Future Habitat Working Group: Summary Report

Amber M. Holdsworth, James R. Christian, Sarah C. Davies, Karen L. Hunter, Devin A. Lyons , Jessica Nephin, Ashley E. Park, Beatrice E. Proudfoot, Chris N. Rooper, Patrick L. Thompson

Fisheries and Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Rd.
Sidney, BC
V8L 4B2

2024

Canadian Technical Report of Fisheries and Aquatic Sciences 3644

Fisheries and Oceans Canada
Pêches et Océans Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans Canada, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques.*

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développement, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 3644

2024

Future Habitat Working Group: Summary Report

by

Amber M. Holdsworth, James R. Christian, Sarah C. Davies, Karen L. Hunter, Devin A. Lyons , Jessica Nephin, Ashley E. Park, Beatrice E. Proudfoot, Chris N. Rooper, Patrick L. Thompson

Fisheries and Oceans Canada
Institute of Ocean Sciences
9860 West Saanich Rd.
Sidney, BC V8L 4B2

Cat. No. Fs97-6/3644E-PDF ISBN 978-0-660-74312-7 ISSN 1488-5379
https://doi.org/10.60825/gf9j-e418

Correct citation for this publication:

Holdsworth, A.M., Christian, J.R., Davies, S.C. Hunter, K.L. Lyons, D.A., Nephin, J., Park, A.E., Proudfoot, B.E., Rooper, C.N., Thompson, P.L. 2024. Future Habitat Working Group: Summary Report. Can. Tech. Rep. Fish. Aquat. Sci. 3644: vi + 24 p. https://doi.org/10.60825/gf9j-e418

TABLE OF CONTENTS

ABSTRACT

Holdsworth, A.M., Christian, J.R., Davies, S.C. Hunter, K.L. Lyons, D.A., Nephin, J., Park, A.E., Proudfoot, B.E., Rooper, C.N., Thompson, P.L. 2024. Future Habitat Working Group: Summary Report. Can. Tech. Rep. Fish. Aquat. Sci. 3644: vi + 24 p. https://doi.org/10.60825/gf9j-e418

In 2020 scientists at Fisheries and Oceans Canada (DFO) formed a transdisciplinary working group to develop methodologies for estimating the effects of climate change on marine organisms and ecosystems in North-eastern Pacific coastal waters. This collaborative network was initially designed for the discussion of relevant projects and issues and meets annually. A subset of that group formed a Technical Working Group (TWG) that implemented a convergence research approach to developing a methodology for Species Distribution Modelling under Climate Change. The group consisted of multi-disciplinary experts from DFO Pacific Region and met bi-weekly. This document summarizes the working group activities including the structure and history of the group, products and an overview of the lessons learned. The group arrived at several key outcomes: 1. environmental monitoring data should be collected concurrently with species sampling across a wide range of environmental conditions with calibrated instruments and standardized sampling protocols; 2. regional ocean downscaling of climate projections should match the species spatial scale (at a resolution fine enough to resolve nearshore areas where many species live) and that further collaborative research is needed to identify regions where we have sufficient species data, identify the resolution needed given the spatial extent of the data and, develop and run dynamical models; 3. tools for statistical downscaling are needed to reduce climate projection uncertainties.

RÉSUMÉ

Holdsworth, A.M., Christian, J.R., Davies, S.C. Hunter, K.L. Lyons, D.A., Nephin, J., Park, A.E., Proudfoot, B.E., Rooper, C.N., Thompson, P.L. 2024. Future Habitat Working Group: Summary Report. Can. Tech. Rep. Fish. Aquat. Sci. 3644: vi + 24 p. https://doi.org/10.60825/gf9j-e418

En 2020, des scientifiques de Pêches et Océans Canada (MPO) ont formé un groupe de travail transdisciplinaire pour développer des méthodologies d'estimation des effets des changements climatiques sur les organismes et écosystèmes marins dans les eaux côtières du nord-est du Pacifique. Ce réseau collaboratif a été initialement conçu pour discuter de projets et de problématiques pertinents. Il s'est réunit chaque année. Une partie du groupe a formé un groupe de travail technique (GTT) qui a mis en œuvre une approche de recherche convergente pour développer une méthodologie de modélisation de la répartition des espèces dans le cadre des changements climatiques. Le groupe était composé d'experts multidisciplinaires de la région du Pacifique du MPO et se réunissait toutes les deux semaines. Ce document résume des activités du groupe de travail, y compris la structure et l'historique du groupe, les produits et un aperçu des leçons apprises. Le groupe est parvenu à plusieurs résultats clés : 1. les données de surveillance environnementale devraient être collectées simultanément à l'échantillonnage des espèces dans un large éventail de conditions environnementales avec des instruments calibrés et des protocoles d'échantillonnage standardisés ; 2. la réduction d'échelle océanique régionale des projections climatiques devrait correspondre aux données spatiales des espèces (à une résolution suffisamment fine pour déterminer les zones côtières où vivent de nombreuses espèces) et que des recherches collaboratives supplémentaires sont nécessaires pour identifier les régions où nous disposons de suffisamment de données sur les espèces, identifier la résolution nécessaire compte tenu de l'étendue spatiale des données, et développer des modèles dynamiques; 3. des outils de réduction d’échelle statistique sont nécessaires pour réduire les incertitudes des projections climatiques.

1. INTRODUCTION

Increased carbon dioxide in the atmosphere has led to warming, acidification and deoxygenation of the global ocean (Gruber 2011). The waters of British Columbia are located at the northern end of the California Current System (CCS) which is one of the major eastern boundary current upwelling systems. Summer upwelling of relatively cold, nutrient rich and oxygen poor waters from the deeper ocean drives productivity and makes the region especially vulnerable to hypoxia and acidification. Regional ocean models project an overall surface warming, intensification of upwelling, and changes in circulation, nutrient and oxygen concentrations ("deoxygenation") and pH ("ocean acidification") (Gruber et al 2012, Holdsworth et al. 2021, Pozo Buil et al. 2021). These environmental changes are expected to lead to population or biomass reduction at higher trophic levels, age-structure changes, local extinction of some species, and overall loss of biodiversity (e.g., Bednaršek et al. 2021). Moreover, when these stressors act concurrently or consecutively, they can have cumulative impacts on organisms that go beyond the effects of any stressor in isolation (Pörtner et al. 2017).

Pacific coast subsistence, recreational, and commercial fisheries and aquaculture are of social and economic importance to Canada (Stroomer and Wilson 2012). There is increasing interest regionally, nationally, and internationally in protecting marine ecosystems. In support of this interest, Fisheries and Oceans Canada science is mandated to “[...] consider climate change impacts on marine ecosystems and species in regional ocean management [...]” (PMO 2021) and is obligated to take into account “[...] the environmental conditions affecting the stock [...]” including climate change (DFO 2022). However, uncertainty regarding the impacts of climate change on marine organisms and ecosystems makes it difficult for decision makers to develop strategies for the future.

Recently, tools have been developed to understand the impacts of projected anthropogenic warming within MPA networks in the Pacific Bioregions (Friesen et al. 2021). These tools are being used for MPA planning initiatives to design and establish MPA networks. However, thus far most analyses have only considered changes in temperature; considering a wider range of environmental conditions could improve these assessments. More work is needed to understand what the projected impacts will be so that adequate protection plans can be formulated.

Some studies have used substrate, depth, and temperature envelopes to characterize species’ habitat (Mahon and Smith 1989). More recent work has included dissolved oxygen (e.g., Bianucci et al. 2016) and there is potential to include other modelled fields such as salinity and pH. For each species, the relevant tolerance envelopes need to be estimated. If habitats can be defined in terms of environmental conditions, future projections of ocean conditions can be used to estimate how the habitat will change. Where possible, the relationships between each species and relevant static environmental variables can be used (substrate, bathymetry, etc.) to further constrain habitats.

Species distribution models (SDMs) leverage empirical species–environment relationships across space to make projections of how species will respond to changes in climate. They are increasingly being applied in marine environments, however, most SDM models to date do not account for oxygen (Cheung et al. 2009; Ready et al. 2010; Morley et al. 2018), and, in some cases, rely on sea surface temperature when modelling benthic species' distributions (Ready et al. 2010; García Molinos et al. 2016).

