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A novel expert-driven methodology to develop thermal suitability curves for cetaceans under a changing climate

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Abstract:	Over the last decades, global warming has contributed to changes in marine species composition, abundance and distribution, in response to changes in oceanographic conditions such as temperature, acidification, and deoxygenation. Experimentally derived thermal limits, which are known to be related to observed latitudinal ranges, have been used to assess variations in species distribution patterns. However, such experiments cannot be undertaken with large marine predators like cetaceans. An alternative approach is to elicit expert's knowledge to derive species' thermal suitability and assess their thermal responses, something that has never been tested before in these taxa. We developed and applied a methodology based on expert-derived thermal suitability curves and projected future responses for each species under different climate scenarios. We tested this approach with ten cetacean species currently present in the biogeographic area of Macaronesia (North Atlantic) under Representative Concentration Pathways 2.6, 4.5 and 8.5, until 2050. Overall, increases in annual thermal suitability were found for Balaenoptera edeni , Globicephala macrorhynchus , Mesoplodon densirostris, Physeter macrocephalus, Stenella frontalis, Tursiops truncatus and Ziphius cavirostris . Conversely, our results indicated a decline in thermal suitability for B. physalus , Delphinus delphis, and Grampus griseus . Our study reveals potential responses in species thermal suitability, for cetaceans and potentially other highly mobile and large predators, and contributes to test this method's applicability as a cost-efficient tool to support conservation managers and practitioners.
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13th May 2022

Dear Associate Editor Martin Drews,

Please find enclosed our manuscript entitled “A novel expert-driven methodology to develop thermal suitability curves for cetaceans under a changing climate” which we consider suitable for publication as an original research paper to the Science of the Total Environment.

We present a simple and novel method that addresses the impacts of climate change in cetacean species using a novel expert driven methodology to support species management. In a context of high uncertainty and lack of readily available data to access the impacts of climate change in large marine predator species such as cetaceans, new approaches are necessary to support managers and practitioners in the definition of conservation measures.

In addition, obtaining enough data to quantify the full thermal range of species is difficult and, in many cases, experimentally derived thermal limits are used. These experiments cannot be undertaken with large marine predators. Therefore, our study presents an alternative approach which allows the integration of expert knowledge to determine species thermal range and quantify potential future range shifts in their distribution.

We believe our paper is in line with the journal’s aims and scope since it provides a novel method that can be applied globally to assess the impacts of climate change in large marine predators.

Thank you for considering our manuscript for publication in the Science of the Total Environment.

Yours sincerely,

Andreia Sousa

Title: A novel expert-driven methodology to develop thermal suitability curves for cetaceans under a changing climate

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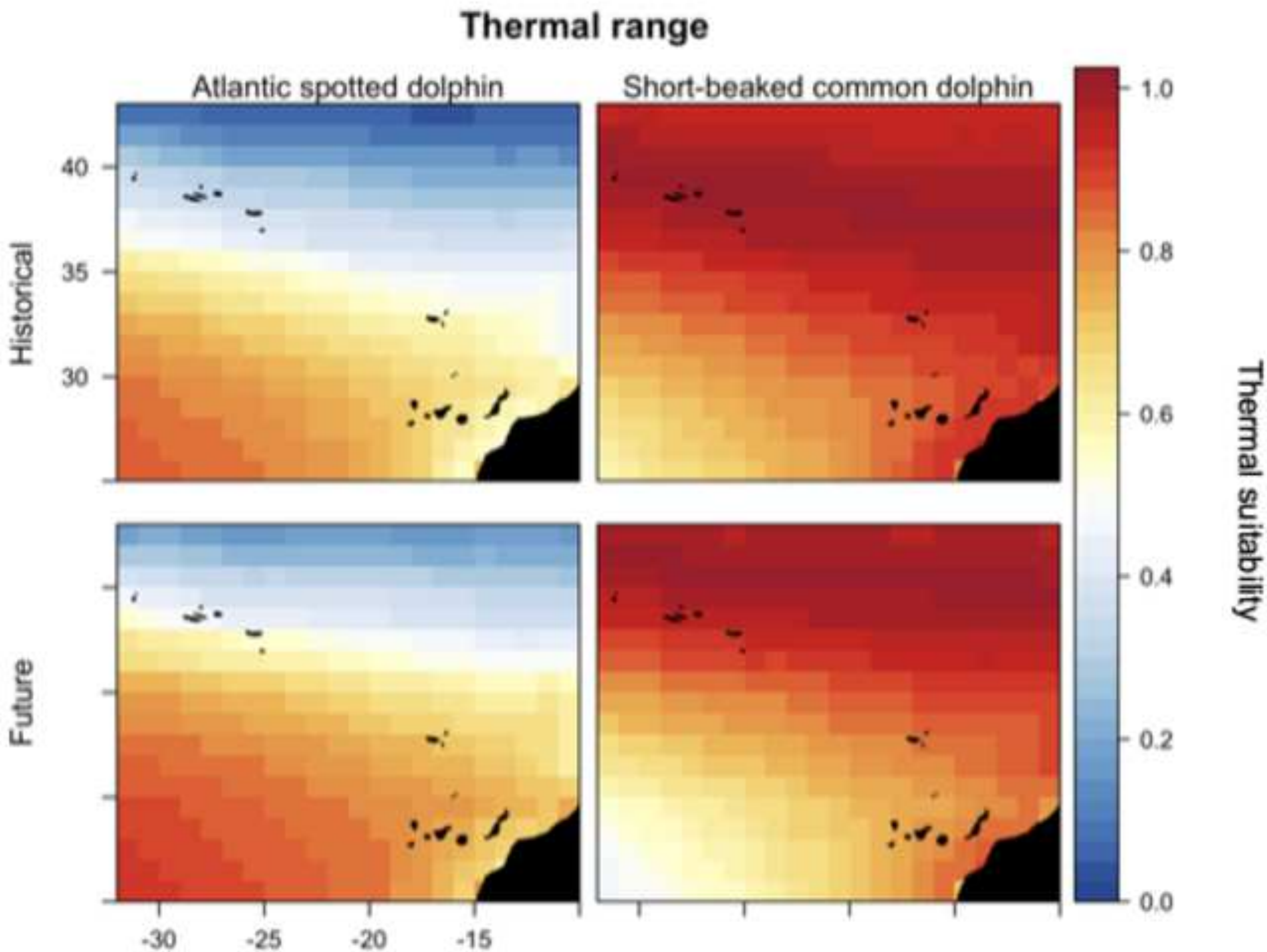
Graphical Abstract



Highlights:

- **Experimentally derived thermal limits can't be performed with large marine species**
- **Expert knowledge was used to derive species' thermal suitability**
- **Species thermal suitability responses were projected under RCP 2.6, 4.5, 8.5**
- **3 species will decrease while 7 will increase future thermal suitability**
- **The method can be applied as a cost-efficient tool to support decision making**

A novel expert-driven methodology to develop thermal suitability curves for cetaceans under a changing climate

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Keywords: Climate change; Cetaceans; Macaronesia; Thermal suitability; expert elicitation; conservation management

Abstract

Over the last decades, global warming has contributed to changes in marine species composition, abundance and distribution, in response to changes in oceanographic conditions such as temperature, acidification, and deoxygenation. Experimentally derived thermal limits, which are known to be related to observed latitudinal ranges, have been used to assess variations in species distribution patterns. However, such experiments cannot be undertaken with large marine predators like cetaceans. An alternative approach is to elicit expert's knowledge to derive species' thermal suitability and assess their thermal responses, something that has never been tested before in these taxa. We developed and applied a methodology based on expert-derived thermal suitability curves and projected future responses for each species under different climate scenarios. We tested this approach with ten cetacean species currently present in the biogeographic area of Macaronesia (North Atlantic) under Representative Concentration Pathways 2.6, 4.5 and 8.5, until 2050. Overall, increases in annual thermal suitability were found for *Balaenoptera edeni*, *Globicephala macrorhynchus*, *Mesoplodon densirostris, Physeter macrocephalus, Stenella frontalis, Tursiops truncatus* and *Ziphius cavirostris*. Conversely, our results indicated a decline in thermal suitability for *B. physalus*, *Delphinus delphis,* and *Grampus griseus*. Our study reveals potential responses in species thermal suitability, for cetaceans and potentially other highly mobile and large predators, and contributes to test this method's applicability as a cost-efficient tool to support conservation managers and practitioners.

Introduction

Human-induced climate change is projected to strongly affect marine ecosystems mainly through increases in ocean temperature, acidification, and deoxygenation (Garcia-Soto et al., 2021; IPCC, 2019; Silvy et al., 2020). These changes are known to affect marine species demography, abundance, distribution, and phenology patterns (Poloczanska et al., 2016).

Species distribution ranges and their boundaries are determined by thermal physiology and by the spatiotemporal distribution of climatic variables combined with other demographic, ecological, evolutionary, habitat-related and anthropogenic factors (Azzellino et al., 2008; Fullard et al., 2000; Khaliq et al., 2014; Lambert et al., 2014; Learmonth et al., 2006). Many species have shown a poleward shift to higher latitudes as a result of tracking the temperatures that define their thermal preference (Becker et al., 2018; Lambert et al., 2011; van Weelden et al., 2021).

For marine vertebrates like cetaceans (i.e., whales, dolphins, and porpoises), the impacts of changes in oceanographic patterns can be

direct or indirect. The former can include species tracking a specific range of water temperatures to avoid physiological stress; while the latter can include changes in prey availability resulting in changes in abundance, distribution, migration patterns, community structure and susceptibility to disease and contaminants (Learmonth et al., 2006; Nunny and Simmonds, 2019; van Weelden et al., 2021).
One of the most documented drivers for observed and projected changes in cetaceans' distribution is the rise in seawater temperature due to global warming (Becker et al., 2018; Chambault et al., 2018; Kaschner et al., 2011; Learmonth et al., 2006; Salvadeo et al., 2010). However, the rate and magnitude of future environmental changes and species responses to those changes are still uncertain (Silber et al., 2017). In this context, understanding how climate change will impact cetaceans is challenging, particularly for conservation organizations mandated to identify and prioritize management actions (Nunny and Simmonds, 2019; Silber et al., 2017).

