Assessing the effectiveness of different datasets at predicting the habitat preference of minke whales (Balaenoptera acutorostrata) in UK waters

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Author's Declaration

I declare that the work presented here was composed by myself and represents work carried out by myself. This work has not been accepted for any previous application for a degree. All sources of reference and information have been specifically acknowledged.

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August 2014

Acknowledgments

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Finally, I must send the biggest of thanks to my amazing family and friends for their continued support, in this and everything I do. You guys ultimately kept me from the brink of insanity and kept me going right to the end.

Thank you.

"It is that range of biodiversity that we must care for – the whole thing – rather than just one or two stars."

– David Attenborough

Abstract

Minke whales are the smallest and most abundant of the baleen whales found in UK waters, and as such may act as important indicators of overall ecosystem health. Understanding the spatial and temporal distribution of a species and their relationship with the environments which they inhabit is a key issue in ecology. In the present study cetacean sightings from multiple UK sources were analysed and generalised additive models (GAMs) created, in order to ascertain how effective different surveying methods are at predicting the habitat preference of minke whales, in relation to a number of fine-scale bathymetric and oceanographic features. Results show that minke whale distribution in UK waters has distinct spatio-temporal variation, with all three studies showing peak minke sightings in the months of July and August. Model results show that each dataset had a different predictive ability, with the country-wide study having a greater ability to predict species presence, than the smaller geographically isolated studies. All datasets showed that depth has a significant influence on the presence of minke whales. While variables such as sea surface temperature, chlorophyll-*a* concentration, eutrophic depth, photosynthetic active radiation and slope were significant only for individual studies. The present study shows how differing methods of data collection can produce significantly different model outputs. From a conservation point of view this study highlights the importance of collaboration between organisations and managers, in order to create the best use of the available data for conservation efforts.

Keywords: Minke whale . *Balaenoptera acustotostrata* . Cetaceans . Habitat Modelling . Generalised Additive Models . Conservation .

Introduction

Understanding the role which fine-scale environmental variation plays in determining the spatial and temporal distribution of a species is a key issue in ecology (Gregr et al., 2013). With the threat of climate change ever increasing it is becoming more and more important to understand the relationships between species and their environments. However, such impacts are difficult to distinguish in the marine environment (Dalla-rosa et al., 2012). As many cetacean species are top predators, but also highly vulnerable to a range anthropogenic effects, they can act as indicators of wider ecosystem health (Hooker & Gerber, 2004). It is predicted that around eighty-eight percent of cetacean species worldwide will be affected by increasing sea temperatures, as a result of climate change, with extinction a possibility for more than twenty percent of geographically isolated cetacean populations (MacLeod, 2009). Hence, now more than ever it is crucial for us to understand the complex interactions at play, between individual and environment, in order to successful conserve marine biodiversity, both now and for future generations.

Habitat models are increasingly being used in wildlife conservation to further our understanding of species ecology (Hirzel et al., 2006; Gregr et al., 2013). These types of models have been used for many years in terrestrial ecology and are becoming increasingly popular for marine species (Redfern et al., 2006). There are many benefits to using species habitat models; results often support or further our understanding of a species niche requirements, help predict future distributions of species and assist in assessing the impacts of a changing environment, including climatic and pollution changes (Guisan and Thuiller, 2005; Hirzel et al., 2006).

Minke whales are the smallest of the baleen whales found in European waters and are widely distributed throughout (Weir et al., 2007). The ICES working group on marine mammal ecology estimates that there are between 13,700 and 38,900 common minke whales in continental shelf waters of the European Atlantic coast (ICES, 2014). The nutrient rich waters around the UK coastline are thought to be important for the species (Evans et al., 2003 & Reid et al., 2003). Minke whales are particularly abundant in Scottish shelf waters, less than 200 metres in depth, during summer months (MacLeod et al., 2004; Robinson et al., 2007). Being opportunistic feeders minke whales are known to show spatial and temporal variation in their diet (Robinson & Tetley, 2007), with a demonstrated dietary preference towards shoaling fish such as Clupeids (e.g. herring, *Clupea harengus*, and sprat, *Sprttus sprattus*), Gadoids (e.g. whiting, *Merlangius merlangus*) and mackerel (*Scomber scombrus*) and sandeels (*Ammodytes spp*) (e.g. Olsen & Holst, 2001; Pierce et al., 2004).

Minke whales are not currently listed as a threatened species; however, given their cosmopolitan distribution minke whales, like most cetacean species, are at risk from a range of anthropogenic impacts. Including; fishery by-catch, mainly from entanglement in creel lines (Northridge et al., 2010), over-exploitation of fundamental prey species by the fishing industry, and disturbance from noise (Croll et al., 2001) caused by shipping, seismic surveying and construction (Bailey et al., 2010; Thompson et al., 2010; Merchant et al., 2014).

Information on the distribution and habitat preference of marine mammals is difficult to gather, yet this information is extremely beneficial for wildlife management and conservation (Elith et al., 2006). Under the European Habitats Directive 1992, member states are required to maintain or restore natural habitats and species of natural fauna, to a favourable conservation status (Council Directive 92/43/EEC). Although Annex IV of the EU Habitats Directive affords protection to all cetacean species in member state waters, only two cetacean species are listed under Annex II as requiring special areas for protection, the harbour porpoise (*Phocoena phocoena*) and bottlenose dolphin (*Tursiops truncatus*). Currently there are no areas specifically for the protection of the harbour porpoise, but there are however Special Areas of Conservation (SACs) dedicated to the protection of bottlenose dolphins in UK waters (the inner Moray Firth, Scotland and Cardigan Bay, Wales), these sites are adjacent to waters known to be used by other cetacean species (e.g. Robison et al., 2007). Around UK waters there are currently a number of non-governmental organisations (NGOs) conducting surveys and collating data on the presence and distribution of minke whales (e.g. Sea

Watch Foundation, NORCET, a joint project run by Sea Watch Foundation, Aberdeen University and the East Grampian Coastal Partnership, and the Cetacean Research and Rescue Unit). As each NGO employs its own surveying methods, uses different platforms and/or relies on opportunistic sightings to be reported by members of the public, it is difficult to standardise the available information. However, it is possible through the use of habitat modelling techniques to produce sufficient outputs form a range of data sources, as numerous authors have shown (see Redfern et al., 2006 for a review).

While prey abundance is widely cited as a major factor which influences cetacean distribution (e.g. Torres et al., 2008), it has also been shown that bathymetric and oceanographic factors, including depth (Weir et al., 2012), slope, substrate type (Robinson et al., 2009), chlorophyll-*a* concentration (Anderwald et al., 2012), sea surface temperature (Tetley, 2008) and tidal fronts (Yen et al., 2004) can influence the distribution of cetacean species, such as minke whales. Torres et al. (2008) also suggested that when predicting cetacean prey distribution, fine-scale oceanographic features, such as the previously mentioned, can have a greater predictive ability than fish catch data from surveys.

The aim of the current project is to ascertain what role which fine-scale environmental predictors play in the spatial and temporal distribution of minke whales in UK waters, and whether or not their presence can be effectively modelled from a range of data sources. In so doing, the intent is to identify characteristics of the different datasets available which make them more or less suitable for habitat modelling and assessment of population status.

Methods

The first dataset used in the following analysis was kindly provided by the Sea Watch Foundation. This organisation collects cetacean sightings from around the UK coastline, these sightings are reported by a network of volunteers from both effort-based surveys and opportunistic sightings. The available database comprises of sightings dating back to 1965, but for the purpose of the current project the data were limited to a subset from 2005 onwards. In this subset, a total of 406 minke whale sightings, with an estimated 777 individuals, were recorded around the UK from 2005 to 2013 inclusive. This equates to approximately 10% of the total data available.

The second dataset that was used in this analysis was provided by Dr Colin MacLeod. The data was collected by the northern North Sea cetacean survey group (NORCET), a project set up jointly by Sea Watch Foundation, University of Aberdeen and the East Grampian Costal Partnership. The work was carried out by a small number of local volunteers who conduct vessel-based surveys, in conjunction with North Link Ferry Company. Surveys are conducted along the ferry route from Aberdeen harbour to Lerwick on the Shetland Isles and Kirkwall on Orkney (Appendix 1). Standard marine mammal observation guidelines were used during each survey. The data provided by NORCET covers the period of 2004 to 2009 inclusive, and a total of 76 minke whale sightings were recorded over this period.

The third dataset used was supplied by Dr Kevin Robinson from the Cetacean Research and Rescue Unit (CRRU). This data was collected during dedicated summer vessel surveys, from May to October. All surveys were conducted in the outer southern Moray Firth, northeast Scotland (Appendix 2), and utilised dedicated offshore transects, coastal transects and opportunistic routes. For detailed survey methodologies see Robinson et al. (2007). Available records cover the period of 2009 to 2013 inclusive and compromise of 114 minke whale encounters with 133 individuals.

