USING PASSIVE ACOUSTICS AND SHORE-BASED SURVEYS TO INVESTIGATE THE DISTRIBUTION OF SMALL ODONTOCETES IN NEARSHORE WATERS AROUND LUNDY

by

By NATALIE SQUIRES, KATY HODGSON BALL, KIMBERLEY BENNETT, STEPHEN VOTIER AND SIMON INGRAM*

Plymouth University, Drake Circus, Plymouth, Devon, PL4 8AA

Corresponding author, e-mail: simon.ingram@plymouth.ac.uk

ABSTRACT

The use of waters around Lundy by dolphins and porpoises was measured using summer shore-based watches and passive acoustic surveillance between July 2011 and July 2012. Common dolphins (*Delphinus delphis*) were the only cetacean species observed during shore-based surveys. C-PODs moored on the Ethel and MV Robert wrecks close to the Lundy coast showed a peak in delphinid vocal activity during August 2011. Passive acoustic detections of harbour porpoises (*Phocoena phocoena*) were highest during ebb tidal phases and most often associated with the tidal rip at the south of the island. These findings show tidal and monthly influences on odontocete behaviour and highlight the value of continuous, passive acoustic monitoring for these highly mobile marine predators around Lundy.

Keywords: *C-POD, Delphinus delphis, Phocoena phocoena, vocalisation, tide*

INTRODUCTION

Bathymetric features such as continental shelf breaks and slopes, shallow banks, seamounts and island chains are often sites of enhanced marine productivity (Ichii *et al.,* 1998 & Lavoie *et al.,* 2000), as well as predator-prey aggregations (Macaulay *et al.,* 1984; Barange, 1994; Munk *et al*., 1995; Springer *et al*., 1996). Islands can produce upwelling, which brings cool, nutrient rich water to the surface layers. Fast tidal currents and heterogeneous underwater topography associated with islands can result in formation of small eddies, which aggregate prey (Schwing *et al*., 1991; Strub *et al*., 1991) and attract marine predators (Schoenherr, 1991; Croll *et al*., 1998; Benson *et al*., 2002). Lundy's location, in the mouth of the Bristol Channel, is characterised by fast-moving, turbulent water, with strong tidal currents, resulting in the regular mixing of the surface layers and the dispersal of plankton and fish. Lundy experiences large tidal ranges of up to 9m and a strong tidal rip occurs around the south end of the island. This productivity and the range of habitats available supports high biodiversity in its waters (Hiscock & Irving, 2012).

Lundy has been a flagship for marine conservation in the UK since 1971, when it was established as a voluntary Marine Nature Reserve, the first Marine Protected Area (MPA) in Britain. In 2009, Lundy Island MPA was the first to be converted to a Marine Conservation Zone (MCZ), a new designation following the implementation of the Marine and Coastal Access Act (Natural England, www.naturalengland.org.uk). Additionally, in 2003 the Devon Sea Fisheries Committee (DSFC) designated a 3.3km^2 area off the east coast of Lundy as a No Take Zone (NTZ), where the removal of marine life is prohibited (Devon and Severn IFCA, 2012). Although the conservation status enjoyed by Lundy's waters, coupled with local oceanographic conditions and hydrographic features, are likely to result in an abundance of prey items attractive to small odontocete species, little is known about the use of Lundy's inshore waters by small odontocetes.

Over recent years, efforts by visitors and volunteers on the island and aboard the island ferry, the MS Oldenburg, have provided sightings records of marine mammals in the waters surrounding Lundy and, in addition, a log has been maintained on the island of sightings made from Lundy. Although opportunistic sightings provide valuable information on species occurrence around Lundy, to understand fine-scale habitat preferences and precise movements requires dedicated surveys and survey methods. Cetacean behaviour and habitat use varies in relation to their reproductive state and diurnal, tidal and seasonal changes in prey availability (Walton 1997; Weir *et al*. 2007). These changes in habitat use are often difficult to discern from opportunistic data and prior to this study limited seasonal and spatial data existed for the use of Lundy inshore waters by small odontocetes.

Overlying these local or short-term variations can be large scale shifts in species ranges, such as the unexplained southerly shift in harbour porpoise distribution over 15 years, revealed by the SCANS (Small Cetacean Abundance in the North Sea) surveys that covered much of the UK and European waters (Hammond *et al.,* 2013). Long-term dedicated monitoring is therefore necessary in order to detect natural and man-made drivers of changes in distribution and habitat use.

Shore-based surveys from vantage points that provide a wide angle of view can be of value in monitoring usage of inshore waters by marine mammals. These methods allow reliable identification of species by trained observers, as well as deriving accurate locations, behaviour and group size (Bailey & Lusseau, 2004). Shore watches can also be used in conjunction with other techniques, such as passive acoustic monitoring (PAM), to provide detailed local information about marine mammal movements and habitat use, and are useful in ground-truthing acoustic detection data (Simon *et al.*, 2010).

Dolphins and porpoises emit high-frequency echolocation clicks whilst foraging and, driven by advances in instrumentation, passive acoustic detection of these sounds has become an increasingly useful survey and monitoring technique (Mellinger *et al*., 2007). C-PODs (Chelonia Ltd) are passive acoustic detection devices that incorporate a hydrophone and data logger to log detected porpoise and dolphin click trains. By using digital waveform characterisation, C-PODs are capable of calculating the timing of a click, the frequency of the click produced, sound pressure level, duration and bandwidth. Dolphin and porpoise click trains can be distinguished by their characteristic dominant click frequencies. Harbour porpoises have an average peak frequency of

128kHz, a source level of 157dB and a bandwidth of 16kHz (Au, 1993). In comparison, delphinids produce a much wider range of frequencies. For example, short-beaked common dolphin, *Delphinus delphis,* have peak frequencies of 23-67kHz, and bandwidths of 17-45kHz (Au, 1993). Due to the high frequency of porpoise clicks, detections by the C-POD are only possible at a relatively short range of ~300m and a 100% on-axis detection rate within only ~100m radius (Tougaard *et al.*, 2006). As the lower frequency of dolphin clicks is less susceptible to attenuation through water, they can be detected at longer ranges (Philpott *et al.,* 2007).

Basic interpretation of behaviour is possible by analysis of Inter Click Intervals (ICI). As porpoises advance on targeted prey items, they have been observed to produce a series of short ICIs, known as a 'buzz' and short ICIs can thus be used to infer foraging behaviour. Carlström (2005) established that the greater the proportion of minimum ICIs (MICI) below 10ms, the more probable it is that feeding behaviour is occurring. T-PODs (the predecessor of C-PODs) and C-PODs have been effectively used in studies to monitor foraging and feeding behaviour and habitat use (Cox and Read, 2004; Philpott *et al.*, 2007; Todd *et al.*, 2009; Rayment *et al.*, 2009; Thompson *et al.*, 2010; Simon *et al.*, 2010; Kyhn *et al.*, 2012).

We undertook systematic shore-based visual observations of dolphins and porpoises and analysed passive acoustic C-POD data to investigate tidal, diurnal and monthly changes in vocal activity and associations between behaviour and depth and habitat type during their summer use of inshore waters around Lundy.

