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The effects of seismic surveying and environmental variables on deep diving odontocete stranding rates along Ireland's coast

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Most deep diving toothed whales rarely come into contact with humans due to their preference for deep offshore waters. In recent years many studies have connected underwater acoustic disturbances with unusual stranding events of deep diving species. Strandings can provide a valuable opportunity to learn about the ecology of stranded specimens and investigate the cause of mortality. The study determines how environmental and anthropogenic variables such as sea surface temperature, wave height, wave period, wind direction and seismic surveying can influence strandings events of deep diving odontocetes. The results of these analyses suggest that the occurrence of offshore seismic surveying operations increase the number of strandings of long-finned pilot whales, which are probably the most abundant deep diving species in the north Atlantic. The study also demonstrates the value of cetacean stranding schemes and how they can be utilised to establish the natural and anthropogenic processes that contribute to stranding events.

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INTRODUCTION

Irish waters are some of the most important habitats for cetacean species in Europe (Berrow, 2001). There have been eight deep diving odontocetes recorded in the waters around Ireland from observations and the examination of stranded specimens. Species include Cuvier's beaked whale (*Ziphius cavirostris*), Sowerby's beaked whale (*Mesoplodon bidens*), northern bottlenose whale (*Hyperoodon ampullatus*), True's beaked whale (*Mesoplodon mirus*) and Gervais' beaked whale (*Mesoplodon europaeus*) of the family *Ziphiidae,* sperm whale (*Physeter macrocephalus*) and pygmy sperm whale (*Kogia breviceps*) of the superfamily *Physeteroidea* and the large oceanic dolphin, long-finned pilot whale (*Globicephala melas*). Each species is adapted to regularly dive to great depths and have evolved mechanisms such as the capability to store as much oxygen in the blood and muscles as possible and turn off non-essential physiological functions when diving (Perrin & Wursig, 2009). However, little is known about the ecology of most of these species compared to coastal species due to their preference for deep waters and inconspicuous behaviour at the surface (Barlow, 1999). Most sightings of deep diving cetaceans off Ireland are observed in deep waters near the continental shelf off the western seaboard and therefore the majority of strandings also occur on the west coast of Ireland (Berrow et al., 2010).

Cetacean strandings come in several forms; most strandings involve solitary dead animals, however mass strandings can number in excess of a hundred individuals (Geraci & Aubin, 1977). Live strandings are more of a rarity and can elicit a rapid response from volunteers to refloat and rescue the animals (Donoghue & Wheeler, 1990). The threats and therefore potential direct or indirect causes of cetacean strandings are varied and include anthropogenic noise (Fernández et al., 2005), ship strike (Laist et al., 2001), bycatch (Félix et al., 1997) plastic ingestion (Lusher et al., 2015), geomagnetic anomalies (Klinowska, 1986), morbillivirus (Van Bressem et al., 2009), bioaccumulation of pollutants (Jepson et al., 2016) and climatic events (Evans et al., 2005). Strandings provide a valuable opportunity to learn more about the ecology and cause of mortality for elusive deep diving toothed whales.

Deep diving species are believed to be more susceptible to damage from acoustic disturbances (Malakoff, 2002; Cox et al., 2006; Stone & Tasker, 2006; DeRuiter et al., 2013). It has been proposed that anthropogenic sound sources may have a broader effect than just directly impacting individuals by causing strandings. It can also negatively impact communication and behaviour which could consequently lead to reduced foraging or reproductive success and increased exposure to additional pressures such as entanglement in fishing nets (Perry, 1998). Environmental variables may also contribute to the number of strandings of deep divers. Several studies have found a link between natural phenomena and stranding rates for deep diving species ranging from global magnetic activity to wind speed (Vanselow et al., 2009; Moura et al., 2016).

The study aimed to investigate how anthropogenic and environmental variables such as seismic surveying, seaquakes, global magnetic activity, wind direction, wind speed, wave height, wave period and sea surface temperature affect the rate of stranding of deep diving odontocete species in Ireland.

METHODS

A. STUDY AREA

The study area comprised the complete coastline of Ireland, which is approximately 7,500km (Boelens et al., 1999) between latitudes 51 and 56°N and longitudes 5 and 11°W. Ireland is separated from Britain to the east by the Irish Sea and the North Channel, to the south is the Celtic Sea and to the west is the northern Atlantic Ocean.

Two major circulation features exist off the west coast of Ireland, the sub-tropical and sub-polar gyres constrained by the area's most significant ocean currents. What is known as the North Atlantic Current (NAC) makes up the southern edge of the sub-polar gyre and sweeps east from the western north Atlantic. The Shelf Edge Current (SEC) is a north flowing slope current along the continental shelf which carries high salinity water in the upper 400m of the water column and below, deep ocean circulation. The SEC has a peak flow of 50cms^{-1} and an average of 10-20cms^{-1} (White & Bowyer, 1997). Up to two thirds of the energy from currents is related to tidal energy around the continental shelf. It also results in approximately half of the energy on the continental slope and one quarter to one third in deep waters.