Different approaches have been used to provide guidance for conservation managers and practitioners and can be classified as trend-based (correlative and mechanistic models) or trait-based (Foden et al., 2019; Pacifici et al., 2015). Trait-based vulnerability assessment approaches relate to the association between species biological traits and projections of relevant climate variables, typically involving scoring by expert-judgement or observations, and resulting in scores, categories or indices for species at risk. Albouy et al. (2020) used an index based on sensitivity and exposure to assess the global vulnerability of marine mammals to climate change. At a regional scale, index-based vulnerability assessments were carried out for marine mammal stocks in the Western North Atlantic, Gulf of Mexico, Caribbean, Pacific and Arctic regions (Lettrich et al., 2019); and for cetaceans in the Madeira Archipelago (Sousa et al., 2019) and the wider Macaronesian area (Sousa et al., 2021). In contrast, trend-based approaches such as correlative models can be used to identify future climate suitable areas for species under different climate scenarios. Lambert et al. (2014) used a combination of habitat and thermal niche models to predict the distribution range of cetacean species in the eastern North Atlantic.

Recently, the use of thermal vulnerability indices has increased (Clusella-Trullas et al., 2021; Khaliq et al., 2014) and experimentally driven thermal tolerance limits present a good correspondence with the environmental temperatures at which individuals are observed to occur (Webb et al., 2020). We define thermal suitability as the thermal niche of a species, i.e., the temperature range at which species occur, where other factors remain equal, such as predation, competition, or habitat heterogeneity. Thermal suitability relates temperature to a species' suitability range and can then be used to parameterise species' thermal response curves.

Experimentally driven thermal performance studies have been undertaken for invertebrates and fish species (e.g., Rendoll-Cárcamo et al., 2020; Underwood et al., 2012) but cannot be performed with cetaceans for ethical reasons (Frohoff and Bekoff, 2018). Thermal suitability has been estimated for some marine mammal populations by correlating sightings with water temperatures (e.g., Chavez-Rosales et al., 2019). However, in regions with sparse sighting data, a novel approach is needed. One such novel approach is to use expert elicitation (Mukherjee et al., 2015) to define the thermal suitability of these species.

In the present study, we evaluated the thermal response of cetaceans using a novel expert elicitation methodology. To that end, we used ten cetacean species from three archipelagos of Macaronesia (Azores, Canary Islands and Madeira) as a model system. Our goals were to: (1) define thermal suitability curves for the selected species; and (2) assess species thermal responses under three different climate change scenarios, namely Representative Concentration Pathways (RCPs) 2.6, 4.5, and 8.5.

Methods

Study area and selected species

The biogeographic region of Macaronesia is located in the Eastern North Atlantic. We included in our study the archipelagos of Azores, Madeira and the Canary Islands (Figure 1). These archipelagos are considered one province within the Lusitanian ecoregion due to the relatively homogenous species composition, oceanographic characteristics, and specific ecosystems (Spalding et al., 2007). We do not include in our study the archipelago of Cape Verde as it has recently been shown to have a significantly different marine biota community structure and biogeographic relationships compared to the remaining archipelagos (Freitas, 2014; Freitas et al., 2019; Spalding et al., 2007).

The Azores archipelago is located ~1300 km off the European mainland, and it comprises nine islands spread over about 600 km. The Madeira archipelago lies ~800 km off the European continent and 600 km off the West African coast and comprises two main islands (Madeira and Porto Santo). The Canary archipelago, located ~100 km off the West African mainland, is composed of eight populated islands.

The physical oceanographic features of this region include the Gulf Stream and associated bifurcations, the Azores Current (a southern branch of the Gulf Stream), the Portuguese and the Canary Currents, and regional dynamics (Barton, 2001; Caldeira and Reis, 2017). Islands obstruct the propagation of these currents and generate lee eddies, island wakes and upwelling features (Barbosa Aguiar et al., 2011; Caldeira and Reis, 2017; Sangrà et al., 2009; Zhou et al., 2000), which enhance ocean productivity around the archipelagos. This in turn drives the aggregation of higher trophic levels, including top marine predators such as cetaceans (Alves et al., 2018; Carrillo et al., 2010; Cartagena-Matos et al., 2021; González García et al., 2018; Herrera et al., 2021; McIvor et al., 2022; Silva et al., 2014; Tobeña et al., 2016).

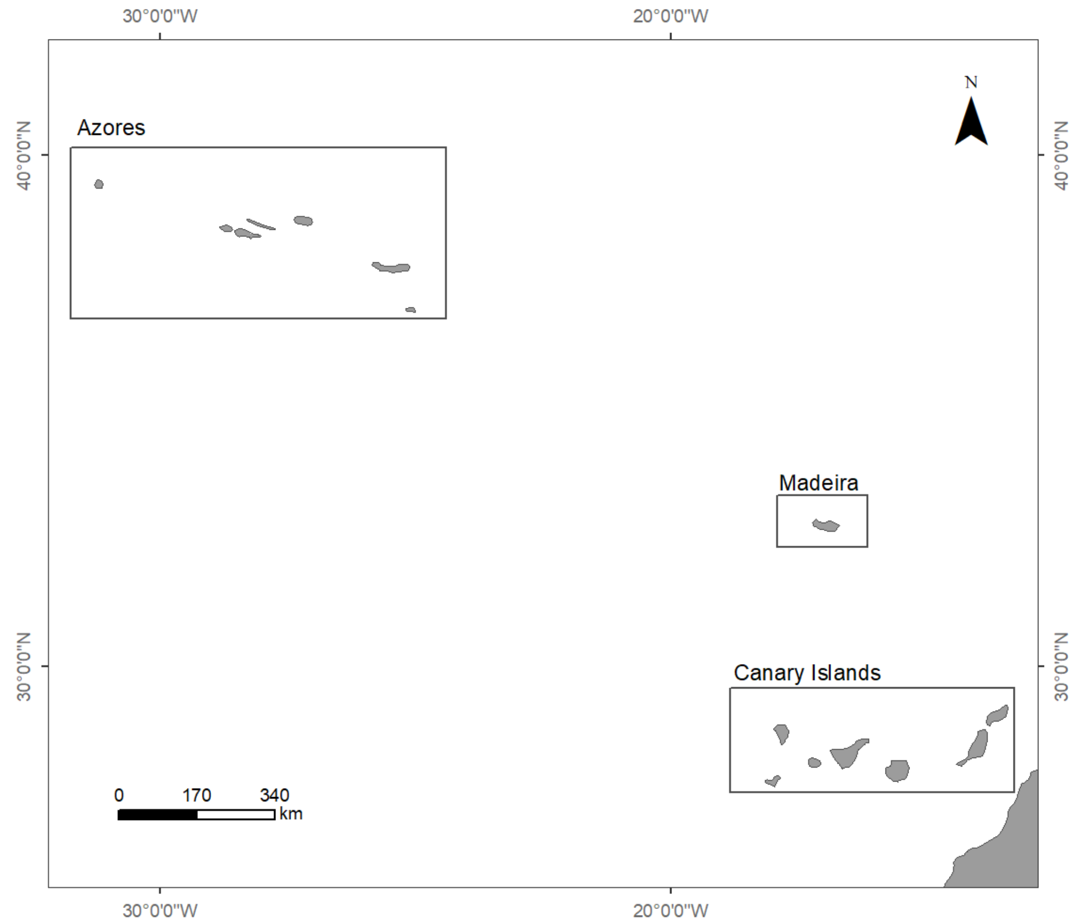

Figure 1 – The biogeographic region of Macaronesia with the Azores, Canary Islands and Madeira archipelagos.

Over 20 species of cetaceans are referenced for Macaronesia, including some resident species that are present year-round and others that are known seasonal visitors (Alves et al., 2018; Cartagena-Matos et al., 2021; Herrera et al., 2021; Silva et al., 2014). A list of cetacean species relevant for the region was selected through literature review and expert judgment, as described in Sousa et al. (2021). The ten selected cetacean species are listed in Table 1 (hereafter all species will be referred to by their common names).

Table 1 – Cetacean species selected for the development of thermal suitability curves, ordered alphabetically by the common name.

Scientific name	Common name
Stenella frontalis	Atlantic spotted dolphin
Mesoplodon densirostris	Blainville's beaked whale
Balaenoptera edeni	Bryde’s whale
Tursiops truncatus	common bottlenose dolphin
Ziphius cavirostris	Cuvier’s beaked whale
Balaenoptera physalus	fin whale
Grampus griseus	Risso’s dolphin
Globicephala macrorhynchus	short-finned pilot whale
Delphinus delphis	short-beaked common dolphin
Physeter macrocephalus	sperm whale

Development of thermal suitability curves

We developed thermal suitability curves for ten cetacean species (Table 1) in Macaronesia using an expert elicitation approach. We used an approach based on Delphi technique principles that minimizes biases frequently encountered with expert judgement, such as groupthink (seeking consensus to avoid conflict) or the halo effect (considering unrelated attributes in scoring; Kuhnert et al., 2010; Linstone & Turoff, 1975; Mukherjee et al., 2015, 2016). While completely eliminating biases from an expert elicitation process is unlikely, we have sought to minimize and qualify the biases where present (Morgan et al., 2014; Mukherjee et al., 2018).

