MARINE ECOSYSTEM IMPACTS AND MANAGEMENT RESPONSES UNDER 21ST CENTURY CLIMATE CHANGE

by

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Submitted in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

at

Dalhousie University
Halifax, Nova Scotia
August 2020

“And while distant projections are necessarily blurry,
the path ahead is not unknowable”
— Ed Yong

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ABSTRACT

Climate change is affecting marine ecosystem structure and function on multiple scales with consequences for ecosystem services, fisheries, and fishery-dependent societies. Projecting future trends and associated uncertainties is important for enhancing understanding of marine processes under climate change, and critical for guiding management and policy at international and national levels. The Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP) represents the first attempt to project marine ecosystem responses to climate change using an ensemble modeling approach, which integrates multiple models to provide a more complete representation of ecosystem processes. Using an ensemble of six global marine ecosystem models within Fish-MIP, I analyzed spatio-temporal changes in marine ecosystems over the 21st century on global to regional scales and evaluated associated challenges for national and international fisheries management. Across major ocean basins, ensemble projections revealed substantial reductions in ecosystem production in most basins except polar, where biomass was projected to increase over the 21st century. Projections across Canada's Exclusive Economic Zone revealed decreasing ecosystem production in the Canadian Pacific and Atlantic, whereas ecosystem production in the Canadian Arctic increased by 2100, albeit with high projection variability indicating a broad range of potential future trajectories. Ensemble projections within the Northwest Atlantic Fisheries Organization (NAFO) convention area demonstrated regional differences in the direction and magnitude of projected changes. Projected biomass increased in northern NAFO regions, which historically have relatively low fisheries landings, and declined in more southern regions with relatively high historical fisheries landings, such as the Grand Banks off Newfoundland, indicating long-term challenges for management authorities. Across all spatial scales, ecosystem changes were generally higher under the high emissions scenario but could be greatly reduced through climate-change mitigation efforts. Reviewing fisheries management policies and legislations in selected nations highlighted growing evidence that many fisheries are experiencing climate-change impacts, yet mandated climate-change adaptation was not explicitly addressed in any of the reviewed active fisheries management policies and legislations. However, some progress towards climate-informed stock assessments and decision-making was identified. Overall, this thesis uses a state-of-the-art ensemble modeling approach to contribute to a broader comprehension of future trajectories of global and regional climate-change impacts on ocean ecosystems and marine living resources. In addition, the assessment of progress in fisheries management towards integrating climate-change adaptation provides necessary stepping-stones to achieve climate-ready fisheries and fisheries management at multiple institutional scales in a changing ocean environment.

LIST OF ABBREVIATIONS USED

ABBREVIATION	DESCRIPTION
3D	3 Dimensional
ABNJ	Area Beyond National Jurisdiction
APECOSM	Apex Predators ECOSystem Model
BOATS	BiOeconomic mArine Trophic Size-spectrum
CCCA	Climate Change Conditioned Advice
CFP	Common Fisheries Policy
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
DBEM	Dynamic Bioclimate Envelope Model
DFO	Fisheries and Oceans Canada
DPBM	Dynamic Pelagic Benthic Model
EBFM	Ecosystem-based Fisheries Management
EEZ	Exclusive Economic Zone
EMFF	European Maritime and Fisheries Fund
ENSO	El Niño Southern Oscillation
ESM	Earth System Model
EU	European Union
FAO	Food and Agriculture Organization
Fish-MIP	Fisheries and Marine Ecosystem Model Intercomparison Project
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory Earth System Model Version 2M
GHG	Greenhouse Gas
HCR	Harvest Control Rule

IFQ	Individual Fisheries Quota
IPCC	Intergovernmental Panel on Climate Change
IPSL-CM5A-LR	Institut Pierre Simon Laplace Model Climate Model 5A Low Resolution
ISI-MIP	Inter-sectoral Impact Model Intercomparison Project
ITQ	Individual Transferable Quota
LME	Large Marine Ecosystem
MIP	Model Intercomparison Project
MPI	Ministry of Primary Industries
MSY	Maximum Sustainable Yield
NAFO	Northwest Atlantic Fisheries Organization
NMFS	National Marine Fisheries Service
NOAA	National Oceanic and Atmospheric Administration
NPP	Net primary production
NZ	New Zealand
OECD	Organization for Economic Co-operation and Development
RCP	Representative Concentration Pathway
SD	Standard deviation
SDG	Sustainable Development Goal
SST	Sea surface temperature
TAC	Total Allowable Catch
TAE	Total Allowable Effort
TURF	Territorial Use Rights for Fisheries
UNCLOS	United Nations Convention on the Law of the Sea
UNFCCC	United Nations Framework Convention on Climate Change
US	United States

ACKNOWLEDGEMENTS

Firstly, I would like to express my heartfelt gratitude to my advisor Heike Lotze for her continuous support throughout my PhD. I am thankful for her patience, motivation, interest, and immense knowledge she shared with me. Her guidance and insights, both dissertation and life related, helped me in all the time of research and writing of my thesis. I could not have imagined having a better advisor, mentor, and friend for my PhD study.

Furthermore, I like to thank my co-supervisor Derek Tittensor, for his help, encouraging support, and motivational reminders of why my research is relevant. I would like to thank my committee members Megan Bailey and Nancy Shackell, who have been very helpful and supportive. I especially appreciate the discussions sparked and questions asked.

My sincere thanks also goes to all my co-authors who I had the privilege to work with over the past years. Their motivation, interest and support was truly remarkable. Special thanks to Faelan Prentice, who always asked the right questions, and Dan Boyce, for sharing his ideas with me and showing incredible patience explaining statistics to me.

My thanks also goes out to all who supported me throughout my PhD: My wonderful lab-mates, for laughter, tears, costumes, and cakes. Coming to the lab, was like coming home. The TOSST program for invaluable financial support and a sense of community. The Writing Center for making me a better writer and teacher. Beaty for helping me setting healthy priorities in the sometimes arduous journey of completing a PhD. Bhupi, Scott, Tommy, Léa, Izzy, and Stephanie, for being my family abroad. And of course, special thanks to my friends all over the world, for love, laughter, postcards, and support

of all kinds. Lastly, and most importantly, I want to thank my family: My Mormor, who has always guided and encouraged me to follow my dreams. My wonderful parents and brothers, for their love, enthusiasm, and unconditional support.

CHAPTER 1
INTRODUCTION

1.1 CLIMATE-CHANGE IMPACTS ON MARINE ECOSYSTEMS

The global ocean is already being affected by anthropogenic climate change, with physical, chemical, and biological changes being observed at local to regional and global scales (Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), 2019; Intergovernmental Panel on Climate Change (IPCC), 2019). Ocean waters are warming, affecting oceanographic dynamics such as currents and water column stratification (IPCC, 2019). Climate-change induced shifts in multiple other physical or biochemical properties have also been observed, such as oxygen concentration, pH, salinity, and sea ice cover, which are decreasing in many regions (Bopp et al., 2013; IPCC, 2019).

Marine life from phytoplankton to whales is responding to these climate-change induced alterations in the environment. In some regions, intensified stratification of the water column is leading to reduced primary production, which can amplify through the food web, manifesting in reduced production at higher trophic levels (Bopp et al., 2013; Kwiatkowski et al., 2018). Among secondary producers, some species are impacted not only by reduced primary production but also by physiological responses in terms of effects on life-history traits such as growth rates, reproductive rates, survival, and body size (Cheung et al., 2013a; Free et al., 2019). Furthermore, as some marine habitats are becoming less suitable with continued climate change, for example due to the combined effects of warming waters and reduced primary production, many marine species are shifting their distribution towards more suitable environments, such as deeper or more offshore, colder waters or towards the poles (Dulvy et al., 2008; Cheung et al., 2013b; Pinsky et al., 2013; Cheung et al., 2010). The combination of individual- and species-level responses can result in altered interspecies interactions, such as predator-prey relationships and competition, leading to changes in ecosystem composition and dynamics (Friedland et al.; 2020; Pinsky et al., 2020).

Continued climate change is projected to increasingly impact ocean ecosystems and marine life (IPCC, 2019; Lotze et al., 2019). By the end of the 21st century, global sea surface temperature is projected to increase by 3˚C under the high emissions scenario, whereas surface pH and oxygen content are projected to decrease in the absence of climate-change mitigation measures (IPCC, 2019). Throughout the 21st century, average global primary production is projected to decline by -8.6% (± 7.9%) (Bopp et al., 2013) and biomass of secondary producers by -17% (± 11%) under the high emissions scenario in response to warming temperatures, reduced primary production, and shifts in other oceanographic properties (Lotze et al., 2019). Regionally, these projected impacts are not uniformly distributed, with many polar regions projected to experience increases in ecosystem productivity and many temperate to tropical regions to face reductions either in line with or above global rates (Bryndum-Buchholz et al., 2019, 2020; Lotze et al., 2019).

These impacts on marine ecosystems also affect the services they provide and the human societies that depend on them (IPCC, 2019; Boyce et al., 2020). Climate-driven marine ecosystem changes are impacting fisheries through changes in the availability of target stocks as they shift in distribution and productivity, as well as catch volume and composition as abundance of target and newly emerging stocks increase or decrease in response (Cheung et al., 2013b; Free et al., 2019). This can directly impact fisheries yields and regional seafood supply, affecting livelihoods and food security, with some regional variation in whether these impacts are positive or negative (Barange et al., 2014; Blanchard et al., 2017). With ongoing climate change, it is critical to understand how future changes may impact marine ecosystems and associated fisheries and their management.

1.2 CLIMATE-CHANGE IMPACTS ON COMMERCIAL FISHERIES AND THEIR MANAGEMENT

Globally, one third of fish stocks targeted by wild capture fisheries are overexploited (Food and Agriculture Organization (FAO), 2018), which represents an ongoing management challenge. With climate change adding additional pressure on marine ecosystems and fish stocks, effective and climate-adaptive management of commercial fisheries is critical for long-term provision of fish protein and to support of millions of livelihoods (FAO, 2018; Gaines et al., 2018; IPCC, 2019).

With target populations changing productivity levels and shifting towards deeper, more offshore waters or polar latitudes, some fisheries operations may be economically challenged in terms of increased travel time to reach profitable fishing grounds, as well as through the decline or loss of targeted resources (Pinsky & Fogarty, 2012; Pershing et al., 2015). Further, regional shifts in species composition, for example due to expanding or shrinking thermal habitats, can affect regional fisheries in terms of catch composition or volume of target species (Cheung et al., 2013b; Friedland et al., 2020). These changing conditions may also allow for new target species to emerge, providing opportunities to exploit new fisheries resources. How these changes may play out at different spatial scales under climate change is critical to understand to inform national and international fisheries management institutions, such as the North Atlantic Fisheries Organization (NAFO), the intergovernmental organization responsible for scientific advice and management of fisheries resources outside national waters in the Northwest Atlantic (Koen-Alonso et al., 2019; see Chapter 2).

Fisheries management needs to adapt to climate-change related shifts in marine resources, both to ensure the sustainability of existing fisheries and to avoid uncontrolled harvesting of emerging resources (Pinsky & Mantua, 2014; Pinsky et al., 2018). Unfortunately, climate-change responsive fisheries management is not yet widely adopted (see Chapter 2, Chapter 5), in part due to the lack of political incentives to acknowledge and prepare for climate-change impacts, rigid institutional structures that impede the adopting of new management approaches, or simply the lack of adaptive capacity (Termeer et al., 2016). Consequently, in regions in which management measures have not been adequately adjusted to climate-related environmental and stock changes, some fisheries have collapsed (Pershing et al., 2015; Le Bris et al., 2018). On the other hand, management measures that account for and effectively respond to climate-change impacts on commercial stocks can help to ensure long-term sustainable fisheries (Gaines et al., 2018; Le Bris et al., 2018). Globally, how do jurisdictions around the world currently adapt – or plan to adapt – to a changing climate and its consequences on their fisheries? This question is important to address to help understand current progress, or lack thereof, and to help facilitate widespread climate-change adaptation in fisheries management.

1.3 MARINE ECOSYSTEM MODELING AND THE ENSEMBLE MODEL APPROACH

Modelling the impacts of climate change on marine ecosystems on a global scale is a relatively new research field, with many global marine ecosystem models having only been created in the past decade (e.g. Cheung et al., 2010; Maury, 2010; Blanchard et al., 2012; Carozza et al., 2013; Jennings & Collingridge, 2015; Tittensor et al., 2018a). These ecosystem models can use the output of Earth System Models (ESMs) to project the ecosystem effects of climate change in the global ocean. The ESMs are forced by scenarios of greenhouse gas (GHG) emissions to derive a spatially explicit global coverage of physical, chemical, and biological (e.g. primary productivity) changes. Until recently, most studies have used one or more ESMs in combination with a specific marine ecosystem model (Cheung et al., 2010; Blanchard et al., 2012; Barange et al., 2014) to simulate climate-change projections. However, with individual models having specific assumptions, structures, and processes, each represents a particular encapsulation of necessarily incomplete and simplified marine ecosystems dynamics (Tittensor et al., 2018a; Lotze et al., 2019). Additionally, a single-model approach makes it difficult to assess the relative importance of sources of uncertainties within projections, which is critical to advance model development and increase the validity of projections (Lotze et al., 2019). To overcome these limitations and understand the strengths and weaknesses of individual models, it is important to force them using standardised inputs and compare and combine them into ensemble projections (Schellnhuber et al., 2013; Tittensor et al., 2018a).

The systematic intercomparison of multiple models is standard for the physical dimensions of climate change (e.g. Coupled Model Intercomparison Project (CMIP), https://esgf-node.llnl.gov/search/cmip5/). However, it has only recently been introduced to the global ocean ecosystem realm (Tittensor et al., 2018a; Lotze et al., 2019). The Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP, www.fishmip.org) brings together multiple marine ecosystem models into a model ensemble, all forced by a standardized set of climate-change inputs and projected emission scenarios and producing standardized outputs (Tittensor et al., 2018a). The ensemble comprises disparate marine ecosystem models that differ widely in terms of how they represent food-web or ecosystem components and the links between them. For example, Fish-MIP includes species-distribution models, size-based models, trophic-dynamic models, and hybrid models (Tittensor et al., 2018a). Hence, the overall ensemble reflects a broader representation of key ecosystem processes, or at least a greater variety of conceptions of this, than any single model (Tittensor et al., 2018a).

Several studies on future climate-change impacts on the global ocean have used the Fish-MIP ensemble outputs (e.g. Blanchard et al., 2017; Lotze et al., 2019); however, they have not been applied and examined at the ocean basin or regional scale. This gap is important to address since climate-related changes in marine ecosystem structure and functioning are expected to differ between regions and across spatial scales (Fossheim et al., 2015). Further, focusing on an ocean basin or regional scale is more relevant for national or regional management of marine biodiversity and fisheries. In this thesis, I use the Fish-MIP ensemble approach to assess future marine ecosystem changes on different temporal scales (annual, 2030s, 2090s) and spatial scales including ocean basins, the Northwest Atlantic Fisheries Organization (NAFO) convention area, and the Canadian Exclusive Economic Zone (EEZ), and examine current and future challenges for national and international fisheries management.

1.4 STRUCTURE OF THESIS

My thesis is divided into six chapters. The general introduction given here is followed by four chapters analyzing climate-change impacts on marine ecosystems at global and regional scales, using the Fish-MIP ensemble-modeling approach, and examining implications for marine fisheries and their management. Throughout Chapters 2-4, I used outputs from the first round of simulations within Fish-MIP that were provided by modeling groups familiar with each global ecosystem model (Tittensor et al., 2018a,b). In Chapter 2, I compare historical and projected climate-change impacts on marine ecosystems across all major ocean basins, including the Arctic Ocean, the North and South Atlantic and Pacific Ocean basins, the Indian Ocean, and the Southern Ocean. This provides a general overview of long-term trends in ecosystem production and structure under 21st century climate change and associated model uncertainties and represents the first study to do this on an ocean basin scale using an ensemble-modeling approach. Chapter 3 focusses on near-future (2030s) and far-future (2090s) climate-change impacts on the North Atlantic Ocean ecosystem, and the potential challenges these changes pose for fisheries and fisheries management in the Northwest Atlantic Fisheries Organization (NAFO) convention area. Understanding future trajectories and underlying projection uncertainties is imperative for ensuring long-term productive and sustainable marine capture fisheries under climate change. In Chapter 4, I then analyze projected 21st century changes within Canada's Exclusive Economic Zone (EEZ) including the Canadian Atlantic, Pacific and Arctic Ocean ecosystems under two contrasting climate-change scenarios. This chapter represents a case study of climate-change impacts on high latitude ecosystems, which are expected to substantially alter with continuing and unmitigated climate change. It provides information on regional differences in the magnitude and direction of climate-related ecosystem changes which can inform regional conservation and management measures. Chapter 5 reviews current national fisheries management policies and legislation across nine nations to compare and assess current progress and gaps around incorporating climate-change adaptation objectives. Based on the review, I formulate five recommendations of how to achieve climate-adaptive fisheries management in the context of explicit climate-adaptation objectives on a national and international fisheries policy and legislative level, as well as on the implementation of explicit management approaches and tools. This provides a way forward for adapting fisheries management and harvesting practices that account for climate-change impacts on marine ecosystems, fish stocks, and the societies that depend on them. Finally, Chapter 6 provides a general summary of my research results and their significance in contributing to current scientific knowledge and fisheries management in a changing ocean. Overall, my work, using a state-of-the-art ensemble-modeling approach across multiple spatial and temporal scales, aims to contribute to an improved understanding of future trajectories of climate-change impacts on our oceans and the living marine resources we depend on.

1.5 STATEMENT OF CO-AUTHORSHIP

This thesis contains three data chapters (Chapters 2, 3 and 4) and one literature review chapter (Chapter 5). Each chapter corresponds to a scientific manuscript structure (Abstract, Introduction, Material and Methods, Results, Discussion, and Conclusion) for publication in a peer-reviewed, scientific journal. For all published chapters, I was the main contributor of the research design, data analyses, and manuscript preparation. The number of co-authors for each data chapter is due to the contribution of individual model results and their interpretation from the different ecosystem model providers, as required by the Fish-MIP co-authorship policy. All co-authors contributed to the manuscripts through providing results, comments, advice and support in the research design and method development, as well as in the interpretation of results. The publication status of each chapter at the time of submission of this thesis is as follows:

Chapter 2 (published): **Bryndum-Buchholz A.**, Tittensor D.P., Blanchard J.L., Cheung W.W., Coll M., Galbraith E.D., Jennings, S., Maury, O., & Lotze H.K. (2019). Twenty-first-century climate-change impacts on marine animal biomass and ecosystem structure across ocean basins. *Global Change Biology*, *25*(2), 459–472. https://doi.org/10.1111/gcb.14512

Chapter 3 (in review after revision): **Bryndum-Buchholz, A.**, Boyce, D.G., Tittensor, D.P., Christensen, V., Bianchi, D., & Lotze, H.K. (2020. Climate-change impacts and fisheries management challenges in the North Atlantic Ocean. *Marine Ecology Progress Series* (In press).

Chapter 4 (published): **Bryndum-Buchholz, A.**, Prentice, F., Tittensor, D.P., Blanchard, J.L., Cheung, W.W., Christensen, V., Galbraith, E.D., Maury, O., & Lotze, H.K. (2020). Differing marine animal biomass shifts under 21st century climate change between Canada's three oceans. *FACETS*, *5*(1), 105-122. https://doi.org/10.1139/facets-2019-0035

Chapter 5 (in preparation for submission): **Bryndum-Buchholz, A.**, Tittensor, D.P., & Lotze, H.K. Climate-change adaptation in fisheries management: Policy, legislation, and implementation.

1.6 DATA ACCESSIBILITY

Fish-MIP data reported in this thesis are archived and publicly available at:

https://doi.org/10.5880/PIK.2018.005

CHAPTER 2
21ST CENTURY CLIMATE-CHANGE IMPACTS ON MARINE ANIMAL BIOMASS AND ECOSYSTEM STRUCTURE ACROSS OCEAN BASINS[1]

2.1 ABSTRACT

Climate-change effects on marine ecosystems include impacts on primary production, ocean temperature, species distributions and abundance at local to global scales. These changes will significantly alter marine ecosystem structure and function with associated socio-economic impacts on ecosystem services, marine fisheries, and fishery-dependent societies. Yet how these changes may play out among ocean basins over the 21st century remains unclear, with most projections coming from single ecosystem models that do not adequately capture the range of model uncertainty. We address this by using six marine ecosystem models within the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP) to analyze responses of marine animal biomass in all major ocean basins to contrasting climate-change scenarios. Under a high emissions scenario (RCP8.5), total marine animal biomass declined by an ensemble mean of 15-30% (±12-17%) in the North and South Atlantic and Pacific, and the Indian Ocean by 2100, whereas polar ocean basins experienced a 20-80% (±35-200%) increase. Uncertainty and model disagreement were greatest in the Arctic and smallest in the South Pacific Ocean. Projected changes were reduced under a low (RCP2.6) emissions scenario**.** Under RCP2.6 and RCP8.5, biomass projections were highly correlated with changes in net primary production and negatively correlated with projected sea surface temperature

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[1] Bryndum-Buchholz, A., Tittensor, D.P., Blanchard, J.L., Cheung, W.W.L, Coll, M., Galbraith, E.D., Jennings, S., Maury, O., & Lotze, H.K. (2019). 21st century climate-change impacts on fish biomass and ecosystem structure across ocean basins. *Global Change Biology*, *25*(2), 459-472.

increases across all ocean basins except the polar oceans. Ecosystem structure was projected to shift as animal biomass concentrated in different size-classes across ocean basins and emissions scenarios. We highlight that climate-change mitigation measures could moderate the impacts on marine animal biomass by reducing biomass declines in the Pacific, Atlantic, and Indian Ocean basins. The range of individual model projections emphasizes the importance of using an ensemble approach in assessing uncertainty of future change.

2.2 INTRODUCTION

Major biological changes in the structure and functioning of marine ecosystems have been associated with a changing climate both in the past (e.g. Harnik et al., 2012; Yasuhara & Danovaro, 2016) and in future projections (e.g. Cheung et al., 2009; Worm & Lotze, 2016; Pecl et al., 2017). These include changes in ocean productivity (Boyce et al., 2010; Moore et al., 2018) and species distribution and abundance (Perry et al., 2005; Cheung et al., 2009; Pinsky et al. 2013; Lefort et al., 2015) at local to global scales. Over the coming century, these changes will have significant consequences for marine ecosystem structure and functioning as well as for ecosystem goods and services, such as the provisioning of food from fisheries and aquaculture, the production of oxygen, and storage of anthropogenic carbon (Vichi et al., 2011; Pörtner et al., 2014). Several studies have projected future changes in marine animals at the scale of Large Marine Ecosystems (LMEs; Blanchard et al., 2012), coastal seas (Barange et al., 2014) and the global ocean (Cheung et al., 2010; Blanchard et al., 2017; Galbraith et al., 2017; Lotze et al., 2019), yet how the ecological changes may play out in different ocean basins have not been comprehensively explored.

With climate change affecting oceanographic and biological dynamics at multiple temporal and spatial scales, rates of change in marine ecosystem structure and functioning are expected to differ between ocean basins (Fossheim et al., 2015). For instance, marine organisms respond to increasing ocean temperatures through distributional shifts, with expected regional shifts toward colder deeper or further offshore (Cheung et al., 2009; Pinsky et al., 2013), as well as global range expansions towards higher latitudes, and range retractions at equatorial boundaries (Cheung et al., 2009, 2013b; Fossheim et al., 2015). Furthermore, regional surface temperatures in polar marine ecosystems are increasing twice as fast as the global average, leading to a borealization of Arctic marine animal communities, with decreasing abundance of species with polar affinity and increasing abundance of boreal species (Hoegh-Guldberg & Bruno, 2010; Fossheim et al., 2015). In contrast, overall species abundance in semi-enclosed seas (i.e., the Mediterranean Sea, Baltic Sea) and tropical ocean basins are expected to decline in the future changing ocean (Cheung et al., 2013b).

Modeling climate-change impacts on marine ecosystems at a global scale is a relatively new research field, with many global marine ecosystem models only developed in the past decade (Maury, 2010; Blanchard et al., 2012; Cheung et al., 2013b; Christensen et al., 2015; Jennings & Collingridge, 2015; Carozza et al., 2016). Using outputs (e.g., temperature, currents, primary productivity, ice cover) from global Earth System Models (ESMs) forced by projected greenhouse gas emissions and concentrations scenarios, such marine ecosystem models can derive global ocean patterns of biological changes. So far, most studies have forced a single marine ecosystem model using one or several ESMs (Cheung et al., 2011; Barange et al., 2012; Blanchard et al., 2012; Jones et al., 2015), which can considerably underestimate the range of projection uncertainty by not accounting for the variability due to differing representations of the underlying marine ecosystem. To address this limitation, it is important to compare models and to combine them into ensemble projections, which can lead to a better understanding of the sources of uncertainty, provide more coherent projections to policy-makers that properly account for this uncertainty, and thus advance the field of marine ecosystem modeling. While such comparisons are technically challenging, they can inform our understanding of the strengths and weaknesses of each modeling approach and help to guide further model improvements and ultimately improve projections of plausible futures (Schellnhuber et al., 2013; Tittensor et al., 2018a).

Here we used models in the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP), an international network that brings together different marine ecosystem modeling approaches (Tittensor et al., 2018a), to better understand and project long-term climate-change impacts on fisheries and marine ecosystems at ocean basin scales. Specifically, we analyzed how consistent or different mean trends and the spread of model projections were across ocean basins. We used six different global marine ecosystem models, forced by two different ESMs and two greenhouse gas emissions scenarios, to analyze future changes in total marine animal biomass, and the biomass of three marine animal size-classes to explore changes in ecosystem structure, across seven major ocean basins around the globe. The six ecosystem models are founded on a broad range of assumptions, from macro-ecological concepts focusing on size groups or body mass classes to species-distribution models based on commercially exploited species. Our aims were to (1) improve our understanding of climate-change induced trajectories of marine animal biomass in different regions of the future ocean over the 21st century; and (2) facilitate marine ecosystem model advances through model intercomparison across different ocean basins.

2.3 MATERIALS AND METHODS

2.3.1 Data sources

Historical (1970-2005) and future (2006-2100) projections of unfished global marine animal biomass (total animal biomass, biomass >10cm, biomass 10-30cm, and biomass >30cm; vertebrates and invertebrates of trophic level >1, except for zooplankton) under different climate-change scenarios were extracted from the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP v1.0; Tittensor et al., 2018a, b; Data access: http://doi.org/10.5880/PIK.2018.005). The projections included outputs from six different global marine ecosystem models (Table A.1): BOATS (Carozza et al., 2016; Carozza et al., 2017), Macroecological (Jennings & Collingridge, 2015), DPBM (Blanchard et al., 2012), DBEM (Cheung et al., 2011), EcoOcean (Christensen et al., 2015), and APECOSM (Maury, 2010). Each marine ecosystem model was forced with standardized output from two Earth System Models (ESMs; Table A.2) and greenhouse gas emissions scenarios (Representative Concentration Pathways, RCPs) following the Fish-MIP simulation protocol (Tittensor et al., 2018a). ESM outputs were derived from the CMIP5 database (https://esgf-node.llnl.gov/search/cmip5/) and bracketed a wide range of projected climate system changes, with GFDL-ESM2M representing moderate and IPSL-CM5A-LR strong changes in, for example, sea surface temperature and oceanic primary productivity (Bopp et al., 2013). ESM outputs were post-processed to provide forcing inputs at the temporal and spatial resolution required by the ecosystem models (typically one degree spatial resolution and one month or one year temporal resolution, and vertically integrated or vertically specific variables; Table A.1, A.2). Which specific ESM output variables were used and how each was implemented depended on the respective ecosystem model. For example, DBEM used SST, NPP, zooplankton carbon concentration, current speed, dissolved oxygen, pH, and salinity to model changes in species' habitat suitability (Table A.1, A.2). In contrast, the Macroecological model used changes in NPP and water temperature to model changes in production of size-structured pelagic communities. Specific details for each ecosystem model, including the spatial, vertical, and temporal resolution of forcing variables are given in Tables A.1 and A.2.

For this study, we selected two contrasting emissions scenarios: RCP2.6 characterizes a low emissions or high climate-change mitigation scenario, assuming that greenhouse gas emissions peak at 2010-2020 and decline substantially until 2100 (van Vuuren et al., 2011); RCP8.5 characterizes a high emissions pathway assuming a continuous increase in emissions until 2100 while not including specific climate-change mitigation targets (Riahi et al., 2011). As projections including fishing impacts were only available for three marine ecosystem models, and spatially explicit future fisheries projections are as yet unavailable, we chose to focus on runs under a no-fishing scenario, thus isolating climate-change effects on marine animal biomass (Tittensor et al., 2018a).

2.3.2 Data analysis

Projected time-series for historical and future marine animal biomass (g C m^{-2}) for BOATS, Macroecological, DPBM, DBEM, EcoOcean, and APECOSM were extracted on a 1x1 degree spatial grid for seven ocean basins: North Atlantic Ocean, South Atlantic Ocean, North Pacific Ocean, South Pacific Ocean, Indian Ocean, Arctic Ocean, and

Southern Ocean (Figure 2.1). The forcing variables of sea surface temperature (SST; °C) and net primary production (NPP; mol m^{-3} s^{-1}) from GFDL-ESM2M and IPSL-CM5A-LR were extracted for the same ocean basins over the same time scales.

For the ocean basin data subsetting, we selected each grid cell centroid located within the respective ocean basin boundaries using ArcMap 10.5 (ESRI, 2017) and combined the individual cells into an ocean basin annual mean using the statistical software R 3.4.3 (R Core Team, 2017).

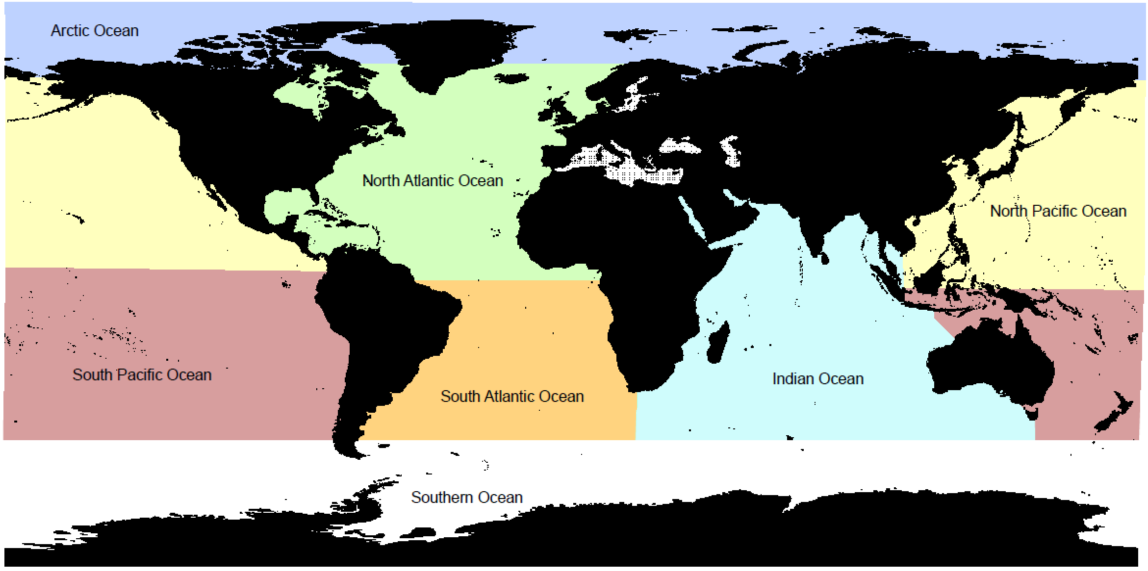


Figure 2.1: Overview of ocean basin boundaries for this study (basin boundaries modified from International Hydrological Organization, 1953). Note that the Mediterranean Sea, Black Sea, and Baltic Sea were excluded from our analysis (gray cross-pattern on map).

2.3.3 Temporal changes in marine animal biomass, SST, and NPP

The marine ecosystem models included in this study account for different species, size-classes or trophic groups of marine animals (Table A.1; Tittensor et al., 2018a). Hence for each ocean basin and individual marine ecosystem model-ESM combination we calculated proportional biomass change time-series by deriving annual mean changes in total marine animal biomass relative to the average of the 1990-1999 (as a historical reference period). These individual time-series of relative change were then averaged to derive an ensemble mean change. We also calculated proportional biomass changes for each ocean basin in the 2090s relative to the 1990s. A similar approach was used for SST and NPP forcing data. As our measure of variability around the ensemble mean of marine animal biomass projections we used a one inter-model standard deviation.

2.3.4 Model agreement in projected biomass changes

Model agreement in projected total biomass changes was assessed for the complete ensemble of all ecosystem model-ESM combinations. As measures of model agreement, we used a robustness index (ensemble mean/inter-model standard deviation; Bopp et al., 2013) as well as the percent model agreement in the direction (increase or decrease) of projected changes in the 2090s relative to 1990s. A robustness index >1 indicated high robustness (SD < mean) and an index <1 low robustness (SD > mean) in marine animal biomass projections across ecosystem models (Bopp et al., 2013). For the percent model agreement, 80-100% of models agreeing on the direction of change in marine animal biomass change was assumed to represent high agreement in the ensemble projections (Bopp et al., 2013).

2.3.5 Sources of variability in ensemble projections

We compared the relative variability or inter-model spread in projected total marine animal biomass changes due to variability in (i) the different ESMs and (ii) the different marine ecosystem models under the low and high emissions scenarios (RCP2.6 and RCP8.5). For i) we calculated the mean standard deviation between individual ecosystem model results forced by GFDL-ESM2M and IPSL-CM5A-LR (n=4: for marine ecosystem models forced by both ESMs). Next, we calculated the mean standard deviation across ecosystem models to derive the mean variability in our ensemble projections due to ESMs. For ii) we calculated the inter-model standard deviation of marine ecosystem models for GFDL-ESM2M and IPSL-CM5A-LR separately. Then we calculated the mean of the standard deviations from both ESMs for each ocean basin to derive the variability due to marine ecosystem models.

2.3.6 Changes in animal size structure

To examine climate-change impacts on ecosystem structure, we analyzed differences in climate-change impacts under RCP2.6 and RCP8.5 on the biomass of marine animals in small (0-10cm), medium (10-30cm) and large (>30cm) size-classes. Because DBEM did not distinguish between size-classes, this model was excluded from this analysis. Ecosystem models that modeled different biomass size-classes account for growth and movement between the size-classes (BOATS: Carozza et al., 2016; EcoOcean: Christensen et al., 2015; DPBM: Blanchard et al., 2011; APECOSM: Maury, 2010). The only exception being the Macroecological model, in which movements of individuals between size-classes was not considered as it is a static representation of the system (Jennings & Collingridge, 2015). Moreover, since BOATS did not have any size-classes <10cm, we could not calculate a small size-class for this model but included it in the medium and large size-classes. Note that excluding BOATS from the small-size class data set did not alter the overall results. For each distinct size-class, we calculated the percent relative change in biomass in the 2090s relative to the 1990s for each ecosystem-ESM combination and used box plots to derive the ensemble mean, median and inter-model variation.

2.3.7 Climate-change mitigation effect on biomass changes

Finally, we assessed climate-change mitigation effects on projected changes in total marine animal biomass for the model ensemble and individual ecosystem model-ESM means by subtracting the annual mean biomass change under RCP8.5 from RCP2.6. The obtained values represent the climate-change mitigation effect in terms of the difference between the projected percentage changes in total animal biomass under the high mitigation scenario (RCP2.6) and the no mitigation/high emissions scenario (RCP8.5).

2.4. RESULTS

2.4.1 Temporal changes in marine animal biomass, SST, and NPP

Our ensemble projections suggest that, in an unfished ocean and hence all impacts due entirely to changes in climate, total animal biomass in all basins except the polar oceans would be consistently lower by the end to the 21st century than at the beginning of the time-series under both low (RCP2.6; Figure 2.2) and high (RCP8.5; Figure 2.3) emissions scenarios (Table 2.1). Under RCP2.6, ensemble projections of total animal biomass in the North Atlantic and North Pacific Oceans projected sharp declines until 2040 (North Atlantic: 13%; North Pacific: 10%) and levelled off afterwards until 2100 (Figure 2.2). In the South Pacific, South Atlantic and Indian Oceans, lower rates of decline in total animal biomass were projected under RCP2.6 (Figure 2.2). In contrast, under RCP8.5, projected changes in total animal biomass reached >20% declines in the North Atlantic and North Pacific, and 10-20% declines in the South Atlantic, South Pacific and Indian Oceans until 2100 relative to the 1990s (Figure 2.3).

In the polar ocean basins, trends in ensemble biomass projections differed. In the Arctic Ocean, projected total animal biomass increased until the 2040s under both emissions scenarios. In subsequent years biomass changes stabilized under RCP2.6 (Figure 2.2) but started to decrease under RCP8.5 (Figure 2.3). Given the rate of increase until the 2040s, total animal biomass in the Arctic Ocean was projected to increase by 45% (±94% standard deviation) under RCP2.6 and 80% (±200%) under RCP8.5 in the 2090s relative to the 1990s (Table 2.1). While all 10 ecosystem-ESM combinations projected increases in animal biomass in the Arctic Ocean by the end of the 21st-century under RCP2.6, only half did so under RCP8.5 (Figure B.3, B.4; Table B.1). However, the magnitude of projected biomass changes in the Arctic varied substantially across models as indicated by the high inter-model standard deviation. In particular, DBEM projected substantially higher increases in animal biomass in the Arctic relative to the other models (Figure B.4), while the variability of projections among the other models was smaller. In the Southern Ocean, projections of total animal biomass showed relatively high variability throughout most of the time-series under both emissions scenarios; however, towards the end of the 21st century, ensemble projections indicated a 10% decline under RCP2.6 (Figure 2.2) and an 15% increase under RCP8.5 (Figure 2.3).

The temporal trends in projected total animal biomass generally corresponded to a combination of historical and future changes in net primary production (NPP) and sea surface temperature (SST) generated by the ESMs. Under RCP2.6, SST in all basins except the polar oceans was projected to increase by ~1°C until the 2040s and level off until 2100, with total animal biomass showing a corresponding 5-10% decline (Figure 2.2). NPP was projected to initially decrease by 3-10% until 2030 and either levelled off or increased in the North Atlantic and Pacific, the South Pacific, and Indian Ocean until 2100 (Figure 2.2). NPP projections under RCP2.6 in the South Atlantic Ocean did not show a clear trend throughout most of the 21st century, however, increased by 1-2% towards the end of the 21st century (Figure 2.2).

Under RCP8.5, ensemble projections of total animal biomass declined continuously until 2100 in the Atlantic Ocean (North Atlantic: 29%; South Atlantic: 13%), Pacific Ocean (North Pacific: 25%; South Pacific: 18.5%) and Indian Ocean (19%). Over the same period, SST was projected to continuously increase and NPP to continuously decrease, except in the South Atlantic for the latter (North Atlantic: +3.5°C and 13% decline in NPP; North Pacific: +4.1°C and 9% decline in NPP; South Pacific: +3.2°C and 5% decline in NPP; Indian Ocean: +3.3°C and 6% decline in NPP; Figure 2.3). In the South Atlantic Ocean, total animal biomass was projected to decline by more than 10% until the end of the 21st century with no substantial concurrent decline in NPP (0.36%) yet an SST increase of +3.4°C (Figure 2.3).

In the Arctic Ocean under RCP2.6, SST was projected to increase by 0.5°C by the 2030s and level off until 2100. NPP projections were relatively variable inter-annually (Figure 2.2, A2) but correlated with the projected SST changes by the end of the 21st century (Figure 2.2, B.1). Under RCP8.5, projections of SST continuously increased up to 2°C by 2100 (Figure 2.3). NPP showed a projected 25% increase until the 2040s with a 6% decrease thereafter, which correlated with the projected trend in total animal biomass changes (Figure 2.3). In the Southern Ocean, projected trends in SST and NPP under RCP2.6 were highly variable with no evidence for an underlying trend. This was reflected in the projected trends in total animal biomass (Figure 2.2). Patterns in projected SST, NPP and total animal biomass were similar under RCP8.5 (Figure 2.3).

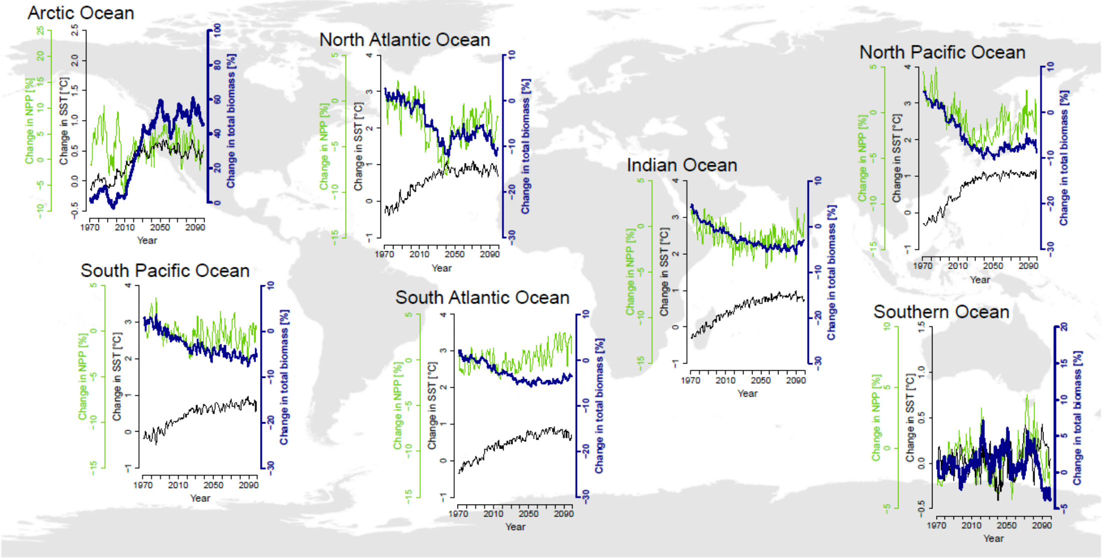


Figure 2.2: Ensemble means of projected historical and future marine animal biomass and environmental drivers (sea surface temperature, SST; net primary production, NPP) across ocean basins under high climate-change mitigation (emissions scenario RCP2.6) for 1970-2100. Total animal biomass and NPP trends are in percent change and SST trends in degree ˚C relative to 1990-1999. Note different axis for each variable and different axis scales in Arctic and Southern Ocean.

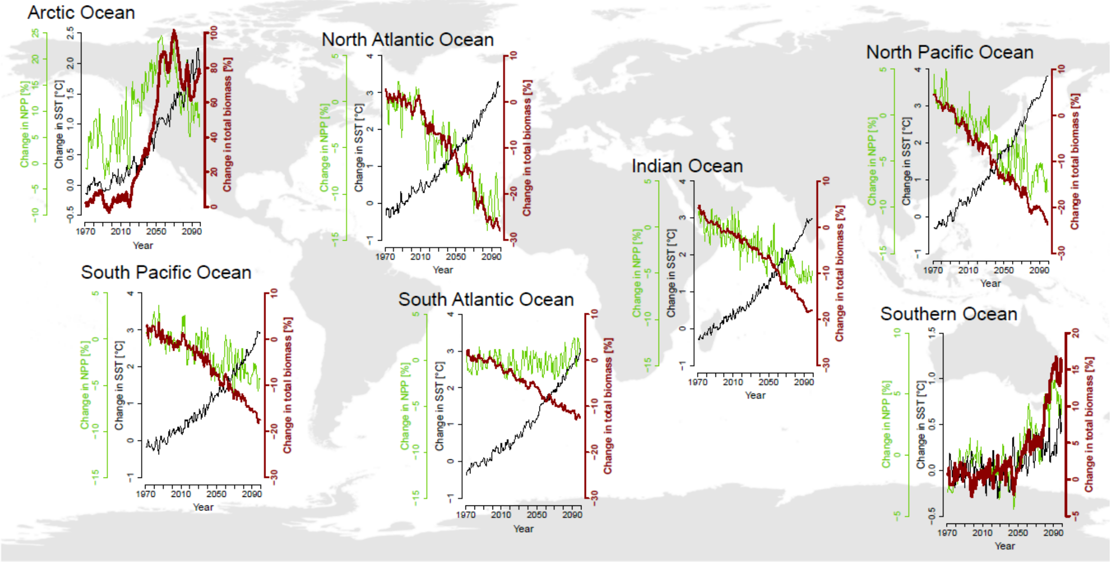


Figure 2.3: Ensemble means of projected and future total marine animal biomass and environmental driver (sea surface temperature, SST; net primary production, NPP) across ocean basins under low climate-change mitigation and strong climate change (emissions scenario RCP8.5) for 1970-2100. Total animal biomass and NPP trends are in percent change and SST trends in degree °C relative to 1990–1999. Note different axis for each variable and different axis scales in Arctic and Southern Ocean.

