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A climate change integrated assessment of whale watching in Macaronesia

"Documento Definitivo"

Doutoramento em Alterações Climáticas e Políticas de Desenvolvimento Sustentável
Especialidade de Ciências do Ambiente

Andreia Gonçalves de Sousa

Tese orientada por:
Dra. Catarina Frazão da Fonseca Ribeiro dos Santos
Dr. José Manuel Viegas de Oliveira Neto Azevedo

Documento especialmente elaborado para a obtenção do grau de doutor

2022

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2022

For my parents, whom I love dearly and support me always

“Temos, sobretudo, de aprender duas coisas: aprender o extraordinário que é o mundo e aprender a ser bastante largo por dentro para o mundo todo poder entrar”

Agostinho da Silva

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To dance and music that give me the joy and strength to keep going.

Abstract

Climate change is occurring at a rapid, widespread, and intensifying rate with natural and human systems witnessing increasingly severe, interconnected and often irreversible impacts. In the ocean, climate change is projected to strongly affect marine ecosystems mainly through increases in ocean temperature, acidification, and deoxygenation. Marine ecosystems provide essential benefits to society through several regulating, provisioning, cultural, and supporting services. These services are particularly relevant in island and coastal states, where the impacts of climate change (such as sea level rise, coastline erosion, and increase in frequency and intensity of extreme weather events) are expected to be most severe. Tourism is one of the main socio-economic activities on islands worldwide, namely in the bioregion of Macaronesia, where whale watching is one of the main activities. The impacts of climate change in whale watching are largely unknown, and studies that integrate the ecological and socio-economic impacts of climate change on the activity are missing. Concurrently, there is the need to provide conservation managers and practitioners with sound scientific knowledge in order to support effective and appropriate management efforts. The main goal of this dissertation is to assess the integrated biological and socio-economic vulnerability of whale watching to climate change to support the long-term sustainability of the activity in the Macaronesia bioregion. The three main research questions defined to achieve this goal are: (i) *What is the ecological vulnerability of cetacean species to climate change?* (ii) *What is the socio-economic vulnerability of whale watching to climate change?* (iii) *How can the management of whale watching be supported under climate change?*

Keywords

Climate change · Vulnerability assessment · Whale watching · Macaronesia

Resumo

As alterações climáticas estão a decorrer de forma rápida, generalizada e intensa, com impactos graves, interligados e irreversíveis nos sistemas naturais e humanos. No oceano, os efeitos das alterações climáticas estão a afetar fortemente os ecossistemas marinhos, principalmente através do aumento da temperatura, da acidificação, e da desoxigenação. Os ecossistemas marinhos proporcionam um conjunto de serviços de aprovisionamento, de regulação, culturais e de suporte. Estes serviços são particularmente relevantes em estados costeiros e insulares, onde se prevê que os impactos das alterações climáticas tenham maiores consequências, como a subida do nível do mar, a erosão costeira ou o aumento da frequência e intensidade de eventos climáticos extremos. O turismo é uma das principais atividades socioeconómicas desenvolvida em estados insulares a nível mundial, nomeadamente na bioregião da Macaronésia, onde a observação de cetáceos é uma das principais atividades. No entanto, os impactos das alterações climáticas na observação de cetáceos são largamente desconhecidos, ao mesmo tempo que faltam estudos que integrem os impactos socioeconómicos e ecológicos das alterações climáticas na atividade. Por outro lado, há a necessidade de apoiar os decisores na conservação da biodiversidade, identificando os esforços de gestão necessários e as lacunas de conhecimento a preencher. O principal objetivo da presente dissertação é, assim, realizar uma avaliação integrada da vulnerabilidade biológica e socioeconómica da atividade de observação de cetáceos às alterações climáticas, por forma a apoiar a sua sustentabilidade a longo prazo na bioregião da Macaronésia. As três principais perguntas de investigação definidas para responder a este objetivo são: (i) *Qual a vulnerabilidade ecológica das espécies de cetáceos às alterações climáticas?* (ii) *Qual a vulnerabilidade socioeconómica da observação de cetáceos às alterações climáticas?* (iii) *Como é que a gestão da atividade de observação de cetáceos pode ser apoiada face às alterações climáticas?*

Palavras-Chave

Alterações climáticas · Avaliação de vulnerabilidade · Observação de cetáceos · Macaronesia

Resumo alargado

O aumento da temperatura média global, devido à emissão de gases com efeito de estufa com origem em atividades antropogénicas, tem levado a um conjunto de alterações no sistema climático com diferentes impactos nos sistemas ecológicos, económicos e sociais. A menos que ocorram reduções imediatas, urgentes e em grande escala nas emissões de gases com efeito estufa, o aquecimento global de 1,5 a 2°C face a níveis pré-industriais será excedido durante o século XXI. Muitas das alterações já observadas e projetadas para o futuro apresentam impactos severos e irreversíveis, com consequências a nível ecológico e socioeconómico.

No oceano, estes impactos traduzem-se num aumento da temperatura, na subida do nível médio do mar, no aumento da frequência e intensidade de furacões e outros eventos extremos, na acidificação e na diminuição de oxigénio dissolvido, entre outros, contribuindo para a perda da biodiversidade marinha e das funções e serviços dos ecossistemas.

O turismo é uma das principais atividades socioeconómicas desenvolvidas em regiões costeiras e estados insulares por todo o mundo. Atividades de ecoturismo marinho, como a observação de cetáceos, podem trazer benefícios socioeconómicos e ambientais para as economias regionais. A Macaronésia, região que consiste nos arquipélagos dos Açores, das Canárias e da Madeira, é um dos principais destinos internacionais para observação de cetáceos. A atividade de observação de cetáceos desenvolveu-se inicialmente nos Açores e nas Canárias e só mais tarde na Madeira, e apresenta características heterogéneas não só entre os diferentes arquipélagos, mas também entre ilhas do mesmo arquipélago. Apesar da crescente atividade de observação de cetáceos na Macaronésia nas últimas décadas, estudos do ponto de vista socioeconómico, ecológico ou climático são escassos.

O principal objetivo da presente dissertação é, assim, realizar uma avaliação integrada da vulnerabilidade biológica e socioeconómica da atividade de observação de cetáceos às alterações climáticas, por forma a apoiar a sua sustentabilidade a longo prazo na bioregião da Macaronésia. As três principais perguntas de investigação definidas para responder a este objetivo são: (i) Qual a vulnerabilidade ecológica das espécies de cetáceos às alterações climáticas? (ii) Qual a vulnerabilidade socioeconómica da observação de cetáceos às alterações climáticas? (iii) Como é que a gestão da atividade de observação de cetáceos pode ser apoiada face às alterações climáticas?

A presente dissertação é composta por sete capítulos: o Capítulo 1 corresponde à introdução geral; os Capítulos 2, 3, 4 e 5 correspondem aos principais capítulos de investigação da

dissertação, onde os resultados são apresentados, analisados e discutidos em detalhe; o Capítulo 6 corresponde à discussão geral e principais conclusões da dissertação, e o Capítulo 7 elenca o trabalho a realizar no futuro.

No que respeita aos capítulos de investigação, os Capítulos 2 e 3 encontram-se já publicados em revistas científicas internacionais sujeitas a revisão por pares, enquanto os Capítulos 4 e 5 foram submetidos e encontram-se em processo de revisão. O Capítulo 2 corresponde à primeira experiência de desenvolvimento de um índice de vulnerabilidade às alterações climáticas para espécies de cetáceos. Antes da sua publicação, os índices de vulnerabilidade existentes na literatura tinham sido desenvolvidos para o ambiente terrestre e para espécies de invertebrados e peixes no ambiente marinho. Os principais objetivos foram: (i) Desenvolver um índice de vulnerabilidade às mudanças climáticas; (ii) Testar esta abordagem e aplicá-la a um estudo de caso no arquipélago da Madeira; (iii) Identificar a vulnerabilidade das espécies de cetáceos na Madeira às alterações climáticas e as principais lacunas de conhecimento; (iii) Reunir impactos observados das alterações climáticas nas espécies de cetáceos através de revisão bibliográfica e avaliar a robustez dos resultados obtidos; (iv) Contribuir para a avaliação da vulnerabilidade das espécies de cetáceos através da identificação dos principais desafios metodológicos e de áreas de investigação futura. Os principais resultados indicaram que o cachalote (*Physeter macrocephalus*), a baleia-comum (*Balaenoptera physalus*), a população do Atlântico de golfinho-roaz (*Tursiops truncatus*), e a baleia-de-Bryde's (*Balaenoptera brydei*) são as espécies mais vulneráveis às alterações climáticas no arquipélago da Madeira.

O Capítulo 3 pretendeu melhorar o índice de vulnerabilidade e alargar a avaliação à região da Macaronésia. Os desafios e limitações identificados no índice desenvolvido no Capítulo 2 foram considerados e o Índice de Vulnerabilidade às Alterações Climáticas de Lettrich et al. (2019) foi adaptado e aplicado. Os principais objetivos foram: (i) Classificar a vulnerabilidade dos cetáceos às alterações climáticas; (ii) Avaliar o potencial para alterações na distribuição das espécies, abundância e fenologia das espécies; (iii) Comparar os resultados obtidos com os resultados de outras avaliações de vulnerabilidade; (iv) Produzir considerações metodológicas e recomendações para a aplicação futura do índice; (v) Identificar limitações e desafios futuros. Os principais resultados indicam que as espécies de cetáceos apresentam uma vulnerabilidade às alterações climáticas de Moderada a Muito alta, em particular as unidades associadas aos arquipélagos que apresentam vulnerabilidades Altas a Muito Altas.

O Capítulo 4 teve como objetivo responder à necessidade de apoiar os decisores com resultados espacialmente explícitos das potenciais respostas térmicas das espécies em diferentes cenários de alterações climáticas. Os principais objetivos foram: (i) Desenvolver curvas térmicas das

espécies; (ii) Avaliar a amplitude térmica atual das espécies e respostas futuras nos cenários Representative Concentration Pathways 2.6, 4.5 e 8.5; (iii) Validar os resultados obtidos com as evidências disponíveis para as espécies da região; (iv) Identificar limitações e desafios para investigação futura. A maioria das espécies de cetáceos (7 em 10) irá aumentar a sua adequação térmica às alterações climáticas, com exceção da baleia-comum, do golfinho-comum e do golfinho-de-Risso.

Por último, o Capítulo 5 teve como objetivo produzir uma avaliação integrada das componentes biológicas e socioeconómicas da atividade de observação de cetáceos face às alterações climáticas. Para atingir este objetivo, foi utilizada a abordagem combinada dos RCP e *Shared Socioeconomic Pathways (SSPs).* Os SSPs europeus foram regionalizados para a atividade de observação de cetáceos (WW-SSPs) e as tendências climáticas futuras foram descritas através de revisão bibliográfica. Quatro cenários diferentes descrevendo a atividade de observação de cetáceos foram então criados, integrando os WW-SSPs, as tendências climáticas futuras e as respostas térmicas das espécies. A integração de todos os componentes da atividade de observação de cetáceos através do desenvolvimento de cenários foi uma abordagem inovadora que se mostrou útil para apoiar os decisores na visualização de diferentes futuros e na avaliação do nível de preparação atual da atividade para responder aos efeitos das alterações climáticas.

Palavras-Chave

Alterações climáticas · Avaliação de vulnerabilidade · Observação de cetáceos · Macaronesia

Table of Contents

Acknowledgements i

Abstract iv

Resumo v

Resumo alargado vi

List of Acronyms and Abbreviations xii

List of Tables xiii

List of Figures xv

Chapter 1. Introduction 1

1.1 Setting the scene *1*

1.2 Objectives and Dissertation Structure *9*

Chapter 2. How vulnerable are cetaceans to climate change? Developing and testing a new index 16

2.1 Abstract *16*

2.2 Introduction *17*

2.3 Methods *19*

2.3.1 Index development approach 19

2.3.1 Application to the case study 21

2.4 Results *22*

2.4.1 Index development 22

2.4.2 Index application to the case study 25

2.5 Discussion *28*

2.5.1 Cetaceans' vulnerability to climate change in the Madeira archipelago 28

2.5.2 Supporting evidence of climate change impacts in cetacean species 30

2.5.3 Case study contributions to cetaceans' vulnerability assessment 33

2.6 Conclusion *34*

Chapter 3. Climate change vulnerability of cetaceans in Macaronesia: Insights from a trait-based assessment 36

3.1 Abstract *36*

3.2 Introduction *37*

3.3 Methods *39*

3.3.1 Definition of scope and scale 40

3.3.2 Scoring process for sensitivity attributes, exposure factors and data quality 44
3.3.3 Calculation of vulnerability scores and data analysis 45

3.4 Results *47*
3.4.1 Macaronesia Units 50
3.4.2 Archipelago-associated Units 51

3.5 Discussion *53*
3.5.1 Climate vulnerability of cetacean species in Macaronesia 53
3.5.2 Comparison with other climate change vulnerability assessments 56
3.5.3 Methodological considerations and further research 60

3.6 Conclusion *62*

Chapter 4. A novel expert-driven methodology to develop thermal suitability curves for cetaceans under a changing climate 63

4.1 Abstract *63*

4.2 Introduction *64*

4.3 Methods *66*
4.3.1 Study area and selected species 66
4.3.2 Development of thermal suitability curves 68
4.3.3 Species thermal responses 71

4.4 Results *72*
4.4.1 Thermal suitability curves 72
4.4.2 Species thermal responses 75

4.5 Discussion *83*

4.6 Conclusions *88*

Chapter 5. Integrated climate, ecological and socioeconomic scenarios for the whale watching sector 89

5.1 Abstract *90*

5.2 Introduction *91*

5.2 Methods *94*
5.2.1 Developing WW-SSPs narratives 95
5.2.2 Case study: Whale watching scenarios for Macaronesia 99

5.3 Results *102*
5.3.1. WW-SSPs narratives 102
5.3.2 Case study: Whale watching scenarios for Macaronesia 108

5.4 Discussion *111*

5.5 Conclusion *113*

Chapter 6. General discussion 115

6.1. General discussion and key findings ... *115*

6.2. Future research ... *121*

References ... **124**

Annex A. Exposure maps for sea surface temperature, salinity, pH and primary productivity ... **160**

... **160**

Annex B. List of sensitivity attributes and exposure factors ... **162**

Annex C. Climate sensitivity, exposure and vulnerability scores and potential distribution, abundance and phenology score responses for Macaronesia and archipelago-associated species management units. ... **169**

Annex D. Climate projection maps from ESRL Climate Change Web Portal ... **173**

Annex E. Confusion matrix of a) sensitivity; b) exposure and c) vulnerability scores. **176**

Annex F. Number of changes in climate vulnerability scores and the average attribute and exposure scores for Macaronesia and archipelago associated species management units. ... **178**

Annex G. Graphical abstract of Chapter 3 ... **180**

Annex H. Annual thermal suitability maps ... **181**

Annex I. Seasonal thermal suitability maps ... **201**

Annex J. Thermal suitability differences ... **244**

Annex K. Description of the data quality scale ... **248**

Annex L. Experts' data quality scores ... **249**

Annex M. Experts' suitability scores ... **250**

Annex N. Suitability scales attributed by experts to the six different methods ... **255**

List of Acronyms and Abbreviations

AFWM	Attribute or Factor Weighted Means
AMJ	April, May, June
AMOC	Atlantic Meridional Overturning Circulation
AZ	Azores
CAN	Canary Islands
CCVI	Climate Change Vulnerability Index
CIMP5	Climate Model Intercomparison Project 5
COVID-19	Coronavirus Disease 2019
CR	Critically Endangered
DQ	Data quality
EEZ	Economic Exclusive Zone
EN	Endangered
ESRL	Earth System Research Laboratory
Eur-SSP	European Shared Socio-economic Pathways
GDP	Gross Domestic Product
IAM	Integrated Assessment Models
IUCN	International Union for the Conservation of Nature
JAS	July, August, September
JFM	January, February, March
LC	Least Concern
LOESS	Local Polynomial Regression Fitting
MAC	Macaronesia
MAD	Madeira
MMCVA	Marine Mammal Climate Vulnerability Assessment
MSFD	Marine Strategy Framework Directive
NAO	North Atlantic Oscillation
NE	Northeast
NOAA	National Oceanic and Atmospheric Administration
NT	Near Threatened
NW	Northwest

OND	October, November, December
RCP	Representative Concentration Pathways
SE	Southeast
SPG	Subpolar Gyre
SRES	Special Report Emissions Scenarios
SSP	Shared Socio-economic Pathways
SST	Sea Surface Temperature
TC	Tropical cyclones
VU	Vulnerable
WW-SSP	Whale watching-Shared Socio-economic Pathways

List of Tables

Table 2-1 - Definition and evaluation of sensitivity factors considered in the development of the cetacean climate change vulnerability index based on criteria derived from Simmonds and Smith (2009). 23

Table 2-2 - Sensitivity categories defined for each sensitivity factors in the vulnerability index with three scores ranging from 1 = the factor does not increase the species' sensitivity, to 3 = the factor strongly increases species' sensitivity. 25

Table 2-3 – Species' sensitivity scores. Scores for each factor and confidence results in brackets. Scores were re-scaled from 0 to 1. Species are ranked by decreasing order of vulnerability. 27

Table 3-1 – Selected species included in the climate change vulnerability assessment and their classification into species management units: Macaronesia unit (MAC) and the archipelago-associated units of Azores (AZ), Canary Islands (CAN) and Madeira (MAD). 43

Table 4-1 – Cetacean species selected for the development of thermal suitability curves, ordered alphabetically by the common name. 68

Table 4-2 – Six methods combining different thermal suitability (TS) and temperature (T) scales, for the development of thermal response curves for cetacean species. 70

Table 4-3 – 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 Representative Concentration Pathways (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. 75

Table 4-4 – Changes in mean seasonal thermal suitability in Autumn (OND), Winter (JFM), Spring (AMJ), and Summer (JAS) for cetacean species in Macaronesia (MAC) in bold and respective archipelagos, Azores (Az), Canary Islands (Can) and Madeira (Mad) for Representative Concentration Pathways (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). 79

Table 5-1 – Key socio-economic elements for whale watching and corresponding explanatory European shared socioeconomic pathways (Eur-SSP) elements from Kok et al. (2018) and Costal tourism SSPs from Merkens et al. (2016). 95

Table 5-2 - Characterization of the different specific elements in each whale watching Shared Socioeconomic Pathways (WW-SSPs) for the period 2025-2055. 106

Table 6-1 - Key findings of the present dissertation. 119

Table B-1 – List of sensitivity attributes and exposure factors with the respective scoring bins. Adapted attributes and included factors are marked with an asterisk. A full description of sensitivity attributes and exposure factors including definitions, background and scoring criteria are described in appendix A in Lettrich et al., 2019. 162

Table C-1 - Climate sensitivity, exposure and vulnerability scores for Macaronesia (MAC) and archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colours indicate Very High (4; red), High (3; orange), Moderate (2; yellow) and Low (1; green) scores. Data quality ranges from 0 to 3. Certainty in scores is represented by: Very High certainty (>95%, black), High certainty (90–95%, dark grey), Moderate certainty (66–90%, light gray) and Low certainty (<66%, white). 169

Table C-2 – Vulnerability scores and potential distribution, abundance and phenology responses for the Macaronesia (MAC) and archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Score colors are indicated with Very High (4; red), High (3; orange), Moderate (2; yellow) and Low (1; green). 171

Table N-1 - Suitability scores attributed by experts to the six different methods. t(numbers) indicate the temperature intervals and species are identified by their acronym (Sf: *Stenella frontalis*; Be: *Balaenoptera edeni*; Bp: *Balaenoptera physalus*; Gma: *Globicephala macrorhynchus*; Dd: *Delphinus delphis*; Pm: *Physeter macrocephalus*; Gg: *Grampus griseus*; Tt: *Tursiops truncatus*; Md: *Mesoplodon densirostris*; Zc: *Ziphius cavirostris*). 255

List of Figures

Figure 1-1 – The Macaronesia biogeographic region represented by the archipelagos of the Azores, Madeira and the Canary Islands. 2

Figure 1-2 - Conceptual model adapted from Meynecke et al., 2017. A simplified representation of climate, biological, socio-economic and management modules and examples of relevant factors within each module. The relation between modules and factors within each module is represented by the arrows in the diagram. 6

Figure 1-3 – Dissertation structure and research questions. 10

Figure 1-4 – Vulnerability as a function of exposure, sensitivity, potential impacts and adaptive capacity (Fritzsche et al., 2014). 13

Figure 1-5 – Integration of future climate trends, species thermal suitability responses and whale watching SSPs into whale watching scenarios. 14

Figure 2-1– Map of the North Atlantic ocean and the Madeira archipelago and Economic Exclusive Zone. Data source: EEZ: Flanders Marine Institute, 2018; Coastline: Portuguese Hydrographic Institute, 2014; Altitude and Depth: ETOPO2 dataset (National Geophysical Data Center, 2006). 21

Figure 3-1 – Map of the Macaronesia biogeographic region, showing the archipelagos of Azores, Madeira and Canary Islands. 41

Figure 3-2 – Vulnerability matrix from Lettrich et al., 2019, showing the component scores of sensitivity/adaptive capacity and exposure to obtain the overall vulnerability score. Numbers in parenthesis indicate the component scores of sensitivity and exposure and the vulnerability score resulting from multiplying sensitivity and exposure [Low vulnerability (1-3), Moderate vulnerability (4-6), High vulnerability (8-9), Very High vulnerability (12-16)]. 46

Figure 3-3 – Climate vulnerability scores which result from the combined biological sensitivity and climate exposure scores for the Macaronesia (MAC) species management units. Colors indicate vulnerability scores: Very High (red), High (orange), Moderate (yellow) and Low (green). Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%). 49

Figure 3-4 – Climate vulnerability scores which result from the combined biological sensitivity and climate exposure scores for the archipelago-associated species management units of

Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colors indicate vulnerability scores: Very High (red), High (orange), Moderate (yellow) and Low (green). Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%). 50

Figure 3-5 - Vulnerability scores and potential distribution, abundance and phenology responses for the Macaronesia (MAC) and archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colours indicate Very High (4; red), High (3; orange), Moderate (2; yellow) and Low (1; green) potential for changes. Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%). 52

Figure 4-1 – The biogeographic region of Macaronesia with the Azores, Canary Islands and Madeira archipelagos. 67

Figure 4-2 - Suitability scores attributed by experts when scoring each of the six different methods proposed for the development of thermal response curves for cetacean species (**Table 4-2**). 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). 71

Figure 4-3 - Species thermal suitability curves for: a) Atlantic spotted dolphin; b) short-beaked common dolphin; c) Bryde's whale; d) fin whale; e) Risso's dolphin; f) short-finned pilot whale; g) bottlenose dolphin; h) sperm whale; i) Blainville's beaked whale; j) Cuvier's beaked whale. Mean data quality values (DQ) is 3 for a); b); c); f); g); h) and 2 for d); e); i); j). DQ values range from zero to three where 0 = No data; 1 = Expert judgment only; 2 = Limited data; 3 = Adequate data (**Annex K**). Mean values are represented by the dots in the solid line and confidence intervals (standard deviation) are represented in the dashed line. Individual experts' scores are presented in Supplementary Material (**Annex M**). 73

Figure 4-4 – Historical (1956–2005) and future (2006–2055) thermal suitability for representative concentration pathway (RCP) 8.5 for short-beaked common and Atlantic spotted dolphin. Scale on the right-hand side represents the lowest (0) and highest (1) thermal suitability. Dashed contour lines indicate a 0.75 thermal suitability. 78

Figure 5-1 – Macaronesia bioregion, depicting the archipelagos of the Azores, Canary Islands and Madeira. 100

Figure 5-2 – Conceptual model of the development of whale watching scenarios that combine the biological, climate and socio-economic modules (adapted from Meynecke et al., 2017) which was integrated in a stakeholder workshop where the preparedness of the sector was assessed under the different scenarios. 101

Figure 5-3 - Changes in thermal suitability for cetaceans in Macaronesia (adapted from Sousa et al., 2022). The scale indicates the changes in thermal suitability between the historical (1956-2005) and the projected (2006-2055) sea surface temperature according to species' thermal curves. Species are identified by their scientific name as follows: *Stenella frontalis* (Atlantic spotted dolphin); *Balaenoptera edeni* (Bryde's whale); *Balaenoptera physalus* (Fin whale); *Globicephala macrorhynchus* (Short-finned pilot whale); *Delphinus delphis* (short-beaked common dolphin); *Physeter macrocephalus* (Sperm whale), *Grampus griseus* (Risso's dolphin); *Tursiops truncatus* (Common bottlenose dolphin); *Mesoplodon densirostris* (Blainville's beaked whale); *Ziphius cavirostris* (Cuvier's beaked whale). Numbers in the upper left and in the bottom indicate latitude and longitude, respectively. 110

Figure A-1 - Historical climate (1956-2005) (left column) and projections (2050-2099) for RCP 8.5 with anomalies for the different variables (right column) in the north Atlantic. (a,b): sea surface temperature (ºC); (c,d):pH; (e,f): salinity (psu); (g-h): primary productivity (1.E^{-9} mol m^{-2}). Data/image provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. This material is not subject to copyright protection. 161

Figure D-1 – Climate projection maps from ESRL Climate Change Web Portal (http://www.esrl.noaa.gov/psd/ipcc/ocn/). Projections were reclassified by scoring bin from the original ESRL projection maps with the following settings: RCP 8.5; model = average of all models; statistic= standard anom (avg historical); time frame= 2006-2055; region= a units' entire distribution range. Variables: Sea surface temperature (a) projected future standard anomaly; (b) change in variability; Sea surface salinity (c) projected future standard anomaly; (d) change in variability; pH at surface (e) projected future standard anomaly; (f) change in variability; Primary productivity (g) projected future standard anomaly; (h) change in variability; Dissolved oxygen concentration at surface (i) projected future standard anomaly; (j) change in variability. 175

Figure E-1 – Confusion matrix of a) sensitivity; b) exposure and c) vulnerability scores. Predicted scores indicate the estimated final scores from the bootstrap analysis. Actual scores indicate the scores obtained by the experts. The confusion matrix depicts the correspondence between the predicted and the actual scores. 177

Figure F-1– Results for Macaronesia species management units indicating (a,b) the number of changes in climate vulnerability scores produced by individual sensitivity attributes and exposure factors and (c,d) the average attribute and exposure scores. 178
Figure F-2 – Results for archipelago-associated species management units indicating (a,b) the number of changes in climate vulnerability scores produced by individual sensitivity attributes and exposure factors and (c,d) the average attribute and exposure scores. 179
Figure G-1 – Graphical abstract with main results of results of Chapter 3. 180
Figure H-1 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Atlantic spotted dolphin under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability............... 182
Figure H-2 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Short-beaked common dolphin under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability. .. 184
Figure H-3 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Bryde's whale under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability. 186
Figure H-4 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for fin whale under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability. 188
Figure H-5 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Risso's dolphin under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability............... 190
Figure H-6 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for short-finned pilot whale under RCP 2.6; 4.5 and 8.5.

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). Dashed contour lines indicate a 0.75 thermal suitability................ 192
Figure H-7 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for bottlenose dolphin under RCP 2.6; 4.5 and 8.5. 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). 194
Figure H-8 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for sperm whale under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability. 196
Figure H-9 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Blainville's beaked whale under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability. .. 198
Figure H-10 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Cuvier's beaked whale under RCP 2.6; 4.5 and 8.5. 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). Dashed contour lines indicate a 0.75 thermal suitability................ 200
Figure I-1 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Atlantic spotted dolphin under RCP 2.6. 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). 202
Figure I-2 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Atlantic spotted dolphin under RCP 4.5. 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). 203

Figure I-3 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Atlantic spotted dolphin under RCP 8.5. 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). 205
Figure I-4 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Short-beaked common dolphin under RCP 2.6. 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). 206
Figure I-5 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Short-beaked common dolphin under RCP 4.5. 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). 208
Figure I-6 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Short-beaked common dolphin under RCP 8.5. 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). 210
Figure I-7 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Bryde's whale under RCP 2.6. 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). 212
Figure I-8 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Bryde's whale under RCP 4.5. 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). 214
Figure I-9 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Bryde's whale under RCP 8.5. 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). 215
Figure I-10 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the fin whale under RCP 2.6. 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). 216
Figure I-11 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the fin whale under RCP 4.5. 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). 218
Figure I-12 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the fin whale under RCP 8.5. 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). 219
Figure I-13 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Risso's dolphin under RCP 4.5. 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). 220
Figure I-14 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Risso's dolphin under RCP 4.5. 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). 222
Figure I-15- Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Risso's dolphin under RCP 8.5. 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). 223
Figure I-16 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the short-finned pilot whale under RCP 2.6.

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). 224

Figure I-17 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the short-finned pilot whale under RCP 4.5. 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). 226

Figure I-18 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the short-finned pilot whale under RCP 8.5. 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). 227

Figure I-19 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the bottlenose dolphin under RCP 2.6. 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). 228

Figure I-20 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the bottlenose dolphin under RCP 4.5. 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). 229

Figure I-21 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the bottlenose dolphin under RCP 8.5. 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). 231

Figure I-22 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the sperm whale under RCP 2.6. 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). 232

Figure I-23 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the sperm whale under RCP 4.5. 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). 233
Figure I-24 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the sperm whale under RCP 8.5. 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). 234
Figure I-25 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Blainville's beaked whale under RCP 2.6. 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). 236
Figure I-26 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Blainville's beaked whale under RCP 4.5. 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). 237
Figure I-27 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Blainville's beaked whale under RCP 8.5. 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). 238
Figure I-28 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Cuvier's beaked whale under RCP 2.6. 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). 240
Figure I-29 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Cuvier's beaked whale under RCP 4.5. 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). 241

Figure I-30 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Cuvier's beaked whale under RCP 8.5. 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). 243

Figure J-1 – Differences in thermal suitability (mean, minimum and maximum) for RCP 2.6, 4.5 and 8.5 for Atlantic spotted dolphin (S. frontalis); short-beaked common dolphin (D. delphis); Bryde's whale (B. edeni); fin whale (B. physalus); Risso's dolphin (G. griseus); short-finned pilot whale (G. macrorhynchus); bottlenose dolphin (T. truncatus); sperm whale (P. macrocephalus); Blainville's beaked whale (M. densirostris); Cuvier's beaked whale (Z. cavirostris). 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 difference between historical (1956-2005) and future (2006-2055) thermal suitability. 246

Figure L-1 - Experts data quality scores for each species. Experts from the Madeira archipelago are identified as MAD#1; MAD#2; from the Azores archipelago as AZO#3; AZO#4 and from the Canary Islands as CAN#5; CAN#6. 249

Figure M-1 - Experts suitability scores for the Atlantic spotted dolphin (*Stenella frontalis*); short-beaked common dolphin (*Delphinus delphis*); Bryde's whale (*Balaenoptera edeni*); fin whale (*Balaenoptera physalus*); Risso's dolphin (*Grampus griseus*); bottlenose dolphin (*Tursiops truncatus*); sperm whale (*Physeter macrocephalus*); Blainville's beaked whale (*Mesoplodon densirostris*); Cuvier's beaked whale (*Ziphius cavirostris*); short-finned pilot whale (*Globicephala macrorhynchus*). 254

Chapter 1. Introduction

1.1 Setting the scene

As climate continues to change at a rapid, widespread and intensifying rate, ecosystems, biodiversity and human systems are witnessing increasingly severe, interconnected and often irreversible impacts (IPCC, 2022a). Changes to the climate system due to increased greenhouse gas emission over the last decades had, and will continue to have, long-lasting impacts on people and ecosystems.

As detailed in Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2019), anthropogenic climate change is the main driver of observed changes in ocean conditions, including ocean warming, increased acidification, decrease in Artic Sea ice extent and thickness, oxygen loss, and global sea level rise. These changes, as well as a weakening of the Atlantic Meridional Overturning Circulation (AMOC) and an increase in the frequency of marine heatwaves and other extreme events are projected to continue over the 21st century.

The global ocean contains 97% of the Earth's water and is a major regulator of the climate system through the uptake and redistribution of natural and anthropogenic carbon dioxide (CO_2) and heat. In addition to its role in the climate system, the ocean provides other services such as, for example, food and water supply, renewable energy, health benefits, cultural values, tourism, trade, and transport (IPCC, 2019). The loss of ecosystems and of the services they provide has cascading and long-term impacts, particularly for communities that depend on them to support the multiple socio-economic activities that sustain people's livelihoods (IPCC, 2022a).

These impacts are particularly severe in islands states, where sea level rise, coastal erosion and the increased frequency and intensity of extreme weather events (such as storms, heatwaves or droughts), threat the existing biodiversity, as well as agriculture, fisheries, and other human activities (Burney, 2009; Nurse et al., 2014).

Tourism is one of the main socio-economic activities on coastal and island nations worldwide (Bojanic and Lo, 2016; Hoyt, 2005). Marine ecotourism activities in particular (e.g. whale watching, diving) have the potential to bring socio-economic benefits to regional economies (Bentz et al., 2016; Cisneros-Montemayor et al., 2010; Ressurreição et al., 2022).

In Macaronesia (**Figure 1-1**), a region in the northeast Atlantic comprised of the Portuguese archipelagos of the Azores (9 islands) and Madeira (2 islands), and the Spanish archipelago of the Canary Islands (7 islands), the tourism sector is one of the main income sources. The Canary Islands are visited by 11.5 million tourists each year while 1.2 million people visited Madeira in 2014 (BEST, 2016) and almost 800 thousand visited the Azores in 2019 (SREA, 2019).

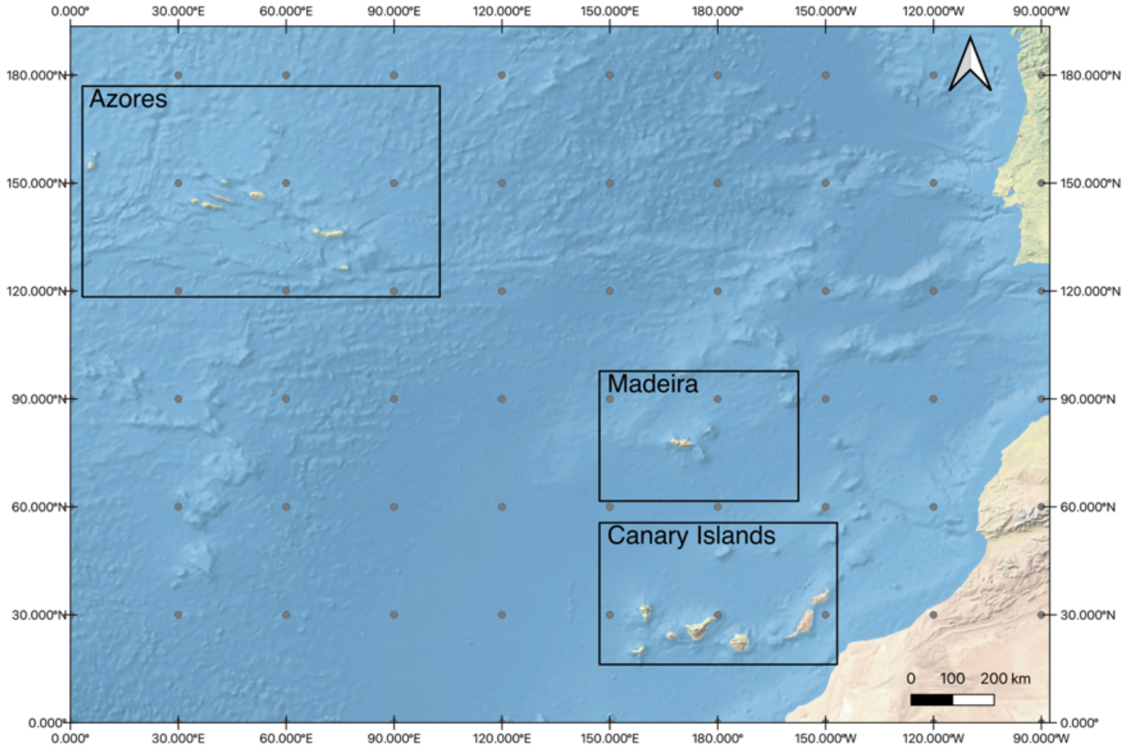

Figure 1-1 – The Macaronesia biogeographic region represented by the archipelagos of the Azores, Madeira and the Canary Islands.

Whale-watching tourism refers to commercial tours where tourists can encounter cetaceans (whale, dolphin, or porpoise species) in their natural habitat (Hoyt, 2001). The industry began to grow through the 1960's and 1970's, mainly in the west coast of the United States, and since the 1980's it has spread worldwide. Estimates for 2008 indicate that nearly 13 million people went whale watching in 119 countries and overseas territories, spending more than USD $2.1 billion (Hoyt, 2001; O'Connor et al., 2009). In Macaronesia, estimates indicate more than 35 million euros in direct income to the region as a result from this activity, representing 13.4% of the total tourism industry (IWC, 2022; Krasovskaya, 2017; Suárez-Rojas et al., 2021).

Macaronesia is one of the main international destinations for whale watching (Suárez-Rojas et al., 2019). The whale watching activity was first developed in the Azores and the Canary Islands, and only later in Madeira, and it has heterogeneous characteristics amongst the different archipelagos and between islands of the same archipelago (Suárez-Rojas et al., 2019). In general, the dimension of the activity and the mass tourism model in the Canary Islands contrasts with the other two archipelagos, while some similarities exist in the legislation and best practices defined for observing and approaching cetaceans (Krasovskaya, 2017; Silva, 2015; Suárez-Rojas et al., 2019).

An intrinsic part of whale watching and its success in ecotourism is its dependence on a high diversity and abundance of species. Oceanic islands are known to have several oceanographic features (e.g., currents) which shape local and regional productivity and enable a high congregation of biodiversity (Caldeira and Reis, 2017; Fernandez et al., 2021; Suárez-Rojas et al., 2019). About 30 cetacean species have been recorded on the archipelagos of Azores, Madeira and the Canary Islands (Alves et al., 2018; Carrillo et al., 2010; Silva et al., 2014). In the Azores, resident populations of sperm whales (*Physeter macrocephalus*), bottlenose dolphins (*Tursiops truncatus*), common dolphins (*Delphinus delphis*) and Risso´s dolphins (*Grampus griseus*) can be found, as well as migratory species such as blue whales (*Balaenoptera musculus*), fin whales (*Balaenoptera physalus*) and sei whales (*Balaenoptera borealis*), which are present in the archipelago especially in the spring and summer (Fernandez et al., 2018; Oliveira, 2005; Silva et al., 2014). In Madeira, populations of Atlantic spotted dolphin (*Stenella frontalis*), the short- beaked common dolphin (*Delphinus delphis*) and bottlenose dolphin (*Tursiops truncatus*) comprise 96% of all sightings (Alves et al., 2018). Other species such as the short-finned pilot whale (*Globicephala macrorhynchus*), the sperm whale (*Physeter macrocephalus*), and Bryde's whale (*Balaenoptera edeni*) also occur frequently in the archipelago (Alves et al., 2018, 2013; Dinis et al., 2016b). The Canary Islands foster resident populations of short-finned pilot whale, bottlenose dolphin and Blainville´s beaked whales (*Mesoplodon densirostris*), as well as transient species such as the Atlantic spotted dolphins and common dolphins (Arranz P. et al., 2008; Carrillo and Ritter, 2010; Herrera et al., 2021; Pecoraro, 2015; Reyes et al., 2015; Servidio et al., 2019; Verme and Iannacone, 2012).

The whale watching activity in Azores began in 1989 (Neves-Graça, 2004), and currently occurs in five different islands (São Miguel, Faial, Pico, Terceira and Santa Maria) with approximately 60% of the whale watching companies concentrated on the island of São Miguel (Bentz et al., 2016; Silva et al., 2013). Over the years, the activity has grown and is now the most practiced activity by tourists visiting the islands (Queiroz et al., 2014). Whale watching regulations were first implemented in 1999, and were revised over the years (Oliveira, 2005). Areas for whale watching were delimited and boat carrying capacities (i.e., maximum number of boats that can be in an area) were established to avoid overcrowding. Legislation on a code of conduct was also approved by the regional government (Regional Legislative Decree No. 10/2003/A), defining guidelines for approaching and observing the animals.

In the Canary Islands, whale watching started in the 1990's and currently occurs in all islands year-round. Yet, the island of Tenerife concentrates approximately 65% of the operator business and receives an estimated 5 million tourists a year (IWC, 2022; Sequeira et al., 2009; Suárez-Rojas et al., 2019). However, the mass tourism model of Tenerife contrasts with, for example, La Gomera, an island which offers exclusively dedicated whale watching tours. In the Canary Islands, the whale watching activity is regulated by the Royal Decree No. 1727/2007, which establishes approach guidelines, environmental and safety standards, and requires a cetacean specialist guide on board. However, the number of illegal boats has increased leading to a decrease in the service price and the quality of the whale watching experience (IWC, 2022). To address this issue, the Tenerife Tourism Corporation (TTC) developed a whale watching quality charter (Carta por la Sostenibilidad del Avistamiento de Cetáceos, 2018) which aims to contribute to the protection of cetacean species and promote Tenerife as a sustainable tourism destination. Adherence to the charter is voluntary, but public authorities are working to increase companies' participation (IWC, 2022).

In Madeira, the activity began in the early 2000s with the first dedicated whale watching company being created in 2007 in Funchal (Ferreira, 2007). Since then, a total of approximately 15 companies began operating, mainly from Funchal, and during the high season (summer) also from Porto Santo (Suárez-Rojas et al., 2019). Initially the whale watching activity followed voluntary guidelines (Ferreira, 2007), which became legally regulated in 2013 by the Regional Legislative Decree No. 15/2013/M.

Despite the regulations and guidelines implemented, impacts of whale watching in cetacean species have been recorded in all Macaronesian archipelagos. In the Azores, sperm whales were found to increase their rate of surfacing and breathing, particularly females accompanied by calves representing some indication of disturbance (Magalhães et al., 2002). Risso's dolphins in the Pico Island exhibited short term changes in behavior (Visser et al., 2011) and delphinid species in swim-with-dolphin programs showed a high degree of neutral and avoidance responses (Cecchetti et al., 2019). In Madeira, Ferreira (2007) found changes in the speed of small delphinids during and after the presence of whale watching boats, while Sambolino et al. (2022) found that island associated individuals of bottlenose dolphins and particularly pilot whales are subjected to intense exposure from whale-watching vessels. Finally, in the Canary Islands, whale watching was found to produce changes in behavior and chronic stress indicated by high levels of cortisol in the population of short-finned pilot whales in Tenerife (Crespo Torres et al., 2016) as well as a change of course speed and group cohesion when approached by boats (Aguilar et al., 2001). Other impacts in the Canary Islands include an increasing number of ship strikes from high-speed ferries (Carrillo and Ritter, 2010).

Despite the importance and long-term increasing trend in the whale watching activity in Macaronesia, there are limited studies on the topic, either from a socio-economic or an ecological perspective. Two reviews of the whale watching activity were undertaken for Macaronesia (Sequeira et al., 2009; Suárez-Rojas et al., 2019), while studies focusing on the socio-economic contribution of the activity were developed for the Azores (e.g., Oliveira, 2005; Ressurreição et al., 2022); the Canary Islands (e.g., Suárez-Rojas et al., 2019) and Madeira (e.g., Krasovskaya, 2017). While some studies focused on tourists' preferences and satisfaction in the region (Bentz et al., 2016; Suárez-Rojas et al., 2019), most studies focused on the biology and ecology of cetacean species (e.g., Visser et al., 2011; González García et al., 2018; Hartman et al., 2015; Alves et al., 2018; Carrillo and Ritter, 2010; Correia et al., 2020; Fernandez et al., 2021, 2018; Herrera et al., 2021) and on the current anthropogenic impacts faced by species (e.g., Cecchetti et al., 2019; Crespo Torres et al., 2016; Ferreira, 2007).

The impacts of climate change on whale watching, these are largely unknown in Macaronesia (Moreno, 2010). At the same time, studies that integrate socio-economic and ecological impacts of climate change on the activity are missing. Concurrently, there is the need to support conservation managers and practitioners, identifying which, when, and where management efforts are necessary, and which research areas need to be further developed to support such efforts (e.g., Lambert et al., 2014; McIvor et al., 2022). To date, only two frameworks were developed to address climate change and the whale watching activity. The first theoretical framework was developed by Lambert et al. (2010) and aimed to evaluate the resilience of whale watching tourism to climate change. Resilience was defined in this framework as the “degree of change in cetacean occurrence experienced before tourist numbers fall below a critical threshold.” The framework considered three variables: a) likelihood of observing a cetacean; b) trip type; and c) tourist type. The quantification of the three variables indicated the level of resilience of the whale watching activity to changes in cetacean occurrence from climate change. The second framework (Meynecke et al., 2017) was developed for the east coast of Australia based on a stakeholders’ participatory approach. This framework identified four key modules: 1) the biological module, focusing on species ecological related factors; 2) the climate module which considers relevant climate variables; 3) the management module related to regulations, enforcement or license conditions of the whale watching activity, and; 4) the socio-economic module, related, for example, to number and type of tourists, profit and costs of the activity.

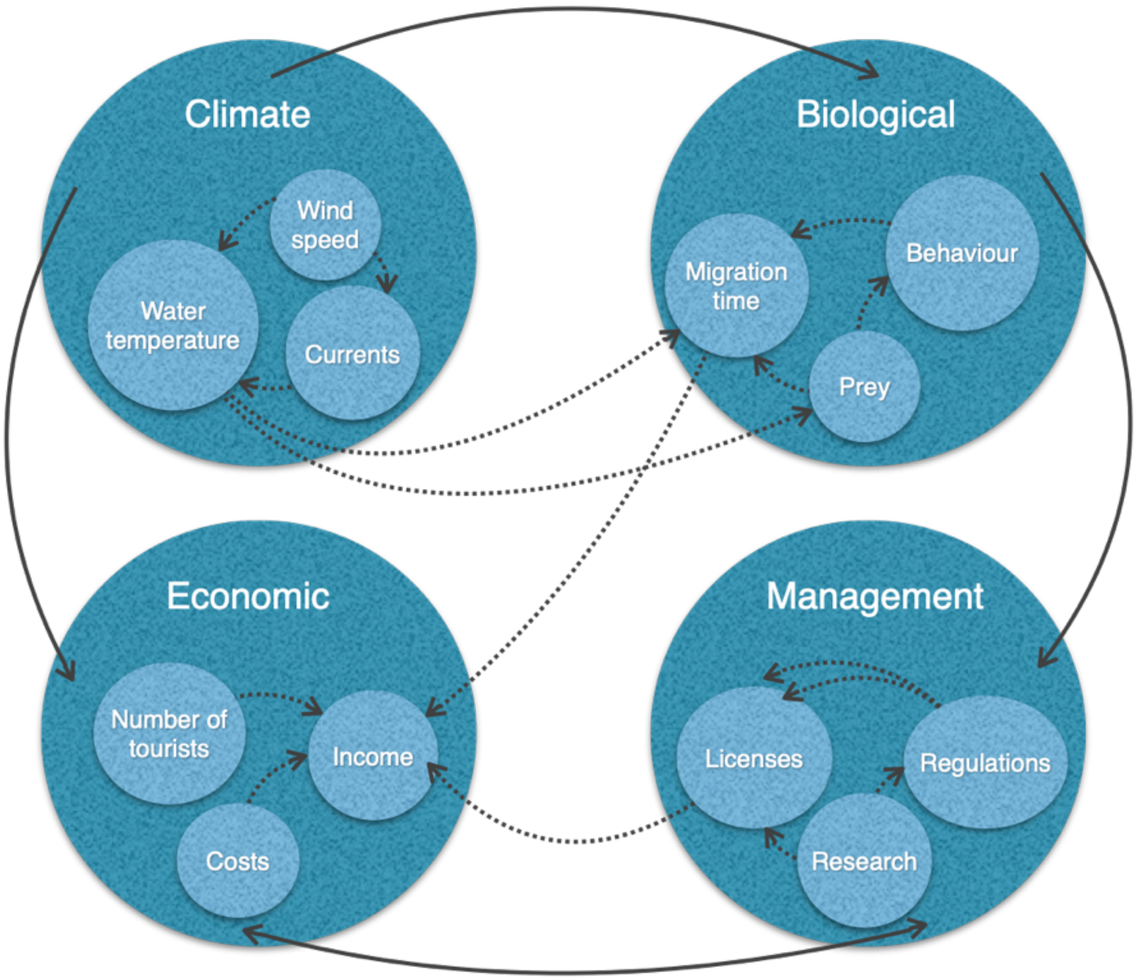

Figure 1-2 - Conceptual model adapted from Meynecke et al., 2017. A simplified representation of climate, biological, socio-economic and management modules and examples of relevant factors within each module. The relation between modules and factors within each module is represented by the arrows in the diagram.

In the present dissertation, the most recent framework from Meynecke et al. (2017) was adopted, beginning with the biological module, by assessing the vulnerability of cetacean species to climate change (**Figure 1-2**). There are three main approaches for assessing species vulnerability to climate change: 1) trend-based (correlative or mechanistic); 2) trait-based; and 3) a combination of both (e.g., Foden et al., 2019; Pacifici et al., 2015). Trend-based approaches can be correlative and aim to describe, for example, species geographic distribution under the current climate to then apply climate projections and infer species future distribution patterns (e.g., Becker et al., 2018; Lambert et al., 2014, 2011). These correlative models have the advantage of producing spatially explicit information and predicting species future distribution using occurrence data and are applicable to a wide range of taxa at different spatial scales (Pacifici et al., 2015). The main sources of uncertainty in correlative approaches are related to the different climate models used to simulate the future climate system, the algorithmic uncertainties in species' distribution models and the biological assumptions considered in the models (Foden et al., 2019; Pacifici et al., 2015). Mechanistic approaches establish relationships between species and their environment based on robust ecological and physiological principles such as physiological tolerances or competition and dispersal (e.g., Meynecke et al., 2017; Palacios et al., 2013; Silber et al., 2016). The main limitation for a wider applicability of mechanistic models relate to the intensive data collection required for species in order to parameterize these models which are costly and time-consuming (Foden et al., 2019; Pacifici et al., 2015; Silber et al., 2017). For marine mammals, correlative approaches using data-driven habitat models have been the most used approach to assess species vulnerability to climate change but are limited in projecting novel environments and in supporting longer time-scale management activities (Silber et al., 2017). Moreover, while methodological advancements are dependent on increasing knowledge of species biology and ecology, as well as improved regional climate projections, managers and conservationists urgently need guidance to prioritize management actions for a large number of species. In areas where there is a lack of available data, such as in Macaronesia, this endeavor is particularly challenging. In addition, there is the need to move from qualitative and descriptive methods and advance current knowledge through the improvement of existing modelling efforts, particularly mechanistic as well as development of novel approaches.

Expert elicitation approaches are a way to address this challenge. These approaches use the expertise of specialists to assess a topic where there is high uncertainty and lack of available data due to physical constraints or lack of resources. Expert elicitation methods have several possible biases, such as groupthink (seeking consensus to avoid conflict) and overconfidence or conservatism (i.e., overestimating or underestimating uncertainties) (Kuhnert et al., 2010; Mukherjee et al., 2016, 2015), which can be minimized through the qualification of such biases and the use of Delphi technique principles (Morgan, 2014; Mukherjee et al., 2018). The Delphi technic aims to construct consensus forecasts from a group of experts in a structured iterative manner (Rowe and Wright, 1999).

In addition to the biological module, the socio-economic and management module also needs to be evaluated (**Figure 1-2**). A comprehensive assessment and understanding of the socio-economy of whale watching is currently limited, particularly in Macaronesia. Most existing studies focus on the current quantification of economic trends from ticket sales, a sociodemographic characterization of the activity (e.g., Krasovskaya, 2017; Nicolau et al., 2007; Oliveira, 2005; Ressurreição et al., 2022; Suárez-Rojas et al., 2019) or on consumption preferences and tourism satisfaction (e.g., Bentz et al., 2016; Suárez-Rojas et al., 2021). Moreover, knowledge of the socio-economic impacts of climate change in the whale watching activity is limited due to the lack of available data and to the uncertainty related to future climate changes. In this context, a scenario framework developed by the climate change community can be used to assess the socio-economic vulnerability of the activity. This framework consists in the development and combination of shared socio-economic pathways (SSPs) and representative concentration pathways (RCPs) (Ebi et al., 2014; Moss et al., 2010; van Vuuren et al., 2014). The SSP and RCP framework define alternative visons of how society and climate may evolve in the coming decades and provide a structure to support integrated studies (O'Neill et al., 2020). SSPs have been developed globally (O'Neill et al., 2014) and for Europe (Kok et al., 2018) and aim to be extended to support the analysis of a wide range of sectors (heath, air pollution, oceans). RCPs, which explore climate change under different levels of radiative forcing, are then intersected with SSPs to represent possible scenarios that explore and evaluate uncertainties which are then used by communities to investigate adaptation and mitigation options.

There is, therefore, a need for developing novel and integrated methodological approaches to assess both the species and the socio-economic vulnerability of whale watching to climate change, in order to inform and anticipate possible impacts for the whale watching community, thus helping to adapt and maintain its sustainability in the long-term.

1.2 Objectives and Dissertation Structure

The present dissertation aims to *assess the integrated biological and socio-economical vulnerability of whale watching to climate change to support the long-term sustainability of the activity.* The Macaronesia bioregion is used as a case study to achieve this goal. The main research questions that have emerged from the theoretical framework were:

1) What is the ecological vulnerability of cetacean species to climate change?
2) What is the socio-economic vulnerability of whale watching to climate change?
3) How can the management of whale watching be supported under climate change?

This dissertation is composed of seven chapters, where Chapter 1 is the general introduction and Chapter 6 correspond to the general discussion, key findings and future research. Chapters 2 to 5 correspond to the main research chapters in this dissertation, where results are presented, analyzed, and discussed in detail. Chapters 2 to 4 address the first research question and Chapter 5 responds to the second and third research questions. Chapters 2, 3, 4 and 5 are published in international peer-reviewed scientific journals. Chapter 2 is published in *Ecological Indicators* and chapters 3,4 and 5 in the journal *Science of the Total Environment.* The dissertation structure is presented in **Figure 1-3**.

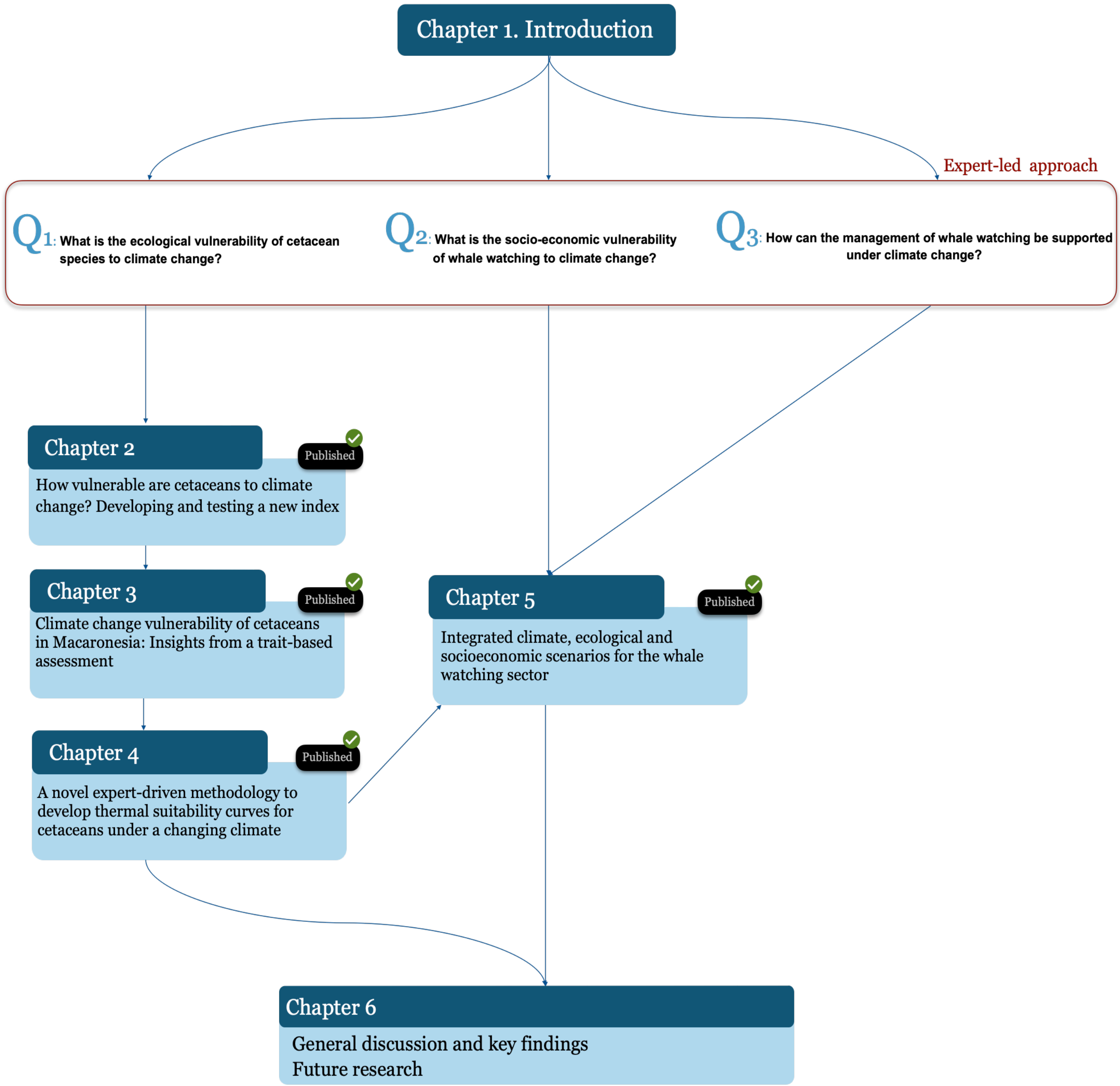

Figure 1-3 – Dissertation structure and research questions.

Chapter 2 was the first attempt at the development of a cetaceans climate change vulnerability index. Climate Change Vulnerability Indexes (CCVI) were initially built for the terrestrial environment and only recently for the marine environment (Hare et al., 2016; Stortini et al., 2015). Prior to this publication (Chapter 2), vulnerability indexes had only been developed for invertebrate and fish species in the marine environment. The developed CCVI followed a semiquantitative, expert-led methodology, with the collaboration of cetacean ecology experts from Madeira. The main objectives were to:

1. Develop a climate change vulnerability index
2. Test the developed approach by applying it to a case study of cetaceans in the Madeira archipelago
3. Identify the vulnerability of cetacean species in Madeira to climate change and main knowledge gaps
4. Review supporting evidence of climate change impacts in cetacean species and evaluate the robustness of our results
5. Provide contributions to cetaceans vulnerability assessment – i.e., identify main challenges and guide further research.

At the same time that Chapter 2 was being developed, the NOAA's Fisheries Office of Science and Technology was developing an index to assess the vulnerability of 108 marine mammal stocks in the western North Atlantic, Gulf of Mexico, and Caribbean, involving 46 experts during approximately 3,5 years (Lettrich et al., 2019).
Lessons learnt in Chapter 2 together with the work developed by Lettrich et al. (2019), were used to improve and extend the vulnerability assessment the remaining archipelagos of Macaronesia (Chapter 3).

In Chapter 3, the key concepts of vulnerability, sensitivity, exposure, potential impacts and adaptation defined in the 4th Assessment Report (AR) of the Intergovernmental Panel on Climate Change (IPCC) were adopted (**Figure 1-4**):

Vulnerability is *'the degree to which geophysical, biological and socio-economic systems are susceptible to, and unable to cope with, adverse impacts of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity'* (Parry et al., 2007) (**Figure 1-4**).

Exposure refers to *'the character, magnitude, and rate of change and variation in the climate'* (IPCC et al., 2001).

Sensitivity determines *'the degree to which a system is adversely or beneficially affected by a given climate change exposure'* (IPCC, 2007).

Adaptive capacity refers to *'the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences'* (Parry et al., 2007).

The main objectives were to:

1. Rank cetacean species vulnerability to climate change
2. Assess species potential distribution, abundance, and phenology changes
3. Compare the obtained results with previous vulnerability assessment outcomes
4. Provide methodological considerations and recommendations for future application of the index
5. Identify limitations and challenges to be addressed by future research

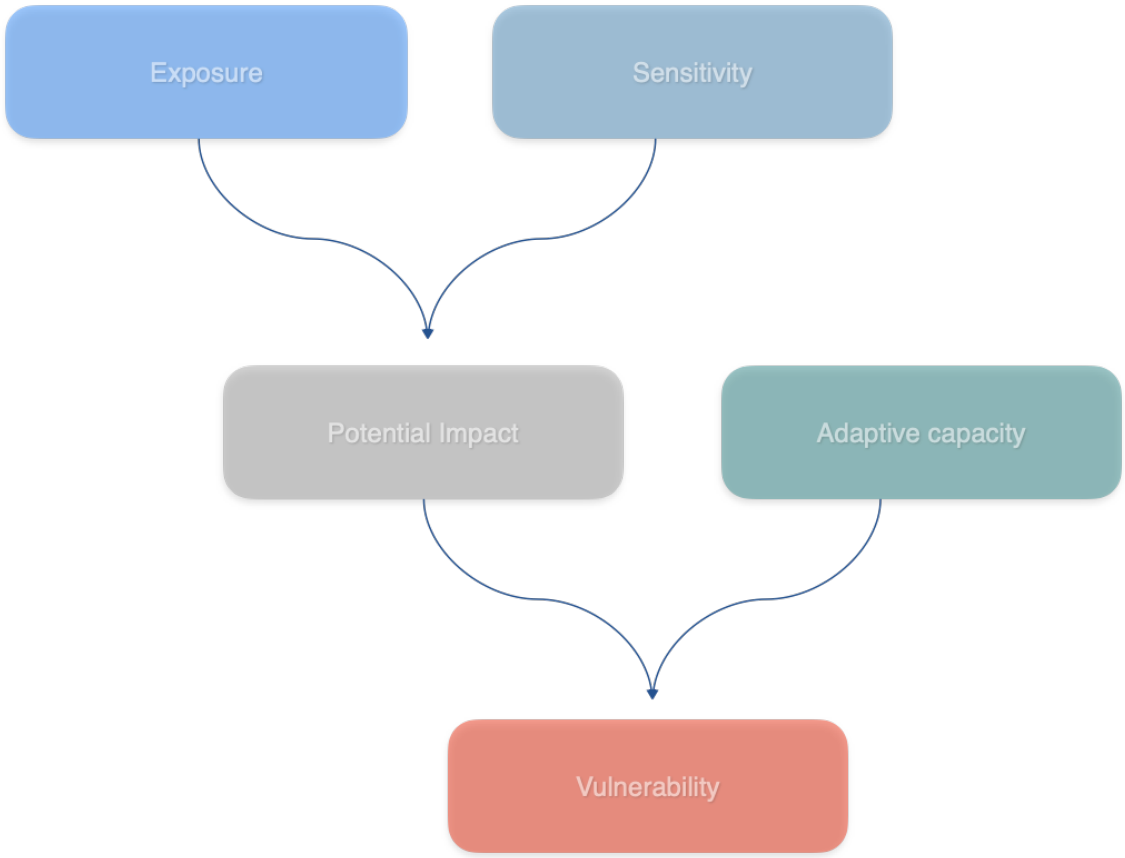

Figure 1-4 – Vulnerability as a function of exposure, sensitivity, potential impacts and adaptive capacity (Fritzsche et al., 2014).

Insights from the CCVI (Chapter 2 and 3), which provided a comparative ranking of species' vulnerability to climate change, brought useful information to assist decision-makers in defining and prioritizing conservation actions. However, particularly for the whale watching companies, a spatially explicit outcome was needed to better understand and plan for the potential climate change effects on species. To this end, a climate change thermal suitability method needed to be developed. Chapter 4 aimed to address stakeholders' needs by providing spatially explicit outcomes of species potential thermal suitability responses under different climate change scenarios. The main objectives were to:

1. Develop species thermal suitability curves
2. Assess species current thermal suitability and future responses under RCP 2.6, 4.5 and 8.5
3. Validate the obtained results with the available evidence for species in the region
4. Identify limitations and challenges to be addressed by future research

Chapter 5 aimed to provide an integrated assessment of the biological (Chapters 2 to 4) and socio-economic components of whale watching to climate change. The SSPs-RCPs framework (Van vurren et al., 2014; O'Neill et al., 2014) was used. European SSPs were downscaled for the whale watching activity (WW-SSPs) and future climate trends were described through literature review. Four whale watching scenarios were then created, integrating WW-SSPs, future climate trends and species thermal suitability responses (**Figure 1-5**). This scenario framework aims to assess and connect the complex interactions and intrinsic uncertainties between ecosystems, climate, and human activities, and to provide information to decision-makers to manage risk and prioritize actions. The main objectives of Chapter 5 were to:

1) Develop whale watching SSP narratives (WW-SSPs) and estimate future trends
2) Develop whale watching scenarios by integrating the climate (future climate trends), the biological (thermal suitability responses) and socio-economic (WW-SSPs) components of the activity
3) Assess, in a stakeholder workshop, the level of preparedness of the activity under the four different whale watching scenarios
4) Identify limitations and provide recommendations for the improvement of the WW-SSPs
5) Identify knowledge gaps and guide further research on the integration of whale watching components in the assessment of climate change impacts.

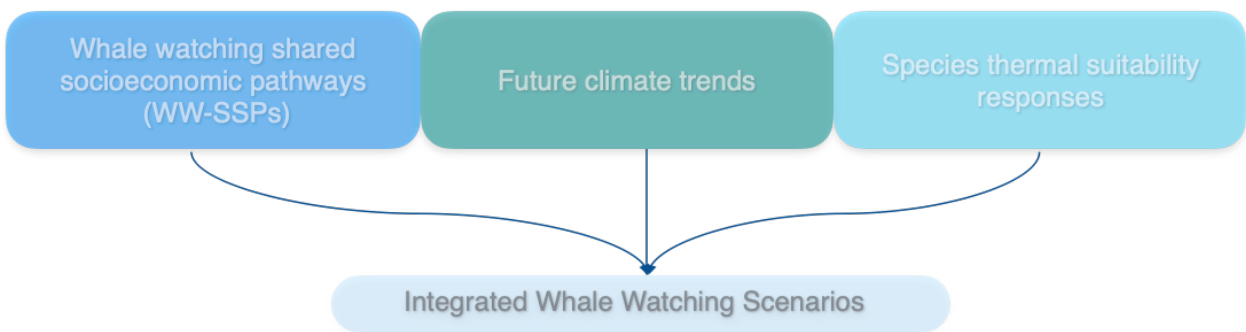

Figure 1-5 – Integration of future climate trends, species thermal suitability responses and whale watching SSPs into whale watching scenarios.

Finally, the information resulting from the work developed in this dissertation was used in a dedicated workshop by policymakers, conservation managers, scientists, company owners and non-governmental organizations to better understand the potential impacts of climate change and to inform and discuss the level of preparedness of the whale watching activity under the different scenarios.

Chapter 2. How vulnerable are cetaceans to climate change? Developing and testing a new index

The material in this chapter is currently published as: Sousa, A., Alves, F., Dinis, A., Bentz, J., Cruz, M.J. & Nunes, J.P. (2019) How vulnerable are cetaceans to climate change? Developing and testing a new index. Ecological Indicators, 98, 9-18. DOI:10.1016/j.ecolind.2018.10.046 (IF2019 4,229; Q1 Environmental Sciences)

2.1 Abstract

Climate change is altering chemical, physical and biological processes in the marine environment. Observed impacts driven by climate have been recorded and include changes in the species geographical distribution, timing of seasonal migrations, breeding biology and behavior of species. A number of qualitative and quantitative methodologies have been developed over the years to assess the vulnerability of animals to climate change. However, for marine species, the development and application of indices is recent, especially for large vertebrates such as marine mammals. In this context, the present study develops a trait-based climate change vulnerability index and applies it to seven cetacean species in the Madeira archipelago (Northeast Atlantic). The development of the index included the selection of sensitivity and exposure factors, the definition of each factor's score range, and the computation of results. It showed that the sperm whale (*Physeter macrocephalus*), the fin whale (*Balaenoptera physalus*), the Atlantic population of bottlenose dolphins (*Tursiops truncatus*) and the Bryde's whale (*Balaenoptera brydei*) were the most vulnerable species. The short-beaked common dolphin (*Delphinus delphis*), the island-associated bottlenose dolphins and the Atlantic spotted dolphin (*Stenella frontalis*) showed the lowest vulnerability to climate change. The outputs are consistent with previously proposed effects on whales and dolphins, considering their ecological similarities and exposure to environmental factors. This study shows that the developed index contributes to prioritize vulnerable species to climate change and to identify knowledge gaps in species ecological traits. The index results can contribute to inform policy makers in the definition of measures for species conservation.

Keywords: climate change; vulnerability assessment; whales and dolphins; Northeast Atlantic

2.2 Introduction

Marine ecosystems provide essential benefits to society through a number of regulatory, provisional, cultural and supporting services. These include food production for human consumption, cultural and recreational activities, the regulation of climate, and nutrient regeneration and supply (Millennium Ecosystem Assessment, 2005; Salomon and Dahms, 2018). However, oceans have been severely altered and depleted during the last century due to overfishing, chemical pollution, noise pollution or marine debris (Palumbi et al., 2009; Worm et al., 2006). In consequence, these services have been severely compromised, leading to the loss of biodiversity and their ecological functions (Duarte, 2000; Worm et al., 2006).

Climate change is causing an additional pressure to marine ecosystems increasingly threatened by these human induced pressures (Hoegh-Guldberg and Bruno, 2010). The effects of increased atmospheric greenhouse gas emissions leading to global warming, originates an increase in ocean heat content, ocean acidification, sea level rise and changes in current systems, contributing to the loss of marine biodiversity and ecosystem functions (EEA, 2016; IPCC, 2014) Observed climate impacts include changes in species geographical distribution, timing of seasonal migrations, breeding biology, and behavior (EEA, 2012; Brooker et al., 2007; EEA, 2016). Several studies have indicated that climate change, together with habitat loss or degradation resulting from human activities, heavily amplifies the vulnerability of species and ecosystems, constituting additional stress to biodiversity (EEA, 2012); Millennium Ecosystem Assessment, 2005; IPCC, 2014).

Several studies have described potential impacts of climate change on cetaceans (whales and dolphins), which are related to changes in the animals' distribution patterns, mainly due to variations in prey abundance or distribution (Learmonth et al., 2006; Simmonds, 2016; Simmonds and Isaac, 2007; Whitehead et al., 2008). Changes in distribution may also lead to competition for resources among species (MacLeod, 2009). Besides these impacts, changes in length and timing of migrations (Ramp et al., 2015) and in reproductive success (Leaper et al., 2006) have also been found. Moreover, higher temperatures may increase susceptibility and incidence of diseases and decreased reproductive capacity (Aguilar and Raga, 1993; Gambaiani et al., 2009; Leaper et al., 2006; Simmonds and Mayer, 1997; Whitehead, 1997). Many cetaceans that have restricted geographic distributions such as arctic species are less likely to adapt to climate change (Kovacs and Lydersen, 2008; Laidre et al., 2008).

The vulnerability of species to climate change can be assessed through qualitative or quantitative analyses such as correlative, mechanistic, trait-based assessments or a combination of these approaches (Pacifici et al., 2015). The choice of the methodology will vary according to the objectives of the assessment and the temporal, spatial and taxonomic scales at which it takes place. The complexity of biological processes and interactions challenge a precise prediction of how species and biological systems will respond to these changes (Cruz et al., 2015; Ramp et al., 2015; Silber et al., 2017; Simmonds and Isaac, 2007). In particular, the difficulty to predict with high levels of certainty how biodiversity will respond to the various climate-induced changes such as habitat fragmentation, biotic interactions, and species-specific variation in migratory and evolutionary capacity is a major factor limiting the assessment of species vulnerability and the development and implementation of adaptation measures for species (Bagne et al., 2011; Girvetz et al., 2014; Heller and Zavaleta, 2009). Despite this, there is still a need to provide policy makers and conservation managers with tools for this purpose. Trait-based indexes are particularly useful for institutions planning to develop adaptation or conservation strategies with limited time and resources. In general, these indexes can evaluate a wide range of taxa, compare and rank vulnerability between species and identify the major factors of vulnerability and important knowledge gaps (Cruz et al., 2015; Young et al., 2015). Challenges in the development of trait-based indices have been previously identified and focus on the selection and definition of sensitivity and exposure factors, namely: i) the potential co-relation between different factors (i.e. several factors measure the same aspect of vulnerability) (Simmonds and Smith, 2009), ii) unclear definition of factors which may lead to a biased application of the index by different experts (Cruz et al., 2015; Lankford et al., 2014; Simmonds and Smith, 2009), and iii) factors that may be relevant for some species but not for others (e.g. dependence on ice for some marine mammal species). Other identified limitations relate to the lack of information on specific parameters hindering their evaluation (Cruz et al., 2015; Simmonds and Smith, 2009). Possible impediments related to the computation of vulnerability scores include the weight attributed to different factors based on their relevance and the subjectivity involved in expert judgment scoring (Hare et al., 2016; Cruz et al., 2015; Lankford et al., 2014). In addition, a reduced number of experts can be a limitation to the robustness of vulnerability assessments. However, it can be difficult to recruit and involve experts with different backgrounds such as ecologists, oceanographers, climatologists or experts in the methodology development itself. Particularly in geographically isolated areas, gathering such expertise can be challenging. In the terrestrial environment, these challenges have been overcome and trait-based indexes have been used successfully to quantify species vulnerability to climate change (Cruz et al., 2015; Davison et al., 2012; Gardali et al., 2012). In the marine environment, the development and application of vulnerability indexes is more recent (e.g., Hare et al., 2016; Stortini et al., 2015), and, to our best knowledge, this is one of the first studies focusing on cetaceans.