Firstly, we defined a temperature range between 14 to 26 ºC, for all cetacean species considering the known temperature range occurring in Macaronesian waters (Martins et al., 2007). Experts were then asked to individually assign a suitability value to each temperature for each species, ranging from 0 (not suitable) to 1 (highly representative of the species preferred temperature range).

To assess which was the most accurate scale for the construction of thermal suitability curves, experts scored six different combinations of temperature and suitability scales (labelled method 1 to 6) (Table 2). A Kruskal–Wallis test with Bonferroni *post-hoc* correction and Tukey's pairwise comparison was applied to test for significant differences in the temperature/suitability scales, as implemented in the R *agricolae* package (Mendiburu, 2020). Given that no significant differences (p-value>0.05) were found between the methods 3, 5 and 6 (Figure 2) we selected the latter one to construct the thermal suitability curves due to its finer resolution scale.

Data quality scores were attributed by experts for each species and represent the extent of evidence available to support the construction of thermal suitability curves. Data quality ranged from 0 (no data), 1 (expert judgment only), 2 (limited data), and 3 (adequate data), as in Lettrich et al. (2019).

Table 2 – Six methods combining different thermal suitability and temperature scale.

Thermal suitability scales	TS1	0	0.5	1									
	TS2	0	0.25	0.5	0.75	1							
	TS3	0	0.17	0.33	0.5	0.67	0.83	1					
Temperature scale (ºC)	T1	14-16	16-18	16-18	16-18	16-18	16-18	16-18					
	T2	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	24-25	25-26

Method 1 = TS1xT1; Method 2 = TS1xT2; Method 3 = TS2xT1; Method 4 = TS2xT2; Method 5 = TS3xT1; Method 6 = TS3xT2

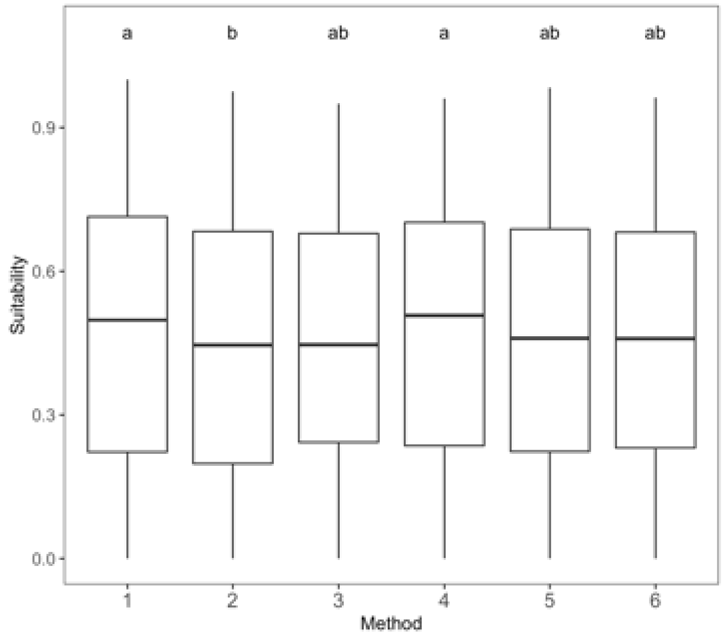

Figure 2 - Mean suitability scores attributed by experts using the six different methods (Table 2). Box represents the upper and lower quartiles, horizontal line inside each box indicates the median, whiskers reach maximum and minimum values. Common letters (a, b, ab) indicate means that are not significantly different (Tukey's pairwise comparison at significance level α=0.05).

Species thermal responses

The suitability/temperature relations provided by experts were used to build a local polynomial regression fitting (LOESS) with a smoothing parameter of 0.5, using the R function "loess".

Historical (1956-2005) and projected (2006-2055) sea surface temperature data from the Climate Model Intercomparison Project 5 (CMIP5) (in ºC, average of all models, with a spatial resolution of 1°x 1°) was obtained from the Earth Systems Research Laboratory (ESRL) web portal (ESRL, 2014). In ESRL, the seasonal output is available in three-month periods as follows: October, November, December (OND); January, February, March (JFM); April, May, June (AMJ); July, August, September (JAS). Scenarios considering RCPs 2.6, 4.5 and 8.5, until 2050, were used in this study. RCPs are scenarios that represent different greenhouse gas concentration trajectories and consider a range of radiative forcing which correspond to the production of 2.6, 4.5, 6, and 8.5 W/m^2 in the year 2100 and serve as a basis for climate projections (IPCC, 2014). The short to mid-century timeframe (2006–2055) was chosen due to the effect of increasing uncertainties with extended timeframes, and the need to produce information to support conservation decisions and responses in the short-term.

The LOESS models for the thermal suitability were projected on the study area to obtain spatially explicit thermal response maps for each species under different RCPs. Annual and seasonal historical and future temperatures (minimum, mean and maximum) were applied to the LOESS regressions to compute species thermal response curves. The difference between future and historical thermal suitability was then calculated and plotted on thermal suitability maps for the selected cetacean species in Macaronesia under different RCPs (see S.M. 1 and S.M.2).

Results

Thermal suitability curves

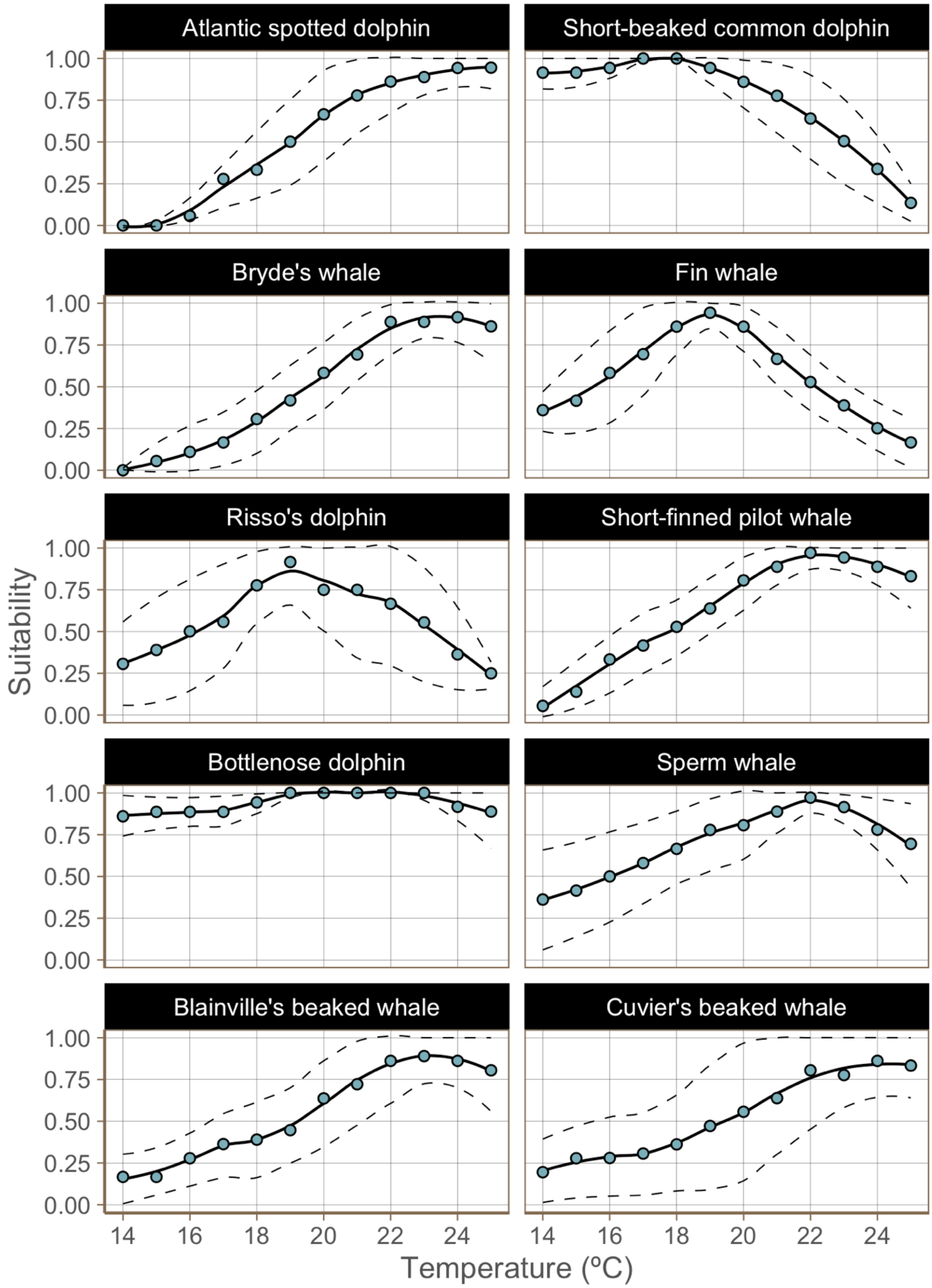

Figure 3 - Species thermal suitability curves for: Atlantic spotted dolphin (*Stenella frontalis*) Data Quality (DQ)= 3; short-beaked common dolphin

(*Delphinus delphis*) DQ= 3; Bryde's whale (*Balaenoptera edeni*) DQ = 3; fin whale (*Balaenoptera physalus*) DQ= 2; Risso's dolphin (*Grampus griseus*) DQ= 2; short-finned pilot whale (*Globicephala macrorhynchus*) DQ= 3; common bottlenose dolphin (*Tursiops truncatus*) DQ= 3; sperm whale (*Physeter macrocephalus*) DQ= 3; Blainville's beaked whale (*Mesoplodon densirostris*) DQ= 2; Cuvier's beaked whale (*Ziphius cavirostris*) DQ= 2. Mean values are represented by the dots in the solid line and confidence intervals (standard deviation) are represented in the dashed line. Data quality values range from zero to three where 0 = No data; 1 = Expert judgment only; 2 = Limited data; 3 = Adequate data (from Lettrich et al., 2019).

