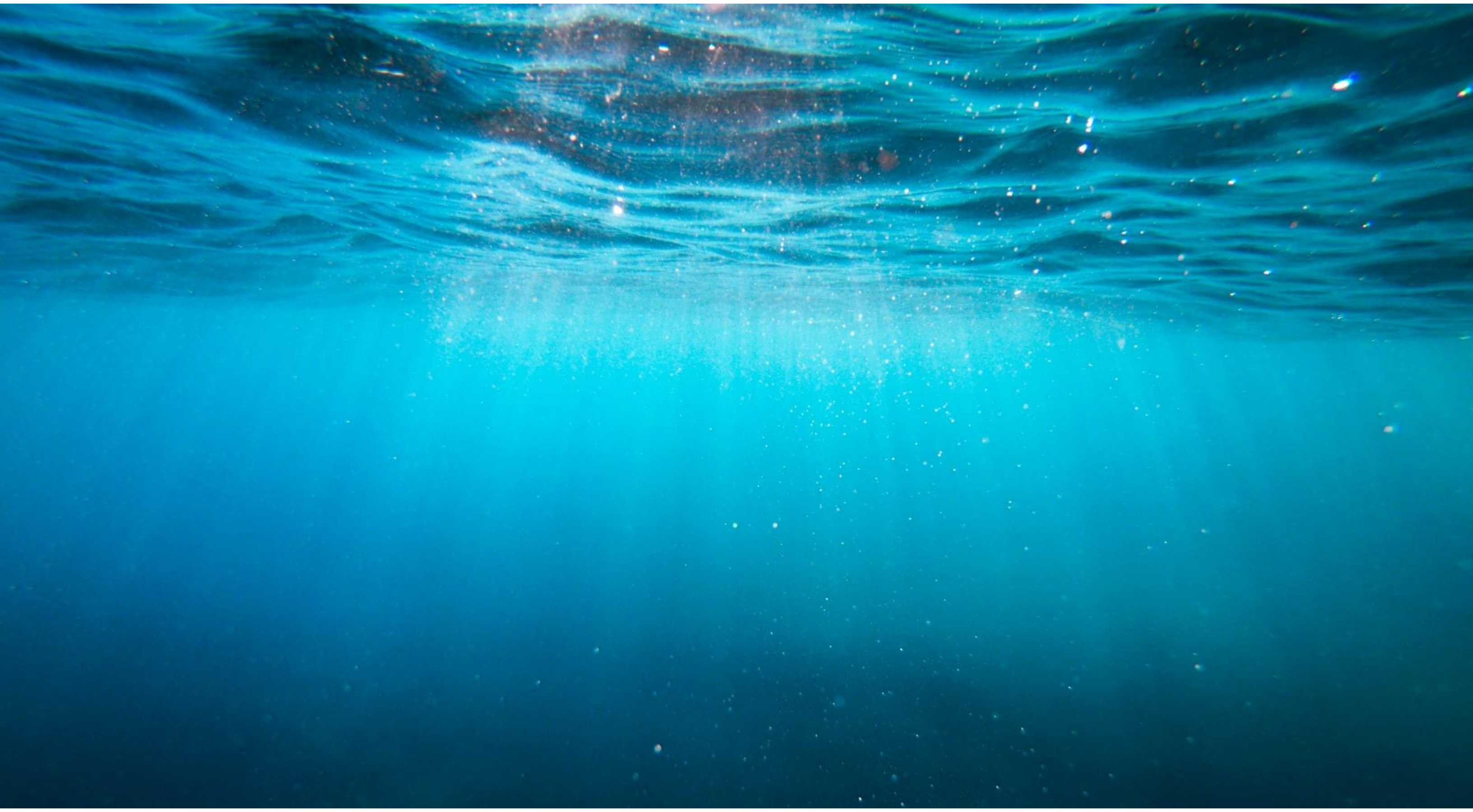

AN INVENTORY OF HIGH-RESOLUTION OCEAN CLIMATE MODELS APPLIED TO ATLANTIC CANADA

Prepared By
Debora Lucatelli
Ryan Horricks
Leah Lewis-McCrea
Gregor Reid

Date
November, 2024

Address
27 Parker Street
COVE
Dartmouth, NS
B2Y 4T5, Canada

Contact
P: 1-902-442-4660
E: info@cmar.ca
W: cmar.ca

V 1.0

Table of Contents

Table of Figures

Tables

Acronyms

ACM: Atlantic Canada Model

AerChemMIP: Aerosols and Chemistry Model Intercomparison Project

AGC: Atlantic Geoscience Center (Canada)

AGCM: Atmospheric General Circulation Model

AM4.0: Atmosphere Model version 4.0

AR: Assessment Reports

AWI: Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (Germany)

AWI-CM: Alfred Wegener Institute-Climate Model

BGC: Biogeochemical

BIO: Bedford Institute of Oceanography (Canada)

BNAM: Bedford Institute of Oceanography North Atlantic Circulation Model

CAM: Community Atmosphere Model

CAMS: Chinese Academy of Meteorological Sciences

CanAM: Canadian Atmospheric Model

CanESM: Canadian Ocean Ecosystem Model

CanOE: Canadian Ocean Ecosystem model

CANOPA: CANadian Océan PArallélisé model

CAS: Chinese Academy of Sciences

CCCma: Canadian Centre for Climate Modelling and Analysis

CCSR: Centre for Climate System Research (Japan)

CERFACS: Centre Européen de Recherche et de Formation Avancée (France)

CFS: the NCEP Climate Forecast System

CGD-NCAR: Climate and Global Dynamics Laboratory at the National Center for Atmospheric Research

CHASER: Chemical AGCM for Study of Atmospheric Environment and Radiative Forcing

CICE: Community Ice CodE

CLM: Community Land Model

CM: Climate Model

CMC: Climate Modelling Center

CMCC: Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici (Italy)

CMIP: Coupled Model Intercomparison Project

CMOC: Canadian Model of Ocean Carbon

CNRM: National Centre for Meteorological Research

COBALTv2: GFDL Carbon, Ocean Biogeochemistry And Lower Trophics version 2

COCO: the CCSR Ocean Component Model

COMDA: Centre for Ocean Model Development for Application

CORE: Co-ordinated Ocean–Ice Reference Experiments

CTEM: Canadian Terrestrial Ecosystem Model

Dal: Dalhousie University (Canada)

DFO: Fisheries and Oceans Canada

diat-HaOCC: The Hadley Centre diatom-Ocean Carbon Cycle model

DMS: Dimethyl sulfide emission

DNAODS: DFO North Atlantic Ocean-ice Downscaling System

DOM: Discrete Ordinate Method

ECCC: Environment and Climate Change Canada

ECHAM: the atmospheric general circulation model of the European Center in HAMburg.

ENSO: El Niño-Southern Oscillation

eORCA1: extended ORCA1 configuration

ESM: Earth System Models

ETOPO1: NOAA 1 Arc-Minute Global Relief Model (Deprecated)

ETOPO2: 2-minute Gridded Global Relief Data (Deprecated)

FIO: The First Institute of Oceanography (China)

GA7.1: Global Atmosphere version 7.1

GCM: General Circulation Model

GFDL: NOAA Geophysical Fluid Dynamics Laboratory Model (USA)

GHG: Greenhouse Gas

GLOMAP: GLObal Model of Aerosol Processes

GLOMAP-mode: GLObal Model of Aerosol Processes Simplified version

GLORYS: Global Ocean ReanalYses and Simulations

GoM: Gulf of Maine

HadGEM: Hadley Centre Global Environment Model (United Kingdom)

HadOCC: The Hadley Centre Ocean Carbon Cycle model

HAMOCC: HAMburg Ocean Carbon Cycle model

HSIMT: High-order Spatial Interpolation at the Middle Temporal level

IAMs: Integrated Assessment Models

INM: Institute for Numerical Mathematics (Russia)

IGPP: Institute of Geophysics and Planetary Physics (USA)

IPPC: Intergovernmental Panel on Climate Change

IPSL: The Institut Pierre Simon Laplace (France)

JSBACH: Jena Scheme for Biosphere Atmosphere Coupling in Hamburg (Germany)

KIOST: Korea Institute of Ocean Science & Technology

KMA: Korea Meteorological Administration

LIM: Louvain-la-Neuve Ice model

LM: Land Model

LMDZ: Laboratoire de Météorologie Dynamique (France)

MAM: Modal Aerosol Modules

MATSIRO: Minimal Advanced Treatments of Surface Interaction and RunOff

MEDUSA: Model of Ecosystem Dynamics, nutrient Utilization, Sequestration and Acidification

