Physical Impacts of Projected Climate Change Within Marine Protected Areas in the Pacific Bioregions

Sarah K. Friesen, Natalie C. Ban, Amber M. Holdsworth, M. Angelica Peña, James Christian and Karen L. Hunter

Fisheries and Oceans Canada
Pacific Region
Pacific Biological Station
3190 Hammond Bay Road,
Nanaimo, B.C. V9T 6N7

2021

Canadian Technical Report of Fisheries and Aquatic Sciences 3422

Fisheries and Oceans Canada Pêches et Océans Canada

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. Il 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 3422

2021

Physical Impacts of Projected Climate Change Within Marine Protected Areas in the Pacific Bioregions

by

Sarah K. Friesen[1,2], Natalie C. Ban[2], Amber M. Holdsworth[3], M. Angelica Peña[3], James Christian[3,4] and Karen L. Hunter[1]

Science Branch
Pacific Region
Ecosystem Sciences Division
Fisheries and Oceans Canada
Pacific Biological Station
3190 Hammond Bay Road
Nanaimo, British Columbia
V9T 6N7

[1] Pacific Biological Station, Fisheries and Oceans Canada, 3190 Hammond Bay Road, Nanaimo BC, V9T 6N7
[2] School of Environmental Studies, University of Victoria, 3800 Finnerty Road, Victoria BC, V8P 5C2
[3] Institute of Ocean Sciences, Fisheries and Oceans Canada, 9860 West Saanich Road, Sidney BC, V8L 4B2
[4] Canadian Centre for Climate Modelling and Analysis, 2474 Arbutus Road, Victoria BC, V8N 1V8

Cat. Fs97-6/3422E-PDF ISBN 978-0-660-37621-9 ISSN 1488-5379

Correct citation for this publication:

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.

ABSTRACT

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.

Marine protected areas (MPAs) can help safeguard marine ecosystems, but are increasingly impacted by climate change. The objective of this technical report is to assess physical impacts within Pacific Region MPAs due to projected future seasonal environmental conditions under Representative Concentration Pathway (RCP) 8.5. We used outputs from two regional ocean models that each have two time periods: the Northeastern Pacific Canadian Ocean Ecosystem Model (NEP36-CanOE) covered 1986-2005 and 2046-2065, while the British Columbia continental margin model (BCCM) covered 1981-2010 and 2041-2070. We evaluated 1) potential temperature and 2) aragonite saturation state for the a) benthic and b) sea surface layers in each bioregion, plus 3) dissolved oxygen for the benthic layer for NEP36-CanOE only. After determining seasonal averages across each Pacific bioregion for each time period, we calculated the change in environmental parameter values between time periods. We developed a spatial analysis tool that calculated summary statistics for each environmental parameter (and change in parameter value) with each federal and provincial MPA in the Pacific bioregions. For the benthic layer, deep offshore MPAs were projected to experience the least change, but were below the hypoxia and aragonite saturation thresholds in both time periods. Shallower MPAs on the continental shelf had greater projected benthic temperature increase, and some remained above the hypoxia and aragonite saturation thresholds in the future time period. Surface conditions were highly variable between MPAs. This technical report may be used to inform MPA planning and management in the Pacific Region, as well as future work on regional climate impacts and ocean modeling efforts.

RÉSUMÉ

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.

Les aires marines protégées (AMP) peuvent contribuer à la préservation des écosystèmes marins, mais elles sont de plus en plus touchées par les changements climatiques. L’objectif de ce rapport technique était d’évaluer les impacts physiques dans les AMP de la région du Pacifique des conditions environnementales saisonnières futures projetées dans le cadre du profil représentatif d’évolution de concentration (RCP) 8,5. Nous avons utilisé les résultats de deux modèles océaniques régionaux qui ont chacun deux périodes : le modèle des écosystèmes de l’océan canadien du Pacifique Nord-Est (NEP36-CanOE) a couvert les périodes 1986-2005 et 2046-2065, tandis que le modèle de la marge continentale de la Colombie-Britannique a couvert les périodes 1981-2010 et 2041-2070. Nous avons évalué 1) la température potentielle et 2) la saturation en aragonite pour a) la surface de la mer et b) les couches benthiques dans chaque biorégion, ainsi que 3) l’oxygène dissous pour la couche benthique dans le NEP36-CanOE uniquement. Après avoir déterminé les moyennes saisonnières dans chaque biorégion du Pacifique pour chaque période, nous avons calculé la variation des valeurs des paramètres du milieu entre les périodes. Nous avons mis au point un outil d’analyse spatiale qui a calculé des statistiques sommaires pour chaque paramètre du milieu (et pour la variation de la valeur du paramètre) concernant chaque AMP fédérale et provinciale dans les biorégions du Pacifique. Pour la couche benthique, selon les projections, les AMP profondes au large subiraient le moins de changements, mais elles étaient sous les seuils d’hypoxie et de saturation en aragonite dans les deux périodes. Les AMP moins profondes du plateau continental avaient une augmentation projetée plus forte de la température, et certaines restaient au-dessus des seuils d’hypoxie et de saturation en aragonite dans la période future. Les conditions de surface étaient très variables entre les AMP. Ce rapport technique peut être utilisé pour étayer la planification et la gestion des AMP dans la région du Pacifique, ainsi que les travaux futurs sur les impacts climatiques régionaux et les efforts de modélisation des océans.

Introduction:

Globally, marine protected areas (MPAs) are important tools for conservation, but their utility as a conservation tool is potentially impacted by climate change (Bruno et al. 2018). Environmental conditions have and will continue to change at unprecedented rates, including warming temperatures, acidification, and deoxygenation (e.g., Harley et al. 2006; Okey et al. 2014). These environmental changes may have direct and indirect impacts on species, and these impacts may be additive, synergistic, or antagonistic (Harley et al. 2006; Kroeker et al. 2017). When exposed to the same changes in ocean state, species will be variably affected depending on their physiological tolerances and dispersal abilities (Magris et al. 2016) and may respond in various ways, including changes in distribution, individual fitness and survival, and phenology (Cheung et al. 2008; Poloczanska et al. 2016).

Ideally, MPAs are situated such that they continue to protect species of conservation interest, even as environmental conditions change and species distributions shift (Carr et al. 2017). While climate change will continue to progress inside and outside MPAs, MPAs may provide refuge from additional pressures like fishing (Carr et al. 2017; McLeod et al. 2009). By reducing further stressors, well-designed MPAs help maintain ecosystem functions, contributing to resistance and recovery from climate impacts (Bellwood et al. 2004; Mcleod et al. 2019; Micheli et al. 2012; Sala and Knowlton 2006). However, other studies suggest that MPAs in which local stressors are removed may decrease ecosystem resistance to climate impacts by protecting species less tolerant to disturbance, yet still enhance ecosystem recovery after acute climate disturbances (Côté and Darling 2010; Mumby et al. 2011).

Climate change impacts will not be uniform across the Pacific Region; MPAs will differ in their exposure to climate stressors and suitability for the species they aim to protect (Bruno et al. 2018). Few MPAs have been sited or managed with climate change in mind (Tittensor et al. 2019; Wilson et al. 2020) and an understanding of regional impacts of climate change is needed. Planners may want to protect locations that are changing more slowly, if those can be identified, where species or communities are more likely to persist (Groves et al. 2012; Keppel et al. 2015). Alternately, planners may prioritize siting MPAs in areas that have high chronic climate impact; a reduction in other stressors may reduce the cumulative stress to below a tolerable threshold for the community, providing more opportunity for local adaptation to the environmental conditions (Jones et al. 2016). Acclimatization or adaptation can help ameliorate the impacts of climate change, although the capacity for local adaptation may be limited if there is high population connectivity between regions experiencing different climate regimes (Jump and Penuelas 2005; Somero 2010). The adaptive capacity of populations is typically higher in areas that undergo higher natural environmental variability as they have greater phenotypic plasticity (Boyd et al. 2016; Morikawa and Palumbi 2019). Management frameworks that condition allowable human activities to account for climate impacts that cannot be managed may be helpful for addressing risk to MPA conservation objectives (Duplisea et al. 2020; Duplisea et al. 2021). Physical impacts are often experienced through changes in both the intensity and frequency of extreme environmental events (Malhi et al. 2020; Tittensor et al. 2019). Given the inherent uncertainty in projecting future regional environmental conditions, it is wise to spread risk by including more representation and replication within MPAs and MPA networks, including representation across the full gradient of climate impact (Jones et al. 2016; McLeod et al. 2009; Wilson et al. 2020). Representation and replication have been frequently incorporated into MPA design (Balbar et al. 2020), but not usually explicitly across a gradient of climate impacts (Jones et al. 2016).

The objective of this study was to assess physical impacts within Pacific Region MPAs based on projected climate conditions in the mid 21st century (2050s and 2060s). The Intergovernmental Panel on Climate Change defines ‘physical impacts’ as the impacts of climate change on geophysical systems (IPCC 2014); in this report, we evaluate projected changes in three environmental parameters due to climate change. The “no-mitigation scenario” Representative Concentration Pathway (RCP) 8.5 is used, but for the period considered, the climate of RCP8.5 differs little from the moderate mitigation scenario RCP4.5 (Holdsworth et al. 2021). We considered existing and proposed federal and provincial MPAs within three out of four Pacific bioregions (Figure 1; the Strait of Georgia was excluded because of data limitations of the ocean models). Using two regional ocean models that have been used to downscale global climate simulations, we evaluated 1) potential temperature and 2) aragonite saturation state at the a) sea surface and b) benthic layers in each bioregion, plus 3) dissolved oxygen for the benthic layer for one regional ocean model (NEP36-CanOE; see below). The benthic layer was the model vertical layer immediately above the sea floor in each ocean model grid cell. For each regional ocean model, we determined seasonal averages of each environmental parameter within two time periods, then calculated the difference. We developed a spatial analysis tool that calculated summary statistics for the environmental parameters within each MPA. This technical report may be used to inform MPA planning and management in each Pacific bioregion, as well as future regional ocean modeling efforts.

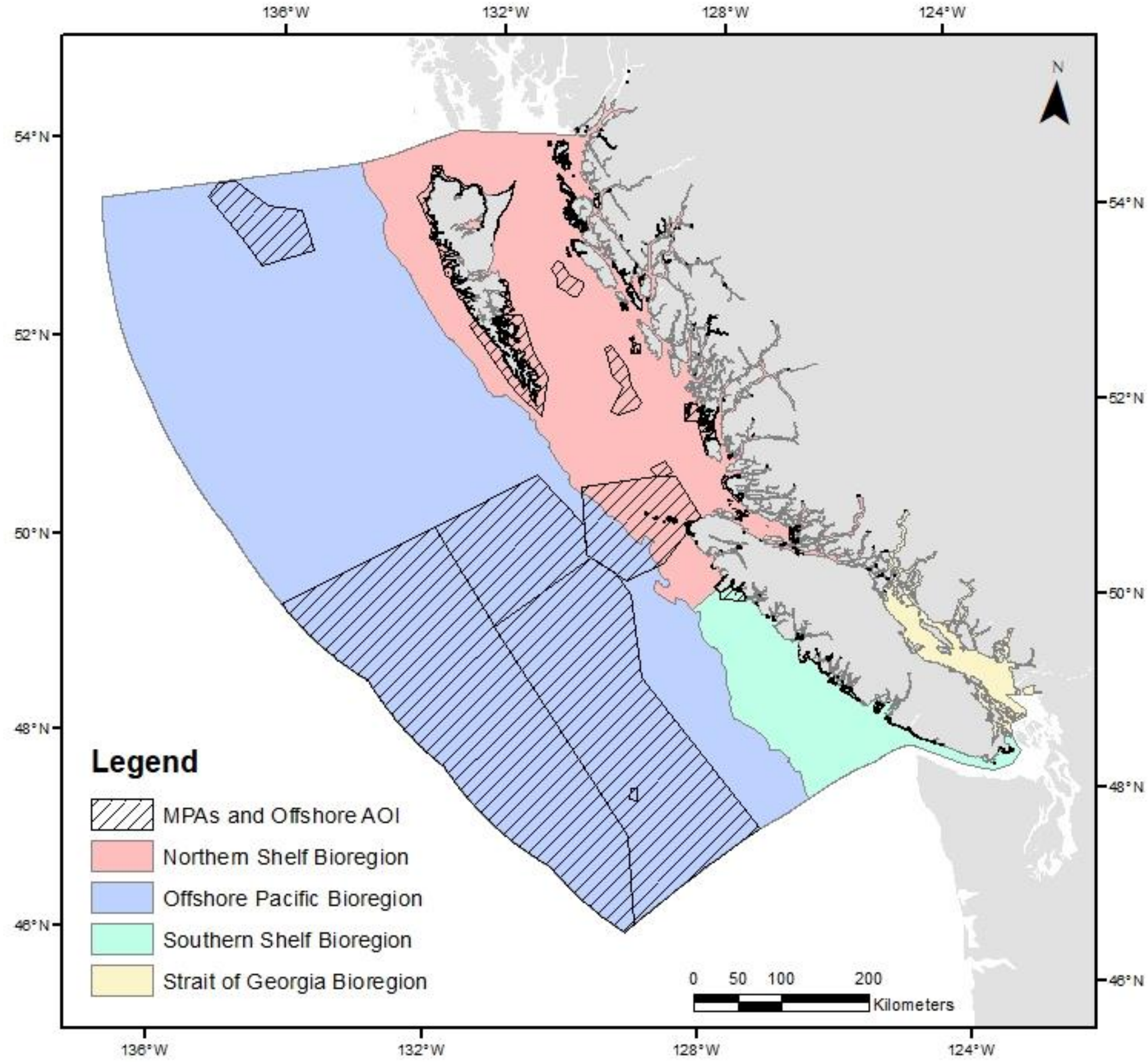


Figure 1. Federal and provincial marine protected areas in the four bioregions in the Pacific Region. The Strait of Georgia was not included in the analysis due to limitations in regional ocean model resolution; MPAs in this bioregion are not shown.

Methods:

Description of regional ocean models

Two regional ocean models have been developed for the British Columbia continental margin and we used these to analyze three Pacific bioregions (Figure 1). Each model has outputs for a historical or hindcast time period, and a projected future time period under RCP8.5. The models have been developed using different frameworks and parameterizations, so using both was helpful for understanding potential changes that may occur in the bioregions. Moreover, the ocean models differ in their spatial coverage, in the forcing imposed at the surface and lateral boundaries, and cover different time periods.

The Northeastern Pacific Canadian Ocean Ecosystem Model (NEP36-CanOE) was developed by Amber Holdsworth, James Christian, and others at Fisheries and Oceans Canada (DFO). This model is a regional configuration of Nucleus for European Modelling of the Ocean (NEMO 3.6; Madec 2008). The NEP36-CanOE model domain spans the Canadian Pacific Ocean east of 140°W and north of 45°N with a spatial resolution of 1/36° (1.5-2.25 km) and 50 vertical levels. Model simulations were downscaled from Historical and Representative Concentration Pathway (4.5, 8.5) experiments with the second generation Canadian Earth System Model (CanESM2) suite of global climate models. A more complete description of the model, forcing fields, and validation with observations can be found in Holdsworth et al. (2021). Because the model was forced with atmospheric climatologies (with augmented winds), model outputs represent climatologies of the historical 1986-2005 period and future 2046-2065 projections. In deep ocean areas (e.g., > 500 m), the NEP36-CanOE model has not been run long enough to reach equilibrium, so model outputs for these areas may not be very different from the CanESM2 outputs from which the initial conditions were obtained.

The ocean circulation-biogeochemical model for the British Columbia continental margin (BCCM) was developed by Angelica Peña and others at DFO. The model is a Regional Ocean Modeling System (ROMS; Haidvogel et al. 2008) implementation and covers the Canadian west coast, extending from the Alaska border (~51 °N) to south of the Columbia River (~47 °N), and out to about 400 km from the shore. The model grid has a horizontal resolution of 3 km and a vertical resolution of 42 non-uniform sigma levels. A detailed description of the BCCM model, forcing fields, and validation with observations is given in Peña et al. (2019). The model outputs used in this study are from a 30-year long hindcast simulation for the period 1981-2010 (Peña et al. 2019) and a future projection for the period 2041-2070. Climate projections from the Canadian regional and global climate model (CanRCM4/CanESM2) were used to create a climate change perturbation (differences between projection under RCP8.5 from 2041 to 2070 and historical simulation from 1981 to 2010) that was added to the BCCM hindcast simulation to carry out the future regional projection (Peña et al. 2018).

Analysis methods

We generated the model output extents used for our analysis by first excluding areas with high data uncertainty using ArcGIS 10.7.1 (ESRI Inc. 2019). The British Columbia coastline is extremely convoluted with many narrow channels and inlets that are not adequately resolved by the models. Therefore, we excluded these nearshore areas (Table 1). We then converted the model output extents to rasters with square 3 x 3 km grid cells using inverse distance squared weighted interpolation to calculate the new grid cell values (IDW tool). This interpolation was done from the centroid of the raster grid cell being calculated and considered any data points within one grid cell's diagonal distance (4243 m). There was no overlap between the model output extents and the Strait of Georgia Bioregion. Models were validated at the discrete locations where observations were available including, for example, lighthouse data and shipboard observations, but these observational data do not cover the entirety of the Pacific Region; see Masson & Fine (2012), Peña et al. (2019), and Holdsworth et al. (2021) for details of validation.

Table 1. Area inside each regional ocean model output extent (BCCM and NEP36-CanOE) for all Pacific Bioregions. Areas outside the model output extents were excluded because there was no available data or high data uncertainty. There was no overlap between the Strait of Georgia Bioregion and either model output extent.

Bioregion	Total area (sq km)	Area inside BCCM extent (sq km)	Proportion of area included by BCCM	Area inside NEP36 extent (sq km)	Proportion of area included by NEP36
Northern Shelf	101,327	82,343	0.81	79,003	0.78
Southern Shelf	28,158	25,118	0.89	23,811	0.85
Offshore Pacific	315,724	300,414	0.95	315,724	1
Strait of Georgia	8970	0	0	0	0

To calculate projected seasonal changes in environmental parameters for each raster grid cell, we subtracted the model output values for the hindcast or historical time period from model output values for the projected future time period. Seasons were split into winter (Dec-Jan-Feb), spring (Mar-Apr-May), summer (Jun-Jul-Aug), and fall (Sep-Oct-Nov) as in Morrison et al. (2014). We determined projected a) benthic changes and b) sea surface changes in: 1) temperature and 2) aragonite saturation state across the entire Northern Shelf Bioregion. We also evaluated projected benthic changes in 3) dissolved oxygen for the bioregion using NEP36-CanOE model outputs only.

For this analysis, we considered the existing federal and provincial MPAs in each bioregion, plus the Offshore Pacific Area of Interest (AOI) being considered for designation as an Oceans Act MPA. Specifically, we identified the marine components of existing federal MPAs (i.e., Oceans Act MPAs, National Marine Conservation Area Reserves, National Park Reserves, Marine National Wildlife Areas, and Migratory Bird Sanctuaries) and provincial MPAs (i.e., Class A Parks, Conservancies, Ecological Reserves, Protected Areas, and Wildlife Management Areas) in the Canadian Protected and Conserved Areas Database (Environment and Climate Change Canada 2020). We did not consider other effective area-based conservation measure (OECM) polygons for this analysis. The MPAs and Offshore Pacific AOI totaled 152 MPA polygons across the three bioregions including the Offshore Pacific AOI, but we subdivided three MPA polygons. First, there are three spatially distinct sites (Northern Reef, Central Reefs, and Southern Reef) within the Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA, so each site was considered a separate MPA polygon for this analysis. Second, the Scott Islands Marine National Wildlife Area overlaps both the Northern Shelf Bioregion and Offshore Pacific Bioregion; both portions of this MPA are large so they were considered as separate MPA polygons to make the summary statistics more meaningful. Third, the Offshore Pacific AOI is an expansive contiguous polygon; it was divided into three very simplified oceanographic zones (coastal upwelling zone, upwelling/downwelling transition zone, and bifurcation zone) as in Du Preez and Norgard (in review); see details of subdivision in Appendix C. We used these zones to compute summary statistics on smaller polygons within the AOI, but it should be noted that the boundaries between these oceanographic zones are highly temporally- and spatially-variable. With these subdivisions, 157 MPA polygons were identified across the three Pacific bioregions.

We developed an ArcGIS geoprocessing tool to compute summary spatial statistics for the environmental parameter values in each included MPA polygon (Appendix A). The first step in the tool's workflow was to include only those MPA polygons with at least 50% area overlap with the model output extents in the analysis (Table 2). Because of this, 23 MPA polygons were included in the BCCM analysis and 16 MPAs were included in the NEP36-CanOE analysis (Figure 2 & 3; Table 2). The environmental parameter rasters were adjusted to 300 m resolution, aligned such that 100 new grid cells of identical value were created within each original grid cell of 3000 m resolution. This change in resolution was done to more closely align the raster resolution with the size of smaller MPAs so that zonal statistics could be properly computed, but did not change the value of any grid cells (ESRI Inc. n.d.). The included MPA polygons were also converted to a raster with 300 m resolution, aligned with the environmental parameter rasters; where multiple MPAs were present within the same raster grid cell, priority was given to the MPA with the smallest total area to ensure that these MPAs were represented within the raster. The tool determined which parameter raster grid cells intersected each rasterized MPA then computed zonal statistics to calculate the mean, minimum, maximum, and range of the intersecting grid cells for each MPA. Any MPA area outside the model output extent was not considered in the calculation. These MPA summary statistics were generated for all environmental parameters in the historical or hindcast time period and projected future time period for both regional ocean models, as well as the change in parameter value between time periods. This technical report presents results for the mean environmental parameter value within MPAs only; result layers for mean, minimum, maximum, and range calculations may be accessed on the DFO Marine Spatial Ecology & Analysis Section's GIS Hub (https://www.gis-hub.ca/group/climate-change-mpas).

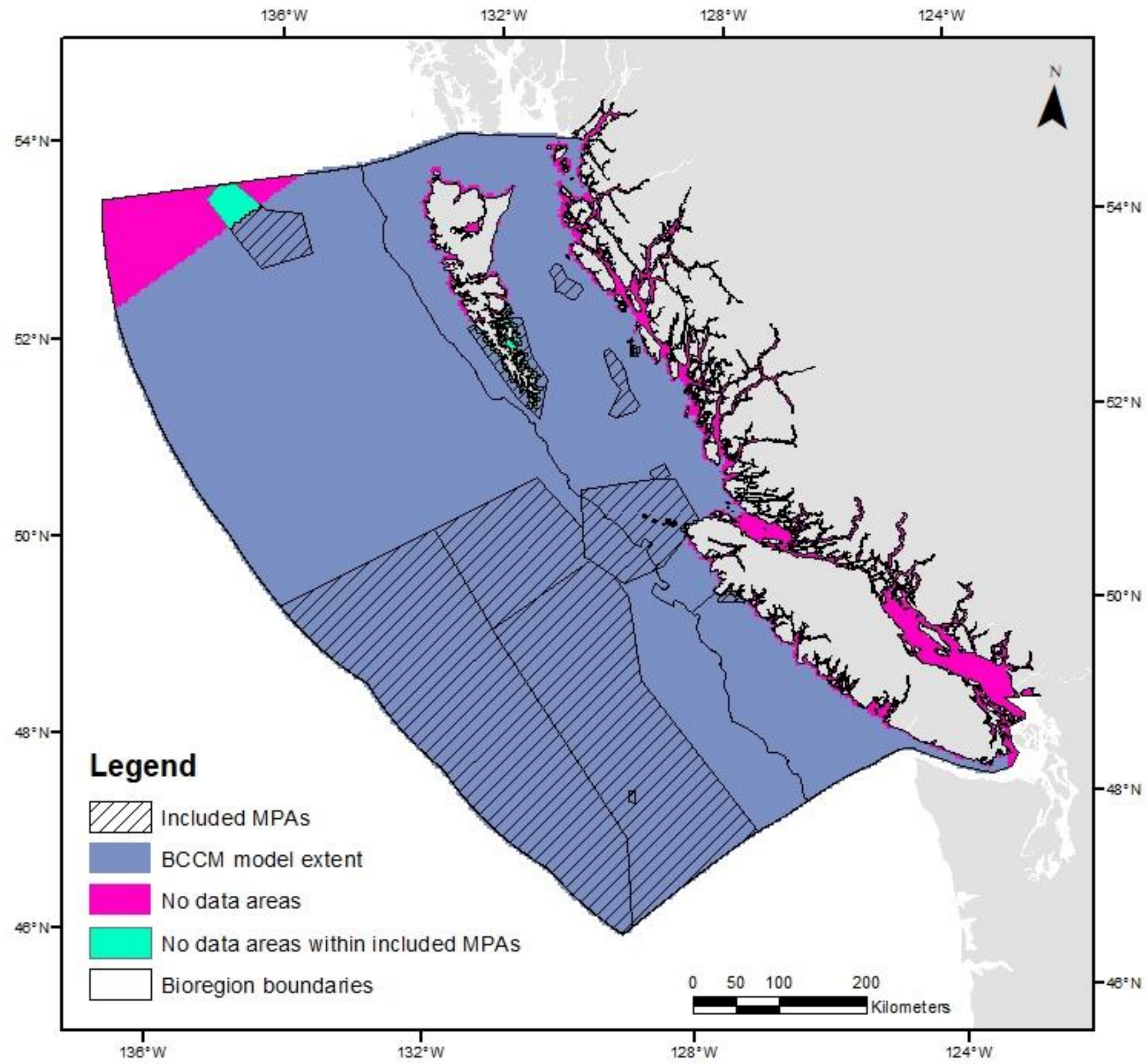


Figure 2. Spatial coverage of the BCCM regional ocean model output within the Pacific bioregions. MPAs were included in the analysis if they had at least 50% area overlap with the BCCM output extent (23 of 157 MPAs). Hatching shows included MPA area within the model output extent, while turquoise shows the area of included MPAs that was outside the model output extent (no data areas). Pink denotes other areas outside the model output extent (no data areas). There was no overlap between the model output extent and the Strait of Georgia Bioregion.