Suitability increases with temperature for the Bryde's whale, short-finned pilot whale, Blainville's beaked whale, and sperm whale, reaching the most suitable temperature at approximately 22ºC (Figure 3). From 22 to 24ºC there is a slight decrease in suitability, more pronounced for the sperm whale. According to the experts, this species showed higher suitability in colder temperatures with a larger standard deviation, when compared to other species in this group.

The fin whale and Risso's dolphin follow a Gaussian thermal suitability curve with the most suitable temperature at approximately 19ºC (Figure

3). The fin whale thermal suitability gradually declines from 20 to 26ºC. The thermal suitability curve of the Risso's dolphin showed the lowest agreement among experts translated by the greater standard deviation, especially in the warmer half of the distribution, from 20 to 26ºC.

The short-beaked common dolphin most suitable temperatures ranged from 14 to 18ºC, with the highest thermal suitability between 17 to 18ºC followed by a steep decrease (Figure 3). By contrast, the Atlantic spotted dolphin increased its thermal suitability towards warmer waters with the highest thermal suitability from 24 to 26ºC (Figure 3). The Cuvier's beaked whale showed a regular increase in thermal suitability in warmer waters, with a high standard deviation and low expert agreement, together with a lower data quality reflecting a higher degree of uncertainty (Figure 3). Finally, the common bottlenose dolphin showed a very high thermal suitability across the whole temperature range with the highest value between 19 to 22ºC (Figure 3).

Confidence in species thermal suitability curves, reflected in standard deviation and data quality scores, is lower for both species of beaked whales, the fin whale and the Risso's dolphin, highlighting the limited data available for experts to define the curves.

Species thermal responses

Overall, annual thermal suitability increases were found for the Bryde’s whale, short-finned pilot whale, Blainville's beaked whale, sperm whale, Atlantic spotted dolphin, common bottlenose dolphin and Cuvier’s beaked whale (Table 3). On the contrary, declines were found for the fin whale, short-beaked common dolphin, and Risso’s dolphin. One of the highest increases in thermal suitability was found for the Atlantic spotted dolphin and the lowest for the short-beaked common dolphin (Table 3 and Figure 4).

Table 3 – Changes in mean annual thermal suitability for cetacean species in Macaronesia (MAC), and in the respective archipelagos of Azores (Az), Canary Islands (Can), and Madeira (Mad) for RCPs 2.6, 4.5 and 8.5 until 2050. Values indicate the difference between historical and future thermal suitability in a scale from 0 (not suitable) to 1 (highly representative of the species preferred temperature range). The colour scale gradient indicates an increase (green) or decrease (red) in thermal suitability.

Species/region	Annual thermal suitability changes		
	RCP		
	2.6	4.5	8.5
Bryde's whale			
MAC	0.116	0.114	0.132
Az	0.105	0.114	0.130
Can	0.121	0.114	0.135
Mad	0.123	0.113	0.131
Fin whale			
MAC	-0.041	-0.053	-0.061
Az	0.082	0.060	0.070
Can	-0.126	-0.118	-0.140
Mad	-0.078	-0.100	-0.113
Short-beaked common dolphin			
MAC	-0.058	-0.060	-0.069
Az	-0.029	-0.043	-0.048
Can	-0.074	-0.069	-0.082
Mad	-0.071	-0.068	-0.078
Risso's dolphin			

MAC	-0.004	-0.016	-0.018
Az	0.105	0.076	0.090
Can	-0.059	-0.060	-0.069
Mad	-0.058	-0.065	-0.074
Short-finned pilot whale			
MAC	0.103	0.102	0.118
Az	0.095	0.107	0.122
Can	0.091	0.090	0.104
Mad	0.122	0.110	0.127
Blainville's beaked whale			
MAC	0.088	0.090	0.103
Az	0.072	0.087	0.098
Can	0.076	0.077	0.089
Mad	0.116	0.106	0.123
Sperm whale			
MAC	0.061	0.057	0.066
Az	0.073	0.072	0.083
Can	0.056	0.050	0.060
Mad	0.054	0.048	0.056
Atlantic spotted dolphin			

MAC	0.116	0.113	0.130
Az	0.105	0.114	0.130
Can	0.098	0.097	0.113
Mad	0.144	0.127	0.147
Common bottlenose dolphin			
MAC	0.016	0.014	0.016
Az	0.041	0.039	0.045
Can	-0.002	-0.002	-0.002
Mad	0.010	0.004	0.005
Cuvier’s beaked whale			
MAC	0.078	0.075	0.087
Az	0.069	0.078	0.088
Can	0.085	0.077	0.092
Mad	0.079	0.070	0.082

The Bryde’s whale, the short-finned pilot whale and the Atlantic spotted dolphin showed the highest increase in thermal suitability under all climate scenarios, especially under RCP 8.5 (Table 3). The first species presents a similar increase in thermal suitability in warm waters in all archipelagos, reflected by the suitability curve (Figure 3). The increase in thermal suitability for the short-finned pilot whale was lower in the Canary Islands since, according to the experts, the species’ thermal suitability decreases slightly from 23 to 26ºC. The Atlantic spotted dolphin showed a higher increase in thermal suitability in Madeira and Azores than in the Canary Islands due to the increase in projected temperatures in future scenarios that appear to be more suitable for this species.

The Blainville's beaked whale, sperm whale, Cuvier’s beaked whale and common bottlenose dolphin are the species exhibiting the lowest increases in thermal suitability under all climate scenarios. For the former species, our results suggest a lower increase in thermal suitability in the Canary Islands. The Cuvier’s beaked whale and sperm whale displayed a minor increase in thermal suitability in all archipelagos.

The common bottlenose dolphin showed high thermal suitability across the whole temperature range (Figure 3) with minor increases in thermal suitability in the future for all archipelagos.

The short-beaked common dolphin showed a decrease in thermal suitability related to their lower suitability values towards higher temperatures. The fin whale and the Risso’s dolphin also decreased their thermal suitability in all archipelagos, except in the Azores where thermal suitability slightly increased in both species.

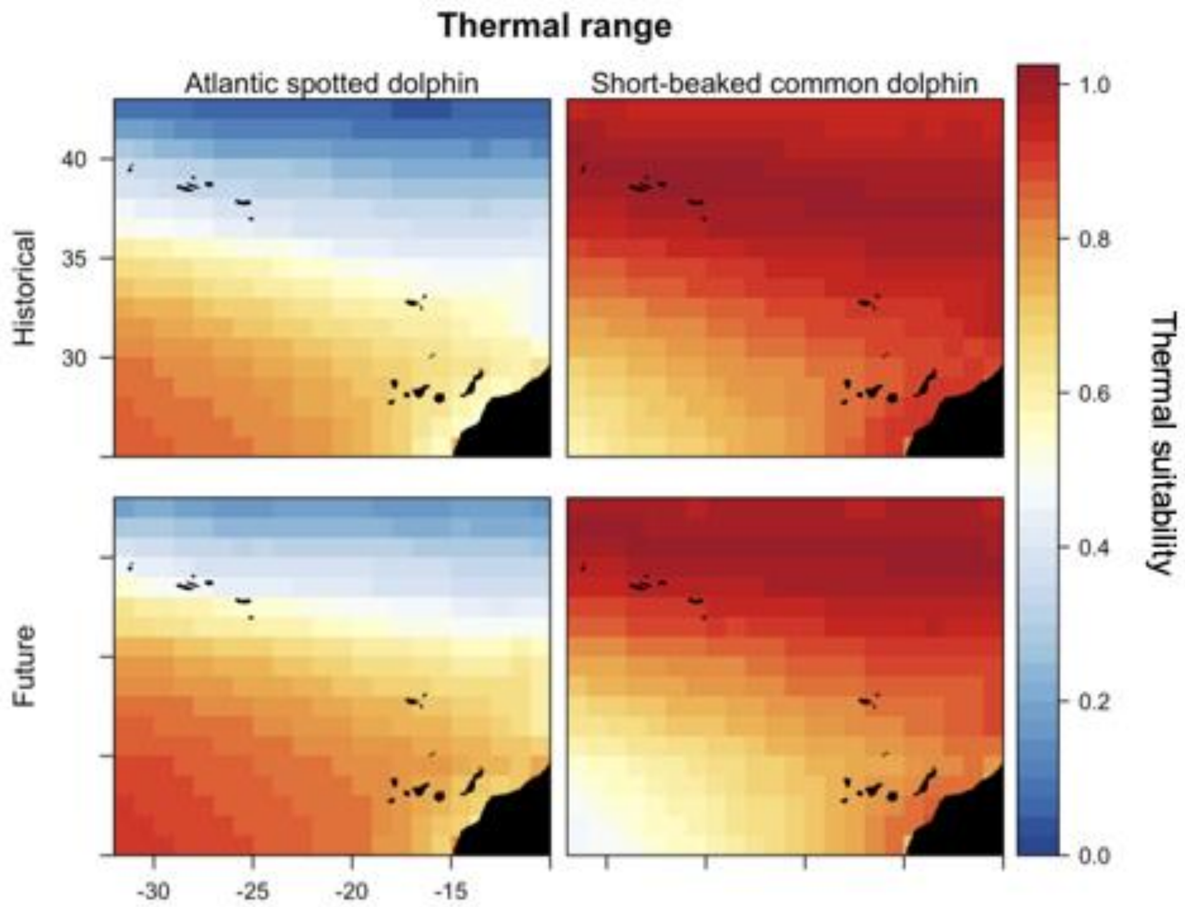

Figure 4 – Example of historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for RCP 8.5 for short-beaked common dolphin and Atlantic spotted dolphin. Numbers in

the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Thermal suitability maps for the remaining species can be found in the supplementary materials (S.M.1 and S.M.2).