Met Office: Meteorological Office of the United Kingdom

MIROC-ES2L: Model for Interdisciplinary Research on Climate, Earth System Version 2 for long-term simulations

MRI: The Meteorological Research Institute (Japan)

MOM: Modular Ocean Model

MPI: Max Planck Institute for Meteorology (Germany)

MPIOM: Max-Planck-Institute Ocean model

NASA: The National Aeronautics and Space Administration

NCC: Norwegian Climate Center

NCEP: National Centers for Environmental Prediction (NOAA)

NCOM: National Center for Atmospheric Research community ocean model (USA)

NDC: Nationally Determined Contribution

NEMO: Nucleus for European Modelling of the Ocean

NERC: United Kingdom and Natural Environment Research Council

NIES: National Institute for Environmental Studies (Japan)

NOAA: National Oceanic and Atmospheric Administration (USA)

NPZD: Nutrient–Phytoplankton–Zooplankton–Detritus model

NS: Nova Scotia, Canada

NTCF: Near Term Climate Forcer

NUIST: The Nanjing University of Information Science and Technology (China)

OGCM: Ocean General Circulation Model

OM: GFDL Ocean/sea-ice Model

OMIP: Ocean Model Intercomparison Project

OPA: Océan PArallélisé model

ORCHIDEE: Organising Carbon and Hydrology In Dynamic Ecosystems

PISCES: Pelagic Interactions Scheme for Carbon and Ecosystem Studies

RCM: Regional Climate Models

RCP: Representative Concentration Pathways

ROMS: Regional Ocean Modeling System

SEIB-DGVM: Spatially Explicit Individual-Based Dynamic Global Vegetation Model

SIS: Sea Ice Simulator

SLCF: Short-Lived Climate Forcers

SODA: Simple Ocean Data Assimilation

SPRINTARS: Spectral Radiation-Transport Model for Aerosol Species

SR: IPCC Special Reports

SSP: Shared Socio-economic Pathway

SST: Sea Surface Temperature

TRIFFID: the Hadley Centre Top-down Representation of Interactive Foliage and Flora Including Dynamics

UKCA: United Kingdom Chemistry and Aerosols

UKCA-Strat Trop: the UKCA stratospheric-tropospheric

UKESM1-0-LL: The United Kingdom Earth System Model Low-resolution

UM: Unified Model

Executive Summary

Climate change is a global threat with far reaching impacts. Melting glaciers are raising sea-levels and the oceans have absorbed approximately 91% of the planet's excess energy and a quarter of anthropogenic carbon emissions. To help understand these effects, several General Circulation Models (GCM) have been developed to support climate change projections. The Intergovernmental Panel on Climate Change (IPCC) reviews these models, to inform the scientific and policy communities on future risks, and potential mitigation outcomes, through the release of Assessment Reports (ARs). Currently, the IPCC-AR6 report considers five core Greenhouse Gas (GHG) emissions scenarios (up to the year 2100) for Shared Socio-economic Pathways (SSP1 to 5), ranging from very low (SSP1-1.9) to very high (SSP5-8.5) emissions scenarios. These categories consider the Representative Concentration Pathways (RCP) from IPCC-AR5, which are based on GHG concentrations in the atmosphere and are divided into four levels. However, the most common emission scenarios used for analyses are low (RCP2.6), intermediate (RCP4.5), and very high (RCP8.5). The decimal value after the pathways' category acronym indicates the resultant level of radiative forcing ($W\ m^{-2}$) for each scenario, by the end of the century. In the marine environment, GCM outputs are applied at a coarse resolution (>1°), which is generally not applicable to most medium and small-scale phenomena that occur along the continental shelf and coastal areas (e.g., upwelling and river run-off). To achieve higher resolution, statistical or dynamical downscaling methods are applied to coarse-resolution GCM outputs. The resultant high-resolution models are defined as Regional Climate Models (RCM).

This report reviews currently available higher resolution (<0.1°) projections for application to Atlantic Canadian waters, with emphasis on sea surface temperature. Thirteen models were identified with 24 ensembles (GCMs used as boundary for downscaling) forcing simulations for fine-resolution scale.

This report should be cited as: Lucatelli, D., Horricks, R., Lewis-McCrea, L., Reid, G. (2024) An inventory of High-Resolution Ocean Climate Models Applied to Atlantic Canada. V1.0. Centre for Marine Applied Research (CMAR), Dartmouth, Nova Scotia, Canada. vii + 30 pp. https://cmar.ca/project/an-inventory-of-high-resolution-ocean-climate-models-applied-to-atlantic-canada

Cover image: Cristian Palmer on Unsplash

1 Introduction

Climate change is a global concern and its effects such as heat waves, drought, floods, and melting ice caps are increasingly impacting the planet (IPCC, 2023). Human activities, such as greenhouse gas (GHG) emission, have increased global warming (*high confidence*) and this is negatively impacting living conditions, globally (IPCC, 2023). The Intergovernmental Panel on Climate Change (IPCC) is a United Nations body that prepares comprehensive Assessment Reports (AR) on the latest climate change information (scientific, technical and socio-economic), its impacts, future risks, and options for reducing these impacts via mitigation and adaptation (IPCC, 2023). The ARs provide guidelines for greenhouse gas inventories that are applied to climate projections. According to IPCC-AR6, there are five core GHG emissions scenarios (up to the year 2100) considering each Shared Socio-economic Pathway (SSP1 to 5). These range from the inclusion of very low (SSP1-1.9) to very high emission (SSP5-8.5) scenarios. The SSPs account for respective Representative Concentration Pathways (RCP), from IPCC-AR5 (IPCC, 2019), which are based on 6 atmospheric GHG concentration scenarios. However, the three most utilized are: low (RCP2.6)[1], intermediate (RCP4.5), and very high (RCP8.5). The decimal value after each pathway's acronym indicates the resultant level of radiative forcing (W m^{-2}) from each scenario by the end of the century (IPCC, 2014). The SSPs cover a wider range of GHG and air pollutant projections with differences in concentration trajectory compared to RCPs. Therefore, radiative forcing estimates in SSPs tend to be higher when comparing related RCPs scenarios (e.g., SSP5-8.5 vs. RCP8.5) (**Table 1**). Because of this, SSPs were considered for direct comparison in the IPCC-AR6 (**Table 2**). Over the last decade, several climate models have developed projections for the end of the 21st century (**Appendix A**). Based on a comprehensive evaluation of these model outputs, the AR6 [Working Group (WG) III] proposed eight new categories of scenarios and pathways (IPCC, 2023). These range from limiting global warming to 1.5 °C (C1 – best-case scenario) to warming which exceeds 4 °C in the worst-case scenario (C8) (**Table 2**).

[1] RCP2.6 represents a high GHG emission mitigation scenario.

Table 1 | Shared Socio-economic Pathway (SSP) and the most closely Representative Concentration Pathways (RCP). The five core SSP scenarios most cited in the literature are highlighted in bold.