METHODS

Data collection

Acoustic data collection: Two C-PODs were provided by Natural England and were deployed, maintained and retrieved by Lundy staff. The first C-POD (the Robert C-POD) was attached to the wreck of the MV Robert, approximately 1km off the eastern coast of the island (Figure 1), which is in low tidal current conditions at 22-28m depth. The C-POD was tied with polypropelene rope to the wreck by scuba divers on 25 July 2011 and retrieved by divers on 10 October 2011. The second C-POD (the Ethel C-POD) was similarly attached by scuba divers to the wreck of the Ethel (Figure 1) located in a tidal stream to the south of the island in water depth of 25-30m. The Ethel C-POD was deployed on 30 July 2011 and retrieved on 14 May 2012. The C-PODs were activated using a continuous scan and high-pass filter of 20kHz. In addition to click detections, the C-PODs also recorded water temperature and angle of the unit from vertical every minute.

Visual data collection: Visual surveys were conducted between 14 May and 3 July 2012 from four cliff-top locations (Figure 1) using a theodolite (Total Station Leica TCR805 PinPoint R100) to track animals remotely from the shore. Sites with the widest field of view were selected at the south, west, north and east of the island: 1. The Devil's Limekiln, which overlooks the Ethel wreck site; 2. Jenny's Cove; 3. North End and 4. Tibbetts Point, which overlooks the Robert wreck site. Sites overlooking the C-PODs were selected to establish exact locations of individuals that could be detected by the C-PODs, as well the size of the pods and identification of species. Additional sites on the west and north sides of the island were selected to determine if the C-POD locations were representative of all Lundy's nearshore waters.

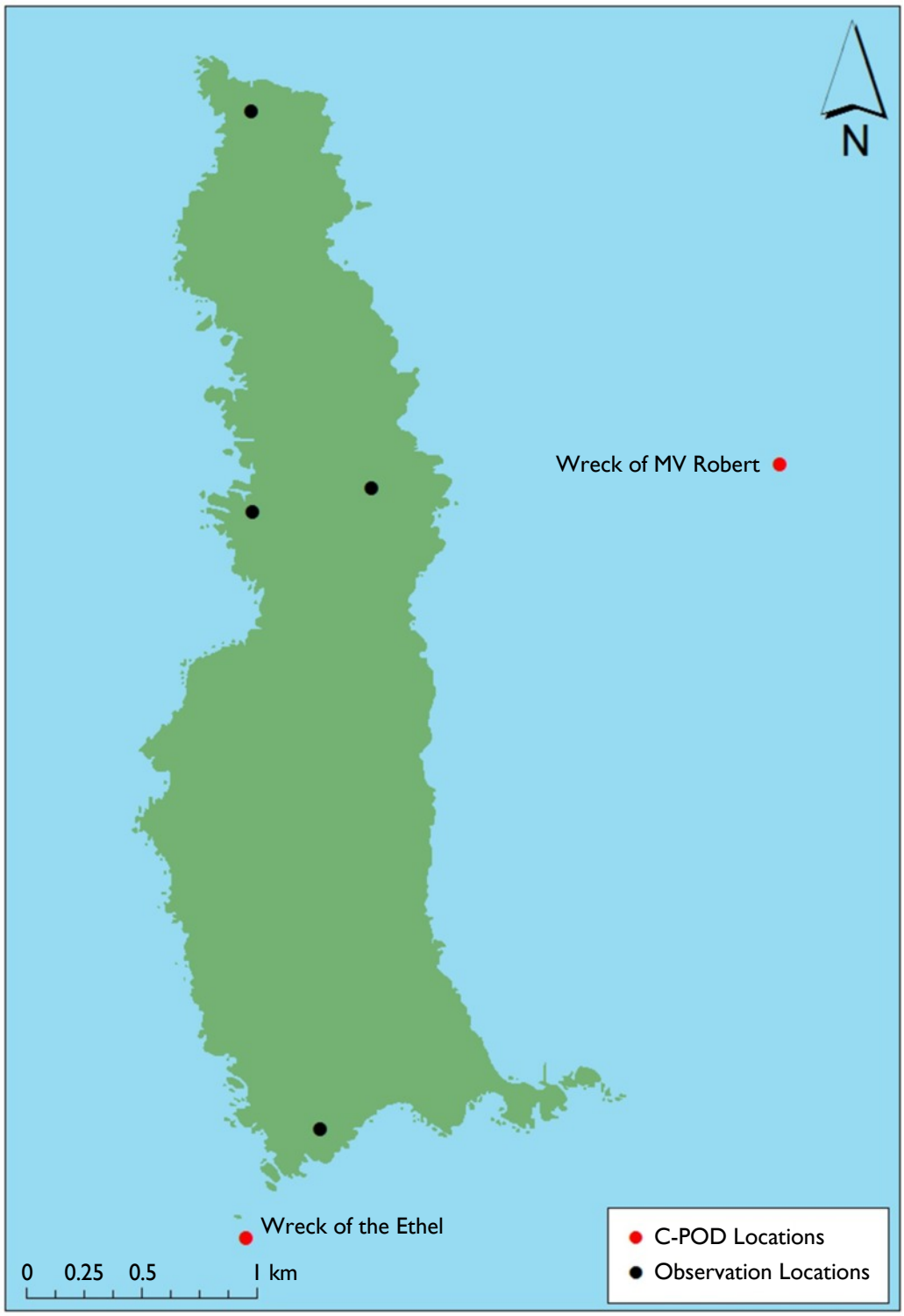

Figure 1: Map of Lundy showing the location of the C-PODs and the observation sites

Surveys were conducted on all days when the wind was <Beaufort scale 4. Surveys were conducted by two trained observers, one recording positional data with the theodolite and one scanning the survey area with 10x30 binoculars. Scans of the field of view were conducted every 30 minutes (scans took approximately ten minutes), recording the position of any odontocetes spotted. Theodolite tracking was carried out whenever an odontocete was first spotted until they disappeared from view. If a track lasted until the next scan, one observer continued the track whilst the other observer performed the scan. The position of the group of cetaceans at the time of the scan was extracted from the track data. If another animal/group of animals were observed during the scan, the tracking of the group of cetaceans would pause whilst the position of the new group was recorded. If the tracking was paused for more than three minutes, that tracking log was ended and a new track was begun. Surveys at each site were conducted to obtain replicate data from the same time of day and state of tide. To control for any differences in survey effort, the number of animals was standardised by calculating the number of animals sighted per hour (aph) by dividing the number of individual animals observed during a survey by the number of hours spent surveying.

Data Analysis

Acoustic data analysis: C-POD data were analysed using the program CPOD.exe (Chelonia Ltd). CPOD.exe records cetacean clicks in trains which are compared with trains from other noise sources, such as rain, crustaceans, moving sediment or pebbles, or propeller cavitation. Trains are placed into one of four classifications in order of their confidence that the train was produced by a cetacean: hi (high), mod (moderate), lo (low), and '?' (doubtful). Only trains in the category of hi and mod were used in subsequent analysis.