Table 4 – Changes in mean seasonal thermal suitability in Autumn (OND), Winter (JFM), Spring (AMJ), and Summer (JAS) for cetacean species in Macaronesia (MAC) and respective archipelagos, Azores (Az), Canary Islands (Can) and Madeira (Mad) for RCP 2.6, 4.5 and 8.5 until 2050. The colour scale gradient indicates an increase (green) or decrease (red) in thermal suitability. Values indicate the difference between historical and future thermal suitability in a scale from 0 (not suitable) to 1 (highly representative of the species preferred temperature range).

Species/region	**Seasonal thermal suitability changes**					
	RCP 2.6		RCP 4.5		RCP 8.5	
	Autumn/Winter	Spring/Summer	Autumn/Winter	Spring/Summer	Autumn/Winter	Spring/Summer

	OND	JFM	AMJ	JAS	OND	JFM	AMJ	JAS	OND	JFM	AMJ	JAS
Bryde's whale												
MAC	**0.118**	**0.090**	**0.101**	**0.095**	**0.118**	**0.085**	**0.101**	**0.078**	**0.127**	**0.099**	**0.117**	**0.079**
Az	0.110	0.059	0.074	0.110	0.116	0.054	0.087	0.086	0.124	0.061	0.098	0.085
Can	0.106	0.108	0.104	0.078	0.106	0.102	0.099	0.070	0.117	0.121	0.117	0.073
Mad	0.139	0.103	0.124	0.096	0.132	0.098	0.117	0.078	0.141	0.114	0.135	0.078
Fin whale												
MAC	**-0.097**	**0.089**	**0.028**	**-0.124**	**-0.085**	**0.095**	**0.027**	**-0.115**	**-0.094**	**0.107**	**0.028**	**-0.117**
Az	-0.018	0.112	0.117	-0.130	0.007	0.114	0.121	-0.124	0.003	0.130	0.138	-0.123
Can	-0.126	0.029	-0.082	-0.112	-0.121	0.058	-0.070	-0.106	-0.135	0.060	-0.086	-0.116
Mad	-0.147	0.126	0.049	-0.131	-0.141	0.115	0.028	-0.114	-0.151	0.132	0.033	-0.114
Short-beaked common dolphin												

MAC	**-0.078**	**-0.006**	**-0.031**	**-0.107**	**-0.074**	**-0.005**	**-0.032**	**-0.110**	**-0.081**	**-0.007**	**-0.038**	**-0.113**
Az	-0.057	0.030	0.021	-0.095	-0.056	0.030	0.015	-0.111	-0.060	0.034	0.017	-0.110
Can	-0.090	-0.048	-0.062	-0.105	-0.084	-0.037	-0.059	-0.103	-0.094	-0.046	-0.070	-0.112
Mad	-0.087	0.000	-0.052	-0.120	-0.083	-0.006	-0.054	-0.116	-0.090	-0.009	-0.061	-0.116
Risso's dolphin												
MAC	**-0.041**	**0.092**	**0.039**	**-0.067**	**-0.028**	**0.102**	**0.036**	**-0.081**	**-0.032**	**0.114**	**0.040**	**-0.083**
Az	-0.014	0.088	0.116	-0.049	0.010	0.083	0.134	-0.074	0.007	0.095	0.151	-0.073
Can	-0.045	0.033	-0.057	-0.075	-0.040	0.070	-0.050	-0.078	-0.045	0.072	-0.061	-0.087
Mad	-0.063	0.156	0.057	-0.078	-0.055	0.152	0.025	-0.090	-0.057	0.174	0.030	-0.089
Short-finned pilot whale												
MAC	**0.089**	**0.098**	**0.104**	**0.035**	**0.087**	**0.097**	**0.100**	**0.019**	**0.093**	**0.113**	**0.116**	**0.019**
Az	0.111	0.098	0.088	0.054	0.115	0.110	0.085	0.025	0.123	0.126	0.097	0.025
Can	0.055	0.105	0.105	0.021	0.058	0.096	0.101	0.014	0.063	0.114	0.119	0.013

Mad	0.100	0.091	0.120	0.031	0.090	0.084	0.115	0.017	0.094	0.098	0.133	0.017
Blainville's beaked whale												
MAC	**0.067**	**0.061**	**0.081**	**-0.006**	**0.065**	**0.055**	**0.082**	**-0.021**	**0.069**	**0.065**	**0.095**	**-0.021**
Az	0.102	0.035	0.041	0.017	0.101	0.033	0.047	-0.017	0.108	0.038	0.054	-0.017
Can	0.018	0.089	0.103	-0.017	0.025	0.077	0.102	-0.021	0.026	0.092	0.118	-0.024
Mad	0.081	0.059	0.098	-0.019	0.069	0.056	0.097	-0.023	0.072	0.066	0.111	-0.023
Sperm whale												
MAC	**0.058**	**0.070**	**0.063**	**0.029**	**0.060**	**0.071**	**0.061**	**0.007**	**0.065**	**0.081**	**0.071**	**0.006**
Az	0.055	0.065	0.071	0.051	0.062	0.066	0.075	0.017	0.065	0.076	0.086	0.017
Can	0.052	0.061	0.045	0.011	0.054	0.065	0.045	0.001	0.059	0.075	0.052	-0.002
Mad	0.066	0.085	0.074	0.025	0.065	0.081	0.064	0.002	0.070	0.094	0.074	0.003

Atlantic spotted dolphin												
MAC	**0.102**	**0.110**	**0.121**	**0.054**	**0.099**	**0.100**	**0.120**	**0.044**	**0.106**	**0.116**	**0.139**	**0.045**
Az	0.129	0.101	0.108	0.068	0.129	0.095	0.112	0.050	0.138	0.108	0.128	0.050
Can	0.068	0.117	0.123	0.044	0.070	0.102	0.121	0.040	0.076	0.123	0.141	0.043
Mad	0.110	0.114	0.131	0.052	0.098	0.103	0.128	0.042	0.103	0.119	0.148	0.042
Common bottlenose dolphin												
MAC	**0.007**	**0.027**	**0.022**	**0.001**	**0.009**	**0.028**	**0.023**	**-0.003**	**0.009**	**0.032**	**0.026**	**-0.003**
Az	0.020	0.010	0.022	0.002	0.027	0.007	0.031	-0.002	0.028	0.008	0.034	-0.002
Can	0.003	0.030	0.006	-0.001	0.002	0.035	0.008	-0.004	0.003	0.040	0.008	-0.006
Mad	-0.002	0.042	0.038	0.003	-0.002	0.043	0.031	-0.002	-0.002	0.050	0.036	-0.001
Cuvier's beaked whale												
MAC	**0.085**	**0.051**	**0.061**	**0.070**	**0.086**	**0.049**	**0.062**	**0.058**	**0.093**	**0.058**	**0.072**	**0.059**
Az	0.075	0.020	0.032	0.084	0.079	0.020	0.041	0.065	0.084	0.023	0.047	0.064

Can	0.080	0.074	0.066	0.058	0.080	0.069	0.064	0.053	0.089	0.082	0.075	0.056
Mad	0.099	0.058	0.086	0.068	0.098	0.059	0.081	0.055	0.105	0.069	0.093	0.055

Seasonal projections for the Bryde’s whale indicate an increase in thermal suitability in all seasons (Table 4), with the highest values in autumn and spring. In winter, the lowest increase in suitability was recorded in Azores. The fin whale showed a decreasing trend in thermal suitability in summer and autumn. The thermal suitability of fin whale increases in winter and spring with the notable exception of spring in the Canary Islands. In winter and spring, the fin whale showed an increase in thermal suitability except for the Canary Islands in spring.

The Risso’s dolphin thermal suitability decreases in summer and autumn and increases in winter and spring (except in spring in the Canary Islands).

The thermal suitability of short-finned pilot whale increases in all seasons and archipelagos with lower gains in the summer.

The sperm whale suitability increases slightly in all seasons and archipelagos. A similar pattern was observed for the Cuvier’s beaked whale while for the Blainville’s beaked whale, the increase in thermal suitability was detected in all seasons except in summer, where a slight decrease was found.

The short-beaked common dolphin showed a decrease in thermal suitability especially in summer and autumn, except in Azores, where there was a slight increase in winter and spring.

Results for the Atlantic spotted dolphin revealed an increase in thermal suitability in all seasons, although lower in summer. In autumn, this species showed the smallest suitability increase in the Canary Islands and the highest in the Azores. For the common bottlenose dolphin minor changes in thermal suitability were obtained across all seasons and scenarios.

Discussion

The use of expert elicitation to define species' temperature suitability curves and responses under different climate scenarios provided a novel approach to assess species projected thermal suitability changes. In addition, it contributes to support decision-making processes in a context of high uncertainty combined with the urgency of guiding conservation and management actions towards vulnerable species, such as cetaceans, in an increasingly impacted world (Alves et al., 2022a; Avila et al., 2018).

Our results suggest that climate change is likely to decrease the thermal suitability of three out of ten cetacean species analysed in Macaronesia, with all remaining seven species showing thermal suitability increases in the future. In general, species for which thermal suitability increases in the future may experience range expansions, while species for which thermal suitability decreases may experience distributional shifts within Macaronesia (see S.M.1 and S.M.2).

Confidence in thermal suitability curves, derived by the standard deviation and data quality scores, reflect the limited knowledge for these species in Macaronesia. In addition, knowledge varies according to the different archipelagos due to the different research focus of the studied species. For example, more information is available for the Risso's dolphin in the Azores than in Madeira or the Canary Islands, while for beaked whales, despite overall limited knowledge for Macaronesia, most information is available for the Canary Islands.