Regional ocean models that downscale climate projections to a finer resolution (e.g., Peña et al. 2023; Holdsworth et al. 2021) offer the opportunity to make projections within British Columbia and Washington waters at spatial resolutions (e.g., <3 km) that are relevant to marine spatial planning (Friesen et al. 2021) and oil spill response initiatives. Hence, a team of experts was formed to identify candidate species, select the appropriate variables, and develop methodological approaches for species distribution modelling using climate projections from regional ocean models.

This report outlines the past and continuing activities of the Future Habitat working group. The overall research strategy is outlined in section 2, the structure of the group is detailed in Section 3, a list of outputs is provided in Section 4, Section 5 outlines the key challenges and outstanding issues, and Section 6 summarizes the research priorities of the Future Habitat Working Group.

2. RESEARCH FRAMEWORK

To research the effects of climate change on marine organisms a wide range of expertise is needed including physical and chemical oceanography, biology, ecology, and statistics. A strategy known as *convergence research* is a transdisciplinary approach to solving complex research problems. The strategy transcends disciplinary boundaries integrating knowledge, tools, and ways of thinking (NRC 2014). This collaborative research takes time as it represents a paradigm shift from traditional, siloed research approaches (Wilson 2019), but it is a crucial strategy for solving complex problems at the intersection of different disciplines. This section will describe the Future Habitat working group as an example of an initiative that used the convergence research approach effectively.

The first step towards addressing the problem of understanding the effects of climate change on marine organisms was to connect researchers from different disciplines. We formed a collaborative team consisting of scientists within two different divisions within the DFO: Ecosystem Sciences and Ocean Sciences. Regular meetings allowed for the discussion of relevant projects and issues. Through these discussions the group arrived at a specific research question about how to understand the effects of climate change on marine species using SDMs. Then, a more focused technical working group (TWG) of relevant experts was formed.

At the outset the group established an open and inclusive culture. The initial progress of the TWG was incremental as we took time to develop a mutual language to facilitate communication across disciplines because different disciplines often use the same terminology in different ways. Over time, we developed new methodologies and explored sources of funding for implementing them. In the end, this convergence research team held an international workshop which led to a peer-reviewed publication (Davies et al. 2023), and two papers examining the effects of climate change on groundfish species (Thompson et al. 2023a: 2023b).

3. WORKING GROUP STRUCTURE

3.1 Future Habitat Working Group:

START DATE: Sept. 15, 2020
LOCATION: Online – MSTeams
CHAIR AND ORGANIZER: Dr. Amber Holdsworth

This collaborative network was designed for the discussion of relevant projects and issues related to climate change impacts on marine organisms. The group consists of all the members and typically meets annually (occasionally two times per year). Working group membership is listed in Appendix 1.

3.2 Technical Working Group for Species Distribution Modelling under Climate Change

DATES: Sept. 23, 2020 - Dec. 8, 2021
LOCATION: Online – MSTeams
CHAIR AND ORGANIZER: Dr. Amber Holdsworth

This group consists of selected technical experts with backgrounds in climate science, statistical modelling, spatial ecology, marine biology, oceanography, and regional ocean modelling and is a subset of the members in (3.1). Meetings were held every two weeks.

4. LIST OF WORK PRODUCTS

4.1 International Workshop: Species Distribution Modelling in a Changing Climate

4.1.1 Workshop details

DATES: March 11-12, 2021
LOCATION: Online – MSTeams
CO-CHAIRS AND ORGANIZERS: Karen Hunter and Dr. Patrick Thompson
Invited Speakers:

- *Dr. Anders Knudby,* Associate Professor, Department of Geography, Environment and Geomatics, University of Ottawa
- *Dr. Laura Pollock,* Assistant Professor, Department of Biology, McGill University
- *Dr. Jeff Price*, Associate Professor, Biodiversity and Climate Change, Tyndall Centre, University of East Anglia

4.1.2 Workshop Outputs:

Davies, S., Thompson, P.L., Gomez, C., Nephin, J., Knudby, A., Park, A., Friesen, S., Pollock, L., Rubidge, E., Anderson, S., Iacarella, J., Lyons, D., MacDonald, A., McMillan, A., Ward, E., Holdsworth, A.M., Swart, N. and Hunter, K.L., 2023. Addressing uncertainty when projecting marine species' distributions under climate change. *Ecography*, 2023(11), e06731. https://doi.org/10.1111/ecog.06731

A workshop summary is available in Appendix 2.

4.2 Scientific projects:

4.2.1 Future projections for groundfish species

Thompson, P.L., Nephin, J., Davies, S.C., Park, A.E., Lyons, D.A., Rooper, C.N., Peña, M.A., Christian, J.R., Hunter, K.L., Rubidge, E. and Holdsworth, A.M., 2023. Groundfish biodiversity change in northeastern Pacific waters under projected warming and deoxygenation. *Phil. Trans. R. Soc. B*, 378, 20220191. https://doi.org/10.1098/rstb.2022.0191

4.2.2 Future projections for Pacific halibut

Thompson, P.L., Rooper, C.N., Nephin, J., Park, A.E., Christian, J.R., Davies, S.C., Hunter, K.L., Lyons, D.A., Peña, M.A., Proudfoot, B., Rubidge, E. and Holdsworth, A.M., 2023. Response of Pacific halibut (*Hippoglossus stenolepis*) to future climate scenarios in the Northeast Pacific Ocean. *Fisheries Research*, 258. https://doi.org/10.1016/j.fishres.2022.106540.

4.2.3 Considering different life-stages separately when projecting habitats

Manuscript in preparation: *Response of different life-stages of groundfish species to future climate scenarios in the Northeast Pacific Ocean*

Appendix 3 provides a history of discussions that led to completed and ongoing research.

5. PROJECTING SPECIES DISTRIBUTIONS UNDER CLIMATE CHANGE: LESSONS LEARNED AND OUTSTANDING ISSUES

This section summarizes the outcomes regarding the research question of how to understand the effects of climate change on marine species using SDMs. The outcomes of each sub-section are briefly summarized in Table 1. The topics covered include (5.1) selection of the species, (5.2) identification of a region of interest, (5.3) selection of the environmental variables used to define the habitat envelopes, (5.4) the development of methodology for future projections, (5.5) how to model groundfish life-stages, (5.6) the need for ocean downscaling, and (5.7) how to quantify uncertainties.

Table 1: Summary of outcomes from the Technical Working Group for species distribution modelling under climate change (section 5).

5.1 Species selection	Consider the resolution of available models, availability of species data, existence of experimentally determined habitat envelopes, and model predictive power.
5.2 Region of interest selection	Determined by the availability of climate model and species data at comparable spatial scales.
5.3 Environmental variable selection	Relevant nvironmental data collected at the same time and location of biological sampling should be used to model species' response to environmental conditions. To avoid extrapolation, the widest possible spatial and temporal extent of observational data should be used to train the SDM.
5.4 Methodology for future projections	The methodology will be informed by the biology of the species, the available observational data, and the scale and extent of the available climate projections. It is important to consider how the conditions experienced by the species in the present climate compare with the projected future conditions; more work is needed to develop methodology for circumstances where extrapolation is required.
5.5 Modelling groundfish life-stages	Some species have different habitat preferences depending on their life-stage. Initial work shows that this could be important to consider, but potential avenues of research are limited by the availability of species data and variability in the size at which individuals reach maturity.
5.6 Global climate models and the need for downscaling research	Climate models are necessarily global and must be downscaled to match the species spatial and temporal scales. Species impacts research is limited by the spatial resolution of climate projections and the availability of downscaling models.
5.7 Quantifying uncertainty	The three main sources of uncertainty are (1) climate model uncertainty, (2) SDM uncertainty, and (3) biological uncertainty. Each should be carefully considered and quantified.

5.1 Species selection

Many candidate species were considered for inclusion in the species projections. Initially, focus was placed on commercially important species, species at risk, and species that may serve as indicators of ecosystem health. Ultimately, the group determined that the selection of species would primarily be driven by data availability.