SSP Scenario	Description from an Emissions/Concentrations and Temperature Perspective	Closest RCP Scenarios
SSP1-1.9	Holds warming to approximately 1.5 °C above 1850–1900 in 2100 after slight overshoot (median) and implied net zero carbon dioxide (CO_2) emissions around the middle of the century.	No equivalently low RCP scenario exists.
SSP1-2.6	Stays below 2.0 °C warming relative to 1850–1900 (median) with implied net zero CO_2 emissions in the second half of the century.	RCP2.6, although RCP2.6 might be cooler for the same model settings.
SSP4-3.4	A scenario between SSP1-2.6 and SSP2-4.5 in terms of end-of-century radiative forcing. It does not stay below 2.0 °C in most CMIP6 runs relative to 1850–1900.	No 3.4 level of end-of-century radiative forcing was available in the RCPs. Nominally, SSP4-3.4 is between RCP 2.6 and RCP 4.5, although SSP4-3.4 might be more 21st century. SSP4-3.4 is close to RCP6.0, which featured lower radiative forcing than RCP4.5 in those decades.
SSP2-4.5	Scenario approximately in line with the upper end of the aggregate Nationally Determined Contribution (NDC) emissions levels by 2030. CO_2 emissions remaining around current levels until the middle of the century. The IPCC Special Reports SR1.5 assessed temperature projections for NDCs to be between 2.7 °C and 3.4 °C by 2100, corresponding to the upper half of projected warming under SSP2-4.5. New or updated NDCs by the end of 2020 did not significantly change the emissions projections up to 2030, although more countries adopted 2050 net zero targets which are in alignment with SSP1-1.9 or SSP1-2.6. The SSP2-4.5 scenario deviates mildly from a 'no-additional-climate-policy' reference scenario, resulting in a best estimate warming around 2.7 °C by the end of the 21st century, relative to 1850–1900.	RCP4.5 and, until 2050, also RCP6.0. Forcing in the latter was even lower than RCP4.5 in the early decades of the 21st century.
SSP4-6.0	The end-of-century nominal radiative forcing level of 6.0 W m^{-2} can be considered a 'no-additional-climate-policy' reference scenario, under SSP1 and SSP4 socio-economic development narratives.	RCP6.0 is nominally closest in the second half of the century, although global mean temperatures are estimated to be generally lower in RCPs compared to SSP4-6.0, as it has very similar temperature projections compared to the nominally lower RCP4.5 scenario in the first half of the century.
SSP3-7.0	An intermediate-to-high reference scenario resulting from no additional climate policy under the SSP3 socio-economic development narrative. CO_2 emissions roughly double from current levels by 2100. SSP3-7.0 has particularly high non-CO_2 emissions, including high aerosols emissions.	Between RCP6.0 and RCP8.5, although SSP3-7.0 non-CO_2 emissions and aerosols are higher than in any of the RCPs.
SSP3-7.0-lowNTCF[2]	A variation of the intermediate-to-high reference scenario SSP3-7.0 but with mitigation of CH_4 and/or short-lived species such as black carbon and other short-lived climate forcers (SLCF). Note that variants of SSP3-7.0-lowNTCF differ in terms of whether methane (CH_4) emissions are reduced.	SSP3-7.0-lowNTCF is between RCP6.0 and RCP8.5, as RCP scenarios generally incorporated a narrow and comparatively low level of SLCF emissions across the range of RCPs.
SSP5-3.4-OS[1] (Overshoot)	A mitigation-focused variant of SSP5-8.5 that initially follows unconstrained emissions growth in a fossil fuel-intensive setting until 2040 and then implements the largest net negative CO_2 emissions of all SSP scenarios in the second half of 21st century to reach SSP1-2.6 forcing levels in the 22nd century.	Not equivalent. Initially, until 2040, similar to RCP8.5.
SSP5-8.5	A high-reference scenario with no additional climate policy. CO_2 emissions roughly double from current levels by 2050. Emissions levels as high as SSP5-8.5 are not obtained by integrated assessment models (IAMs) under any of the SSPs other than the fossil-fueled SSP5 socio-economic development pathway.	RCP8.5, although CO_2 emissions under SSP5-8.5 are higher towards the end of the century. CH_4 emissions under SSP5-8.5 are lower than under RCP 8.5. When used with the same model settings, SSP5-8.5 may result in slightly higher temperatures than RCP8.5.

Modified from Chen et al. (2023).

[2] NTCF: Near Term Climate Forcer. The Aerosols and Chemistry Model Intercomparison Project (AerChemMIP) variant of SSP3-7.0-lowNTCF (Collins et al., 2017) only reduced aerosol and ozone precursors compared to SSP3-7.0, not methane. The SSP3-7.0-lowNTCF variant by the integrated assessment models also reduced methane emissions (Gidden et al., 2019). This creates differences between SSP3-7.0-lowNTCF and SSP3-7.0 in terms of methane concentrations and some fluorinated gas concentrations that have hydroxide (OH^-) related sinks (Meinshausen et al., 2020).

Table 2 | Relationship of scenarios and pathways considered in the IPCC Assessment Report 6. C1-C8: Global mean temperature change categorizations, based on their projected global warming over the 21st century, with likelihood among models' pathway in parentheses.

Category	Category Description	GHG emissions scenarios	
		SSPs	RCPs
C1	Limit warming to 1.5°C (>50%) with no or limited overshoot[3]	SSP1-1.9 (Very low)	
C2	return warming to 1.5°C (>50%) after a high overshoot		
C3	Limit warming to 2°C (>67%)	SSP1-2.6 (low)	RCP2.6
C4	Limit warming to 2°C (>50%)		
C5	Limit warming to 2.5°C (>50%)		
C6	Limit warming to 3°C (>50%)	SSP2-4.5 (intermediate)	RCP4.5
C7	Limit warming to 4°C (>50%)	SSP3-7.0 (high)	
C8	Exceed warming of 4°C (>50%)	SSP5-8.5 (very high)	RCP8.5

RPC: Representative Concentration Pathway; SSP: Shared Socio-economic Pathway; GHG: Greenhouse Gases. Modified from (IPCC, 2023).

To anticipate future climate change scenarios, the scientific community has developed several General Circulation Models (GCM) and Earth System Models (ESM) incorporating coupled atmosphere, ocean, land, and sea ice components, with ESM also including biogeochemical processes (Flato et al., 2019; Brickman et al., 2021). The climate projections are based on an ensemble of the most recent climate models, to avoid bias and diminish the intrinsic variation among them (Flato et al., 2019). The IPCC coordinates the simulation, analyses, and reports on these models in the Coupled Model Intercomparison Project (CMIP), currently in Phase 6 (CMIP6). The CMIP is applied to develop historical simulations (1850-2014) and project GHG emission scenarios (i.e., RCPs and SSPs) up to the year 2100 (IPCC, 2023). The models are calibrated using historical data to verify their consistency under climate forcing and sensitivity, thus improving the confidence of future climate projections (Eyring et al., 2016). They simulate the physics, chemistry, and biology of land, ocean, atmosphere, and cryosphere, permitting the exploration of complex interactions. Most of these models operate at the global scale and consequently, the resolution is coarse (~1° Lat./Long.), which can create bias and misrepresentation of regional processes (Taylor et al., 2012; Srivastava et al., 2020; Brickman et al., 2021).

High-resolution (i.e., fine scale) models require greater computational effort, which may restrict model operation to research groups with applicable expertise and computing power (Flato et al., 2019; Society, 2021; Morris et al., 2022; Gebrechorkos et al., 2023). Several working groups have developed methods to downscale global models and increase resolution (<0.1° Lat./Long.). These are referred to as Regional Climate Models (RCMs) (Lavoie et al., 2020; Brickman et al., 2021). There are two primary methods applied for downscaling; statistical and dynamical (Guo et al.,

[3] Limited overshoot refers to exceeding 1.5 °C global warming by up to about 0.1 °C, high overshoot by 0.1 - 0.3 °C, in both cases for up to several decades.

2013; Long et al., 2016; Lanzante et al., 2018; Lavoie et al., 2019; Lavoie et al., 2020). Statistical downscaling has two steps: a) training - to establish a correlation between observational data and GCM estimates over the same period; and b) future projection - which extracts proxy observations from GCM future projections based on the training correlation results (Dixon et al., 2016; Morris et al., 2022). Statistical downscaling allows for a recalibration of the raw GCM output for future projections, grounded on the observations generated from the historical period (training step), to generate data at a higher spatial resolution than the GCM (Dixon et al., 2016; Lanzante et al., 2018; Morris et al., 2022). Alternatively, dynamical downscaling creates an RCM, based on physical environmental components of the same complexity as a GCM, but encompasses a limited area to achieve higher resolution (Brickman et al., 2021; Pozo Buil et al., 2023). Dynamically downscaled RCM incorporates similar components (e.g., physical and biogeochemical) and code as a GCM. However, it is important to acknowledge that RCMs are driven at their lateral boundaries by the output from a GCM and might inherit their errors and biases (Pozo Buil et al., 2023).

Downscaling methods may carry biases derived from the GCM limited observational data and/or spatial resolution. To help mitigate this issue, some bias adjustments (previously referred to as "*correction*") can be applied. A widespread example is the "*delta method*", in which the mean differences (delta) in some climate value, obtained from a climate model projection, is added to the observed historical data (Flato et al., 2019; Pozo Buil et al., 2023). This method provides reliable use of projected changes from different climate models, since it eliminates the climatological bias of each model (Flato et al., 2019). It can be argued that dynamical downscaling surpasses statistical downscaling by maintaining the physical relationships between different climate variables. This approach is capable of simulating a higher-resolution model for a specific area (requiring a similar computational effort of a global model), which enables the resolution to better describe critical processes such as ocean eddies, convections, and precipitation extremes (Flato et al., 2019). On the other hand, statistical downscaling is inexpensive to implement, requiring far less computational resources (Lanzante et al., 2018). Nevertheless, it requires a broad historical observational database (at least 10 years to detect trends in sea surface temperature (SST)), which is generally limited to a few variables, mainly temperature (IPCC, 2019). Overall, both methods are common, and model choice reflects the computational resources and data availability over the region of interest.