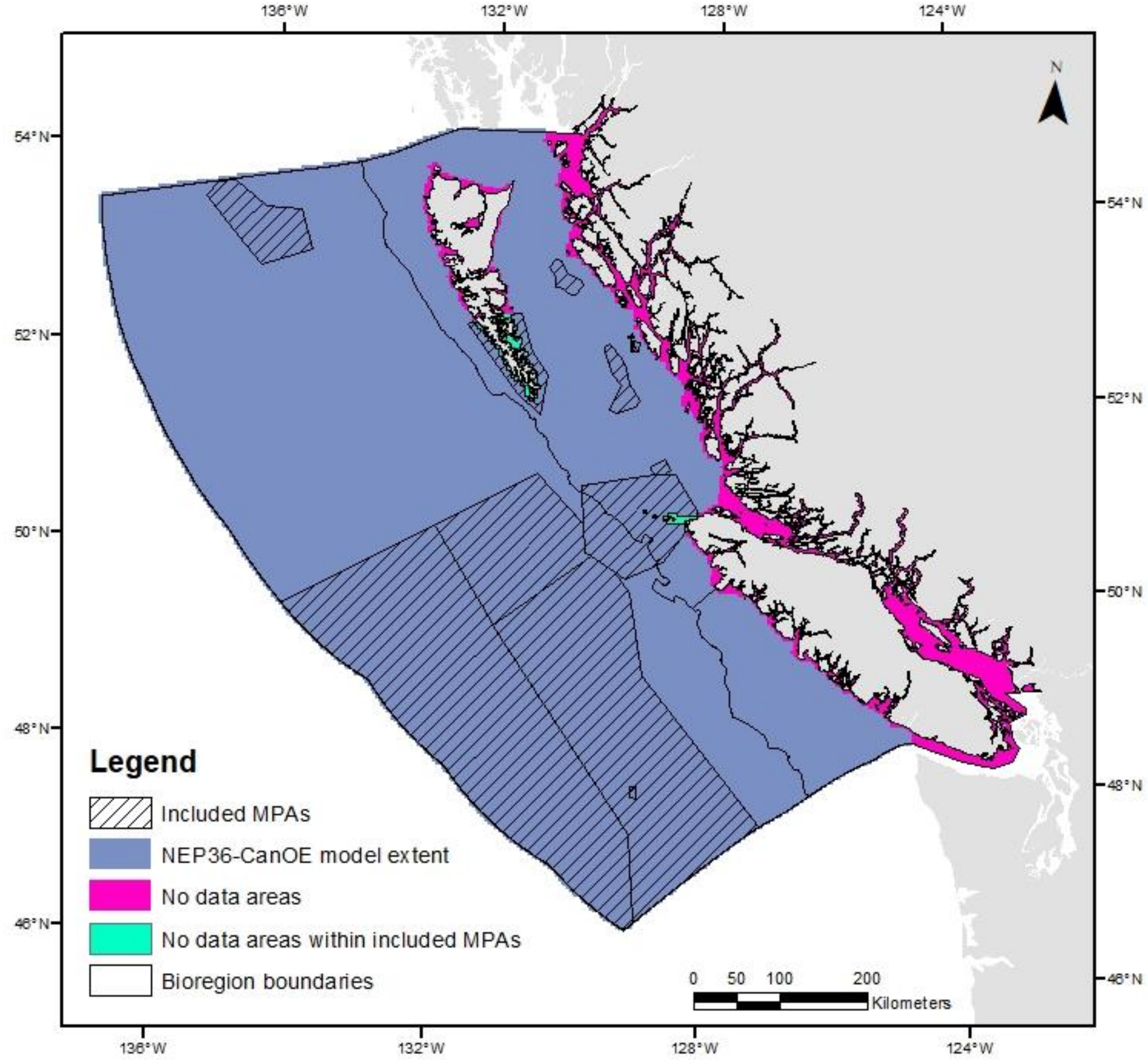


Figure 3. Spatial coverage of the NEP36-CanOE regional ocean model output within the Pacific bioregions. MPAs were included in the analysis if they had at least 50% area overlap with the NEP36-CanOE output extent (16 of 157 MPAs). There were no included MPAs in the Southern Shelf Bioregion. Hatching shows included MPA area within the model output extent, while turquoise shows the area of included MPAs that is outside the model output extent (no data areas). Pink denotes other areas outside the model output extent (no data areas). There was no overlap between the model output extent and the Strait of Georgia Bioregion.

Table 2. Number of federal and provincial MPAs in each Pacific bioregion and in each regional ocean model output extent (BCCM and NEP36-CanOE). MPAs were included if they had at least 50% area overlap with the regional ocean model output extent. There were no Southern Shelf Bioregion MPAs that overlapped the NEP36-CanOE extent. There was no overlap between either model output extent and the Strait of Georgia Bioregion (57 MPAs).

Protected area type	Type	Northern Shelf			Southern Shelf			Offshore Pacific		
		Bioregion	BCCM	NEP36	Bioregion	BCCM	NEP36	Bioregion	BCCM	NEP36
Oceans Act MPA	Federal	3*	3*	3*	0	0	0	2	2	2
National Marine Conservation Area	Federal	1	1	1	0	0	0	0	0	0
National Park	Federal	0	0	0	1	0	0	0	0	0
Marine National Wildlife Area	Federal	1**	1**	1**	0	0	0	1**	1**	1**
Migratory Bird Sanctuary	Federal	0	0	0	2	0	0	0	0	0
Protected Area	Provincial	4	0	0	0	0	0	0	0	0
Provincial Park	Provincial	38	2	0	18	0	0	0	0	0
Conservancy	Provincial	63	2	0	0	0	0	0	0	0
Ecological Reserve	Provincial	11	7	5	6	1	0	0	0	0
Wildlife Management Area	Provincial	2	0	0	1	0	0	0	0	0
Offshore Pacific Area of Interest	Proposed Federal	0	0	0	0	0	0	3***	3***	3***

* Each spatially distinct site (Northern Reef, Central Reefs, and Southern Reef) within the Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA was considered a separate MPA for this analysis.

** The Scott Islands Marine National Wildlife Area was located in both the Northern Shelf and the Offshore Pacific Bioregions. The area in each bioregion was considered a separate MPA for this analysis.

*** The Offshore Pacific Area of Interest was subdivided into three very simplified oceanographic zones (coastal upwelling zone, upwelling/downwelling transition zone, and bifurcation zone; Du Preez and Norgard (in review)) that were considered separate potential MPA polygons for this analysis.

Results:

The BCCM and NEP36-CanOE model output extents excluded 10% and 8% of the total Pacific Region area, respectively (Table 1). However, the proportion of excluded area varied greatly between bioregions, ranging from 0% to 100% area excluded for the Offshore Pacific and Strait of Georgia Bioregions respectively in the NEP36-CanOE output (5% to 100% area excluded in the BCCM output). Despite the relatively small proportion of area excluded from the model outputs, the majority of Pacific Region MPAs were excluded from the analysis as most are small and located in the nearshore (Table 2; 85% excluded from BCCM, 90% from NEP36-CanOE).

Benthic Layer Results

Benthic aragonite saturation state, dissolved oxygen, and temperature declined with depth (Figure B1-B6). In both future time periods, the deep areas within the Pacific Region were projected to have a mean aragonite saturation state (Ω_A) less than 1, where aragonite shells begin to dissolve (Langdon and Atkinson 2005). Specifically, the regional ocean models agreed that the benthic layer for the entire Offshore Pacific Bioregion was below the aragonite saturation threshold in both time periods; the exception to this was one pixel on the SGaan Kinghlas-Bowie Seamount summit with $\Omega_A > 1$ in the historical time period for the NEP36-CanOE outputs. Relatively deep areas within the Northern Shelf and Southern Shelf Bioregions were also below the aragonite saturation threshold in both time periods, with the extent of these areas increasing in the future. The spatial extent of areas with $\Omega_A < 1$ was larger for the BCCM model outputs than for NEP36-CanOE, and aragonite saturation state was lower for BCCM than NEP36-CanOE across the bioregions (Figure B1 & B2). Relatively shallow areas generally had greater decrease in aragonite saturation state between the time periods (Figure B10-B12), while deep offshore areas were more stable but were largely already unsaturated. The northwest portion of the Offshore Pacific Bioregion showed a positive change in aragonite saturation state between the time periods; areas showing increases were more extensive for the BCCM model outputs than for NEP36-CanOE.

Hypoxic benthic areas ($[O_2] < 62.5$ µmol/L) were projected to expand to more areas in the future time period in all three bioregions across the abyssal plain and continental slope (Figure B4-B6). Within these hypoxic zones, some areas showed small to moderate dissolved oxygen decline, while other areas were stable or increasing (Figure B16-B18).

The ocean models agreed that benthic temperature was projected to be relatively stable in deep continental slope and offshore areas, while shallower areas were projected to have higher temperatures and exhibit greater temperature change (Figure B1-B3). There were some areas in the Offshore Pacific Bioregion with projected warming; these were seamount locations with shallower depths than the surrounding areas (Figure B3). In general, there were greater projected benthic temperature changes in NEP36, although the time difference between the periods considered is smaller. For detailed model output results and discussion, see Peña *et al*. (2018, 2019) and Holdsworth *et al*. (2021) for the BCCM and NEP36-CanOE ocean models, respectively.

All MPAs included in the analysis were exposed to physical impacts in the benthic layer (Figures 4-7, Tables 3 & 4). Several MPAs showed $\Omega_A > 1$ in the historical or hindcast time period but $\Omega_A < 1$ in the future time period; the Sartine Island and Duke of Edinburgh Ecological Reserves exhibited this change for the BCCM outputs, while the Scott Islands Marine National Wildlife Area and Gwaii Haanas National Marine Conservation Area Reserve exhibited this for the NEP36-CanOE outputs. Overall, the Offshore Pacific Bioregion MPAs (n = 6) had the least change in benthic environmental conditions between time periods, but these conditions were hypoxic and had $\Omega_A < 1$. While benthic species in these MPAs have evolved for life in extreme but stable environments (Canessa et al. 2003; DFO 2019), the expansion of hypoxic and/or undersaturated areas may impact benthic conservation priority species within Offshore Pacific Bioregion MPAs and deep MPAs on the continental shelf. It is also important to note that declining saturation state does not have to reach the saturation threshold to exclude some species (Langdon and Atkinson 2005).

Dissolved oxygen concentrations were projected to increase in portions of the SGaan Kinghlas-Bowie Seamount MPA, three Offshore Pacific AOI zones, and Northern and Central Hecate Strait and Queen Charlotte Sound Glass Sponge Reef MPAs; however, all of these polygons showed a decrease in average dissolved oxygen across the entire MPA, and only the Hecate Strait MPA polygons were well above the hypoxia threshold (Figure 7 & B16-B18). The largest decreases in dissolved oxygen were on the continental shelf west of Vancouver Island, including portions of the Scott Islands Marine National Wildlife Area and the Checleset Bay Ecological Reserve; while these areas were not projected to become hypoxic in the future time period, the oxygen decrease could be limiting for species with higher dissolved oxygen tolerance thresholds (Table 3 & 4).

Shallower MPAs were projected to experience greater benthic temperature change (up to 2°C), which may impact the distribution and biomass of benthic species within these MPAs (Figures 4-7). MPA areas that were projected to experience a seasonal temperature change <1°C were uniformly below the aragonite saturation threshold in the future time period in both models, and also below the hypoxia threshold in NEP36-CanOE; some of these MPA areas with projected temperature change <1°C were also below the aragonite saturation and/or hypoxia threshold in the historical or hindcast time period. On the continental shelf, there were areas above and below the aragonite saturation threshold within individual MPAs (5-8 MPAs for BCCM; 3-4 MPAs for NEP36-CanOE); the minimum seasonal average temperature change projected for these MPAs was ~1°C for the BCCM model and <1.5°C for the NEP36-CanOE model (e.g., the Scott Islands Marine National Wildlife Area had seasonal average changes of 0.69-1.05°C and 0.98-1.43°C for the BCCM and NEP36-CanOE models, respectively; Tables 3 & 4).

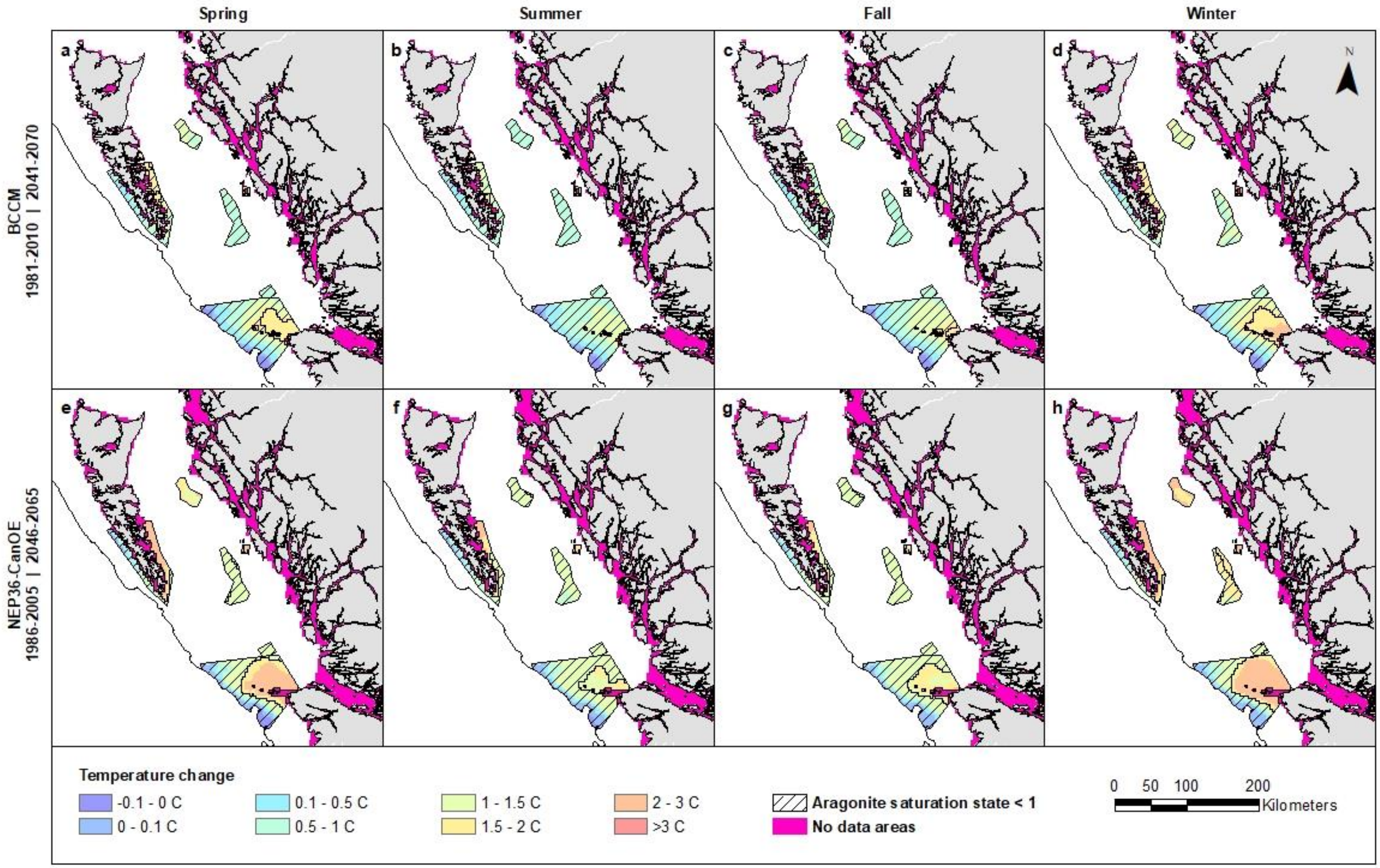


Figure 4. Seasonal mean benthic environmental parameters within MPAs in the Northern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). n = 16 for BCCM; n = 10 for NEP36-CanOE. Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Only MPA area that overlaps each of the model domains is shown.

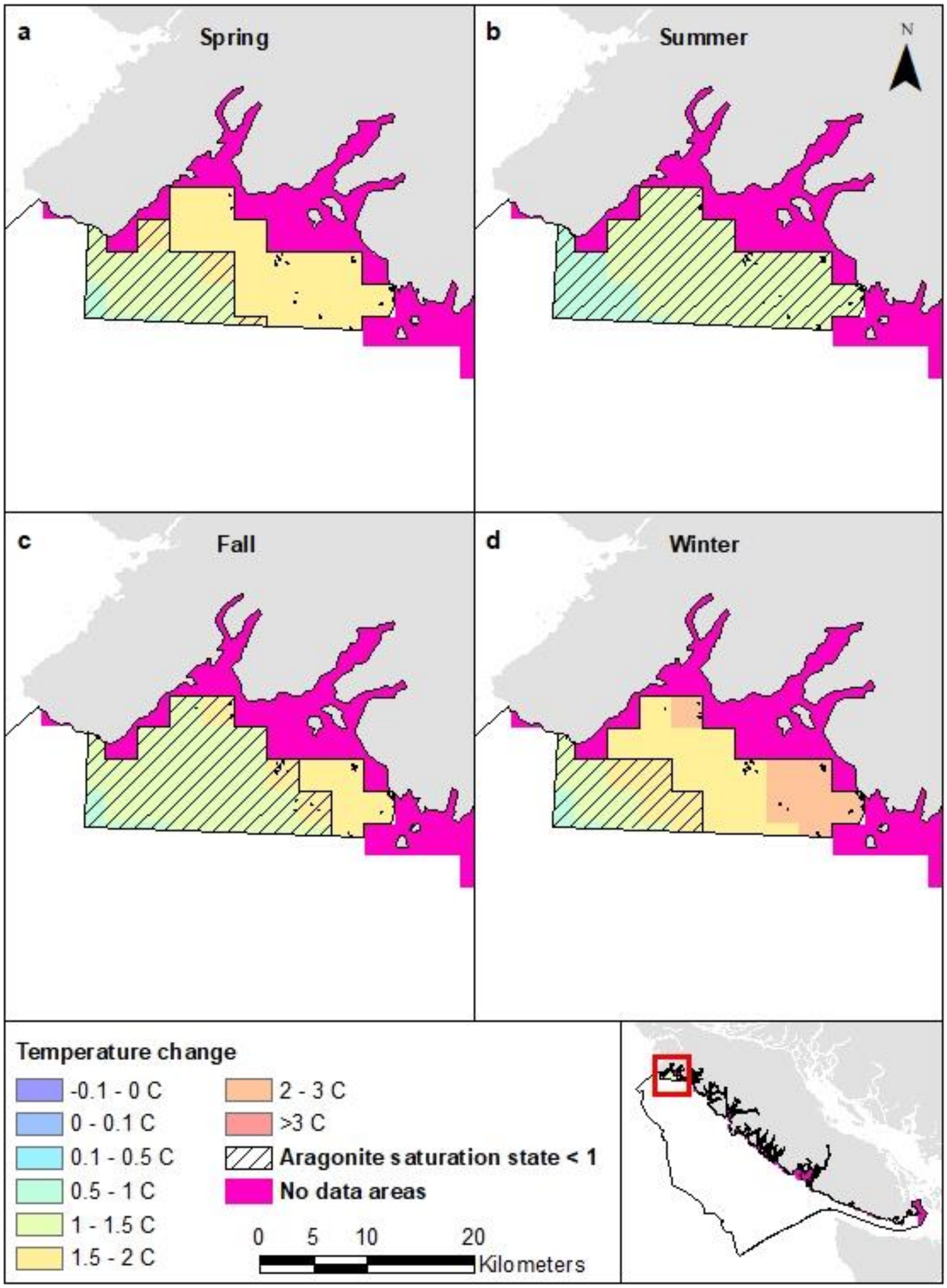


Figure 5. Seasonal mean benthic environmental parameters within the MPA (n = 1, i.e., Checleset Bay Ecological Reserve) in the Southern Shelf Bioregion using BCCM regional ocean model outputs. Temperature change is the difference in temperature values between two time periods: 1981-2010 and 2041-2070. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). Only MPA area that overlaps the model domain is shown. No MPA area overlapped the NEP36-CanOE outputs.

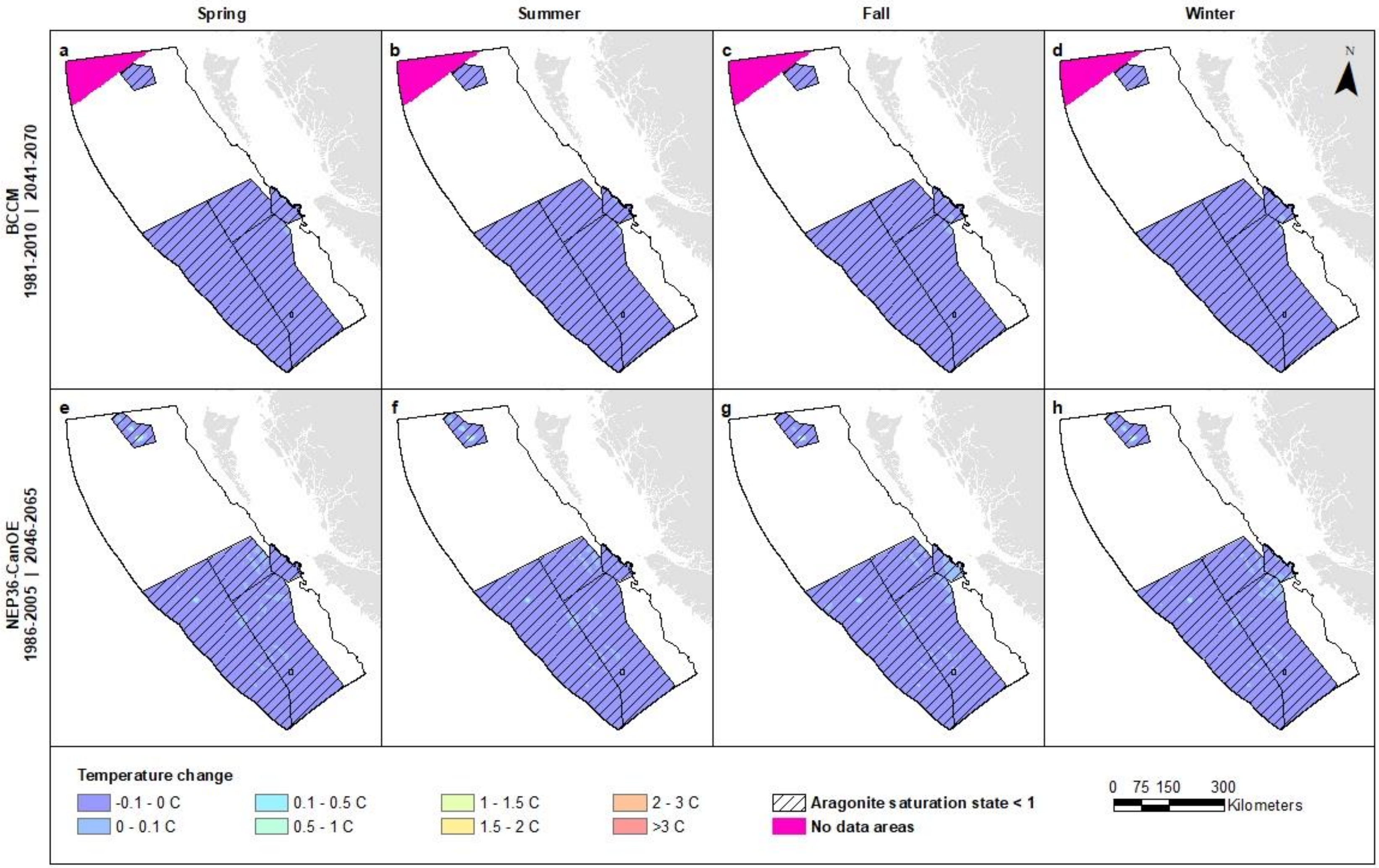


Figure 6. Seasonal mean benthic environmental parameters within MPAs and Offshore Pacific AOI oceanographic zones (n = 6) in the Offshore Pacific Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Only MPA area that overlaps each of the model domains is shown.