For species that have tolerance envelopes that are experimentally determined, habitats can be clearly defined for the historical climate and projected into the future in accordance with changing ocean conditions. However, such data are lacking for most species in the region and laboratory tolerance experiments do not always accurately capture how species respond to environmental conditions in situ. SDMs can be used to relate environmental variables (e.g., depth, temperature, dissolved oxygen, pH) to observations of species' abundance.

There were several reasons for excluding important species. For some species (particularly nearshore species), the resolution of available regional climate projections is not well suited to making projections (e.g., kelp and eelgrass). For other species, there was insufficient data over the species' range, a lack of regional climate model data at sufficient resolution, or poor model predictive power in cross validation or temporal forecast assessment.

5.2 Defining the region of interest

The intersection of the available regional ocean model data and the species selected defines the region of interest. The region must be resolved well by the available regional ocean model, and comparisons between the model and observations should be made to determine the model bias.

5.3 Environmental variable selection

When identifying the relevant climatic and non-climatic environmental variables, ability to use data fields (e.g., T and O2) to describe the species' habitat under current conditions, and the uncertainty of how those responses may change in a future climate should be considered (Davies et al. 2023).

Variable selection is necessarily guided by the available observational data, and the existence of mechanistic ecological linkages between the species occurrence/abundance and observed environmental conditions. When possible, environmental data collected at the same time and location as biological sampling should be used to model species' response to environmental conditions. Beyond these data, we must rely on observational climatologies, or modelled data to fill in the gaps.

To capture the extent of variability in the predictor variables, it is important to include the widest spatial and temporal extent of observational data to train the SDM. By training on the full range of conditions, one can reduce or, in some cases, eliminate the need for extrapolation beyond the training data when projecting into the future (Muhling 2020, Davies et al. 2022).

B.C. waters are at mid-latitudes and the conditions projected for the future are within the range of conditions experienced by species along the eastern Pacific continental margin for many variables. For the groundfish project, many climatic variables were considered as predictors including temperature, oxygen, salinity, and pH. Temperature data and limited oxygen data were available from the trawl surveys that extend along the eastern Pacific coast from Alaska to California. To fill in the missing oxygen data we considered several options including using the regional model hindcast. However, the regional ocean models do not accurately resolve variability in oxygen concentrations at the required spatial and temporal resolutions to relate to the species data. Oxygen distribution in global ocean models is often biased (Oschlies et al. 2018) and the reanalysis products that are currently available do not include oxygen or were too coarse in resolution. After considering many options, we decided to use observations from biological sampling programs that measured bottom oxygen (including the International Pacific Halibut Commission ocean profile data) to fill in the gaps. Seawater density was found to be a useful proxy for the statistical oxygen model. In the end, we found that a model with pressure, density, temperature, and season as fixed effects plus a spatial random field was able to predict withheld oxygen observations with a coefficient of determination R^2 of 0.95 (Thompson et al. 2023b). Acidification is an important factor influencing marine life, especially benthic species. However, the only way to include acidification variables such as pH and aragonite saturation state would be by using associated modelled values because observations were not available. Unfortunately, the regional model data for pH and aragonite saturation state was only available for B.C. waters.

For the static variables, we had hoped to use substrate, but there was a lack of data across the species' range. The inclusion of depth as a predictor was discussed at length by the group at multiple meetings. Some studies advocate for excluding depth as a predictor to allow species to move to different depth ranges as a result of changes in other habitat variables (Morley et al. 2018, Hare et al. 2012). However, many unobserved variables change with depth (e.g., food availability, light, pressure, competition), so depth can be considered a proxy variable for these. Moreover, excluding depth as a predictor for groundfish could result in overestimating the sensitivity of species to temperature and oxygen changes when their current distributions are determined by depth-correlated non-climatic variables. Including the depths from the coast-wide trawl surveys allows for the possibility that groundfish species will be displaced within their depth ranges, constrained by changes in temperature and oxygen. Using cross-validation, we were able to show that the model loses predictive power when depth is excluded (Figure 1).

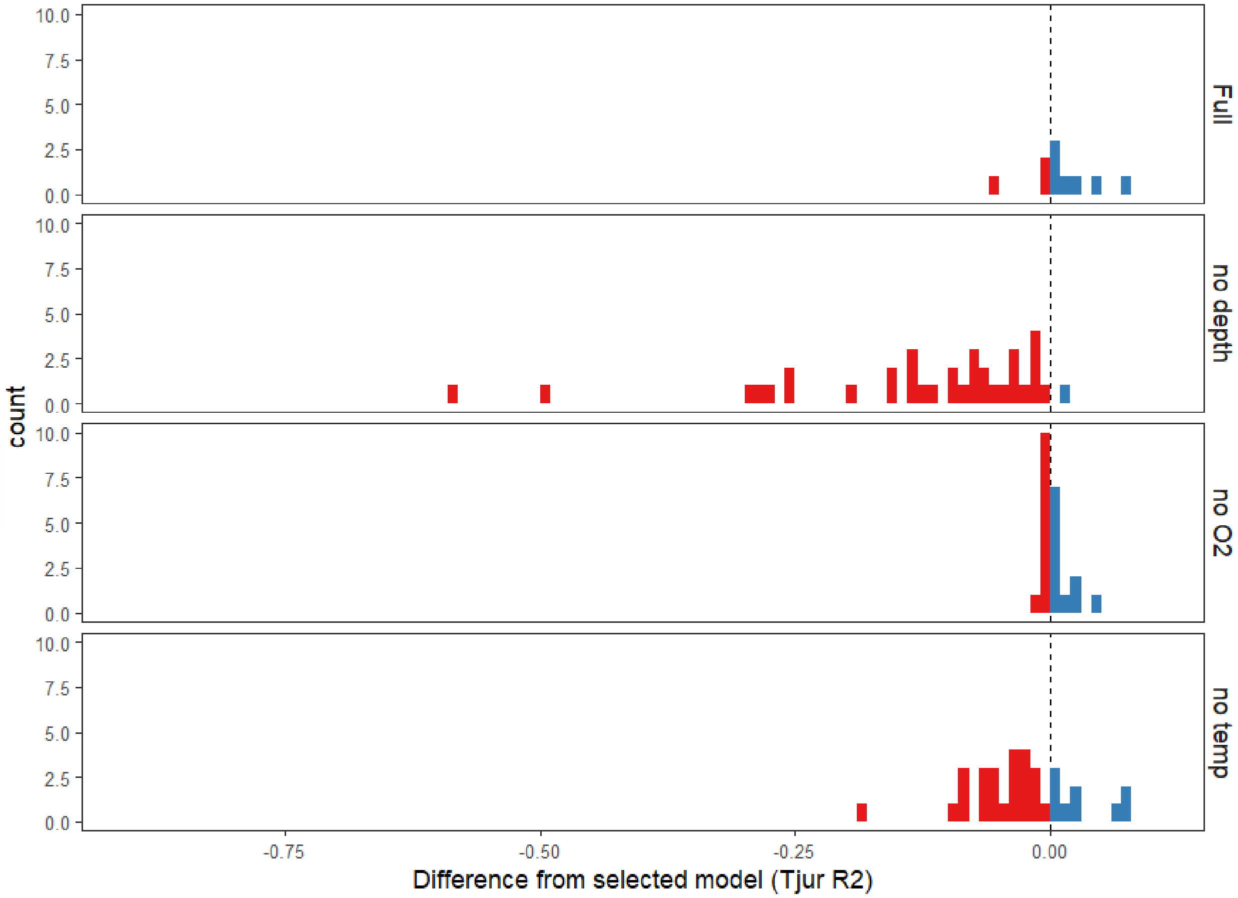

Figure 1: The difference in forecasting accuracy (Tjur R2) between our selected model and the non-selected models. Each model type is shown as a row, with the name shown on the right-hand margin. The selected model was either the full model (depth, temperature, and oxygen as predictors) or the model without oxygen if a reasonable breakpoint and slope for oxygen could not be estimated. Each count is for a single species out of the 32 species that met the criteria of having a forecasting Tjur R2 greater than 0.2. This figure demonstrates that SDM forecasting accuracy generally decreases considerably when depth is not included as a predictor. This figure was adapted from Figure S8 in Thompson et al. 2023b.