Projections from climate change ocean models have wide application to multidisciplinary research and government management. The use of these model outputs now goes beyond the traditional domain of oceanographers and climate scientists (Society, 2021). As such, researchers and decision makers are required to have a basic understanding of how these models work, what they predict, the resolution at which they operate and their limitations. The ongoing developments of GCM and RCM ocean models in overlapping time and space can make advancements difficult to follow for potential users not directly involved in developing the models. An updated inventory of available ocean models, their stage of development, capacity, and resolution is therefore beneficial to help guide users when considering the application of model outputs.

Consequently, this report aims to summarize the high-resolution coupled models with an emphasis on SST projections, and their application to the northwestern Atlantic Ocean, with a focus on Canadian waters.

2 Material and Methods

Information for model summaries was sourced from scientific literature, internet databases and personal communication with Canadian researchers (e.g., Diane Lavoie and David Brickman). This review focused on high resolution (<0.1°) (**Table 3**) climate models projecting SST in the Atlantic Canada waters. Model summaries are presented herein with additional supplementary material (Supplementary tables S1-S2).

3 Results

A total of 13 models are used with 24 ensemble forcings (GCMs used as boundary for downscaling), to achieve high-resolution RCMs for Atlantic Canada. Most models were developed by Canadian institutions (DFO/BIO, Dalhousie, ECCC) and the National Oceanic and Atmospheric Administration (NOAA, USA) (**Table 3**). Of the 24 ensemble forcings described in this report, 12 use CMIP5 simulations and nine use the most recent simulations, CMIP6 (IPCC, 2022). Monthly output frequency was most common (76%) for projection scenarios and hindcasts (**Figure 1**). The National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory Models (GFDL) ESMs were most applied as boundary conditions and downscaled for future climate projections in Atlantic Canadian waters (**Table 3**).

All simulations included SST and projected climate change up to 2050 or the end of the century (2100) for the RCP8.5 or SSP5-8.5 scenarios. Other RCP and SSP scenarios were also considered in the original papers, however the focus of this report is on the 8.5 radiative forcing projections.

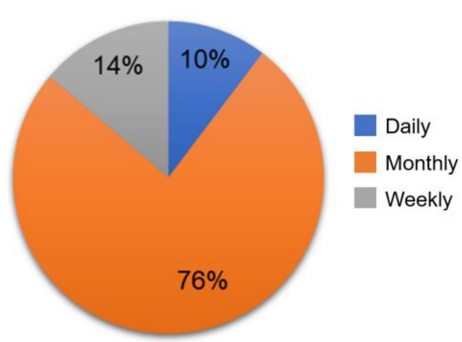

Figure 1 | Minimum time steps applied by the RCM projections for the northwestern Atlantic Ocean.

Table 3 | Fine-resolution (<10 km) climate models applied to the Atlantic Canadian Coast. Model simulations were based on CMIP5 or CMIP6 (*). A latitude or longitude of 0.1° ≈ 11 km.

Type	Model (Developer)	Ensemble/Forcing	Inst.	ACW Reference	Res.	Down-scaling
Regional Climate Model (RCM)	ACM (Dal)	BNAM	DFO/Dal	Rutherford et al. 2024	1/12°	Dynamical
		CM2.6			0.1°	
	BNAM (DFO/BIO)	CanESM2	DFO	Brickman et al. 2016	1/12°	Dynamical
		GFDL-ESM2M				
		HadGEM2-ES				
		IPSL-CM5A-LR				
		MIROC-ESM				
		MPI-ESM-LR				
		CORE		Brickman et al. 2021		Dynamical
				Greenan et al. 2019		
				Brickman & Wang (pers. Comm.)		
	CANOPA (DFO/BIO)	CRCM	DFO	Han et al. 2022	1/12°	Dynamical
	DNAODS (DFO)	ERI (Reanalysis)	DFO	Han et al. 2021 (hindcast)	1/12°	N/A
	ROMS (IGPP)	GFDL-ESM	DFO	Brickman et al. 2021	0.063°	Dynamical
		GFDL-ESM2M				
		HadGEM2				
		IPSL-CM5A-MR				
General Circulation Model (GCM)	CM2.6 (NOAA GFDL)	CM2.6	Dal	Fennel K. (pers. comm.)	0.1°	N/A
			DFO	Greenan et al. 2019		
			NOAA	Griffies et al. 2014		
				Kleisner et al. 2017		
				Saba et al. 2016		
	CanESM5 (CCCma/ECCC)	CanESM5-CanOE*	DFO	Kristiansen et al. 2022	1/12°	Statistical
	CMCC (CMCC)	CM2-SR5*	DFO			
		CanESM2				
	GFDL-ESM4 (NOAA GFDL)	GFDL-ESM4*	DFO			
	IPSL-CM6A-LR (IPSL)	IPSLCM6A-LR*	DFO			
	MIROC-ES2L (MIROC)	MIROC-ES2L	DFO			
	MPI-ESM1.2-LR (MPI)	MPI-ESM1.2-LR	DFO			
	UKESM1-0-LL (Met Office/NERC)	UKESM1-0-LL*	DFO			

CMIP: Coupled Model Intercomparison Project; Inst: Institution applying the model; ACW Reference: Research publications covering Nova Scotian waters including Gulf of Maine and Gulf of Saint Laurence; Res.: Horizontal resolution. See all abbreviations in the list of **Acronyms**

4 Fine Resolution Model Summary

Several RCMs have been developed to infer the effects of climate change at high resolution for specific domains, such as the Gulf of St Lawrence, Scotian Shelf, and the Gulf of Maine. Mean SST is the most common variable modelled for climate projections. Projected SST enables researchers to predict potential effects in the marine environment (e.g. biodiversity and ice-melting) and ocean dependent industries (e.g. fisheries, aquaculture, and transportation).

4.1 Regional Climate Models

4.1.1 ACM – Atlantic Canada Model

Institution: Dalhousie University (Dal)

Abstract: modified from Brennan et al. (2016); Rutherford and Fennel (2018)

The Atlantic Canada Model (ACM) is derived from ROMS v3.5, a terrain-following, free-surface, primitive equation ocean model, presenting 30 vertical levels (10 m minimum water depth) and about 10 km horizontal resolution (240x120 horizontal grid cells). The model domain covers the Gulf of Maine, Scotian Shelf, East Newfoundland Shelf, Grand Banks, and Gulf of St. Lawrence (36.1-53.9 °N and 74.7-45.1°W) (Brennan et al., 2016). It is composed by Generic Length Scale (GLS) as a vertical mixing scheme; the atmospheric surface forcing is from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim global atmospheric reanalysis; and the high-order spatial interpolation at the middle temporal level (HSIMT) advection scheme for tracers. The ACM includes simulation with virtual dye tracers, physical and biogeochemical factors. The present-day model simulation runs for 16 years from 1999 to 2014, where the first year is considered the model spin-up. The ACM was applied to Canadian waters by Rutherford et al. (2024) to elucidate the role of the North Atlantic circulation as a driver for biogeochemical distribution, and also projects sea bottom temperature along the region. The developers ensembled the ACM with two models (for downscale purposes): the DFO-BNAM projecting (see **Section 4.1.2.**) an RCP8.5 for 2066-2080 (**Figure 2a**) and the GDLF-CM2.6 (see **Section 4.2.**) considering an RCP6.0 2065-2080 projection (**Figure 2b**).

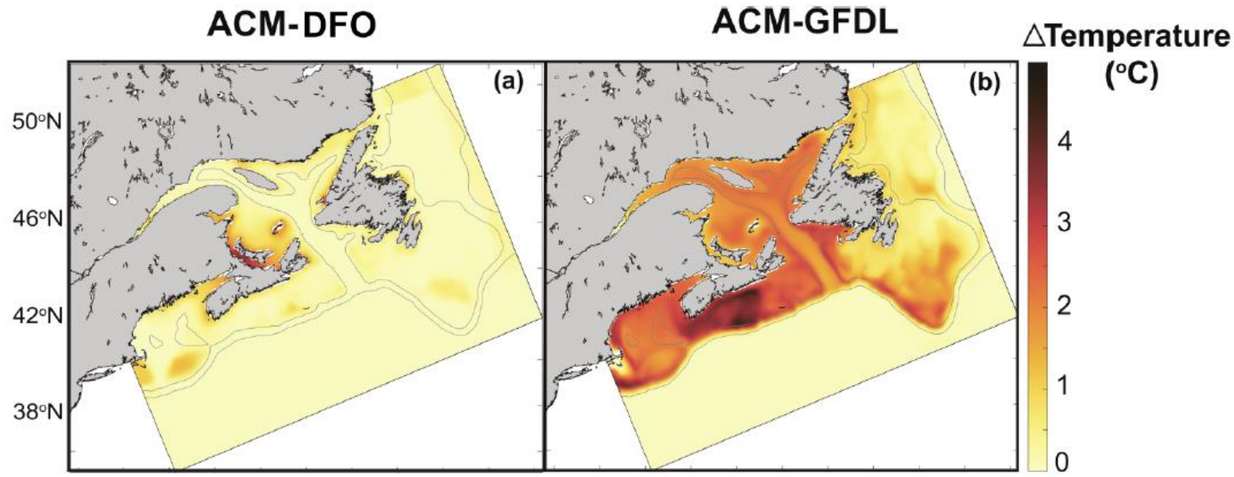

Figure 2 | Output of the Atlantic Canada Model (ACM) from bottom average changes (future minus present) in temperature in Atlantic Canadian waters. a) ACM-DFO/BNAM: RCP8.5 for 2066-2080; b) ACM-GFDL: RCP6.0 for 2065-2080. Modified from Rutherford et al. (2024).