2.4.2 Model agreement in projected biomass changes

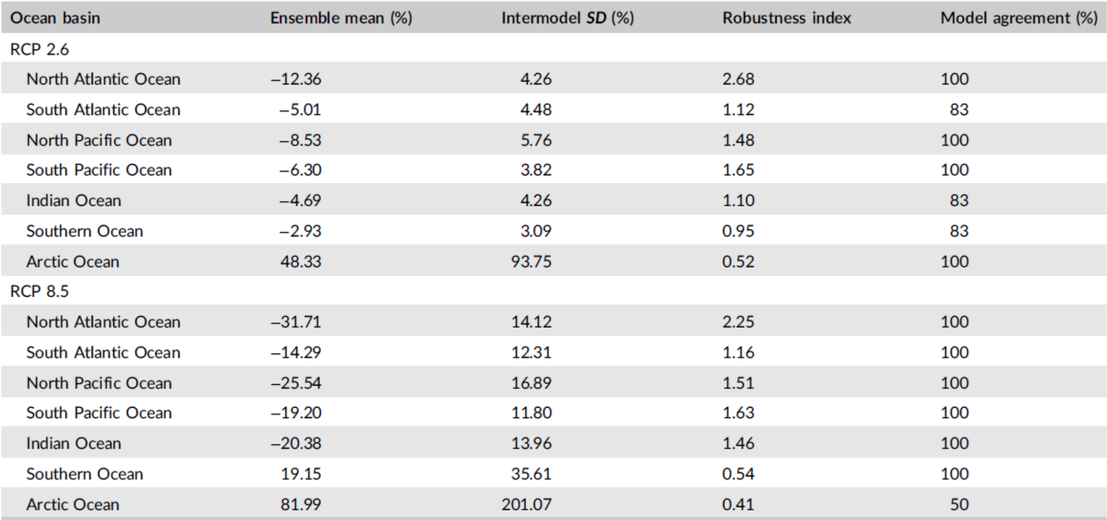
Our metrics of model agreement within the model ensemble revealed high robustness (>1) and high percentage model agreement in the direction of projected biomass changes (>80-100%) in all basins except the polar basins under both emissions scenarios (Table 2.1). For both RCP2.6 and RCP8.5 the highest robustness index of >2 was found in the North Atlantic Ocean (Table 2.1). In contrast, projections in the polar ocean basins under both emissions scenarios had low robustness indices (<1). Model agreement in the direction of change was high in both polar oceans under RCP2.6, but only in the Southern Ocean under RCP8.5 (Table 2.1). In the Arctic Ocean, under RCP8.5 only 50% of the included ecosystem models agrees on the direction of change in projected total animal biomass (Table 2.1, B.1; Figure B.3, B.4). Model spread, represented as one inter-model standard deviation of the ensemble mean, was lower under RCP2.6 than RCP8.5 across all ocean basins (Table 2.1; Figure B.3). Model spread ranged from ±3 to 6% under RCP2.6 across all basins except for the Arctic Ocean with ±94% (Table 2.1). Under RCP8.5, model spread was higher, ranging from ±12 to 17% in all ocean basins except for ±35% for the Southern Ocean and ±200% for the Arctic Ocean (Table 2.1).

2.4.3 Sources of variability in ensemble projections

Projections forced by GFDL-ESM2M and IPSL-CM5A-LR differed between most ocean basins (i.e., North Atlantic, North Pacific, Southern Ocean, Arctic Ocean; Figure B.3). However, the mean variability in total marine animal biomass projections under both emissions scenarios due to the ESMs was of similar magnitude to the mean variability due to the marine ecosystem models across all ocean basins (RCP2.6: 2-7%; RCP8.5: 4-10%) except in the Arctic Ocean (Figure B.5).

In the Arctic Ocean, mean variability of total animal biomass projections due to the marine ecosystem models was ~40% greater under RCP2.6 and ~70% greater under RCP8.5 than the mean variability due to the different ESMs (Figure B.5).

Table 2.1: Overview of ensemble projected of total marine animal biomass under climate change in different ocean basins.



Ocean basin	Ensemble mean (%)	Intermodel *SD* (%)	Robustness index	Model agreement (%)
RCP 2.6				
North Atlantic Ocean	−12.36	4.26	2.68	100
South Atlantic Ocean	−5.01	4.48	1.12	83
North Pacific Ocean	−8.53	5.76	1.48	100
South Pacific Ocean	−6.30	3.82	1.65	100
Indian Ocean	−4.69	4.26	1.10	83
Southern Ocean	−2.93	3.09	0.95	83
Arctic Ocean	48.33	93.75	0.52	100
RCP 8.5				
North Atlantic Ocean	−31.71	14.12	2.25	100
South Atlantic Ocean	−14.29	12.31	1.16	100
North Pacific Ocean	−25.54	16.89	1.51	100
South Pacific Ocean	−19.20	11.80	1.63	100
Indian Ocean	−20.38	13.96	1.46	100
Southern Ocean	19.15	35.61	0.54	100
Arctic Ocean	81.99	201.07	0.41	50

Note. Shown are the ensemble mean percent change in total animal biomass in 2090s relative to 1990s based on ensemble projections (*n* = 10 ecosystem model–Earth System Model combinations), and three ensemble agreement metrics: one intermodel standard deviation of the ensemble mean, robustness index (Bopp et al., 2013), and model agreement (%) in the direction of change. Robustness index >1 indicates high robustness; model agreement represents the agreement in the direction of change. RCP2.6 represents a strong climate-change mitigation scenario, RCP8.5 a high emissions scenario.

2.4.4 Changes in animal size structure

Our analysis of relative changes in the projected biomass of animals in different size-classes (large-sized animals: >30cm, medium-sized animals: 10-30cm, small-sized animals <10cm) showed that projected biomass in all size-classes decreased in the Pacific, Atlantic and Indian Ocean basins under RCP8.5 by the end of the 21st century (Figure 2.4). In the North and South Atlantic Ocean, a greater decrease in the mean biomass of medium-sized animals (North Atlantic: 29%; South Atlantic: 17%) was projected compared to small animals (North Atlantic: 24.5%; South Atlantic: 10%) and large (North Atlantic: 24%; South Atlantic: 12%) (Figure 2.4). The reverse was observed in the North Pacific Ocean, with mean projected biomass decreases of 13.5% in medium-sized animals, while biomass of large and small animals decreased by 21% and 23% respecitvely (Figure 2.4). The overall trends in the South Pacific Ocean did not change substantially across size-classes (small-sized animals: 13%; medium-sized animals: 12%; large-sized animals: 12%; Figure 2.4).

Similarly, in the Indian Ocean, projected trends in biomass under RCP8.5 did not differ substantially among size-classes (small-sized animals: 13.5%; medium-sized animals: 12%; large-sized animals: 14%; Figure 2.4). In contrast, the biomass of animals in all size-classes in the Southern Ocean were projected to increase by the end of the 21st century, with mean biomass of large animals projected to increase by ~10%, medium-sized animals by 5%, and small animals by 3% (Figure 2.4). In the Arctic Ocean, only biomass of large animals was projected to increase (by 5%), while mean biomass of medium-sized animals decreased by 10% and biomass of small animals by 5% (Figure 2.4). Under RCP2.6, biomass of all three size-classes in the Arctic Ocean was projected to increase, ranging from 15% for large animals to 5-7% for the medium and small size-classes, while only large animal biomass was projected to increase (2%) in the Southern Ocean (Figure B.6). The trends in projected biomass in different size-classes in the Pacific, Atlantic and Indian Ocean basins under RCP2.6 were similar in direction but smaller in magnitude than trends under RCP8.5 (Figure 2.4, B.6).

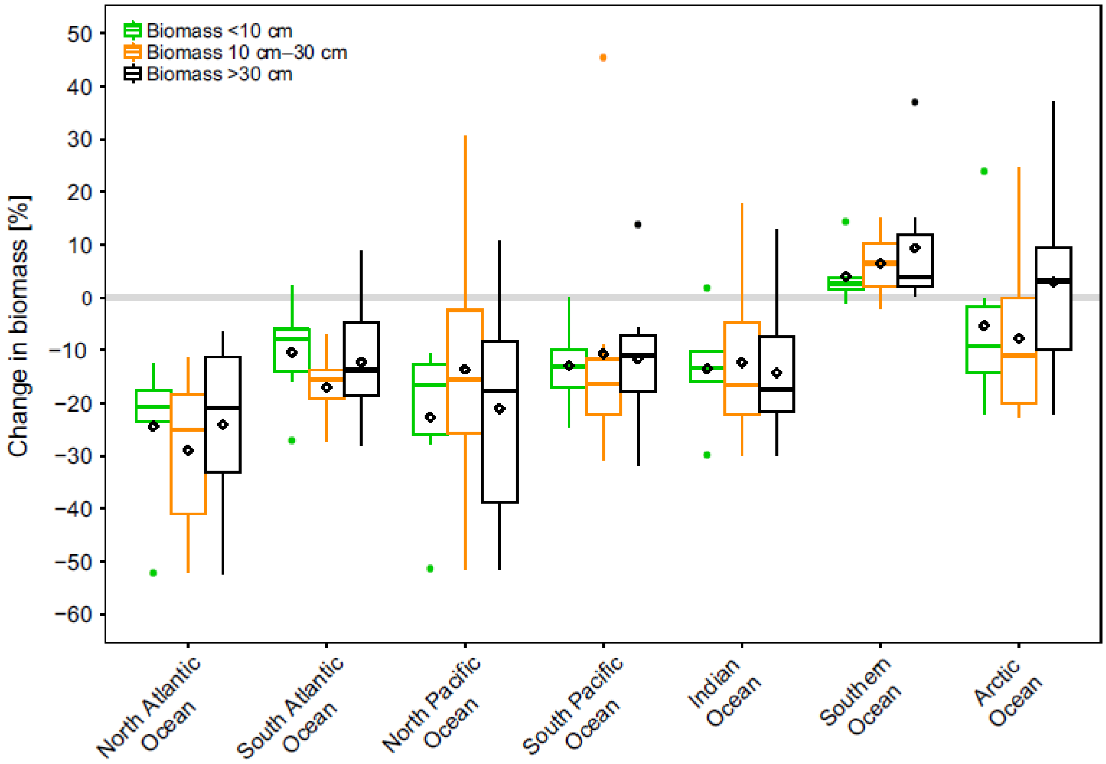


Figure 2.4: Model projections for marine animal biomass of three size-classes across ocean basins under climate change for the high emissions scenario RCP8.5. Marine animal size-classes: Small marine animals <10 cm (n = 6 ecosystem–Earth System Model combinations); medium-sized marine animals 10–30 cm (n = 8); and large marine animals >30 cm (n = 8). All changes are the mean of the 2090s relative to the 1990s. Boxplots: the upper and lower hinges correspond to the first and third quartiles; the upper/lower whiskers extend to the highest/lowest value within 1.5 times the interquartile range; horizontal lines within boxes correspond to the median; diamonds represent the mean; outlier dots represent data beyond the end of the whiskers. For changes under RCP2.6, see Appendix Figure B.6.

2.4.5 Climate-change mitigation effect on biomass changes

The climate-change mitigation effect on projected ensemble mean changes in total marine animal biomass was minor until 2050 in all ocean basins (mean mitigation effect over 2006-2049: +0.02%, ±1.87%; Figure 2.5) except for the Arctic Ocean, where climate-change mitigation was projected to lead to greater increases in mean animal biomass under the high mitigation scenario (RCP2.6) than under the no mitigation scenario (RCP8.5) until 2050 (mean mitigation effect over 2006-2049: +10.5%, ±7.4%;

Figure 2.5). After 2050, climate-change mitigation was projected to have a positive effect on biomass changes in most ocean basins, meaning climate-change mitigation would dampen projected climate-change induced biomass decreases (mean mitigation effect over 2050-2100: North Atlantic: 13%, ±5%; South Atlantic: 5%, ±2%; North Pacific: 10%, ±4%; South Pacific: 7%, ±3%; Indian Ocean: 9%, ±4%; Figure 2.5). However, for the Arctic and Southern Ocean, climate-change mitigation reduced the projected biomass increase towards the end of the 21st century (mean mitigation effect over 2050-2100: Arctic Ocean: -28%, ±13%; Southern Ocean: -7%, ±6%; Figure 2.5).

Climate-change mitigation effects on total animal biomass projections from 2050-2100 differed notably in magnitude between individual ecosystem models in all ocean basins except in the North Atlantic and South Pacific Ocean (Figure B.7). BOATS, Macroecological, and DBEM showed the largest climate-change mitigation effects from 2050-2100 in all ocean basins except polar basins, ranging from 9-13% (±3-5%) for BOATs to 6-20% (±4-8%) for the Macroecological model, and 8-17% (±3-7%) for DBEM. In comparison, mean climate-change mitigation effects from 2050-2100 reached 4-5% (±2%) for APECOSM, 3-4% (±1-2%) for DPBM, and 2-9% (±1-3%) for EcoOcean. In the Arctic and Southern Ocean, climate-change mitigation effects from 2050-2100 differed in magnitude and trend compared to the other basins (Figure B.7). Notably, in the Arctic Ocean all models, except for DBEM, showed a mean positive climate-change mitigation effect ranging from 4-10% (± 4-7%), while that for DBEM was -172% (±54%). In the Southern Ocean, most models showed a negative climate-change mitigation effect from 2050-2100, with DBEM showing a larger mitigation effect of -28% (±23%) than the other models (APECOSM -3% (±4%), BOATS -1.5% (±2), DPBM 0.2% (±2.5%), Macroecological model -3% (±4%), EcoOcean -4% (±5%)).

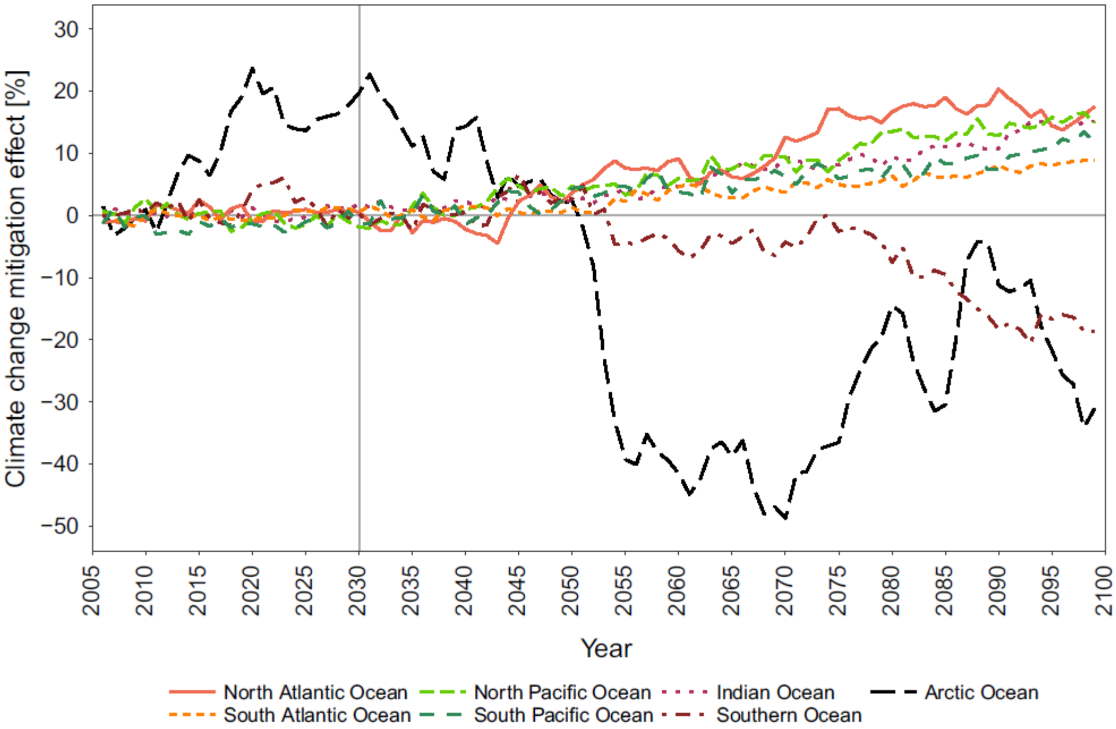


Figure 2.5: Climate-change mitigation effect (RCP2.6–RCP8.5) on ensemble projections of total marine animal biomass. Vertical line: target year for most UN Sustainable Development Goals.

2.5 DISCUSSION

Our ensemble models projected consistently lower marine animal biomass by the end of the 21st century compared to the end of the 20th century in all ocean basins except the polar oceans, where mean marine animal biomass was projected to increase, though with substantial variability between models. Variation around ensemble projections was generally lower under the strong climate-change mitigation scenario (RCP2.6) than the high emissions scenario (RCP8.5), and highest in the Arctic Ocean compared to all other ocean basins. Although we do not explicitly simulate mitigation pathways, our results based on the difference between RCP2.6 and RCP8.5 suggest that effective climate-change mitigation policies have the potential to substantially lower the magnitude of climate-change impacts on marine animal biomass across all ocean basins through 2100.

2.5.1 Ensemble projections in different ocean basins

In the North Atlantic and North Pacific, projected total marine animal biomass declined less under the strong mitigation (RCP2.6, 10% decline) than the high emissions scenario (RCP8.5, 20% decline), in line with the lower magnitude of projected changes in SST (RCP2.6: ~1˚C increase; RCP8.5: 3-4˚C increase) and NPP (RCP2.6: 3-5% decrease; RCP8.5: 8-13% decrease). In the South Atlantic, South Pacific and Indian Ocean, projected biomass declines were similar under RCP8.5 (~20%) yet reached only ~5% under RCP2.6 by the mid-21st century and levelled off afterwards. In these three ocean basins, projected NPP decreased less than in the North Atlantic and North Pacific, which is primarily due to differences in stratification and nutrient supply regimes in the Earth System Models (ESMs) used to force the marine ecosystem models in this study (Doney, 2010; Capotondi et al., 2012; Dunne et al., 2012; Dufresne et al., 2013). Thus, the differences in projected biomass declines between the two emissions scenarios can be partially explained by differences in environmental drivers the modelled marine organisms experience in the simulated future ocean, such as effects on the physiology of marine organisms (e.g. metabolic rates, growth, survival and trophic interactions) and availability of habitat (Cheung et al., 2009; Fu et al., 2016; Worm & Lotze, 2016). If a habitat becomes unsuitable for a given population, for example due to thermal stress, population size may decline as ecophysiological performance is negatively affected or species may shift their distribution to cooler waters (Pörtner, 2001; Pörtner & Knust, 2007; Cheung et al., 2013b). These effects play out differently in the different ecosystem models due to their varying structures and characterization of processes (Tittensor et al., 2018a), thus influencing the projected biomass trends. For example, projections by the species distribution model DBEM are strongly affected by changes in the availability of suitable habitat due to shifting temperature fields, ice cover and primary production. In comparison, biomass dynamics in the size-structured models are driven by size-dependent processes such as production and energy transfer (Macroecological, BOATS) or detailed size-dependent feeding processes, growth and mortality (DPBM) and size-dependent movement (APECOSM) which are all affected by changes in environmental forcing variables (Table A.2).

Ensemble projections in the Arctic suggested a 60% increase of total animal biomass until the mid-21st century followed by a stabilization under RCP2.6 and a decrease of 80% under RCP8.5 towards the end of the 21st century. In the Southern Ocean, conversely, ensemble projections showed only a slight biomass decrease (~10%) towards the end of the 21st century under RCP2.6 yet a continuous increase to ~15% under RCP8.5. The projected biomass increases in polar oceans until the mid-21st century can be attributed to processes such as immigrating marine animals from warmer waters as new habitats become available (Cheung et al., 2009), increasing water temperatures and primary production enhancing growth and survival (Frainer et al., 2017), and longer growing seasons influencing phenology (Racault et al., 2012). In our ecosystem model ensemble, the magnitude of the mean biomass increases in both the Arctic and Southern Ocean were primarily influenced by DBEM, which models species-specific habitats for commercial fish and invertebrates (Cheung et al., 2011). In the 1990s (our historical reference period), DBEM has only a few commercial species with relatively low biomass levels in the Arctic and Antarctic; thus, any newly invading commerical species and increasing growth results in large proportional changes in biomass. Thus, these results can be partly explained by the specific focus of this model. In contrast, all other ecosystem models (Macroecological, BOATS, DPBM, EcoOcean, and APECOSM) project bulk changes in marine animal biomass across different size-classes, functional and trophic groups due to changes in environmental factors affecting metabolic rates, energy transfer as well as trophic relationships (see Table A.1) and can include commercial and non-commercial species. Therefore, these models generally start with higher initial biomass in polar oceans meaning that proportional changes in the future are lower.

In the second half of the 21st century, the projected stabilization of biomass changes in the Arctic and Southern Ocean under RCP2.6 can be explained by changes in the forcing variables driven by strong climate-change mitigation policies (van Vuuren et al., 2011), as indicated by the levelling off in projected SST and NPP trends (Figure B.1, B.2). In contrast, under the high emissions scenario (RCP8.5), in which greenhouse gas emissions are projected to increase until 2100 (Riahi et al., 2011), the decline in projected total marine animal biomass in the Arctic may be attributed to continuing changes in the physical and biogeochemical environment, with consequences for the entire trophic network (Hillebrand et al., 2018). Indeed, longer-term projections of changes in ocean ecosystems until 2300 suggest a strong decline in ocean productivity in the Northern Hemisphere and its shift towards the Southern Ocean (Moore et al., 2018; Figure 2.3). In the Arctic, the projected late 21st century biomass decline under RCP8.5 was concurrent with a projected 20% decline in NPP during that period, likely attributed to enhanced stratification due to changes in water temperature and salinity with melting sea ice and permafrost (Fu et al., 2016). Large decreases in sea ice cover could also enhance light levels, leading to higher seasonal NPP (Leung et al., 2015). The loss of sea ice can also directly affect sea ice-dependent marine animals in both the Arctic and Southern Ocean, which rely on sea ice for reproduction, feeding or survival, ranging from krill (Antarctic krill in the Southern Ocean, *Calanus* copepods in the Arctic) to Arctic cod (*Boreogadus saida*) to many whale species, such as narwhales (*Monodon monoceros*) and killer whales (*Orcinus orca)* (Stenson & Hammill, 2014; Hillebrand et al., 2018; Macias-Fauria & Post, 2018). With krill and copepods representing a significant link between phytoplankton and higher trophic levels, sea ice loss is expected to lead to substantial modifications in the existing Arctic and Antarctic ecosystems and associated commercial and subsistence fisheries (Mcbride et al., 2014; Moore et al., 2018). However, only half of the marine ecosystem models accounted for changing ice dynamics (Table A.2), yet these did not necessarily agree on the direction of biomass change (Figure B.3, B.4); consequently, it is difficult to determine how much the projected biomass changes in the polar basins are due to changing ice cover and its implications for polar food webs.

2.5.2 Variability around ensemble projections

We used an ensemble model approach which included six marine ecosystem models forced with two different ESMs and different RCPs to project past and future marine animal biomass under different climate-change scenarios (Tittensor et al., 2018a, 2018b). The ensemble approach has the advantage that ecosystem models characterized by different model structure, processes and underlying assumptions are more likely to capture relevant features in complex ocean ecosystems than any single model (Spence et al., 2017; Tittensor et al., 2018a). The ensemble approach also allows for the ability to quantify uncertainties due to marine ecosystem models, which remains important information for policy-makers and managers but is unavailable from single model projections. Here we used metrics including variability around the ensemble mean, a robustness index and model agreement in the direction of change (Bopp et al., 2013; Tittensor et al., 2018a). Comparing results of different ecosystem models can also help to understand how projections are affected by different model structures and ecological processes. Thus, ensemble projections and model inter-comparison projects have emerged as an extremely useful approach in climate-impact sciences (Schellnhuber et al., 2013; Spence et al., 2017; Tittensor et al., 2018a).

High variability and uncertainty of ensemble results were detected in the Arctic and Southern Ocean. As discussed above, this may be partly due to the fact that DBEM projections of changes in habitat and associated population dynamics specifically focused on commercial fish and invertebrates (Cheung et al., 2011; Cheung et al., 2012), which are currently very low in abundance and may therefore lead to proportionally larger relative biomass changes in these regions due to changes in projected SST, NPP, ice cover, and other environmental variables. However, the general trends in biomass change projected in the polar oceans by DBEM did not differ from most of the other ecosystem models, suggesting broad agreement in the direction of projected changes over the coming century despite varying magnitudes. Overall, a general projected increase in total marine animal biomass in the Arctic and Southern Ocean, yet a decrease in the North and South Atlantic and Pacific and Indian Oceans may occur by the end of the 21st century under both emissions scenarios, which corresponds with the IPCC's Fifth Assessment

Report and other single- and multi-model studies (Pörtner et al., 2014; Blanchard et al., 2017).

2.5.3 Changes in ecosystem structure

In most ocean basins, the greater projected declines in biomass of medium-sized animals may be explained by the decline of their smaller-sized prey. In comparison, the reduced relative declines in the projected biomass of large animals may result from model structures and parameterizations which result in larger animals having access to a larger pool of available food sources (both medium- and small-sized animals), slower turnover times which result in lagged responses to changing ecosystem dynamics**,** as well as food competition effects due to increasing competition for small-sizes animals with the medium-sized animals (Perry et al., 2005; Lefort et al., 2015).

2.5.4 Climate-change mitigation

Based on our model ensemble, climate-change mitigation that reduces greenhouse gas emissions in line with RCP2.6 (van Vuuren et al., 2011) was projected to lessen the decreases in total marine animal biomass by 10-20% compared to the high emissions scenario (RCP8.5) in all non-polar oceans, but also dampen increases in polar oceans. Thus, with successful climate-change mitigation, declines in marine animal biomass in the North and South Atlantic and Pacific and the Indian Oceans could potentially be alleviated, particularly after the 2050s. This result was consistent across all ecosystem models, only differing in the magnitude of the climate-change mitigation effect. Along with recent projections of the mitigation effects on the timing of emergence of climate-change impacts on environmental drivers (Henson et al., 2017), our results suggest that climate-change impacts on marine ecosystems can be substantially reduced by successfully implementing mitigation measures. In the Arctic and Southern Ocean, climate-change mitigation also reduced projected impacts and led to lower changes in biomass, which resulted in reduced proportional biomass increases or even declines. However, the individual ecosystem models showed contrasting trends, with only DBEM projecting substantially reduced biomass increases. As discussed above, this result is likely due to different model structures and taxonomic scope. By slowing the pace of climate change and reducing impacts, climate-change mitigation would provide time and opportunity for adaptation and development of proactive ocean policies, such as in the context of marine conservation efforts and fisheries management strategies (Blanchard et al. 2017; Henson et al., 2017).

2.5.5 Caveats and future steps

The use of outputs from two ESMs (GFDL-ESM2M and IPSL-CM5A-LR) to force the marine ecosystem models represents a relatively small range of the set of ESMs available. However, as GFDL-ESM2M represents relatively weak and IPSL-CM5A-LR relatively strong changes in sea surface warming and net primary production over the 21st century, they bracket the spread of projections reasonably well (Bopp et al., 2013). Furthermore, most other ESMs in the CMIP5 database do not provide or have not stored the necessary monthly, depth-resolved outputs of different size groups of phyto- and zooplankton required by several of the global marine ecosystem models within Fish-MIP (Tittensor et al., 2018a; Table A.2). By choosing two ESMs representing the high and low end of projected future climate-change scenarios, our projected mean future change is comparable to the overall CMIP5 ensemble mean (Bopp et al., 2013). Future studies may have the possibility of including a larger range of ESMs and their outputs through the upcoming CMIP6, which will also provide higher resolution of biogeochemical variables (Ruane et al., 2016).

Another caveat is that coastal ecosystems and upwelling areas account for a large proportion of global primary production; however, the ESMs provide limited resolution of physical and biogeochemical processes in these systems (Holt et al., 2017; Bonan & Doney, 2018). To improve projections of biomass changes in these systems, regional downscaling of global ESMs is desirable to incorporate climate and ecosystem features at a higher resolution (Holt et al., 2017).

The selected ocean basins comprise areas that range from highly productive regions i.e. nutrient rich upwelling ecosystems (Canary and Benguela Current in the Atlantic Ocean, California and Humboldt Current in the Pacific Ocean) to low productivity regions i.e. warm, nutrient-poor subtropical gyres in the Atlantic, Pacific and Indian Ocean (Hoegh-Guldberg & Poloczanska, 2017). We acknowledge that our analysis does not account for regionalization within each ocean basin, which might mask substantial regional variation in marine animal biomass under global change. Future research could focus on a region by region scale using the Fish-MIP data to further our understanding on regionalized climate-change impacts on marine life.

While our ensemble model projections and analysis of model agreement contribute information on potential future changes in marine animal biomass and the spread of uncertainty around these changes, our study represents only the beginning of a systematic collaborative marine ecosystem model evaluation and intercomparison. To comprehensively improve ecosystem models participating in Fish-MIP, future effort should focus on improving our understanding of the mechanisms that drive individual model responses to forcing variables, such as by separating the forcings temperature and

NPP (Carozza et al. in press), evaluating uncertainty within and across models, and attempting to refine individual model predictions under climate change.

2.5.6 Implications and conclusions

At present, trends in greenhouse gas emissions are consistent with those assumed in the high emissions scenario (RCP8.5; Peters et al., 2012), under which total marine animal biomass was projected to decline by at least 10-20% in all but the polar ocean basins, where projected biomass increased by at least 15-80% over the 21st century. Such changes would have socio-economic and food security impacts on regional and global scales (Pörtner et al., 2014; Blanchard et al., 2017**).** However, we have also demonstrated the level of these changes can be greatly reduced through climate mitigation efforts – such as adopting policies on national and global scales that reduce the sources and enhance the sinks of long-lived anthropogenic greenhouse gases (Bonan & Doney, 2018) and moving towards meeting international climate mitigation agreements, such as the Paris Agreement within the United Nations Framework Convention on Climate Change.

2.6 ACKNOWLEDGEMENTS

We acknowledge the immense effort of all marine ecosystem modelers who contributed their expertise, time, and feedback to this study and the Fish-MIP initiative, particularly, T. Silva, D. Carozza, D. Bianchi, T. Eddy, N. Barrier, P. Verley, V. Christensen, and J. Steenbeek for running Fish-MIP simulations and providing ecosystem model outputs. We also thank L. Bopp, J. Dunne, C. Stock, and T. Roy for providing ESM outputs, M. Büchner, J. Volkholz, and J. Schewe for technical support, and D. Boyce for valuable discussions and comments. Financial support was provided by the German Federal

Ministry of Education and Research (BMBF, grant no. 01LS1201A1) and through the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP). ABB acknowledges financial support from the NSERC CREATE Transatlantic Ocean Science and Technology Program, HKL from the Natural Sciences and Engineering Research Council (NSERC) of Canada, and DPT from the Kann Rasmussen Foundation Denmark. The authors declare that they have no conflict of interest.

2.7 AUTHOR CONTRIBUTIONS

Concept and design by ABB. Data preprocessing and analyses by Andrea Bryndum-Buchholz, discussion and writing by Andrea B. Buchholz, Heike K. Lotze, Derek P. Tittensor, William W.W.L. Cheung, Olivier Maury, Julian L. Blanchard, Eric D. Galbraith, Simon Jennings, and Marta Coll.

CHAPTER 3

DIFFERING MARINE ANIMAL BIOMASS SHIFTS UNDER 21ST CENTURY CLIMATE CHANGE BETWEEN CANADA'S THREE OCEANS[2]

3.1 ABSTRACT

Under climate change, species composition and abundances in high-latitude waters are expected to substantially reconfigure with consequences for trophic relationships and ecosystem services. Outcomes are challenging to project at national scales, despite their importance for management decisions. Using an ensemble of six global marine ecosystem models we analyzed marine ecosystem responses to climate change from 1971-2099 in Canada's Exclusive Economic Zone (EEZ) under four standardized emissions scenarios. By 2099, under business-as-usual emissions (RCP8.5) projected marine animal biomass declined by an average of -7.7% (± 29.5%) within the Canadian EEZ, dominated by declines in the Pacific (-24% ± 24.5%) and Atlantic (-25.5% ± 9.5%) areas; these were partially compensated by increases in the Canadian Arctic (+26.2% ± 38.4%). Lower emissions scenarios projected successively smaller biomass changes, highlighting the benefits of stronger mitigation targets. Individual model projections were most consistent in the Atlantic and Pacific, but highly variable in the Arctic due to model uncertainties in polar regions. Different trajectories of future marine biomass changes will require regional-specific responses in conservation and management strategies, such as adaptive planning of marine protected areas and species-specific

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[2] Bryndum-Buchholz, A., Prentice, F., Tittensor, D.P., Blanchard, J.L., Cheung, W.W.L., Christensen, V., Galbraith, E.D., Maury, O., & Lotze, H.K. (2020). Differing Marine animal biomass shifts under 21st century climate change between Canada's three oceans. *FACETS*. *5*(1), 105–122.

management plans, to enhance resilience and rebuilding of Canada's marine ecosystems and commercial fish stocks.

3.2 INTRODUCTION

Climate change is already altering the physical and biogeochemical properties of the ocean, with impacts on species abundances, distributions, ecosystem functioning, and the provision of ecosystem services (Cheung et al., 2016; Worm & Lotze, 2016). Rising temperatures and enhanced stratification alter primary productivity, changes in which can then amplify through food webs with consequences for higher trophic levels (Kwiatkowski et al., 2018; Lotze et al., 2019). Other stressors, such as ocean acidification and oxygen declines, are impacting ocean productivity, nutrient and carbon cycling, leading to metabolic consequences and behavioural changes in many species (Doney et al., 2009; Keeling et al., 2010). Species range shifts are already occurring and expected to continue into the future, particularly in high-latitude and polar waters, resulting in reconfigurations of ecological communities (Cheung et al., 2010; Poloczanska et al., 2013). Therefore, projections of climate-change impacts in the fast-changing oceans of high-latitude countries such as Canada, where commercial and subsistence fisheries are economically, nutritionally, and socially valuable, are urgently needed to inform fisheries management and marine conservation.

Canada has one of the longest coastlines in the world and borders three different oceans—the Atlantic, Pacific, and Arctic—making it a pertinent case-study for investigating marine biomass responses to climate change within its Exclusive Economic Zone (EEZ). To do so requires the use of coupled physical, biogeochemical, and ecological models. Using outputs such as water temperature, primary production, and other physical and biochemical variables from Earth System Models (ESMs) as forcing variables, marine ecosystem models can be used to project changes in animal biomass, species distributions, and food webs (Bopp et al., 2013; Lefort et al., 2015; Tittensor et al., 2018a). Individual ecosystem models are based on model-specific building blocks, such as species types, size classes or functional groups, and ecological processes considered are unique to each model, and hence they vary in their response to changing ocean conditions (Tittensor et al., 2018a). Past studies have typically used single marine ecosystem models, forced by one or several ESMs to derive patterns of biological changes on multiple scales (Blanchard et al., 2012; Barange et al., 2014; Jones et al., 2015), which can underrepresent the variety of underlying ecosystem processes and underestimate the range of projection uncertainty (Bryndum-Buchholz et al., 2019). Combining projections from multiple ecosystem models into ensembles allows the quantification of mean trends and an assessment of variation in projections due to differing model structures, parameters, and processes (Tittensor et al., 2018a). Such model intercomparison projects (MIPs) are commonly used in climate impact research and have proven invaluable in the understanding of physical climate-change projections (e.g. Bopp et al., 2013) yet have only recently been adopted for global ocean ecosystems (Tittensor et al., 2018a; Lotze et al., 2019).

We used ensemble projections from the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP; Tittensor et al., 2018a) to quantify spatio-temporal changes in marine animal biomass within the Canadian EEZ under multiple climate-change scenarios over the 21st century. We analyzed outputs from six global marine ecosystem models forced with standardized outputs from two ESMs under four emissions scenarios (Tittensor et al., 2018b). We compared mean trends and variation in total marine animal biomass due to changing climate conditions, and quantified responses to differences in projected climate-change mitigation efforts in Canada's Pacific, Atlantic, and Arctic oceans, as well as examined the policy and management consequences of our findings.

3.3 MATERIALS AND METHODS

3.3.1 Data sources

We extracted historical (1970-2005) and future (2006-2099) spatially explicit projections of marine animal biomass (total marine animal biomass; including all vertebrates and invertebrates of trophic level >1, excluding zooplankton) from six global marine ecosystem models included in Fish-MIP simulation round 2a: APECOSM, BOATS, DBEM, DPBM, EcoOcean, and Macroecological (Tittensor et al., 2018b; Table A.1). Each ecosystem model was forced with standardized outputs from two ESMs (GFDL-ESM2M and IPSL-CM5A-LR; APECOSM and DPBM runs were only available for IPSL-CM5A-LR in Fish-MIP simulation round 2a) provided by the Coupled Model Intercomparison Project Phase 5 (CMIP5, http://cmippcmdi.llnl.gov/cmip5/) under four contrasting greenhouse gas (GHG) concentration scenarios (Representative Concentration Pathways, RCPs; further referred to as emissions scenarios; DBEM runs were only available for RCP2.6 and RCP8.5 in the Fish-MIP simulation round 2a). One of the ESMs, GFDL-ESM2M, projects moderate changes in variables such as sea surface temperature (SST) and oceanic net primary productivity (NPP) over the 21st century, while IPSL-CM5A-LR projects stronger SST warming and NPP declines (Bopp et al., 2013). The four RCPs were: RCP2.6, a low emissions and strong mitigation scenario, assuming peak emissions by 2010-2020 with a substantial reduction until 2100 (van

Vuuren et al., 2011); RCP4.5 and RCP6.0, two stabilization emissions scenarios that level off at intermediate GHG concentration levels by 2100 (Masui et al., 2011; Thomson et al., 2011); and RCP8.5, a high business-as-usual emissions pathway, assuming continuous emissions increase until 2100 (Riahi et al., 2011). In this study, we focus on Fish-MIP model runs under no-fishing scenarios, since spatially explicit future projections of fishing at global scales are as of yet unavailable, and outputs that include a simplified fishing projection (using an assumption of constant and spatially unchanged fishing pressure at 2005 levels to 2100) are only available for three marine ecosystem models (Tittensor et al., 2018a, 2018b). Therefore, our analysis isolates the climate-change signal on marine animal biomass.

3.3.2 Study area

Our study area spanned the entire Canadian Exclusive Economic Zone (EEZ) across three oceans (Figure 3.1). The Canadian Pacific along the coast of British Columbia is characterized by warm waters carried onshore by the North Pacific Current (Okey et al., 2014). Canada's Atlantic Ocean ranges from the Gulf of Maine to northern Labrador and is influenced by the warm Gulf Stream and cold Labrador Current (Saba et al., 2016). The Canadian Arctic spans the entire northern Canadian coast and is characterized by cryospheric elements sensitive to warming (Prowse et al., 2009a, 2009b; Dufresne et al., 2013).

3.3.3 Data analysis

Historical and future projected timeseries of total marine animal biomass were extracted on a common 1° x 1° grid for the Canadian EEZ from each marine ecosystem model, ESM, and emissions scenario combination.

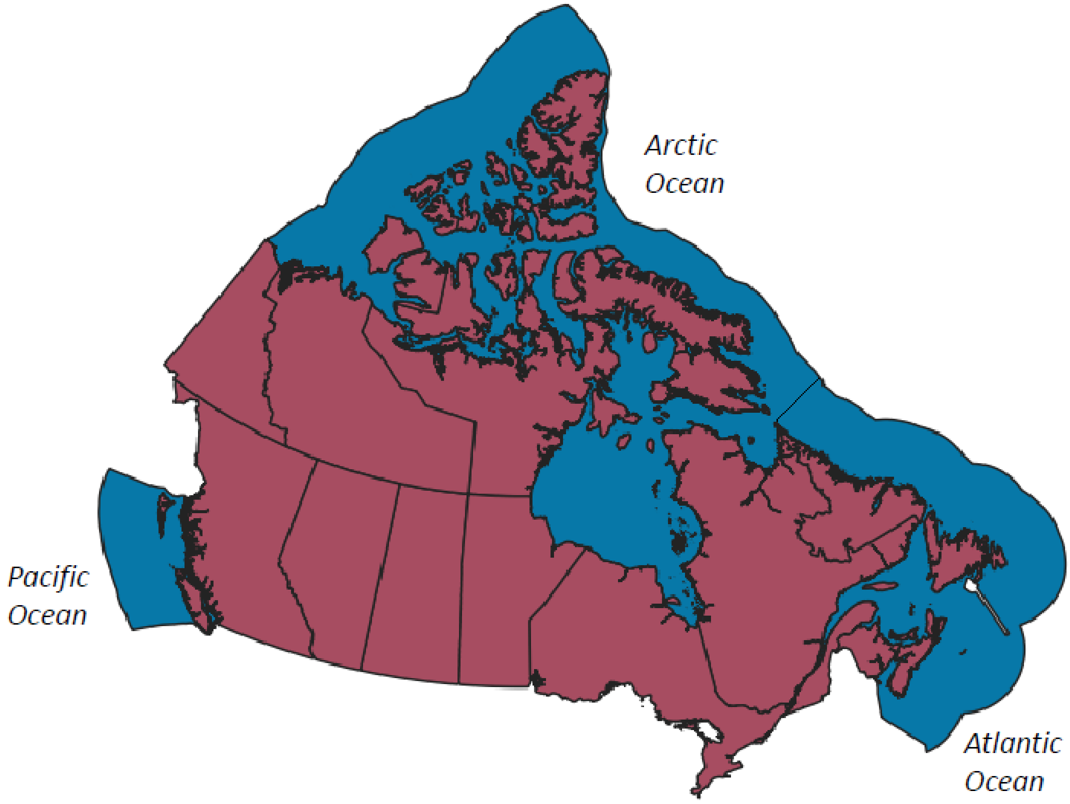

Figure 3.1: Delineation of the Arctic, Atlantic, and Pacific Oceans in Canada's Exclusive Economic Zone (EEZ). Country shapefile retrieved from www.diva-gis.org. EEZ outline modified from Flanders Marine Institute (2018).

Biomass projections by DBEM, the only model with a 0.5° x 0.5° grid resolution, were averaged over each 1° x 1° grid cell. To analyze climate-driven biomass changes in each area of the EEZ, we first calculated the annual spatially weighted (by latitude-longitude grid cell size) mean biomass across each of Canada's three oceans (Pacific, Atlantic, Arctic) for each ecosystem-ESM combination and emissions scenario. Next, we derived time series of the annual percent biomass change from 1971 to 2099 relative to the average of 1990-99 (defined as the historical reference period) for EEZs and grid cells. Defining the 1990s as the historical reference period allowed us to compare future projected biomass changes over the course of the 21st century and its last decade (2090s) to the last decade of the 20th century. Lastly, we calculated the ensemble mean relative biomass change (in percent for each model; different ecosystem models include different components, hence are not directly comparable in absolute terms) and model spread, expressed as one inter-model standard deviation of the ensemble mean, over all ecosystem-ESM combinations for each grid cell and ocean. A similar approach was used to derive projected changes in SST (in ˚C) and NPP (in percent) forcing data for GFDL-ESM2M and IPSL-CM5A-LR. In addition to mapping the ensemble mean and the inter-model standard deviation, we also mapped the model agreement, defined as the percentage of model projections agreeing on the direction of change, ranging from 50% (half of models indicate a decline, half indicate an increase) to 100% (all models agree on direction of change).

We then assessed the climate-change mitigation effect for the model ensemble by subtracting the annual mean biomass change per grid cell under the high mitigation pathway (RCP2.6) from the no-mitigation pathway (RCP8.5). The obtained values represent the climate-change mitigation effect in terms of the difference between the projected biomass changes under the two contrasting emissions scenarios.