The data supplied by both Sea Watch Foundation and NORCET were presence-only data. However, as presence-absence datasets have a greater predictive ability (Hirzel et al., 2006; MacLeod et al., 2008) absence data was generated for each. Absence data was taken from the presence of other cetacean species (i.e. pseudo-absence). For the Sea Watch Foundation database all non-minke whales records were assigned a number using the *RAND* function in Excel, records were then sorted by their random number and the first 1625 entries were used as absence records, omitting the pseudo-absence records for 2006, as there were no minke whale presence records available for that year. The data provided by the CRRU was also presence-only data and therefore the same processes were carried out. In the case of Sea Watch foundation and CRRU, this allowed for minke whale sightings to be no less than 20% of the total dataset, as recommended by Zuur et al. (2007). As the NORCET database was smaller it was viable to use all non-minke whale sightings as absence records.

From a statistical point of view there was only one response variable, the presence or absence of *B. acustorostrata.* Table 1 summarises the explanatory variables which were available for inclusion in the models including; sea surface temperature, chlorophyll-*a* concentration, eutrophic depth, photosynthetic active radiation and salinity for CRRU data only, along with the bathymetric variables; depth, slope and aspect. This information was provided by Vasilis Valavanis at the Hellenic Centre for Marine Research. For each of the variables provided for use in analysis the standard deviation was also available. However, as there was a correlation between the mean values and standard deviation of number of variables, only the mean values were used in the analysis.

Table 1. Explanatory variables which were available (the standard deviation for SST, CHL, ZEU, PAR, DEP, SLO and ASP was also available).

Variable	**Nominal**	**Comment**
Month	Yes	
Year	Yes	
SST	No	Sea surface temperature (^{o}C)
CHL	No	Chlorophyll a concentration (mg/m^3)
ZEU	No	Eutrophic depth (m)
PAR	No	Photosynthetic active radiation (E/m^2/d)
DEP	No	Depth (m)
SLO	No	Slope (radians)
ASP	No	Aspect (radians)
SAL	No	Salinity (only available for CRRU data)
Latitude	No	
Longitude	No	

Exploratory data analysis was carried out to identify outliers and highlight potential issues which could reduce model performance (see Zuur et al., 2010 for review). With a large number of explanatory variables it can be difficult to find the optimal model, especially as a number of explanatory variables are possibly highly correlated with each other. Therefore, to tackle this problem correlated variables were identified, using the ‘pairs’ function in BRODGAR (Appendix 3a, b & c). Of the variables, those with a Pearson’s correlation coefficient of 0.7 or greater were deemed to be highly correlated; therefore, one of the variables was removed from analysis.

To find the optimal set of explanatory variables univariate generalised additive models (GAMs), with a binomial probability distribution for the response variable and a logit link function, were run in BRODGAR, using a backwards selection method (Appendix 4). This method was used to determine which variables were most significant and to reduce the number of variables included in the final model. Due to the tendency of GAMs to over fit data, smoothers were applied and constrained to a maximum *k* value of 4 (3 degrees of freedom). All models were fitted using BRODGAR 2.7.4 software (www.brodgar.com), a menu-based interface for R using version R 3.1.0 (R Development Team, 2008).

The most appropriate model was chosen based on a combination of the Akaike Information Criterion (AIC) value and the percentage of deviance which the model explained. The ‘final’ model was the model with the lowest AIC given that all explanatory variables within the model were statistically significant, with no obvious patterns in the residuals. Latitude and longitude were excluded from all models *a priori* as they were only representative of unexplained variation.

Results

Sea Watch Foundation

The raw data provided showed that the number of minke whale sightings varied annually (Fig. 1). The data also showed that sightings of minke whales gradually increased from April onwards, with peak sightings in the month of August (Fig. 2).

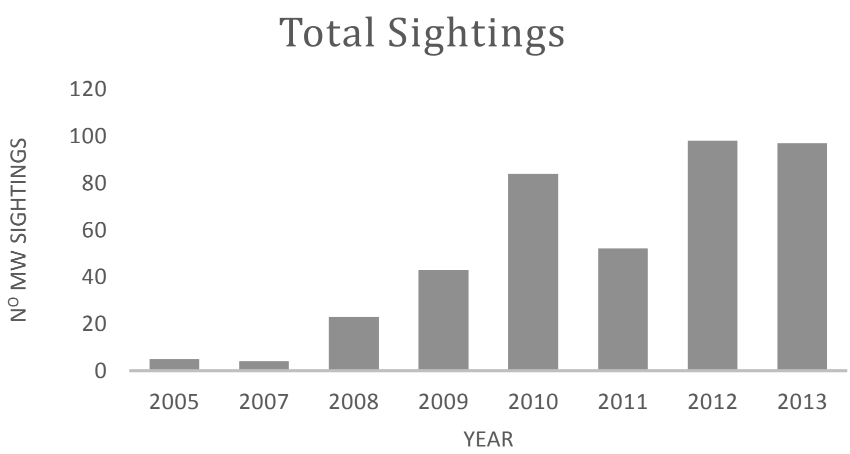


Figure 1. Minke whale sightings recorded by Sea Watch Foundation from 2007 to 2013 inclusive.

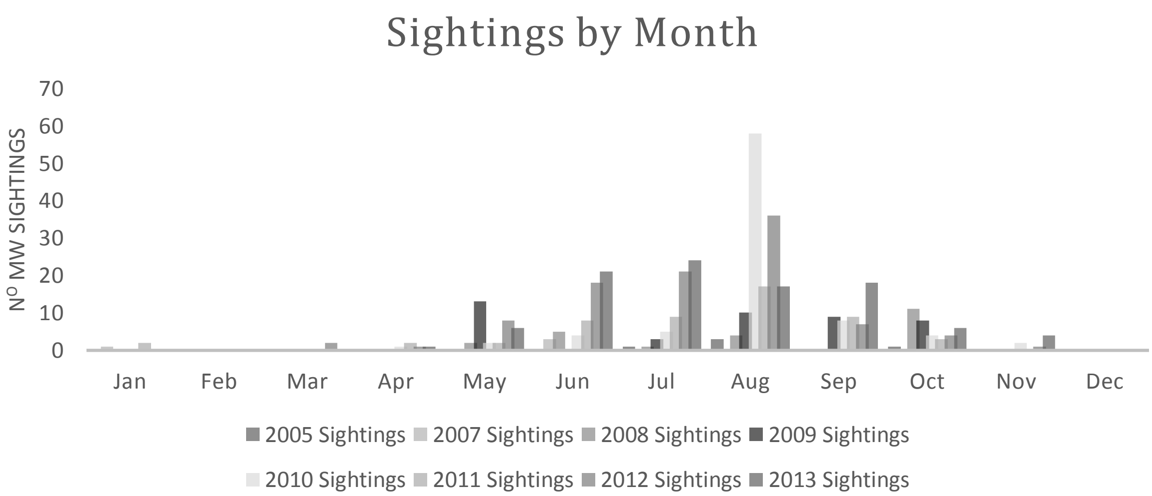


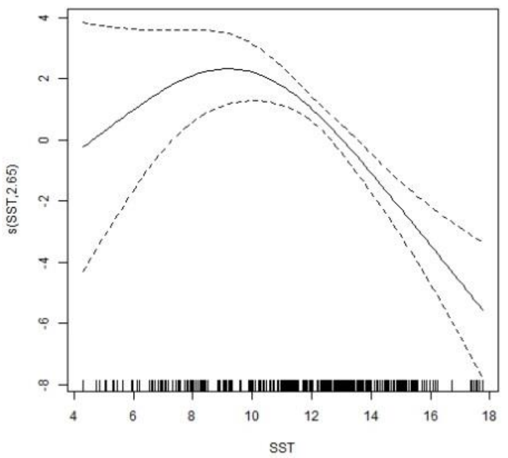
Figure 2. Sea Watch Foundation minke whale sightings by month, 2007 – 2013 inclusive.

Results from generalised additive models for minke whale presence in relation to environmental parameters are summarized in table 2. The final model included 7 significant explanatory variables; sea surface temperature, eutrophic depth, photosynthetic active radiation, depth, slope, aspect and month. The effects of chlorophyll-*a* concentration and year were non-significant when included in the GAM and were therefore removed from the final model. The final model explained 48.2% of deviance and had an AIC value of 523.88.