4.1.2 BNAM – Bedford Institute of Oceanography North Atlantic Circulation Model (Brickman et al., 2016b)

Institution: Bedford Institute of Oceanography (BIO), Fisheries and Oceans Canada (DFO)

Abstract: Modified from Brickman et al. (2021)

The BNAM is a high-resolution model of the North Atlantic Ocean, designed to resolve the interaction of the Gulf Stream and Labrador Current at the tail of the Grand Banks, to more precisely simulate the changes in Maritime Canadian waters. This model runs present condition (hindcasts) and future (scenarios projection) climate modes. BNAM is based on NEMO2.3 (Nucleus for European Modelling of the Ocean, version 2.3) ocean circulation and includes an ocean component OPA (Océan PArallélisé). BNAM uses the Co-ordinated Ocean–Ice Reference Experiments (CORE) normal year atmospheric forcing; GLORYS (Global Ocean ReanalYses and Simulations) as a climatology open boundary condition (monthly); and DRAKKAR project river runoff compilation. The model domain covers 7°N – 75°N and 100°W – 25°E with a nominal resolution of 1/12° (about 6 km grid cell in the Gulf of Maine). It has a maximum of 50 vertical levels, with level thickness increasing from 1 m at the surface to 200 m at a depth of 1250 m and reaches a maximum value of 460 m at the bottom of the deep basins (maximum depth 5730 m). Results are typically presented spatially as future climate changes (i.e., the differences between the present condition and future state). This approach allows the model output to be added to present climate conditions derived from a variety of sources (using delta method). BNAM has been used to downscale ESMs (i.e., CanESM2, GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM, MPI-ESM-LR) for determining climate variation, including SST, in Canadian waters

(**Figure 3**) (Brickman and Drozdowski, 2012; Brickman et al., 2016a). BNAM-CORE (anomalies derived from ESMs added to normal year forcing) was used in the Gulf of Maine (**Figure 4**) (Greenan et al., 2019; Brickman et al., 2021).

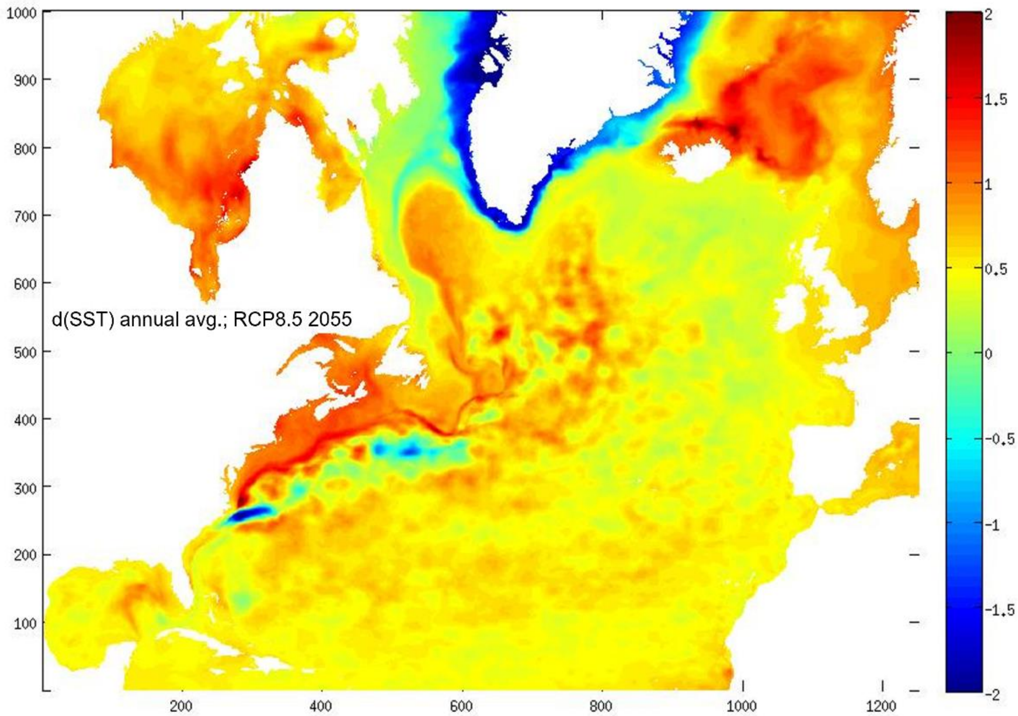

Figure 3 | Projected Sea Surface delta Temperature (°C) in 2055 for RCP8.5 using BNAM. Model output conceded by Dave Brickman (pers. comm. 2023) from Bedford Institute of Oceanography (DFO-BIO).

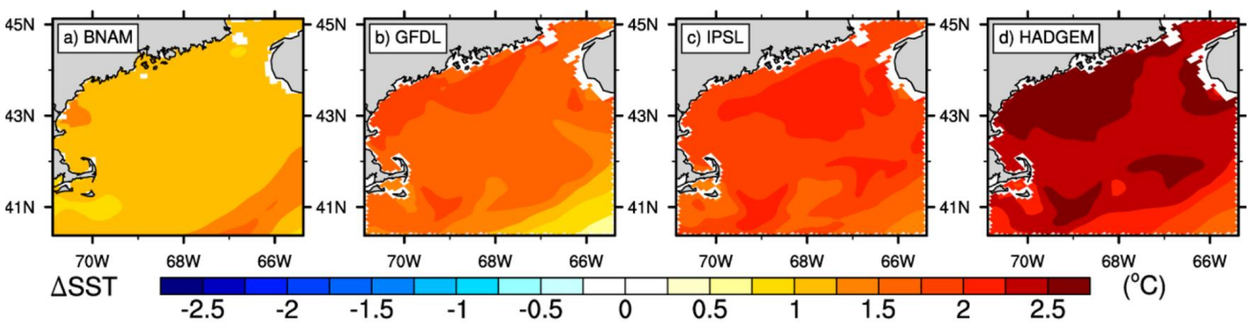

Figure 4 | Comparison of annual mean change in sea surface temperature (SST) between four model projection for 2050 under the RCP8.5 scenario at Gulf of Maine. a: BNAM; b: GFDL-ESM2M; c: IPSL-CM5A-MR; d: HadGEM. BNAM output from Brickman et al. 2021. See **Acronyms** for full text.

Ensembles

CanESM2 (modified from Arora et al., 2011)

Developed by Canadian Centre for Climate Modelling and Analysis (CCCma-ECCC), CanESM2 is the updated version of CanESM1 which includes the atmospheric general circulation model component of CanAM4. The physical ocean component of CanESM2 differs from CanESM1 to include higher resolution (1.41°Long. x 0.94°Lat.) and improved physical parameterizations (40 levels with approximately 10 m depth resolution). The effects of explosive volcanoes from 1850–2005 are also included by prescribing stratospheric aerosol distribution following the CLIVAR C20C protocol. This model, ensembled with other ESMs, was applied as future climate anomaly forcing by Brickman et al. (2016) for Atlantic Canada to achieve high-resolution (1/12°) output (**Figure 5**).