5.4 Methodology for future projections

Response curves for the selected species (section 5.1) are determined from correlation of occurrence or abundance with the selected environmental variables (section 5.3). These empirically derived species response curves can then be applied to climate projections to determine habitat change. In general, the details of the methodology will be informed by an understanding of the biology of the species, as well as the available observational data, and scale and extent of the available climate projections.

The methodology for the groundfish, halibut, and life-stages work is briefly described below. The reader is encouraged to refer to the published papers for a more complete description.

There are two regional model projections available for the Canadian Northeastern Pacific at about 3 km resolution: BCCM (Peña et al. 2023) and NEP36-CanOE (Holdsworth et al. 2021) (Appendix 4). Both downscale the Canadian Earth System Model version 2 and use the same emission scenarios. We used the BCCM hindcast (1986-2005) as a baseline and applied the delta values (future minus historical) from the two regional ocean models to generate the future fields. This method is a version of an approach known as the pseudo-global-warming method (Kimura and Kitoh, 2007).

We compared the model bathymetries and biases in the historical period to ensure compatibility with the available data. There were some differences in the location of the continental shelf between the bottom depths in the models and those measured from the trawl surveys. In NEP36, there was a positive bias for dissolved oxygen in the historical period with large delta values (Figure 2). When added to the BCCM historical baseline, the NEP36 delta resulted in negative oxygen concentrations in the future fields. To align the historical baselines, we calculated proportional deltas adjusted to the BCCM baseline (H_{BCCM}/H_{NEP} $(F_{NEP}-H_{NEP})$) and then added these deltas to the baseline hindcast (BCCM).

Before proceeding with the future projections, we investigated how the conditions experienced by the species in the present climate compared with the projected future conditions for the study region. The trawl data used for the groundfish study extended from California to Alaska, but the study region was limited to B.C. and Washington waters. As noted in section 4.2, we found that projected future conditions for temperature and oxygen were within the range of the training conditions.

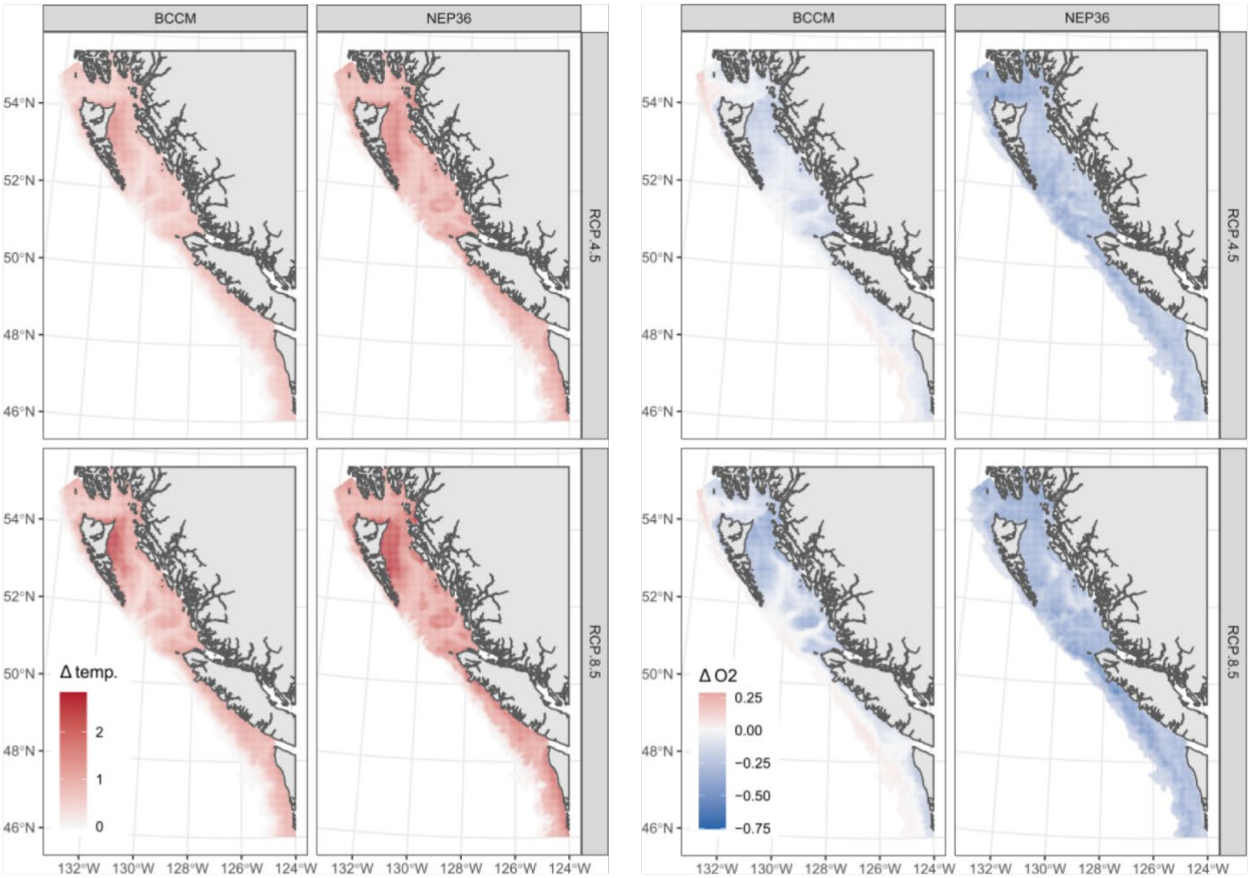

Figure 2: The change in temperature (left) and oxygen (right) between the future (2046-2065) and historical period (1986-2005) for BCCM (left columns) and NEP36 (right columns) under RCP 4.5 (top rows) and RCP 8.5 (bottom rows). This figure was adapted from Figures S4 and S5 of Thompson et al. 2023b.

We created climatological averages for both future and historical periods of at least 20 years in length from the regional model outputs to average out natural variability and focus on the impacts of climate change. The SDM was applied to the historical and future climatologies and the difference between the two gives the projected change in species occurrence under climate change.

Different methods can be useful to determine how well the model is performing. Latitudinal cross-validation involves training the model on some latitudes and testing on the withheld latitudes. Temporal forecasting involves withholding time periods from the training data and testing on the withheld data. More details of the application of these tests can be found in the associated manuscripts (Thompson et al. 2023a; 2023b).

5.5 Modelling groundfish life-stages

Knowing how the different life-stages will be impacted by future stressors is important because these species may have different habitat preferences depending on the life-stage. If environmental niches depend on length or maturity stages, then the response to future temperature and oxygen concentration will be life-stage-dependent. Species distribution models can be used to investigate how species at different life-stages will be affected by anthropogenic climate change.

Data acquisition was identified as a key challenge with respect to groundfish life-stage analysis. The collection of life-stage data is very time consuming and resource intensive, which means that these data are limited relative to occurrence or abundance data. There was a large amount of variability in the data for length at maturity for some species. Further, juveniles often use nearshore habitats which are not captured sufficiently by the survey data and there is a lack of fine-scale regional ocean models available for species projections in the nearshore. For many of the species sampled in the trawl surveys, larval and 1 and 2 year old fish are not sampled.

Another challenge is the methodology for modelling the different stages using species distribution modelling. Modelling the different life-stages separately may be difficult if there are spatial or temporal patterns in maturity at length, or gear selectivity factors that vary across the different surveys. For example, there can be temporal changes in maturity at length related to selection of larger individuals by fishing gear, or changes in maturity at length due to faster or slower growth caused by environmental conditions.

Sablefish was selected as an initial candidate species to explore because of their commercial importance, broad range in the Northeast Pacific, information on length-at-maturity, evidence of plasticity in growth and maturity across the range that may be related to oceanographic features (Kapur et al. 2020) and their distinct spatial separation in life history stages. Sablefish are also well studied and well sampled by trap and trawl surveys in BC waters, so there is extensive data and life history information for the species. Preliminary results show that the optimal conditions for sablefish depend on the life-stage (Table 2) with juveniles (ages < 3-5) preferring warmer, shallower areas with more oxygen.