The objective of this study was to develop a climate change vulnerability index for cetaceans' species and apply it in Madeira (Northeast Atlantic), an oceanic archipelago located in a warm-temperate latitude. It aimed at informing policy makers and identifying adaptation measures as a part of the archipelago's climate adaptation strategy. Our index follows the design developed by Hare et al. (2016) and accesses relevant factors that contribute to cetaceans' vulnerability. The advantages and limitations of this methodology are also considered. Finally, strategies for further improvement of the index in future vulnerability assessments are discussed.

2.3 Methods

2.3.1 Index development approach

The climate change vulnerability index for cetacean populations in the Madeira archipelago was constructed based on the selection of exposure and sensitivity factors relevant for cetacean species identified in Laidre et al. (2008) and Simmonds and Smith (2009). The assessment methodology was developed by Hare et al. (2016) for fishes and invertebrates to climate change in the NE U.S. Continental Shelf.

The index was developed in four steps:

In order to determine sensitivity factors relevant for cetacean species, a list of 16 potential factors was collected from two existing studies (Laidre et al., 2008; Simmonds and Smith, 2009). These factors were evaluated according to a set of criteria identified by Simmonds and Smith (2009): i) Data availability; ii) Objective definition; iii) Enabling differentiation, i.e., if the factor could contribute to differentiate vulnerability between species; and iv) No overlap, i.e., if the factor would measure a unique aspect of vulnerability and was not correlated with another listed factor. All factors that fulfilled these criteria were included in the index.

Exposure factors - sea surface temperature, salinity, pH and primary productivity - were obtained from NOAA's Earth System Research Laboratory (ESRL) online tool (http://www.esrl.noaa.gov/psd/ipcc/). Historical climate data from 1956-2005 and climate projection anomalies for the RCP 8.5 scenario (2050-2099) (IPCC, 2014) for the NE ocean were considered for evaluation in the index (Figure A-1).

For each sensitivity and exposure factor, three categories were defined reflecting the factor's contribution to the vulnerability of cetacean species. This contribution ranged between low (1) and high (3).

Factors were scored following the method developed by Hare et al. (2016), which is based on expert evaluation and considers three category scoring bins for each factor; experts are assigned five tallies to be distributed in the three score bins. The attributed factors' scores are based on the scientific literature and general knowledge available. Thus, in the case of Hare et al. (2016), experts who were certain about a category of sensitivity or exposure scored all five tallies in one scoring bin, while experts who were less certain in scoring a factor could distribute their tallies in two or three scoring bins. Local cetacean experts were recruited for this case study (see below).

Scores were calculated by summing all factors' results and multiplying them by the respective category score (1, 2 or 3). An average of the sensitivity and exposure scores was obtained. The vulnerability score was calculated as the product of sensitivity and exposure (Vulnerability = sensitivity * exposure).

A confidence assessment was performed for each factor and for the overall vulnerability results. Confidence was assessed as the sum of the data quality score and the experts score distribution of each factor (Factors confidence=experts distribution score + data quality). The experts score was measured through the experts' distribution of tallies in the different scoring bins for each factor.

A value was also assigned to reflect the quality of the data used to score the different factors based on the information available: (2) limited data, (1) expert judgment, or (0) no data available; following Hare et al. (2016). All scores were normalized and scaled from 0 to 1 (
Table **2-1**). The confidence level for sensitivity and exposure factors was calculated similarly. The confidence level of vulnerability results was calculated as the average of sensitivity and exposure confidence results, in percentage. Knowledge gaps, in sensitivity and exposure factors were identified based on the lowest confidence levels. Hare et al. (2016) identified four steps in the climate vulnerability assessment process. The first three steps (step one: Scoping and Planning; step two: Assessment Preparation; step three: scoring) were applied identically in this study. In the analysis (fourth step) the calculations used for estimation of sensitivity, exposure, overall vulnerability and the confidence assessment differed from Hare et al. (2016) considering these metrics can only be applied with additional number of experts (see case study details below).

2.3.1 Application to the case study

This method was applied to the cetaceans in the Madeira archipelago. The archipelago is located in the Northeast Atlantic and is composed by two main islands and two sub-archipelagos: Madeira and Porto Santo, and Desertas and Selvagens, respectively (Figure 2-1). The Economic Exclusive Zone (EEZ) of this archipelago comprises 446108 km^2. There are 26 confirmed cetacean species in the Madeira archipelago (Ferreira et al., 2017; Freitas et al., 2012), out of approximately 90 known species (Jefferson et al., 2015), which makes Madeira a location with a high cetacean diversity.

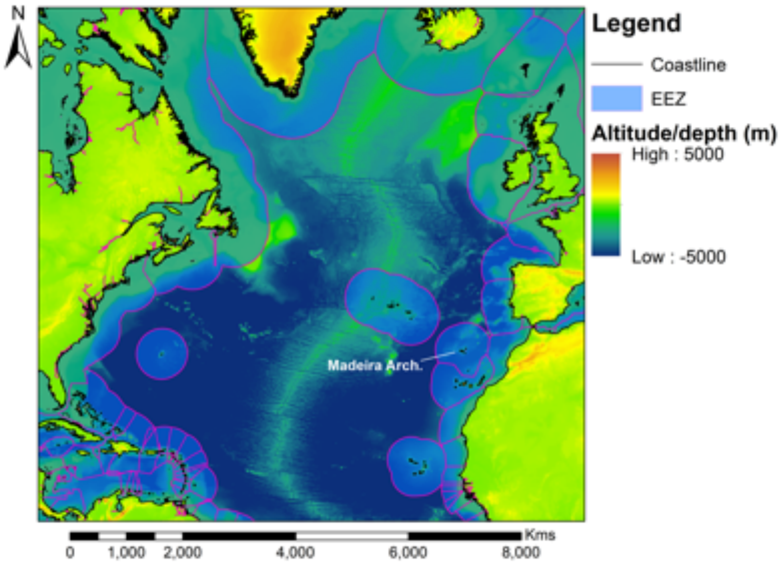

Figure 2-1– Map of the North Atlantic ocean and the Madeira archipelago and Economic Exclusive Zone. Data source: EEZ: Flanders Marine Institute, 2018; Coastline: Portuguese Hydrographic Institute, 2014; Altitude and Depth: ETOPO2 dataset (National Geophysical Data Center, 2006).

The index factors were scored based on expert knowledge; in this case, two experts on Madeira's cetaceans (F. Alves and A. Dinis) were consulted and jointly evaluated each species and scored each factor resulting in a single assessment per species. When experts disagreed in the score attribution, an average between both scores was obtained.

Experts selected a group of species to apply the vulnerability index based on their Regional International Union for the Conservation of Nature (IUCN) Red List status (Freitas, 2004). From the twelve species for which a conservation status was attributed, six were evaluated as data deficient (DD) and therefore were not considered in this study. The remaining six species evaluated in this study were: the fin whale (*Balaenoptera physalus*) classified as Endangered (EN), sperm whale (*Physeter macrocephalus*) classified as Vulnerable (VU), and short-finned pilot whale (*Globicephala macrorhynchus*), Atlantic spotted dolphin (*Stenella frontalis*), common bottlenose dolphin (*Tursiops truncatus*) (hearafter just bottlenose dolphin) and short-beaked common dolphin (*Delphinus delphis*) classified as Least Concern (LC). Additionally, Bryde's whale (*Balaenoptera brydei*) was included in the list of target species in the present study given that, despite not being evaluated in Freitas (2004) (because it only started being recorded in Madeira in 2003; Freitas et al., 2012), it has been identified among the four most frequently sighted species in Madeira since 2005 (Alves et al., 2010, 2018). Altogether, the seven target species considered in this study comprise over 88% of all cetacean sightings occurred in Madeira between 2005 and 2015 (Alves et al., 2018).

In addition to the migratory populations, bottlenose dolphins and short-finned pilot whale have island-associated individuals using Madeiran waters on a regular basis (i.e. resident and/or temporary migrants) (Alves et al., 2019, 2013; Dinis et al., 2016a, 2016b), and therefore were analyzed as independent populations.

2.4 Results

2.4.1 Index development

The selection of sensitivity factors for the cetacean climate change vulnerability index showed that only two were overlapping: the maximum rate of population increase and the reproductive rate, as they measure related aspects of population dynamics (

Table **2-1**). Since data availability for both factors was very limited, they were not included the index. Other excluded factors presented lack of available data, such as life-history related factors (e.g. reproductive rate), ecological factors (e.g. site fidelity) and factors related to changes of environmental conditions (e.g. environmental tolerances, phenological cues, changes in trophic web) and their direct impact on species and ecosystems. Overall, this evaluation excluded eight factors and added seven factors to the index: population size, geographic distribution, diet diversity, migrations, human activities, genetic variability and IUCN status (

Table **2-1**).

Table 2-1 - Definition and evaluation of sensitivity factors considered in the development of the cetacean climate change vulnerability index based on criteria derived from Simmonds and Smith (2009).

Factors	Definition (reference)	Criteria				
		Data availability	Objective definition	Enabling differentiation	Not overlapping	Selected factors
Population Size (North Atlantic)	More numerous species have potentially more options for adapting or reestablishing themselves in local or new areas (Laidre et al., 2008).	√	√	√	√	√
Geographic distribution (North Atlantic)	Widely distributed species can be less vulnerable than narrowly distributed species (adapted from Laidre et al., 2008).	√	√	√	√	√
Diet diversity	The ability to consume a variety of prey species should result in decreased sensitivity (Laidre et al., 2008).	√	√	√	√	√
Migrations (extent and frequency)	Migratory species are characterized as more vulnerable due to a potential specific temporal or seasonal reliance on a certain habitat (Laidre et al., 2008).	√	√	√	√	√
Human Activities	Species subjected to increased human activities and other stressors may be less able to adapt to changes in climate (identified in Simmonds and Smith (2009), and defined in this study).	√	√	√	√	√
Genetic Variability	Species with high genetic variability that are subjected to other stressors may be less able to adapt to changes in climate (Young et al., 2011).	√	√	√	√	√
IUCN Status	The IUCN global and regional status (IUCN, 2017; Simmonds and Smith, 2009) provides additional relevant information on the conservation status on species in risk.	√	√	√	√	√
Individual site fidelity	Summer or wintering grounds, haul-out areas or denning areas under 25 000 km^2. Heavy reliance on localities with predictable environmental conditions increases species sensitivity (Laidre et al., 2008).	X	√	√	√	X
Environmental tolerances	Possibility of exceedance of species' physiological tolerances, e.g. temperature or pH range (from IUCN, 2007, cited in Simmonds and Smith, (2009)	X	√	√	√	X

Factors	Definition (reference)	Criteria				
		Data availability	Objective definition	Enabling differentiation	Not overlapping	Selected factors
Environmental cues	Dependence on specific environmental triggers or cues that are likely to be disrupted by climate change (e.g. migratory species; certain temperatures for calf rearing; Simmonds and Smith (2009).	X	X	X	√	X
New competition	Likelihood of other species moving into habitat areas, leading to competition and/or adverse effects (Simmonds and Smith, 2009).	X	√	√	√	X
Population health	Health indicators for poor body condition and/or respiratory problems that may be affecting a critical part of the population (Simmonds and Smith, 2009).	X	√	√	√	X
Changes in trophic web	Sensitivity of species to changes in to altered patterns of primary and secondary production, or other trophic web changes due to climate change (Laidre et al., 2008).	X	√	√	√	X
Reproductive rate	Scaled quantification of reproductive rate (Simmonds and Smith, 2009).	X	√	√	√	X
Maximum rate of population increase	Species with a high growth potential are more able to take advantage of good environmental conditions while those with low growth potential tend to be more vulnerable to extinction (Laidre et al., 2008).	X	√	√	X	X

For each of the seven selected factors, three vulnerability categories were established according to the previously defined methodology and with the support of the two local cetacean experts (Table 2-2).

Three sensitivity factors - genetic variability, diet and human activities, proved challenging to evaluate and categorize. Genetic variability is difficult to define due to the necessary selection of genetic indicators to be applied to a wide range of species. Since there are several measures of genetic variability there is not a specific indicator or threshold to distinguish among categories. Thus, this study followed the approach used by Young et al. (2011) for terrestrial species where the factor is scored qualitatively as a measure of relative variability in comparison to the genetic variability measured in related species. The diet factor categories were distinguished by one, more than two or three varieties of prey comprising > 20% of a species diet (Table 2-2).

Table 2-2 - Sensitivity categories defined for each sensitivity factors in the vulnerability index with three scores ranging from 1 = the factor does not increase the species' sensitivity, to 3 = the factor strongly increases species' sensitivity.

Sensitivity factors	Category - scores (1 to 3)	Reference
Population size	<100.000 - SCORE = 3	Laidre et al., 2008
	100.000-500.000 - SCORE = 2	
	>500.000 - SCORE = 1	
Geographic distribution	restricted to a specific area - SCORE = 3	Defined by experts in this study
	widespread in the Northeast Atlantic but restricted by habitat (e.g. coastal or inshore waters) - SCORE = 2	
	widespread in the Northeast Atlantic - SCORE = 1	
Diet diversity	One prey type comprises > 20% of its diet - SCORE = 3	Laidre et al., 2008
	Two prey types comprise > 20% of its diet - SCORE = 2	
	Three or more prey types comprise > 20% of its diet - SCORE = 1	
Migrations	Whole population undertakes an annual migration of >1000km along defined routes and specific sites used through the year -SCORE = 3	Laidre et al., 2008
	Population undertakes smaller migrations or substantial regional shifts - SCORE = 2	
	Population stays in the same general region throughout the year - SCORE = 1	
Human activities	Human activities contribute to an increase in species vulnerability - SCORE = 3	Defined by experts, in this study
	Human activities do not increase nor decrease species vulnerability - SCORE = 2	
	Human activities contribute to a decrease in species vulnerability - SCORE = 1	
Genetic variability	Low genetic variability compared to other evaluated cetacean species - SCORE = 3	In this study
	Medium genetic variability compared to other evaluated cetacean species - SCORE = 2	
	High genetic variability compared to other cetacean species - SCORE = 1	
IUCN Status	Critically Endangered (CR), Endangered (EN) or Vulnerable (VU) - SCORE = 3	Defined by IUCN. Categories defined by experts in this study
	Near Threatened (NT) - SCORE = 2	
	Least Concern (LC) - SCORE = 1	

2.4.2 Index application to the case study

The results of the experts' assessment are shown in Table 2-3. The scoring reflected species' specificities; for example, in the geographic distribution factor, scorings for the island-associated species reflected the larger degree of site fidelity in these species for the Madeira archipelago. It should be noted that information on the percentage of main prey type consumed by a species was often not available, and experts had to use an estimate to score the diet factor. Exposure factors were evaluated considering the spatial distribution of each factors' anomalies in the North Atlantic. Experts attributed the same score to all exposure factors for each species since the latitudinal variation was the same. This was essentially attributed to the distribution range of species, i.e. species which migrate to the Arctic are more exposed since they experience a broad range of variation as opposed to island-associated species for which variation in exposure factors is small.

The experts' evaluation of both sensitivity and exposure factors resulted in a ranking of cetacean species vulnerability to climate change (Table 2-3). The sensitivity factors that contributed most to species vulnerability were (small) population size, (impact of) human activities, and migration patterns. Confidence levels are lower for human activities factor since there is little evidence to support how these activities will evolve in the future. Species with the highest exposure scores were fin whales, bottlenose dolphins and common dolphins. Island-associated individuals had a lower exposure factor due to their site fidelity patterns in Madeira. Data quality for sensitivity factors was higher for bottlenose dolphin (both oceanic and island-associated individuals), short-beaked common dolphins and island-associated short-finned pilot whales. The lowest result was attributed to Bryde's whales. These results reflect the available information for these species. Data quality for all exposure factors was considered equally adequate based on the source of the information provider - the NOAA's Climate Change Web Portal.

The most vulnerable species were sperm and fin whale and the least vulnerable species were the short-beaked common dolphin, together with the island-associated individuals of bottlenose dolphin and Atlantic spotted dolphins (Table 2-3). In the vulnerability assessment, the confidence levels were higher for island associated bottlenose dolphins (81%) with all other species having a higher than 70% confidence level, except for sperm whale (69%). It should be noted that confidence calculations differ from Hare et al. (2016), since in this study the two experts performed a single joint assessment and agreed in the scoring of data quality and distribution of tallies, with the exception of the IUCN status for the sperm whale (in which case an average was calculated).

Table 2-3 – Species' sensitivity scores. Scores for each factor and confidence results in brackets. Scores were re-scaled from 0 to 1. Species are ranked by decreasing order of vulnerability.

	Sensitivity											Exposure				Vulnerability	
	Factors score (CONFIDENCE)																
Species	Population size	Geographic distribution	Diet diversity	Migrations	Human activities	Genetic variability	IUCN Status	Score	Distribution of tallies	Data quality	Confidence	Score	Distribution of tallies	Data quality	Confidence	Score	Confidence
Balaenoptera physalus (Fin whale)	1 (0.8)	0.0 (1.0)	0.8 (0.8)	0.9 (0.8)	0.6 (0.4)	0.1 (0.6)	1.0 (0.8)	0.63	0.7	0.8	75%	0.8	0.5	1	75%	0.5	75%
Physeter macrocephalus (Sperm whale)	0.8 (0.6)	0.0 (1.0)	0.8 (0.8)	0.8 (0.8)	0.6 (0.4)	0.7 (0.4)	0.9 (0.4)	0.65	0.4	0.8	60%	0.4	0	1	50%	0.26	69%
Tursiops truncatus (Bottlenose dolphin)	0.7 (0.6)	0.0 (1.0)	0.0 (1.0)	0.4 (0.8)	0.6 (0.4)	0.0 (1.0)	0.0 (0.8)	0.24	0.7	0.9	80%	0.8	0.5	1	75%	0.19	78%
Balaenoptera brydei (Bryde's whale)	0.8 (0.6)	0.0 (1.0)	0.0 (1.0)	0.4 (0.6)	0.6 (0.2)	0.8 (0.6)	0.5 (0.6)	0.44	0.6	0.7	65%	0.4	0	1	50%	0.18	70%
Globicephala macrorhynchus (Short-finned pilot whale)	0.9 (0.6)	0.1 (0.8)	0.8 (0.8)	0.5 (1.0)	0.6 (0.4)	0.1 (0.6)	0.0 (0.6)	0.43	0.5	0.8	65%	0.4	0.5	1	75%	0.17	72%
Globicephala macrorhynchus (Short-finned pilot whale) **Isl.associated**	1.0 (1.0)	0.8 (0.8)	0.8 (0.8)	0.2 (0.8)	0.8 (0.6)	0.1 (0.6)	0.0 (0.8)	0.53	0.7	0.9	80%	0.3	0.5	1	75%	0.16	77%
Delphinus delphis (Common dolphin)	0.4 (0.6)	0.0 (1.0)	0.0 (1.0)	0.5 (1.0)	0.6 (0.4)	0.1 (0.8)	0.0 (0.8)	0.23	0.7	0.9	80%	0.6	0	1	50%	0.14	78%
Tursiops truncates (Bottlenose dolphin) **Isl.associated**	1.0 (1.0)	0.8 (0.8)	0.0 (1.0)	0.4 (0.8)	0.8 (0.6)	0.0 (1.0)	0.0 (0.8)	0.43	0.8	0.9	85%	0.3	0	1	50%	0.13	81%
Stenella frontalis (Spotted dolphin)	0.4 (0.4)	0.0 (1.0)	0.0 (1.0)	0.4 (0.6)	0.6 (0.2)	0.1 (0.8)	0.0 (0.8)	0.21	0.6	0.8	70%	0.4	0	1	50%	0.09	72%

2.5 Discussion

2.5.1 Cetaceans' vulnerability to climate change in the Madeira archipelago

This study shows that the index that we developed and trialled appears to function well in the assessment of species vulnerability to climate change. The index identifies and weighs relevant sensitivity and exposure factors providing a ranking of species vulnerability. The index proved useful in a context where limited information on observed and projected impacts of climate change for cetaceans in Madeira is available. Furthermore, most of the evidence on impacts of climate change derives from studies in species distribution changes. These studies provide information on geographic distribution, migration patterns and diet and show highly scored confidence levels. Other factors that require further research are human activities and their additional consequences on species vulnerability to climate change.

Of the seven cetacean species analyzed in this study, the vulnerability score identified the sperm whale as the most vulnerable, with a score of 0.52. This is due to high scores in both sensitivity factors (0.65, the highest score) and exposure factors (0.8, the highest score attributed to other two species: the fin whale and the bottlenose dolphin). The high sensitivity is due mostly to the low genetic variability and diet diversity, as well as one of the highest IUCN status and the highest migration score.

The second most vulnerable species is the fin whale, with a vulnerability score of 0.50. This value is markedly close to the vulnerability score obtained for the sperm whale. In fact, the sensitivity scores of both species are very similar (0.6 and 0.65 respectively) although the genetic variability of sperm whales is considerably lower according to ocean-wide genetic studies (Lyrholm et al., 1999). In addition, exposure factors were scored similarly for both species despite the difference in male and female migratory pat- terns of sperm whales. While males are known to migrate to polar areas in the summer, females and calves distribute in tropical and subtropical areas. In Madeira, sperm whales are present throughout the year, mainly by groups of females and immatures (Freitas et al., 2012). However, even if females and calves are less exposed since they have more restricted distribution areas, males are essential to the population survival and overall vulnerability.

The highest IUCN score is attributed to fin whales. Considering the importance of the IUCN ranking in this assessment, we note that if the fin whale were to lose its endangered status to a lower status, the vulnerability score would decrease by 0,5 (0.45 vulnerability score) and 1 (0.39 vulnerability score) for Near Threatened and Least Concern, respectively. Despite not affecting the overall ranking, this may not be the case if IUCN status changes in conjunction with other factors. For diet diversity, the high sensitivity is due to North Atlantic fin whales consuming pelagic schooling fishes but mostly crustaceans such as northern krill *Meganyctiphanes norvegica* (Ryan et al., 2013). As for the migratory patterns of fin whales, they follow the generally accepted model of baleen whale migration worldwide, which describes seasonal movements from feeding grounds (high latitudes) and breeding grounds (low latitudes). Wide-ranging migratory species such as fin whales are more vulnerable to effects of climate change (Gauffier et al., 2018), leading to a higher score in the migration factor. In the nearby Azores archipelago (central North Atlantic), Silva et al. (2013) suggest that along their migratory route, fin whales alternate between periods of active migration and periods of area restricted habitat use. In Madeira, this species is observed with higher incidence in spring and summer (Freitas, 2004), suggesting that Madeira could also be a stopover area along their migratory route. Therefore, this species experiences more variations in exposure factors when compared with other species.

The next species in the vulnerability rank are the bottlenose dolphin and the Bryde's whale, with a vulnerability score of 0.19 and 0.18, respectively. In this case it is worth noting that, although the overall vulnerability score is similar, there is a marked difference in the contribution of sensitivity factors and exposure factors for each species vulnerability score. The sensitivity score for the Bryde's whale (0.44) is twice that of the bottlenose dolphin (0.24) due to two factors: i) genetic variability which was assumed low for Bryde's whale based on the available evidence for the Gulf of Mexico (Rosel and Wilcox, 2014), and ii) the IUCN category which was scored higher based on expert judgment. Bryde's whales are the least known of the large baleen whales and knowledge on their taxonomy, distribution and abundance is limited (Kato and Perrin, 2018). Their global IUCN status is Data Deficient, and their regional status was not attributed due to the limited information and their limited presence in the waters of Madeira (Freitas, 2004). However, since 2003 when they were first sighted in Madeira (Freitas et al., 2012), some individuals have demonstrated a seasonal residence during the summer (Alves et al., 2010). In contrast, the difference in the exposure factors score is of the same magnitude, except that it is higher for the bottlenose dolphin (0.8) than for the Bryde's whale (0.4). Bottlenose dolphins have a wider distribution range including in oceanic and coastal areas in the North Atlantic and are subject to higher variation in exposure factors while Bryde's whales have their northern limit distribution range around Madeira archipelago.

The following species in the vulnerability score rank is the Atlantic population and the island-associated individuals of short-finned pilot whales. The main difference in sensitivity factors (0.43 and 0.53, respectively) is due to the high sensitivity score in the population size, geographic distribution, and impact of human activities factors for the island-associated individuals. These individuals demonstrate a large degree of variability in site fidelity with an estimate 140 (95% CI: 131–151) individuals using the southern and eastern waters of Madeira (Alves et al., 2015). Thus, the low vulnerability score is mostly due to a low exposure factor score (0.3), in fact, lower than the score attributed to all other species in this study due to their island-associated patterns of occurrence in Madeira.

The least vulnerable species are the common dolphin, the island- associated bottlenose dolphins and the spotted dolphin, with vulnerability scores of 0.14, 0.13 and 0.09 respectively. The common dolphin and spotted dolphin show similar sensitivity scores for all contributing factors, and the difference in vulnerability scores was mostly due to different scores in exposure factors (0.6 and 0.4, respectively). This scoring is due to common dolphins' distribution being further north than spotted dolphins which increases their exposure to climate factors.

Similarly, to island-associated short-finned pilot whales, bottlenose dolphins in Madeira show large variability in residency pattern, with resident, transient and migrant individuals. Dinis et al. (2016b) found that, of the 400 dolphins found in southern Madeira, approximately 45.8% were resident dolphins. The island-associated individuals are less exposed to changes in climate factors and the main difference in sensitivity factors scoring is due to the diet of short-finned pilot whales consisting primarily of squid (Desportes and Mouritsen, 1993; Mintzer et al., 2008).

The confidence levels reflect the amount and accuracy of the information used to score each species in this study. Confidence levels are higher for island-associated species where most research studies take place. In Madeira, dolphin species have been probably more studied than baleen whales (Freitas et al., 2012; reviewed in Alves et al., 2018), which is reflected in the confidence levels of sensitivity factors. Total confidence levels (i.e., vulnerability confidence levels) are high for all species due to the confidence attributed to exposure factors being 50% or higher; the weight of the sensitivity confidence scores have a lower contribution to total confidence levels. Comparing confidence levels readily informs which species and factors have greater knowledge gaps, which can provide an indication of where research efforts are necessary.

2.5.2 Supporting evidence of climate change impacts in cetacean species

Cetaceans' direct responses to climate change are difficult to discern due to other confounding factors such as the ones originated by anthropogenic activities. Nonetheless, several studies have gathered evidence of the impact of climate change leading to several modifications in cetacean species such as: distribution changes (e.g., Lambert et al., 2014), changes in timing and length of migrations (e.g., Ramp et al., 2015), lower conception rate and changes in community composition and structure (e.g., MacLeod et al., 2005). For some of the species accessed in this study, evidence of the impact of climate change has been described (see below), mostly related to changes in distribution patterns, which corroborates with the results of the vulnerability index for these factors. This shows that in fact the most relevant factors scored in the index are the ones for which some evidence has been observed.

For fin whales in the Mediterranean, Azzellino et al. (2008) found that a change in sea surface temperature led to a change in the species' distribution patterns. Nøttestad et al. (2015) also found changes in the distribution of baleen whales in the Norwegian Sea, namely minke whales (*Balaenoptera acutorostrata*) and fin whales (*Balaenoptera physalus*) due to changes in prey species. In particular, it is suggested that elevated sub-surface temperatures may be driving changes in the distribution and aggregation of macro-zooplankton which is becoming less available leading to a distribution overlap with pelagic fish which is becoming a more abundant dominant prey. Ramp et al. (2015) found temporal and spatial changes in migration patterns of North Atlantic fin whales related to rising sea surface temperature and earlier ice break-up. This agrees with the index scoring of migration patterns and exposure factors for this species.

Sperm whales in the Mediterranean were also found to change their distribution patterns with changes in sea surface temperature, similarly to fin whales (Azzellino et al., 2008). In the Atlantic, rises in sea surface temperature led to changes in movement patterns of sperm whales, probably related to changes in squid prey species distribution. This was reported by Pierce et al. (2007) in the North Sea resulting in an increase in strandings and by Robinson et al. (2005) in the Northeast Atlantic where shifts in the North Atlantic Oscillation could affect squid prey species. The high scoring of migration and diet together with exposure factors for sperm whales supports the index results. In addition, in the Galapagos, periods of warmer sea water (usually caused by El Niño events) have been associated with a decrease in reproductive success of sperm whales (Whitehead, 1997). For short-finned pilot whales, increasing sea surface temperatures in the North Atlantic may cause a northward range shift, which may lead to interspecies hybridization with the long-finned pilot whale (*Globicephala melas*) (Miralles et al., 2016).

Kerosky et al. (2012) found an increase in Bryde's whales detected calls in the Southern California Bight between 2000 and 2010, indicating a potential seasonal range expansion. The authors suggest that these individuals may be following prey outside their boundary distribution range and may therefore be affected by long-term climate variability. For bottlenose dolphins a number of studies have related changes caused by climate change. In the Mediterranean, bottlenose dolphin populations were found to spend more time and effort in feeding activities due to reduced prey availability (Bearzi et al., 1999; Politi, 1998). Lusseau et al., 2004) reported that group sizes of bottlenose dolphins in Moray Firth (UK) varied from year to year in relation to large scale ocean climate variation; since local indices of prey abundance vary with climate and availability of prey affect predator group sizes, changes in social organization of cetaceans' population occur, as they tend to live in smaller groups when there were less salmon. Also, in the Northeast coast of Scotland, Wilson et al. (2004) found evidence of a recent range expansion beyond the bottlenose dolphins' northern limit that may be related to changes in prey abundance and/or distribution generated by climate variation. Finally, the alteration of the distribution and availability of key prey species in the Adriatic Sea, possibly due to climatic shifts led to a change in distribution patterns of bottlenose dolphin populations (Blanco et al., 2001).

Common dolphins in Northwest Scotland have been shown to have expanded their range in a poleward shift, altering the species' distribution (MacLeod et al., 2005). Similarly, to bottlenose dolphins, changes in distribution and availability of prey species in the Adriatic Sea attributable to climate change led to a change in distribution pat- terns of common dolphin populations (Blanco et al., 2001). Finally, in the Alboran Sea, a potential reduction in common dolphins' suitable habitat may occur due to an increase in sea surface temperature (Cañadas and Vázquez, 2017).

In Madeira, few studies have been conducted on the observed impacts of climate change on marine species. These show that non-indigenous fish in marine waters of Madeira were found to be range expansions from tropical and subtropical areas that are extending their northern limit, possibly due to climate change (Freitas and Canning-Clode, 2014). The arrival and increase in tropical fish species such as *Abudefduf saxatilis*, *Aluterus scriptus*, *Canthidermis sufflamen*, *Caranx crysos* and *Gnatholepis thompsoni* may lead to a significant change in the faunal composition of Madeira (Bianchi et al., 1999; Freitas and Canning-Clode, 2014; Wirtz et al., 2008).

In Madeira there are limited observations of changes in cetacean species potentially attributed to climate change. It is suggested that island-associated individuals of short-finned pilot whales and bottlenose dolphins rely on the archipelago's oceanographic features for feeding and breeding (Alves et al., 2015; Dinis et al., 2017), which may differ under climate change. Moreover, tropical species such as the Bryde's whale and the Atlantic spotted dolphin have been recorded in Madeira only in 1997 and 2003, respectively (Freitas et al., 1998, 2012), and nowadays are among the most four frequently sighted cetacean species (Alves et al., 2018). A similar explanation to that of the Southern California Bight (Kerosky et al., 2012) can be proposed to explain that scenario, i.e., an increase in temperature is altering the northern limit of distribution of several fish species, which may have resulted in an increase in the number of Bryde's whales in the area.

2.5.3 Case study contributions to cetaceans' vulnerability assessment

The limited availability of ecological information on cetacean species and evidence of the observed impacts of climate change, as described above, creates a challenge when attempting to predict changes in cetacean species due to climate change. The index developed in this study can assist in the prioritization of species vulnerability, which makes it a useful tool for decision-makers prioritizing conservation and adaptation measures for cetaceans under climate change. This useful- ness can be expanded, since marine mammals, namely cetacean species, have been considered prime sentinel species of ecosystem health (Bossart, 2011; Moore, 2008). These species are top predators with long life spans and thus provide indications of changes in marine ecosystems.

From an economic standpoint these populations are also particularly relevant for tourism and are a key economic activity, particularly in insular ecosystems. This accentuates the necessity to preserve cetacean species with informed, science-based policies. In Madeira, the most recent estimates (O'Connor et al., 2009) indicate that the Archipelago grew its whale watching activity by 73% between 1998 and 2008 as it became an essential part of the archipelagos' proceeds. It accounts for 7% of Europe's whale watchers and together with Azores islands has the largest portion for Europe with approximately 23% of total revenues (O'Connor et al., 2009). This makes the vulnerability assessment of cetacean species an important part of a larger socio- economic vulnerability assessment in Madeira and similar archipelagos.

The implications of climate change for species management are challenging to address due to lack of information and baseline data on cetacean populations. The collection of long-term data through monitoring schemes are essential to provide robust evidence on population changes that can promote modeling advances in the projection of species distribution under climate change (Silber et al., 2017; Simmonds, 2016). Concrete management actions generally focus on the reduction of existing human pressures on populations or on flexible approaches in the management of marine protected areas. In Madeira, the main threat to cetacean populations are the interactions with the whale watching boats and maritime traffic (Cunha, 2013; SRA, 2014). The interactions of cetaceans with fishing vessels are reduced and there are only a few records of by-catch (Nicolau et al., 2014). In 2016, a site for the protection of cetacean species was created by the regional government with a total area of 681,980 ha to protect the critical habitat areas for bottlenose dolphins and other cetacean species as well as the loggerhead turtle (*Caretta caretta*) and the mediterranean monk seal (*Monachus monachus*). The site is currently under assessment for approval by the European Commission to integrate the Natura 2000 network. In the future the assessment of species vulnerability to climate change should be integrated in the development of adequate conservation actions for the Madeira archipelago.

This study is a first attempt at the use of trait-based indices to assess the vulnerability cetacean species to climate change in this region. The method used includes the integration of sensitivity and exposure factors and provides a more holistic approach and, consequently, a more accurate grading of each species' vulnerability. The detailed specification of factors, such as human activities, can be improved in the future to provide a better assessment of impacts in a particular population or study area. The method can be adapted as needed and applied to other species and locations.

This is also an exploratory study and while the results can be useful as preliminary information to scientists and policy makers it can and should be expanded upon as more information is obtained. The structure of this study allows data input to be improved upon. More information can be added when available and the inclusion of experts as needed for each study to provide more reliable results is also possible. In the future we aim to include additional experts and extend the vulnerability assessment to the Macaronesia region which would increase our expert pool and allow for the discuss the management implications at a broader scale.

Species and factors that need more data are readily identifiable with the evaluation of confidence levels. For example, human activities, population size or genetic diversity are a few of the factors with low confidence levels. These reflect the amount and accuracy of the data, with lower confidence levels indicating substantial knowledge gaps.

2.6 Conclusion

This study developed a trait-based index to assess the vulnerability of cetacean species to climate change. Different methods for vulnerability assessment have been developed in recent years and continue to be improved, particularly for the marine environment. This exploratory study presents a contribution to this effort. The most vulnerable species are fin and sperm whale, bottlenose dolphin and Bryde's whale. The main factors determining differences between species are diet diversity, migrations, IUCN status and exposure. Other factors may be more relevant for other species in other areas. In general confidence levels are high but some factors such as the degree to which human activities may influence species vulnerability to climate change should be further investigated.

The challenges and limitations associated with this index were addressed where possible. In the future, however, new information on species ecology can be used to update the index and obtain a more comprehensive ranking of vulnerability for the species found in Madeira.

A broader use of the index will allow its further development and improvement. It can be used as a foundation for the development of other indexes in other locations and with other species. In addition, integrative and new approaches for assessing the vulnerability of species to climate change will continue to be developed and improved and will contribute to the evolution of the method presented in this study. This method can be used together with distribution models or scenario-based approaches, complementing the information they present.

Acknowledgments

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Chapter 3. Climate change vulnerability of cetaceans in Macaronesia: Insights from a trait-based assessment

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3.1 Abstract

Over the last decades global warming has caused an increase in ocean temperature, acidification and oxygen loss which has led to changes in nutrient cycling and primary production affecting marine species at multiple trophic levels. While knowledge about the impacts of climate change in cetacean's species is still scarce, practitioners and policymakers need information about the species at risk to guide the implementation of conservation measures. To assess cetacean's vulnerability to climate change in the biogeographic region of Macaronesia, we adapted the Marine Mammal Climate Vulnerability Assessment (MMCVA) method and applied it to 21 species management units using an expert elicitation approach.

Results showed that over half (62%) of the units assessed presented Very High (5 units) or High (8 units) vulnerability scores. Very High vulnerability scores were found in archipelago associated units of short-finned pilot whales (*Globicephala macrorhynchus*) and common bottlenose dolphins (*Tursiops truncatus*), namely in the Canary Islands and Madeira, as well as Risso's dolphins (*Grampus griseus*) in the Canary Islands. Overall, certainty scores ranged from Very High to Moderate for 67% of units. Over 50% of units showed a high potential for distribution, abundance and phenology changes as a response to climate change.

With this study we target current and future information needs of conservation managers in the region, and guide research and monitoring efforts, while contributing to the improvement and validation of trait-based vulnerability approaches under a changing climate.

Keywords: Climate change; Vulnerability assessment; Cetaceans; Macaronesia

3.2 Introduction

Over the past two decades, an increase in greenhouse gas emissions and subsequent global warming has strongly affected the world's ocean through rapid physiochemical changes (IPCC, 2007, 2014). The rate of ocean warming has more than doubled since the 1970's, and marine heat-related events have increased in frequency, duration and intensity, being projected to continue as such in the future (IPCC, 2019). Since the 1980's, the ocean pH has declined 0.017–0.027 units per decade due to the absorption of 20-30% of total anthropogenic CO_2 emissions (IPCC, 2019). Oxygen loss, together with the expansion of oxygen minimum zones, has increased by 3–8% between 1970 and 2010 (IPCC, 2019). Additionally, sea level rise is increasing globally due to ocean thermal expansion, glacier mass loss and increasing rates of ice loss from the Greenland and Antarctic ice sheets (Leuliette and Nerem, 2016). These observed and projected changes in the ocean's physical–chemical properties contribute to changes in the seasonality, abundance and distribution of marine species. Beyond its impact on cetaceans (such as reducing reproductive success, (Kershaw et al., 2021), these changes affect ecosystem services with relevant ecological, economic and social impacts on human wellbeing (IPCC, 2019; Pecl et al., 2017).

To help predict and possibly minimize the negative impacts of climate change on ecosystems, conservation scientists, managers and practitioners need to develop a set of approaches to estimate species vulnerability to climate change. Accordingly, in the last decade an increasing number of assessments on the vulnerability of biodiversity to a changing climate have been carried out. The main goal of these assessments is to identify species that are at higher risk and support policymakers in identifying and prioritizing adaptation management options (Foden and Young, 2016; Foden et al., 2019).

There are three general types of approaches that can be used to assess the vulnerability of species to climate change: (1) trait-based approaches (Foden et al., 2013); (2) trend-based approaches, namely mechanistic and correlative models (Jeschke and Strayer, 2008; Kearney et al., 2010; Monahan, 2009); and (3) combined approaches, that result from the association of the first two approaches (Willis et al., 2015). Trend-based approaches focus on modelling tools, either correlative models (considering the observed distribution range of species and anticipating potential climate suitable areas) based on future climate projections or mechanistic models (which incorporate biological processes and interactions, such as species physiological tolerances or energy balance equations and are generally used to determine species' extinction risk) (Pearson et al., 2014). Additionally, trait-based approaches provide ranks of species vulnerability by integrating species biological characteristics (sensitivity and adaptive capacity) with exposure to climate change based on climate projections of relevant environmental variables (Foden et al., 2019; Stortini et al., 2015).

Trait-based indexes have the advantage of providing rapid assessments of multiple taxa when relevant data on species traits is available. They have low requirements for detailed information on species distribution, or extensive knowledge of modelling techniques (Foden and Young, 2016; Foden et al., 2019; Pacifici et al., 2015). For such reasons, they have been increasingly used by the marine ecology community, and the number of related publications has more than doubled from 2010 to 2016 (Beauchard et al., 2017). Indeed, trait-based indexes have been widely developed and applied to marine invertebrates, fishes and coral reefs (Chin et al., 2010; Crozier et al., 2019; Hare et al., 2016; Pecl et al., 2014), and some studies also integrate social-ecological factors related to ship traffic disturbance (Fliessbach et al., 2019), fishing communities (Greenan et al., 2019) or fish farming (Soto et al., 2019).

As for marine mammals, trait-based vulnerability assessments are a recent topic, with new indexes being developed in the last few years (Ferrara, 2017; Hauser et al., 2018; Sousa et al., 2019). Earlier attempts at marine mammal climate vulnerability assessments were developed for arctic species through the quantification of sensitivity indicators (Laidre et al., 2008) that were latter extended to other cetacean species by Simmonds and Smith (2009). Globally, the assessment of marine mammals' vulnerability to climate change has highlighted the loss of functional diversity, as well as the associated impacts on the ecosystem from the potential extinctions of marine mammals (Albouy et al., 2020). Regional efforts have also been carried out to develop vulnerability indexes for marine mammal stocks in the Western North Atlantic, Gulf of Mexico, Caribbean, Pacific and Arctic regions (Lettrich et al., 2019), as well as for cetacean species in the Madeira Archipelago (Sousa et al., 2019). However, trait-based indexes present a number of limitations related to different sources of uncertainty, such as the choice of traits, knowledge gaps, unknown thresholds for each trait, and the links between species traits and the impacts of climate change (Lankford et al., 2014). Because of such uncertainties, and the relatively recent nature of these indexes, trait-based methods require further development and validation (Foden and Young, 2016; Foden et al., 2019; Pacifici et al., 2015).

The present study aims to contribute to the development and validation of such methods by assessing the vulnerability of cetaceans to climate change in the biogeographic region of Macaronesia. Results are intended to be used to support informed decision-making and effective conservation under a changing ocean. This was accomplished by adapting and applying the methodology developed by Lettrich et al. (2019) for marine mammals in the United States (US) and expanding the index developed by Sousa et al. (2019) to the entire Macaronesia region.

3.3 Methods

The method used to assess the vulnerability of cetacean species to climate change in Macaronesia was largely adapted from the Marine Mammal Climate Vulnerability Assessment (MMCVA) developed by the US National Oceanic and Atmospheric Administration (Lettrich et al., 2019). The MMCVA developed a more robust approach than the one previously developed for the Madeira archipelago (Sousa et al., 2019), including a broader geographic range and the contributions of a larger expert working group in the design and test of the methodology, over a period of 3 years. The MMCVA method was established to assess the vulnerability of marine mammal stocks to climate change in US waters, considering species' biological and ecological traits as sensitivity attributes, and climate variables as exposure factors. Then, the method uses expert judgement to evaluate such attributes and factors and produces estimates of species vulnerability to climate change – for detailed information on the MMCVA method see (Lettrich et al., 2019). The present study also takes the work of Sousa et al. (2019) forward by using an optimized approach and extending the assessment of cetacean species conducted in Madeira to the entire Macaronesia region (i.e., the Azores, Canary Islands and Madeira), including a larger number of species and consulted experts in the assessment.

In the present work, the climate change vulnerability assessment consisted of three main steps: 1) definition of scope and scale; 2) scoring process for sensitivity attributes, exposure factors and data quality; and 3) calculation of vulnerability scores and data analysis. Modifications to the MMCVA method were exclusively made on the selection of exposure factors to best reflect the species under study and on the scoring bins of two sensitivity attributes (habitat specificity and site fidelity) to suit our study area specificities (see Sensitivity attributes and climate exposure factors). Details on methodological aspects of each step are provided in the following sub-sections.

3.3.1 Definition of scope and scale

3.3.1.1 Study area

The biogeographic region of Macaronesia comprises two Portuguese archipelagos, the Azores and Madeira, and the Spanish archipelago of the Canary Islands (Figure 3-1). Azores is the northernmost archipelago of Macaronesia encompassing nine islands. Madeira lies approximately 840 km SE of the Azores and 630 km NW of the African continent and is composed of two main islands (Madeira and Porto Santo). The Canary archipelago is situated about 400 km south of Madeira and 115 km off the West African mainland and is composed of seven main islands (Figure 3-1)

There has been an ongoing debate on whether the Macaronesia biogeographic region should include the archipelago of Cape Verde (Vanderpoorten et al., 2007). Studies have showed that the marine biota community structure and biogeographic relationships in Cape Verde differ from the remaining North Atlantic archipelagos (Freitas, 2014; Freitas et al., 2019). Indeed, the Azores, Madeira and Canary Islands were considered a single marine ecoregion in the Lusitanian province whereas Cape Verde is biogeographically within the West African Transition province (Spalding et al., 2007). For these reasons, in the present study only the archipelagos of Azores, Canary Islands and Madeira were considered.

The Macaronesian islands have an exclusively volcanic origin with complex oceanographic and topographic features facilitated by the narrow continental shelfs and the occurrence of great depths (over 1500 m) relatively close to shore (Geldmacher et al., 2000; Santos et al., 1995; Valdés and Déniz-González, 2015). The main ocean currents influencing this dynamic region are the Azores and the Canary Currents, which form two of the boundaries of the North Atlantic Gyre, together with the Gulf stream along the East Coast of the United States (E.D. Barton, 2001; Cropper, 2013). Furthermore, islands create oceanographic disturbances of oceanic flow, known as the “island mass effect”, which result in the presence of lee eddies, island wakes and upwelling features (Caldeira and Reis, 2017). These conditions foster a high number of cetacean species in each archipelago (over 20 species; Alves et al., 2018; Carrillo et al., 2010; Silva et al., 2014), contributing to the classification of Macaronesia as a world biodiversity hotspot (Myers et al., 2000).

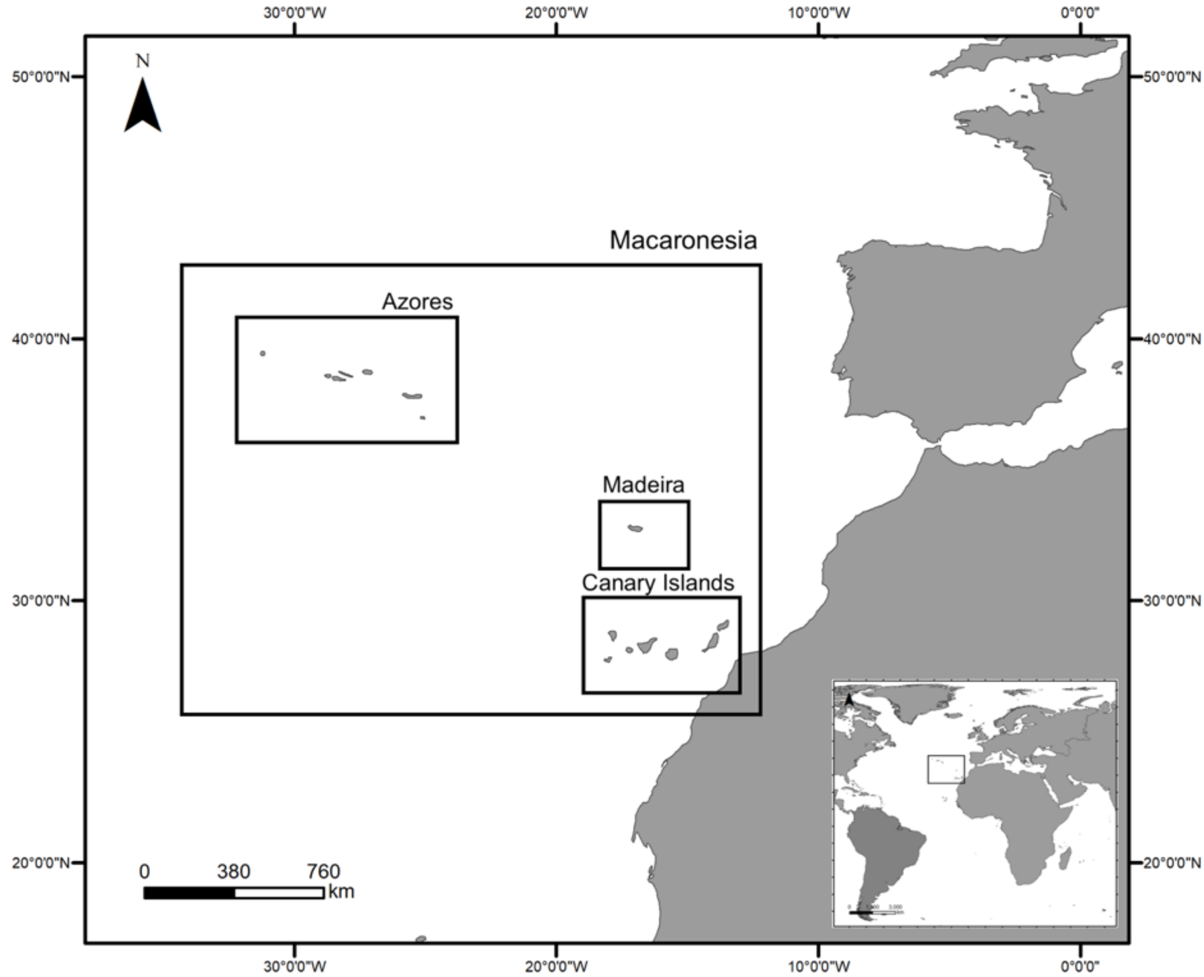


Figure 3-1 – Map of the Macaronesia biogeographic region, showing the archipelagos of Azores, Madeira and Canary Islands.

3.3.1.2 Experts selection and consultation

In order to support the development of the climate vulnerability assessment, and further validate it, six experts on cetacean ecology with knowledge and expertise on both the overall study area and on each of the archipelagos of Macaronesia (two experts per archipelago) participated in the present study.

The participatory process took place for four months, between February and July 2020, in a fully online format because of travel restrictions related to the COVID-19 pandemic. A total of six on-line workshops were performed. In the first workshop (February 19, 2020) experts were consulted to select cetacean species and management units for the assessment (see species selection below), and to validate sensitivity attributes and exposure factors in order to ensure their adequacy for cetacean species in Macaronesia.

Experts were then given time to individually score each units' exposure factors and sensitivity attributes. Once the individual scores were collected, preliminary results from archipelago-associated management units were discussed in three dedicated workshops, one for each archipelago (May 4, 2020 – Madeira; May 14, 2020 – Azores; June 2, 2020 – Canary Islands), with the participation of the corresponding archipelago experts. Similarly, preliminary results for Macaronesia management units were discussed in a workshop with all six experts (May 22, 2020).

After the workshops, experts were given time to independently analyze results and change their scores if desired (this way ensuring impartiality and avoiding peer-pressure to reach a consensus). The final scores from all units were collected, and further discussed and validated in a final workshop with all six experts (July 23, 2020).

3.3.1.3 Species selection

The process of species selection was initiated using a list of indicator species created specifically for the Macaronesia region with the purpose of assessing the Good Environmental Status (GES) of European marine waters under the Marine Strategy Framework Directive (MSFD) (MISTIC SEAS, 2016). These indicator species were classified into management units, defined as "animals of a particular species in which management of human activities are performed" (ICES, 2014).

To ensure that other relevant species were not excluded from our study, the list of indicator species was crosschecked with species that are known to be relevant for the whale watching industry in Macaronesia (i.e., species identified as being frequently encountered by those vessels), and species that can be used as indicators of climate-related range changes (e.g., species whose northern distribution range limit is in at least one of the Macaronesian archipelagos) (MacLeod, 2009).

The final list of selected species was then classified into four management units, namely the "Macaronesian unit" and three "archipelago-associated units" (Azores, Canary Islands and Madeira). Species in the Macaronesian unit correspond to individuals that use the entire region as a single habitat, but that are seen in archipelagic waters during a short period of time (days to weeks), based on long-term data such as photo-identification.

Classification of species into archipelago-associated units was defined as individuals that are resident (or island-associated) or exhibit multi-year and year-round site fidelity to one archipelago. Overall, this classification distributed 10 individual cetacean species into 21 species management units – 10 Macaronesia units (MAC) and 11 archipelago-associated units (Table 3-1).

The 11 archipelago-associated units were scored by the two experts from each archipelago and the 10 Macaronesia units were scored by all six experts.

Table 3-1 – Selected species included in the climate change vulnerability assessment and their classification into species management units: Macaronesia unit (MAC) and the archipelago-associated units of Azores (AZ), Canary Islands (CAN) and Madeira (MAD).

Common name	**Scientific name**	**Species Management unit**
Atlantic spotted dolphin	*Stenella frontalis*	MAC
Bryde's whale	*Balaenoptera edeni*	MAC
Fin whale	*Balaenoptera physalus*	MAC
Short-finned pilot whale	*Globicephala macrorhynchus*	MAC, MAD, CAN
Short-beaked common dolphin	*Delphinus delphis*	MAC, AZ
Sperm whale	*Physeter macrocephalus*	MAC, AZ
Risso's dolphin	*Grampus griseus*	MAC, AZ, CAN
Common bottlenose dolphin	*Tursiops truncatus*	MAC, AZ, CAN, MAD
Blainville's beaked whale	*Mesoplodon densirostris*	MAC, CAN
Cuvier's beaked whale	*Ziphius cavirostris*	MAC, CAN

3.3.1.4 Sensitivity attributes and climate exposure factors

All 11 sensitivity attributes defined in the MMCVA (Lettrich et al., 2019) were used. From those, two attribute scoring bins description (Site fidelity and Habitat specificity) were slightly modified to suit the study area (Table B-1). In the case of site fidelity, the description of scoring bins was adapted to fit the different geographic scales of our study area, from the Macaronesia region to the archipelagos level, and to the island-specific level. Habitat specificity was modified to consider the reliance on features vulnerable to climate conditions in all life stages since there were no differences in the habitat used in specific life stages for cetacean species in Macaronesia.

Five of the original nine exposure factors presented in Lettrich et al. (2019) were used in this study (Table B-1). Excluded factors were air temperature, precipitation, ice cover and sea level rise. The first three factors were considered not to directly affect cetaceans in Macaronesia given that in the original MMCVA they were defined as mainly relevant for pinnipeds, some ice-associated or coastal cetacean populations (i.e., bowhead, killer whales, belugas) (Lettrich et al., 2019). Sea level rise is a relevant factor mainly for some particular shoreline habitats and areas with extended continental shelfs. It was therefore not considered to be relevant for Macaronesia where coastal waters tend to exceed depths of 1,500 m (Geldmacher et al., 2000; Santos et al., 1995; Valdés and Déniz-González, 2015).

Primary productivity was included as an additional exposure factor due to its direct effect on the distribution, diversity and abundance of cetacean species in Macaronesia (Correia et al., 2020; González García et al., 2018; Tobeña et al., 2016).

3.3.2 Scoring process for sensitivity attributes, exposure factors and data quality

Each sensitivity attribute and exposure factor selected was scored individually by experts. The scoring process consisted in the attribution of five tallies across four scoring bins: Low (=1); Moderate (=2); High (=3) and Very High (=4) (Table B-1). For sensitivity attributes' scoring, experts distributed their tallies according to available evidence from the literature and their own knowledge and experience on the selected cetacean units. When considering exposure factors, scores were attributed according to the degree of change projected for each factor (based on climate projection maps) within the distribution range of each cetacean unit (the latter was assessed by experts through literature review).

Climate projection maps used to determine exposure scores were obtained from the Earth Systems Research Laboratory (ESRL) web portal (ESRL, 2014). These maps were scaled to fit the criteria of the scoring bins, allowing for a clearer visualization and interpretation of each exposure factor (

Figure D-1). The North Atlantic region was selected in order to encompass the potential distribution range of all considered cetacean species (Silva et al., 2013). "Circulation" was the only exposure factor for which projections were not available, hence information from literature and expert judgment were used to score it.

For comparability purposes, and following the original method by (Lettrich et al., 2019), this study used the Representative Concentration Pathway (RCP) 8.5 scenario and a short to mid-century timeframe (2006-2055). The choice of RCP 8.5 is also justified as it is the climate change pathway that allows to capture the high-end tail of the uncertainty envelope associated with climate impacts (Riahi et al., 2011). Given the level of uncertainty surrounding the ecological and biological effects of climate change on cetacean species and the lack of substantial change in the magnitude of projected potential climate changes we adopted the precautionary principle by selecting the RCP 8.5 (Foden et al., 2019). The short to mid-century timeframe was selected for similar reasons, but also because the final aim of this study was to assist decision-making processes and support adaptation measures that target species' conservation. Despite the intrinsic value of analyzing the effect of climate change on cetaceans until the end of the century, the combination of increasing uncertainties in longer time frames and the need to produce salient information for conservation decisions taken now dictated the choice (Foden and Young, 2016).

Each sensitivity attribute and exposure factor were classified regarding the quality of the evidence underpinning the experts' choices. Data quality values ranged from zero to three, supporting the degree of evidence available to assign the distribution of tallies in the scoring bins: 0 = No data; 1 = Expert judgment only; 2 = Limited data; 3 = Adequate data (Lettrich et al., 2019). Regarding exposure factors, only the quality of the information on the distribution range of each cetacean unit was assessed by the experts, not the quality of the climate models used, as in Lettrich et al. (2019).

3.3.3 Calculation of vulnerability scores and data analysis

3.3.3.1 Climate vulnerability

Climate vulnerability scores were calculated through a three-step approach, following the methods of Hare et al. (2016) and Lettrich et al. (2019). First, each Attribute or Factor Weighted Means (AFWM) were calculated for each attribute/factor, based on the distribution of experts tallies in the scoring bins, as follows:

$$AFWM = \frac{\left((B_1 \times 1) + (B_2 \times 2)(B_3 \times 3)(B_4 \times 4)\right)}{(B_1 + B_2 + B_3 + B_4)}$$

where B_n is the number of tallies in scoring bin n.

Each exposure factor was scored for both a change in mean and a change in variability. The highest factor weighted mean value (either from a change in mean or a change in variability) was the one considered as the mean score for that factor (Lettrich et al., 2019).
Second, using the obtained AFWM values, scores for sensitivity and exposure components were calculated using the logic model developed by Hare et al. (2016). The overall vulnerability to climate change of each cetacean unit was thus calculated by multiplying sensitivity and exposure component scores. Component scores varied from Low (=1) to Moderate (=2), High (=3), and Very High (=4), and the crossing between both component scores provided a vulnerability category for each unit (Figure 3-2).

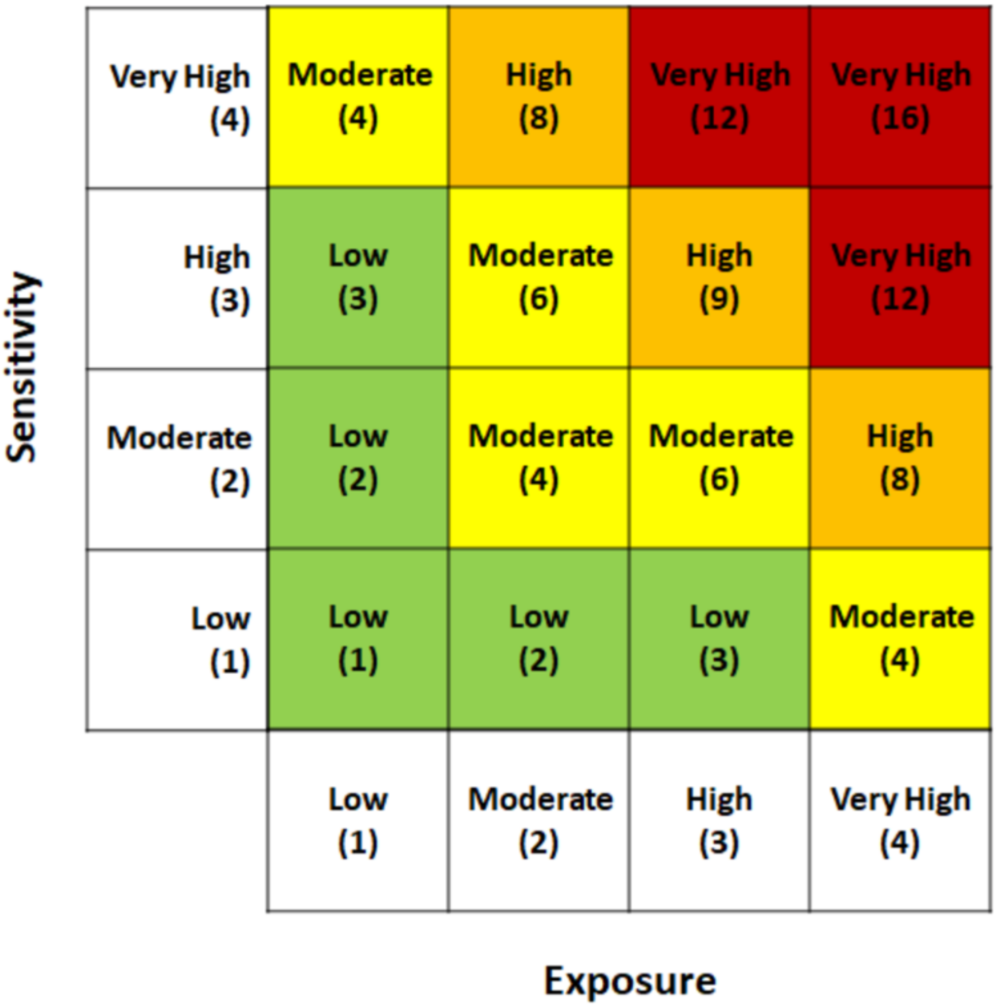


Figure 3-2 – Vulnerability matrix from Lettrich et al., 2019, showing the component scores of sensitivity/adaptive capacity and exposure to obtain the overall vulnerability score. Numbers in parenthesis indicate the component scores of sensitivity and exposure and the vulnerability

score resulting from multiplying sensitivity and exposure [Low vulnerability (1-3), Moderate vulnerability (4-6), High vulnerability (8-9), Very High vulnerability (12-16)].

3.3.3.2 Certainty and data quality

Data quality was calculated for each sensitivity attribute and exposure factor, and vulnerability score, as an average of all experts' scores.

Certainty in sensitivity, exposure and vulnerability scores were calculated with a bootstrap analysis (Hare et al., 2016), using R software. The bootstrap analysis resampled the aggregate of all experts' scores and created simulated samples from the original dataset. Scores attributed by experts were drawn 10,000 times randomly with replacement and the proportion of outcomes was counted for each scoring bin, resulting in the correspondent certainty scores. Calculated scores for attributes, factors, and vulnerability were compared against predicted bootstrap scores, resulting in a metric to evaluate certainty. Certainty scores were classified as very high (>95%), high (90–95%), moderate (66–90%) or low (<66%).

3.3.3.3 Sensitivity analysis

To investigate which attributes and factors were the most influential in determining vulnerability for each unit, a sensitivity analysis was performed following Hare et al. (2016). The analysis consisted of removing one attribute or factor at a time and re-calculating the overall vulnerability score.

3.3.3.4 Potential for distribution, abundance and phenology changes

The potential for changes in distribution, abundance and phenology was assessed based on the relation of each sensitivity attribute to potential responses in a unit's geographic distribution, abundance or phenology. These responses were calculated considering only the sensitivity attributes that showed a relationship with each response category (Lettrich et al., 2019). The response scores and respective certainty were calculated similarly to the overall vulnerability scores.

3.4 Results

From the 21 species management units that were assessed, over half (62%) presented Very High (5 units) or High (8 units) vulnerability scores. From these, 10 units were archipelago-associated and only three were Macaronesian. At the lower range of the vulnerability scale, eight species management units have Moderate (7 units) to Low (1 unit) vulnerability scores, and of these nearly all (7 units) are Macaronesian (**Figure 3-3** and **Figure 3-4**).

Certainty scores show that 29% of the species management units fall under the High to Very High certainty category (>90%), 38% in the Moderate (66-90%), and 33% in the Low category (<66%) (**Figure 3-3** and **Figure 3-4**). Overall, the actual vulnerability scores were very similar (20 out of 21) to the predicted bootstrap vulnerability scores (Figure E-1c). Data quality scores for exposure factors were higher than for sensitivity attributes.

However, neither these nor the combined data quality scores show a general relation with higher or lower attributes, factors, or vulnerability scores (Table C-1).

Sensitivity analysis showed that the most influential sensitivity attributes, common to all units, are migration, generation length, and habitat specificity. Regarding exposure factors the same analysis showed that sea surface temperature (mean), ocean acidification (mean) and dissolved oxygen (mean) were the most influential in determining vulnerability (

Figure D-1a, D.1e, D.1 i). In general, the variance in sensitivity attributes scoring was higher than for exposure factors (Figure F-1c, F.1d, Figure F-2c, F2.d). Sensitivity attributes for archipelago-associated species management units showed a higher variance in scores when compared to Macaronesia (Figure F-1c,Figure F-2c).

Overall, results show a high potential for changes in distribution, abundance, and phenology, with all three categories typically scoring higher for archipelago-associated species management units than for Macaronesian (**Figure 3-5**). In general, no clear relationship between climate vulnerability scores and potential changes in distribution, abundance, or phenology was found (Table C-2).

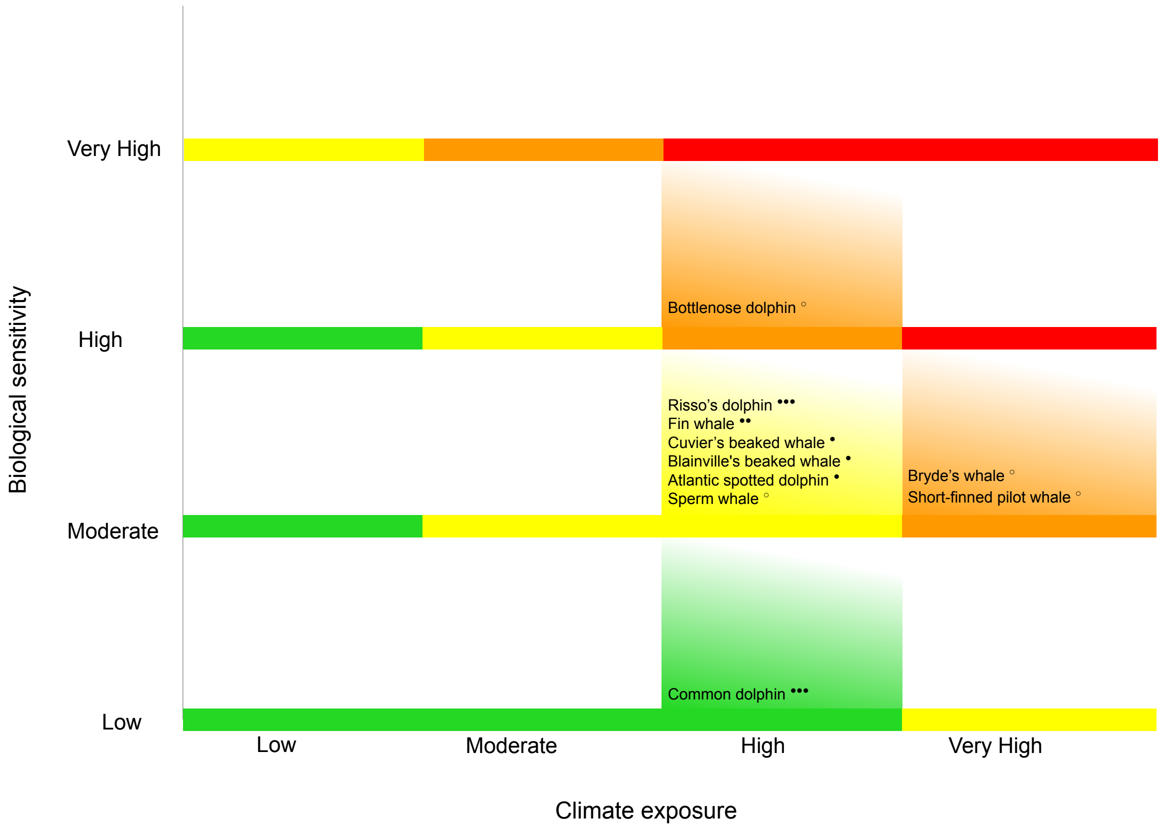


Figure 3-3 – Climate vulnerability scores which result from the combined biological sensitivity and climate exposure scores for the Macaronesia (MAC) species management units. Colors indicate vulnerability scores: Very High (red), High (orange), Moderate (yellow) and Low (green). Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%).

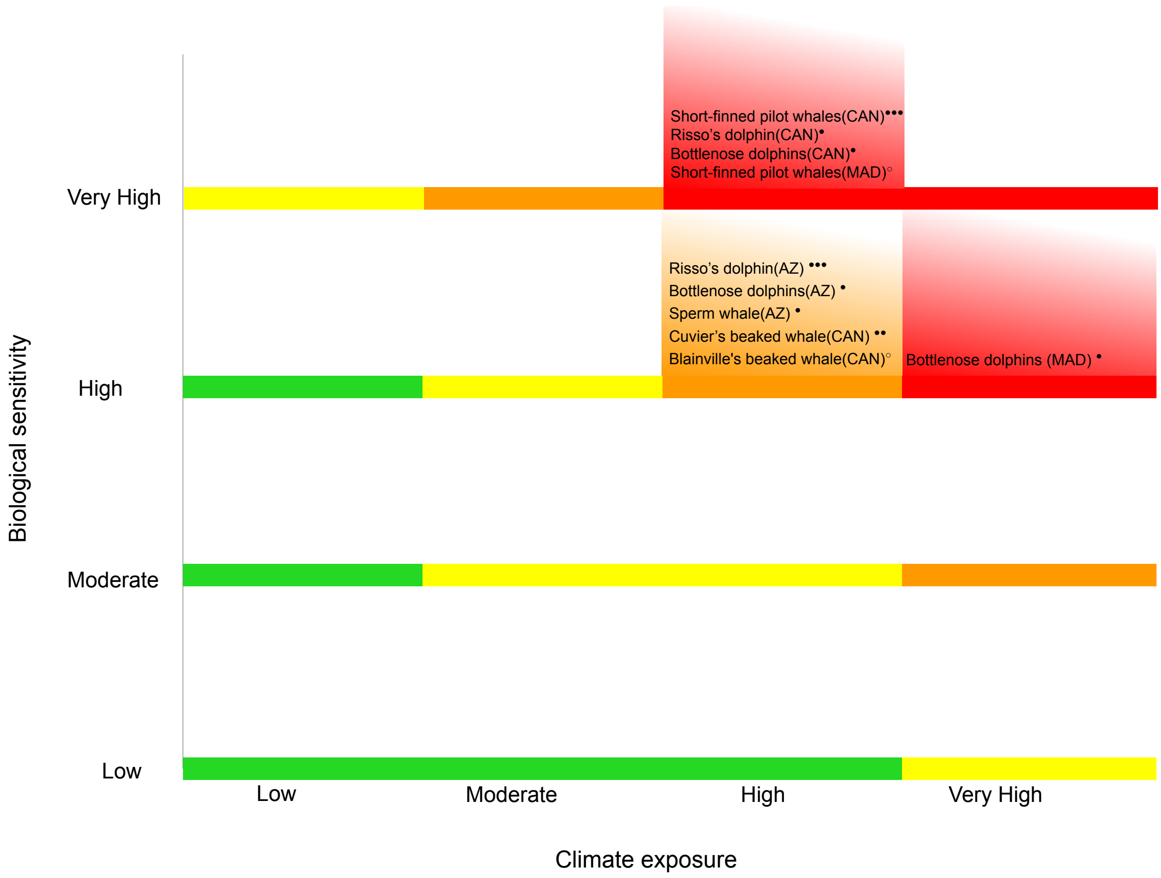


Figure 3-4 – Climate vulnerability scores which result from the combined biological sensitivity and climate exposure scores for the archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colors indicate vulnerability scores: Very High (red), High (orange), Moderate (yellow) and Low (green). Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%).

3.4.1 Macaronesia Units

The majority (6 out of 10) of Macaronesia species management units presented a Moderate vulnerability score, while covering the full range of certainty scores (**Figure 3-3**). Bottlenose dolphin, Bryde's whale and short-finned pilot whale showed a High vulnerability to climate change, with a low certainty score (<66%). Bryde's whale and short-finned pilot whale displayed Moderate sensitivity and Very High exposure, while the Bottlenose dolphin exhibited High sensitivity and High exposure. The common dolphin had the lowest vulnerability score as a result of its Low sensitivity and High exposure values, with a Very High certainty score (>95%).

The most influential attributes determining vulnerability in Macaronesia were generation length, habitat specificity and migration (Figure F-1c). The only exposure factors that contributed to changes in vulnerability scores were sea surface temperature (mean), ocean acidification (mean) and dissolved oxygen (mean) (Figure F-1d).

Macaronesia species management units showed High (50%) and Moderate (50%) potential for changes in distribution, with most certainty scores in the Very High range (**Figure 3-5**).

Most units exhibited a Moderate potential for changes in abundance, except for common dolphin, Atlantic spotted (hereafter referred as spotted dolphin) and common bottlenose dolphin (hereafter referred as bottlenose dolphin), which showed a Low potential (**Figure 3-5**).

Spotted dolphin, fin whale and Bryde's whale presented a High potential for phenology changes, while the bottlenose dolphin presented a Low phenology response score, and a low certainty score (**Figure 3-5**).

