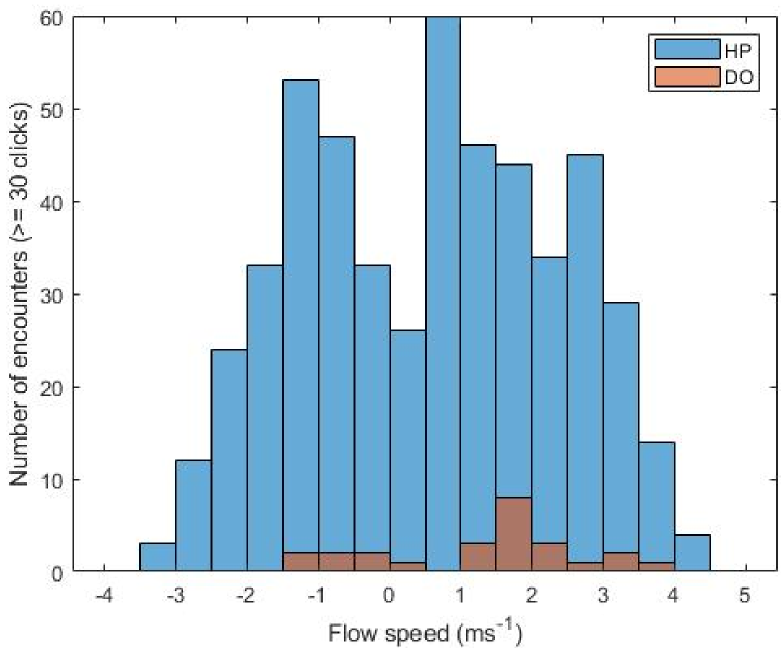


Figure 14. Summary of all cetacean encounters (colour coded by species/species group) as a function of tidal flow speed at the onset of the encounter. Negative flow speeds represent ebb tide and positive flow speeds represent flood tide. These data must be interpreted with caution. For example, fewer detections at high flow speeds does not necessarily indicate there were fewer porpoises, as it is confounded by increased noise and hence reduced detection ability.

A key output from the PAM data analyses will be the 3D locations of echolocation clicks in relation to the turbine. Localisation using the PAMGuard 3D localisers has undergone several stages of refinement. An important step of this process was the calibration of the algorithm by localising sounds with a known location. Fieldwork to collect this data, here referred to as pinger trials, was carried out on 6th August 2018 by personnel from SMRU and SAMS (Scottish Association for Marine Science). An additional aim of the pinger trials was to assess the ability of the PAM system to detect and localise VEMCO fish tags. Tagging seals that typically do not vocalise underwater with VEMCO tags, could potentially allow the use of PAM for 3D tracking. VEMCO fish tags emit high frequency (170 or 180 kHz) sounds (~ 5 ms duration per second) with reported source levels of 143 dB re 1µPa @1m.

The pinger trials were conducted on the ERI Aurora, operated by the University of the Highlands and Islands. The vessel mobilised from Gills Bay harbour with personnel from SMRU and SAMS on board and the PAM system was monitored from the substation. Porpoise and dolphin-like signals were generated synthetically in an audio file with a sample rate of 1MHz. These signals were played underwater through a Neptune Sonar D/140 spherical transducer ("the pinger") driven by Sony Xplod 1200W power amplifier, via a National Instruments USB-6251 multifunction DAQ card using the PAMGuard software. PAMGuard also recorded the vessels GPS position every second from a GlobalSat WAAS (satellite differential) enabled GPS receiver which had a nominal accuracy of < 3m. When the turbine was operating, the pinger was deployed at a maximum depth of 10m, which provided a minimum clearance of at least 3m above the rotating blades. When the turbine was stopped and the blades locked in the Y position, the pinger was lowered to a maximum depth of 15m. A 3 kg weight was used to ensure the artificial porpoise maintained the desired depth and a video camera (oriented to point downwards) was mounted above this to monitor the turbine proximity during drifts. Once positioned approximately 100 m upstream of the turbine, the vessel engines and echosounder were cut to reduce noise and the vessel was allowed to drift with the current over the turbine. For a number of the drifts, VEMCO pinger tags operating at 170 or 180 kHz were deployed from a suspended cable.

Frequent communication with MeyGen and SIMEC Atlantic Energy personnel was required prior-to and during activities to minimise risk when operating in proximity to the turbine. Twenty two drifts were conducted using the artificial porpoise pinger and / or the VEMCO pinger tags. The pinger was used on 11 drifts, the 170 kHz VEMCO tag on 9 drifts and the 180kHz VEMCO tag on 14 drifts (both the pinger and a VEMCO tag were used on 11 drifts). Drift tracks relative to the turbines are shown in Figure 15. Several drifts passed over the monitored turbine and it was possible to visualise the turbine blades and the nacelle using the video camera; the closest approach was approximately 1m from the centre position of the turbine.

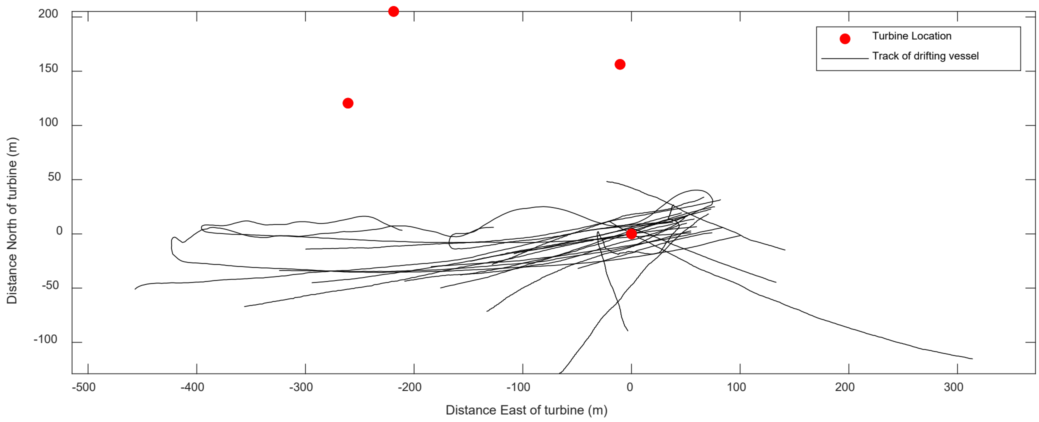


Figure 15. Track lines of the vessel drifts conducted on 6th August 2018 past the Atlantis AR1500 turbine.

Further, a total of sixteen drifts were made to deploy and recover SAMS drifting hydrophones. Analysis of these data will be completed by SAMS and the resulting noise measurements will help determine the level of noise present in the water column at different distances from the turbine.

Results from the pinger trials were used to validate the PAMGuard localisation algorithms and to make further analytical refinements including improved error estimation. Figure 16 shows the true horizontal range of the pinger from the hydrophones (as determined from the GPS position of the vessel) in comparison to the horizontal range estimated by the PAM localiser, whereby 'perfect' localisations would fall along the black line. Localisation accuracy is relatively good out to approximately 30 m from the turbine, which is to be expected given that the aperture of the hydrophone array is approximately 10 m. Points in blue have Chi^2 values >10 and are likely to be removed during post-processing. Localisations with $Chi^2 < 10$ are considered for further analysis but will still be subject to additional manual checks. It should be noted that the 'true' horizontal range is liable to a small degree of inaccuracy that can be attributed to GPS error (typically <3 m) and/or error in the position of the suspended pinger relative to the vessel.