Table 2: Optima for sablefish life-stages.

Species	O_2 (ml/l)	T (°C)	depth (m)
Juvenile	1.34	7.53	216
Adult	1.14	6.76	294

These preliminary results indicate that modelling different life-stages could be important for understanding and interpreting the impacts of climate change for some species, and that analysis on additional species is warranted.

Criteria were developed to assess the groundfish trawl data for species suitable for life-stage analysis. This included: whether length at maturity information was available for the species; whether length information was compatible among the NOAA West Coast, DFO Pacific, and NOAA Alaska bottom trawl surveys; whether there was sufficient length data across the three datasets for juveniles and adults; and whether there was a clear maturity threshold cut-off for the species between juvenile and adult life stages. There are approximately a dozen species that meet the criteria for inclusion in the life-stage analysis.

Future analysis includes comparing results using a threshold cut-off for juvenile and adult life stages and a continuous distribution of length for each species. The results will allow us to determine whether spatial distribution and niche differentiation is maturity- or size-based for each species.

5.6 Global climate models and the need for downscaling research

Climate models are necessarily global. Future climates can be simulated by regional ocean-only or atmosphere-only models only by downscaling the projections of Global Climate Models. Earth System Models (ESMs) are run for hundreds, or thousands of years, so computational constraints dictate that the grid spacing is relatively coarse compared to the species data used for the SDM models. A consequence of the coarse resolution is that many processes which drive the regional dynamics of the system are unresolved. For example, coarse grids can smooth out topographic features which are essential to directing the flow of the winds, and the winds, in turn, affect ocean circulation and biogeochemistry. To obtain climate fields at an appropriate resolution, ESM outputs must first be downscaled.

Methods employed to downscale climate model data and can be roughly grouped into two categories: statistical downscaling and dynamical downscaling. Dynamical downscaling involves running a mechanistic 3D model in the region of interest and is very computationally expensive. Statistical downscaling is much less expensive computationally but requires training data at the target resolution and with an overlapping historical period. To date, statistical downscaling has been applied primarily in terrestrial environments, and oceanographers have mostly focused their effort on dynamical downscaling. But recent work has shown that statistical methods can be used in combination with dynamical models to quantify model uncertainty (Hermann et al. 2019, Kristiansen et al, 2024).

Because of their computational cost, regional models cannot span a large geographical area. Yet, the best practice when fitting the SDM model is to use data from the species' entire range. To take advantage of using these modelled variables as predictors, it may be possible to "stitch together" multiple regional models. However, few regional model projections that include ocean biogeochemical cycles exist at sufficient resolution.

More downscaling research is needed to progress the development of climate impacts assessments using species distribution models. For example, *Nereocystis sp.* (bull kelp) prefers temperatures of 5-17°C (Vadas 1972), and are limited by light attenuation to depths less than about 30 m. There is available occurrence data for this and other coastal species, but existing regional ocean models lack the spatial resolution needed to accurately represent these nearshore environments. The lack of actionable climate data at the appropriate resolution limits the quality of any projected distribution one could currently construct for coastal taxa such as kelps, eelgrass, Dungeness crab and some juvenile fish (see section 5.1).

5.7 Quantifying uncertainty

Projecting future distributions of species under climate warming scenarios involves three sources of uncertainty: (1) climate model uncertainty, (2) SDM uncertainty, and (3) biological uncertainty (e.g., species' interactions, dispersal limitation, local adaptation). Climate model uncertainty can be further decomposed into three distinct sources of uncertainty: (1) internal variability, (2) model uncertainty, and (3) scenario uncertainty (Hawkins and Sutton, 2009). These uncertainties propagate into the SDM projections. Moreover, if regional downscaling of global climate model projections is conducted, there are additional uncertainties that arise from the downscaling method. More details of the quantification of uncertainty can be found in the Workshop summary (Appendix 2) and Davies et al. (2023).

Regional models typically only downscale from a single global model projection due to limited computational resources, which makes it difficult and sometimes impossible to quantify the global model uncertainty (Drenkard et al. 2021). Scenario uncertainty can be quantified by running the same model with multiple scenarios; often the most extreme scenarios are selected. Quantifying the regional model uncertainty involves running multiple models with the same scenario. Fortunately, in our case two regional models were available for the region of interest, allowing for the quantification of regional model uncertainty. We evaluated scenario uncertainty and it was found to be small on the timescale examined (through ~2060) (Holdsworth et al. 2021).

The advancement of statistical downscaling methodology for our region has the potential to reduce the computational resources needed and allow for greater quantification of the climate related uncertainties. These technologies exist, but more research is needed to identify which methods can and should be used for a given application within DFO Pacific Science.

6. RESEARCH PRIORITIES AND FUTURE WORK

6.1 How can we improve regional climate impacts research?

Environmental monitoring data

- when possible environmental data should be collected concurrently with species sampling
- measuring instruments involved in data collection should be regularly calibrated and maintained according to industry standards or manufacturer recommendations to improve the reliability of the data collected.
- observations should be collected across a wide range of environmental conditions to reduce uncertainty in future projections
- sampling protocols across regions and surveys should be standardized
- data should be made available from a centralized and standardized database

Regional model projections matching the data spatial scale

There is a need for regional ocean downscaling of climate projections at a resolution fine enough to resolve nearshore areas where many species live. Collaborative research is needed to:

- identify regions where we have sufficient species data
- identify the resolution needed given the spatial extent of the data
- develop and run a dynamical model and/or evaluate the feasibility of statistical downscaling as an alternative

Once a high resolution model is available for the region of interest, it’s worth exploring the potential application of statistical downscaling methods to help quantify model uncertainties (Hermann et al. 2019). We recommend further study and development of tools for these purposes.

6.2 Species of interest for future collaboration

- cold water corals and sponges
- sand lance
- eelgrass
- kelp
- pelagic species
- salmon

6. REFERENCES

Bednaršek, N., Newton, J. A., Beck, M. W., Alin, S. R., Feely, R. A., Christman, N. R., et al. (2020b). Severe biological effects under present-day estuarine acidification in the seasonally variable Salish Sea. *Sci. Total Environ.* 765:142689. doi: 10.1016/j.scitotenv.2020.142689

Bianucci, L., Fennel, K., Chabot, D., Shackell, N., & Lavoie, D. (2016). Ocean biogeochemical models as management tools: a case study for Atlantic wolffish and declining oxygen. *ICES Journal of Marine Science*, *73*(2), 263-274.

Cheung, W.W.L., Lam, V.W.Y., Sarmiento, J.L., Kearney, K., Watson, R. & Pauly, D. (2009). Projecting global marine biodiversity impacts under climate change scenarios. Fish and Fisheries, 10, 235–251.

Davies, S., Thompson, P.L., Gomez, C., Nephin, J., Knudby, A., Park, A., Friesen, S., Pollock, L., Rubidge, E., Anderson, S., Iacarella, J., Lyons, D., MacDonald, A., McMillan, A., Ward, E., Holdsworth, A.M., Swart, N. and Hunter, K.L., 2023. Addressing uncertainty when projecting marine species' distributions under climate change. *Ecography*, 2023(11), e06731.

DFO (2022). Guidelines for Implementing the Fish Stocks Provisions in the Fisheries Act. Fisheries and Oceans Canada. https://www.dfo-mpo.gc.ca/reports-rapports/regs/sffcpd/guidelines-lignes-directrices-eng.htm

Drenkard, E.J., Stock, C., Ross, A.C., Dixon, K.W., Adcroft, A., Alexander, M., Balaji, V., Bograd, S.J., Butenschön, M., Cheng, W. and Curchitser, E., 2021. Next-generation regional ocean projections for living marine resource management in a changing climate. *ICES Journal of Marine Science*, *78*(6), pp.1969-198.

Friesen, S.K., Ban, N.C., Holdsworth, A.M., Peña, M.A., Christian, J. and Hunter, K.L. 2021. Physical Impacts of Projected Climate Change Within Marine Protected Areas in the Pacific Bioregions. Can. Tech. Rep. Fish. Aquat. Sci. 3422: iv + 60 p.