3.4.2 Archipelago-associated Units

The most vulnerable archipelago-associated species management units, with a Very High vulnerability score, were the short-finned pilot whale and the bottlenose dolphin in the Canary Islands and Madeira, and the Risso's dolphin in the Canary Islands (**Figure 3-4**). All the above units scored Very High in sensitivity attributes and High in exposure factors, with the exception of bottlenose dolphin in Madeira with High sensitivity and Very High exposure. In general, the units of Madeira and the Canary Islands showed a higher vulnerability to climate change than the Azores units. The majority of units showed a Moderate certainty in vulnerability scores. The lowest vulnerability and certainty scores were attributed to the common dolphin in Azores.

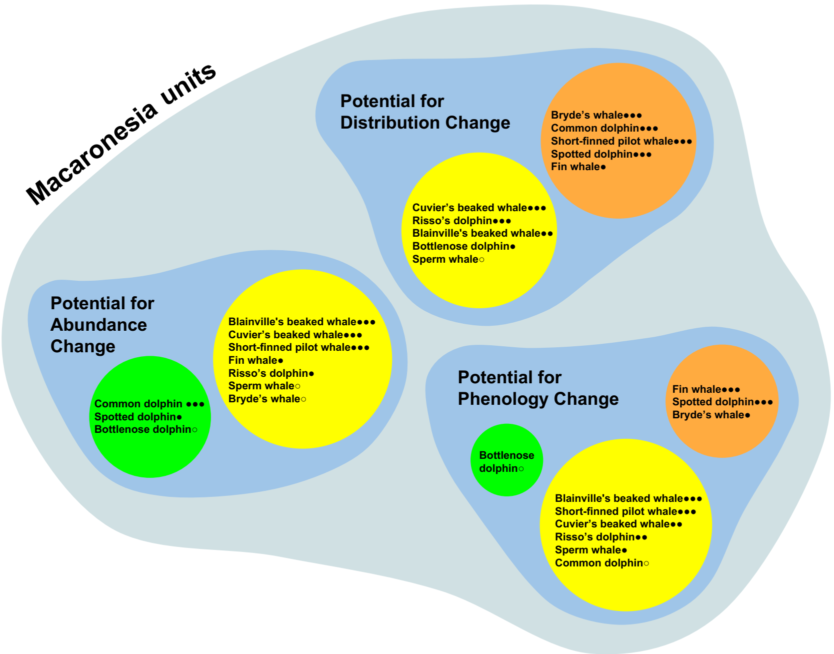
The most influential attributes determining vulnerability in archipelago-associated units were migration, site fidelity and home range (Figure F-2c). Prey/diet specificity and habitat specificity were the attributes that showed a higher variability in scoring (Figure F-2c).

Sea surface temperature (mean) and ocean acidification (mean) were the two most influential exposure factors contributing to the vulnerability scores, followed by dissolved oxygen (Figure F-2b, 2d).

The majority of archipelago-associated species management units displayed a High potential for distribution change. The certainty of these results varied from Very High to Moderate.

Most units exhibited a High potential for changes in abundance except for the common dolphin in the Azores which showed a Moderate potential (**Figure 3-5**).

Most archipelago-associated units scored High for potential changes in phenology, with a Very high to Moderate certainty scores. The exceptions were Blainville's beaked whale in the Canary Islands (Moderate potential) and the sperm whale in Azores (Low potential) (**Figure 3-5**).



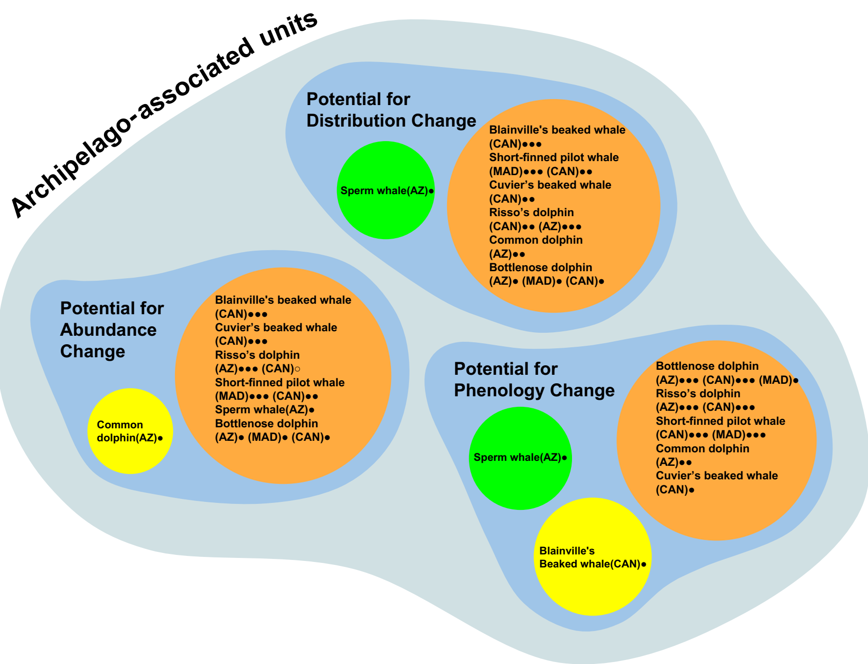


Figure 3-5 - Vulnerability scores and potential distribution, abundance and phenology responses for the Macaronesia (MAC) and archipelago-associated species management units

of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colours indicate Very High (4; red), High (3; orange), Moderate (2; yellow) and Low (1; green) potential for changes. Symbols indicate certainty scores: ••• very high certainty (>95%); •• high certainty (90–95); • moderate certainty (66–90%) and ○ low certainty (<66%).

3.5 Discussion

3.5.1 Climate vulnerability of cetacean species in Macaronesia

The assessment conducted for cetaceans in Macaronesia identified the sensitivity attributes and exposure factors that contribute to each species management unit's vulnerability to climate change. The most influential sensitivity attributes explaining vulnerability in all units were: (a) migration; (b) generation length (c) site fidelity; (d) habitat specificity and (e) home range (Figure F-1c, Figure F-2c).

Migratory baleen whale species undertake extensive movements between tropical breeding grounds in winter and high latitude foraging areas in summer. For example, fin whales migrate every year to North Atlantic feeding grounds, mostly in springtime (Carrillo et al., 2010; Silva et al., 2013) or undertake shorter migrations, both in space and time (Valente et al., 2019). Sperm whales also migrate but vary their movements according to sex and age. While adult females and immature individuals move mostly within the Macaronesia (i.e., travel between different islands or even archipelagos, every year or season), adult males are known to perform long-range movements, and generally live at higher latitudes returning periodically to warmer waters for reproductive purposes (Clarke, 1956; Steiner et al., 2012; Whitehead, 2003).

Using migratory behavior as a proxy for the ability of a species to disperse, migratory species may have a greater ability to adapt to changing conditions and seek areas with suitable conditions compared to non-migratory species (Gardali et al., 2012; (ZSL), 2010).

Nevertheless, migratory species can still be affected by environmental changes across their entire range (Ramp et al., 2015). Archipelago-associated species management units are known to have stronger residency patterns, with more restricted movements. For example, Risso's dolphins in the Azores or in the Canary Islands, form resident groups that exhibit strong habitat preferences (Hartman et al., 2015; Sarabia-Hierro and Rodríguez-González, 2019). However, information available to accurately comprehend and evaluate the movements of archipelago-associated units is currently insufficient. Nonetheless, some archipelago-associated units were recently found to move to neighbouring archipelagos. Examples include a core resident group of short-finned pilot whales in Madeira (i.e., the group with more photographic-captures, seen year-round during at least 17 years) that made a round trip to the Azores (Alves et al., 2018) or the case of seasonal visitors of the same species in Madeira that were also captured in the Canary Islands (Alves et al., 2019). Similarly, bottlenose dolphins' migrant individuals in Madeira (n=14), equivalent to regular or occasional visitors in this study, were seen in Azores (n=1) and in the Canary Islands (n=13) (Dinis et al., 2021).

These observations support the notion that archipelago-associated individuals can be, at times, part of their respective Macaronesia species management unit and that, conversely, transient individuals will also spend time in archipelagos and may occasionally be a part of their respective species management units (Alves et al., 2019, 2013).

Longer generation lengths together with other traits such as shorter lifetime reproductive potential and lower reproductive plasticity provide little opportunity for rapid evolutionary adaptation under a changing climate (Lettrich et al., 2019; Silber et al., 2017).

Obtaining information on generation length is especially onerous for cetaceans, because of their remote oceanic habitats, their extended longevity, and the difficulties in obtaining age specific data (Taylor et al., 2007). Several methods have been used to overcome this lack of data, such as: (i) extrapolate generation length estimates for a given species using life-history and demographic data of other species, based on the general patterns of taxonomic relatedness and body size (Cooke et al., 2018); (ii) use a demographic model to estimate both the percentage of mature individuals of the current population and the generation length of a pre-disturbed population (Cooke et al., 2018); or (iii) use data from captive animals to extrapolate age for wild populations, although this approach has associated problems, as conditions for species in captivity and in the wild differ substantially (Cooke et al., 2018).

Bottlenose dolphins have a general generation length of approximately 20 years (Pacifici et al., 2014), which also accounted for its higher sensitivity score. However, due to the previously mentioned difficulties in obtaining age specific data (Taylor et al., 2007), these scores should be considered with caution, even if the expert's judgment about the overall data quality of the sensitivity attributes found in the literature is high. Data quality scores presented refer to the average sensitivity attributes and not to individual attribute scores (Table C-1).

The habitat specificity attribute considers a units' reliance on physical features that are more or less resilient to climate conditions. If a habitat tends to be less affected by climate change, its populations are also expected to be less affected. The Macaronesia region is characterized by a high density of volcanic peaks, some of them rising up as oceanic islands (Morato et al., 2013). Oceanographically, the presence of a submarine peak or an island will disturb the ocean currents and produce perturbations that ultimately have biological consequences (Caldeira et al., 2014; Caldeira and Reis, 2017). These disturbances known as "island wakes", are areas with intense eddy activity that influence the availability and transport of organic matter in the ocean. They can have an effect on the biological productivity and concentration of prey, particularly if connected with oceanic fronts (E.D. Barton, 2001). Macaronesia is a region where bathymetric and oceanographic features interact in complex ways, providing the habitat that supports the many cetacean species recorded in the area.

Risso's dolphins in the Canary Islands have a higher sensitivity than in the Azores. Coastal population of Risso´s dolphins in the eastern Canary Islands have been reported to be highly habitat specific and exhibit a high site fidelity (Sarabia-Hierro and Rodríguez-González, 2019). Due to the limited studies focusing on this area, the residency patterns described may be a result of sample bias, therefore not excluding the possibility of a lower degree of site fidelity. In Azores, results off Pico island show relatively restricted home ranges for Risso's dolphins (Hartman et al., 2015) and specific habitat conditions for groups with new-borns and calves (Hartman et al., 2014). Differences in sensitivity scores between these two species' units are an example of how habitat specificity and site fidelity can contribute to influence overall vulnerability.

The high sensitivity of bottlenose dolphin relates to their distribution which is directly or indirectly linked to the habitat they occupy, and the availability and distribution of prey. Resident individuals of bottlenose dolphins (all archipelago units) tend to be coastal, with potential spatial overlaps with human coastal development. Their home range can vary from small to large displacements (Ballance, 1992; Robinson et al., 2012) depending on food availability, reproductive cycle, season and calf care (Bearzi and Politi, 1999; Würsig et al., 1991). Bottlenose dolphins in the Canary Islands are highly mobile within the archipelago (Tobeña et al., 2014). In addition, insufficient ecological and genetic data on bottlenose dolphins in the Canary Islands (Carrillo et al., 2010) limits the knowledge available to score this unit. However, and despite the current insufficient information to identify any ecotypes, there might be individuals with relatively small home ranges, showing mainly local movements, which are dependent on specific conditions more sensitive to climate change. On the contrary, common dolphins in the Azores are sighted year-round in the entire archipelago and occur in a wide range of environmental conditions (González Garcia, 2019; Silva et al., 2014). This unit was therefore expected to be less sensitive than other archipelago associated units with more specific preferences, a characteristic that is supported by our results.

In addition, the Macaronesia unit of common dolphin, has the lowest sensitivity scores of all assessed units. They show a very seasonal occurrence pattern in Madeira, with more sightings during the first semester of the year, peaking in spring (Alves et al., 2018). A similar pattern, but with a wider temporal distribution, occurs in Azores, where the species is sighted all year around, but declines during summer months (Silva et al., 2014). Moreover, the species is generally associated with cold and productive regions, occupying a wide area in the proximity of the islands or seamounts (Fernandez et al., 2018; Tobeña et al., 2016). Therefore, they might move through the archipelagos following productive water masses, but with a high degree of plasticity. In fact, in other areas the species has been documented to have an opportunistic feeding behaviour, with a wide range of potential preys (Santos et al., 2013).

The exposure factors that were most influential to species' vulnerability across all units were: (i) sea surface temperature; (ii) ocean acidification; and (iii) dissolved oxygen. These were also the factors for which the highest magnitude of change is projected.

Bryde's whale, short-finned pilot whales and Bottlenose dolphin (Canary Islands unit) exhibited the highest exposure score of all units because their distribution overlaps with areas of high projected climate changes, when compared to the remaining units (
Figure D-1). The first two species are known to have a tropical and warm-temperate distribution (Kato and Perrin, 2018; Olson, 2018), with their northern, central and eastern Atlantic limit at the latitude of Azores (Alves et al., 2019; Steiner et al., 2008). In Madeira, Bryde's whales were only first recorded in 2003 (Freitas et al., 2012) but since 2005 are amongst the most encountered species in the region (Alves et al., 2018). In the Azores, it was first sighted in 2004, and since then, occasional occurrences have been reported in the archipelago, with some exceptional years where Bryde's whales were observed in several consecutive months (Azevedo et al., 2018).

3.5.2 Comparison with other climate change vulnerability assessments

Exploring and comparing results from multiple trait-based indexes is an important step to further advance and validate vulnerability assessments for marine species under changing climates.

When comparing the results of our work with recently published studies, similarities and differences were found, namely in taxonomic groups, study areas and/or methodologies. The main differences identified were related to: (1) the full list of species selected, and management units defined; (2) the overall study area; (3) the sensitivity attributes and exposure factors considered (even in the cases of similar climate modelling approaches like the use of projection maps from ESRL); (4) the definition of scoring bins for each indicator; and (5) the computation of results (e.g., the use of logic models).

Results show that the overall climate vulnerability scores differ from the previous assessment for the Madeira archipelago (Sousa et al., 2019). In that study, sperm whales and fin whales were identified as the most vulnerable species, being highly scored for both exposure and sensitivity, whereas in the present study most vulnerable species corresponded to the archipelago-associated units of bottlenose dolphins (Canary Islands and Madeira), Risso's dolphins and short-finned pilot whales (both in the Canary Islands). Still, some similarities could be found, namely for island associated (or archipelago-associated) individuals of bottlenose dolphins in Madeira which showed a lower sensitivity than island associated individuals of short-finned pilot whales in both studies. Common and spotted dolphins also showed a low vulnerability in both studies. Differences between both studies can be related with the number and type of sensitivity attributes and exposure factors considered, as well as their definition and scoring categories. For example, Genetic variability and IUCN Status were attributes only considered in Sousa et al., 2019 while Generation Length and Habitat specificity were only considered in this study (Table B-1). Also, Diet diversity was defined in Sousa et al., 2019 in three scoring categories (One prey type comprises > 20% of a species diet – Score = 3; Two prey types comprise > 20% of a species diet – Score = 2; Three or more prey types comprise > 20% of a species diet – Score = 1) different from the ones defined in this study (Table B-1). Additionally, the present study defined Macaronesia and archipelago-associated species management units, while Sousa et al. (2019) considered the North Atlantic populations of 7 cetacean species and island associated individuals of short-finned pilot whales and bottlenose dolphins.

When comparing the results of our approach to a similar expert-based scoring method developed by Hare et al. (2016) to assess the vulnerability to climate change, of 82 marine fish and invertebrate species in the Northeast U.S, we found a similar high potential for changes in species distribution (over 50% of analysed species management units). In our study, we found certainty scores for distribution response to be high for 43% of units, while vulnerability certainty scores varied from Moderate to Low. Whereas Hare et al. (2016) found that certainty results for distribution change potential were low (<66%) when compared to the certainty in vulnerability results. Results also differ when comparing climate vulnerability scores with species potential for distribution change. Hare et al. (2016) found that climate vulnerability was negatively correlated to potential for a distribution shift, meaning that species which are highly vulnerable to climate change also have a lower potential to change their distribution and vice versa, something not found in our study. Differences between both studies may indicate that, contrary to fish and invertebrate species, cetaceans are more likely to have a high potential for distribution change due to their high mobility and endothermicity despite their vulnerability to climate change. Cetacean species have a broader range of temperature tolerance compared to fish, making them more resilient to changes in climate. However, due to their lack of isotherm tracking behavior, their responses to potential changes in food resources are also less predictable (Silber et al., 2017).

The recently developed method applied in our study was also used to assess the vulnerability of marine mammal stocks in the Northwest Atlantic, Gulf of Mexico and Caribbean. In that study, Lettrich et al. (*in preparation*) found greater vulnerability to be correlated with greater potential for distribution change and that most stocks scored high for distribution change. Potential for abundance change and phenology change were directionally similar to distribution change (i.e., greater vulnerability correlated to greater likelihood of change), but the correlation was not as strong as for distribution.

In our study we found a high potential for distribution, abundance and phenology change but none showed a relation with high vulnerability.

Poleward shifts in the distribution of different marine species have been recorded since the 1950's with an average range shift of 52 ± 33.3 km per decade (IPCC, 2019) and at a rate six time faster than in terrestrial species (Lenoir et al., 2020). The rate and direction of distribution changes result from the interaction of climatic factors such as local temperature, ocean currents and oxygen gradients across depth, latitude and longitudinal gradients and non-climatic factors such as fishing (IPCC, 2019; Poloczanska et al., 2013).

For cetacean species, an increase in species richness has been predicted from tropical regions to higher latitudes above 40° (Kaschner et al., 2011; Whitehead et al., 2008). This redistribution of species was predicted to affect 88% of cetacean species globally due to changes in water temperature driven by climate change (MacLeod, 2009).

In mid-latitude regions, evidence for climate change impacts in cetacean species is generally documented by range shifts with range contractions of cold-water species such as the minke whale, northern bottlenose whale and white-beaked dolphin, and a northwards expansion of warmer water species such as striped dolphin, short-beaked common dolphin, and Cuvier's beaked whale (Evans and Waggitt, 2020; Lambert et al., 2014).

In addition to shifts in distribution, we assessed the potential for abundance and phenology responses to climate change. In general, for all units assessed, we found shifts in abundance and phenology to be High. In the North-East Atlantic, evidence of changes in distribution, abundance, and feeding ecology of cetacean species have been documented (Nøttestad et al., 2015; Víkingsson et al., 2015). Víkingsson et al. (2015) found an increase in the abundance of Central North Atlantic humpback (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*). The increase in fin whale's abundance, together with an expansion of its distribution, may be a response to the increase in the abundance of their main prey (euphausiids). In addition, a decrease in the abundance of minke whales (*Balaenoptera acutorostrata*) in the Icelandic continental shelf may also be a response to changes in the local abundance of sand eel, capelin and euphausiids. In the Norwegian sea, higher densities of toothed whales, killer whales (*Orcinus orca*) and long-finned pilot whale (*Globicephala melas*) were recorded and were potentially linked to elevated average surface temperatures along with a reduction in zooplankton biomass and an increase in abundances of pelagic planktivorous fish (Nøttestad et al., 2015). Changes in phenology were investigated for fin and humpback whales which showed an earlier arrival and departure from their summer feeding ground in the Gulf of St. Lawrence (Canada) over three decades (Ramp et al., 2015). Earlier ice break-up and increasing sea surface temperature, which likely triggered earlier primary production, were strongly related to the earlier arrival trend in both species (Ramp et al., 2015).

The high potential for abundance, distribution and phenology changes found in our study, further highlights that if climate change impacts increase, changes in cetacean species as a response to environmental changes may also become more common in the future. These changes create a challenge for policy and conservation planning by increasing the need to anticipate species' responses driven by climate change (Evans and Waggitt, 2020; Silber et al., 2017). In addition, non-climate stressors can be exacerbated or modified by climate change as a result of climate driven shifts in human behavior (Alter et al., 2010). For example, increased shipping activities in the arctic as a result of a reduction in sea ice will likely lead to increased mortality or injury events on cetaceans due to ship strikes. In our study area no major local impacts have been currently identified, with the exception of ship strikes from high-speed ferries in the Canary Islands (Carrillo and Ritter, 2010). Nevertheless, other human induced impacts such as an increased reliance on marine species in the future can produce serious knock-on effects leading to changes in prey availability or increased bycatch on cetaceans' populations (Alter et al, 2010; Simmonds, 2017).

Despite differences between the previously mentioned studies, the improved method used in this study, provided an optimized version of the previous work developed for the Madeira archipelago (Sousa et al., 2019) and a solid evolution in the use of this sort of trait-based methods for the assessment of climate change vulnerability.

3.5.3 Methodological considerations and further research

There are several methodological challenges in addressing the vulnerability of species to climate change. In a recent study from Wheatley et al. (2017) results showed that different vulnerability assessment methods were not consistent with one another because they consider different input variables and combine and measure those variables in different ways. These aspects present a challenge in sorting out the causes of differences in vulnerability rankings (Comte et al., 2019). In addition, there is a high degree of uncertainty about the relationship between species traits and the impact of climate change as well as the limited baseline knowledge on species ecology to carry out such assessments (Foden et al., 2019; Lankford et al., 2014). Another source of uncertainty is the use of expert elicitation which presents a set of bias such as group thinking (i.e., social pressure to minimize individual separation from the group), overconfidence or conservatism (i.e., overestimating or underestimating uncertainties) or anchoring (i.e., the tendency to anchor subsequent scores around an initial estimate) (Kuhnert et al., 2010; Mukherjee et al., 2016, 2015). There are several recommendations to address such uncertainties, namely the use of multiple experts to provide an estimate of the uncertainty based on the aggregation of multiple responses. Nevertheless, expert elicitation methods can be a powerful tool when there is limited data available (Kuhnert et al., 2010).

The number of experts assessing archipelago associated units was limited to two per archipelago while for Macaronesia units the assessment was made by all six experts. Generally, gathering cetacean ecology experts in geographically isolated areas such as islands can be a challenging. While we increased the number of experts from the previous assessment (Sousa et al., 2019) a larger expert group would be beneficial in future assessments.

According to Hare et al. (2016), there will never be a complete agreement between expert-based assessments and more detailed, empirical, or process-oriented assessments or approaches. Wheatley et al. (2017) argued that climate vulnerability assessments should not be used interchangeably. Such assessments of vulnerability are proposed to be used more as scoping studies rather than expecting the clear identification of robust priorities for investment (Comte et al., 2019). Notwithstanding their limitations, trait-based indexes are valuable tools that can help to rapidly assess many taxa and are able to identify specific areas or species in need of more in-depth studies and analysis (Foden et al., 2019; Pacifici et al., 2015).

The question is then how confident we are in a given assessment and if we are making meaningful interpretations that can be useful for conservation practitioners and policymakers? Considering the results from different assessments, the uncertainty in the perceived vulnerability of species to climate change and the potential impact in conservation management decisions, we provide the following suggestions.

Firstly, the communication of the framework used in the assessment and the associated uncertainties helps to provide the context in which results were obtained (e.g., the factors considered, how they were measured, which species and units were defined, and which study area was considered). An effective communication can support the informed use of results in the definition of adaptation strategies for species (Foden et al., 2019).

Secondly, research and monitoring of cetacean species is of uttermost importance in order to increase our knowledge on species' ecological traits. Baseline data on species ecology will help to identify changes in abundance, distribution and phenology and to validate the frameworks being used in the assessment of future climate change impacts. Trait-based vulnerability assessments, such as the one used in this study, can provide guidance for future monitoring and research studies (Hare et al., 2016).

Lastly, studies have advocated the use of different approaches such as the combination of trait-based methods with distribution modelling (Reside et al., 2019; Silber et al., 2017; Willis et al., 2015) and the use of an ensemble of climate vulnerability assessments and scenario planning exercises to produce an array of potential species responses to climate change (Borggaard et al., 2019; Wade et al., 2017). In this particular study and considering the use of climate scenarios, we have used RCP 8.5 that agrees closely with historical total cumulative CO_2 emissions (within 1% for 2005 to 2020) and is especially useful to inform short to mid-century decision-making (Schwalm et al., 2020). Overall, due to the unpredictability of future emissions and variability in historical emissions trends recommendations are to use a wide range of emission scenarios as input to analyses of future climate change (Pedersen et al., 2020).

3.6 Conclusion

We have built on the previous work for the Madeira archipelago, by applying a recently developed index and extending the study area of the assessment to Macaronesia, while including a larger poll of experts. This study contributed to the assessment of the vulnerability of cetacean in Macaronesia and to the debate on the comparability and agreement of results from different trait-based vulnerability assessments.

This methodology has the advantage of contributing to a systematic evaluation based on the most relevant sensitivity attributes and exposure factors for species under a changing climate. Additionally, it produces a species vulnerability rank that can, together with its underlying attributes, factors and data quality scores, support conservation and monitoring efforts while considering known uncertainties and knowledge gaps.

Further research should focus on the harmonization and validation of trait-based indexes to increasingly provide more comprehensive assessments. We highlight the importance of trait-based indexes as a valuable exploratory method that can provide valuable insights into which species will most likely be affected by climate change.

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Chapter 4. A novel expert-driven methodology to develop thermal suitability curves for cetaceans under a changing climate

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4.1 Abstract

Over the last decades, global warming has contributed to changes in marine species composition, abundance and dis- tribution, 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 on free-swimming large marine predators with wide-range distribution, 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 in these taxa. We developed and applied a methodology based on expert-derived thermal suitability curves and projected future responses for several species under different climate scenarios. We tested this approach with ten cetacean spe- cies 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 cetaceans' thermal suitability, and potentially in other highly mobile and large predators, and it tests this method's applicability, which is a novel application for this purpose and group of species. It aims to be a cost-efficient tool to support conservation managers and practitioners.

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

4.2 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). 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. Trait-based vulnerability assessment approaches relate to the association between species biological traits and projections of relevant climate variables, typically using expert elicitation and published literature to assess species' risk based on 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).

A recent advancement in trend-based approaches using thermal vulnerability indices has increased (Clusella-Trullas et al., 2021; Khaliq et al., 2014) and experimentally derived thermal tolerance limits present a good correspondence with species' thermal suitability (Webb et al., 2020). In the present study, 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 based on occurrence coincident with various temperatures.

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 or tag data with water temperatures (e.g., Chavez-Rosales et al., 2019; Chambault et al., 2022). 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 employed correlative approaches from trend- based assessments and expert elicitation approaches from trait-based assessments to evaluate 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.

4.3 Methods

4.3.1 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 4-1**). 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).

Over 30 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). An initial list of indicator species defined for Macaronesia under the Marine Strategy Framework Directive (MSFD) (MISTIC SEAS, 2016) together with two additional criteria relevant for this study, namely: 1) species frequently sighted by the whale watching vessels and therefore relevant for the activity, and 2) species which can potentially indicate climate-related changes (e.g., species whose northern distribution range limit is in at least one of the Macaronesian archipelagos) were discussed with the experts. The ten selected cetacean species include island-associated that are resident year- round or that exhibit multi-year site fidelity to at least one archipelago as well as individuals that use the entire region of Macaronesia as a single hab- itat and that are visitors in waters close to the archipelagos during a short period of time (days to weeks). The ten selected cetacean species are listed in **Table 4-1** (hereafter all species will be referred to by their common names).

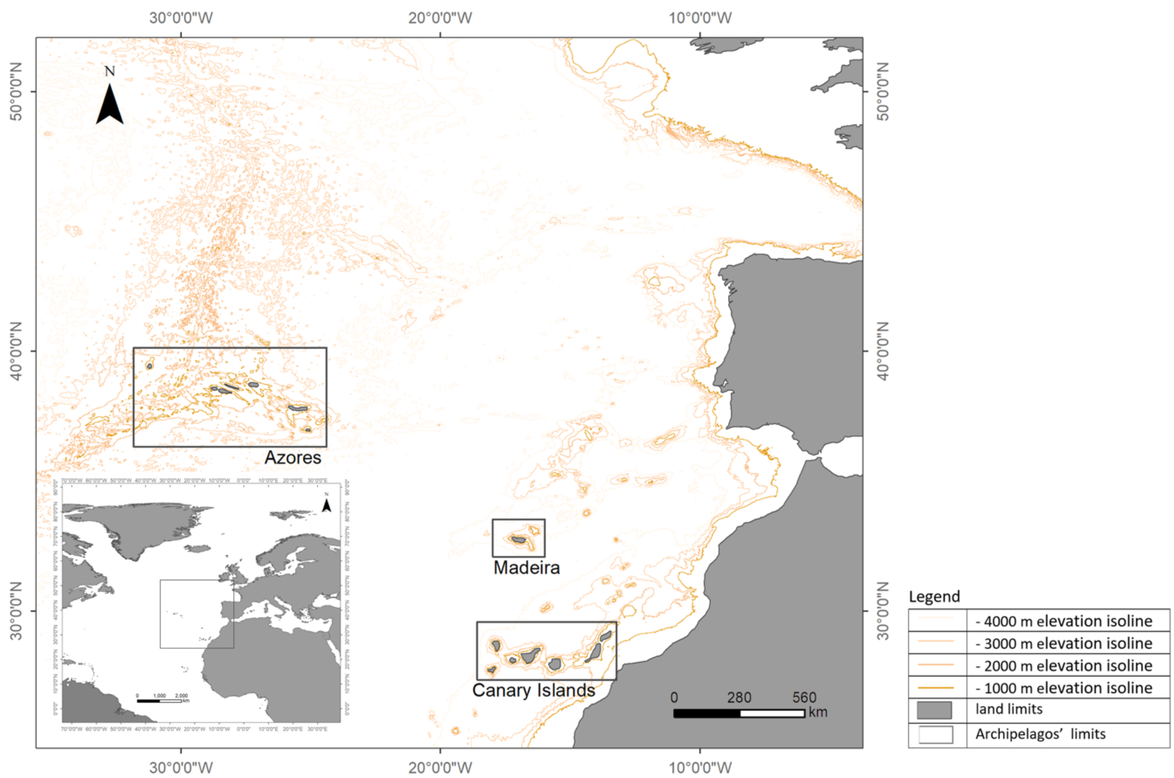

Figure 4-1 – The biogeographic region of Macaronesia with the Azores, Canary Islands and Madeira archipelagos.

Table 4-1 – 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	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

4.3.2 Development of thermal suitability curves

We developed thermal suitability curves for ten cetacean species (**Table 4-1**) in Macaronesia using an expert elicitation approach. Experts were selected through a snowball sampling method which is a chain referral method where individuals identify others which are a part of the targeted population (Goodman, 1961) This method is generally used in contexts where it is challenging to gather expertise due, for example, to low numbers of individuals that can be geographically dispersed such as in the bioregion of Macaronesia (Parker et al., 2019). This sampling method resulted in the selection of six experts on cetacean ecology in each archipelago (two experts per archipelago; L. González; M. Fernandez – Azores; F. Alves, A. Dinis – Madeira; M. Morales, P. Arranz – Canary Islands) and on the Macaronesia region at large. In the present study experts were asked to: 1) define the temperature and suitability scales and 2) score the six methods (i.e., the different combinations of temperature and suitability scales) and the data quality for each species.

Firstly, we defined a temperature range between 14 and 26 °C, for all cetacean species considering the known temperature range occurring in Macaronesian waters (Martins et al., 2007) and a thermal suitability range 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 jointly discussed and defined six different combinations of temperature and suitability scales (labelled method 1 to 6) (**Table 4-2**) and were then asked to individually assign a suitability value (from the discrete scales defined - TS1; TS2; TS3 in **Table 4-2**) to each temperature for each species. 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 F., 2021). Given that no significant differences (p-value>0.05) were found between the methods 3, 5 and 6 (**Figure 4-2**) 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 their thermal suitability curves. Data quality ranged from 0 (no data), 1 (expert judgment only), 2 (limited data), and 3 (adequate data) as described in Lettrich et al. (2019) and available in **Annex L**. Data quality scores were averaged for each species (**Figure 4-3**).

Table 4-2 – Six methods combining different thermal suitability (TS) and temperature (T) scales, for the development of thermal response curves for cetacean species.

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	18-20	20-22	22-24	24-26						
	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

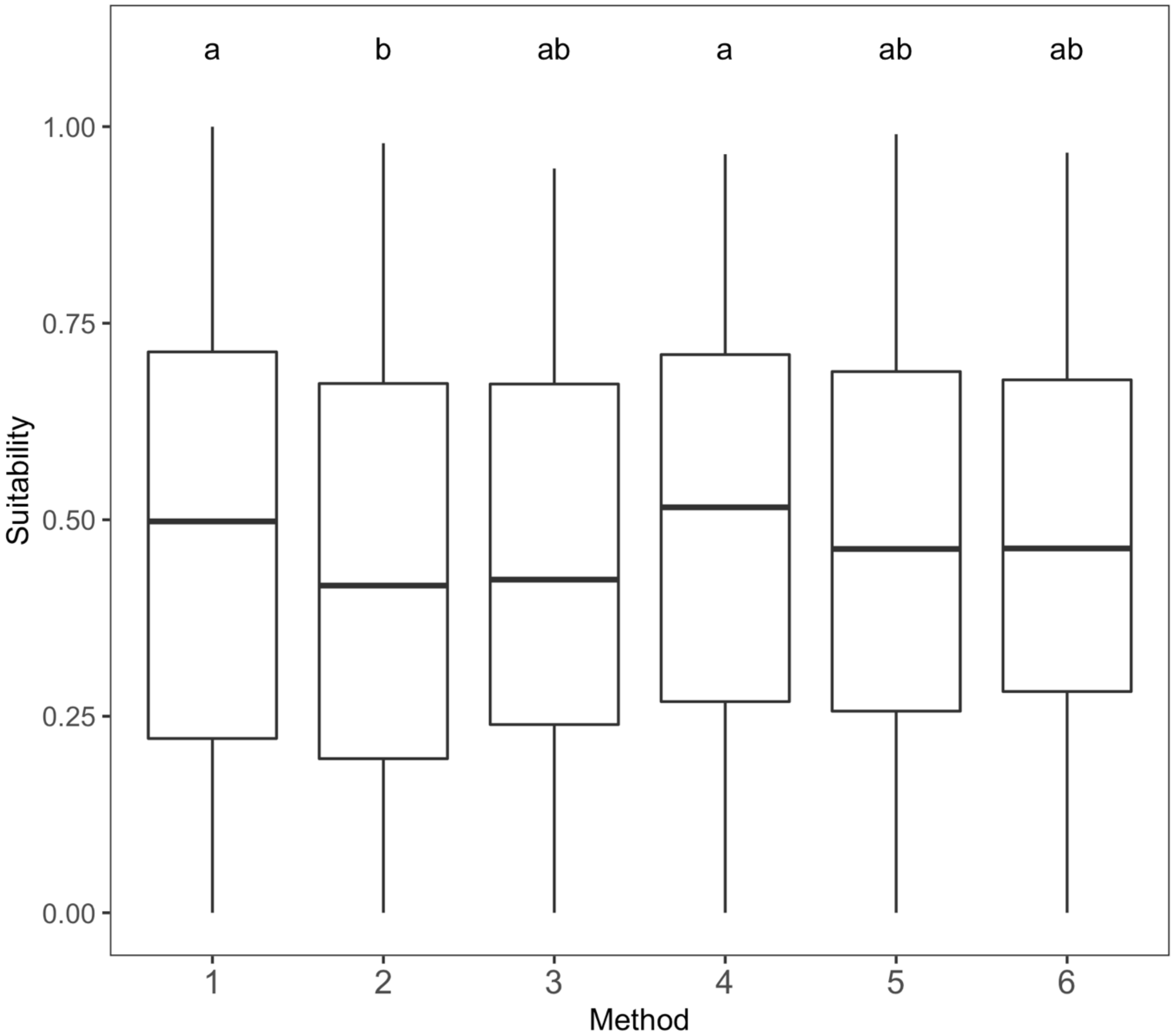

Figure 4-2 - Suitability scores attributed by experts when scoring each of the six different methods proposed for the development of thermal response curves for cetacean species (**Table 4-2**). Box represents the upper and lower quartiles, horizontal line inside each box indicates the median, whiskers 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).

4.3.3 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 °C, average of all models, with a spatial resolution of 1° × 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 (limits identified in **Figure 4-1**) under different RCPs (see Annex H and I). Plots were built in R using the ggplot package (Wickham, 2016).

4.4 Results

4.4.1 Thermal suitability curves

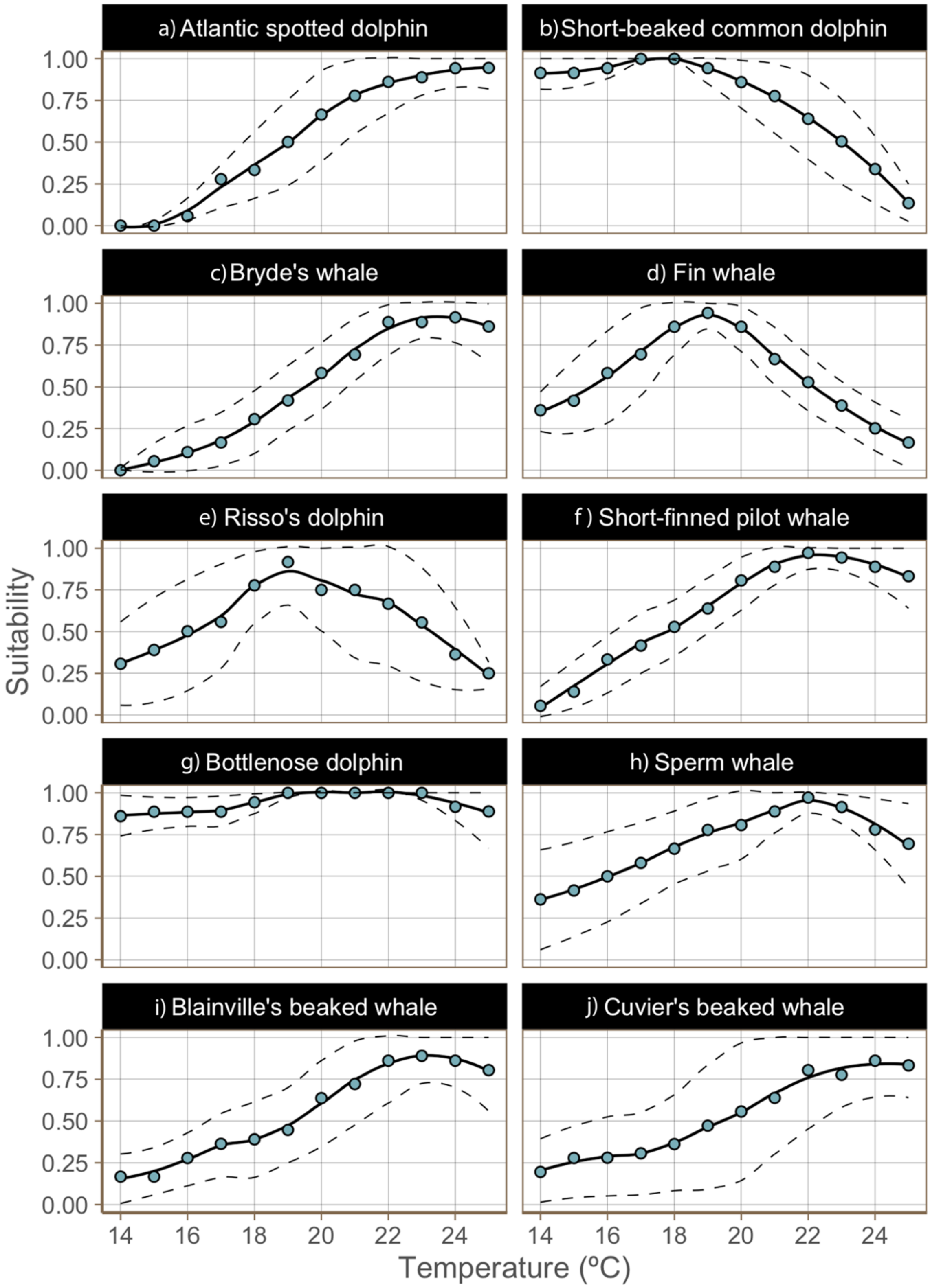

Figure 4-3 - Species thermal suitability curves for: a) Atlantic spotted dolphin; b) short-beaked common dolphin; c) Bryde's whale; d) fin whale; e) Risso's dolphin; f) short-finned pilot whale; g) bottlenose dolphin; h) sperm whale; i) Blainville's beaked whale; j) Cuvier's beaked whale. Mean data quality values (DQ) is 3 for a); b); c); f); g); h) and 2 for d); e); i); j). DQ values

range from zero to three where 0 = No data; 1 = Expert judgment only; 2 = Limited data; 3 = Adequate data (**Annex K**). Mean values are represented by the dots in the solid line and confidence intervals (standard deviation) are represented in the dashed line. Individual experts' scores are presented in Supplementary Material (**Annex M**).

As a result of expert's judgment, 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 22 °C. From 22 to 24 °C 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 (**Figure 4-3**).

The fin whale and Risso's dolphin follow a Gaussian thermal suitability curve with the most suitable temperature at approximately 19 °C. The fin whale thermal suitability gradually declines from 20 to 26 °C. 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 26 °C (**Figure 4-3**).

Expert judgment revealed that the short-beaked common dolphin most suitable temperatures ranged from 14 to 18 °C, with the highest thermal suitability between 17 and 18 °C followed by a steep decrease. By contrast, the Atlantic spotted dolphin increased its thermal suitability towards warmer waters with the highest thermal suitability from 24 to 26 °C. 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. Finally, according to the experts, the bottlenose dolphin showed a very high thermal suitability across the whole temperature range with the highest value between 19 and 22 °C (**Figure 4-3**).

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.

4.4.2 Species thermal responses

Overall, increases between historical and future projection of mean annual thermal suitability were found for the Bryde's whale, short-finned pilot whale, Blainville's beaked whale, sperm whale, Atlantic spotted dolphin, bottlenose dolphin and Cuvier's beaked whale. 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 4-3** and **Figure 4-4**).

Table 4-3 – 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 Representative Concentration Pathways (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
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

Thermal suitability maps for the remaining species can be found in the supplementary materials (**Annex H, I, J**).

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. The first species presents a similar increase in thermal suitability in warm waters in all archipelagos, reflected by the suitability curve. 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 26 °C (**Figure 4-3**). 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 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 bottlenose dolphin showed high thermal suitability across the whole temperature range with minor increases in thermal suitability in the future for all archipelagos (**Figure 4-3**).

The short-beaked common dolphin showed a decrease in thermal suit- ability 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.

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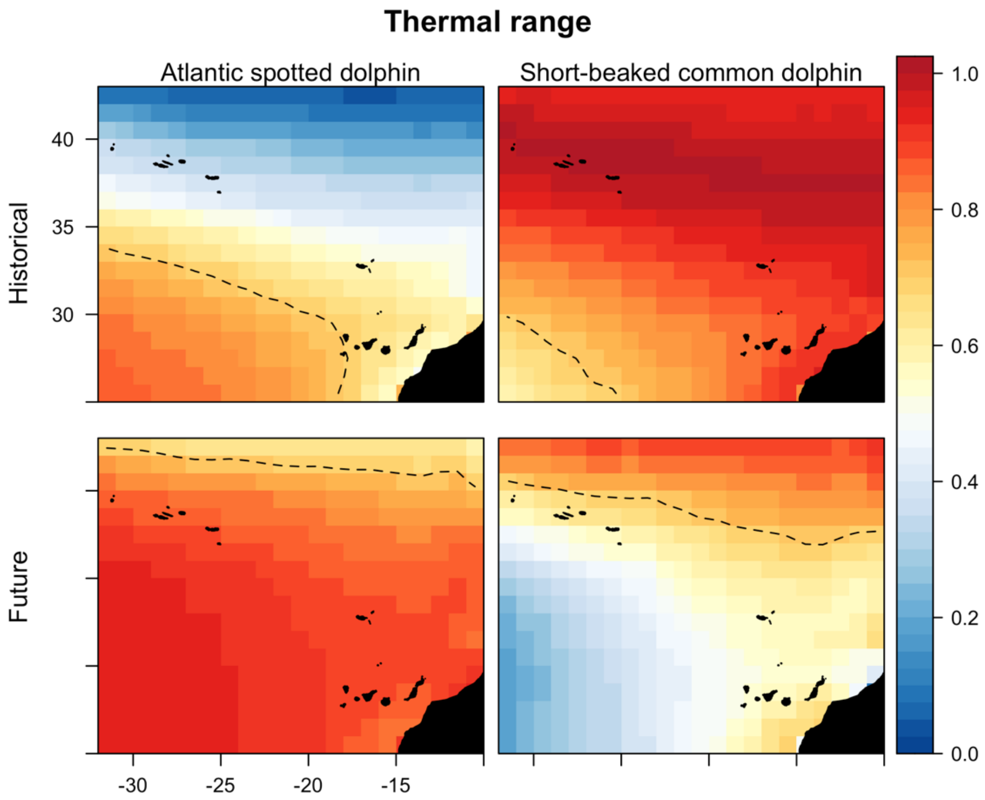

Figure 4-4 – Historical (1956–2005) and future (2006–2055) thermal suitability for representative concentration pathway (RCP) 8.5 for short-beaked common and Atlantic spotted dolphin. Scale on the right-hand side represents the lowest (0) and highest (1) thermal suitability. Dashed contour lines indicate a 0.75 thermal suitability.

Table 4-4 – Changes in mean seasonal thermal suitability in Autumn (OND), Winter (JFM), Spring (AMJ), and Summer (JAS) for cetacean species in Macaronesia (MAC) in bold and respective archipelagos, Azores (Az), Canary Islands (Can) and Madeira (Mad) for Representative Concentration Pathways (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
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, 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 (**Table 4-4**).

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 suit- ability 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 bottlenose dolphin minor changes in thermal suitability were obtained across all seasons and scenarios.

4.5 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 **Annex M and N**).

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 among 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 20 °C to 24 °C) 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 18 °C) 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 23 °C (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 world- wide, 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.

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 bottlenose dolphin habitat in the region has been recently characterized by a preference for waters close to coast (<1000 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 Azores, the fin whale ecological niche was shaped by low water temperature at 100 m depth (<18 °C), while for Madeira the preference for high chlorophyl levels was identified as a limiting factor (Fernandez et al., 2021, 2018). 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). 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. There are a number of biases in the elicitation of expert judgment to score species thermal suitability curves. Data availability differs in the different archipelagos and while minimizing this bias is challenging, experts used their data quality scores as a reflection of the data available to them score each species. This approach can provide an indication of potential thermal suitability changes and can complement other methodologies such as mechanistic modeling 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. For species that are 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 behavior, 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 behavior 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 is 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 and Caldeira, 2021; Montoto-Martínez et al., 2021; Sambolino et al., 2022). Increasing knowledge on ongoing non-climate impacts, would allow for a better understanding of the potential interactions with species climate projected changes to support conservation efforts.

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 and tagging data to validate expert-based curves and to monitor species with standardized protocols across all archipelagos of Macaronesia. This would increase the existing knowledge on oceanographic and climate processes as well as on species relationship with the environment. Recently, more couple climate model experiments (Eyring et al., 2016) have become available, which should also be used in future research.

4.6 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 modeling 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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Chapter 5. Integrated climate, ecological and socioeconomic scenarios for the whale watching sector

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5.1 Abstract

Unprecedented human induced changes to the climate system have already contributed to a variety of observed im- pacts to both ecosystems and populations. Decision-makers demand impact assessments at the regional-to-local scale to be able to plan and define effective climate action measures. Integrated socio-ecological assessments that properly consider system uncertainties require the use of prospective scenarios that project potential climate impacts, while accounting for sectoral exposure and adaptive capacity. Here we provide an integrated assessment of climate change to the whale watching sector by: 1) extending the European Shared Socio-economic Pathways (Eur-SSPs) and developing four whale watching SSP narratives (WW-SSPs) and 2) characterize each key element comprised in the WW-SSPs for the time period 2025–2055. We applied this approach in a case study for the Macaronesia region where we developed scenarios which integrate the socio-economic (WW-SSPs), climate (RCPs) and ecological (species' thermal suitability responses) dimensions of whale watching. These scenarios were used by local stakeholders to identify the level of preparedness of the whale watching sector. When confronted with scenarios that combine this ecological dimension with projected climate changes and the four different socioeconomic narratives, stakeholders assessed the whale watching sector in Macaronesia as being somewhat prepared for a Sustainable World and a Fossil Fuel Development World, but somewhat unprepared for a Rivalry World. No consensus was reached regarding the sector's preparedness level under an Inequality World scenario. Our study demonstrates the importance of considering multiple dimensions when assessing the potential challenges posed by climate change and provides a needed resource to help the whale watching sector in Macaronesia, and elsewhere, in its effort to devise efficient climate action policies and strategies.

Keywords: Integrated assessment; shared socio-economic pathways; climate change; cetaceans; whale watching

5.2 Introduction

According to the 6th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), anthropogenic climate change is widespread, rapid, and intensifying (IPCC, 2022a). Unless immediate, urgent, and large-scale reductions in greenhouse gas emissions occur, global warming of 1.5–2 °C will be exceeded during the 21st century. Many observed and projected changes in the climate system due to past and future greenhouse gas emissions show severe and irreversible impacts which can lead to great socioeconomic and ecological effects (IPCC, 2022a). The global ocean is a major regulator of the climate system through the uptake and redistribution of natural and anthropogenic carbon dioxide (CO_2) and heat. In addition to its role in the climate system, the ocean provides other ecosystem services such as, for example, food and water supply, renewable energy, health benefits, cultural values, tourism, trade, and transport (IPCC, 2019).

Tourism is one of the main socio-economic activities on coastal and island nations worldwide (e.g., Bojanic and Lo, 2016; Hoyt, 2005). Tourism in some areas, namely islands, depends on cultural ecosystem services associated with recreation and eco-tourism (Balzan et al., 2018). Marine eco-tourism activities (e.g., whale watching, diving) have the potential to bring socio-economic and environmental benefits to regional economies (Bentz et al., 2016; Cisneros-Montemayor et al., 2010; Ressurreição et al., 2022).

Whale watching tourism refers to commercial tours where tourists can observe cetaceans (whale, dolphin, or porpoise species) in their natural habitat (Hoyt, 2001). In Macaronesia, which comprises the volcanic archipelagos of Azores and Madeira (Portugal) and the Canary Islands (Spain) in the North Atlantic Ocean, the whale watching activity has been growing over the last decades (Bentz et al., 2016; Krasovskaya, 2017; Sequeira et al., 2009). Although the activity has different characteristics in the different archipelagos, and among islands within the same archipelago, recent estimates indicate more than 35 million euros in direct income to the region (IWC, 2022; Krasovskaya, 2017; Suárez-Rojas et al., 2021). In the Azores and Madeira, this activity has a smaller dimension, with an estimated number of 112, 263 tourists in 2017 in the Azores (DRT, 2018) and 129,158 in 2015 in Madeira (Krasovskaya, 2017), against an estimated number of 724,000 tourists in 2017 in Tenerife, where most of the activity takes place, in the Canary Islands (IWC, 2022).

Climate change is expected to impact whale watching until the end of the century, although the extent to which such effects will be felt is largely unknown (Moreno, 2010). To understand the potential effects of climate change in whale watching, a recent framework was developed using a participatory approach to explore the direct and indirect influence of climate- related impacts on this activity (Meynecke et al., 2017). This framework identified four key modules: 1) the biological module, consisting of species ecological related factors; 2) the climate module, related to relevant climate variables; and the 3) socioeconomic and 4) management module, related to factors such as the number of tourists and enforcement or regulations, respectively.

Scenarios have been widely used to assess climate impacts and better understand the complex interactions and associated uncertainties between the climate system, ecosystems, and human activities (e.g., Borggaard et al., 2020; Haward et al., 2013; O'Neill et al., 2017). A scenario framework has been developed by the climate community encompassing two main components: 1) a set of shared socioeconomic pathways (SSPs); and 2) representative concentration pathways (RCPs) (Ebi et al., 2014; Moss et al., 2010; van Vuuren et al., 2014). Global SSPs are scenarios that describe plausible and alternative visions of how society may evolve in the coming decades from a range of demographic, economic, technological, social, and environmental elements defined until 2100 (O'Neill et al., 2014, 2017; Riahi et al., 2017). SSPs do not consider impacts of climate change nor mitigation or adaptation responses (Kriegler et al., 2012; Riahi et al., 2017) and were designed as such to be used across a large number of studies with a variety of risk assessments and policies (O'Neill et al., 2014). Concurrently, RCPs result from emissions trajectories that represent different levels of radiative forcing, ranging from 1.9 to 8.5 W/m^2 in the year 2100, and generate climate projections that do not correspond to specific societal pathways. Therefore, the combination of SSPs and RCPs constitutes a framework that can be used in studies where climate risk and adaptation options are assessed simultaneously (O'Neill et al., 2020; Riahi et al., 2017; van Vuuren et al., 2014).

Qualitative descriptions of societal factors described in Global SSPs narratives, were quantified for a subset of factors called basic elements which are: Population (includes education and gender share), Urban share, and Gross Domestic Product (GDP) (Riahi et al., 2017). They were then used in integrated assessment models (IAM), together with other factors related to the physical climate system and considering a number of policies that are coherent with the narratives. This allowed for the iterative development of the narratives, basic elements and policy options for the baseline scenarios (which exclude climate policy). The combination of socio-economic factors, climate projections, and policy assumptions allow for the development of integrated scenarios, facilitating research, data analysis, and informing policymaking (O'Neill et al., 2020).

The development of SSPs proposed by O'Neill et al. (2014) focused on two stages – the basic and the extended SSPs. The basic SSPs aim to provide enough detail and comprehensiveness to distinguish between the different storylines. Each element in each pathway is defined by the challenges presented to adapt and mitigate climate change. In a second stage, the basic SSPs were extended to provide additional qualitative and quantitative trends to support specific sectoral and regional analysis. The aim of this two-stage approach was to provide a minimum set of assumptions that could rapidly be available for use by a wide range of research communities enabling regional and sectoral extensions of the basic SSPs. The addition and application of extended SSPs were recently developed with the aim of informing decisions at a variety of different scales and sectors (e.g., Maury et al., 2017; Merkens et al., 2016; Reimann et al., 2018).

For example, for Europe, four qualitative storylines (Eur-SSPs) with the respective characterization of each key element for three time slices (2010–2040; 2040–2070; 2070–2100) were developed (Kok et al., 2018) and are summarized as follows: Eur-SSP1 - We are the World, describes a more sustainable future, characterized by global cooperation and less energy and material intensive lifestyles; Eur-SSP3 - Icarus is characterized by regional rivalry and conflict where countries struggle to maintain minimal living standards in a context of high environmental degradation; Eur-SSP4 - Riders on the Storm, a future controlled by a small political and business elite and with high social inequity, but where Europe becomes an important eco- nomic and political player, with a strong stance on green-energy technology; and Eur-SSP5 - Fossil-fuelled Development, which describes a fossil-fuel driven world with a lack of environmental concerns that lead to damages which are counteracted by technological development and available resources, in a market driven society albeit with a high social equity. An Eur-SSP2 was not developed due to the moderate change in all elements in this scenario and to minimize the risk of being chosen by stakeholders as the best estimate (Kok et al., 2018). In another example, Merkens et al. (2016) developed coastal SSP narratives based on a series of coastal migration elements which promote settlement at the coast. For each coastal migration element assumptions were adopted from the global SSP key elements and interpreted based on the characteristics of each coastal SSP. The five developed coastal SSP narratives are: SSP1 – Green Coast, which describes a shift towards a more sustainable pathway with low impact tourism, resulting in well-managed coastal zones; SSP2 – No Wind of Change, coastal which follow historical patterns of socioeconomic development with moderate tourism and with a rapid population growth in some areas and a declining population in other areas; SSP3 – Troubled Waters, focus on national and regional issues which leads to no international tourism and the loss of attraction in both coastal and inland urban areas for human settlement; SSP4 – Fragmented Coast, is characterized by high inequalities with a socioeconomic fragmented population where tourism is high only for elites and where population growth is higher near coastal urban areas where economic activities are concentrated and; SSP5 – Coast Rush, is a highly globalized world where robust economic growth and international tourism leads to high population growth and development in the coastal zone.

Integrated assessments can be defined as "methods of analysis that combine results and models from the physical, biological, economic, and social sciences, and the interactions between these components, in a consistent framework, to evaluate the status and the consequences of environmental change and the policy responses to it." (IPCC, 2022b). Integrated assessments consider all relevant climate and non-climate drivers and their interactions and are increasingly being used to support integrated policy responses (e.g., Bindoff et al., 2019; Dowlatabadi and Granger Morgan, 1993; Holman et al., 2005; Nicholls et al., 2008; Sebesvari et al., 2016). However, integrated assessments of climate change are often challenging due to the large uncertainties and to the need to integrate inter and transdisciplinary knowledge to support decision-making (Holman et al., 2005; Meynecke et al., 2017). With regards to whale watching, the need for integrated and coordinated approaches has been acknowledged as a key aspect for the management and sustainability of the activity (Fernandes and Rossi-Santos, 2018; Meynecke et al., 2017; New et al., 2015).

Therefore, the present work aims to contribute to address the need for, and improvement of, integrated studies by developing whale watching scenarios that can serve as an impact and vulnerability assessment approach to support decision-making. The specific objectives of this study were to 1) extend the Eur-SSPs (Kok et al., 2018) to the whale watching sector (WW-SSPs) and to 2) characterize each key element comprised in the WW-SSPs for the time period 2025–2055. We then applied the whale watching scenarios that combine WW-SSPs with future climate scenarios (RCPs) and cetaceans' thermal response curves to a case study in the biogeographic region of Macaronesia.

5.2 Methods

5.2.1 Developing WW-SSPs narratives

The first step in developing SSP narratives for the whale watching sector was to identify the key elements relevant for the activity. Key and specific elements are the socio-economic factors that characterize the whale watching activity and these were identified and listed from two previously published frameworks on whale watching and climate change (Lambert et al., 2010; Meynecke et al., 2017). The initial key elements list was presented and discussed in a stakeholder workshop in the archipelago of Azores.

The workshop took place on 27th September 2018 with 15 local stake- holders (whale watching company owners, biologists, researchers, and members of the regional government) in the island of São Miguel. Stake- holders were selected with the support from members of the regional government which provided information on the registered whale watching companies as well as local environmental and socio-economic researchers. Stakeholders were directly contacted by email and phone. In this first work- shop, whale watching elements were presented and discussed, validating the original list, improving existing elements and/or incorporating new ones. In the Canary Islands and Madeira, 4 online meetings (two in each archipelago) were carried out with whale watching companies. These served to ensure that all the elements previously identified in Azores were also relevant for the Canary Islands and Madeira.

The second step was to select the key elements of the Eur-SSPs that would frame the WW-SSPs for the time period of 2025–2055. We followed the approach of Merkens et al. (2016), where elements from the global SSPs (O'Neill et al., 2014a) were used as explanatory variables for a set of coastal SSP elements. Explanatory elements are qualitative elements from the global SSPs such as economic or technology development which were used as a general frame for the coastal SSPs narratives and for the assumptions that characterize the key elements in each coastal SSP (Merkens et al., 2016). Here, we identified the Eur-SSP elements from Kok et al. (2018) as explanatory variables for the assumptions adopted in the whale watching narratives. Qualitative elements from the Eur-SSPs were selected to extract the assumptions adopted in the whale watching pathways and coastal tour- ism SSPs were used directly from Merkens et al. (2016) (**Table 5-1**).

Table 5-1 – Key socio-economic elements for whale watching and corresponding explanatory European shared socioeconomic pathways (Eur-SSP) elements from Kok et al. (2018) and Costal tourism SSPs from Merkens et al. (2016).

Whale watching [Reference]		Selected Eur-SSPs Elements
Key elements	**Specific elements**	
Tourists	Number (Meynecke et al., 2017)	*Coastal Tourism SSPs**
	Preferences (Bentz et al., 2016; Cornejo-Ortega et al., 2018; Mohamed, 2013; Suárez-Rojas et al., 2019; Torres-Matovelle and Molina-Molina, 2019; Warren, 2012)	Education investments Environmental respect
	Type (Lambert et al., 2010)	Education investments Environmental respect Economic development
Costs (Meynecke et al., 2017)	Fuel	Economic development Technology development Quality of Governance
	Wages	Economic development Education investments Quality of Governance
	Assets	Economic development Technology development
	Insurance	Economic development Social cohesion
Income (Meynecke et al., 2017)	Ticket price	Economic development
Regulations (Meynecke et al., 2017)	Licenses	Quality of Governance Economic development Environmental respect
	Protected areas	
	Enforcement	
Knowledge (Meynecke et al., 2017)	Monitoring	Quality of Governance Economic development
	Research	
	Education	

Anthropogenic activities and main associated pressures (MISTIC SEAS II, 2018; MSFD - Annex III, 2015)	**Fisheries** (by-catch; prey availability; marine litter) **Maritime transport** (anthropogenic sound; death or injury by collision; input of contaminants) **Nautical tourism** (anthropogenic sound; input litter; disturb species) **Military exercises** (anthropogenic sound; death or injury) **Aquaculture** (input of contaminants and organic matter) **Renewable energy** (anthropogenic sound) **Seabed mining** (anthropogenic sound; destruction of seabed habitats)	Environmental respect Quality of governance Technology development
Dimension of activity (Meynecke et al., 2017)	Number of operators Number of vessels	Economic development

* In this particular element, coastal SSPs were used directly from Merkens et al., 2016.

The tourist numbers element was characterized directly from the coastal tourism SSPs (Merkens et al., 2016). This element was complemented with additional assumptions on tourists' preferences and type for whale watching in Europe (**Table 5-1**).

We considered that education, income, and environmental values influence tourists decisions to undertake an activity (Cohen et al., 2014; Cornejo-Ortega et al., 2018; Li and Cai, 2011; Tkaczynski and Rundle-Thiele, 2018), while recognizing the complexity of factors involved in decision-making such as participants personality, attitude, preferences, or satisfaction (Bentz et al., 2016; Shahrivar, 2012; Vieira et al., 2018). In general, whale watchers consider important that tours are environmental-friendly and educational. Studies show that satisfaction factors vary according to different regions, nationalities or gen- der (Bentz et al., 2016; Musa, 2002). Most studies show that seeing whales, cost of trip, boat type, low crowding and closeness to the animals are important factors for tourist satisfaction (Bentz et al., 2016; Cornejo-Ortega et al., 2018; Mohamed, 2013; Suárez-Rojas et al., 2021; Torres-Matovelle and Molina-Molina, 2019; Warren, 2012). In our study, we considered two whale watchers typologies – the "generalist" and the "specialist" – which vary according to their different level of interest in observing a cetacean species (Lambert et al., 2010).

In regard to energy, in particular fuel, there are several factors that can influence its cost such as supply and demand, weather forecasts, global markets, imports and exports, and government regulations (Bilgen, 2014; Costantini et al., 2007; Umbach, 2010). While recognizing the contribution of all these factors, we assumed the cost of fuel to be related to a supply and demand behaviour and linked to economic and technological development. We also considered that governmental regulations are related to the quality of governance which in turn can promote the evolution of the energy sector by replacing conventional energy with alternative sources of renewable energy (Abolhosseini et al., 2014; Bilgen, 2014; Kumar and Managi, 2009). Costs for maintenance of assets and infrastructure are related to technologic and economic developments which are driven by energy needs and mate- rial resource intensity (Allwood et al., 2013). We assumed costs of insurance to be linked to market concentration as well as to challenges for adaptation. Market concentration is driven by economic development and social cohesion which are in turn associated to the distribution of wealth within society. We assumed that a higher level of education is linked to higher wages (Albert and Davia, 2005). The price of tour and company's in- come will be affected by the economic power of tourists (Tkaczynski and Rundle-Thiele, 2018). We assumed that regulations, namely number of licenses and the extension of protected areas, as well as enforcement of procedures (e.g., code of conduct), and monitoring, research, and education, are associated with the quality of governance and economic development which ensure that financial and human resources are available to invest in the implementation and enforcement of such regulations (Bennett and Dearden, 2014; Lockwood et al., 2012). Anthropogenic activities were assumed to be related to ecosystem health and environmental respect (McKinley and Fletcher, 2012) and to the quality of governance and technology development which contribute to the management of these activities (Yadav and Gjerde, 2020).

A qualitative characterization of the different specific elements in each whale watching Shared Socioeconomic Pathways (WW-SSPs) for the period 2025–2055 was performed by the authors, with the exception of tourist numbers, and validated in a stakeholder workshop (details in section 5*.2.2 Case study: Whale watching scenarios for Macaronesia)*.

5.2.2 Case study: Whale watching scenarios for Macaronesia

The Macaronesian archipelagos of the Azores, Madeira, and Canary Islands (**Figure 5-1**) were selected as a case study since they are considered a biodiversity hotspot, renowned for its diversity of species, ecosystems, and landscapes (BEST, 2016; Myers et al., 2000). A large number of cetacean species (over thirty) have been recorded in Macaronesia (Alves et al., 2018; Carrillo and Ritter, 2010; Silva et al., 2014). This largely contributed to the development of the whale watching industry in this region over the past decades making Macaronesia one of the main international destinations for this activity (Suárez-Rojas et al., 2019).

We developed four whale watching scenarios for the biogeographic region of Macaronesia for the timeframe 2025–2055. These scenarios integrate WW-SSPs (socio-economic module) with future climate trends (climate module) and cetaceans' thermal suitability responses (biological module)

Figure 5-2). For simplicity, scenarios took the name of the WW-SSPs, i.e., Scenario 1: *Whale watching in a sustainable world*; Scenario 3: *Whale watching in a Rivalry world*; Scenario 4: *Whale watching in an inequality world*; Scenario 5: *Whale watching in a fossil fuel development world*.

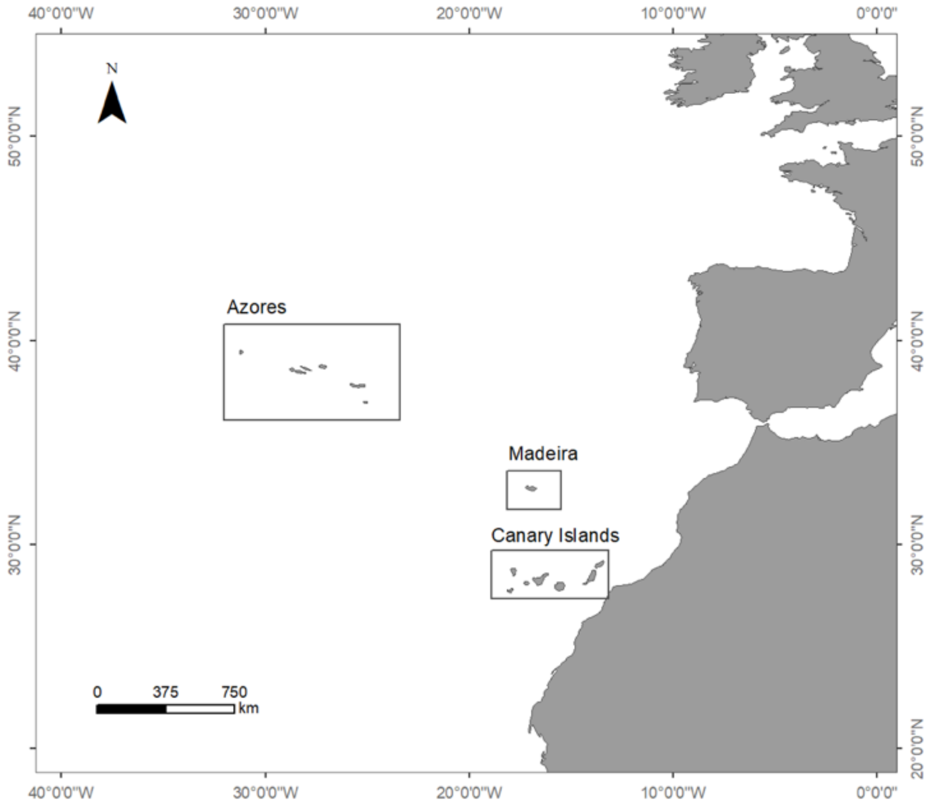

Figure 5-1 – Macaronesia bioregion, depicting the archipelagos of the Azores, Canary Islands and Madeira.

WW-SSPs were developed as detailed in section 5.2.1. Future climate trends were obtained through literature review to feed the climate module. Similarly, cetaceans' thermal habitat suitability curves under RCP 4.5 were developed through expert judgement and responses to changes in sea surface temperature were projected (Sousa et al., 2022) and further used to feed the biological module

Figure 5-2). We selected RCP 4.5 because, from the three most commonly applied RCPs (2.6; 4.5; 8.5), it is the one for which integrated assessment models found feasible outcomes across all SSPs (O'Neill et al., 2020). The short to mid-century timeframe (2006–2055) was selected to assist decision-making processes and support adaptation measures that target species' conservation.

Finally, the developed scenarios were presented and validated through collaboration with 13 stakeholders from Macaronesia in a workshop on 28- 29th June 2021. Local stakeholders included whale watching company owners, biologists, researchers, and members of the regional government from each archipelago of Macaronesia. Stakeholders in Azores were identified from the first workshop and in Madeira and the Canary Islands were selected through a snowball sampling method were individuals assist in identifying other individuals in a subject area (Goodman, 1961; Parker et al., 2019).

Additionally, stakeholders were asked to identify the level of preparedness (from very prepared, somewhat prepared, somewhat unprepared, and very unprepared) of the whale watching sector in their archipelago, under different scenarios.

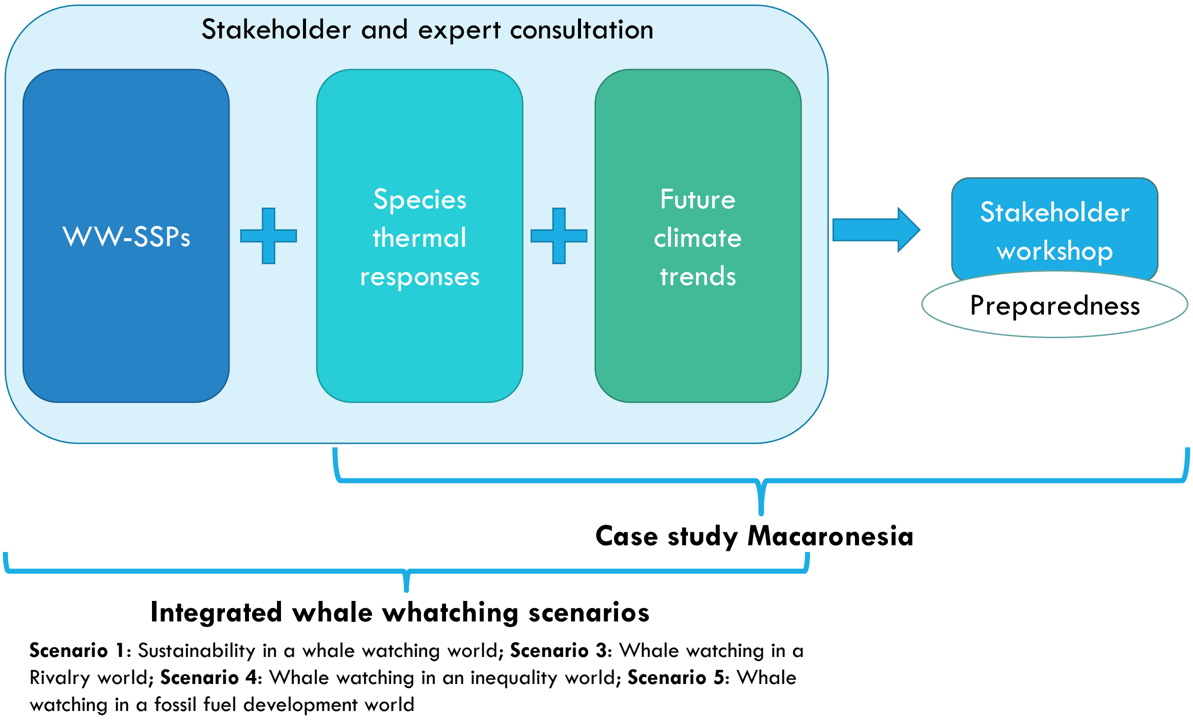

Figure 5-2 – Conceptual model of the development of whale watching scenarios that combine the biological, climate and socio-economic modules (adapted from Meynecke et al., 2017) which was integrated in a stakeholder workshop where the preparedness of the sector was assessed under the different scenarios.

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5.3 Results

5.3.1. WW-SSPs narratives

The four WW-SSPs narratives that were developed (based on the four considered Eur-SSPs), together with future trends for each specific element in the different SSPs are presented in **Table 5-2** and detailed in the following sub-sections.