3.4 RESULTS

3.4.1 Temporal changes in total marine animal biomass, SST, and NPP

The climate-change effects on marine animal biomass varied across Canada's three oceans. In the Canadian Arctic, ensemble mean total marine animal biomass increased over the 21st century relative to 1990-99 (Figure 3.2a). The greatest magnitude in projected biomass change and largest inter-model standard deviation was found under RCP8.5 (26.2% ± 38.4% in 2099 relative to 1990s) while projected changes under RCP4.5 (8.2% ± 11.4%) and RCP6.0 (7.2% ± 19.7%) were smaller, and those under

RCP2.6 (9.6% ± 18%) intermediate (Figure 3.2a). Projections under RCP4.5 and 6.0 were influenced by the lack of projections from DBEM in the ensemble (see Methods), an ecosystem model which otherwise showed some of the strongest changes under RCP8.5 and 2.6 in the Arctic area (see Figure C.1a). Biomass projections under both RCP2.6 and RCP8.5 decreased by 3-4% between 2070 and 2090 relative to the 1990s before showing an increasing trend during the 2090s. For all emissions scenarios, the variation around the projected biomass increase was greater than the ensemble mean, indicating high uncertainty in projecting biomass changes in this polar region (Figure 3.2a). Comparing individual model runs under RCP8.5 (Figure C.1a) revealed that two ecosystem-ESM combinations (Macroecological‒IPSL-CM5A-LR, DPBM‒IPSL-CM5A-LR) showed biomass declines, while all other combinations projected biomass increases.

In contrast to the polar region, the projected ensemble mean animal biomass in the Canadian Pacific and Atlantic areas decreased over the 21st century. In the Canadian Pacific, total projected biomass declines ranged from -8% (± 9.5%) under RCP2.6 to -24% (± 24.5%) under RCP8.5, with projections from RCP4.5 (-21.5% ± 20%) and RCP6.0 (24.5 ± 24.8%) showing intermediate declines by 2099 (Figure 3.2a). The variation around projected biomass decreases was slightly greater than the mean for all RCPs (Figure 3.2a), with all ecosystem-ESM combinations showing biomass declines under RCP8.5 (Figure C.1b) except for two (DBEM‒GFDL-ESM2M, EcoOcean‒GFDL-ESM2M). Projected total biomass in the Canadian Atlantic declined by -9.3% (± 4.2%) under RCP2.6 and -25.5% (± 9.5%) under RCP8.5 and showed intermediate declines under RCP4.5 (-16.5% ± 8%) and RCP6.0 (-16.7% ± 6.8%) by the end of the 21st century (Figure 3.2a). Here, the variation (SD) was lower than the ensemble mean for all scenarios, indicating higher consistency across individual projections in the Canadian Atlantic, with all ecosystem-ESM combinations showing biomass declines (Figure C.1c). Overall, the model spread of biomass projections was largest in the Arctic area and lowest, and thus most consistent, in the Atlantic area, and in general variability was greater under higher emissions scenarios (Figure 3.2a).

The projected increase in biomass under all four emissions scenarios in the Canadian Arctic was concurrent with projected increases in SST and NPP under both ESMs (Figure 3.2b, 3.2c). GFDL-ESM2M projected SST increases of 0.45˚C (RCP2.6) and 2.4˚C (RCP8.5), where IPSL-CM5A-LR projected larger SST increases, reaching 0.7 ˚C (RCP2.6) and 4˚C (RCP8.5) by 2099 (Figure 3.2b). NPP projections increased between 4.5% (GFDL-ESM2M) and 8% (IPSL-CM5A-LR) under RCP2.6; under RCP8.5 NPP increased between 16% (IPSL-CM5A-LR) and 24% (GFDL-ESM2M by 2099 (Figure 3.2c). In the Canadian Pacific and Atlantic oceans SST was projected to increase in similar magnitude compared to the Arctic SST projections for both ESMs under all four emissions scenarios; however, NPP projections decreased for IPSL-CM5a-LR in the Pacific EEZ (-5.6% under RCP2.6; -26.5% under RCP8.5) and for both ESMs in the Atlantic EEZ (IPSL-CM5a-LR: -5% under RCP2.6; -4.7% under RCP8.5; GFDL-ESM2M: -0.45% under RCP2.6; -5.6% under RCP8.5) (Figure 3.2b, 3.2c). Projections of the two ESMs were generally more consistent in the Atlantic and Arctic compared to the Pacific, and more variable under higher emissions scenarios.

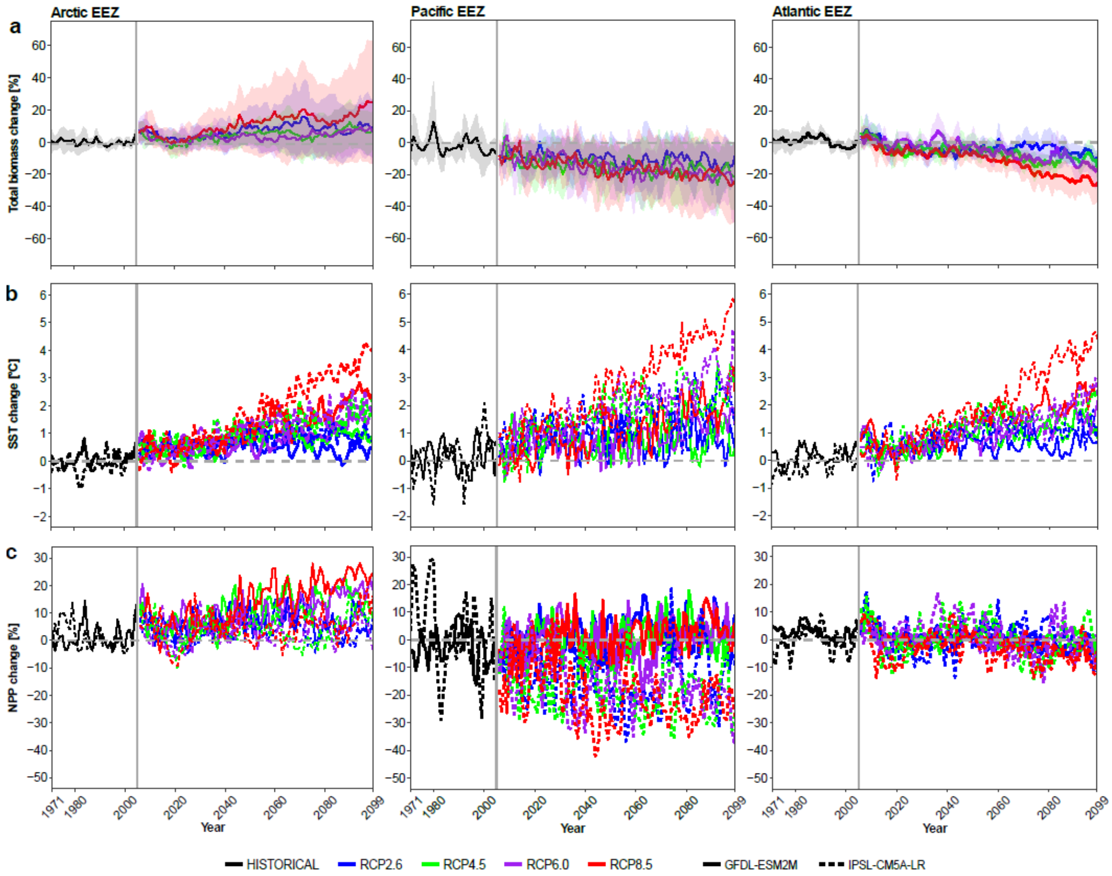

Figure 3.2: Model projections of (a) total marine animal biomass, (b) sea surface temperature (SST), and () net primary production (NPP) in Canada's three oceans from 1971-2099 under four emissions scenarios (RCP2.6, RCP4.5, RCP6.0, RCP8.5). Trends are depicted as the projected annual mean change relative to 1990-99 with total marine animal biomass and NPP as percent change and SST in ºC. (a) are ensemble model projections with one inter-model standard deviation (SD, shading). Ensemble results in (a) are averaged across marine ecosystem model-Earth System Model combinations (total marine animal biomass, n = 10). In (b) and (c) solid lines are GFDL-ESM2M projections; dashed lines area IPSL-CM5a-LR projections. The vertical solid grey line denotes the separation of historical and future projections. Note different y-axes values among figure panels.

3.4.2 Spatial patterns of change in total marine animal biomass

Within the Canadian Arctic, projected animal biomass under RCP2.6 increased moderately in the Hudson Bay by the end of the 21st century, while greater increases were observed throughout other areas within the Arctic EEZ, in particular around the islands of the central Arctic Ocean and the Beaufort Sea (Figure 3.3a).

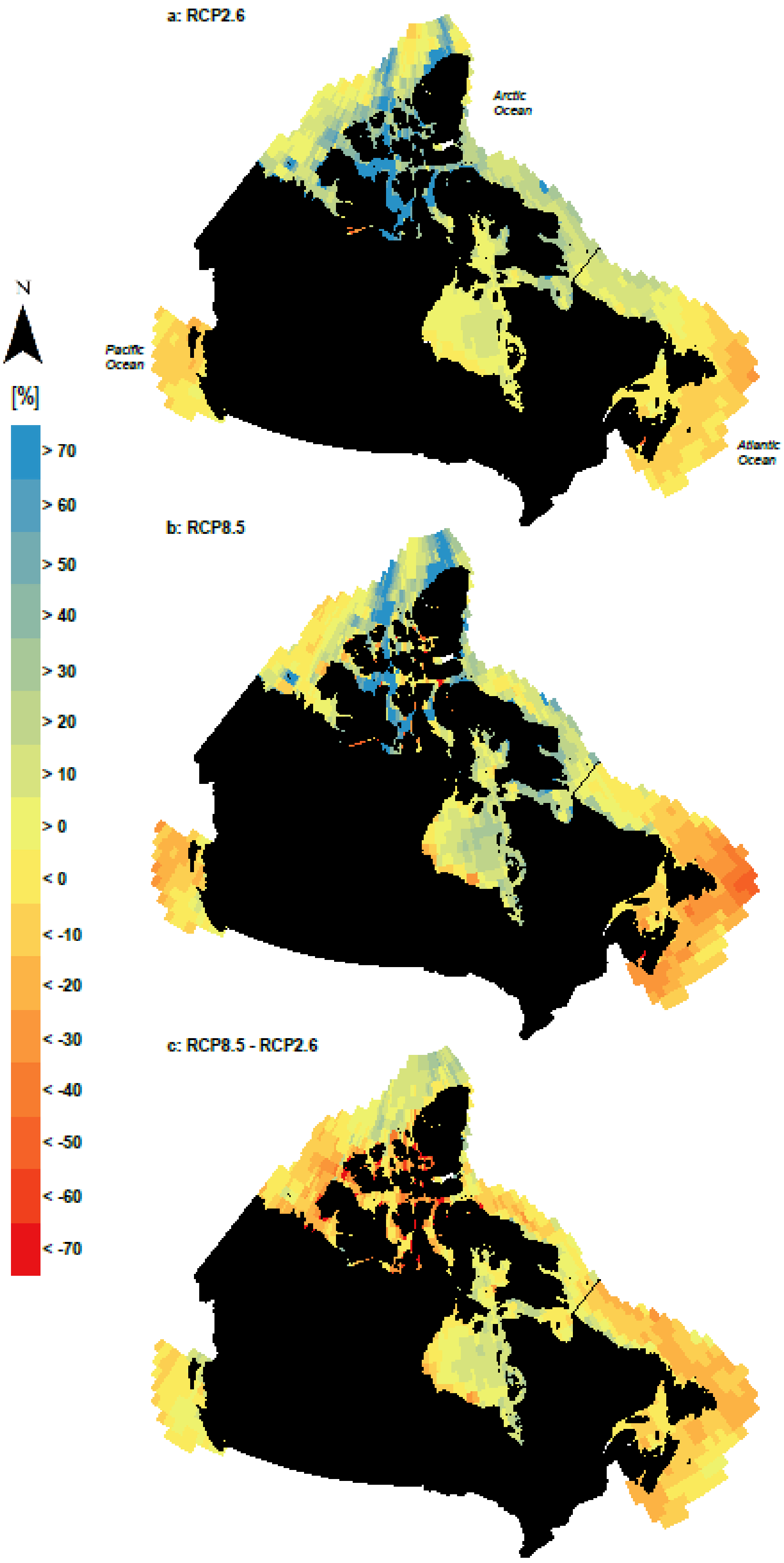

Figure 3.3: Spatial patterns of ensemble projections of total marine animal biomass for (a) RCP2.6, (b) RCP8.5, and (c) climate-change mitigation effect (RCP8.5-RCP2.6) in Canada's three oceans. Ensemble biomass projections represent a mean percent change in total marine animal biomass in 2090-99 relative to 1990-99 (a and b). Values in (c) represent the climate-change mitigation effect in terms of the difference between the projected biomass changes under the high mitigation scenario (RCP2.6) and no mitigation effect (RCP8.5). For better visualization of patterns, percent biomass change values were capped at +/-75%. Black line separates Canadian Arctic and Atlantic oceans. Country shapefile retrieved from www.diva-gis.org. EEZ outline modified from Flanders Marine Institute (2018).

Similarly, under RCP8.5, projected animal biomass increased in many regions of the Canadian Arctic; however, it decreased along the western coast of the Hudson Bay, the northern Beaufort Sea, and in some parts of the central Arctic Ocean (Figure 3.3b). Within the Pacific and southern regions of the Canadian Atlantic Ocean, projected biomass consistently declined by the end of the 21st century, with stronger declines under RCP8.5 than RCP2.6 (Figure 3.3a, 3.3b). In contrast, projected biomass in the northern Atlantic regions of the EEZ increased under both emissions scenarios (Figure 3.3a, 3.3b).

Reduced emissions through climate-change mitigation would lead to a dampening of projected biomass changes under the current GHG emissions trajectory (RCP8.5) across Canada's three oceans (Figure 3.3c). This climate-change mitigation effect (RCP8.5-RCP2.6) was the weakest in the Pacific area of the EEZ, where projected biomass decreases were only slightly reduced (light yellow = <0% to -10%) compared to projected decreases under RCP8.5 (Figure 3.3c). In the Canadian Atlantic, climate-change mitigation consistently reduced projected biomass decreases under RCP8.5 by <0% to -20% (Figure 3.3c). Climate-change mitigation had the strongest effect across the Canadian Arctic, especially in the Arctic Archipelago (Figure 3.3c), where climate-change mitigation would result in lower biomass increases (-30% to -70%) across the region.

Model spread (inter-model standard deviation of the ensemble mean) was generally higher in projections under RCP8.5 than RCP2.6; however, it was spatially consistent in terms of areas with high and low standard deviations (Figure 3.4a, 3.4b). Under both emissions scenarios, standard deviations were lower in the Pacific and Atlantic than the Arctic area of the EEZ, with the exception of the Hudson Bay, which showed similar standard deviations (Figure 3.4a, 3.4b). Model agreement on the direction of projected biomass changes across ecosystem models was also higher under RCP2.6 than RCP8.5 (Figure 3.4c, 3.4d). Under RCP2.6, model agreement was more consistent at the southern latitudes of the study area (i.e. the Atlantic and Pacific areas of the EEZ) and in the central Arctic Ocean, while ecosystem models agreed less on the direction of projected biomass changes in the Hudson Bay, the Beaufort Sea, and the northern regions of the Canadian Arctic Ocean (Figure 3.4c).

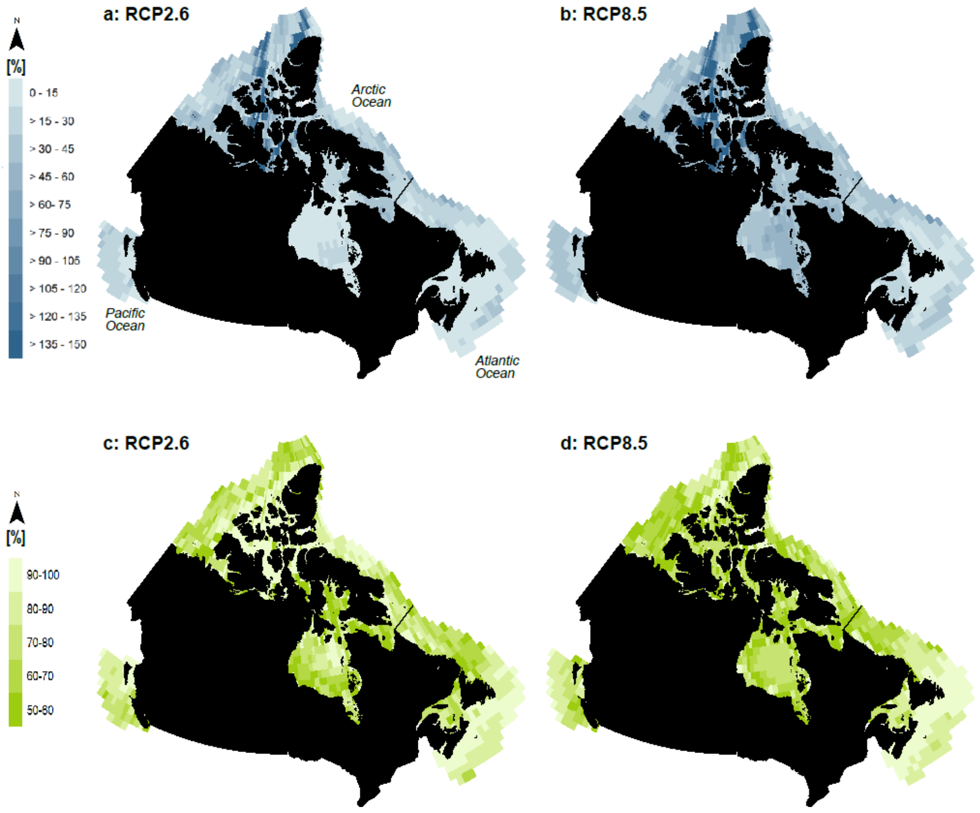

Figure 3.4: Model spread and model agreement of the ensemble mean biomass change in 2090-99 relative to 1990-99 under RCP2.6 and RCP8.5 in Canada's Exclusive Economic Zone (EEZ). The model spread is depicted as one inter-model standard deviation [%] of the ensemble mean for (a) RCP2.6 and (b) RCP8.5. Model agreement [%] represents the percentage of models agreeing in the direction of projected biomass change for (c) RCP2.6 and (d) RCP8.5. For better visualization of patterns, percent inter-model standard deviation values were capped at 150%. Black line separates Canadian Arctic and Atlantic oceans. Country shapefile retrieved from www.diva-gis.org. EEZ outline modified from Flanders Marine Institute (2018).

3.5 DISCUSSION

Findings from this study support the expectation that climate change is having and will continue to have large impacts on marine ecosystems in mid- to high-latitude shelf seas, such as those in Canada. However, there are regional differences in the direction and magnitude of the projected marine animal biomass changes and hence consequences for management and policy. These are largely driven by the differences in projected changes in oceanographic drivers amongst the different regions as well as differences in the representation of the regional ecosystem structure by the models.

In the Canadian Arctic Ocean, our results suggest an overall increase in mean total marine animal biomass over the 21st century under the high emission scenario (RCP8.5); however, high uncertainty around the ensemble mean indicates a broad range of potential future trajectories. Some areas of projected biomass declines under RCP8.5 include parts of the central Arctic and along the coasts of Hudson Bay and the northern Beaufort Sea. The high variability of biomass projections in the Arctic compared to the Atlantic and Pacific areas may be partly explained by an underrepresentation or divergent representation of key structures and dynamics in existing ecosystem models. It may also be due to a general lack of available data for parameterization, a limited structural understanding of the Arctic ecosystem, or to general global models not being tailored to these polar ecosystems e.g. not adequately accounting for the effects of seasonal ice coverage (Steiner et al., 2015). This is consistent with global ensemble studies suggesting a higher uncertainty of projected future changes in polar regions (Bryndum-Buchholz et al., 2019; Lotze et al., 2019).

Comparing across ecosystem models, most models projected biomass increases in the Canadian Arctic Ocean, with DBEM projecting the largest biomass increases under both RCP2.6 and RCP8.5 (Figure C.1, C.2). DBEM represents the distribution of commercial species only, which have relatively low initial biomass levels in the Arctic compared to the broader biomass compositions simulated by the other five ecosystem models (APECOSM, DPBM, BOATS, EcoOcean, and Macroecological) in our ensemble. These represent a range of different size-classes, functional or trophic groups, including commercial and non-commercial groups with higher initial biomass levels (Table A.1, Bryndum-Buchholz et al., 2019). Because many commercial species in DBEM are projected to invade the Arctic over the course of the 21st century, relative changes in biomass are amplified compared to other ecosystem models (Cheung et al., 2009, 2016; Bryndum-Buchholz et al., 2019). Starting with higher initial biomass levels (i.e. including commercial and non-commercial groups) may lead to relatively lower future biomass changes in other models in comparison to DBEM (Bryndum-Buchholz et al., 2019), and these aspects should be borne in mind when interpreting the results in this region.

Overall, our multi-model mean of projected biomass trends in the Canadian Arctic is strongly influenced by DBEM and EcoOcean, which are the only models that are spatially resolved within the Canadian Arctic Archipelago (Figure C.2, C.3). Projections of coastal dynamics within the Arctic Ocean are still very uncertain and ESMs diverge in their projections of primary production and other physical and biochemical factors within the region (Vancoppenolle et al., 2013; Steiner et al., 2015).

Another interesting observation is he projected biomass declines between the 2070s and 2090s under both RCP8.5 and RCP2.6 in the Arctic Ocean (Figure 3.2a), which are concurrent with declines in NPP (Figure 3.2c) and may represent the onset of a projected long-term decrease in ocean productivity within the Arctic Ocean over the next centuries until (Moore et al., 2018). Moreover, the strong response in biomass changes after the 2070s observed in DBEM-GFDL-ESM2M (Figure C.1a) could be due to few commercial species reacting strongly to changing ocean conditions and driving the projected mean trend. In contrast, 5 out of 6 ecosystem models are not species-specific and may respond less drastically to future changes in the Canadian Arctic.

Spatially, areas of biomass changes in the Arctic are projected to expand or intensify in magnitude under RCP8.5 compared to RCP2.6. Only BOATS projected biomass increases for the majority of the Arctic under both emissions scenarios. DBEM's Arctic projections shifted from largely biomass increases under RCP2.6 to declines under RCP8.5, particularly in the northern and central Arctic areas of the EEZ and the Hudson Bay. EcoOcean projected biomass increases across the Arctic area of the EEZ, except for some declines in northern regions under both emissions scenarios. Importantly, in our study, only the DBEM and EcoOcean models directly incorporate changing ice cover into their biomass projections, which might lead to an underrepresentation of ice-cover related dynamics in the Arctic ecosystem in the ensemble as a whole (Tittensor et al., 2018a).

The further incorporation of sea ice cover, thickness, seasonality, or other physical attributes specific to polar oceans as forcing factors into marine ecosystem models may help refine projections of ecosystem changes in the Canadian Arctic Ocean. Model development in this direction is paramount, given the drastic changes already being observed within the Arctic Ocean. Arctic mean summer surface water temperatures have increased by +1°C per decade from 1982 to 2018, with drastic associated changes is seasonal sea ice cover and associated phytoplankton communities and primary production (Tremblay et al., 2012; Timmermans & Ladd, 2019). In response to warming waters, sea ice has been decreasing in all regions of the Arctic over the past three decades (Meier et al., 2014). Consequently, plankton communities and overall marine productivity is changing. For instance, in coastal areas such as the Canadian Arctic Archipelago, primary production is increasing in response to enhanced upwelling due to more favorable winds and deeper seaward retreat of ice (Tremblay et al., 2012). Pelagic phytoplankton communities, on the other hand, are shifting towards small picophytoplankton due to warming and freshening of surface layers, potentially impacting the entire Arctic marine food web (Tremblay et al., 2012).

In the Atlantic and Pacific areas of the Canadian EEZ, our model ensemble projected consistent decreases in total marine animal biomass over the 21st century under all four emissions scenarios. These results are in line with findings showing that ocean warming increases biological energy dissipation in ecosystems and enhances water column stratification thus reducing primary production. Both processes can cause a strong decrease of marine animal biomass (Lefort et al., 2015; Cheung et al., 2016; Guiet et al., 2016; Worm & Lotze, 2016) that amplifies along food chains (Lefort et al., 2015; Lotze et al., 2019). Compared to the Canadian Arctic, biomass projections in the Canadian Atlantic and Pacific oceans were more consistent among ecosystem models and the variability in the ensemble mean was smaller both temporally and spatially. The size-structured ecosystem models BOATS, DPBM, and Macroecological projected the strongest biomass decreases within the Atlantic and Pacific areas of the EEZ. These models focus on metabolic rates and biomass flow, with biomass projections primarily responding to changes in primary production and SST (Blanchard et al., 2012; Jennings & Collingridge, 2015; Carozza et al., 2018). EcoOcean, a trophodynamic ecosystem model, and APECOSM, a composite 3D ecosystem model, projected overall weaker biomass declines.

Under the high emissions scenario, NPP increased strongly within the Arctic area of the EEZ yet decreased in the Canadian Atlantic Ocean and was highly variable in the Pacific area of the EEZ by the 2090s. The higher variability in projected NPP within the Canadian Pacific could partly be attributed to the influence of inter and intra-decadal climate variations, such as the Pacific Decadal Oscillation and the El Niño Southern Oscillation (Talloni-Alvarez et al., 2019). The variability of both climate phenomena has increased in recent years, impacting SST in the Canadian Pacific with consequences for marine productivity (Hunter & Wade, 2015).

On the timescale examined in this study, the ocean, land, atmosphere, and their coupling control the supply of nutrients to coastal waters and therefore phytoplankton growth and NPP (Blanchard et al., 2012). Warming waters can enhance ocean stratification, leading to nutrient limitation in the euphotic zone and reduced NPP (Cabré et al., 2015), while loss of sea ice in the Arctic can enhance NPP due to a longer growing window (Boyce & Worm, 2015; Worm & Lotze, 2016). The evolution of NPP dynamics plays a critical role in model projections of upper trophic levels as primary production is the only source of energy fueling the entire upper ocean food web (Kwiatkowski et al., 2018; Tittensor et al., 2018a; Lotze et al., 2019).

SST was projected to increase throughout the Canadian EEZ over the 21st century under RCP2.6 and RCP8.5. Under RCP8.5, Bopp et al., (2013) found a global mean SST increase of 2.73ºC (± 0.72ºC) by 2100 based on 10 ESMs, slightly lower than the average trends we found in the Canadian EEZ (3.6ºC ± 0.5ºC). Changes in SST affect the physiology, the dissipative processes of metabolism including food intake, growth, reproduction, maturation and maintenance (Guiet et al., 2016), survival, abundance, and distribution of marine species (Sarmiento et al., 2004; Brander 2010; Grady et al., 2019) with overall impacts on ocean biomass (Lefort et al., 2015; Cheung et al., 2016; Lotze et al., 2019).

SST and NPP were the main forcing variables considered in all six ecosystem models used in this study (Tittensor et al., 2018a). Several other physical and biochemical factors are also influenced by climate change, such as pH, oxygen content, light penetration, marine currents, vertical distribution of primary production or sea ice cover (see above, Bopp et al., 2013). However, not all the ecosystem models in our analysis use these variables and represent the corresponding processes (Tittensor et al., 2018a). This heterogeneity in ecosystem model configuration is reflected in the varying individual biomass projections. Some marine ecosystem models in our ensemble respond strongly to temperature changes affecting metabolic rates in the modelled higher trophic levels (BOATS, DPBM, Macroecological), other models, such as EcoOcean, respond strongly to NPP changes. DBEM considers pH, oxygen, and sea ice cover as additional drivers to determine evolving habitat niches and species distribution (Tittensor et al., 2018a; Bryndum-Buchholz et al., 2019).

3.5.1 Study limitations and future research

Notwithstanding the aforementioned points on incorporation of ice dynamics and differing biotic community compositions in the individual marine ecosystem models, there are other aspects that need to be recognized when interpreting our results. A challenge in mapping ensemble mean biomass changes was the inconsistent spatial coverage among ecosystem models, due to different ecosystem models using their own specific grids and land/sea masks (Figure C.2, C.3). Open ocean regions had greater coverage (≥5 models) than coastal and island regions (2-3 models). Low model coverage in some Arctic grid cells (e.g. the central Arctic Archipelago) reduced the number of ecosystem models incorporated into the ensemble mean, yielding some results being dominated by EcoOcean and DBEM (Figure C.2, C.3).

Further, our study relied on outputs of global ESMs and global marine ecosystem models to represent all of Canada's EEZ across the three oceans, because there are no consistent regional climate and ecosystem models that could be used for such an ensemble approach. Generally, global ESMs provide limited resolution of processes in coastal or polar regions (Bonan & Doney et al., 2018; Derksen et al., 2018). Advancements in ESM representation and resolution of high-latitude coastal zones and relevant processes, especially in the context of the complex Canadian Arctic Archipelago, will help to improve projections for those regions. Additionally, environmental changes (i.e. dramatic changes in water temperature and oxygen concentration) occurring in shelf ecosystems, as found within the Atlantic area of the Canadian EEZ, may only be resolved by high resolution ESMs (Claret et al., 2018). Improving ESM projections will be crucial to understanding change in polar regions such as the Canadian Arctic, given their importance for fisheries and other ecosystem services, and for the conservation of marine and polar biodiversity.

The approach of regionally downscaling global ESMs can potentially help to incorporate climate and ecosystem dynamics at a higher resolution (Holt et al., 2017). However, regional downscaling can be problematic, as changing resolution within models can introduce additional uncertainty, giving less confidence in projected outcomes (Bopp et al., 2013; Holt et al., 2017; Tittensor et al., 2018a). As such, our results should be considered with broad spatial and temporal trends in mind, as opposed to seeking highly specific regional insights, and we caution that these projections may fail to capture important potential changes that might threaten the coastal oceans in the future. Developing standardized, high resolution regional models that are specifically tailored to deal with the above-mentioned issues is paramount to push forward our understanding of climate-change impacts in complex coastal marine ecosystems and the societies that depend on them.

Another limitation of our analysis is that it represents ecosystem responses to climate change in an unfished ocean; however, fisheries exploitation is strongly altering the structure of populations and ecosystems leading to modified responses to future climate, in terms of reduced capacity to buffer the perturbations and exacerbated climate effects on marine ecosystems (Planque et al., 2010). Hence, our ensemble results may be conservative, especially in regions of current high fishing intensity within the Canadian EEZ, such as the Canadian Maritimes. Yet, a recent study by Lotze et al., (2019), using the reduced Fish-MIP model ensemble that includes a fishing effect, suggests that under current levels of fishing pressures, fishing might not substantially alter the relative effect of climate change on a global scale. How the fishing effect might play out more precisely, both globally and regionally, requires improved integration of fishing scenarios into marine ecosystem models, as currently under development in the Fish-MIP's second simulation round.

3.5.2 Implications and conclusions

Our ensemble projections suggest that ecosystem productivity in the Canadian Pacific and Atlantic Oceans will be negatively impacted by climate change over the 21st century, which may have substantial consequences for fisheries, socio-ecological systems, ecosystem management, and biodiversity conservation in these regions. In contrast, new economic opportunities as well as potential conflicts and challenges to resource management and marine conservation may develop in the Canadian Arctic. Our results can help inform several aspects of long-term planning and policy development in the Canadian EEZ.

First, planning for national climate-change adaptation and mitigation, such as efforts by Environment and Climate Change Canada (Environment and Climate Change Canada (ECCC), 2016a), requires a solid understanding of the expected changes, including their timelines, spatial patterns, and uncertainties. Moreover, as Canada is committed to international agreements (ECCC, 2016a) including the United Nations Sustainable Development Goals (notably SDG 13, climate action, and SDG 14, life below water), understanding projected changes in Canada's three oceans is essential. Additionally, we clearly demonstrate the benefits to be gained from climate-change mitigation in Canada's Atlantic and Pacific Ocean, where our strong mitigation scenario (RCP2.6) lessened the projected declines in marine animal biomass. Considering Arctic ecosystems in Canadian climate-change mitigation efforts is essential, as unmitigated changes within the Arctic will have dramatic consequences that reach far beyond regional ecosystems and socio-economic systems (Whiteman et al., 2013; Flato et al., 2019). Changes due to a warming Arctic Ocean include sea ice loss, permafrost melting, ocean acidification, and altered ocean and atmospheric circulation. Theses changes are impacting Arctic marine and terrestrial ecosystems at a rate faster than most ecosystems could adapt to naturally (Wassmann et al., 2011). Beyond these regional impacts, changes in the Arctic are also affecting the functioning of the Earth System at the global scale (Whiteman et al., 2013).

Second, the study highlights potential risks and vulnerabilities within different marine regions in the Canadian EEZ, which is an essential component of developing ocean management that is adaptive to climate change. Our results could support Fisheries and Oceans Canada in their efforts to adapt fisheries and marine ecosystem management for a changing environment over the 21st century. For example, planning for potential fish biomass declines in the Atlantic and Pacific may necessitate measures to avoid further overexploitation, support rebuilding, and enhance ecosystem resilience, with differing levels of change requiring differing responses. Despite these general ecosystem changes, individual fish stocks may show varying responses to climate change, including impacts on their distribution, reproduction and biomass production (Pinsky et al., 2013; Stortini et al., 2015; Britten et al., 2016; Free et al., 2019), which will need to be considered in species-specific management plans.

Third, given Canada's commitment to increase its marine protected areas and to biodiversity conservation as a Party to the Aichi Biodiversity Targets (ECCC 2016a, 2016b), an understanding of when and where changes in marine animal biomass and productivity will occur is critical, particularly to future-proof current conservation and management actions. For example, our results projected strong latitudinal changes in Atlantic and Arctic marine ecosystems, which will require long-term and dynamic planning and management of marine protected areas given the likelihood that many species will shift towards polar waters over time.

Finally, our analysis represents an important case study for climate-change impacts on a northern high-latitude country and its oceans. Based on our model ensemble, we highlight potential climate-change impacts on marine biomass in the

Canadian EEZ, which could be dampened by implementing effective climate-change mitigation strategies. While our study does not explicitly simulate mitigation pathways of global GHG emissions, our results based on the difference between RCP8.5 and RCP2.6 suggest that strong mitigation policies can lower the magnitude of climate-change impacts on marine animal biomass across Canada's three oceans. These impacts need to be recognized in order to proactively respond to ecosystem reconfigurations in the face of climate change, especially given the additional impacts of exploitation and other stressors which will be overlaid. Overall, our high model agreement in projecting marine biomass changes indicates broad confidence in the expected direction of change, while the high variability around the ensemble mean highlights uncertainty in the magnitude of projected changes and points to the potential for improvements of model projections, especially for the Canadian Arctic Archipelago.

3.6 ACKNOWLEDGEMENTS

We would like to thank S. Jennings, T. Silva, D. Carozza, D. Bianchi, M. Jones, T. Eddy, N. Barrier, P. Verley, M. Coll, and J. Steenbeck for running Fish-MIP simulations and providing ecosystem model outputs; L. Bopp, J. Dunne, C. Stock, and T. Roy for providing ESM outputs; M. Büchner, J. Volkholz, and J. Schewe for technical support. Financial support was provided by the German Federal Ministry of Education and Research (BMBF, grant no. 01LS1201A1) through the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) and the Canada First Research Excellence Fund Ocean Frontier Institute (OFI): Safe and Sustainable Development of the Ocean Frontier (Module G). ABB acknowledges financial support from the NSERC CREATE Transatlantic Ocean Science and Technology Program; Faelan Prentice from OFI; Derek

P. Tittensor from the Kanne Rasmussen Foundation Denmark; Villy Christensen, William W.W.L. Cheung, and Heike K. Lotze from the Natural Sciences and Engineering Research Council (NSERC) of Canada; EDG from the European Research Council under the European Union's Horizon 2020 research and innovation program (No 682602); Olivier Maury from the French Agence Nationale de la Recherche and Pôle de Calcul et de Données Marines; and William W.W.L. Cheung from the Nippon Foundation Nereus program and the Social Sciences and Humanities Research Council (SSHRC) of Canada through the Oceans Canada Partnership.

3.7 AUTHOR CONTRIBUTIONS

Concept and design by Andrea B. Buchholz. Data preprocessing and analyses by Andrea B. Buchholz, discussion and writing by Andrea B. Buchholz, Faelan Prentice, Heike K. Lotze, Derek P. Tittensor, William W.W.L. Cheung, Olivier Maury, Julia L. Blanchard, Eric D. Galbraith, and Villy Christensen.

CHAPTER 4
CLIMATE-CHANGE IMPACTS AND FISHERIES MANAGEMENT CHALLENGES IN THE NORTH ATLANTIC OCEAN[3]

4.1 ABSTRACT

Climate-induced changes in the world's oceans will have implications for fisheries productivity and management. Using a model ensemble from the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP), we analyzed future trajectories of climate-change impacts on marine animal biomass and associated environmental drivers across the North Atlantic Ocean and within the Northwest Atlantic Fisheries Organization (NAFO) convention area and evaluated potential consequences for fisheries productivity and management. Our ensemble results show that the magnitude of projected biomass changes increased over time and from a low (RCP2.6) to high (RCP8.5) emissions scenario. Within individual NAFO divisions, however, projected biomass changes differed in the magnitude and sometimes the direction of change between near (the 2030s) and far future (the 2090s) and contrasting emissions scenarios. By the 2090s, most NAFO divisions with historically (1990-1999) high fisheries landings were projected to experience biomass decreases of 5-40%, while arctic and subarctic divisions with lower historical landings were projected to experience biomass increases between 20-70% under RCP8.5. Future trajectories of sea surface temperature and primary production corroborated that the far future, high emissions scenario poses the greatest risk to marine ecosystems and the greatest challenges to fisheries management.

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[3] Bryndum-Buchholz, A., Boyce, D.G., Tittensor, D.P., Christensen, V., Bianchi, D., & Lotze, H.K. (2020). Climate-change impacts and fisheries management challenges in the North Atlantic Ocean. *Marine Ecology Progress Series,* (In press).

Our study summarizes future trends of marine animal biomass and underlying uncertainties related to model projections under contrasting climate-change scenarios. Understanding such climate-change impacts on marine ecosystems is imperative for ensuring that marine fisheries remain productive and sustainable in a changing ocean.

4.2 INTRODUCTION

Globally, climate change is impacting marine life, ranging from fundamental biological processes, such as growth, survival and reproduction, to changes in the abundance and distribution of species, with consequences for ecosystem structure and function (Poloczanska et al., 2013; Worm & Lotze, 2016; Lotze et al., 2019). Yet climate-change effects are spatially heterogeneous, with some regions experiencing much higher rates of changes (e.g. in sea surface temperature, primary production) than the global average (Popova et al., 2016; Ramirez et al., 2017). As climate change alters the abundance and distribution of commercially targeted species, their spatial and temporal availability to marine fisheries is affected, with consequences for fishing operations and management (Cheung et al., 2010; McIlgorm et al., 2010; Blanchard et al., 2012, 2017). Thus, understanding future trajectories of marine animal biomass under climate change is critical for adapting fisheries management and marine conservation strategies.

The North Atlantic Ocean harbors highly productive fishing grounds, including the historically prominent Grand Banks and Flemish Cap off Newfoundland (Department of Fisheries and Oceans (DFO), 2012). However, large areas in this region have already undergone significant cumulative climate-related changes in oceanographic conditions (Greenan et al., 2018; Ramirez et al., 2017; IPCC, 2019) and have experienced substantial changes in regional fisheries production (Pershing et al., 2015; Britten et al., 2016). Such changes in regional fisheries production are thought to be influenced by regional climate change, fishing practices, or a combination of both (Britten et al., 2016). Failing to consider the interaction of fisheries management regimes and climate-change impacts in efforts to preserve the reproductive potential of commercial fish stocks can lead to regional fisheries collapses (Le Bris et al., 2018).

Water temperatures in the Northwest Atlantic, including surface, upper-ocean (0-300m) and bottom temperatures, are warming at globally extreme rates and are projected to further increase nearly three times faster than the global average (Pershing et al., 2015; Saba et al., 2016). Hence, the Northwest Atlantic can act as an indicator of how ocean warming effects may be manifested. Additionally, the enhanced ocean warming in the Northwest Atlantic has been accompanied by an increase in salinity and reduced oxygenation rates due to changes in water mass distribution related to the retreat of the equatorward-flowing Labrador Current and a northerly shift of the Gulf Stream (Saba et al., 2016; Claret et al., 2018). Ecosystem responses to these rapid changes in oceanographic conditions have important implications for marine living resources and their regional management. One prominent example is the Gulf of Maine Atlantic cod (*Gadus morhua*) fishery, in which stocks were continuously overfished despite reduced recruitment and increased mortality in the region's cod population, as the impacts of warming were not adequately recognized in management metrics (Pershing et al., 2015).

The response of fisheries to ongoing climate change is only one consideration; for long-term fisheries development, national and international ocean governance and fisheries management also play an important role (Costello et al., 2016; Mullon et al., 2016; Galbraith et al., 2017). Effective management can provide a buffer against the impacts of a warming ocean. Few fisheries management authorities are in the process of integrating climate-change considerations in their management objectives, with traditional fisheries management measures being the favored approach (Soomai, 2017; VanderZwaag et al., 2017). This highlights the need for providing comprehensive and accessible scenarios of long-term biological and ecological changes within respective regulatory areas to effectively work towards sustainable management of marine fisheries under climate change.

Fisheries in the North Atlantic Ocean are managed by international and national management agencies. For instance, the Northwest Atlantic Fisheries Organization (NAFO) is responsible for the management of high seas fisheries (NAFO Regulatory Area), whereas fish stocks within the 200-mile limit, representing each country’s exclusive economic zone, are managed through respective federal governments - in Canada through Fisheries and Oceans Canada (DFO) and in the United States through the National Oceanic and Atmospheric Administration (NOAA Fisheries). Fisheries management decisions are most often based on information from stock assessments that are used to set total allowable catches, fishing mortality limits, and regulate spatial or temporal fisheries closures (Cheung et al., 2019). With changing ocean conditions, the effectiveness of traditional management measures can deteriorate, as stock assessments rarely account for the effect of changing oceanographic conditions on population dynamics (Cheung et al., 2019). Consequently, to ensure long-term effective fisheries management, climate-change impacts need to be considered as part of management frameworks. Facing climate change, fisheries management organizations can make use of short- and long-term projections of changes in fish biomass and include information about climate impacts on populations to set reference points for management.

One approach to examining climate-change impacts on the ocean is to use marine ecosystem models to project future changes in animal biomass, species distribution, and food-web changes under different climate-change scenarios (Tittensor et al., 2018a). Combining individual model projections into ensembles allows the quantification of mean trends and, unlike single model assessments, the uncertainty in projected responses due to different model structures, parameters, and representations of ecological processes (Mora et al., 2013; Tittensor et al., 2018a). This need is particularly acute for marine ecosystem models, where the underlying heterogeneity of model types is substantial (Tittensor et al., 2018a).

The goal of this study was to analyze future trajectories of climate-change impacts on marine animal biomass across the North Atlantic Ocean and identify implications for fisheries productivity and management in the NAFO convention area. To do so, we utilized results from the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP, Tittensor et al., 2018a, 2018b) which provides outputs of marine animal biomass from six global marine ecosystem models that were forced by two Earth System Models under contrasting greenhouse gas emissions scenarios (also referred to as Representative Concentration Pathways or RCPs) following a standardized simulation protocol. The use of global models allowed us to cover the entire North Atlantic Ocean and NAFO convention area, and to apply an ensemble modeling approach which provides an indication of the variation or uncertainty in projections (Tittensor et al., 2018a). We evaluated changes in marine animal biomass >10cm, which can be interpreted as centers of secondary or harvestable biomass production, as well as projected changes in the major oceanographic drivers that may influence biomass trajectories. Lastly, we explored how projected ecological changes may affect fisheries distribution and production by analyzing the relationship between historical fisheries landings and projected biomass changes across NAFO divisions. Our results provide important long-term context for fisheries management and decision-makers to plan for – and adapt to – changing ocean ecosystems into the future.

4.3 MATERALS AND METHODS

4.3.1 Study region

This study focused on the projected impacts of climate change on marine animal biomass across the North Atlantic Ocean, to give a general context for expected ocean ecosystem changes, and within the NAFO convention area (Figure 4.1) to evaluate the consequences for fisheries productivity and management.

4.3.2 Data sources

We derived spatially explicit historical (1970-2005) and future (2006-2100) projections of unfished marine biomass of animals >10cm (g C m^{-2}, vertebrates and invertebrates, excluding zooplankton; representing potentially harvestable biomass) from the Fish-MIP simulation round 2a (Fish-MIP v1.0, Tittensor et al., 2018a, 2018b). The time brackets related to historical (observed) and future (projected) periods as per the Earth System Model output for CMIP5 and similarly standardized for the Fish-MIP simulation protocol. Outputs of marine animal biomass were generated by six global marine ecosystem models with different ecological structures and processes (Table A.1, A2), each providing a standardized measure of bulk harvestable biomass production of animals >10cm. Individual and combined ecosystem model outputs have been compared to empirical data across different temporal and spatial scales with generally good agreement (e.g., Blanchard et al., 2012; Christensen et al., 2015; Galbraith et al., 2017, Lotze et al., 2019).

