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Cetaceans as sentinels for informing climate change policy in UK waters

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ABSTRACT

Climate change is predicted to have profound consequences for marine ecosystems. Due to the growing political and social drive to address its impacts, monitoring and mitigating climate change is a priority in marine policy in the UK. Cetaceans have been proposed as informative sentinel species for monitoring ocean health. Here, strandings data from four UK cetacean species were assessed for their use as a tool to aid policy makers monitoring climate change in marine environments. Data on stranded cetaceans were collected from 1990 to 2018 and differences in the proportions of stranded cold water adapted and warm water adapted species assessed using Generalised Linear Models (GLM), with 6-year periods and four regions of the UK included as explanatory variables. This modelling approach showed an increase in the proportion of stranded warm water adapted species over time across the UK and that differences in proportion of strandings between cold water and warm water adapted species can be detected between regions and 6-year periods, chosen as metrics to coordinate with reporting cycles for policy assessment needs. As such, these results show the potential for utilising strandings data to identify changing oceanic trends at the appropriate spatial and temporal scales for policy reporting in the UK. However, development of these analyses with a more detailed examination of these data at a finer resolution, incorporating other data sources, such as distribution trends and dietary stable isotope data, may be required before it is applicable as an indicator for trends in changes in climate.

1. Introduction

Unless there is an imminent and profound reduction in global carbon emissions, models suggest a unidirectional progress to a warmer earth, with mean sea surface temperatures projected to increase by 0.035 °C per year and warm an additional 2.8 °C by 2100 [1,2]. As such, climate change is predicted to have profound consequences for marine ecosystems [3]. Climate driven changes to marine ecosystems, such as warming oceans, increased ocean acidification, decreased oxygen levels and altered patterns of ocean circulation [4–6], are on course to eventually push regional environmental variables beyond the range of natural tolerances for marine life [3]. This may have consequences for the majority of marine organisms as changes in ocean temperature and chemistry could lead to altered behaviour, distribution, physiological functioning, population dynamics and demographic parameters, with a subsequent impact on wider ecosystem functions [4]. To avoid the dangerous effects of climate change, there is now a global commitment to effectively monitor and mitigate climate change by resolving to keep the planet's average global temperature below a 2 °C rise from pre-industrial levels [7–9]. In line with these plans, the UK has domestic and European level policy commitments, such as the 25 Year Environment Plan[1] and Marine Strategy Framework Directive[2] respectively, to monitor and mitigate climate change in the marine environment.

Due to their position as top predators, often feeding at high trophic levels [10,11], some cetacean species are likely to be heavily impacted by the effects of climate change. Climate change may impact the health of cetacean species through habitat change or loss, changes in prey distribution and abundance, temperature stress and extreme weather

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[1] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/693158/25-year-environment-plan.pdf
[2] https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

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events [12]. Climate change may also impact cetacean health indirectly through changes in pathogen interactions, alterations in predator-prey dynamics, increased exposure or susceptibility to toxicants, such as mercury and polychlorinated biphenyls (PCBs), and increased interactions with anthropogenic activities, such as bycatch and ship strike, as new areas, such as polar regions, become accessible to fishing industries and shipping. This is already evident in coastal Arctic waters, where the impacts of climate change have been greatest to date [10,13,14].

In order to monitor impacts of climate change, the use of sentinel species has been proposed [15,16]. Sentinel species act as "canaries in the mine" [15], serving as indicators of their environment, which can be monitored to gain early warnings about potential wider ecosystem change [11]. Cetaceans have already been proposed as useful sentinel species for monitoring ocean and human health due to their position as top predators, their sensitivity to bioaccumulation of toxicants, and their sharing of similar coastal habitats with, and similar trophic position to, humans [11,17,18]. Cetaceans are highly mobile, potentially allowing them to migrate to more favourable conditions in the face of environmental change [3]. In addition, cetaceans are charismatic megafauna that typically stimulate an exaggerated human behavioural response and therefore changes or alterations in cetacean populations are more likely to be observed and noted than in other marine species, which increases their value as sentinels for change [11,19]. Thus, long-term monitoring of cetaceans could provide a useful gauge of changing oceanic conditions.

In the UK, a response to climate change is evident in reported range shifts in some species, with warmer water adapted species occurring more frequently or in greater abundance, and cold water adapted species becoming less common [20–22]. These changes in abundance and distribution are suspected to be driven, at least in part, by range shifts in cetacean prey, as notable shifts of fish species due to climate change have already been documented in the North Sea, Irish Sea and wider North Atlantic [23–26]. Twelve species of cetacean regularly occur in UK waters [27]. An ideal indicator species for monitoring climate change should have a wealth of distribution data, such as strandings data; and specific, relevant ecology, such as clear thermal tolerances, feeding specialisation and distributional limits which mean they could be influenced by climate change [12,28]. Given their ecology, behaviours and volume of stranding data, four cetaceans commonly recorded in UK waters have been identified as potentially suitable as indicators of climate change: Atlantic white-sided dolphins (*Lagenorhynchus acutus*); short-beaked common dolphins (*Delphinus delphis*); striped dolphins (*Stenella coeruleoalba*); and white-beaked dolphins (*Lagenorhynchus albirostris*).