Gruber, N. (2011). Warming up, turning sour, losing breath: ocean biogeochemistry under global change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 369.1943 : 1980-1996.

Gruber, N., Hauri, C. Lachkar, Z., Loher, D., Frölicher, T.L. , Plattner, G.K.(2012). Rapid progression of ocean acidification in the California Current System. *Science*, 337 (6091) , 220-223

García Molinos, J., Halpern, B. S., Schoeman, D. S., Brown, C. J., Kiessling, W., Moore, P. J.., ... & Burrows, M. T. (2016). Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change*, *6*(1), 83-88.

Hare, J. A., Manderson, J. P., Nye, J. A., Alexander, M. A., Auster, P. J., Borggaard, D. L., ... & Biegel, S. T. (2012). Cusk (*Brosme brosme*) and climate change: assessing the threat to a candidate marine fish species under the US Endangered Species Act. ICES Journal of Marine Science, 69(10), 1753-1768.

Hawkins, E., & Sutton, R. (2009). The potential to narrow uncertainty in regional climate predictions. Bulletin of the American Meteorological Society, 90(8), 1095-1108.

Hermann, A.J., Gibson, G.A., Cheng, W., Ortiz, I., Aydin, K., Wang, M., Hollowed, A.B., and Holsman, K.K., 2019. Projected biophysical conditions of the Bering Sea to 2100 under multiple emission scenarios. ICES Journal of Marine Science, 76(5), pp.1280–1304. Available at: doi: 10.1093/icesjms/fsz043.

Holdsworth, A. M., Zhai, L., Lu, Y. and Christian, J. R. (2021). Future Changes in Oceanography and Biogeochemistry Along the Canadian Pacific Continental Margin. *Front. Mar. Sci.* 8:602991. doi: 10.3389/fmars.2021.602991

Kapur, M., Haltuch, M., Connors, B., Rogers, L., Berger, A., Koontz, E., Cope, J., Echave, K., Fenske, K., Hanselmanf, D. and Punt, A.E. (2020). Oceanographic features delineate growth zonation in Northeast Pacific sablefish. Fisheries Research, 222. https://doi.org/10.1016/j.fishres.2019.105414

Kimura, F., & Kitoh, A. (2007). Downscaling by pseudo global warming method. The Final Report of ICCAP, 4346, 435.

Kristiansen, T., Butenschön, M. and Peck, M.A., 2024. Statistically downscaled CMIP6 ocean variables for European waters. Scientific Reports, 14(1), p.1209.

Muhling, B.A., Brodie, S., Smith, J.A., Tommasi, D., Gaitan, C.F., Hazen, E.L., Jacox, M.G., Auth, T.D. and Brodeur, R.D., 2020. Predictability of species distributions deteriorates under novel environmental conditions in the California Current System. *Frontiers in Marine Science*, *7*, p.589.

Mahon, R. & Smith, R. W. (1989). Demersal fish assemblages on the Scotian Shelf, Northwest Atlantic: spatial distribution and persistence. *Canadian Journal of Fisheries and Aquatic Sciences*, 46, 134–152.

Morley, J.W., Selden, R.L., Latour, R.J., Frölicher, T.L., Seagraves, R.J. & Pinsky, M.L. (2018). Projecting shifts in thermal habitat for 686 species on the North American continental shelf. *PLoS One*, 13, e0196127. 10.1371/journal. pone.0196127

National Research Council, Division on Earth, Life Studies, Board on Life Sciences, & Committee on Key Challenge Areas for Convergence. (2014). Convergence: Facilitating transdisciplinary integration of life sciences, physical sciences, engineering, and beyond.

Nephin, J., Gregr, E.J., St. Germain, C., Fields, C., and Finney, J.L. (2020). Development of a Species Distribution Modelling Framework and its Application to Twelve Species on Canada's Pacific Coast. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/004. xii + 107 p

Oschlies, A., Brandt, P., Stramma, L., & Schmidtko, S. (2018). Drivers and mechanisms of ocean deoxygenation. *Nature Geoscience*, 11, 467–473. https://doi.org/10.1038/s41561-018-0152-2

Ovaskainen, O., Tikhonov, G., Norberg, A., Guillaume Blanchet, F., Duan, L., Dunson, D., ... & Abrego, N. (2017). How to make more out of community data? A conceptual framework and its implementation as models and software. *Ecology Letters*, 20(5), 561-576.

Peña, M.A. and Fine, I., 2024. Future physical and biogeochemical ocean conditions under climate change along the British Columbia continental margin. *Atmosphere-Ocean*, *62*(1), pp.2-23.

PMO. 2021. Minister of fisheries, oceans and the Canadian Coast Guard mandate letter. Available from https://www.pm.gc.ca/en/mandate-letters/2021/12/16/minister-fisheries-oceans-and-canadian-coast-guard-mandate-letter.

Pörtner, H. O., Bock, C., and Mark, F. C. (2017). Oxygen-and capacity-limited thermal tolerance: bridging ecology and physiology. *Journal of Experimental Biology* 220 (15), 2685-2696.

Pozo Buil, M., Jacox, M.G., Fiechter, J., Alexander, M. A., Bograd, S. J., Curchitser, E. N., Edwards, C. A., Rykaczewski, R. R. and Stock, C. A. (2021). A Dynamically Downscaled Ensemble of Future Projections for the California Current System. *Front. Mar. Sci.* 8:612874. doi: 10.3389/fmars.2021.612874

Ready, J., Kaschner, K., South, A.B., Eastwood, P.D., Rees, T., Rius, J., Agbayani, E., Kullander, S. & Froese, R. (2010). Predicting the distributions of marine organisms at the global scale*. Ecological Modelling,* 221, 467–4

Stroomer, C., & Wilson, M. (2012). *British Columbia's fisheries and aquaculture sector, 2012 Edition*. BC Stats.

Thompson PL, Anderson SC, Nephin J, Haggarty DR and others (2022) Disentangling the impacts of environmental change and commercial fishing on demersal fish biodiversity in a northeast Pacific ecosystem. Mar Ecol Prog Ser 689:137-154. https://doi.org/10.3354/meps14034

Thompson, P.L., Rooper, C.N., Nephin, J., Park, A.E., Christian, J.R., Davies, S.C., Hunter, K.L., Lyons, D.A., Peña, M.A., Proudfoot, B., Rubidge, E. and Holdsworth, A.M., 2023. Response of Pacific halibut (*Hippoglossus stenolepis*) to future climate scenarios in the Northeast Pacific Ocean. *Fisheries Research*, 258. https://doi.org/10.1016/j.fishres.2022.106540.

Thompson, P.L., Nephin, J., Davies, S.C., Park, A.E., Lyons, D.A., Rooper, C.N., Peña, M.A., Christian, J.R., Hunter, K.L., Rubidge, E. and Holdsworth, A.M., 2023. Groundfish biodiversity change in northeastern Pacific waters under projected warming and deoxygenation. *Phil. Trans. R. Soc. B*, 378, 20220191. https://doi.org/10.1098/rstb.2022.0191

Vadas, R. L. (1972). Ecological implications of culture studies on *Nereocystis luetkeana* 1. *Journal of Phycology*, 8(2), 196-203.

Wilson, N., (2019). On the Road to Convergence Research. *BioScience*, 69(8), 587-593. doi:10.1093/biosci/biz066

7. APPENDICES

The appendices provides supplementary information to the main document. Section 7.1 lists the members of the Working group and their contact information, section 7.2 provides a summary of the Workshop, section 7.3 provides a history of the WG, and section 7.4 provides a list of acronyms.

7.1 Future Habitat Working Group Members

Bianucci, Laura <Laura.Bianucci@dfo-mpo.gc.ca>

*Christian, James <James.Christian@dfo-mpo.gc.ca>

*Davies, Sarah <Sarah.Davies@dfo-mpo.gc.ca>

Dosser, Hayley <hayley.dosser@ec.gc.ca>

Dudas, Sarah <Sarah.Dudas@dfo-mpo.gc.ca>

Evans, Rhian <Rhian.Evans@dfo-mpo.gc.ca>

Finney, Jessica <Jessica.Finney@dfo-mpo.gc.ca>

Jeffery, Sharon <Sharon.Jeffery@dfo-mpo.gc.ca.