B. STRANDING RECORDS

Records of cetaceans stranded on the coastline of Ireland were provided by the Irish Whale and Dolphin Group (IWDG). The IWDG have operated a stranding recording scheme since 1991 in which details of reported strandings are validated and published before being added to a database. The number of strandings recorded for each year has been steadily rising since the establishment of the cetacean stranding scheme in 1991 but began to plateau at approximately 105-150 strandings since 2002-2003 (Berrow et al., 2010). Since 2003 the stranding scheme has been well established and recorded numbers of strandings are consistent from year to year. Therefore the scheme is considered sensitive enough to recognise unusual stranding events. However, due to the remoteness and length of the Irish coastline the probability of some strandings being discovered and then reported may be low.

Stranding events were used in the analysis, these can be single or mass stranding and the individual(s) may have been alive or dead at the time of stranding. By counting the events rather than individuals it is possible that mass strandings may be underestimated. However, if the numbers of animals are used rather than events, mass strandings would be overemphasized and species prone to stranding in mass would be disproportionately represented. There were relatively few mass strandings so the analysis was more reliable. The definitions used by Klinowska (1985) for single and mass strandings were followed, unless there is evidence of individuals originating from the same social unit, two or more animals of the same species or location were recorded as distinct stranding events.

A database exclusively containing the total number of strandings for deep diving species, long-finned pilot whale, sperm whale, pygmy sperm whale, Cuvier's beaked whale, northern bottlenose whale, Sowerby's beaked whale, True's beaked whale and unidentified beaked whales was extracted. The database was examined for the total amount of stranding events for each species per year. Average values were obtained to get the annual stranding rates over the period, 2003-2015.

C. ANTROPOGENIC AND ENVIRONMENTAL VARIABLES

Data for the environmental variables wind speed (kn), wave height (m), sea surface temperature (°C), wind direction (°T) and wave period (s) were collected from the weather buoy network on the publicly accessible website data.marine.ie. Data from four weather buoys located off the west coast of Ireland in relatively close proximity to the deep waters overlying the continental slope were used (Figure 1). These buoys were chosen as the majority of strandings took place along the western seaboard and the deep diving cetacean species that are the focus of the research are most often observed in the deep waters to the west of the continental slope. In addition, each weather buoy did not record continuously for each environmental variable throughout the study period. The buoy M1 was located off the west coast (53.1266°N, 11.2°W) and was in operation from February 2003 to July 2007. Off the southwest (51.2162°N, 10.5506°W), M3 was in operation throughout the study period 2003-2015. The M4 buoy was originally located to the northwest (54.6667°N, 9.0667°W) from April 2003 to May 2007, at which point it was moved further offshore (55.0182°N, 9.7467°W) where it logged data for the rest of the study period. The furthest offshore weather buoy was M6 to the west (53.182°N, 15.73°W) and it recorded information from September 2006 until the end of the study period.