Atlantic white-sided, short-beaked common and white-beaked dolphins have historically been recorded in the top ten most abundant cetaceans sighted in UK waters [29]. Striped dolphins were rarely recorded around the UK prior to the 1980s, but sightings and strandings of this species have steadily increased over the past thirty years [20,30,31]. These four species have differing thermal tolerances, with short-beaked common and striped dolphins preferring warmer ocean temperatures with warm temperate distributions, and Atlantic white-sided and white-beaked dolphins adapted to cooler ocean temperatures, with cold temperate to low Arctic distributions [21,32,33]. All four species commonly strand in the UK waters [31]. Sightings and strandings data in Atlantic white-sided and white-beaked dolphins have decreased in the UK over the past three decades [21,22,34]. Conversely reports of short-beaked common and striped dolphins have increased over this time period [21,34]. These findings indicate that these species are, potentially, useful as sentinel species to monitor climate change, in that they are already showing ecological responses to changing oceans, may have restricted thermal tolerances, have sufficient stranding frequency to support statistical modelling analyses and have the requisite ecological traits to serve as sentinels.

Since 1990, monitoring programmes for cetaceans have been established around the UK [31,35,36], with infrastructure and standardised protocols for consistent sampling and analysis, which is essential for effective surveillance [17]. Data from long term scientific programmes are essential to policy makers and advisors, and they require long term monitoring programmes in order to design, implement and evaluate effective environmental policies [37,38]. It is a priority to maximise the value and use of data from long term surveillance programmes and, as such, it is important to identify what can be detected from these data sources to aid UK policy commitments at the appropriate reporting time scales in the regions of interest.

The collection of strandings data in the UK over the past three decades[3] provides an extensive surveillance dataset at long term temporal and UK-wide spatial scales [39,40]. Strandings data can provide several population indicators relevant to monitoring strategies [40], such as life history [41,42], diet [43,44], distribution [39,45], nutritional status [46,47], disease burden [48,49] and environmental contaminants [50–52]. Despite this, strandings data are often under-used for population monitoring purposes [53,54], and whether these data can be used to detect climate change driven variation around the UK, and for policy assessments, has yet to be explored. Here, strandings data collected between 1990 and 2018 are used to assess (1) if stranding patterns of four cetacean species with potentially varying thermal niches around the UK have altered over time; and (2) whether these patterns are detectable at different spatial and temporal scales useful for policy and, may therefore, be an effective tool for UK policy makers as a sentinel for ecosystem change.

2. Materials and methods

2.1. Strandings data collection

Strandings data were collected by the UK Cetacean Strandings Investigation Programme (CSIP) between 1990 and 2018, throughout the UK, according to the protocol and methodology outlined by Deaville et al. [31]. Data were selected to include four species of cetacean: Atlantic white-sided, short-beaked common, striped and white-beaked dolphins. These data were then grouped into two categories to represent warm water adapted species (short-beaked common and striped dolphins) and cold water adapted species (Atlantic white-sided and white-beaked dolphins). Strandings where the individual could not be identified to the species level were not included in the analysis.

2.2. Data analysis

All data exploration and statistical analyses were carried out using R v3.6.3 [55].

2.2.1. Response variable

The number of recorded strandings can be affected by multiple factors including; recording effort; stranding location; environmental factors, such as temperature, currents, and wind influencing carcase drift; anthropogenic factors, such as vessel release point following bycatch or ship-strike; and additional biological factors, such as species abundance and distribution, and location of mortality, among others. All of these can have a significant impact on the likelihood of an animal stranding and/or being detected [30,39,56,57] leading to bias in distribution of reported strandings around the UK coastline. Counts or frequency data being prone to a number of these biases can complicate the interpretation of results, particularly when trying to compare between species occupying potentially different movement patterns and ecological niches. Converting count data to proportions for analysis is a good method to standardise data sets and limit the effect of such biases [58]. As such, species were categorised as a binary response (cold water

[3] http://ukstrandings.org/

adapted = 0, warm water adapted = 1) for the analyses and Generalised Linear Models (GLM) used to explore the influence of explanatory variables on the changes in proportion of strandings of warm water adapted species.