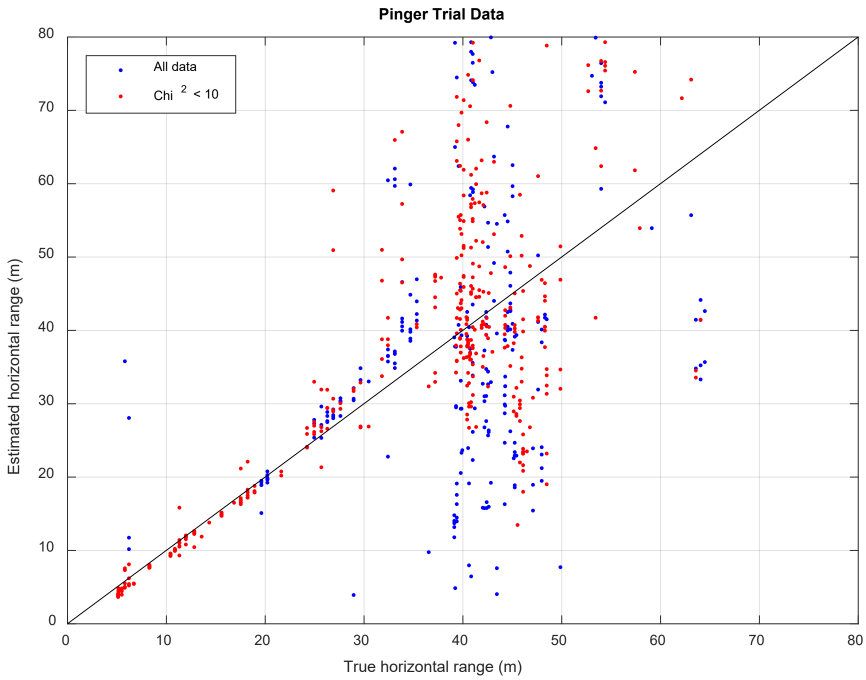


Figure 16. A comparison of the measured horizontal range between the transducer (pinger) and the hydrophones (x-axis) and the horizontal range predicted by the PAMGuard localisation algorithm (y-axis). The black line represents where the algorithm estimate matches the measured range. Points in red have Chi^2 of <10 and would be considered for further analysis. The localisation algorithm predicts close to the measured horizontal range up to approximately 30 m.

Error estimation is important to describe uncertainty in the localisations, given that the true position of an animal is not known. 'Real error' estimates were obtained from the pinger trial data by calculating the difference between the known pinger position and that predicted by the localisation algorithm. Figure 17 shows the increase in real localisation error as measured (blue) and the estimated error as predicted by the localisation algorithm (red), with increasing range from the sound source. The magnitude of the measured and estimated error is roughly consistent until ~37 m range. There is larger discrepancy between the real and estimated error below 10 m range than between 10 and 30 m, which is most likely driven by inaccuracy in the true location of the pinger. As previously mentioned, this can be caused by GPS error (typically <3 m) and/or error in the position of the suspended pinger relative to the vessel. Accounting for this, the magnitude of error close to the turbine (< 10 m) is most likely within the order of 1-2 metres.

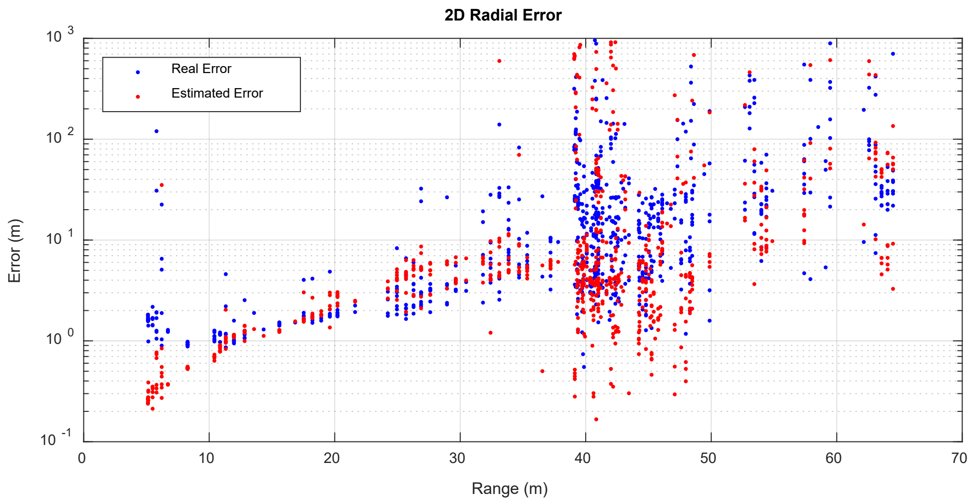


Figure 17. A comparison of localisation error as a function of range, as predicted by the localisation algorithm (red) and calculated directly from the measured positions (blue). The algorithm predicts error well until approximately 37 m range.

Figure 18 shows preliminary localisation results of a harbour porpoise encounter. Each localised click from the encounter is shown by a diamond. It can be seen that the error (represented by the yellow lines) is asymmetric and errors of localisations close to the turbine are generally smaller than those at greater distances. In this example, an animal moves from the right of the frame to within close proximity of the turbine. The localisations to the left of the turbine also indicate an animal moving toward the turbine approximately ten seconds later.

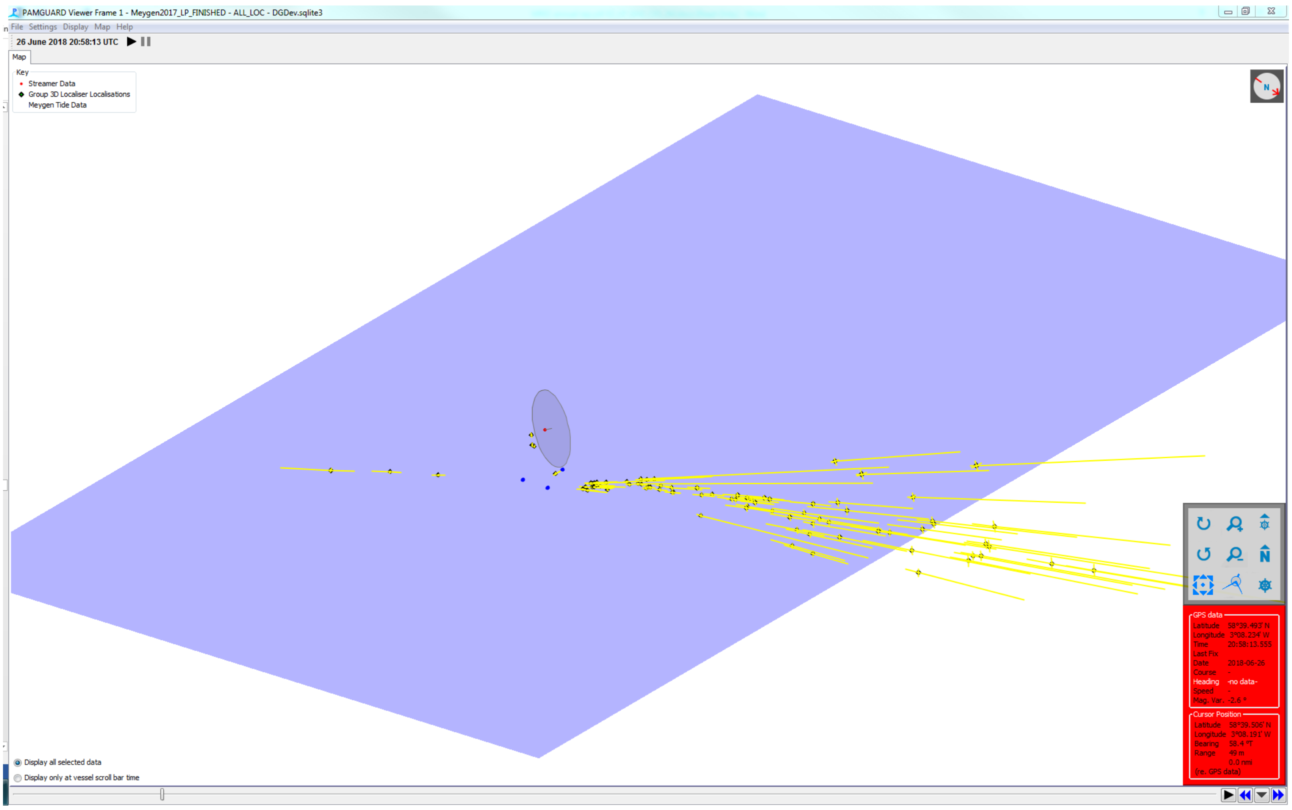


Figure 18. A localised harbour porpoise encounter relative to the turbine rotors (shaded disk) on the PAMGuard Viewer display. Blue dots indicate the positions of the hydrophone clusters. All localised clicks from the encounter are shown (diamonds) with the associated localisation error (yellow line). In this instance an animal moves from the right of the frame to within close proximity of the turbine. The localisations to the left of the turbine also show an animal moving toward the turbine approximately ten seconds later. This localisation is preliminary and may be subject to change as ongoing quality checks proceed.