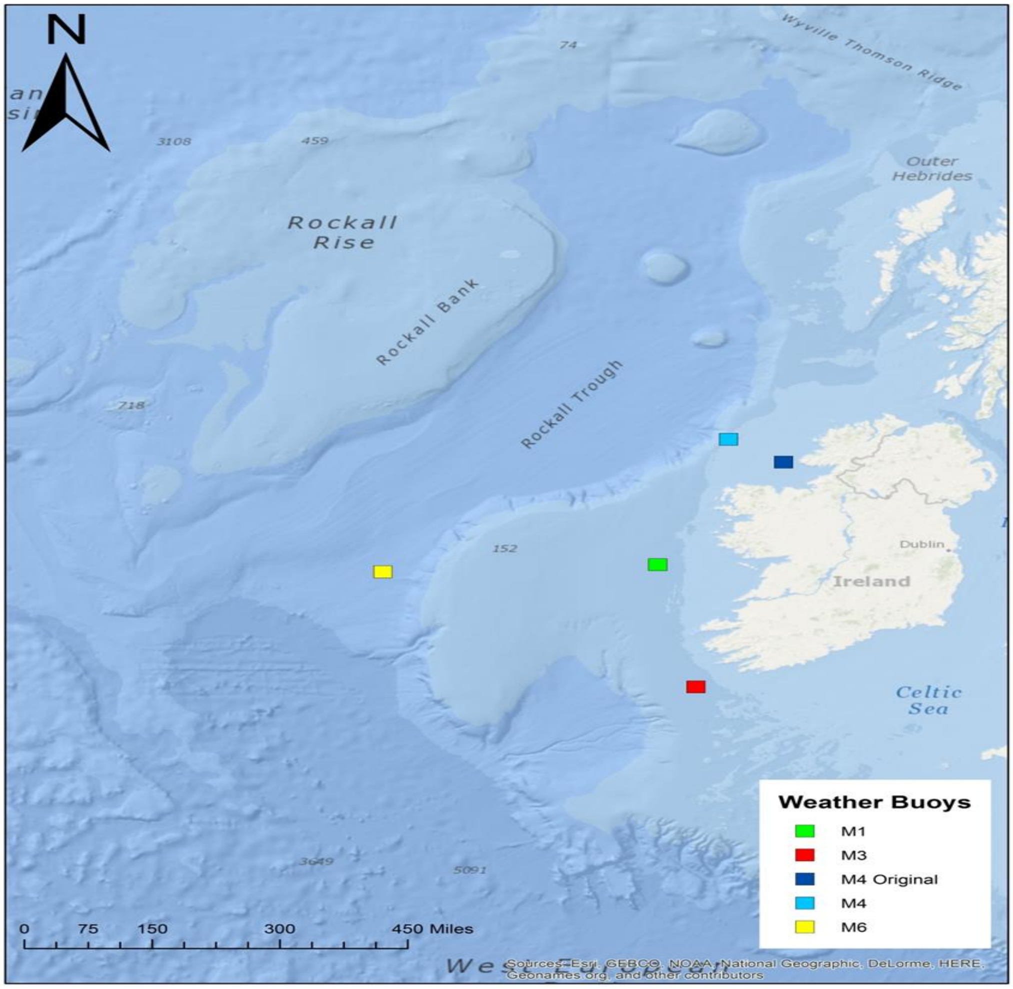

Figure 1. Weather buoys used to obtain environmental data wind direction, wind speed, wave height, wave period, sea surface temperature and sea surface temperature off Irish coast.

The daily global magnetic activity Aa-index data was obtained from the publicly accessible International Service of Geomagnetic Indices website (isgi.unistra.fr). The index is a worldwide geomagnetic activity index that quantifies the daily disturbance level of the earth's magnetic field. The Aa-index is obtained from averaging the 8 daily aa-index values. The aa-index is recorded at three-hour intervals and is derived from K indices which are transformed into amplitudes and then averaged using weighting factors that account for variations in geomagnetic disturbance intensities between northern and southern hemispheres and has units of 1 nT, a unit of measurement of the strength of a magnetic field. The K-index is an integer ranging from 0-9, it is derived from maximum variations of horizontal components observed on a magnetometer during three hour intervals. As the relationship of the K-scale to magnetometer variations is non-linear, the average of a set of K indices is not used. Therefore, each K is converted to a linear scale resulting in the equivalent three-hour interval range aa-index. It is measured at two approximately antipodal observatories, Canberra, Australia in the southern hemisphere and Hartland, England in the northern hemisphere. Enlarged Aa-index values signify increased magnetic activity, whereby a value of 140nT would indicate a magnetic storm and a value of 5nT would show little activity.

Information on the occurrence of underwater earthquakes was attained from the Observatories and Research Facilities for European Seismology website (orfeus-eu.org/odc/navigator.html). Underwater earthquakes located between latitudes 58°N and 45°S and longitudes 5°E and 30°W were recorded. Data was available at depths between 20-1000m and magnitudes between 4.4 and 10, using the magnitude scales Richter magnitude (ML), body wave magnitude (Mb) and moment magnitude (Mw).

Data on two-dimensional (2D) and three-dimensional (3D) seismic surveys carried out from 2003 to 2015 in waters under Irish jurisdiction was obtained from the Integrated Petroleum Affairs System (IPAS) database on the Department of Communications, Energy and Natural Resources website (gisdcenr.gov.ie/internetIPAS/servlet/internet/IPAS2ISeismicSurveySearch). The start and end date of each survey was used to ascertain the periods when seismic surveying operations were taking place for the analysis. Information on the number of days air guns were operated during each survey was unavailable. It is likely that air guns were not used every day over the course of a seismic survey as travel to and from survey sites and poor weather conditions can restrict their use.

D. STATISTICAL ANALYSES

The number of strandings for each group was calculated for 10 day intervals over the study period and used as response variables in the analysis and the total number of sea quakes and seismic surveying days and average wind speed, wind direction, wave height, wave period and sea surface temperature for 10 day intervals were used as explanatory variables. The effects of anthropogenic and natural variables on stranding events were investigated by performing multiple regression analysis using Generalized Linear Models. The fit of the model was examined by taking into account the ratio of residual deviance divided by degrees of freedom. When ratios were close to 1, it was believed that the model provided a good fit to the data (Crawley, 2007). However when it was considerably more or less than 1, it was understood that the model was over- or under-dispersed. The response variables included total number of stranding events and long-finned pilot whales which were modelled with a Poisson distribution and *Ziphiidae* and *Physeteroidea* using a quasi-Poisson distribution to correct for over- or under-dispersion (Szinwelski et al., 2012). The explanatory variables for each model were the magnetic activity Aa-index, the occurrence of seaquakes and seismic surveying activity, wind direction, wind speed, wave height, wave period and sea surface temperature. Initial maximal models were refined by removing non-significant parameters and using the Akaike's Information Criterion (AIC). The AIC method indicates the degree of the quality of a model by balancing complexity in contrast to goodness of fit (Akaike, 1974). Using this method, the superior model has the lowest AIC value. Statistical analyses were carried out using the statistical software R v.3.3.3 (R Core Team, 2015).