2.2.2. Explanatory variables

To assess whether changes in the proportions of strandings data can be identified within a time frame relevant to policy needs, strandings were grouped into 6-year periods to coincide with the length of key reporting cycles such as the European Commission (EC) Habitats Directive[4] Article 17 status assessments [59,60], EC Marine Strategy Framework Directive (MSFD)[5] [61] and OSPAR assessments[6] [62]. To consider UK regional differences in strandings [20,21,29], strandings were divided into one of the two Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) management regions in UK waters, OSPARII or OSPARIII.[7] To account for latitudinal differences in strandings, north and south zones within these regions were created along the 55° latitude parallel. This line was chosen as the north/south divide between the western region of the UK (OSPARIII) due to its position just north of the Solway Firth, dividing the water bodies of the Irish and Celtic Seas, and Western English Channel from the West of Scotland, Malin Shelf and North Atlantic [63]. No key partition was identified for the east (OSPARII), so the 55° latitude parallel was extended to split the eastern region in order to match the western partition (Fig. 1).

Annual mean sea surface temperature (SST) was used as a climatic explanatory variable in the model, as it is a major driver of marine ecosystems globally and due to its potential to cause changes in population structure in marine ecosystems, [3,64,65], which may have an impact on stranding patterns. SST was obtained from National Oceanic and Atmospheric Administration (NOAA) Climate Data Record (CDR) of Sea Surface Temperature[8] using Google Earth Engine (GEE). Annual means of all raster cells of SST for each year for each of the four regions (Fig. 1) were calculated and added to the strandings dataset. Annual mean SST was used ahead of monthly mean SST in order to comply with the resolution of the analysis and avoid the impact of potential seasonality of strandings in the model. Although the North Atlantic Oscillation (NAO) and Atlantic Multidecadal Oscillation (AMO) have been reported as climatic variables that can influence stranding patterns around the UK, this is primarily linked to variation in pressure and other weather variables [66,67] causing variation in stranding frequencies. As such AMO and NAO were not used as climatic variables for this study.

2.2.3. Statistical analyses

GLMs are regularly used to assess changes in proportions of binary response data [68]. A GLM fitted with a binomial error distribution and logit link was used for the analyses, in order to assess the changes in proportion of warm water adapted species stranding due to explanatory variables in the model. In order to select the best model representing the system, first a global model was produced with a binary response variable (cold water adapted = 0, warm water adapted = 1) and 'annual mean SST', 'cycle' (6-year cycle period) and 'region' as explanatory variables as an interaction term.

All explanatory variables in this global model were assessed for multicollinearity by using Variance Inflation Factors (VIF) calculated with the 'check_collinearity' function in the *performance* package in R [69]. As could be expected, significant collinearity was found, with 'annual mean SST' and 'region' having a VIF of 9.00 and 9.65 respectively, greater than the critical threshold of 5.0 [70,71]. As identifying differences between regions was a key aim of this study, 'region' was kept as a variable in final model, with 'annual mean SST' removed. Collinearity tests were re-run, leaving no evidence of collinearity between the variables (see Supplementary Information Table S1).

To generate the model set from the global model, the 'dredge' function from the *MuMIn* package was used, which generates a model selection table of models with combinations of fixed effect terms in the global model [72]. A table of all the levels for the response and explanatory variables included in the global model can be found in Supplementary Information Table S2, with the formula for the global model, $y \sim x1 + x2 + x1 * x2$, where y = a binary response variable of strandings (cold water adapted = 0, warm water adapted = 1) and x1 and x2 represent categorical variables, 'cycle' and 'region' respectively. Models in the set were ranked by small sample size corrected Akaike Information Criterion (AICc) values [73–75]. As inference using AICc can be made more reliable by removing models which are more complex versions of others [73,76], the 'nested' function from the *MuMIn* package was used on the model selection table. To assess goodness of fit, pseudo R^2 was calculated for the model using the 'r2' function from the *sjmisc* package [77–79]. Post-hoc tests were undertaken between interactions found to have a significant effect on strandings data, using the 'emmeans' function in the *emmeans* package [80].

As it was not included in the final model, to examine how annual mean SST has changed over the study period, annual mean SST was included as a response variable in a linear mixed effects model, with 'year' as a numerical explanatory variable and 'region' as a random effect, using the 'lmer' function in the *lme4* package [81]. As linear mixed models do not provide estimates for each level of a random effect, to investigate the relationship between annual mean SST over time for each region, individual linear models per region were run, with annual mean SST as a response variable, 'year' as a numerical explanatory variable, using the 'lm' function in the *stats* package [55].