Table 2. Results of the final GAM showing the approximate significance of each variable on minke whale presence. edf = estimated degrees of freedom. Significance levels of *P*-values are represented by: '***' <0.001, '**' <0.01, '*' <0.05 & '.' <0.1

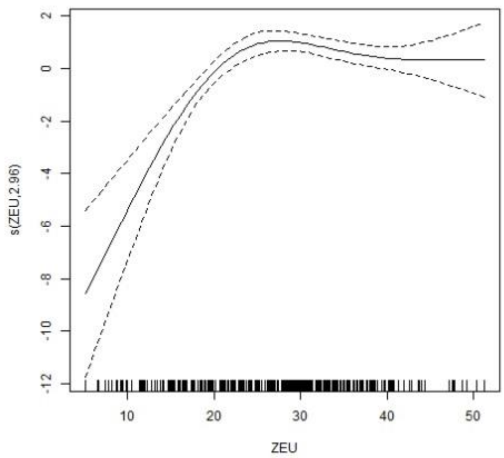
Variable	**edf**	**Chi. Sq**	***P*-Value**
SST	2.645	36.57	$6.61e^{-08}$ ***
ZEU	2.964	36.87	$4.93e^{-08}$ ***
PAR	2.877	12.88	0.004877 **
DEP	2.944	27.95	$3.74e^{-06}$ ***
SLO	2.857	17.67	0.000513 ***
ASP	2.849	15.54	0.001399 **
Month	8.795	40.41	$6.35e^{-06}$ ***

Relationships between minke whale presence and the explanatory variables are shown in figure 3. The results show that minke whales were most frequently sighted in depths of 20 to 60 m, with aspects between 115^o to 172^o and a slope between 0.28^o to 0.57^o. Minke whales were present over a range of sea surface temperatures from 4 to 18^{o}C, but sightings were most frequent at temperatures of 11 to 15^{o}C. Minke presence was recorded over a range of photosynthetic active radiation levels, with a peak between 25 and 35 E/m^2/d. Minke presence was recorded in waters with eutrophic depths from 5 to 55m, but most frequently in waters with euphotic depths between 25 and 30 m. The model output for month shows an increase in minke whale presence from May to July, with a sharp decline in presence towards the latter months of the year.



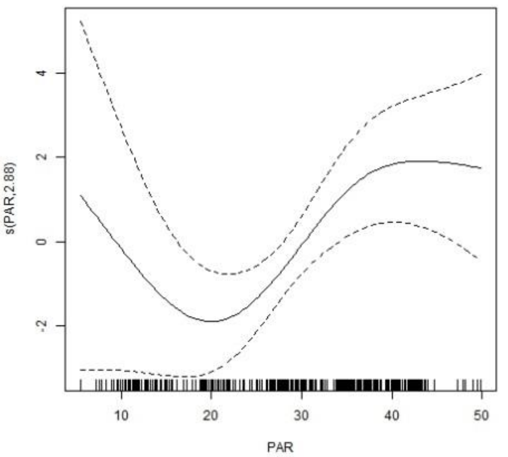
s(SST,2.65)
4
2
0
-2
-4
-6
-8
4
6
8
10
12
14
16
18
SST

A.



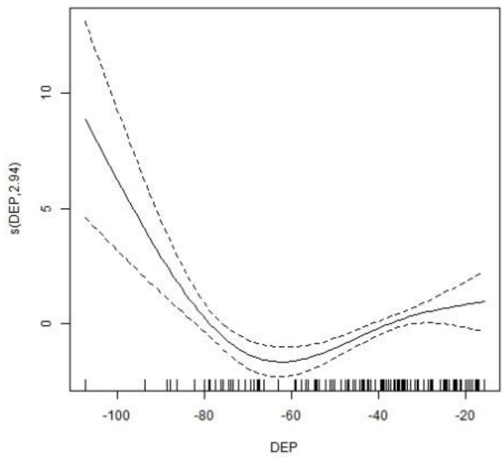
s(ZEU,2.96)
2
0
-2
-4
-6
-8
-10
-12
10
20
30
40
50
ZEU

B.



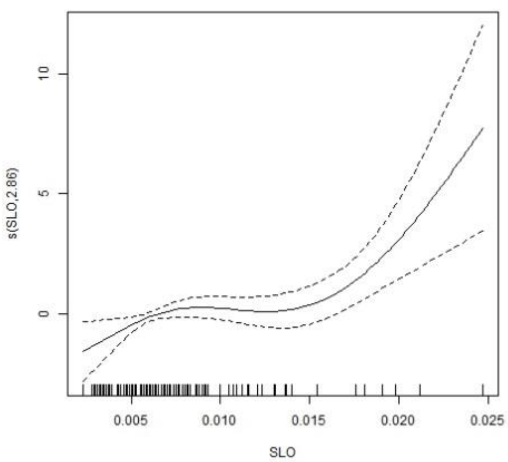
s(PAR,2.88)
4
2
0
-2
10
20
30
40
50
PAR

C.



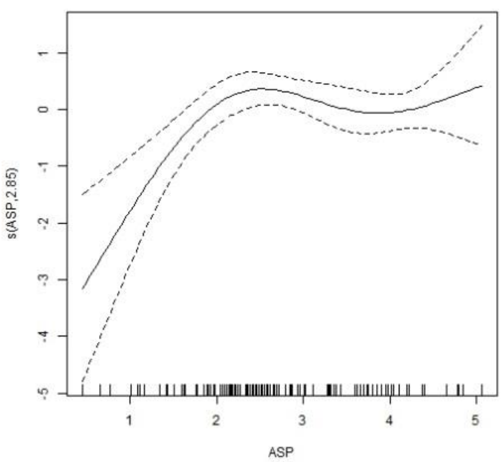
s(DEP,2.94)
10
5
0
-100
-80
-60
-40
-20
DEP

D.



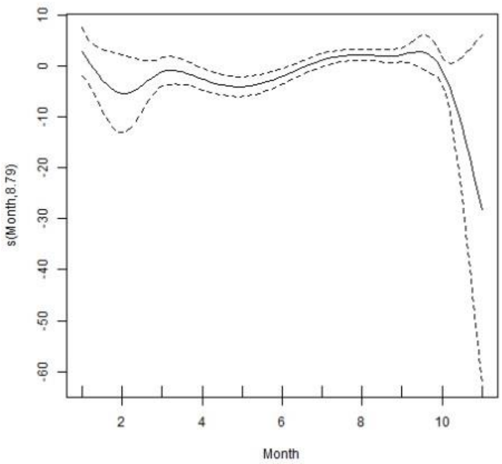
s(SLO,2.86)
10
5
0
0.005
0.010
0.015
0.020
0.025
SLO

E.



s(ASP,2.85)
1
0
-1
-2
-3
-4
-5
1
2
3
4
5
ASP

F.



G.

Figure 3. Smoothers for effects (solid line, with approximate 95% CI shown as dashed lines) of explanatory variables on the presence of minke whales. Showing the partial effects of (A) sea surface temperature (B) eutrophic depth (C) photosynthetic active radiation (D) depth (E) slope (F) aspect (G) month.

NORCET

Similar to the Sea Watch Foundation data, the NORCET raw data also showed that minke whale sightings varied from year to year (Fig. 4), with peak sightings recorded in 2006. The data also showed peak minke whale sightings during the summer months, June and July, with 21 and 22 sightings recorded respectively (Fig. 5).

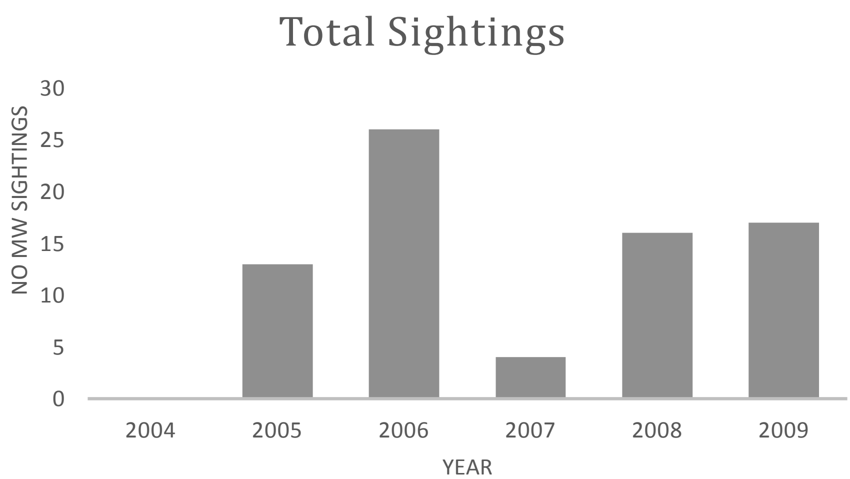


Figure 4. Total minke whale sightings recorded by the NORCET group from 2004 to 2009 inclusive.