RESULTS

A total of 258 stranding events comprising deep diving species occurred (Table 1) between 2003 and 2015. Live strandings made up 12.4% (n=32) and mass strandings accounted for 2.7% (n=7) of records. The number of stranding events per year ranged from 2 in 2010 to 29 in 2015 with a mean value of 19.8 events per year. Events involving two or more individuals ranged from 0-2 times per year, the high occurring in 2015 with a mean value of 0.5 per year. An average of 2.5 live strandings took place each year, with a maximum of 6 in 2013 and 2009.

Table 1. Total and average number of stranding events per year 2003-2015 for deep diving odontocete species in Ireland.

	Long-Finned Pilot Whale	Cuvier's beaked whale	Sowerby's beaked whale	Northern bottlenose whale	True's beaked whale	Unidentified beaked whale	Pygmy sperm whale	Sperm whale	Total
2003	3	0	0	0	0	0	0	3	6
2004	13	1	2	0	0	1	0	3	20
2005	5	2	0	1	0	0	1	4	13
2006	14	1	2	3	0	1	0	1	22
2007	13	1	0	0	0	0	0	2	16
2008	17	4	1	0	0	3	0	1	26
2009	13	3	3	2	1	0	2	4	28
2010	2	0	0	0	0	0	0	0	2
2011	13	2	0	1	0	0	0	2	18
2012	21	3	0	1	0	0	0	3	28
2013	21	1	0	0	3	0	1	2	28
2014	13	6	0	1	0	0	0	2	22
2015	15	7	1	1	0	0	1	4	29
Total	163	31	9	10	4	5	5	31	258
Average	12.5	2.4	0.7	0.8	0.3	0.4	0.4	2.4	19.8

Long-finned pilot whale was the most frequently stranded deep diving species with 163 events (Figure 2) over the 12-year period which accounted for 63.2% of the total number of strandings. The species would strand an average 12.5 times per year with a high of 21 in 2012 and 2013 and low of 2 in 2010, although it is interesting to note that one of the two events in 2010 was a live stranding involving 33 individuals. Long finned pilot whales mass strand and live strand most regularly of all the deep diving cetaceans, 4 and 17 times respectively. Only two years passed without a long-finned pilot whale live stranding, 2005 and 2011.