3. Results

3.1. Model and post-hoc results

The final dataset contained 3596 individual strandings: 261 (Atlantic white-sided dolphins); 2644 (short-beaked common dolphins); 302 (striped dolphins); 389 (white-beaked dolphins). A map of stranding locations, by cold water and warm water adapted species, from this dataset can be found in Supplementary Information Fig. S3. A single parsimonious model remained following these analyses, with an interaction term between 'cycle' and 'region', and this model was considered the best fit to the data. The results from the most parsimonious model fitted to the data are presented in Table 1. Positive estimates indicate an increased proportion of strandings of warm water adapted species and a decreased proportion of strandings in cold water adapted species over time compared to the baseline (1990–1995 for Cycle; OSPARII_N for Region; 1990–1995:OPSARII_N for Cycle:Region); negative estimates, the opposite. Model results and post hoc tests indicate variability in proportion of warm water adapted species strandings between regions and cycles (Supplementary Information Table S4) (Fig. 2). The pseudo R^2 value of the model was 0.42.

Post-hoc comparisons indicate that all regions were significantly different in proportions of strandings of warm water adapted species. OSPARII North had the lowest proportion of strandings of warm water species of the four regions (Supplementary Information Table S4) (Fig. 2). OSPARIII North was only slightly, though significantly higher (Supplementary Information Table S4), and the highest proportion of strandings of warm water adapted species found in the OSPARIII South (Fig. 2). Overall northern regions had significantly lower proportion of

[4] https://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm

[5] https://ec.europa.eu/environment/marine/eu-coast-and-marine-policy/marine-strategy-framework-directive/index_en.htm

[6] https://oap.ospar.org/en/ospar-assessments/intermediate-assessment-2017/climate-and-ocean-acidification/climate-and-marine-biodiversity/

[7] https://www.ospar.org/convention/the-north-east-atlantic

[8] https://developers.google.com/earth-engine/datasets/catalog/NOAA_CDR_OISST_V2_1

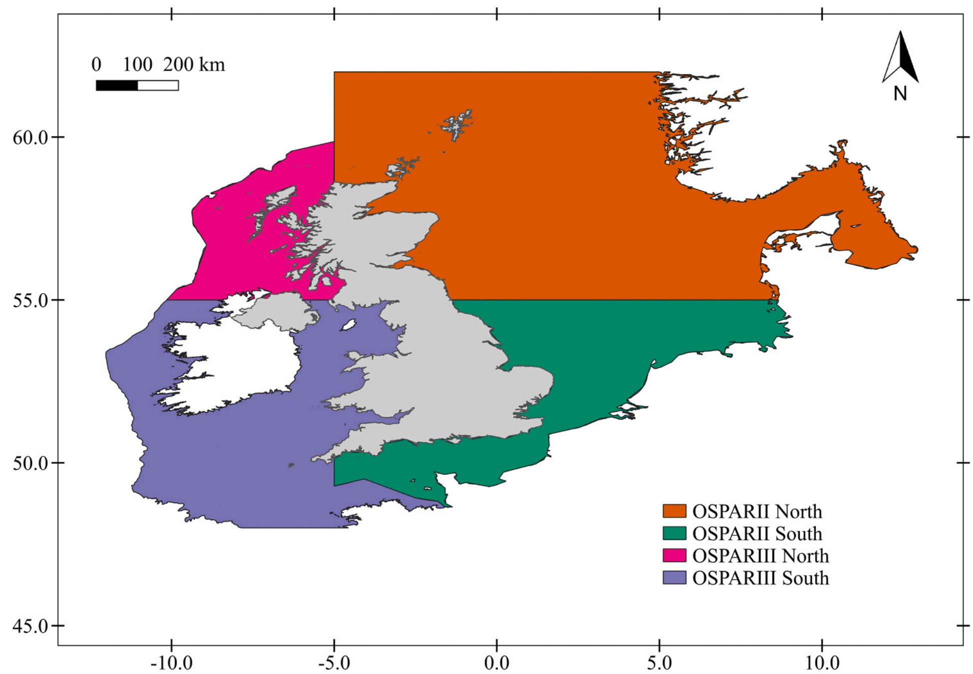

Fig. 1. Map of the UK with four regions partitioned for analysis. The horizontal line indicates the 55° latitude parallel used as a north/south divide. All other lines indicate borders between OSPARII, OSPARIII and other regions. Grey region indicates areas in which strandings are used as assessment for the study.

Table 1
Results from the single parsimonious model fitted to the data. Estimates with standard error, 97.5% confidence limits (CL) for the model estimates and associated p values. Significant results are highlighted in bold.