WW–SSP1: Whale watching in a sustainable world

In Europe and worldwide, there is a shift towards a sustainable development pathway with a high commitment towards less resource intensive lifestyles. There is a greater focus on well-being over economic growth, which is supported by high levels of political and societal awareness on the importance of environmental quality. As a result, there are high cetaceans encounter rates for the whale watching activity. Environmental pressures are reduced, and a good environmental status is effectively maintained, with low impact on species. Sustainable tourism practices with low impact together with the reduction in long-range travel and the absence of mass tourism reduce the number of tourists and whale watchers. Under this pathway, the low number of tourists leads to a reduced number of operators and vessels. Whale watchers are mainly specialists who are highly interested in observing cetacean species. Ticket prices are high due to the steady economic development. Environmental-friendly conditions including commitment to existing regulations by tour operators and the educational components of the activity are valued in this pathway.
Costs are high for fossil fuels due to lower supply and strong environ- mental policies. There is a high incentive for the use of alternative clean energy sources (e.g., electric energy) which translates into higher costs that are recovered in overall revenues. Steady economic growth and investment in education lead to higher wages. Costs are high for maintenance of assets and infrastructure due to low material growth, low material resource and low energy intensity. Costs of insurance are low in a context of fair trade and low challenges for adaptation.

In this pathway, sustainable whale watching practices are conducted with a reduced number of operators and tourists, both with high environmental concerns, promoting sustainable practices with low impact on cetacean species and a focus on sustainability.

WW–SSP3: Whale watching in a regional rivalry world

This pathway focuses on the increase of national and regional blocks, which result in a widespread fragmentation and division at the decision-making level. There is low social cohesion, education, health, and technological investments. The environment degrades with severe ecosystem failures due to an intensive material consumption and low priority for environmental protection. Environmental degradation and increasing environmental pressures lead to lower cetaceans sighting rates. Tourism is restricted, with no international tourism, which leads to a low number of whale watchers. Short range tourism is mostly confined to national borders/regional blocks with a reduction in the number of tourists. Ticket prices and profit margins are low due to low economic development. The whale watching activity is characterized by a strong reduction in number of operators and vessels because of low economic and technological development. Due to low investments in education and low environmental respect, tourists' satisfaction is low. The activity is less focused on education, re- search or monitoring with little to no respect for regulations. The costs of whale watching activity are high for fossil fuels due to high demand, and low incentive for the use of alternative clean energy (e.g., electric energy) because technology is scarce and only available at high costs. Costs for maintenance of assets and infrastructure are low due to lack of economic resources and increasing resource intensity and fossil fuel use. Strong inequalities and low economic and education investments lead to lower labour force wages. Costs of insurance are high due to high challenges for adaptation and unregulated prices due to market concentration.

In this pathway, whale watching is characterized by a low number of operators and tourists, with a reduced number of tours and lower sighting rates due to a degraded environment with high impacts on cetacean species.

WW–SSP4: Whale watching in an inequality world

This pathway is characterized by a high social inequity that results in unequal investments in human capital, leading to large social disparities across and within countries. There is a powerful political and business elite and a lower income working class. Europe becomes a leader in green technologies with energy supply controlled by the elite. A powerful European government enforces environmental policies and commits to reduce the depletion of natural resources that are focused locally on important areas of middle and high income classes, thus creating pocket areas of environmental protection. Environmental pressures are locally mitigated resulting in the reduction of local pressures. Cetaceans sighting rates will vary depending on the area.

Tourism is high for the elites and low for most of the population leading to a decrease in number of tourists and, consequently, to a reduction in the number of operators and vessels. However, the high economic power of the elites allows for high ticket prices.

The elite is characterized by high educational and environmental values, supports environmental-friendly conditions for whale watching and the fulfilment of regulations.

Cost of fuel is high for fossil fuels and for the use of alternative clean energy due to a controlled energy supply (ran by an oligarchy of green business developers). Wages are low due to lower income for the working class in a labour-intensive work environment. Costs for assets and infrastructures are high due to market concentration of suppliers, namely for low-carbon energy technologies. Insurance costs are high due to high challenges for adaptation together with market concentration.

In this pathway, whale watching is characterized by a reduced number of elite tourists and a reduced number of operators and tours. The environment is locally protected with low impacts for cetacean species.

WW–SSP5: Whale watching in a fossil fuel development world

In a market driven, fossil fuel dependent world, populations adopt energy intensive lifestyles. Economic and social development are strongly dependent on the exploitation of fossil fuels particularly shale gas in Europe. The environment degrades but there is faith in technological solutions to manage ecological and social systems including geo-engineering. The environment is locally degraded; however, successful technological innovations address these changes allowing for an efficient search for species with guar- anteed sightings. Environmental pressures are also mitigated with technology and regulations that effectively create locally protected areas to ensure that the activity takes place. Tourism is very high, characterized by mass tourism where an increasing number of whale watchers – mainly generalists – that are able to pay high ticket prices due to high economic development. The whale watching activity is characterized by a high number of operators and vessels due to strong economic development and high number of tourists where preferences related to environmental-friendly and educational tours may not be fully met. Considering the high number of tourists crowding takes place with high impact on cetacean species that are mitigated by technological developments. In addition, the likelihood of observing a cetacean species is lower but also counteracted by technology.

Costs of fossil fuels are low due to the continuous extraction of fossil fuels. Costs for maintenance of assets and infrastructure are low due to a strong focus on technological solutions fuelled by the exploitation of fossil fuel resources. High education investments and economic growth lead to higher wages of the working staff. Insurance costs are low due to low challenges for adaptation, despite losses due to extreme weather events. Business competition and high income ensure competitive and accessible prices of insurances.

In this pathway, whale watching is characterized by an increasing number of operators and tourists in a degraded environment with high impacts for cetacean species that are mitigated by technology.

Table 5-2 - Characterization of the different specific elements in each whale watching Shared Socioeconomic Pathways (WW-SSPs) for the period 2025-2055.

Elements	Specific elements	WW-SSP1 Sustainability	WW-SSP3 Regional Rivalry	WW-SSP4 Inequality	WW-SSP5 Fossil fuel development
Tourists	Tourist numbers	↓	↓	↑ elites ↓ lower class	↑
	Tourist satisfaction	↑	↓	↑	↓
	Tourist type	↑ specialist ↓ generalist	↓ specialist ↓ generalist	↑ specialist ↓ generalist	↓ specialist ↑ generalist
Costs	Fuel	↑	↑	↑	↓
	Wages	↑	↓	↓	↑
	Assets	↑	↓	↑	↓
	Insurance	↓	↑	↑	↓
Income	Ticket price	↑	↓	↑	↑
Regulations	Licenses	↓	↓	↓	↑
	Protected areas	↑	↓	↑	↑
	Enforcement	↑	↓	↑	↑
Knowledge	Monitoring	↑	↓	↑	↑
	Research	↑	↓	↑	↑
	Education	↑	↓	↑	↑

Anthropogenic activities (main associated pressures in **Table 5-1**)	Fisheries Maritime transport Nautical tourism Military exercises Aquaculture Renewable energy	↓	↑	↓	↓
Dimension of activity	Number of operators Number of vessels	↓	↓	↓	↑

↑ high, ↓ low

5.3.2 Case study: Whale watching scenarios for Macaronesia

5.3.2.1 Future climate trends

The most relevant climate variables for the whale watching activity identified by local stakeholders in Macaronesia were wind speed, wave height, frequency and intensity of extreme events that influence the number of days with suitable sea conditions, and atmospheric conditions that influence tourists' comfort levels. Comfort levels influence destination choices, which in turn impact the number of tourists traveling to each archipelago.

Tourists' thermal discomfort level for the Canary Islands projected, through the application of the humidity index, an increase of 11.5 (RCP2.6) and 27.2 (RCP 8.5) number of days per year with a discomfort level greater than 35 °C, for the period 2046–2065 (SOCLIMPACT, 2020). For the Azores archipelago an increase of 27.1 (SRES B1) and 35.5 (SRES A1B1) days with discomfort levels great than 35 °C, for the period 2031–2050, were projected. For Madeira an increase of 0.6 (RCP 2.6) and 5.2 (RCP 8.5) days with discomfort levels were projected for the period 2046–2065 (SOCLIMPACT, 2020).

Integrated climate assessments that respond to the potential impacts of changes in coastal-to-open-ocean environments are strongly dependent on wave-climate projections (height, length, and directions) and associated levels of confidence (Morim et al., 2018). Like in other oceanic areas, future wind and wave climate trends in the Macaronesia region are constrained by large uncertainties surrounding future North Atlantic storminess (Bricheno and Wolf, 2018), including extratropical cyclone development (cyclogenesis) and storm tracks in the region (Harvey et al., 2012; Aarnes et al., 2017; Lobeto et al., 2021). These uncertainties in current projections are dominated by climate model-driven uncertainty (Morim et al., 2019). Additionally, the scientific community's efforts have focused more on sampling inter-model and/or inter-scenario uncertainty than on the intra-model variance originated in the chaotic nature of the climate system, making up for an influence of uncertainty that is currently greater than the actual projected changes (Morim et al., 2018).

In the North Atlantic Ocean, the scientific consensus points to a projected decrease in annual and seasonal mean significant wave height ($\overline{H}s$) and in extreme wave heights (Hs), that is more pronounced under RCP 8.5 and generally consistent with projected wind changes (Aarnes et al., 2017; Lemos et al., 2021; Lobeto et al., 2021; Morim et al., 2018). Expected changes in surface wave climates are a response to changes in the frequency, intensity and position of forcing winds and storms and to changes in sea-ice and associated im- pact on fetch conditions (Fox-Kemper et al., 2021).

Several explanations have been put forward for the projected decreases in the North Extratropical Atlantic region. These include the expected enhanced warming of the Artic and extratropical regions that may reduce the North- South temperature gradient, thus decreasing baroclinic instability and cyclo- genesis (Aarnes et al., 2017). Additionally, projected increases in the occurrence of weather types that are dominated by high-latitude storm tracks (above 50° N) and atmospheric blocking patterns, along with decreases in the occurrence of lower-latitude storm tracks and negative North Atlantic Oscillation (NAO) patterns, are consistent with scenarios of a generalized de- crease in $\overline{Hs}$ and extreme Hs, (Lemos et al., 2021). This can be partly explained by the spatial patterns and the north Atlantic's relatively narrow coastal geometry, since a projected displacement of storm tracks to higher latitudes, where the presence of land masses with sheltering effect is larger, will make available open ocean areas for wave generation – fetches – limited, and in turn reduce wave heights (Semedo et al., 2015; Lemos et al., 2021).

Climate extreme events are projected to be affected by changes in ocean conditions. Future climate trends in frequency and magnitude of extreme events, such as tropical cyclones (TC), still demonstrate low confidence and high uncertainty (van Oldenborgh et al., 2017; Weinkle et al., 2012). TC are likely to decrease in frequency or remain unchanged (Christensen et al., 2013). Also, a decrease in the number of extratropical cyclones in the North Atlantic basin is expected (Michaelis et al., 2017; Zappa et al., 2013). Moreover, the number of tropical storms in the North Atlantic may decrease driven by its sensitivity to Atlantic Meridional Overturning Circulation (AMOC) and Subpolar Gyre (SPG) variations (IPCC, 2019).

5.3.2.2 Cetaceans' thermal suitability responses

In Macaronesia, species' thermal suitability responses under RCP 4.5, showed that 3 out of 10 cetacean species are likely to decrease their thermal suitability, while the remaining 7 are likely to increase (**Figure 5-3**).

A higher increase in thermal suitability was found for Bryde's whale (*Balaenoptera brydei*), short-finned pilot whale (*Globicephala macrorhynchus*) and spotted dolphin (*Stenella frontalis*), while a lower increase in suitability was found for Blainville's beaked whale (*Mesoplodon densirostris*), sperm whale (*Physeter macrocephalus*), Cuvier's beaked whale

(*Ziphius cavirostris*) and common bottlenose dolphin (*Tursiops truncatus*) (Sousa et al., 2022) (**Figure 5-3**).

Species thermal suitability responses consider exclusively sea surface temperature. However, 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. 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). Despite these limitations, future thermal suitability responses are a simple and easy to apply method, targeted for decision-makers, which provides a rapid assessment of a large number of species (Sousa et al.,2022).

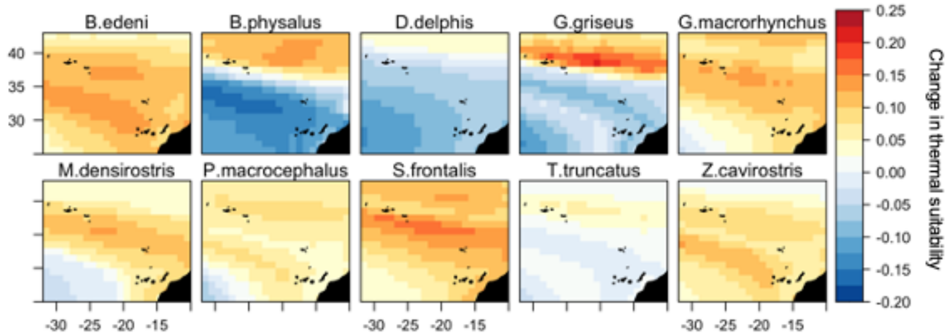

Figure 5-3 - Changes in thermal suitability for cetaceans in Macaronesia (adapted from Sousa et al., 2022). The scale indicates the changes in thermal suitability between the historical (1956-2005) and the projected (2006-2055) sea surface temperature according to species' thermal curves. Species are identified by their scientific name as follows: *Stenella frontalis* (Atlantic spotted dolphin); *Balaenoptera edeni* (Bryde's whale); *Balaenoptera physalus* (Fin whale); *Globicephala macrorhynchus* (Short-finned pilot whale); *Delphinus delphis* (short-beaked common dolphin); *Physeter macrocephalus* (Sperm whale), *Grampus griseus* (Risso's dolphin); *Tursiops truncatus* (Common bottlenose dolphin); *Mesoplodon densirostris* (Blainville's beaked whale); *Ziphius cavirostris* (Cuvier's beaked whale). Numbers in the upper left and in the bottom indicate latitude and longitude, respectively.

5.3.2.2 Stakeholder workshop

Overall, stakeholders in Macaronesia considered whale watching to be *somewhat prepared* for a Sustainable world (69%; n=13) and for a Fossil fuel development world (46%; n=13) and *somewhat unprepared* for a Rivalry world (62%, n=13). Stakeholders were divided between whale watching being *somewhat prepared* (31%, n=13) and *somewhat unprepared* (39%, n=13) for an inequality world. A *very unprepared* whale watching was identified in scenario 4 (15%, n=13) and especially in scenarios 3 (31%, n=13) and 5 (31%, n=13).

5.4 Discussion

The WW-SSPs developed in this study consider consistent and plausible scenario pathways for the whale watching sector. These scenarios were useful in raising awareness, communicating and debating the effects of climate change on the whale watching activity with decision makers and stake- holders of Macaronesia.

When extending Eur-SSPs narratives at smaller scales and to specific sectors, the assumptions defined for some key elements are often simplified. For example, there are several factors that can influence the cost of energy or tourist's satisfaction that are challenging to fully capture in the development of narratives. Tourists' satisfaction is characterized by multiple drivers that vary according to different regions, nationalities or gender (Bentz et al., 2016; Musa, 2002). In addition, several assumptions considered in each narrative scenario can be open to different interpretations (Zandersen et al., 2019). For example, in SSP4 we assumed that there was an interest in the protection of the environment by a highly educated elite. However, a balance between a protected environment and socio- economic interests by the elite may also take place. In addition, a marine environment protected by the elite only “in pockets” or an environment protected only in ones' “own backyard”, such as the one described for SSP5, can be challenging to contemplate, and the spatial implications of such “pockets” or “backyard areas” difficult to assess.

Further research on the application and comparability of whale watching scenarios in other geographical areas can offer additional insights into the uncertainty and multiple interpretations considered in the narratives. While we consider that the key elements and assumptions used in our study have a generic nature and can be applied to the whale watching activities in most regions, there may be small scale specificities which can be revised and incorporated in the scenarios. In addition, we used mainly a top-down approach in the development of scenarios but these were discussed and validated through stakeholder and expert consultation. Other approaches to extend SSPs using both top-down and bottom-up approaches have been carried out with different levels of participatory involvement, where local and regional actors co-produce the narratives (Nilsson et al., 2017; Zandersen et al., 2019). Currently, there is not a commonly agreed best practice to downscale SSPs; however, work on reproducible and consistent methods to apply the SSP-RCP framework at regional and local scales is recommended (O'Neill et al., 2020).

Other recommendations to improve the SSP-RCP framework have been identified by O'Neill et al. (2020) such as the need to capture widely different yet plausible societal futures. For example, futures with low or limited growth that can maintain economic stability, societal cohesion, and an investment in innovation without additional growth (Hickel et al., 2021) or futures that are driven by disruptive technological, social, political or environmental events (e.g., Foster, 2020; Kuhnhenn, 2018; O'Neill et al., 2020; Otero et al., 2020).

Additionally, it has been acknowledged that SSPs do not explicitly address the relationship between human development and nature and fail to incorporate social-ecological feedbacks that underestimate, for example, the effects of tipping points (e.g., fisheries collapse) (Rosa et al., 2017).

To overcome this limitation, we have included in our scenarios cetaceans' thermal response curves which aim to provide information on the potential effects of climate change on species that are an integral element of the whale watching activity.

When developing WW-SSPs for Macaronesia the current characteristics of the whale watching activity in each archipelago and in islands within each archipelago determine the understanding of future narratives and the range of adaptation options to be considered. For example, Azores and Madeira would likely be better able to adapt to an environmentally driven SSP1 world as opposed to the Canary Islands. In the Canary Islands, particularly in Tenerife, the continuation of the current mass tourism model will limit the sector's sustainability in this scenario.

The environmental and socioeconomic elements in Scenario 3 will generate very challenging conditions for the sector, making it very difficult to sustain a profitable business in any of the archipelagos. The Macaronesia whale watching sector's natural dependence on international tourism in a scenario of low ticket prices, high costs of fossil fuels and low environmental status will create a problematic setting for the activity, from both a natural and human point of view.

In Scenario 4, a scenario dominated by inequality and elite driven tour- ism the whale watching sector will require greater adaptation efforts in all archipelagos. This is a scenario where potentially small companies would disappear and an investment in a high-end whale watching product will need to occur, driving even larger disparities in human and social capital.

Scenario 5 implies a whale watching activity where pressures on cetaceans and the environment would be substantial because of a mass tourism driven world where dilapidation of natural and social capital will be counteracted by technological developments.

Although recognizing that this is a social-ecological and environmentally challenging pathway, the participating stakeholders emphasized that it is difficult to assess the future evolution of the sector in this scenario. The main reason being that economic growth and technological innovation are expected to counteract environmental degradation, creating the conditions for a continuous expansion of a sector which prides itself in being sustainable.

In this study, we used the best available climate projections for the North Atlantic, which include the Macaronesia bioregion, while acknowledging that existing information is limited and uncertain. Climate impact assessment studies require high temporal and spatial resolution climate projections, which can be obtained by downscaling data from global climate models using different techniques. These techniques have several limitations, particularly in islands, due to the limited available climate and meteorological data, the difficulties in capturing the effect of islands' topographic complexity that influence small scale atmospheric phenomena (e.g., precipitation regime), and the large computation capacities required to compute the number of simulated scenarios (Christensen et al., 2007; Tomé, 2013). Future research in areas such as Macaronesia would benefit from increasing the efforts to downscale climate projections for island regions.

5.5 Conclusion

To the best of our knowledge, this is the first study to extend the Eur- SSPs to the whale watching sector. Additionally, a case study to integrate the socioeconomic pathways, climate trends and species impact assessment and test the use of scenarios for adaptation planning was developed for Macaronesia. From our perspective, despite the listed limitations, obtained results were useful to initiate a debate on the potential changes to the whale watching activity driven by climate change and to support and inform adaptation planning for the first time in the Macaronesia region.

Further work to quantify each whale watching key element should be carried out to support the creation of integrated impact models. To achieve a coherent quantification of WW-SPPs specific elements, standardized in- formation on key whale watching elements should be collected by the Regional Government in each archipelago of Macaronesia.

Chapter 6. General discussion

6.1. General discussion and key findings

As identified in Chapter 1, the main aim of this dissertation was to assess the integrated biological and socio-economical vulnerability of whale watching to climate change in order to support the long-term sustainability of the activity, using Macaronesia as a case study. Three main research questions were addressed, and the corresponding key findings are presented below and summarized in Table 6-1.

I. What is the ecological vulnerability of cetacean species to climate change?

This question was addressed in Chapters 2, 3 and 4. Chapters 2 and 3 focused on the development of a new assessment methodology – a Climate Change Vulnerability Index (CCVI) for cetacean species. While Chapter 2 focuses on the Madeira case study, Chapter 3 applies an improved version of the same methodology to a larger region – Macaronesia. In Chapter 2, the most vulnerable species identified for the Madeira archipelago were the sperm whale (*Physeter macrocephalus*), the fin whale (*Balaenoptera physalus*), the Atlantic population of bottlenose dolphins (*Tursiops truncatus*), and the Bryde's whale (*Balaenoptera brydei*). In Chapter 3, the archipelago associated units of short-finned pilot whales (*Globicephala macrorhynchus*) and common bottlenose dolphins (*Tursiops truncatus*) in the Canary Islands and Madeira, and of Risso's dolphins (*Grampus griseus*) in the Canary Islands were identified as the most vulnerable management units. "Very high" to "high" vulnerability scores were obtained for 62% of the species management units, mainly archipelago associated, and "very high" to "moderate" certainty scores were obtained for 67% of the units, randomly distributed between archipelago associated units and Macaronesian units. In both cases (Chapters 2 and 3), certainty and data quality scores were high for most species. This indicates, first, that there is a high level of agreement among experts, and second, that despite limited data, experts can confidently assess most management units. The work developed in Chapter 2 was exploratory, addressing the lack of methodological tools to support decision-making, and providing a simple and easy to apply solution – the CCVI – in the context of limited data, high uncertainty, and a large number of species to be assessed. While such work showed promising results, it also

highlighted limitations that needed to be further improved. The later were addressed in Chapter 3.
Nevertheless, caution is needed when using information from index-based vulnerability assessments due to the need to further mature these approaches (see Chapter 7, Future research). For now, recommendations are to use these approaches as scoping studies, rather than as a definitive indication of which management and conservation measures should be undertaken. The context of the assessment, as well as associated uncertainties, should also be communicated to decision-makers in order to ensure informed decisions. Most importantly, investment on research and monitoring of cetacean species is crucial to improve our understanding of climate driven impacts. Baseline information on cetacean ecology is lacking, which challenges the identification of climate related changes.

In addition to assessing the vulnerability to climate change of the most relevant cetacean species for Macaronesia, information on potential geographic changes in species occurrence is of extreme relevance to support whale watching companies. This need was addressed in Chapter 4, in which a novel methodology was developed – using expert-led thermal suitability curves – to obtain species responses to sea surface temperature (SST) changes under three climate scenarios (RCP 2.6, 4.5 and 8.5). Increases in thermal suitability were found for Bryde's whale (*Balaenoptera edeni*), short-finned pilot whale (*Globicephala macrorhynchus*), Blainville's beaked whale (*Mesoplodon densirostris*), sperm whale (*Physeter macrocephalus*), spotted dolphin (*Stenella frontalis*), bottlenose dolphin (*Tursiops truncatus*) and Cuvier's beaked whale (*Ziphius cavirostris*), while a decline in thermal suitability was found for fin whale (*B. physalus*), common dolphin (*Delphinus delphis*), and Risso's dolphin (*Grampus griseus*). Confidence in thermal suitability curves was high for all species except for the beaked whales, the fin whale, and the Risso's dolphin. Overall, species projected thermal suitability changes provided potentially useful spatially explicit information to decision-makers. Notwithstanding, species distribution patterns depend on a variety of environmental features besides temperature, such as depth, slope, or chlorophyll concentration, which help predict habitat preferences based on species ecological requirements (e.g., Forcada, 2018; Fernandez et al., 2021). Environmental threats, such as marine transportation or nautical tourism also shape species' distribution patterns. Finally, species adaptive capacity (in, e.g., behavior, life history traits, genetic diversity) to climate changes is largely unknown and this must be taken into consideration when interpreting results.

II. What is the socio-economic vulnerability of whale watching to climate change? And III. how can the management of whale watching be supported under climate change?

In Chapter 5, the socio-economic impacts of climate change for whale watching were identified by downscaling the European Shared Socio-economic Pathways (Eur-SSPs) and integrating climate trends and species responses to climate change. Whale watching scenarios were discussed and validated by stakeholders providing, for the first time, information on potential climate change impacts in all components of the activity.

Stakeholders acknowledged they were somewhat prepared for a sustainable and for a fossil fuel development world. The sustainable world would be closer to what is currently the whale watching activity in Madeira and Azores, as opposed to the Canary Islands where there is currently a mass tourism model. The Canary Islands aim to transform and direct the current activity to a more sustainable model, which will take a greater adaptation effort in comparison to the remaining archipelagos. On the other hand, it is more prepared for a fossil fuel development world, which shows more similarities with present day business model. In a rivalry world the sector is somewhat unprepared due to the socio-economic challenges of sustaining a business in a world where there is a degradation of natural, social and economic resources. Finally, in an inequality world, driven by the elite, stakeholders were divided between the sector being somewhat prepared and somewhat unprepared since potentially small companies would disappear, and a greater adaptation effort would need to take place to provide an activity tailored to the elite.

Species thermal suitability responses were considered for RCP 4.5 and were found to be the same in all whale watching scenarios. Also, the general tendency of future climate was similar for all Macaronesian archipelagos. Moreover, the SSP narratives and trends were the main driver of workshop discussions on the preparedness of the whale watching sector. This was possible because the additional information on the ecological and climate components was available for stakeholders to incorporate in their decision-making process. For example, in a scenario where financial and material resources are limited, the fact that ocean waves are not projected to increase means that there needs to be less effort allocated to adapt boats or to rebuild coastal infrastructures.

In practice, therefore, even though a quantitative model was not available to integrate all whale watching components, there was still a level of integration provided by the local stakeholders which enabled discussions on the level of preparedness of the sector. The scenario exercise proved useful for stakeholders to reflect and explore different worlds and the level of adaptation their daily activity would need to undertake in the different contexts presented. The workshop also allowed for sharing of experiences and good practices for the betterment of the activity in each archipelago. Lastly, the integration of the ecological, climate and socio-economic information was helpful to better understand the interdependence and interconnected impacts of climate change on the whale watching activity.

Inherent limitations from the downscaling of Eur-SSPs to whale watching-SSPs were related to the simplified assumptions made for each key element (e.g., factors influencing tourists' decisions to go on a whale watching tour were narrowed down and limited to education, income and environmental values, when in reality there is a complexity of cultural and socio-economic factors that influence tourists' decisions). Also, narrative scenarios can be open to different interpretations and different approaches which reflect the flexibility of the framework but also limits its reproducibility (O'Neill et al., 2020).

Chapter 5 attempted to integrate all the components of whale watching to provide a broader picture of the potential interconnected impacts. This integration is relevant when supporting decision-makers since it provides an holistic overview of the potential impacts on the whale watching activity. In the future this integration should move towards modelling of these components to provide quantitative outcomes under different climate change scenarios. The quantification and interrelation of the different elements of the activity are challenging mainly due to the lack of consistent and standardized data collection in long time frames.

Table 6-1 - Key findings of the present dissertation.

1. Cetacean species show a moderate to very high vulnerability to climate change, with archipelago-associated units showing high to very high vulnerability scores.
Most Macaronesian management units have a Moderate vulnerability to climate change while archipelago associated units have a High to Very High vulnerability. The most influential sensitivity attributes found to determine vulnerability were (a) migration, (b) generation length, (c) site fidelity, (d) habitat specificity, and (e) home range. Overall, archipelago-associated units have stronger residency patterns, related to the specific habitat they occupy, and the availability and distribution of prey which in turn shapes their sensitivity to climate change. Moreover, sea surface temperature, ocean acidification and dissolved oxygen were the most influential exposure factors contributing to species vulnerability to climate change. Most units also had a high potential for climate-related responses, such as changes in abundance, phenology, and distribution. Generally, certainty in vulnerability scores varied from Very High to Moderate for all units assessed. Overall, results were supported by the available evidence on species biology and ecology, including the observed changes in distribution potentially driven by climate change. Inconsistencies in vulnerability assessments have been recently documented (Hare et al., 2016; Wheatley et al., 2017; Comte et al., 2019). However, studies cannot be directly compared because the methodologies used differ and, even though the overall objectives are similar, the results are specific to the questions asked in each case (e.g., future thermal suitability vs trait-based vulnerabilities) (Hare et al., 2016; Wheatley et al., 2017). While there will never be a complete agreement between different approaches, the use of expert judgment and of vulnerability indexes is valuable to gather current knowledge and guide research and monitoring studies. The important contribution of this assessment was to rapidly rank the vulnerability of a large number of species to climate change and to inform managers about the areas and species where further research is prioritary.
2. With climate change, the ocean temperature in Macaronesia will be more suitable to most cetacean species. Exceptions are the fin whale, the common dolphin and Risso's dolphin.

Most species are likely to increase their thermal suitability in the future (7 out of 10) while the remaining three are likely to decrease. The novelty in this approach was the use of expert judgement to create thermal suitability curves for species for which experimental thermal limits cannot be determined. Confidence in species thermal suitability curves was high for most species. Results were supported by the available information on species distribution patterns and by the most relevant factors that shape their distribution (e.g., sea surface temperature or chlorophyll concentration). Using sea surface temperature is a simplified way to address species future suitability- a multiplicity of physical and biological factors shaping species distribution patterns were not considered in this approach. Notwithstanding, in a context of limited data and high uncertainty of how species will respond to climate change this method provided a simple and rapid manner to support decision-makers.

3. Integrated climate, ecological and socioeconomic scenarios are useful to assess the preparedness of the whale watching sector

Whale watching SSPs were developed to characterize four different socio-economic future world scenarios. Together with future climate trends for Macaronesia and the assessment of species vulnerability, these scenarios were used by whale watching stakeholders to discuss potential consequences for the activity.

Limitations from downscaling European SSPs for whale watching include the simplification of key elements assumptions, the lack of a common best practice to downscale SSPs, the need to capture different societal futures that, for example, consider low or limited economic growth, and the lack of explicit incorporation of nature and socio-ecological feedbacks. In addition, downscaled climate projections are lacking for island regions such as Macaronesia. Despite the listed limitations, the integration of all whale watching components through the development of scenarios was a novel approach which supported decision-makers on visualizing different futures and on how to adapt their activity accordingly. It contributed to the first holistic debate focused on how climate changes may affect the activity in Macaronesia, and provided insights into areas where further research is needed.

4. The whale watching sector in Macaronesia is somewhat prepared for Sustainable world and Fossil Fuel Development world scenarios, and somewhat unprepared for a Rivalry world scenario. In an Inequality world whale watching is divided between being somewhat prepared and somewhat unprepared.

In a sustainable world whale watching has a smaller scale with high environmental concerns and practices and a reduced impact on cetacean species. In a fossil fuel development world, characterized by a large number of operators and tourists and a degraded environment, impacts on ecosystems and cetacean species are expected to be counteracted by technology. Stakeholders identified being somewhat prepared for such distinct worlds given the characteristics of their current activity, however highlighted that a sustainable world is one that we should collectively aim for. Contrariwise, stakeholders considered themselves to be somewhat unprepared for a Rivalry world scenario given its socio-economic and environmental degradation, characterized by a low number of operators and of cetacean sighting rates. Stakeholders considered this would be the most challenging scenario of all and that the activity might cease to exist altogether.

Finally in an elite driven world, stakeholders were divided between being somewhat prepared and somewhat unprepared. This scenario, that is characterized by an overall low number of tourists, where elite numbers are high but much lower numbers originate from the remaining population, could result in the disappearance of small companies while also amplifying large socio-economic differences in Macaronesian islands.

Discussions focused mainly in the socio-economic part of the activity given that the future climate trends and species thermal responses showed a similar trend in all scenarios. In addition, particularly for future climate trends, most projections do not indicate hazardous outcomes, however there is a high uncertainty in climate wave and storm models that should be taken into account. Nevertheless, both climate trends and species responses provided specific information for Macaronesia that was able to be integrated in scenarios and in the decision-making process.

6.2. Future research

The harmonization and validation of climate change vulnerability indexes should be made by applying it to other contexts and assessing the consistency of results, as well as comparing them with current evidence on species climate impacts. Assessments should be reviewed and updated over time to incorporate new available information. Further research should also focus on the statistical analysis of assessment performance that can explain variations and evaluate consistency, quantitively, among studies.

Additionally, future studies should contribute to a better understanding of the relationship between species traits and climate change, which would provide experts with detailed information to score the index attributes and factors. To achieve this, the long-term data collection on cetaceans' ecology can improve baseline information and provide evidence on observed and projected impacts. While recognizing the challenges in assessing species responses to extreme events, these should also be further investigated considering their potentially devastating impacts on species and ecosystems (Harris et al., 2020).

The species thermal suitability method should be applied to other areas at different scales (global to local) and to other species, for comparison and validation of this methodology. Increasing the number of experts can also be useful when designing species thermal suitability curves. In the future, this approach can also be designed into a global scale tool that should be able to provide thermal suitability curves for species and their responses under different climate change scenarios.

In addition, research on how environmental variables influence the current and future distribution of cetaceans in Macaronesia will contribute to a more comprehensive assessment of climate-driven impacts. Increasing knowledge on species habitat preferences can contribute to identify the most relevant environmental variables and guide the future applicability of the thermal suitability method to specific species.

A related topic is the link between climate and human impacts on cetacean species. Currently, monitoring and evaluation of the interaction between climate and human impacts is needed to understand the full range of impacts faced by species (Alter et al., 2010) , and support the definition of adequate conservation measures.

The whale watching SSPs developed in this work can be applied to different contexts to assess and compare key elements and to clarify the assumptions made in this work. In addition, other scenarios can be co-developed with stakeholders providing different narratives for whale watching in the future. The quantification of key elements is also essential to support the development of quantitative integrated scenarios and analyses. To achieve this, a systematic and standardized long term data collection on the socio-economic elements of whale watching should be carried out in Macaronesia to provide a coherent quantification and comparability of results across all three archipelagos.

Additional studies combining vulnerability indexes, species distribution models and scenario-based approaches are needed to provide a more comprehensive overview of potential climate change effects.

Finally, there is a lack of downscaled regional climate models for islands (Christensen et al., 2007; Tomé, 2013) which is mainly due to the limited meteorological data available and to the coarse representation of islands' complex topography and its influence on atmospheric conditions. Further research should focus on improving downscaling techniques that are able to reproduce more accurately the past, present and future local climate of islands.

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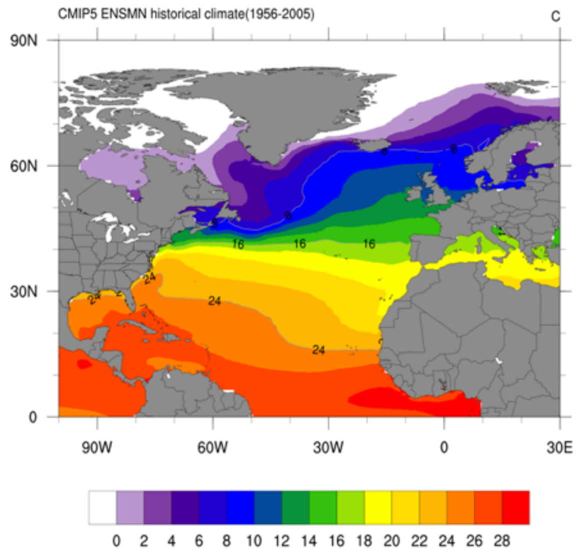
Annex A. Exposure maps for sea surface temperature, salinity, pH and primary productivity

a)



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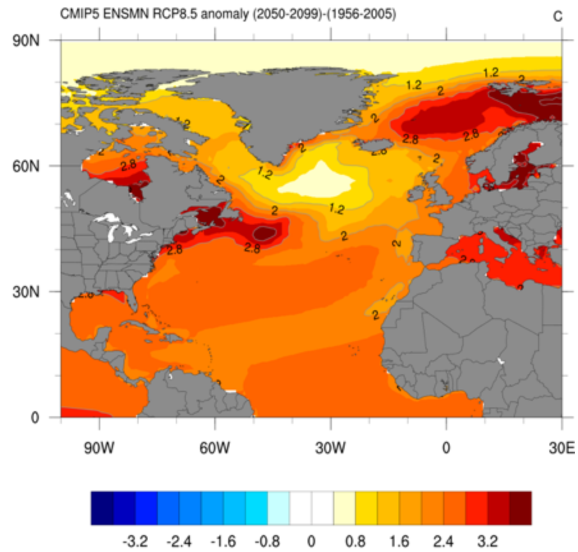
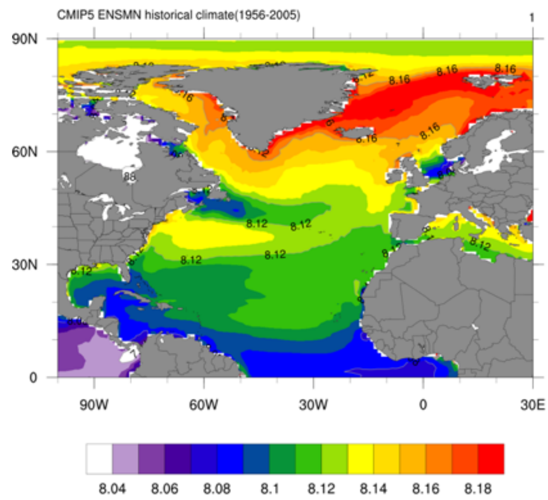
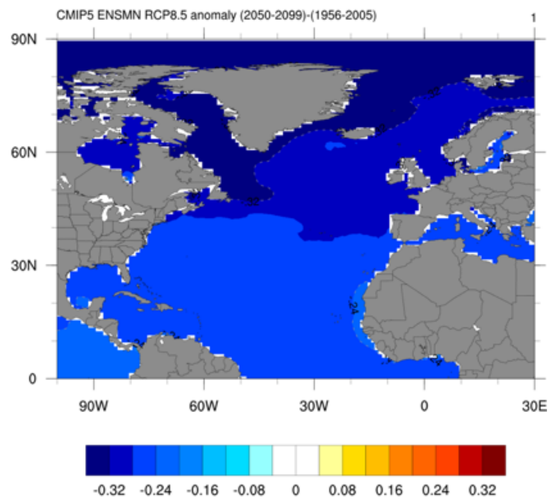


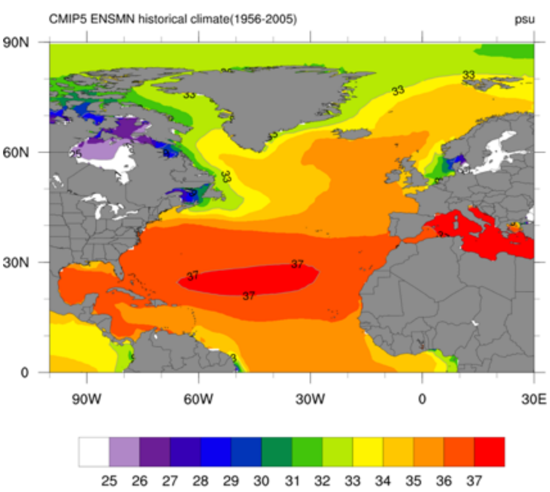
c)



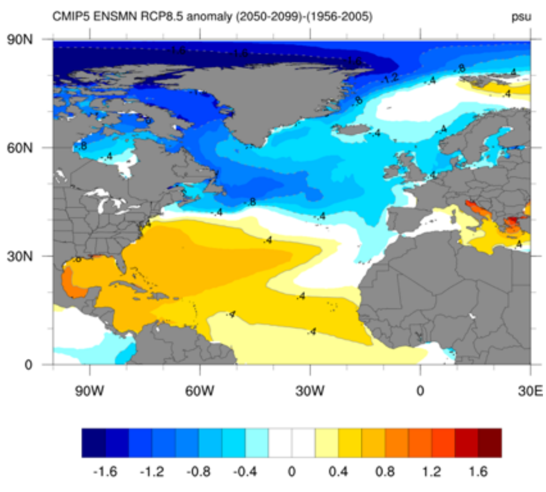
d)



e)



f)



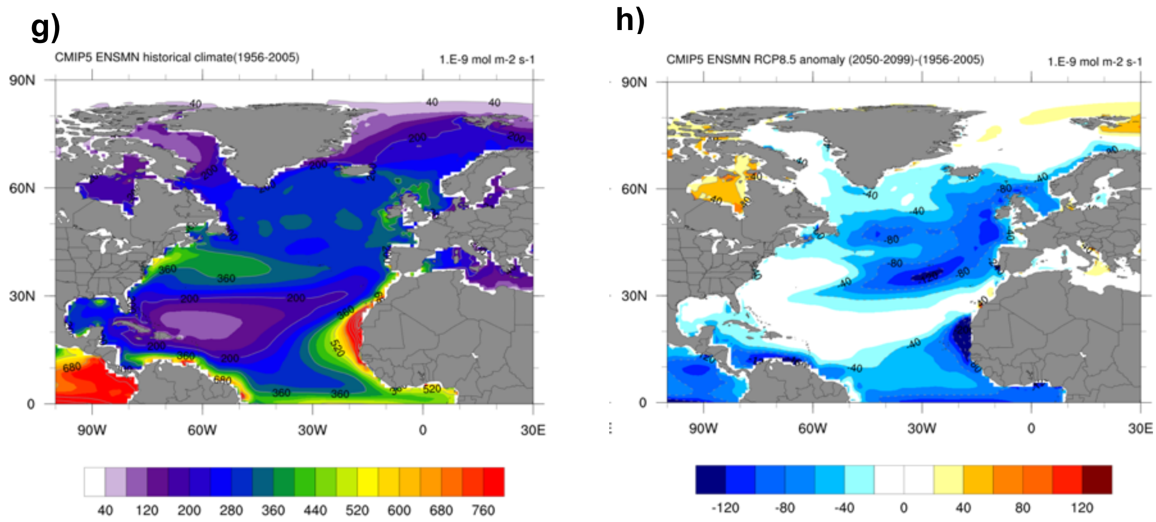


Figure A-1 - Historical climate (1956-2005) (left column) and projections (2050-2099) for RCP 8.5 with anomalies for the different variables (right column) in the north Atlantic. (a,b): sea surface temperature (ºC); (c,d):pH; (e,f): salinity (psu); (g-h): primary productivity ($1.E^{-9}$ mol m^{-2}). Data/image provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/. This material is not subject to copyright protection.

Annex B. List of sensitivity attributes and exposure factors

Table B-1 – List of sensitivity attributes and exposure factors with the respective scoring bins. Adapted attributes and included factors are marked with an asterisk. A full description of sensitivity attributes and exposure factors including definitions, background and scoring criteria are described in appendix A in Lettrich et al., 2019.

Sensitivity attributes	Scoring bins
Prey/Diet Specificity	**Low**: Generalist; feeds on a wide range of prey types and sizes **Moderate**: Generalist; feeds on a limited number of prey types or sizes, but a wide variety of species within those types **High**: Specialist; exhibits strong preference for one prey type for the majority of its caloric intake, but is capable of switching prey types **Very High**: Specialist; reliant on one prey type, often a single genus or family, for the majority of its caloric intake, and is unable to switch to other prey types
Habitat Specificity*	**Low:** Stock exclusively utilizes physical features resilient to climate conditions **Moderate:** Stock utilizes a variety of features, but is not reliant on physical features vulnerable to climate conditions such as fronts, eddies and upwelling. **High:** Stock relies moderately on biogenic habitat or physical features vulnerable to climate conditions. **Very High:** Stock relies greatly on physical features vulnerable to climate conditions such as fronts, eddies and upwelling.
Site Fidelity *	**Low:** Individuals display no site fidelity **Moderate:** Individuals display a low degree of site fidelity (i.e., archipelagos or regions such as Macaronesia)

<table>
<tr><td></td><td colspan="6">High: Individuals display a high degree of site fidelity (i.e., specific archipelagos)
Very High: Individuals display a high degree of site fidelity i.e., specific islands within each archipelago.</td></tr>
<tr><td rowspan="6">Lifetime Reproductive Potential</td><td colspan="2" rowspan="2"></td><td colspan="4">Female Reproductive Lifespan</td></tr>
<tr><td>≥ 25 yr</td><td>20 yr ≤ x < 25 yr</td><td>15 yr ≤ x < 20 yr</td><td>< 15 yr</td></tr>
<tr><td rowspan="4">Female Reproductive Interval</td><td>≤ 2 yr</td><td>Low</td><td>Low</td><td>Low</td><td>Moderate</td></tr>
<tr><td>2 yr < x ≤3 yr</td><td>Low</td><td>Moderate</td><td>Moderate</td><td>High</td></tr>
<tr><td>3 yr < x ≤ 4 yr</td><td>Low</td><td>Moderate</td><td>High</td><td>Very High</td></tr>
<tr><td>>4 yr</td><td>Moderate</td><td>High</td><td>Very High</td><td>Very High</td></tr>
<tr><td>Generation Length</td><td colspan="6">Low: < 10 years
Moderate: 10 years ≤ x < 20 High: 20 years ≤ x <30 years
Very High: ≥ 30 years</td></tr>
<tr><td>Reproductive Plasticity</td><td colspan="6">Low: Reproduction of the stock is described by all of the following:</td></tr>
</table>

	a) pupping/calving season is 4 months or longer; b) mating and pupping/calving do not require ephemeral or space-limited habitat; c) less than half of the stock mates or gives birth in the same location; and d) a seasonal-specific behavior or physical trait entailing significant metabolic or time preparation is not required for successful mating, birth, or nursing **Moderate:** Reproduction of the stock is described by **all** of the following: a) pupping/calving season is greater than 1 month but less than 4 months; and b) more than half of the stock mates or gives birth in the same location **High:** Reproduction of the stock is described by **only one** of the following: a) pupping/calving season is 1 month or less; b) mating or pupping/calving requires ephemeral or space-limited habitat; c) entire stock mates or gives birth in the same location; or d) a seasonal-specific behavior or physical trait entailing significant metabolic or time preparation is required for successful mating, birth, or nursing **Very High:** Reproduction of the stock is described by **more than one** of the following:

	a) pupping/calving season is 1 month or less; b) mating or pupping/calving requires ephemeral or space-limited habitat; c) entire stock mates or gives birth in the same location; or d) a seasonal-specific behavior or physical trait entailing significant metabolic or time preparation is required for successful mating, birth, or nursing
Migration	**Low:** Annual migration; multiple migratory pathways **Moderate:** Annual migration; single migratory pathway **High:** Seasonal migration **Very High:** No migration; local movement only
Home Range	**Low:** Individuals' home ranges are broad (e.g., include much of an ocean basin) **Moderate:** Individuals' home ranges are moderate to large (e.g., spend the majority of time along coasts, within continental shelf waters, or along the continental slope, but may utilize deeper waters) **High:** Individuals typically remain in bays or archipelagos and seldom travel farther but could if needed **Very High:** Individuals' home ranges are relatively small (e.g., confined to bays or archipelagos) and are limited from traveling farther by a combination of geographic features, physical capabilities, and behaviors
Stock Abundance	**Low:** Stock comprises > 10,000 individuals **Moderate:** Stock comprises 1,001-10,000 individuals **High:** Stock comprises 101-1,000 individuals **Very High:** Stock comprises < 100 individuals
Stock Abundance Trend	**Low:** Increasing abundance trend over past 10-year period **Moderate:** Stable abundance trend over past 10-year period **High:** Declining abundance trend over past 10-year period **Very High:** Rapidly declining abundance trend over past 10-year period

<table>
<tr><td>Cumulative Stressors</td><td colspan="3">Low: Stock currently experiences 1 or fewer additional stressors
Moderate: Stock currently experiences 2 or 3 additional stressors
High: Stock currently experiences 4 or 5 additional stressors
Very High: Stock currently experiences greater than 5 additional stressors or has one additional stressor that accounts for more than half of annual mortality</td></tr>
<tr><td>Climate exposure factors</td><td colspan="3">Scoring bins</td></tr>
<tr><td rowspan="5">Sea Surface Temperature (Mean/standard anomaly)

Sea Surface Temperature (Variability/variance ratio)</td><td></td><td>Projected mean vs historical variance</td><td>Projected change in variability</td></tr>
<tr><td>Low</td><td>|x| < 0.5 std dev</td><td><1.15</td></tr>
<tr><td>Moderate</td><td>0.5 std dev ≤ |x| < 1.5 std dev</td><td>1.15 ≤ x <1.54</td></tr>
<tr><td>High</td><td>1.5 std dev ≤ |x| < 2.0 std dev</td><td>1.54 ≤ x < 1.78</td></tr>
<tr><td>Very high</td><td>|x| ≥ 2.0 std dev</td><td>≥ 1.78</td></tr>
<tr><td rowspan="5">Primary productivity* (Mean/standard anomaly)

Primary productivity* (Variability/variance ratio)</td><td></td><td>Projected mean vs historical variance</td><td>Projected change in variability</td></tr>
<tr><td>Low</td><td>|x| < 0.5 std dev</td><td><1.15</td></tr>
<tr><td>Moderate</td><td>0.5 std dev ≤ |x| < 1.5 std dev</td><td>1.15 ≤ x <1.54</td></tr>
<tr><td>High</td><td>1.5 std dev ≤ |x| < 2.0 std dev</td><td>1.54 ≤ x < 1.78</td></tr>
<tr><td>Very high</td><td>|x| ≥ 2.0 std dev</td><td>≥ 1.78</td></tr>
<tr><td rowspan="5">Salinity (Mean/standard anomaly)

Salinity (Variability/variance ratio)</td><td></td><td>Projected mean vs historical variance</td><td>Projected change in variability</td></tr>
<tr><td>Low</td><td>|x| < 0.5 std dev</td><td><1.15</td></tr>
<tr><td>Moderate</td><td>0.5 std dev ≤ |x| < 1.5 std dev</td><td>1.15 ≤ x <1.54</td></tr>
<tr><td>High</td><td>1.5 std dev ≤ |x| < 2.0 std dev</td><td>1.54 ≤ x < 1.78</td></tr>
<tr><td>Very high</td><td>|x| ≥ 2.0 std dev</td><td>≥ 1.78</td></tr>
</table>

<table>
<tr><td>Ocean Acidification (Mean/standard anomaly)</td><td rowspan="2">
<table>
<tr><th></th><th>Projected mean vs historical variance</th><th>Projected change in variability</th></tr>
<tr><td>Low</td><td>|x| < 0.5 std dev</td><td><1.15</td></tr>
<tr><td>Moderate</td><td>0.5 std dev ≤ |x| < 1.5 std dev</td><td>1.15 ≤ x <1.54</td></tr>
<tr><td>High</td><td>1.5 std dev ≤ |x| < 2.0 std dev</td><td>1.54 ≤ x < 1.78</td></tr>
<tr><td>Very high</td><td>|x| ≥ 2.0 std dev</td><td>≥ 1.78</td></tr>
</table>
</td></tr>
<tr><td>Ocean Acidification (Variability/variance ratio)</td></tr>
<tr><td>Dissolved Oxygen (Mean/standard anomaly)</td><td rowspan="2">
<table>
<tr><th></th><th>Projected mean vs historical variance</th><th>Projected change in variability</th></tr>
<tr><td>Low</td><td>|x| < 0.5 std dev</td><td><1.15</td></tr>
<tr><td>Moderate</td><td>0.5 std dev ≤ |x| < 1.5 std dev</td><td>1.15 ≤ x <1.54</td></tr>
<tr><td>High</td><td>1.5 std dev ≤ |x| < 2.0 std dev</td><td>1.54 ≤ x < 1.78</td></tr>
<tr><td>Very high</td><td>|x| ≥ 2.0 std dev</td><td>≥ 1.78</td></tr>
</table>
</td></tr>
<tr><td>Dissolved Oxygen (Variability/variance ratio)</td></tr>
<tr><td>Circulation</td><td>Low: Stock distribution overlaps almost exclusively with large boundary currents or tidal

Moderate: currents Majority of stock distribution overlaps with large boundary currents or tidal currents. Stock may also interact with mesoscale features such as fronts or eddies.

High: Majority of stock distribution overlaps with currents that are expected to have a high magnitude of change such as estuarine circulation, nearshore density currents, and/or wind driven currents. Stock may also interact with mesoscale features such as fronts or eddies.

Very High: Stock distribution overlaps almost exclusively with currents that are expected to have a high magnitude of change</td></tr>
</table>

	such as estuarine circulation, nearshore density currents, and/or wind driven currents.

Annex C. Climate sensitivity, exposure and vulnerability scores and potential distribution, abundance and phenology score responses for Macaronesia and archipelago-associated species management units.

Table C-1 - Climate sensitivity, exposure and vulnerability scores for Macaronesia (MAC) and archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Colours indicate Very High (4; red), High (3; orange), Moderate (2; yellow) and Low (1; green) scores. Data quality ranges from 0 to 3. Certainty in scores is represented by: Very High certainty (>95%, black), High certainty (90–95%, dark grey), Moderate certainty (66–90%, light gray) and Low certainty (<66%, white).

Species (Units)	Sensitivity			Exposure			Vulnerability		
	Score	Data quality	Certainty (%)	Score	Data quality	Certainty (%)	Score	Data quality	Certainty (%)
Bottlenose dolphin (CAN)	4	3	72	3	3	98	12	3	73
Bottlenose dolphin (MAD)	3	3	97	4	2	84	12	2	84
Risso's dolphin (CAN)	4	2	76	3	3	64	12	2	85
Short-finned pilot whale (CAN)	4	3	99	3	3	97	12	3	99
Short-finned pilot whale (MAD)	4	3	37	3	3	58	12	3	63
Blainville's beaked whale (CAN)	3	2	65	3	3	97	9	3	63
Bottlenose dolphin (AZ)	3	2	73	3	3	98	9	2	71
Bottlenose dolphin (MAC)	3	3	56	3	3	100	9	3	56
Cuvier's beaked whale (CAN)	3	2	95	3	3	97	9	3	92

Risso's dolphin (AZ)	3	2	98	3	2	100	9	2	97
Sperm whale (AZ)	3	2	84	3	2	98	9	2	82
Bryde's whale (MAC)	2	2	55	4	3	80	8	3	54
Short-finned pilot whale (MAC)	2	2	100	4	3	56	8	3	56
Blainville's beaked whale (MAC)	2	2	77	3	2	93	6	2	72
Common dolphin (AZ)	2	2	41	3	2	81	6	2	33
Cuvier's beaked whale (MAC)	2	2	66	3	2	100	6	2	66
Fin whale (MAC)	2	2	86	3	3	63	6	3	91
Risso's dolphin (MAC)	2	2	99	3	3	100	6	2	98
Sperm whale (MAC)	2	2	55	3	3	80	6	2	55
Spotted dolphin (MAC)	2	2	84	3	3	91	6	2	78
Common dolphin (MAC)	1	2	100	3	2	100	3	2	100

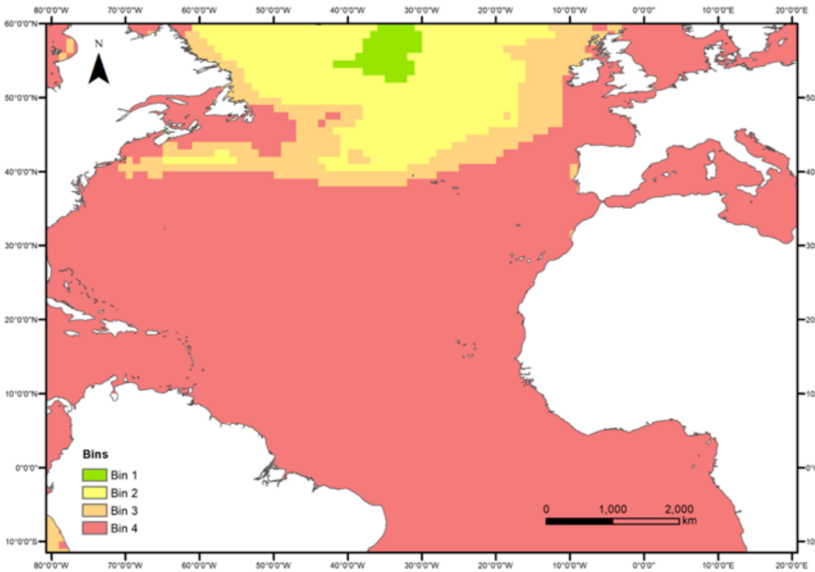
Table C-2 – Vulnerability scores and potential distribution, abundance and phenology responses for the Macaronesia (MAC) and archipelago-associated species management units of Azores (AZ), Canary Islands (CAN) or Madeira (MAD). Score colors are indicated with Very High (4; red), High (3; orange), Moderate (2; yellow) and Low (1; green).

Species (Units)	Vulnerability score	Potential for distribution change	Potential for abundance change	Potential for phenology change
Bottlenose dolphin (CAN)	4	3	3	3
Bottlenose dolphin (MAD)	4	3	3	3
Risso's dolphin (CAN)	4	3	3	3
Short-finned pilot whale (CAN)	4	3	3	3
Short-finned pilot whale (MAD)	4	3	3	3
Blainville's beaked whale (CAN)	3	3	3	2
Bottlenose dolphin (AZ)	3	3	3	3
Cuvier's beaked whale (CAN)	3	3	3	3
Risso's dolphin (AZ)	3	3	3	3
Sperm whale (AZ)	3	1	3	1
Common dolphin (AZ)	2	3	2	3
Bottlenose dolphin (MAC)	3	2	1	1
Bryde's whale (MAC)	3	3	2	3
Short-finned pilot whale (MAC)	3	3	2	2
Blainville's beaked whale (MAC)	2	2	2	2

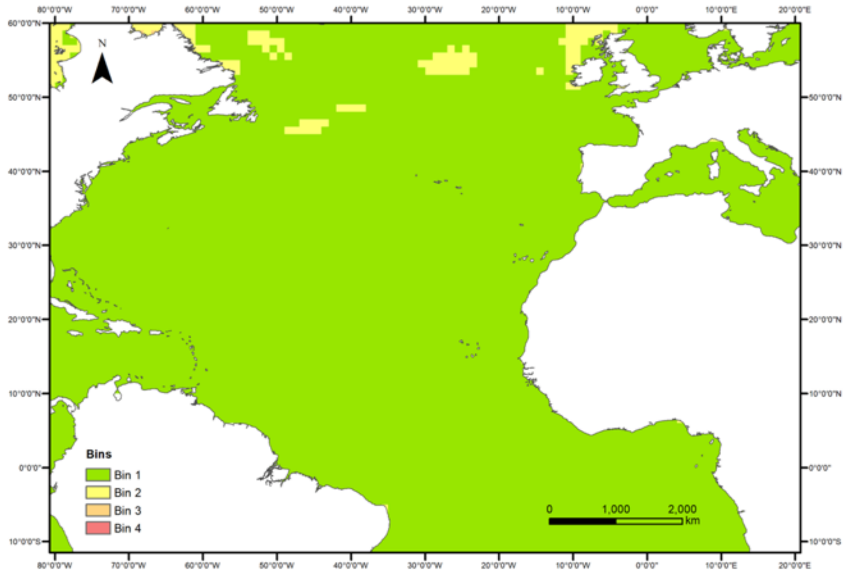
Cuvier's beaked whale (MAC)	2	2	2	2
Fin whale (MAC)	2	3	2	3
Risso's dolphin (MAC)	2	2	2	2
Sperm whale (MAC)	2	2	2	2
Spotted dolphin (MAC)	2	3	1	3
Common dolphin (MAC)	1	3	1	2

Annex D. Climate projection maps from ESRL Climate Change Web Portal

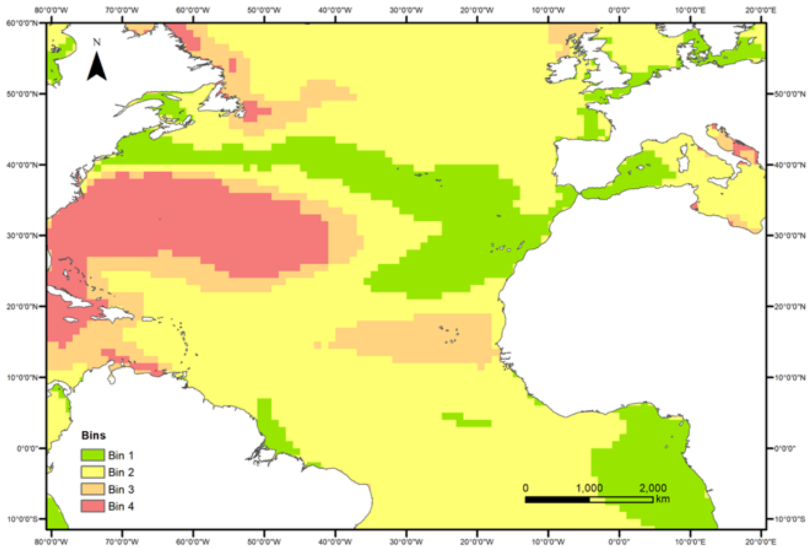
a)



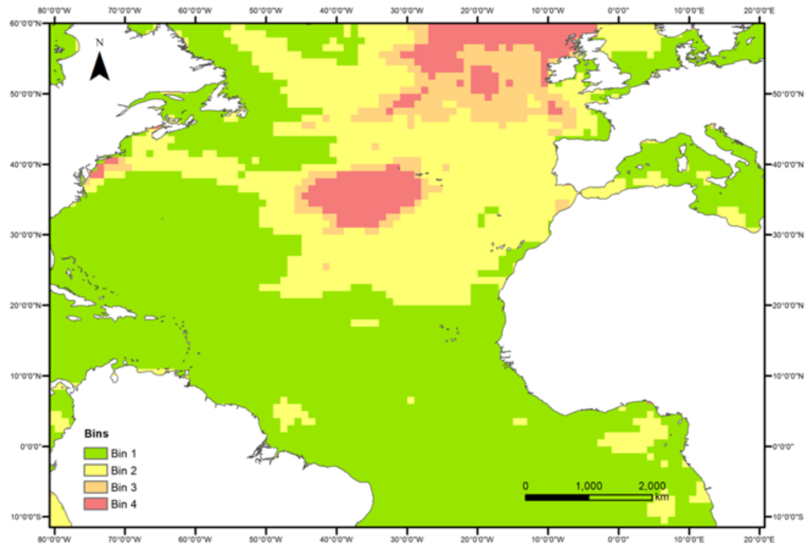
b)



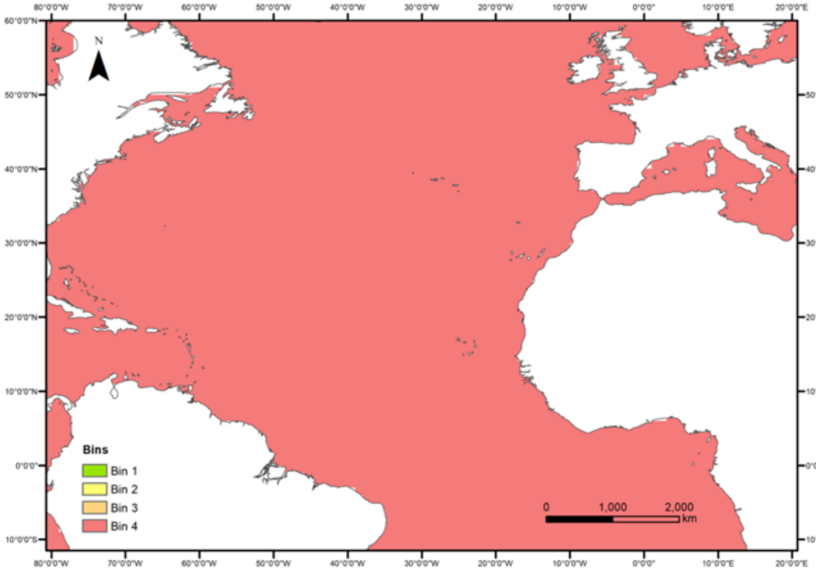
c)



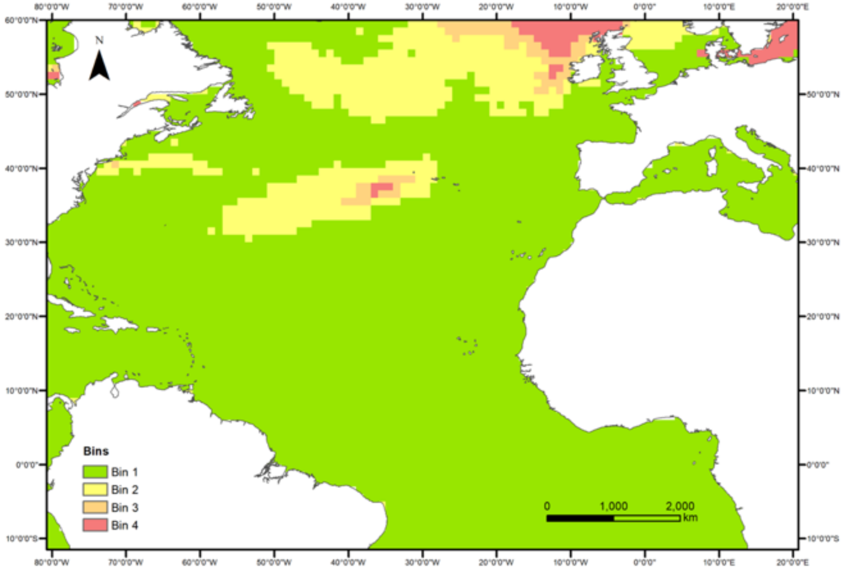
d)



e)


N
Bins
Bin 1
Bin 2
Bin 3
Bin 4
0 1,000 2,000
km

f)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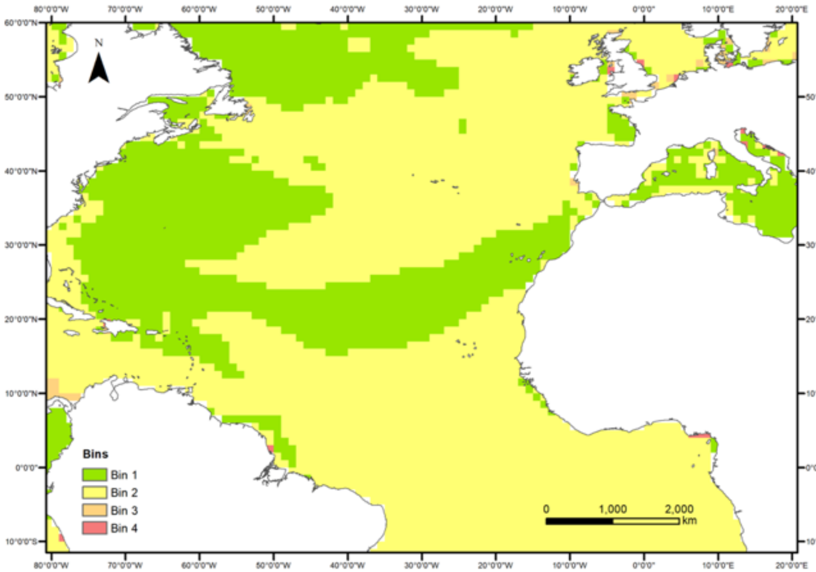
g)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Bin 4
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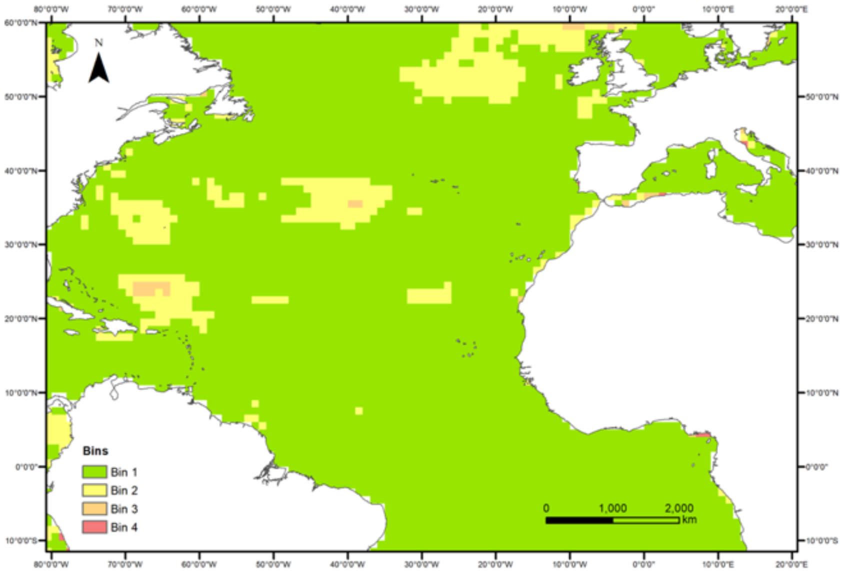
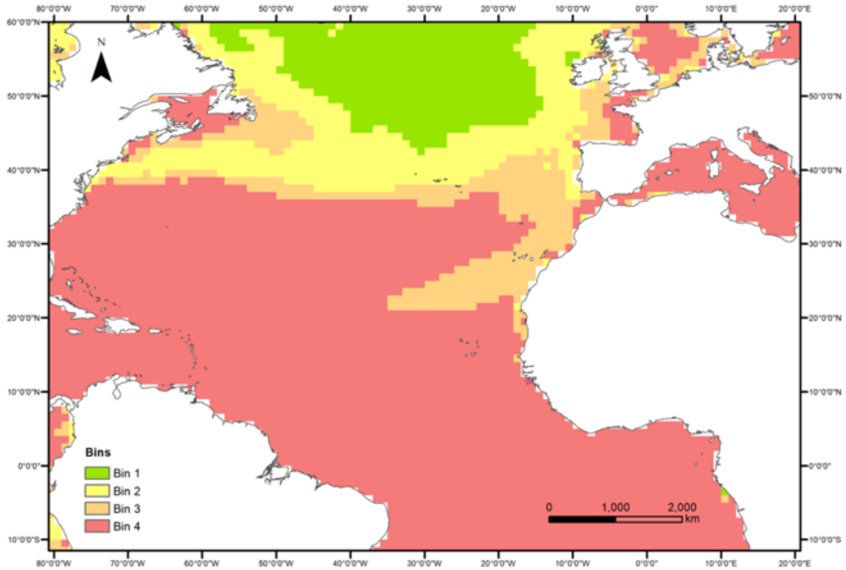
km

h)


N
Bins
Bin 1
Bin 2
Bin 3
Bin 4
0 1,000 2,000
km

i)



j)

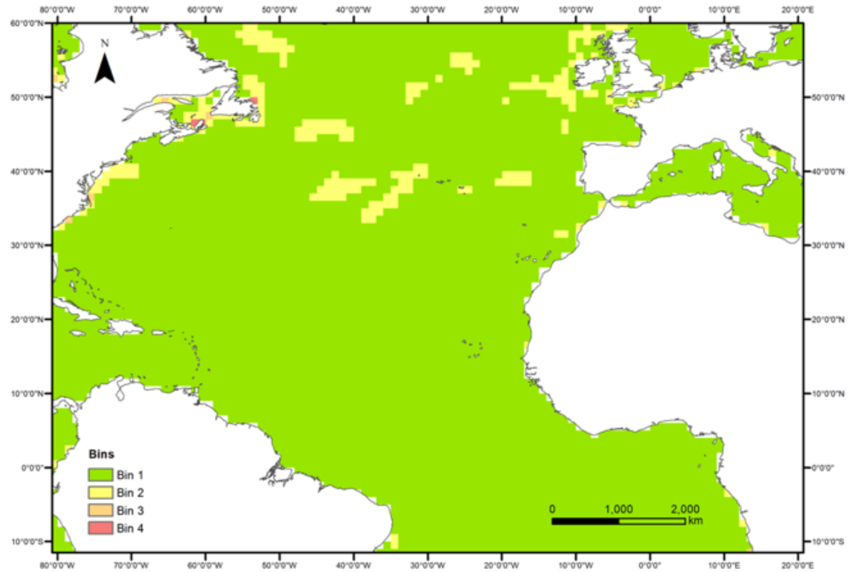


Figure D-1 – Climate projection maps from ESRL Climate Change Web Portal (http://www.esrl.noaa.gov/psd/ipcc/ocn/). Projections were reclassified by scoring bin from the original ESRL projection maps with the following settings: RCP 8.5; model = average of all models; statistic= standard anom (avg historical); time frame= 2006-2055; region= a units' entire distribution range. Variables: Sea surface temperature (a) projected future standard anomaly; (b) change in variability; Sea surface salinity (c) projected future standard anomaly; (d) change in variability; pH at surface (e) projected future standard anomaly; (f) change in variability; Primary productivity (g) projected future standard anomaly; (h) change in variability; Dissolved oxygen concentration at surface (i) projected future standard anomaly; (j) change in variability.

Annex E. Confusion matrix of a) sensitivity; b) exposure and c) vulnerability scores.

a)

Predicted sensitivity score	Actual sensitivity score: L	M	H	VH
L	1			
M		8		
H		1	7	1
VH				3

b)

Predicted exposure score	Actual exposure score: L	M	H	VH
L	0			
M		0		
H			18	
VH				3

c)

Predicted vulnerability	Actual vulnerability score: L	M	H	VH
L	1			
M		6		
H		1	8	
VH				5

Figure E-1 – Confusion matrix of a) sensitivity; b) exposure and c) vulnerability scores. Predicted scores indicate the estimated final scores from the bootstrap analysis. Actual scores indicate the scores obtained by the experts. The confusion matrix depicts the correspondence between the predicted and the actual scores.

Annex F. Number of changes in climate vulnerability scores and the average attribute and exposure scores for Macaronesia and archipelago associated species management units.