Once a database containing all localised clicks has been created, these data will require manual validation. The next stage will be to undertake additional modelling of the positional data that is likely to take two forms, depending on the final dataset:

1. Point-based approach, whereby the density of porpoise clicks around the turbine will be calculated in relation to turbine operation (on/off) to assess potential impacts on the near-field distribution of harbour porpoises. The varying detection and localisation range as a function of noise will be factored in accordingly.
2. Track-based approach, whereby the probability that individual encounters passed through the rotor swept disk will be quantified. Individual tracks will not be related to turbine operations until the final stages in order to prevent interpretive bias.

Data collected during the pinger trials were also useful in determining the practicality of tracking seals instrumented with VEMCO fish tags. Exploration of the VEMCO fish tag drifts in PAMGuard revealed poor ability to detect both the 170 kHz and 180 kHz tags, even at close ranges (within 15 m of the turbine) during quiet conditions (slack tide). This meant that the signal was not generally detected on all of the hydrophone clusters simultaneously. Further, localising the pinger tags to provide 3D tracking appeared highly challenging; this was due to the acoustic signal waveforms being distorted by multiple reflections from the turbine structures making it difficult to measure accurate timing differences between arrivals on each hydrophone channel.

When this is considered in light of the seal telemetry data that shows a low probability of tagged seals moving close to the turbine (section 2.3.2.3), it was decided that passive acoustic tracking of seals in this way was not practically viable at this stage.

1.3.2.3 Harbour seal telemetry

A total of 40 GPS/UHF tags and 40 UHF dive loggers have been deployed on harbour seals in the Inner Sound since September 2016 (10 seals in Sept/Oct 2016, 14 seals in April 2017, and 16 seals in April 2018; Table 2). Results from the 2016/2017 tag deployments were presented in previous Annual Reports. Of the sixteen tagged seals in 2018, 12 have collected location data and 12 have collected high resolution dive data, and transmitted these to the shore base stations (Table 2).

Capture and handling procedures for the tag attachment are outlined by Sharples *et al*. (2012). Each seal was fitted with a high-resolution UHF/GPS tag that attempted to record locations whenever a seal surfaced (maximum resolution of every three minutes), and used the Fastloc algorithm (Hazel, 2009) to process and store the GPS data on-board. Each seal was also fitted with a time-depth recorder (TDR) which uses pressure to estimate depth at 10 second intervals. When a seal surfaced, it attempted to transmit location to a series of autonomous archival base stations on shore, using UHF telemetry. All data was also stored on-board the tag until a seal hauled out within line-of-sight of a base station at which point all data from both the GPS and TDR unit were transmitted. Data were manually downloaded from the base stations several times a month. Location data from the seals were cleaned to remove erroneous locations using thresholds of residual error (<25) and the number of satellites (>4) as per Russell *et al*. (2015). Additionally, speed over the ground was calculated between pairs of locations and the second location was removed when the estimated speed over the ground was greater than 7 $m.s^{-1}$ (a conservative estimate, given a constant transit speed above this was unlikely when coupled with maximum expected tidal flow rates in the region).

The duration that each GPS tag transmitted data ranged from 10.9 and 146.1 days (mean = 81.2 days; SD = 38.4). Sampling frequency for the GPS tags remained high throughout the deployment periods with a modal, binned range of time between locations of 3 – 3.5 minutes (Figure 20).

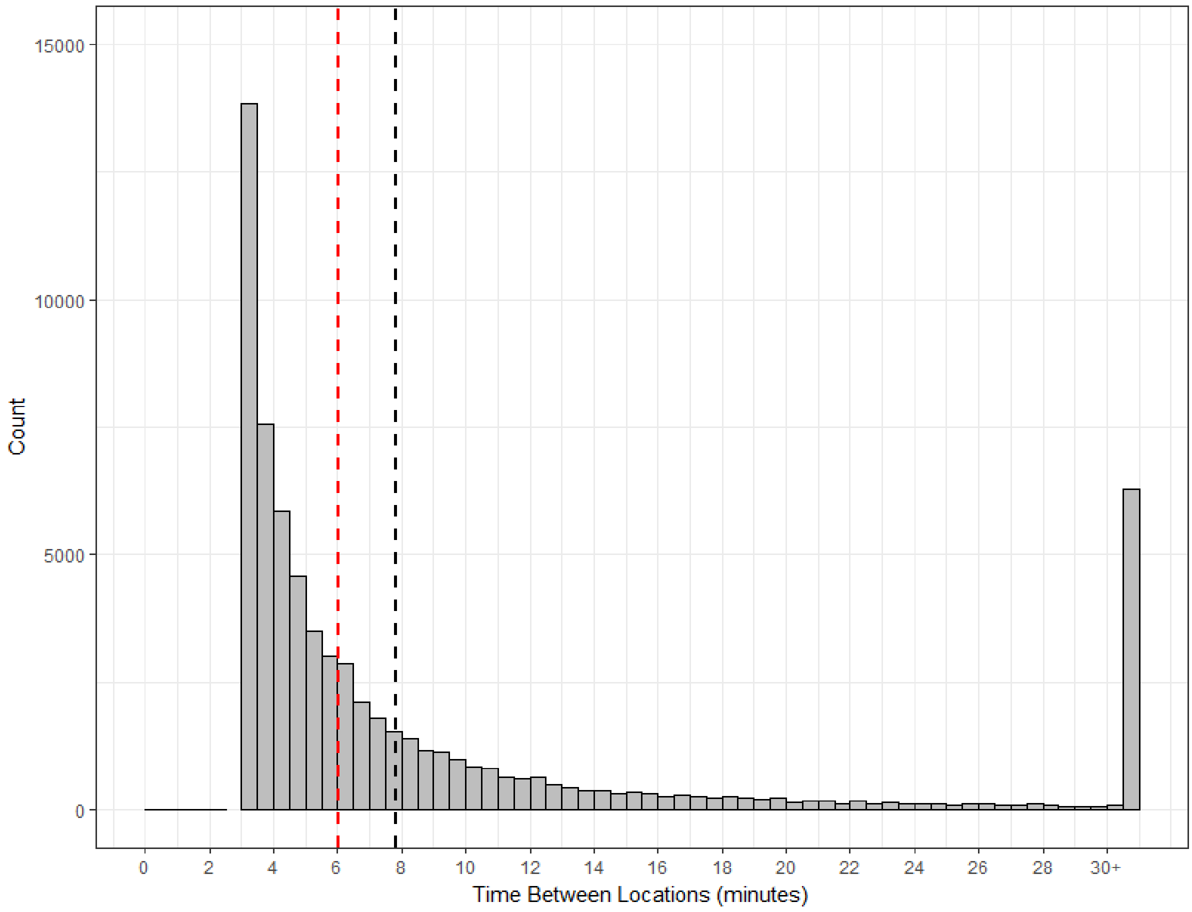


Figure 19. Frequency of time difference between location fixes. The black, dashed, vertical line indicates the mean time between all locations (7.8 minutes). The red, dashed, vertical line indicates the median time between all locations (6 minutes).