The increase in suitability for the Bryde's whale, a tropical and subtropical species (Kato and Perrin, 2018) was projected for Madeira, Canary Islands and for the Azores, except for the winter months in Azores where water temperatures are colder. Our results support the known limit distribution range of this species in the region with its upper limit latitude in the Azores (Steiner et al., 2008). Bryde's whale is amongst the most sighted species in Madeira (Alves et al., 2018) and the most sighted rorqual species in the Canary Islands (Herrera et al., 2021); while in Azores, despite exceptional years in which whales were observed in consecutive months, only occasional sightings have been recorded (Azevedo et al., 2021). Habitat preferences for the Madeira archipelago support the relevance of warm surface waters (specifically between 20ºC to 24ºC) as well as low surface chlorophyll concentration to shape the species' distribution (Fernandez et al., 2021). In Madeira, several individuals are known to exhibit long-term site fidelity, with a maximum recapture interval of 12 years, and at least seven individuals were seen both in Madeira and the Canaries (Ferreira et al., 2021). Together with the fact that this species is commonly sighted accompanied by calves and feeding in both archipelagos highlights the ecological importance of this area for Bryde's whale (Alves et al., 2010; Ferreira et al., 2021). Bryde’s whale may potentially be tracking warm waters that are increasing latitudinally and that may be more productive, therefore extending their distribution range (González Garcia, 2019).

Similarly, the short-finned pilot whale, which is also a tropical to subtropical species (Olson, 2009), is projected to increase its suitability in the future. The increase in suitability is lower for the Canary Islands due to current temperatures being already very suitable for the species. In Macaronesia, pilot whales are commonly sighted, especially in Madeira and the Canary Islands (Alves et al., 2019; Herrera et al., 2021; Silva et al., 2014) where island-associated animals are described (Alves et al., 2015, 2013; Servidio et al., 2019). This species shows varying degrees of site fidelity and year-round occupancy in the different archipelagos, which support an ecological connectivity network in Macaronesia (Alves et al., 2019). In Madeira, the short-finned pilot whales were found to prefer warmer waters (over 18ºC) and low/moderate chlorophyll values (Fernandez et al., 2021). In the West Atlantic, it is suggested that this species’ latitudinal distribution may be limited to regions targeting steep bathymetric gradients in order to foster an effective foraging strategy (Thorne et al., 2017). Core foraging regions for this species in Hawai’i and in the Macaronesian archipelagos were also associated with intermediate slope waters (Abecassis et al., 2015; Fernandez et al., 2021; Servidio, 2014), in which potential climate change effects are unknown but may cause the displacement of animals.

Sperm whales are present year-round in all archipelagos and are mostly sighted in Azores (Clarke, 1956; Silva et al., 2014; van der Linde and Eriksson, 2020), but also in Madeira (Alves et al., 2018) and in the Canary Islands (Carrillo et al., 2010; Fais et al., 2016; Herrera et al., 2021). Sperm whales show a high thermal suitability coincident with their wide temperature range. In Azores and Madeira, habitat suitability preferences seem to be linked to sea surface temperature with a peak around 23ºC (Fernandez et al., 2021, 2018).

The Blainville’s beaked whale showed an increase in thermal suitability with a low confidence and data quality due to the limited information for this species. Few island-associated populations have been described worldwide, covering the Hawai’i, Bahamas, and the Macaronesian archipelagos of Madeira and the Canaries (Badenas et al., 2022; Claridge, 2006; Dinis et al., 2017; McSweeney et al., 2007; Reyes Suárez, 2018). Abecassis et al. (2015) associated the species’ movements with specific topographic and oceanographic variables such as bathymetry, temperature at depth, and a high density of midwater micronekton, that are known to influence these animals’ distribution, which mainly relate with temperature at depth. Blainville's beaked whale in Madeira was found to have a restricted ecological niche with preference for warm waters and steep relief areas close to major canyons (Fernandez et al., 2021). In the Canary Islands, Blainville's beaked whales approach the seafloor to feed and have a preferred distribution around 1500 m depth contour (Arranz et al., 2014).

Cuvier's beaked whales occur in all archipelagos year-round, but most information is only available for the Canary Islands where the species shows a high level of residency in some islands such as El Hierro, Lanzarote and Fuerteventura (Arranz et al., 2014; Fernández et al., 2013). The species shows an increasing suitability towards warmer temperatures which explains the projected increase in thermal suitability in October, November and December in the future.

Risso's dolphins are present in all the archipelagos, however with differences in abundance and distribution patterns. Individuals are most sighted in the Azores and the Canary Islands (Hartman et al., 2008; Sarabia-Hierro and Rodríguez-González, 2019) and only occasionally in Madeira (Alves et al., 2018). Most of the information available on their spatial-temporal distribution comes from the Azores, where the species shows a high degree of site fidelity at least in Pico Island (Hartman et al., 2014). In the Canary Islands, mostly in the eastern islands, the species is known to occur, but little information is available (Sarabia-Hierro and Rodríguez-González, 2019). Risso’s are mostly observed in temperate waters from mid-latitude areas (Jefferson et al., 2014). Consequently, the decrease in thermal suitability might be related to their preference for colder waters. Nevertheless, it is also known that they also occur in tropical areas, such as the Maldives (Jefferson et al., 2014), suggesting that the species might adapt to changes in the thermal habitat.

Common bottlenose dolphins are a cosmopolitan species occurring in all Macaronesian archipelagos year-round and known to have a wide range of suitable temperatures (Dinis et al., 2021; Wells and Scott, 2009). The common bottlenose dolphin habitat in the region has been recently characterized by a preference for waters close to coast (<1,000 m), with almost no seasonal variation (Correia et al., 2021; Dinis et al., 2016; Fernandez et al., 2021; Silva et al., 2014).

The short-beaked common dolphin is a temperate water species in the Atlantic (Perrin, 2009) with a preference for colder waters in Macaronesia. It shows a seasonal presence in Madeira mainly during winter and spring (from December to June, (Alves et al., 2018; Fernandez et al., 2021), in the Canary Islands from December to May (Carrillo et al., 2010; Herrera et al., 2021), and a year-round presence in the Azores (Silva et al., 2014). In the region of Macaronesia, the distribution of common dolphins has been found to be influenced by depth and associated with lower sea surface temperatures (Correia et al., 2021; Fernandez et al., 2021). Our study projected a decrease in thermal suitability in the future, with increasing temperatures for Macaronesia. Similarly, for the Northeast Atlantic, Lambert et al. (2011) found a potential northward range expansion of common dolphin distribution as temperatures increase over time.

The Atlantic spotted dolphin also has a seasonal presence in Madeira and the Azores, mainly occurring from May to October (Alves et al., 2018; Fernandez et al., 2021; Silva et al., 2014). Our results show an increase in thermal suitability in the Azores and in Madeira from October to March which may suggest a future extension of their presence in autumn and winter months. In the Canary Islands the species occurs throughout the year with relative fewer sightings in the summer months (June to August; Herrera et al., 2021). Atlantic spotted dolphins appear to have a strong relation with warm water temperatures, potentially linked to the distribution of their preferred prey. This may be a good indicator species for climate driven changes in Macaronesia (Saavedra et al., 2018).

In the Azores, the fin whale has been recorded in winter, spring and summer (Romagosa et al., 2020; Silva et al., 2014) while in Madeira it has been sighted mostly in summer and autumn (Fernandez et al., 2021).

Presence of fin whales in the Canary Islands has been recorded in spring and summer (Carrillo et al., 2010). In Madeira and Azores, the fin whale ecological niche was shaped by low water temperature at 100 m depth (<18ºC), while for Madeira the preference for high chlorophyl levels was identified as a limiting factor (Fernandez et al., 2021). Compared to Madeira, the extended presence of fin whales in the Azores may be explained by the complex topography and higher number of long-lived eddies occurring in the Azores which modulate and increase oceanic productivity in the archipelago (Fernandez et al., 2021).

Species occurrence patterns relate to a combination of physical and biological features which show that different environmental variables besides temperature can influence species movements and distribution (Forcada, 2009). In addition, species can occur in waters within core temperatures of their thermal niche and select, in that range, preferred habitat characteristics regardless of temperature (Correia et al., 2021; Lambert et al., 2011). Our method focuses exclusively on species thermal suitability which may prove to be most relevant for taxa with a clear relation with temperature. Increasing knowledge on species habitat preferences can therefore contribute to identify the most relevant environmental variables and guide the future applicability of the thermal suitability method to specific species. Also, we developed thermal suitability curves for populations in the Macaronesia region, targeting the scale at which conservation and management actions take place (Alves, et al., 2022b). However, it should be noted that the temperature range of these species is wider when compared to the populations assessed in our study area.

The method developed in our study can serve as a simple and easy to apply tool that offers a rapid assessment targeted for decision-makers. This approach can provide an indication of potential thermal suitability changes and can complement other methodologies such as mechanistic modelling or vulnerability indexes towards a more comprehensive understanding of climate change impacts. We acknowledge that species' habitat preferences are dependent on a set of environmental variables and their interaction with complex ocean dynamics, and that considering one absolute environmental variable (sea surface temperature) is a simple but limited approach to project how species will respond to a changing climate.