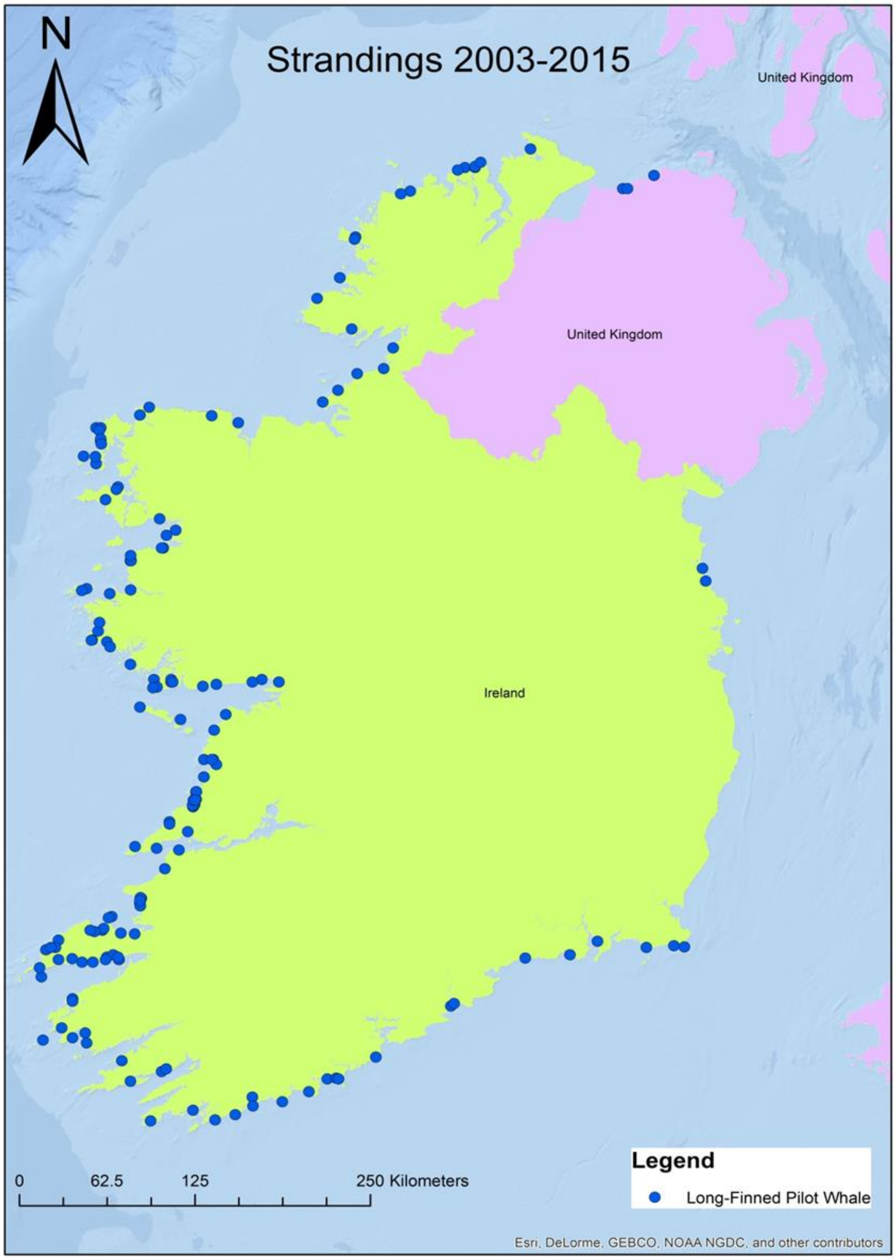

Figure 2. Long-finned pilot whale stranding events on Ireland's coast 2003-2015.

Beaked whales were involved in a total of 59 events (Figure 3), with Cuvier's beaked whale contributing towards the majority of beaked whale strandings (52.5%; n=31), unidentified beaked whales stranded 5 times. The next most frequently stranded beaked whale was northern bottlenose whale (n=10), followed by Sowerby's beaked whale (n=9) and True's beaked whale (n=4). Although the Cuvier's beaked whale stranded most out of the family it did not mass strand. Other beaked whale species live stranded on 8 occasions and mass stranded on 3 occasions.