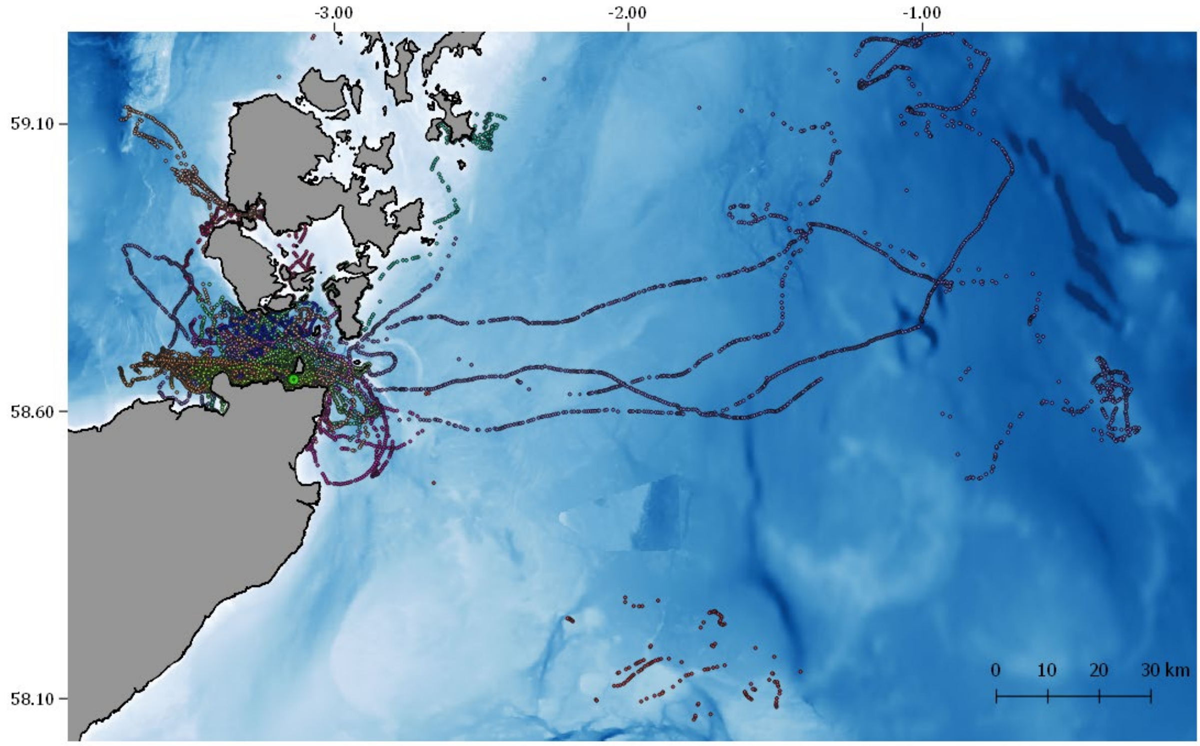
From the seals tagged in 2018, a total of 504 seal days of data were collected which included 53,484 GPS locations and 757 foraging trips (Figure 20). These seals spent ~12% of their time within the Inner Sound and ~0.001% within the MeyGen lease area.

The relatively low percentage of time that seals spent within the lease area was also reflected in the low numbers of GPS locations recorded close to the turbine; a total of 3 GPS locations were recorded within 50m of a turbine and the closest GPS location was 37m from a turbine (Figure 21). Further, when tracks were linearly interpolated (a straight line) between GPS locations, a total of 19 tracks passed within 50 m of any turbine. However, it is important to highlight that the assumption of straight line travel between locations is unlikely to be valid so interpretation should be treated with caution.

Table 2. Capture metrics for 40 seals tagged in the Pentland Firth between October 2016 and April 2018. Note that tags that failed to transmit any data are shown by an asterisk in the GPS Body Number column.

Tagging Date	Capture Location	Sex	Flipper Tag ID	GPS Body Number	TDR Body Number	Length (cm)	Axial Girth (cm)	Mass (Kg)
28-Sep-16	Brough Bay	M	593	65254	51031	153	110	89.2
29-Sep-16	Brough Bay	F	594	65231	51019	110	80	33.6
30-Sep-16	Gills Bay	F	595	65199	51025	148	110	91.6
30-Sep-16	Scotland's Haven	M	596	65191	51011	144	110	92.6
01-Oct-16	Scotland's Haven	M	599	65201	51009	115	104	85
01-Oct-16	Scotland's Haven	M	598	65334	51020	165	116	106.2
01-Oct-16	Scotland's Haven	M	597	65246	51030	155	96	75.4
01-Oct-16	Scotland's Haven	M	D006	65242	51026	147	116	100.2
02-Oct-16	Scotland's Haven	M	D008	65446	51022	154	115	93
02-Oct-16	Scotland's Haven	M	D007	65239	51029	153	114	102
02-Apr-17	Ham	M	D112	65257*	51104	149	108	87
02-Apr-17	Ham	M	D113	65500	51120	147	101	81.4
02-Apr-17	Ham	M	D111	65243	51105	151	110	92.6
03-Apr-17	Harrow Harbour	F	D115	65507	51109	147	112	103.4
03-Apr-17	Harrow Harbour	M	D114	65513	51111	137	99	73.6
07-Apr-17	Harrow Harbour	F	D116	65195*	51101	142	115	103.2
07-Apr-17	Brough Bay	F	D118	65502	51119	143	121	110.7
07-Apr-17	Harrow Harbour	M	598	65504	51100	159	116	112
07-Apr-17	Ham	M	D117	65499	51112	156	112	108
08-Apr-17	Harrow Harbour	F	D120	65506	51114	146	109	86.4
08-Apr-17	Ham	M	D119	65505	51116	148	99	74.6
09-Apr-17	Harrow Harbour	F	D121	65496	51115	142	105	88.4
13-Apr-17	Gills Bay	F	D122	65503	51108	146	106	97.6
13-Apr-17	Gills Bay	F	D123	65512*	51117	135	103	76
16-Apr-18	Brough Bay	F	D195	64315*	51129	151	108	92.7
17-Apr-18	Brough Bay	F	D197	64313	51128	139	118	93.9
17-Apr-18	Brough Bay	F	D196	64312	51134	151	111	97.1
18-Apr-18	Castle Mey	F	D198	64318	51125	138	104	88.5
18-Apr-18	Ham	M	D199	64304	51124	143	99	76.9
18-Apr-18	Ham	M	D200	64305	51130	153	115	101.7
19-Apr-18	Castle Mey	F	D248	64321*	51131	135	102	77.7
19-Apr-18	Castle Mey	F	D249	64308	51122	145	104	84.3
20-Apr-18	Brough	M	D250	64309	51121	140	105	78.7
21-Apr-18	Gills Bay	F	D253	64316	51110	138	103	85.9
21-Apr-18	Gills Bay	F	D252	64301	51132	137	103	83.1
21-Apr-18	Gills Bay	F	D251	64300	51102	142	111	93.1
21-Apr-18	Gills Bay	F	D248	64303	51136	135	102	77.7
22-Apr-18	Gills Bay	M	D254	64320*	51127	155	112	101.9
22-Apr-18	Gills Bay	M	D255	64314*	51126	145	105	86.7