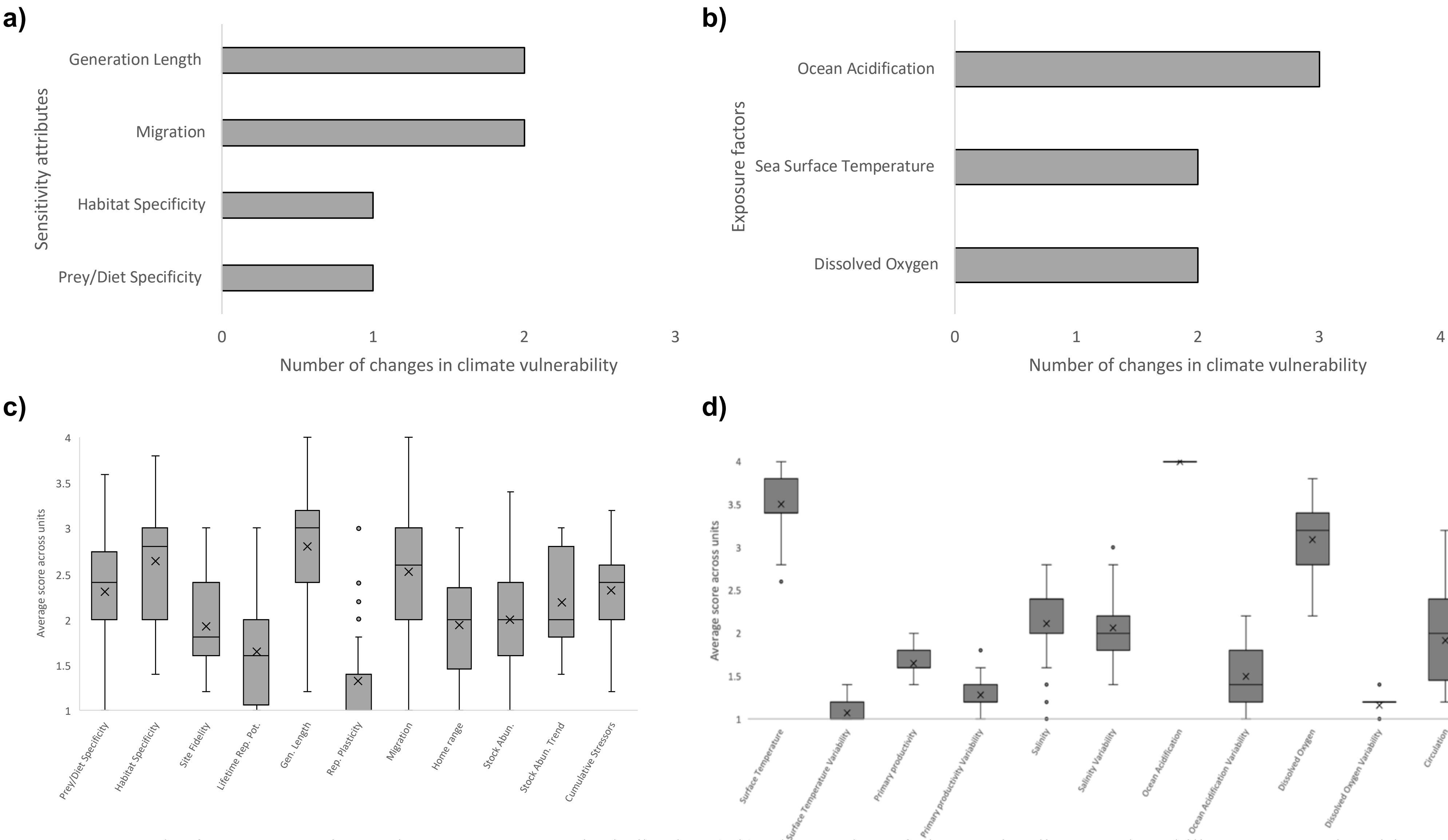


Figure F-1– Results for Macaronesia species management units indicating (a,b) the number of changes in climate vulnerability scores produced by individual sensitivity attributes and exposure factors and (c,d) the average attribute and exposure scores.

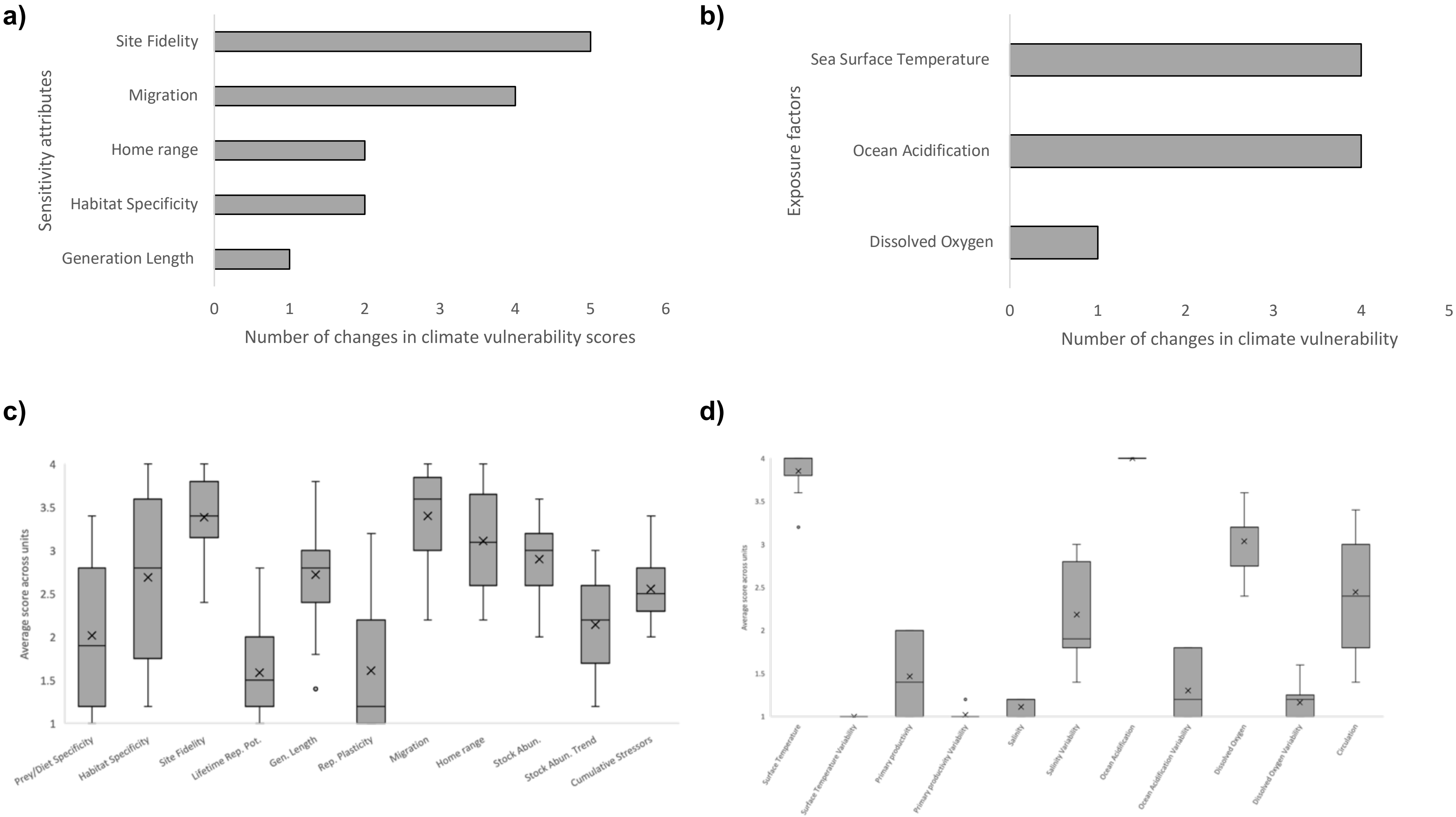


Figure F-2 – Results for archipelago-associated species management units indicating (a,b) the number of changes in climate vulnerability scores produced by individual sensitivity attributes and exposure factors and (c,d) the average attribute and exposure scores.

Annex G. Graphical abstract of Chapter 3

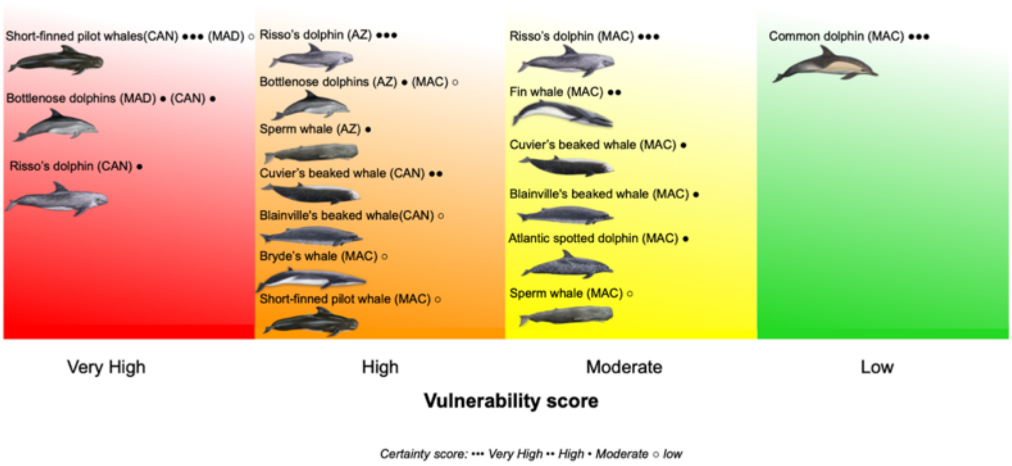
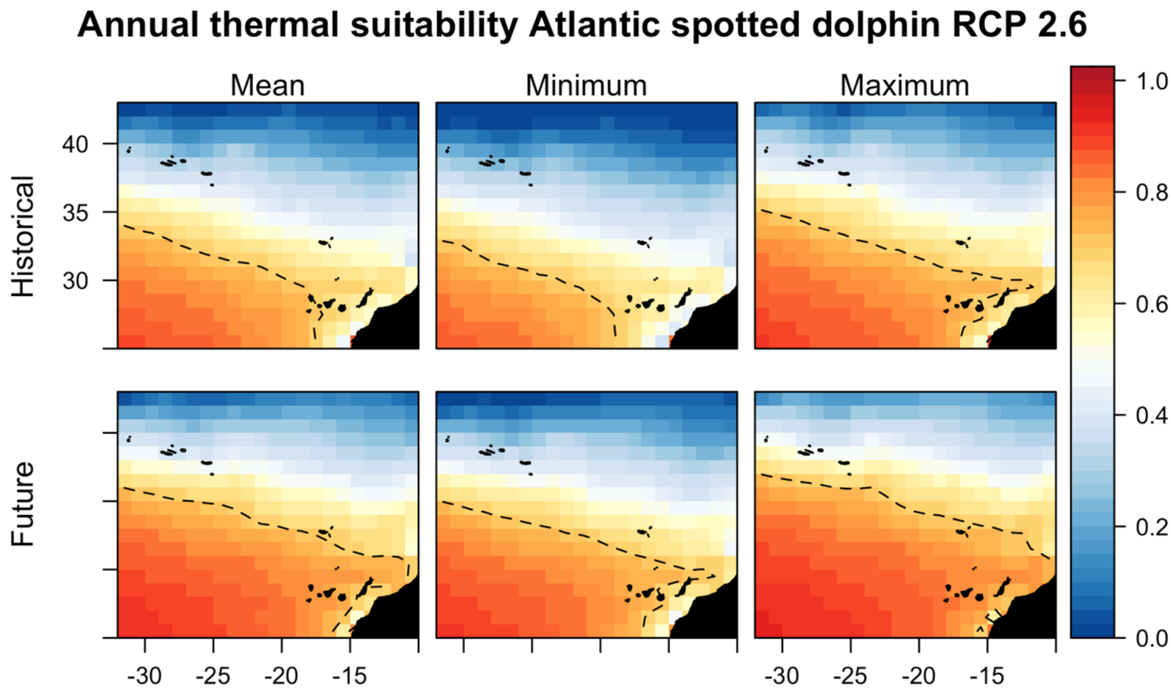


Figure G-1 – Graphical abstract with main results of results of Chapter 3.

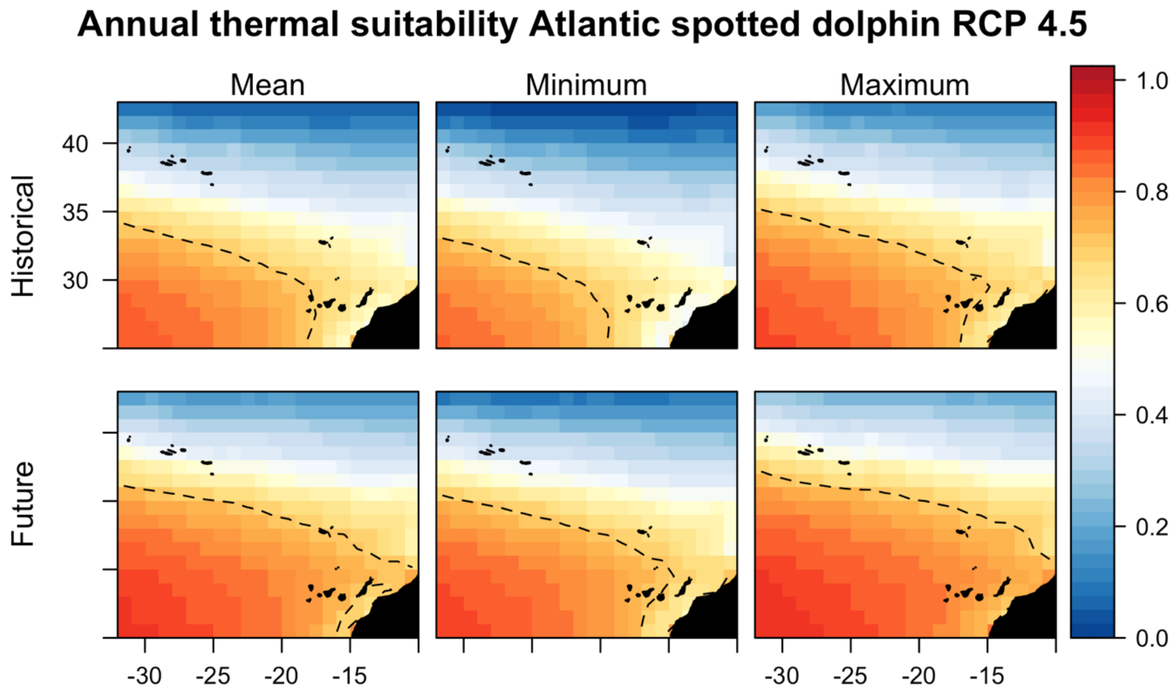
Annex H. Annual thermal suitability maps

Atlantic spotted dolphin

RCP 2.6



RCP 4.5



RCP 8.5

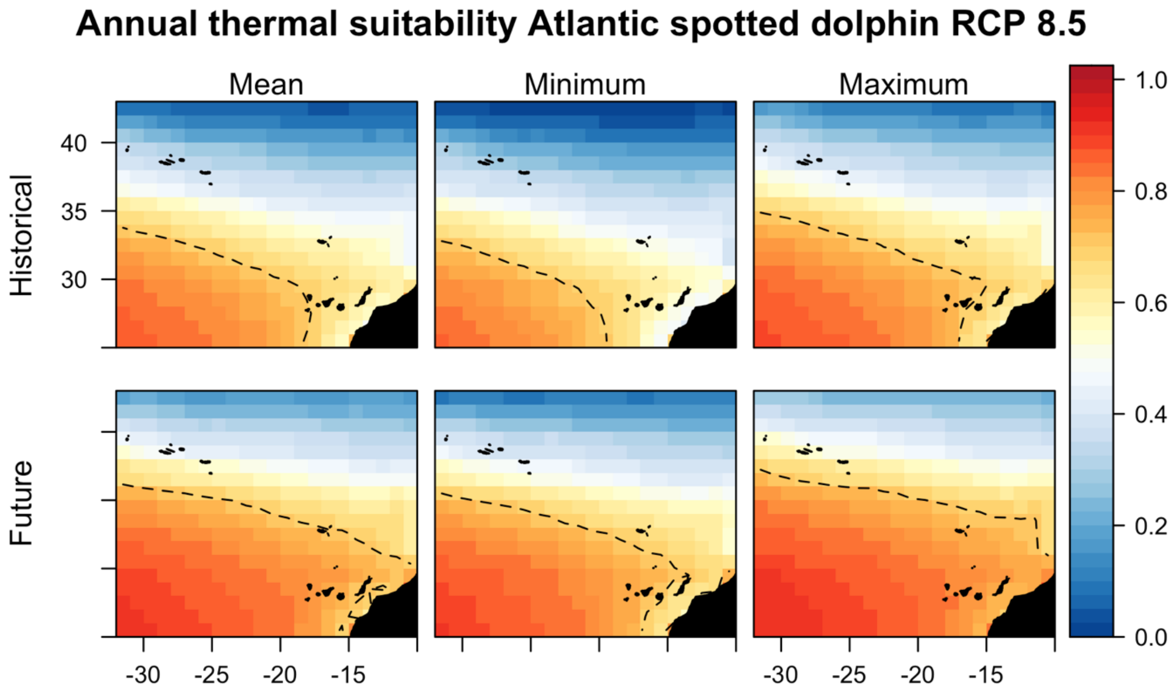
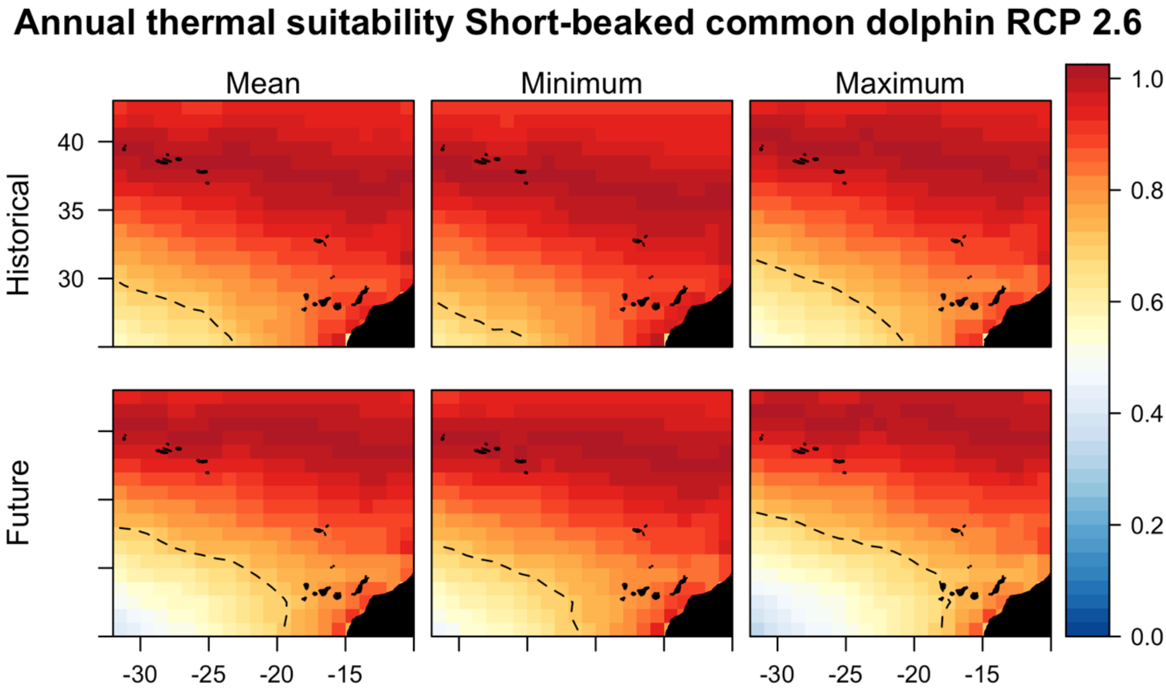


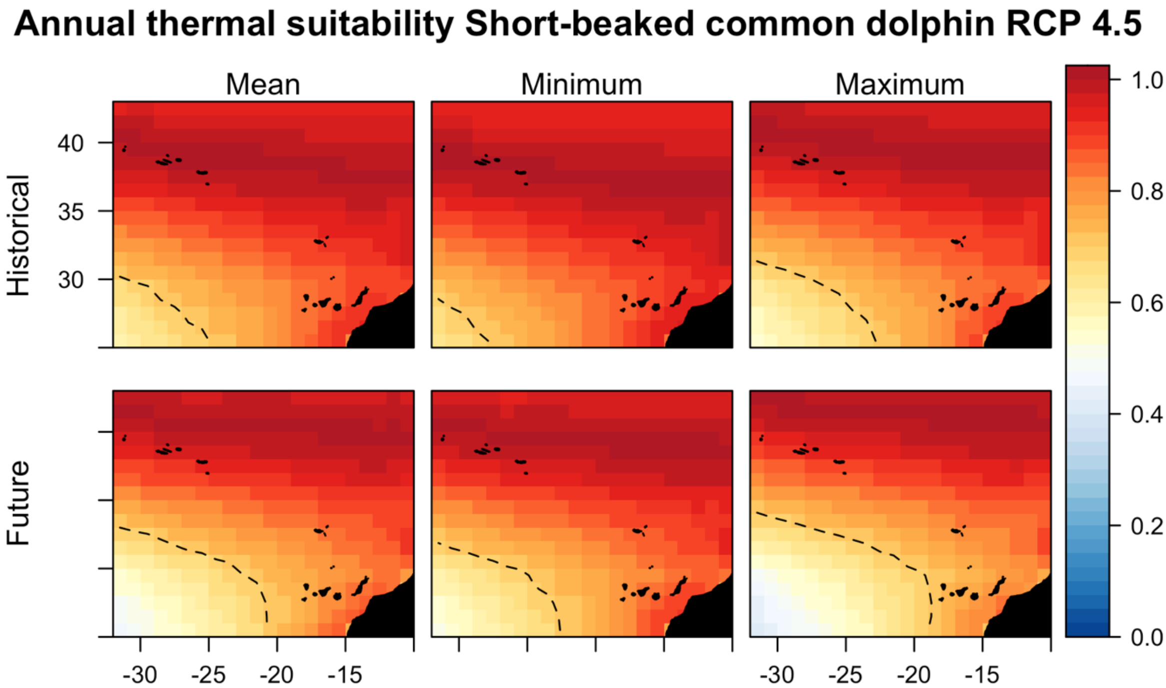
Figure H-1 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Atlantic spotted dolphin under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Short-beaked common dolphin

RCP 2.6



RCP 4.5



RCP 8.5

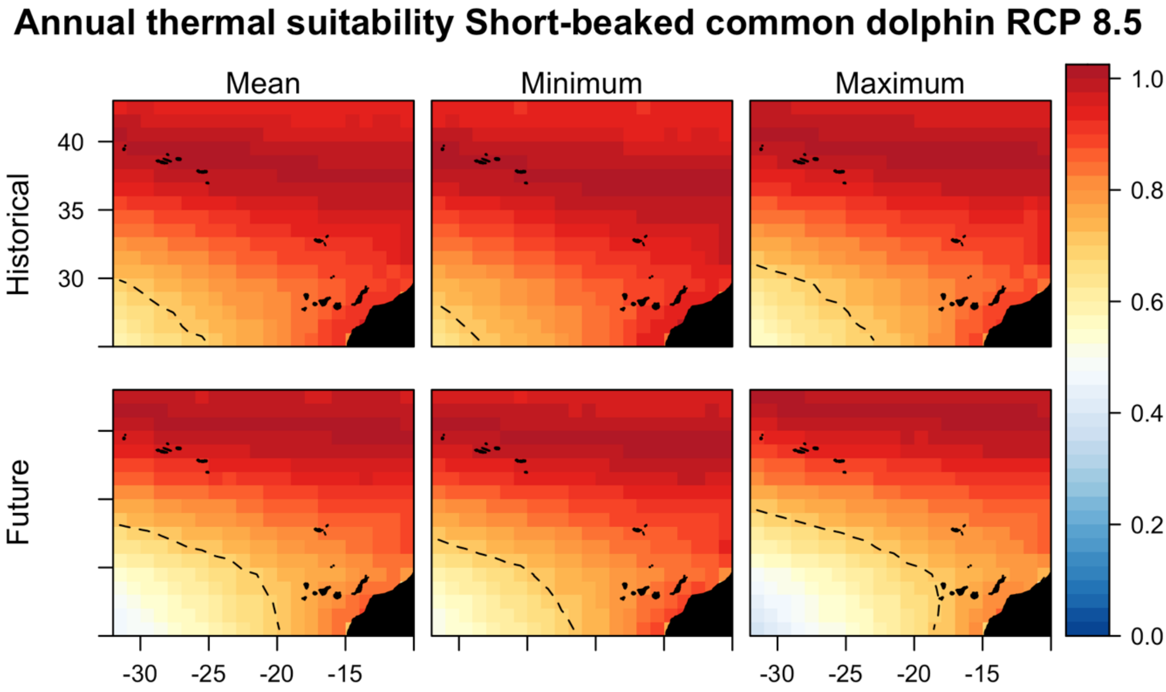
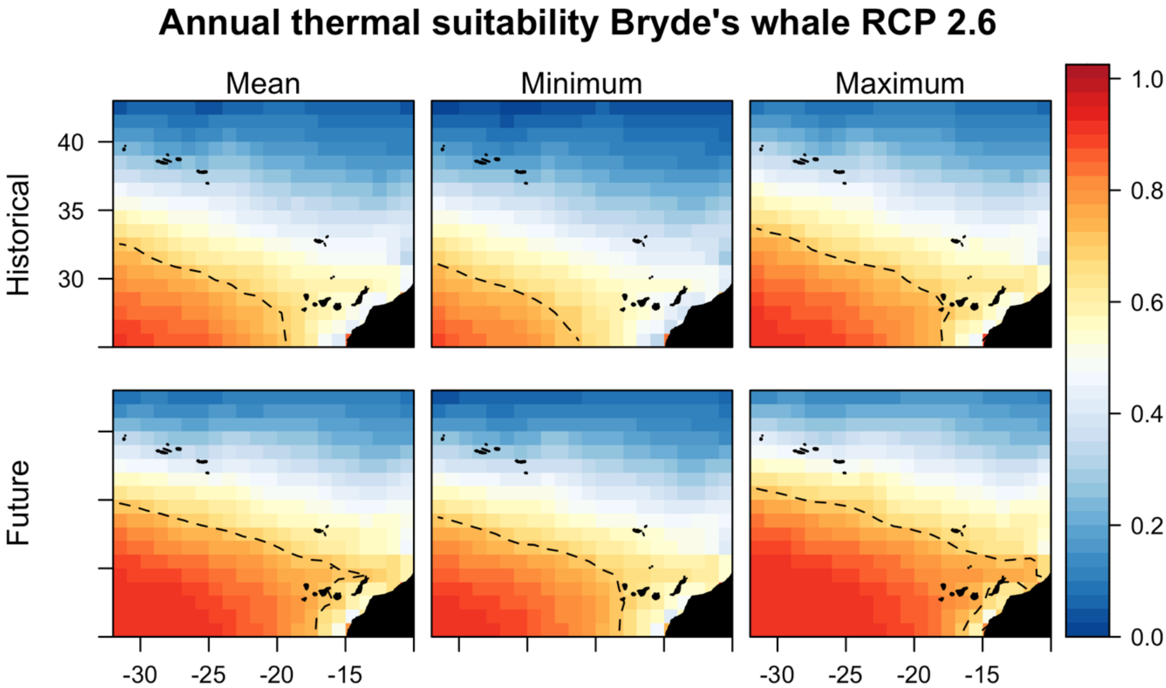


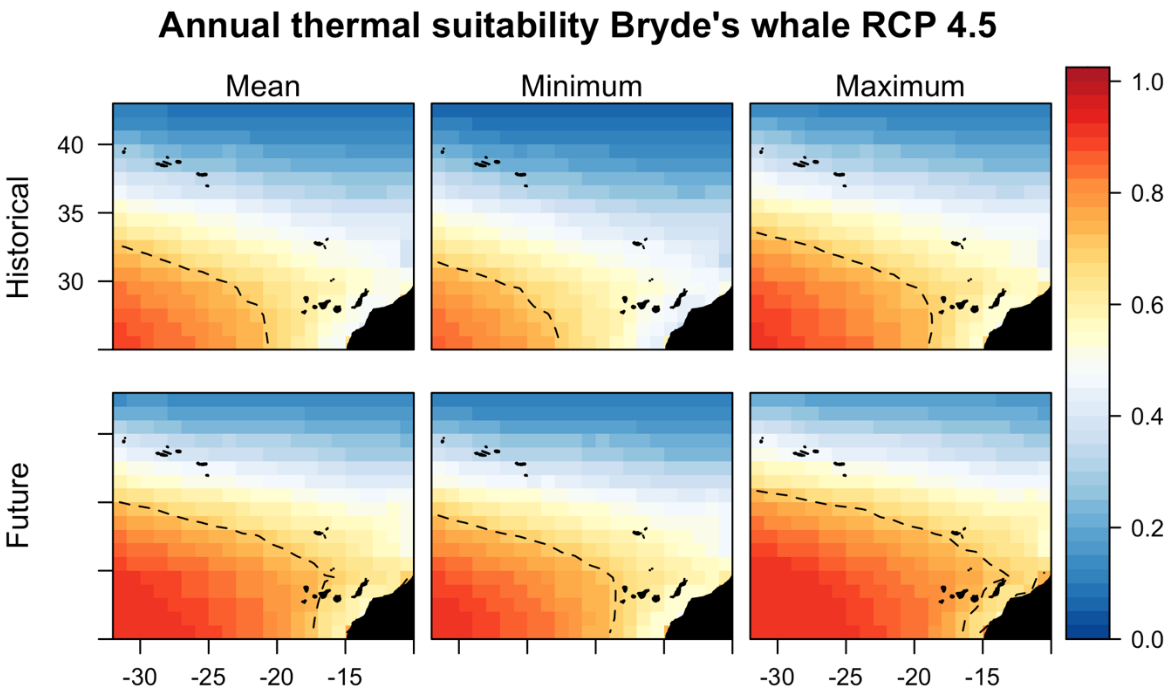
Figure H-2 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Short-beaked common dolphin under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Bryde's whale

RCP 2.6



RCP 4.5



RCP 8.5

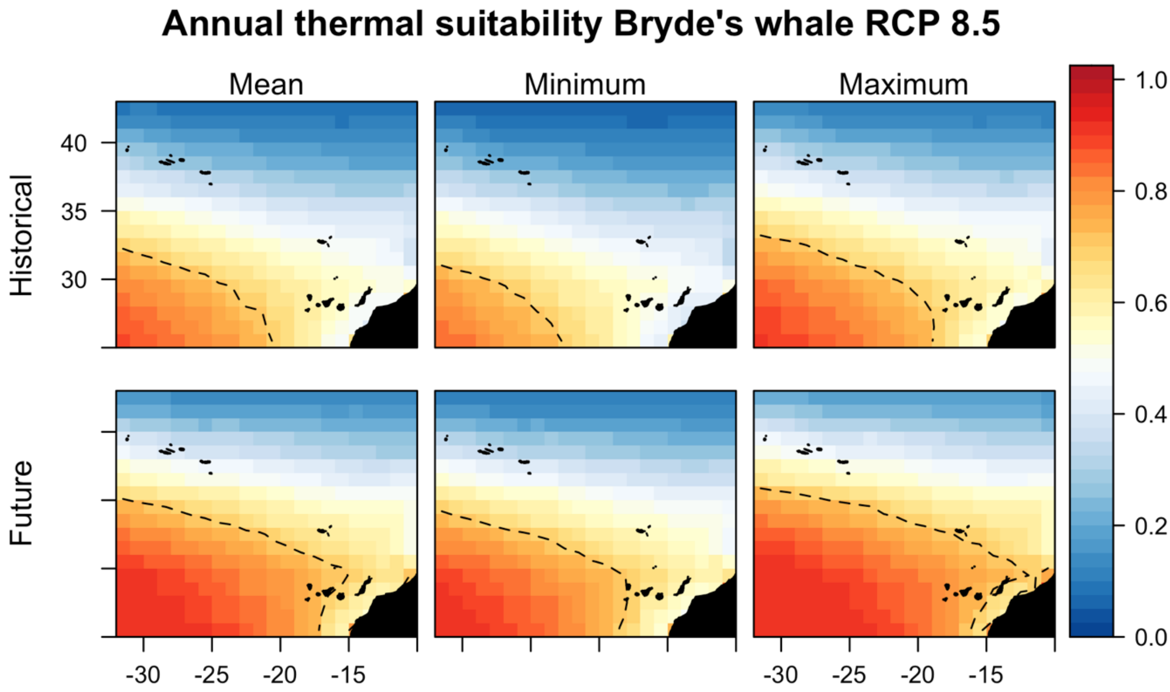
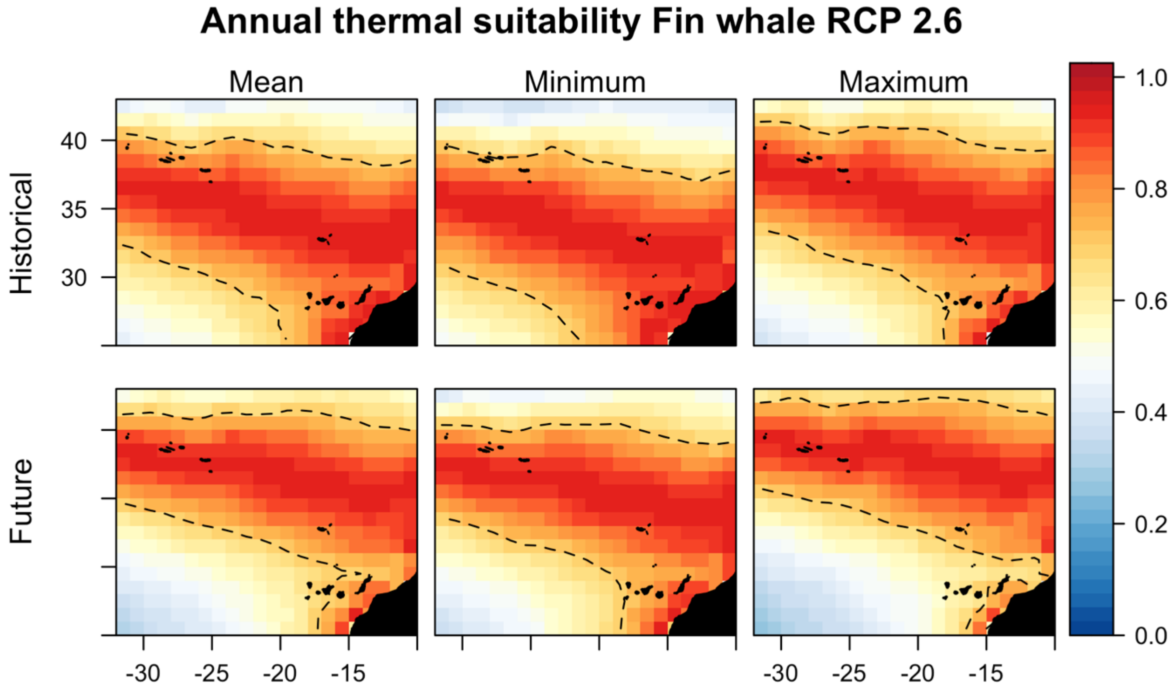


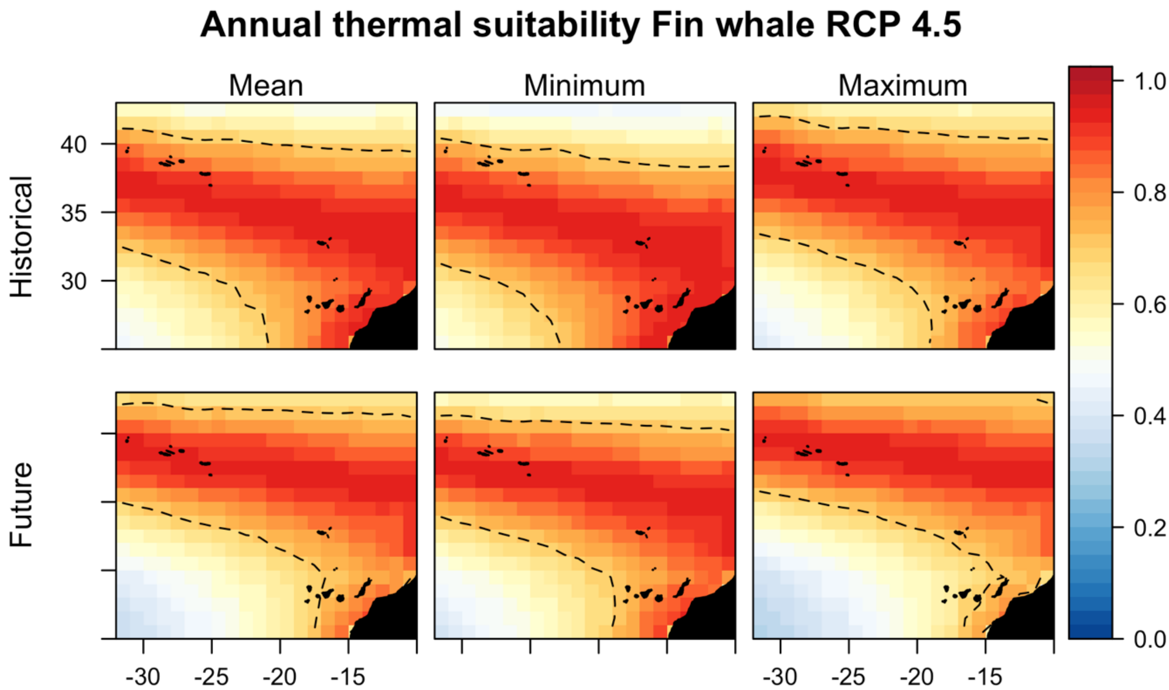
Figure H-3 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Bryde's whale under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Fin whale

RCP 2.6



RCP 4.5



RCP 8.5

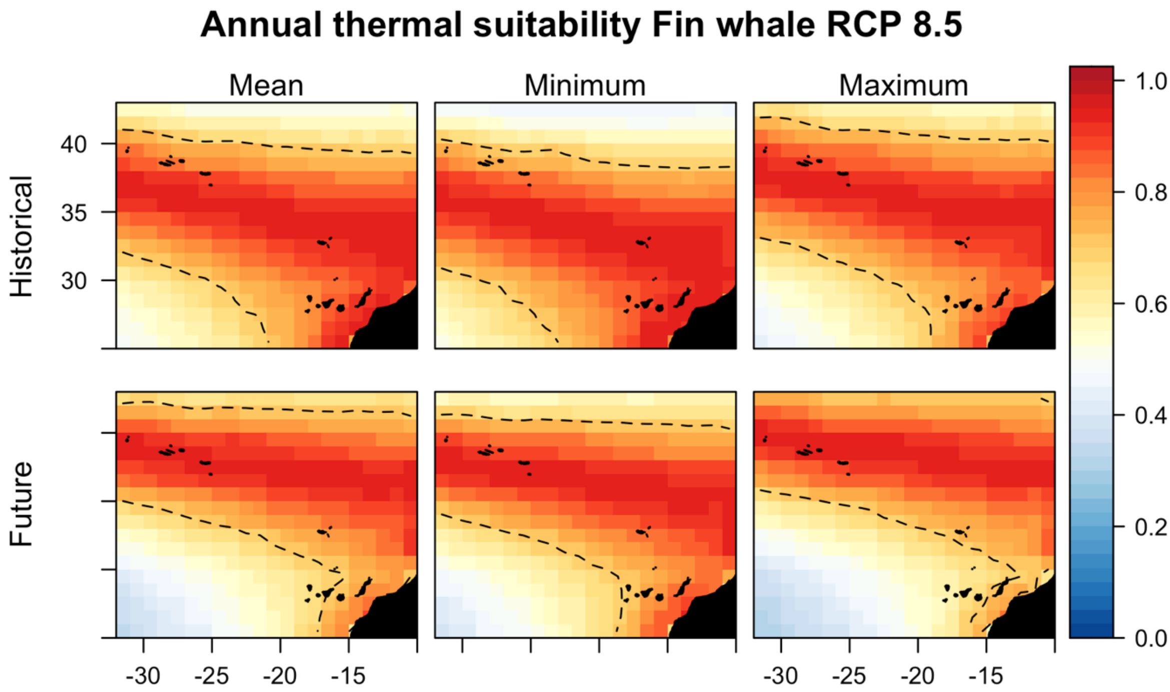
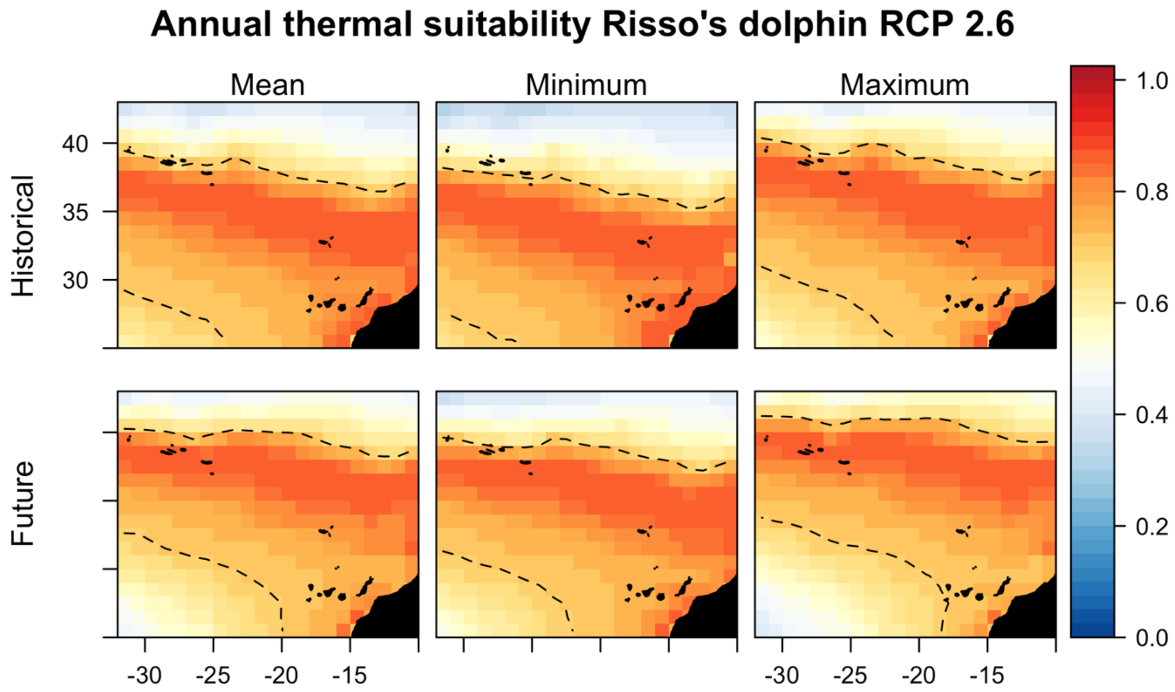


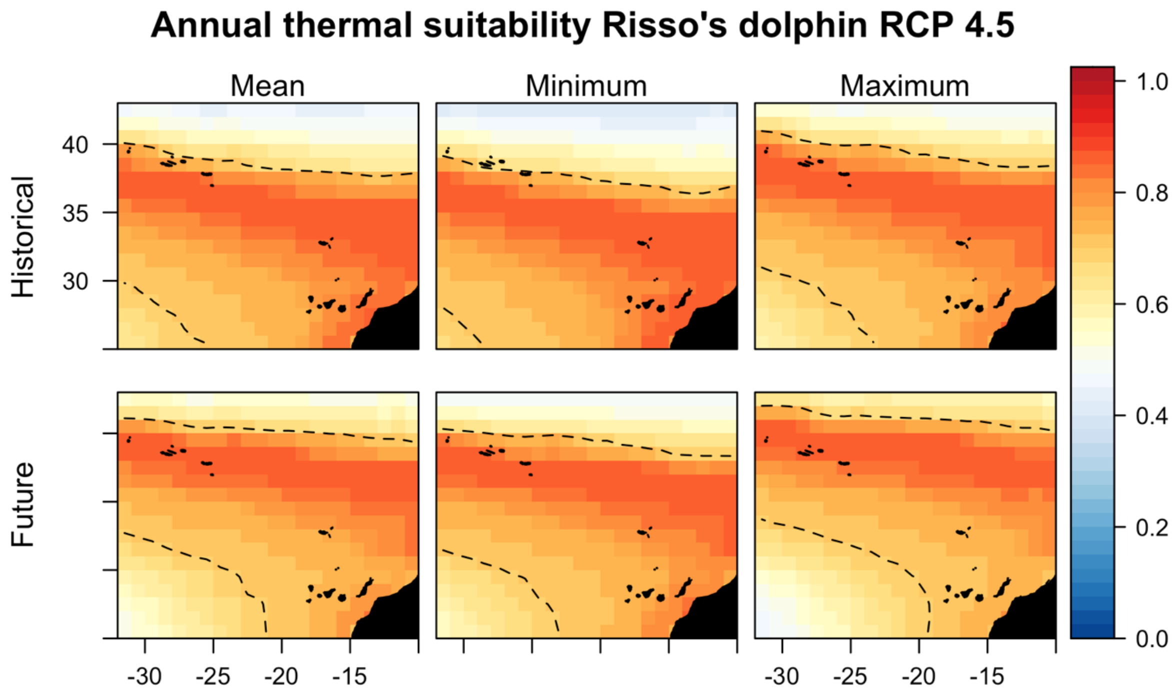
Figure H-4 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for fin whale under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Risso's dolphin

RCP 2.6



RCP 4.5



RCP 8.5

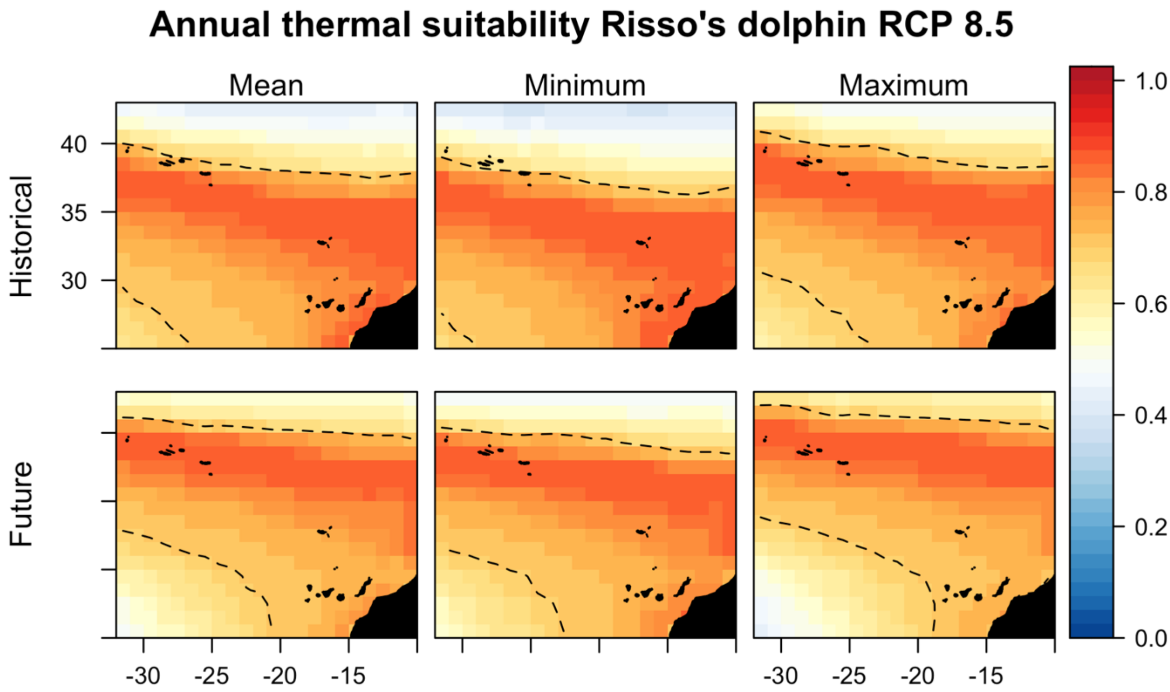
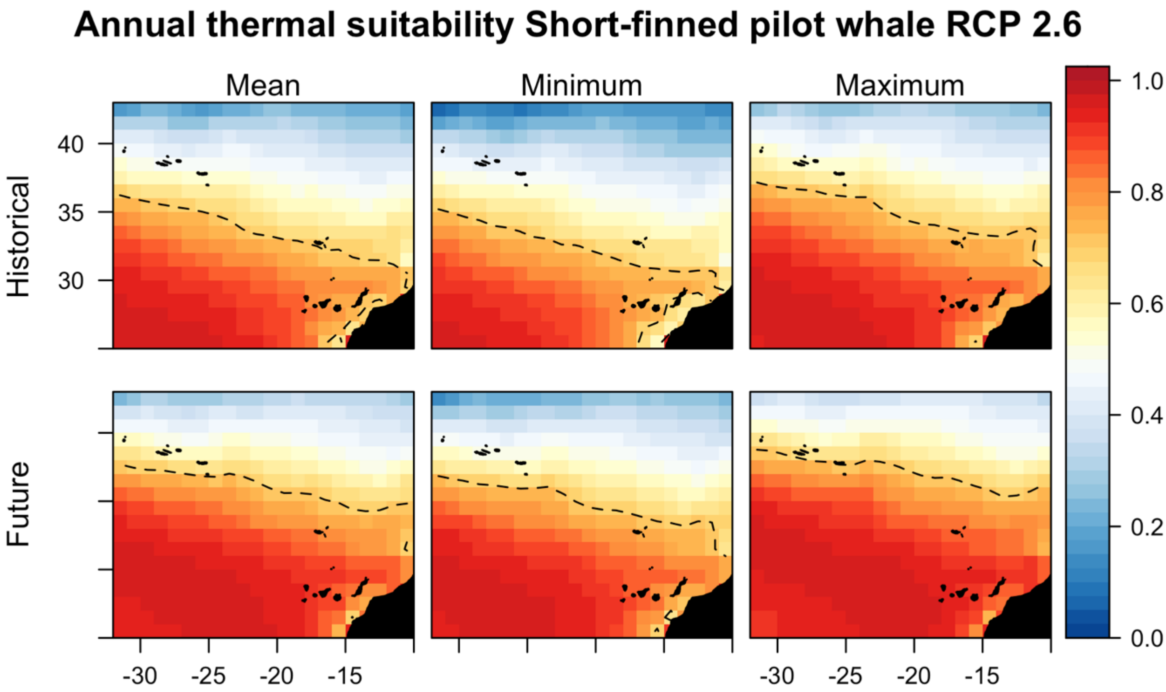


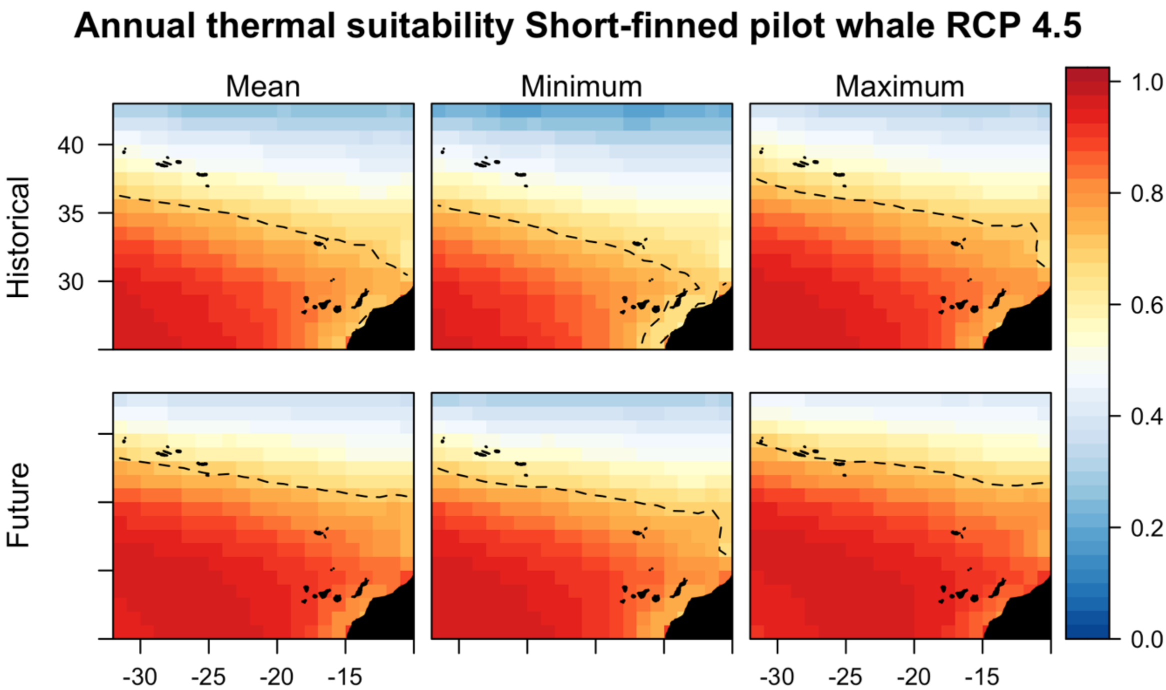
Figure H-5 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Risso's dolphin under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability

Short-finned pilot whale

RCP 2.6



RCP 4.5



RCP 8.5

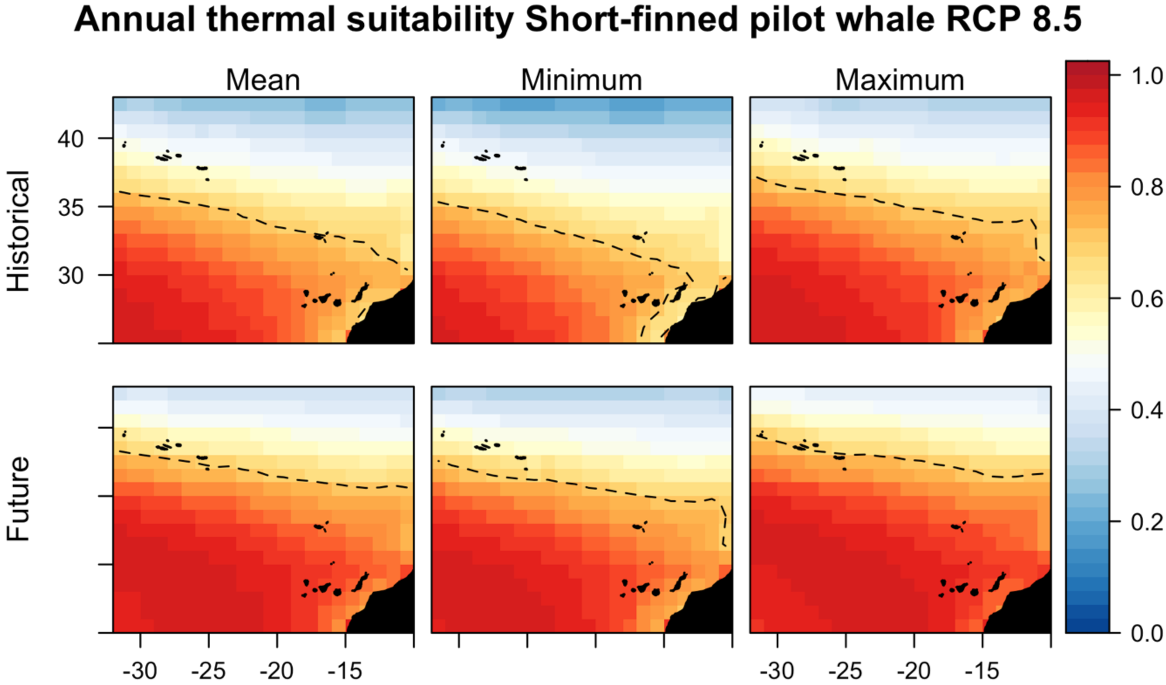
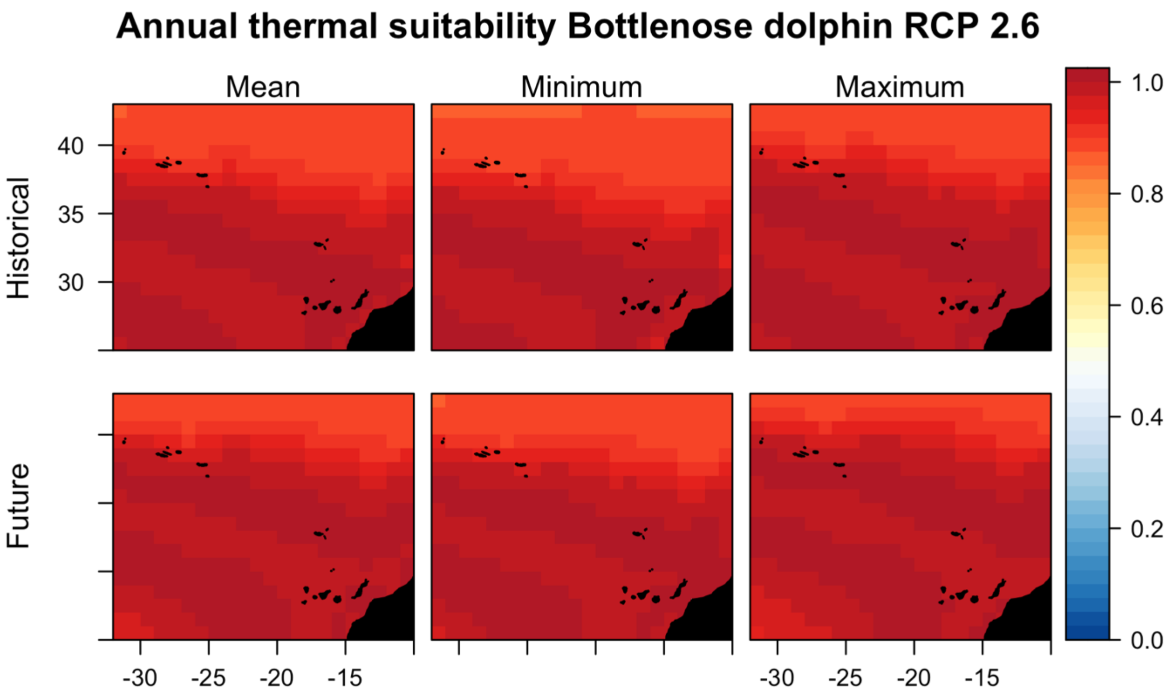


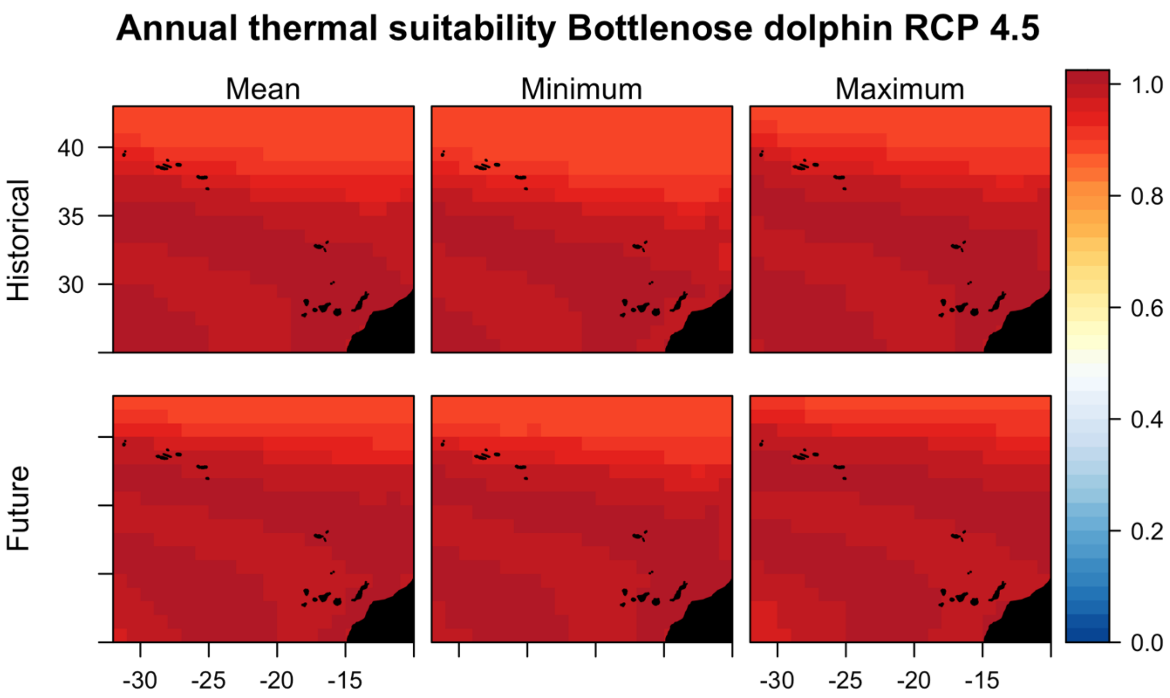
Figure H-6 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for short-finned pilot whale under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Bottlenose dolphin

RCP 2.6



RCP 4.5



RCP 8.5

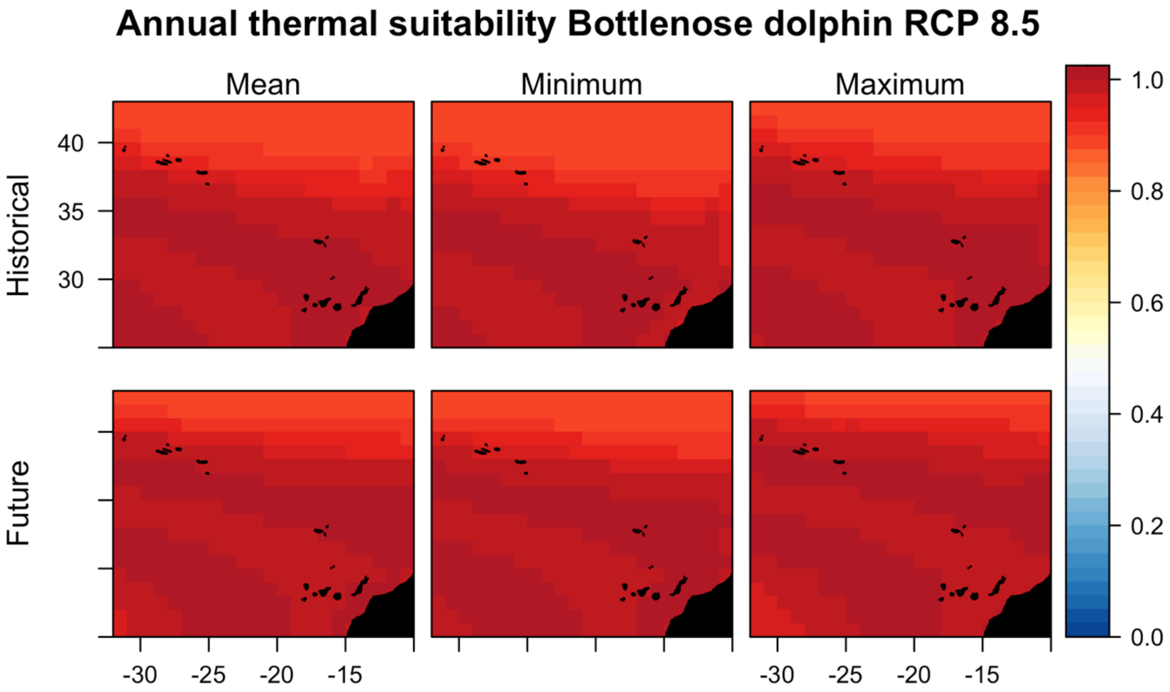
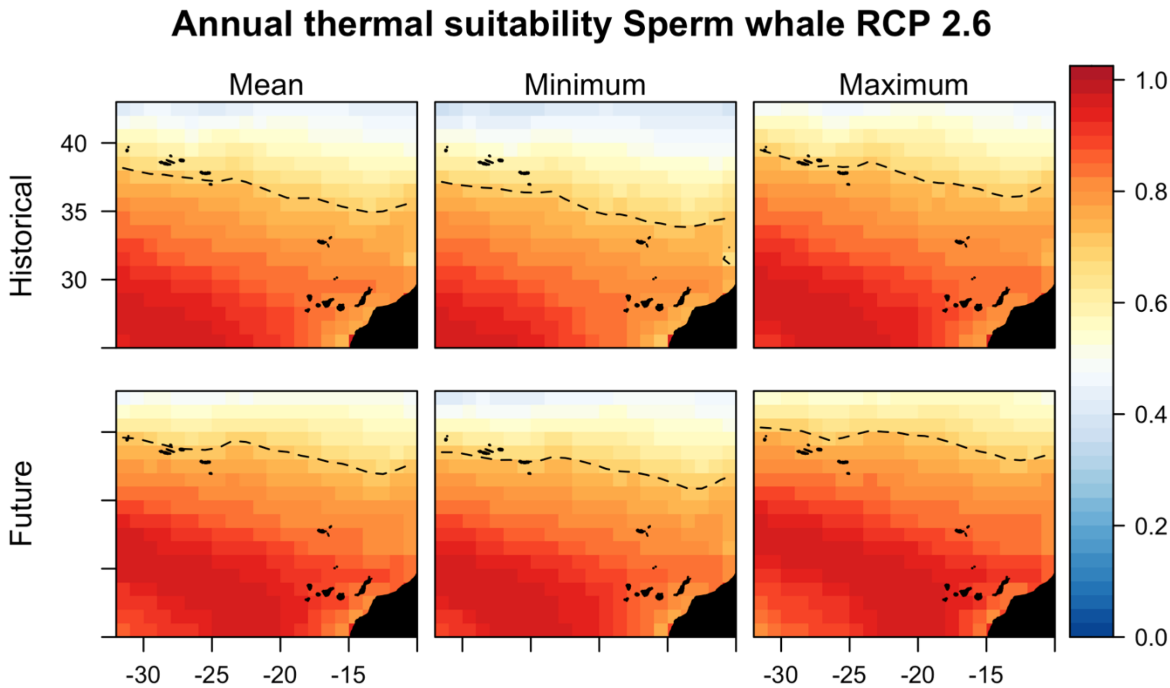


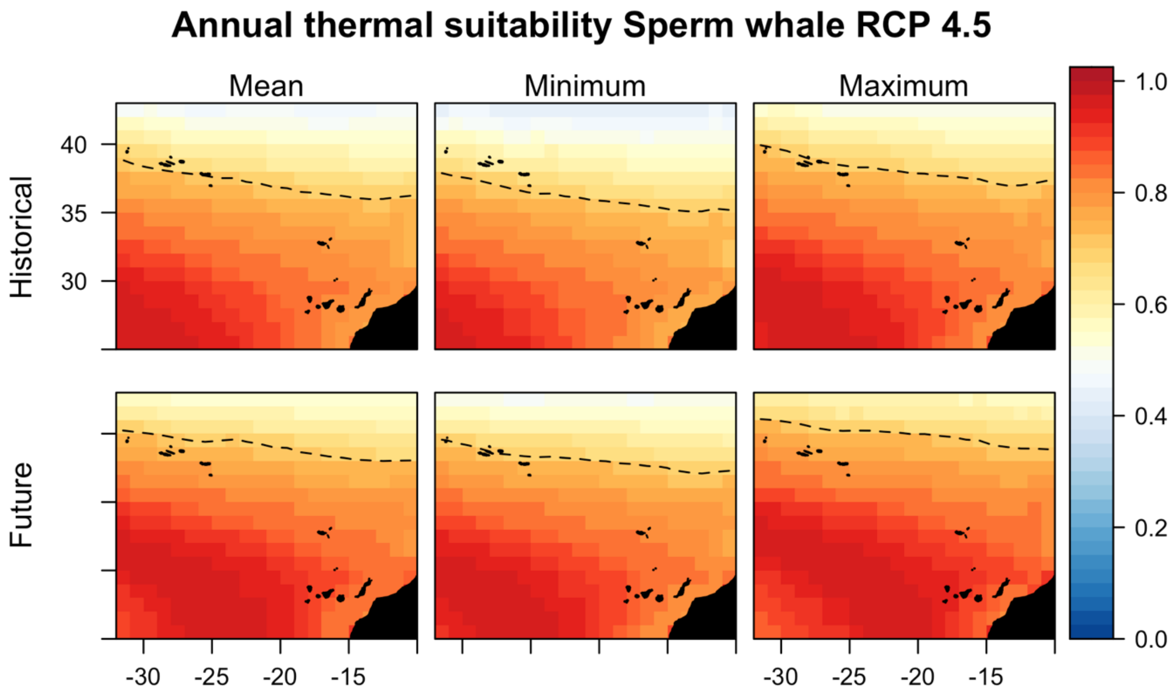
Figure H-7 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for bottlenose dolphin under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Sperm whale

RCP 2.6



RCP 4.5



RCP 8.5

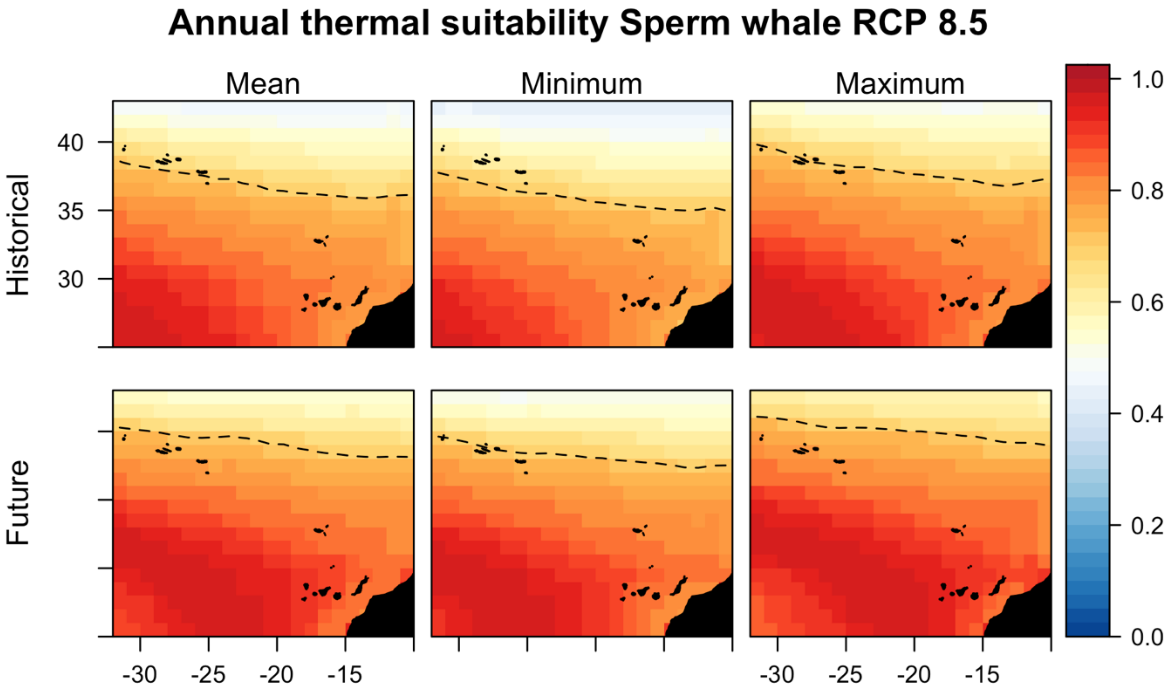
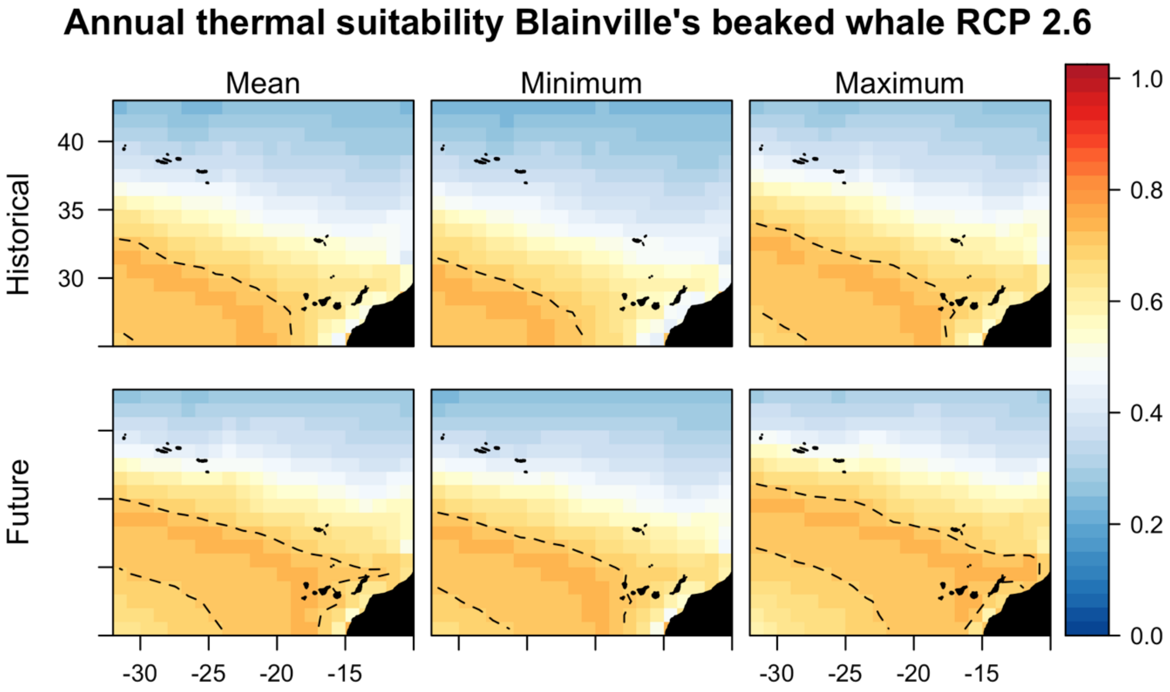