The Kerno Classifier of the CPOD.exe program detects 'continuous noise' which is most commonly attributed to noise from sediment transport. In locations that experience rapid tidal flow it is common for elevated levels of tonal high-frequency ultrasound to saturate the ability of the C-PODs to log dolphin or porpoise clicks for limited periods of time. The percentage of time lost during these 'maxed out' periods was logged by the C-PODs.

Three parameters were derived from the CPOD.exe program to describe cetacean activity (Chelonia, 2012 & Brandt *et al.*, 2009). Detection Positive Hours (DPH) per day was used to compare acoustic activity between months. For shorter time frames, such as tidal cycles, Detection Positive Minutes (DPM) per hour was used to give more appropriate resolution of the data. Minimum Inter-Click Interval (MICI) is the minimum amount of time between successive clicks per click train and was used here to infer foraging behaviour; feeding was assumed to occur when MICI was <10ms (Carlström, 2005).

Spatial and temporal patterns in median DPH between months and between sites were investigated. Only months in which recordings were available for the entire duration of the month were used. This allowed comparison of August 2011 with September 2011 for the Robert C-POD and comparison between August, September and October 2011 for the Ethel C-POD. Comparisons of overall porpoises DPH per

day were made between the Ethel C-POD and the Robert C-POD to identify differences between sites. As dolphins were only detected by the Robert C-POD, no site comparison was possible for these animals. The average tilt angle of the C-PODs (where 0° is an absolutely vertical unit) were compared to investigate and verify differences in water flow conditions at the two C-POD sites for the duration of the sample period. Tides were divided into four tidal phases of three hours duration: low tide and high tide (which both consisted of the hour of slack water at high and low tide and each hour either side), flood tide (the ~three hours between low and high tide) and ebb tide (the ~three hours between high tide and low tide). Differences in DPM and MICI between states of the tide and between spring and neap tide were also investigated.

Visual data analysis: The theodolite measures horizontal angles from an arbitrarily selected reference point and vertical angles relative to a gravity referenced level vector. All four observation locations and their respective 'zero' positions were surveyed using a differential GPS (Trimble SPS750) with an accuracy of ±10 cm. The positional error associated with sightings increases with distance and is a function of the height of the observation platform. The height of the theodolite above the sea surface was obtained using predictive tide tables and calibrating each measurement against a known point on the tidal cycle. Height above the sea surface, the position of the theodolite station and a 'zero' reference point on a map of the coastline were used to convert angular measurements of an animal or group positions, into x/y coordinates on a map using the method from Gailey and Ortega-Ortiz (2000).

To convert horizontal and vertical degree readings of the theodolite x and y position coordinates, it is necessary to know the angle between the horizontal zero reference point and the baseline of an orthogonal grid system, in this case Ordnance Survey GB. The x/y co-ordinates were derived based on calculations described by Lerczak and Hobbs (1998). The x/y coordinates calculated for the track data were entered into ArcMap GIS. The C-POD positions were also displayed to show overlap between the detection ranges of the C-PODs and observed cetaceans.

Behaviours were classified following the procedure of Shane (1990), where continuous directional movement was classed as travelling; jumping, tail slaps, physical contact between individuals was classed as socializing; chasing prey, bursts of high directional swimming, lunging and splashing was classed as foraging; slow, non-directional swimming was classed as milling (bunching up); and very slow swimming in one general direction was classed as resting. There were too few observations to perform statistical analysis relating behaviour to depth or tidal phase.

RESULTS

Acoustic data

C-POD deployments: Timing and duration of recordings and number of detection positive days for porpoise and dolphins and mean DPM per day for each C-POD are given in Table 1. Mean detections of porpoise by the Robert C-POD were 4.37 DPM per day ±6.19 (SD). Mean detections of dolphins were 5.14 DPM per day ±12.25 (SD). The

Ethel C-POD detected mainly porpoise activity, with a mean of 4.37 DPM per day ±6.19 (SD), and only recorded 4 DPM of dolphin clicks in total. No continuous noise was logged by the Robert C-POD. The median tilt angle for the Ethel C-POD (median=12.05, range 9.8-16.1) was generally twice that of the Robert C-POD (median=4.1, range 1.2-9.3) indicating that the Ethel C-POD was located in an area of stronger tidal activity, and frequently detected continuous ambient noise of 20 kHz.

C-POD	Start	End	# Days	# Hours	Detection positive days (porpoise)	Detection positive days (dolphins)
Robert	25/07/11	01/10/11	67	1627.5	28	22
Ethel	30/07/11	06/11/11	99	2379.11	75	2

Table 1: Start and end dates and recording durations from the C-PODs

Effect of Month on acoustic activity: Dolphins and porpoises were significantly more acoustically active during August 2011 than September or October 2011. For the Ethel C-POD porpoise DPH per day was significantly greater during August 2011 (Kruskal Wallis, df=2, $p<0.01$, median=2, range=0-9) than September (median=1, range=0-5) and October 2011 (median=1, range=0-8). For the Robert C-POD dolphin DPH per day was significantly greater during August 2011 (W=1187.5, df=31, $p<0.01$, median=1, range=0-5) than September 2011 (median=0, range=0-1). No significant difference was detected in DPH per day of porpoises detected by the Robert C-POD.

Effect of Tide on habitat use: Porpoise acoustic activity at the Ethel C-POD was significantly greater during the strong ebb tidal flow ($X^2=129.94$, $p<0.05$, df=2) than during other tidal states, with 44% of detections made during ebb tide (Figure 2). Significantly more detections were also made by the Ethel C-POD during spring tides than neap tides (Mann Whitney U, W=2037.0, df=51, $p<0.05$, median=2, range=0-9) (median=0, range 0-6) (Figure 3). Porpoise detections made by the Robert C-POD were also significantly more frequent during ebb tide ($X^2=90$, $p<0.05$, df=3), with 34% of total detections made during ebb tide (Figure 2); however, no significant difference was observed between spring and neap periods (Mann Whitney U test, W=1121.5, df=34, $p>0.05$) at this site. There was a significant difference in dolphin detections by the Robert C-POD between tidal states ($X^2=34.53$, $p<0.05$, df=3). Significantly more detections were made during the high tide (33%) and the low tide (31%) slack periods (Figure 2) than in flowing ebb and flood tides. No significant difference was found between spring and neap tides at the Robert site (Mann Whitney U, W=1210.0, df=34, $p>0.05$).