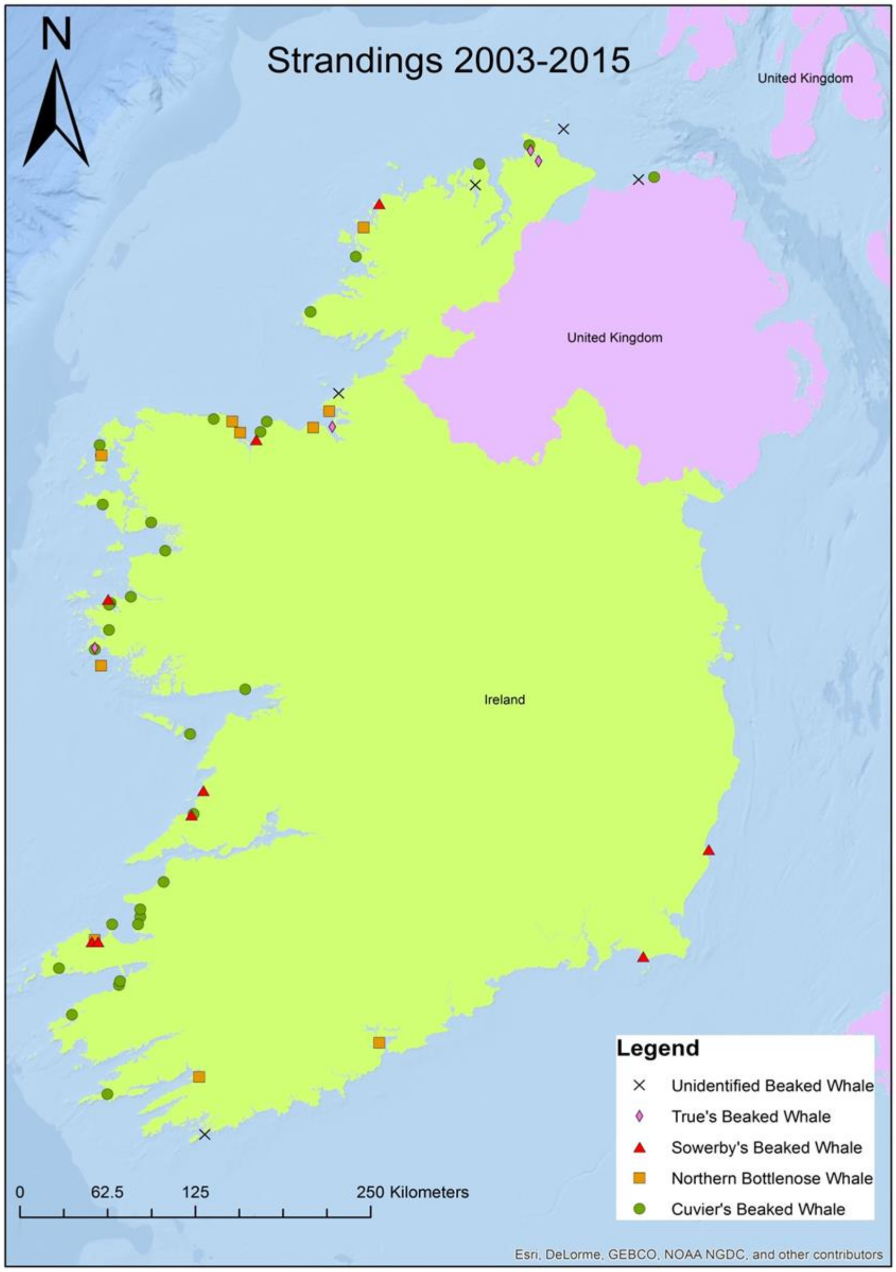

Figure 3. Beaked whale (Ziphiidae) stranding events on Ireland's coast 2003-2015

The sperm whale consistently stranded over the time period with only one year in which it was not recorded. The number of strandings each year never deviated far from the mean of 2.4 and the maximum was 4 in 2005, 2009 and 2015. The species had the second most live strandings along with the northern bottlenose whale (n=4). There were only 5 strandings of pygmy sperm whale and 2 of those involved live individuals. In total, 36 stranding events included the sperm whale superfamily *Physeteroidea* (Figure 4).

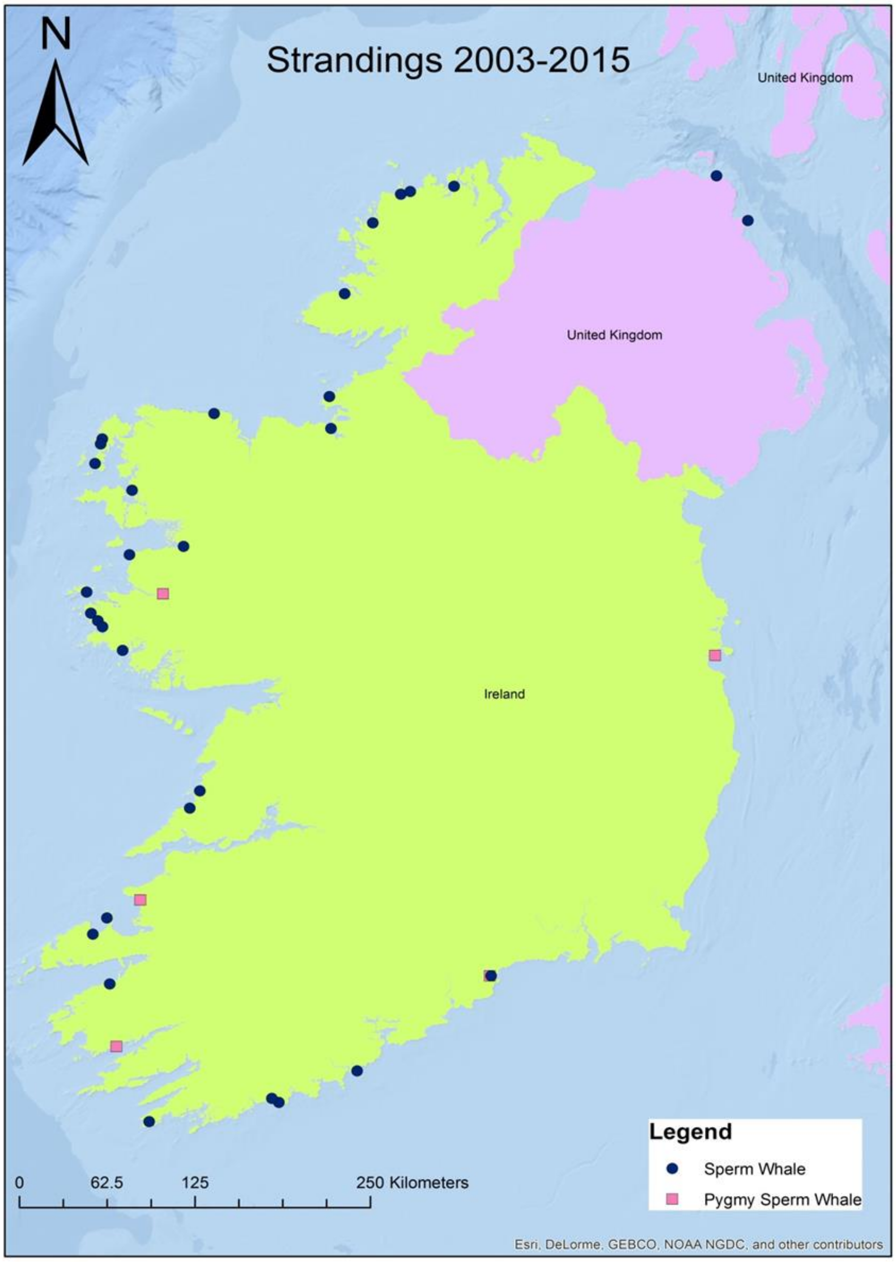

Figure 4. Sperm whale and pygmy sperm whale of the superfamily Physeteroidea stranding events on Ireland's coast 2003-2015.