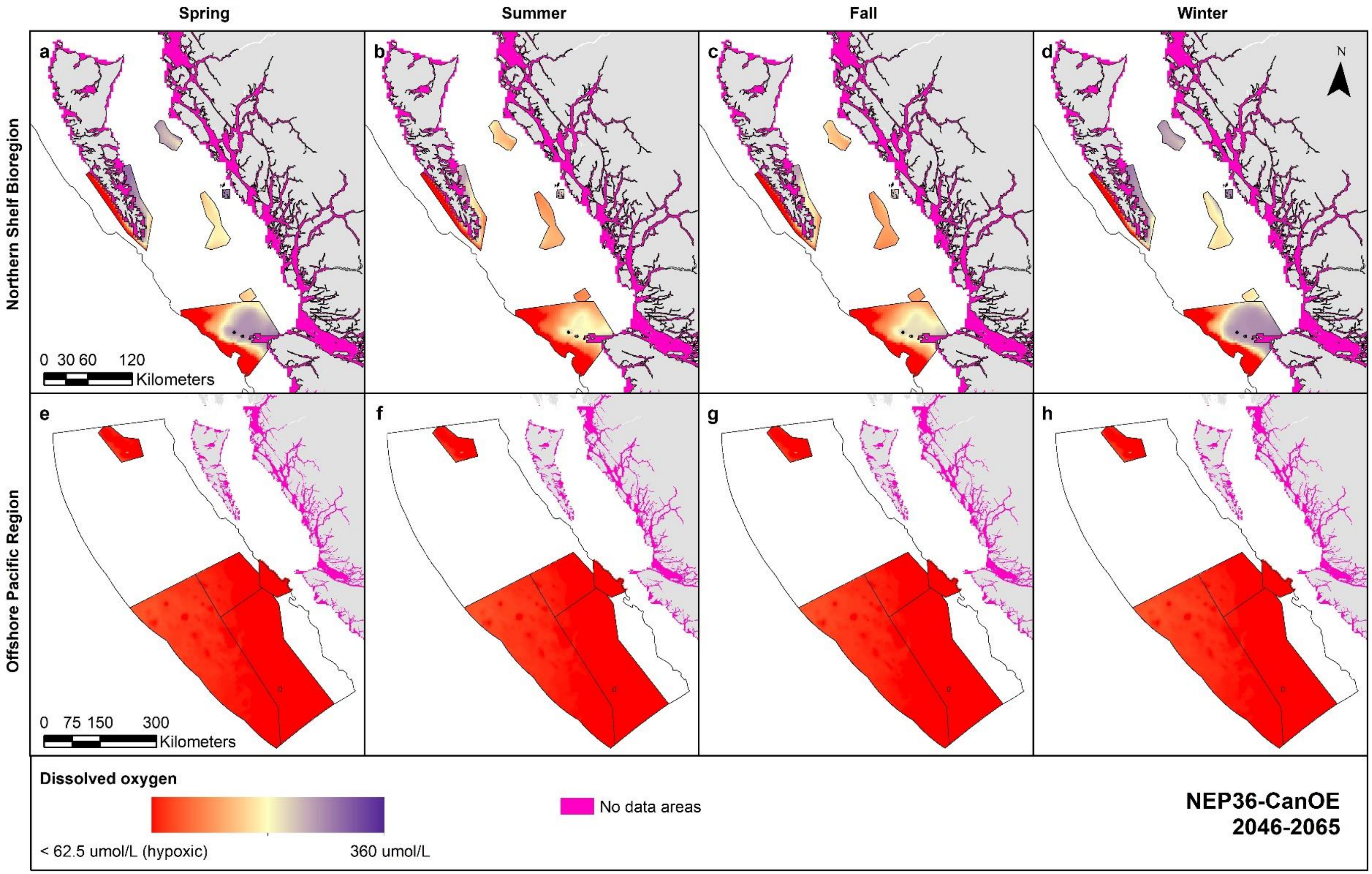


Figure 7. Projected future seasonal mean benthic dissolved oxygen (in µmol/L) within MPAs in the Pacific Region using outputs from the NEP36-CanOE regional ocean model. There are 10 MPAs in the Northern Shelf Bioregion (a-d) and 6 MPAs in the Offshore Pacific Bioregion (e-h). No MPAs had at least 50% overlap with the NEP36-CanOE outputs in the Southern Shelf Bioregion. Bright red indicates hypoxic areas where the mean dissolved oxygen is less than 62.5 µmol/L. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

Sea Surface Layer Results

Spatial patterns in projected sea surface environmental parameters were quite variable between seasons and differed between the two regional ocean models (Figure B7-B9). There was minimal area with $\Omega_A < 1$ projected in some seasons for the historical or hindcast period (0-1360 km^2 or up to 0.3% of each model's included extent in the Pacific Region) and some expansion of these areas into the future time period for both ocean models. However, different locations were identified with $\Omega_A < 1$ by each ocean model (i.e., along the eastern edge of Graham Island for the NEP36-CanOE outputs compared to parts of the Juan de Fuca Strait and along the western edge of Vancouver Island for the BCCM outputs; Figure B7 & B8). Changes in surface aragonite saturation state were variable across the Pacific Region, but generally negative (Figure B13-B15). However, there was an increase in surface aragonite saturation state in a small area east of Graham Island. All surface temperatures were projected to increase between time periods, but the magnitude of change was variable across seasons (Figure B7-B9). Broadly, greater temperature change was projected across the Pacific Region in the summer and fall relative to other seasons for the BCCM ocean model outputs, compared to the spring and fall relative to other seasons for the NEP36-CanOE model (Figure B7-B9). Select areas exhibited projected change < 1.5°C or > 3°C for an individual season, but these were not consistent between the two ocean models. Projected temperature changes within all bioregions and MPAs were generally greater than 2°C but less than 3°C for both ocean models (Figure 8-10; Table 3 & 4). All MPAs included in the analysis were potentially exposed to physical impacts at the sea surface based on the model outputs. No low change MPAs were identified; the greatest physical impact to the surface layer within MPAs appears to be through projected temperature change, rather than aragonite saturation state.

Table 3. Seasonal mean environmental parameters (temperature and aragonite saturation state) within MPAs in the Pacific Region using BCCM regional ocean model outputs. The hindcast time period is 1981-2010, while the projected future time period is 2041-2070. Seasons were delineated as: spring (Spr; Mar-Apr-May), summer (Sum; Jun-Jul-Aug), fall (Sep-Oct-Nov), and winter (Win; Dec-Jan-Feb). Only MPA area that overlapped the model domain was considered in the mean calculation. Red shading highlights MPAs with $\Omega_A < 1$ or temperature change > 2 °C; yellow shading highlights MPAs with temperature change 1-2 °C.

MPA	BCCM Regional Ocean Model															
	Sea Bottom Temperature (°C)								Sea Surface Temperature (°C)							
	Hindcast				Projected Future				Hindcast				Projected Future			
	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win
SGaan Kinghlas – Bowie Seamount MPA	1.47	1.47	1.46	1.47	1.42	1.41	1.40	1.41	7.59	12.94	12.16	7.40	9.93	15.83	14.99	9.68
Endeavour Hydrothermal Vents MPA	1.55	1.55	1.55	1.55	1.53	1.53	1.53	1.53	9.54	14.67	14.75	9.57	11.82	17.03	17.50	11.73
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Northern Reef	6.46	5.78	6.28	7.16	7.62	6.63	7.30	8.54	8.43	13.18	11.48	7.88	10.62	15.42	13.94	9.98
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Central Reefs	5.79	5.38	5.52	6.11	6.69	6.12	6.30	7.12	8.72	13.55	11.81	8.12	10.91	15.98	14.38	10.30
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Southern Reef	5.56	5.16	5.31	5.87	6.34	5.87	6.15	6.78	9.07	13.90	12.08	8.37	11.22	16.16	14.51	10.52
Scott Islands Marine National Wildlife Area – area in Northern Shelf Bioregion	5.66	5.56	5.95	5.94	6.59	6.25	6.78	6.99	9.19	13.57	12.42	8.56	11.34	15.69	14.96	10.78
Scott Islands Marine National Wildlife Area – area in Offshore Pacific Bioregion	1.96	1.96	1.97	1.97	1.94	1.94	1.95	1.96	8.98	13.94	13.03	8.43	11.18	16.13	15.62	10.65
Gwaii Haanas National Marine Conservation Area	5.69	5.81	6.04	6.00	6.76	6.66	6.81	7.08	8.38	12.74	11.35	7.91	10.57	15.42	13.70	9.97
Anne Vallee (Triangle Island) Ecological Reserve	7.95	8.40	8.92	8.31	9.63	9.46	10.22	10.11	9.23	13.26	12.21	8.63	11.35	15.34	14.77	10.84
Beresford Island Ecological Reserve	7.83	7.80	8.63	8.28	9.45	8.93	10.01	10.17	9.28	13.21	12.20	8.58	11.38	15.21	14.72	10.80
Byers/Conroy/Harvey/ Sinnett Islands Ecological Reserve	7.98	8.95	9.59	8.25	9.91	10.21	11.26	10.29	8.67	13.25	11.53	7.95	10.83	15.32	14.02	10.10

Moore/Mckenney/Whitmore Islands Ecological Reserve	7.74	8.25	9.02	8.25	9.58	9.46	10.56	10.23	8.72	13.33	11.52	8.00	10.89	15.54	14.05	10.15
Sartine Island Ecological Reserve	7.72	7.81	8.45	8.16	9.32	8.87	9.72	9.92	9.27	13.29	12.24	8.62	11.39	15.36	14.79	10.85
Checleset Bay Ecological Reserve	8.01	8.32	8.85	8.09	9.58	9.45	10.21	9.87	9.49	13.03	12.10	8.36	11.54	15.06	14.53	10.50
Duke of Edinburgh (Pine/Storm/Tree Islets) Ecological Reserve	7.53	7.39	8.15	8.18	9.12	8.55	9.50	9.94	9.15	13.04	11.38	8.17	11.25	15.38	13.87	10.29
Tow Hill Ecological Reserve	7.53	11.14	10.27	6.75	9.62	13.60	12.64	8.84	7.80	12.96	10.69	6.51	9.97	15.76	13.34	8.68
K'uuna Gwaay Conservancy	7.52	8.57	8.79	7.85	9.38	10.17	9.98	9.58	8.20	12.98	10.95	7.58	10.34	16.09	13.26	9.54
Lucy Islands Conservancy	7.42	7.98	9.09	7.87	9.41	9.17	10.84	9.89	8.09	12.45	10.77	7.39	10.31	14.65	13.17	9.56
Kitson Island Marine Park	7.71	9.15	9.83	7.76	9.83	10.36	11.70	9.86	7.85	11.70	10.43	7.09	10.04	13.60	12.55	9.30
Lanz and Cox Islands Park	8.45	9.19	10.10	8.63	10.31	10.43	11.86	10.70	9.27	13.31	12.07	8.51	11.37	15.35	14.56	10.71
Offshore Pacific Area of Interest – Upwelling/ Downwelling Transition Zone	1.60	1.60	1.60	1.60	1.57	1.57	1.57	1.57	8.61	13.90	13.43	8.31	10.81	16.39	16.09	10.45
Offshore Pacific Area of Interest – Coastal Upwelling Zone	1.56	1.57	1.57	1.57	1.54	1.54	1.54	1.54	9.32	14.54	14.35	9.20	11.58	16.87	17.07	11.44
Offshore Pacific Area of Interest – Bifurcation Zone	1.41	1.42	1.42	1.42	1.39	1.39	1.39	1.39	8.93	14.20	14.47	9.13	11.15	16.70	17.30	11.38
MPA	**Sea Bottom Aragonite Saturation State**								**Sea Surface Aragonite Saturation State**							
	Hindcast				**Projected Future**				**Hindcast**				**Projected Future**			
	Spr	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**
SGaan Kinghlas – Bowie Seamount MPA	0.51	0.51	0.51	0.51	0.51	0.51	0.51	0.51	2.00	2.53	2.43	1.79	1.49	1.96	1.84	1.32
Endeavour Hydrothermal Vents MPA	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	2.14	2.25	2.34	2.02	1.54	1.67	1.75	1.47
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Northern Reef	1.04	0.90	0.92	1.10	0.78	0.69	0.70	0.82	2.02	2.43	2.09	1.62	1.59	1.92	1.63	1.23
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Central Reefs	0.89	0.84	0.82	0.87	0.68	0.65	0.64	0.66	2.08	2.42	2.13	1.68	1.61	1.91	1.66	1.27
Hecate Strait and Queen Charlotte Sound Glass	0.79	0.76	0.76	0.80	0.61	0.60	0.58	0.61	2.09	2.41	2.14	1.71	1.63	1.91	1.66	1.29

Sponge Reefs MPA – Southern Reef																
Scott Islands Marine National Wildlife Area – area in Northern Shelf Bioregion	0.95	0.86	0.87	0.97	0.73	0.66	0.66	0.75	2.06	2.35	2.14	1.75	1.57	1.85	1.65	1.32
Scott Islands Marine National Wildlife Area – area in Offshore Pacific Bioregion	0.52	0.52	0.52	0.52	0.51	0.52	0.51	0.51	2.14	2.36	2.27	1.85	1.58	1.80	1.71	1.37
Gwaii Haanas National Marine Conservation Area	0.99	0.95	0.90	0.97	0.77	0.73	0.69	0.75	1.96	2.37	1.99	1.60	1.52	1.85	1.53	1.20
Anne Vallee (Triangle Island) Ecological Reserve	1.38	1.24	1.23	1.41	1.00	0.84	0.85	1.02	2.02	2.32	2.07	1.72	1.55	1.82	1.60	1.31
Beresford Island Ecological Reserve	1.34	1.12	1.18	1.41	0.98	0.78	0.83	1.05	1.98	2.30	2.05	1.68	1.54	1.82	1.59	1.28
Byers/Conroy/Harvey/Sinnett Islands Ecological Reserve	1.62	1.46	1.47	1.57	1.21	1.02	1.07	1.19	2.00	2.36	2.04	1.60	1.57	1.87	1.61	1.23
Moore/Mckenney/Whitmore Islands Ecological Reserve	1.52	1.32	1.35	1.53	1.13	0.94	0.98	1.15	2.02	2.38	2.05	1.62	1.59	1.89	1.61	1.24
Sartine Island Ecological Reserve	1.30	1.13	1.14	1.35	0.94	0.78	0.80	0.99	2.02	2.32	2.08	1.71	1.56	1.84	1.61	1.30
Checleset Bay Ecological Reserve	1.32	1.10	1.17	1.33	0.98	0.77	0.84	1.01	1.88	2.18	1.94	1.55	1.48	1.71	1.54	1.20
Duke of Edinburgh (Pine/Storm/Tree Islets) Ecological Reserve	1.29	1.10	1.11	1.33	0.95	0.80	0.80	0.99	1.94	2.17	1.81	1.56	1.55	1.79	1.47	1.21
Tow Hill Ecological Reserve	1.65	1.97	1.75	1.39	1.34	1.57	1.37	1.10	1.87	2.39	1.90	1.37	1.51	1.91	1.51	1.09
K’uuna Gwaay Conservancy	1.42	1.44	1.30	1.33	1.07	1.05	0.91	0.98	1.87	2.40	1.85	1.45	1.47	1.90	1.44	1.09
Lucy Islands Conservancy	1.58	1.37	1.43	1.54	1.20	0.97	1.07	1.18	1.73	1.25	1.68	1.54	1.38	0.95	1.34	1.19
Kitson Island Marine Park	1.68	1.56	1.54	1.54	1.28	1.09	1.15	1.18	1.25	0.60	1.20	1.31	1.00	0.45	0.91	1.03
Lanz and Cox Islands Park	1.58	1.37	1.45	1.57	1.17	0.94	1.04	1.18	1.98	2.29	2.02	1.66	1.54	1.82	1.58	1.27
Offshore Pacific Area of Interest – Upwelling/ Downwelling Transition Zone	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	2.13	2.32	2.33	1.89	1.57	1.72	1.74	1.38
Offshore Pacific Area of Interest – Coastal Upwelling Zone	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	2.15	2.28	2.33	1.98	1.55	1.69	1.75	1.45
Offshore Pacific Area of Interest – Bifurcation Zone	0.53	0.53	0.53	0.53	0.54	0.53	0.53	0.53	2.07	2.24	2.36	2.00	1.51	1.66	1.76	1.42

Table 4. Seasonal mean environmental parameters (temperature, aragonite saturation state, and dissolved oxygen) within MPAs in the Pacific Region using NEP36-CanOE regional ocean model outputs. The historical time period is 1986-2005, while the projected future time period is 2046-2065. Seasons were delineated as: spring (Spr; Mar-Apr-May), summer (Sum; Jun-Jul-Aug), fall (Sep-Oct-Nov), and winter (Win; Dec-Jan-Feb). Only MPA area that overlapped the model domain was considered in the mean calculation. Dissolved oxygen was evaluated for the benthic layer only. Red cells highlight MPAs with $\Omega_A < 1$, dissolved oxygen < 62.5 µmol/L, or temperature change > 2 °C; yellow cells highlight MPAs with temperature change > 1 °C.

MPA	NEP36-CanOE Regional Ocean Model															
	Sea Bottom Temperature (°C)								Sea Surface Temperature (°C)							
	Historical				Projected Future				Historical				Projected Future			
	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win	Spr	Sum	Fall	Win
SGaan Kinghlas – Bowie Seamount MPA	1.84	1.84	1.85	1.85	1.85	1.86	1.85	1.86	6.28	13.11	11.38	6.47	8.86	16.08	14.36	8.83
Endeavour Hydrothermal Vents MPA	1.84	1.84	1.84	1.84	1.84	1.84	1.85	1.84	8.59	15.03	13.80	8.75	11.07	17.36	17.23	11.16
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Northern Reef	6.38	6.02	6.61	7.13	8.02	7.22	7.94	9.14	7.28	12.85	11.20	7.38	9.84	14.67	13.58	9.69
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Central Reefs	6.28	5.74	5.80	6.41	7.54	6.85	6.97	7.99	7.53	13.79	11.77	7.55	10.02	16.11	14.37	9.93
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Southern Reef	6.16	5.73	5.91	6.46	7.31	6.78	7.09	7.67	7.80	13.15	11.79	7.92	10.29	15.35	14.16	10.27
Scott Islands Marine National Wildlife Area – area in Northern Shelf Bioregion	5.76	5.54	6.12	6.21	7.08	6.52	7.17	7.63	8.00	12.96	11.79	7.99	10.43	14.95	13.97	10.34
Scott Islands Marine National Wildlife Area – area in Offshore Pacific Bioregion	2.02	2.00	2.01	2.02	2.00	1.99	2.02	2.02	7.97	14.23	12.47	7.82	10.48	15.88	14.80	10.06
Gwaii Haanas National Marine Conservation Area	5.60	6.66	6.50	5.86	7.16	7.98	7.71	7.40	7.34	13.40	11.04	7.34	9.91	15.97	13.45	9.70
Anne Vallee (Triangle Island) Ecological Reserve	7.73	9.32	10.41	8.12	10.11	10.99	12.01	10.47	7.87	12.12	11.44	8.07	10.29	14.28	13.44	10.44
Beresford Island Ecological Reserve	7.43	7.10	8.71	8.24	9.73	8.52	10.29	10.54	8.04	11.62	11.23	8.00	10.48	13.58	13.33	10.40

Byers/Conroy/Harvey/ Sinnett Islands Ecological Reserve	7.22	9.80	10.38	7.62	9.65	11.70	12.47	9.89	7.37	11.99	11.33	7.56	9.84	14.12	13.93	9.86
Moore/Mckenney/ Whitmore Islands Ecological Reserve	7.13	9.02	10.00	7.64	9.54	10.86	11.92	9.91	7.35	12.27	11.41	7.59	9.84	14.36	13.98	9.88
Sartine Island Ecological Reserve	7.56	8.18	9.47	8.18	9.86	9.71	11.09	10.50	7.94	12.17	11.36	8.06	10.35	14.23	13.36	10.45
Offshore Pacific Area of Interest – Upwelling/ Downwelling Transition Zone	1.76	1.77	1.77	1.77	1.75	1.75	1.76	1.75	7.58	14.51	12.91	7.63	10.02	16.70	15.54	9.74
Offshore Pacific Area of Interest – Coastal Upwelling Zone	1.79	1.79	1.79	1.79	1.78	1.78	1.78	1.78	8.42	14.87	13.74	8.41	10.84	17.07	16.59	10.67
Offshore Pacific Area of Interest – Bifurcation Zone	1.66	1.66	1.66	1.66	1.64	1.64	1.65	1.64	8.10	14.80	13.64	8.31	10.52	17.16	16.80	10.73

MPA	**Sea Bottom Aragonite Saturation State**								**Sea Surface Aragonite Saturation State**							
	Historical				**Projected Future**				**Historical**				**Projected Future**			
	Spr	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**
SGaan Kinghlas – Bowie Seamount MPA	0.46	0.46	0.46	0.46	0.45	0.45	0.45	0.45	1.78	2.42	2.18	1.69	1.40	1.81	1.66	1.25
Endeavour Hydrothermal Vents MPA	0.47	0.46	0.46	0.46	0.47	0.47	0.47	0.47	2.07	2.38	2.35	1.97	1.58	1.72	1.80	1.46
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Northern Reef	1.52	1.23	1.29	1.60	1.12	0.88	0.90	1.18	1.89	2.32	2.01	1.74	1.42	1.73	1.53	1.27
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Central Reefs	1.28	1.08	1.10	1.32	0.95	0.78	0.77	0.98	1.95	2.37	2.07	1.76	1.45	1.77	1.57	1.29
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Southern Reef	1.26	1.04	1.10	1.34	0.91	0.73	0.77	0.97	1.98	2.36	2.09	1.85	1.48	1.78	1.58	1.33
Scott Islands Marine National Wildlife Area – area in Northern Shelf Bioregion	1.22	1.04	1.12	1.28	0.91	0.75	0.81	0.95	2.01	2.27	2.09	1.86	1.49	1.69	1.55	1.34

Scott Islands Marine National Wildlife Area – area in Offshore Pacific Bioregion	0.46	0.47	0.46	0.46	0.45	0.45	0.45	0.45	2.01	2.37	2.21	1.82	1.52	1.76	1.67	1.32
Gwaii Haanas National Marine Conservation Area	1.24	1.22	1.20	1.24	0.94	0.91	0.89	0.93	1.86	2.24	1.95	1.72	1.39	1.71	1.48	1.26
Anne Vallee (Triangle Island) Ecological Reserve	1.90	1.82	1.88	1.84	1.39	1.29	1.33	1.33	1.95	2.10	2.00	1.86	1.43	1.57	1.45	1.34
Beresford Island Ecological Reserve	1.79	1.49	1.67	1.82	1.31	1.03	1.16	1.32	2.00	2.00	1.96	1.86	1.48	1.49	1.44	1.34
Byers/Conroy/Harvey/ Sinnett Islands Ecological Reserve	1.86	1.89	1.90	1.77	1.36	1.38	1.40	1.28	1.90	2.14	2.01	1.79	1.40	1.61	1.53	1.29
Moore/Mckenney/ Whitmore Islands Ecological Reserve	1.84	1.81	1.86	1.77	1.34	1.30	1.34	1.28	1.90	2.17	2.03	1.79	1.40	1.64	1.54	1.29
Sartine Island Ecological Reserve	1.84	1.65	1.78	1.83	1.35	1.15	1.25	1.33	1.96	2.10	1.98	1.86	1.44	1.57	1.43	1.35
Offshore Pacific Area of Interest – Upwelling/ Downwelling Transition Zone	0.46	0.46	0.46	0.46	0.46	0.46	0.45	0.46	1.93	2.41	2.31	1.81	1.47	1.76	1.70	1.28
Offshore Pacific Area of Interest – Coastal Upwelling Zone	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	2.06	2.38	2.34	1.92	1.55	1.73	1.76	1.40
Offshore Pacific Area of Interest – Bifurcation Zone	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.45	2.00	2.43	2.36	1.91	1.54	1.76	1.79	1.41

MPA	**Sea Bottom Dissolved Oxygen (μmol/L)**							
	Historical				**Projected Future**			
	Spr	**Sum**	**Fall**	**Win**	**Spr**	**Sum**	**Fall**	**Win**
SGaan Kinghlas – Bowie Seamount MPA	64.0	63.4	62.3	63.3	61.7	60.6	59.5	60.7
Endeavour Hydrothermal Vents MPA	49.3	48.8	49.2	49.5	48.8	48.7	48.5	49.3
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Northern Reef	264.4	192.2	195.9	274.6	258.9	179.3	176.5	266.6
Hecate Strait and Queen Charlotte Sound Glass	200.6	164.1	169.9	208.0	198.2	153.2	148.1	204.4

Sponge Reefs MPA – Central Reefs								
Hecate Strait and Queen Charlotte Sound Glass Sponge Reefs MPA – Southern Reef	189.4	150.9	167.8	206.9	183.3	132.9	147.0	199.7
Scott Islands Marine National Wildlife Area – area in Northern Shelf Bioregion	178.1	144.4	155.9	188.3	165.1	124.8	135.0	176.4
Scott Islands Marine National Wildlife Area – area in Offshore Pacific Bioregion	46.9	48.1	47.2	46.6	41.0	41.9	40.3	39.5
Gwaii Haanas National Marine Conservation Area	194.5	164.6	167.8	196.9	180.9	149.2	151.4	183.1
Anne Vallee (Triangle Island) Ecological Reserve	298.6	258.6	259.8	292.6	282.0	238.4	241.8	277.4
Beresford Island Ecological Reserve	285.9	224.6	243.1	288.8	268.2	201.7	221.9	275.1
Byers/Conroy/Harvey/ Sinnett Islands Ecological Reserve	311.3	270.1	267.2	297.5	295.0	253.0	249.4	283.5
Moore/Mckenney/Whitmore Islands Ecological Reserve	308.5	261.7	263.3	297.0	292.0	243.8	244.3	283.3
Sartine Island Ecological Reserve	292.0	243.3	252.0	290.2	275.9	220.9	232.6	275.7
Offshore Pacific Area of Interest – Upwelling/ Downwelling Transition Zone	62.7	62.6	62.2	63.0	60.3	60.3	59.2	60.2
Offshore Pacific Area of Interest – Coastal Upwelling Zone	54.0	53.8	53.4	53.9	52.2	51.9	51.3	52.1
Offshore Pacific Area of Interest – Bifurcation Zone	72.9	72.3	71.5	72.7	72.5	71.6	70.3	72.0