24-Apr-18	Brough Bay	M	55128	64302	51118	153	112	90.1



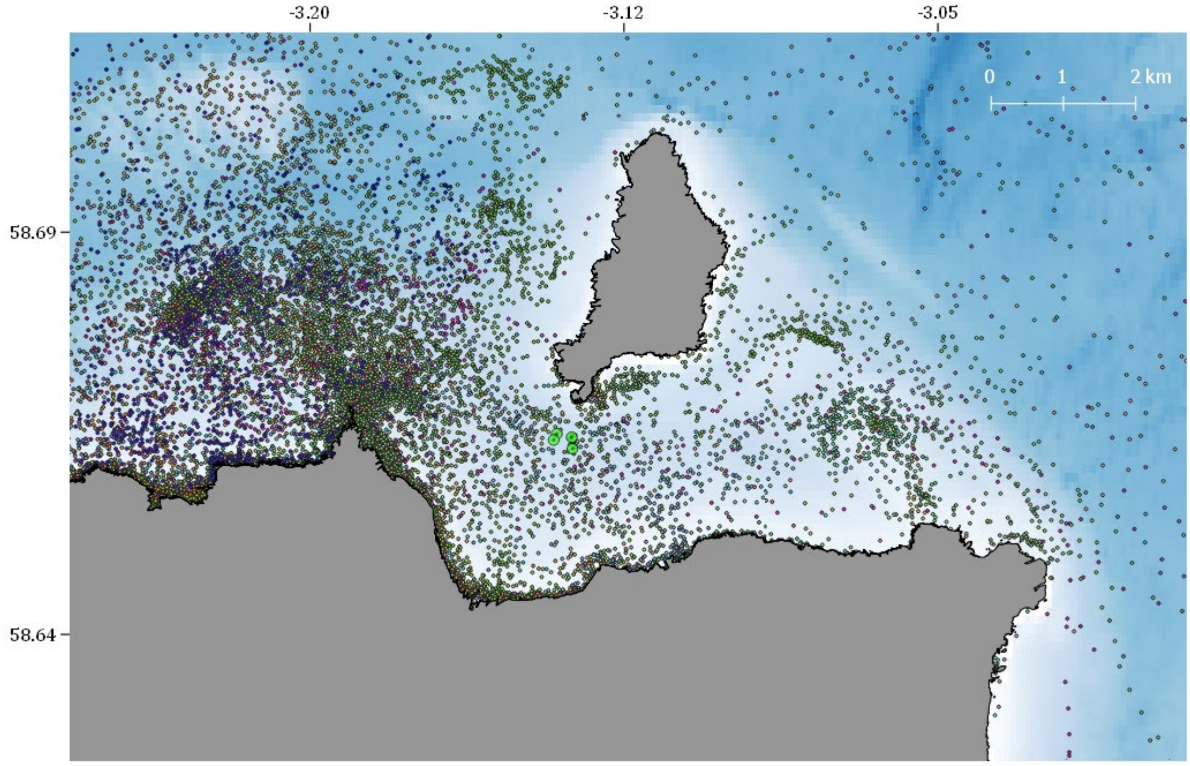


Figure 20: Raw GPS locations from all downloaded tags (upper) from the April 2018 deployment and from those that spent time within the Inner Sound (lower). Underlying bathymetry is provided on a blue scale with darker regions indicating deeper areas. Bathymetry data was downloaded from the European Marine Observation and Data Network (EMODNET) digital terrain model. Turbine locations are denoted by the larger green circles.

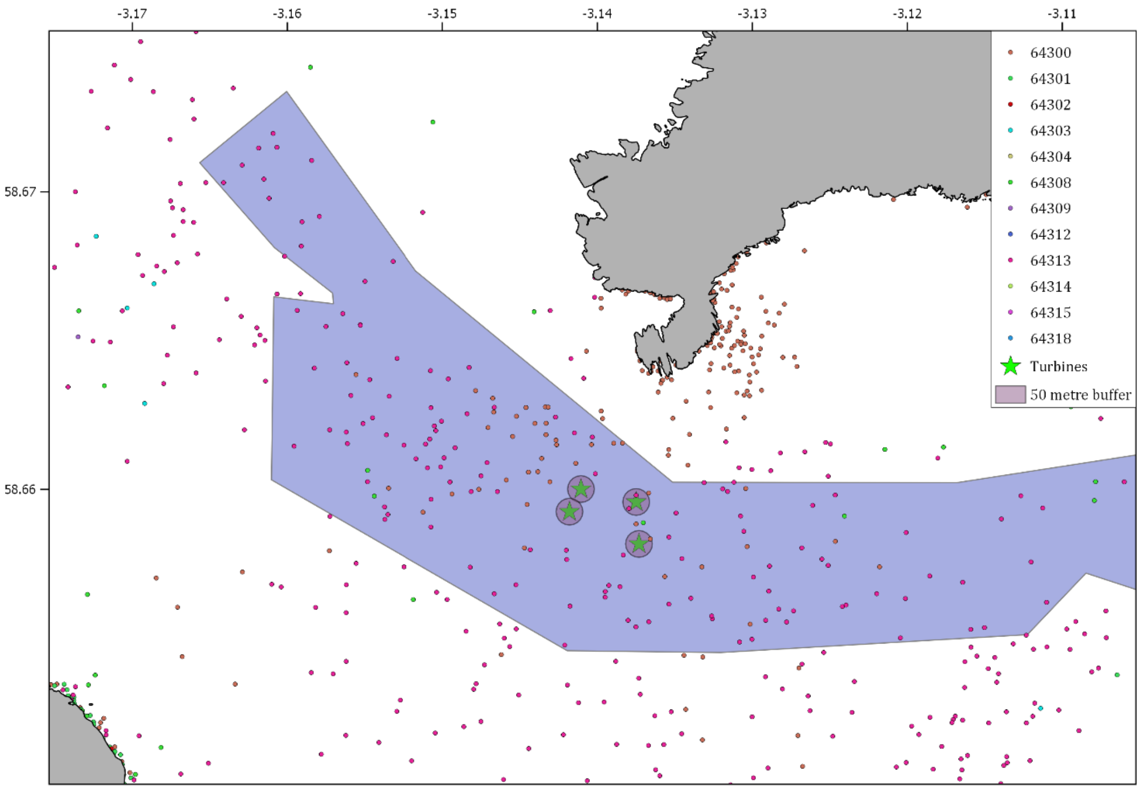


Figure 21: GPS locations of tagged seals close to the turbines from the 2018 deployment. Note the 50 metre buffer around each turbine with a total of 3 locations within these buffers. The lease site is delineated by the blue polygon.

Table 3. Summary of the data from 33 seals (18 male, 15 female) for which GPS data was received during the 2016-2018 deployments.

	Data Summary: UHF/GPS
Number of tagged seals:	33
Total number of locations for all tags:	168659
Number of locations in the Inner Sound for all tags	13783
Percentage of time spent in the Inner Sound for all tags:	16
Number of locations in the lease site for all tags:	195
Percentage of time spent in the lease site for all tags:	<0.01
Number of locations within 100m boundary of each turbine:	4
Number of tagged seals within 100m of each turbine:	3
Closest location distance (m) to the turbines:	35.15
Date/time (GMT) of closest location distance in the report period:	11/04/2017 20:11

To assess the effects of the turbine installation on harbour seal distribution spatial usage before and after installation was quantified. Specifically, broad scale changes before and after installation were compared, and the influence of tidal phase on changes was quantified. In the absence of operational data for all turbines, tidal phase was used as a proxy of flow rate of the turbines, with higher flow rates assumed to be indicative of faster rotation. An additional assumption was made that when the turbines were in the water, they were continually operational however we know from anecdotal evidence that this is also not the case so results must be treated with caution.

Data were split and assigned to either the pre or post-deployment period. Given the heavy skew towards post-operational data, improved predictive power was sought by including historical tracking data from a telemetry deployment on harbour seals at the same sites from 2011 and 2012. These data were from SMRU GPS-GSM tags and locations were filtered using the same protocols as the UHF-GPS tags.

A use-availability design was used to model spatial distribution which required random generation of a series of a pseudo-absence points. Each pseudo-absence was linked to an observed presence point and is a way of representing the available area within the study site which was not being used by the individual at the time it was observed. The response relative to the covariates was then modelled the as a binomial process where 1 = presence and 0 = absence. The models were fit using smoothing algorithms from the R package, MRSea (Scott-Hayward *et al*., 2017). The package was specifically designed to examine survey data in the context of marine renewable energy developments and has been modified here for use with telemetry data similarly to (Russell *et al.,* 2016). A 2-dimensional Spatially Adaptive Smoothing Algorithm (SALSA) with a Complex Region Spatial Smoother (CReSS) was used to model spatial usage.