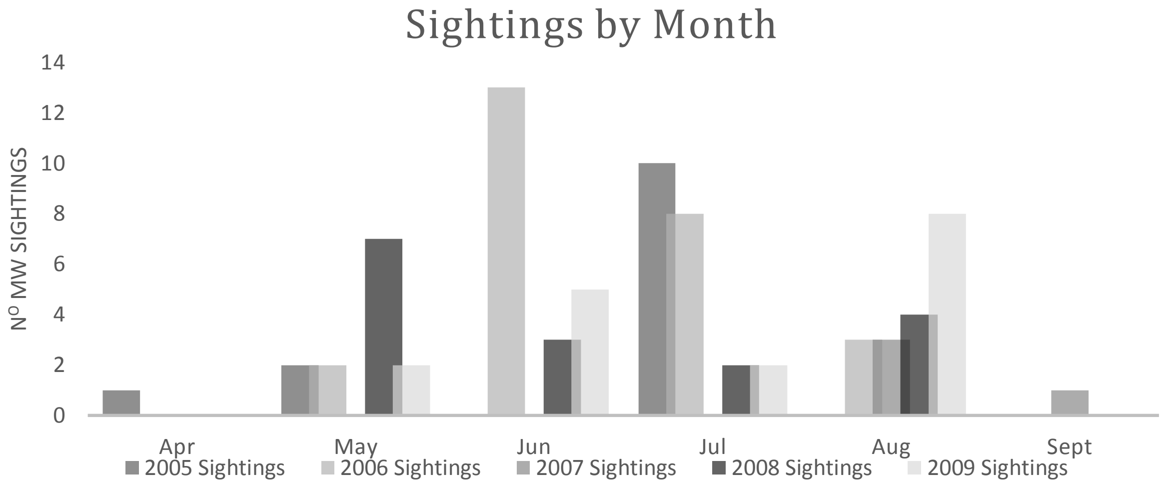


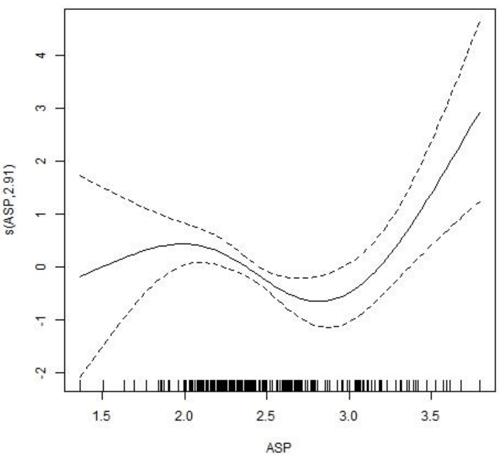
Figure 5. Monthly minke whale sightings by NORCET, 2005 to 2009 inclusive

Results from generalised additive models for the NORCET data are summarised in table 3 below. The final model contained only three significant explanatory variables. None of the oceanographic variables were found to be significant when included in the final model. Only depth, aspect and year were significant. The final model explained 10.3% of deviance and had an AIC value of 435.57.

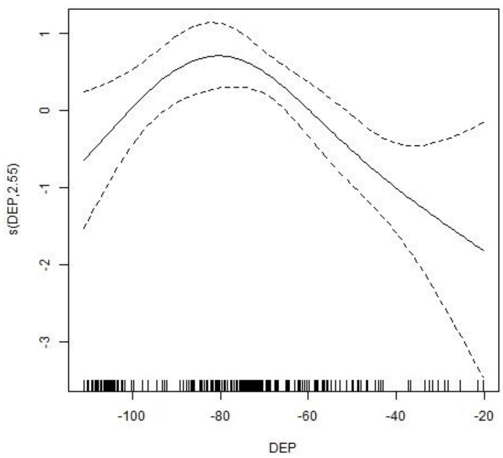
Table 3. Results of the final GAM showing the approximate significance of each variable on minke whale presence. edf = estimated degrees of freedom. Significance levels of *P*-values are represented by: '***' <0.001, '**' <0.01, '*' <0.05 & '.' <0.1

Variable	**edf**	**Chi-sq**	***P*-value**
DEP	2.552	14.84	0.001824 **
ASP	2.910	13.93	0.002988 **
Year	2.793	17.16	0.000652 ***

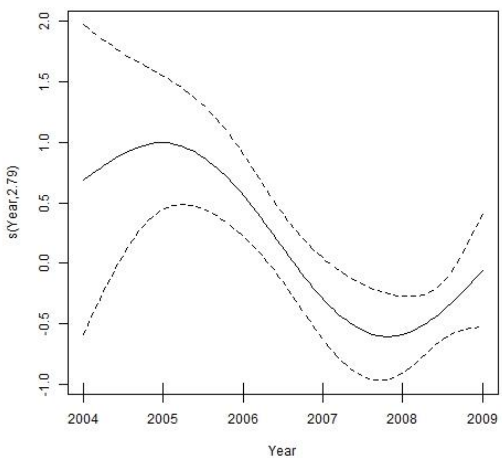
The model outputs and relationships between explanatory variables and minke presence are shown below in figure 6. The results show that the encounter rate of minke whales peaks between 60 and 80 m. Sightings were most frequent in areas with an aspect of between 114^{o} and 143^{o}. The model output for year shows a decline in the presence of minke whales from 2005 to 2007, with a slight increase from 2008 onwards.



A.



B.



C.

Figure 6. Smoothers for effects (solid line, with approximate 95% CI shown as dashed lines) of explanatory variables on the presence of minke whales. Showing the effects of (A) aspect (B) depth (C) year.

CRRU

Across the 5 year study period a total of 234 surveys were conducted, over 447 survey days. Within this period 114 encounters with minke whales were recorded. The raw data provided by the CRRU again showed that the presence of minke whales in their study area varied from one year to the next, with the most sightings recorded during the 2010 field season (Fig. 7). Monthly sightings also showed variation with the peak number of minke whales sighted in the months of June and July (Fig. 8).

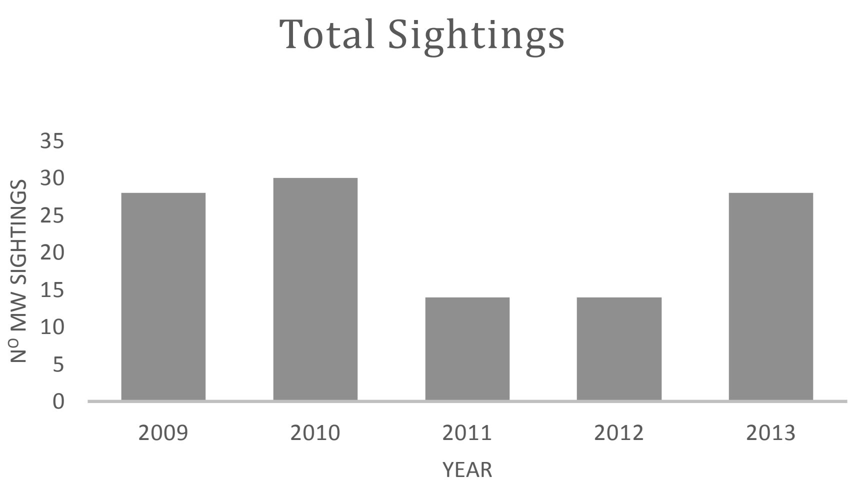


Figure 7. Total minke whale sightings by the CRRU from 2009 to 2013 inclusive.

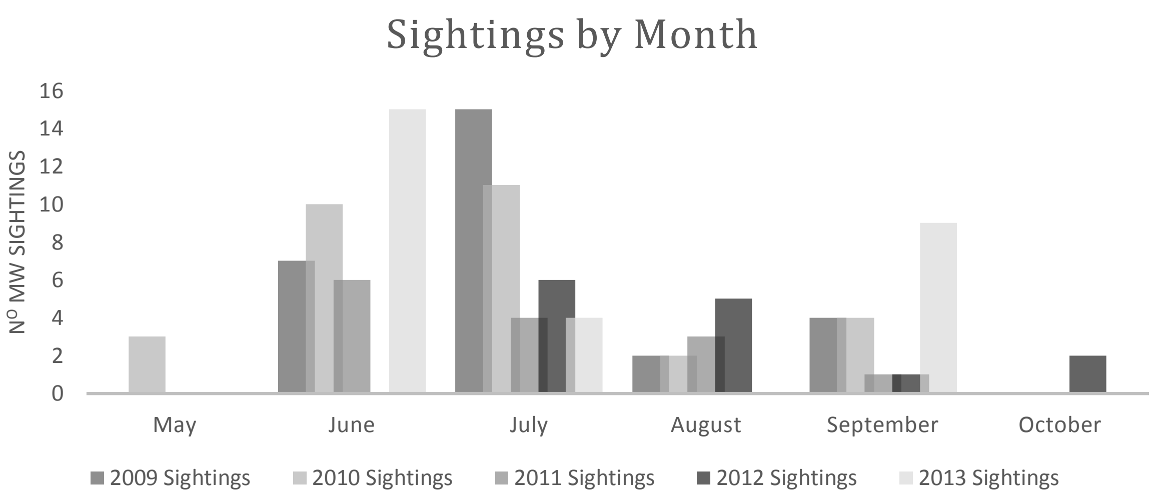


Figure 8. CRRU monthly minke whale sightings, 2009 to 2013 inclusive

Results from generalised additive models for the CRRU data are summarised in table 4 below. The final model contained three significant explanatory variables; depth, chlorophyll-*a* concentration and month which had a significant effect on the presence on minke whales. The final model explained 16.4% of deviance and had an AIC value of 507.49.

Table 4. Results of the final GAM showing the approximate significance of each variable on minke whale presence. edf = estimated degrees of freedom. Significance levels of *P*-values are represented by: '***' <0.001, '**' <0.01, '*' <0.05 & '.' <0.1

Variable	**edf**	**Chi-sq**	***P*-value**
CHL	2.435	14.201	0.00228 **
DEP	1.954	49.145	$1.22e^{-10}$ ***
Month	1.000	8.977	0.00274 **

The generalised additive model outputs, showing the relationship between minke whale presence and the explanatory variables can be seen in figure 9. Results show and increase in minke presence at chlorophyll-*a* concentrations between 0 and 5 mg/m^3, which tails off at levels greater than 10 mg/m^3. Again, minke whales were sighted over a range of depths, from 0 to 140 m, with peak sightings in depths between 50 and 60 m, with a decline in presence in waters shallower than 40 m. Model outputs for month shows a linear relationship between the presence of minke whales and month, with a steady decline in presence from mid-July onwards.