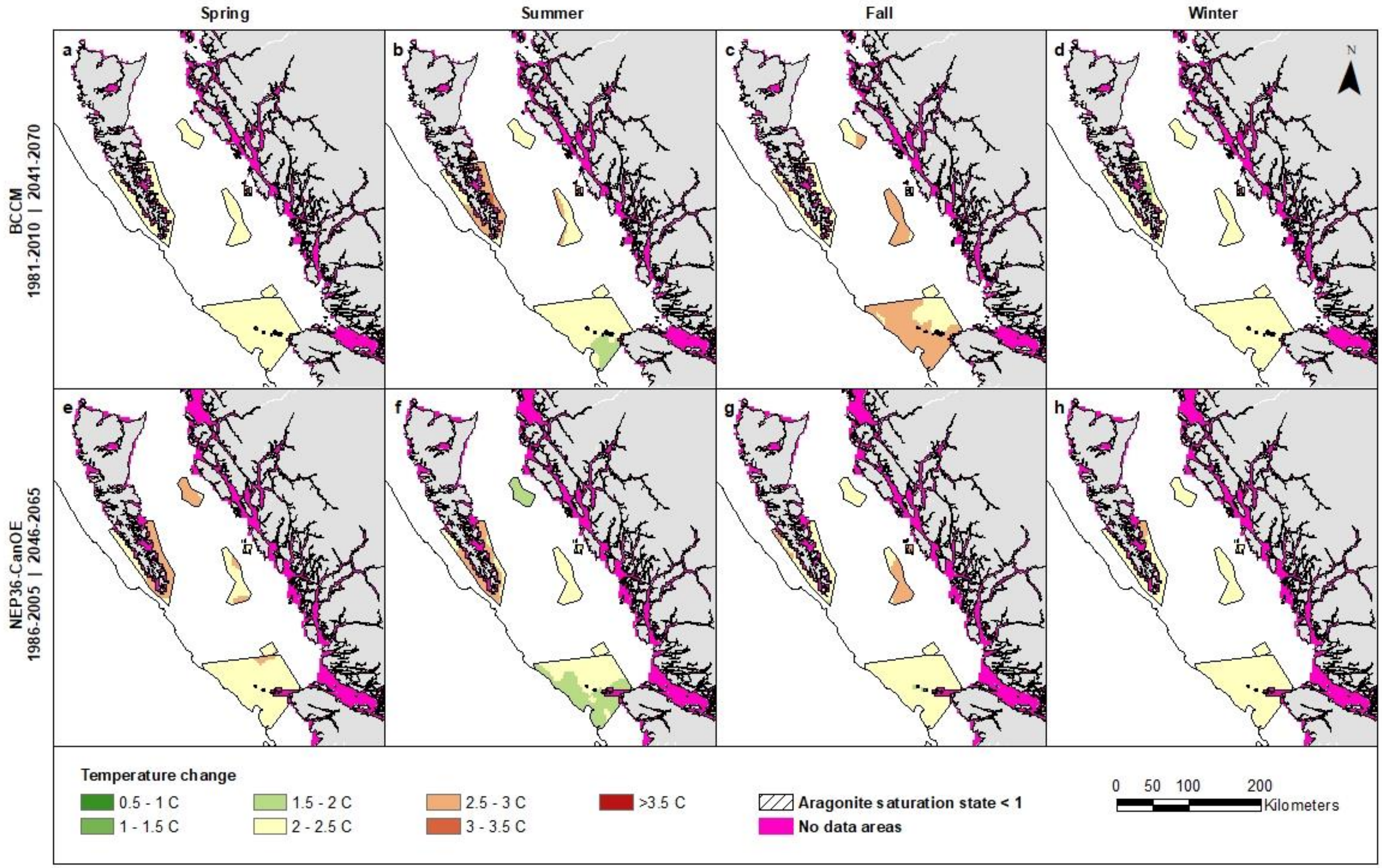


Figure 8. Seasonal mean sea surface environmental parameters within MPAs in the Northern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). n = 16 for BCCM; n = 10 for NEP36-CanOE. Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Only MPA area that overlaps each of the model domains is shown.

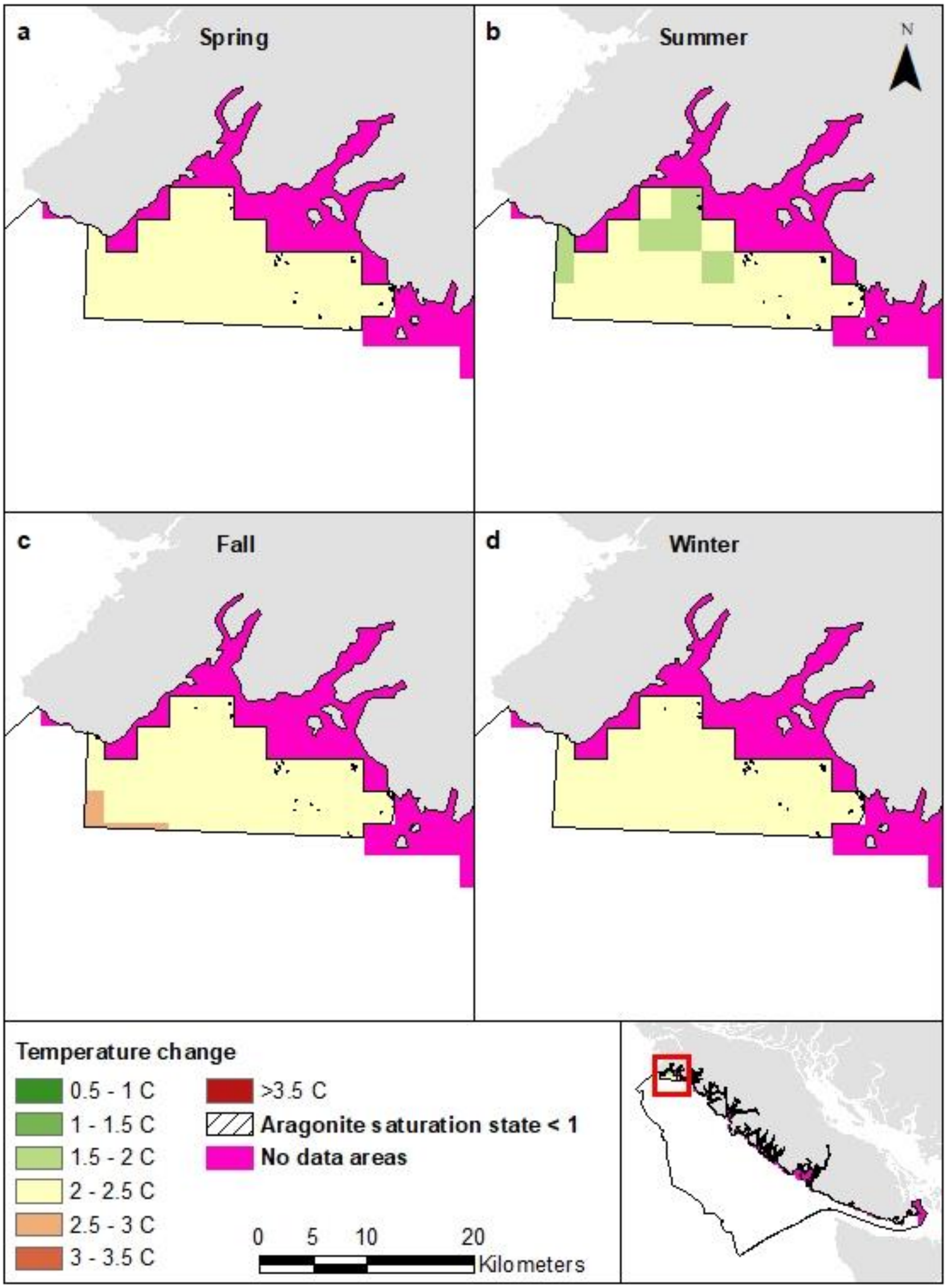


Figure 9. Seasonal mean sea surface environmental parameters within the MPA (n = 1, i.e., Checleset Bay Ecological Reserve) in the Southern Shelf Bioregion using BCCM regional ocean model outputs. Temperature change is the difference in temperature values between two time periods: 1981-2010 and 2041-2070. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). Only MPA area that overlaps the model domain is shown. No MPA area overlapped the NEP36-CanOE outputs.

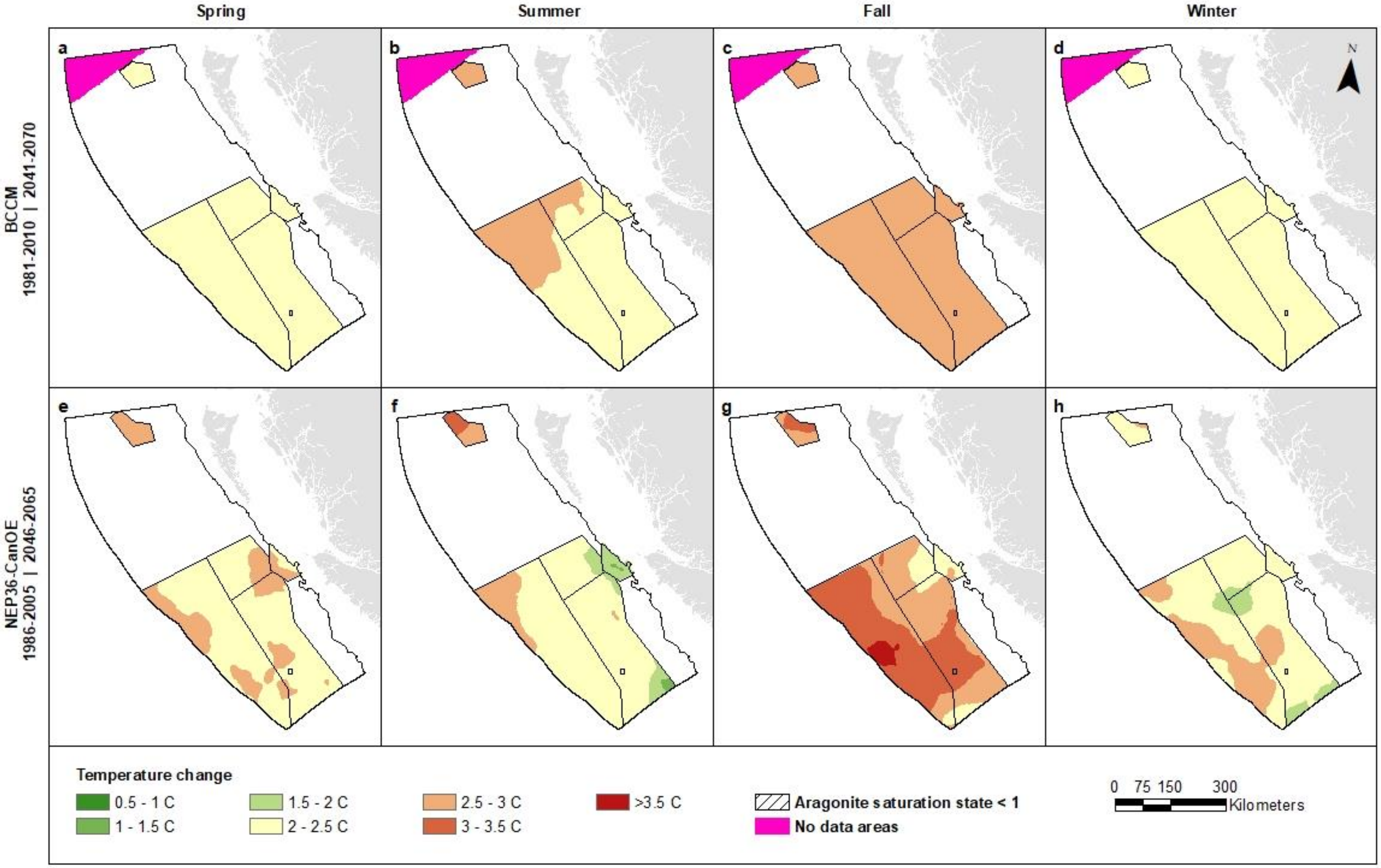


Figure 10. Seasonal mean sea surface environmental parameters within MPAs and Offshore Pacific AOI oceanographic zones (n = 6) in the Offshore Pacific Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Only MPA area that overlaps each of the model domains is shown.

Discussion:

Two regionally downscaled climate ocean models were used to project change across three of Canada's Pacific Bioregions; we could not clearly identify any MPAs or AOI zones without exposure to climate change (i.e., no change in environmental conditions across time periods). The difference in environmental conditions between the modeled time periods suggests future shifts in the physical environment currently experienced by organisms within bioregions and MPAs. This result is in line with other studies that have found climate change threatens MPAs globally (Bruno et al. 2018). While the model outputs projected the Offshore Pacific Bioregion to be fairly stable between the time periods, oceanographic surveys have already shown deoxygenation and acidification on offshore seamounts in the bioregion, with consequences for resident species (Ross et al. 2020). There is evidence that many species are shifting deeper, presumably following temperature gradients to remain within their physiological tolerance range (Dulvy et al. 2008; Li et al. 2019). However, species shifts may be limited by the expansion and shoaling of areas that are hypoxic or below the aragonite saturation threshold (Okey et al. 2014; Ross et al. 2020). As individual species' physiological tolerance may be more or less sensitive than these general thresholds (e.g., Chu and Tunnicliffe 2015), it is important to consider species-specific thresholds in assessing climate vulnerability and predicting distribution shifts (Deutsch et al. 2015; Pörtner and Farrell 2008). MPAs are designed and managed with multiple species in mind, yet physiological tolerance range information is limited or nonexistent for many species, particularly tolerance ranges in complex natural conditions and in interaction with ecological and other environmental parameters.

MPA design and management can facilitate species range shifts and adaptation as ocean conditions change (Jones et al. 2016; Tittensor et al. 2019; Wilson et al. 2020). It is important that protected areas represent and replicate different environments in the region (Margules and Pressey 2000), and enhance connectivity to aid in species' range shifts and facilitate recovery after acute climate impacts (Groves et al. 2012; Wilson et al. 2020). Habitat patches that are suitable now should be represented, as well as areas that are projected to be suitable in the future to continue protecting species as their distributions shift (Jones et al. 2016). This is particularly important as Whitney (2019) projected species turnover in the majority of federal and provincial MPAs in the Northern Shelf Bioregion by 2060 under RCP8.5. Representation should also include the full range of physical impacts and variability due to climate change, including climate refugia (Jones et al. 2016; Tittensor et al. 2019; Wilson et al. 2020). Species may be more likely to persist in climate refugia where there is little environmental change, plus these areas may buy more time for species to adapt to changing conditions (Morelli et al. 2016; Tittensor et al. 2019). However, Ban et al. (2016) found little evidence of refugia in British Columbia. In contrast, areas with high historical environmental variability may provide greater climate resilience in local populations due to greater phenotypic plasticity or adaptation (Boyd et al. 2016; Morikawa and Palumbi 2019). For example, varied temperature stress regimes can bolster MPA resistance and recovery following acute thermal stress events (Magris et al. 2015). Climate change adaptation strategies can increase climate resilience in MPAs (Tittensor et al. 2019; Wilson et al. 2020). However, operationalizing these considerations into MPA design and management first requires an understanding of the regional climate impacts, and second an understanding of risk to species and ecosystems of concern as well as the management objectives aimed at protecting them at appropriate space and time scales (Duplisea et al. 2021). Thus, our report provides a starting point for future decision making. In addition, the custom spatial analysis tool can be used on draft MPAs or OECMs to determine how they replicate or complement existing MPAs in a bioregion.

Regional downscaling of global climate simulations is an invaluable tool for assessing future environmental conditions, but this necessarily constrained our analysis. Both regional ocean models have limited spatial resolution, and are unable to meaningfully resolve nearshore areas where the majority of Pacific MPAs are located. The Strait of Georgia Bioregion was excluded because the coarse resolution of both models does not allow for an accurate representation of this small region. This limitation highlights the need for higher resolution ocean downscaling of climate projections in British Columbia’s complex nearshore areas in order to inform MPA management and monitoring. While other ocean models have been developed that cover nearshore areas in British Columbia (e.g., Khangaonkar et al. 2019), they do not have the same coast-wide extent, so the BCCM and NEP36-CanOE were more appropriate for our purpose. With different grids, vertical coordinates, and parameterizations, the model solutions differ in their representation of the physics and biogeochemistry for the region. By using two models, we were able to compare the results and determine where the models agreed that there was more or less physical impact from climate change. NEP36-CanOE was not run long enough to reach equilibration in the deep offshore regions, so the results in those regions may not be much different than the global model (CanESM2). Where possible, it would be desirable to integrate the downscaled outputs from several global climate models into an ensemble and evaluate multiple scenarios (such as RCP4.5 or RCP6.0) to get an idea of the uncertainty in the projections (e.g., Frölicher et al. 2016). Naturally, there is uncertainty associated with models in general and with projecting future environmental conditions, but the BCCM and NEP36-CanOE model projections enable planning for the potential impacts of climate change where it would otherwise not be possible (Clark et al. 2001). In addition, while both models have been validated with observational data for the hindcast or historical time periods, these data are not evenly distributed across the Pacific Region; see Masson & Fine (2012), Peña et al. (2019), and Holdsworth et al. (2021) for details of validation.

Our analysis placed additional constraints on the ocean model outputs, both temporally and with respect to depth. While the regional model outputs were available at a finer temporal scale, we averaged environmental parameters by seasons across each time period. This averaging is important as acute stress events and variability may play a larger role than long-term changes in the mean in determining individual survival and MPA suitability (Mumby et al. 2011; Pinsky et al. 2019). We then used these seasonal mean values to obtain an average for each MPA; in most cases, an average of averages is not appropriate. However, the average parameter value for every grid cell was calculated using the same number of ocean model output layers, so this is not a concern as our MPA values are identical to the weighted average values. We constrained the analysis to only the sea surface and benthic layers from each ocean model. NEP36-CanOE has 50 fixed vertical depth layers (Holdsworth et al. 2021) and BCCM has 42 non-uniform vertical depth layers (Peña et al. 2019). The sea surface layer thickness is

0.5 m for NEP36-CanOE and 0.3 to ~1.6 m for BCCM, while the benthic layer thickness in both models ranges from metres to hundreds of metres (Holdsworth et al. 2021; Peña et al. 2019). While both layers provide reasonable representation of the boundary layers, it would be useful to integrate multiple depth layers in future analyses.

This report has identified MPAs that are exposed to projected climate change in the Pacific Region, and evaluates the associated future physical impact on three environmental parameters, but integrating climate considerations into the management of existing MPAs or the siting of new MPAs was outside the report scope. Additional work is needed to understand climate risk in this Region, especially how physiological tolerance ranges and other biological parameters shape particular species' vulnerability. Our results can serve as a starting point for future analyses, while our custom ArcGIS geoprocessing tool could be used to assess existing or draft MPAs, other effective area-based conservation measures, fishing closures, or other spatial boundaries in any of these three Pacific Bioregions. This analysis can help ensure that new MPAs complement and/or replicate the climate variability and physical impact projected for existing MPAs, in order to represent the full range of environmental conditions (Wilson et al. 2020).

Acknowledgements

We are grateful to Matthew Poirier for assisting with development of the ArcGIS geoprocessing tool. This research was partially sponsored by the NSERC Canadian Healthy Oceans Network and its Partners: Fisheries and Oceans Canada and INREST (representing the Port of Sept-Îles and City of Sept-Îles).

References:

Balbar, A.C., Daigle, R.M., Heaslip, S.G., Jeffery, N.W., Proudfoot, B., Robb, C.K., Rubidge, E., and Stanley, R. 2020. Approaches for assessing and monitoring representation, replication, and connectivity in marine conservation networks. DFO Canadian Science Advisory Secretariat Research Document 2020/050. Ottawa, Canada.

Ban, S.S., Alidina, H.M., Okey, T.A., Gregg, R.M., and Ban, N.C. 2016. Identifying potential marine climate change refugia: A case study in Canada's Pacific marine ecosystems. Global Ecology and Conservation **8**: 41-54. doi:10.1016/j.gecco.2016.07.004.

Bellwood, D.R., Hughes, T.P., Folke, C., and Nyström, M. 2004. Confronting the coral reef crisis. Nature **429**: 827-833. doi:10.1038/nature02691.

Boyd, P.W., Cornwall, C.E., Davison, A., Doney, S.C., Fourquez, M., Hurd, C.L., Lima, I.D., and McMinn, A. 2016. Biological responses to environmental heterogeneity under future ocean conditions. Global Change Biology **22**(8): 2633-2650.

Bruno, J.F., Bates, A.E., Cacciapaglia, C., Pike, E.P., Amstrup, S.C., Van Hooidonk, R., Henson, S.A., and Aronson, R.B. 2018. Climate change threatens the world's marine protected areas. Nature Climate Change **8**: 499-503. doi:10.1038/s41558-018-0149-2.

Canessa, R., Conley, K., and Smiley, B. 2003. Bowie Seamount Pilot Marine Protected Area: An ecosystem overview. Canadian Technical Report of Fisheries and Aquatic Science 2461. Ottawa, Canada.

Carr, M.H., Robinson, S.P., Wahle, C., Davis, G., Kroll, S., Murray, S., Schumacker, E.J., and Williams, M. 2017. The central importance of ecological spatial connectivity to effective coastal marine protected areas and to meeting the challenges of climate change in the marine environment. Aquatic Conservation: Marine and Freshwater Ecosystems **27**: 6-29. doi:10.1002/aqc.2800.

Cheung, W.W.L., Lam, V.W.Y., and Pauly, D. 2008. Modelling present and climate-shifted distribution of marine fishes and invertebrates. University of British Columbia, Vancouver, BC.

Chu, J.W.F., and Tunnicliffe, V. 2015. Oxygen limitations on marine animal distributions and the collapse of epibenthic community structure during shoaling hypoxia. Global Change Biology **21**(8): 2989-3004. doi:10.1111/gcb.12898.

Clark, J.S., Carpenter, S.R., Barber, M., Collins, S., Dobson, A., Foley, J.A., Lodge, D.M., Pascual, M., Pielke Jr, R., Pizer, W., Pringle, C., Reid, W.V., Rose, K.A., Sala, O., Schlesinger, W.H., Wall, D.H., and Wear, D. 2001. Ecological forecasts: An emerging imperative. Science **293**: 657-660.

Côté, I.M., and Darling, E.S. 2010. Rethinking ecosystem resilience in the face of climate change. PLoS Biology **8**: e1000438. doi:10.1371/journal.pbio.1000438.

Deutsch, C., Ferrel, A., Seibel, B., Pörtner, H.-O., and Huey, R.B. 2015. Climate change tightens a metabolic constraint on marine habitats. Science **348**: 1132-1136.

[DFO] Fisheries and Oceans Canada. 2019. Biophysical and ecological overview of the Offshore Pacific Area of Interest (AOI). DFO Canadian Science Advisory Secretariat Science Response 2019/011. Ottawa, Canada.

Du Preez, C., and Norgard, T. in review. Identification of representative seamount areas in the Offshore Pacific Bioregion and proposed Offshore Pacific Marine Protected Area, Canada. DFO Canadian Science Advisory Secretariat Science Advisory Report 2021/##.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R., and Skjoldal, H.R. 2008. Climate change and deepening of the North Sea fish assemblage: A biotic indicator of warming seas. Journal of Applied Ecology **45**: 1029-1039. doi:10.1111/j.1365-2664.2008.01488.x.

Duplisea, D.E., Roux, M.-J., Hunter, K.L., and Rice, J. 2020. Resource management under climate change: A risk-based strategy to develop climate-informed science advice. DFO Canadian Science Advisory Secretariat Research Document 2019/044. Ottawa, Canada.

Duplisea, D.E., Roux, M.-J., Hunter, K.L., and Rice, J. 2021. Fish harvesting advice under climate change: A risk-equivalent empirical approach. PLoS One **16**(2): e0239503. doi:10.1371/journal.pone.0239503.

Environment and Climate Change Canada. 2020. Canadian Protected and Conserved Areas Database. Available from https://www.canada.ca/en/environment-climate-change/services/national-wildlife-areas/protected-conserved-areas-database.html [accessed October 2020].

ESRI Inc. 2019. ArcGIS Desktop 10.7.1. Redlands, USA.

ESRI Inc. n.d. How the zonal statistics tools work. Available from https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/how-zonal-statistics-works.htm [accessed October 2020].

Frölicher, T.L., Rodgers, K.B., Stock, C.A., and Cheung, W.W.L. 2016. Sources of uncertainties in 21st century projections of potential ocean ecosystem stressors. Global Biogeochemical Cycles **30**: 1224-1243. doi:10.1002/2015GB005338.

Groves, C.R., Game, E.T., Anderson, M.G., Cross, M., Enquist, C., Ferdaña, Z., Girvetz, E., Gondor, A., Hall, K.R., Higgins, J., Marshall, R., Popper, K., Schill, S., and Shafer, S.L. 2012. Incorporating climate change into systematic conservation planning. Biodiversity and Conservation **21**: 1651-1671. doi:10.1007/s10531-012-0269-3.

Haidvogel, D.B., Arango, H., Budgell, W.P., Cornuelle, B.D., Curchitser, E., Di Lorenzo, E., Fennel, K., Geyer, W.R., Hermann, A.J., Lanerolle, L., Levin, J., McWilliams, J.C., Miller, A.J., Moore, A.M., Powell, T.M., Shchepetkin, A.F., Sherwood, C.R., Signell, R.P., Warner, J.C., and Wilkin, J. 2008. Ocean forecasting in terrain-following coordinates: Formulation and skill assessment of the Regional Ocean Modeling System. Journal of Computational Physics **227**: 3595-3624. doi:10.1016/j.jcp.2007.06.016.