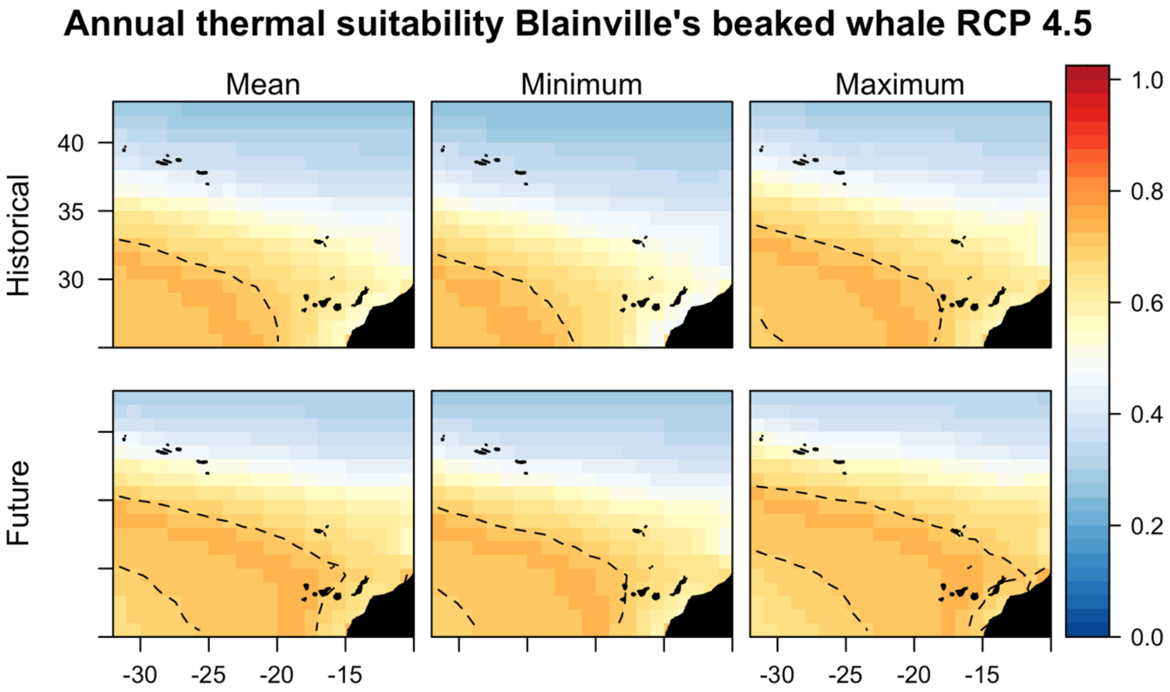
Figure H-8 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for sperm whale under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Blainville’s beaked whale

RCP 2.6



RCP 4.5



RCP 8.5

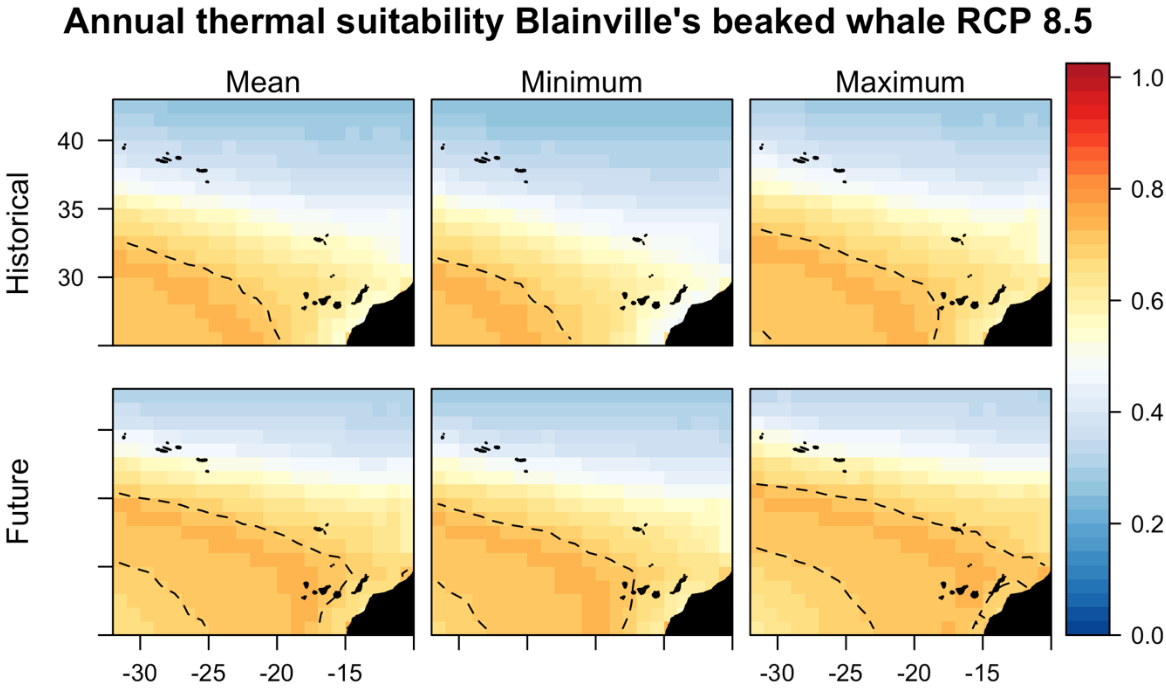
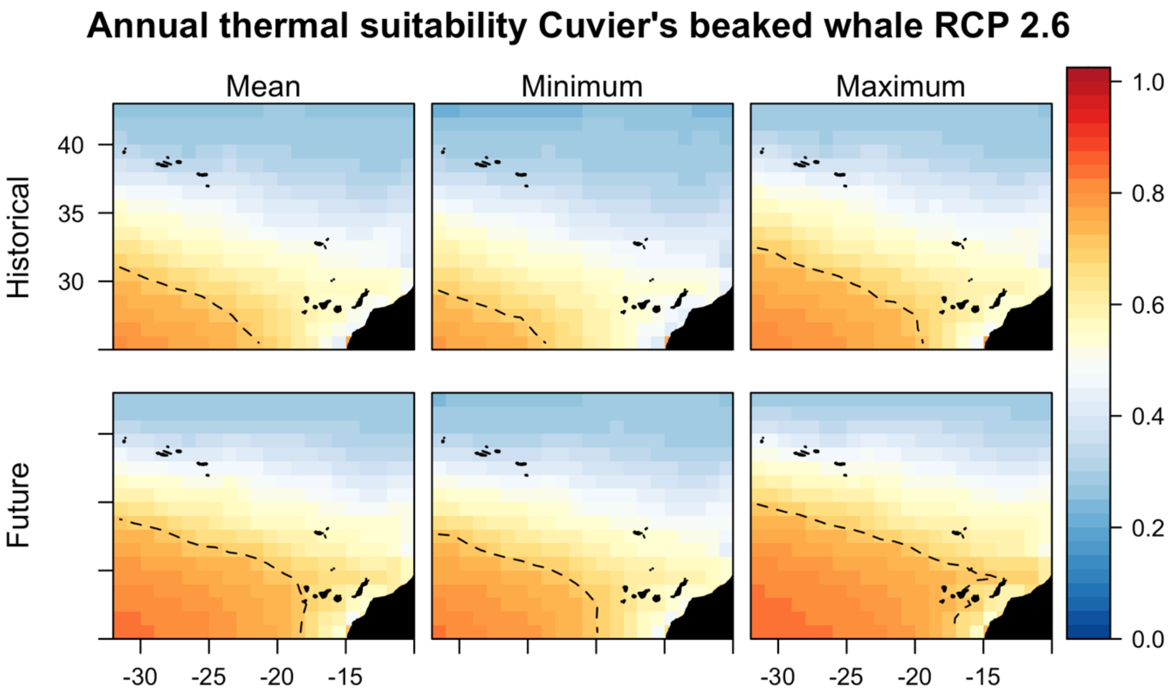


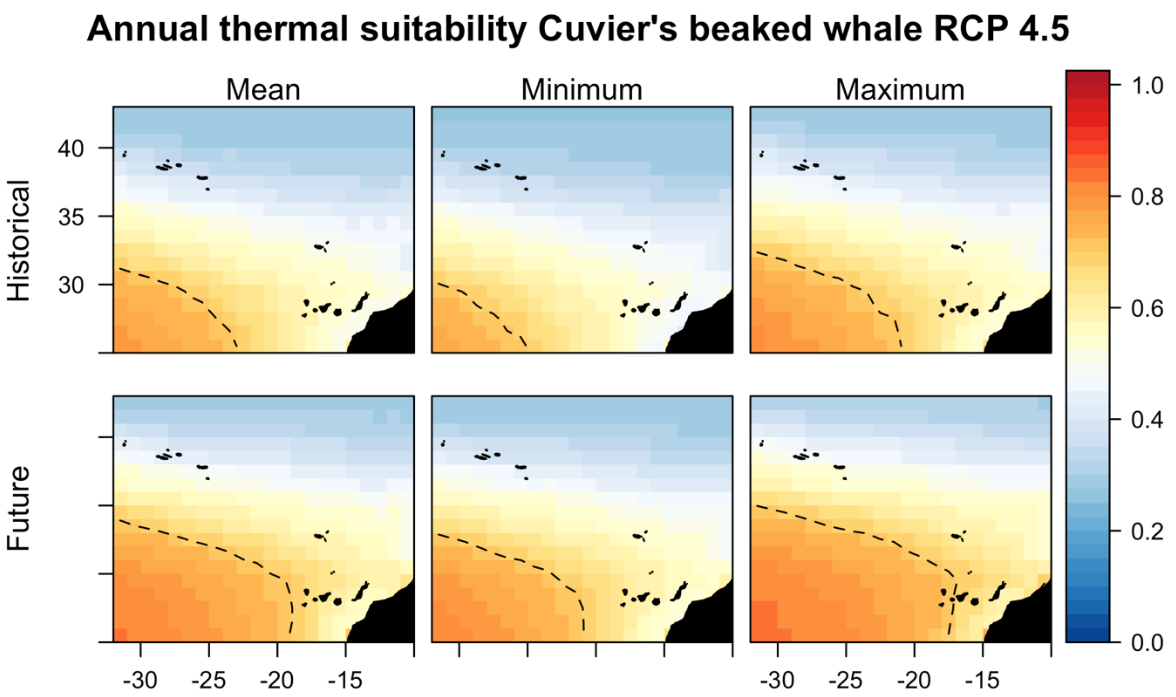
Figure H-9 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Blainville's beaked whale under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Cuvier's beaked whale

RCP 2.6



RCP 4.5



RCP 8.5

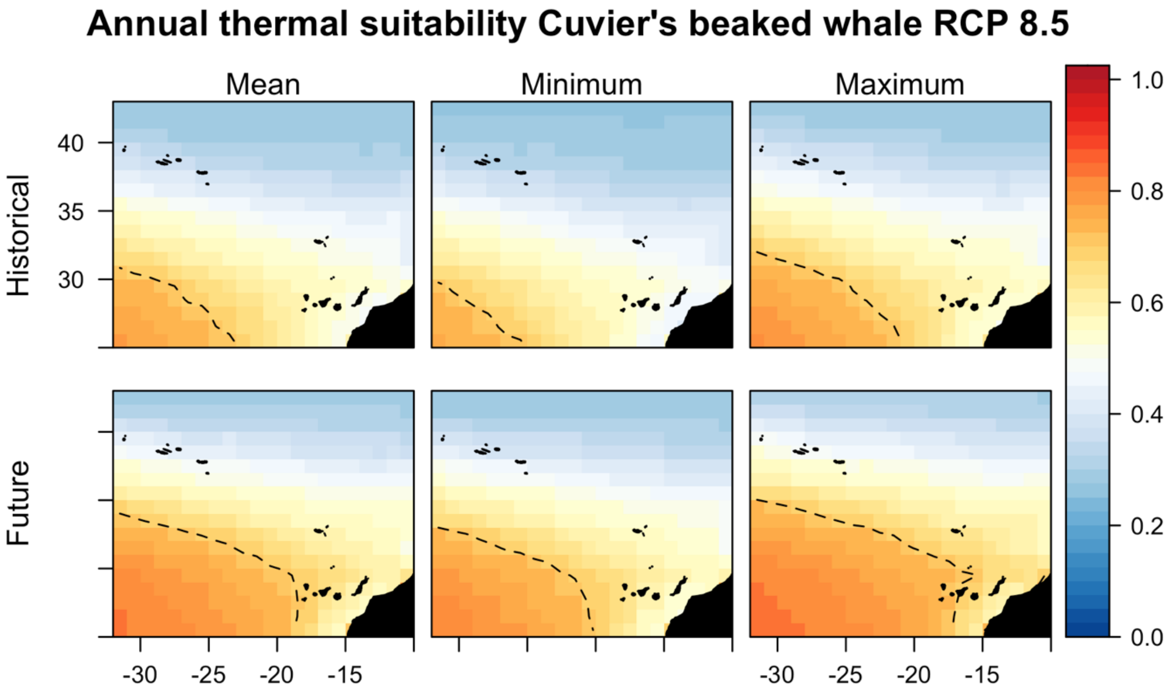


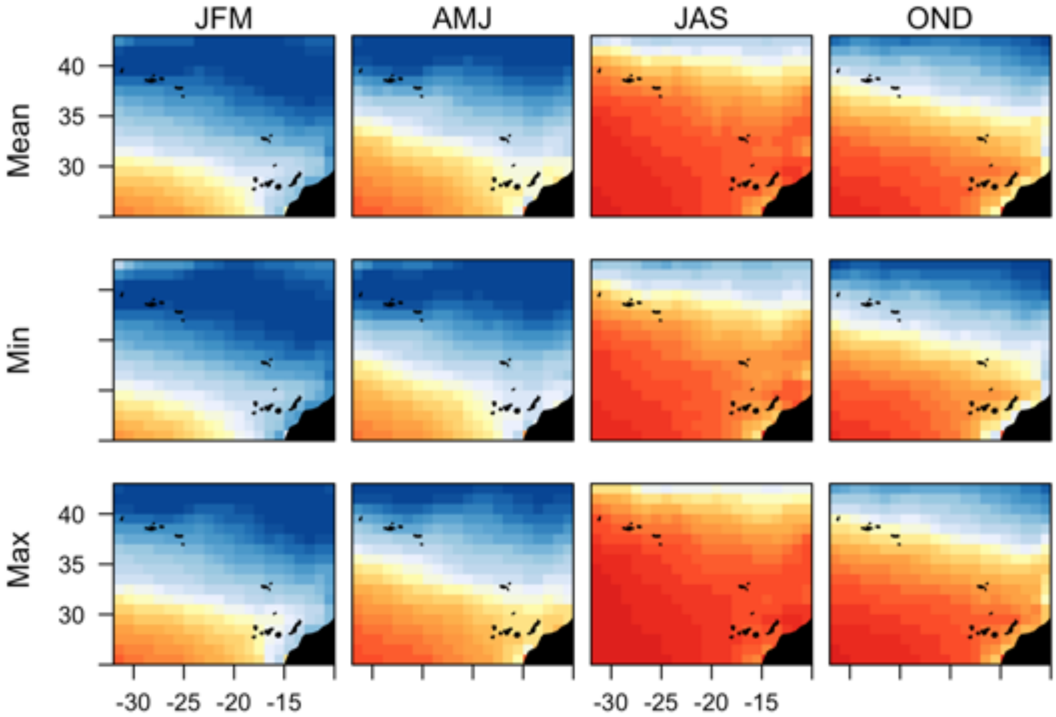
Figure H-10 - Annual historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for Cuvier's beaked whale under RCP 2.6; 4.5 and 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1). Dashed contour lines indicate a 0.75 thermal suitability.

Annex I. Seasonal thermal suitability maps

Atlantic spotted dolphin

RCP 2.6

Historical (1956-2005)



Future (2006-2055)

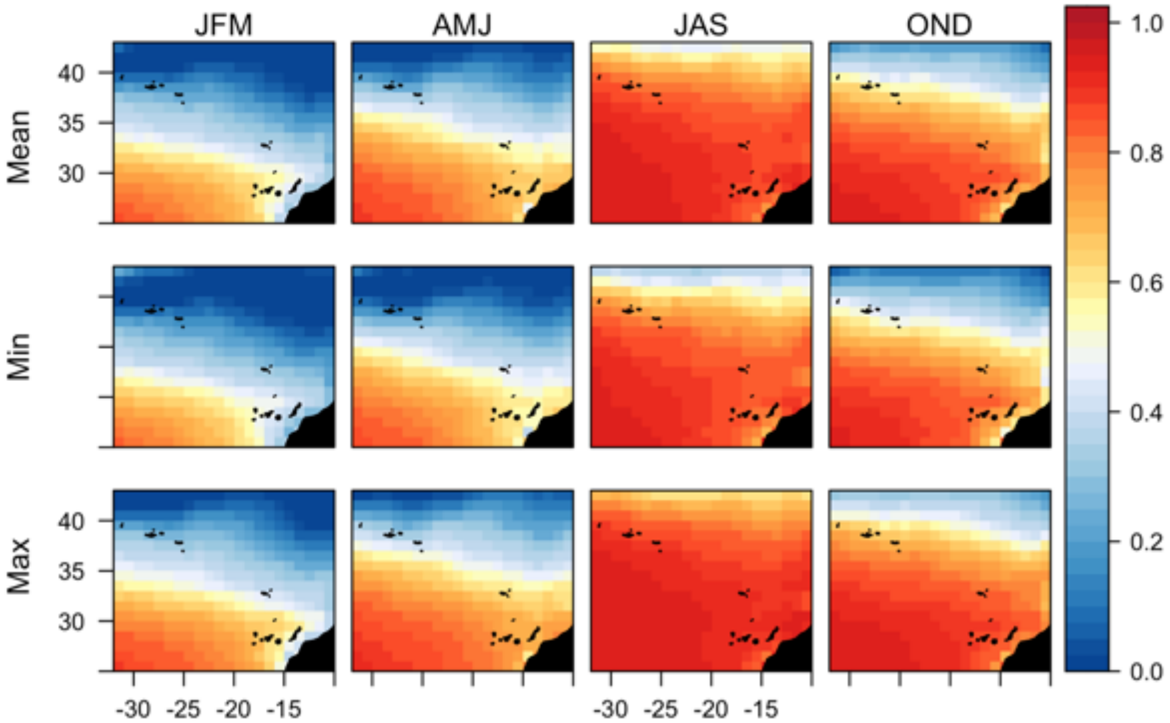
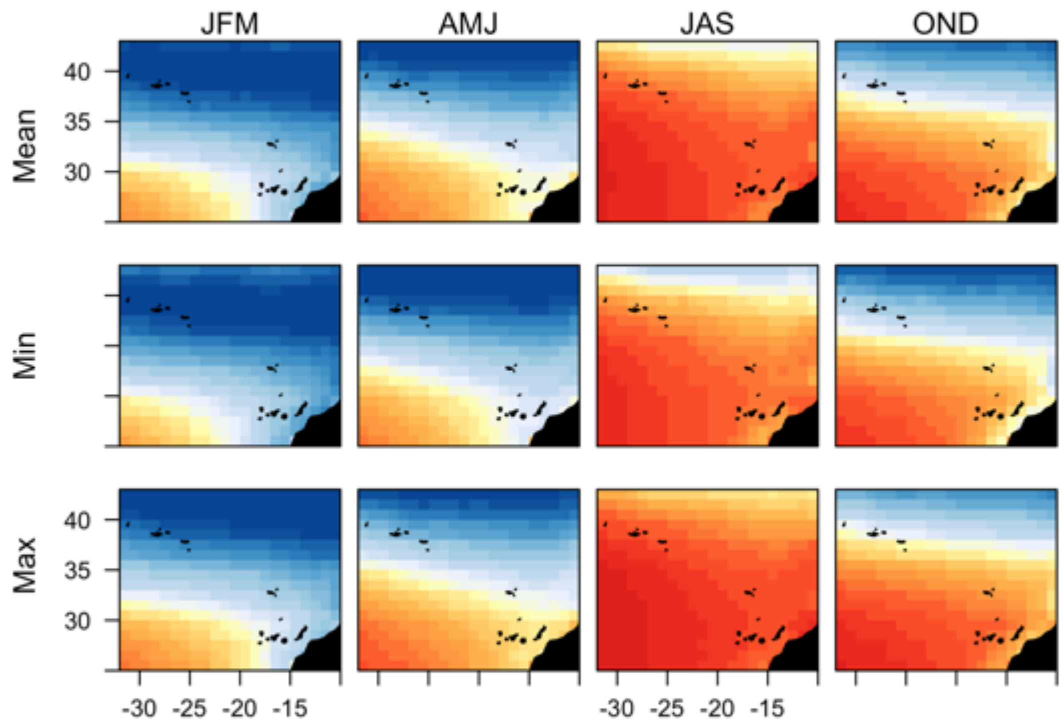


Figure I-1 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Atlantic spotted dolphin under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Atlantic spotted dolphin RCP 4.5

Historical (1956-2005)



Future (2006-2055)

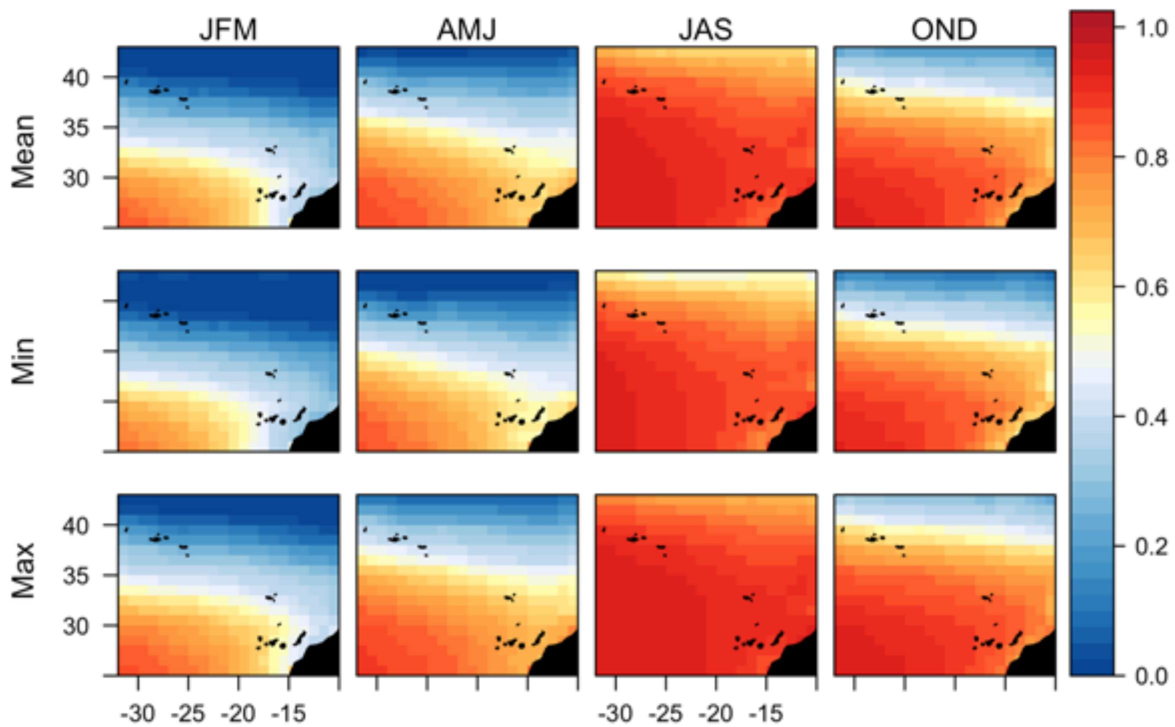
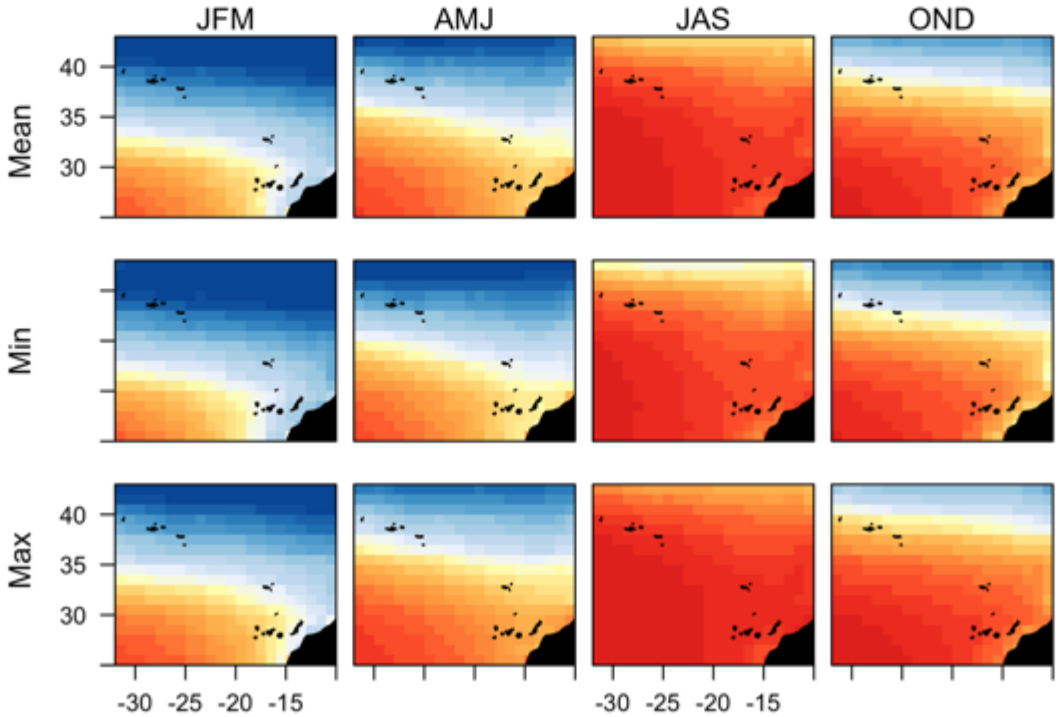


Figure I-2 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Atlantic spotted dolphin under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively.

The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Atlantic spotted dolphin RCP 8.5

Historical (1956-2005)



Future (2006-2055)

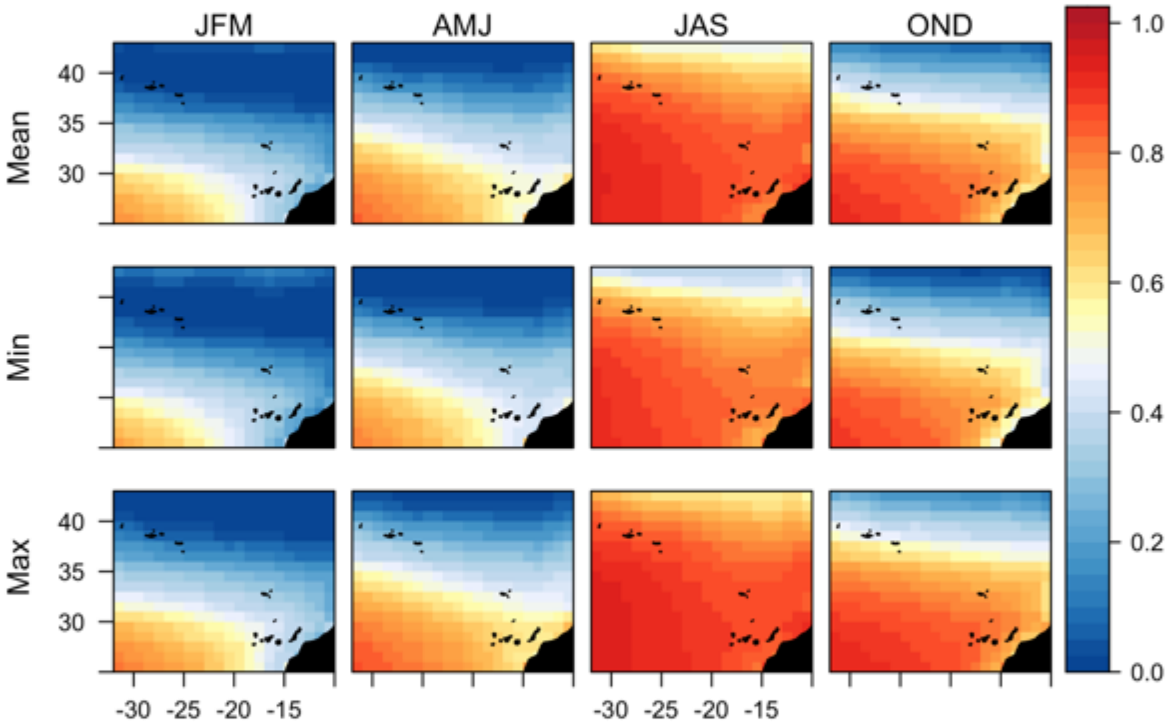


Figure I-3 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Atlantic spotted dolphin under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

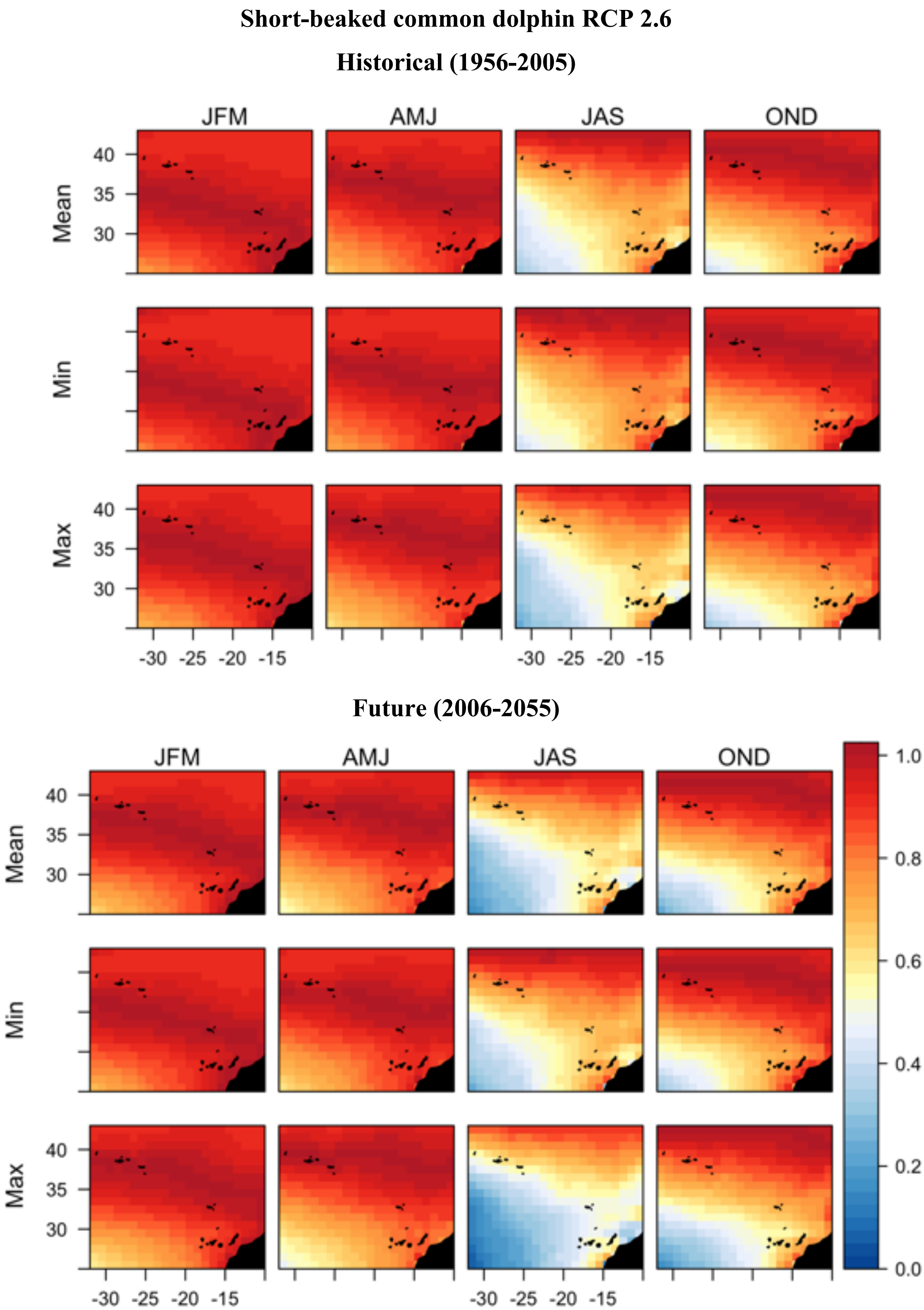


Figure I-4 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Short-beaked common dolphin under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively.

The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

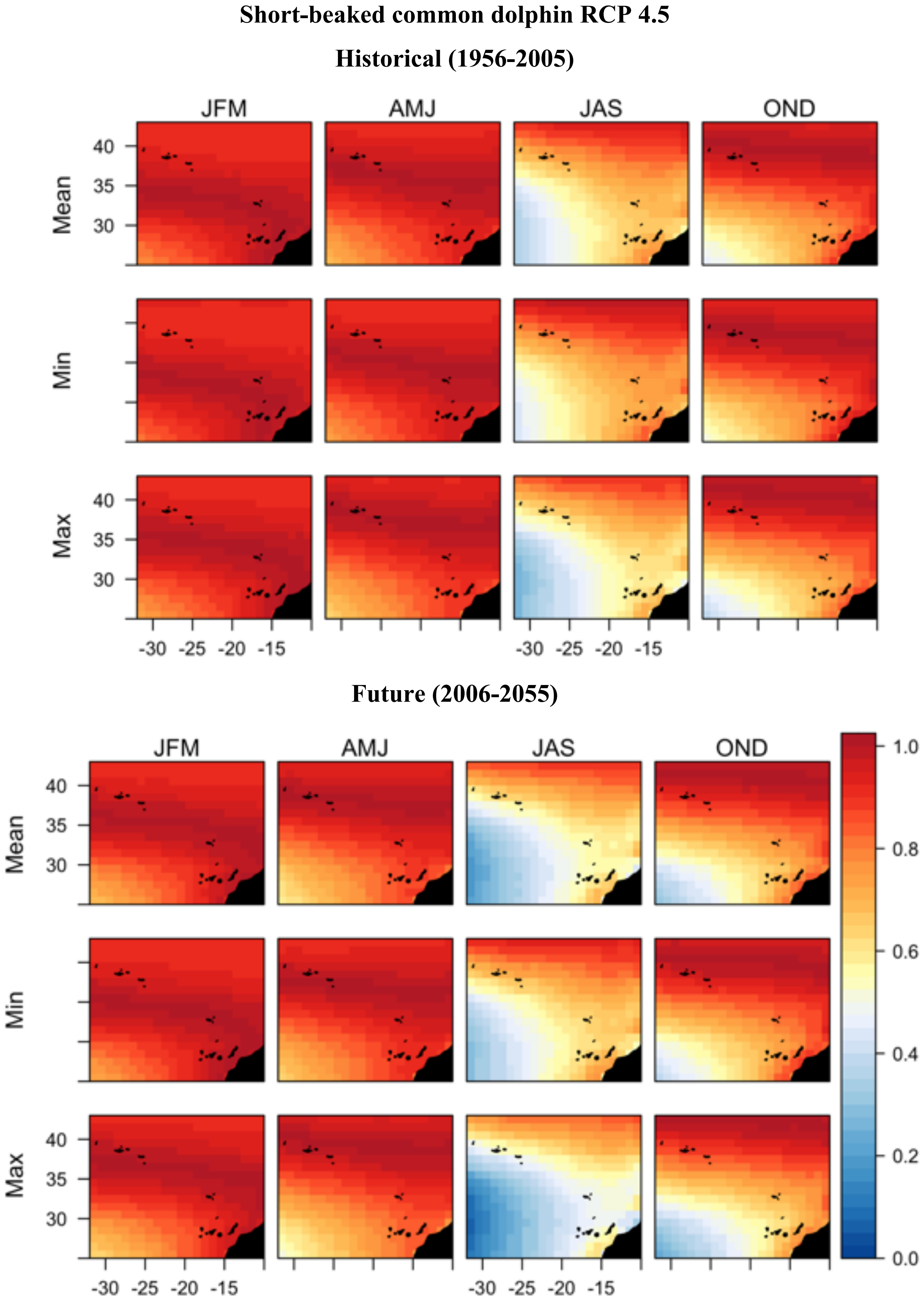


Figure I-5 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Short-beaked common dolphin under RCP 4.5.

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).

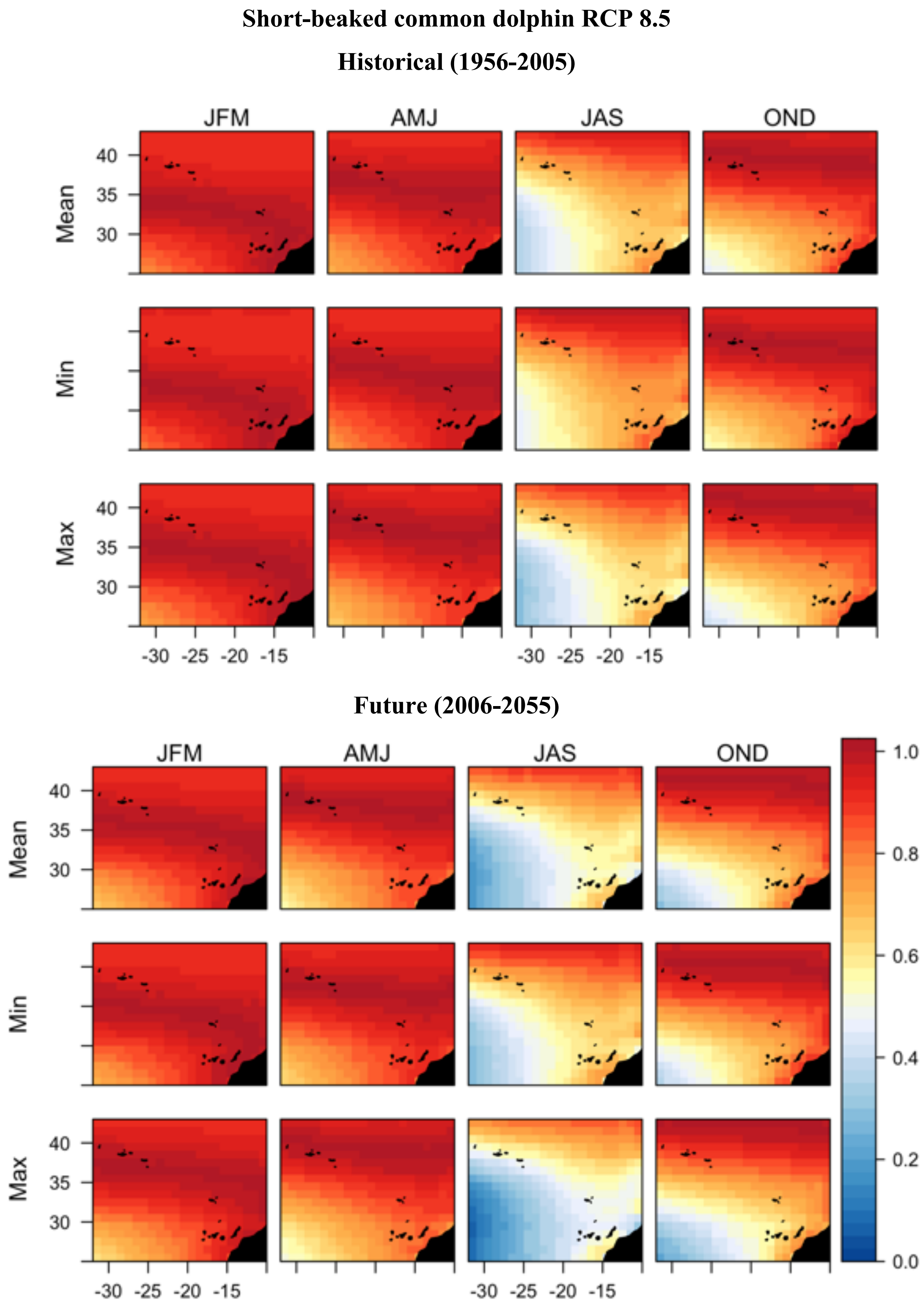


Figure I-6 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Short-beaked common dolphin under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively.

The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

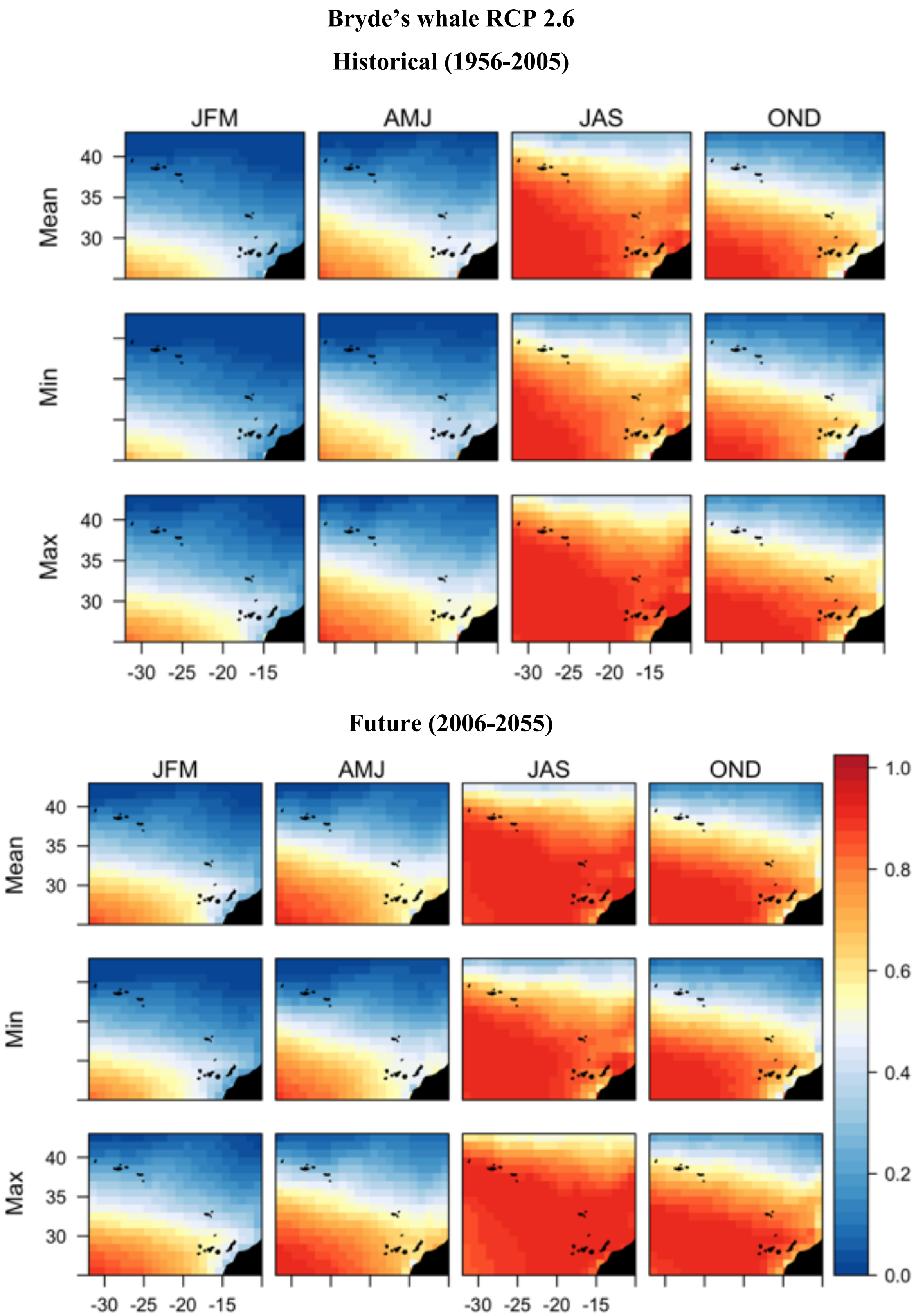
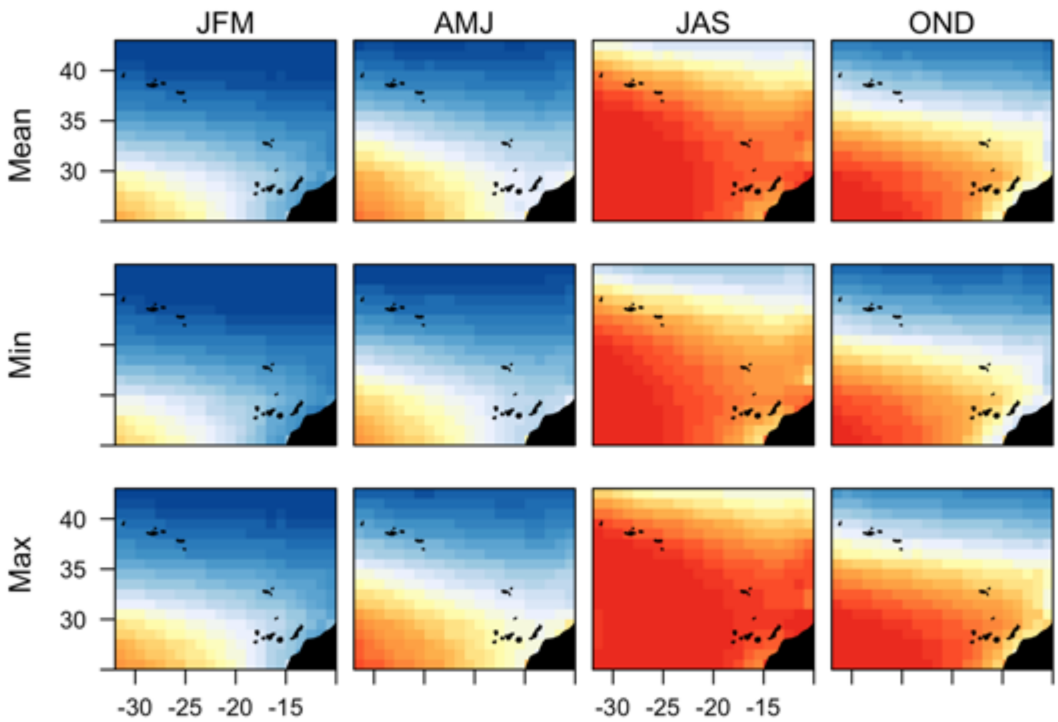


Figure I-7 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Bryde's whale under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal

suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Bryde's whale RCP 4.5

Historical (1956-2005)



Future (2006-2055)

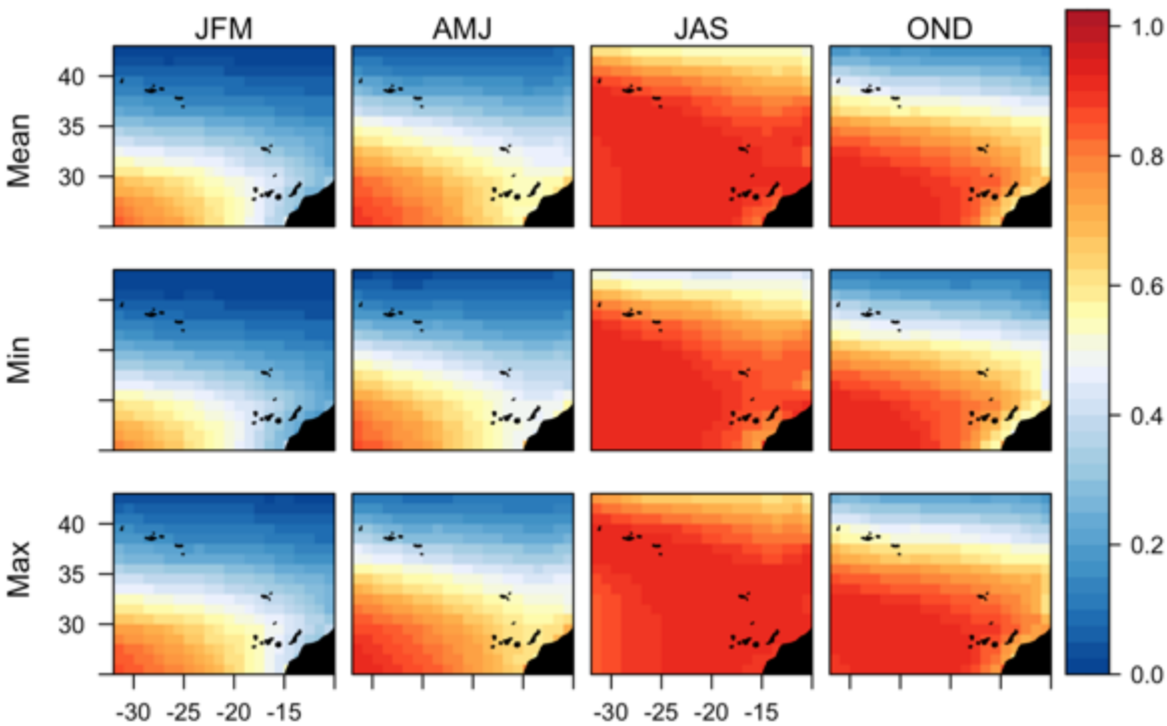
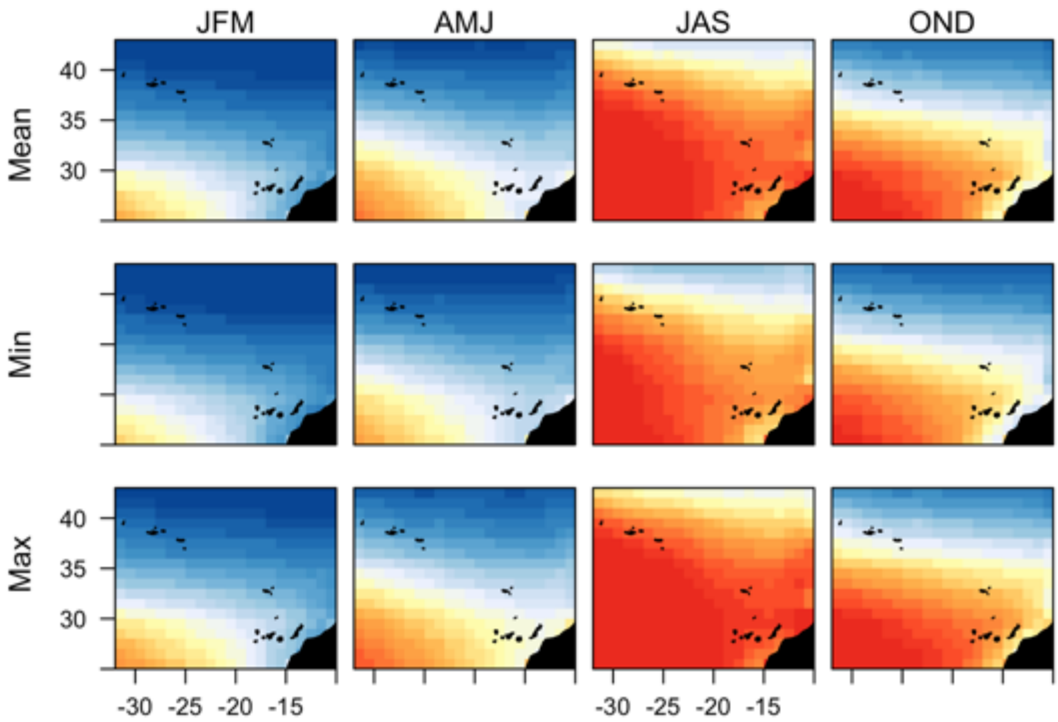


Figure I-8 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Bryde's whale under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Bryde's whale RCP 8.5

Historical (1956-2005)



Future (2006-2055)

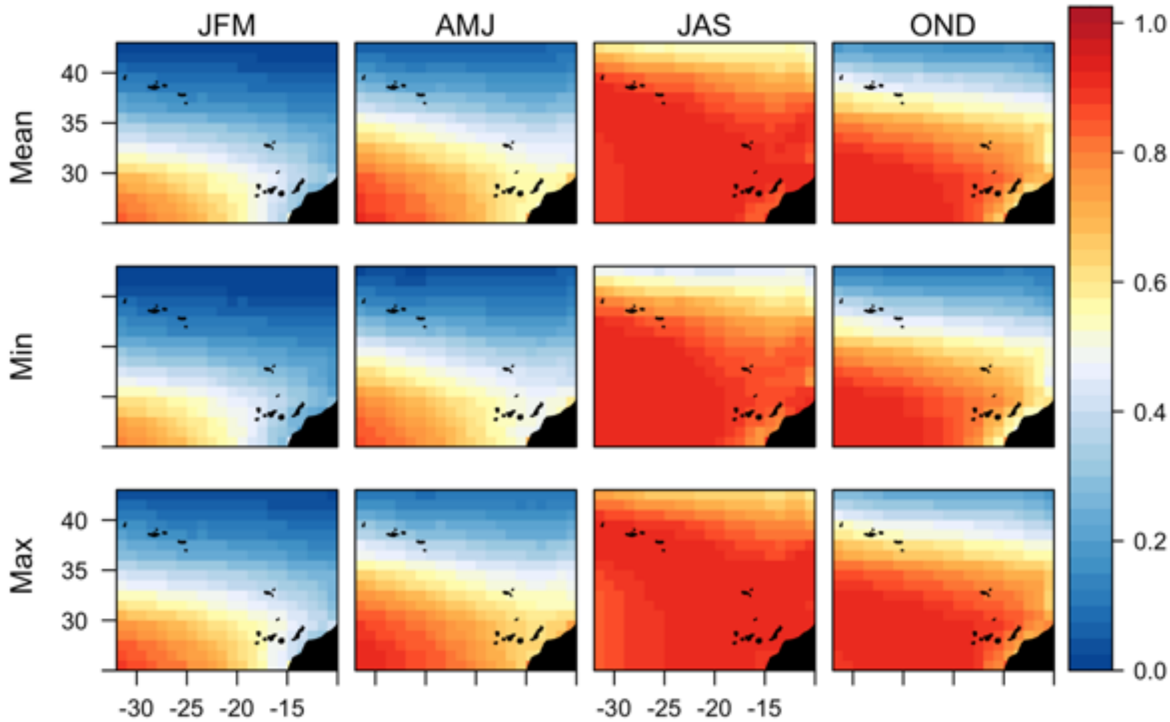


Figure I-9 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Bryde's whale under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

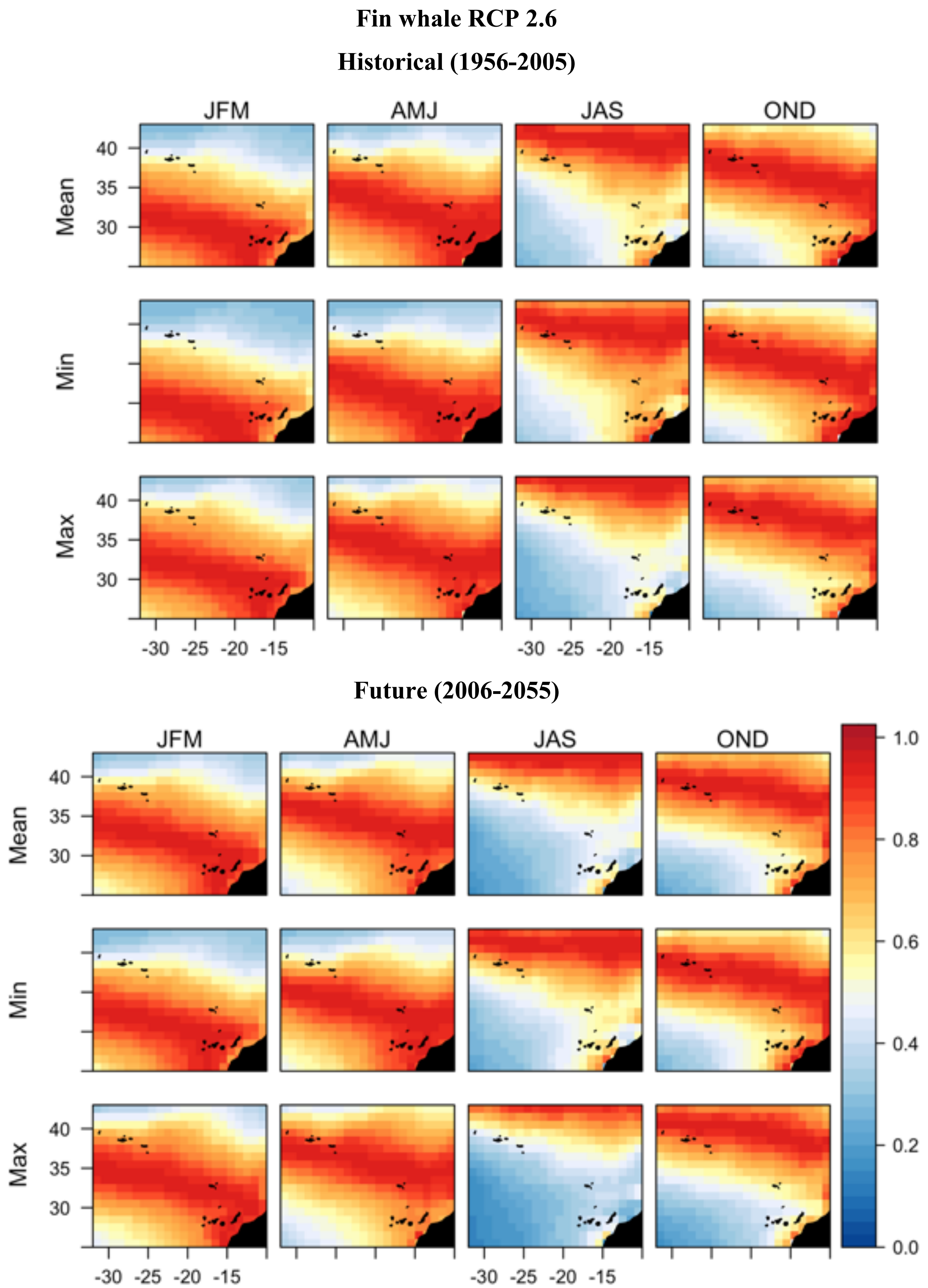
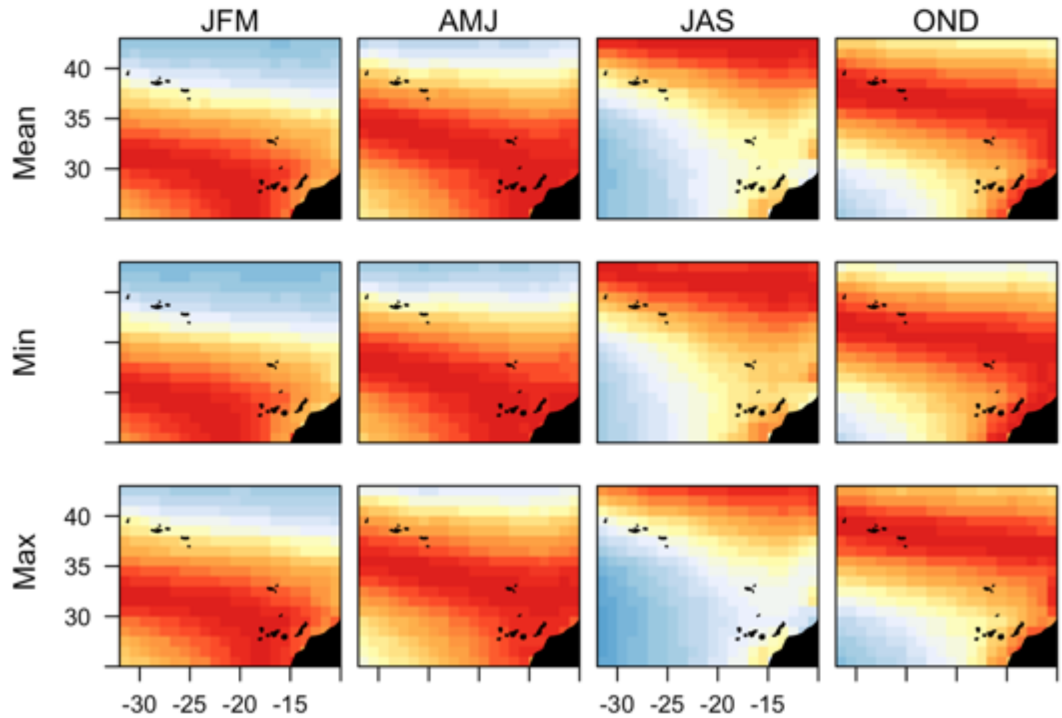


Figure I-10 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the fin whale under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal

suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Fin whale RCP 4.5

Historical (1956-2005)



Future (2006-2055)

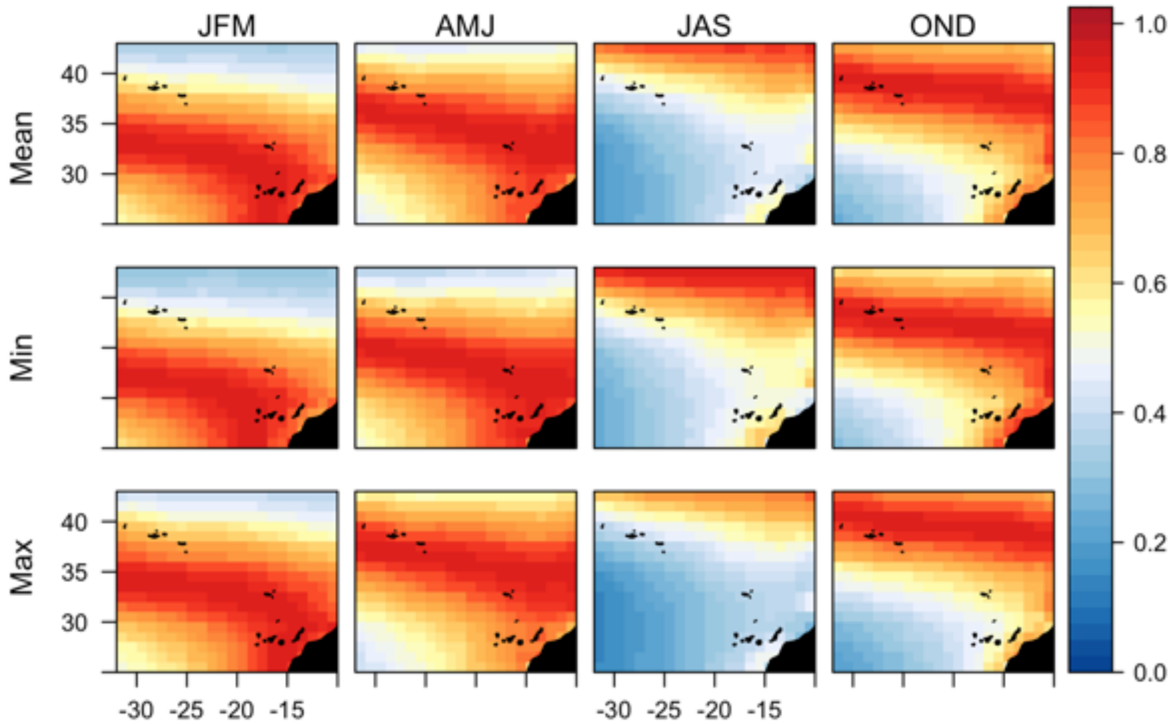
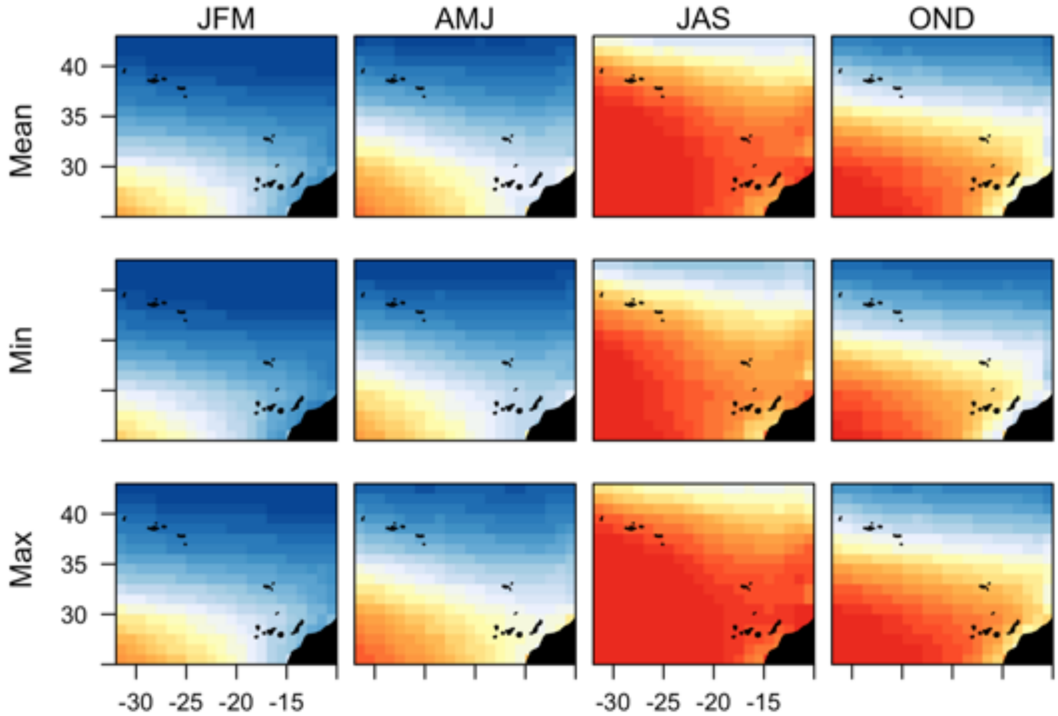


Figure I-11 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the fin whale under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Fin whale RCP 8.5

Historical (1956-2005)



Future (2006-2055)

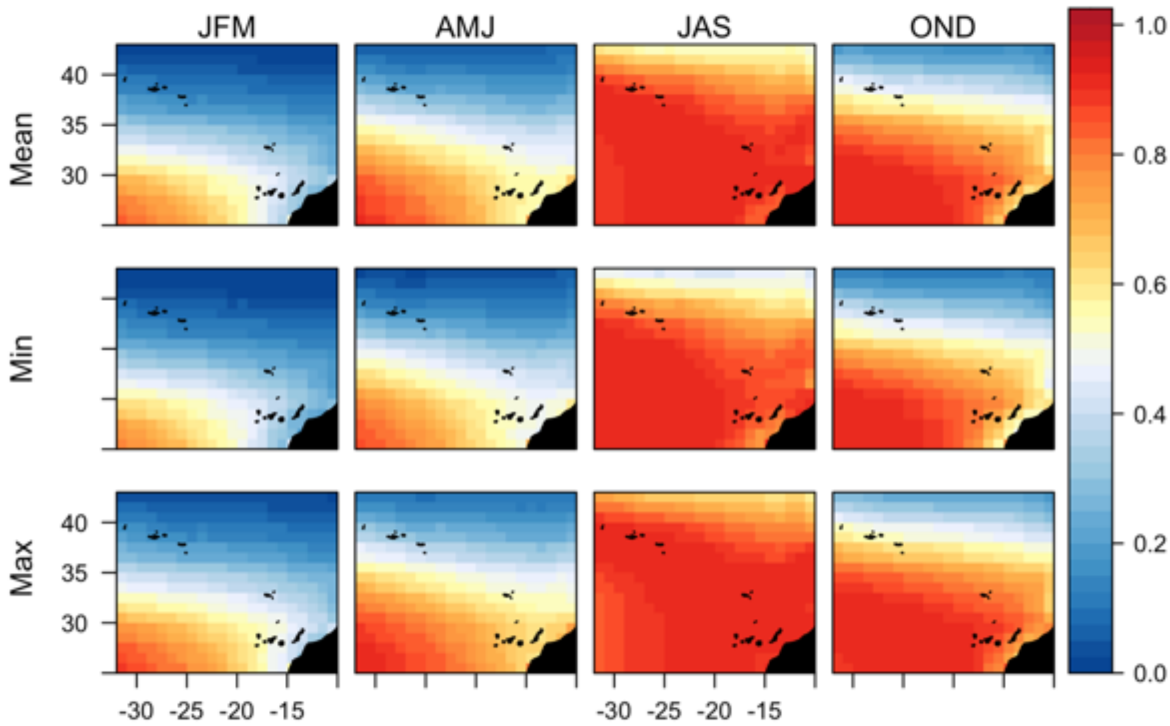


Figure I-12 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the fin whale under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

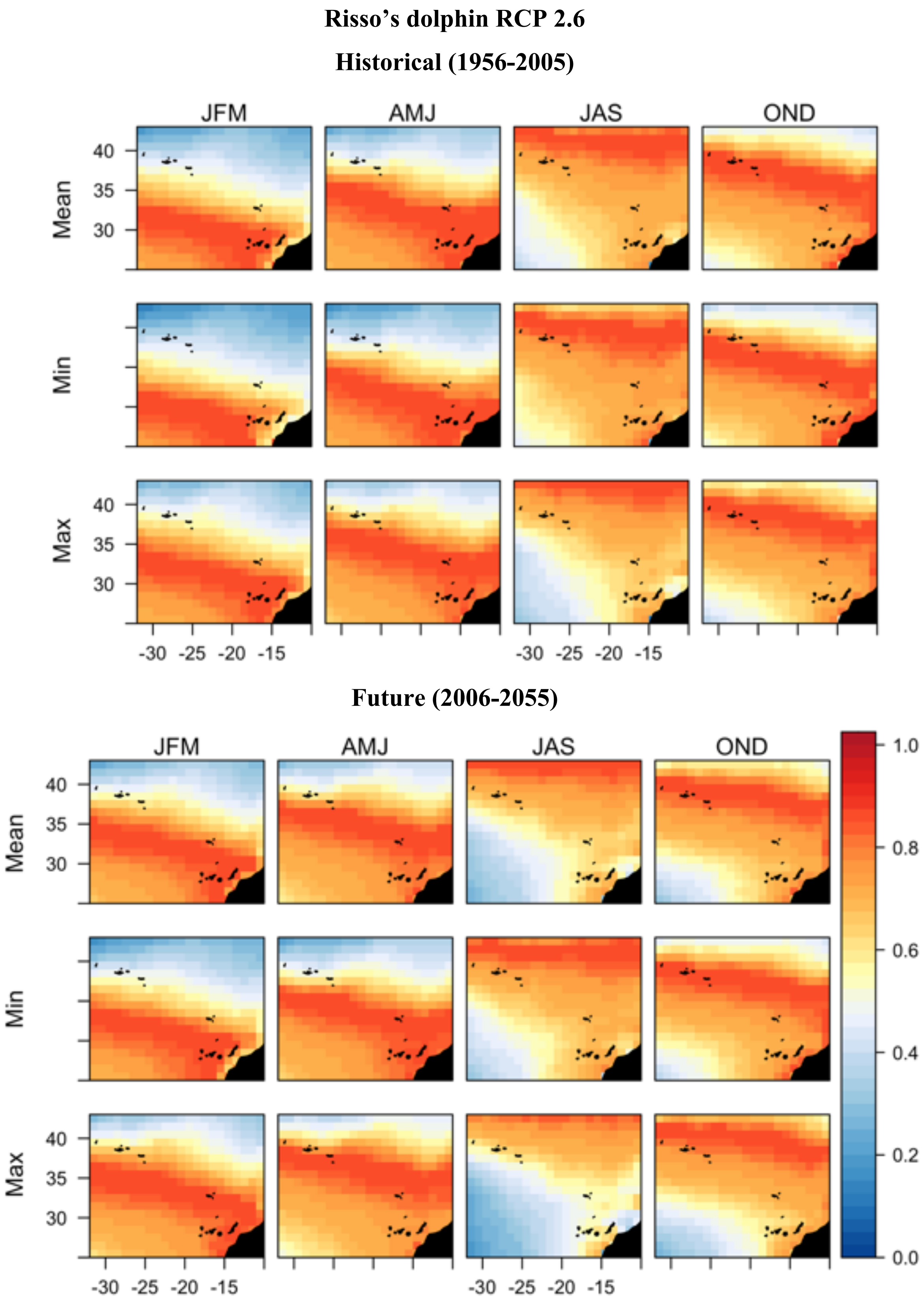


Figure I-13 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Risso's dolphin under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal

suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Risso's dolphin RCP 4.5

Historical (1956-2005)