Models were fitted within a generalised estimating equation (GEE) framework in the R package 'geepack'. This allows for the likely serial auto-correlation between sequential observations, beyond the processes specified by the model. This results in robust estimation of standard errors as errors within defined 'panels' are permitted to be correlated while errors between panels are assumed independent. We fit the model with separate panels for each individual's (tag) presence data. Pseudo-absences were randomly generated and therefore assumed to be independent of each other and to the presence data, so were each fit within separate panels. This separation of presence and pseudo-absence data as well as between individual ensured that serial autocorrelation was accounted for while not underestimating the errors within the presence data. Explanatory covariates used to model the presence-absence distribution were tidal phase (time around high water) and location (lon-lat of the centre point of each grid-cell) as continuous variables and turbine presence (impact) as a factor variable. An interaction term between impact and tidal phase was also fit as can be seen in Equation 1.

Equation 1.

$$\text{presence} \sim s(\text{ lat} + \text{lon }) + s(\text{ Tidal Phase}) : \textit{factor}(\text{impact}), \textit{family} = \text{binomial}, \textit{id} = \text{tag}$$

Where *id* is the blocking panel, *family* is the response distribution, and *s* is the β-spline term.

The exponent of the linear-predictor from the logistic model was used to predict relative abundance pre and post deployment (Beyer *et al.*, 2010; Russell *et al.,* 2016). Maps below highlight key areas of seal usage both pre and post-deployment for high and low water slack tidal phases, and combined peak flow rate for both flood and ebb. Usage was significantly different between pre and post turbine deployment for all explanatory variables (Table 4); further, usage changes were spatially explicit, with some areas showing little discernible change (Figure 22 -25).

Table 4. Marginal p-values generated from repeated ANOVA tests for each covariate. Asterisks indicate significance at the 0.05 level and (:) indicate interaction terms.

Covariate	Marginal p-values
Impact	0.0095*
Location (lat + lon)	<0.0001*
Tidal Phase	0.019*
Impact : Location (lat+lon) : Tidal Phase	0.03*

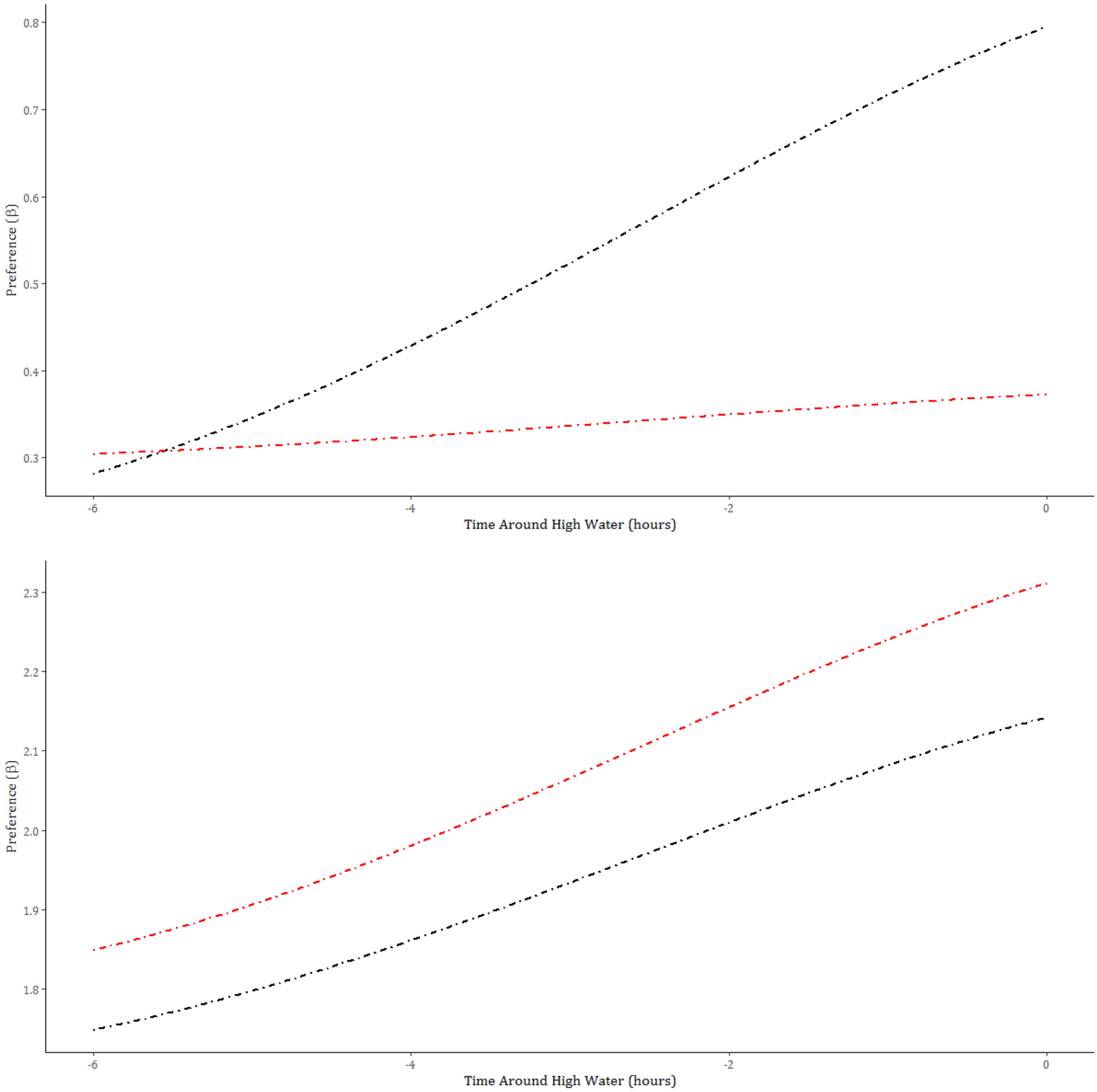


Figure 22. Coefficient estimates of usage with tidal phase for (top) a grid cell including 3 turbines and (bottom) grid cell representing a putative foraging location ~3km west of the turbine array site. Foraging location was determined from a visual observation of GPS location concentrations across the study period (large concentrations of offshore locations indicative of likely foraging hotspots) and can also be seen in the hotspots of usage in Figures 24 to 26. Black lines show pre impact and red lines show post-impact predictions. For illustrative purposes, time around high water is limited to the flood tide period only; cyclic splines have not yet been resolved for the full tidal cycle.

In general, seal usage showed a pattern of reduced usage within the inner sound, post-deployment. While total numbers of post deployment seal locations was markedly higher than pre-deployment (76,522 and 144,470 locations for pre and post deployment respectively), overall usage in the inner sound was lower. Post-deployment hot-spots of usage were centred around the western inner sound in contrast to a more uniform pattern of usage pre-deployment (Figure 23 to Figure 25). Further, this pattern appeared to vary between tidal states.

High Water Usage

There was an apparent increase in usage post-deployment in offshore areas, most notably around the putative foraging location ~3 km west of the turbine array site (Figure 23). However, areas relatively close the turbine array, specifically in grid-cells to the immediate area east of the turbines, predicted usage decreased markedly during high tide (Figure 23).

Low Water Usage

Seal usage in the grid-cells containing the turbines showed marked differences before and after turbine deployment at slack, low tide (Figure 24). Relatively minor increases in usage were apparent at the same putative foraging site described above; however, most grid-cells showed either no change or reductions in post-deployment usage (Figure 24).