Each ecosystem model was forced with standardized outputs from two Earth System Models under contrasting RCPs following the Fish-MIP simulation protocol (Tittensor et al., 2018a). The two Earth System Models, GFDL-ESM2M (Dunne et al., 2012) and IPSL-CM5A-LR (Dufresne et al., 2013) provided the necessary depth- and time-resolved physical and biogeochemical forcing variables required by Fish-MIP models (Table A.1, A2; Tittensor et al., 2018a) and derived from the Coupled Model Intercomparison Project Phase 5 (CMIP5, http://cmip-pcmdi.llnl.gov/ cmip5/). However, GFDL-ESM2M did not provide monthly depth-resolved phytoplankton and zooplankton data needed by DPBM and APECOSM, which were thus only run with IPSL-CM5A-LR, resulting in n = 10 marine ecosystem model-Earth System Model combinations (referred to as 'model combination' hereafter). GFDL-ESM2M and IPSL-CM5A-LR outputs span a wide range of projected Earth system changes under the specific RCPs, with GFDL-ESM2M representing moderate and IPSL-CM5A-LR strong changes in sea surface temperature (SST) and net primary productivity (NPP), while other variables (e.g. pH, oxygen concentrations) were more similar (Bopp et al., 2013). For our study, we selected RCP2.6 and RCP8.5 to bracket a broad range of greenhouse gas emissions trajectories. RCP2.6 represents a low emissions or strong mitigation scenario assuming emissions peak between 2010-2020 and decline substantially until 2100 (van Vuuren et al., 2011). RCP8.5 characterizes a no-mitigation and worst-case pathway assuming emissions continuous to increase until 2100 (Riahi et al., 2011).

All ecosystem model projections were output on a 1° x 1° global grid, except DBEM, which used a 0.5° x 0.5° grid. Within Fish-MIP, projections that included fishing impacts on animal biomass were only available for three of the six marine ecosystem models, and these used a very simplified future fishing scenario (fishing effort held constant at 2005 levels) because spatially explicit future fisheries projections are as yet unavailable in a standardized form. Hence, we chose to only analyze runs under a no-fishing scenario; thus, focusing specifically on isolating climate-change impacts (Tittensor et al., 2018a).

We extracted annual total fisheries landings data from 1990-1999 for all fisheries and targeted species managed by NAFO for each division using the STATLANT 21A Data Extraction Tool (https://www.nafo.int/ Data/STATLANT). The 1990-1999 timeframe was chosen to correspond with our historical reference period in biomass projections (see next section). Additional time series (1980-1989, 2000-2009) for total landings were extracted for sensitivity analyses.

4.3.3 Data analysis

4.3.3.1 Projected changes in the North Atlantic Ocean

Projected time series of historical and future marine biomass of animals >10cm for each model combination under RCP2.6 and RCP8.5 were extracted from the Fish-MIP database for the North Atlantic Ocean. We selected each grid cell centroid located in the North Atlantic Ocean (Figure 4.1) using ArcMap 10.5 and calculated area-weighted annual mean biomass changes for each 1˚ x 1˚ grid cell using the statistical software R (v3.4.3). DBEM's 0.5˚ x 0.5˚ resolution was adjusted to a 1˚ x 1˚ grid by averaging over each 1˚ x 1˚ grid cell.

For each grid cell and model combination, we standardized annual biomass time series to percent change relative to the mean 1990-1999 biomass as a historical reference period for the last decade of the 20th century. We then calculated mean percent biomass changes to 2030-2039 as a near-future time frame (the 2030s), which includes the target year 2030 of the United Nations Sustainable Development Goals (SDGs), and to 2090-2099 as the last decade of the 21st century as a far-future time frame (2090s) relative to the 1990s. We used calculations of relative rather than absolute biomass changes because different ecosystem models cover different components (e.g. size classes, trophic groups, species) of the marine ecosystem and their absolute biomass estimates are not directly comparable. These grid-cell specific relative changes were then averaged over all model combinations to derive an ensemble mean. We note that most grid cells contain a full ensemble (n=10), except nearshore cells with often n=6 or less (Figure D.1) due to differences in nearshore resolution and how land-sea masks are applied across models; however, previous sensitivity analyses comparing the full to reduced model ensembles did not drastically change the overall magnitude or direction of results (Bryndum-Buchholz et al., 2019; Lotze et al., 2019).

To evaluate the variability of individual projections around the ensemble mean, we used two measures: variability in the magnitude of projected changes was calculated as the standard deviation (SD, %) around the ensemble mean (referred to as model spread), and variability in the direction of projected changes (i.e. increase/decrease) was calculated as the percent model agreement (Bopp et al., 2013). The model agreement can range between 50% (half the models in the ensemble agree on the direction of change) and 100% (all models agree on the direction of change). Generally, 80-100% represents high model agreement in the ensemble projections (Bopp et al., 2013).

4.3.3.2 Projected changes in the NAFO convention area

Within the NAFO convention area, we extracted spatially explicit ensemble mean biomass changes and calculated the model spread (SD) and percent model agreement for each NAFO division (n=35). We first mapped spatial patterns of projected changes in the ensemble mean biomass, and the model spread and model agreement across the NAFO convention area in the 2030s and 2090s relative to the 1990s under both emissions scenarios.

We used a similar approach to examine changes in historical and projected SST and NPP across NAFO divisions. We calculated mean relative changes in SST and NPP in the 2030s and 2090s relative to the 1990s for each Earth System Model under the two contrasting emissions scenarios and derived the ensemble mean (n=2) for each NAFO division. We then related changes in NPP to those in SST for each NAFO division to examine underlying shifts in oceanographic conditions under different climate-change scenarios.

4.3.3.3 Relationship of projected biomass changes to fisheries landings

To evaluate the potential impacts of future climate change on fisheries production, we related mean projected biomass changes (%) from the 1990s historical reference period to the 2030s and 2090s for both RCP2.6 and RCP8.5 to mean total fisheries landings in each NAFO division during 1990-1999 (standardized by area, kg km^{-2}). The biomass projections and landings data both span the same area of interest and the 1990s baseline decade. We used weighted log-linear regression models to analyze the relationship between mean projected biomass changes (%, dependent variable) and mean fisheries landings (kg km^{-2}, independent variable) across NAFO divisions (Equation 1). We excluded NAFO divisions 6A-6H from the regression analysis, as fisheries landings were only recorded for 1990-1992. Further, we log-transformed the dependent variable (fisheries landings) to satisfy statistical assumptions of linearity and a constant relationship between the variance and the mean for the residuals, based on a visual assessment. We accounted for the fact that some divisions showed higher model spread (SD) around the ensemble mean biomass change by adding inverse variance weights (1/SD) to the regression model. Larger weights were assigned to biomass projections with smaller SD, hence higher model agreement around the ensemble mean, giving them more influence in the regression analysis. The equation representing our modelling approach is thus:

$$\Delta_i = \beta_0 + \beta_1 \log_{10}(L_i) + \varepsilon_i \qquad (1)$$

where $\varepsilon_i \sim N(0, \sigma^2\omega_i)$, Δ_i is the relative change in projected future biomass, L_i is the average landings data within each NAFO division i, and β_0 and β_1 are the estimated intercept and slope, respectively. ε_i is the error term and ω_i the weighting for division i (inverse variance weights), and σ^2 is the variance.

As a sensitivity analysis to account for variability in fisheries landings over time, we ran additional regression models with NAFO landings averaged over 1980-1989 or 2000-2009 instead; our results were robust to these differences.

4.4 RESULTS

4.4.1 Projected changes in the North Atlantic Ocean

Our ensemble projections of trends in marine animal biomass >10cm revealed much greater changes in the long term (by the 2090s) than near future (by the 2030s), and much greater changes under RCP8.5 than RCP2.6 (Figure 4.1). Thereby, biomass was generally projected to increase in arctic and subarctic areas yet decline in most temperate and subtropical areas.

In the near future (the 2030s), projected changes relative to the 1990s showed spatially larger areas of biomass decrease under RCP8.5 compared to RCP2.6 (Figure 4.1). Notably, a region between 40-50˚N latitude off the western European coast showed consistently higher declines compared to other regions in the North Atlantic under both emissions scenarios (Figure 4.1). The model spread in the 2030s was lower under RCP2.6 than RCP8.5 (Figure D.2), with consistently high spread (±50% SD) above 60˚N and in large parts of the Mediterranean Sea under both emissions scenarios. Model agreement in the direction of projected biomass changes by the 2030s was higher under RCP2.6 than under RCP8.5 (Figure D.2). Under RCP8.5, model agreement did not differ substantially between near and far future biomass changes (Figure 4.2, D.2).

In the distant future (by the 2090s), projected biomass changes under RCP2.6 generally followed a similar spatial pattern compared to near-future changes (Figure 4.1). However, areas of projected biomass increase were larger, and areas of biomass decrease smaller compared to RCP8.5, with overall lower magnitudes of change. Also, the model spread was lower under RCP2.6 and model agreement generally higher than under RCP8.5 (Figure 4.2). Under RCP8.5, in the 2090s, several areas of high biomass increase (25-75%) occurred above 60˚N, off West Africa (20-30˚N) and in the Gulf of Mexico

(Figure 4.1); however, they also showed high model spread (±50% SD) and low model agreement (<80%) on the direction of change (Figure 4.2). In contrast, areas of largest biomass decline were found between 35-60˚N, along the West African coastline (0-10˚N), and in most of the Caribbean Sea (Figure 4.1), with low model spread (below ±20% SD) and high model agreement (>80%) providing confidence in ensemble results (Figure 4.2, D.5, D.6).

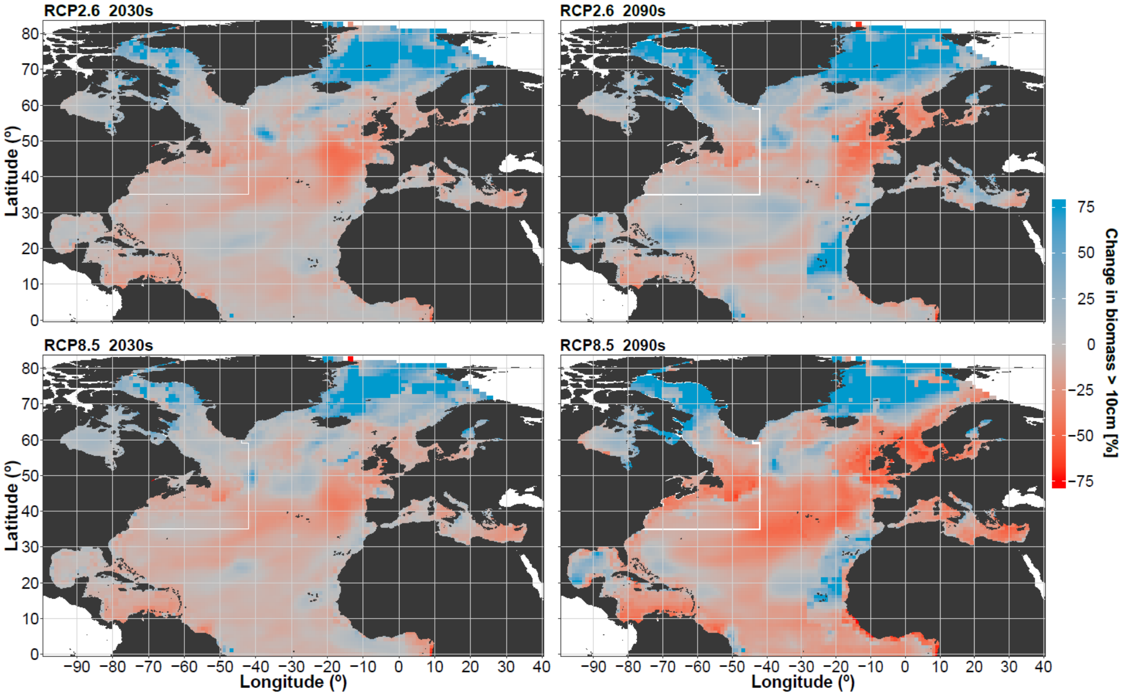

Figure 4.1: Spatial patterns of ensemble projections for RCP2.6 (top) and RCP8.5 (bottom) in the North Atlantic Ocean. Shown are the multi-model mean changes (%) in biomass of marine animals >10cm in the 2030s (left) and 2090s (right) relative to the 1990s. The white outline indicates the NAFO convention area. Country shapefile retrieved from https://www.naturalearthdata.com. NAFO convention area shapefile modified from https://www.nafo.int/Data/GIS.

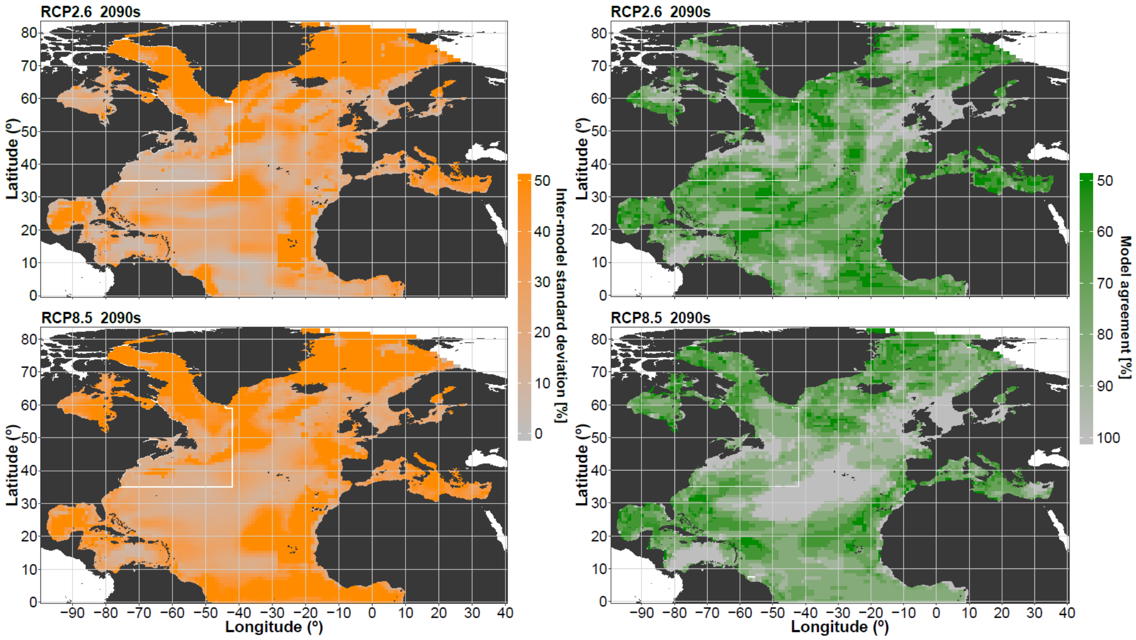

Figure 4.2: Spatial patterns of model variability (left) and model agreement (right) in ensemble projections for RCP2.6 and RCP8.5 in the North Atlantic Ocean in the 2090s relative to the 1990s. Model variability is represented as the inter-model standard deviation (SD, %) of the projected ensemble mean biomass changes, while model agreement denotes the percent of models agreeing on the direction of change. The white outline indicates the NAFO convention area. Results for the 2030s are shown in Fig. S2. Country shapefile retrieved from https://www.naturalearthdata.com. NAFO convention area shapefile modified from https://www.nafo.int/Data/GIS.

4.4.2 Projected changes in the NAFO convention area

Projected changes in marine animal biomass >10cm, NPP and SST across the individual NAFO divisions differed in magnitude and some cases direction of change between the near (the 2030s) and far (the 2090s) future relative to the historical reference period (the 1990s) as well as between the two emissions scenarios RCP2.6 and RCP8.5 (Figure 4.3, 4.4, D.3).

By the 2030s, under RCP2.6, biomass was projected to decrease in most divisions, while some regions in the northern divisions 0A-B and 1A showed projected biomass increases by up to 75% (Figure D.3A). The projected near-future biomass changes were similar under RCP8.5 (Figure 4.3A). By the 2090s, biomass projections showed again similar patterns under RCP2.6 (Figure D.3C); however, expanding and exacerbated biomass declines were projected under RCP8.5 (Figure 4.3C). Most of the NAFO convention area below 60˚N was projected to experience large biomass declines (-10% to -40%), with peak declines in NAFO subarea 3, while biomass was projected to increase in NAFO divisions 0A, 0B, 1A, and 1B (Figure 4.3C).

The spatial trends in projected biomass changes generally corresponded to a combination of projected changes in NPP and SST generated by the Earth System Models (Figure 4.4). In the near future (Figure 4.4A), most NAFO divisions were projected to experience an SST increase of <1˚C (median 0.78˚C under RCP2.6, 0.86˚C under RCP8.5), with only few attaining values up to 1.5˚C – 1.8˚C, and only one area (Division 2J) showing a slight SST decrease under RCP2.6. However, the majority of NAFO divisions experienced an increase in NPP under RCP2.6 (85% of NAFO divisions, median 12% change) but a decrease in NPP under RCP8.5 (94% of NAFO divisions, median -9.5% change). By the 2090s (Figure 4.4B), there were distinct differences in both SST and NPP between RCP2.6 and RCP8.5. Under RCP2.6, projected SST changes were slightly greater (median 0.83˚C) and NPP changes lower (median 8.6%) than those in the 2030s. Under RCP8.5, projected SST changes were much greater (median 3˚C), reaching 4˚C in several divisions (e.g. 3M, 3N, 3Ps, 4T, and 4S), while NPP mostly declined (86% of NAFO divisions, median -9.5%).

4.4.3 Relationship of projected biomass changes to fisheries landings

Projected biomass changes showed negative relationships with mean fisheries landings in the NAFO convention area, with similar slopes under both emissions scenarios in the near future (Figure 4.3B), yet a more negative slope under RCP8.5 than RCP2.6 in the far future (Figure 4.3D; Table D.1). The variation around the analyzed relationship increased, (SD around the slopes, Table D.1), between near and far future changes under both emission scenarios, while the fit (Adj. R^2) remained similar.

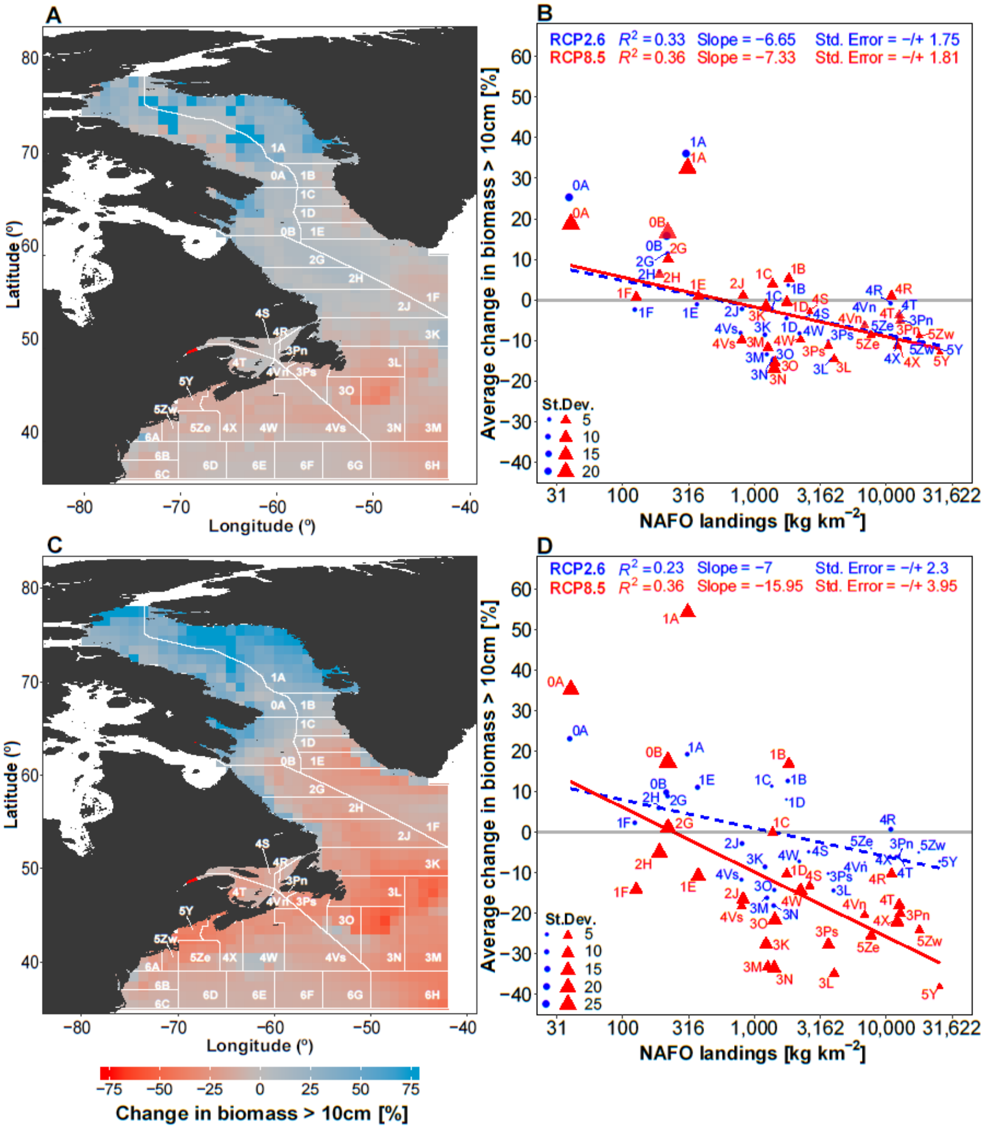

Figure 4.3: Future ensemble mean changes (%) in biomass of animals >10cm under RCP8.5 in the 2030s (A) and 2090s (C) relative to the 1990s, and their respective relationships to average annual fisheries landings in the 1990s (kg km^{-2}) across individual NAFO divisions (B, D). The dashed lines in (B, D) represent inverse-variance weighted linear regressions. Landings values are presented on a log scale. Spatial results for projected biomass changes under RCP2.6 are shown in Fig. S3, and relationships with fisheries landings in the 1980s and 2000s in Fig. S4. Country shapefile retrieved from http://www.diva-gis.org/gdata. NAFO division shapefile retrieved from https://www.nafo.int/Data/GIS.

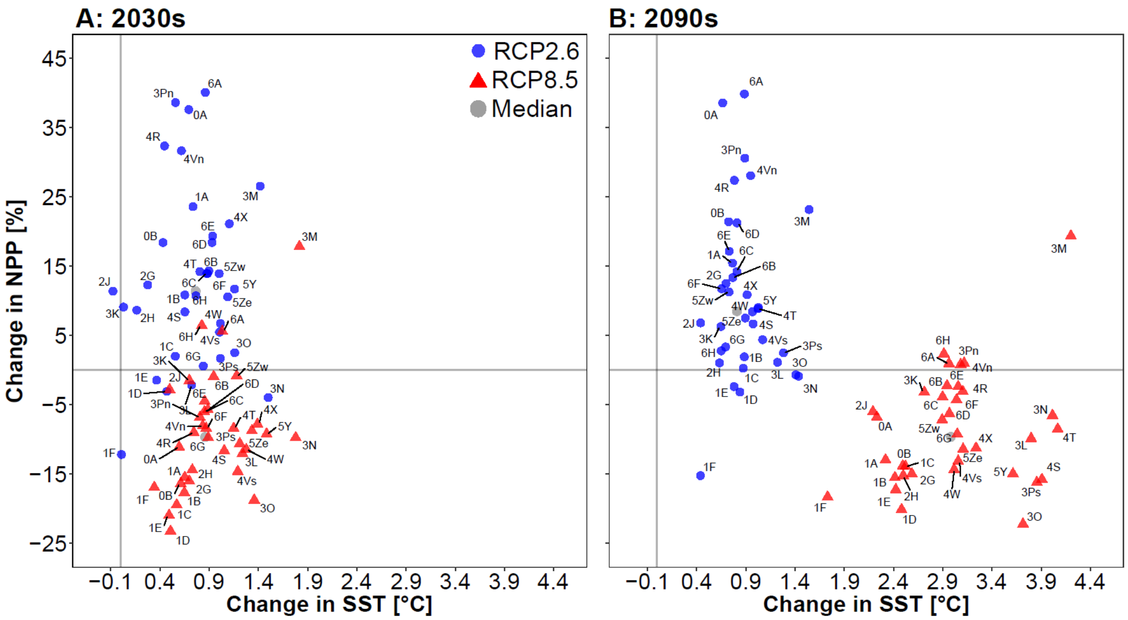

Figure 4.4: Projected relative changes in NPP (%) and SST (ºC) across Earth System Models (n = 2) under RCP2.6 (blue) and RCP8.5 (red) across individual NAFO divisions in the 2030s (A) and 2090s (B) relative to the 1990s. The larger grey dots represent the median values of projected NPP and SST across the entire NAFO convention area. Grey lines represent 0% and 0ºC change.

Under RCP2.6 and RCP8.5, projected biomass decreased in most NAFO divisions with mean fisheries landings of >1000 kg km^{-2}. Divisions that showed projected biomass increases included northern divisions (Subarea 0, 1, and 2) with mostly lower mean landings (<1000 kg km^{-2}, Fig. 3). Notably, by the 2090s, divisions with lower landings (i.e. 0A, 0B, and 1A) were projected to experience biomass increases between 20-70% under RCP8.5; however, most divisions with higher landings were projected to experience biomass decreases between 5-40% (Figure 4.3D). Our sensitivity analyses also revealed negative relationships between projected biomass changes and mean landings in the 1980s and 2000s under both emissions scenarios for near and far future changes (Figure D.4) and corroborated the results of our selected 1990s time frame, since mean landings across NAFO divisions did not differ substantially between the different decades (Figure 4.3, D.4).

4.5 DISCUSSION

This study highlights that climate change will have substantial impacts on marine ecosystems and the future of marine living resources in the North Atlantic Ocean, which will pose challenges to fisheries management. Understanding the magnitude of effects and their consequences is therefore critical for the development of sustainable fisheries into the future. Our ensemble projections reveal that the largest biomass changes and fisheries management challenges will manifest in the long-term towards the end of the 21st century and under the worst-case emissions scenario compared to the near future (the 2030s) and strong mitigation scenario. Moreover, our results highlight regional differences in the direction and magnitude of projected changes in marine animal biomass and underlying environmental drivers across NAFO divisions; projections show potential biomass increases and associated benefits in northern regions with historically low fisheries landings compared to biomass declines in more southern regions with historically high fisheries landings. Our ensemble modeling approach highlights regions with a strong agreement and low variability among individual model projections and regions with strong differences which offers valuable insights into model uncertainties that can be used to improve individual Earth System and ecosystem models (e.g. their structure, processes and resolution) and their utility to inform fisheries management.

4.5.1 Projected changes in the North Atlantic Ocean

Across the North Atlantic, spatial patterns of projected biomass changes were similar in the near (the 2030s) and far future (the2090s); however, the magnitude of change increased over time and from strong mitigation (RCP2.6) to a worst-case (RCP8.5) scenario. These results demonstrate the potential benefits of climate-change mitigation under the Paris Agreement (United Nations Framework Convention on Climate Change, 2015). Notably, regions above 60˚N and off Northwest Africa were projected to experience large biomass increases, indicating emerging ecosystem conditions that favor oceanic productivity due to climate change, such as warming polar waters and increased primary production; however, the high variability and low model agreement in these regions, likely due to uncertainties in Earth System Model projections in polar and upwelling areas (Bopp et al., 2013), suggest a broad range of potential future trajectories. In contrast, nearshore waters along the North American East Coast, the United Kingdom and Ireland, and along the West African coastline are projected to experience overall biomass declines under both emissions scenarios, highlighting climate-change related decreases in marine ecosystem production related to warming-induced increased stratification and reduced primary production. In these regions, low model variability and high agreement suggest greater certainty in future trajectories.

The spatial patterns of projected biomass changes are concurrent with observed and projected changes in two key drivers of marine ecosystem dynamics — temperature and primary production. In the North Atlantic, the highest rates of warming over the last three decades have been observed at the Gulf Stream Front and in the Labrador Sea in the west, and on the European continental shelf above 50°N in the east (Taboada & Anadón, 2012; Pershing et al, 2015), with consequences for nutrient cycling, phytoplankton concentrations and fish recruitment (Boyce & Worm, 2015; Britten et al., 2016). For example, in Canadas's Atlantic waters, rising temperatures and declining phytoplankton levels have already led to lower production potential over recent decades (Bernier et al., 2018); under RCP8.5, our results show continued high warming and NPP declines leading to substantial biomass decreases by 2100. In the North Sea, NPP has declined since the 1980s as a function of increasing SST and decreasing riverine nutrient input, leading to reduced higher trophic level biomass and fish stock recruitment (Capuzzo et al., 2017). Future projections suggest further NPP decreases by up to 70% by 2100 (Barange et al., 2018) and 10-60% decreases in the biomass of key commercial fish stocks within UK waters under RCP2.6 and RCP8.5 (Fernandes et al., 2017); our results project biomass decreases of at least 75% in several Northeast Atlantic, areas including the Irish, Celtic and North Seas.

Generally, our ensemble results agree with observed and projected spatial trends in North Atlantic ecosystems but highlight regional variation in biomass projections. This regional variation in biomass decreases and increases can help identify regions with disadvantages (losers) and benefits (winners), respectively, for fishery-dependent societies in terms of consequences for seafood supply, fisheries operations, and challenges for marine management and conservation (Blanchard et al., 2017; Greenan et al., 2018). Eventually, the socio-economic and environmental impacts of climate change will also depend on future trajectories of commercial fisheries, aquaculture, and other human activities, including their politically adaptive and mitigative capacities (Blanchard et al., 2017; Galbraith et al., 2017; Lotze et al., 2019).

4.4.2 Projected changes in the NAFO convention area

The NAFO convention area spans major fishing grounds along the coasts of the Northeast US, Atlantic and Arctic Canada and Greenland, which have supported people for centuries and longer. Our ensemble projections suggest substantial changes in future marine animal biomass across NAFO divisions, yet projected changes differed in magnitude and some cases direction between the near (the 2030s) and far (the 2090s) future relative to the historical reference period (the 1990s) and between low and high emissions scenarios.

Projected biomass declines were consistently higher within NAFO divisions 3L-3O, which include the Grand Banks of Newfoundland and the Flemish Cap, historically two of the richest fishing grounds in the world, supported by constant mixing of the cold and nutrient-rich Labrador Current and the warm Gulf Stream (DFO, 2012). Water temperatures in these regions are anticipated to increase by more than 3°C over the 21st century (RCP8.5), likely related to changes in large-scale ocean circulation, in particular a northward expansion of the subtropical gyre or shift of the Gulf Stream (Saba et al., 2016; Greenan et al., 2018), with considerable impacts on this highly productive shelf ecosystem and the fisheries it supports. Although warm-adapted species may move in from the south, projected decreases in NPP under RCP8.5 will limit possible secondary production. We caution, however, that projected changes in Northwest Atlantic circulation patterns remain uncertain, due to the limited capability of Earth System Models to represent complex oceanographic processes within this region and for fine scales and coastal areas (Sgubin et al., 2017).

Within Northeast US waters (NAFO divisions 5Y, 5Zw, 5Ze, 6A-6D), our projections also suggest strong biomass declines, particularly under RCP8.5, related to declining NPP and increasing SST. Recent observations indicate clear distributional shifts in more than 30 commercial fish stocks that are consistent with warming (Nye et al., 2009). For example, in the Gulf of Maine, a substantial reduction in recruitment and increasing mortality rates in Atlantic cod (*Gadus morhua*) populations have been observed, due to extreme water temperatures (Pershing et al., 2015). In the future, major US Atlantic fish stocks are projected to decline due to changes in thermal habitats, especially after 2060 (Shackell et al., 2014). Some of these species will move into Canadian waters from the south, with cold-adapted invertebrate and fish species moving further north or towards deeper or more offshore waters in search of colder habitats (Pinsky et al., 2013; Shackell et al., 2014; Stortini et al., 2015). These changes will alter regional food-web structure and species composition. On the other hand, an influx of warm-water species from the south may have increased marine diversity and productivity within some regions of the US northeast in recent decades (Friedland et al., 2019).

In the northern NAFO divisions 0A-0B and 1A-1B, which include Baffin Bay, the Davis Strait and the Labrador Sea, our ensemble projected biomass increases by the 2090s under both emissions scenarios, indicating enhanced ocean production and poleward shifts of marine animals as new habitats become available. In recent decades, polar regions have been warming at some of the highest rates on the globe (Hoegh-Guldberg & Bruno, 2010) resulting in longer growing seasons for phytoplankton, increased primary production, and loss of sea-ice opening new habitats that sustain growth and survival for shifting species (Cheung et al., 2009; Frainer et al., 2017; Andrews et al., 2019). Overall, gradual to substantial changes in species distribution are expected by the 2030s and 2090s, respectively, which will affect animal biomass, species diversity, community organization, and ecosystem functions and services (Cheung et al. 2009, 2010; Worm & Lotze, 2016).

Across the NAFO convention area, projected SST increased in most divisions under both emissions scenarios, whereas NPP mostly increased under RCP2.6 yet decreased under RCP8.5. Both water temperature and primary production are critical drivers of marine ecosystem dynamics and important forcing variables in our model ensemble (Bopp et al., 2013; Worm & Lotze, 2016; Tittensor et al., 2018a). Several other physical and biochemical factors are also influenced by climate change, such as pH, oxygen concentration, salinity, and sea-ice cover, which were considered by some ecosystem models (Table A1, A2; Tittensor et al., 2018a). Interestingly, by the 2030s, projected changes in SST did not differ in magnitude between emissions scenarios; however, distinct differences between RCP2.6 and RCP8.5 were projected by the 2090s. These patterns highlight the importance of implementing long-term effective climate-change mitigation measures to avoid extreme ocean warming and potentially deleterious effects on marine ecosystems.

In NAFO divisions 3K, 3M, 3O, 3Pn, and 3Ps, projected animal biomass declined despite increases in NPP under RCP2.6 (but decreases under RCP8.5) for both the 2030s and 2090s, which may indicate a response to increasing water temperatures, rather than nutrient or prey limitations. As individual ecosystem models differ in the configuration of fundamental structures, taxonomic groups, and ecological processes, this response within the model ensemble was likely influenced by size-structured models (BOATS, Macroecological, DPBM, see Table A.1 and Figure D.5, D.6), which focus on metabolic rates and energy flow, leading to biomass projections responding strongly to SST changes (Jennings & Collingridge, 2015; Carrozza et al., 2016; Bryndum-Buchholz et al., 2019; Lotze et al., 2019). In NAFO subarea 5, strong negative biomass responses to declining NPP and increasing SST were projected under RCP8.5 both in the near and far future. Here, the ensemble projections were likely influenced by models that respond more strongly to a combination of temperature, NPP, and additional drivers, such as pH and oxygen, affecting habitat availability and species distribution (e.g. EcoOcean, DBEM, see Table A.1, Figure D.5, D.6, and Lotze et al., 2019).

4.4.3 Relationship of projected biomass changes to fisheries landings

Climate change is already impacting regional and global fisheries, and the societies that depend on them, driving the need for resilient and adaptive, ideally pro-active management solutions (e.g., Allison et al., 2009; Cheung et al., 2013b; Free et al., 2019; Barange, 2019). In the Northwest Atlantic, regional fisheries production is already responding to rising sea temperatures and expected to continue to change with global warming (Cheung et al., 2010). For example, the Gulf of Maine (NAFO division 5Y) lobster fishery has been recording record-breaking landings; however, the warmer southern New England (NAFO divisions 5Zw and 6A) fisheries have collapsed (Le Bris et al., 2018). The differences between the two lobster fisheries were primarily attributed to differences in their management and above-average increasing water temperatures (Le Bris et al., 2018). In Atlantic Canada, higher water temperatures favor lobster populations, which are rapidly increasing on the Scotian Shelf, whereas two other high value but cold-water invertebrate species – the northern shrimp *(Pandalus borealis)* and northern snow crab *(Chionoecetes opilio)* – have been declining on the Scotian Shelf and Newfoundland-Labrador Shelf over the past decade (Bernier et al., 2018; DFO, 2018a, 2019a). These examples highlight current and potential future challenges for fisheries management under rapidly changing ocean conditions.

Our ensemble projections indicate potential future trajectories of harvestable biomass under climate change relative to the 1990s, which we then compared to fishing levels in the 1990s within NAFO divisions. The nature of the relationships provides information about potential climate-driven future changes in animal biomass that may influence fisheries production and thus be relevant for managers. For instance, forecasted biomass declines in divisions with traditionally high fish landings may suggest that fisheries may become less productive, or that fishers may need to spatially shift fishing efforts as target species move into other divisions. Additionally, forecasted biomass in northern NAFO divisions, which are historically more lightly exploited, largely increased, indicating that fisheries may become more productive in these divisions. Understanding how fish biomass will change, relative to its historical distribution will be important to proactively manage the fisheries. Our ensemble models do not include fishing pressure or management effects on marine biomass, and no direct link between our biomass projections and fisheries landings was assumed. We expected more southern NAFO subareas (3, 4, 5, and 6) to be more negatively affected by climate change, as these regions are in warmer, more temperate waters, compared to the colder, more northern subareas (0, 1, and 2). Our results corroborate these expectations; negative climate-change impacts on potential future harvestable biomass in southern divisions coincide with regions of traditionally higher fisheries landings, such as the Grand Banks of Newfoundland, the Scotian Shelf, and the Gulf of Maine, all of which already reporting climate-change related fisheries harvest reductions (Pershing et al., 2015; DFO 2018a, 2019a; Bernier et al., 2018; Le Bris et al., 2018).

Interestingly, the relationship between projected biomass changes and historical fisheries landings remains very similar between the 2030s and 2090s under the strong mitigation scenario (RCP2.6). Under the worst-case scenario (RCP8.5), however, the regression slopes differed compared to RCP2.6 as well as between near and far future changes, highlighting that long-term climate-change mitigation efforts are paramount to avoid extreme changes in future harvestable biomass and associated socio-economic implications for Northwest Atlantic fishing communities. Some fisheries may become less profitable as stocks become less productive or shift their distribution with climate change. In response, fishing effort may redistribute, which can lead to overfishing and exacerbated population declines if not adequately accounted for in fisheries management (Pinsky & Fogarty, 2012). Hence, future fisheries management frameworks will not only need to explicitly account for long-term climate-change effects on harvestable biomass, but also consider human responses to these changes (Pinsky & Fogarty, 2012).

4.4.4 Implications for fisheries management

How can we ensure the sustainability of commercial fisheries and targeted fish stocks under global change? This question applies to species and ecosystem conservation, but also to the adaptability and resilience of the institutions in charge of managing national and international fisheries (Rayfuse, 2012, 2019). Given the current level of overfishing in many fisheries worldwide and the anticipated climate-change impacts on ocean productivity, this study underlines the need for climate-adaptive fisheries management, which includes proactive management strategies that aim to mitigate, adapt, or respond to climate-change impacts, to achieve long-term fisheries sustainability on regional and global scales (Wilson et al., 2018; Barange, 2019).

Our ensemble results highlight substantial climate-change induced biomass changes within most of the temperate North Atlantic and NAFO convention area under two contrasting emissions scenarios, indicating challenges for the long-term sustainable management of marine living resources. Management measures by regional and national fisheries management agencies must be fully integrated with a comprehensive scientific understanding of the ecological (and socio-economic) consequences of climate change and develop an increased ability to continually adapt to new ecological realities arising from changing environmental conditions (Miller et al., 2010; Rayfuse, 2019). Our results may help to identify and evaluate climate-adaptation strategies, which is imperative to proactively develop fishery policies that facilitate required changes in current management systems (Mills et al., 2013). However, considering long-term natural and anthropogenic climate change in traditional fisheries sciences, such as stock assessments that guide management decisions, has proven difficult to implement (Pinsky & Mantua, 2014; Marshall et al., 2019).

In addition to our ensemble projections, finer-scale regional or species-specific ecosystem models may be of value for some fisheries management frameworks, as most fishing effort occurs in coastal or shelf regions, and many fisheries are managed based on single-species stock assessments (Guiet et al., 2019; Marshall et al., 2019). For fisheries management frameworks to account for climate change, marine ecosystem models ideally need to provide spatially resolved species-specific forecasts under different fishing mortality levels for a range of climate-change scenarios and time scales (e.g. seasonal, 2, 5 or 10 years). Such forecasts could support management agencies, such as DFO, which is already providing seasonal forecasts of Pacific salmon production and associated fishing opportunities and consequences (DFO, 2018b). When implemented at the appropriate spatial and temporal resolutions, utilizing marine ecosystem models within fisheries management frameworks can facilitate incorporating climate change into ecosystem monitoring, stock assessments, spatial management, international agreements, and management of emerging fisheries (Pinsky & Mantua, 2014). Our ensemble projections, for instance, indicate spatial shifts of harvestable biomass production indicating potential future consequences for local fishing communities in terms of access and reduced catches (Greenan et al., 2018; Rogers et al., 2019). Such long-term projections may facilitate setting long-term management and conservation measures, for example, redefining stock boundaries as populations shift to enable more accurate stock assessments (Pinsky & Mantua, 2014). Further, boundaries of fisheries closures and marine conservation areas could in some instances be dynamically re-evaluated to ensure long-term effective management and conservation outcomes under global change (Tittensor et al., 2019).

4.4.5 Limitations and future research

Our ensemble projections carry certain limitations that need to be considered. First, individual global marine ecosystem models in our model ensemble did not resolve every grid cell in our study region, due to different marine ecosystem models using their specific grids and land-sea masks. Generally, open ocean regions had greater model coverage than nearshore, coastal regions (Figure D.1). Consequently, low model coverage in some coastal grid cells reduced the number of marine ecosystem models incorporated into the ensemble model mean.

Second, model projections based on global Earth System Models are often less reliable in coastal or polar regions (Bonan & Doney, 2018; Derksen et al., 2018) as their resolution can be too coarse to capture small-scale oceanic dynamics, such as varying mixing patterns, upwelling, open-ocean connection, and marginal sea currents (Holt et al., 2009; Tittensor et al., 2018a). However, they could be improved through increased spatial resolution or coordinated regional downscaling to capture small-scale dynamics (Holt et al., 2017; Stock et al., 2017). Moreover, future ensemble projections of marine ecosystems will likely be refined with the integration of fully three-dimensional depth-resolved monthly biogeochemical variables provided through CMIP6 (Ruane et al., 2016; Tittensor et al., 2018a).

Third, fishing is an important human impact on marine ecosystems and will add to climate-induced stresses on global and regional scales (Frank et al., 2005; Pershing et al., 2015; Free et al. 2019). Given that spatially explicit future fisheries scenarios are yet unavailable for most models within Fish-MIP (Tittensor et al., 2018a), our study did not include any fishing effects, thus isolating the climate-change signal upon which fisheries impacts will be superimposed. Considering our focus on implications for fisheries management institutions, future fisheries scenarios should ideally recognize the complexities of fisheries management under global change, e.g. increasing fishing costs due to increasing energy costs and inefficient transboundary fish stock agreements due to geographical shifts of commercially targeted stocks (Maury et al., 2017; VanderZwaag et al., 2017; Tittensor et al., 2018a; Cheung et al., 2019). This remains a major challenge, especially in aligning any such scenarios to common socio-economic scenarios used to drive other sectors, such as the Shared Socioeconomic Pathways, that define alternative trajectories in society and ecosystems in a world without climate policies (O'Neill et al., 2014), or the Oceanic Socioeconomic Pathways addressing policy-relevant scenarios for future ocean uses (Maury et al., 2017). In addition to including dynamic fishing scenarios, future marine ecosystem model development should aim at incorporating other human drivers and regional stressors, such as freshwater runoff, nutrient loading, and habitat alteration, as well as marine conservation efforts (i.e. increasing coverage of marine protected areas), which are important influences in coastal fisheries (Murawski et al., 2005; Cabral et al., 2019).

Finally, the information provided by global and regional marine ecosystem models, such as projected marine animal biomass changes, can be directly incorporated in the scientific advice of fisheries management organizations. One approach, which has been proposed by DFO, is a conceptual risk assessment that incorporates climate-change related information into their science advice in context of stock assessments (DFO, 2019b). This “climate change conditioned advice” identifies appropriate variables reflecting climate change that affect the dynamics of a resource and links these to the risk assessment component of the advice (DFO, 2019b).

4.6 CONLUSIONS

Our ensemble projections in the North Atlantic Ocean and within the NAFO convention area demonstrate substantial changes in future marine fish biomass with climate change. Our findings suggest benefits from effective climate-change mitigation under the Paris Agreement by keeping global temperature rise in this century well below 2˚C above pre-industrial levels. We identified a strong relationship between areas of projected future declines in harvestable biomass and historically important fishing grounds, such as the Grand Banks off Newfoundland, the Scotian Shelf, and the Gulf of Maine, indicating long-term challenges for the responsible management authorities. Understanding climate-change impacts on marine ecosystems and associated commercial fisheries provides an important link in achieving the UN Sustainable Development Goals (SDGs), as our oceans and their goods and services directly affect the progress in meeting the goals for food security (SDG1), livelihoods (SDG2), and wellbeing for a growing human population (SDG3), and for sustaining life below water (SDG14) (Singh et al., 2019).