Harley, C.D.G., Hughes, A.R., Hultgren, K.M., Miner, B.G., Sorte, C.J.B., Thornber, C.S., Rodriguez, L.F., Tomanek, L., and Williams, S.L. 2006. The impacts of climate change in coastal marine systems. Ecology Letters **9**: 228-241. doi:10.1111/j.1461-0248.2005.00871.x.

Holdsworth, A.M., Zhai, L., Lu, Y., and Christian, J.R. 2021. Future changes in oceanography and biogeochemistry along the Canadian Pacific continental margin. Frontiers in Marine Science **8**: 602991.

[IPCC] Intergovernmental Panel on Climate Change. 2014. Summary for policymakers. *In* Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment

Report of the Intergovernmental Panel on Climate Change. *Edited by* C.B. Field and V.R. Barros and D.J. Dokken and K.J. Mach and M.D. Mastrandrea and T.E. Bilir and M. Chatterjee and K.L. Ebi and Y.O. Estrada and R.C. Genova and B. Girma and E.S. Kissel and A.N. Levy and S. MacCracken and P.R. Mastrandrea and L.L. White. Cambridge University Press, Cambridge, United Kingdom and New York, USA. pp. 1-32.

[IUCN] Interional Union for Conservation of Nature. 2008. Guidelines for applying protected area management categories. Gland, Switzerland.

[IUCN WCPA] International Union for Conservation of Nature World Commission on Protected Areas. 2019. Guidelines for recognizing and reporting other effective area-based conservation measures. Gland, Switzerland.

Jones, K.R., Watson, J.E.M., Possingham, H.P., and Klein, C.J. 2016. Incorporating climate change into spatial conservation prioritization: A review. Biological Conservation **194**: 121-130.

Jump, A.S., and Penuelas, J. 2005. Running to stand still: Adaptation and the response of plants to rapid climate change. Ecology Letters **8**(9): 1010-1020. doi:10.1111/j.1461-0248.2005.00796.x.

Keppel, G., Mokany, K., Wardell-Johnson, G.W., Phillips, B.L., Welbergen, J.A., and Reside, A.E. 2015. The capacity of refugia for conservation planning under climate change. Frontiers in Ecology and the Environment **13**(2): 106-112.

Khangaonkar, T., Nugraha, A., Xu, W., and Balaguru, K. 2019. Salish Sea response to global climate change, sea level rise, and future nutrient loads. Journal of Geophysical Research **124**(6): 3876-3904.

Kroeker, K.J., Kordas, R.L., and Harley, C.D.G. 2017. Embracing interactions in ocean acidification research: Confronting multiple stressor scenarios and context dependence. Biology Letters **13**: 20160802. doi:10.1098/rsbl.2016.0802.

Langdon, C., and Atkinson, M.J. 2005. Effect of elevated pCO2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. Journal of Geophysical Research **110**: C09S07.

Li, L., Hollowed, A.B., Cokelet, E.D., Barbeaux, S.J., Bond, N.A., Keller, A.A., King, J.R., McClure, M.M., Palsson, W.A., Stabeno, P.J., and Yang, Q. 2019. Subregional differences in groundfish distributional responses to anomalous ocean bottom temperatures in the northeast Pacific. Global Change Biology **25**: 2560-2575. doi:10.1111/gcb.14676.

Madec, G. 2008. NEMO ocean engine. Note Du Pôle De Modélisation. Institut Pierre-Simon Laplace (IPSL), France No 27, ISSN No 1288-1619.

Magris, R.A., Heron, S.F., and Pressey, R.L. 2015. Conservation planning for coral reefs accounting for climate warming disturbances. PLoS One **10**(11): e0140828. doi:10.1371/journal.pone.0140828.

Magris, R.A., Treml, E.A., Pressey, R.L., and Weeks, R. 2016. Integrating multiple species connectivity and habitat quality into conservation planning for coral reefs. Ecography **39**: 649-664. doi:10.1111/ecog.01507.

Malhi, Y., Franklin, J., Seddon, N., Solan, M., Turner, M.G., Field, C.B., and Knowlton, N. 2020. Climate change and ecosystems: Threats, opportunities and solutions. Philosophical Transactions of the Royal Society B Biological Sciences **375**: 20190104. doi:10.1098/rstb.2019.0104.

Margules, C.R., and Pressey, R.L. 2000. Systematic conservation planning. Nature **405**: 243-253.

Masson, D., and Fine, I. 2012. Modeling seasonal to interannual ocean variability of coastal British Columbia. Journal of Geophysical Research: Oceans **117**: C10019. doi:10.1029/2012JC008151.

McLeod, E., Salm, R., Green, A., and Almany, J. 2009. Designing marine protected area networks to address the impacts of climate change. Frontiers in Ecology and the Environment **7**: 362-370. doi:10.1890/070211.

Mcleod, E., Anthony, K.R.N., Mumby, P.J., Maynard, J., Beeden, R., Graham, N.A.J., Heron, S.F., Hoegh-Guldberg, O., Jupiter, S., MacGowan, P., Mangubhai, S., Marshall, N., Marshall, P.A., McClanahan, T.R., Mcleod, K., Nyström, M., Obura, D., Parker, B., Possingham, H.P., Salm, R.V., and Tamelander, J. 2019. The future of resilience-based management in coral reef ecosystems. Journal of Environmental Management **233**: 291-301. doi:10.1016/j.jenvman.2018.11.034.

Micheli, F., Saenz-Arroyo, A., Greenley, A., Vazquez, L., Espinoza Montes, J.A., Rossetto, M., and de Leo, G.A. 2012. Evidence that marine reserves enhance resilience to climatic impacts. PLoS ONE **7**(7): e40832. doi:10.1371/journal.pone.0040832.

Morelli, T.L., Daly, C., Dobrowski, S.Z., Dulen, D.M., Ebersole, J.L., Jackson, S.T., Lundquist, J.D., Millar, C.I., Maher, S.P., Monahan, W.B., Nydick, K.R., Redmond, K.T., Sawyer, S.C., Stock, S., and Beissinger, S.R. 2016. Managing climate change refugia for climate adaptation. PLoS One **11**(8): e0159909. doi:10.1371/journal.pone.0159909.

Morikawa, M.K., and Palumbi, S.R. 2019. Using naturally occurring climate resilient corals to construct bleaching-resistant nurseries. Proceedings of the National Academy of Sciences of the United States of America **116**(21): 10586-10591. doi:10.1073/pnas.1721415116.

Morrison, J., Callendar, W., Foreman, M.G.G., Masson, D., and Fine, I. 2014. A model simulation of future oceanic conditions along the British Columbia continental shelf. Part I: Forcing fields and initial conditions. Atmosphere-Ocean **52**(1): 1-19. doi:10.1080/07055900.2013.873014.

Mumby, P.J., Elliott, I.A., Eakin, C.M., Skirving, W., Paris, C.B., Edwards, H.J., Enríquez, S., Iglesias-Prieto, R., Cherubin, L.M., and Stevens, J.R. 2011. Reserve design for uncertain responses of coral reefs to climate change. Ecology Letters **14**: 132-140. doi:10.1111/j.1461-0248.2010.01562.x.

Okey, T.A., Alidina, H.M., Lo, V., and Jessen, S. 2014. Effects of climate change on Canada's Pacific marine ecosystems: A summary of scientific knowledge. Reviews in Fish Biology and Fisheries **24**: 519-559. doi:10.1007/s11160-014-9342-1.

Peña, A., Fine, I., and Masson, D. 2018. Towards climate change projections of biogeochemical conditions along the British Columbia coast. *In* Report of Working Group 29 on Regional Climate Modeling, Chapter 13, Pages 114-124. *Edited by* C.J. Jang and E. Curchister. North Pacific Marine Science Organization (PICES) Scientific Report No. 54, 177 p., Sidney, Canada.

Peña, M.A., Fine, I., and Callendar, W. 2019. Interannual variability in primary production and shelf-offshore transport of nutrients along the northeast Pacific Ocean margin. Deep-Sea Research Part II **169**: 104637.

Pinsky, M.L., Eikeset, A.M., McCauley, D.J., Payne, J.L., and Sunday, J.M. 2019. Greater vulnerability to warming of marine versus terrestrial ectotherms. Nature **569**(7754): 108-111. doi:10.1038/s41586-019-1132-4.

Poloczanska, E.S., Burrows, M.T., Brown, C.J., García Molinos, J., Halpern, B.S., Hoegh-Guldberg, O., Kappel, C.V., Moore, P.J., Richardson, A.J., Schoeman, D.S., and Sydeman, W.J. 2016. Responses of marine organisms to climate change across oceans. Frontiers in Marine Science **3**: 62. doi:10.3389/fmars.2016.00062.

Pörtner, H.O., and Farrell, A.P. 2008. Physiology and climate change. Science **322**: 690-692.

Ross, T., Du Preez, C., and Ianson, D. 2020. Rapid deep ocean deoxygenation and acidification threaten life on Northeast Pacific seamounts. Global Change Biology **26**: 6424-6444. doi:10.1111/gcb.15307.

Sala, E., and Knowlton, N. 2006. Global marine biodiversity trends. Annual Review of Environment and Resources **31**: 93-122. doi:10.1146/annurev.energy.31.020105.100235.

Somero, G.N. 2010. The physiology of climate change: How potentials for acclimatization and genetic adaptation will determine ‘winners’ and ‘losers’. Journal of Experimental Biology **213**: 912-920. doi:10.1242/jeb.037473.

Tittensor, D.P., Beger, M., Boerder, K., Boyce, D.G., Cavanagh, R.D., Cosandey-Godin, A., Ortuño Crespo, G., Dunn, D.C., Ghiffary, W., Grant, S.M., Hannah, L., Halpin, P.N., Harfoot, M., Heaslip, S.G., Jeffery, N.W., Kingston, N., Lotze, H.K., McGowan, J., McLeod, E., McOwen, C.J., O’Leary, B.C., Schiller, L., Stanley, R.R.E., Westhead, M., Wilson, K.L., and Worm, B. 2019. Integrating climate adaptation and biodiversity conservation in the global ocean. Science Advances **5**: eaay9969.

Whitney, C.K. 2019. Adaptive capacity, coastal communities, and marine conservation planning in the face of climate change. Doctoral dissertation. School of Environmental Studies, University of Victoria, Victoria, Canada.

Wilson, K.L., Tittensor, D.P., Worm, B., and Lotze, H.K. 2020. Incorporating climate change adaptation into marine protected area planning. Global Change Biology **26**(6): 3251-3267. doi:10.1111/gcb.15094.

Appendix A: User manual for MPA spatial analysis tool

Introduction

This geoprocessing tool has been developed to evaluate 1) sea surface and 2) benthic a) temperature, b) aragonite saturation state, and c) dissolved oxygen within MPAs in three of Canada's Pacific Bioregions. The tool uses zonal statistics to calculate the mean, minimum, maximum, and range of environmental parameter values within each MPA polygon (or other spatial boundaries of interest). The analysis is completed using two different regional ocean models (BCCM and NEP36-CanOE) that have different spatial extent and resolution so there are separate input rasters and results for each ocean model. The user determines whether the input rasters are the parameter values for a historical or hindcast time period and a projected future time period, or the change in parameter values between the time periods. Only MPA polygons with >50% overlap with each ocean model's output extent are included in the analysis for that ocean model. The result is a feature class for each summary statistic that contains polygons of the MPA area included in the analysis and a separate field for each input raster that shows the mean parameter value within each MPA. Temperature and dissolved oxygen values are reported in ºC and µmol/L respectively.

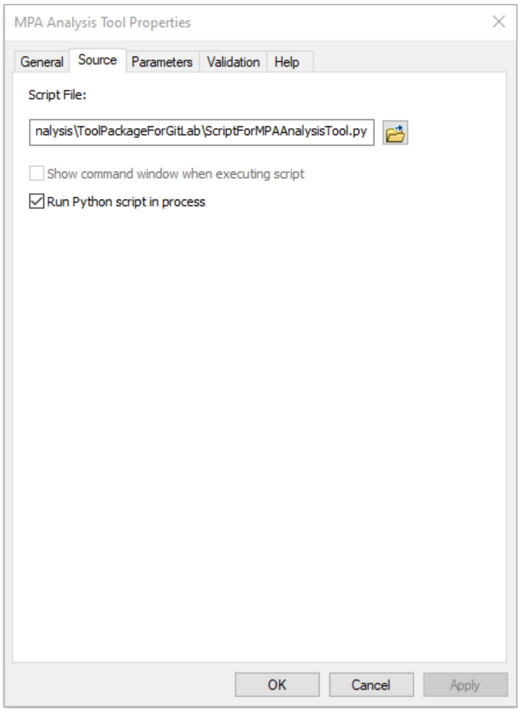
Using the Tool

The geoprocessing tool has been designed to run in ArcGIS and is saved in an ArcGIS toolbox (MPA_Analysis_Tool.tbx\MPAAnalysisTool) as 'MPAAnalysisTool'. In order to run the tool, an active license is needed for ArcGIS and the Spatial Analyst extension. The tool's source code is saved in a Python script (ScriptForMPAAnalysisTool.py). In order to use this tool, make sure that the Python script ('ScriptForMPAAnalysisTool.py') is connected to the ArcGIS Tool:

1. Navigate to where 'MPAAnalysisTool' is saved in ArcCatalog or ArcMap and right click on it
2. On pop up menu, select 'Properties'
3. On the 'Source' tab, check that the 'Script File' location matches where the Python script is stored on your computer (Figure A1)
4. Make sure that the 'Run Python script in process' box is checked (Figure A1)

To run the tool:

1. Double click on 'MPAAnalysisTool' in ArcCatalog or ArcMap
2. Enter parameters into dialog box (Figure A2)
3. Click 'OK' to begin geoprocessing



Script File: nalysis\ToolPackageForGitLab\ScriptForMPAAnalysisTool.py

☐ Show command window when executing script

☑ Run Python script in process

Figure A1. Dialog box showing location of source python script file

Tool Parameters

The data package is split into a folder for each of the three Pacific Bioregions (Northern Shelf, Southern Shelf, and Offshore Pacific), with identical file structure within each bioregion's folder. The tool parameter locations are described here for the Northern Shelf Bioregion only, but are equivalent for the other bioregions

Bioregion: The polygon feature class containing the bioregion extent. The file that may be used is saved as: NSB_Inputs\InputFeatureClasses.gdb\NorthernShelfBioregion

MPAs: The feature class containing the marine protected area polygons. The analysis may be run on any set of polygons. The feature class used in the analysis for this technical report is saved as: NSB_Inputs\InputFeatureClasses.gdb\NSB_AllProtectedAreas

MPA ID Field Name: The field containing unique MPA IDs within the 'MPAs' feature class; all fields are listed in the drop down menu. The IDs must be numeric

BCCM Ocean Extent: The polygon feature class with the included area extent of the BCCM ocean model for the Pacific bioregion of interest. The file that must be used is saved as: NSB_Inputs\InputFeatureClasses.gdb\BCCM_NSB_OceanExtent

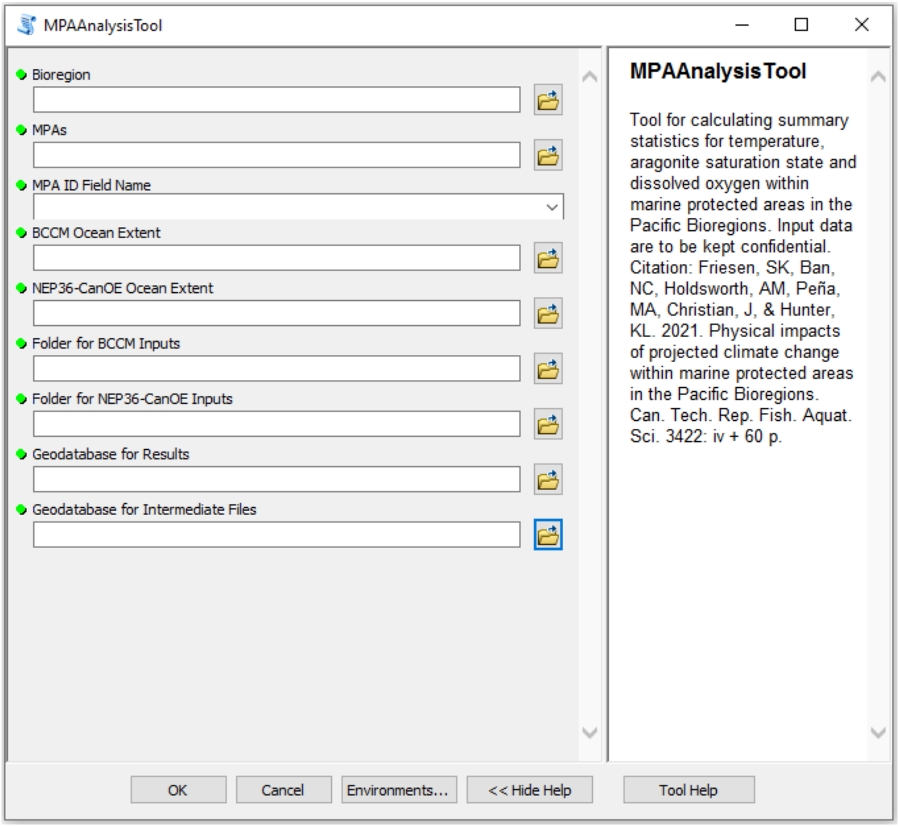
NEP36-CanOE Ocean Extent: The polygon feature class with the included area extent of the NEP36-CanOE ocean model for the Pacific bioregion of interest. The file that must be used is saved as: NSB_Inputs\InputFeatureClasses.gdb\NEP36_NSB_OceanExtent

Folder for BCCM Inputs: The folder containing raster TIFFs of parameter values across the bioregion for the BCCM ocean model. These rasters may contain the absolute parameter values for the time periods, or the change in parameter values between time periods. Temperature and dissolved oxygen values are reported in °C and µmol/L respectively. The folders to be used are saved as:
NSB_Inputs\mean_bccm_nsb_layers
NSB_Inputs\change_nsb_bccm

Folder for NEP36-CanOE Inputs: The folder containing raster TIFFs of parameter values across the bioregion for the NEP36-CanOE ocean model. These rasters may contain the absolute parameter values for the time periods, or the change in parameter values between time periods. Temperature and dissolved oxygen values are reported in °C and µmol/L respectively. The folders to be used are saved as:
NSB_Inputs\mean_nep36_nsb_layers
NSB_Inputs\change_nsb_nep36

Geodatabase for Results: The output geodatabase for results of the analysis. Geodatabase must exist before running tool. Recommend specifying an empty geodatabase as any pre-existing output files will be overwritten.

Geodatabase for Intermediate Files: The geodatabase where intermediate files created by the analysis will be stored. The geodatabase must exist before running tool, but may be deleted after tool has completed processing.



MPAAnalysisTool

Tool for calculating summary statistics for temperature, aragonite saturation state and dissolved oxygen within marine protected areas in the Pacific Bioregions. Input data are to be kept confidential. Citation: Friesen, SK, Ban, NC, Holdsworth, AM, Peña, MA, Christian, J, & Hunter, KL. 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.

Figure A2. Geoprocessing tool dialog box in ArcGIS

Naming Convention

Each input raster file name indicates the ocean model, parameter, sea layer, season, and time period:

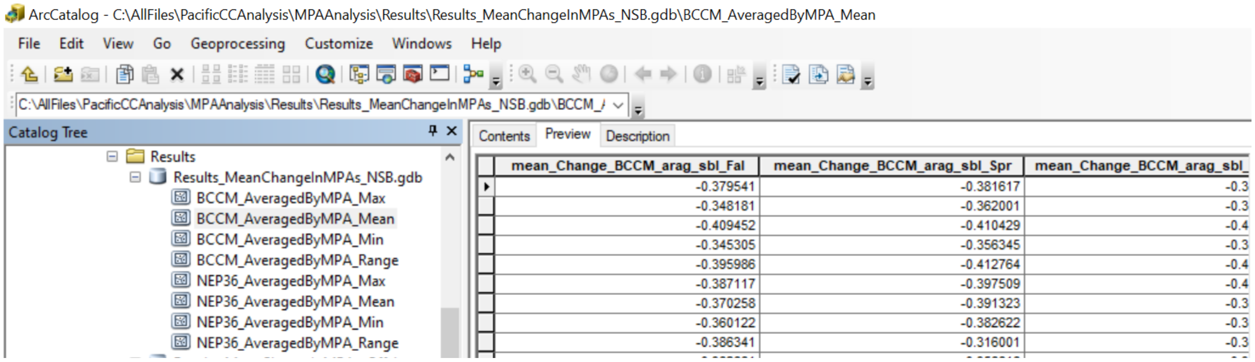
- ocean model: NEP36-CanOE [NEP36] or BCCM
- parameter: aragonite saturation state [arag], temperature [temp], or dissolved oxygen [oxyg]
- sea layer: sea surface layer [ssl] or sea bottom layer [sbl]
- time period: historical or hindcast period [hi], projected future period [RCP85], or change in parameter values between time period [change]
- season: spring [Spr], summer [Sum], fall [Fal], or winter [Win]

Examples:
BCCM_temp_ssl_RCP85_Win
NEP36_oxyg_sbl_hi_Spr
Change_NEP36_arag_sbl_Fal

The results are exported as a feature class containing the MPA polygons that were included in the analysis (>50% overlap with the ocean model extent). A separate output feature class is generated for each ocean model and summary statistic calculated (Figure A3). All fields that were present in the input MPA feature class will still be present in the output feature class, plus a field for each input raster processed (Figure A3). Field names will match the input rasters plus a prefix for the summary statistic calculated:

- mean – “mean_”
- minimum – “min_”
- maximum – “max_”
- range – “rng_”

Example:
max_BCCM_temp_ssl_RCP85_Win



- Results
  - Results_MeanChangeInMPAs_NSB.gdb
    - BCCM_AveragedByMPA_Max
    - BCCM_AveragedByMPA_Mean
    - BCCM_AveragedByMPA_Min
    - BCCM_AveragedByMPA_Range
    - NEP36_AveragedByMPA_Max
    - NEP36_AveragedByMPA_Mean
    - NEP36_AveragedByMPA_Min
    - NEP36_AveragedByMPA_Range

mean_Change_BCCM_arag_sbl_Fal	mean_Change_BCCM_arag_sbl_Spr	mean_Change_BCCM_arag_sbl_
-0.379541	-0.381617	-0.3
-0.348181	-0.362001	-0.3
-0.409452	-0.410429	-0.4
-0.345305	-0.356345	-0.3
-0.395986	-0.412764	-0.4
-0.387117	-0.397509	-0.4
-0.370258	-0.391323	-0.3
-0.360122	-0.382622	-0.3
-0.386341	-0.316001	-0.3

Figure A3. Example result geodatabase showing output feature classes (left) and subset of one output feature class’ attribute table showing field names for mean environmental parameter values (right).

Appendix B: Environmental parameter maps for the sea surface and benthic layers across the Pacific bioregions

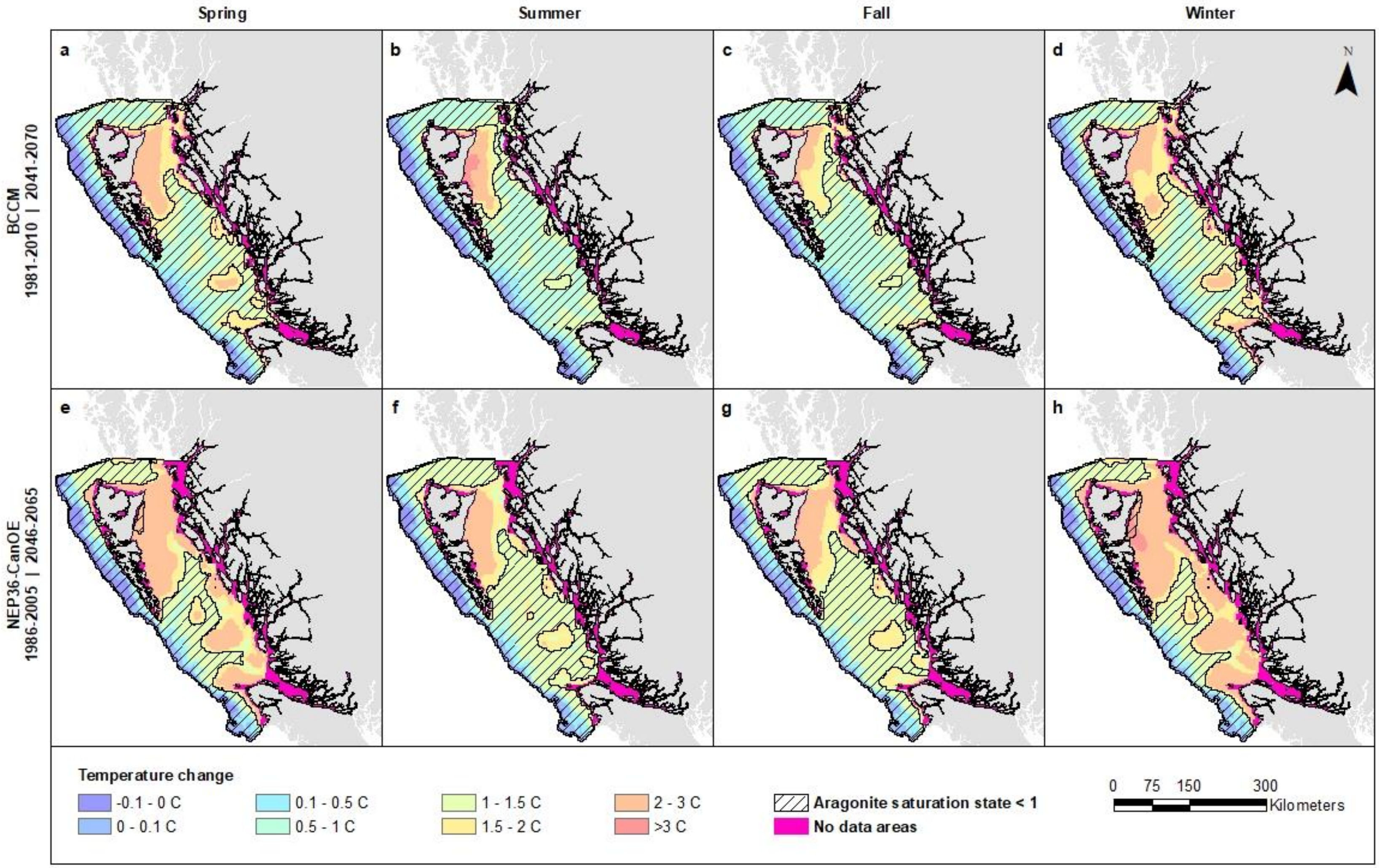


Figure B1. Seasonal mean benthic environmental parameters within the Northern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Note that the model domains do not extend to the inlets and nearshore.