One of the traits of marine mammals is endothermy, which offers them a broader temperature range tolerance and may increase species resilience to increasing water temperatures. Despite species being less likely to be affected physiologically, their responses are more challenging to predict when compared to fish and zooplankton/invertebrates that follow isotherm lines (Learmonth et al., 2006; Silber et al., 2017). Furthermore, biological traits such as long lifespan, low birth rate, and long generation time provide limited opportunity for rapid evolutionary adaptation, which makes reliance on other characteristics such as behavioural responses a relevant ability for species adaptation to climate change (Learmonth et al., 2006; Lettrich et al., 2019; Silber et al., 2017). In addition, other ecological traits contributing to species sensitivity to climate change such as behaviour, life history or genetic diversity can contribute to species adaptive capacity and resilience to climate (Clusella-Trullas et al., 2021; Silber et al., 2017). However, the ability to assess how species will respond, either through evolutionary changes and phenotypic plasticity or by tracking suitable temperatures, is unknown.

The present approach also does not consider the cumulative effects of other environmental threats such as the impact of maritime transport, nautical tourism or military exercises on species survival. Furthermore, changes in human behaviour and economic activities resulting from climate driven shifts can also have considerable effects on cetacean species (Alter et al., 2010). For example, species may be affected by the acoustic disturbance, habitat disruption or collisions caused by the construction of energy infrastructure built in an effort to reduce fossil fuel consumption and increase the focus on renewable energy (Alter et al., 2010). The development of wave energy and offshore wind farms in Macaronesia are currently under discussion (Calado et al., 2021) and may affect cetaceans if these construction areas overlap with species' distribution areas. In Macaronesia, except for ship collisions from ferries in the Canary Islands (Carrillo and Ritter, 2010), no major direct local impacts have currently been identified. However, other pressures that affect cetacean species and that should be monitored in the region include the input of contaminants and anthropogenic sound, marine litter and disturbance from whale watching activities (e.g., Arranz et al., 2021; Cardoso & Caldeira, 2021; Montoto-Martínez et al., 2021; Sambolino et al., 2022).

Additionally, we used the annual and seasonal mean sea surface temperature to derive species historical and future thermal suitability. However, species responses to extreme conditions such as marine heatwaves may be larger than expected (Cheung and Frölicher, 2020), even if the principal driver of these events comes from long-term climate change (Collins et al., 2019; Laufkötter et al., 2020). Another source of uncertainty comes from the lack of downscaled climate models that offer regional-scale climate projections (Christensen et al., 2007; Tomé, 2013).

Finally, future research should focus on using sightings data to validate expert-based curves and to monitor species with standardized protocols across all archipelagos of Macaronesia. This would increase the knowledge base on oceanographic and climate processes as well as on species ecology and their relationship with the environment. Moreover, as more recent coupled climate models' experiments under the Climate Model Intercomparison Project 6 (CMIP6) (Eyring et al., 2016) become available, these should also be used in future research.

Conclusions

The results highlight the potential future thermal responses of cetaceans in Macaronesia and implications for species' distribution changes.

Challenges in obtaining experimentally driven thermal limits or *in situ* measures of environmental temperature associated with species sightings limit our use of these methods, particularly in large marine predators such as cetaceans.

Our approach allowed for the development of thermal suitability curves and responses to be rapidly derived for cetaceans using expert elicitation in support of decision-making under climate change. These results can prepare managers and conservationists with potential future outcomes and can serve as inputs to broader habitat modelling exercises. Further application and validation of this approach can be conducted in other areas or applied at a basin-wide or global scale while increasing the poll of experts involved in the design of the thermal suitability curves.

Research that helps to further understand the main environmental variables influencing the current distribution of cetacean species in Macaronesia, as well as projected future distribution changes, is welcome to develop a greater understanding of climate-driven impacts.

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Supplementary material

S.M. 1: Annual thermal suitability maps

S.M. 2: Seasonal thermal suitability maps

Conflict of interest

The authors declare that there is no conflict of interest.

Data availability statement

The data that supports the findings of this study are available in the supplementary material of this article.

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Figure 1

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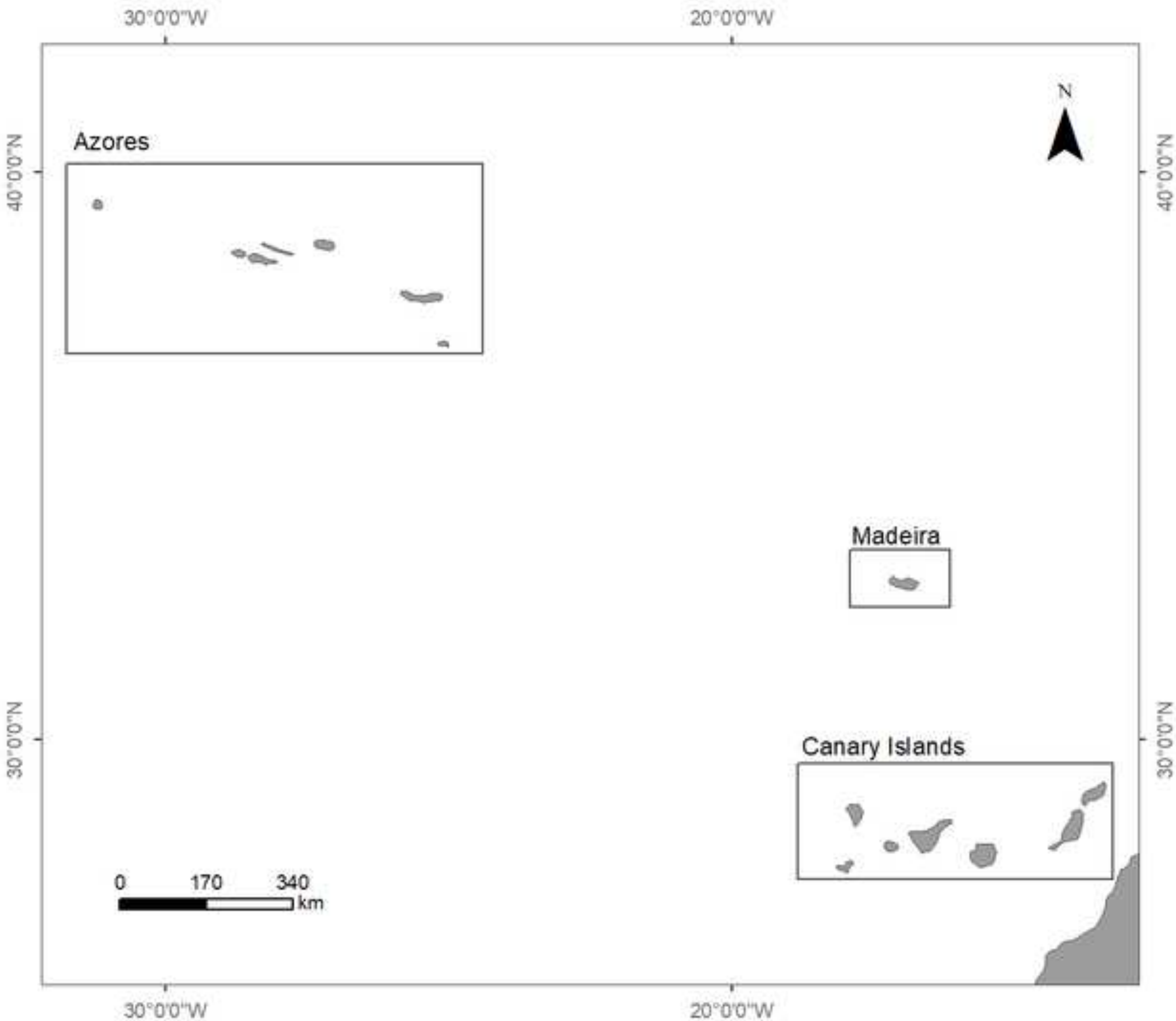
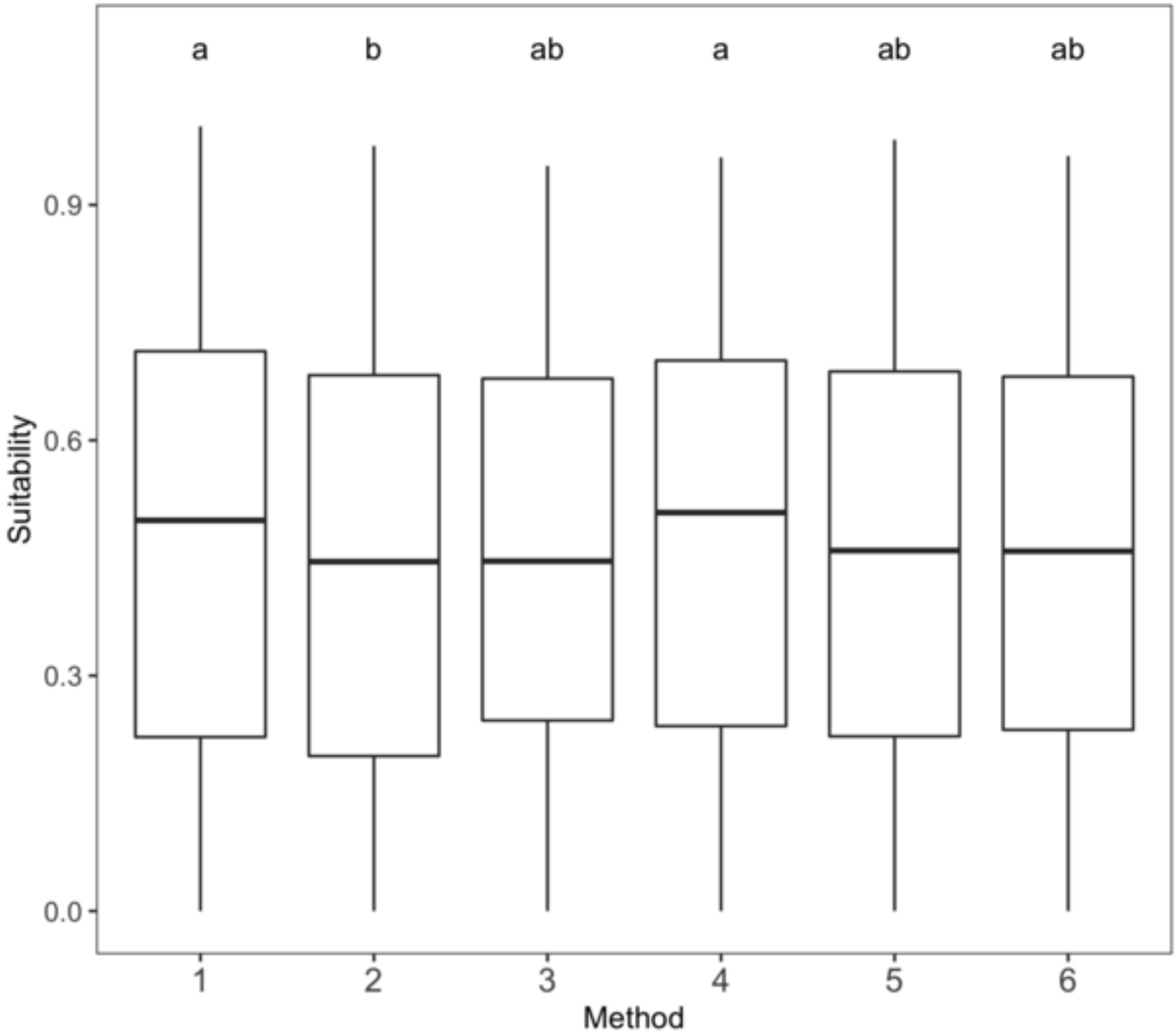