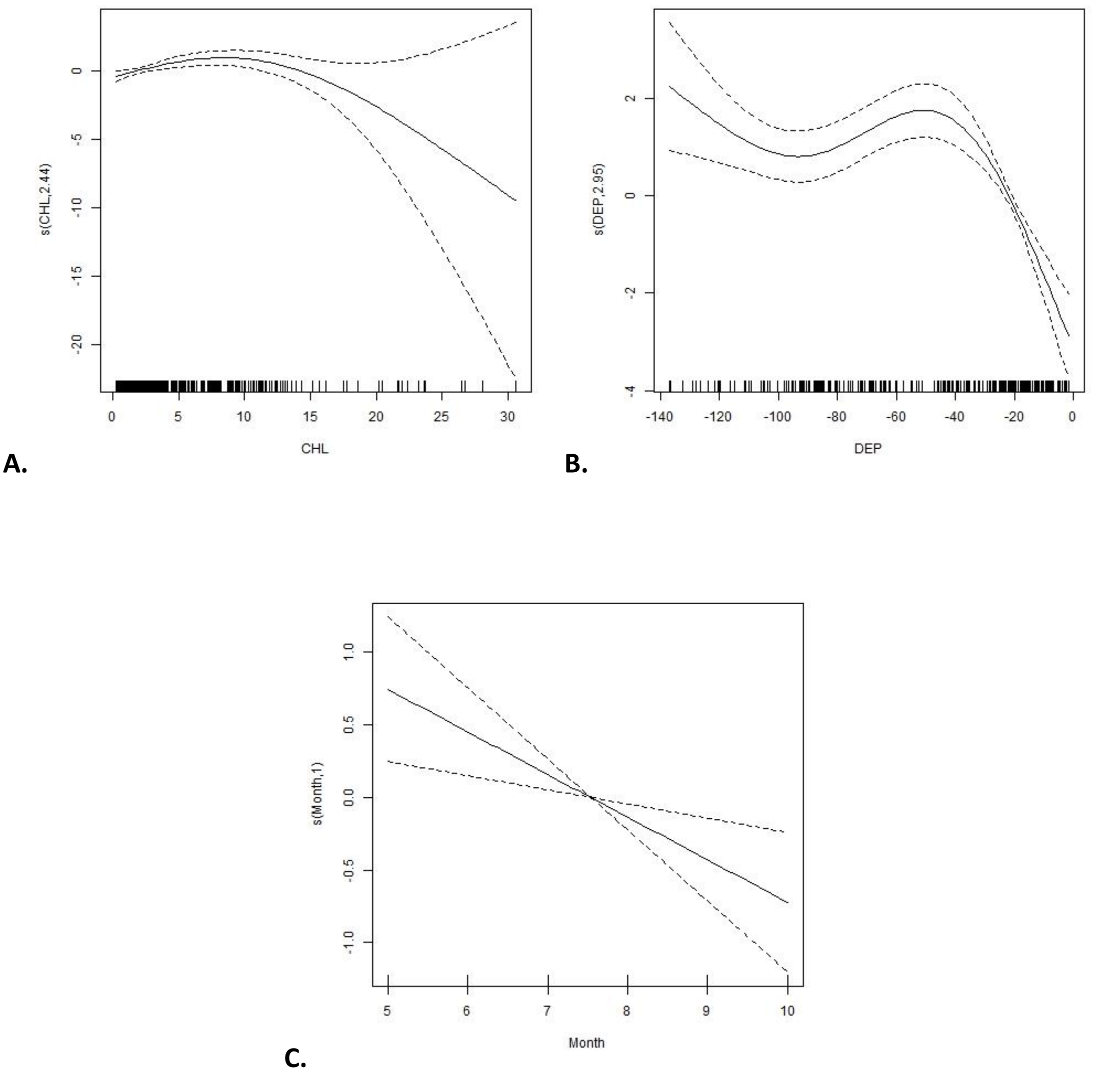


Figure 9. Smoothers for effects (solid line, with approximate 95% CI shown as dashed lines) of explanatory variables on the presence of minke whales. Showing the effects of (A) chlorophyll-*a* concentration (B) depth (C) month.

Comparing Models

An informal comparison of the three models was done, by comparing the models ability to predict the spatial and temporal presence of minke whales, without the inclusion of environmental variables. The results of these models are summarised below in tables 5a, b and c. These results show that the Sea Watch Foundation study is able to significantly explain both spatial and temporal variation in presence, while the NORCET and CRRU studies explain less spatio-temporal variation.

Table 5. Outputs from GAMs used to compare the effectiveness of each dataset. edf = estimated degrees of freedom. Significance levels of *P*-values are represented by: '***' <0.001, '**' <0.01, '*' <0.05 & '.' <0.1

a) Sea Watch Foundation

Variable	edf	Chi-Sq	*P*-value
Month	2.811	57.08	$2.78e^{-12}$ ***
Year	2.561	23.4	$3.39e^{-05}$ ***
Latitude	2.551	174.97	$<2e^{-16}$ ***
Longitude	2.941	94.61	$<2e^{-16}$ ***
Time	2.615	10.47	0.014 *
%DE = 33.9			
AIC = 1372.23			

b) NORCET

Variable	edf	Chi-Sq	*P*-value
Year	2.792	19.94	0.00016 ***
Latitude	2.364	12.85	0.00490 **
%DE = 7.96			
AIC = 440.27			

c) CRRU

Variable	edf	Chi-Sq	*P*-value
Month	1	10.852	0.000988 ***
Latitude	2.32	41.095	$8.8e^{-09}$ ***
Longitude	2.49	7.428	0.052085 .
%DE = 12.3			
AIC = 530.27			

Discussion

The general aim of the present study was to ascertain whether cetacean sightings data, collected in various ways, can effectively model the habitat preference of minke whales in UK waters. Furthermore, this study also looked at the relationships between fine-scale bathymetric and oceanographic factors and the presence of minke whales.

As expected for a large mobile species, the habitat model outputs showed that both the bathymetry of an area and temporally variable oceanographic factors can significantly influence the presence of minke whales frequenting UK waters. The final models for each dataset available showed that minke whale presence varied both spatially and temporally and was associated with a number of physical and oceanographic variables; sea surface temperature, photosynthetic active radiation, eutrophic depth, chlorophyll-*a* concentration, sea bed aspect, slope and sea depth.

Final models for the three datasets explained between 10% and 48% of the deviance, an acceptable performance for this type of ecological data (see Zuur et al., 2007). The final model for the Sea Watch Foundation data explained the greatest percentage of deviance at 48.2%, while both the NORCET and CRRU final models explained less than 20% of the deviance, 10.3% and 16.4% respectively. Compared with the Sea Watch Foundation the relatively small sample sizes available for both NORCET and CRRU may have been a limiting factor. However, it has previously been shown that variable and non-uniform spatio-temporal distribution is common in geographically isolated baleen whale studies, such as the NORCET and CRRU studies (Friedlaender et al., 2006; Robinson et al., 2009).

Informal comparison of the three datasets, with no environmental variables included, provided further evidence that the Sea Watch Foundation dataset had the greatest ability to capture both the spatial and temporal variation in minke whale presence in UK waters. Although the NORCET data was unable to capture longitudinal variation this is not surprising, as the survey is conducted on a north to south route. Additionally, as the surveys are only conducted during summer months this study does not teach us much about seasonality. However, it does provided information on the local year to year and north to south trends in minke whale presence in the northern North Sea. Similarly, the CRRU data was also provided from a small scale survey, which is seasonally limited to the summer months. However, the dedicated survey effort and coverage during the summer months is good enough to capture both spatial and monthly variations in minke whale presence in the Moray Firth study area.

It could be argued that neither the NORCET nor CRRU studies provide a great deal information about spatio-temporal variation in minke whale presence in UK waters, although both studies are useful on a localised scale. In both cases the success of the study relies entirely on volunteers, the NORCET volunteer group utilise a platform of opportunity to conduct their studies, free of cost to any end-users of the data. While volunteers with CRRU pay a fee to take part in a hands-on internship, with all fees contributing to the running cost of the project. Neither study receives government funding, which makes them extremely useful for mangers, as there are no additional cost to them to collect and use the data, as the studies are already being conducted. From all analysis it is clear that the Sea Watch Foundation study is the most useful in terms of explaining the spatial and temporal variations in minke whale presence; it is also potentially extremely useful in terms of its use for management. Like both the NORCET and CRRU studies the sightings are also collected by volunteers and processed by a charity, which helps to keep costs low. Additionally, the volunteers with Sea Watch Foundation are not geographically limited and cover the majority of the UK coastline, which provides us with a bigger picture of minke whale distribution around the UK coastline. However, the Sea Watch Foundation dataset which was analysed is based on coastal observations, and unfortunately does not tell us anything about offshore distribution. Although Sea Watch Foundation does collect offshore sightings from boat-based surveys, this dataset was not available at the time of the present study.