4.7 ACKNOWLEDGEMENTS

We thank all marine ecosystem modelers who contributed to the Fish-MIP initiative, particularly E. Galbraith, J. Blanchard, O. Maury, S. Jennings, W. Cheung, T. Silva, D.

Carozza, D. Bianchi, T. Eddy, N. Barrier, P. Verley, M. Coll, and J. Steenbeek for running Fish-MIP simulations and providing ecosystem model outputs; L. Bopp, J. Dunne, C. Stock, and T. Roy for providing Earth System Model outputs; and M. Büchner, J. Volkholz, and J. Schewe for technical support. We also thank N. Shackell for valuable discussions and comments. Financial support was provided by the German Federal Ministry of Education and Research (BMBF Grant No 01LS1201A1) through the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). Andrea B. Buchholz acknowledges financial support from the NSERC CREATE Transatlantic Ocean Science and Technology Program (TOSST); Daniel G. Boyce from the Ocean Frontier Institute (OFI); Derek P. Tittensor from the Jarislowsky Foundation and the Kanne Rasmussen Foundation, Denmark; Heike K. Lotze and Villy Christensen from the Natural Sciences and Engineering Research Council (NSERC) of Canada (RGPIN-2014-04491 and RGPIN-2019-04901, respectively). The authors declare that they have no conflict of interest.

4.8 AUTHOR CONTRIBUTIONS

Concept and design by Andrea B. Buchholz and Daniel G. Boyce. Data preprocessing and analyses by Andrea B. Buchholz, discussion and writing by Andrea B. Buchholz, Daniel G. Boyce, Derek P. Tittensor, Heike K. Lotze, Daniele Bianchi and Villy Christensen.

CHAPTER 5

CLIMATE-CHANGE ADAPTATION IN FISHERIES MANAGEMENT: POLICY, LEGISLATION, AND IMPLEMENTATION

5.1 ABSTRACT

Climate change is altering marine ecosystems and commercial fisheries throughout the world, demanding climate-adaptive policies for conserving and managing living marine resources. In the recent past, international climate-change agreements and policies have been established, moving climate-adaptation and mitigation strategies on a national policy scale forward. In some regions, fisheries management systems are beginning to address wider ecosystem dynamics within stock assessments and decision-making, which may facilitate resilience to environmental disruptions due to climate change in addition to harvesting. Nonetheless, there remains a shortfall in terms of directly incorporating climate-change adaptation into fisheries management approaches and tools. Based on government documents and the primary literature, this review assesses the current state of implementation of climate-change adaptation into fisheries management policies and legislations across nine national case studies. The overarching goal is to understand current and expected climate-change impacts on marine ecosystems and fisheries and the key elements and gaps in existing fisheries management policies and legislations. Across case studies, political recognition of the need to address climate-change adaptation in fisheries management is increasing; albeit, formal mandates of climate-adaptation objectives in fisheries management are largely missing. Based on the review, recommendations for management approaches and/or tools to achieve climate-adaptive fisheries management regimes are developed. Overall, this study will help to inform and broaden the scope of management approaches and tools to accelerate the move towards

adaptive fisheries management that accounts for climate-change impacts on fish stocks, fisheries, and the societies that depend upon them.

5.2 INTRODUCTION

Climate change, together with overfishing, is considered a major threat to the global ocean (IPBES, 2019). Changing ocean conditions are influencing marine ecosystems in multiple ways: shifting species abundances and distributions, altering ecosystem structure and functioning, and affecting the goods and services that we rely upon for human well-being (Cheung et al., 2009, 2013b; Pinsky et al., 2013; Blanchard et al., 2017; Lotze et al., 2019). Many marine species respond to changes in temperature, oxygen content and other biogeochemical properties with distributional shifts, changes in growth and reproduction rates, and ecosystems may also be altered through changes in trophic structure (Cheung et al., 2013a). Many commercially important fish and invertebrates are shifting their distribution towards more polar, offshore, or deeper waters to remain in their preferred thermal range (Cheung et al., 2013b; Worm & Lotze, 2016).

These changes are altering marine ecosystems and are impacting regional fisheries production (Pinsky et al., 2013; Poloczanska et al., 2016; Lotze et al., 2019). Increasing ocean temperatures have already reduced fisheries production around the globe, with some regions having experienced up to 35% declines in the Maximum Sustainable Yield (MSY) of important fish stocks since the 1930s (Free et al., 2019). With climate change, some traditional fisheries may be lost while others will find newly emerging opportunities. As a consequence, fisheries profits, the provision of seafood and fisheries-dependent livelihoods will be affected in some regions (Lam et al., 2016; Blanchard et al., 2017; IPCC, 2019). Thus, adaptability within fishing management systems will be imperative as climate change continues to alter the distribution and abundance of targeted fish stocks (Rice et al., 2017).

Marine fisheries have significant impacts on fish stocks and marine ecosystems, which can act synergistically with other stressors, such as climate change, affecting resilience (Halpern et al., 2015; Sumaila & Tai, 2019) and highlighting the need for effective management to ensure the sustainability of fisheries operations and the continued provision of fish protein and nutrients to a growing human population (Sumaila et al., 2014). This is especially pertinent given that overfishing remains a major challenge for today's wild capture fisheries, with many fish stocks being harvested beyond biologically sustainable levels (34.2% of FAO assessed marine fish stocks) (FAO, 2020a). Overfishing can weaken the overall health of marine ecosystems and fish stocks, as habitats and population and trophic structures are disrupted through intensive and selective fishing efforts (Halpern et al., 2015; Sumaila & Tai, 2019). On the positive side, some regions have effective and comprehensive fisheries management practices in place and exhibit healthy fish stocks near target levels or rebuilding (Worm et al., 2009; Hilborn et al., 2020). Effective, adaptive, and proactive management frameworks are critical to limit or mitigate the threat of climate change impacting the ability of fisheries to provide a vital global food source and support millions of livelihoods (Gaines et al., 2018; FAO, 2018; IPCC, 2019). Failing to adapt current fisheries management frameworks to climate change will exacerbate the impact on human society and risk global food security in the long-term (Gaines et al., 2018; Free et al., 2020).

Climate change demands the implementation of effective climate-resilient fisheries management policies and legislations, which can be defined as "[…] precautionary, efficient, and responsive […] that address climate uncertainty, explicitly consider feedbacks within coupled marine social-ecological systems and integrate tools and policies at multiple spatiotemporal scales." (Holsman et al., 2019). Traditionally, most fisheries management policies, legislations, as well as management approaches and tools do not consider the effects of climate change. However, many existing management approaches (i.e. ecosystem or multi-species approaches) and tools (i.e. stock assessments, biological reference points) can be enhanced or modified to incorporate and adapt to the effects of climate change.

Existing management approaches need to be routinely evaluated and updated to ensure that they are flexible, responsive, and adaptable to both natural and anthropogenic changes (McIlgorm et al., 2010). For example, the Ecosystem-based Fisheries Management (EBFM) approach could be enhanced in terms of managing for climate-change induced impacts on population age structures, key habitats and species, designing appropriate marine reserves, and applying marine ecosystem models to hind- and forecast ecosystem changes (Chavez et al., 2017). Climate-responsive biological reference points (i.e. stock size, stock age structure) in combination with defined thresholds that, if approached, cause reduced or ceased fishing mortality, can facilitate climate-informed decision-making and enhance the precautionary approach to fisheries management (Kelly et al., 2015; Chavez et al., 2017). Moreover, adapting national fisheries management to climate change can occur in the context of the overarching policy interests (and capacities) of individual countries, such as to ensure the sustainable use of marine resources, protect fish and fish habitat, or to facilitate the economic growth of coastal communities and promote ocean industries (Ogier et al., 2016).

The goal of this review is to assess the current state of implementation of climate-change adaptation into fisheries management policies and legislations. Existing fisheries management policies and approaches for nine countries were selected for their existing application of effective fisheries management policies, legislations, and practices. Based on published government reports and documents, non-governmental organization (NGO) reports, and peer-reviewed literature, following key questions were addressed: (1) What are the observed and expected climate-change impacts on each country's marine ecosystems and fisheries, in terms of two key ecological processes: species distribution shifts and changing stock and ecosystem productivity? (2) What are the cornerstones of their fisheries management policies and legislations? (3) Do the policies and legislations include an EBFM approach and/or consider climate-change adaptation? (4) What are the gaps in the fisheries management policies and legislations, as well as management approaches and tools with respect to climate-change adaptation? (5) Based on the above, what management approaches and/or tools can be recommended to achieve adaptive fisheries management regimes? Ultimately, this review will help to inform and broaden the scope of management approaches and tools to accelerate the move towards adaptive fisheries management that accounts for climate-change impacts on commercial fish stocks, fisheries, and the societies that depend on them.

5.3 MATERALS AND SCOPE

Fisheries management policies and legislations, including statutory laws, acts, and bills for nine different countries as case studies were reviewed, compared, and synthesized. The countries were as follows: Australia, Canada, Chile, European Union (EU), Iceland, Japan, New Zealand (NZ), South Africa, and United States of America (US) (Figure 5.1). The selection of case studies was based on the following criteria: (1) Publicly accessible fisheries management policies and legislations; (2) Fisheries management legislations are implemented; (3) Diversity (across case studies) in observed and expected climate-change impacts on industrialized fisheries based on published primary literature (e.g. Free et al. 2019, Lotze et al. 2019). The number of case studies was restricted to keep the review at a tractable size. Australia, Chile, New Zealand, and South Africa represent southern hemisphere case studies and Canada, the EU, Iceland, Japan, and the US represent case studies from the northern hemisphere (Figure 5.1). The case studies vary in their contribution to the global catch (based on average 2008-2017), with Australia on the lower end, contributing 0.2% to the global catch, and the US on the higher spectrum, contributing 6% to the global catch (Figure 5.1).

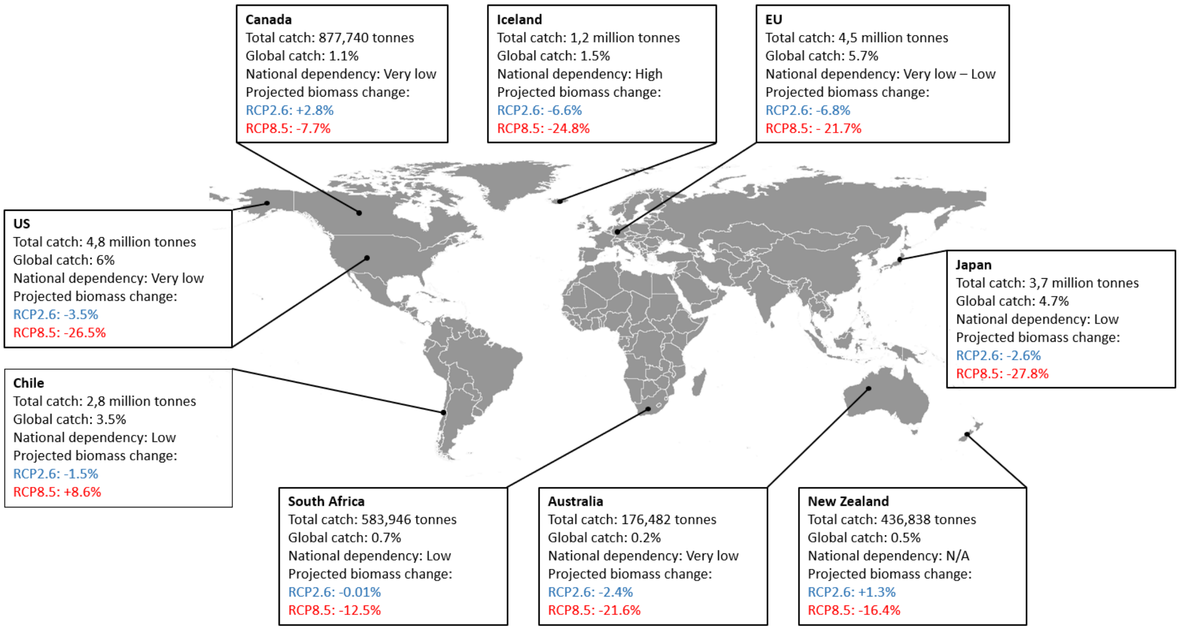

Figure 5.1: Overview of fisheries characteristics and projected changes in the marine ecosystems of each case study's Exclusive Economic Zone. Total catch and percentage of global catch are based on averages between 2008-2017; data derived from FAO (2020b). National fisheries dependency indicators are from Barange et al., (2014) and combine the effects of food, economic and employments provision by national fisheries (no data provided for New Zealand). Projected changes in marine biomass per EEZ are the total percent change in total biomass due to climate change only between a baseline of 2006-2016 and 2090-2099, provided by Boyce et al., (2020).

With a primary focus on industrialized fisheries within the Exclusive Economic Zones (EEZs) of each case study, the approach was as follows:

(i) Before analyzing individual case studies, scientific literature on existing fisheries management approaches and tools in the context of climate-change impacts and adaptation were reviewed, to provide an overview of progress in adapting fisheries management to date. Here, fisheries management approaches were defined as a "particular way of managing fisheries that give rise to or require certain methods or tools", such as EBFM, fisheries co-management and adaptive fisheries management. Fisheries management tools were defined as "an entity of instruments to support implementation of fisheries management legislations and approaches, ultimately aiming to support organizational processes, such as tools that regulate how much fish are taken from the ocean (e.g. selectivity controls, temporal and spatial fisheries closures, effort limits, and catch limits)".

(ii) Next, for each case study, observed and projected climate-change impacts on marine ecosystems and fisheries were reviewed, based on the primary literature, and the main patterns summarized. Here, the review focused on two ecosystem processes that have been associated with climate-change impacts on marine ecosystems and fish stocks and that directly affect marine capture fisheries: (1) spatial distribution shifts of fish stocks; (2) regional changes in stock and ecosystem productivity.

(iii) Further, for each case study, active fisheries management policies and legislations, as well as management approaches and tools as described by the respective government agency or ministry, were reviewed to assess the basis of fisheries management and whether it included an EBFM approach and/or climate-change adaptation. The latter was sub-sectioned into three components: (1) was ‘climate change’ stated in the policy or legislation, (2) were climate change and/or climate-change adaptation addressed in decision-making, and (3) in stock assessments. The focus on EBFM was justified as this management approach is considered to facilitate climate-change adaptability and resilience in marine capture fisheries (e.g. Pikitch et al., 2004; Ogier et al., 2016; Levin et al., 2018; Townsend et al., 2019). Here, we used the definition of EBFM as considering “indirect and direct interactions between fisheries, non-target species, and ecosystem processes [to] inform harvest recommendations." (Zador et al., 2017). The three subsections within the focus on climate-change adaptation were based on the following rationale: Stating ‘climate change’ in official government documents such as policies and legislations indicates political awareness of climate change and may point towards a political willingness to prepare for climate change and its consequences. Decision-making and stock assessments are two key processes in fisheries management, which determine implementation of management tools such as total allowable catch, annual catch quotas, or seasonal fisheries closures. Hence, assessing whether climate change is considered in decision-making and stock assessments is important when reviewing climate-change adaptation progress in fisheries management.

(iv) Next, gaps within and across the different management frameworks and case studies in the context of climate-change adaption were evaluated.

(v) Lastly, a list of recommended management approaches and tools was synthesized, based on the analyses above, to progress towards achieving adaptive fisheries management under climate change that attempts to minimize its impacts on fisheries resources. The review is ordered around sections that reflect each of these individual questions.

5.4 PROGESS TO DATE: CLIMATE-ADAPTATION IN FISHERIES MANAGEMENT

A variety of management approaches and tools that allow fisheries management to adapt to climate-change impacts on fisheries resources exist (Pinsky & Mantua, 2014; Busch et al., 2016; Lindegren & Brander, 2018). Ideally, depending on the social and ecological context, available fisheries management approaches and tools should be adaptively applied in combination with each other (Pinsky & Mantua, 2014). An EBFM approach is considered an effective fisheries management approach in the face of climate change (Table 5.1), as a full range of stressors can be addressed, including directed fishing, bycatch, and habitat destruction, all of which can reduce ecosystem and population resilience to climate impacts (McLeod & Leslie, 2009). As climate change affects ecosystems as a whole and alters species interactions, for example changes in predator-prey dynamics, mismatches due to species range shifts, and habitat changes or loss leading to reduced ecosystem productivity (Skern-Mauritzen et al., 2018), single-species management approaches can be ill-fitting under global change. EBFM, (Table 5.1) in combination with tactical management tools (Table 5.2) that reduce fishing mortality, bycatch, and habitat destruction, such as Harvest Control Rules (HCRs) or fishing quotas, can facilitate climate-change adaptation in fisheries management and the wider socio-economic fisheries system (Pinsky & Mantua, 2014).

The application of climate-adaptive management approaches and tools in fisheries management, however, is currently limited (Lindegren & Brander, 2018). The limited progress towards climate-change adaptation in fisheries management can be attributed to a lack of political incentives to acknowledge and prepare for climate change and its consequences (Termeer et al., 2016). Further, rigid institutional structures often foster a reluctance to adopt new approaches (Termeer et al., 2016), especially in the context of considering climate-change effects in stock assessments (Skern-Mauritzen et al., 2016) or formally responding to climate-induced species range shifts (Miller & Munro, 2004; Marzloff et al., 2017; Dubik et al., 2019). Explicitly including climate change in stock assessments requires accounting for current and future climate-change impacts on stock and ecosystem productivity, as estimated stock productivity and biological reference points, including MSY, can be significantly affected (Karp et al., 2019). However, incorporating the effects of climate change on stock productivity into stock assessments entails additional financial investments in ecosystem monitoring and data collection to adequately cover essential ecosystem processes, as well as the development of robust regional marine ecosystem models (National Oceanic and Atmospheric Administration (NOAA) Fisheries, 2018; Skern-Mauritzen et al., 2016).

Distributional shifts in fish stocks can impair existing management jurisdictions, such as EEZ (Gaines et al., 2018; Pinsky et al., 2018). As stocks decline within a given EEZ due to climate-induced range shifts, initial management incentives for long-term sustainable harvesting can become obsolete as new incentives are created to overharvest before fish stocks ultimately leave the EEZ (Diekert & Nieminen, 2017). Some evidence of this pattern has been observed in New England fisheries, where fishing effort declined more slowly in southern regions compared to northern regions, indicating compensatory behavior for northward shift in target species (Pinsky & Fogarty, 2012).

Table 5.1: Overview of fisheries management approaches with climate-adaptive characteristics (modified from Ogier et al., 2016).

Management approach	Key elements	Key references
Ecosystem-based fisheries management (EBFM)	• Explicitly considers impacts of harvesting on all ecosystem components, including target and non-target species, habitat, and ecological communities. • Considers social, economic, and ecological factors, facilitating broader socio-economic climate-change adaptation. • Recognizes importance of environmental changes, such as productivity, climate variability, and climate change. • Facilitates climate-change adaptation by enhancing the resilience of natural ecosystems and ecosystem services. • Accounts for gradual or abrupt changes through managing for the long-term.	McLeod & Leslie, 2009; Fletcher et al., 2010; Ogier et al., 2016; Hornborg et al., 2019; Lidström & Johnson, 2020
Time-area fisheries closures (static/dynamic)	• Can minimize bycatch, hence reducing wider ecosystem impacts of fishing and enhancing ecosystem resilience towards climate-change impacts. • Aims at reducing or preventing human-caused disturbance of habitats that are essential for certain species and life-history stages, enhancing species and ecosystem resilience. • Depending on objective, spatial closures can be moved to adjust to climate-change induced shifts in species distributions.	Hobday & Hartman, 2006; Pinsky & Mantua, 2014
Marine protected areas/ Marine reserves	• Well-designed and effectively managed marine reserve networks can reduce local threats, and contribute to achieving multiple objectives regarding fisheries management, biodiversity conservation and adaptation to changes in climate and ocean chemistry. • Can enhance resilience of vulnerable ecosystems in the face of climate change.	Green et al., 2014; Pinsky & Mantua, 2014
Adaptive fisheries management	• Emphasizes learning from management decisions and inclusion of feedback in subsequent rounds of decision-making, promoting adaptive-capacity of fisheries management measures. • Iterative process that reduces uncertainty with an explicit, goal-oriented structure. Hence, allows progress in the absence of complete information, which is important for long-term climate-change adaptation. • Aims to integrate ecological, social, and economic factors, facilitating broader socio-economic climate-change adaptation. • Short- and long-term resource management.	Walters, 1986; Allen et al., 2011; Williams, 2011

Table 5.1 continued

Management approach	Key elements	Key references
Active adaptive fisheries management	• Version of adaptive fisheries management, with highly coupled relationship between management and learning about the effectiveness through experimentation and monitoring outcomes. • Involves designing conservation measures for managers to learn efficiently about the system so that future management is improved, bearing in mind the needs of managing the system in the present.	Walters, 1986; McCarthy & Possingham, 2007; Ogier et al., 2016
Fisheries co-management	• The responsibility for resource management and decision-making is shared between the government and stakeholders. • Can build adaptive capacity of fisheries to climate change, as acceptance of climate-change adaptation strategies can be enhanced • Long-term planning can be enhanced. • Flexible in coping with increased complexity and uncertainty imposed by climate change.	Berkes et al.,1991; Sen & Nielsen, 1996; Nursey-Bray et al., 2018
Adaptive fisheries co-management	• Combination of the iterative process in adaptive management and the shared responsibility of co-management. • Characterized by learning and science, which promotes fisheries and ecological resilience to climate-change impacts. • Equally concerned about social, institutional, ecological, and resource dimensions, facilitating broader socio-economic climate-change adaptation. • Emphasis on complex adaptive systems i.e. ecosystem dynamics and cross-scale interactions. • Facilitates autonomous adjustment in fisheries management measures leading to higher adaptability to climate change. • Can build adaptive capacity by creating more stability, productivity, and overall greater institutional flexibility to change.	Grafton, 2010; Plummer et al., 2012; Ogier et al., 2016; Nursey-Bray et al., 2018
Territorial Use Rights for Fisheries (TURF)	• Spatial property rights that grant access privileges and fishing rights to exploit fisheries resources within the designated area. • Improves ecosystem resilience in the face of climate change, as human stressors are usually minimized, leading to high abundance, species richness and biomass of target and non-target species. • Facilitates sense of stewardship for the entire ecosystem, which may lead to reduced fishing mortality and increased fish stock resilience to environmental change.	Christy, 1992; Ojea et al., 2017; Quynh et al., 2017

Table 5.2: Overview of commonly used fisheries management tools

Management tool	Main characteristics	Reference
Harvest Control Rule (HCR)	Pre-agreed guidelines that determine the allowable harvest based on stock status indicators. Range from constant-catch strategies to multi-step rules with variable allowable catches based on thresholds.	Kritzer et al., 2019
Individual Fisheries Quota (IFQ)	Right to harvest a certain amount of fish of an aggregate quota or total allowable catch (TAC) during a specific time period.	Acheson et al., 2015
Individual Transferable Quota (ITQ)	Transferable right to catch a certain amount of fish of an aggregate quota or total allowable catch (TAC) during a specific time period.	Acheson et al., 2015
Total Allowable Catch (TAC)	Total allowable catch for a given species for a certain amount of time.	Acheson et al., 2015
Total Allowable Effort (TAE)	Maximum level of fishing effort that can be applied to a fish stock during specific time period, commonly defined by days-at-sea and total number of operating fishing vessels.	International Seafood Sustainability Foundation (ISSF), 2020

These range shifts in commercial fish stocks in some cases also require proactive development of effective transboundary agreements that explicitly take climate change into account (VanDerzwaag et al., 2017; Gaines et al., 2018). However, economic and regulatory constraints within fisheries governance systems often hamper responses to climate-driven changes, leading to overharvesting and stock declines (Pinsky & Fogarty, 2012).

5.5 OBSERVED AND PROJECTED CLIMATE-CHANGE IMPACTS ON MARINE ECOSYSTEM AND FISHERIES ACROSS CASE STUDIES

Climate change is affecting and will continue to affect marine ecosystems and associated fisheries across the selected case studies (Figure 5.1; Table 5.3), with most projected to experience marine biomass declines within their EEZs under a high climate-change mitigation (RCP2.6) and worst-case emissions scenario (RCP8.5) (Boyce et al., 2020). For example, marine ecosystems across Canada’s three oceans are responding to climate-change related impacts, such as marine heatwaves and food web changes (Bernier et al., 2018; Grant et al., 2019), with current and future consequences for commercially important fish stocks (Table 5.3). Ecosystem projections for Canadian waters indicate an accelerating decrease in marine animal biomass in the Canadian Pacific and Atlantic; however, accelerating biomass increases in the Canadian Arctic (Bryndum-Buchholz et al., 2020). In the Canadian Pacific, marine ecosystems are already responding to climate-change related marine heatwaves, warmer rivers, and food web changes, with negative impacts on Pacific salmon populations (Grant et al., 2019; Table 5.3). Regions in the Canadian Arctic have already experienced impacts linked to climate change, such as declining catches in important subsistence fish species, such as Arctic cisco (*Coregonus autumnalis*), Pacific herring (*Clupea pallasii*), and Arctic char (*Salvelinus alpinus*) (Wesche & Chan, 2010). In contrast, Atlantic Canada has seen substantial increases in American lobster (*Homarus americanus*) abundance and catches, partly due to an influx of lobsters through the southern boundary in response to thermal habitat expansion, leading to emerging favorable habitats in the region (Shackell et al., 2014; Bernier et al., 2018; Table 5.3).

American lobster fisheries in the warmer southern New England region, however, are decreasing or have collapsed due to lack of harvest adjustments in response to climate-driven changes in lobster abundance (Le Bris et al., 2018). Similarly, Gulf of Maine cod (*Gadus morhua*) stocks have ultimately collapsed partly due to rapidly warming ocean temperatures, adding an additional stressor on the overfished cod stock by reducing recruitment and increasing natural mortality (Pershing et al., 2015). Yet, other commercial species are moving northwards into the US Northeast shelf region in response to expanding thermal conditions, such as Red hake (*Urophycis chuss*), leading to increased diversity and productivity, despite overall declining fishing pressure in the region (Friedland et al., 2020). To successfully manage fisheries in context of changing patterns of productivity and availability, existing management processes need to become anticipatory and flexible (Mumby et al., 2017; Gaines et al., 2018).

In response to changing ocean conditions, marine species are shifting toward cooler, often more northern waters (Brander et al. 2003; Table 3), transforming the structure and functioning of regional ecosystems (e.g. Lind et al., 2018; Staby et al., 2018; Chan et al., 2019). Since 2005, within EU waters, European hake (*Merluccius merluccius*), a warm water species, has shown one of the most substantial changes in distribution, expanding into the northern North Sea (ICES, 2017a; Staby et al., 2018). The range expansion of European hake into the North Sea has led to dramatically increased catches, despite no directed fishery in the region (ICES, 2017a; Staby et al., 2018). European hake is being caught as part of a mixed demersal fishery, in which only a small quota is allocated towards it; consequently, the quota no longer matches the regional abundance (ICES, 2017b). Another example is the distributional shift of Atlantic mackerel (*Scomber scombrus)* during their spawning and summer feeding migration. They are now entering the Icelandic EEZ (Berge et al., 2015; Table 5.3), and emerging mackerel fisheries in Icelandic waters have led to a complicated management crisis for the stock between the different nations involved, which were and continue to be unable to reach an agreement on sharing the allowed catch (Popescu & Poulsen, 2012). With the northward expansion of Atlantic mackerel, Bluefin tuna (*Thunnus thynnus*), a highly migratory top predator of Atlantic mackerel, has been observed beyond its usual distributional range, indicating changes in ecosystem structure in the region between eastern Greenland and Iceland, due to changing environmental conditions (Mackenzie et al., 2014).

Within Australia, warming ocean temperatures in South-East Australian waters are driving southward species range shifts, impacting ecosystem structure and functioning in some regions. For example, the long-spined sea urchin (*Centrostephanus rodgersii*) has been expanding its range southward and has caused barren habitats along the Tasmanian rocky reef system due to overgrazing of habitat forming seaweeds (Pagányi et al., 2018). Further, climate-change induced oceanographic alterations have affected life-history traits, such as size at maturity and size at migration, of the commercially important Wester rock lobster (*Panulirus cygnus*), affecting fisheries production (Caputi et al., 2009).

Observed changes in Chile and South Africa are difficult to attribute to climate change due to high natural variability in the ecosystem (Augustyn et al., 2017). Nevertheless, observations and projections point towards climate-change induced alterations in the ecosystems and their associated fisheries (Augustyn et al., 2017; Yáñez et al., 2017; Table 5.3). Chile's Jack mackerel (*Trachurus murphyi*) and Peruvian anchovy (*Engraulis ringens*) stocks abundances and regional distributions are highly variable, due to the strong influence of the El Niño Southern Oscillation (ENSO) (Arias Schreiber et al., 2011). A poleward extension of Peruvian anchovy in southern Chile has been observed, indicating southward emergence of available habitats in which anchovies can reproduce (Bustos et al., 2008; Table 5.3). Future Chilean jack mackerel landings are projected to increase between 10% (high emissions scenario) and 13% (low emissions scenario by 2065 (relative to 2015) under average fishing effort levels for 2010-2012, highlighting potential positive ecological, economic, and social consequences in the region (Brochier et al., 2013; Yáñez et al., 2017).

In South Africa, the economically important Western rock lobster (*Jasus lalandii*) fishery on west coast has experienced drastic declines since 1990s, mainly due to overharvesting and changes in distributional and productivity (Department of Environmental Affairs, 2013; Cochrane et al., 2020). Since the early 2000s, the proportion of Western rock lobster catches caught on the west coast has decreased from ~70% to <10%, whereas catches on the south coast have increased equivalently (Blamey et al., 2015). The abundances of other small pelagics, such as South African anchovy (*Engraulis capensis*) and sardine (*Sardinops sagax*), show high annual fluctuations, hence clear climate-change signals in abundance trends are difficult to determine (Augustyn et al., 2017). With continuing climate change upwelling is expected to increase in the Southern Benguela system off South Africa, leading to regionally increasing primary production which can propagate through the food chain, resulting in higher overall ecosystem productivity and marine animal biomass, indicating positive fisheries outcomes if adequate management is in place that carefully monitors the ecosystem (Lockerbie & Shannon, 2019). Projections of the South African anchovy fishery show a potential benefit from future ocean changes, as food availability increases (enhanced abundance of larger zooplankton species) due to increasing upwelling; however, the sardine fishery is projected to decline, due to decreasing sardine productivity in response to changes in the trophic environment and increasing water temperatures (Augustyn et al., 2017).

Whether climate change has already impacted marine life in New Zealand is not conclusive (Pinkerton, 2017), due to insufficient data. However, changes in ocean chemistry along the New Zealand coastline have been observed and is projected to accelerate into the future (Law et al., 2018), highlighting potential future changes in commercially important species, i.e. Pāua (*Haliotidae* spp.) and the New Zealand cockle (*Austrovenus stutchburyi*) (Lundquist et al., 2011; Renwick et al., 2016). In Japan, declines in Japanese mackerel species (e.g. Pacific chub mackerel (*Scomber japonicus*), Japanese horse mackerel (*Trachurus japonicus*)) and Hokkaido chum salmon (*Oncorhynchus keta*) have been observed due to climate-change associated increases in sea surface temperature (Kaeriyama et al., 2014), which can be expected to accelerate with continuing global warming and affect recruitment rates into regional fisheries (Yatsu et al., 2005).

Table 5.3: Overview of observed and projected long-term (mid-to end 21st century projections) climate-change impacts on selected fish stocks in terms of changes in stock size and distributional range shifts for each country used as a case study.

Country	Fishery	Changes in stock size		Changes in distribution		Key references
		Observed changes	Projected changes	Observed changes	Projected changes	
Australia	Australian western rock lobster	↓	↓	Deeper	Deeper	Caputi et al., 2009, de Lestang & Caputi, 2015, Plagányi et al., 2018
	Long-spined sea urchin (South-West Australia)	↑	↑	South	No data	
Canada	Chinook salmon	↓	↓	No data	No data	Grant et al., 2019 Wesche & Chan, 2010 Wilson et al., 2020a
	Arctic char	↓	↓	No data	No data	
	American lobster (Nova Scotia)	↑	↓	North	North	
Chile	Chilean jack mackerel	~	↑	No data	No data	Yañez et al., 2017 Bustos et al., 2008, Brochier et al., 2013
	Peruvian anchovy	~	↓	South	South	
EU	Atlantic mackerel	↑	↓	North-West	North	Berge et al., 2015

Table 5.3 continued

Country	Fishery	Changes in stock size		Changes in distribution		Key references
		Observed changes	Projected changes	Observed changes	Projected changes	
EU	European hake (North Sea)	↑	No data	North-East	No data	Staby et al., 2018
Iceland	Atlantic cod	↑	↓	North	North	Drinkwater, 2005 Valtysson & Jónsson, 2018
	Atlantic mackerel	↑	↑	North	No data	Berge et al., 2015
Japan	Japanese mackerel	↓	↓	No data	No data	Kaeriyama et al., 2014
	Hokkaido chum salmon	↓	↓	No data	No data	
New Zealand	Pāua	No data	↓	No data	No data	Lundquist et al. 2011, Renwick et al. 2016
	New Zealand cockle	No data	↓	No data	No data	
South Africa	Western rock lobster	↓	↓	South/East	No data	Augustyn et al. 2017, Boavida-Portugal et al., 2018
	European anchovy	~	↑	No data	No data	Augustyn et al., 2017, Cochrane et al., 2020
USA	Red hake	↑	↑	North	North	Friedland et al., 2020
	Pacific cod	↓	↓			Yang et al., 2019
	American lobster	↓	↓	North	North	Le Bris et al., 2018
	Gulf of Maine cod	↓	↓			Pershing et al., 2015

5.5.1 Summary

All regions are experiencing climate-change related impacts in their national waters and associated commercial fisheries. In some locations, marine productivity is changing, regionally manifested in either decreasing or increasing fisheries productivity. Due to climate-induced range shifts in some marine species, new fisheries are emerging, such as for Atlantic mackerel in Iceland; in others, existing fisheries are declining or even disappearing, as for the Gulf of Maine cod fisheries. These impacts are likely to accelerate into the future, particularly under high emissions scenarios, challenging the individual fisheries management systems that are currently in place. The common problems emerging from the case studies are changes in regional ocean productivity that are already affecting fishing operations and national as well as international fisheries management. Some management systems are not responding adequately causing overharvesting of stocks and even fisheries collapse (i.e. Pershing et al., 2015; Le Bris et al., 2018).

5.6 FISHERIES CHARACTERISITCS AND MANAGEMENT IN EACH CASE STUDY

Each case study exhibits specific fisheries characteristics, with large differences in average catches and global catch contribution (Figure 5.1; FAO, 2020b). Estimated national fisheries dependencies, in terms of combined effects of food, economic and employment provision by national fisheries, ranges between '*Very low'* to *'low'* in most case studies, with Iceland being the exception in showing high fisheries dependence (Figure 5.1; Barange et al., 2014). In the following, I will review fisheries characteristics and cornerstones of management policies and legislations for each case study in alphabetical order.

5.6.1 Australia

Australia's fisheries governance already includes key climate-adaptive management components considered to enhance the resilience of fishing industries to climate change (Table 5.4). Jurisdiction over fisheries is split; states and territories manage the commercial, recreational, and traditional fisheries, while large-scale, off-shore industrial fisheries are predominantly managed through the Commonwealth of Australia (Smith et al., 2014). Fisheries management legislations and policies are largely similar between state and national jurisdictions (Smith et al., 2014). Both the Commonwealth fisheries, which are managed under the *Fisheries Management Act 1991,* as well as all state fisheries legislations have adopted EBFM (Smith et al., 2007; Smith et al., 2014; Ogier et al., 2016). Concepts of adaptive fisheries management have also been implemented in terms of harvest strategies, for example for Commonwealth fisheries in 2007 through the *Harvest Strategy Policy*; harvest strategies are also adopted in several State jurisdictions for important commercial fisheries (DAFF, 2007; Smith et al., 2014). Harvest strategies for Commonwealth fisheries include ongoing monitoring and assessment of fish stocks and the amount of harvest, as well as formal decision rules or harvest control rules (HCRs) (Department of Agriculture and Water Resources, 2018; Table 2). Harvest strategies are required to account for climate-change impacts on stock productivity in their development and implementation, in terms of setting of reference points including dynamic reference points that acknowledge system-level effects of climate change and other anthropogenic stressors (Sainsbury, 2008; Department of Agriculture and Water Resources, 2018).

5.6.2 Canada

Historically, Canada's *Fisheries Act* and its associated regulations have facilitated continuous overfishing and slow rebuilding of critical fish stocks (Baum & Fuller, 2016). Until its most recent amendment in 2019 (*Bill C-68*), Canada's *Fisheries Act* did not require legal provisions to prevent overfishing or mandate rebuilding of troubled stocks (DFO, 2019a; Lake, 2019). With the recent amendment, Fisheries and Oceans Canada (DFO) are required to manage fish stocks sustainably and put rebuilding plans in place for those stocks that are considered depleted (Lake, 2019). Further, *Bill C68* reinstated the protection of all fish habitats, removing the restriction of only protecting habitat related to commercial, recreational or Aboriginal fisheries (DFO, 2019b). Despite neither the *Fisheries Act* nor *Bill C-68* explicitly addressing climate change (Table 5.4), these recent developments in Canadian fisheries management policies may move decision-making towards principles of transparency and ecosystem-based management, and hence facilitate climate-adaptation in Canadian fisheries (Table 5.1).

To date only a few Canadian fish stocks are assessed and managed considering the impacts of climate change (DFO, 2019c). Canadian Pacific salmon are adaptively managed with future rapid changes in mind by including climate, oceanographic and ecological variables in their stock analyses, interpretation, and provision of stock status advice (DFO, 2019c; Table 5.1, 5.4). The Pacific salmon assessment framework is based on the premise that, by protecting genetic diversity, resilience to future climate and habitat changes within the given population can be retained (Rice et al., 2017).

Genetic diversity within a population in part determines the capacity to respond to climate change, essentially as genetic variation for adaptive evolution to environmental changes are being conserved and is an important source of resilience (Healey, 2009; Sgrò et al., 2010). Further, in an attempt to facilitate climate-change impact incorporation into Canadian fisheries management, DFO has proposed a risk-based conceptual framework to systematically include climate change into science advice (Climate Change Conditioned Advice or CCCA), with an initial focus on fisheries stock assessments (DFO, 2019c). Implementation of this conceptual framework is proposed to be routinely assessed and adapted, which would move Canadian fisheries management towards an adaptive management approach (DFO, 2019c; Table 5.1).

5.6.3 Chile

Chile's *General Law on Fisheries and Aquaculture* from 1991 resulted in the management of fisheries resources with a focus on social and economic rather than biological or environmental (e.g. climate change) criteria. With a recent amendment in 2013, the law aspires to science-based rather than political- and/or commercial-based decision-making (Undersecretariat for Fisheries and Aquaculture, 2013). Since 2013, fisheries in Chile have been managed using international management standards, such Biological Reference Points and MSY (Undersecretariat for Fisheries and Aquaculture, 2013). Additionally, with its amendment in 2013, the EBFM framework has been incorporated Chilean fisheries law (Table 5.1, 5.4), explicitly requiring Chile to transition to EBFM; however, a timeline or target year for this transition is not defined in the law (Porobic et al., 2018).

In the early 2000s, after systematic overcapacity and overfishing in Chile's major industrial fisheries (vessels over 12m length), such as the southern pelagic fishery for Chilean jack mackerel and Common sardine (*Clupea bentincki*), Chile introduced an ITQ system (Gómez-Lobo et al., 2011; Table 5.2, 5.4). Quotas are fully transferable and divisible, and last 20 years with the possibility of renewal (Undersecretariat for Fisheries and Aquaculture, 2013). ITQs are recognized to alleviate excessive overfishing, and hence may facilitate stock rebuilding and resilience to climate change, especially if quotas are based on climate-change informed stock assessment and associated precautionary reference points (Chavez et al., 2017), which is not, as of yet, the case for Chilean fisheries (Table 5.4).

Small-scale or artisanal fisheries for economically important marine invertebrates and macroalgal species are managed under a Territorial User Rights for Fisheries

(TURF) policy (1991 Fishery and Aquaculture Law N° 18892) (Table 5.1), and enforced through the *Management and Exploitation Area for Benthic Resources* regulation (Castilla, 2010). TURFs give exclusive access rights over a defined spatial area, facilitating a sense of ownership and stewardship for the ecosystem and targeted resources, which can incentivize long-term sustainable management (Ojea et al., 2017). TURF fisheries can promote ecosystem sustainability and hence may be better in withstanding climate-change impacts (Hilborn et al., 2003). With the TURF implementation in Chile, areas under this management legislation have been shown to sustain high biomass densities of reef-fishes and macro-invertebrates, and an overall higher species richness, in comparison to open access areas (Gelcich et al., 2015).

Several Chilean fisheries are overexploited or overfished, making them highly vulnerable to climate-change impacts (Lovatelli & Cortés, 2017). Long-term climate-change impacts on marine resources are not explicitly accounted for in Chile's *General Law on Fisheries and Aquaculture* (Table 5.4); however, in 2015, the *Adaptation Plan to Climate Change for Fisheries and Aquaculture* was established as a framework to develop policy strategies to identify priorities as well as to provide tools with respect to climate-change adaptation, something that is missing in the current fisheries management law (Yañez et al., 2017; Porobic et al., 2018). Additionally, a recent pilot project has been launched that aims at strengthening the climate-change adaptation capacity of Chilean fisheries and aquaculture (Lovatelli & Cortés, 2017). This project aims at identifying and overcoming weaknesses in the institutional framework and current commercial fishing practices, with a focus on technological innovation (Lovatelli & Cortés, 2017).

5.6.4 European Union (EU)

One of the cornerstones of the EU's *Common Fisheries Policy* (CFP) is the concept of *fixed relative stability*, representing a structure within EU fisheries management that is supposed to ensure a secure share of the TAC between EU member countries (Sobrino & Sobrido, 2017). TACs for most commercial fish stocks are set by the EU commission based scientific advice by e.g. the International Council for the Exploration of the Sea (ICES) for stocks in the North-East Atlantic, the Scientific, Technical and Economic Committee for Fisheries (STECF), and the General Fisheries Commission for the Mediterranean (GFCM) for stocks in the Mediterranean and the Black Sea (European Commission, 2020a; FAO 2020c) Based on *fixed relative stability* concept, a fixed percentage of the TAC, which is referred to as the *relative stability key*, is allocated as tradable national quotas to each member country for further allocation to their respective national fishing fleets or vessels (Harte et al., 2019;Table 5.4). The recent amendment of the CFP in 2013 mandated that all European fish stocks are to be brought to a state where they can produce MSY by 2020, partly by implementing an EBFM approach as well as a discard ban (European Union, 2013). The discard ban, which has been gradually phased in since 2015, tackles the systematic problem of discards due to the *fixed relative stability* concept, which encouraged economic discarding of unwanted catch or undersized fish in EU fisheries (Sobrino & Sobrido, 2017).

The CFP does not explicitly address climate-change and is a rigid fisheries governance system that has a low ability to adapt to the challenges climate change is expected to bring to fisheries management regimes (Aranda et al., 2019; Table 5.4). TAC allocation through the *fixed relative stability* concept has not changed since its implementation 30 years ago, despite observed and further expected distribution shifts of fish stocks (Burden et al., 2017; Harte et al., 2019). Despite allowing quotas to be traded among EU member states, which gives the CFP an element of flexibility, climate-change induced range shifts highlight that effective matching of catches to member state specific quotas is paramount to adapt European fisheries to climate change; however, so far efforts have been slow and uncoordinated (Harte et al., 2019).

Through the *EU Adaptation Strategy*, which was launched in 2013, the EU has successfully catalyzed efforts to "facilitate the climate-proofing of the CFP'" and to improve climate-informed decision-making at EU level in key sectors, including fisheries (European Commission, 2013; Table 5.4). Further, congruent with the *Adaptation Strategy,* the European Maritime and Fisheries Fund (EMFF) has started to prioritize climate-change adaptation and mitigation in their efforts to foster "innovative, competitive and knowledge-based fisheries" that promote "sustainable and resource efficient fisheries" (European Commission, 2013). One of the fisheries adaptation actions prioritized by the EMFF are the facilitation of stock recovery and enhancement of ecosystem resilience through temporary or permanent termination of fishing activities (European Commission, 2015). For fishing communities impacted by such actions, fisheries diversification and/or financial compensation funds are being proposed by EMFF (European Commission, 2015). However, the EMFF legislation does not include climate-adaptation of the CFP itself (Smithers et al., 2018), limiting its contribution to fundamental changes for future climate-adaptive EU fisheries policies.