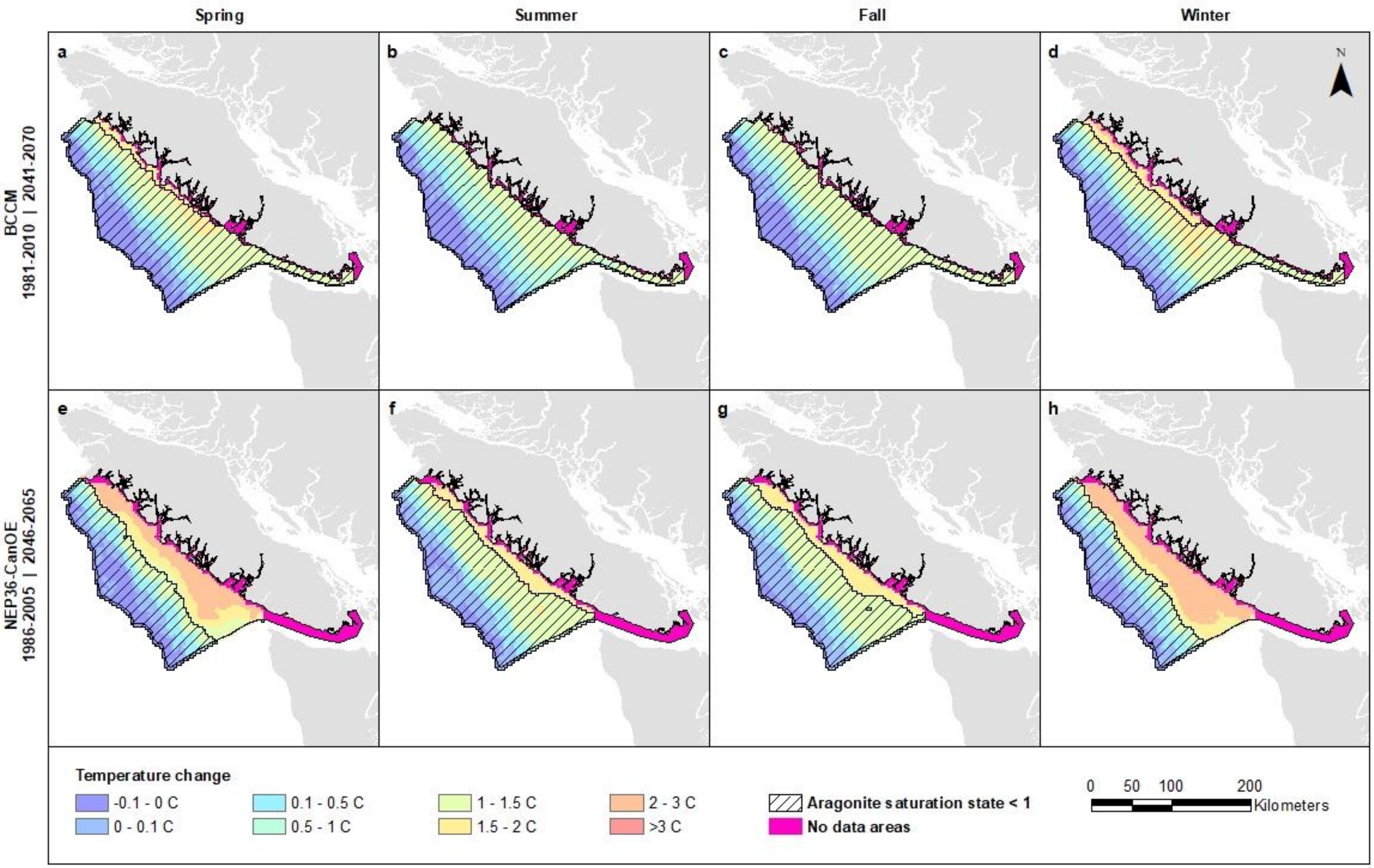


Figure B2. Seasonal mean benthic environmental parameters within the Southern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Note that the model domains do not extend to the inlets and nearshore.

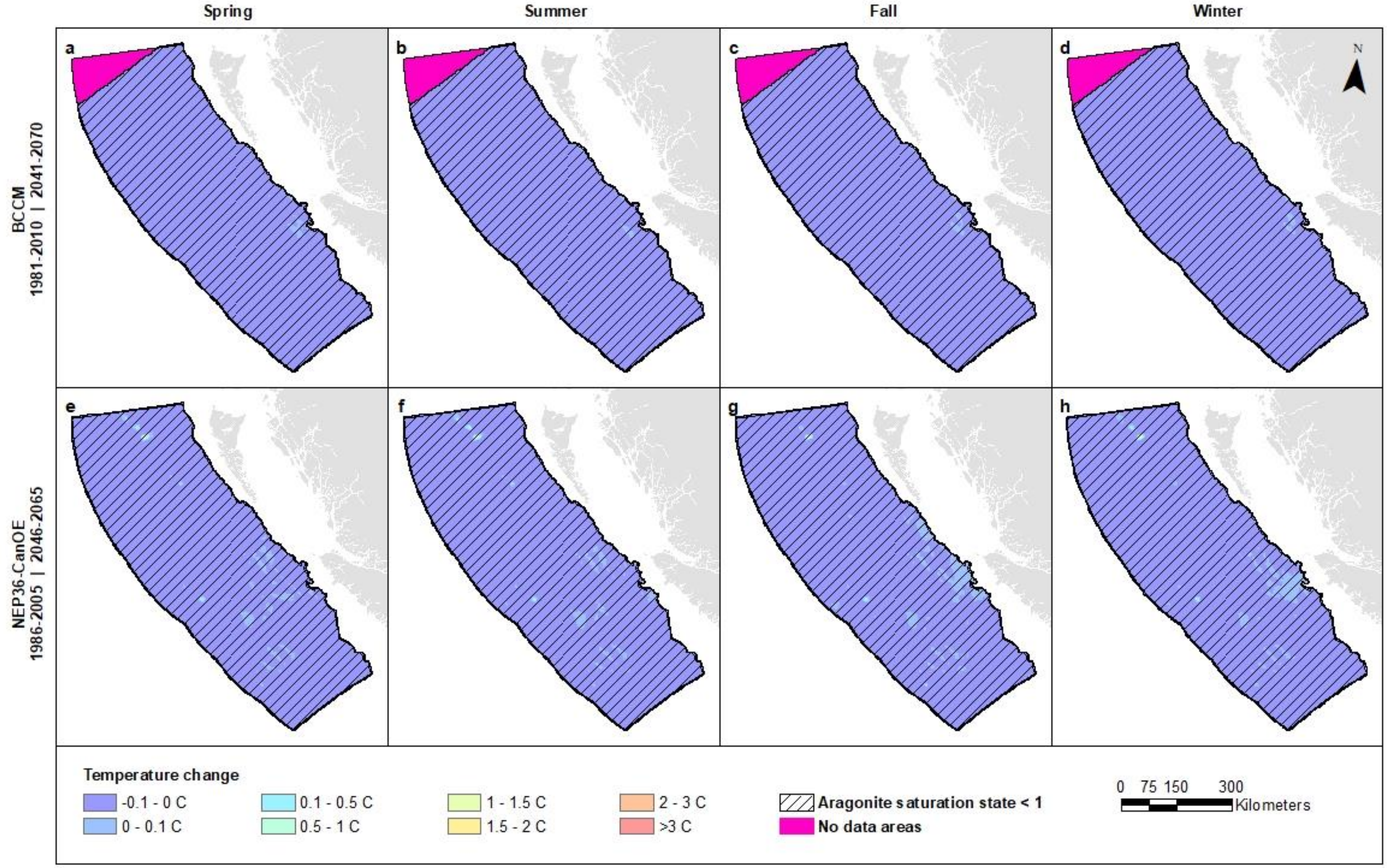


Figure B3. Seasonal mean benthic environmental parameters within the Offshore Pacific Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Note that the model domains do not extend to the inlets and nearshore.

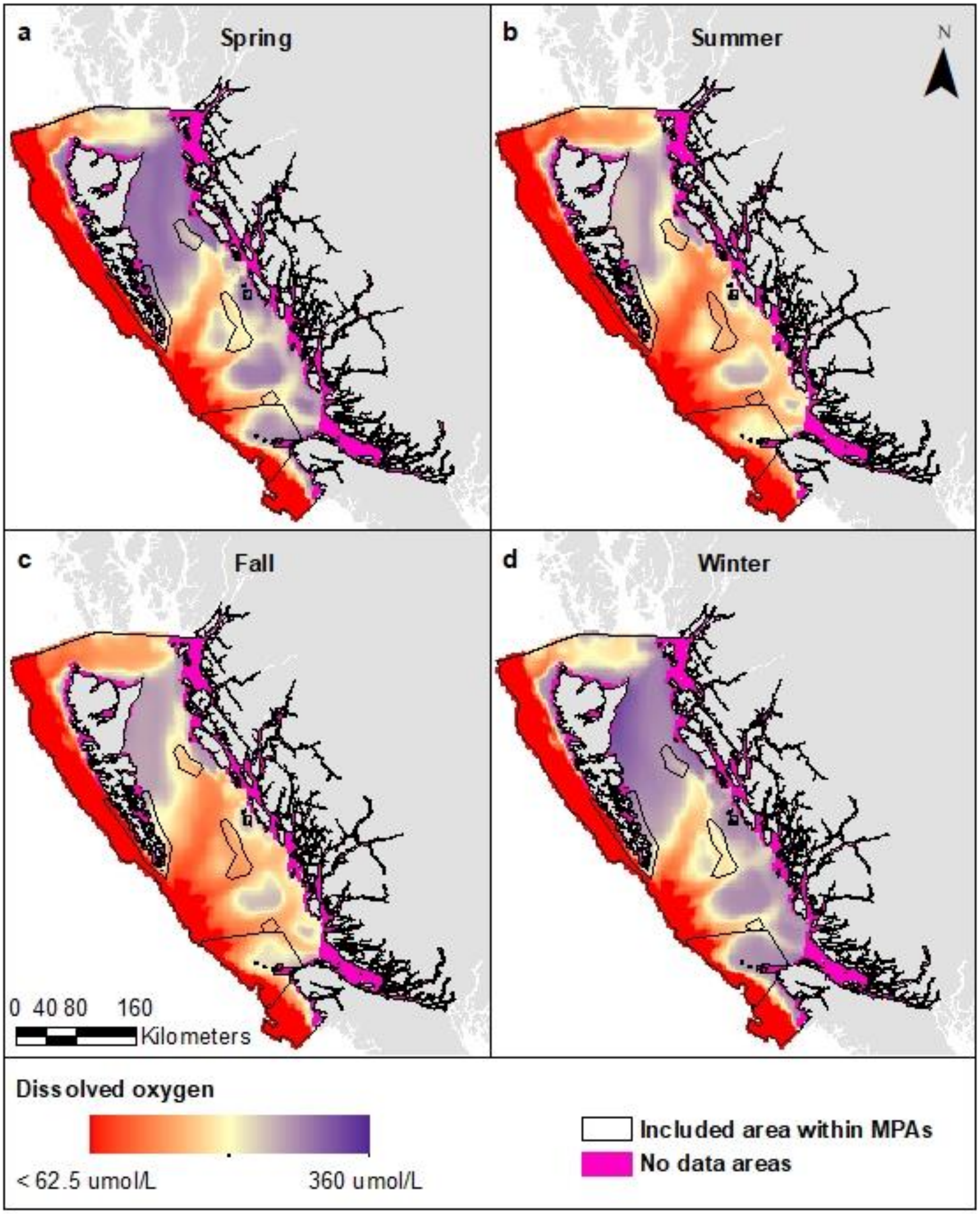


Figure B4. Projected future seasonal mean benthic dissolved oxygen (in µmol/L) in the Northern Shelf Bioregion using outputs from the NEP36-CanOE regional ocean model. Bright red indicates hypoxic areas where the mean dissolved oxygen is less than 62.5 µmol/L. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). Black outlines indicate the included area within marine protected areas in each analysis. Note that the model domains do not extend to the inlets and nearshore.

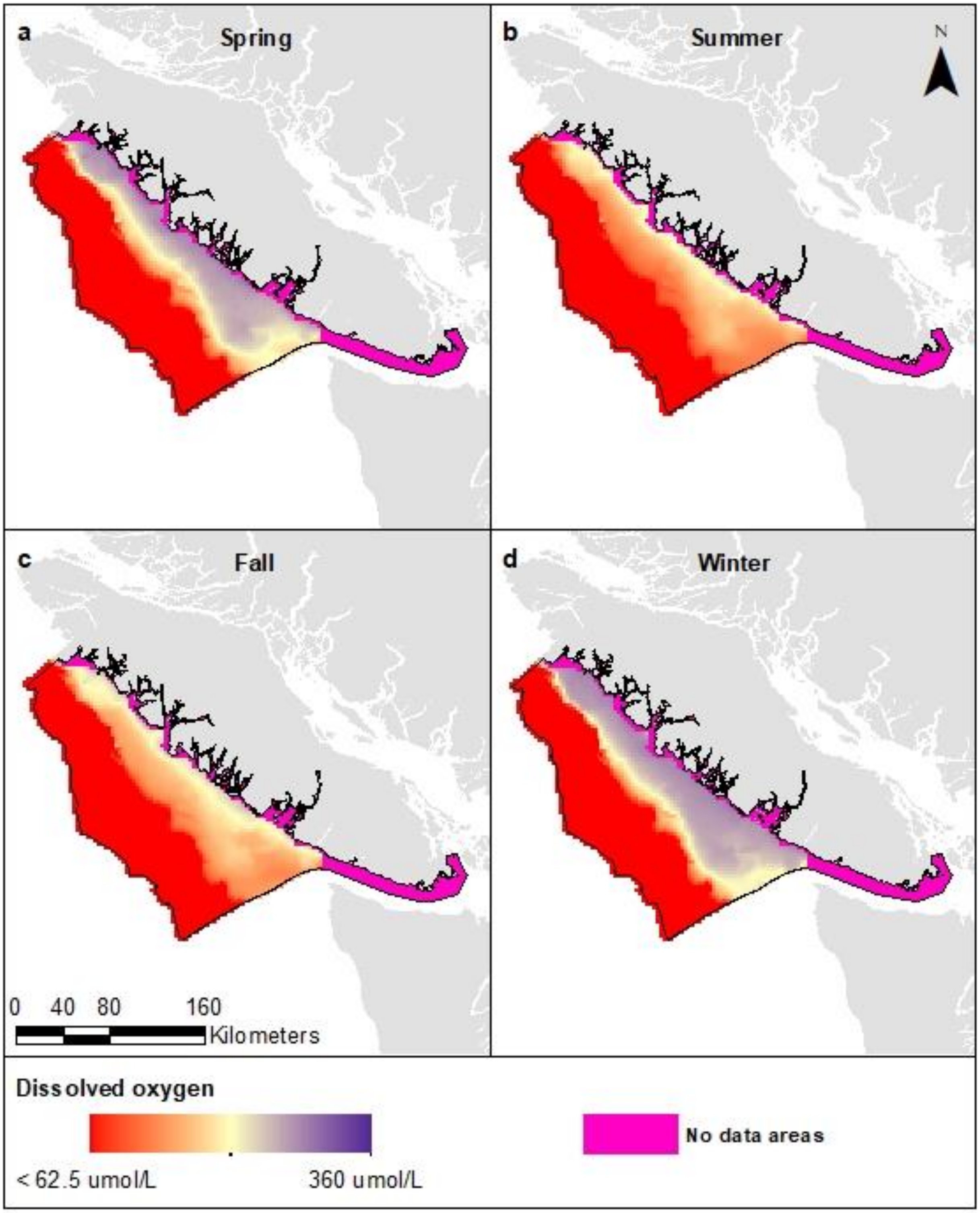


Figure B5. Projected future seasonal mean benthic dissolved oxygen (in µmol/L) in the Southern Shelf Bioregion using outputs from the NEP36-CanOE regional ocean model. Bright red indicates hypoxic areas where the mean dissolved oxygen is less than 62.5 µmol/L. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). No MPAs had at least 50% overlap with the NEP36-CanOE outputs in the Southern Shelf Bioregion. Note that the model domains do not extend to the inlets and nearshore.

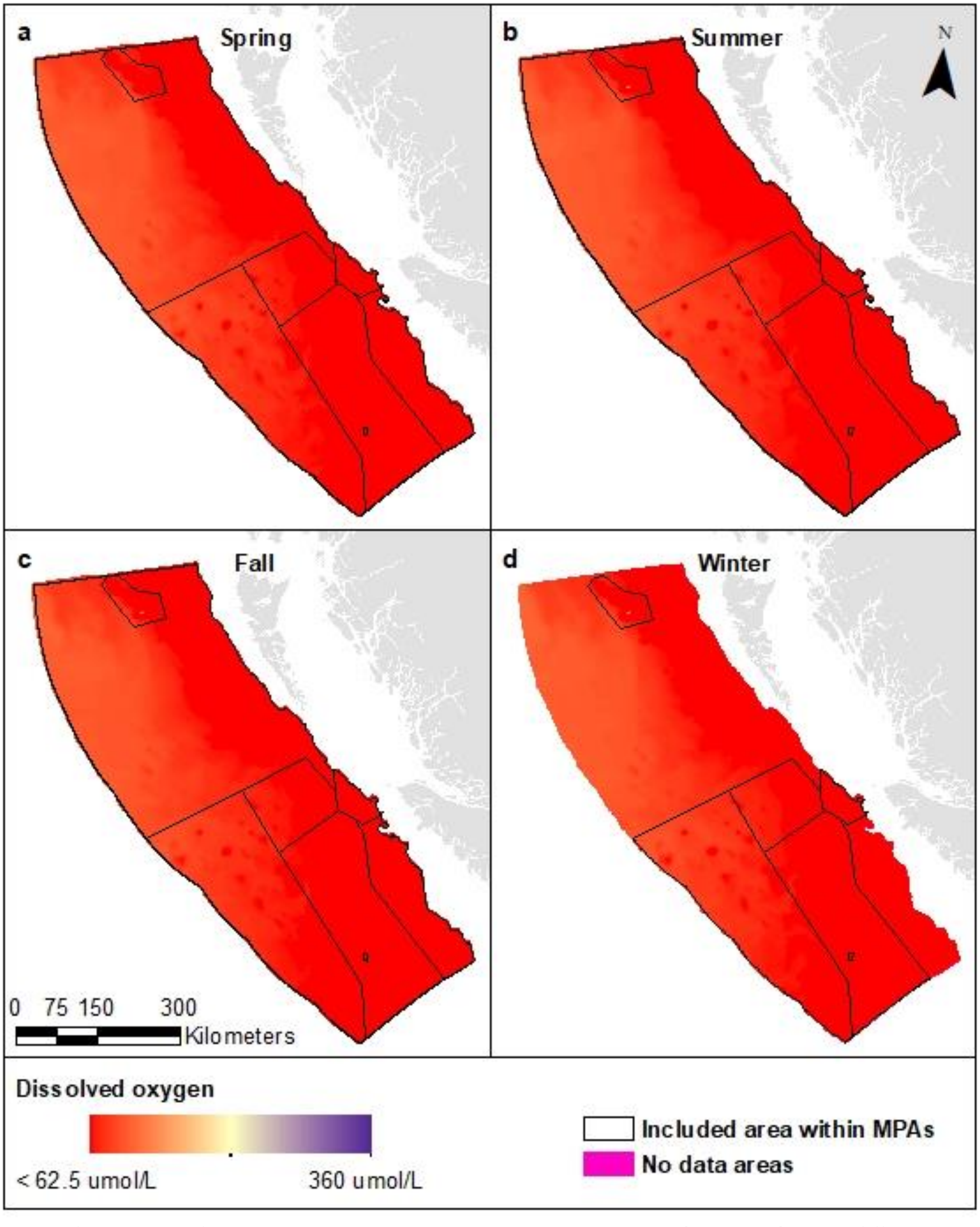


Figure B6. Projected future seasonal mean benthic dissolved oxygen (in µmol/L) in the Offshore Pacific Bioregion using outputs from the NEP36-CanOE regional ocean model. Bright red indicates hypoxic areas where the mean dissolved oxygen is less than 62.5 µmol/L. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

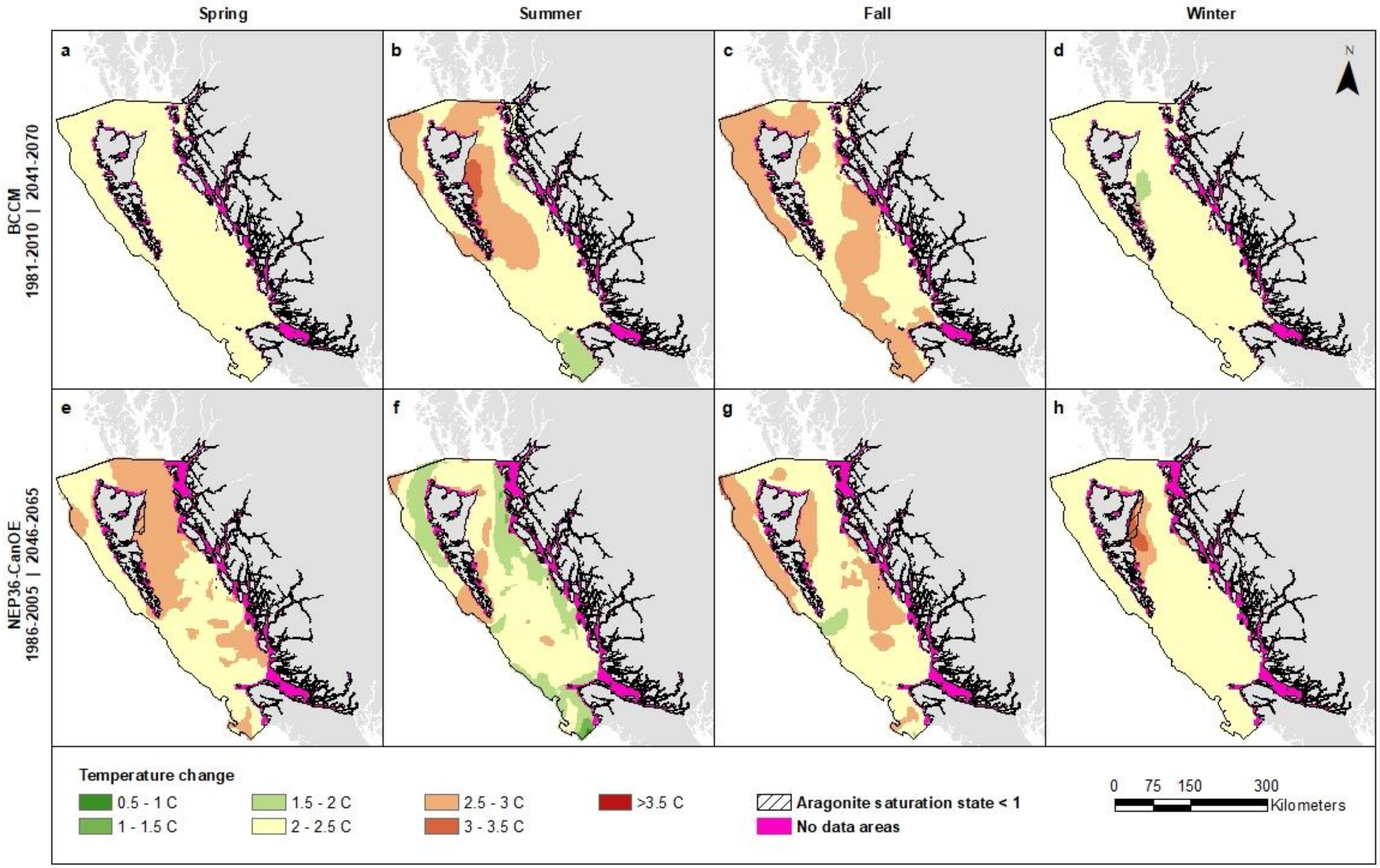


Figure B7. Seasonal mean sea surface environmental parameters within the Northern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Note that the model domains do not extend to the inlets and nearshore.