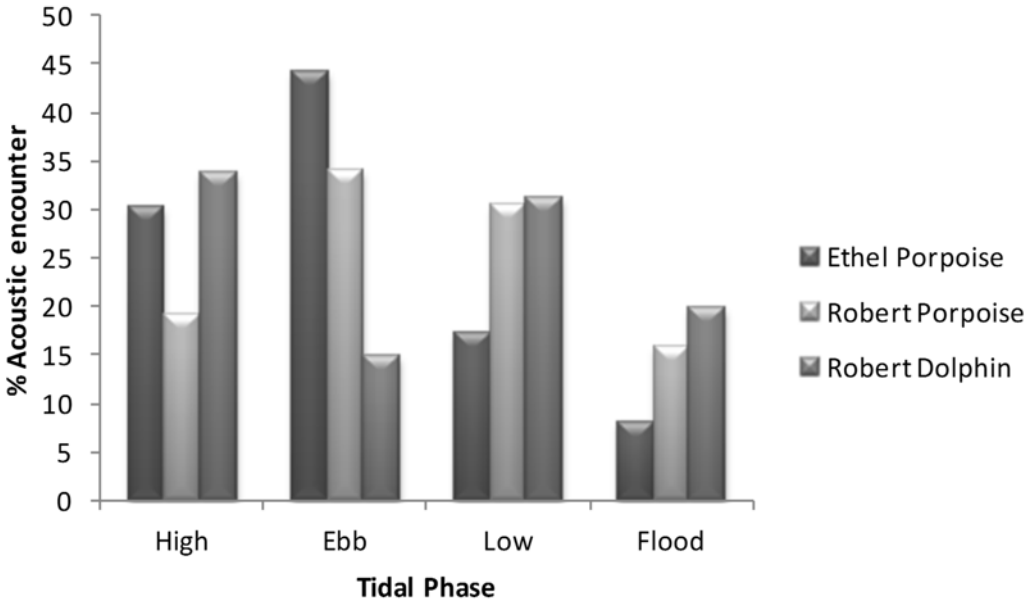

Figure 2: Percentage of total acoustic encounters during each tidal phase for Robert and Ethel C-PODs for porpoise and dolphins

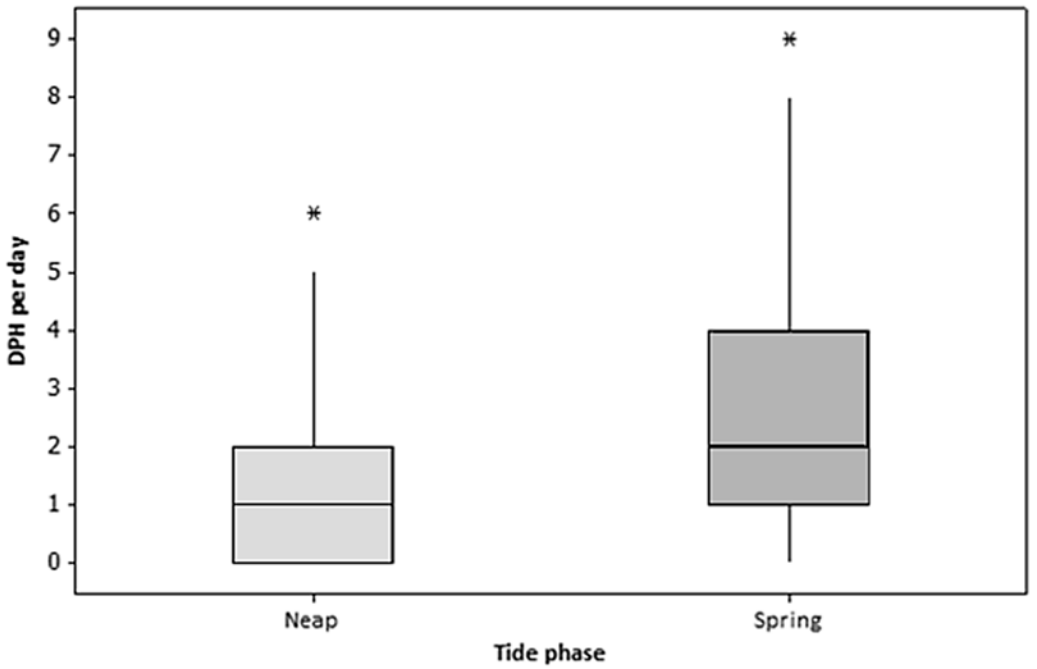

Figure 3: Box plots of the DPH per day of *Phocoena* detections during spring tides and neap tides detected by the Ethel C-POD

Tidal effects on interclick intervals: MICIs below 10ms can be indicators of foraging (Carlström, 2005). At the Robert, the highest proportion (80%) of porpoise MICIs below 10ms were during low tide slack periods, whereas at the Ethel, the highest proportion of MICIs below 10ms (63%) were during the ebb tide suggesting different foraging behaviours by porpoise at the two sites (Figure 4). Dolphin MICI at the Robert also varied significantly between tidal phases (Kruskal Wallis test, H (adjusted for ties)=23.45, df=3, $p<0.001$), with the median MICI being lower during the low (median=25265, range 2735-88160) and flood (median=45564, range 2260-67970) tides than the high (median=46010, range 9595-90830) and ebb phases (median=50690, range 3570-70095) (Figure 4).

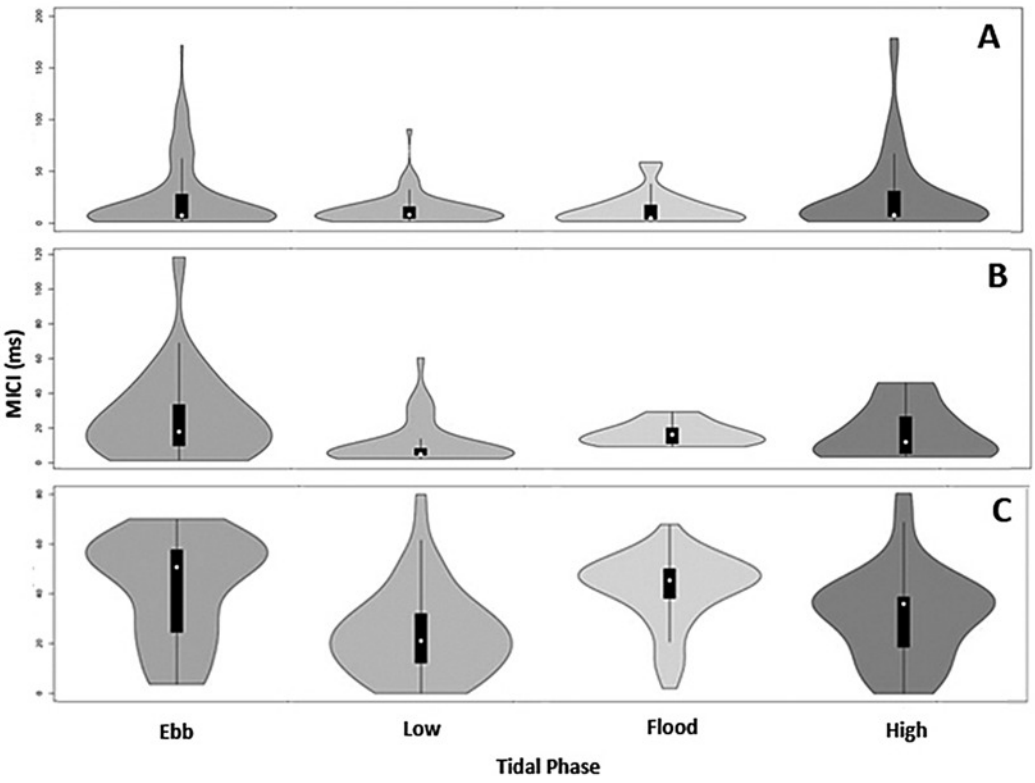

Figure 4: Distribution during each tidal phase of: A) *Phocoena* MICI (ms) detected by the Ethel C-POD; B) *Phocoena* MICI (ms) detected by the Robert C-POD; C) Dolphin MICI (ms) detected by the Robert C-POD

Visual data

31 watches spanning 182 hours were conducted throughout May and June 2012. Cetaceans were observed in six of these watches. Effort was low in June due to poor weather and sea state conditions.