The effects of seismic surveying and natural variables on the number of strandings over 10 day periods for all deep diving species, long-finned pilot whales, beaked whales (*Ziphiidae*) and the sperm whale superfamily *Physeteroidea* were investigated using GLM regression (Table 2).

Table 2. Summary of significant parameters from minimal adequate models examining relationships between deep diving odontocete stranding events and natural and anthropogenic variables including associated parameters, Akaike's Information Criterion (AIC), slope estimates, standard errors, t values, z values and p values.

Group	Parameter	AIC	Estimate	Standard Error	t value	z value	P value
All Species	Sea Temperature	909.45	-0.177	0.045	-	-3.961	<0.001
	Seismic		0.025	0.017	-	2.137	0.033
	Wave Height		0.419	0.132	-	3.163	0.002
	Wave Period		-0.379	0.177	-	-2.137	0.033
	Wind Direction		0.005	0.002	-	2.732	0.006
Long-fined Pilot Whale (*Globicephala melas*)	Sea Temperature	709.98	-0.121	0.052	-	-2.328	0.020
	Seismic		0.041	0.013	-	3.105	0.002
	Wave Height		0.224	0.070	-	3.189	0.001
Beaked Whales (*Ziphiidae*)	Sea Temperature	-	-0.184	0.094	-1.952	-	0.052
	Wave Height		0.720	0.298	2.413	-	0.016
	Wind Direction		0.012	0.004	2.811	-	0.005
Sperm Whales (*Physeteroidea*)	Sea Temperature	-	-0.313	0.105	-2.994	-	0.003

The initial model examined the effects of each variable on stranding events of all deep diving species together over the study period. Seismic surveying (p = 0.033), wave height (p = 0.002) and wind direction (p = 0.006) each had a positive significant effect. Significant and negative relationships were observed for sea surface temperature (p < 0.001) and wave period (p = 0.033). Two significant positive relationships existed for long-finned pilot whale stranding events, namely seismic surveying (p = 0.002) (Figure 5) and wave height (p = 0.001). A single negative relationship occurred between long-finned pilot whale strandings and sea surface temperature (p = 0.02). A marginally significant negative relationship was present between beaked whales and sea surface temperature (p = 0.052). A positive and significant interaction was observed for the species with wave height (p = 0.016) and wind direction (p = 0.005). A single negative and significant interaction existed between strandings of *Physeteroidea* and sea surface temperature (p = 0.003).

The interactions suggest that long–finned pilot whales, *Ziphiidae* and *Physeteroidea* are each more likely to strand during periods of lower sea surface temperature. Long-fined pilot whales and *Ziphiidae* stranding events were more numerous when the elevation of waves was high. The long-finned pilot whale also stranded more often over the study period during the occurrence of seismic surveying operations. A total of 43 seismic surveys were conducted in Irish waters from 2003 to 2015. These consisted of 23 2D surveys and 20 3D surveys. The duration of 2D surveys ranged from 3-128 days with an average of 35 days. The average length of 3D surveys was 36 days and ranged from 4-119 days. A total of 1,527 days of seismic surveying occurred over the 12-year study period, of these 814 days were 2D and 713 days were 3D. Of the 2D surveys, 10 occurred in the Celtic Sea to the south, 5 around the Rockall Basin to the west and northwest, 4 in the Porcupine Basin to the west and south west, 3 off the west coast of Ireland and a single survey took place around the Goban Spur to the southwest. Of the 20 3D seismic surveys, 8 occurred in the Porcupine Basin, 7 in the Celtic Sea, 3 took place in the Slyne Basin to the west, 1 in the Rockall Basin and another single survey around Erris Ridge to the northwest. Beaked whale (*Ziphiidae*) stranding events were more frequent when the value in degrees for wind direction was higher, in other words winds originating from the west.