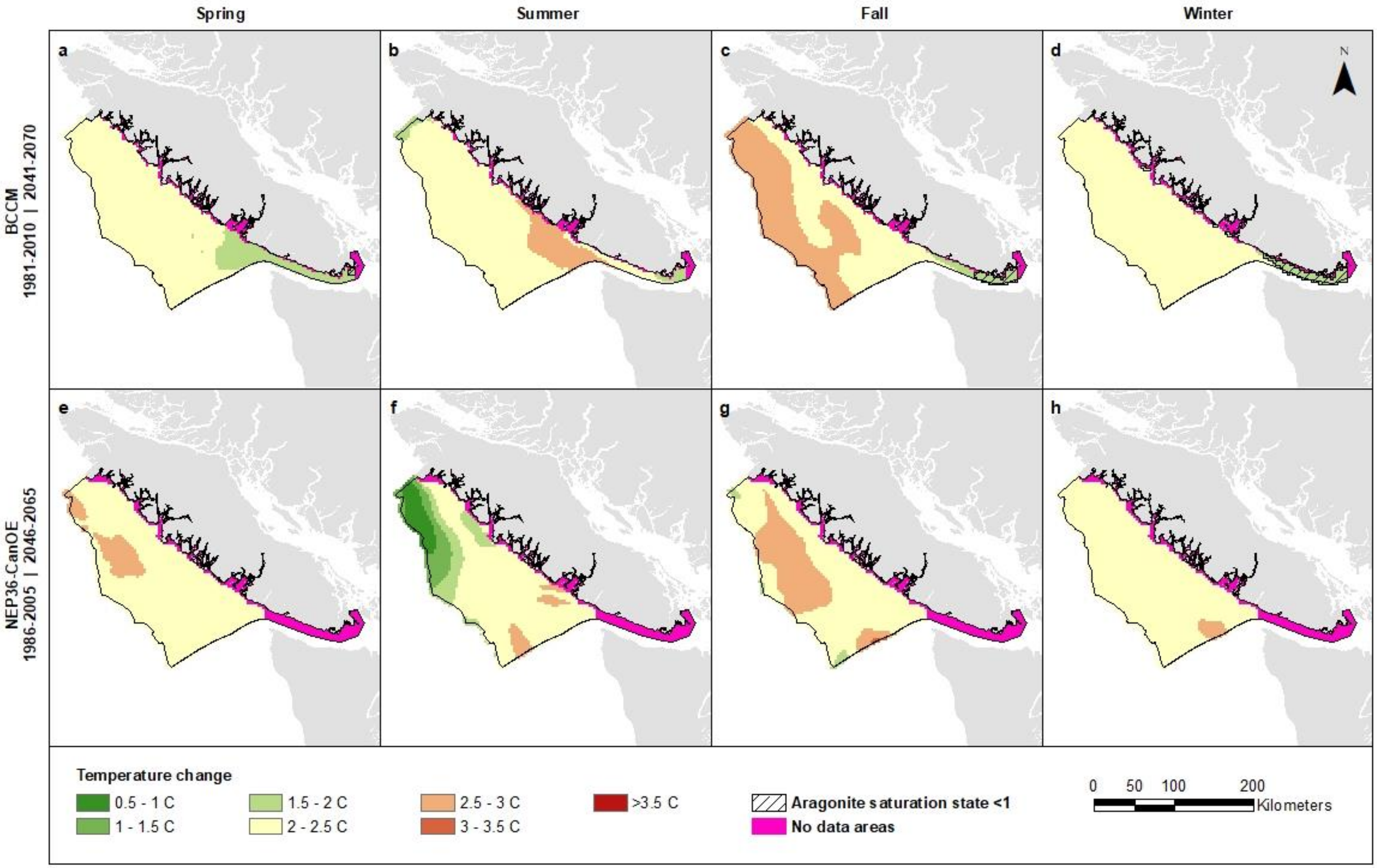


Figure B8. Seasonal mean sea surface environmental parameters within the Southern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Note that the model domains do not extend to the inlets and nearshore.

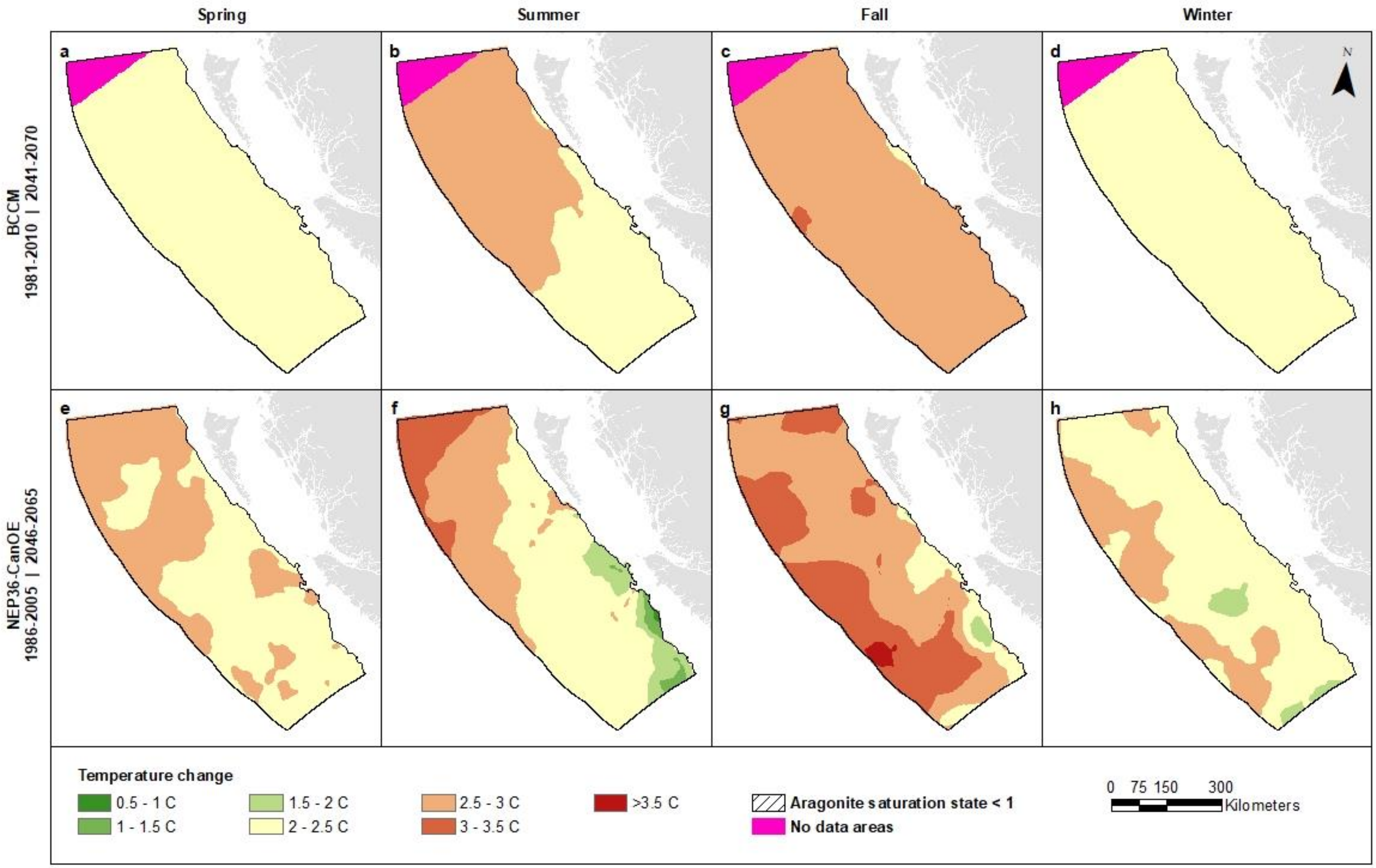


Figure B9. Seasonal mean sea surface environmental parameters within the Offshore Pacific Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Temperature change is the difference in temperature values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Hatching shows areas where the projected future mean aragonite saturation state (Ω_A) is less than 1, the threshold at which aragonite shells begin to dissolve [no sea surface areas with $\Omega_A < 1$ within this bioregion]. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Note that the model domains do not extend to the inlets and nearshore.

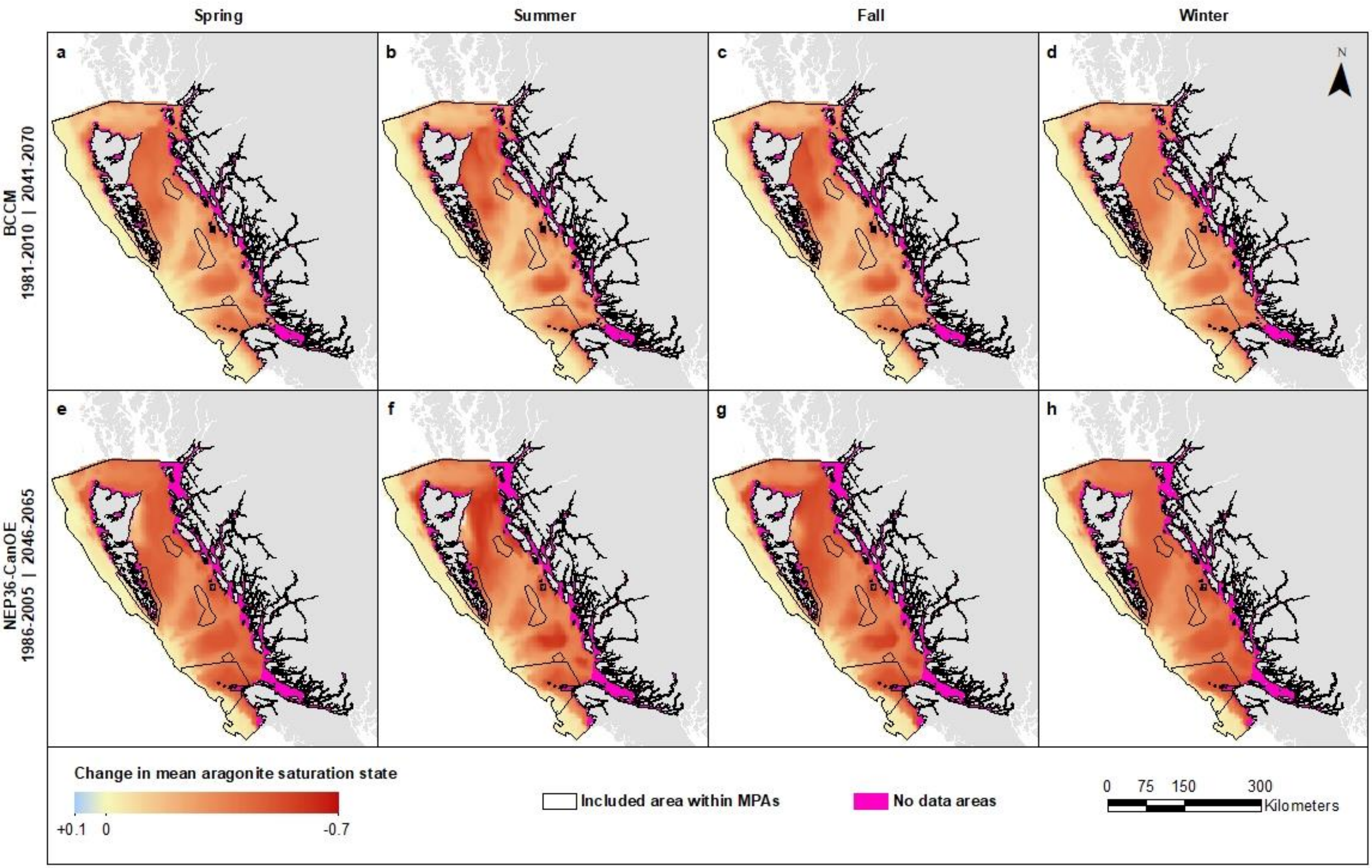


Figure B10. Change in seasonal mean benthic aragonite saturation state (Ω_A) within the Northern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Change is the difference in aragonite saturation state values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

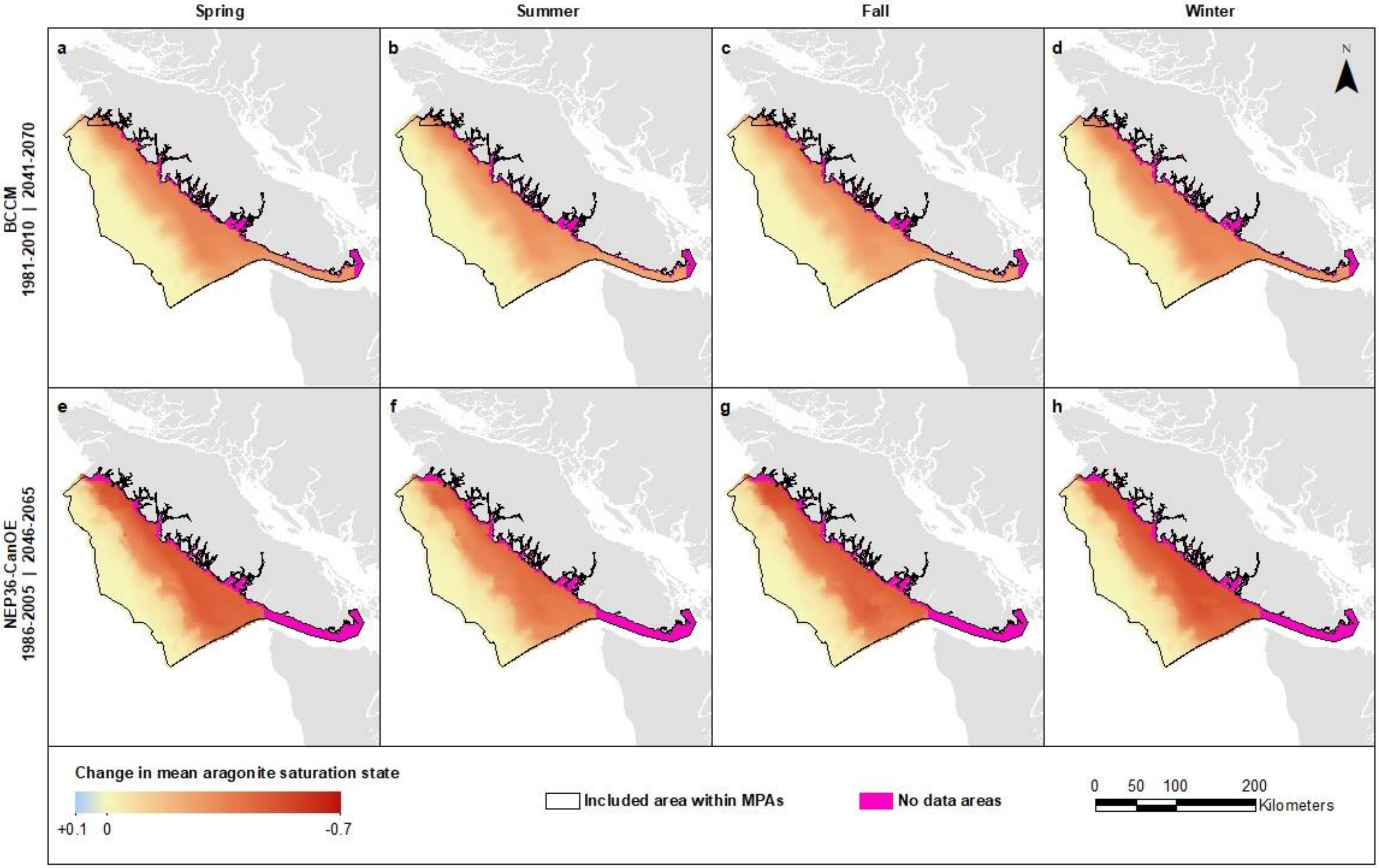


Figure B11. Change in seasonal mean benthic aragonite saturation state (Ω_A) within the Southern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Change is the difference in aragonite saturation state values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Black outline indicates the included area within the MPA in the BCCM analysis. Note that the model domains do not extend to the inlets and nearshore.

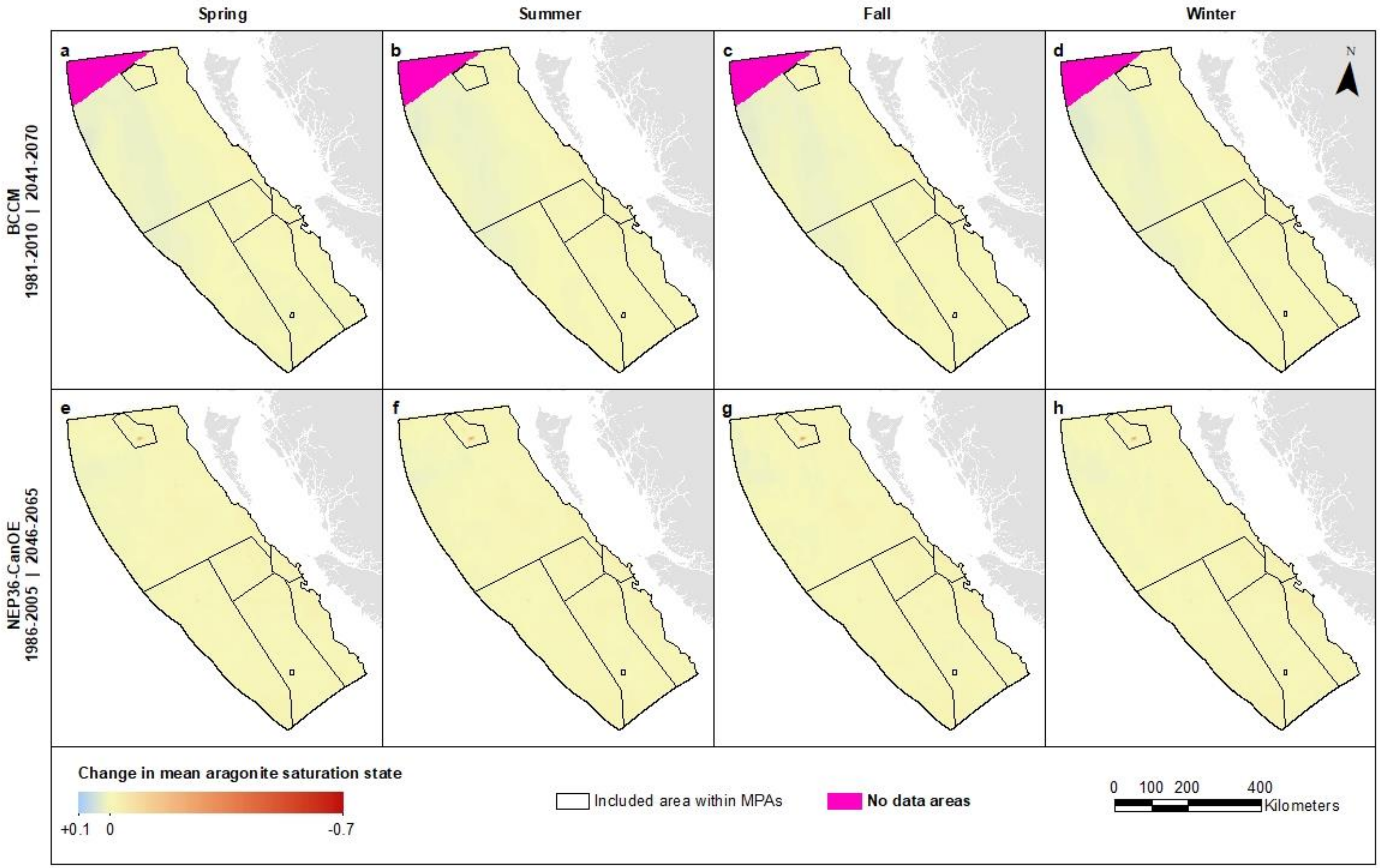


Figure B12. Change in seasonal mean benthic aragonite saturation state (Ω_A) within the Offshore Pacific Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Change is the difference in aragonite saturation state values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

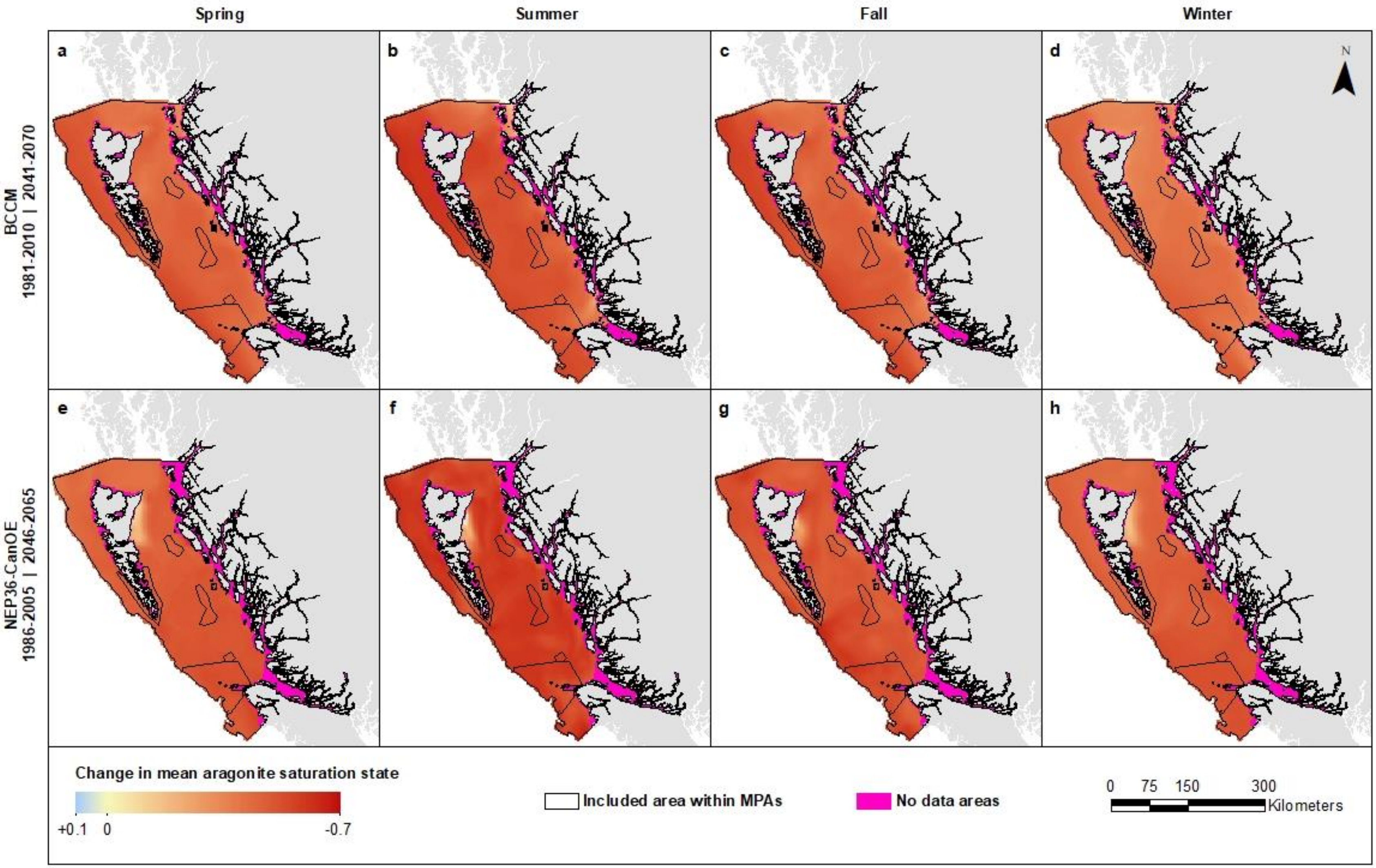


Figure B13. Change in seasonal mean surface aragonite saturation state (Ω_A) within the Northern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Change is the difference in aragonite saturation state values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

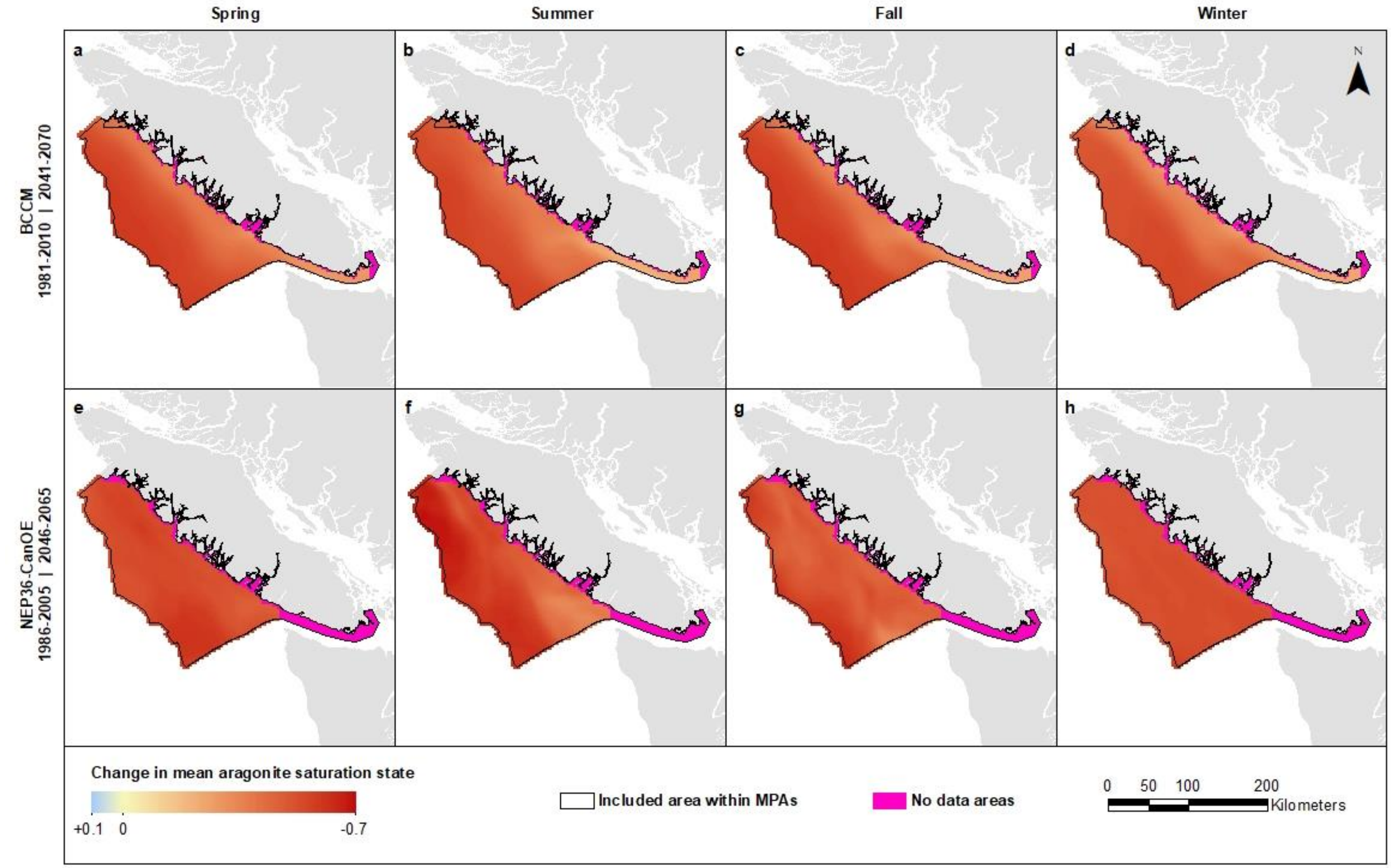


Figure B14. Change in seasonal mean surface aragonite saturation state (Ω_A) within the Southern Shelf Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Change is the difference in aragonite saturation state values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Black outline indicates the included area within the MPA in the BCCM analysis. Note that the model domains do not extend to the inlets and nearshore.