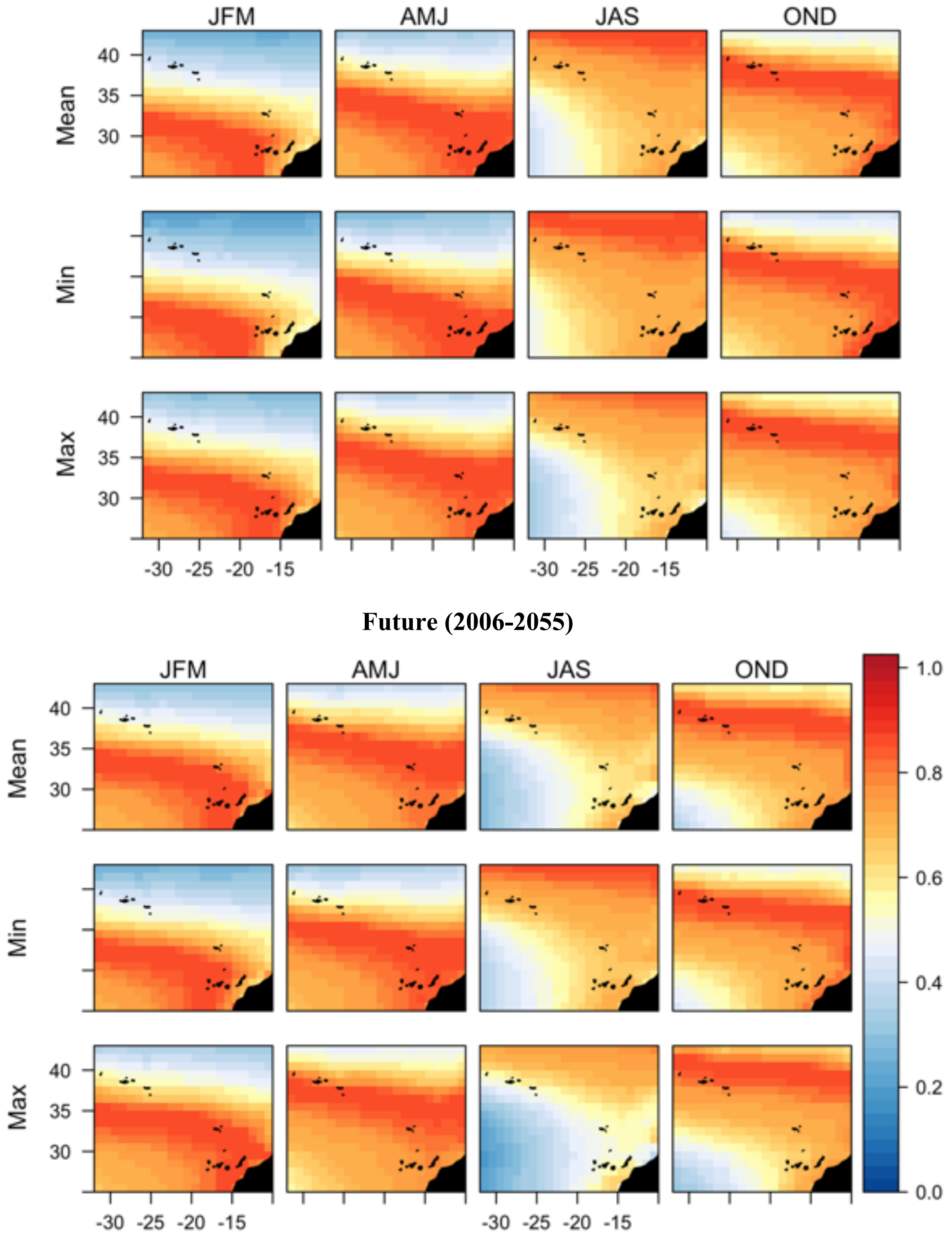
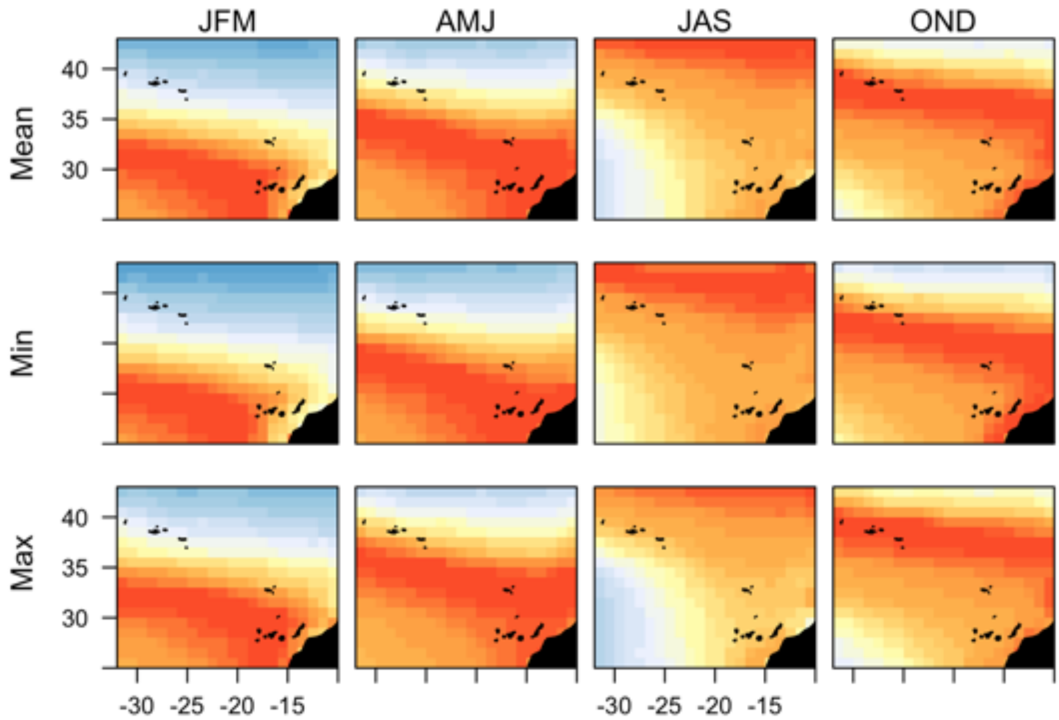


Figure I-14 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Risso's dolphin under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Risso's dolphin RCP 8.5

Historical (1956-2005)



Future (2006-2055)

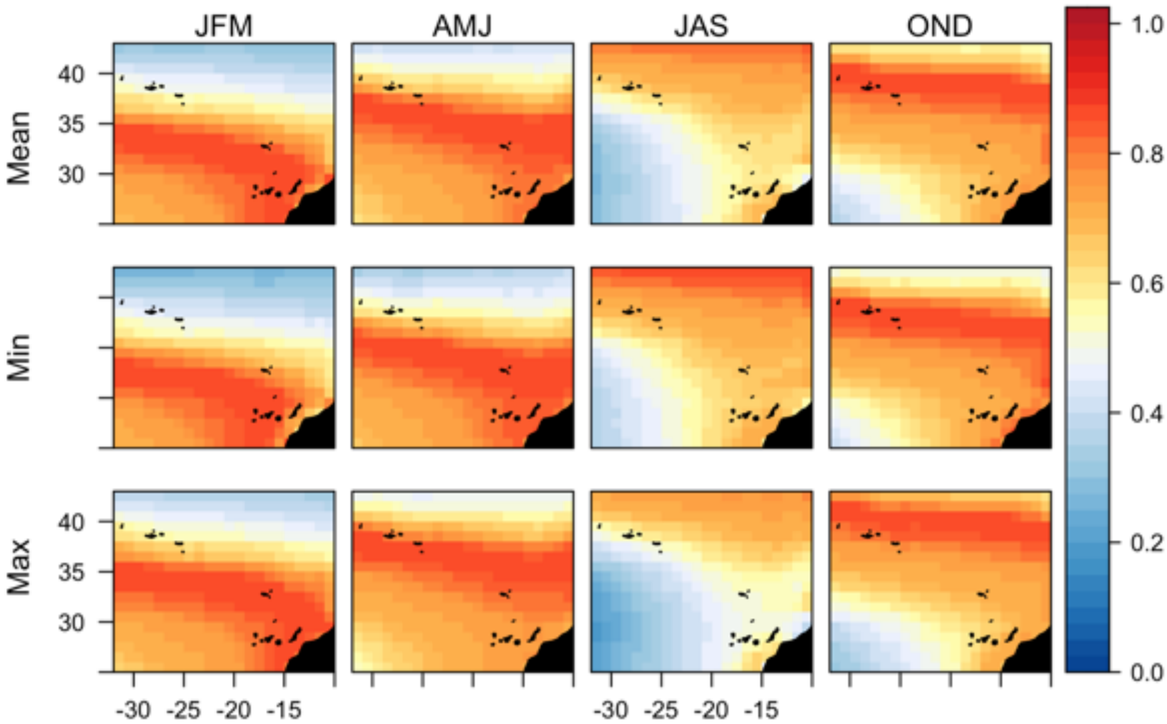
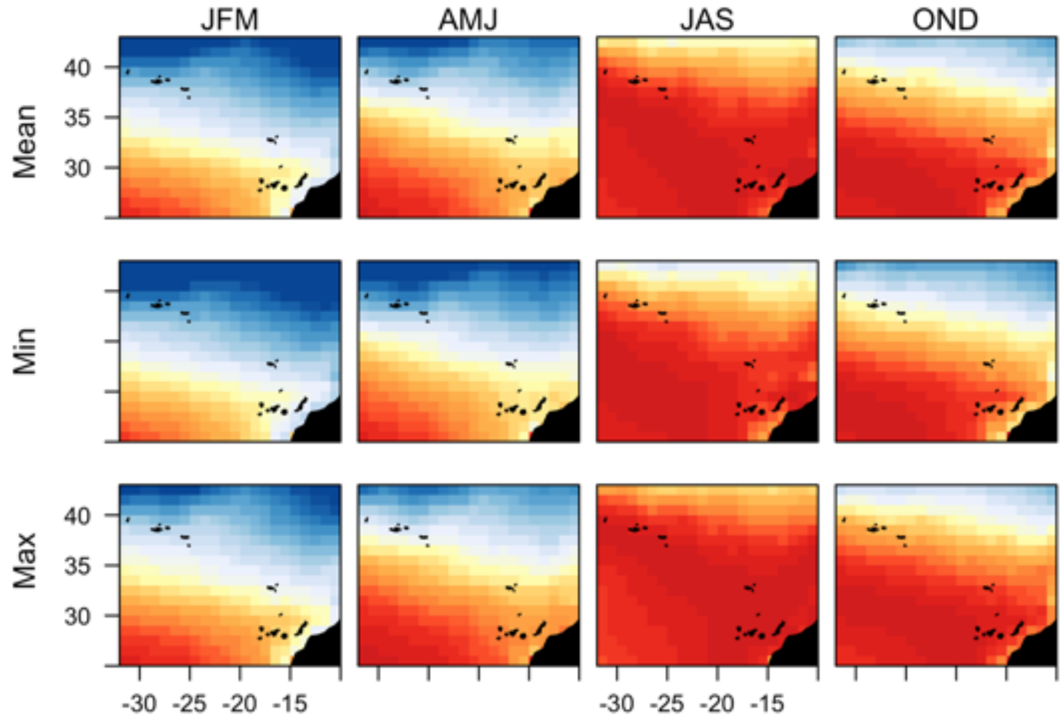


Figure I-15- Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Risso's dolphin under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Short-finned pilot whale RCP 2.6

Historical (1956-2005)



Future (2006-2055)

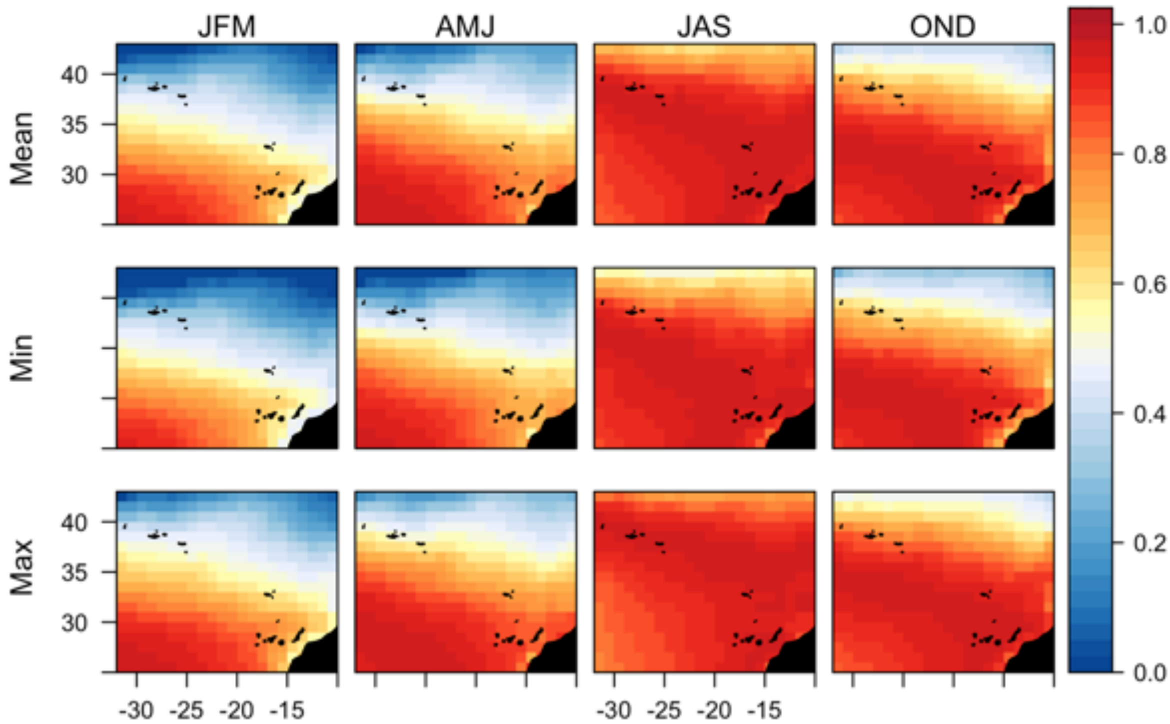
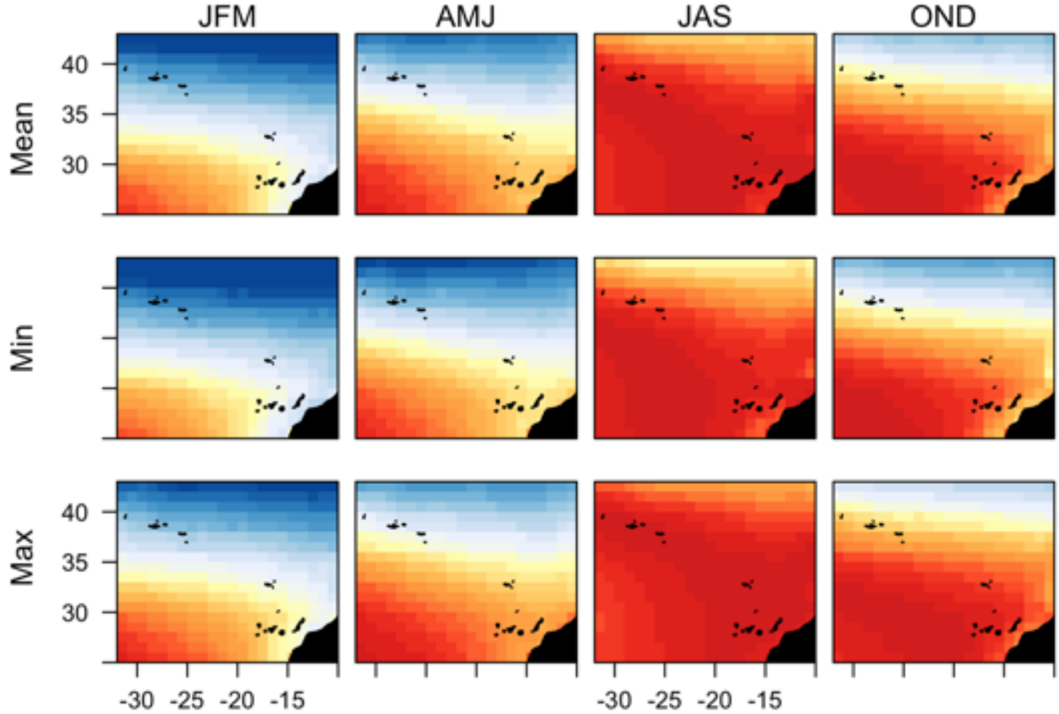


Figure I-16 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the short-finned pilot whale under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively.

The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Short-finned pilot whale RCP 4.5

Historical (1956-2005)



Future (2006-2055)

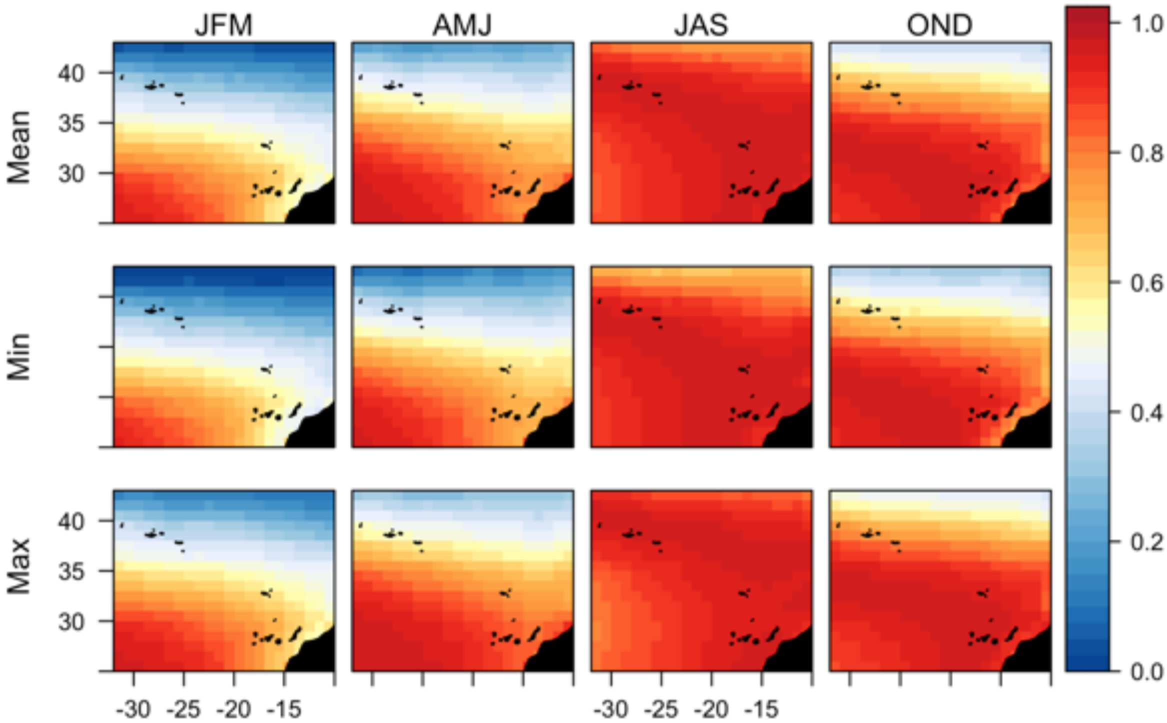
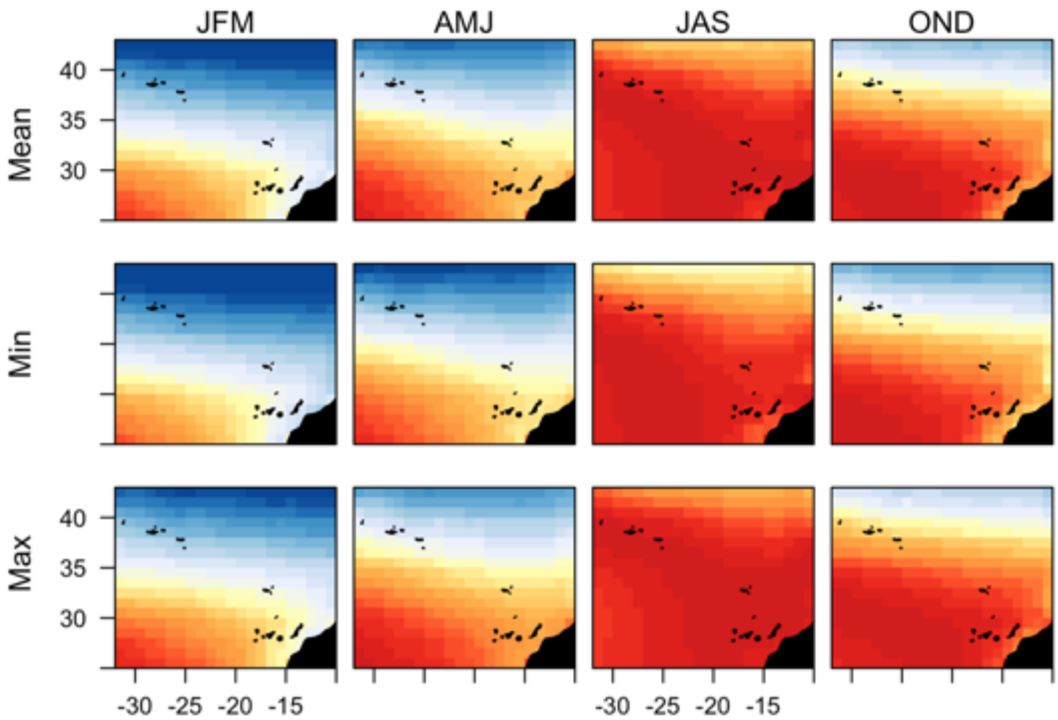


Figure I-17 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the short-finned pilot whale under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Short-finned pilot whale RCP 8.5

Historical (1956-2005)



Future (2006-2055)

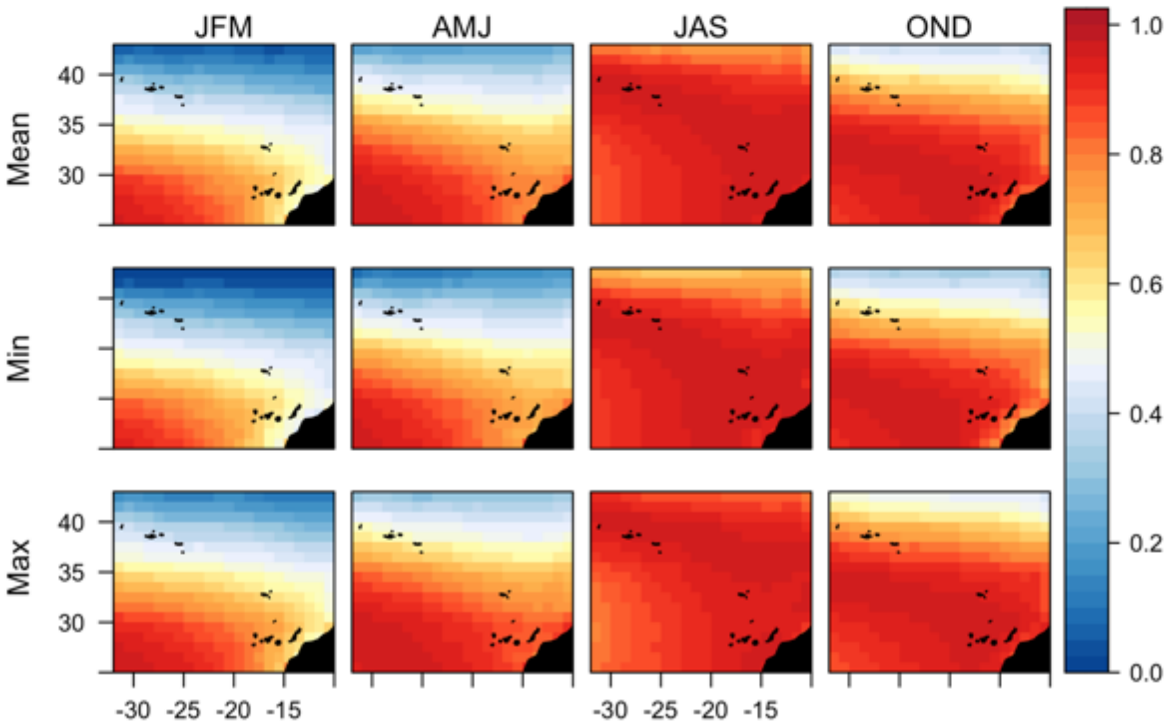


Figure I-18 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the short-finned pilot whale under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

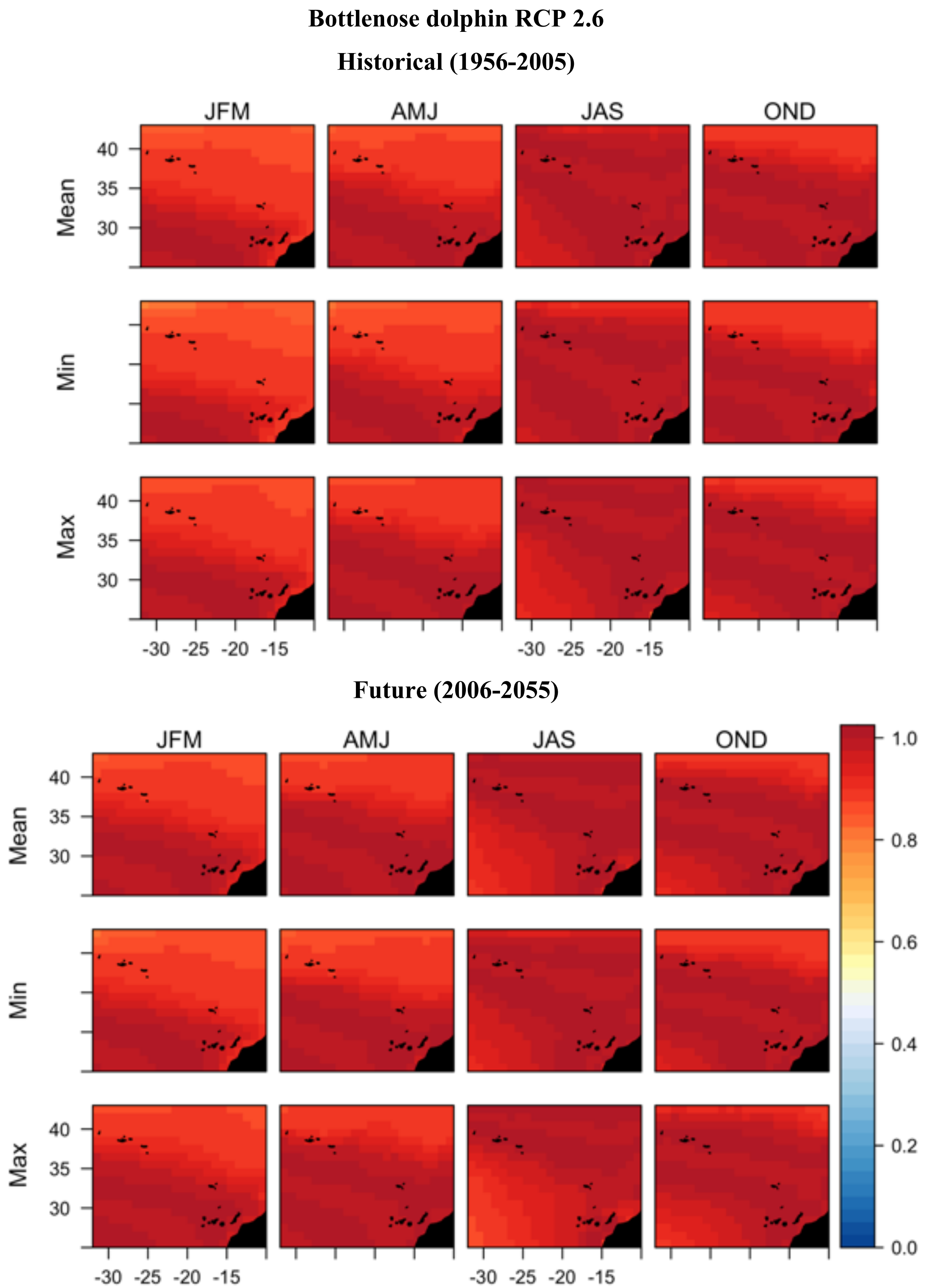


Figure I-19 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the bottlenose dolphin under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

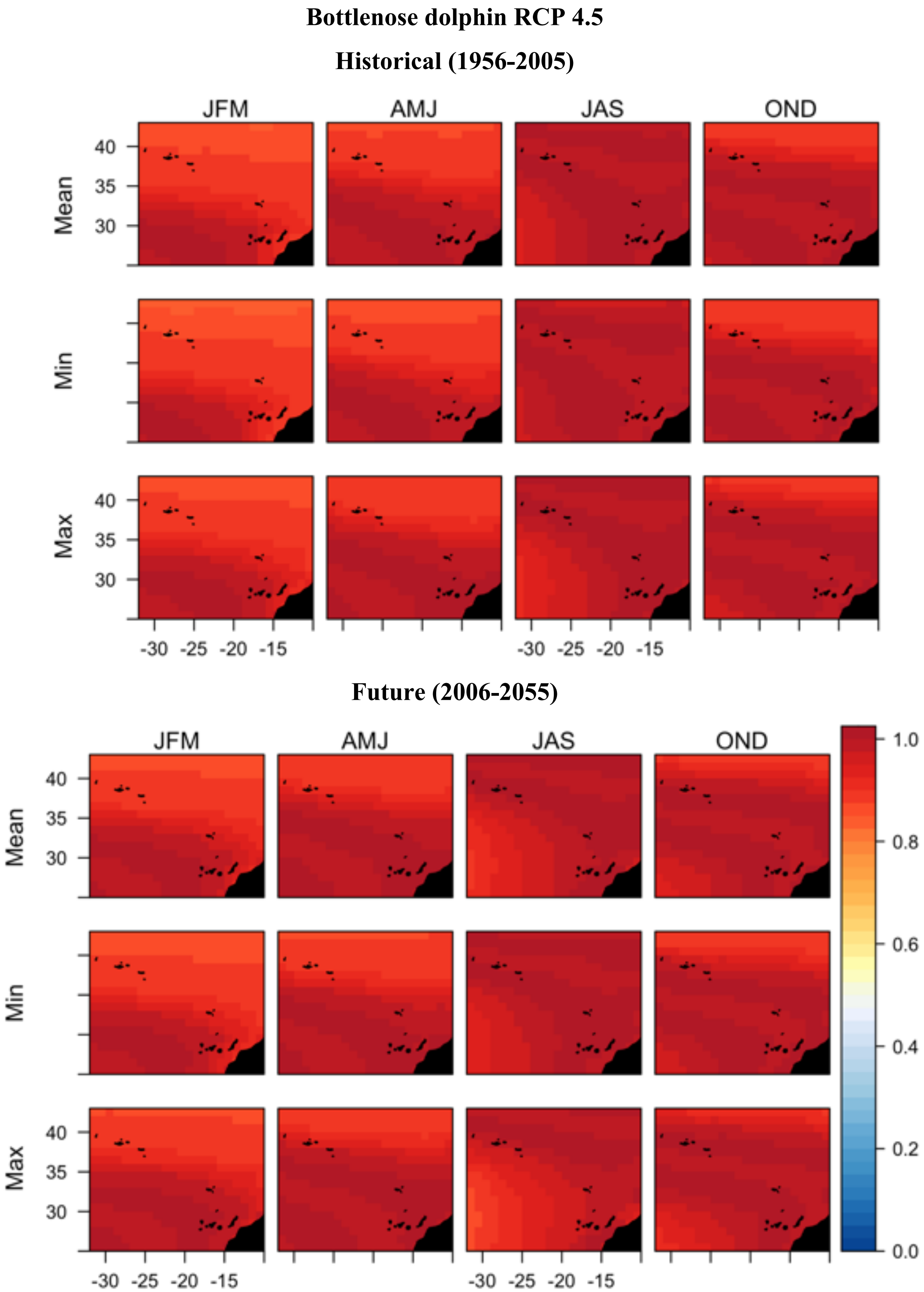
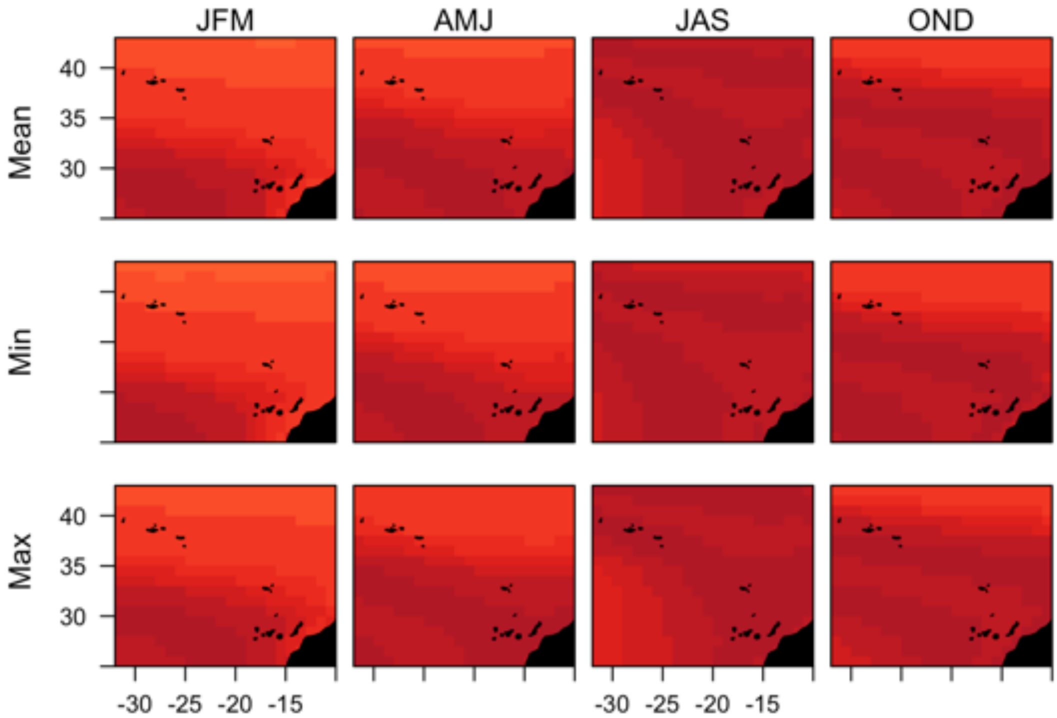


Figure I-20 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the bottlenose dolphin under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Bottlenose dolphin RCP 8.5

Historical (1956-2005)



Future (2006-2055)

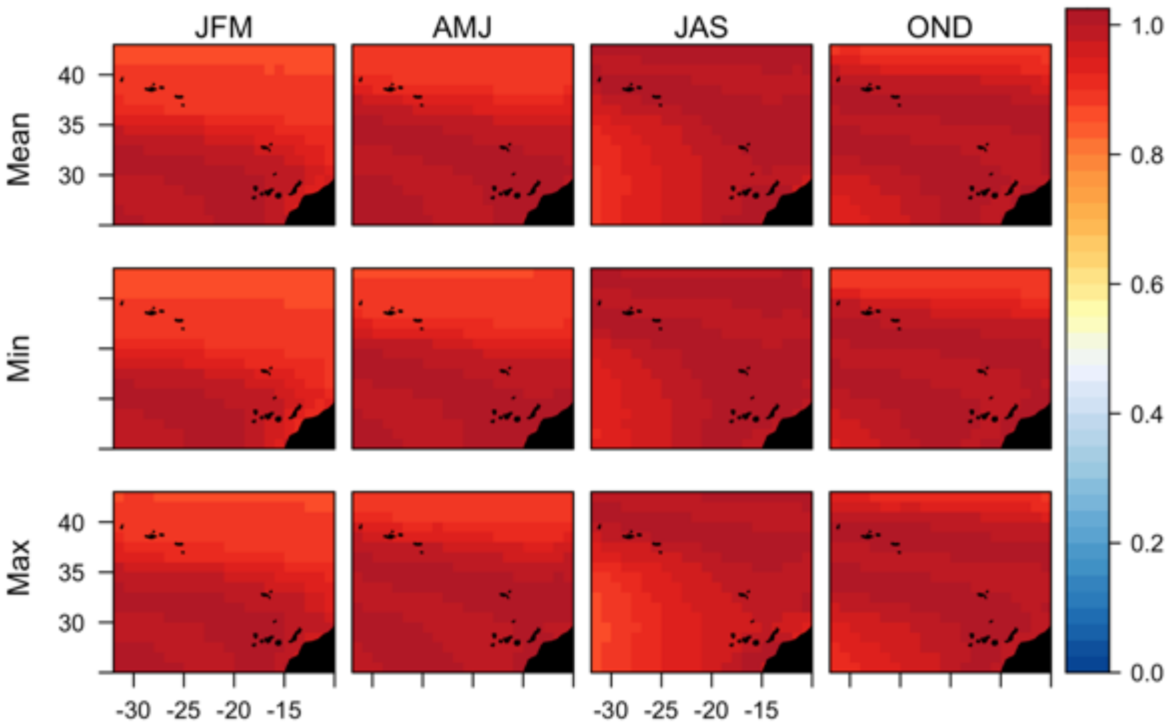
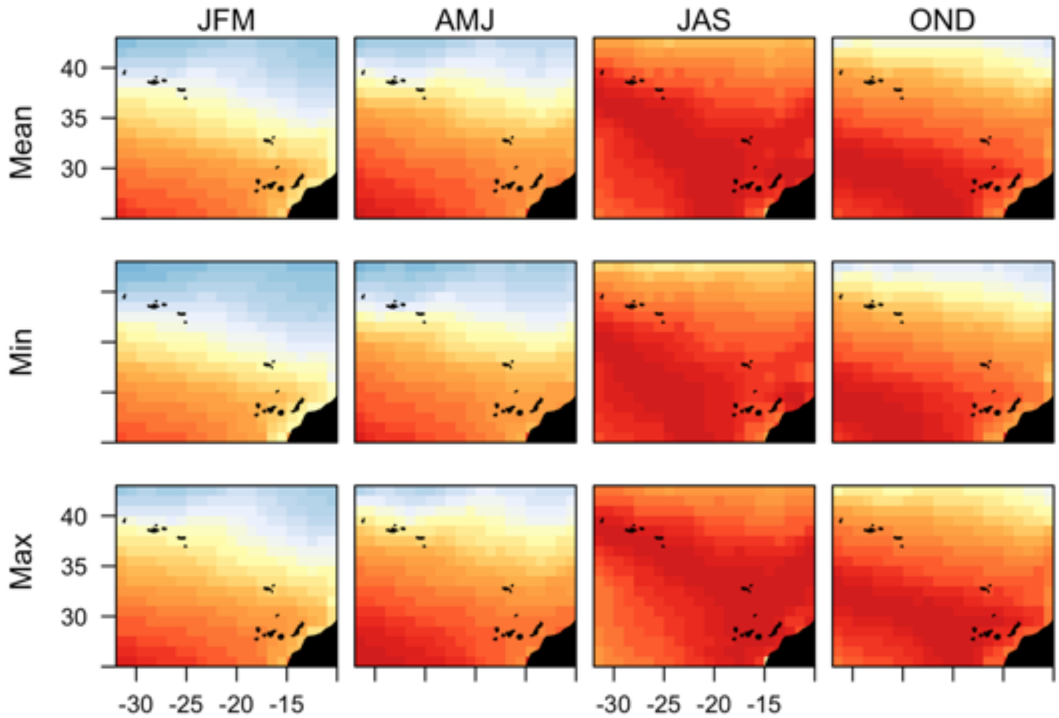


Figure I-21 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the bottlenose dolphin under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Sperm whale RCP 2.6

Historical (1956-2005)



Future (2006-2055)

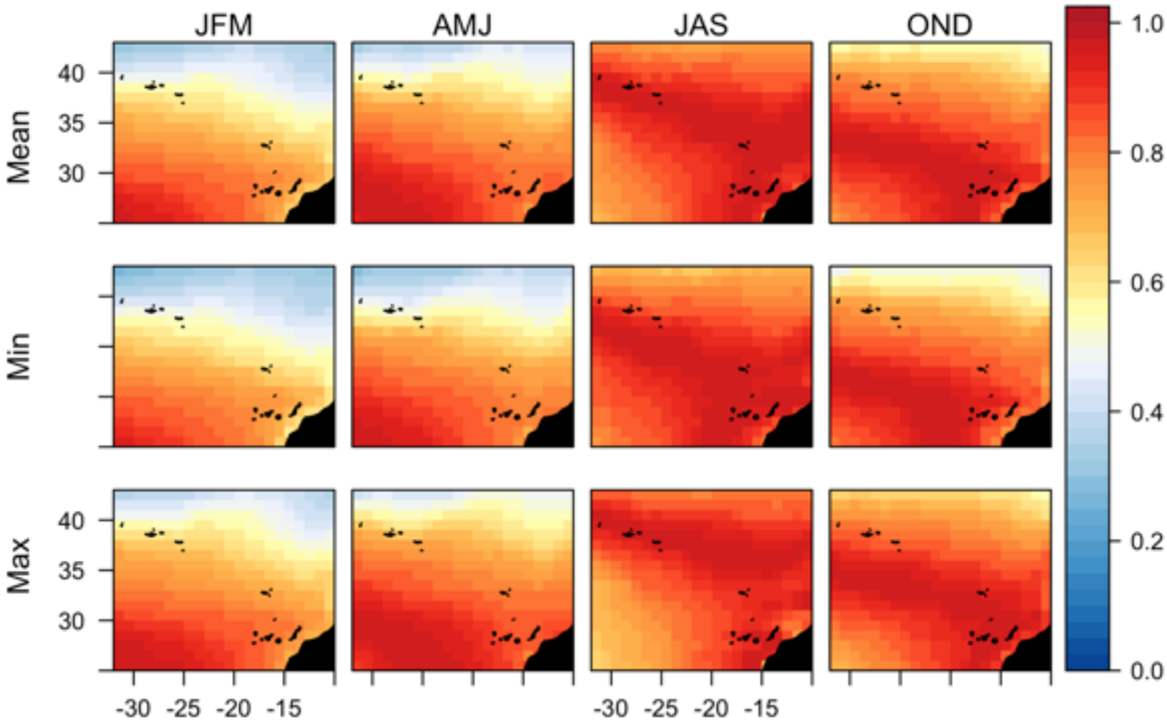


Figure I-22 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the sperm whale under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

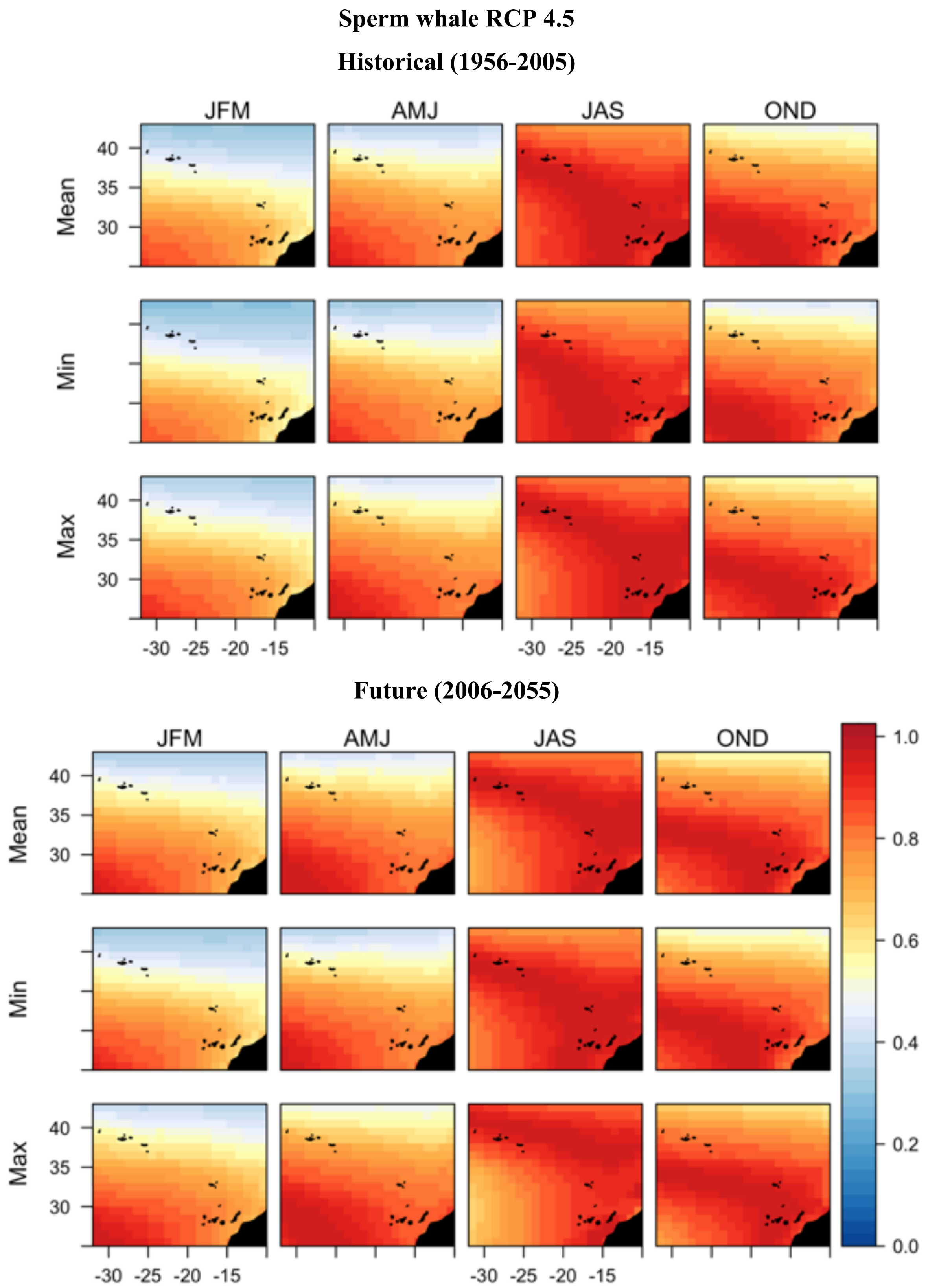
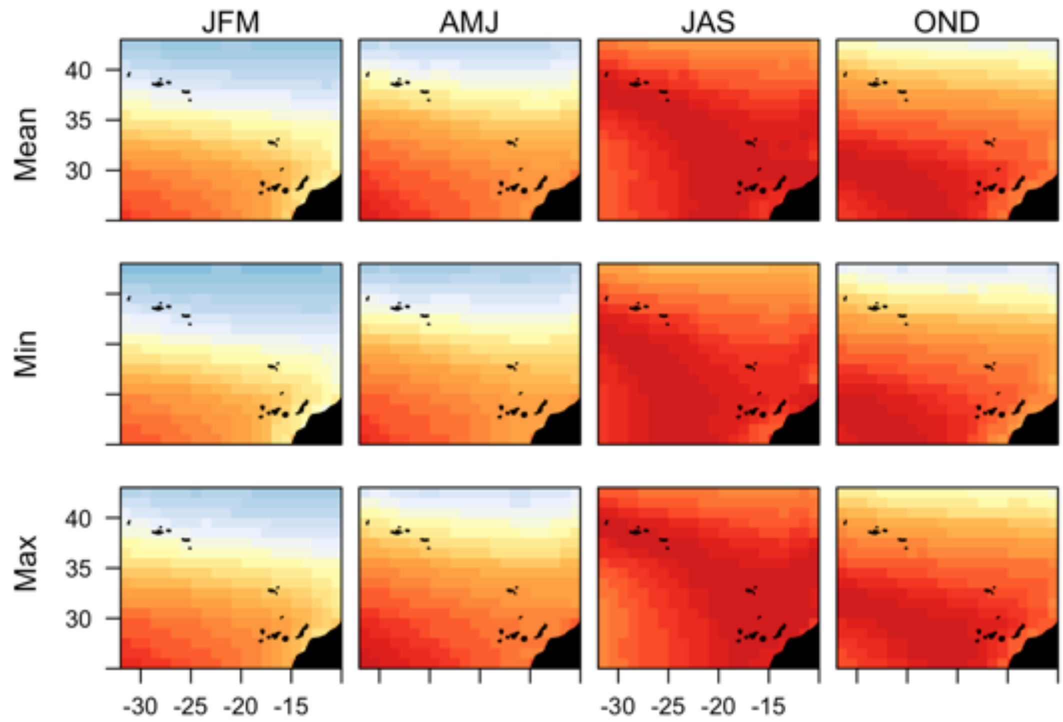


Figure I-23 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the sperm whale under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal

suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Sperm whale RCP 8.5

Historical (1956-2005)



Future (2006-2055)

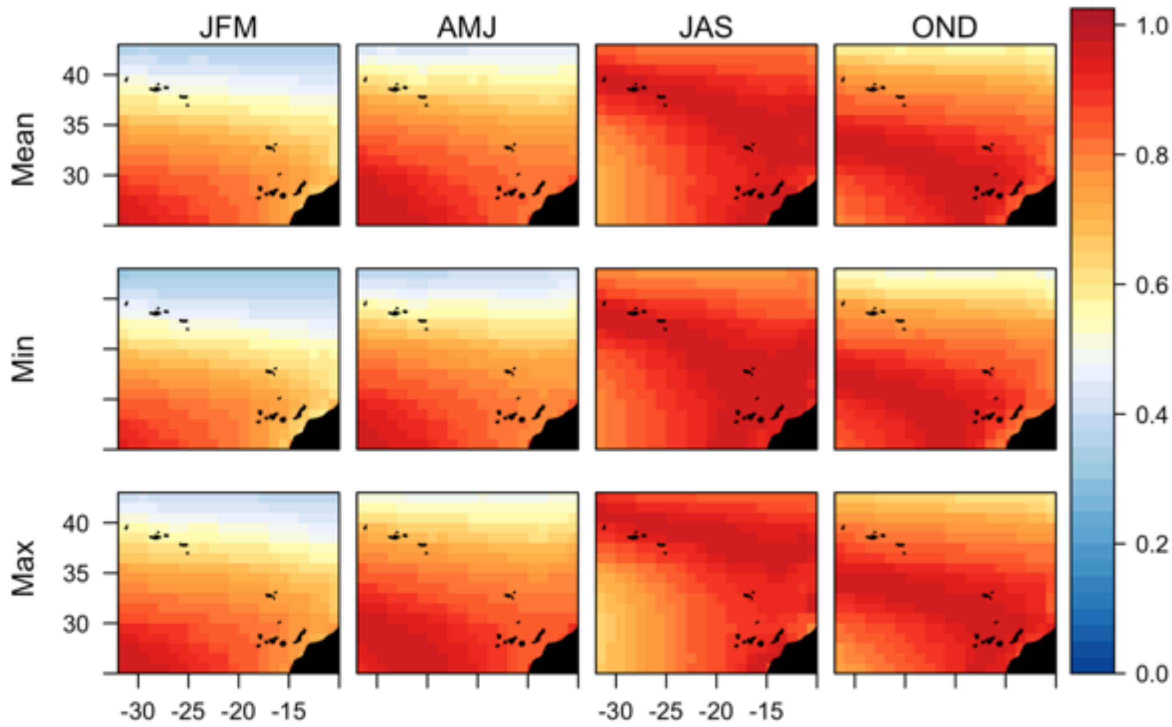
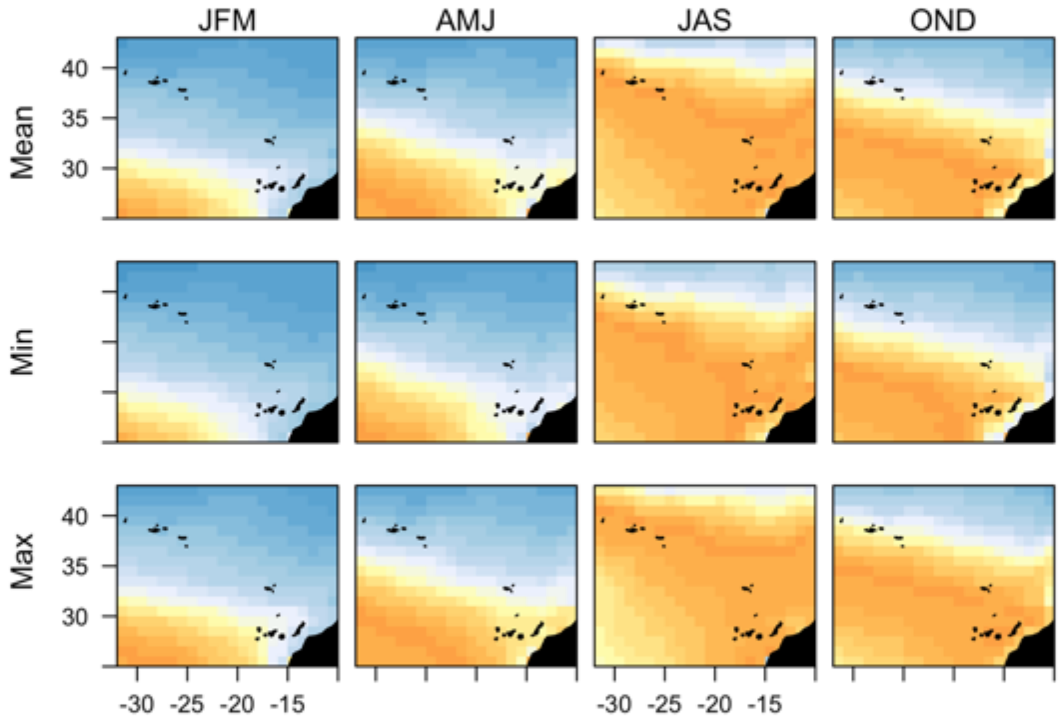


Figure I-24 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the sperm whale under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Blainville's beaked whale RCP 2.6

Historical (1956-2005)



Future (2006-2055)

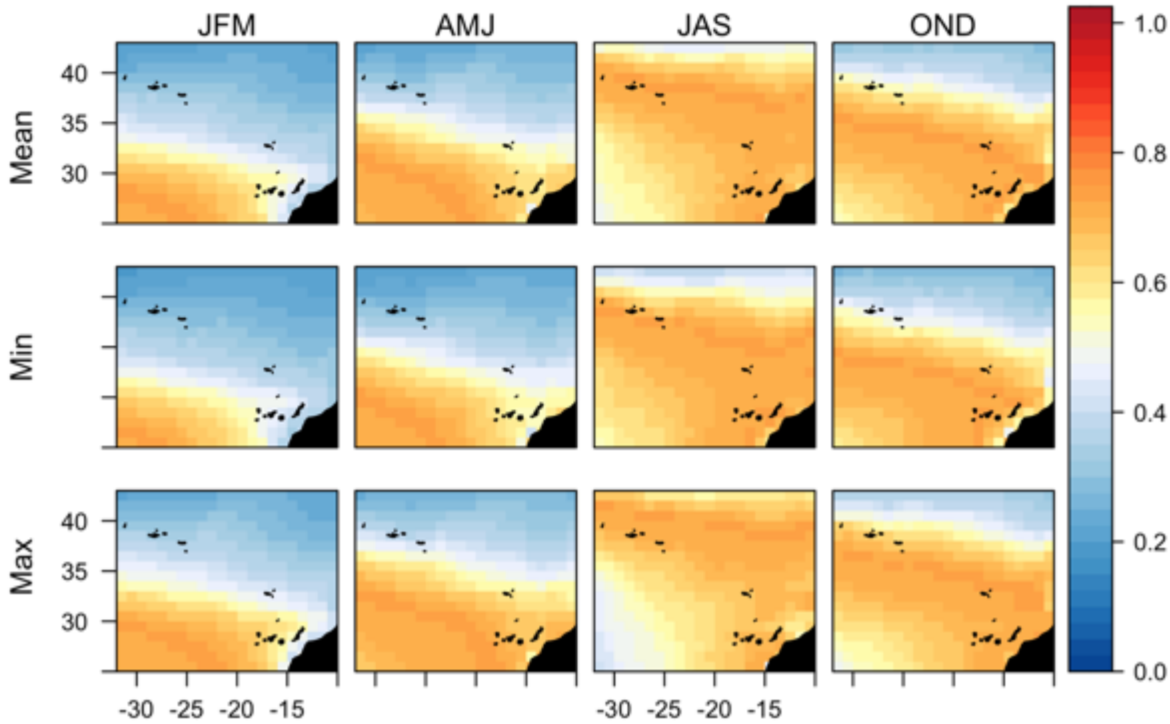


Figure I-25 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Blainville's beaked whale under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

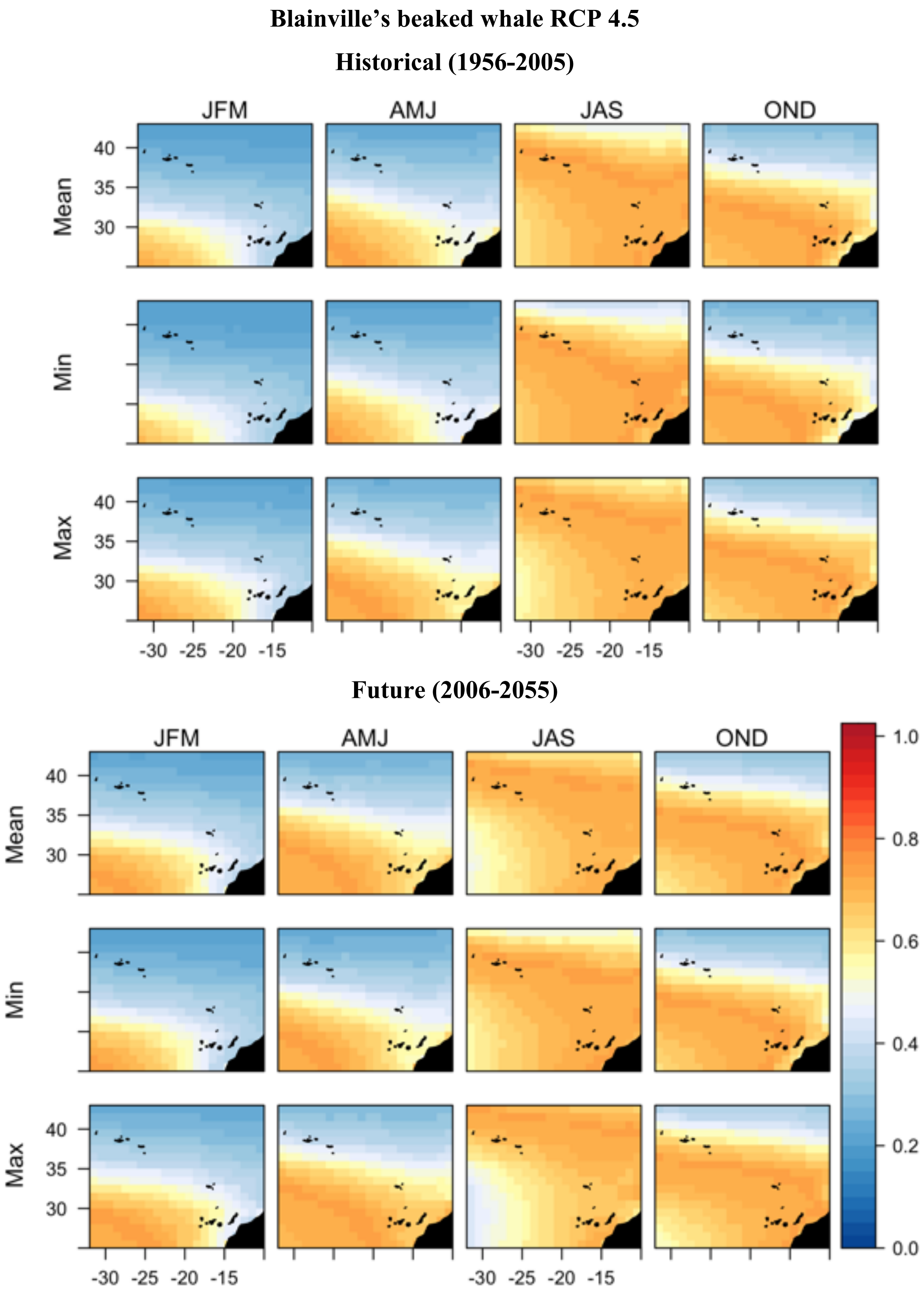
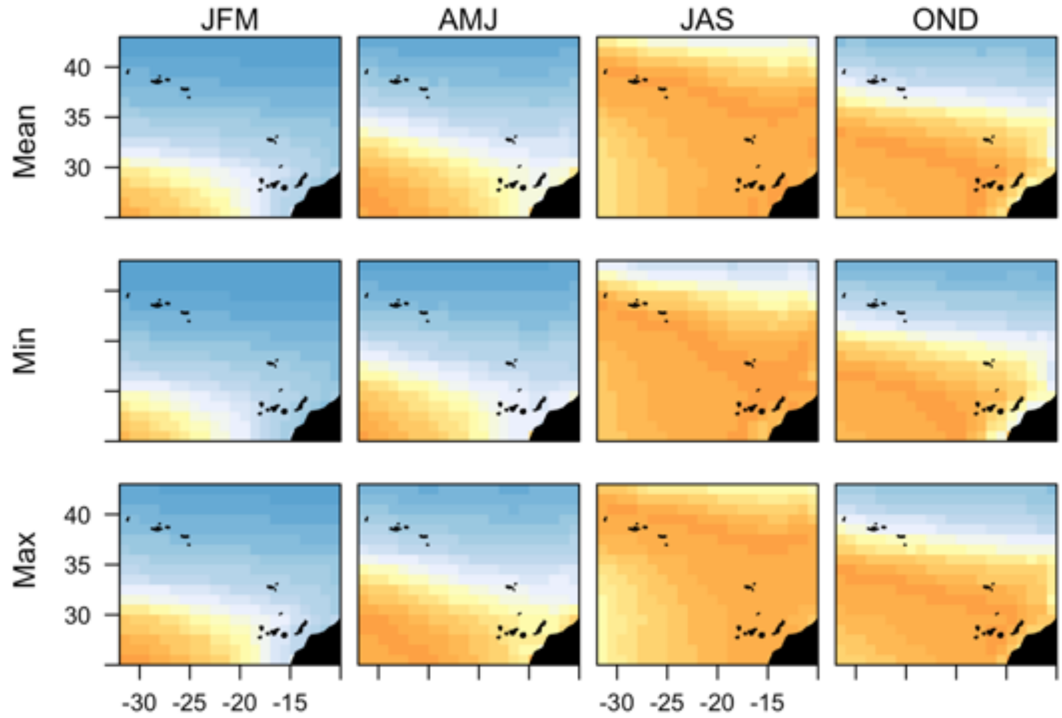


Figure I-26 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Blainville's beaked whale under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively.

The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Blainville's beaked whale RCP 8.5

Historical (1956-2005)



Future (2006-2055)

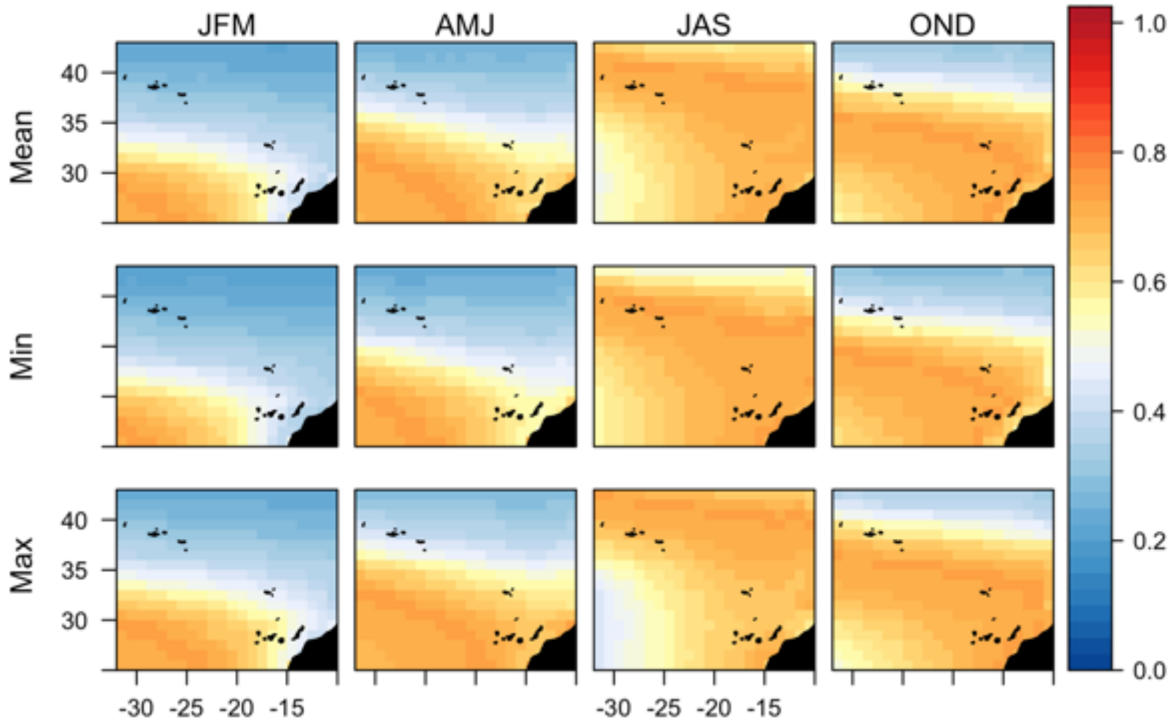
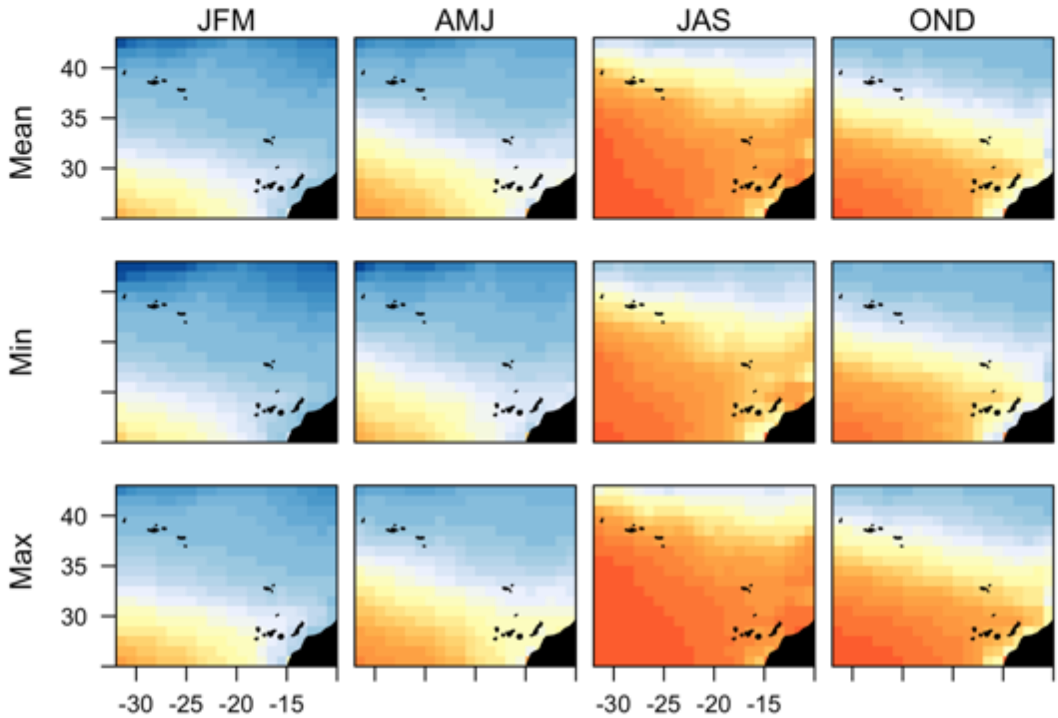


Figure I-27 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Blainville's beaked whale under RCP 8.5.

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).