Finally, as part of the *European Green Deal* and its *Farm to Fork Strategy,* which was recently published by the European Commission (European Commission 2020b), an accelerated shift towards sustainable fish and seafood production has been proposed. This includes efforts to rebuild fish stocks o sustainable levels as well as a 2022 reassessment on how climate-change adaptation is being addressed within the CFP, which indicates a movement towards climate-informed management in the EU (European Commission, 2020b).

5.6.5 Iceland

Fisheries in Iceland are primarily managed on the basis of TACs and ITQs (Popescu & Poulsen, 2012; Table 5.4). Iceland was on the forefront of fisheries governance to set HCRs for marine fish stocks, including Atlantic cod, pollock (*Pollachius pollachius*), Atlantic herring (*Clupea harengus*), and capelin (*Malleus villosus*); fishing mortality for these stocks is precautionary and regularly adjusted based on stock biomass measures (Government of Iceland, 2018; Table 5.2). While the objective of the *Fisheries Management Act* is to conserve and efficiently utilize Icelandic marine resources in order to ensure sustainability of the fisheries, the policy does not explicitly account for the broader ecosystem or long-term climate-change impacts (FAO, 2020d). However, in addition to the ITQ system, Iceland has been successfully implementing other marine fisheries management measures to secure sustainable harvesting of the respective resources, including area and fishing gear restrictions, as well as time-area closures (Table 5.4) to protect vulnerable habitats (Organization for Economic Co-Operation and Development (OECD), 2017). Hence, some Icelandic fisheries management measures can be considered to account for the broader marine ecosystem context (OECD, 2017).

With ongoing climate-change related impacts on stock abundance and distribution, Iceland is both losing and gaining fisheries within its territorial waters, highlighting the need for responsible harvesting in unison with comprehensive international agreements between all nations involved in each individual fishery (EU

Parliament, 2012; Valtýsson & Jónsson, 2018). The capelin stock, for example, which is a transboundary stock between Iceland, Greenland and Norway, has been declining in the Icelandic EEZ due to migration shifts towards northern waters, likely due to climate-change induced increase in ocean temperatures (Carscadden et al., 2013; Valtýsson & Jónsson, 2018). However, all three parties use the Icelandic HCR for capelin as the basis for management, facilitating long-term sustainable harvesting (Government of Iceland, 2018). In contrast, since a lucrative Atlantic mackerel fishery has developed in Icelandic waters due to climate-induced distributional stock shifts, the stock is currently experiencing uncontrolled exploitation rates throughout the nations involved in the fishery, due to a lack of consensus with respect to transnational catch shares, threatening its sustainability (EU Parliament, 2012; Berge et al., 2015).

5.6.6 Japan

Commercial fisheries in Japan are managed predominantly by input control in terms total allowable effort (TAE), and by TAC in combination with individual fishing quotas (IFQs) (Table 5.4), usually established and distributed by local Fishery Cooperative Associations based on advice from fisheries scientists (Makino, 2011; Marti et al., 2017; Tokunaga et al., 2019). TACs are set based on scientifically estimated stock sizes for a few selected species, taking historical catch levels and estimations of potential future catches into account (Marti et al., 2017; Tokunaga et al., 2019). A discard ban has of yet not been implemented in Japanese fisheries regulations (Marti et al., 2017). Recent amendments to the *Fisheries Act* in 2018 have improved Japan's fisheries law in terms of "ensur[ing] [the] sustainable use of marine resources" (as cited in Toshio, 2019). Moreover, with the amendment Japan has established a commitment to implement more vigorous stock assessments to move towards the use of MSY reference points as well as to expand the scope of TAC managed fisheries and to introduce ITQs (Tokunaga et al., 2019).

Japanese fisheries management has historically paid little attention to the ecosystem context; with the exception of the coastline of Japan's Shiretoko peninsula, a highly productive region managed through an integrated marine management plan (Makino, 2011, 2017). However, recent legislation now recognizes that the managed fish stocks are an integral part of the marine ecosystem as a whole, which requires protection from human pressures such as fisheries (Makino, 2017). Yet, decision-makers in Japan's fisheries management do not considering climate-change impacts on its living marine resources (Table 5.4), despite of many of Japan's fisheries being vulnerable due to ongoing overfishing (Toshio, 2019). Nevertheless, Japan is starting to recognize climate change as a threat to its resources and economy and has the intention to systematically monitor its territorial waters for climate-change impacts on fisheries resources (Government of Japan, 2015), which is a critical step towards adapting fisheries management to climate change.

5.6.7 New Zealand (NZ)

New Zealand's (NZ) *Fisheries Act* is based on a quota management system, which gives exclusive and transferable shares of the TACs to license holders (Lock & Leslie, 2007; Ministry of Primary Industries, 2015; Table 5.4). In the decision-making process, the *Fisheries Act* recognizes interests of key stakeholders, including Maori, environmental, commercial and recreational interests, requiring consultation of representatives that have an interest in a given fish stock or the effects of fishing on marine ecosystems (Hale et al., 2017). In addition to assessing fish stocks to set annual TACs, the responsible Ministry for Primary Industries uses explicitly defined fisheries plans, which include annual fisheries operating plans that monitor performance of each fishery that targets highly migratory/pelagic fish, deep-water species, shellfish, inshore finfish, and freshwater fish (Hale et al., 2017).

The decision-making process in NZ fisheries management lacks formal consideration of wider ecosystem effects of commercial fishing practices (Hale et al., 2017; Slooten et al., 2017). However, within its purpose and principles, the *Fisheries Acts* does consider ecosystem effects of fishing (Table 5.4), requiring that fisheries effects on marine biodiversity be considered and that habitats of particular significance for fisheries should be protected (Hale et al., 2017). The recently developed *Biodiversity Action Plan* aims at NZ having moved "towards an ecosystem approach to fisheries management that includes enhanced recordings of bycatch from the sea and improved understanding of the rates of change in marine biodiversity" by 2020 (Department of Conservation, 2016).

Long-term climate-change impacts on NZ's commercial fisheries are not directly considered in stock assessments or decision-making frameworks (Pinkerton, 2017; Table 5.4). However, climate-change effects on NZ fisheries are addressed as part of the "*Aquatic Environment and Biodiversity Annual Review",* which reviews interactions between the seafood industry and the marine environment (Pinkerton, 2017). Commercially targeted fish stocks are primarily assessed based on traditional single-species assessments models that largely ignore climate-recruitment relationships and ecosystem effects to calculate MSY (WWF New Zealand, 2015; Slooten et al., 2017). An exception is, for example, the NZ hoki fishery (*Macruronus novaezelandiae*), which recognizes climate-change effects on stock-productivity when setting annual catch limits (Livingston & O'Driscoll, 2011). Annual catch limits for hoki are based on recent recruitment rates instead of historical values as traditionally used, despite unknown reasons for recent hoki recruitment trends (Livingston & O'Driscoll, 2011), indicating a pro-active management process for that fishery.

5.6.8 South Africa

South Africa's large-scale commercial fisheries are regulated through TACs or TAE (Table 5.4), applied through a proportional allocation system (Clark, 2006). Most commercial fisheries are managed though TAE only, including restricting vessel number or gear, crew number or sea days. The South coast rock lobster (*Palinurus gilchristi*) is the only fishery that is managed through a combination of TAC and effort restriction (FAO, 2020e). Additionally, so called Operational Management Procedures are followed in the main commercial fisheries (e.g. South African anchovy (*Engraulis encrasicolus*) and sardine (*Sardinops sagax*), representing management procedures based on seasonal stock status (FAO, 2020e). For instance, if the biomass of a particular fish stock is estimated, based on research-surveys and fishing mortality, to be below pre-determined critical levels, agreed annual reductions in TACs are automatically imposed, with the aim to ensure resource sustainability and industry viability (FAO, 2020e).

The *Marine Living Resources Act* considers EBFM (Table 5.4), which may support South Africa's fisheries to move towards the resilience of commercially and ecologically important species in the face of climate change. However, the major commercial fish stocks are assessed using single-species models, essentially ignoring wider ecosystem effects on stock recruitment and fisheries exploitation (de Moor et al., 2015). Long-term climate-change impacts on South African fisheries resources are not considered in the *Marine Living Resources Act.*

5.6.9 United States of America (US)

Fisheries in the US are managed through the *Magnuson-Stevens Fishery Conservation and Management Act (*also referred to as *Magnuson-Stevens Act*), under which eight regional Fishery Management Councils are in charge of management plans within their area of authority (National Marine Fisheries Service (NMFS), 2018). The status of US fish stocks is reported annually, summarizing the number of stocks that are overfished, subject to overfishing and under rebuilding (NMFS, 2018). Overfished stocks are legally mandated to rebuild, ideally within a 10 year time frame, if possible, in absence of any fishing (Benson et al., 2016). EBFM is considered in US fisheries management strategies (Table 5.4) as the most effective approach to achieve desired management objectives (Busch et al., 2016; Gregg et al., 2016). With the *National Ocean Policy* of 2010, US fisheries management policy officially considered the effects of climate change on marine resources and associated management regimes; however, in 2018 the *National Ocean Policy* was formally revoked by the Trump administration, changing the emphasis from conservation and climate change to economic and security concerns (Malakoff, 2018).

Nevertheless, NOAA Fisheries has developed a Climate Science Strategy as a "proactive approach to increase the production, delivery, and use of climate-related information" (NOAA Fisheries, 2019) to fulfill its mandates for fisheries management and protected species conservation in a changing climate (Busch et al., 2016). This strategy characterizes seven objectives, including developing climate informed reference points, identifying robust management strategies, and predicting future states of ecosystems and fisheries resources, that provide decision-makers with key information needed to reduce impacts and increase resilience under changing ocean conditions (Busch et al., 2016; NOAA Fisheries, 2019). The implementation of the strategy is managed through customized Regional Action Plans that focus on building regional capacity to efficiently address the objectives of the strategy (NOAA Fisheries, 2019).

5.6.10 Summary

Most case study nations are managing their commercial fisheries using a similar set of standard management approaches and tools (Table 5.1, 5.2, 5.4). All cases studies are applying access restrictions or harvest limitations through time-area closures, TACs, and fishing quotas on some or all of the respective stocks each country is targeting (Table 5.4). Seven out of nine case studies are explicitly addressing an EBFM in their fisheries policies and legislations (Table 5.4). There is increasing evidence that many fisheries in each case study region are already experiencing the impacts of climate change (see Section 5.5 above, Table 5.3), yet mandated climate-change considerations in stock assessments are generally lacking (Table 5.4). However, there is some progress towards addressing climate change in stock assessments and associated reference points. Australia, Iceland, and the US are using HCRs for selected valuable fish stocks, which is a modern fisheries management approach considered to build inherent resilience to adverse effects of climate change and scientific uncertainty in the management context. Additionally, the US and Canada are setting their reference points for selected fish stocks based on climate-change informed stock assessments. Despite of the lack mandated climate-change considerations in tactical fisheries management, some case study regions have or are in the process of developing formal climate-change informed decision-making frameworks (Table 5.4).

Table 5.4: Overview of main fisheries policies and legislations, management approaches and tools, as well as whether EBFM and climate-change adaptation are being considered in the respective fisheries policies and legislations of the case studies. Climate-change considerations are subdivided into decision-making (Is climate change and climate-change adaptation part of the decision-making process?), stock assessments (Are stock assessments climate-change informed?), and policy/legislation (Does the policy/legislation explicitly mention "climate change" or "climate-change adaptation"?)

Country	**Fisheries Policy/ Legis-lation**	**Management approaches/ tools**	**EBFM**		**Climate change**	
				Decision-making	**Stock-assessments**	**Policy /Legis-lation**
Australia	Fisheries Management Act (1991)	ITQ, TAC, HCRs, Co-management, Time-area closures	Yes	Yes[‡]	No[†]	No
Canada	Fisheries Act (1865)	ITQ, TAC, TURF, Time-area closures, Co-management, Community-based management	Yes	Yes[‡]	No[†]	No
Chile	General Law on Fisheries and Aqua-culture (1991)	ITQ. TAC, TURF, Time-area closures	Yes	Yes[‡]	No	No
EU	Common Fisheries Policy (1983)	ITQ, TAC TAC (except in Mediterranean), Time-area closures	Yes	Yes[‡]	No	No
Iceland	Fisheries Management Act (1990)	TAC, ITQ, HCRs, Time-area closures	No[§]	No	No	No
Japan	Fisheries Act (1949)	TAC, TAE, IFQ, TURF	No[§]	No	No	No
New Zealand	Fisheries Act (1996)	ITQ, TAC, Fisheries Operating Plans, Time-area closures	Yes	No	No	No

Table 5.4 continued

Country	Fisheries Policy/ Legislation	Management approaches/ tools	EBFM	Climate change		
				Decision-making	Stock-assessments	Policy /Legislation
South Africa	Living Marine Resources Act (1998)	TAC, TAE, Operational Management Procedures, Time-area closures	Yes	Yes‡	No	No
US	Magnuson-Stevens Act (1976)	ITQ, TAC, IFQ, HCRs, TURF, Co-management, Time-area closures	Yes	Yes	No†	No

†Not mandated; however, formal efforts are being made ‡Not fully established; however, formal efforts are being made §Ecosystem approach applied in some regions/fisheries. Abbreviations: EBFM=Ecosystem-based Fisheries Management; IFQ=Individual Fisheries Quota; ITQ=Individual Transferable Quota; TAC= Total Allowable Catch; TAE=Total Allowable Effort; TURF=Territorial Use Rights for Fishing; HCRs=Harvest Control Rules.

5.7 GAPS IN CLIMATE-CHANGE ADAPTATIONS IN FISHERIES MANAGEMENT POLICY, LEGISLATION, AND IMPLEMENTATION

None of the active fisheries management policies reviewed in this study explicitly address climate-change impacts on fisheries and marine ecosystems or mandate climate-change informed stock-assessments and/or decision-making. However, Australia and the US already include key aspects of climate-change adaptive fisheries management, indicating a high institutional capacity to achieve climate resilient fisheries. Few other countries herein consider climate-change effects in their stock assessments (i.e. Canadian Pacific salmon fishery, NZ hoki fishery); however, progress in developing climate-informed reference points is visible (i.e. Iceland). Nevertheless, most countries do have some adaptive management approaches in place, such as annual or <5 year periodic adjustments to target biomasses, harvest quotas or seasonal-area closures (Table 5.2). These measures can facilitate long-term sustainable fisheries under climate change if implemented using reference points that are based on recent observations of species, fisheries, and ecosystem productivity (Holsman et al., 2019); however, most of the management measures applied by the case studies assume long-term stationarity in environmental conditions and species productivity and rarely incorporate climate-change impacts. Here, Japan lags behind the other case studies, as systematic stock assessments and reference points throughout their commercial fisheries have only recently been mandated, and without addressing climate-change impacts on stocks and ecosystems. Japan’s fishing industry will have to move towards more sustainable fishing practices and regulations in order to adapt to the changing global climate in the near and farther future.

Setting climate-informed and adaptive quotas for individual stocks, based on stock assessments that include recent rather than historical observations is an important step towards building climate-resilient fisheries (Tanaka, 2019) However, climate-change impacts occur on an ecosystem level, rather than single stocks, which implies that existing management efforts need to move towards an EBFM approach. Most of the fisheries management policies reviewed (except Iceland and Japan) mandate an ecosystem approach or address ecosystem effects of commercial fishing practices (Table 5.4). This highlights the increased recognition of the importance to shift traditional single-species fisheries management to ecosystem approaches on national policy levels; however, actual efforts to implement EBFM on the ground have shown to be challenging (e.g. Gelcich et al., 2019 (Chile); Marshall et al., 2019 (US)). The implementation of EBFM in Chile is considered a useful approach to face global challenges such as climate change and food security; however, the transition to EBFM needs to overcome key institutional issues in terms of improving transparency and clear protocols for knowledge and capacity building (Gelcich et al., 2019; Porobic et al., 2019). In the US, despite of being at the forefront of climate-adaptive fisheries management approaches, including EBFM, many stock assessments are not incorporating ecological interactions in assessment models, but opt to include those interactions as background or qualitative considerations, mostly due to lack of available data-sets needed such as predator-prey data based on stomach contents (Marshall et al., 2019).

Most countries have or are in the process of developing formal climate-change informed decision-making frameworks e.g. Canadian framework of CCCA (DFO, 2019c), NOAA's Climate Science Strategy (NOAA Fisheries, 2019), Chile's Adaptation Plan to Climate Change for Fisheries and Aquaculture (Yañez et al., 2017). The Canadian CCCA was only recently proposed by DFO in 2018 and represents an important step in adapting Canadian fisheries management to climate-change impacts. In contrast, NOAA's Climate Science Strategy has been successfully implemented in selected regional fisheries management councils in the US through climate change regional actions plans (Busch et al., 2016). As of yet, New Zealand, Japan, and Iceland have not developed formal climate-informed decision-making procedures or plans, which may hamper the improvement of their fisheries management under changing conditions.

Based on my analysis, the most promising existing synthesis of management approaches is climate-informed EBFM that incorporates adaptive HCRs, ideally based on climate-informed stock assessments and decision-making, because shifts in ecosystems that affect stock dynamics, including species distributions and ecosystem productivity, are being addressed and management adjusted in a timely manner that facilitates long-term sustainable harvesting under climate change (Figure 5.2). Here Australia and the US are on the forefront of, at least in some instances, achieving efficient and effective fisheries management in a changing ocean. Obviously, the implementation of such management approaches depends on national and institutional capacity, which differs among the case studies.

5.8 THE FUTURE FOR CLIMATE-ADAPTIVE FISHERIES MANAGEMENT

International climate-change agreements and policies have resulted in climate-adaptation and mitigation strategies moving forward on a national policy scale (Figure 5.3). Political recognition of the need to address climate-change adaptation in fisheries management is beginning to increase; albeit formal mandates for climate-adaptation objectives in fisheries management are largely missing (Table 5.4). Ideally, fisheries management systems should be prepared to quickly respond and adapt to climate-change-induced and fishery-induced fluctuations in marine ecosystems and harvested fish stocks. This will allow for climate-informed decision-making on catch allocations, as well as for responsive time-area fisheries closures (Karp et al., 2018). Below, based on my analysis, recommendations to improve management of fisheries under climate change are described.

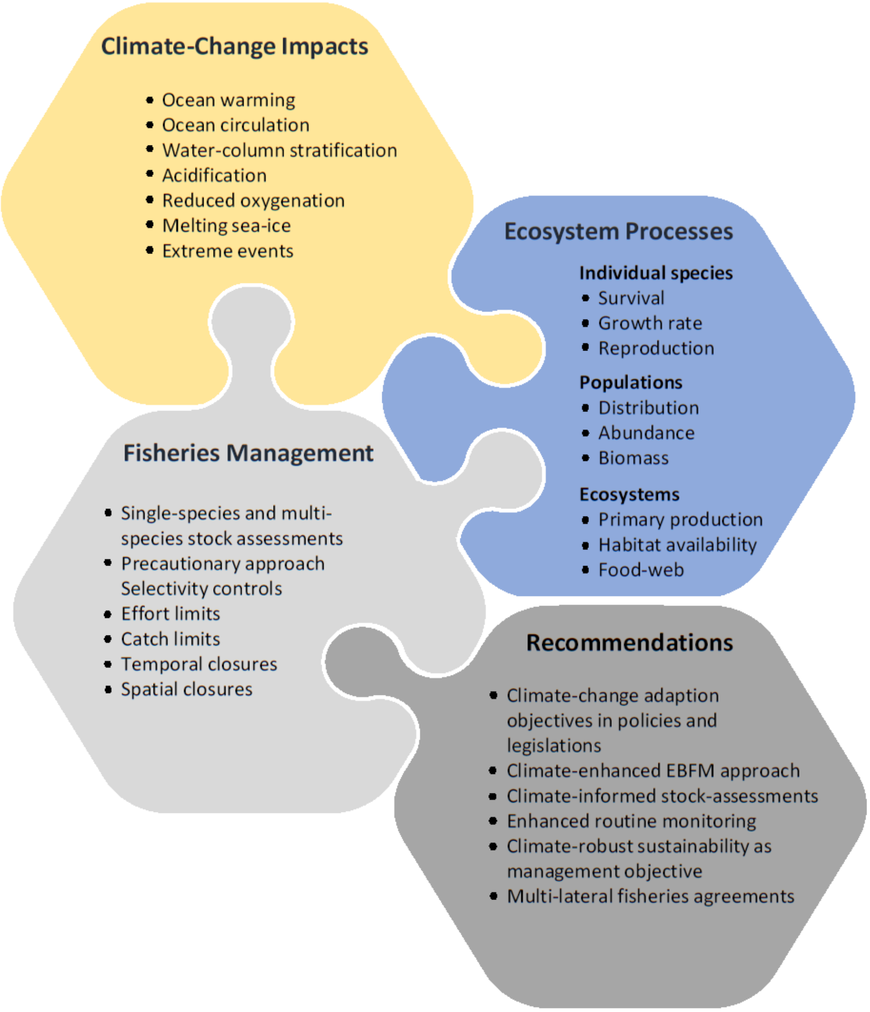

Figure 5.2: Overview of climate-change impacts on marine ecosystem processes and fisheries management, and recommendations to achieve climate-adaptive fisheries management.

5.8.1 Recommendation 1: Explicit climate-change adaptation objectives in fisheries management policies and legislations

Developing and implementing climate-change adaptive fisheries management depends strongly on political awareness and a willingness to prepare for climate change and its far-reaching consequences (Lindegren & Brander, 2018). International policies or agreements, which explicitly mandate climate-change adaptation in their objectives, such as the 2016 Paris Agreement, can spur political awareness and support (Lindegren & Brander, 2018; see Figure 5.3 for climate and fisheries policy/legislation timeline).

In fact, just within three years after the Paris Agreement came into force, Australia, Canada, Japan (for the first time since 1949), and New Zealand amended their fisheries legislation, emphasizing the need for long-term sustainable fisheries while addressing the wider ecosystem effects of fisheries (Figure 5.3). However, despite of an increasing political awareness of the importance of healthy oceans for climate-change mitigation, policy incentives to facilitate explicit climate-change adaption objectives in national and regional fisheries management legislation are missing, which can translate into insufficient or absent implementation of actual adaptation measures (Lindegren & Brander, 2018; Tittensor et al., 2019). This seems like a missed opportunity for those four countries that just rewrote their fisheries legislation, given their obligations to mitigate and build resilience to climate change, not only the Paris Agreement but also international commitments such as the UN Sustainable Development Goals.

To increase policy-driven incentives to explicitly address climate-change adaptation via legislation, investments in climate adaptation and the outcomes achieved should be transparent (Banks, 2009). Transparency on the legislative level can increase accountability and hence enhance progress (Preston et al., 2011).

Further, the development of measurable progress indicators and/or targets can be important incentives for climate-adaptative management policies and legislations, as recommended by Tittensor et al. (2019) in context of climate integration into management plans and policy for marine protected areas. A quantifiable target in the context of fisheries management legislation (assuming fish stocks are assessed) could state “implement harvest strategies that include climate-informed HCRs for all commercial fisheries”. This target should be explicitly tied to a measurable indicator, e.g. the percentage of commercial fisheries operated based on climate-informed HCRs.

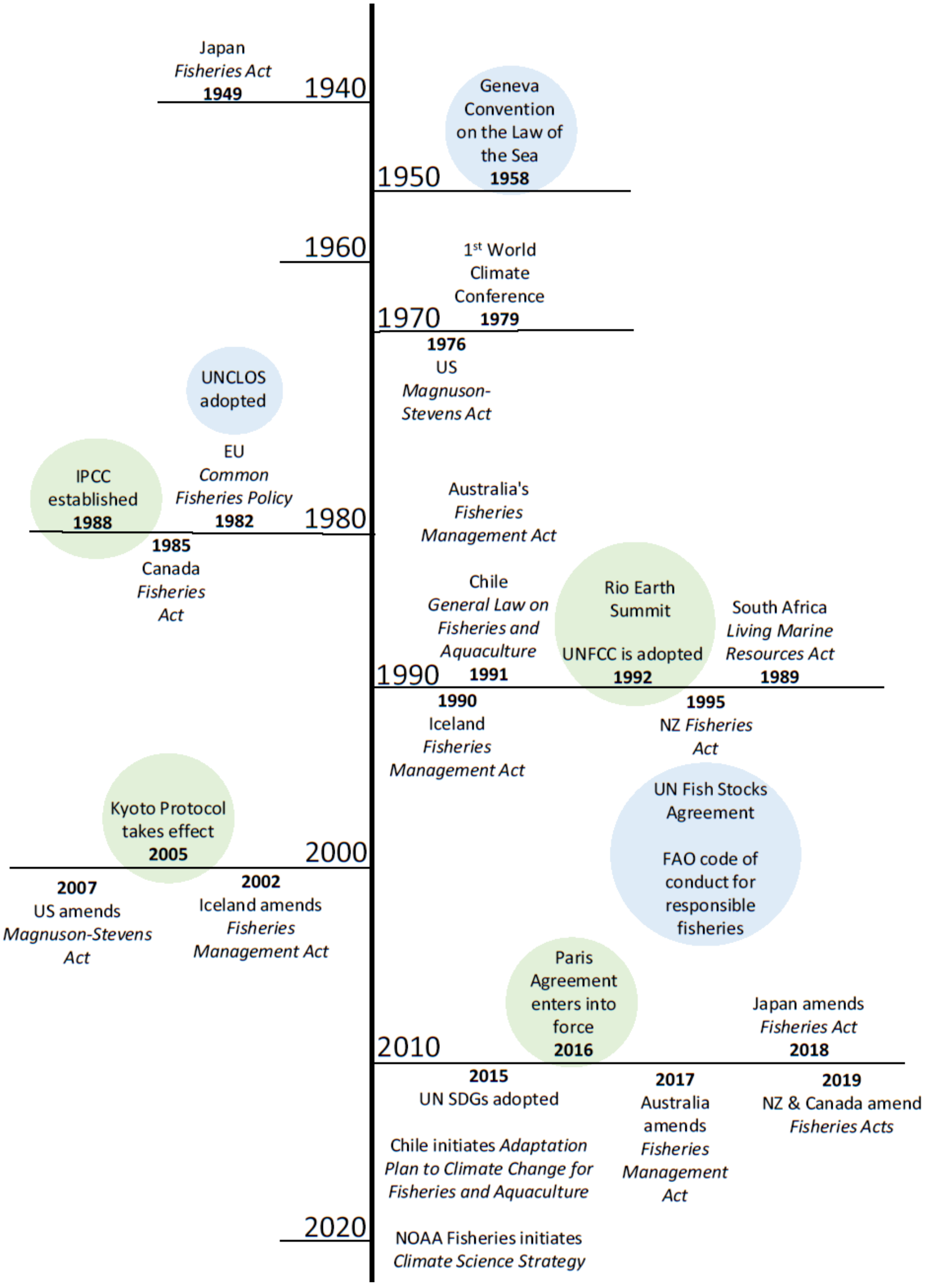

Figure 5.3: Timeline of development in international climate agreements/policies and international/national fisheries agreements/policies/legislations. National fisheries policies/legislations are limited to case studies. Green shading annotated UN climate-change agreements. Blue shading annotates UN fisheries agreements and guidelines. Abbreviations: IPCC = Intergovernmental Panel on Climate Change; UNCLOS = United Nations Convention on the Law of the Sea; UNFCC = United Nations Framework Convention on Climate Change; SDGs = Sustainable Development Goals.

In so doing, the progress and pace of adaption can be assessed and reported, which can further our understanding of challenges and deficiencies in adaptation efforts more effectively (Berrang-Ford et al., 2011). Climate-informed HCRs that are regularly adjusted based on detected biomass changes of a given stock, rather than changes in stock productivity, which can be difficult to detect and often based on historical data, is considered to build stock resilience and can act as a critical first step to reduce adverse effects of climate change on many stocks (Kritzer et al., 2019).

5.8.2 Recommendation 2: Climate-enhanced EBFM approach

As climate change does not impact single species in isolation from each other, but rather affects marine ecosystems as a whole, altering habitats and food-web dynamics that impact commercial species and their prey (Pikitch et al., 2004; Skern-Mauritzen et al., 2018), achieving climate-adaptive fisheries needs an EBFM approach that includes climate-change impacts on ecosystems and fish stocks. By so doing, the resilience of the ecosystem and ecosystem services can both be enhanced (Table 5.1). Implementing EBFM for the short- and long-term requires the support of robust ecosystem science, including ecosystem modelling, ideally based on comprehensive ecosystem monitoring data (i.e. biophysical, multispecies, food-web, or end-to-end ecosystem models; Townsend et al., 2019; see Recommendation 3).

Marine ecosystem models that are scaled to the ecosystem or management unit are valuable tools for hindcasts and future scenarios, in terms of changes in thermal habitats of commercial stocks and associated distribution shifts, as well as changes in ecosystem and stock productivity, to support the implementation, evaluation, and decision-making in the EBFM context (Kleisner et al., 2017; Townsend et al., 2019).Using model-based scenarios in the management context remains challenging due to increasing uncertainties with increasing model complexity and projected time-frame (Skern-Mauritzen et al., 2018; Fulton et al., 2019). However, uncertainty in model projections do not imply lack of relevance for fisheries management (Skern-Mauritzen et al., 2018). For example, uncertainties around projections can be comprehensively assessed through sensitivity analyses and coordinated ensemble-modeling approaches (Tittensor et al., 2018; Fulton et al., 2019; Lotze et al., 2019).

Ideally, the EBFM approach would include climate-informed ecosystem-based reference points that account for multi-species interactions and fishery operations, and which are translated into adaptive management decisions, such as TACs or HCRs (Guo et al. 2019; Marshall et al. 2019; Tanaka, 2019; Table 5.1, 5.2). Routinely, reference points, such as MSY, are mostly based on single-species models, that do not account for ecosystem level ecological processes, and may result in ecosystem overfishing, especially in a rapidly changing ocean where ecosystems are shifting into previously unobserved states (Pikitch et al., 2004; Link, 2018; Tanaka, 2019). Here, for example, multi-species and/or ecosystem models can address the effect of harvesting on species with key ecosystem functions, such as zooplankton or forage fish (i.e. herring, mackerel or capelin), and assess cumulative impacts of harvesting and climate change on a particular system, rather than managing interacting fish stock individually, which can provide more robust MSY values (Skern-Mauritzen et al., 2018; Walters et al., 2005). NOAA has initiated the implementation of “next generation stock assessments” that call for “holistic and ecosystem-linked stock assessments” to address fisheries and climate-change related ecosystem and stock changes, suggesting, among others, the use of ensemble modeling to inform management with a more complete characterization of uncertainties (see Lynch et al., 2018 for details), which has also shown to be useful when assessing data-poor stocks, (Rosenberg et al., 2018), which often include non-target species, hence are critical to assess in an EBFM context.

5.8.3 Recommendation 3: Enhanced monitoring of marine resources and ecosystems

The need for science-based decision-making in fisheries management is exacerbated in a rapidly changing world. In this context, to adapt existing fisheries management approaches and tools to a changing climate, it is paramount to enhance routine monitoring of marine living resources and the ecosystems they live in by expanding spatial and temporal coverage of surveys and using integrated ocean observing systems and advanced sampling techniques (i.e. gliders, sail-drones and underwater drones, eDNA) in order to identify, detect and adapt to non-linear changes and extreme events in our oceans, especially when moving towards climate-adaptive EBFM systems (Kelly et al., 2015; Karp et al., 2018). Routine monitoring and data collection is a matter of scale and institutional capacity; however, it also emphasizes the need to enhance collaboration and coordination between management systems (Kelly et al., 2015), which is becoming easier and easier in our increasingly digitalized and technology focused world. Here, the development and increasing utilization of citizen-scientist networks and mobile applications, for example jellyfish watch (https://www.jellywatch.org/#2/26.5/3.0) and eOceans (https://www.eoceans.co/home), may help to track global changes and detect early warning signs of change, such as abrupt changes in regional species abundance and distribution, as well as newly emerging species into a specific region, that can be considered in adaptive decision-making or development of climate-informed reference points, facilitating climate-adaptive fisheries management. In addition, based on monitoring data, the development of ecosystem indicators such as mean trophic level or mean temperature of the catch (as indicators of ecosystem changes due to e.g. climate-change induced range shifts of fish populations form southern (warmer) waters into northern (colder) waters; Cheung et al, 2010, 2013b), as well as species composition and recruitment patterns (Cheung et al., 2013b; Karp et al., 2018) are important, and can be used to track changes in distribution of fish populations, as well as ecosystem function and structure, related to climate change and early warning signals of change. Regular and publicly available ecosystem reports, which present and interpret monitoring data while considering climate-change effects in a standardized manner, will be useful to establish ecosystem thresholds and decision criteria (Busch et al., 2016; Bernier et al., 2018; see Recommendation 2). For example, the North Pacific Fishery Management Council, one of the US regional management councils, sets annual fisheries quotas for the high value Alaskan groundfish fishery based, among others, on ecosystem information, provided by annual Ecosystem Report Cards that summarize ecosystem indicators, such as bottom temperature and sea-ice retreat (Zador et al., 2017).

5.8.4 Recommendation 4: Shift in management objectives to climate-robust sustainability

The implementation of climate-adaptive fisheries management requires an overall paradigm shift in management objectives from short-term economic profit that fosters overcapacity and overfishing towards objectives for ecological and economic sustainability in the long term (Johnson & Welch, 2009). Arguably, some regions are progressing in terms of shifting their management objectives towards long-term ecological and economic sustainable fisheries, such as Australia and the US. Shifting the current paradigm towards long-term ecological and economic sustainability could, for example, be achieved through adjusting current sustainability reference points that reduce catch quotas as stock production changes due to climate change. Ideally, stock assessments as the basis of reference points should explicitly incorporate ecosystem and climate-change considerations and interactions between species and fisheries, to address potential climate-change impacts on ecosystem and stock productivity (Marshall et al., 2019; see Recommendation 2). In addition, achieving a paradigm shift requires decision-making under higher levels of uncertainty due to the uncertain nature of future climate-change impacts (Lawler et al., 2010); "[…] increasing uncertainty with increasing complexity […] [is no] reason for inaction […] (Skern-Mauritzen et al., 2018). This step is only feasible in a fishing nation with high adaptive capacity, as nations with limited capacities are unlikely to cope with reductions in catch quotas, unless specific funds to support a fundamental paradigm shift, such as the EMFF in the EU, are established internationally (Johnson & Welch, 2009). If adaptive capacity is low, in terms of e.g. low socio-economic status, which do not allow for direct catch or effort reductions as a climate-change adaptive measure, other institutional changes are necessary that establish adaptive fishing rights, such as changing seasonal fishing operations in response to climate-change induced distribution shifts of fish populations by diversifying fisheries towards multi-species fisheries (Johnson & Welch, 2009).

5.8.5 Recommendation 5: Preparing for the need of multilateral fisheries agreements

As stocks shift in distribution in response to changing ocean conditions, the need for new or strengthened multilateral management will be increasingly required (Gaines et al., 2018). However, as of yet, many existing international fisheries agreements—bilateral and multilateral—for shared fish stock management do not explicitly account for climate-change related shift fish stock distributions (Oremus et al., 2020). New or strengthened international institutions and agreements are needed to ensure that management remains sustainable as stocks shift between jurisdictions, including agreements within and between Regional Fisheries Management Organizations (RFMOs) as well as for stocks moving out of EEZs into Areas Beyond National Jurisdiction (ABNJ) (Free et al., 2020; Oremus et al., 2020). Countries that share fish stocks are encouraged to allow trades of fishing permits or quotas across international borders, which would provide flexibility within international fisheries agreements and allow future resource users access to fisheries not yet in their waters and incentivize good management, instead of overfishing of the leaving resource (Pinsky et al., 2018; Free et al., 2020). Further, side payments, which can act as a compensation and incentive to harvest a leaving resource less extensively, may increasingly needed to be negotiated between nations in order incentivize sustainable management and harvesting of shared resources (Diekert & Nieminen, 2017; Oremus et al., 2020). Bilateral fisheries agreements, that include side payments, already exist, for example in the Pacific salmon fishery between the U.S. and Canada (Miller & Munro, 2004), and in the Barents Sea Atlantic herring fisheries between Norway and Russia (Miller & Munro, 2004).

5.9 CONCLUSIONS

This review provides an overview of the current state of integration and implementation of climate-change adaption in national fisheries management policies and practices. Political recognition of the need to address climate-change adaptation in fisheries management is beginning to increase, mostly through the objective of EBFM; albeit, formal mandates of climate-adaptation objectives in fisheries management are largely missing in the case studies described here. Climate change demands improved dynamic and adaptive management approaches, that have the potential to mitigate future climate-change impacts through enhancing ecosystem resilience, enabling the continuing provision of fish protein to an ever-growing human population. However, to further move towards climate-adaptive fisheries management and to achieve UN's Sustainable Development Goals (SDGs), including SDGs for "Zero Hunger" (SDG 2), "Global Health and Wellbeing" (SDG 3), "Climate Actions" (SDG 13), and "Life Below Water" (SDG 14), is only conceivable if international and national management policies/agreements become strengthened.

5.10 ACKNOWLEDGEMENTS

Thanks to Nancy Shackell, Aaron MacNeil, and Megan Bailey for their detailed comments. Thanks to Daniel G. Boyce for providing data on country specific biomass projections.

CHAPTER 6
GENERAL DISCUSSION

6.1. SUMMARY OF THESIS

Projecting climate-change impacts using an ensemble-modeling approach is considered the “gold-standard” in climate-impact sciences, because model ensembles can represent a broader spectrum of potential trajectories in a changing climate, and projection uncertainties around the ensemble mean trend can be systematically assessed (Tittensor et al., 2018a; Lotze et al., 2019; Boyce et al., 2020). The Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP; Tittensor et al., 2018a; www.fishmip.org) represents the first attempt to project the responses of marine ecosystems to climate change on a global scale using an ensemble modeling approach. This state-of-the-art approach is paramount to enhance our understanding of marine ecosystem processes under climate change and can shed light on the path ahead in the context of adapting management regimes to ensure the conservation of marine biodiversity and sustainability of commercial fisheries.

The central objectives of my thesis were to use the Fish-MIP ensemble projections to help answer critical aspects regarding the future of marine ecosystems. These included: (i) assessing projected changes in marine ecosystems on multiple temporal and spatial scales using mean trends and associated uncertainties (Chapters 2, 3, and 4), (ii) using ensemble projections to evaluate potential future impacts on commercial fisheries and challenges to their management (Chapter 3), and (iii) examining current progress towards integrating climate-change adaptation in fisheries management (Chapter 5).

In Chapter 2, I compared projected marine animal biomass and ecosystem changes across all major ocean basins using the Fish-MIP ensemble-modeling approach. The results highlighted substantial reductions in ecosystem production in most ocean basins, except the polar basins where marine biomass was projected to increase over the 21st century. Chapter 3 represents the first study using ensemble projections to evaluate marine ecosystem changes over the 21st century within the Canadian Atlantic, Pacific and Arctic Exclusive Economic Zone (EEZ) under different climate-change scenarios. Ecosystem projections across Canada's three oceans revealed decreasing ecosystem production in the Canadian Pacific and Atlantic EEZs and increasing ecosystem production in the Canadian Arctic over the 21st century. High projection variability in the Canadian Arctic indicated a broad range of potential future changes, whereas projections in the Canadian Atlantic and Pacific were more consistent. In Chapter 4, I analyzed near- and far-future climate-change impacts on the future of living marine resources in the North Atlantic Ocean and discussed challenges to fisheries management institutions in the region, using the Northwest Atlantic Fisheries Organization (NAFO) as a regional case study. Results highlighted regional differences in the direction and magnitude of projected changes, with potential biomass increases and associated fisheries benefits in northern NAFO management divisions which have relatively low historical fisheries landings. However, more southern management divisions with relatively high historical fisheries landings were projected to experience biomass declines, indicating long-term challenges for management authorities. In Chapter 5, I reviewed current national fisheries management policies and legislations of nine nations from around the world to examine climate-change adaptation within policies and legislations, as well as the same in management approaches and tools. Results revealed that mandated climate-change adaptation is not explicitly addressed in any current fisheries management policy or legislation in the nine case studies. Also, climate-change considerations in stock assessments are largely lacking, despite increasing evidence that many fisheries are already experiencing impacts. However, results also showed evidence of some progress towards implementing climate-informed stock assessments and decision-making. Based on my review, I then derived five recommendations that can help to improve fisheries management and achieve climate-adaptive fisheries in a changing climate. Specifically, I suggest incorporating explicit climate-adaptation objectives in fisheries policy and legislation, as well as implementing specific management approaches and tools.

Ensemble projections of marine ecosystem responses provide a broad context for expected ocean changes that can help to inform the long-term sustainable management and conservation of marine biodiversity and fisheries. The anticipated changes in marine ecosystems and fisheries production have important implications for the provision of the essential goods and services that human populations rely on in terms of food security, incomes and livelihoods, and cultural values. The assessment of progress towards climate-change adaptation in fisheries management provides needed stepping-stones to achieve climate-ready fisheries and fisheries management at multiple scales, ranging from international agreements to regional management implementations. Together, these analyses of present-day management and future changes will help to guide progress towards achieving climate-resilient fisheries that account for long-term climate-change impacts on targeted fish stocks and the ecosystems they rely on. In the following section, I discuss the strengths and limitations of my work and outline directions for future research.

6.2 STRENGTHS, LIMITATIONS AND NEXT STEPS IN MARINE ECOSYSTEM ENSEMBLE MODELING

This thesis has utilized an ensemble-model approach to project global and regional marine ecosystem responses under 21st century climate change. Using an ensemble-model approach allowed for a systematic analysis of projection uncertainty, highlighting a broad spectrum of potential future trajectories in ecosystem changes throughout the 21st century. Several recent studies have used individual ecosystem models to project global marine ecosystem changes in a changing climate (e.g. Cheung et al., 2010; Christensen et al., 2015); however, because different models have their own structure, assumptions, uncertainties, biases, limitations, and sensitivities, model outcomes differ (Eddy, 2019). For example, global marine ecosystem models such as DBEM (Cheung et al., 2010), a species distribution model, projects larger declines in global ecosystem productivity than EcoOcean (Christensen et al., 2015), a trophodynamic model that specifies, unlike DBEM, species interactions via predator-prey relationships. Such differences in model outcomes and projections are difficult to assess when using a single model approach, which can hinder the consideration of projection uncertainty in global climate policy and agreements, such as the IPCC framework, which evaluates projections based on the amount of evidence and evidence agreement (Eddy, 2019; IPCC, 2019). This is where model ensembles can provide important insight in terms of how many models within the ensemble project changes in the same direction (increase or decrease) and by how much the magnitude of projected changes varies (Eddy, 2019). Providing a more nuanced understanding of future trajectories of change and their uncertainties can also facilitate the inclusion of model projections into fisheries management, which can be valuable in adapting marine fisheries to climate change (see Chapter 5).

The ensemble output analyzed in this thesis represents projections under climate-change impacts only, because as of yet spatially resolved future fishing scenarios are not yet available for the global Fish-MIP model ensemble. However, marine capture fisheries have substantial impacts on marine ecosystems, which can exacerbate climate-related effects on marine ecosystems and the living resources they support (Halpern et al., 2015). Hence, ensemble results in this thesis may be conservative in terms of the magnitude in projected biomass changes. On a global scale, however, the climate-change effect in fished compared to un-fished biomass projections within Fish-MIP simulations did not differ substantially (Lotze et al., 2019). Nevertheless, incorporating future fisheries scenarios into the model ensemble would be an important next step, including alternate future fishing scenarios, such as different effort trajectories and marine protected area coverage, into the Fish-MIP model ensemble, which could help to evaluate benefits and risks of different fisheries management scenarios in a changing ocean (Tittensor et al., 2018a).

Furthermore, the global model output evaluated in this thesis projects ecosystem changes on a coarse spatial scale, as the global Fish-MIP models relied on output from global ESMs, which provide limited spatial resolution of coastal or shelf regions (Bonan & Doney, 2018; Derksen et al., 2018; Tittensor et al., 2018a). In this context, a step forward would be to advance ESM representation and resolution in coastal and shelf regions, for example through regional downscaling (Holt et al. 2017; Claret et al., 2018). Another option would be to use and compare results based on global and regional ESM outputs to assess temporal and spatial variation in projected changes, which could advance model development on both global and regional scales. Lastly, incorporating the next round of ESM outputs (CMIP6), which provide updated climate scenarios and more detailed three-dimensional data on some biogeochemical variables, would advance Fish-MIP results to the next round of CMIP6 projections (Ruane et al., 2016; Tittensor et al., 2018).