Figure 2



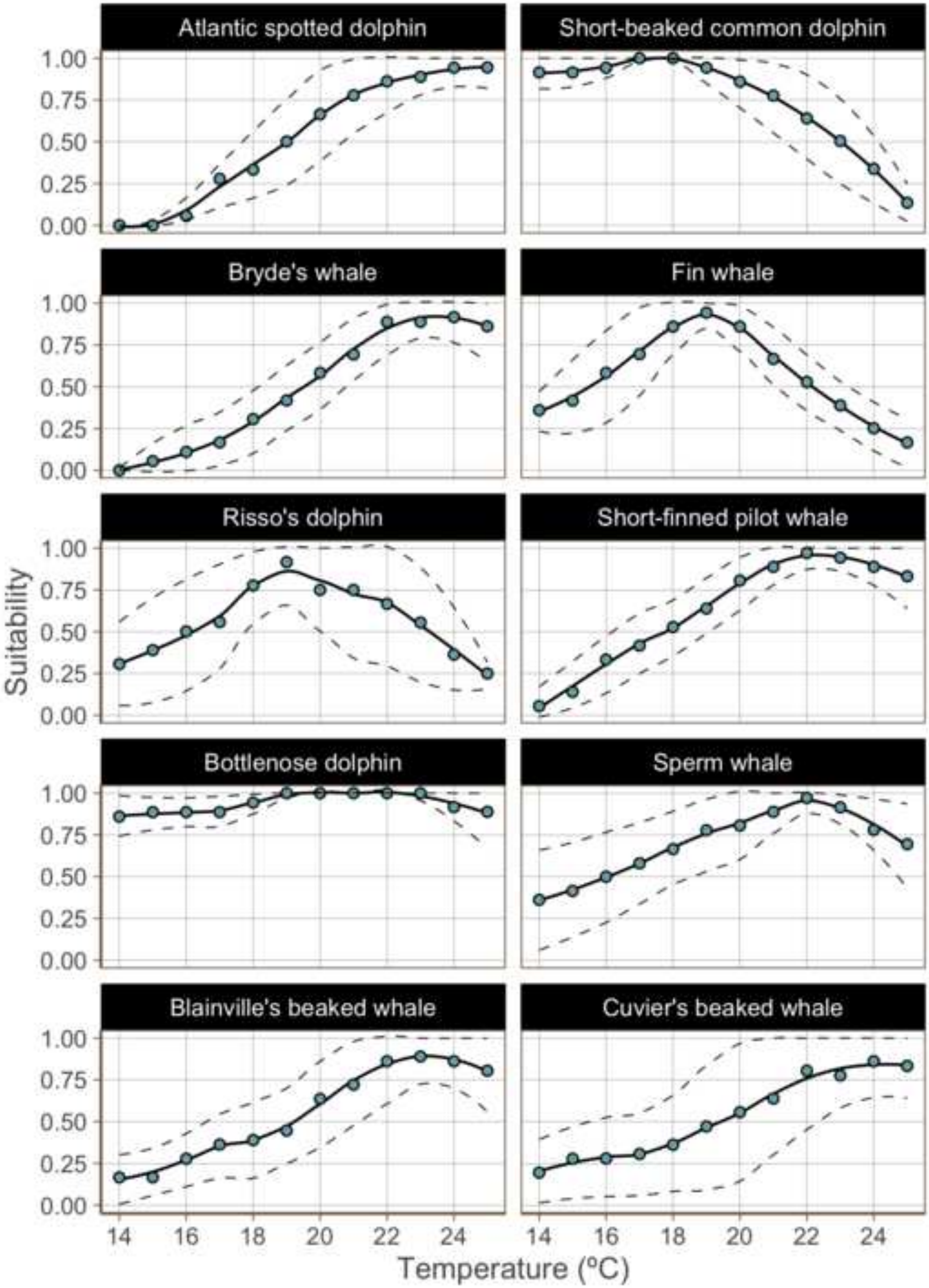
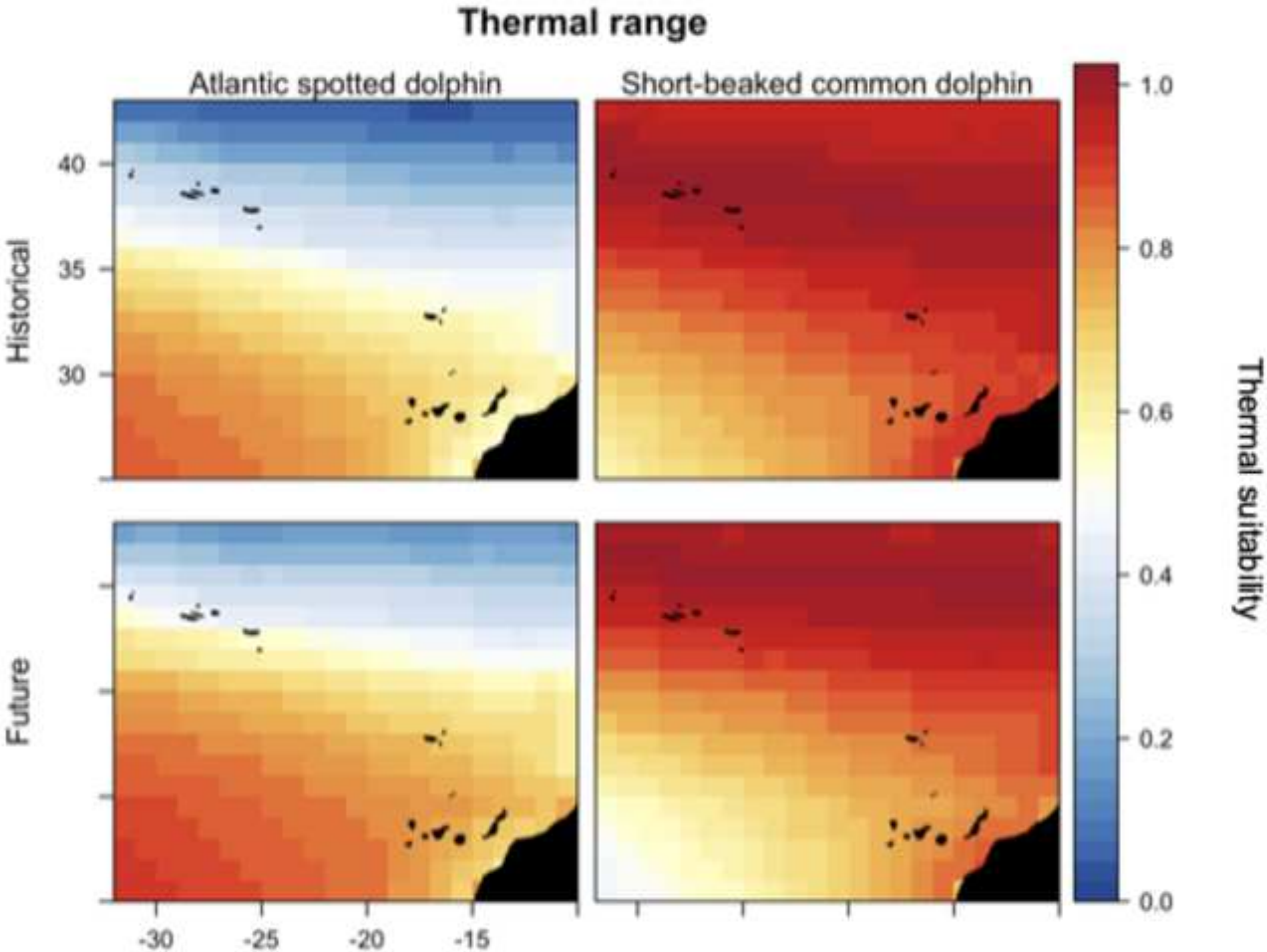

Atlantic spotted dolphin
Short-beaked common dolphin
Bryde's whale
Fin whale
Risso's dolphin
Short-finned pilot whale
Bottlenose dolphin
Sperm whale
Blainville's beaked whale
Cuvier's beaked whale
Suitability
1.00
0.75
0.50
0.25
0.00
14
16
18
20
22
24
Temperature (ºC)

Figure 4

Click here to access/download;Figure;Figure 4.tiff



Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRediT author statement

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