All ten tracks were of groups of short beaked common dolphins (Figure 5 – opposite). Groups ranged from one to 60 individuals with a mean pod size of 28. The majority (70%) of cetacean sightings were observed from the east coast observation site, with the remaining 30% of sightings occurring off the south coast. Once spotted, dolphin groups remained in the area for a mean of three hours. Cetaceans did not tend to travel into the shallower areas, close to shore, very often (Figure 5). When they did, the most frequent behaviour observed was foraging. Small sample size prevented statistical analysis of the differences in behaviour between depth ranges. The highest number of tracks occurred in the 20-50m depth range. The most common depth bands in which foraging was observed were 10-20m and 20-50m. Travelling was observed mostly in the deeper (20-50m) depth category, and resting activity was observed in the mid-depth range (10-20m). Benthic habitat types around Lundy are divided into kelp forest, mud, muddy gravel, sandy gravel and rocky reef (Smith & Nunny, 2012). Sample sizes here were too small to detect differences in behaviour between habitat types although the greatest number of foraging tracks occurred over a sandy bottom type with lower numbers over mud, muddy gravel and rocky reef. Foraging behaviour tended to occur more frequently during high, ebb and flood tides than at low tide, but sample size was too small for statistical analysis (Figure 6). Travelling was observed more frequently at high and ebb tides. No differences in resting activity was observed between tidal states.