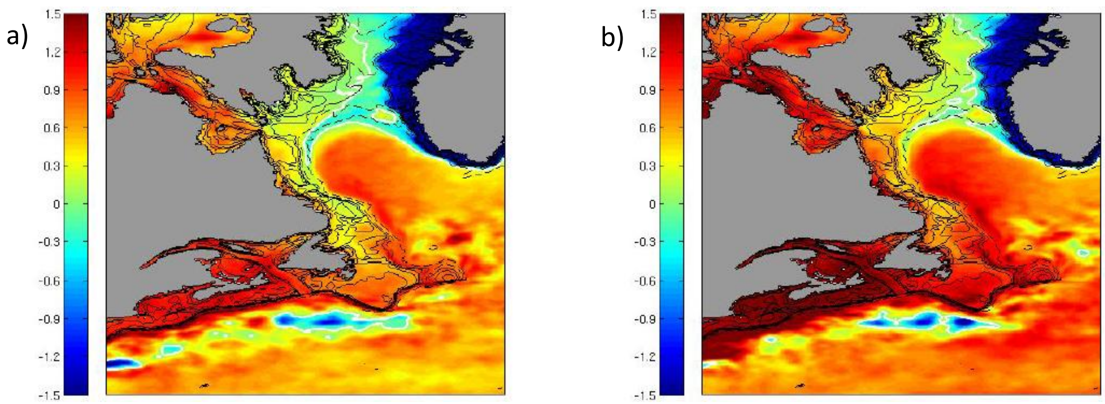

Figure 5 | Predicted annual mean change in Sea Surface Temperature (°C) (0 m) for RCP8.5. a: 2055 projected temperature minus PC annual average; b: 2075 projected temperature minus PC annual average. dT: Delta temperature. PC: Present Climate. Forcing combinations: CanESM2+GFDL-ESM2M+HadGEM2-ES+IPSL-CM5A-LR+MIROC-ESM+MPI-ESM-LR. Modified from Brickman et al. 2016. See **Acronyms** section for full text.

GFDL-ESM2M – GFDL Earth System Models version 2 (Dunne, 2012)

GFDL-ESM was developed by NOAA Geophysical Fluid Dynamics Laboratory (GFDL) to improve the understanding of how the Earth's biogeochemical cycles, including human influences, interact with the climate system. The simulation tools are based on an atmospheric circulation model coupled with an oceanic circulation model, with representations of land, sea ice, and iceberg dynamics. It incorporates interactive biogeochemistry, including the carbon cycle. GFDL-ESM2M (version 2) evolved from the CM2.1 climate model (Delworth et al., 2006) with the addition of ocean physics and pressure-based vertical coordinates applied along the developmental path of GFDL's Modular Ocean Model version 4.1. It also includes the land model LM3. The model has been applied for CMIP5 projections including an 1860 control, historical, and four future scenarios

(RCP2.6, 4.5, 6.0, and 8.5) for the end of the century. A dynamic downscale (using a delta value) was applied by Brickman et al. (2021) using Regional Ocean Modeling System (ROMS) (**Figure 4**), while Kristiansen et al. (2022) statistically downscaled ESM2M for ensemble to other ESMs in the Newfoundland area.

HadGEM2-ES

Developed by the Meteorological Office (Met Office) of the United Kingdom, the Hadley Centre Global Environment Model Version 2 (HadGEM2) includes a coupled atmosphere-ocean configuration, with an optional vertical extension in the atmosphere that includes a well-resolved stratosphere, and an Earth-System configuration with dynamic vegetation (TRIFFID), ocean biology (HadOCC and diat-HaOCC), and atmospheric chemistry (UKCA). Dimethyl sulfide (DMS) emission was included for carbon cycle being generated by ocean biology (i.e., phytoplankton). The key features targeted in this model were the physical performance of El Niño-Southern Oscillation (ENSO) and northern continent land-surface temperature biases. The standard atmospheric component has 38 levels extending to a height of ~40 km, with a horizontal resolution of 1.25° x 1.875° (Lat. x Long.), and global grid of 192 x 145 cells. This is equivalent to a surface resolution of about 208 km x 139 km at the Equator, reducing to 120 km x 139 km at 55° of latitude. The oceanic component has a resolution of 1° between the poles and 30° North/South, with a progressive increase in resolution towards the Equator up to 1/3° (360 x 216 grid points in total), and 40 vertical levels (a resolution of 10 m near the surface). HadGEM2 was used to project climate change for CMIP5 application in Atlantic Canada waters (Brickman et al., 2016a; Brickman et al., 2021). Brickman et al. (2021) projected future climate, utilizing ROMS for the Gulf of Maine. This simulation was forced with the average output (delta method) from HadGEM and two other models (GFLD-ESM2M and CM5A-MR) under the present (hindcasts, **Figure 8**), RCP4.5 and 8.5 scenarios for the year 2050. This method provided a high-resolution (7 km horizontal grid) model for the region. The latest version, HadGEM3, is available but has not yet been applied in Canadian waters.

IPSL-CM5A – IPSL Climate Model version 5 (Dufresne, 2013)

The fifth version of Institut Pierre-Simon Laplace (IPSL) Climate Model (CM) has contributed to the CMIP5. The IPSL-CM5A model is a full earth system model, with an extension of IPSL-CM4 with the ocean component from the Nucleus for European Modelling of the Ocean (NEMO). The model components include the atmospheric model from the Laboratoire de Météorologie Dynamique (LMDZ); the ocean model NEMO, including the Louvain-la-Neuve Sea Ice Model (LIM2), and marine biogeochemistry PISCES (Pelagic Interactions Scheme for Carbon and Ecosystem Studies); and the land model ORCHIDEE (Organising Carbon and Hydrology In Dynamic Ecosystems). The atmospheric model has two standard resolutions: IPSL-CM5A-LR (low resolution) with 1.9° x 3.75°

(96 x 96, and 39 levels) of resolution; and the IPSL-CM5A-MR (mid-resolution) which is 1.25° x 2.5° (144 x 143, and 39 levels). The CM5A-LR was implemented for Atlantic Canadian waters by Brickman et al. (2016a) (**Figure 5**), while the CM5A-MR was incorporated in an averaged projection (ROMS) by Brickman et al. (2021) (**Figure 4**). Both applied downscaling methods to achieve high-resolution climate change projections.

MIROC-ESM - Model for Interdisciplinary Research on Climate, Earth System Model

This is a previous version of the MIROC-ES2L applied for the CMIP5. The main interactively coupled components were SPRINTARS for aerosol, GCM with sea-ice CCSR Ocean Component Model (COCO) for ocean, the land surface Minimal Advanced Treatments of Surface Interaction and RunOff (MATSIRO), the CHemical AGCM for Study of atmospheric Environment and Radiative forcing (CHASER), ocean ecosystem NPZD (Nutrient-Phytoplankton-Zooplankton-Detritus), and Spatially Explicit Individual-Based Dynamic Global Vegetation Model (SEIB-DGVM) as terrestrial ecosystem component dealing with dynamic vegetation and land-atmosphere interactions. It was downscaled using BNAM to project future climate for the Northwest Atlantic Shelf Region simulations (Brickman et al., 2016a) (**Figure 5**).

MPI-ESM-LR - Max Planck Institute for Meteorology ESM (Giorgetta et al., 2013)

The MPI-ESM-LR is a previous version of the MPI-ESM1.2-LR developed for the CMIP5. The low-resolution version MPI-ESM-LR has been run with T63L47 (192 x 96 grid points; 47 vertical layers) with atmospheric component ECHAM6, ocean MPIOM GR15 (ca. 1.5° and 40 vertical levels), land and vegetation JSBACH and biogeochemistry HAMOCC5. This climate model was downscaled by (Brickman et al., 2016a), interpolated to other models using BNAM to generate a climate projection for the Northwest Atlantic shelf (**Figure 5**).

4.1.3 CANOPA – CANadian Océan PArallélisé model (Brickman and Drozdowski, 2012)

Institution: Fisheries and Oceans Canada (DFO), Bedford Institute of Oceanography (BIO)

Abstract: Modified from Brickman and Drozdowski (2012)

CANOPA (CANadian Océan PArallélisé model) is based on the Nucleus for European Modelling of the Ocean (NEMO) system written in Océan PArallélisé code, version 9.0 (OPA 9.0). A thermodynamic-dynamic sea-ice model, Louvain-la-Neuve Sea Ice Model version 2 (LIM2), is coupled to the circulation model. Bathymetry incorporated into the model is combined data from the Atlantic Geoscience Centre (AGC) ETOPO2 (ETOPO2v2) and the DFO (DFO Gulf Region); datasets were interpolated onto a regular 1/30° x 1/30° grid (77°-38°W to 35°-5°7N) using optimal interpolation routine. The grid domain covers the Atlantic coast of Canada (72-55°W to 38-52°N; 234j x 197i cells) with a horizontal resolution of 1/12° (~6 x 8 km) and 46 horizontal levels (from

6 m close to the surface to 250 at depth in the ocean). All available coincident temperature and salinity (TS) data (from DFP database) for a region larger than the model domain, were extracted from the database and an optimal interpolation technique was used to create monthly TS fields on a regular 0.25° x 0.25° grid, with vertical levels varying with depth from 10 to 500 m intervals. For river runoff, the monthly average of the 78 rivers included by (Lavoie et al., 2020) obtained with a simple hydrological model (Lambert et al., 2013) that uses precipitation and air temperature outputs from the Canadian Regional Climate Model (CRCM) downscaling of the ESMs atmospheric conditions. A biogeochemical (GSBM) model was added by Lavoie et al. (2021) to simulate biogeochemical cycles. The model has been used to project future biogeochemical (Lavoie et al., 2020; Lavoie et al., 2021; Siedlecki et al., 2021) and physical (Brickman et al., 2018) conditions in the Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine over CMIP5 (**Figure 6**).