	Estimate	SE	z value	p value	CL
(Intercept)	-1.53	0.31	-5.00	**< 0.001**	-2.17, − 0.96
Cycle					
1996–2001	0.72	0.37	1.95	**0.05**	0.01, 1.48
2002–2007	0.54	0.38	1.41	0.16	-0.2, 1.31
2008–2013	0.77	0.37	2.10	**0.04**	0.07, 1.52
2014–2019	1.13	0.36	3.15	**< 0.001**	0.45, 1.87
Region					
OSPARII_S	2.34	0.35	6.66	**< 0.001**	1.68, 3.06
OSPARIII_N	1.63	0.44	3.70	**< 0.001**	0.78, 2.52
OSPARIII_S	4.88	0.55	8.91	**< 0.001**	3.89, 6.07
Cycle:Region					
1996–2001:OSPARII_S	0.88	0.50	1.76	0.08	-0.1, 1.87
2002–2007:OSPARII_S	2.31	0.52	4.46	**< 0.001**	1.3, 3.35
2008–2013:OSPARII_S	0.17	0.46	0.37	0.71	-0.74, 1.06
2014–2019:OSPARII_S	1.13	0.50	2.24	**0.03**	0.14, 2.13
1996–2001: OSPARIII_N	-0.56	0.53	-1.05	0.29	-1.62, 0.47
2002–2007: OSPARIII_N	-0.47	0.54	-0.86	0.39	-1.55, 0.6
2008–2013: OSPARIII_N	-0.91	0.53	-1.73	0.08	-1.96, 0.11
2014–2019: OSPARIII_N	0.48	0.52	0.91	0.36	-0.56, 1.5
1996–2001: OSPARIII_S	1.29	1.16	1.11	0.27	-0.7, 4.31
2002–2007: OSPARIII_S	-0.11	0.69	-0.15	0.88	-1.52, 1.23
2008–2013: OSPARIII_S	0.13	0.77	0.17	0.87	-1.4, 1.7
2014–2019: OSPARIII_S	1.56	1.16	1.35	0.18	-0.42, 4.58

strandings of warm water adapted species compared to southern, and OSPARII regions significantly lower proportion of strandings of warm water adapted species compared to OSPARIII (Supplementary Information: Table S4) (Fig. 2). In addition, these regional differences were consistently found within different cycles (Supplementary Information: Table S5). Results indicate that although warm water adapted species stranded across all four regions, strandings of cold water adapted species were primarily limited to northern regions. OSPARIII South, in particular, had very few strandings of cold water adapted species.

The proportion of strandings of warm water adapted species increased over time in the UK, with the 1990–1995 cycle having significantly lower proportion of strandings of warm water adapted species compared to the 2014–2019 cycle (estimate = −1.92, p value = <0.001 (Supplementary Information: Table S4). Regionally, this pattern was seen in three of the four regions, with the 1990–1995 cycle having significantly lower proportion of strandings of warm water adapted species compared to the 2014–2019 cycle in OSPARII North (estimate = −1.13, p value = 0.01), OSPARII South (estimate = −2.26, p value = <0.001) and OSPARIII North (estimate = −1.61, p value = <0.001) (Supplementary Information: Table S6). In addition, the two northern OSPAR region areas saw a greater amount of change over time in strandings of warm water adapted species compared to the southern OSPAR regions (Fig. 2).

3.2. SST results

Linear mixed modelling indicated that annual mean SST significantly increased over time in the UK (estimate = 0.021, p value = <0.001), and was comparable to the rate of change in species composition. Annual mean SST values, with trend lines and confidence intervals are presented in Fig. 3. Regionally, individual linear models indicate that annual mean SST significantly increased over time (Fig. 3) in OSPARII North (estimate = 0.03, p value = 0.001), OSPARIII South (estimate = 0.03, p value = 0.01) and OSPARIII North (estimate = 0.02, p value = <0.01). There was not a significant increase in annual mean SST in OSPARIII South. OSPARIII South had the warmest mean annual SST (13.25, SE = 0.34), followed by OSPARIII North (11.18, SD=0.33), OSPARIII South (10.80, SD=0.50), and OSPARII North (10.03, SD=0.40).