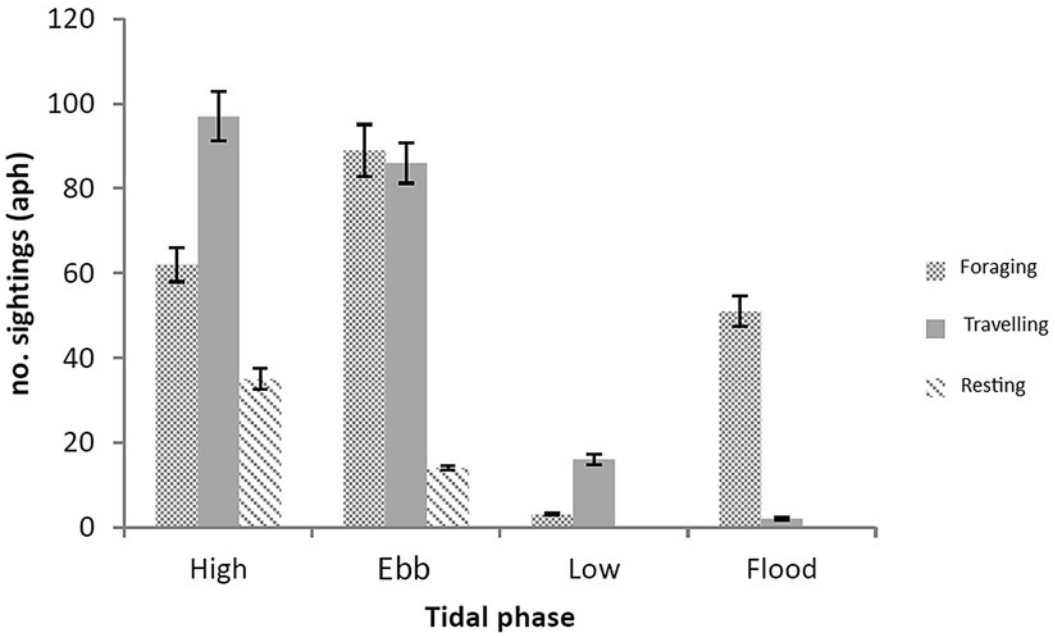

Figure 6: Behaviour observed during different tidal phases ± STDEV

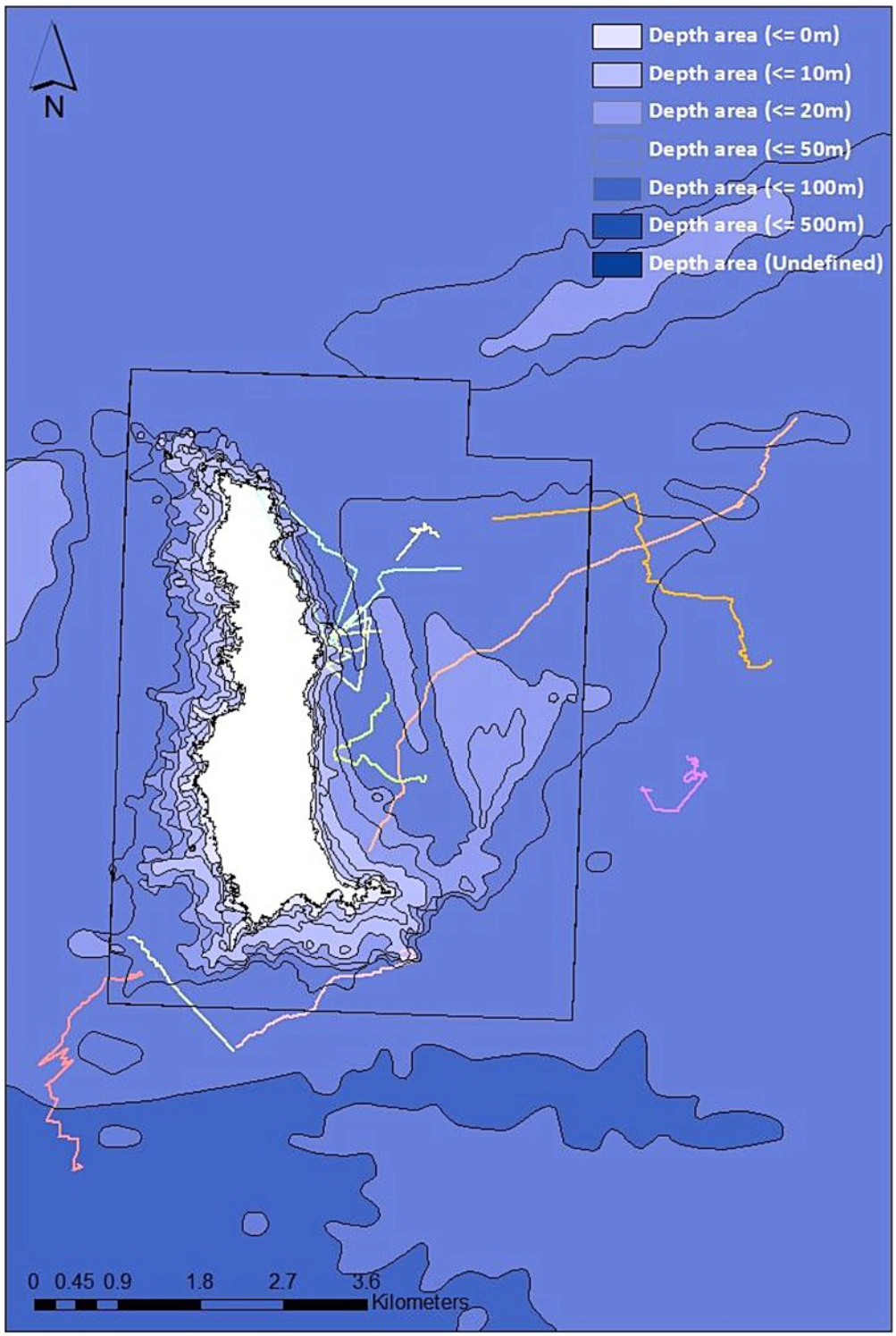

Figure 5: All dolphin tracks overlaid on depth contours

DISCUSSION

Species using Lundy waters

The majority of the cetacean detections by the C-PODs were of porpoises, with some dolphin detections, which were assumed to be short beaked common dolphins based on records from visual observations (J. Waller, pers. comm.). However, common dolphins were the only odontocete species observed during the visual surveys between May and July 2012. They were only sighted on the east and south sides of the island. No sightings of harbour porpoises were recorded. Since porpoises were detected acoustically, the lack of porpoise sightings suggests that visual surveys were adversely affected by poor weather resulting in underestimates of the numbers of porpoises using the area, a problem identified in other studies (Palka, 1995).

Monthly change in activity

For all species detected by the two C-PODs, there was decrease in acoustic activity from August through to September and October. Studies in UK waters have suggested an offshore-inshore movement of both porpoises and dolphins, and a study conducted by Goold (1998) over two consecutive years showed a significant decrease in dolphin detections in the Celtic Sea between September and October. However, as surveys were only made over a limited period, it is impossible to identify seasonal patterns in the 2011 or 2012 data, highlighting the need for longer and continuous data collection over successive years.

Tidal influences on behaviour

Our data suggest harbour porpoises using Lundy inshore waters are more likely to forage during the ebb tide and in conditions where tidal flow is strongest, especially at the Ethel site. These observations support those made by Pierpoint (2008), whose visual observations indicated that foraging by harbour porpoises in the Ramsey Sound, South Wales, was almost entirely restricted to the ebb tidal phase when individuals maintained their position in the tidal stream for prolonged periods of time. Abundance of prey also foraging during high tidal flow may be an additional explanation for harbour porpoise tidal distribution (Goodwin, 2008). Our data show that the tidal stream at the south end of Lundy is particularly important for porpoises. Data indicated that porpoises were more likely to forage in tidal rips, particularly during ebb tides. Specifically, during 2011 most harbour porpoise detections were logged by the Ethel C-POD, at the south end of the island, during ebbing tides.

In contrast, acoustic activity of porpoises detected by the Robert C-POD was high during the low tide (34%). At this site, only 29% of porpoise MICI were <10 ms during the ebb tidal phase and instead the low tide had the largest (80%) proportion of MICI <10 ms. This suggests that at this site, foraging activity was more likely to occur during low-tide periods.

The majority of observations of dolphins occurred during ebbing tides, whereas dolphin detections by the C-PODs were lowest during ebb tides. This discrepancy most likely arose from the low sample size of the visual observations although tidal related changes in echolocation behaviour cannot be ruled out. These data suggest that dolphins do not appear to concentrate foraging activity at the same state of tide as porpoises.

Association with depth and habitat type

The highest number of cetacean tracks occurred in the 20-50m depth range, with animals rarely coming close to the shore. Foraging behaviour by common dolphins occurred between 10 and 50m in the waters around the island. Studies of other dolphin species show that sightings can vary significantly with both water depth and seabed gradient (Ingram & Rogan, 2002). Frequency of dolphin sightings is often reported to be highest in the deeper parts of coastal habitat, with steep seabed gradients (Baumgartner, 1997; Wilson *et al.*, 1997; Hastie *et al.*, 2006; Ingram & Rogan, 2002). Similar findings have been found for harbour porpoises in UK waters (Booth *et al.* 2013). Deeper water may be associated with greater prey abundance, or deep areas with steep seabed gradients may increase foraging efficiency, either by aiding detection and/or manipulation, or by providing barriers against which to herd prey (Ingram & Rogan, 2002; Hastie *et al*, 2006). Here we were unable to make any inferences about the depth or habitat preferences of the dolphins using Lundy as a result of small sample sizes.

Use of C-PODs to infer usage and foraging behaviour

This study has demonstrated the value of C-PODs for monitoring odontocetes around Lundy over extended periods of time and in all weather and tidal conditions. In particular, PAM has revealed significant use of the island's waters, particularly in tidally active areas, by porpoises, when elevated sea states due to tidal currents may have constrained visual detections. Visual survey effort was also considerably hampered by inclement weather conditions, particularly throughout June 2012, which was a very wet month, with an average of 182mm of rain recorded in southwest Britain by the Met. Office (www.metoffice.gov.uk/climate/uk). Due to the necessity of a clear field of view when conducting surveys of this nature (Evans & Hammond, 2004) precipitation prevented any surveying on the affected days. Harbour porpoises are particularly difficult to identify during poor sea states (Northridge *et al.*, 1995; Evans and Hammond, 2004). For this reason, data from shore-based surveys are biased: behaviour and sightings were only recorded in good weather, and responses of animals during poor weather remained unobserved.

Dolphin sightings were made at both of the C-POD locations; therefore it can be assumed that the positions of the two C-PODs are appropriate and in locations where detections are likely if echolocating animals are present.

During times of high tidal activity continuous noise was logged by the Ethel C-POD which resulted in a considerable amount of 'maxed out' time periods where the C-POD was not making any click detections (Chelonia, 2012). As porpoises were most acoustically active during high tidal flow it is likely that a proportion of echolocation was missed as a result of tidal noise and that actual detections rates were likely higher than recorded. This suggests that at the Ethel site in particular we were likely to underestimate actual foraging events and overall vocal activity. An absence of detections may also have been due to reduced vocalisation activity rather than an absence of cetaceans (Verfuß *et al.*, 2007). However, porpoises are understood to use echolocation primarily as a sensory system to understand their

environment rather than as a communication function. It is therefore unlikely that they will be silent whilst present in an area and we are confident that the observed changes in porpoise vocal activity reflect a change in usage of the area.

Environmental factors, including changes in temperature, salinity and water depth can all affect the nature of sound waves, causing them to bend when travelling through water bands of different properties (Medwin, 2005). For species emitting low frequency clicks which can be acoustically detected from long distances (several km) this could result in refraction of the sound waves, which might go undetected by the C-PODs. Although only one click is necessary for the C-POD to log a DPM, off-axis porpoise echolocation beams may go undetected . Furthermore, as porpoises emit high frequency sounds which are susceptible to attenuation in the water column, they are only detected by the C-POD at short range (maximum ~300m). Therefore, although their detection is unlikely to be affected by changes in the water properties it may be range limited and ground-truthing of the C-PODs is required to determine the range over which each C-POD can detect different species. This requires simultaneous shore-based surveys and C-POD recording, which was not possible in this study.