*Holdsworth, Amber <Amber.Holdsworth@dfo-mpo.gc.ca>

*Hunter, Karen <Karen.Hunter@dfo-mpo.gc.ca>

*Lyons, Devin < devin.lyons@science.ubc.ca>

*Mcmillan, Andrew <Andrew.Mcmillan@dfo-mpo.gc.ca>

*Nephin, Jessica <Jessica.Nephin@dfo-mpo.gc.ca>

*Park, Ashley <Ashley.Park@dfo-mpo.gc.ca>

*Peña, Angelica <Angelica.pena@dfo-mpo.gc.ca>

*Proudfoot, Beatrice <Beatrice.Proudfoot@dfo-mpo.gc.ca>

Robinson, Cliff <Cliff.Robinson@dfo-mpo.gc.ca>

*Rooper, Chris <Chris.Rooper@dfo-mpo.gc.ca>

*Rubidge, Emily <Emily.Rubidge@dfo-mpo.gc.ca>

Steiner, Nadja <Nadja.Steiner@dfo-mpo.gc.ca>

*Thompson, Patrick <Patrick.Thompson@dfo-mpo.gc.ca>

* members of the Technical Working Group

7.2 Workshop Summary: Species Distribution Modelling in a Changing Climate

7.2.1 Workshop Details

Delivered on-line via MS TEAMS on March 11 and 12, 2021

Co-Chairs and Organizers: Karen Hunter, Climate Response Research Program and Dr. Patrick Thompson, Seascape Ecology Program, Ecosystem Science Division

Invited Speakers:
Dr. Anders Knudby, Associate Professor, Department of Geography, Environment and Geomatics, University of Ottawa
Dr. Laura Pollock, Assistant Professor, Department of Biology, McGill University
Dr. Jeff Price, Associate Professor, Biodiversity and Climate Change, Tyndall Centre, University of East Anglia

Break-out Co-facilitators: Sarah Davies, Jessica Nephin; Break-out Monitors: Sarah Friesen, Andrew McMillan. Future Habitat Technical Working Group (OSD/ESD) contributed to the planning of the workshop.

Participants: Fifty-one participants from three countries and all DFO regions were invited or sought invitation. We surveyed participants prior to the workshop. Replies (n=32) showed high DFO-PAC participation, but overall good representation from other regions and the USA (NOAA). Participants tended to underestimate their level of expertise (Figure A1).

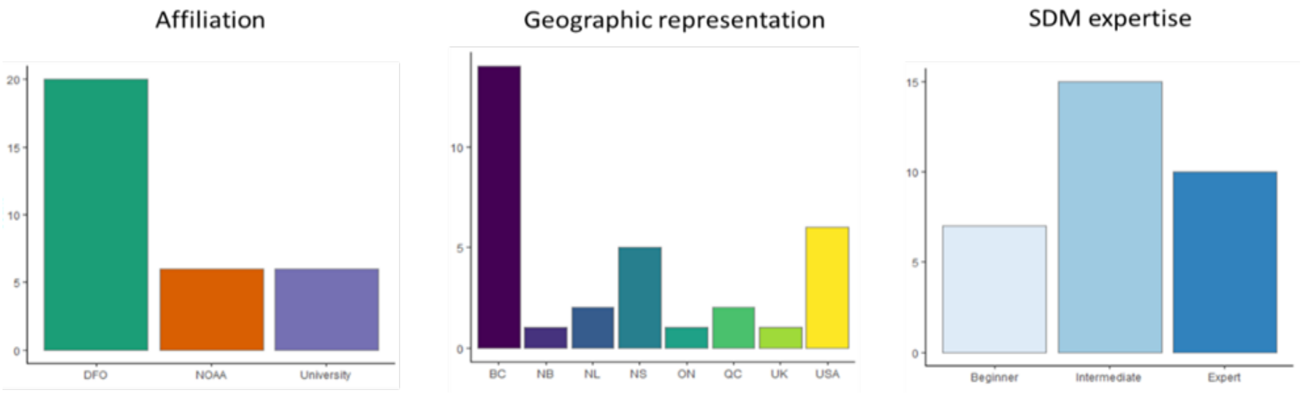

Figure A1. Affiliation, geographic representation and SDM expertise of workshop participants.

7.2.2 Context

DFO Science has considerable expertise in using species distribution models (SDMs) to predict current species distributions. The main goal of the workshop was to discuss challenges, solutions, and best practices for applying SDMs under future climates. The workshop was delivered via three themes: 1) Challenges with using SDMs for future climates, 2) Sources of uncertainty and error, and 3) Addressing uncertainty and error.

Co-chairs used Easy-Retro, a participatory, online platform with a voting function to engage participants in discussion and prioritization of findings in two separate break-out groups for each theme. Co-chairs and co-facilitators combined the prioritized results and discussed these in plenary. A thorough list of considerations for each theme was identified. A workshop report/paper will be published to make the workshop findings broadly available.

1st session – Challenges for using SDMs for Future Climates

Eight significant challenges were identified. Solutions for many of the challenges were discussed and recommended e.g., collinearity of predictors (e.g., depth and temperature) may shift when the climate changes.

Solution 1. Integrate knowledge from physiological experiments to inform species responses.

Solution 2. SDMs need to be trained on species' entire temporal and spatial distribution.

Solution 3. Estimate species resilience using historical response to climate variability and extreme events.

2nd session – Sources of Uncertainty and Error

Significant sources of uncertainty and error were identified for climate model, SDM and eco-evolutionary aspects. Break-out #3 identified challenges; e.g. Climate model spatial scale may be too broad to match biological responses; overfitted models may predict current distributions but give poor future projections; species interactions prevent tracking of abiotic niche.

3rd session – Addressing Uncertainty and Error

Solutions were summarized into minimizing uncertainty, addressing remaining uncertainty, and other solutions. Clearly stated study questions, assumptions and caveats, open communication of uncertainty, and building a community of experts from a variety of fields were the highest priority aspects of discussion.

Climate model uncertainty: Assess uncertainty by using multiple climate models (model uncertainty), multiple scenarios (scenario uncertainty) and multiple ensemble members for each model (internal variability)

SDM uncertainty: Assess uncertainty at multiple points during the analysis (e.g. species response curves)

Eco-evolutionary uncertainty: Present model projections as hypotheses, and highlight “no-regrets" regions of higher model certainty (i.e. areas where species are projected to remain present, as opposed to areas that may become favourable).

7.3 History of Future Habitat Working Group and Technical Working Group Meetings and Activities

October 2019

This project was initiated by Dr. A. Holdsworth who had recently produced climate projections for the Northeastern Pacific continental shelf (Holdsworth et al. 2021). Following discussions at the PICES Annual Meeting, K. Hunter agreed to collaborate on further research that would use existing regional climate projections together with available species data to project the impacts of climate change for marine species. Such a project would require knowledge of many different disciplines: climate science, biology, statistics, oceanography, etc. A group of potential collaborators was formed to further discuss species selection and methodology with the goal of developing a science proposal. This group was named “Future Habitat.”

Jan.- June 2020:

Since regional climate projections were already available, we began by considering many candidate marine fish species to decide whether the species could be modelled at the resolution of the available regional models. We explored available data looking for habitat envelopes for these species in terms of the modelled environmental conditions. We considered species which are important commercially, species at risk and species which may be indicators of ecosystem health, but ultimately we concluded that the choice of species would be dictated by the availability of data. We found that experimental data which investigate species’ responses to ecosystem stressors was limited. Given the lack of available experimental data, a decision was made to use species distribution models to link species observations to their habitat. The initial idea was to build on the statistical methods developed under the species distribution modelling quantitative framework (Nephin et al. 2020). The relationships would then be used to understand how projected changes in habitat would affect a particular species.

July 2020 -Sept. 2020:

The idea to convene a workshop on species distribution modelling under climate change was developed and presented to the DFO Aquatic Climate Change Adaptation Services (ACCASP) program. Funding was secured to hold a workshop on using species distribution models for climate change projections in the spring of 2021.