4. Discussion

Despite its acknowledged utility for policy makers, primarily in

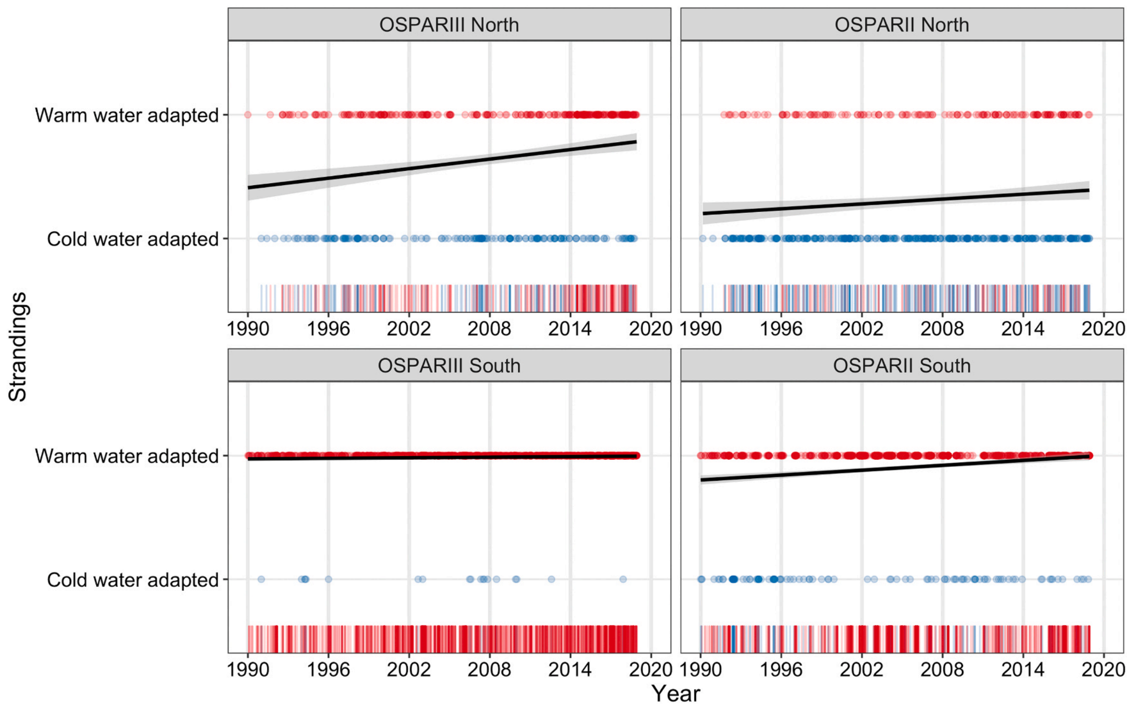

Fig. 2. The trend in frequency of strandings of warm water and cold water adapted species over time by region. Trend lines with 95% error are presented. Frequency ofstrandings of each group is indicated by rug lines on the x axis. Grey breaks indicate the 6-year cycle periods.

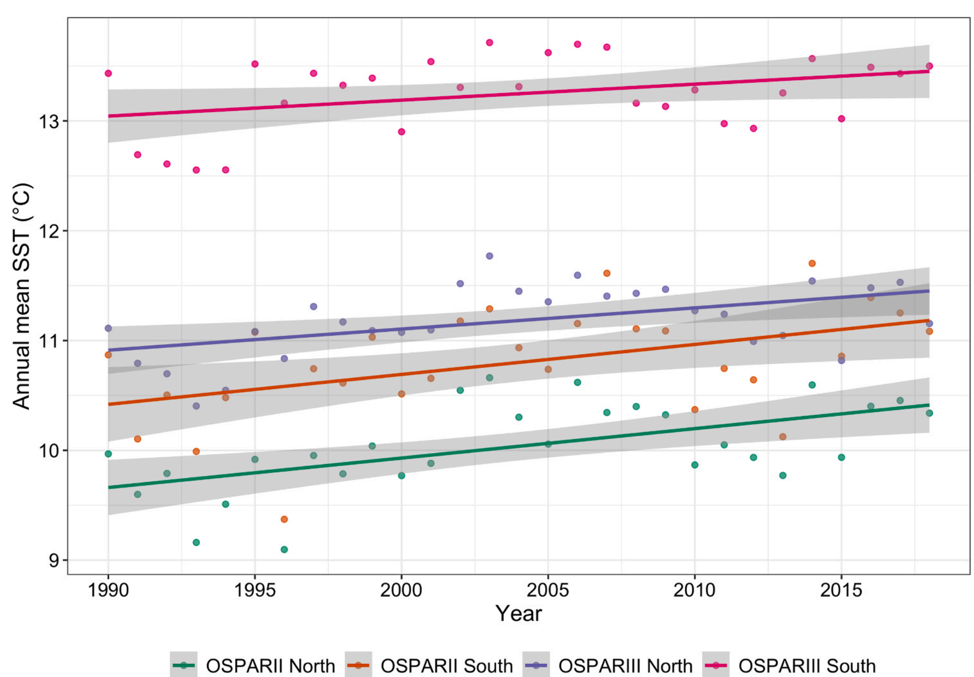

Fig. 3. Annual mean SST, 1990 – 2018, for four UK regions. Trend lines with 95% error are presented for each region.