CONCLUSION

The use of passive acoustic devices during this study has allowed the collection of continuous, informative data on the use of the inshore waters of Lundy, irrespective of weather conditions and available personnel. These data have shown that harbour porpoises and dolphins use Lundy's inshore waters throughout summer, but utilise them in different ways. Tidal state and currents seem particularly important for harbour porpoises. Since the collection of these data is relatively independent of environmental conditions, the ongoing use of C-PODs to monitor the use of Lundy by small odontocetes, within and between tidal states, seasons and years will provide a valuable contribution to understanding the basic biology of these animals as well as a valuable monitoring tool for the ecology of the island and surrounding waters. These data could contribute to our understanding of long-term shifts in habitat use and the effects of anthropogenic factors, such as offshore wind developments, on cetacean populations. A larger array of C-PODs would allow calibration of each device and maximise detection, as well as build in redundancy. Such acoustic data sets would benefit from supplementary long-term or repeated visual observations, for more accurate species identification or verification, to determine the range for each C-POD, and to corroborate assumptions about behavioural state. If utilised effectively and combined with supplementary visual observations such passive acoustic devices facilitate the collection of data necessary to meet the conservation and management requirements of harbour porpoises and dolphin species.

ACKNOWLEDGEMENTS

The authors would like to thank the Lundy Field Society for a travel grant to support the observational work on the island; the Lundy staff, particularly Derek Green, Donald Malone and Derren Fox for logistical support; Natural England for the provision of the C-PODs and access to the data; the Appledore and Ilfracombe dive

clubs and personnel who deployed and retrieved the C-PODs. We are also grateful to Mel Parker at Natural England for facilitating this project; the captain and crew of the Oldenburg for their comments and knowledge about the historical sightings records and Dr Keith Hiscock for his valuable support and insight. We also thank two anonymous reviewers whose comments and advice greatly improved this paper.

REFERENCES

Au, W.W. 1993. *The Sonar of Dolphins*. New York: Springer.

Bailey, H. & Lusseau, D. 2004. Increasing the Precision of Theodolite Tracking: Modified Technique to Calculate the Altitude of Land-based Observation Sites. *Marine Mammal Science*, 20, 880–885.

Barange, M. 1994. Acoustic Identification, Classification and Structure of Biological Patchiness on the Edge of the Agulhas Bank and its Relation to Frontal Features. *African Journal of Marine Science,* 14, 333–347.

Baumgartner, M.F. 1997. The distribution of Risso's dolphin *(Grampus griseus)* with respect to the physiography of the northern gulf of Mexico. *Marine Mammal Science*, 13, 614–638.

Benson, S.R. Croll, D.A., Marinovic, B.B., Chavez, F.P. & Harvey, J.T. 2002. Changes in the Cetacean Assemblage of a Coastal Upwelling Ecosystem during El Nino 1997-98 and La Nina 1999. *Progress in Oceanography*, 54, 279-291.

Booth, C.G., Embling, C., Gordon, J., Calderan, S.V. & Hammond, P.S. 2013. Habitat preferences and distribution of the Harbour Porpoise *Phocaena phocaena* west of Scotland. *Marine Ecology Progress Series*, 478, 273-285.

Brandt, M.J., Diederichs, A. & Nehls, G. 2009. Investigations into the Effects of Pile Driving at the Offshore Wind Farm Horns Rev II and the FINO III Research Platform. *Report to DONG Energy*, Germany, 33.

Chelonia 2012. C-POD specification (on-line – cited 02/02/2012). Available from http://www.chelonia.co.uk/cpod_specification.htm.

Carlström, J. 2005. Diel Variation in Echolocation Behaviour of Wild Harbour Porpoises. *Marine Mammal Science*, 21, 1-12.

Cox, T.M. & Read, A.J. 2004. Echolocation Behaviour of Harbour Porpoises *Phocoena phocoena* around Chemically Enhanced Gill Nets. *Marine Ecology Progress Series*, 279, 275-282.

Croll, D.A., Tershy, B.R., Hewitt, R.P., Demer, D., Fiedler, P.C., Smith, S.E., Armstrong, W., Popp, J.M., Kiekhefer, T., Lopez, V.R. & Urban, J. 1998. An Integrated Approach to the Foraging Ecology of Marine Birds and Mammals. *Deep-Sea Research part II*, 45, 1353-1371.

Evans, P.G.H. & Hammond, P.S. 2004. Monitoring Cetaceans in European Waters. *Mammal Review,* 34, 131-156.

Gailey, G. & Ortega-Ortiz, J. 2000. User's Manual Pythagoras Version 1.0: Theodolite Cetacean Tracking.

Goodwin, L. 2008. Diurnal and Tidal Variations in Habitat Use of the Harbour Porpoise (*Phocoena phocoena*) in Southwest Britain. *Aquatic Mammals*, 34, 44-53.

Goold, J.C. 1998. Acoustic Assessment of Populations of Common Dolphin off the West Wales Coast, with Perspectives from Satellite Infrared Imagery. *Journal of the Marine Biological Association of the United Kingdom,* 78, 1353-1364.

Hammond, P.S., Macleod, K., Berggren, P., Borchers, D.L., Burt, M.L., Cañadas, A., Desportes, G., Donovan, G.P., Gilles, A., Gillespie, D.M., Gordon, J.C.D., Hiby, L., Kuklik, I., Leaper, R., Lehnert, K., Leopold, M., Lovell, P., Øien, N., Paxton, C.G.M., Ridoux, V., Rogan, E., Samarra, F.I.P., Scheidat, M., Sequeira, M., Siebert, U., Skov, H., Swift, R.J., Tasker, M., Teilmann, J., Van Canneyt, O. & Vázquez, J.A. 2013. Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biological Conservation*, 164: 107-122.

Hastie, G.D., Wilson, B., Thompson, P.M. 2006. Diving Deep in a Foraging Hotspot: Acoustic Insights into Bottlenose Dolphin Dive Depths and Feeding Behaviour. *Marine Biology*, 148, 1181-1188.

Hiscock, K. & Irving, R. 2012. *Protecting Lundy's marine life: 40 years of science and conservation.* Lundy Field Society, 108pp.

Ichii, T., Katayama, K., Obitsu, N., Ishii, H. & Naganobu, M. 1998. Occurrence of Antarctic Krill (*Euphausia superba*) Concentrations in the Vicinity of the South Shetland Islands: Relationship to Environmental Parameters. *Deep Sea Research*, 45, 1235-1262.

Ingram, S.N. & Rogan, E. 2002**.** Identifying Critical Areas and Habitat Preferences of Bottlenose Dolphins *Tursiops truncatus. Marine Ecology Progress Series,* 244, 247-255.