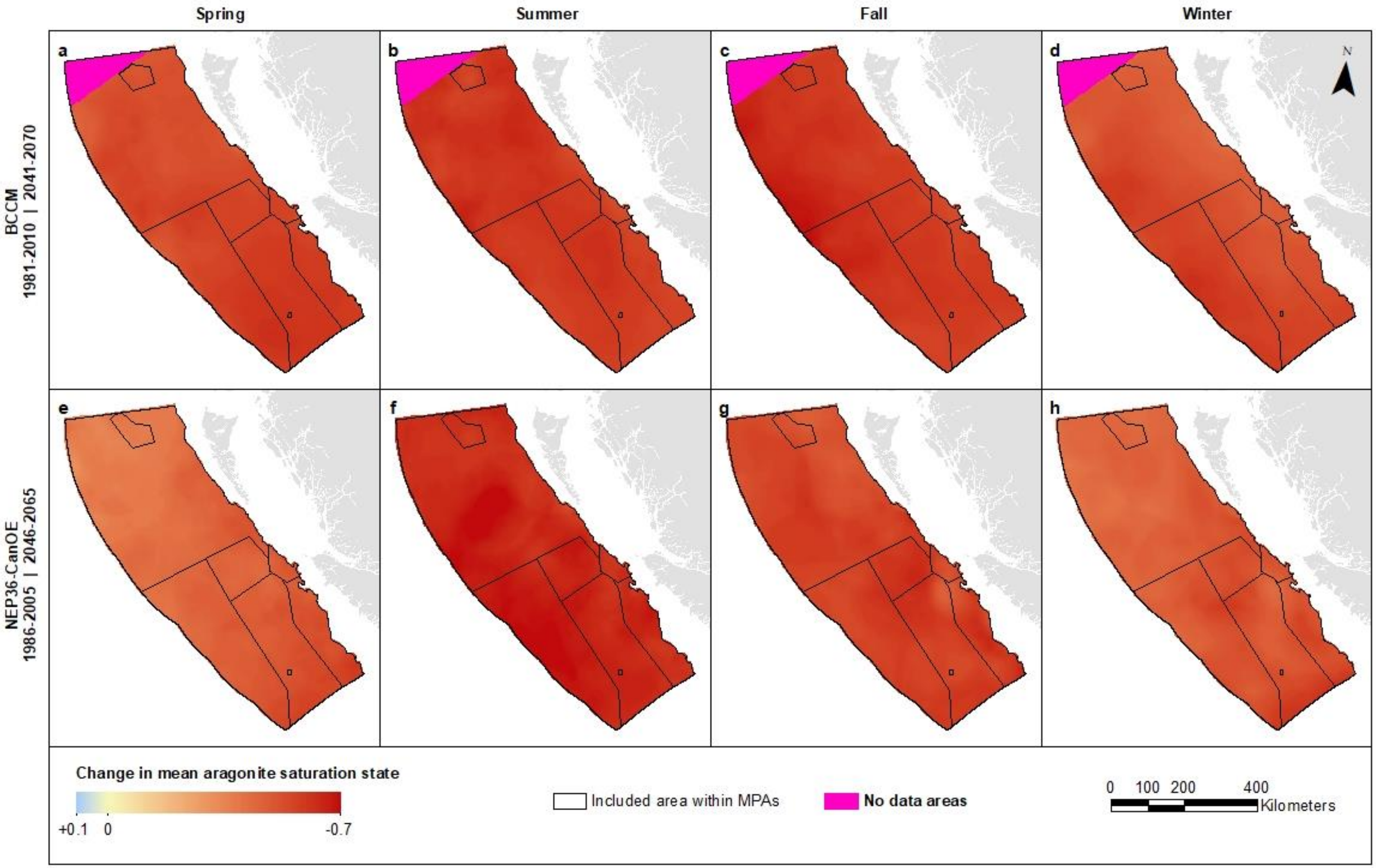


Figure B15. Change in seasonal mean surface aragonite saturation state (Ω_A) within the Offshore Pacific Bioregion using outputs from two regional ocean models: BCCM (a-d) and NEP36-CanOE (e-h). Change is the difference in aragonite saturation state values between two time periods: BCCM spans 1981-2010 and 2041-2070, while NEP36-CanOE spans 1986-2005 and 2046-2065. Seasons were delineated as: (a)(e) spring (Mar-Apr-May), (b)(f) summer (Jun-Jul-Aug), (c)(g) fall (Sep-Oct-Nov), and (d)(h) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

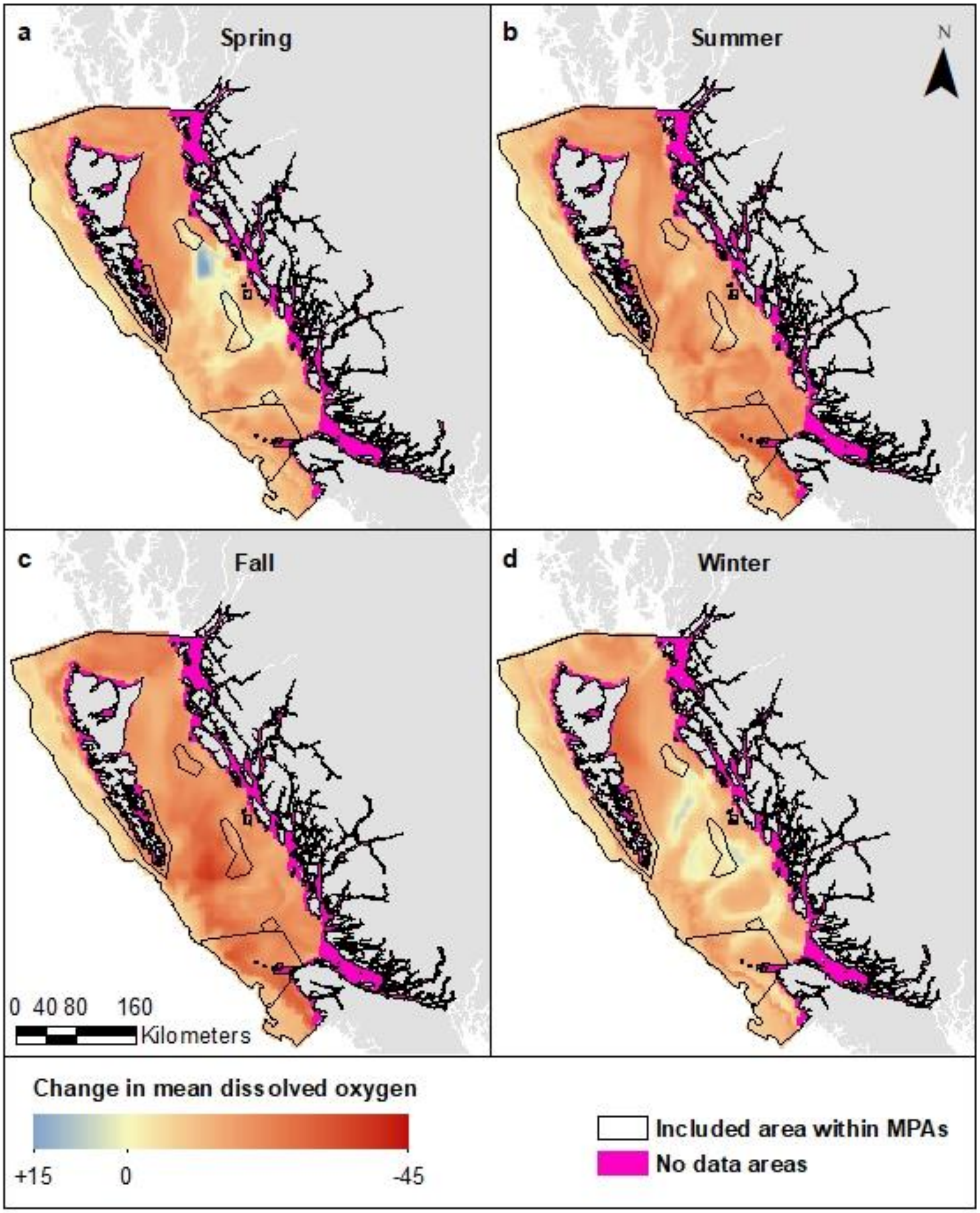


Figure B16. Change in seasonal mean benthic dissolved oxygen (in µmol/L) within the Northern Shelf Bioregion using outputs from the NEP36-CanOE regional ocean model. Change is the difference in dissolved oxygen values between two time periods: 1986-2005 and 2046-2065. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

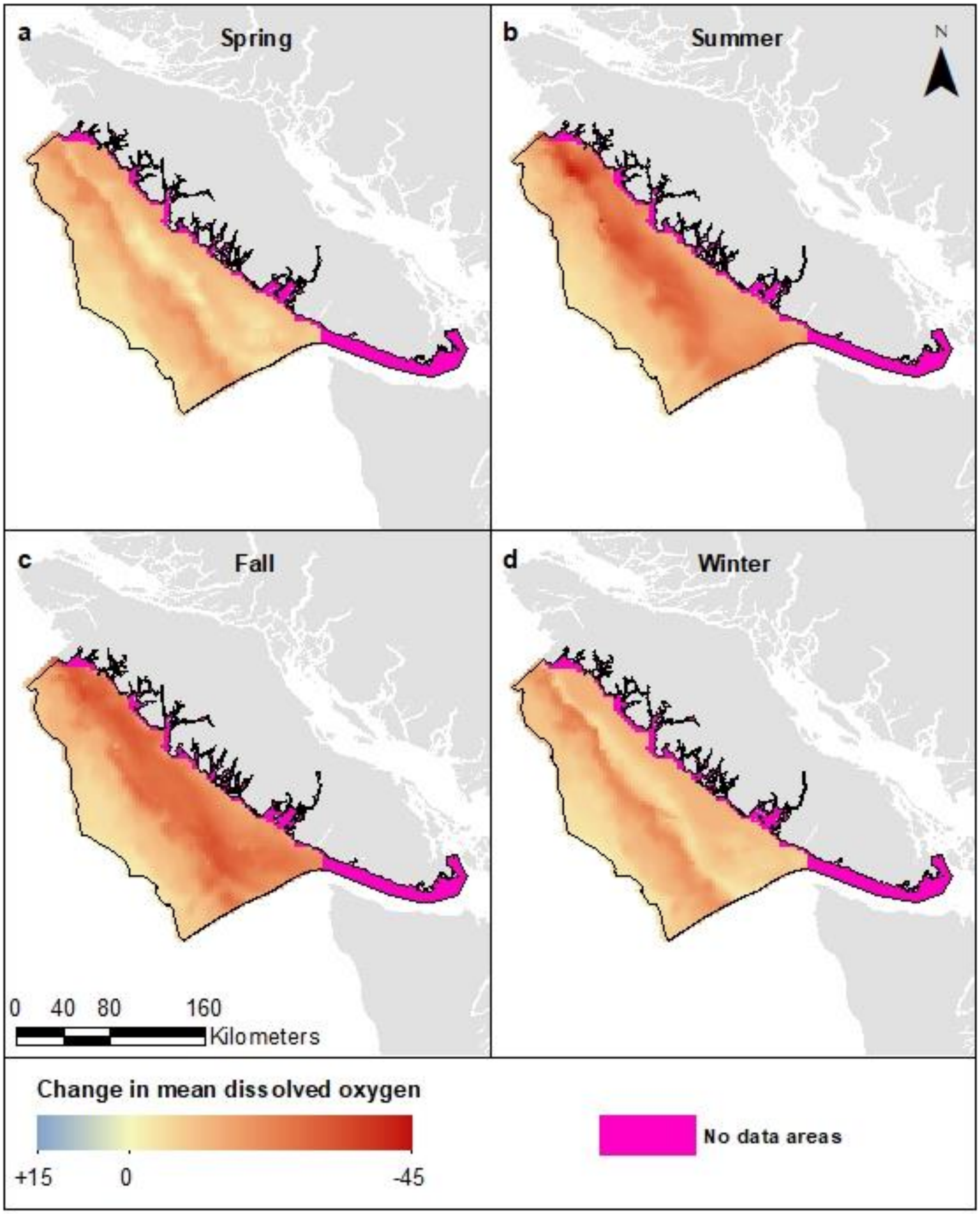


Figure B17. Change in seasonal mean benthic dissolved oxygen (in µmol/L) within the Southern Shelf Bioregion using outputs from the NEP36-CanOE regional ocean model. Change is the difference in dissolved oxygen values between two time periods: 1986-2005 and 2046-2065. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). No MPAs had at least 50% overlap with the NEP36-CanOE outputs in the Southern Shelf Bioregion. Note that the model domains do not extend to the inlets and nearshore.

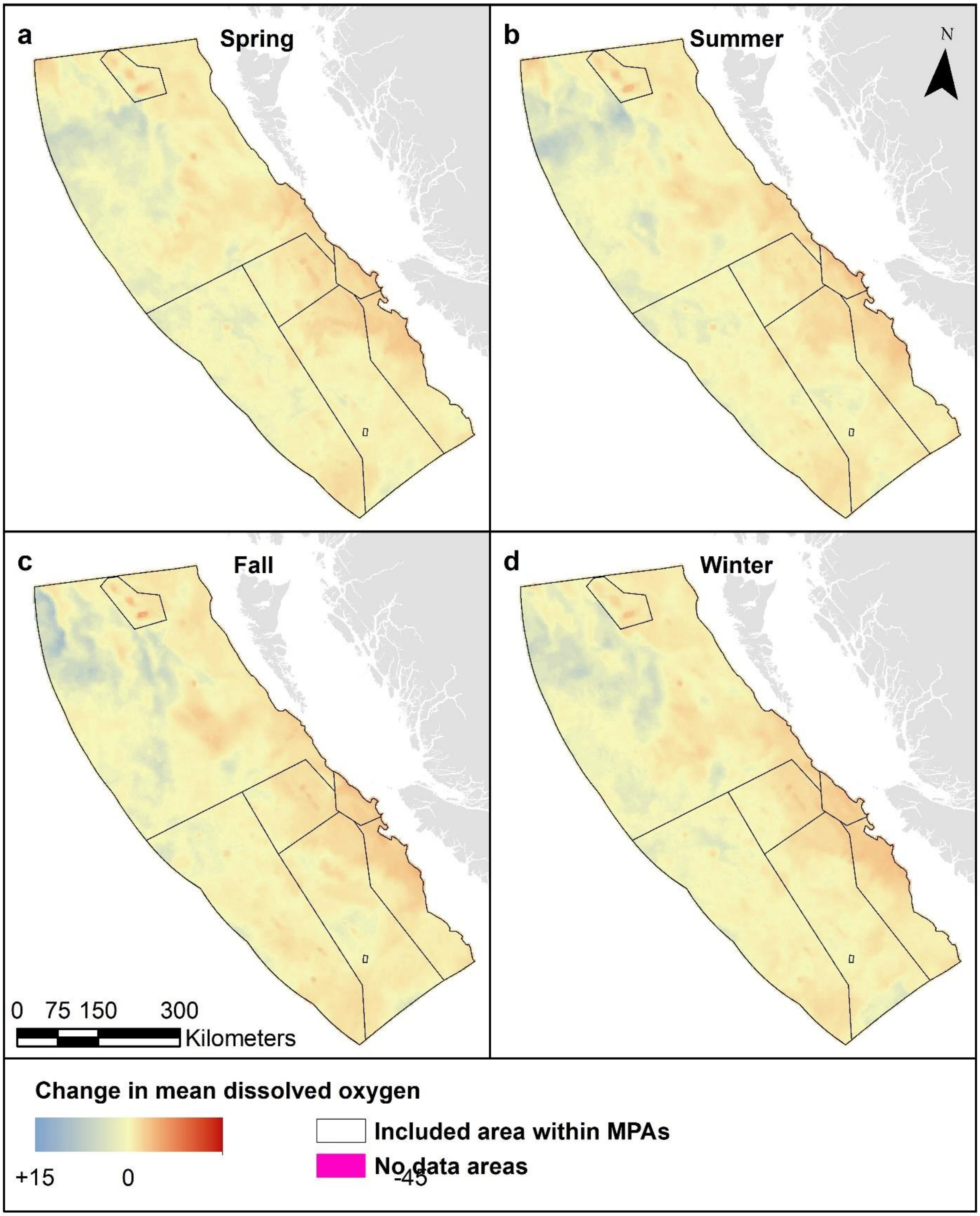


Figure B18. Change in seasonal mean benthic dissolved oxygen (in µmol/L) within the Offshore Pacific Bioregion using outputs from the NEP36-CanOE regional ocean model. Change is the difference in dissolved oxygen values between two time periods: 1986-2005 and 2046-2065. Seasons were delineated as: (a) spring (Mar-Apr-May), (b) summer (Jun-Jul-Aug), (c) fall (Sep-Oct-Nov), and (d) winter (Dec-Jan-Feb). Black outlines indicate the included area within MPAs in each analysis. Note that the model domains do not extend to the inlets and nearshore.

Appendix C: Supplementary information

Glossary

Aragonite saturation state (Ω_A): A measure of the tendency for aragonite to form or to dissolve. Aragonite is one of the two most abundant crystalline forms of calcium carbonate ($CaCO_3$) in the ocean. Organisms require calcium and carbonate ions for the formation of aragonite shells and skeletons. Increased dissolution of carbon dioxide (CO_2) in the ocean reduces the availability of carbonate ions $[CO_3^{2-}]$, decreasing the aragonite saturation state. $\Omega_A > 1$ indicates supersaturation which is conducive to shell formation, while $\Omega_A < 1$ indicates undersaturation which is conducive to shell dissolution. Some calcifying organisms may experience biological impairment of aragonite shell production at Ω_A well in excess of 1 (Langdon and Atkinson 2005).

Benthic layer: The model vertical layer immediately above the sea floor in each ocean model grid cell.

Exposure: The presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected [definition from IPCC (2014)].

Marine protected area: A clearly defined geographical space recognized, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values [definition from (IUCN 2008)].

Other effective area-based conservation measure (OECM): A geographically defined area other than a Protected Area, which is governed and managed in ways that achieve positive and sustained long-term outcomes for the in situ conservation of biodiversity, with associated ecosystem functions and services and, where applicable, cultural, spiritual, socioeconomic, and other locally relevant values [definition from IUCN WCPA (2019)].

Physical impacts: The impacts of climate change on geophysical systems [definition from IPCC (2014)]. In this report, we evaluate projected changes in three environmental parameters due to climate change.

Surface layer: The first vertical layer of the model, at the ocean surface, in each ocean model grid cell.

Oceanographic subdivision of Offshore Pacific Area of Interest

The Offshore Pacific AOI was divided into three very simplified oceanographic zones (coastal upwelling zone, upwelling/downwelling transition zone, and bifurcation zone; Figure C1) as in Du Preez and Norgard (in review). The oceanographic zones were originally presented in DFO (2019). Two modifications were made to the Du Preez and Norgard (in review) zones: 1. The northwest corner of the AOI was outside of all three zones, so it was added to the bifurcation zone polygon. 2. The boundaries of the coastal upwelling and bifurcation zones overlapped by 1 – 11 km and precedence was given to the bifurcation zone in these areas. This precedence was set because the geoprocessing tool rasterized the MPAs, giving priority to the polygon with the smallest total area in grid cells where multiple MPAs were present, so the coastal upwelling zone would regain up to 3 km of the overlapped area during the rasterization and subsequent spatial analysis. Each zone was considered as a separate MPA polygon in this study.

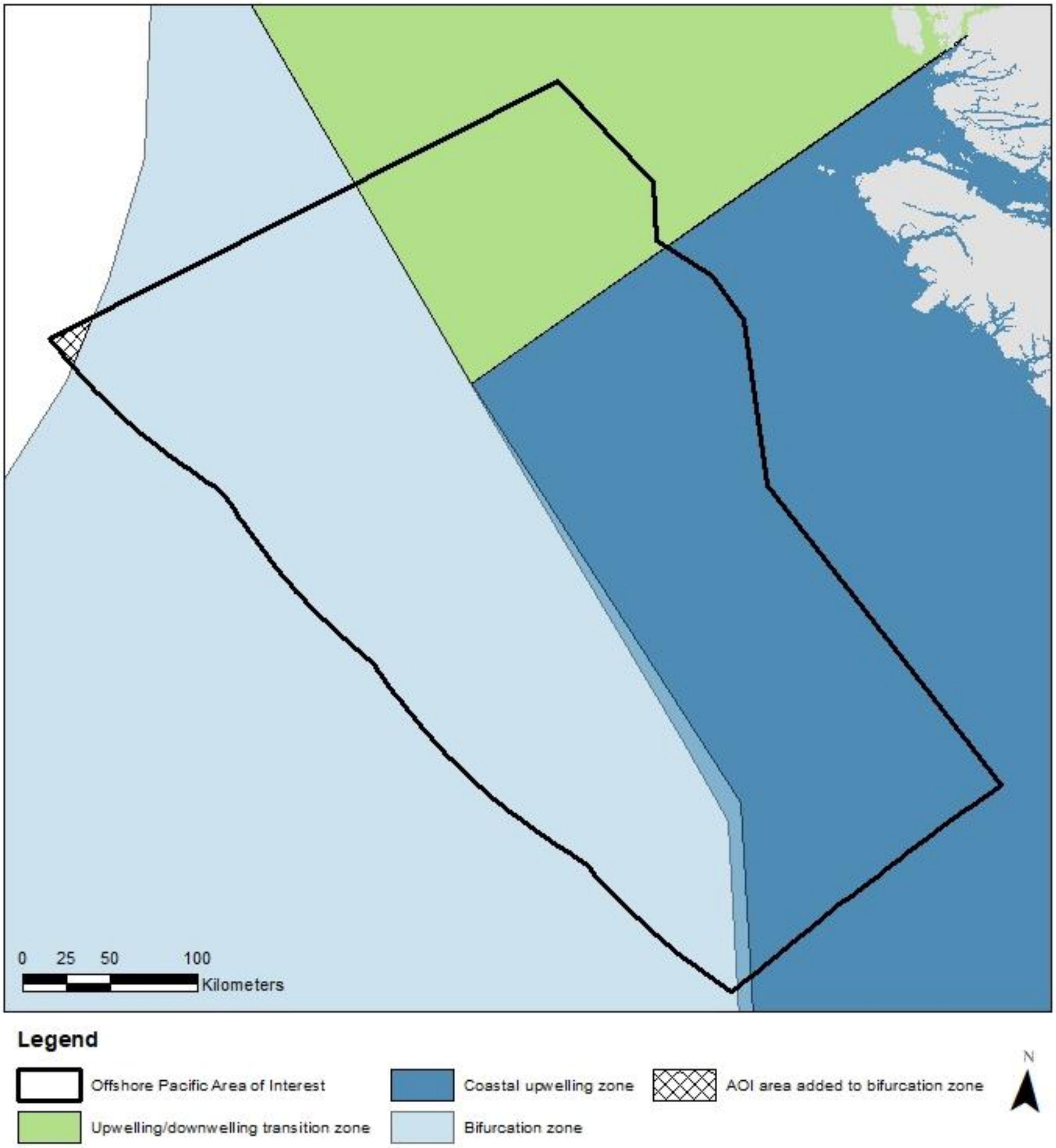


Figure C1. Subdivision of the Offshore Pacific Area of Interest into three simplified oceanographic zones (coastal upwelling zone, upwelling/downwelling transition zone, and bifurcation zone) as in Du Preez and Norgard (in review). Each zone was considered as a separate MPA polygon in the physical impact analysis.