This thesis contributes information on projected future changes in global and regional marine ecosystems and the spread of uncertainty around those changes (Chapter 2, 3, and 4). However, results using the Fish-MIP model-ensemble represent only the beginning of a systematic marine ecosystem model evaluation and inter-comparison. To comprehensively improve the ecosystem models participating in Fish-MIP, at least two main questions still need to be answered: (1) What are the mechanisms driving individual model responses to forcing variables and fishing effort? (2) How do the global ecosystem model projections differ from regional ecosystem model projections? Addressing these questions are an essential part of a model inter-comparison project and can help to increase confidence in the model output provided (Randall et al., 2007). In large part, most of the global ecosystem models in the Fish-MIP ensemble respond to effects of increasing temperature and changes in net primary production (NPP); however, the magnitude in the response differs among individual models. To understand the mechanisms driving the differences in individual model projections, controlled simulation experiments can be conducted, in which simulations are run based on isolated drivers and hence the effects of individual drivers are separated out. Addressing the second question will advance global ecosystem models in terms of assessing biases and identifying the scales at which they can be applied, and the situations in which regional ecosystem models need to be used. The direct comparison of regional and global marine ecosystem models is possible within Fish-MIP since its regional marine ecosystem models were forced by the same standardized variables, and hence are responding to the same historical and projected environmental variation (Tittensor et al., 2018a). To compare global and regional ecosystem model projections, output from global models can be subsampled over areas covered by the regional models.

6.3 OUTLOOK AND IMPLICATIONS FOR FISHERIES MANAGEMENT AND CONSERVATION

Using ensemble modelling to explore challenges for fisheries management on a sub-national and international level can provide critical information on when and where changes in the marine environment and targeted fish stocks will occur, to guide effective climate-adaptive responses within fisheries management systems. Projections of ecosystem changes within a country's EEZ, as assessed in Chapter 3 for the Canadian EEZ, can inform regional management authorities about long-term changes in ecosystem productivity and distributional changes within national waters. These insights are important as they can directly impact regional fisheries production and associated livelihoods, especially if existing management measures are not adjusted to climate-related changes (Pershing et al., 2015; Le Bris et al., 2018). Additionally, in countries in which national fisheries are managed by multiple regional management bodies, such as the US and Australian fisheries, EEZ specific ecosystem projections can facilitate sub-national collaboration, enhancing adaptive capacity within a country.

Similarly, ecosystem projections that span both national and international waters, such as evaluated in Chapter 4 for the North Atlantic Ocean and NAFO, can guide international management institutions, responsible for shared fisheries resources between nations as well as in the high seas (beyond the EEZ of countries), achieving climate-adaptive fisheries, especially in context of shifting distributions of major fish stocks across boundaries. This is pertinent, given the current and potentially increasing likelihood of fisheries conflicts due to shifting fish stocks (Mendenhall et al., 2020) and the fact that most international fisheries management organizations do not consider climate-related distribution shifts within their policy frameworks (Rayfuse, 2019; Oremus et al., 2020). The ensemble projections of ecosystem changes, as presented in this thesis, have their limitations, which need to be considered in the context of informing fisheries management in a changing climate. Fisheries management authorities operate on annual to decadal timescales, for example in the allocation of annual quotas or total allowable catch, the setting of harvest control rules every 5 years, or the decadal re-licensing of commercial fishing permits. Furthermore, marine fisheries predominantly harvest in coastal areas, which support the richest areas of marine biodiversity in the world (Stewart et al., 2010). The Fish-MIP ensemble used in this thesis, however, projects long-term ecosystem changes on a relatively coarse spatial grid, which does not resolve coastal dynamics in detail. Nevertheless, Fish-MIP ensemble projections provide valuable information on broader ecosystem changes.

As discussed in the previous section (Section 6.2), the projected ecosystem changes in this thesis represent responses under different climate-change scenarios only; socioeconomic scenarios, including scenarios of different fishing effort trajectories, are not considered in the model ensemble. Guiding policy processes for achieving long-term sustainability of marine fisheries harvest and food security under climate change requires not only climate-change scenarios, as represented by the Representative Concentration Pathways (RCPs), but also scenarios of wider socioeconomic trajectories (Maury et al., 2017). In this context, the Shared Socioeconomic Pathways (SSPs) have been developed, that provide narratives of future societal developments in terms of "changes in demographic, human development, economy and lifestyle, policies and institutions, technology, and environmental and natural resources“ (O’Neill et al., 2017). In the socioeconomic context of pelagic fisheries, a “sectoral extension” (Maury et al., 2017) has been developed in the form of Oceanic System Pathways (OSPs) that provide future scenarios of biodiversity and ecosystem services, including economic (e.g. wild fish demand, fishing costs), governance (e.g. inter-state relationships among developed, emerging, and developing countries), and management (e.g. importance of sustainability in management objectives, degree of compliance with management) (see Maury et al., 2017 for details). However, the OSPs only include oceanic fisheries; expanding them to include coastal and subsistence fisheries could enhance their usefulness as a tool for scenario planning within fisheries management.

The comprehensive review of climate-change adaptation in current fisheries management and legislation (Chapter 5) across nine nations from around the world provided important information and recommendations to move towards climate-change informed fisheries management; however, it focused on the management of industrial fisheries, mostly in developed and temperate countries. Hence, in future research it would be important to (1) expand the scope to include developing and/or tropical countries, and (2) review the management of small-scale fisheries under climate change. Expanding the scope towards developing countries would address the effect of adaptive capacity of the responsible fisheries management institutions on effective climate-adaptation, which may differ between developed and developing countries. In the context of fisheries management, adaptive capacity refers to the institutional capacity to manage marine living resources while adapting to climate change, involving “production of knowledge to underpin management decisions” and “development of regulations to govern economic incentives towards [i.e.] sustainab[ility], and “enforcement of regulations” (Harsem & Hoel, 2013). Furthermore, developing countries are often highly dependent on fisheries resources in terms of e.g. direct consumption of fish protein and support of livelihoods through small-scale fishing operations, increasing their vulnerability to climate-change related ecosystem disruptions compared to developed countries (Boyce et al., 2020). Including case studies of tropical countries is valuable, as climate-change impacts on tropical marine ecosystems can manifest differently and have different socio-economic consequences than in temperate or polar regions (Cheung et al., 2009; Boyce et al., 2020). For example, addressing coral reef fisheries in terms of climate-change induced changes on the reefs themselves, associated small-scale fisheries and the underlying management strategies. Coral reefs support the livelihoods of millions of people and are at them same time highly vulnerable to climate-change induced stresses, such as bleaching due to increasing temperatures and extreme events, and ocean acidification, that can negatively impacts marine fish production and compromise livelihoods of fisheries dependent communities (Cinner et al., 2012; Hoegh-Guldberg et al., 2017; Booth et al., 2018).

Finally, analyzing future marine ecosystem changes in the context of existing regional management organizations (Chapter 3) is important for moving towards climate-adaptive fisheries management and practices. Here, future research could expand this analysis by linking ensemble-model projections of marine ecosystem changes to spatial management and conservation measures such as marine protected areas (MPAs) and marine reserves. Expanding the focus on MPAs and marine reserves is relevant for marine biodiversity conservation in a changing climate, as effectively enforced MPAs that prohibit any extraction of marine resources and/or prevent illegal and detrimental harvesting, can increase local biodiversity and protect threatened species and sensitive or essential habitats (McCook et al., 2010; Sala et al., 2018). Additionally, MPAs are promoted as fisheries management tools, in terms of supporting adjacent fisheries through e.g. increased ecosystem productivity and abundance of target species (Roberts et al., 2001; Hilborn et al., 2004). However, current management policies and plans for marine protected areas and marine reserves largely lack climate-adaptation strategies (Tittensor et al., 2019; Wilson et al., 2020).

Finally, with continuing climate-change effects on marine ecosystems such as the availability of essential habitats (e.g. nursery or spawning grounds), abundance of vulnerable species, or distribution of commercially targeted species, current and future placements of MPAs and marine reserves need to be re-evaluated in terms of their effectiveness and continuing relevance under climate change (Tittensor et al., 2019). Ensemble projections of future ecosystem structure and productivity changes can help to assess future management scenarios over the 21st century and facilitate moving towards climate-adaptive marine spatial management. This is important for continuing efforts in marine biodiversity conservation and sustainable fisheries management, as well as for meeting international agreements and the UN Sustainable Development Goals (particularly SDG13 and SDG14).

APPENDIX A

Table A.1: Overview of marine ecosystem models included in the ensemble projections (modified from Tittensor et al., 2018a and Lotze et al., 2019).

Fish-MIP model	Model description	Key ecological processes	Spatial and temporal scale for Fish-MIP simulations	Vertical resolution	Taxonomic scope	Reference
BiOeconomic mArine Trophic Size-spectrum **(BOATS)**	Size-structure model. Combines marine biogeochemistry with size-based trophic theory and metabolic constraints to calculate the production of commercially-harvested fish across multiple size spectra.	Applies empirical parameterizations to describe phytoplankton community structure, trophic transfer of primary production from phytoplankton to fish, fish growth rates, and natural mortality of fish. No direct or passive movement of fish, larvae or eggs between grid cells.	1 x 1˚ grid Monthly mean timestep	None (2-dimensional domain). NPP is vertically-integrated through the water column. Temperature changes with SST.	3 size groups (small, medium, large) defined by their asymptotic mass of all commercial fish.	Carozza et al., 2016
Macroecological Model	Static size-structure model. Uses minimal input parameters together with ecological and metabolic scaling theory to calculate mean size composition and abundance of marine animals (including fish).	Simple characterization of marine ecosystems in terms of body mass distribution and marine animal abundance based on estimates of predator-prey mass ratios, transfer efficiency and changing metabolic demands with body	1 x 1˚ grid Annual mean timestep	Single vertical (surface-integrated) layer.	180 body mass classes. Species are not resolved.	Jennings & Collingridge, 2015

		mass and temperature. Animal movement is not included.				
Dynamic Pelagic Benthic Model **(DPBM)**	Dynamic size-and trait based model. Incorporates a pelagic predator size-spectrum with a benthic detritivore size-spectrum.	Individual processes of predation, food-dependent growth, natural mortality, and reproduction give rise to emergent size spectra for each functional group (pelagic predator and benthic detritivore).	1 x 1˚ grid Monthly mean timestep	2 vertical layers (sea surface and sea floor). No vertical transport or movement.	1 pelagic predator and 1 benthic detritivore size spectrum, with 100 size classes each.	Blanchard et al., 2012
Dynamic Bioclimate Envelope Model **(DBEM)**	Species distribution model based on bioclimatic envelopes (niche) defined for each species. Simulates changes in species abundance and carrying capacity (as a function of the environment and species' habitat preferences) under environmental change.	Population dynamics are dependent of habitat suitability and movement of adult species driven by a gradient of habitat suitability and population density. Larval dispersal is driven by currents and temperature. Growth, reproduction, and natural mortality are dependent on oxygen, pH, and temperature.	0.5 x 0.5˚ grid Annual mean ocean conditions	Vertical layers (sea surface and bottom) defined by species niche preferences.	892 commercial fish and invertebrate species.	Cheung et al., 2010
EcoOcean	Trophodynamic model, based on species interactions and energy transfer across trophic levels. Ecosim-with-Ecopath (EwE) framework	Combines a food web model comprising a mass-balance component (Ecopath; input: biomass, production/biomass ratio,	1 x 1˚ grid Monthly mean timestep	Vertical layers defined by food web interactions and habitat preference patterns;	51 trophic biomass groups; including all trophic level and taxonomic groups (marine	Christensen et al., 2015

	designed to evaluate the impacts of fisheries and climate change on marine resources and ecosystems.	consumption/biomass ratio, diet composition, catches), a temporal dynamic predator-prey component (Ecosim), and a spatio-temporal dynamic component which is a function of grid cell specific habitat attributes i.e. pH, water depth, temperature, and bottom type (Ecospace).		vertical movement and transportation through the establishment of trophic links and the generation and consumption of dead organic matter linking pelagic organisms to demersal and benthic organisms.	mammals, birds, fish, invertebrates, primary producers and bacteria)	
Apex Predators ECOSystem Model **(APECOSM)**	3D dynamic energy budget Eulerian model of size-structured marine populations and communities, based on individual environmentally driven bio-energetics, trophic interactions and behaviors, that are upscaled to populations and communities.	Size-based predation, food- and temperature-driven growth, reproduction and senescence. Includes environmental impacts on vertical and horizontal movements and schooling.	1 x 1˚ grid Monthly mean timestep	3D explicit vertical movement considered.	Explicit size-based communities including 3 communities (epipelagic, migratory, mesopelagic); 95 species length lasses and 100 size classes	Maury, 2010

Table A.2: Overview of layer configuration and selected forcing variables used in the marine ecosystem models included in the ensemble projections. Forcing variables were provided by the two Earth System Models GFDL-ESM2M (1˚ by 1˚ grid cell, 50 depth levels) and IPSL-CM5A-LR (1˚ by 1˚ degree grid cell, 31 depth levels). Layers included surface, bottom, depth-integrates surface to bottom, or depth resolved, depending on each ecosystem model's requirements.

Fish-MIP model	**Depth integration**	**Current speed**	**Sea temperature**	**Dissolved oxygen conc.**	**NPP - primary organic carbon production**	**Phytoplankton carbon conc.**	**Zooplankton carbon conc.**	**pH**	**Salinity**	**Ice coverage**	**Mixed layer depth**
BOATS	Integrated over full water column	N/A	Upper ocean temperature (average of upper 75m)	N/A	Depth integrated primary production (full water column)	N/A	N/A	N/A	N/A	N/A	N/A
Macroecological	Integrated over full water column	N/A	Sea surface temperature (0-200m)	N/A	Depth integrated primary production (assumed to be allocated to the mixed layer depth or euphotic depth if deeper)	Large/ small phytoplankton	N/A	N/A	N/A	N/A	Areas shallower than mixed layer depth (or euphotic depth if deeper) treated as productive zone

DPBM	2 layers, surface (0-100m) and bottom.	N/A	Sea surface/ bottom temperature	N/A	Depth integrated primary production	Large/ small phytoplankton	N/A	N/A	N/A	N/A	Mixed layer depth incl.
DBEM	Vertical dimension is dependent on species specific min/max depth limits	Zonal meridional velocity	Sea surface/ bottom temperature	Incl.	Depth integrated primary production	Large/ small phytoplankton	N/A	Sea surface pH	Sea surface/ bottom salinity	Incl.	N/A
EcoOcean	Vertical dimension is dependent on depth distribution from species/ functional groups	N/A	Sea surface (150 m)	N/A	N/A	Large/ small phytoplankton	Large/ small zooplankton	N/A	N/A	Incl. (not floating ice)	N/A

APECOSM	3D depth-resolved	Zonal, meridionaland vertical velocity	Vertically (3D) resolved sea temperature	Incl.	N/A	Large/small phytoplankton	Large/small zooplankton.	pH incl.	N/A	Incl.	N/A

APPENDIX B

Table B.1: Overview of projected changes in total marine animal biomass under climate change (Emissions scenario RCP2.6 and RCP8.5) for individual ecosystem models and ocean basins. All changes are represented as the average of 2090-2099 relative to the average of 1990-1999. Light grey shading: changes <5%; grey shading: changes between 5-10%; dark grey shading: changes >10%.

Ecosystem model	Ocean basin	RCP 2.6	RCP 8.5
APECOSM	North Atlantic Ocean	-11.19%	-15.67%
	South Atlantic Ocean	-3.65%	-9.19%
	North Pacific Ocean	-2.81%	-10.50%
	South Pacific Ocean	-2.81%	-9.22%
	Indian Ocean	-1.36%	-9.44%
	Southern Ocean	-1.06%	4.53%
	Arctic Ocean	2.22%	-12.66%
BOATS	North Atlantic Ocean	-16.42%	-39.51%
	South Atlantic Ocean	-9.69%	-29.95%
	North Pacific Ocean	-12.22%	-37.97%
	South Pacific Ocean	-10.12%	-27.29%
	Indian Ocean	-10.96%	-31.53%
	Southern Ocean	-0.81%	4.31%
	Arctic Ocean	23.78%	17.68%
EcoOcean	North Atlantic Ocean	-8.78%	-23.84%
	South Atlantic Ocean	1.66%	-0.76%
	North Pacific Ocean	-15.25%	-21.96%
	South Pacific Ocean	-1.30%	-5.99%
	Indian Ocean	0.43%	-3.35%
	Southern Ocean	-3.50%	8.95%
	Arctic Ocean	12.24%	13.70%
DBEM	North Atlantic Ocean	-12.00%	-42.96%
	South Atlantic Ocean	-9.87%	-8.73%
	North Pacific Ocean	-2.17%	-16.34%
	South Pacific Ocean	-9.97%	-34.34%
	Indian Ocean	-3.53%	-36.08%
	Southern Ocean	-7.53%	91.68%
	Arctic Ocean	239.07%	491.57%
DPBM	North Atlantic Ocean	-6.74%	-18.69%
	South Atlantic Ocean	-2.32%	-7.72%
	North Pacific Ocean	-5.34%	-12.87%
	South Pacific Ocean	-4.91%	-11.19%
	Indian Ocean	-4.48%	-11.14%
	Southern Ocean	0.62%	1.95%
	Arctic Ocean	4.61%	-7.13%

Macroecological	North Atlantic Ocean	-19.03%	-49.62%
	South Atlantic Ocean	-6.20%	-29.42%
	North Pacific Ocean	-13.43%	-53.60%
	South Pacific Ocean	-8.69%	-27.16%
	Indian Ocean	-8.23%	-30.76%
	Southern Ocean	-5.30%	3.47%
	Arctic Ocean	8.09%	-11.25%
Ensemble mean	**North Atlantic Ocean**	**-12.36%**	**-31.71%**
	South Atlantic Ocean	**-5.01%**	**-14.29%**
	North Pacific Ocean	**-8.53%**	**-25.54%**
	South Pacific Ocean	**-6.30%**	**-19.20%**
	Indian Ocean	**-4.69%**	**-20.38%**
	Southern Ocean	**-2.93%**	**19.15%**
	Arctic Ocean	**48.33%**	**81.99%**

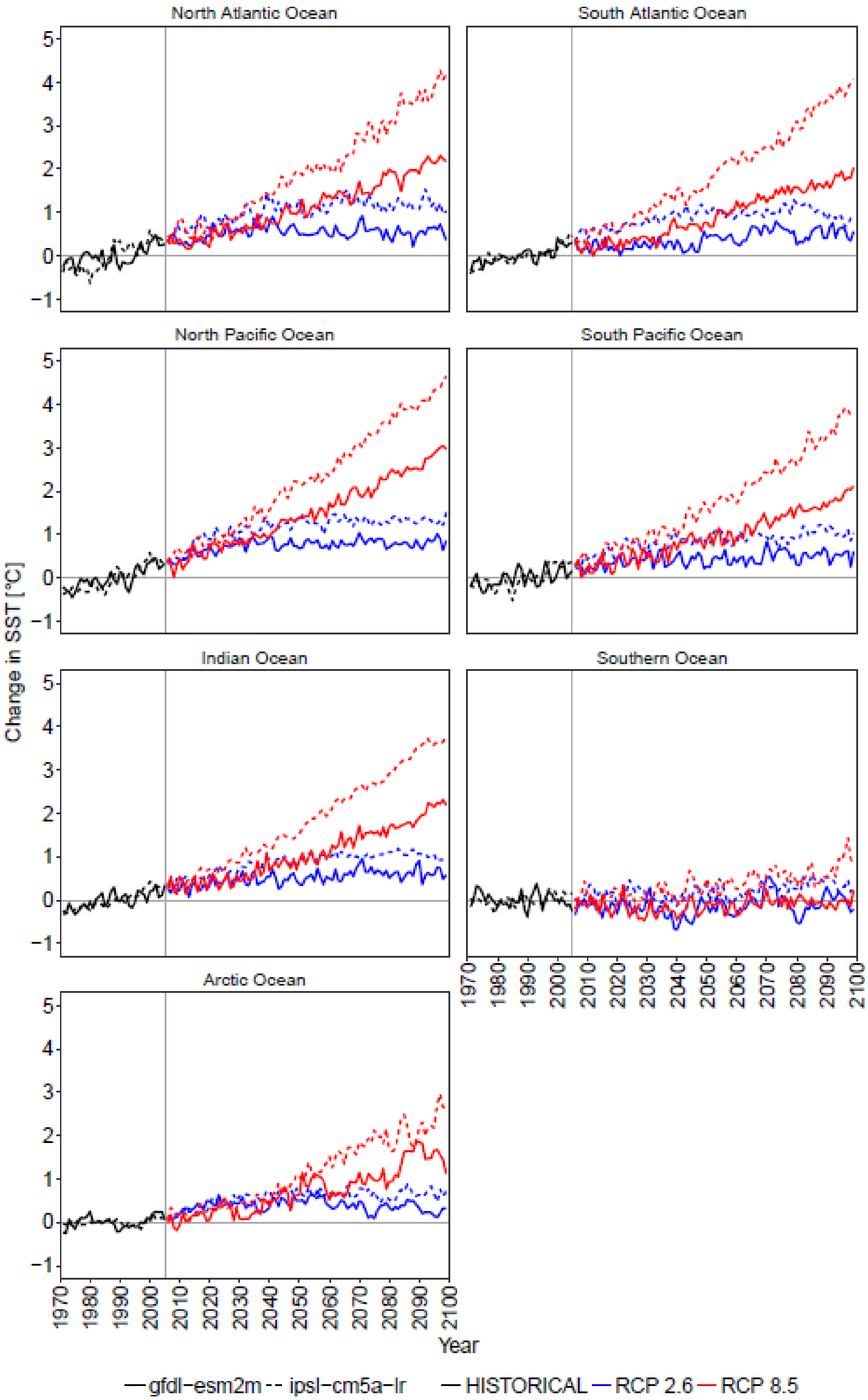

Figure B.1: Earth System Model projections for sea surface temperature (SST) across ocean basins under climate change (RCP2.6 and RCP8.5) for 1970-2100. SST trends in degree °C relative to 1990-1999.

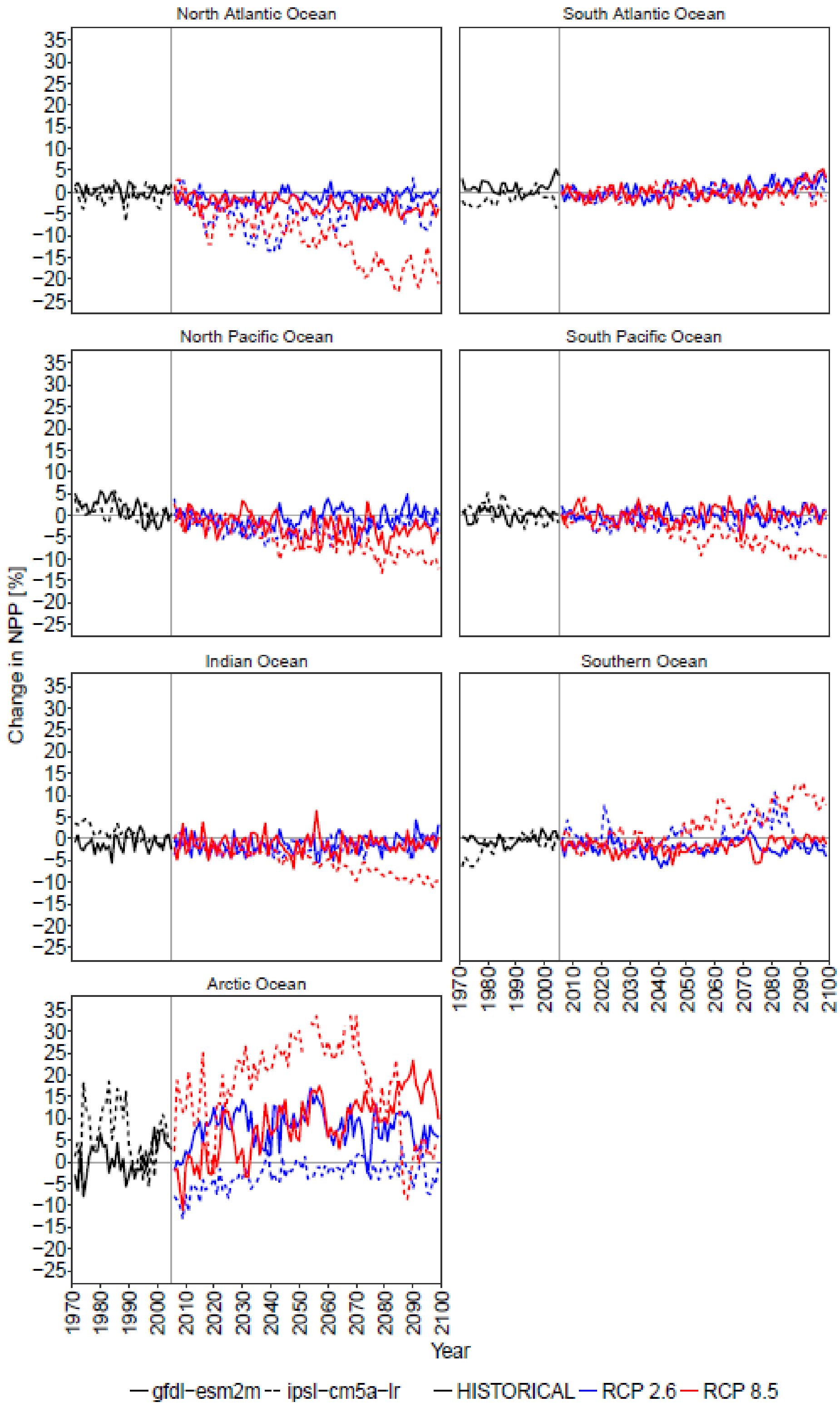

Figure B.2: Earth System Model projections for net primary production (NPP) across ocean basins under climate change (RCP2.6 and RCP8.5) for 1970-2100. Trends are relative (%) to the average of 1990-1999.

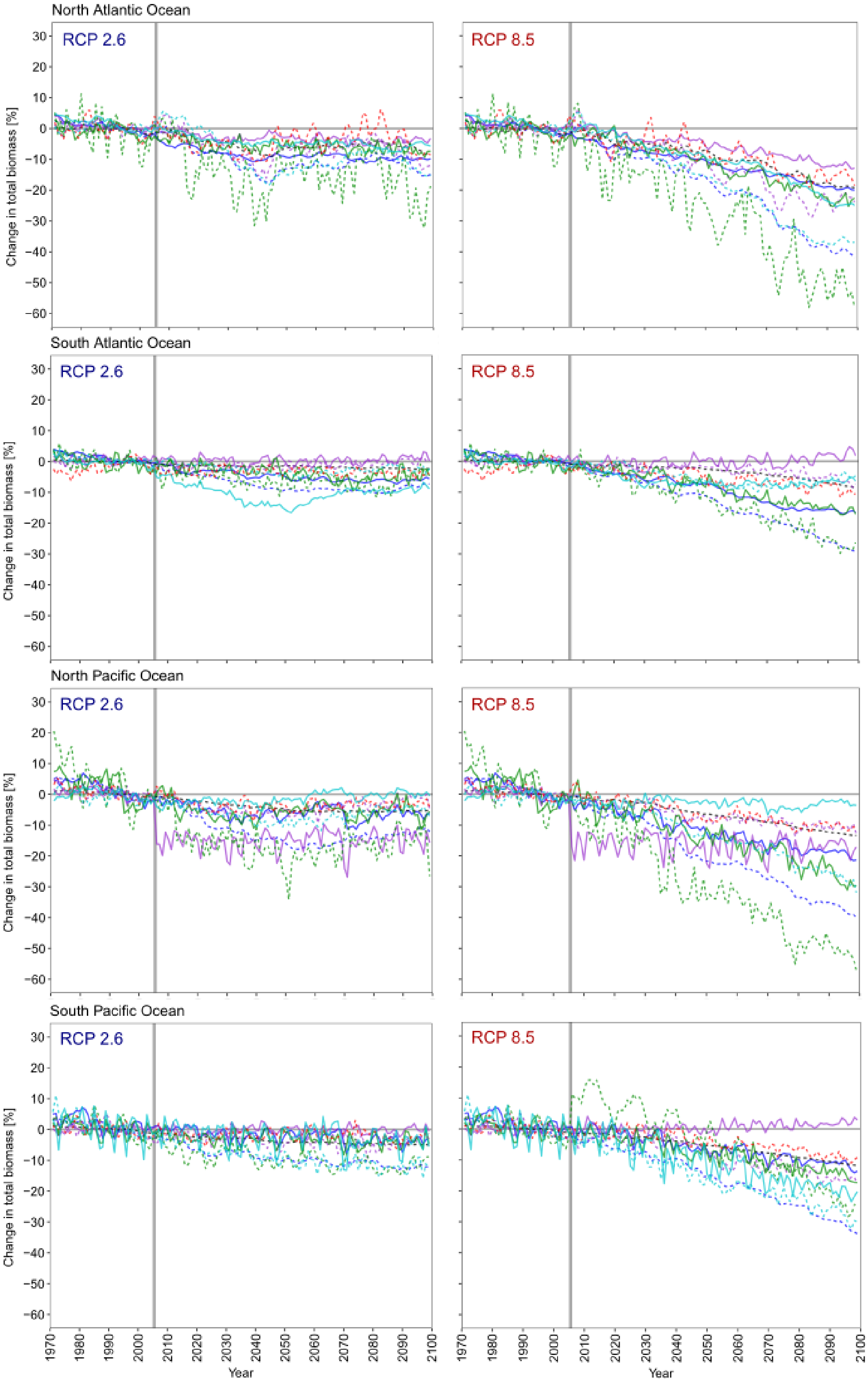

Figure B.3: Individual model projections for total marine animal biomass across ocean basins under climate change (Emissions scenarios RCP2.6 and RCP8.5) for 1970-2100. Vertical grey line separates historical trends (1970-2005) and future projections (2006-2100). All trends are relative (%) to the average of 1990-1999.

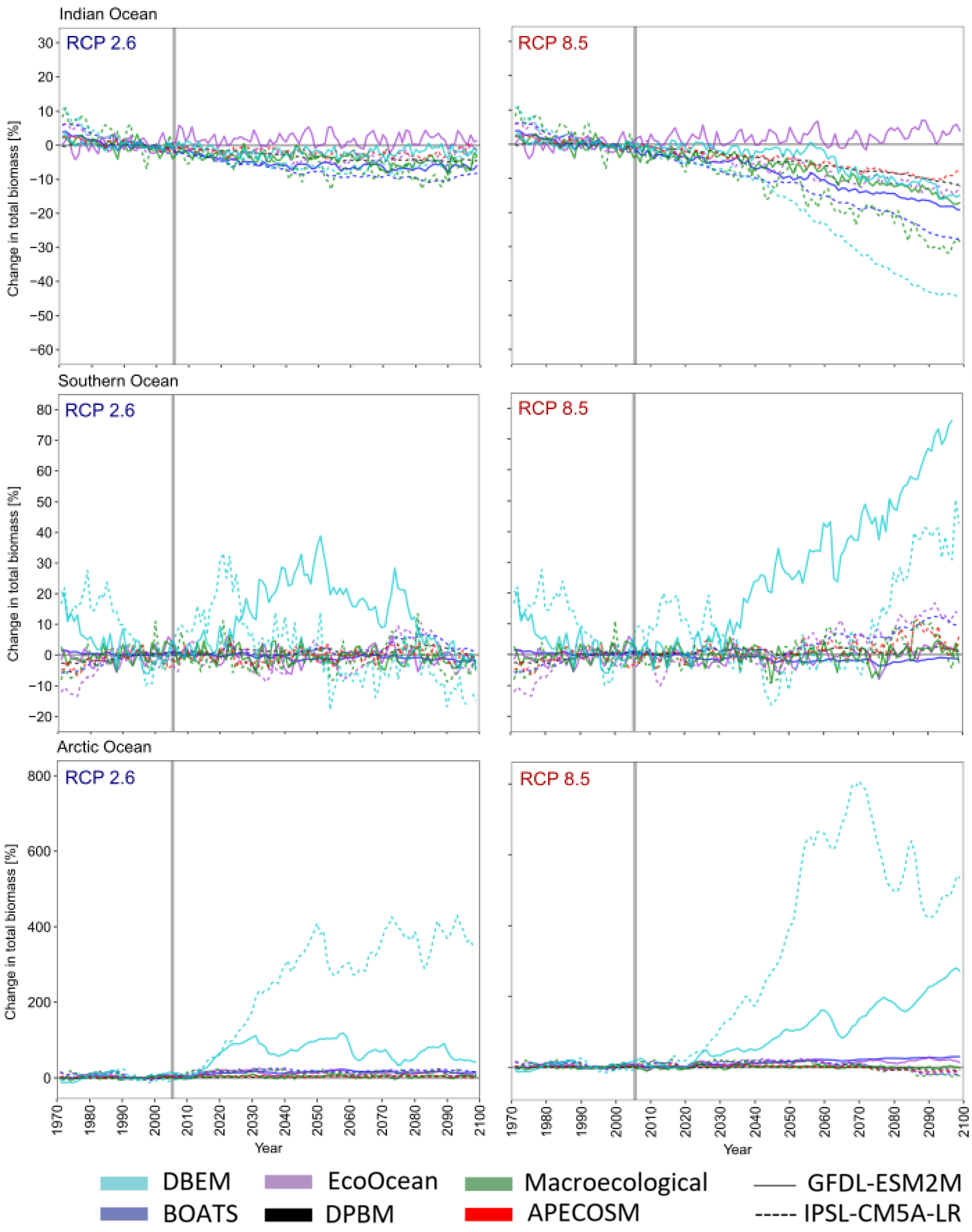

Figure B.3 continued: Individual model projections for total marine animal biomass across ocean basins under climate change (Emissions scenarios RCP2.6 and RCP8.5) for 1970-2100. Vertical grey line separates historical trends (1970-2005) and future projections (2006-2100). All trends are relative (%) to the average of 1990-1999.

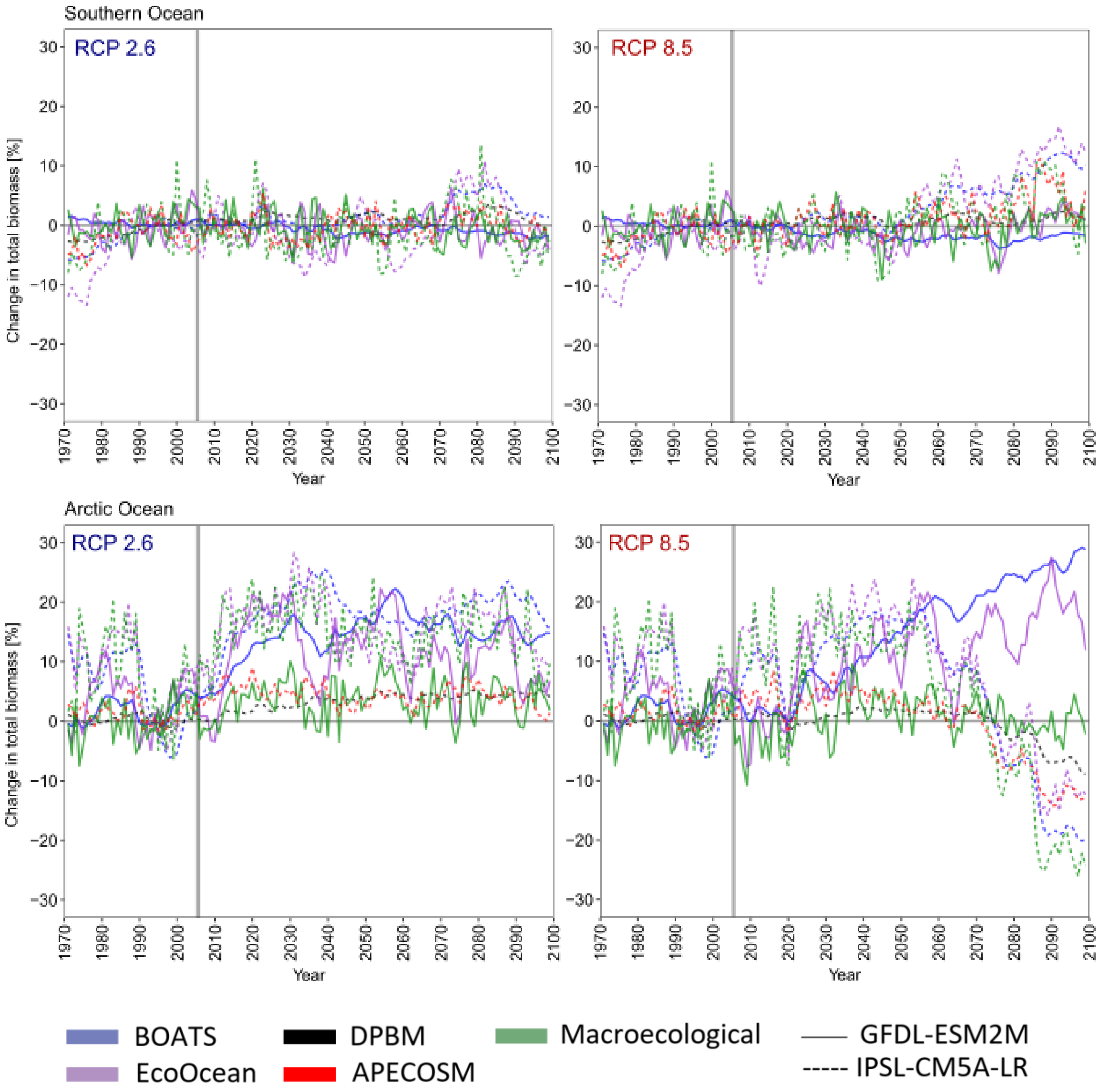

Figure B.4: Individual model projections for total marine animal biomass in the Arctic Ocean and Southern Ocean without DBEM under RCP2.6 and RCP8.5 for 1970-2100. DBEM is excluded to visualize temporal trends of the other ecosystem models in the polar ocean basins. Vertical grey line separates historical trends (1970-2005) and future projections (2006-2100). All trends are relative (%) to the average of 1990-1999.

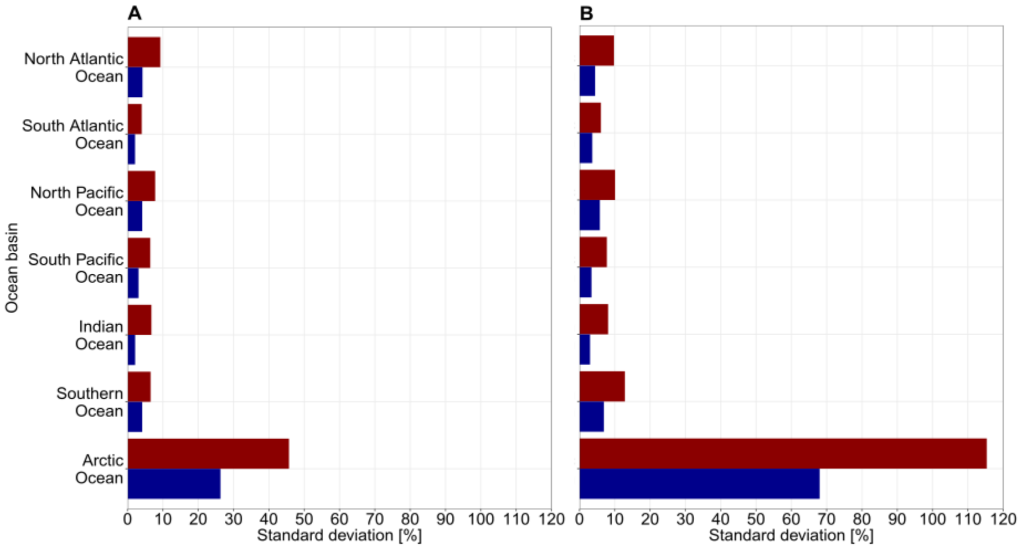

Figure B.5: Variability in projections in total marine animal biomass as mean standard deviation due to different Earth System Models and different ecosystem models under RCP2.6 (blue) and RCP8.5 (red). A: Earth System Model variability. B: Marine ecosystem model variability.

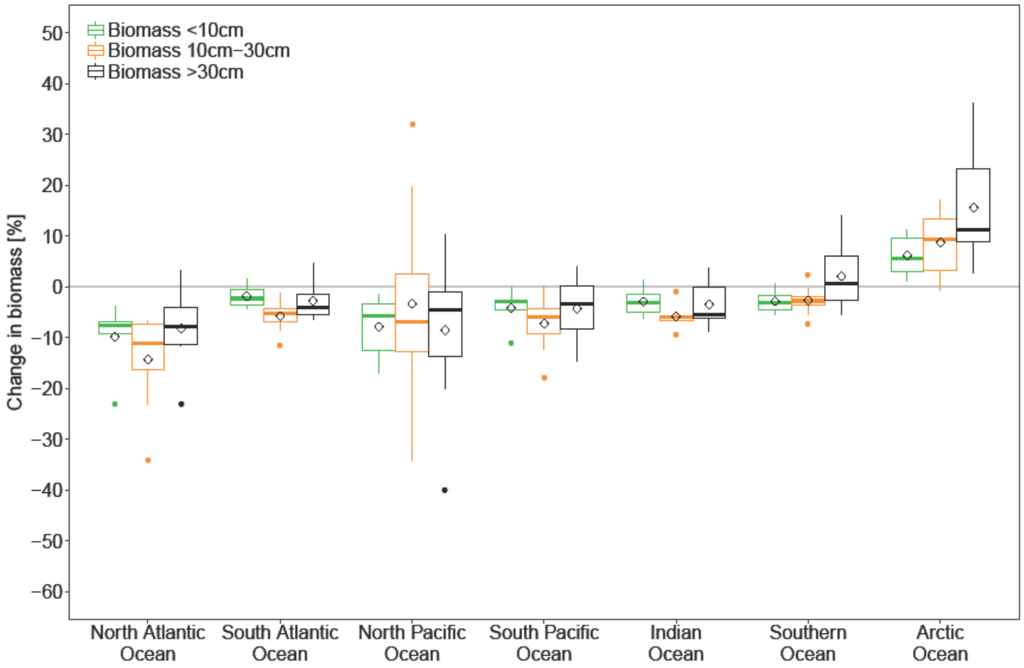

Figure B.6: Model projections for marine animal biomass of three size ranges across ocean basins under climate change for the emissions scenario RCP2.6. Green: small marine animals <10cm (n-6); orange: medium-sized marine animals 10–30cm (n=8); black: large marine animals >30cm (n=8). All changes are the average of the 2090s relative to the 1990s. Boxplots: the upper and lower hinges correspond to the 1st and 3rd quartiles; the upper/lower whisker extends to the highest/lowest value that is within 1.5 times the interquartile range; horizontal line within the box corresponds to the median; diamonts represents the mean. Outlier dots are representing data beyond the end of the whiskers.