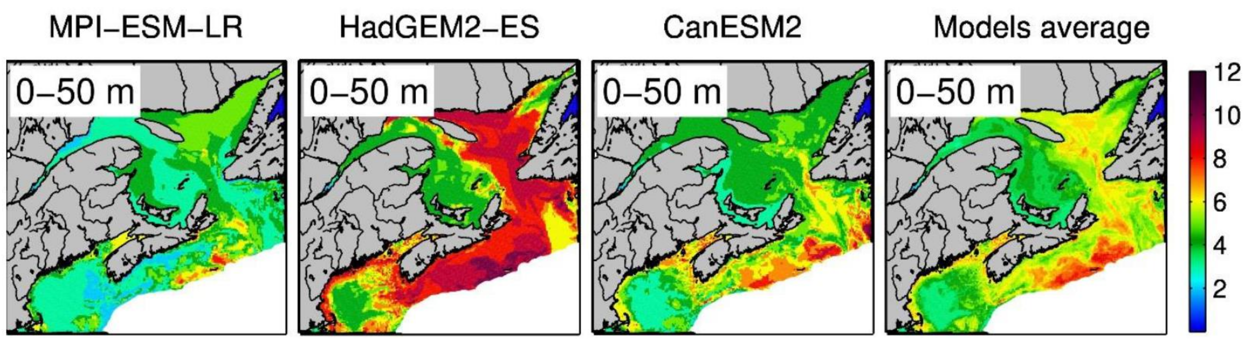

Figure 6 | Sea surface temperature output from CANOPA model downscaled from three Earth System Models (MPI-ESM-LR, HadGEM2-ES, CanESM2) using a RCP8.5 for 2100. Modified from Lavoie et al. (2020).

4.1.4 DNAODS - DFO North Atlantic Ocean-ice Downscaling System (Han et al., 2021)

Institution: The Northwest Atlantic Fisheries Centre/DFO, the Gulf Fisheries Centre/DFO, the Institute of Ocean Sciences/DFO, and the Bedford Institute of Oceanography (BIO).

Abstract: modified from Han et al. (2021)

The DNAODS (DFO North Atlantic Ocean-ice Downscaling System) consists of a high-resolution model for the Northwest Atlantic region nested to a low-resolution model for the North Atlantic. The numerical ocean-ice model used in the DNOADS is based on the NEMO3.6 ocean circulation model and version 2 of the Louvain-la-Neuve Ice model (LIM2). The z-coordinate approach allows the free surface and the bottom layer to vary as a function of geographical locations. The Northwest Atlantic grid domain is from 35°N to 64°N, and 35°W, with a horizontal resolution of 1/12°. It presents 50 vertical layers, from 1.5 m to a maximum spacing depth of 215 m, and a bathymetric Global Relief Model ETOPO1. A second grid domain is also available for DNAODS covering the North Atlantic from 7°N to 66°N, with a horizontal resolution of 1/4°. The ECMWF (6-hourly) reanalysis interim product is used as atmospheric forcing at the sea surface. The Simple

Ocean Data Assimilation (SODA 3.4.2) monthly mean product and major tides are used as lateral open boundary conditions. A monthly climatology of the model ocean temperature, salinity, currents, and sea ice extents, over the northwestern Atlantic, has been generated to help understand interannual and decadal oceanographic variability in this region. Projection runs included RCP 4.5 and 8.5, from 1980-2099. DNAODS was used to run a hindcast simulation (1980-2018) for the northwestern Atlantic by Han et al. (2021) (**Figure 7**) and it is indicated by Han et al. (2022) to downscale HadGEM2-ES for climate projections.

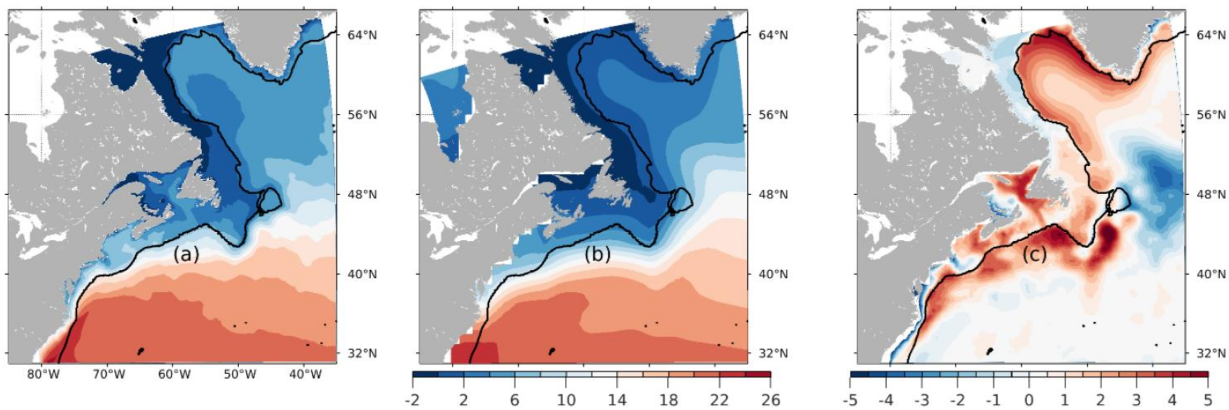

Figure 7 | Output of DNAODS model's Sea surface temperature (°C) for July from a 26-year model run (1980-2005). a: hindcast model output, b: the EN4 (Met Office) observational dataset, and c: difference between model and EN4 dataset. Modified from Han et al. (2021).

4.1.5 ROMS - Regional Ocean Modeling System (Shchepetkin and McWilliams, 2003, 2005)

Institution: Institute of Geophysics and Planetary Physics (IGPP), the United States of America

Abstract: modified from Brickman et al. (2021)

The Regional Ocean Modeling System (ROMS) is a free-surface, terrain-following, primitive equations ocean model that includes accurate and efficient physical and numerical algorithms, and various coupled models for biogeochemical, bio-optical, sediment, and sea ice applications (Shchepetkin and McWilliams, 2003, 2005). It has horizontal grid spacing of 7 km (720 x 360 grid points) and 40 vertical levels [version configuration by Kang and Curchitser (2013)]. The initial conditions and oceanic boundary forcing were derived from 5-day averages from the Simple Ocean Data Assimilation (SODA v2.1.6; 5-day averages), surface forcing from CORE version 2 (6-hour), and daily freshwater flux from rivers from the continental discharge data set.

In Nova Scotia, the ROMS climate change simulations were downscaled using the delta method to derive the initial and boundary conditions from ESMs. Brickman et al. (2021) applied ROMS (Control simulation) to downscale GFDL-ESM (ESM2M), IPSL model (CM5AMR), and HadGEM2 climate configuration under the RCP8.5 by 2050 (**Figure 8**).