The Future Habitat Working Group met and the decision was made to move forward with the creation of a Technical Working Group (TWG) that would consist of multi-disciplinary experts from the Pacific Region. The meetings began on Sept. 23rd and the core membership included S. Davies, Dr. A. Holdsworth, K. Hunter, Dr. D. Lyons, A. McMillan, J. Nephin, A. Park, Dr. P. Thompson, and Dr. E. Rubidge. The group would meet every two weeks with the goal of adapting the existing species distribution framework that focused on spatial prediction to one that could handle future projections.

Oct. - Jan. 2021:

Workshop planning continued throughout the winter.

Relevant papers were discussed and added to a general repository (Muhling 2020, Aruajo Thuillier 2009, Morley et al. 2018, Thorson 2016, Wilkenson et al 2020). Key ideas and topics included: 1) how does model performance vary under different validation approaches? 2) Do some SDM methods perform consistently better than others when projecting species responses to changes in climate? 3) how do we develop better ways of quantifying uncertainty?

February 2021-April 2021:

Types of model fitting methods (e.g., Nephin et al. 2020) were presented by J. Nephin, and Dr. P. Thompson presented the Hierarchical Modelling of Species Communities (HMSC) (Ovaskainen et al. 2017) model framework that he had applied in a recent project. Since many members of the technical working group were familiar with the groundfish trawl data and these data had already been successfully used with the HMSC framework (Thompson et al. 2022), the group decided to use these data and Dr. P. Thompson would take the lead on a paper examining climate impacts on groundfish (Section 3.2).

Discussions around variable selection (Section 5.2) and methodology (Section 5.4) eventually led to a simple model with fixed effects for depth, temperature, oxygen and survey region. The model would be trained on data from the entire Pacific coast (Alaska to California) and the projections would be made in British Columbia and Washington waters where the regional ocean models are available.

The workshop described in more detail above, was held in March.

Dr. J. Christian presented to the group on the uncertainty in climate projections. He showed that natural variability is very large in the North Pacific compared to anthropogenic trends.

Dr. C. Rooper joined the TWG.

May 2021-July 2021:

Dr. S. Dudas visited the group for a discussion of modelling cold water coral. There was concern about lack of quality datasets for corals since some observation methods (e.g. trawl nets) removed coral and trawl surveys tend to avoid rocky and rugose substrates occupied by corals for sake of gear preservation.

Methodologies for projecting climate impacts for nearshore species such as kelp and eelgrass were discussed. The lack of nearshore environmental data collected concurrently with species data was highlighted as a key challenge. Another challenge is the scale mismatch between existing regional climate projections and the spatial resolution needed to adequately model these ecosystems.

Discussion about how to model different life-stages began: e.g., how to define life-stages, the challenges of data acquisition and quality (Section 5.5). Sablefish and Pacific Ocean Perch were suggested as good candidate species to start with. S. Davies and A. Park meet with experts (K. Holt, L. Lacko, L. Rogers) to explore data possibilities for the life-stages project. Different surveys may classify life-stages in different ways making the data more challenging to compare. S. Davies corresponded with Dr. I. Perry. He advised that larval fish data are not robust and Bongo nets don't sample them very well. Some of the trawl data are not useful due to lack of sex/maturity identifications. The group decided to investigate whether there are enough data to model different life-stages of the selected fish species when separating juveniles and adults using fork lengths as a proxy for age, and whether the modelled response curves of juveniles and adults will be different.

S. Davies takes the lead on a paper to address uncertainty in SDM and develops an outline with the help of workshop participants.

Davies, S., Thompson, P.L., Gomez, C., Nephin, J., Knudby, A., Park, A., Friesen, S., Pollock, L., Rubidge, E., Anderson, S., Iacarella, J., Lyons, D., MacDonald, A., McMillan, A., Ward, E., Holdsworth, A.M., Swart, N. and Hunter, K.L., 2023. Addressing uncertainty when projecting marine species' distributions under climate change. *Ecography*, 2023(11), e06731. https://doi.org/10.1111/ecog.06731

A meeting of the General Working Group was held on June 15, 2021. Preliminary results developed by the TWG were presented, an initial set of figures were discussed for the multispecies groundfish paper (Thompson et al. 2023b) and the members of the general working group provided their feedback. After this meeting, the methodology was further refined.

Thompson, P.L., Nephin, J., Davies, S.C., Park, A.E., Lyons, D.A., Rooper, C.N., Peña, M.A., Christian, J.R., Hunter, K.L., Rubidge, E. and Holdsworth, A.M., 2023. Groundfish biodiversity change in northeastern Pacific waters under projected warming and deoxygenation. *Phil. Trans. R. Soc. B*, 378, 20220191. https://doi.org/10.1098/rstb.2022.0191

We identified gaps in the available oxygen data for the *multi-species groundfish model* and discussed ways to supplement these data.

B. Proudfoot joined the TWG.

July 2021-Sept. 2021:

The multi-species paper was drafted by lead author Dr. P. Thompson and it was sent around to the group for feedback.

Dr. M.A. Peña joined the TWG. A decision was made to use the BCCM hindcast that Dr. Pena developed as a baseline for future projections using both BCCM and NEP36 future projections. There are differences between the regional model bathymetries; possibilities for addressing these discrepancies were discussed. Trawl temperatures and oxygen concentrations were compared with the BCCM hindcast and broad agreement was found.

Dr. C. Rooper proposes a separate paper that details the SDM Pacific halibut projections for an upcoming journal special issue (Thompson et al. 2023a).

Thompson, P.L., Rooper, C.N., Nephin, J., Park, A.E., Christian, J.R., Davies, S.C., Hunter, K.L., Lyons, D.A., Peña, M.A., Proudfoot, B., Rubidge, E. and Holdsworth, A.M., 2023. Response of Pacific halibut (*Hippoglossus stenolepis*) to future climate scenarios in the Northeast Pacific Ocean. *Fisheries Research*, 258. https://doi.org/10.1016/j.fishres.2022.106540.

Statistical downscaling of global climate model data is discussed. More research is needed on this technology and its implementation within the context of our team's objectives.

The possibility of including global model projections to help quantify uncertainty was discussed.

October - Dec. 2021:

Discussions are held on the best way to incorporate the two different regional ocean models into the SDM projections. Evaluation of the ocean models against the available observations indicate that NEP36 values are biased high for dissolved oxygen. The BCCM model is selected as the baseline historical simulation for the SDM projections and a delta value from NEP36 (Future-historical) will be used. Negative values in the future fields were possible when using absolute deltas since oxygen concentrations are substantially higher in NEP36 relative to the BCCM hindcast used as a baseline. Hence, the group decided to use proportional deltas for oxygen (the relative difference between the baseline and future periods) for NEP36 and BCCM to ensure that future oxygen conditions, used to model habitat, would not be negative. The proportional deltas are calculated as (H_{BCCM}/H_{NEP} (F_{NEP}-H_{NEP})) where H_{BCCM} is the historical value from the BCCM model, H_{NEP} is the historical value from the NEP36 model and, F_{NEP} is the value from the NEP36 future climatology. In this way the bias in the NEP36 model is corrected to the historical baseline from BCCM.

S. Davies, A. Park, Dr. P. Thompson and B. Proudfoot meet independently to advance the life-stages proof-of-concept work for sablefish. M. Wyeth and Dr. C. Rooper join their team. They work on refining the list of species.

The group decided that the time is right to discontinue our regular meetings as members have other time commitments and the initiated work can progress without regular meetings. A summary report was drafted in advance of the next meeting of the general working group.

7.4 Acronyms and Abbreviations

ACCASP - Aquatic Climate Change Adaptation Services Program

BC - British Columbia

BCCM - British Columbia Coastal Model

CanOE - Canadian Ocean Ecosystem Model

CMIP - Coupled Model Intercomparison Project

DFO - Fisheries and Oceans Canada

MPA - Marine Protected Area

NEP36 - NorthEastern Pacific 1/36 degree model

PICES - North Pacific Marine Science Organization

SDM - species distribution modelling

TWG - Technical Working Group

NOAA – National Oceanic and Atmospheric Administration (U.S.)

RCP – Representative Concentration Pathway

ESM – Earth System Model

GCM – Global Climate Model