Environmental Variables

Knowledge of the factors which can dictate the occurrence of cetacean species is key when identifying crucial habitats, designating protected areas and detecting spatial overlaps between anthropogenic activities and key habitats (Weir et al., 2012). It is widely accepted that cetacean distribution is strongly driven by the availability of target prey, with each species likely to fulfil a dietary niche over fine-scale spatio-temporal distribution (Bearzi, 2005). Distribution in any given area is likely to vary year to year depending on the local availability of target prey (Hammond et al., 2013). For all of the datasets used in the present study minke whale presence was greatest during summer months, between June and August (Fig. 2, 5 & 8), which coincides with the main feeding period for rorqual whales (Stevick et al., 2002). As opportunistic feeders minke whales are well adapted to exploit local seasonal abundances of suitable prey species, and are known to have a highly adaptable diet comprising of shoaling and benthic fish, as well as copepods (Perrin & Brownell, 2009). Dietary studies of minke whales have shown that their diet is mainly comprised of sandeels, *Ammodytes spp.*, with the diet of a number of minke whales which stranded around the Scottish coastline 62-87% sandeel species (Pierce et al., 2004). Other favourable prey includes Clupeids (e.g. herring, *Clupea harengus*, and sprat, *Sprttus sprattus*), Gadoids (e.g. whiting, *Merlangius merlangus*) and mackerel (*Scomber scombrus*).

Sandeels spawn between December and January, in habitats with coarse sand or fine gravel (Wright & Begg, 1997), at preferred depths of 20-70 m, which are believed to offer protection from predators (Wright et al., 2000). Sandeel larvae hatch in February-May, and after 1-3 months are fully developed, it is during this time, between May and August, that the larvae are most mobile in the water column (Wright & Bailey, 1996), and most vulnerable to predation. This is consistent with our results, which shows minke presence in UK waters to peak during the summer months of June to August. This also supports the hypothesis that minke whale presence is closely related to the availability of prey species and agrees with findings from Robinson et al. (2009), which suggests that the arrival of minke whales in the outer Moray Firth each year is linked to juvenile sandeels emerging from the sediment and entering the water column.

For all models depth was found to be a significant variable. Minke whale sightings from all sources were often recorded at relatively shallow depths of 10-60 m. Similarly, Weir et al. (2012) also found depth to be a highly significant factor influencing the habitat presence of multiple cetacean species in the tropical waters between Gabon and Angola. Coastal areas with shallow depths of 20-50 m are known to promote up-wellings in nutrient rich areas (Yen et al., 2004) and these areas are often characterised by greater productivity, due to the increased levels of tidal mixing which occurs (Robinson & Tetley, 2007). These areas are also particularly beneficial to sandeels, as the juveniles require a tidally active area which allows maximum oxygen flow into their burrows (Baumgartner, 2008).

Models results showed that the temporally variable environmental factors; sea surface temperature, chlorophyll-*a* concentration, photosynthetic active radiation and eutrophic depth also had a significant influence on the presence of minke whales around the UK coastline.

Evidence from the Hebrides on the west coast of Scotland, suggests that the increase in sea temperature during the late spring and early summer months prompts minke whales to make a northwards movement towards shallower coastal waters (MacLeod et al., 2007; Bannon, 2012). Studies have shown that the activity and density of sandeels increases with increased sea temperatures, making them more readily available in the water column for predators, such as the minke whale (Tetley et al., 2008; Anderwald et al., 2012). This increase in activity could partially explain the increase in minke whale presence at temperature of 11^{o}C to 15^{o}C, as shown in Sea Watch Foundation model outputs. However, studies have also shown that sandeels which develop in warmer temperature tend to have a lower calorific content (Wanless et al., 2005). This reduction in energy content is thought to be driven by climatic changes, due to the changes in the essential fatty acids produced by phytoplankton at increased temperature (Litzow et al., 2006; Bannon, 2012).

Changes in the distribution of minke whales, driven by shifts in prey induced by climate change, have been identified in other parts of the world. Kasamatsu et al. (2000) noted changes in their distribution in the Amundsen and Bellingshausen Seas of Antarctica, over an eight year period between 1982 and 1990, thought to be driven by changes in prey distribution due to increasing sea temperatures and declining sea ice coverage.

Chlorophyll-*a* concentration was found to have a significant impact on the presence of minke whales in the CRRU study area of the outer Moray Firth, northeast Scotland. Minke whales, like other cetacean species are thought to exploit areas of high chlorophyll-*a* concentration, with correlations between cetacean presence and high chlorophyll-*a* concentrations previously demonstrated. Anderwald et al. (2012) found significant correlations with minke whales and high chlorophyll-*a* levels on the west coast of Scotland. While Pierce et al. (2010) found a similar relationship with bottlenose dolphins in Galician waters in northwest Spain. Surface chlorophyll-*a* levels can be used as indication of primary productivity, with elevated levels presumably supporting greater levels of phytoplankton and zooplankton production, which in turn attracts larger concentrations of piscivorous fish, pinnipeds and cetaceans, although there is normally a time-lag between peak chlorophyll-*a* levels and secondary production. Interestingly, peak chlorophyll-*a* levels in the study area were recorded in May of each year, while peak minke whale presence was recorded in either June or July of each year. Other studies have also demonstrated this time-lag between peak chlorophyll-*a* levels and baleen whale presence, with blue and fin whales showing a time-lag of several weeks following the spring bloom in the North Pacific (Stafford et al., 2009).

Photosynthetic active radiation, the amount of solar input going into a system, and eutrophic depth, the depth at which photosynthetic active radiation falls to 1% of its surface value, were both found to be significant in the Sea Watch Foundation model. Although, chlorophyll-*a* concentration was not significant in this model, both photosynthetic active radiation and eutrophic depth directly influence the level of photosynthesis which can occur and in turn chlorophyll-*a* concentration. Areas with a greater eutrophic depth, or water clarity, often offer more opportunity for photosynthesis to occur, hence increased concentrations of phytoplankton and zooplankton. As sandeels are known to exploit areas of greater productivity to feed during summer months, it is not surprising that both photosynthetic active radiation and eutrophic depth were found to have a significant effect on the presence of minke whales.

Applications for Conservation

Studies such as this one are vital for increasing our understanding of the complex interactions at play between cetaceans and the environments which they inhabit. The findings from this study have shown the strength of using fine-scale bathymetric and oceanographic factors to predict the presence of coastally occurring minke whales. It is through studies like this one that we are able to expand our knowledge of the factors which influence species distribution, and by doing so it becomes easier to develop and implement strategies for the conservation and management of a species.

In recent years the attention of conservation planning has shifted, from species-specific conservation measures to a more holistic approach, which for example focuses on designing well-connected and ecologically coherent networks of marine protected areas (MPAs), which are able to protect biodiversity *in situ* (Guisan & Thuiler, 2005). However, the effectiveness of MPAs as a conservation tool is a topic of continued debate (e.g. Edgar et al., 2014). Although, many consider them essential measures required to meet the conservation commitments set out by a number of international frameworks, for example; ASCOBANS (1994), OSPAR (1998) and the EU Habitats Directive (1992). Hooker & Greber (2004) suggested that cetaceans could be used as 'flagship' species for marine conservation, due to their charismatic nature and ability to stimulate public interest in the protection of a specific area. Cetacean presence in an area, which may also be equally essential for the conservation of a less attractive species, could prompt the introduction of additional protection measures for the area.

Habitat modelling has become particularly useful in identifying areas of importance for top level predators (Tetley, 2004); predictions from these models can be used to detect changes in a species temporal usage of important areas (Canadas et al., 2005). This information can then be used to determine the environmental factors (biotic and abiotic) which are essential to maintain favourable conditions for species conservation. Due to the limited data required to create habitat models, their development is well recognised as a priority in ecological conservation (Schweder, 2003). A variety of models are available to predict the habitat use and distribution of marine species (Loiselle et al., 2003), however different models can occasionally produce different results and therefore care needs to be taken when interpreting model outputs. For example, when using any type of absence data, like pseudo-absence in this study, the absence of the target species does not necessarily mean that the habitat is unsuitable, but that the species, by chance, was not recorded in that specific location. Without careful consideration for the data and model results suitable sites could be overlooked, which can have detrimental impacts for species conservation. Recently new approaches for choosing the best fit model have been employed, based on model averaging (i.e. model weightings according to goodness of fit).

These types of studies are essential when it comes to monitoring the impacts that climate change is having on our marine environments and the species within them. However, our efforts to reduce these impacts may also be having a negative impact on our cetacean communities. UK waters, and specifically those around Scotland, have massive potential for marine renewable energy developments (The Scottish Government, 2013). Although these developments are essential for future generations, as they can aid in reducing our carbon emissions by being fossil fuel and pollution-free during operation, the devices may pose a threat to many marine species, including cetaceans. The impacts of construction and operational noise of these devices are relatively poorly known, but are increasingly the focus of attention (e.g. ICES, 2014). Noise, however, is known to have an impact on cetacean species (Dolman et al., 2007; Bailey et al., 2010; Thompson et al., 2013). The physical presence of such devices in the water also creates obstructions and potential sources of injury (Wilson et al., 2006). Therefore, a detailed understanding of the seasonal patterns and changes in species habitat use is essential when planning for marine renewable energy developments.