determining cause of death and identifying risk from threats and pressures [82–84], the potential of cetacean strandings data for more novel applications for policy has rarely been explored. Here, strandings data were used to identify changing oceanic trends through changes in species composition in cetacean strandings at the appropriate spatial and temporal scales for policy reporting in the UK. Statistical modelling suggests that the proportion of warm water adapted species in the UK has increased over time. This increased trend differed between regions of the UK and was detectable within the identified time periods chosen to reflect common policy assessment and reporting cycles (6-year periods). The data also suggest habitats in the two northern OSPAR region areas are those seeing the greatest change in species composition, while southern areas, particularly OSPARIII South, are seeing little change. This is potentially due to southern regions previously being the edge of warm-water adapted species ranges from the south and with warming oceans, this edge range appears to have moved north resulting in the change in proportion of strandings of warm-water adapted species in northern regions, but little change in southern areas which were historically, already part of their range. Monitoring changes in free ranging populations can be used as an effective method for monitoring climate change [85–87]. This study shows that cetacean strandings data has the potential to be a useful surveillance tool for monitoring changing marine ecosystems for policy makers, government agencies and advisors such as for the 25 Year Environment Plan, Marine Strategy Framework Directive and OSPAR assessments.

Previous research has suggested a recent increase in abundance of warm water adapted and a decrease in abundance of cold water adapted species, potentially due to warming waters around the UK [20–22]. This was also evident in this study with an increase in proportion of strandings in warm water adapted species (short-beaked common and striped dolphins) from 1990 to 2019 in three out of four regions, potentially reflecting the changing distribution in populations of UK cetacean species over time [36,88]. This pattern was not seen in one region, OSPARIII South, but this is probably a result of this region having a consistently low proportion of strandings of cold water adapted species throughout the time period (Fig. 2) and being a region that is potentially out of the putative habitat range extents of cold water adapted species. Change was also greatest in the two northern OSPAR region areas, which may have further relevance for policy as it may impact conservation of other species and also may be a potential predictor of other economically relevant changes, e.g., fish stocks. That change was greatest in the northern regions compared to southern regions is perhaps unsurprising, considering southern regions had relatively few strandings of cold water adapted species across the time period, likely due to the southern OSPAR regions (particularly OPSARII South), being outside the putative habitat range for the cold water adapted species included in this study. This indicates that when investigating change in UK strandings across these four species, use of strandings records above the 55° latitude parallel would be most applicable, where there is clear overlap in occurrences of these four species and therefore opportunity to clearly identify changes in proportions of strandings across the four species over time.

Due to collinearity issues, which can result in incorrect identification of relevant predictors in a statistical model [89], annual mean SST was not included as a climatic variable in the final model. However, modelling of annual mean SST data for the regions indicated a significant increase in annual mean SST over time and a significant increase in annual mean SST in three out the of four UK regions. OSPARIII South had the highest annual mean SST and this aligned with the highest proportion of strandings of warm water adapted species. Likewise, OSPARII North had the lowest annual mean SST and the lowest proportion of strandings of warm water adapted species. As this increase in annual mean SST is comparable to the rate of change in species composition, increasing SSTs could potentially be a driver of the population changes seen in this investigation. Model estimates indicated that northern regions had greater change in SST compared to southern regions, which may further explain the differences between the regions in regard to changes in proportions of warm water adapted species.

Studies on the four species used in this study suggest that short-beaked common and white-beaked dolphins, and Atlantic white-sided and striped dolphins, have similar benthic and pelagic habitat preferences, respectively, with Atlantic white-sided and striped dolphins preferring deeper waters and steeper slopes, and short-beaked common and white-beaked dolphins preferring shallower shelf waters [34,90,91]. The northward expansion of warm water species may thereby induce competition for existing niches, with thermophilic species increasing at the expense of cold water adapted species [92,93]. It has been reported that short-beaked common dolphins may outcompete white-beaked dolphins where these species co-occur [34,90], suggesting that the results seen here could be driven by inter-specific competition. In addition, distributions of potential prey of these species have altered significantly over the past 30 years [24,94–96]. Shifting prey distributions due to climate change can have significant impacts on marine megafauna such as cetaceans [97]. Both Atlantic white-sided and white-beaked dolphins have been reported as specialist foragers [98–100]. As such, it may be more difficult for Atlantic white-sided and white-beaked dolphins to adapt to changes in prey distribution and composition. Hence short-beaked common and striped dolphins, who have more flexible diets [101,102], may outcompete Atlantic white-sided and white-beaked dolphins following prey shifts due to temperature changes. Detailed data on prey preferences and prey distributions of Atlantic white-sided and white-beaked dolphins in the study region over time would be required to assess this.

Different trends in proportions of strandings of warm water adapted species were detectable over the 6-year time periods and regions as used in this study. These time periods were selected as being relevant to those used for reporting and by policy makers in the UK and Europe, enabling outputs with potential to align with policy directives, such as the Habitats Directive [103,104] and Marine Strategy Framework Directive [105,106], and may be particularly relevant to OSPAR assessments which are undertaken in 6-year cycles and have a directive to monitor climate impacts on marine biodiversity. To be an effective metric in order to aid and inform policy makers, trends should be detectable at different spatial and temporal scales, as well as between different reporting periods [107]. Using the proportion of strandings of warm water adapted species, therefore, may be a useful tool for policy makers in providing outputs as it fulfils the criteria of detecting trends at appropriate scales.