Peak Flow Usage

Seal usage in the grid-cells containing turbines showed relatively minor changes between pre and post-deployment, with low usage estimated for both during peak flow periods (Figure 25). However, a marked reduction in usage was apparent immediately south of the turbine array site, indicating a reduction in seals using the channel overall. Similar to the high and low water patterns, increased usage was apparent at the putative foraging site described above (Figure 25).

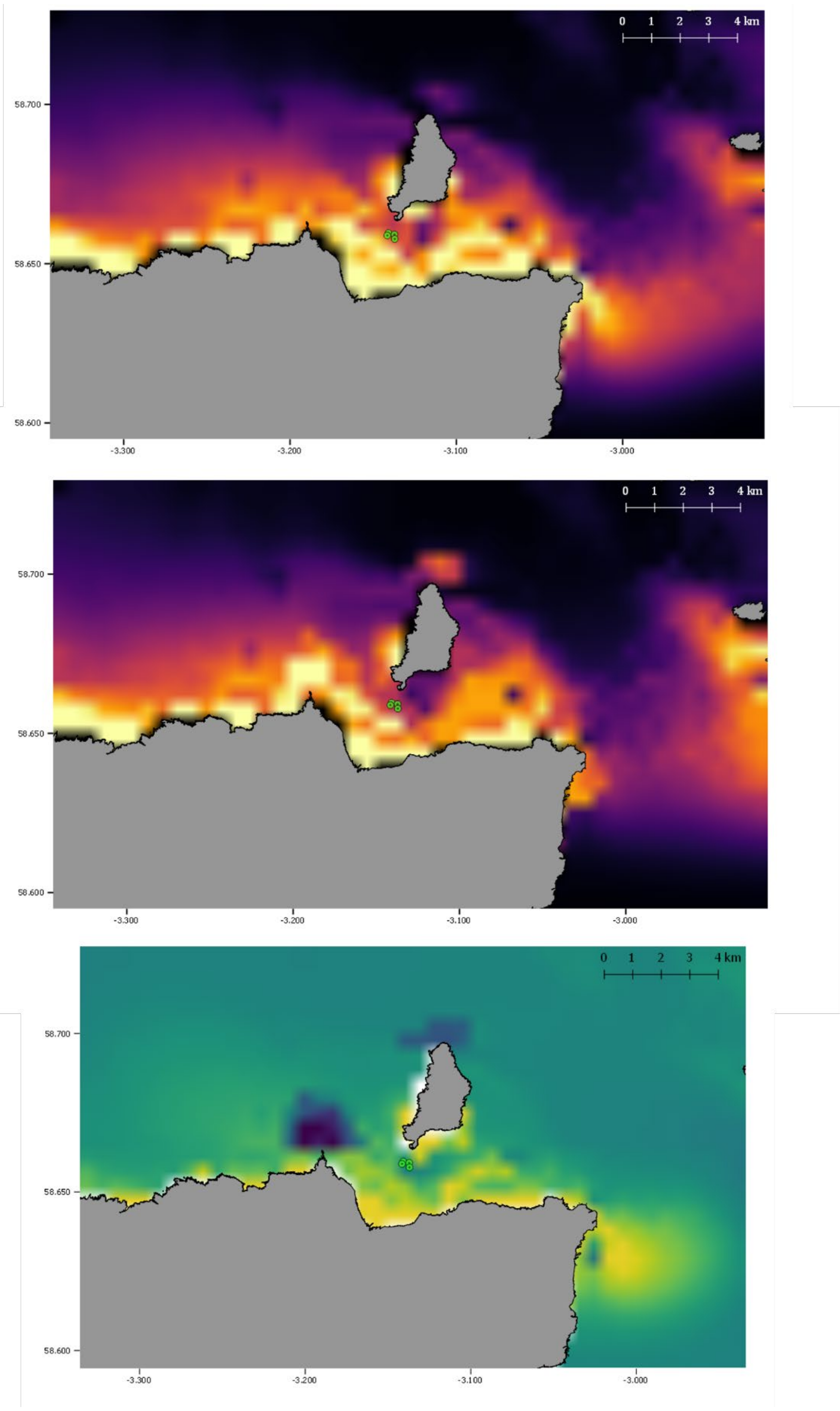


Figure 23. Predicted relative harbour seal usage at slack, high water (upper) pre and (middle) post deployment of the turbines. Usage is colour coded from high (yellow) to low (dark purple) usage. The turbine locations are shown by the green points. Changes in predicted usage (lower) are shown on a colour scale of dark blue (indicating an increase in post-deployment usage) to yellow (indicating a decrease in post-deployment usage). Predictions were projected onto 500 metre by 500 metre grid cells and then blended using a bilinear, resampling algorithm to represent smoothed usage.

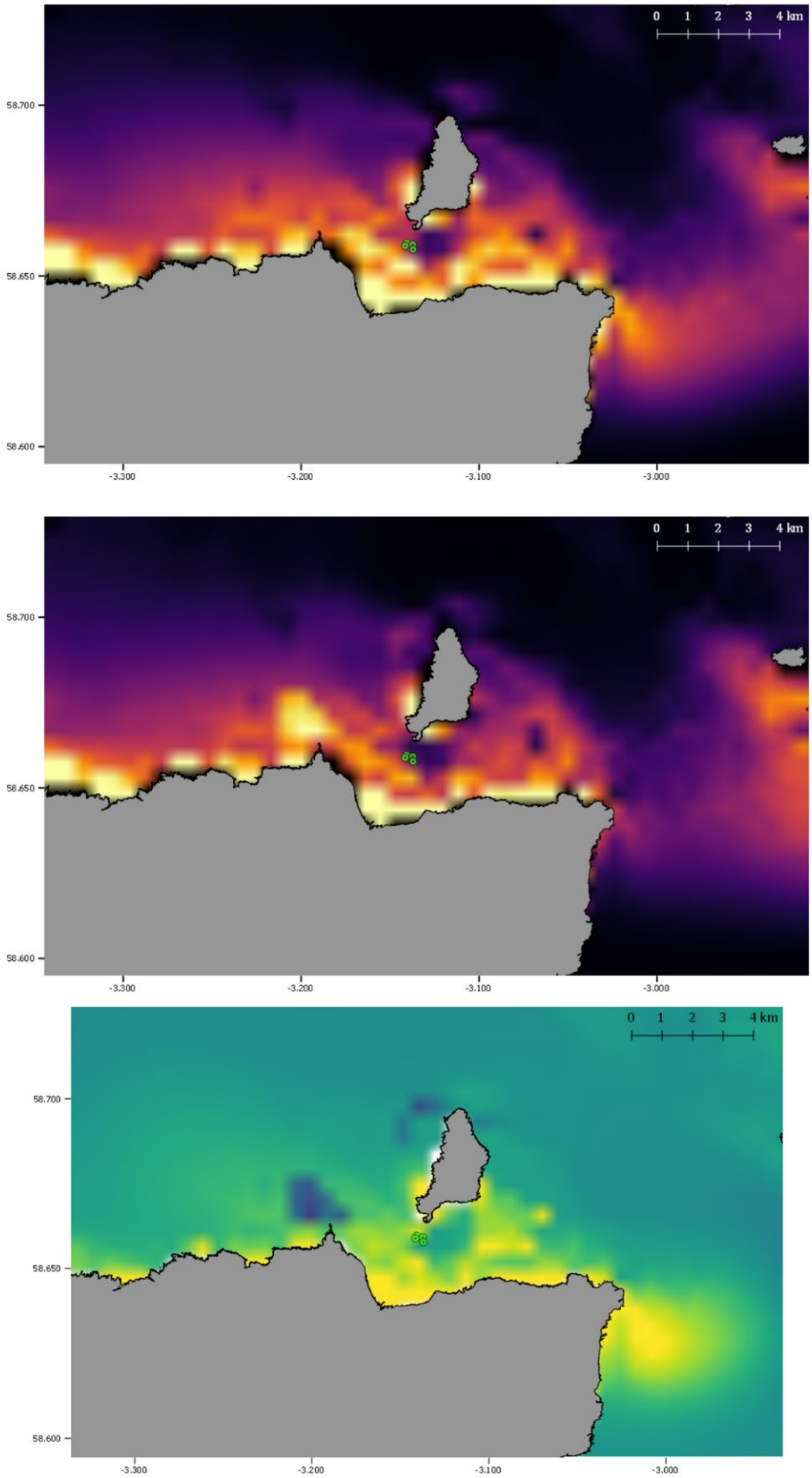


Figure 24. Predicted relative harbour seal abundance at slack, low water (upper) pre and (middle) post deployment of the turbines. Usage is colour coded from high (yellow) to low (dark purple) usage. The turbine locations are shown by the green points. Changes in predicted usage (lower) are shown on a colour scale of dark blue (indicating an increase in post-deployment usage) to yellow (indicating a decrease in post-deployment usage). Predictions were projected onto 500 metre by 500 metre grid cells and then blended using a bilinear, resampling algorithm to represent smoothed usage.