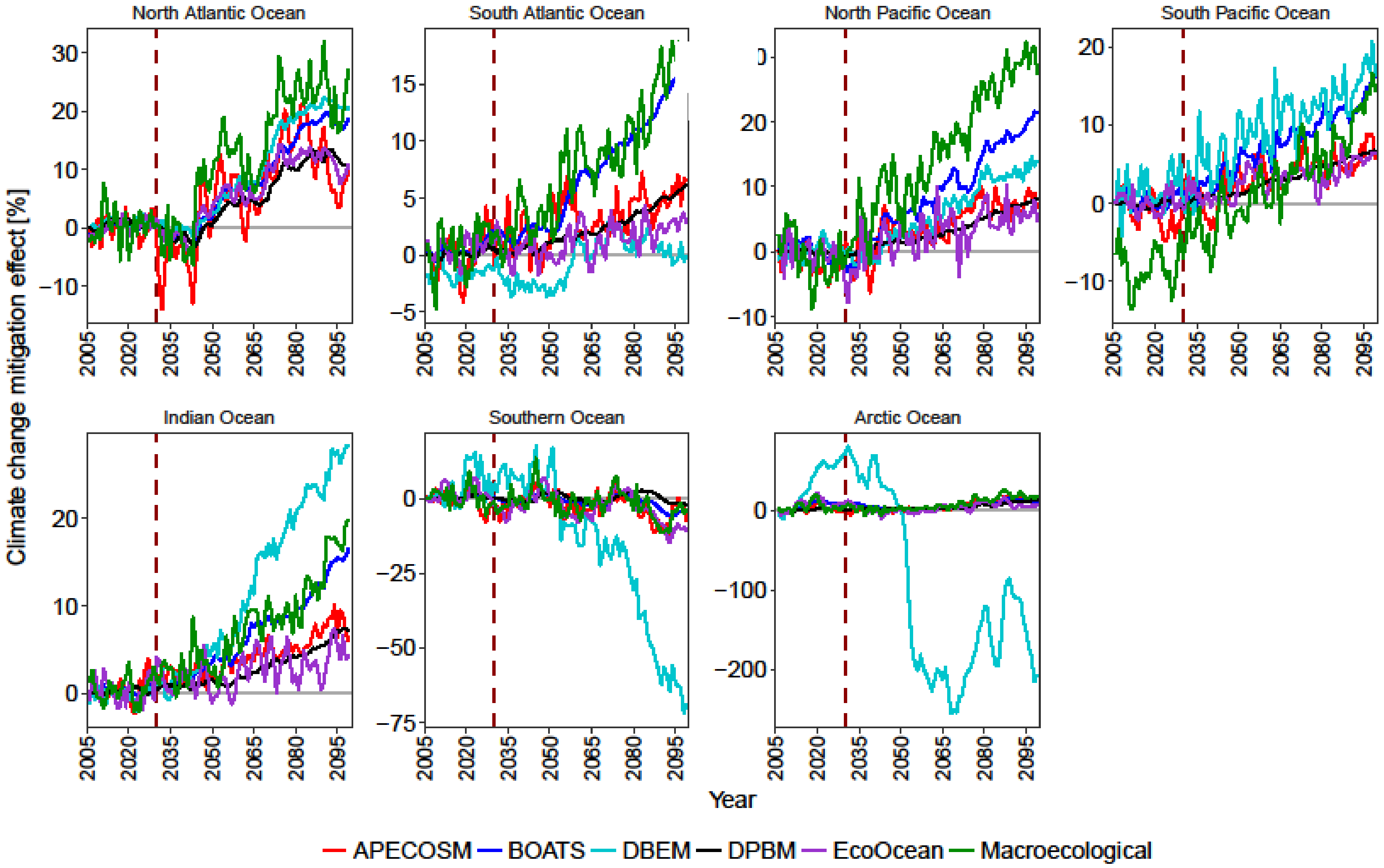

Figure B.7: Climate-change mitigation effect (RCP2.6 – RCP8.5) on model projections of total marine animal biomass. Vertical dashed line: target year (2030) for most UN Sustainable Development Goals.

APPENDIX C

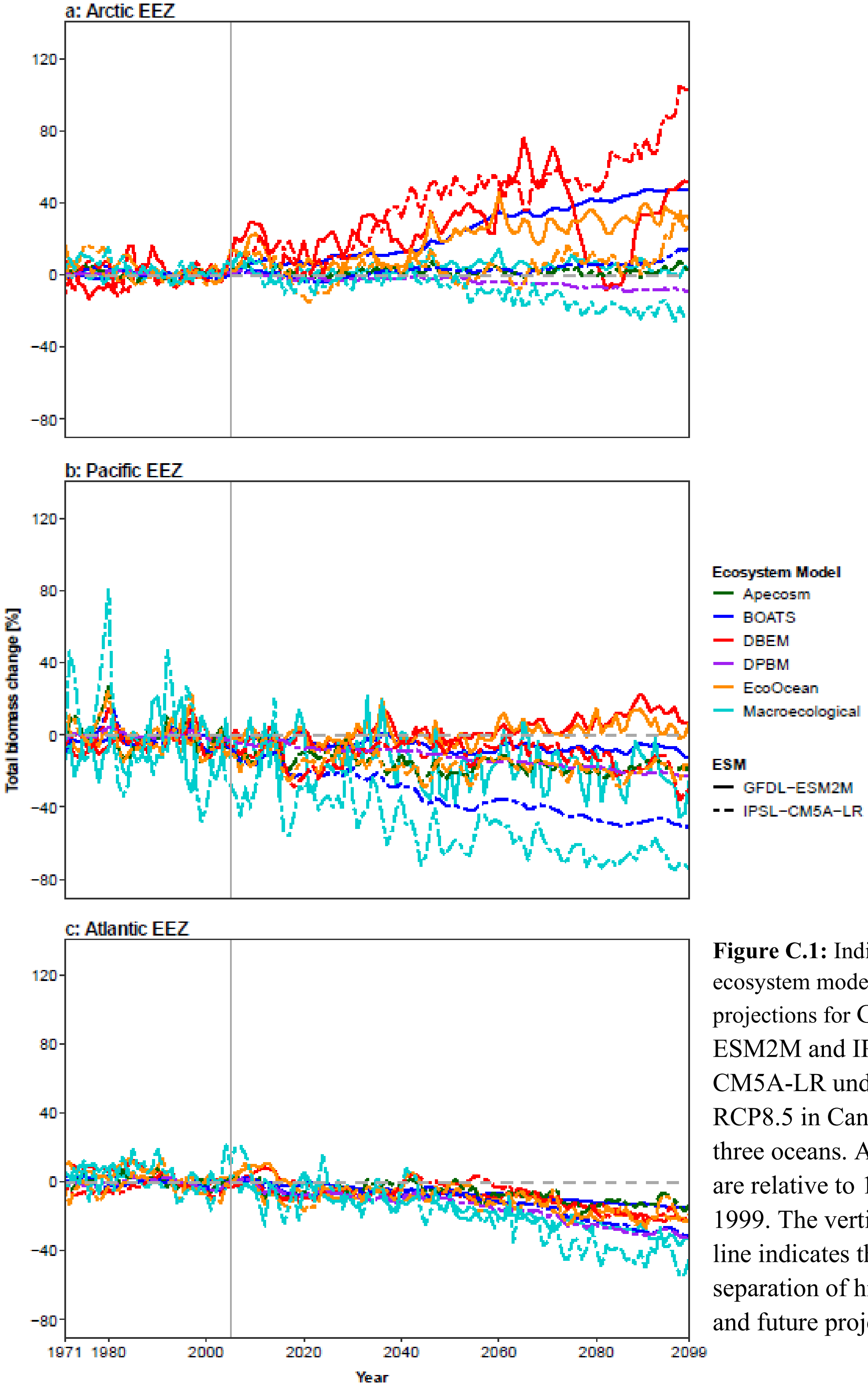

Figure C.1: Individual ecosystem model projections for GFDL-ESM2M and IPSL-CM5A-LR under RCP8.5 in Canada's three oceans. All trends are relative to 1990-1999. The vertical grey line indicates the separation of historical and future projections.

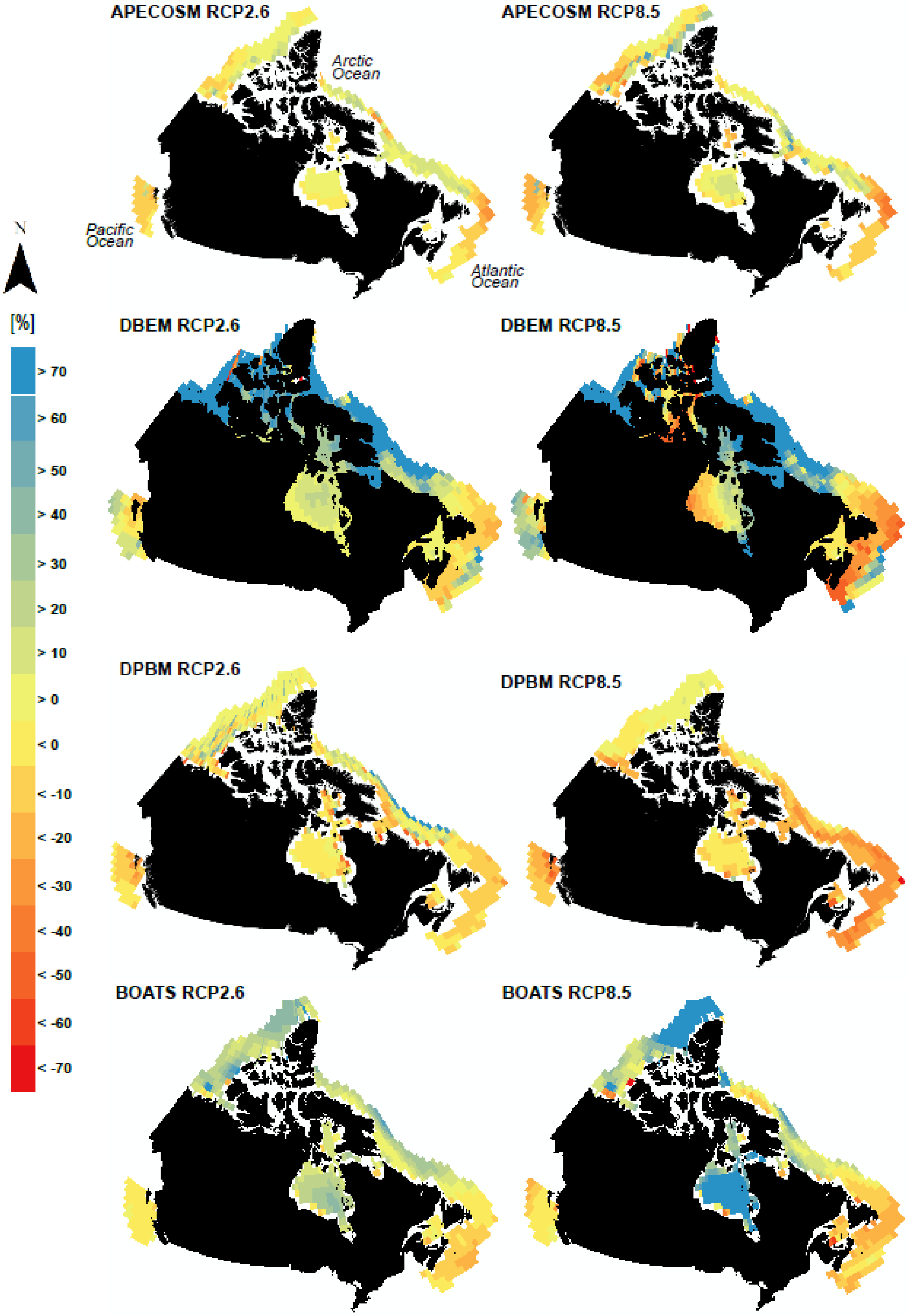

Figure C.2: Spatial patterns of APECOSM, DBEM, DPBM, and BOATS projections of total marine animal biomass under RCP2.6 (left) and RCP8.5 (right) in Canada's three oceans. For better visualization of patterns, percent biomass change values were capped at +/-75%. Country shapefile retrieved from www.diva-gis.org. EEZ outline modified from Flanders Marine Institute (2018).

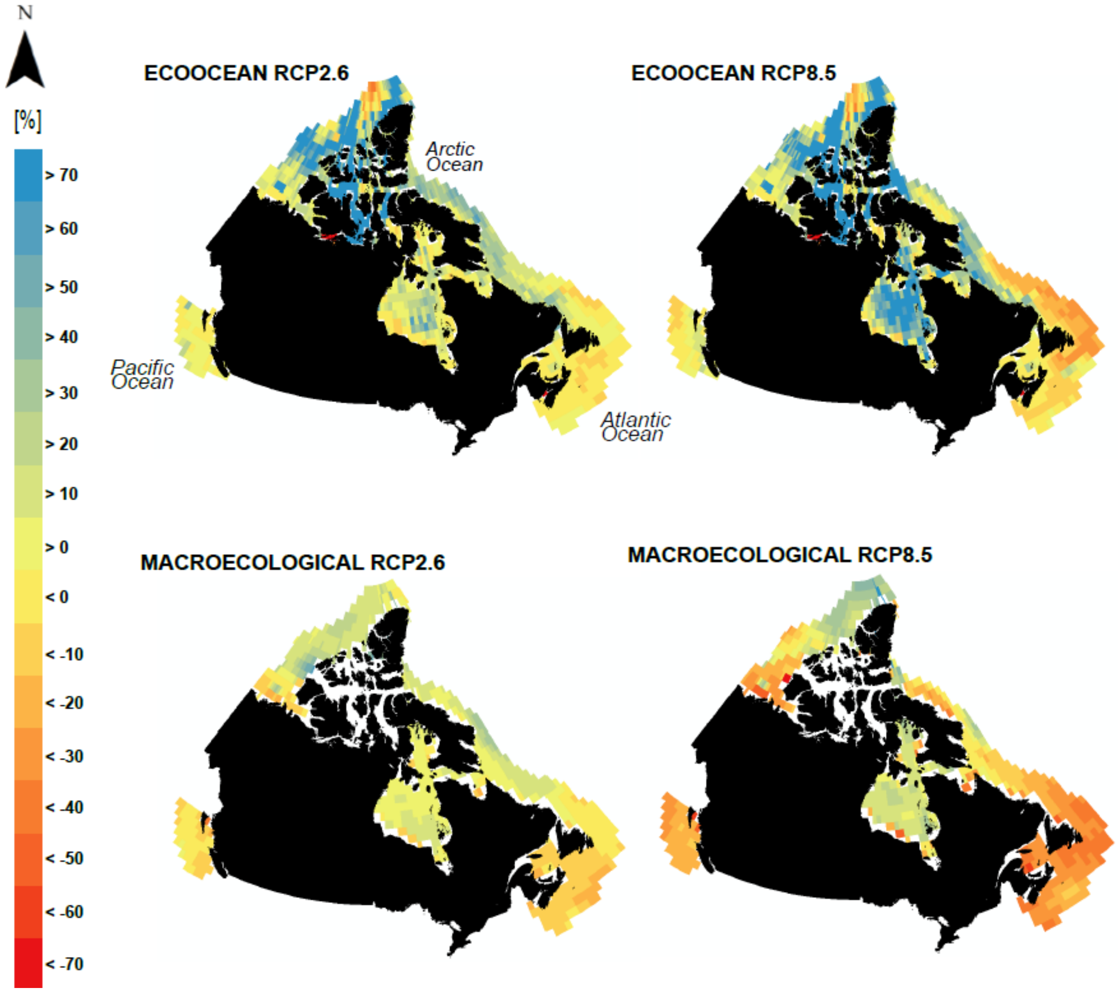

Figure C.3: Spatial patterns EcoOcean and Macroecological projections of total marine animal biomass RCP2.6 (left) and RCP8.5 (right) in Canada's three oceans. For better visualization of patterns, percent biomass change values were capped at +/-75%. Country shapefile retrieved from www.diva-gis.org. EEZ outline modified from Flanders Marine Institute (2018).

APPENDIX D

Table D.1: Summary of weighted log-linear regression of mean projected biomass changes under two contrasting emissions scenarios (RCP2.6, RCP8.5) and mean fisheries landings for (A) 1990s, (B) 1980s, and (C) 2000s across NAFO divisions.

A	Estimate	Std. Error	Adj. R^2	Pr(>|t|)
RCP2.6 2030s biomass changes				
NAFO landings 1990s	-6.650	1.755	0.3337	<0.001
RCP8.5 2030s biomass changes				
NAFO landings 1990s	-7.334	1.814	0.3623	<0.001
RCP2.6 2090s biomass changes				
NAFO landings 1990s	-7.003	2.297	0.235	0.005
RCP8.5 2090s biomass changes				
NAFO landings 1990s	-15.951	3.952	0.3616	<0.001
B Sensitivity analysis	Estimate	Std. Error	Adj. R^2	Pr(>|t|)
RCP2.6 2030s biomass changes				
NAFO landings 1980s	-7.044	1.580	0.4114	<0.001
RCP8.5 2030s biomass changes				
NAFO landings 1980s	-7.778	1.628	0.447	<0.001
RCP2.6 2090s biomass changes				
NAFO landings 1980s	-7.781	1.872	0.376	<0.001
RCP8.5 2090s biomass changes				
NAFO landings 1980s	-16.499	3.477	0.4434	<0.001
C Sensitivity analysis	Estimate	Std. Error	Adj. R^2	Pr(>|t|)
RCP2.6 2030s biomass changes				
NAFO landings 2000s	-7.538	2.492	0.2319	0.005
RCP8.5 2030s biomass changes				
NAFO landings 2000s	-8.079	2.618	0.2399	0.004
RCP2.6 2090s biomass changes				
NAFO landings 2000s	-6.552	3.270	0.1005	0.05
RCP8.5 2090s biomass changes				
NAFO landings 2000s	-17.292	5.889	0.2201	0.006

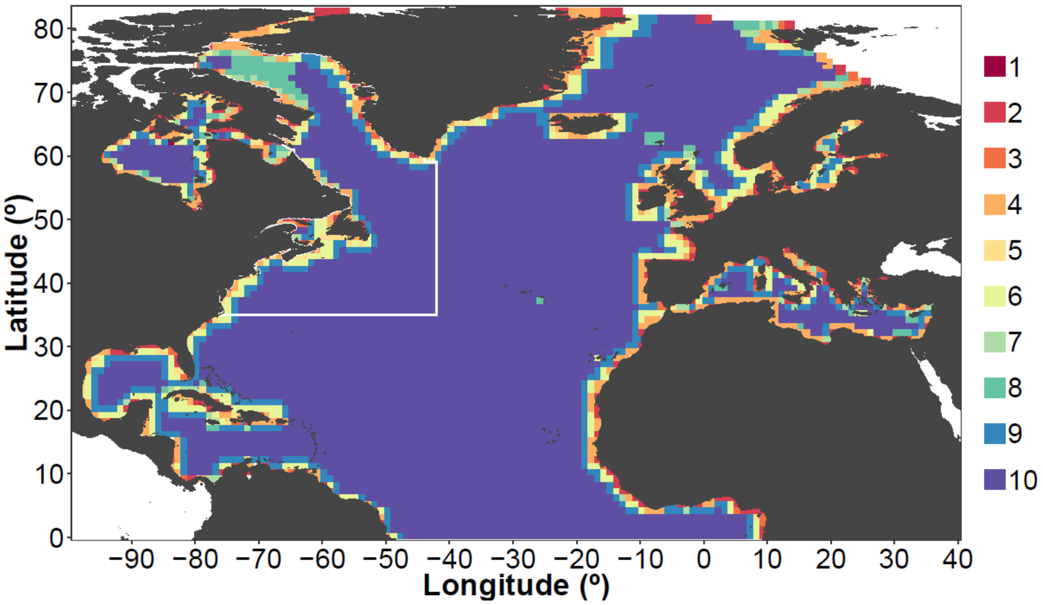

Figure D.1: Model coverage per 1˚ x 1˚ grid cell in the North Atlantic Ocean. Color codes and numbers represent the number of marine ecosystem model-Earth System Model combinations per grid cell. White outline denotes the NAFO convention area.

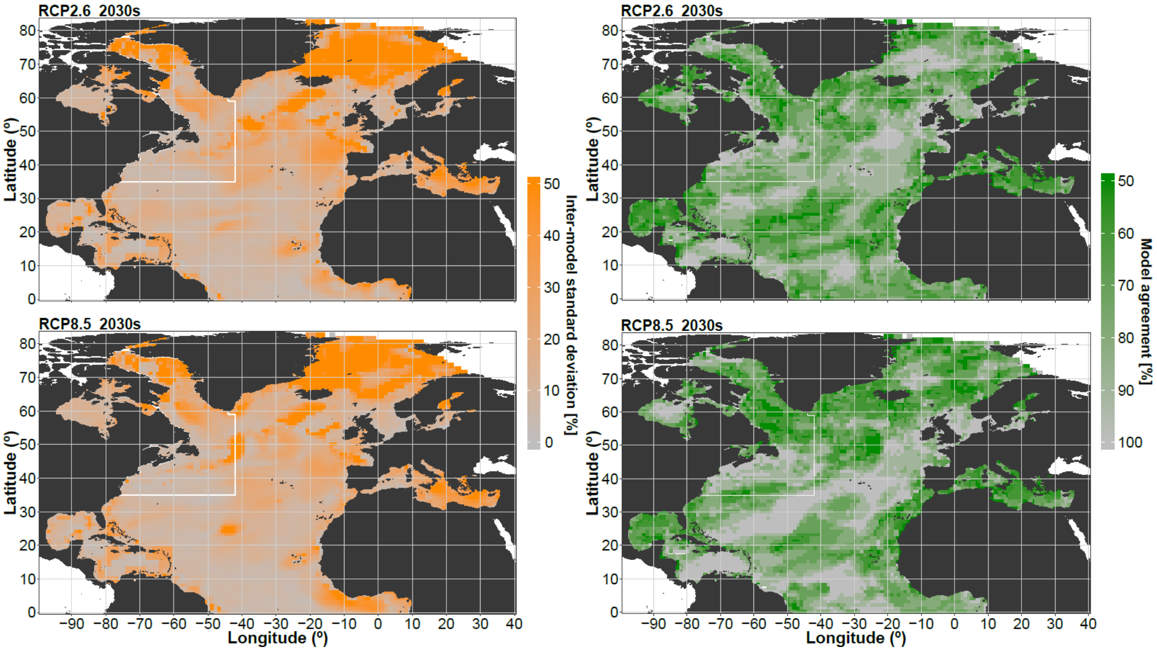

Figure D.2: Spatial patterns of model variability (left) and model agreement (right) in ensemble projections for RCP2.6 and RCP8.5 in the North Atlantic Ocean. Model variability is represented as the inter-model standard deviation (%) of the projected ensemble mean biomass changes in the 2030s relative to the 1990s, while model agreement denotes the percent of models agreeing on the direction of change. White outline denotes the NAFO convention area. Country shapefile retrieved from https://www.naturalearthdata.com. NAFO convention area shapefile modified from https://www.nafo.int/Data/GIS.

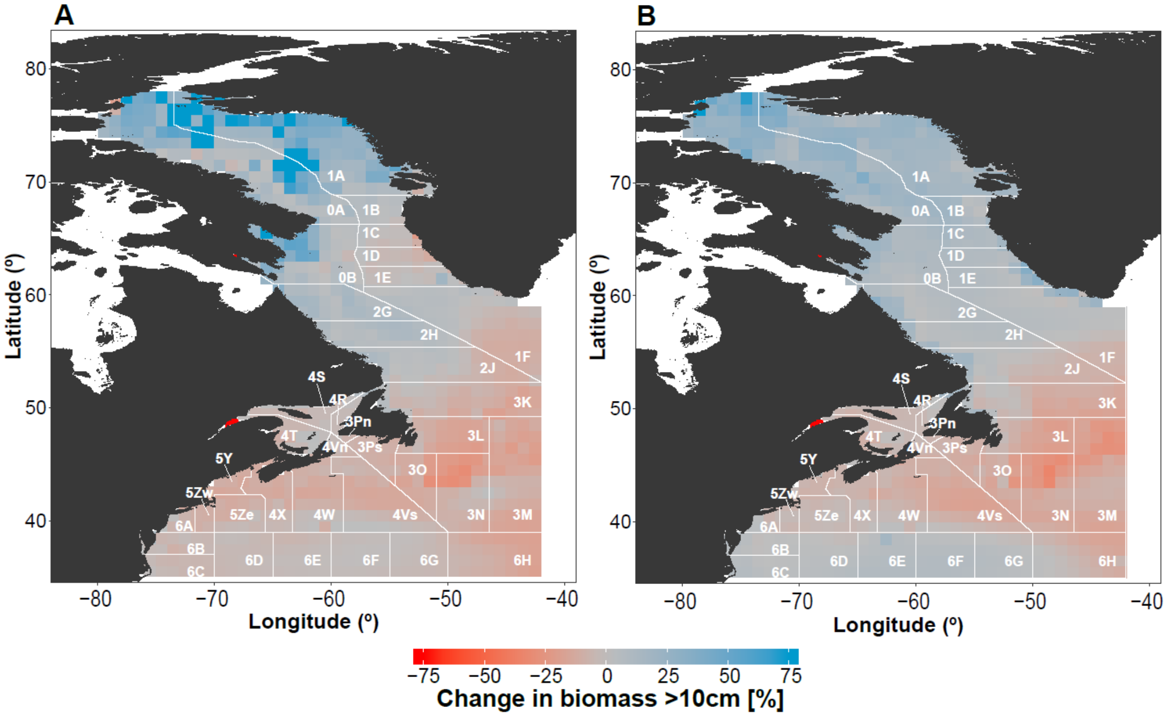

Figure D.3: Future ensemble mean changes (%) in biomass of animals >10cm under RCP2.6 in the 2030s (A) and 2090s (B) relative to the 1990s across individual NAFO divisions. NAFO division shapefile retrieved from https://www.nafo.int/Data/GIS.

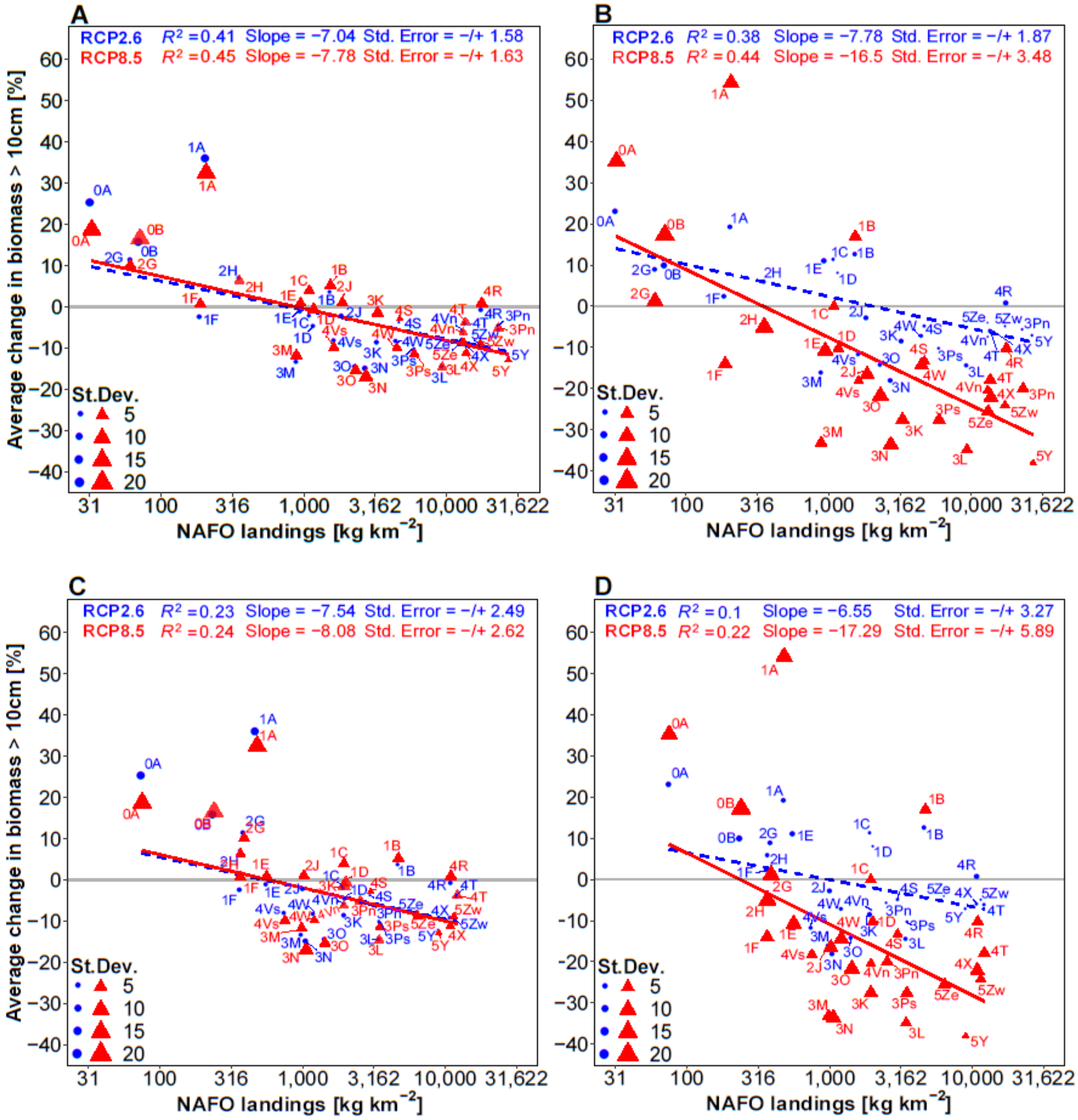

Figure D.4: Relationships between future ensemble mean changes (%) in biomass of animals >10cm under RCP2.6 (blue) and RCP8.5 (red) in the 2030s (A, C) and 2090s (B, D) relative to the 1990s and fisheries landings in the 1980s (A, B) and 2000s (C, D) across individual NAFO divisions. The gray line represent 0% change. Landings values are presented on a log scale.

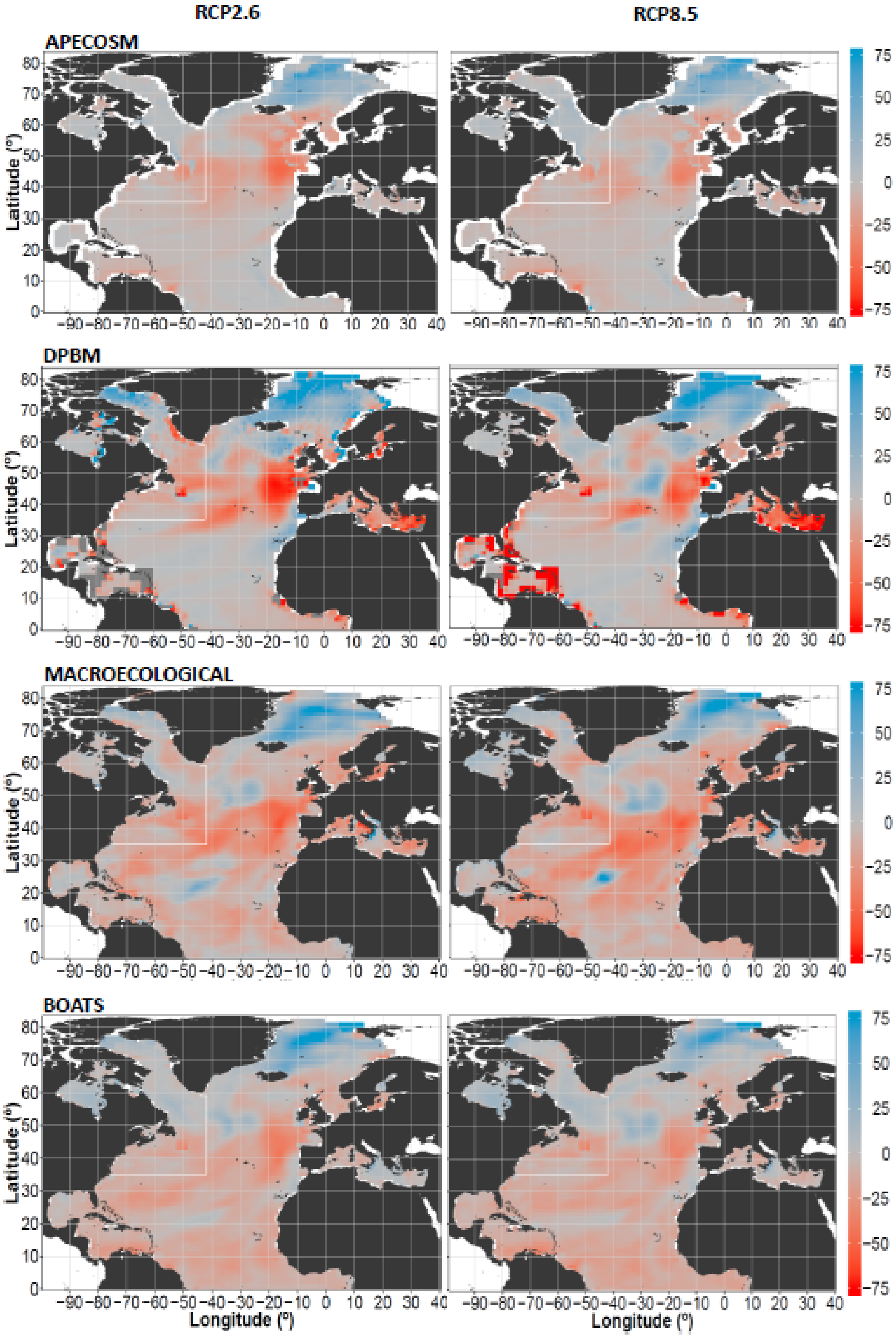

Figure D.5: Future individual marine ecosystems model projections of mean changes (%) biomass of animals >10cm under RCP2.6 (left) and RCP8.5 (right) in the 2030s relative to the 1990s. White outline denotes the NAFO convention area.

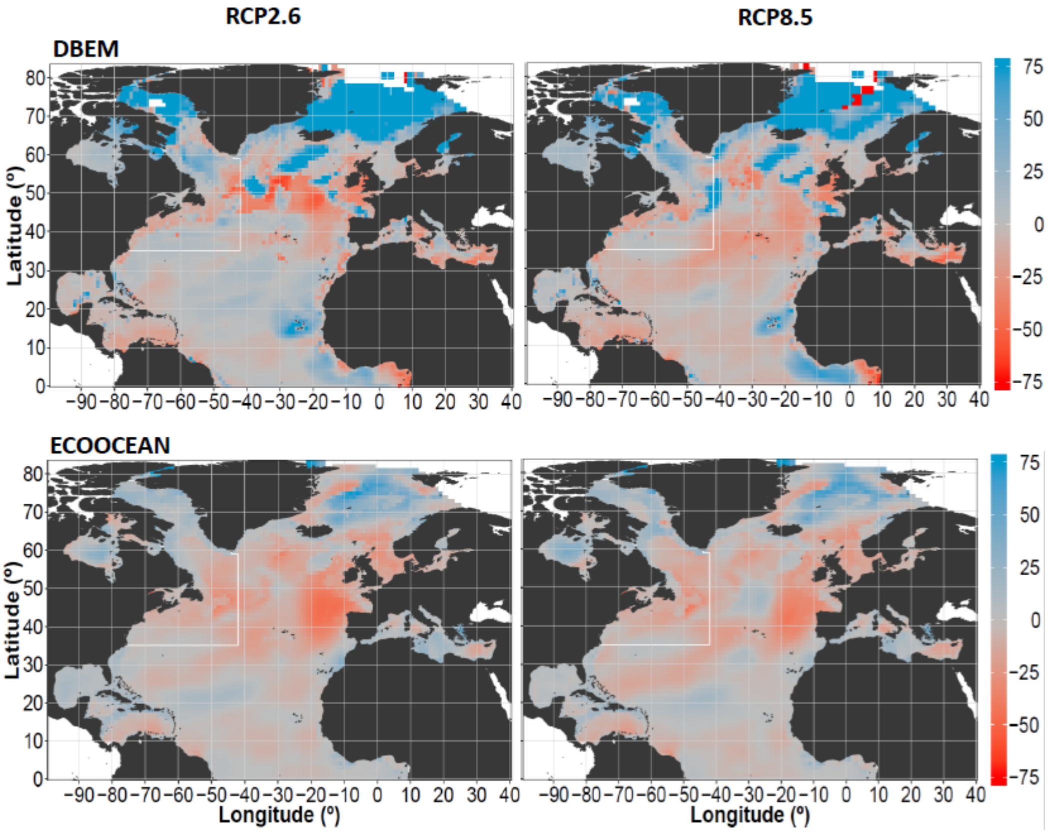

Figure D.5 continued: Future individual marine ecosystem model projections of mean changes (%) in biomass of animals >10cm under RCP2.6 (left) and RCP8.5 (right) in the 2030s relative to the 1990s. White outline denotes the NAFO convention area. Country shapefile retrieved from https://www.naturalearthdata.com. NAFO convention area shapefile modified from https://www.nafo.int/Data/GIS.

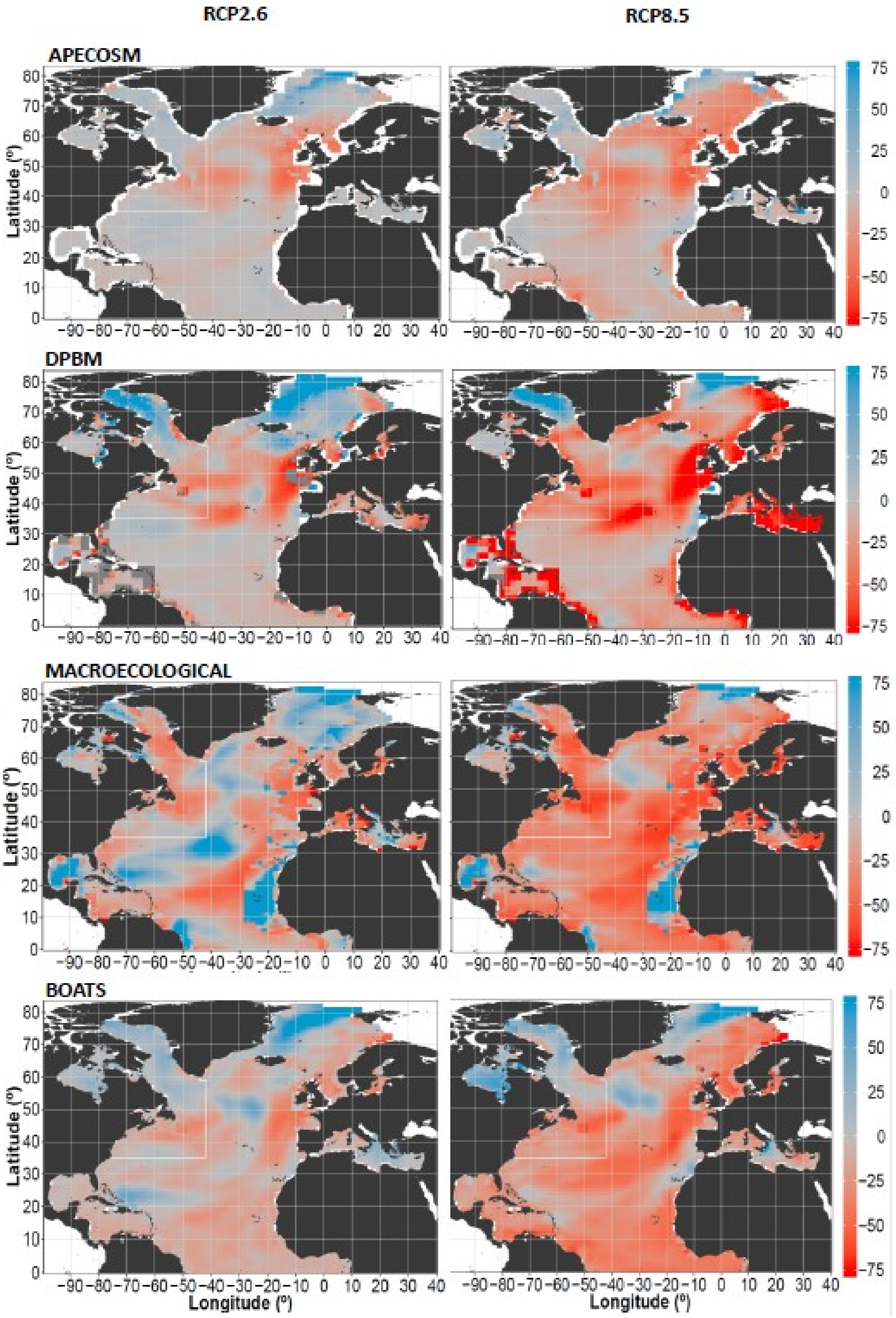

Figure D.6: Future individual marine ecosystem model projections of mean changes (%) in biomass of animals >10cm under RCP2.6 (left) and RCP8.5 (right) in the 2090s relative to the 1990s. White outline denotes the NAFO convention area.

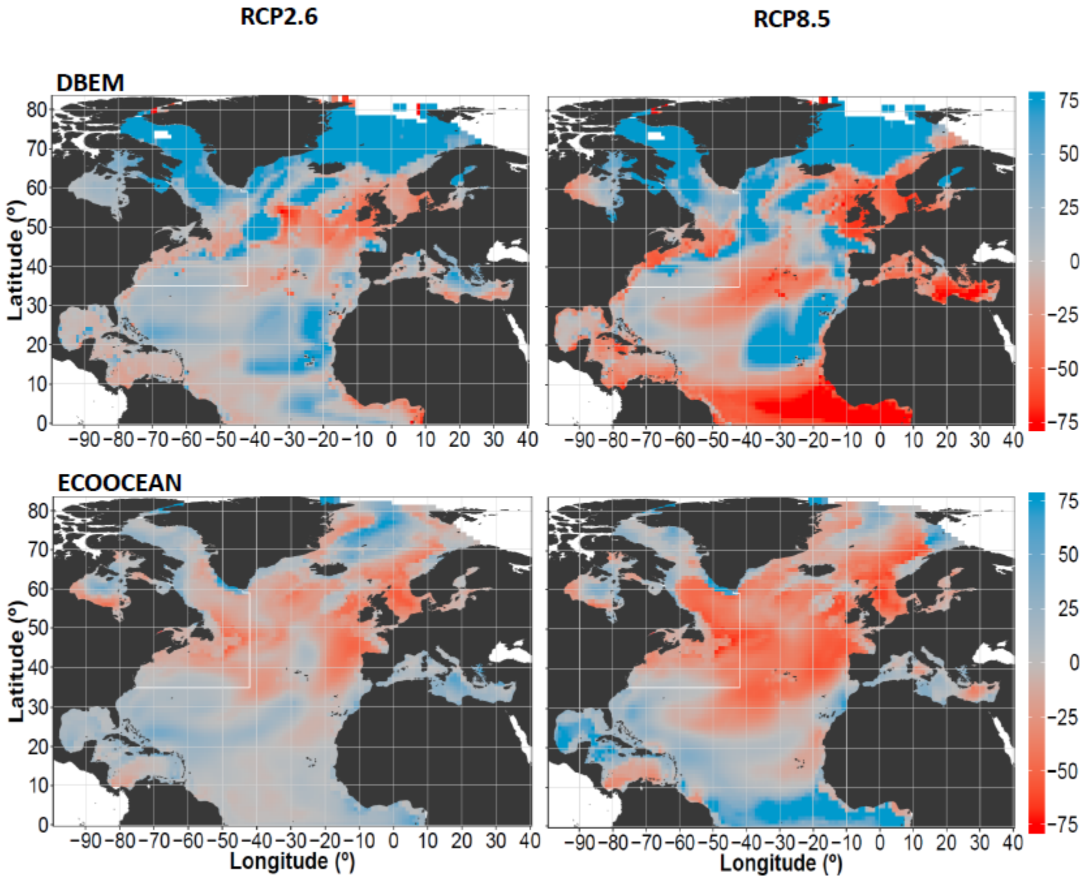

Figure D.6 continued: Future individual marine ecosystem model of mean changes (%) in biomass of animals >10cm under RCP2.6 (left) and RCP8.5 (right) in the 2090s relative to the 1990s. White outline denotes the NAFO convention area. Country shapefile retrieved from https://www.naturalearthdata.com. NAFO convention area shapefile modified from https://www.nafo.int/Data/GIS.

APPENDIX E

Other work I have co-authored and is relevant, but not included in this thesis:

Lotze, K.L., Tittensor, D.P., **Bryndum-Buchholz, A.**, Eddy, T.D., Cheung, W.W.L., Galbraith, E.D., Barange, M., Barrier, N., Bianchi, D., Blanchard, J.L., Bopp, L., Buechner, M., Bulman, C.M., Carozza, D.A., Christensen, V., Coll, M., Dunne, J.P., Fulton, E.F., Jennings, S., Jones, M.C., et al. (2019). Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proceedings of the National Academy of Sciences*, *116*(26), 12907-12912. https://doi.org/10.1073/pnas.1900194116.

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Tittensor, D.P., Eddy, T.D., Lotze, H.K., Galbraith, E.D., Cheung, W.W.L., Barange, M., Bopp, L., **Bryndum-Buchholz, A.**, Buechner, M., Bulman, C., Carozza, D.A., Christensen, V., Coll, M., Dunne, J.P., Fernandes, J.P., Fulton, E.A., Hobday, A.J., Jennings, S., et al. (2018a). A protocol for the intercomparsion of marine fishery and ecosystem models: Fish-MIP v1.0. *Geoscientific Model Development*, *11*(4), 1421-1442. https://doi.org/10.5194/gmd-11-1421-2018

Tittensor, D.P., Lotze, H.K., Eddy, T.D., Galbraith, E.D., Cheung, W.W.L., **Bryndum-Buchholz. A.**, Barange, M., Barrier, N., Bianchi, D., Blanchard, J.L., Bopp, L., Carozza, D.A., Christensen, V., Coll, M., Jennings, S., Jones, M., Maury, O., Silva, T.A.M., Steenbeek, J., et al. (2018b). ISIMIP2a Simulation Data from Marine Ecosystems and Fisheries (Fish-MIP; global) Sector. GFZ Data Services. https://doi.org/10.5880/ PIK.2018.005

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