Biological and ecological conclusions and population inferences derived from proportion data from populations should be treated with caution. Given the spatio-temporal scale of these analyses and the question of interest for this study, proportion was considered the most appropriate response variable for detecting patterns of interest. However, small changes in proportions can vastly alter model outcomes [58]. In addition, trends in cetacean strandings can result from multiple factors, including variation in reporting effort, physical metrics influencing carcase drift, changes in levels of anthropogenic pressures such as bycatch, as well as natural climatic variation [57,108,109]. These all influence the number of animals that end up stranded, reported, and recorded by stranding programmes [42], and as such, strandings can be a complex representation of cetacean populations. Fundamentally, although this study has shown that proportion data from opportunistic strandings events can detect ocean level changes in population dynamics in wild cetacean populations, less can confidently be said about the ecological mechanisms driving this result.

Seasonality is an important feature of many natural systems, and includes features such as temperature and photoperiod, as well as pressure, wind, and human activity [110,111], all of which can have significant patterns on stranding events in cetaceans [57,109]. However, integrating seasonality into analyses can be complex, requiring finer spatial and temporal resolution data [111], and as such was not undertaken as part of this of this investigation. A dedicated study, integrating seasonality into future analyses, with more fine scale resolution data, will be important to further investigate the ecological drivers of these findings.

There is a need to undertake more detailed and comprehensive assessments of stranded animals in order to assess metrics of health, life history and diet parameters [54]. Without these data, inferring any underlying causal process, and hence deriving effective mitigation, is almost impossible. As such, additional metrics derived from strandings research could assist to further assess the drivers of changes in cetacean distributions around the UK. For example, stable isotope analysis of elements, such as nitrogen (δ15N) and carbon (δ13C), and fatty acid analysis, can provide information from cetacean strandings on ecological interactions between cetacean species and their prey and help unravel complex ecological questions [112,113]. Although stomach contents analysis has been used to investigate ecological questions in cetaceans in the past, it is not always a viable option on stranded animals, due to differences in digestion rates of prey species, and carcass deterioration [114–116]. Both stable isotope and fatty acid analysis have been previously used to investigate trophic interactions [113], diet

[117,118], and resource partitioning [119,120] in cetacean species. Should there be dietary specialisation within species, dietary overlap, or resource partitioning, between co-occurring species, this should be reflected in stable isotope signatures taken from body tissues during necropsy examinations. As such, complimentary analyses, such as fatty acid and stable isotope analysis, could be utilised as a next step to further investigate the hypotheses developed from this result to shed light on the level of competition that may exist between these species.

5. Conclusions

Monitoring changes in marine environments is vital to assess the impacts of climate change. Cetacean strandings data has been proposed for development as a tool for monitoring climate change, due to the long temporal, standardised data sets that are available. To our knowledge, this is the first investigation into the use of UK cetacean strandings data as a tool to aid policy makers with the development of climate change monitoring. A proportional increase in strandings of warm water species was detected over time, primarily in northern regions, reflecting changes in abundance and distribution of warm water and cold water adapted species. These trends were detectable between different policy relevant regions and temporal periods. In addition, a significant increase in annual mean SST was found over the same period, indicating that increasing sea surface temperatures in UK waters due to climate change may be correlated with changes in species composition of cetacean populations around the UK. However, the definitive drivers of these changes have yet to be determined, and more detailed investigations, at a finer spatial and temporal scale, integrating seasonality, can potentially shed further light on these findings. Furthermore, the use of analyses such as stable isotope analysis could provide useful insight into overlapping feeding strategies and shed light on potential competition as a driver for the shift in distribution. Monitoring programmes are needed to investigate the impact climate change can have on marine environments and novel use of these data will maximise the value of these programmes. These findings show that collected strandings data can identify changes in cetacean populations and can be a useful tool for advisory bodies and policy makers to monitor climate change around the UK.

CRediT authorship contribution statement

Michael J. Williamson: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Mariel T.I. Ten Doeschate:** Investigation, Data curation, Methodology, Supervision, Validation, Writing - review & editing. **Andrew C. Brownlow:** Investigation, Data curation, Writing - review & editing**. Rob Deaville:** Investigation, Data curation, Writing - review & editing. **Nicola L. Taylor:** Conceptualization, Project administration, Methodology, Supervision, Validation, Writing - review & editing.

Declaration of Competing Interest

All authors declare that they have no competing interests.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2021.104634.

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