Kyhn, L.H., Tougaard, J., Thomas, L., Rosager Duve, L., Stenback, J., Amundin, M., Desportes, G. & Teilmann, J. 2011. From Echolocation Clicks to Animal Density – Acoustic Sampling of Harbour Porpoises with Static Dataloggers. *Journal of the Acoustic Society of America*, 131, 550-560.

Lavoie, D., Simard, Y., Saucier, F.J. 2000. Aggregation and Dispersion of Krill at Channel Heads and Shelf Edges: the Dynamics in the Saguenay-St. Lawrence Marine Park. *Canadian Journal of Fisheries and Aquatic Sciences,* 57, 1853-1869.

Lerczak, J.A. & Hobbs, R.C. 1998. Calculating Sighting Distances from Angular Readings during Shipboard, Aerial and Shore-based Marine Mammal Surveys. *Marine Mammal Science*, 14, 590-598.

Macaulay, M.C., English, T.S. & Mathisen, O.A. 1984. Acoustic Characterization of Swarms of Antarctic krill (*Euphausia superba*) from Elephant Island and Bramfield Strait. *Journal of Crustacean Biology,* 4, 16-44.

Mellinger, D.K., Stafford, K.M., Moore, S.E., Dziak, R.P. & Matsumoto, H. 2007. An Overview of Fixed Passive Acoustic Observation Methods for Cetaceans. *Oceanography*, 20, 36-45.

Medwin, H. 2005. *Sounds in the sea: from acoustics to acoustical oceanography*. Cambridge University Press.

Munk, P., Larsson, P.O., Danielsen, D. & Moksness, E. 1995. Larval and Small Juvenile Cod *Gadus morhua* Concentrated in the Highly Productive Areas of a Shelf Break Front. *Marine Ecological Progress Series,* 125, 21-30.

Northridge, S.P., Tasker, M.L., Webb, A. & Williams, J.M. 1995. Distribution and Relative Abundance of Harbour Porpoises (*Phocoena phocoena*), White-Beaked Dolphins (*Lagenorhynchus albirostris*), and Minke Whales (*Balaenopteua acutorostrata*) around the British Isles. *International Council for the Exploration of the Sea, Journal of Marine Science*, 52, 55-66.

Palka, D. 1995. Influences on Spatial Patterns of Gulf of Maine Harbour Porpoises. In Blix A.S. *et al.* (eds) *Whales, seals, fish and man.* Amsterdam: Elsevier Science, pp. 69-76.

Philpott, E., Englund, A., Ingram, S. & Rogan, E. 2007. Using T-PODs to investigate the Echolocation of Coastal Bottlenose Dolphins. *Journal of the Marine Biological Association*, 87, 11-17.

Pierpoint, C. 2008. Harbour Porpoise (*Phocoena phocoena*) Foraging Strategy at a High Energy, Nearshore Site in Southwest Wales, UK. *Journal of the Marine Biological Association of the United Kingdom*, 88, 1167-1173.

Rayment, W., Dawson, S. & Slooten, L. 2009. Use of T-PODs for Acoustic Monitoring of Cephalorhynchus Dolphins: a Case Study with Hector's Dolphins in a Marine Protected Area. *Endangered Species Research*, 10, 333-339.

Schoenherr, J.L. 1991. Blue Whales Feeding on High Concentrations of *Euphausiids* around Monterey Submarine Canyon. *Canadian Journal of Zoology*, 69, 583-594.

Schwing, F.B., Husby, D.M., Garfield, N. & Tracy, D.E. 1991. Mesoscale Oceanic Response to Wind Events off Central California in Spring 1989: CTD Survey and AVHRR Imagery. *Californian Cooperation Oceananic Fisheries Investigations Reports*, 32, 47-61.

Shane, S.H. 1990. Behaviour and Ecology of the Bottlenose Dolphin at Sanibel Island, Florida. In S. Leatherwood & R.R. Reeves (eds), *The bottlenose dolphin* 369-386. Academic Press, San Diego.

Simon, M., Nuuttila, H., Reyes-Zamudio, M.M., Ugarte, F., Verfuß, U. & Evans, P.G.H. 2010. Passive Acoustic Monitoring of Bottlenose Dolphin and Harbour Porpoise in Cardigan Bay, Wales, with Implications for Habitat Use and Partitioning. *Journal of the Marine Biological Association of the United Kingdom*, 90, 1539-1545.

Smith, P. & Nunny, R. 2012. Mapping of Sedimentary Marine Biotopes around Lundy, UK. *Journal of the Lundy Field Society*, 3, 41-74.

Springer, A.M., McRoy, C.P., Flint, M.V. 1996. The Bering Sea Green Belt: Shelf-edge Processes and Ecosystem Production. *Fisheries Oceanography,* 5, 205-223.

Strub, T.P., Kosro, P.M., Huyer, A. 1991. The Nature of Cold Filaments in the California Current System. *Journal of Geophysical Research*, 92, 14743-14768.

Thompson, P.M., Lusseau, D., Barton, T., Simmons, D., Rusin, J. & Bailey, H. 2010. Assessing the Responses of Coastal Cetaceans to the Construction of Offshore Wind Turbines. *Marine Pollution Bulletin,* 60, 1200-1208.

Todd, V.L.G., Pearse, W.D., Tregenza, N.C., Lepper, P.A. & Todd, I.B. 2009. Diel Echolocation Activity of Harbour Porpoises (*Phocoena phocoena*) around North Sea Offshore Gas Installations. *International Council for the Exploration of the Sea, Journal of Marine Science*, 66, 734-745.

Tougaard, J., Poulsen, L.R., Amundin, M., Larsen, F., Rye, J. & Teilmann, J. 2006. Detection Function of T-PODs and Estimation of Porpoise Densities. In: R. Leeney & N.J.C. Tregenza (eds). *Proceedings of the Workshop; Static Acoustic Monitoring of Cetaceans*. 46.

Verfuß, U.K., Honnef, C.G., Meding, A., Dähne, M., Mundry, R. & Benke, H. 2007. Geographical and Seasonal Variation of Harbour Porpoise (*Phocoena phocoena*) Presence in the German Baltic Sea Revealed by Passive Acoustic Monitoring. *Journal of the Marine Biological Association of the United Kingdom*, 87, 165-176.

Walton, M.J. (1997). Population Structure of Harbour Porpoises *Phocoena phocoena* in the Seas around the UK and Adjacent Waters. *Preceedings of the Royal Society*, 264, 89- 94.

Weir, C.R., Stockin, K.A. & Pierce, G.J. 2007. Spatial and Temporal Trends in the Distribution of Harbour Porpoises, White-beaked Dolphins and Minke Whales off Aberdeenshire (UK), North-western North Sea. *Journal of the Marine Biological Association of the United Kingdom*, 87, 327-338.

Wilson, B., Thompson, P.M. & Hammond, P.S. 1997. Habitat Use by Bottlenose Dolphins: Seasonal Distribution and Stratified Movement Patterns in the Moray Firth, Scotland. *Journal of Applied Ecology*, 34, 1365-1374.