Data Limitations

The Sea Watch Foundation data which was supplied for this study was originally collected for a JNCC study looking at the distribution of bottlenose dolphins and harbour porpoise in UK waters, and therefore a number of minke whale records were omitted from the available dataset. However, due to the fact that there was no active selection process in relation to the inclusion of minke whale records, the subset is unlikely to be biased. Nevertheless, smaller sample sizes normally imply some loss of precision.

A further limitation of the study is study species itself. Minke whales are notoriously difficult to detect as they spend the majority of their lives beneath the ocean surface. Presence can therefore only be recorded during surface events, such as lunge feeding and breathing, which can be few and far between, limiting the accuracy of the data available. The quality of each study and the available records can almost always be improved by increasing the time spent surveying or by expanding the survey areas, however, as all studies used here were charities this is not always an option, due to financial constraints.

Conclusions

This study has provided further evidence that cetacean sightings data, collected in a variety of ways, can be used to effectively develop habitat preference models for coastally occurring minke whales in UK waters. However, it has been shown that each dataset can provide different information on which habitats are suitable, although this is most likely due to the geographical constraints of the two small scale studies. The present study has also shown that the presence of minke whales in UK waters is highly variable in space and time. The factor which seemed to have the biggest influence on the presence of the species was a fixed bathymetric variable (depth). The other variables which were shown to play a significant roles in species presence are all highly correlated with the productivity of an area (chlorophyll-*a* concentration, photosynthetic active radiation & eutrophic depth). It has been suggested that using fine-scale environmental factors, such as these, are indeed better predictors of cetacean species presence than the fish distribution data which was traditionally used.

In terms of species conservation the results of this study provide us with further clarity on the importance of UK coastal waters for foraging minke whales during summer months. With an estimated 13,700 and 38,900 individuals in European waters it is increasingly important for all those involved in cetacean research to collaborate closely, in order to provide managers with robust information on how and where is best to implement effective protection measures for this species and others. Ultimately, these decisions will be based on both biological and non-biological factors, and are too often restricted by their economic impacts. However, we must keep in mind that the consequences of the decisions we make today are not likely to be felt until future generations.

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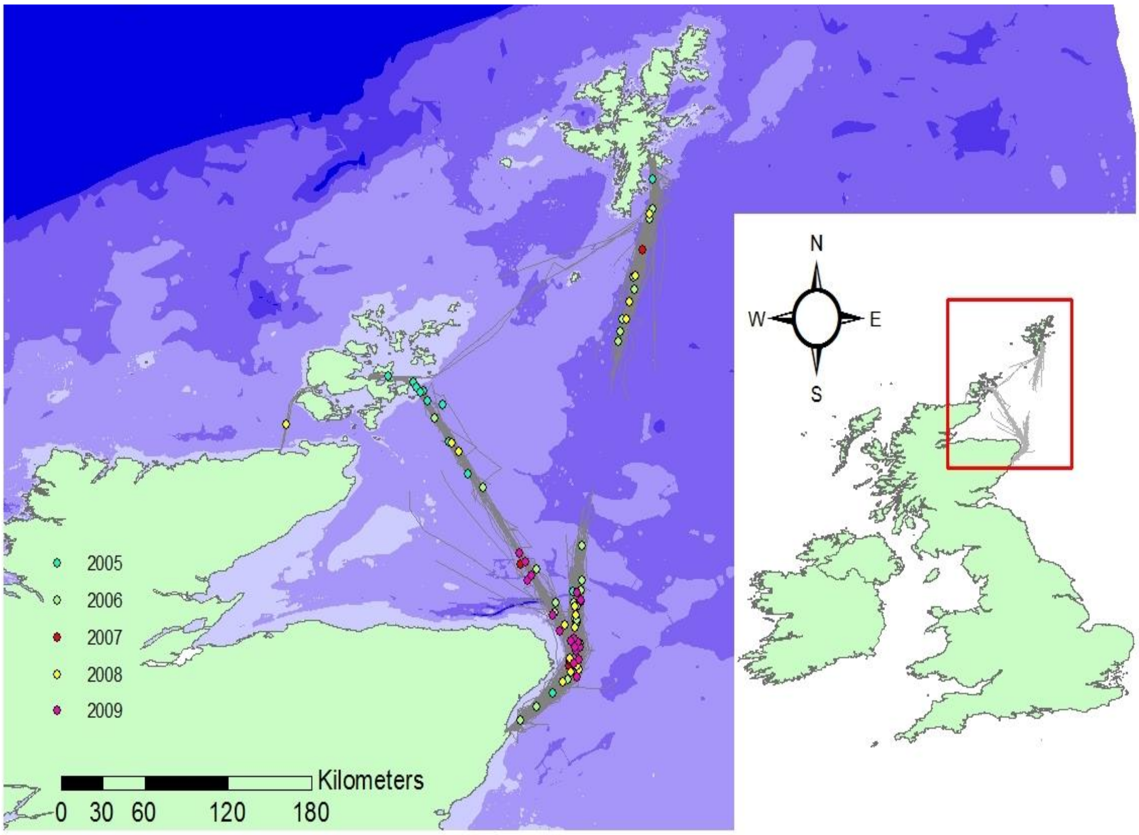
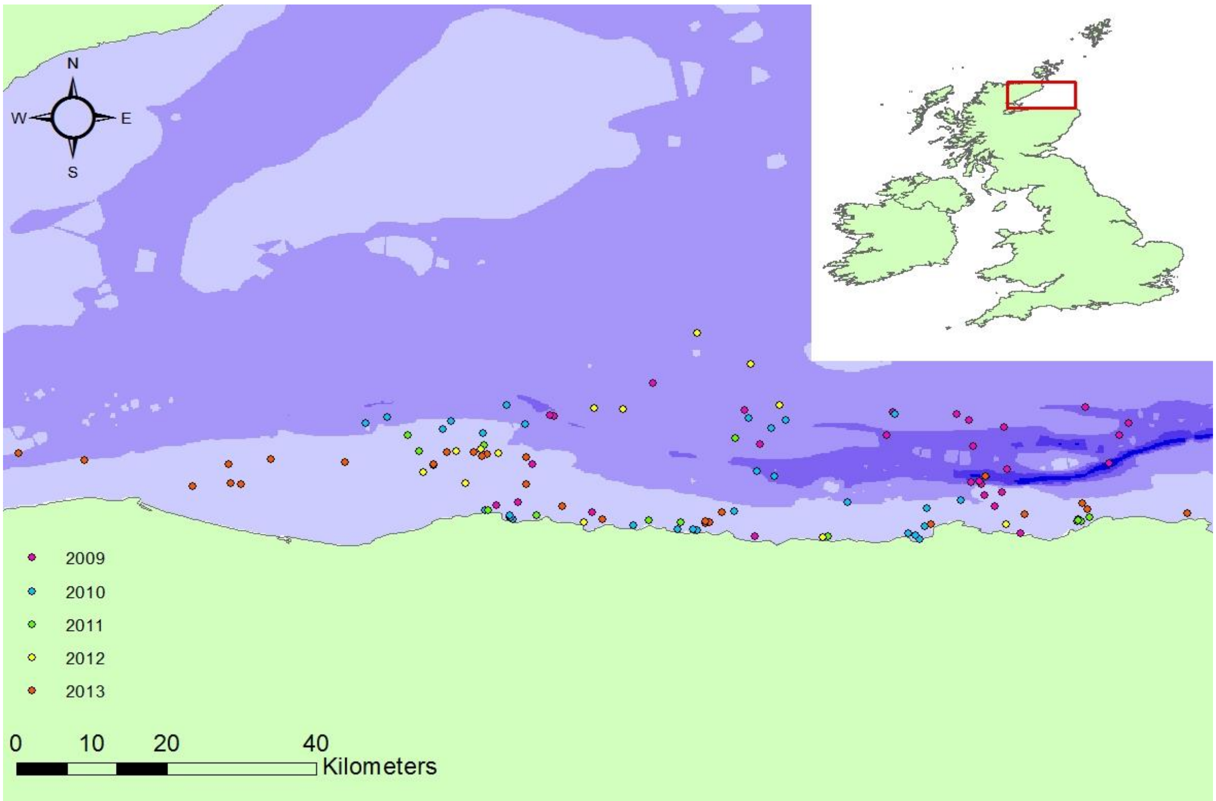
Appendices

Appendix 1. NORCET ferry tracks and minke whale sightings, 2004-2009 inclusive.