Cuvier's beaked whale RCP 2.6

Historical (1956-2005)



Future (2006-2055)

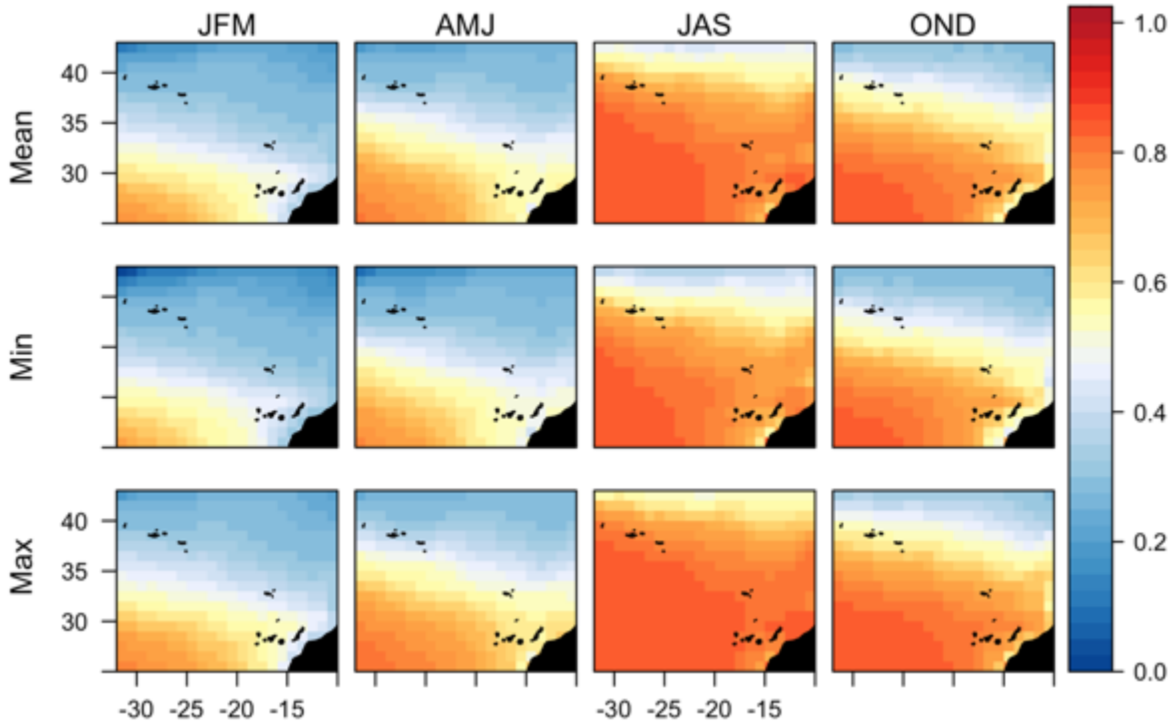


Figure I-28 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Cuvier's beaked whale under RCP 2.6. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

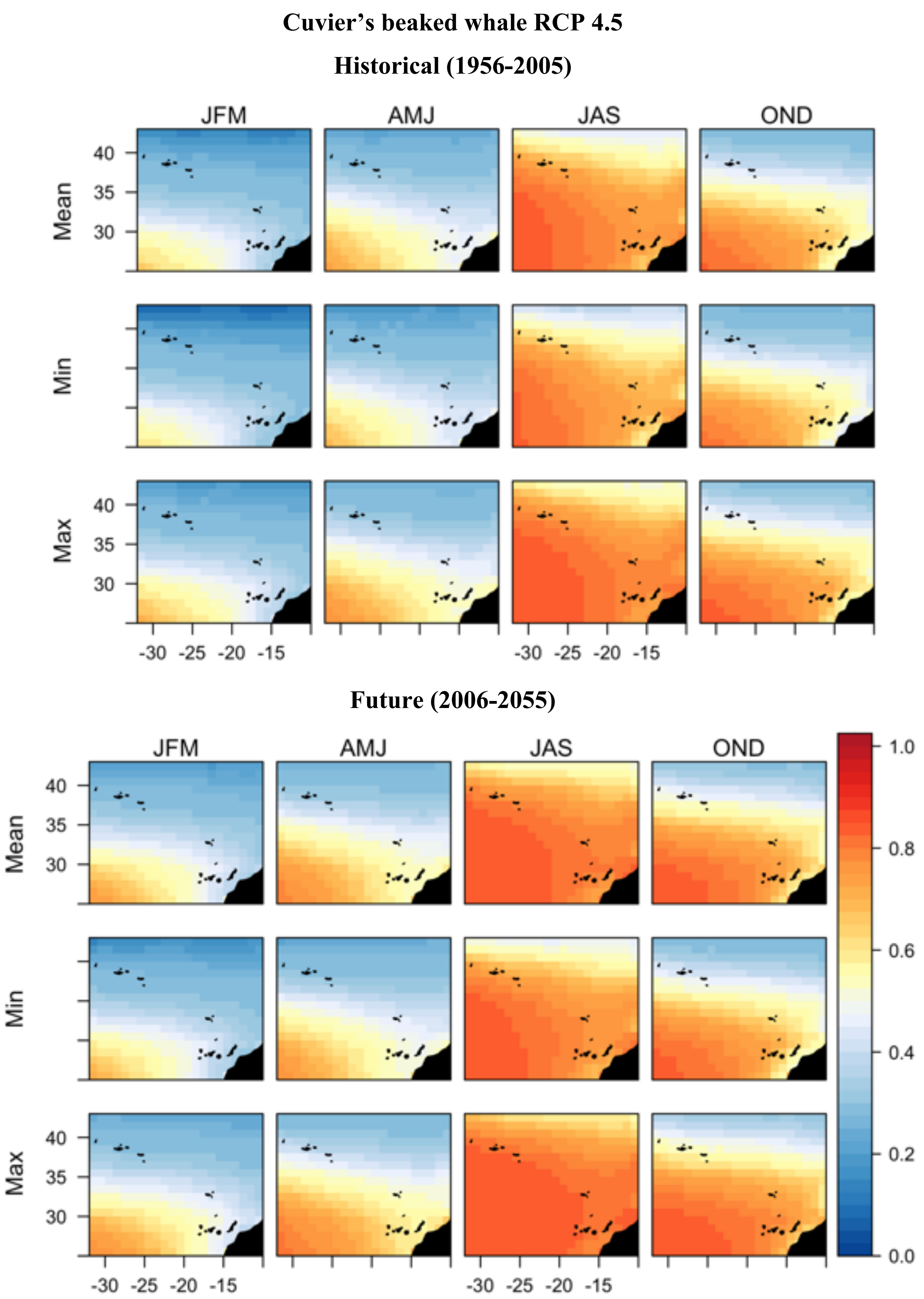
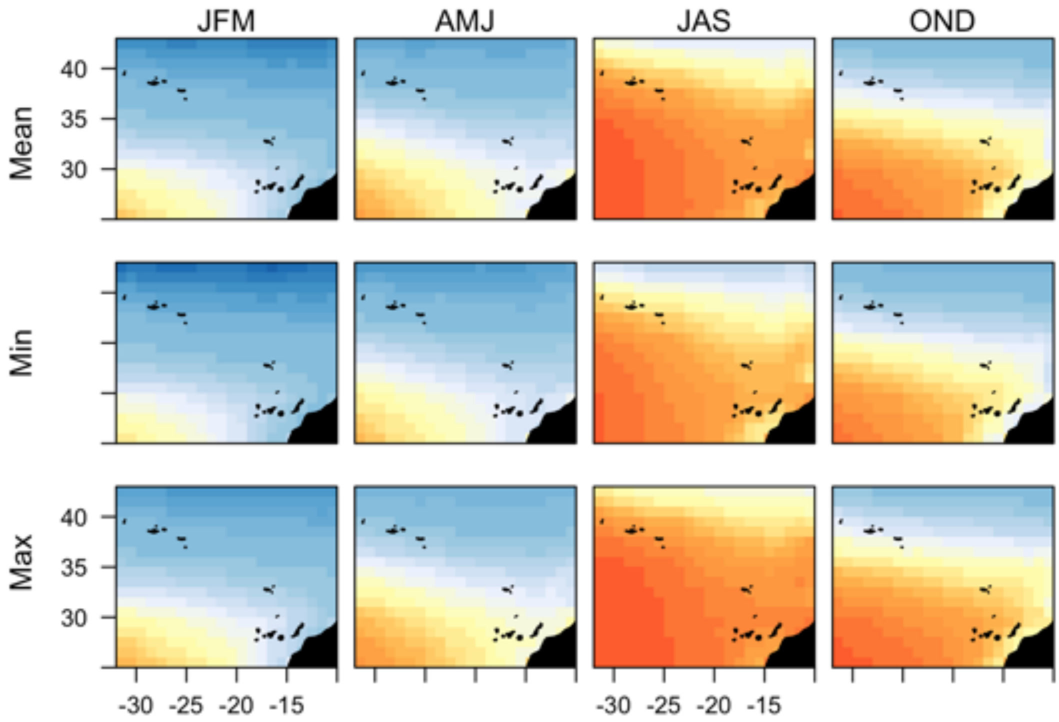


Figure I-29 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Cuvier's beaked whale under RCP 4.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Cuvier's beaked whale RCP 8.5

Historical (1956-2005)



Future (2006-2055)

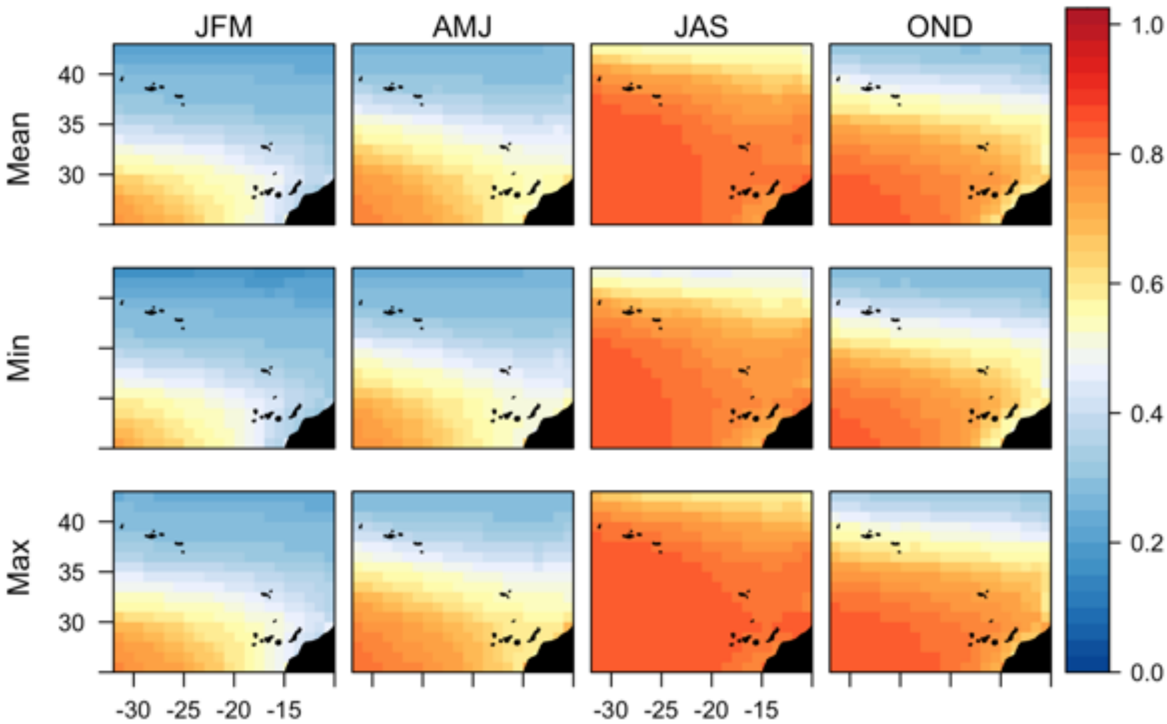
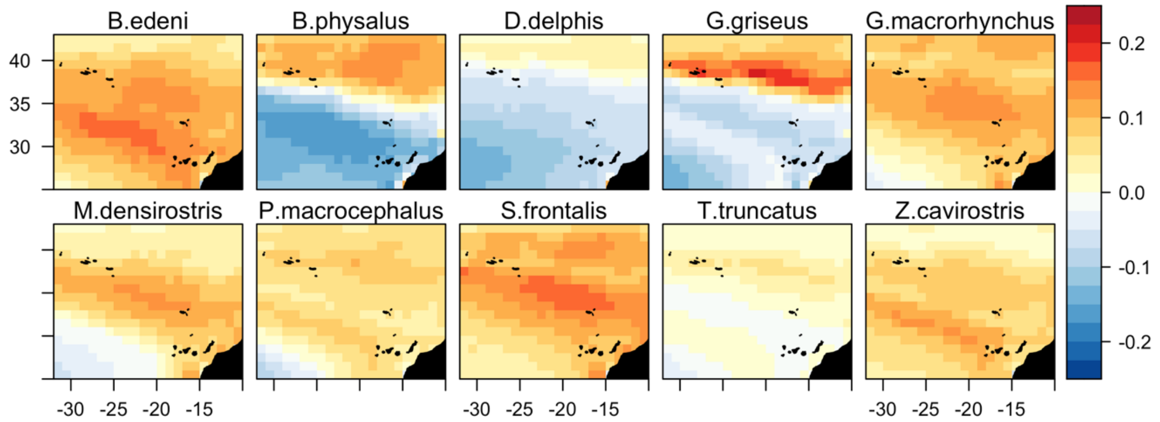


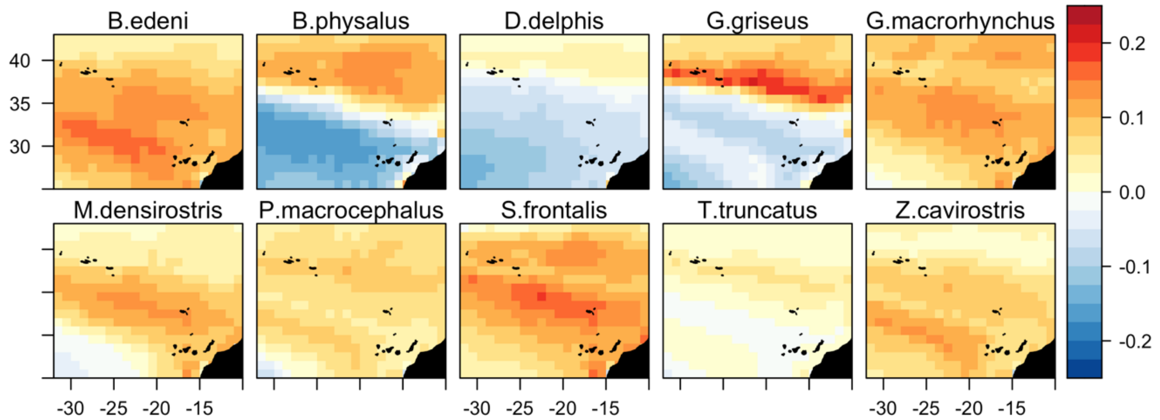
Figure I-30 - Seasonal historical (1956-2005) and future (2006-2055) thermal suitability maps (mean annual sea surface temperature) for the Cuvier's beaked whale under RCP 8.5. Numbers in the upper left and in the lower left map indicate latitude and longitude, respectively. The thermal suitability scale on the right-hand side represents the lowest (=0) and highest thermal suitability (=1).

Annex J. Thermal suitability differences

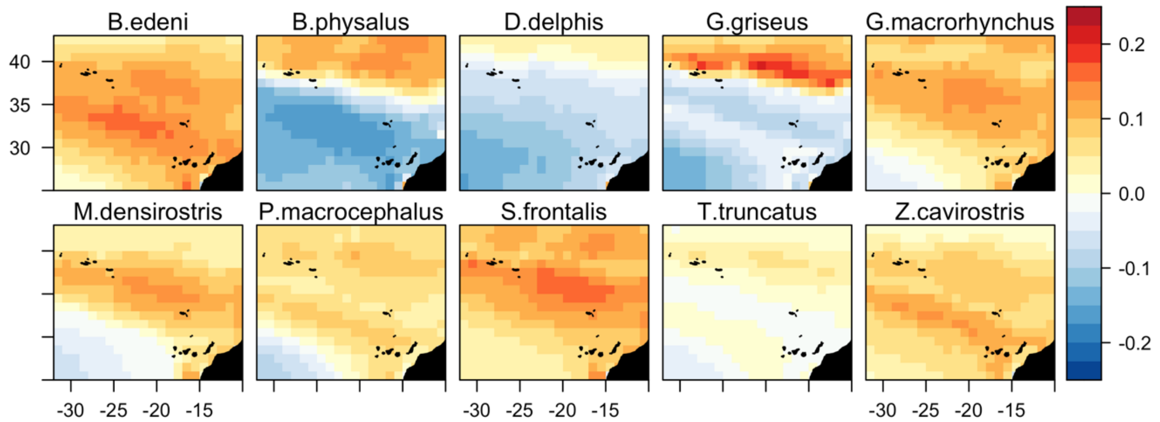
Mean thermal suitability differences scenario 2.6



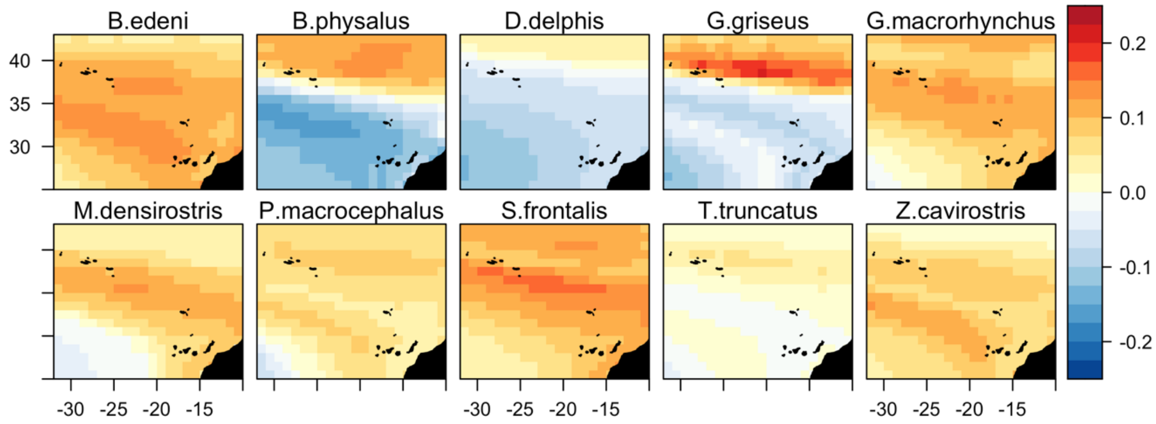
Minimum thermal suitability differences scenario 2.6



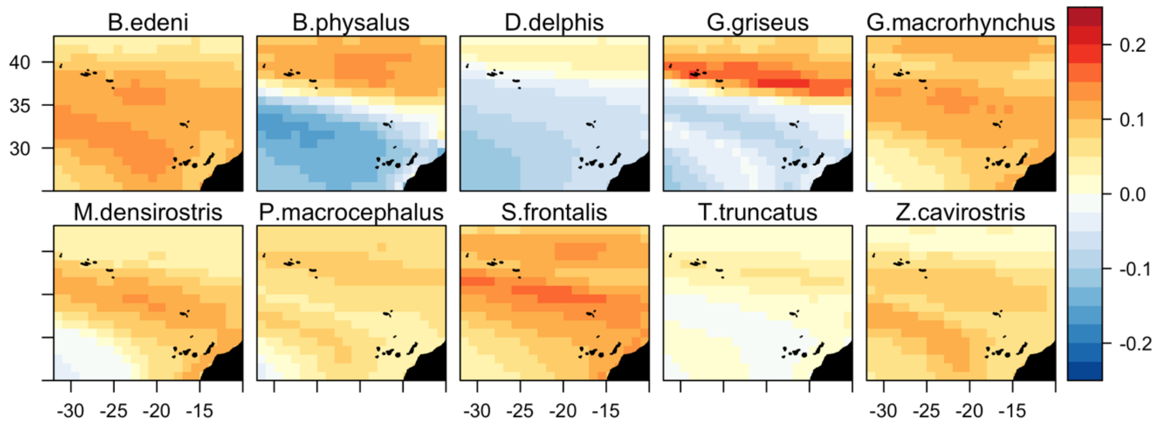
Maximum thermal suitability differences scenario 2.6



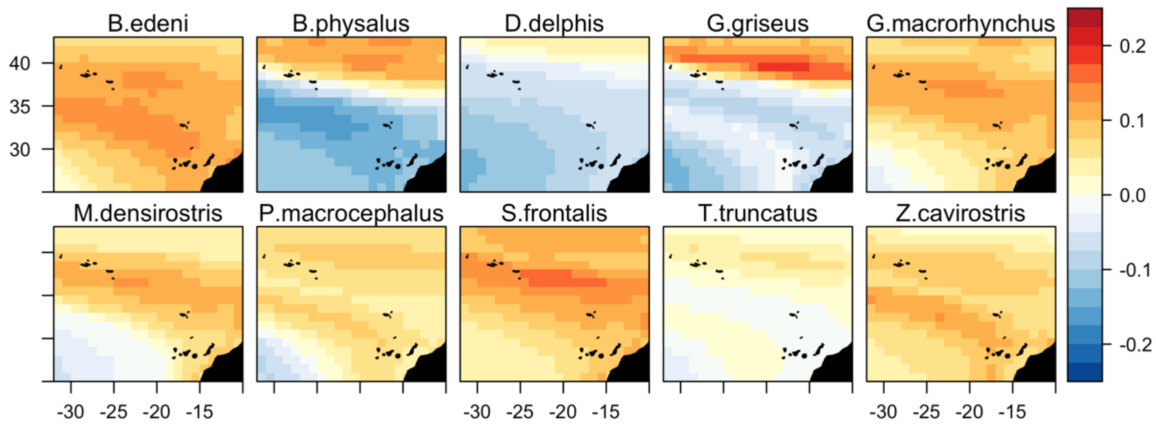
Mean thermal suitability differences scenario 4.5



Minimum thermal suitability differences scenario 4.5



Maximum thermal suitability differences scenario 4.5



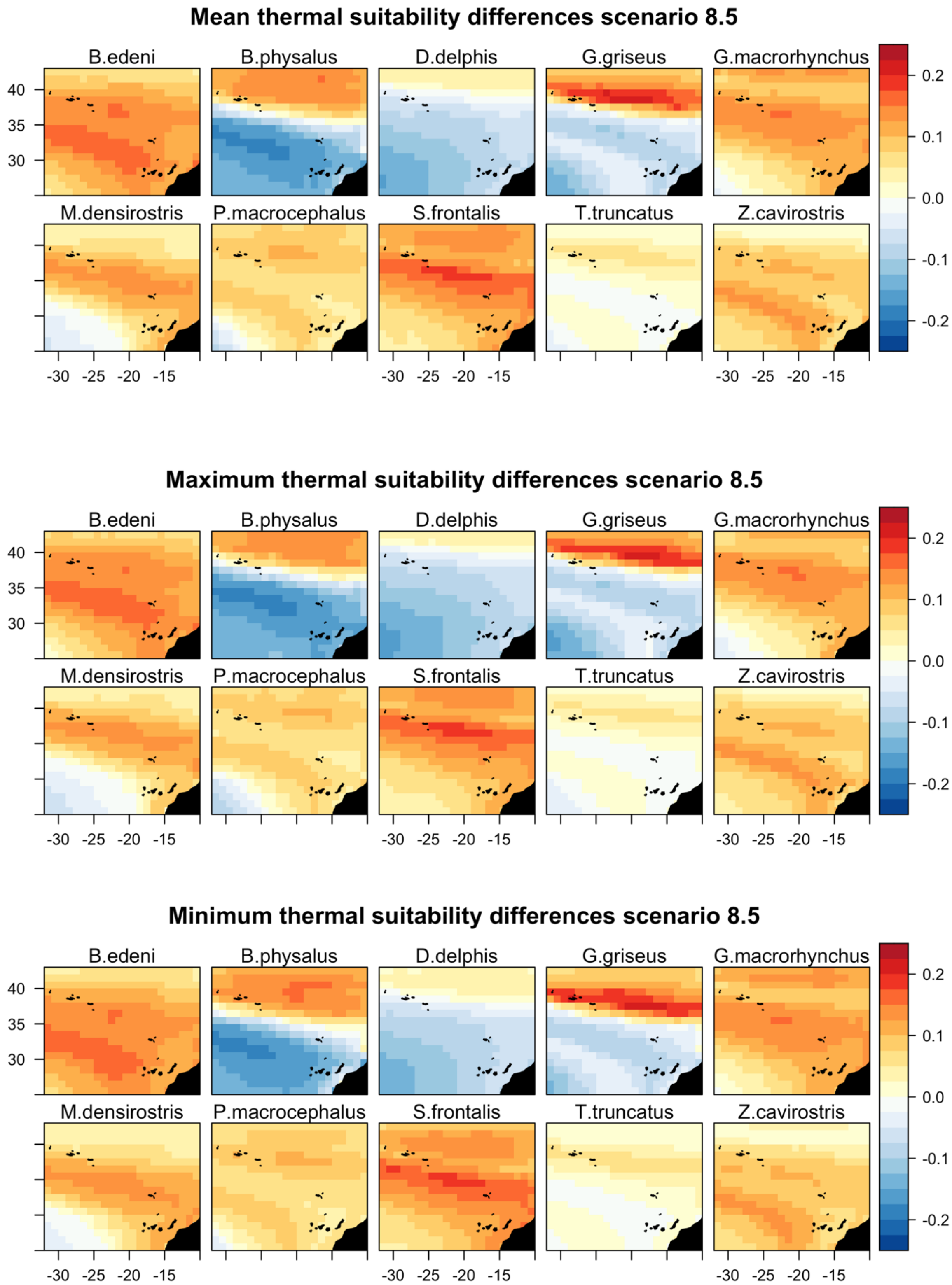


Figure J-1 – Differences in thermal suitability (mean, minimum and maximum) for RCP 2.6, 4.5 and 8.5 for Atlantic spotted dolphin (*S. frontalis*); short-beaked common dolphin (*D. delphis*); Bryde's whale (*B. edeni*); fin whale (*B. physalus*); Risso's dolphin (*G. griseus*); short-finned pilot whale (*G. macrorhynchus*); bottlenose dolphin (*T. truncatus*); sperm whale (*P.*

macrocephalus); Blainville's beaked whale (*M. densirostris*); Cuvier’s beaked whale (*Z. cavirostris*). 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 difference between historical (1956-2005) and future (2006-2055) thermal suitability.

Annex K. Description of the data quality scale

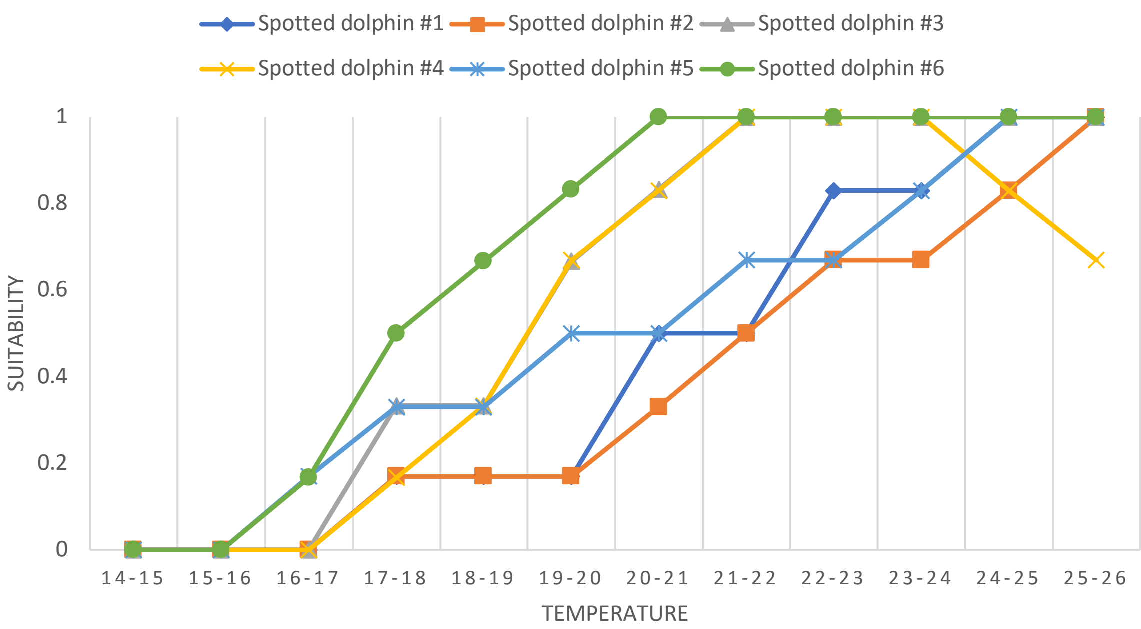
Data quality scale	
0	No Data. No information to base and attribute a score on. Very little is known about the species or related species and there is no basis for forming an expert opinion.
1	Expert Judgement. The attribute score reflects the expert judgement of the reviewer and is based on their general knowledge of the species, or related species, and their relative role on the ecosystem.
2	Limited Data. The score is based on data which has a higher degree of uncertainty. The data used to score the attribute may be based on related or similar species, come from outside the study area or the reliability of the source may be limited.
3	Adequate Data. The score is based on data which have been observed, modelled or empirically measured for the species in question and comes from a reputable source.

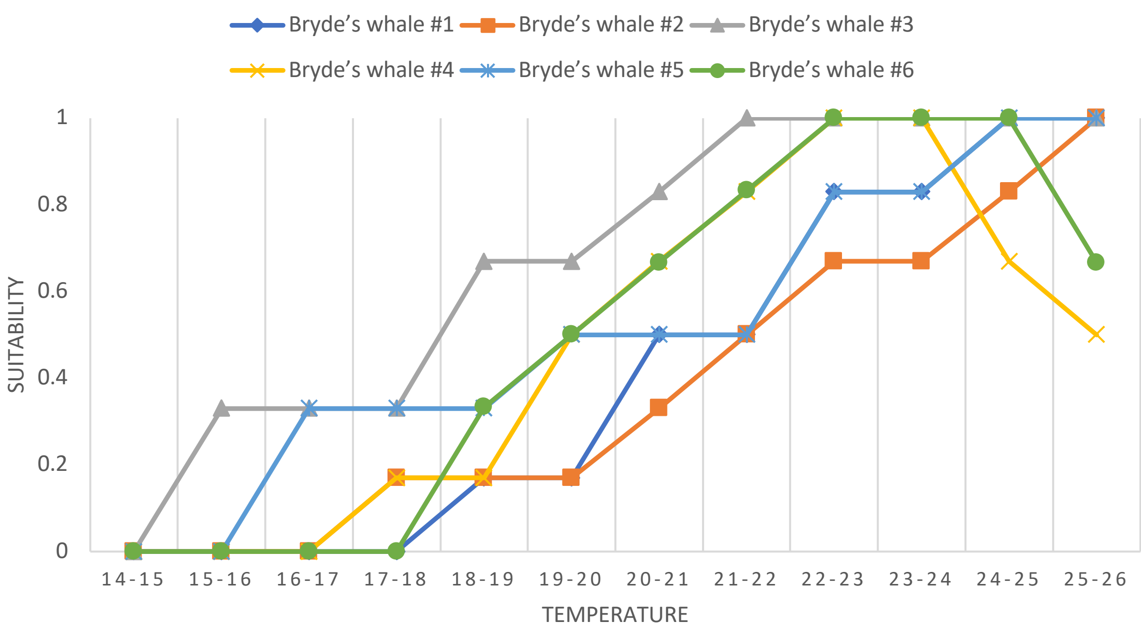
Annex L. Experts' data quality scores

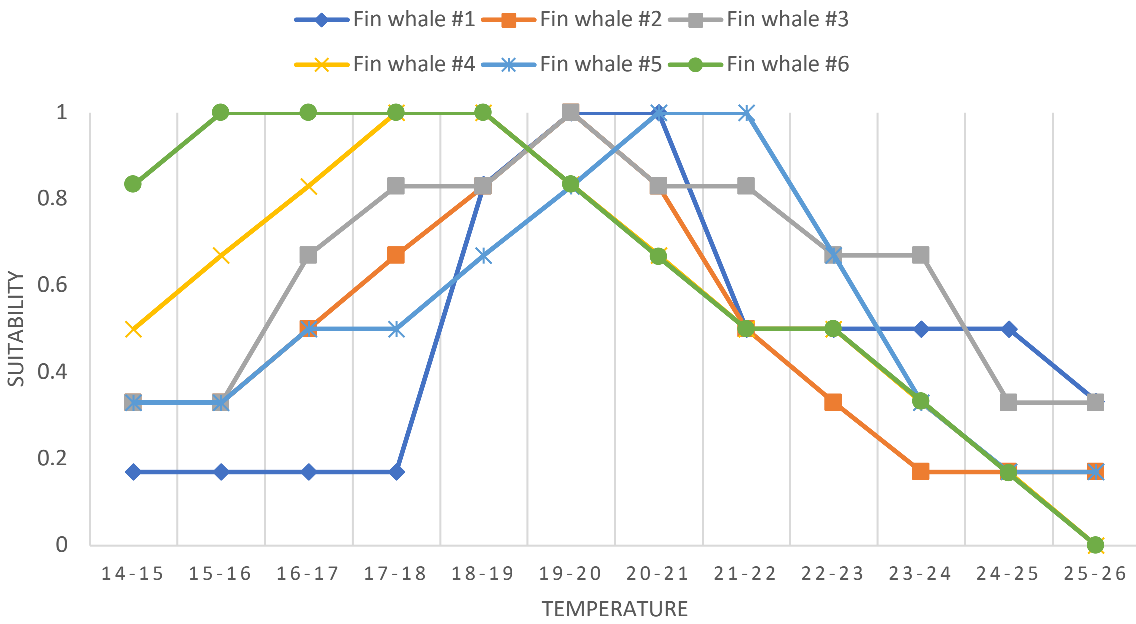
Species	**Data quality**					
	MAD#1	**MAD#2**	**AZO#3**	**AZO#4**	**CAN#5**	**CAN#6**
Spotted dolphin	3	3	3	3	2	2
Bryde's whale	3	3	3	3	1	2
Fin whale	2	2	3	3	1	2
Pilot whale	3	3	3	3	2	2
Common dolphin	3	3	3	3	2	2
Sperm whale	3	3	3	3	2	2
Risso's dolphin	2	2	3	3	1	2
Bottlenose dolphin	3	3	3	3	2	2
Blainville's beaked whale	2	3	2	3	0	2
Cuvier's beaked whale	2	2	2	1	0	2

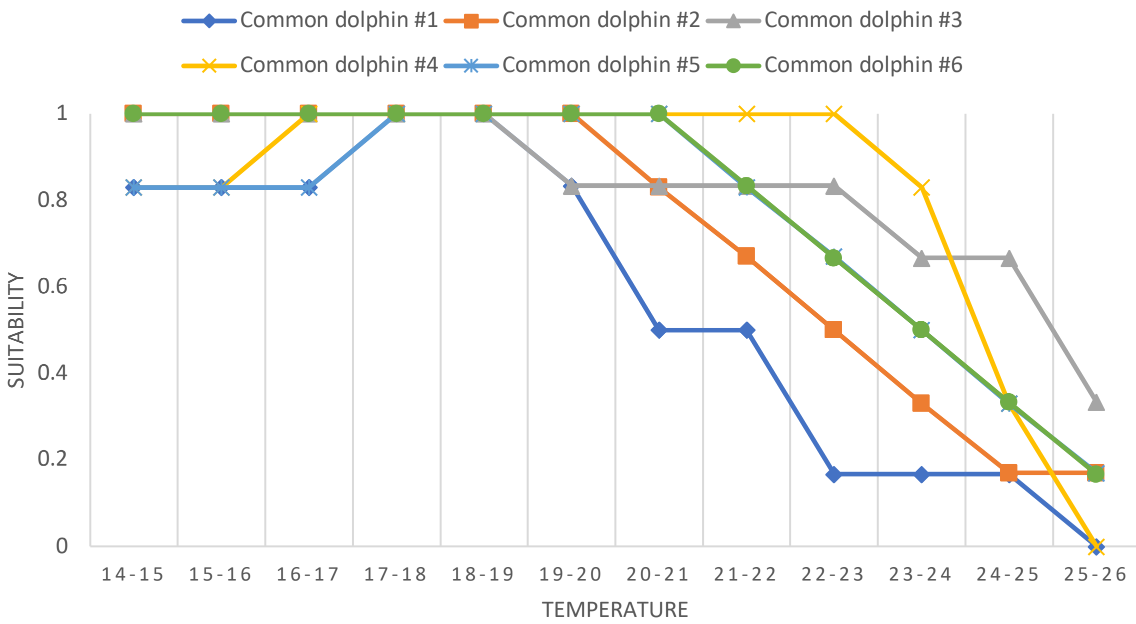
Figure L-1 - Experts data quality scores for each species. Experts from the Madeira archipelago are identified as MAD#1; MAD#2; from the Azores archipelago as AZO#3; AZO#4 and from the Canary Islands as CAN#5; CAN#6.

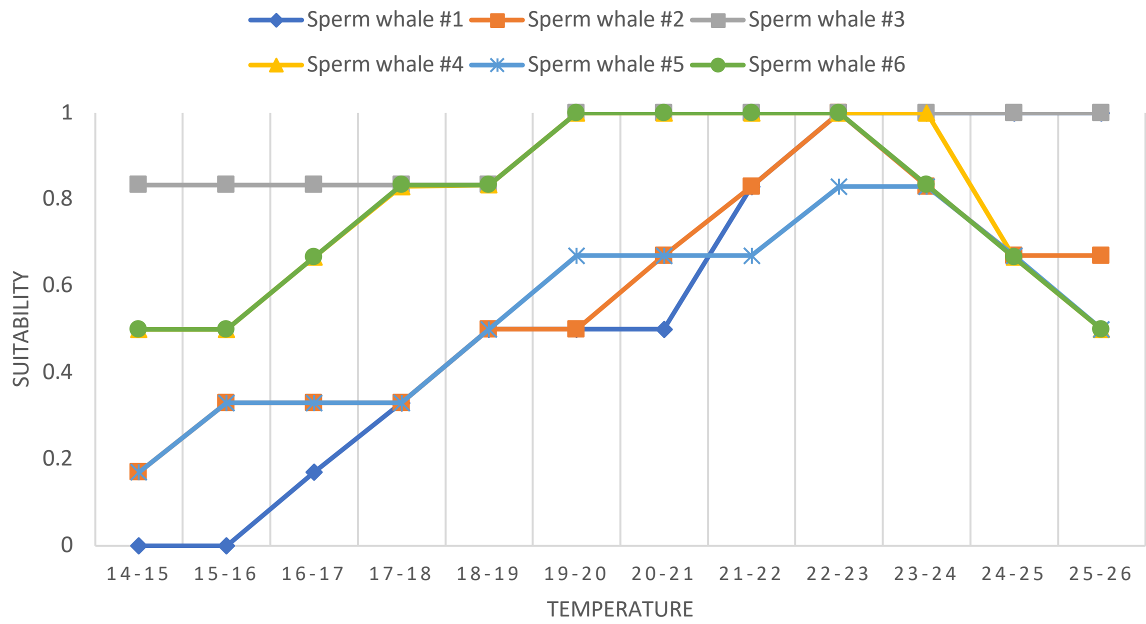
Annex M. Experts' suitability scores



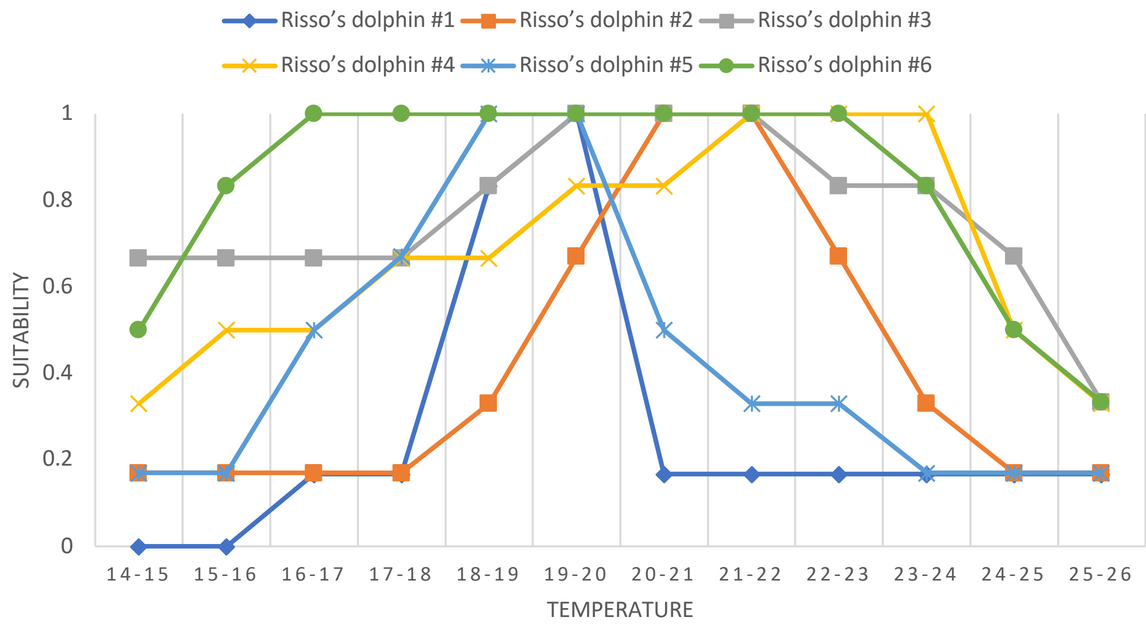



Fin whale #1
Fin whale #2
Fin whale #3
Fin whale #4
Fin whale #5
Fin whale #6
SUITABILITY
1
0.8
0.6
0.4
0.2
0
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
23-24
24-25
25-26
TEMPERATURE

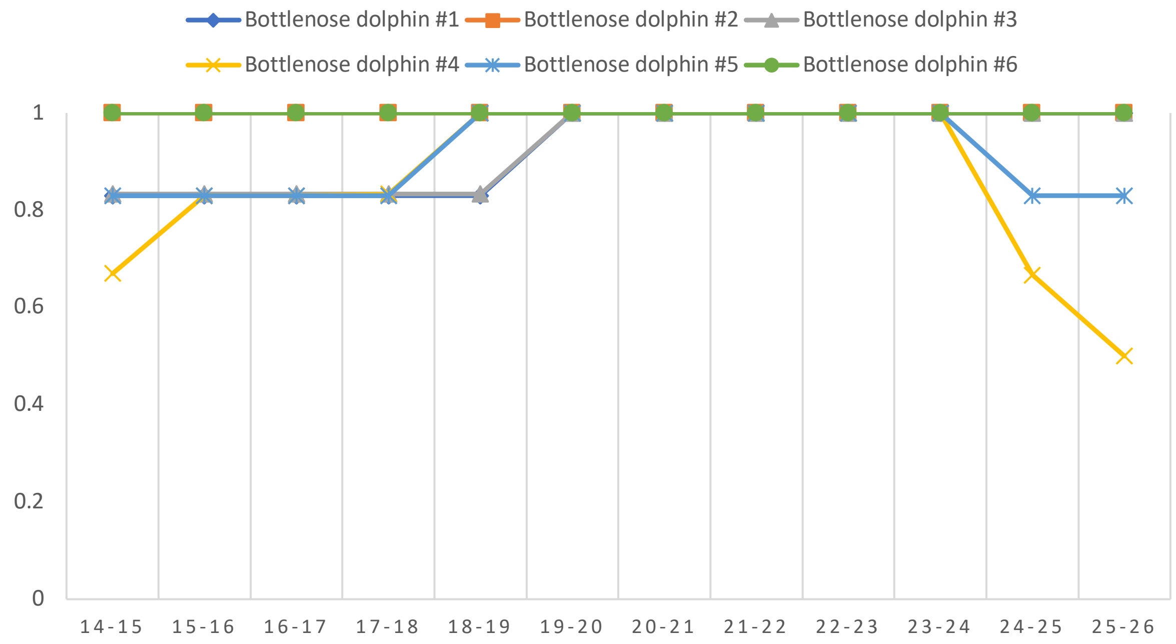

Common dolphin #1
Common dolphin #2
Common dolphin #3
Common dolphin #4
Common dolphin #5
Common dolphin #6
SUITABILITY
1
0.8
0.6
0.4
0.2
0
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
23-24
24-25
25-26
TEMPERATURE

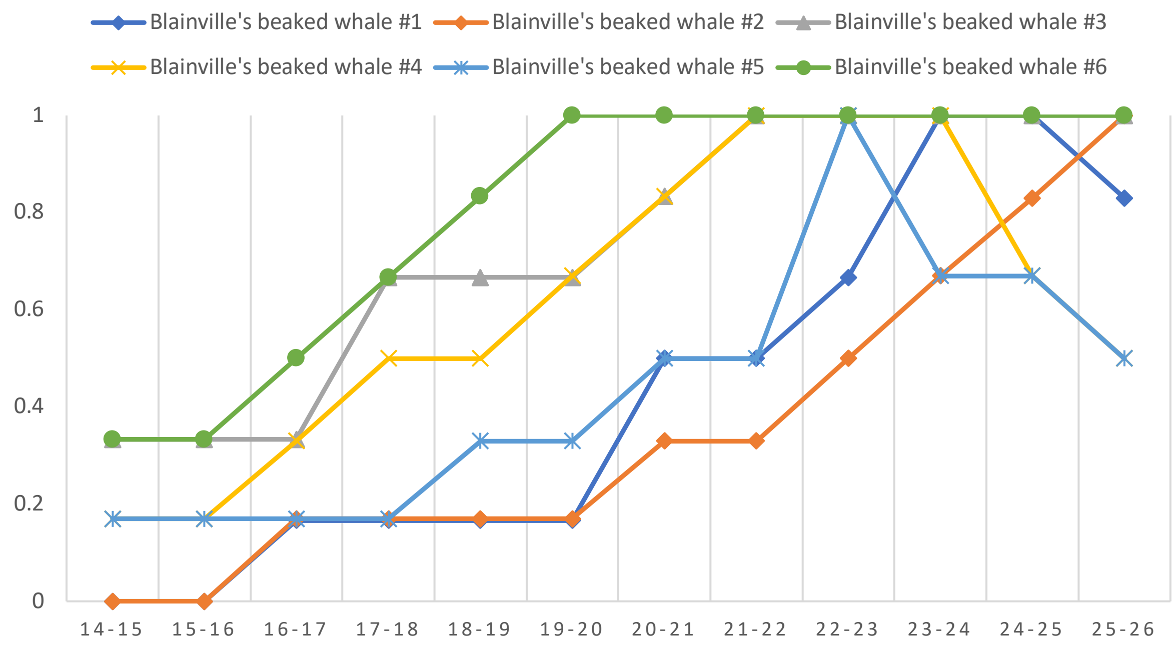


Sperm whale #1
Sperm whale #2
Sperm whale #3
Sperm whale #4
Sperm whale #5
Sperm whale #6
SUITABILITY
1
0.8
0.6
0.4
0.2
0
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
23-24
24-25
25-26
TEMPERATURE



Risso's dolphin #1
Risso's dolphin #2
Risso's dolphin #3
Risso's dolphin #4
Risso's dolphin #5
Risso's dolphin #6
SUITABILITY
1
0.8
0.6
0.4
0.2
0
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
23-24
24-25
25-26
TEMPERATURE


Bottlenose dolphin #1
Bottlenose dolphin #2
Bottlenose dolphin #3
Bottlenose dolphin #4
Bottlenose dolphin #5
Bottlenose dolphin #6
1
0.8
0.6
0.4
0.2
0
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
23-24
24-25
25-26


Blainville's beaked whale #1
Blainville's beaked whale #2
Blainville's beaked whale #3
Blainville's beaked whale #4
Blainville's beaked whale #5
Blainville's beaked whale #6
1
0.8
0.6
0.4
0.2
0
14-15
15-16
16-17
17-18
18-19
19-20
20-21
21-22
22-23
23-24
24-25
25-26

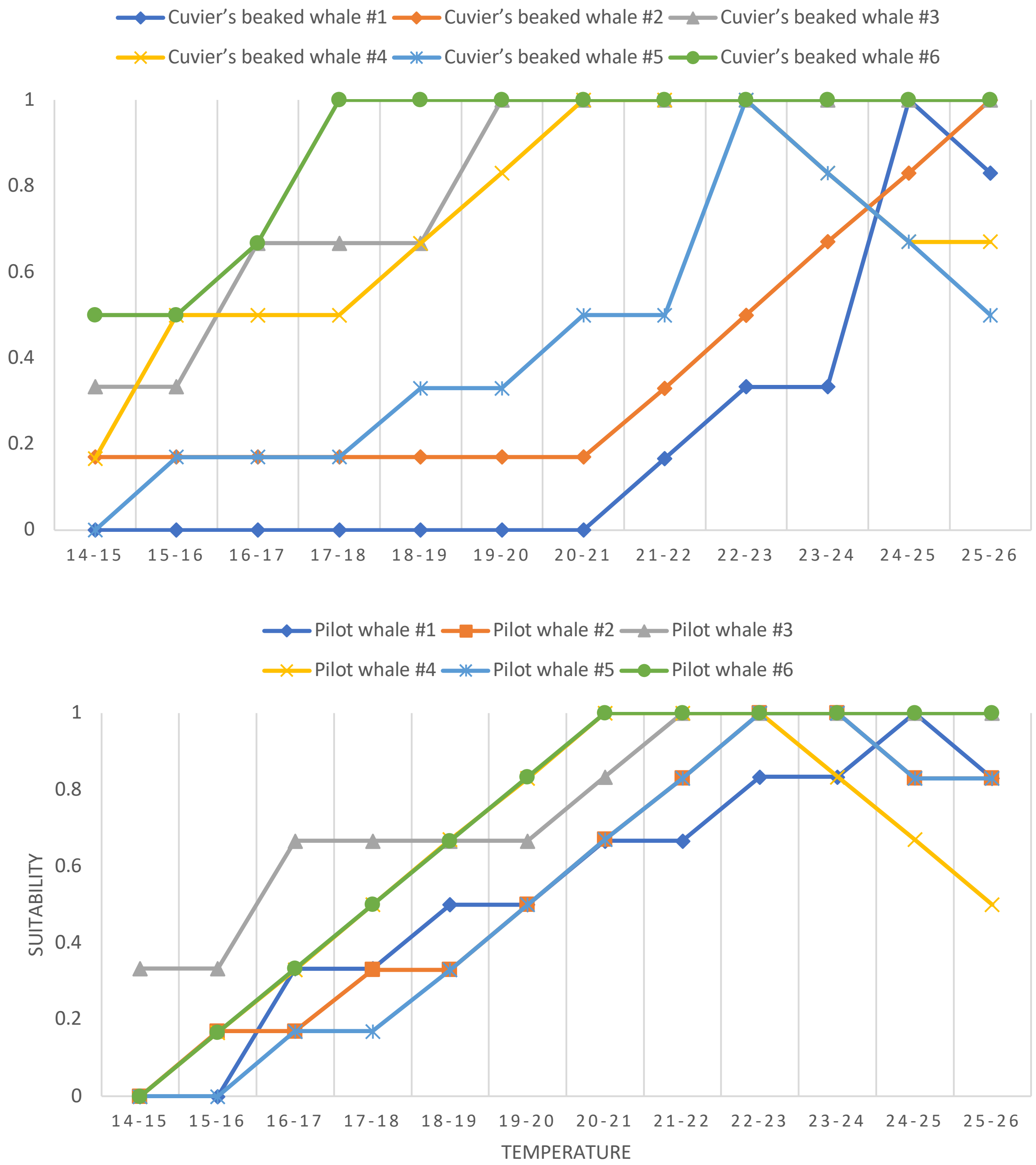


Figure M-1 - Experts suitability scores for the Atlantic spotted dolphin (*Stenella frontalis*); short-beaked common dolphin (*Delphinus delphis*); Bryde's whale (*Balaenoptera edeni*); fin whale (*Balaenoptera physalus*); Risso's dolphin (*Grampus griseus*); bottlenose dolphin (*Tursiops truncatus*); sperm whale (*Physeter macrocephalus*); Blainville's beaked whale (*Mesoplodon densirostris*); Cuvier's beaked whale (*Ziphius cavirostris*); short-finned pilot whale (*Globicephala macrorhynchus*).

Annex N. Suitability scales attributed by experts to the six different methods

Table N-1 - Suitability scores attributed by experts to the six different methods. t(numbers) indicate the temperature intervals and species are identified by their acronym (Sf: *Stenella frontalis*; Be: *Balaenoptera edeni*; Bp: *Balaenoptera physalus*; Gma: *Globicephala macrorhynchus*; Dd: *Delphinus delphis*; Pm: *Physeter macrocephalus*; Gg: *Grampus griseus*; Tt: *Tursiops truncatus*; Md: *Mesoplodon densirostris*; Zc*: Ziphius cavirostris*).

	METHOD 1							METHOD 2						
		Temperature							Temperature					
	Species	t1416	t1618	t1820	t2022	t2224	t2426	Species	t1416	t1618	t1820	t2022	t2224	t2426
EXPERT 1	Sf	0	0	0.5	0.5	1	1	Sf	0	0.25	0.25	0.5	1	1
	Be	0	0	0	0.5	1	1	Be	0	0	0.25	0.5	1	1
	Bp	0	0	1	0.5	0.5	0.5	Bp	0	0.25	0.75	0.75	0.5	0.5
	Gma	0	0.5	0.5	0.5	1	1	Gma	0	0.5	0.5	0.75	1	1
	Dd	0	1	0.5	0.5	0.5	0	Dd	0	1	0.75	0.5	0.25	0
	Pm	0	0	0.5	0.5	1	0.5	Pm	0	0.25	0.5	0.75	1	0.75
	Gg	0	0	0	0.5	0.5	0	Gg	0	0	0.25	0.5	0.25	0
	Tt	0	0.5	1	1	1	1	Tt	0	0.5	0.75	1	1	1
	Md	0	0	0.5	0.5	1	1	Md	0	0	0.25	0.5	0.75	0.75
	Zc	0	0	0	0	0.5	0.5	Zc	0	0	0	0	0.25	0.5
EXPERT 2	Sf	0	0	0.5	0.5	1	1	Sf	0	0	0.25	0.5	0.75	1
	Be	0	0	0	0.5	1	1	Be	0	0	0.25	0.5	0.75	1
	Bp	0.5	0.5	0.5	0.5	0.5	0	Bp	0.25	0.5	0.75	0.5	0.25	0
	Gma	0	0.5	0.5	0.5	1	1	Gma	0	0.25	0.5	0.5	1	0.75

	Dd	1	1	1	0.5	0.5	0	Dd	1	1	1	0.5	0.25	0
	Pm	0.5	0.5	0.5	1	1	0.5	Pm	0.25	0.25	0.5	0.75	0.75	0.5
	Gg	0.5	0.5	0.5	0.5	0.5	0.5	Gg	0.25	0.25	0.25	0.25	0.25	0.25
	Tt	1	1	1	1	1	1	Tt	1	1	1	1	1	1
	Md	0	0.5	0.5	0.5	0.5	0.5	Md	0	0.25	0.25	0.25	0.5	0.75
	Zc	0.5	0.5	0.5	0.5	0.5	0.5	Zc	0.25	0.25	0.25	0.25	0.25	0.25
EXPERT 3	Sf	0	0	0.5	0.5	1	0.5	Sf	0	0	0.25	0.75	1	0.5
	Be	0	0	0	0.5	1	0.5	Be	0	0	0	0.5	1	0.25
	Bp	0.5	1	1	0.5	0.5	0	Bp	0.25	1	0.75	0.5	0.25	0
	Gma	0.5	0.5	0.5	1	1	0.5	Gma	0.25	0.25	0.5	1	1	0.5
	Dd	0.5	1	1	1	1	0.5	Dd	0.5	1	1	1	1	0.25
	Pm	0.5	0.5	0.5	1	1	0.5	Pm	0.5	0.75	0.75	1	1	0.5
	Gg	0.5	0.5	1	1	1	0.5	Gg	0.25	0.5	0.75	1	1	0.5
	Tt	0.5	0.5	1	1	1	0.5	Tt	0.25	0.5	1	1	1	0.5
	Md	0	0.5	0.5	1	1	0.5	Md	0	0.25	0.25	1	1	0.25
	Zc	0.5	0.5	0.5	1	1	0.5	Zc	0.25	0.25	0.5	1	1	0.25
EXPERT 4	Sf	0	0	0.5	1	1	1	Sf	0	0.25	0.5	0.75	1	1
	Be	0	0	0	1	1	1	Be	0	0	0.25	0.5	1	0.75
	Bp	0.5	1	1	0.5	0	0	Bp	0.75	1	1	0.75	0.25	0
	Gma	0	0	1	1	1	1	Gma	0	0.25	1	1	1	1
	Dd	1	1	1	0.5	0.5	0.5	Dd	1	1	1	0.75	0.5	0.25
	Pm	0.5	0.5	1	1	1	0.5	Pm	0.5	0.75	1	1	1	0.75
	Gg	0.5	1	1	1	1	0.5	Gg	0.5	0.75	1	1	1	0.5
	Tt	1	1	1	1	1	1	Tt	1	1	1	1	1	1
	Md	0	0.5	0.5	1	1	1	Md	0.25	0.5	0.75	1	1	1
	Zc	0.5	1	1	1	1	1	Zc	0.5	0.75	1	1	1	1
EXPERT 5	Sf	0.5	1	1	1	1	0.5	Sf	0.5	1	1	0.75	0.75	0.5

	Be	0.5	1	1	1	1	0.5	Be	0.5	1	1	1	0.75	0.5
	Bp	0.5	1	1	1	0.5	0.5	Bp	0.75	1	1	1	0.5	0.25
	Gma	1	1	1	1	0.5	0.5	Gma	0.75	1	1	0.75	0.5	0.25
	Dd	0.5	1	1	1	0.5	0.5	Dd	0.5	1	1	0.75	0.75	0.5
	Pm	1	1	1	1	0.5	0.5	Pm	1	1	1	0.75	0.5	0.25
	Gg	0.5	1	1	0.5	0.5	0.5	Gg	0.75	1	1	0.75	0.5	0.25
	Tt	1	1	1	1	1	1	Tt	0.75	1	1	1	1	0.75
	Md	1	1	1	0.5	0.5	0.5	Md	1	1	1	0.75	0.5	0.25
	Zc	1	1	1	0.5	0.5	0.5	Zc	1	1	1	0.75	0.5	0.25
EXPERT 6	Sf	0	0	0.5	1	1	0.5	Sf	0	0	0.5	0.75	0.75	0.5
	Be	0	0	0.5	1	0.5	0	Be	0	0.25	0.5	0.75	0.5	0.25
	Bp	0	0.5	0.5	0.5	0.5	0.5	Bp	0	0.5	0.5	0.5	0.5	0.5
	Gma	0	0	0.5	1	0.5	0	Gma	0	0	0.5	1	0.75	0.25
	Dd	0	0	0.5	1	0	0	Dd	0	0	0.75	1	0	0
	Pm	0	0	0.5	1	1	0.5	Pm	0	0.25	0.75	1	0.75	0.5
	Gg	0	0.5	1	0.5	0	0	Gg	0	0.5	0.75	0.25	0	0
	Tt	0	0	0.5	0.5	0.5	0.5	Tt	0	0.25	0.5	0.75	0.75	0.5
	Md	0	0	0	1	0.5	0	Md	0	0	0	0.75	0.25	0
	Zc	0	0	0	1	0.5	0	Zc	0	0	0	0.75	0.25	0

	METHOD 3						
	Species	Temperature					
		t1416	t1618	t1820	t2022	t2224	t2426
EXPERT 1	Sf	0	0.17	0.17	0.5	0.83	1
	Be	0	0	0.17	0.5	0.83	1
	Bp	0	0.17	0.83	0.67	0.5	0.5
	Gma	0	0.33	0.5	0.67	0.83	1
	Dd	0	1	0.83	0.5	0.17	0
	Pm	0	0.33	0.5	0.83	1	0.83
	Gg	0	0.17	0.33	0.5	0.33	0.17
	Tt	0	0.5	0.67	1	1	1
	Md	0	0.17	0.17	0.5	0.67	0.67
	Zc	0	0	0	0.17	0.33	0.5
EXPERT 2	Sf	0	0.17	0.17	0.33	0.67	1
	Be	0	0.17	0.17	0.33	0.67	1
	Bp	0.33	0.5	0.67	0.33	0.17	0.17
	Gma	0.17	0.33	0.5	0.67	1	0.83
	Dd	1	1	1	0.67	0.33	0.17
	Pm	0.33	0.33	0.5	0.67	0.83	0.5
	Gg	0.17	0.17	0.17	0.33	0.17	0.17
	Tt	1	1	1	1	1	1
	Md	0	0.17	0.33	0.33	0.5	0.67
	Zc	0.17	0.17	0.17	0.17	0.33	0.33
EXPERT 3	Sf	0	0	0.33	0.83	1	0.33
	Be	0	0	0	0.33	1	0.17
	Bp	0.17	1	0.83	0.33	0.17	0
	Gma	0.17	0.33	0.67	1	1	0.5

	Dd	0.33	1	1	1	1	0.17
	Pm	0.5	0.83	0.83	1	1	0.5
	Gg	0.33	0.5	0.67	1	1	0.5
	Tt	0.17	0.5	1	1	1	0.5
	Md	0	0.17	0.33	1	1	0.33
	Zc	0.17	0.33	0.67	1	1	0.33
EXPERT 4	Sf	0	0.17	0.5	0.83	1	1
	Be	0	0	0.17	0.67	1	0.67
	Bp	0.83	1	1	0.67	0.33	0.17
	Gma	0.17	0.33	0.83	1	1	1
	Dd	1	1	1	0.83	0.5	0.33
	Pm	0.5	0.67	1	1	1	0.83
	Gg	0.67	0.83	1	1	1	0.5
	Tt	1	1	1	1	1	1
	Md	0.33	0.67	0.83	1	1	1
	Zc	0.5	0.67	1	1	1	1
EXPERT 5	Sf	0.83	1	1	1	0.83	0.67
	Be	0.67	1	1	0.83	0.67	0.5
	Bp	0.67	1	1	0.83	0.67	0.5
	Gma	0.83	1	1	0.83	0.67	0.33
	Dd	0.67	1	1	0.83	0.67	0.5
	Pm	0.83	1	0.83	0.83	0.67	0.33
	Gg	0.83	1	0.83	0.83	0.5	0.33
	Tt	0.83	1	1	0.83	0.83	0.67
	Md	1	1	0.83	0.83	0.5	0.33
	Zc	1	1	0.83	0.83	0.5	0.33
EXPERT 6	Sf	0	0	0.67	0.83	0.67	0.33

	Be	0.17	0.33	0.67	0.83	0.67	0.17
	Bp	0	0.33	0.33	0.5	0.5	0.5
	Gma	0	0	0.33	1	0.83	0.33
	Dd	0	0	0.67	1	0	0
	Pm	0.17	0.33	0.67	1	1	0.67
	Gg	0	0.33	0.83	0.33	0	0
	Tt	0.17	0.33	0.5	0.83	0.67	0.33
	Md	0	0	0	0.83	0.33	0
	Zc	0	0	0	0.83	0.33	0

	METHOD 4												
		Temperature											
	Species	t1415	t1516	t1617	t1718	t1819	t1920	t2021	t2122	t2223	t2324	t2425	t2526
EXPERT 1	Sf	0	0	0	0	0.5	0.5	0.5	0.5	1	1	1	1
	Be	0	0	0	0	0	0	0.5	0.5	1	1	1	1
	Bp	0	0	0	0	1	1	0.5	0.5	0.5	0.5	0.5	0.5
	Gma	0	0	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	1
	Dd	0	0	1	1	0.5	0.5	0.5	0.5	0.5	0.5	0	0
	Pm	0	0	0	0	0.5	0.5	0.5	0.5	1	1	0.5	0.5
	Gg	0	0	0	0	0	0	0.5	0.5	0.5	0.5	0	0
	Tt	0	0	0.5	0.5	1	1	1	1	1	1	1	1
	Md	0	0	0	0	0.5	0.5	0.5	0.5	1	1	1	1
	Zc	0	0	0	0	0	0	0	0	0.5	0.5	0.5	0.5
EXPERT 2	Sf	0	0	0	0	0.5	0.5	0.5	0.5	1	1	1	1
	Be	0	0	0	0	0	0	0.5	0.5	1	1	1	1
	Bp	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0	0
	Gma	0	0	0.5	0.5	0.5	0.5	0.5	1	1	1	1	0.5
	Dd	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0	0
	Pm	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	0.5	0.5	0.5
	Gg	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Tt	1	1	1	1	1	1	1	1	1	1	1	1
	Md	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Zc	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
EXPERT 3	Sf	0	0	0	0	0.5	0.5	0.5	1	1	1	0.5	0.5
	Be	0	0	0	0	0	0	0	0.5	1	1	0.5	0
	Bp	0	0.5	1	1	1	0.5	0.5	0.5	0.5	0.5	0	0
	Gma	0	0.5	0.5	0.5	0.5	0.5	1	1	1	1	0.5	0

	Dd	0.5	0.5	1	1	1	1	1	1	1	1	0.5	0
	Pm	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1	0.5	0.5
	Gg	0.5	0.5	0.5	0.5	0.5	1	1	1	1	1	0.5	0.5
	Tt	0.5	0.5	0.5	0.5	1	1	1	1	1	1	0.5	0.5
	Md	0	0	0.5	0.5	0.5	0.5	0.5	1	1	1	0.5	0.5
	Zc	0.5	0.5	0.5	0.5	0.5	0.5	1	1	1	0.5	0.5	0.5
EXPERT 4	Sf	0	0	0	0.5	0.5	0.5	1	1	1	1	1	1
	Be	0	0	0	0	0	0	1	1	1	1	1	0.5
	Bp	0.5	1	1	1	1	1	0.5	0.5	0.5	0	0	0
	Gma	0	0	0	0.5	0.5	1	1	1	1	1	1	1
	Dd	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0
	Pm	0.5	0.5	0.5	0.5	1	1	1	1	1	1	0.5	0.5
	Gg	0.5	0.5	1	1	1	1	1	1	1	0.5	0.5	0
	Tt	1	1	1	1	1	1	1	1	1	1	1	1
	Md	0	0	0.5	0.5	0.5	1	1	1	1	1	1	1
	Zc	0.5	0.5	1	1	1	1	1	1	1	1	1	1
EXPERT 5	Sf	0.5	0.5	1	1	1	1	1	1	1	1	0.5	0.5
	Be	0.5	0.5	1	1	1	1	1	1	1	0.5	0.5	0.5
	Bp	0.5	0.5	1	1	1	1	1	1	1	0.5	0.5	0.5
	Gma	1	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5
	Dd	0.5	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5
	Pm	1	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5
	Gg	0.5	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5
	Tt	1	1	1	1	1	1	1	1	1	1	1	1
	Md	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5
	Zc	1	1	1	1	1	1	1	0.5	0.5	0.5	0.5	0.5
EXPERT 6	Sf	0	0	0	0	0.5	0.5	0.5	1	0.5	0.5	0.5	0

	Be	0	0	0	0.5	0.5	0.5	0.5	1	0.5	0.5	0	0
	Bp	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Gma	0	0	0	0	0.5	0.5	1	1	0.5	0.5	0	0
	Dd	0	0	0	0	0.5	0.5	1	1	0	0	0	0
	Pm	0	0	0	0	0.5	0.5	1	1	1	1	0.5	0
	Gg	0	0	0.5	0.5	0.5	1	0.5	0	0	0	0	0
	Tt	0	0	0	0	0.5	0.5	0.5	1	0.5	0.5	0.5	0.5
	Md	0	0	0	0	0	0	0.5	1	0.5	0.5	0	0
	Zc	0	0	0	0	0	0	0.5	1	0.5	0.5	0	0

	METHOD 5												
	Species	Temperature											
		t1415	t1516	t1617	t1718	t1819	t1920	t2021	t2122	t2223	t2324	t2425	t2526
EXPERT 1	Sf	0	0	0.25	0.25	0.25	0.25	0.5	0.5	1	1	1	1
	Be	0	0	0	0	0.25	0.25	0.5	0.5	1	1	1	1
	Bp	0	0	0.25	0.25	0.75	0.75	0.75	0.75	0.5	0.5	0.5	0.5
	Gma	0	0	0.5	0.5	0.5	0.5	0.75	0.75	1	1	1	1
	Dd	0	0	1	1	0.75	0.75	0.5	0.5	0.25	0.25	0	0
	Pm	0	0	0.25	0.25	0.5	0.5	0.75	0.75	1	1	0.75	0.75
	Gg	0	0	0	0	0.25	0.25	0.5	0.5	0.25	0.25	0	0
	Tt	0	0	0.5	0.5	0.75	0.75	1	1	1	1	1	1
	Md	0	0	0	0	0.25	0.25	0.5	0.5	0.75	0.75	0.75	0.75
	Zc	0	0	0	0	0	0	0	0	0.25	0.25	0.5	0.5
EXPERT 2	Sf	0	0	0	0.25	0.25	0.25	0.25	0.5	0.75	0.75	1	1
	Be	0	0	0	0	0.25	0.25	0.25	0.5	0.75	0.75	1	1
	Bp	0.25	0.25	0.5	0.5	0.75	0.75	0.5	0.5	0.25	0.25	0.25	0
	Gma	0	0.25	0.25	0.5	0.5	0.5	0.5	0.75	1	1	1	0.75
	Dd	1	1	1	1	1	1	0.75	0.5	0.5	0.25	0.25	0
	Pm	0.25	0.25	0.25	0.25	0.5	0.5	0.75	0.75	0.75	0.5	0.5	0.5
	Gg	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
	Tt	1	1	1	1	1	1	1	1	1	1	1	1
	Md	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.5	0.75	0.75
	Zc	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
EXPERT 3	Sf	0	0	0	0	0.25	0.25	0.75	1	1	1	0.5	0.5
	Be	0	0	0	0	0	0	0	0.5	1	1	0.25	0
	Bp	0	0.25	0.75	1	1	0.75	0.5	0.25	0.25	0.25	0	0
	Gma	0	0.25	0.25	0.25	0.5	0.75	1	1	1	1	0.5	0.25

	Dd	0.25	0.5	1	1	1	1	1	1	1	0.75	0.25	0
	Pm	0.5	0.5	0.75	0.75	0.75	1	1	1	1	1	0.75	0.5
	Gg	0.25	0.5	0.5	0.5	0.75	0.75	1	1	1	1	0.5	0.25
	Tt	0.25	0.25	0.5	0.75	1	1	1	1	1	1	0.5	0.5
	Md	0	0	0.25	0.25	0.25	0.5	0.75	1	1	1	0.5	0.25
	Zc	0.25	0.25	0.25	0.5	0.5	0.5	1	1	1	0.5	0.25	0.25
EXPERT 4	Sf	0	0	0.25	0.5	0.75	0.75	1	1	1	1	1	1
	Be	0	0	0	0	0.25	0.25	0.5	0.75	1	1	1	0.75
	Bp	0.75	1	1	1	1	0.75	0.75	0.75	0.5	0.25	0	0
	Gma	0	0.25	0.25	0.5	0.75	1	1	1	1	1	1	1
	Dd	1	1	1	1	1	1	1	0.75	0.75	0.5	0.5	0.25
	Pm	0.5	0.5	0.75	0.75	1	1	1	1	1	1	0.75	0.5
	Gg	0.5	0.75	1	1	1	1	1	1	1	0.75	0.5	0.25
	Tt	1	1	1	1	1	1	1	1	1	1	1	1
	Md	0.25	0.25	0.5	0.75	0.75	1	1	1	1	1	1	1
	Zc	0.5	0.5	0.75	1	1	1	1	1	1	1	1	1
EXPERT 5	Sf	0.5	0.75	1	1	1	1	0.75	0.75	0.75	0.75	0.5	0.5
	Be	0.5	0.75	1	1	1	1	1	1	0.75	0.5	0.5	0.25
	Bp	0.5	0.75	1	1	1	1	1	1	0.75	0.5	0.5	0.25
	Gma	0.75	0.75	1	1	1	1	1	0.75	0.5	0.5	0.5	0.25
	Dd	0.5	0.75	1	1	1	1	1	0.75	0.75	0.75	0.5	0.5
	Pm	0.75	1	1	1	1	1	0.75	0.75	0.5	0.5	0.5	0.25
	Gg	0.75	0.75	1	1	1	1	0.75	0.75	0.75	0.5	0.5	0.25
	Tt	0.75	1	1	1	1	1	1	1	1	1	0.75	0.75
	Md	1	1	1	1	1	0.75	0.75	0.75	0.75	0.5	0.5	0.25
	Zc	1	1	1	1	1	0.75	0.75	0.75	0.75	0.5	0.5	0.25
EXPERT 6	Sf	0	0	0	0	0.25	0.5	0.75	1	0.75	0.5	0.5	0.25

	Species	t1415	t1516	t1617	t1718	t1819	t1920	t2021	t2122	t2223	t2324	t2425	t2526
	Be	0	0	0.25	0.25	0.25	0.5	0.75	1	0.75	0.5	0.25	0
	Bp	0	0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	Gma	0	0	0	0	0.25	0.5	0.75	1	0.75	0.5	0.25	0.25
	Dd	0	0	0	0	0.75	0.75	1	1	0	0	0	0
	Pm	0	0	0.25	0.25	0.5	0.75	0.75	1	1	0.75	0.5	0.25
	Gg	0	0	0.25	0.5	0.75	0.75	0.25	0	0	0	0	0
	Tt	0	0	0.25	0.25	0.5	0.5	0.75	1	0.75	0.5	0.5	0.25
	Md	0	0	0	0	0	0	0.75	1	0.25	0.25	0	0
	Zc	0	0	0	0	0	0	0.75	1	0.25	0.25	0	0

	METHOD 6												
		Temperature											
	Species	t1415	t1516	t1617	t1718	t1819	t1920	t2021	t2122	t2223	t2324	t2425	t2526
EXPERT 1	Sf	0	0	0	0.17	0.17	0.17	0.5	0.5	0.83	0.83	1	1
	Be	0	0	0	0	0.17	0.17	0.5	0.5	0.83	0.83	1	1
	Bp	0.17	0.17	0.17	0.17	0.83	1	1	0.5	0.5	0.5	0.5	0.33
	Gma	0	0	0.33	0.33	0.5	0.5	0.67	0.67	0.83	0.83	1	0.83
	Dd	0.83	0.83	0.83	1	1	0.83	0.5	0.5	0.17	0.17	0.17	0
	Pm	0	0	0.17	0.33	0.5	0.5	0.5	0.83	1	1	1	1
	Gg	0	0	0.17	0.17	0.83	1	0.17	0.17	0.17	0.17	0.17	0.17
	Tt	0.83	0.83	0.83	0.83	0.83	1	1	1	1	1	1	1
	Md	0	0	0.17	0.17	0.17	0.17	0.5	0.5	0.67	1	1	0.83
	Zc	0	0	0	0	0	0	0	0.17	0.33	0.33	1	0.83
EXPERT 2	Sf	0	0	0	0.17	0.17	0.17	0.33	0.5	0.67	0.67	0.83	1
	Be	0	0	0	0.17	0.17	0.17	0.33	0.5	0.67	0.67	0.83	1

	Bp	0.33	0.33	0.5	0.67	0.83	1	0.83	0.5	0.33	0.17	0.17	0.17
	Gma	0	0.17	0.17	0.33	0.33	0.5	0.67	0.83	1	1	0.83	0.83
	Dd	1	1	1	1	1	1	0.83	0.67	0.5	0.33	0.17	0.17
	Pm	0.17	0.33	0.33	0.33	0.5	0.5	0.67	0.83	1	0.83	0.67	0.67
	Gg	0.17	0.17	0.17	0.17	0.33	0.67	1	1	0.67	0.33	0.17	0.17
	Tt	1	1	1	1	1	1	1	1	1	1	1	1
	Md	0	0	0.17	0.17	0.17	0.17	0.33	0.33	0.5	0.67	0.83	1
	Zc	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.33	0.5	0.67	0.83	1
	Sf	0	0	0	0.33	0.33	0.67	0.83	1	1	1	1	1
	Be	0	0.33	0.33	0.33	0.67	0.67	0.83	1	1	1	1	1
	Bp	0.33	0.33	0.67	0.83	0.83	1	0.83	0.83	0.67	0.67	0.33	0.33
	Gma	0.33	0.33	0.67	0.67	0.67	0.67	0.83	1	1	1	1	1
EXPERT 3	Dd	1	1	1	1	1	0.83	0.83	0.83	0.83	0.7	0.7	0.3
	Pm	0.83	0.83	0.83	0.83	0.83	1	1	1	1	1	1	1
	Gg	0.67	0.67	0.67	0.67	0.83	1	1	1	0.83	0.83	0.67	0.33
	Tt	0.83	0.83	0.83	0.83	0.83	1	1	1	1	1	1	1
	Md	0.33	0.33	0.33	0.67	0.67	0.67	0.83	1	1	1	1	1
	Zc	0.33	0.33	0.67	0.67	0.67	1	1	1	1	1	1	1
	Sf	0	0	0	0.17	0.33	0.67	0.83	1	1	1	0.83	0.67
	Be	0	0	0	0.17	0.17	0.5	0.67	0.83	1	1	0.67	0.5
	Bp	0.5	0.67	0.83	1	1	0.83	0.67	0.5	0.5	0.33	0.17	0
	Gma	0	0.17	0.33	0.5	0.67	0.83	1	1	1	0.83	0.67	0.5
EXPERT 4	Dd	0.83	0.83	1	1	1	1	1	1	1	0.83	0.33	0
	Pm	0.5	0.5	0.67	0.83	0.83	1	1	1	1	1	0.67	0.5
	Gg	0.33	0.5	0.5	0.67	0.67	0.83	0.83	1	1	1	0.5	0.33
	Tt	0.67	0.83	0.83	0.83	1	1	1	1	1	1	0.67	0.5
	Md	0.17	0.17	0.33	0.5	0.5	0.67	0.83	1	1	1	0.67	0.5

	Zc	0.17	0.5	0.5	0.5	0.67	0.83	1	1	1	0.83	0.67	0.67
EXPERT 5	Sf	0	0	0.17	0.33	0.33	0.5	0.5	0.67	0.67	0.83	1	1
	Be	0	0	0.33	0.33	0.33	0.5	0.5	0.5	0.83	0.83	1	1
	Bp	0.33	0.33	0.5	0.5	0.67	0.83	1	1	0.67	0.33	0.17	0.17
	Gma	0	0	0.17	0.17	0.33	0.5	0.67	0.83	1	1	0.83	0.83
	Dd	0.83	0.83	0.83	1	1	1	1	0.83	0.67	0.5	0.33	0.17
	Pm	0.17	0.33	0.33	0.33	0.5	0.67	0.67	0.67	0.83	0.83	0.67	0.5
	Gg	0.17	0.17	0.5	0.67	1	1	0.5	0.33	0.33	0.17	0.17	0.17
	Tt	0.83	0.83	0.83	0.83	1	1	1	1	1	1	0.83	0.83
	Md	0.17	0.17	0.17	0.17	0.33	0.33	0.5	0.5	1	0.67	0.67	0.5
	Zc	0	0.17	0.17	0.17	0.33	0.33	0.5	0.5	1	0.83	0.67	0.5
EXPERT 6	Sf	0	0	0.17	0.5	0.67	0.83	1	1	1	1	1	1
	Be	0	0	0	0	0.33	0.5	0.67	0.83	1	1	1	0.67
	Bp	0.5	0.67	0.83	1	1	1	0.83	0.67	0.5	0.33	0.17	0
	Gma	0	0.17	0.33	0.5	0.67	0.83	1	1	1	1	1	1
	Dd	1	1	1	1	1	1	1	0.83	0.67	0.5	0.33	0.17
	Pm	0.5	0.5	0.67	0.83	0.83	1	1	1	1	0.83	0.67	0.5
	Gg	0.5	0.83	1	1	1	1	1	1	1	0.83	0.5	0.33
	Tt	1	1	1	1	1	1	1	1	1	1	1	1
	Md	0.33	0.33	0.5	0.5	0.5	0.67	0.83	1	1	1	1	1
	Zc	0.5	0.5	0.17	0.33	0.33	0.5	0.67	0.83	1	1	1	1