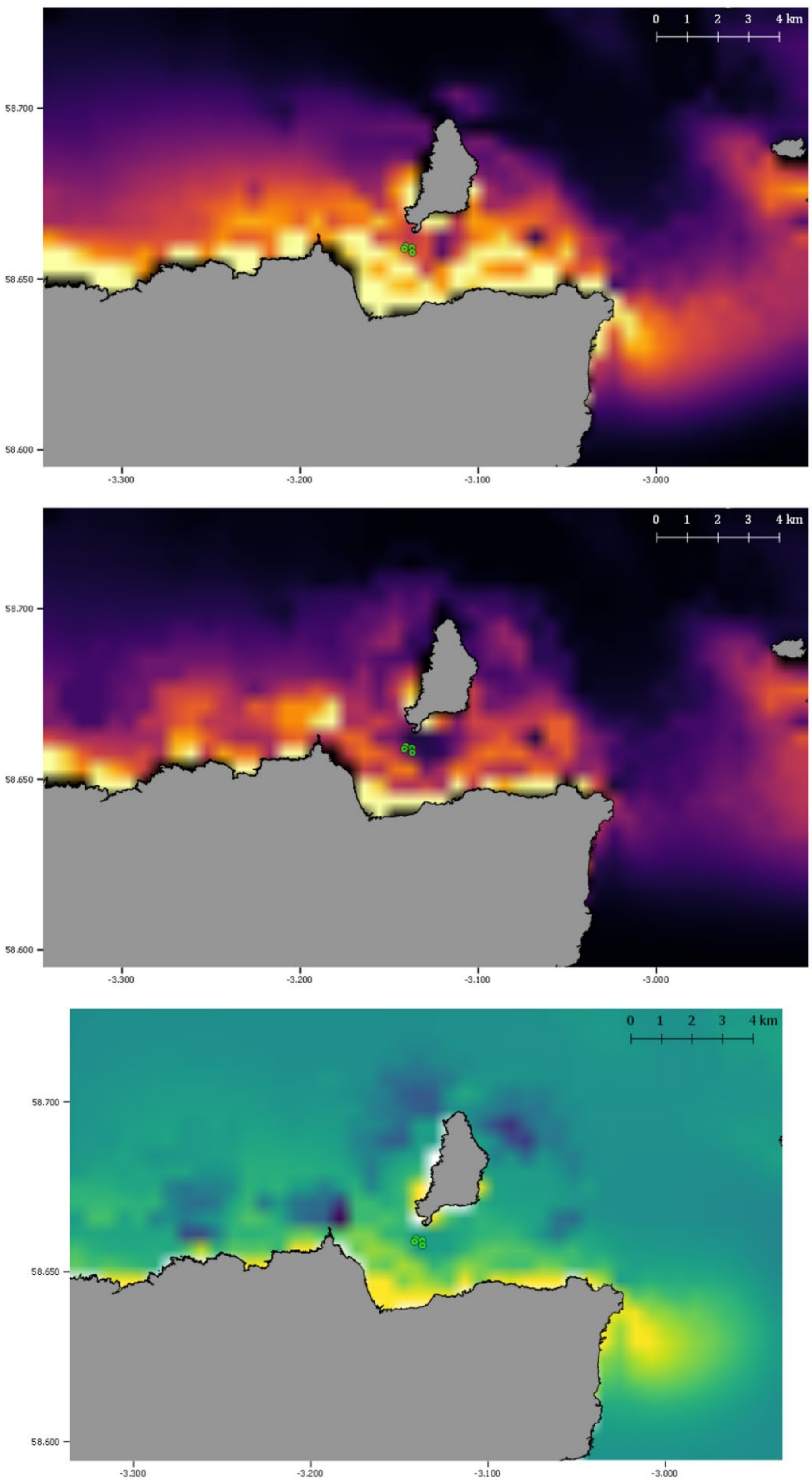


Figure 25. Predicted relative harbour seal abundance at peak flow conditions (upper) pre and (middle) post deployment of the turbines. Usage is colour coded from high (yellow) to low (dark purple) usage. The turbine locations are shown by the green points. Changes in predicted usage (lower) are shown on a colour scale of dark blue (indicating an increase in post-deployment usage) to yellow (indicating a decrease in post-deployment usage). Predictions were projected onto 500 metre by 500 metre grid cells and then blended using a bilinear, resampling algorithm to represent smoothed usage.

Future analyses will incorporate turbine operational data, the release of which has been agreed with SIMEC Atlantis Energy Ltd. An enhanced model will include operational data as a continuous covariate in replacement of tidal phase as a proxy for operation. Final analyses will also include the propagation of uncertainty and predictions at a population level. This will provide estimates which can be used in collision risk models to assess the changes in the probability of collision across various turbine operational states.

1.3.3 Deliverable 3: Monthly reports of detections of marine mammals

Routine access to the PAM PC using remote desktop software is carried out at least twice a week to make system operational checks; this includes a check of the software stability, disk space, and that data are being stored to the correct location. Data are also remotely backed up to USB hard drives connected to the PAM PC as required. The critical data collected are binary output files from PAMGuard, which contain information on detected echolocation clicks and whistles, noise level measurements and other diagnostic information. The volume of data varies depending on noise levels, but is generally in the region of two to four Gbytes per day. These data are currently backed up to secure network storage managed by the University of St Andrews and two additional copies are being kept at SMRU on large external hard drives.

Monthly PAM reports for the period October 2017 to September 2018 have been delivered. As noted above, an agreement was made with the steering group, to discontinue monthly reporting following completion of the September 2018 report so efforts could be concentrated on analysing the data collected until that point. Further, monthly seal telemetry reports summarising the GPS tag data have been provided for the periods between September 2016 and June 2017. For the April 2018 tag deployments, data were summarised in the quarterly reports.

1.3.4 Deliverable 4: A final report detailing the frequency and nature of the fine scale interactions between marine mammals and an operational tidal turbine

This work will commence after data collection and analysis carried out as part of Deliverables 2 and 3.

1.3.5 Deliverable 5: PhD thesis on the fine scale movements of top predators around a tidal turbine

A PhD studentship (partly funded by Scottish Natural Heritage through the Marine Alliance for Science and Technology Scotland) will utilise GPS and dive data to track seals and investigate: a) how these animals utilise tidal areas, and b) how they behave in relation to an operating tidal turbine. The studentship will quantify seal movement and activity budgets in 3-dimensions to expand our understanding of foraging behaviour in tidal stream environments and will assess the effects of the turbine array on harbour seal distribution. These aim to produce enhanced estimates of collision risk for seals around tidal turbine arrays.

1.4 Future tasks

Development of a final report detailing the frequency and nature of the fine scale interactions between marine mammals and an operational tidal turbine from data collected up to September 2018 (inclusive), including recommendations on monitoring equipment and protocols for the future detection and tracking of marine mammals around tidal turbines.

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