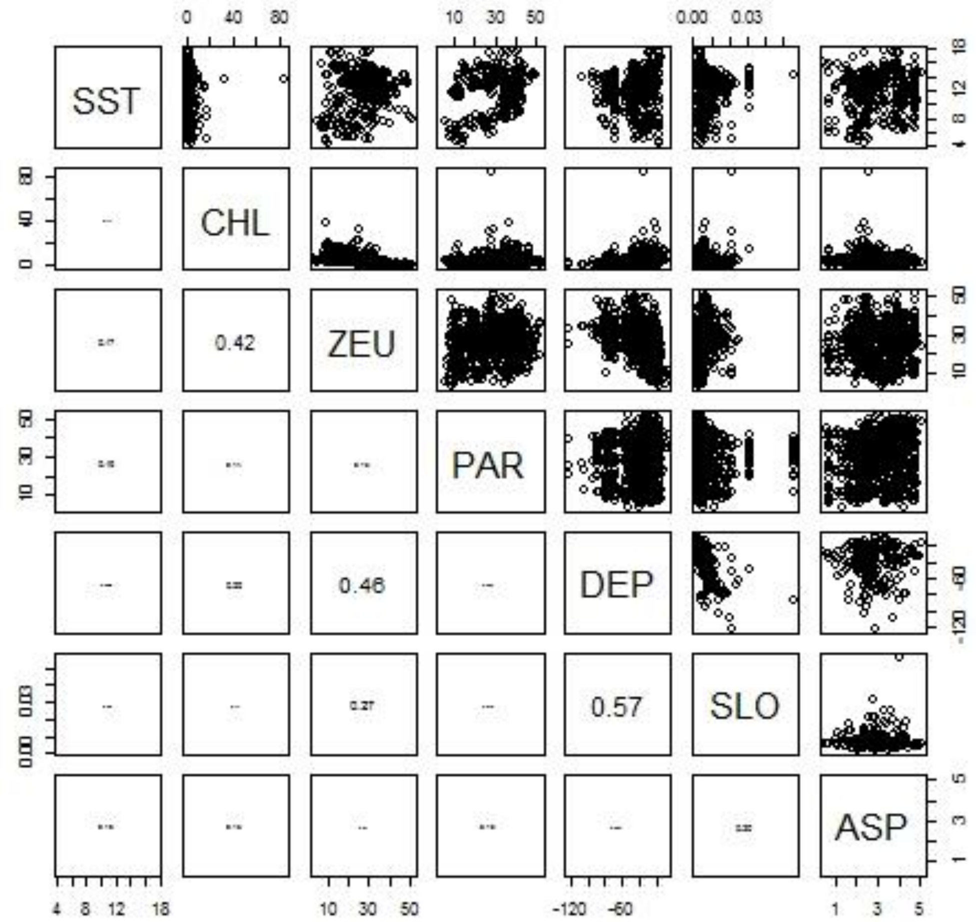


Appendix 2. CRRU minke whale sightings, 2009-2013 inclusive.

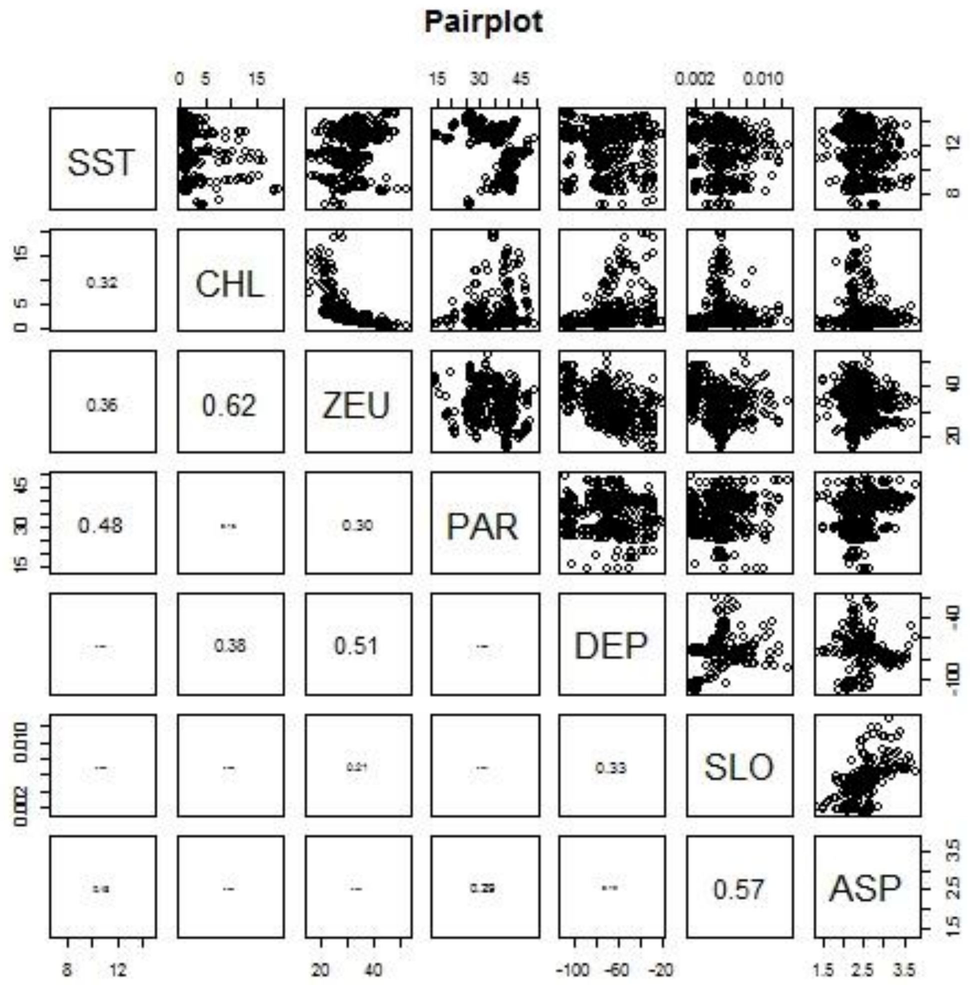


Appendix 3. Pairplots

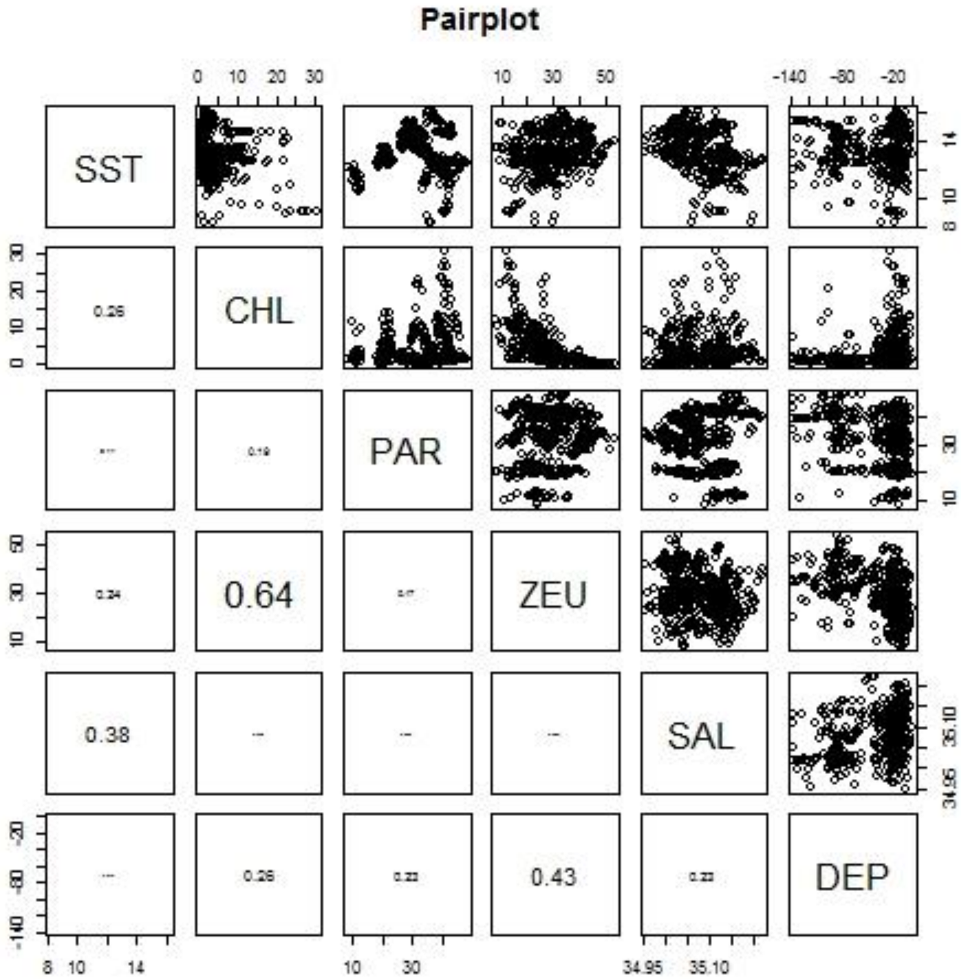
A) Sea Watch Foundation



B) NORCET


Pairplot
SST
CHL
ZEU
PAR
DEP
SLO
ASP
0.32
0.36
0.62
0.48
0.30
0.38
0.51
0.33
0.29
0.57

C) CRRU



Pairplot
SST
CHL
PAR
ZEU
SAL
DEP
0.26
0.19
0.24
0.64
0.38
0.26
0.23
0.43
0.23

Appendix 4. Method for Backward Selection of Generalised Additive Modelling in BRODGAR