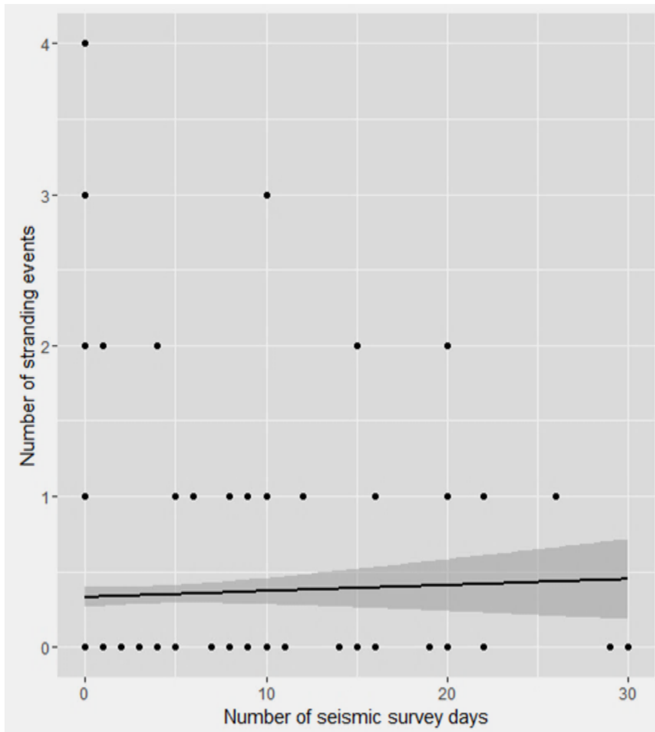

Figure 5. Relationship between number of long-finned pilot whale stranding events and number of seismic surveying days for 10 day intervals, 2003 to 2015. Shaded areas indicate 95% confidence intervals.

DISCUSSION

The strandings of deep diving cetacean species provide a valuable opportunity to carry out research on animals that are challenging to study in their natural habitats (Evans & Hindell, 2004; Byrd et al., 2014). Stranding networks can be used to identify unusual stranding events that may be a result of natural or anthropogenic effects. The significant correlations between the number of stranding events and environmental variables demonstrate that natural factors have an effect on the stranding rates of deep diving species. The significant variables may make stranding events more likely rather than being the primary reason for stranding. Perhaps due to their preference for deep offshore waters these factors may have more of an influence as floating carcasses have a longer distance to travel before landfall, compared to coastal species. A significant negative relationship between total strandings and wave period existed; as the time interval between the arrivals of consecutive waves decreases it can increase the stranding rate, therefore more frequent waves in time increase the number of strandings. Enlarged wave height tended to increase the number of total strandings, long-finned pilot whale strandings and beaked whale strandings; taller waves may have the capability of carrying carcasses or debilitated individuals further inshore in comparison to smaller waves. Wind direction also had a positive relationship with total strandings and beaked whale strandings; as the value for wind direction increased so did the number of strandings. Over the study period the average wind direction was 209°T which is wind originating from south to southwest; however the highest observed value of 279°T is a west to east wind. Therefore as the value for wind direction increased it indicated a more westerly wind and strandings increased when it occurred. The influences of natural processes had significant positive and negative effects on the number of strandings of deep diving species in Ireland. Strandings were more frequent when the waters around Ireland were cooler, this may be due to whale migration into Irish waters to follow food. Decreased sea surface temperature increased the frequency of long-finned pilot whale, *Ziphiidae* and *Physeteroidea* strandings. Increased wave height led to more long-finned pilot whale and *Ziphiidae* stranding events. The occurrence of westerly winds led to an increase in strandings compared to more southerly winds. A shorter wave period also resulted in more strandings.

This analysis also indicated that the occurrence of seismic surveying operations off the coast of Ireland may have increased the number of stranding events for long-finned pilot whales and all species grouped together. Long-finned pilot whales consisted of 63.2% of the total number of stranding events of deep diving species. This species is also most likely to mass strand (Evans et al., 2005). Changes in behaviour and vocalisation patterns, deviation from migration route, auditory system impairment and increase in strandings have been described as the effects of seismic surveying on cetaceans (Engel et al., 2004; Parente & de Araújo, 2005). The results suggest that this species may be particularly susceptible to anthropogenic noise emanating from seismic surveys, perhaps due to the species higher abundance in the north east Atlantic compared to other deep diving odontocete species. However, due to the unavailability of alternative anthropogenic data sources only the presence of seismic surveying activities was modelled with strandings. There are multiple anthropogenic activities that are thought to negatively impact deep diving odontocetes such as naval sonar, shipping noise, plastic ingestion, ship strike and net entanglement and future research should examine links between such pressures and stranding rates.

The present study has shown the scientific value of using stranding schemes to increase knowledge on the impacts of environmental processes and anthropogenic disturbances on deep diving cetaceans. The results indicate that several of the variables have had significant positive and negative influences on the stranding patterns of deep diving toothed whales off Ireland over a period of 12 years. However, as there are multiple alternative reasons for stranding that have not been included in the study, the cause of death of stranded individuals must be determined by carrying out post mortem examinations. Ireland is currently lacking a post mortem scheme for stranded cetaceans and without it; the cause of death cannot be unequivocally established. In addition, an underwater noise register should be established to obtain information on intense noise in the marine environment and generate baseline data.

CONCLUSION

The study investigated the effect of seismic surveys and environmental variables on stranding rates of deep diving species in Ireland. Recent research has established links between strandings of deep diving odontocetes and anthropogenic noise. The study found a significant positive interaction between the presence of seismic surveying activities and strandings of long-finned pilot whales, probably the most abundant deep diving species in the north Atlantic. Environmental variables were also found to have an effect on stranding rates. They may have a strong effect on drifting carcasses or debilitated individuals. The study also emphasises the scientific value of cetacean stranding schemes to interpret the effects of environmental and anthropogenic variables on cetaceans and recognise unusual stranding events.

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