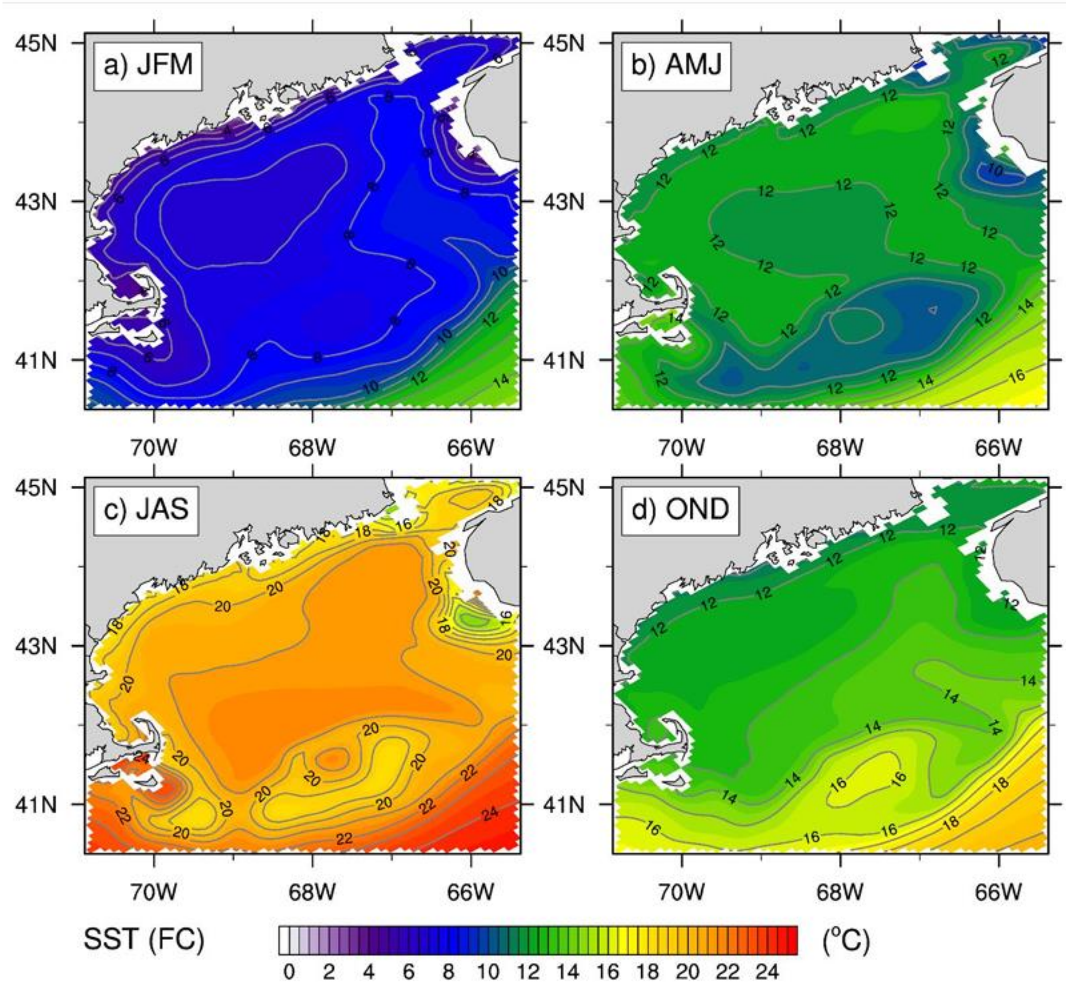

Figure 8 | Output of Gulf of Maine (GoM) 2050 seasonal mean sea surface temperature (SST) – ROMS model (delta method of GFDL-ESM2+IPSL-CM5A-MR+HadGEM2) future climate (FC) simulation. a: Winter (JFM); b: Spring (AMJ); c: Summer (JAS); d: Fall (OND). Modified from Brickman et al. 2021 supplemental figures – S5.

Ensembles

See **Section 4.1.2** for more details on the ensemble forcings ESM2M, CM5AMR, and HadGEM2.

4.2 General Circulation Models

4.2.1 CM2.6 - GFDL NOAA Climate Model 2.6

Institution: National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory Model (GFDL), the United States of America.

Abstract: Delworth et al. (2012)

The CM2.6 is a coupled atmosphere-ocean-land-sea ice global model which uses mesoscale eddy parameterization in the tracer budgets, closely configured according to Dunne (2012), and an ocean grid with nominal 0.10° spacing. The horizontal grid uses the tripolar configuration from Murray (1996). The ocean models provide a 50-cell vertical grid configuration, down to 5500 m. The upper ocean has 10 m thick grid spacing, with the deepest cell at 210 m thick. CM2.6 uses Modular Ocean Model (MOM4.1) for the ocean components; LM3 as the land model; and GFDL Sea Ice Simulator (SIS) for the sea ice component. The model has been applied for the CMIP5 projection under the RCP8.5 (2060-2080) scenario (**Figure 9**). CM2.6 was applied to generate detailed outputs for the Canada Atlantic waters, with a focus on the Gulf of Saint Lawrence and the Gulf of Maine (Saba et al., 2016; Kleisner et al., 2017; Greenan et al., 2019), and globally (Griffies et al., 2015).

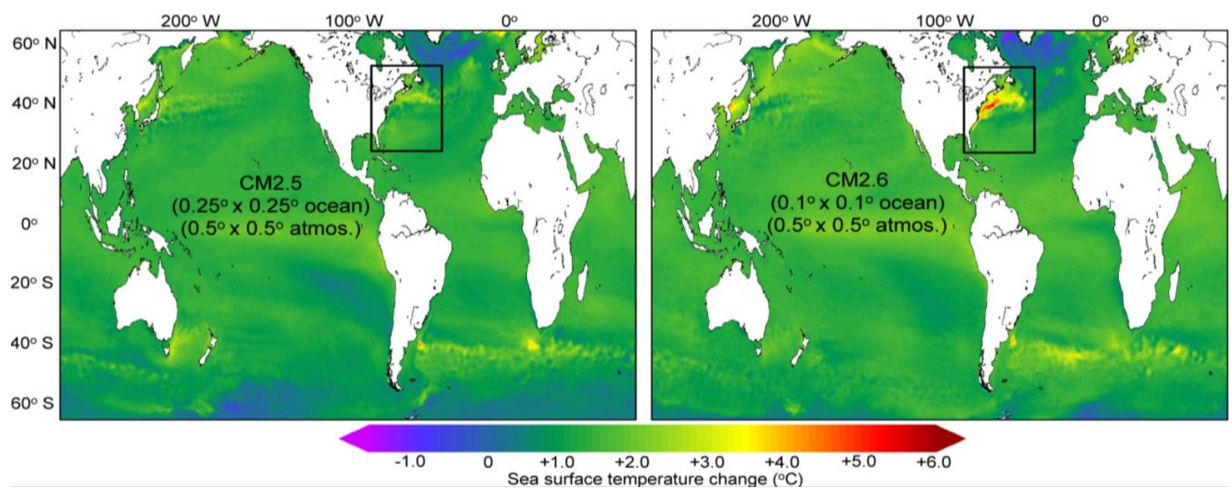

Figure 9 | Output of GFDL-CM2.6 (compared to CM2.5) for Global and Northwest Atlantic Sea surface and upper-ocean temperature change after a doubling of global atmospheric CO_2 (CO_2 perturbation 1% / yr) which is comparable to RCP8.5. Modified from Saba et al. (2016)

4.2.2 CanESM - Canadian Ocean Ecosystem Model (Arora and Matthews, 2009; Christian et al., 2010)

Institution: Canadian Centre for Climate Modelling and Analysis (CCCma), Environment and Climate Change Canada (ECCC).

Abstract: modified from Arora and Matthews (2009)

The Canadian Earth System Model (CanESM) is a global carbon-climate ESM designed to simulate climate variability and change. It uses the atmospheric general circulation model CanAM (Canadian Atmospheric Model) with a horizontal grid of ~2.81°. The most recent versions, CanESM2 and CanESM5, present a higher resolution grid, applied in regional studies around Nova Scotia. The physical ocean component (OGCM3.5) is based on the National Center for Atmospheric Research community ocean model (NCOM1.3). The ocean-atmosphere carbon dioxide (CO_2) flux is simulated by the Canadian Model of Ocean Carbon (CMOC) which incorporates an inorganic chemistry module and an ecosystem model. To achieve fine-resolution projections, an integrated ensemble with other ESM was used.

CanESM5-CanOE (modified from Christian et al., 2022)

CanESM5-CanOE (Canadian Ocean Ecosystem model) is the latest update of CanESM to support CMIP6. It encompasses multiple food chains, flexible phytoplankton elemental ratios, and a prognostic iron cycle. CanESM5 consists of the Canadian atmospheric model CanAM5 (128 Long. x 64 Lat.; 49 levels) with an embedded land-surface scheme, terrestrial biogeochemistry (CLASS-CTEM) and ocean model NEMO3.4 (horizontal resolution 1°, telescoping to 1/3° in the tropics, and 45 vertical levels ranging in thickness from ~6 m near the surface to ~250 m in the deep ocean). It also includes sea-ice (LIM2) and Canadian-developed biogeochemistry modules (CMOC and CanOE), and the Ocean Model Intercomparison Project (OMIP) to incorporate carbon chemistry. The native nominal resolution for atmosphere, aerosol, land, and land-ice is 500 km, with ocean ice resolution at 100 km. The CanESM5-CanOE has been applied in the Atlantic Canada (Kristiansen et al., 2022) region; downscaled (statistical) and interpolated with other models to project future scenarios with higher-resolution (1/12°) (**Figure 10**).

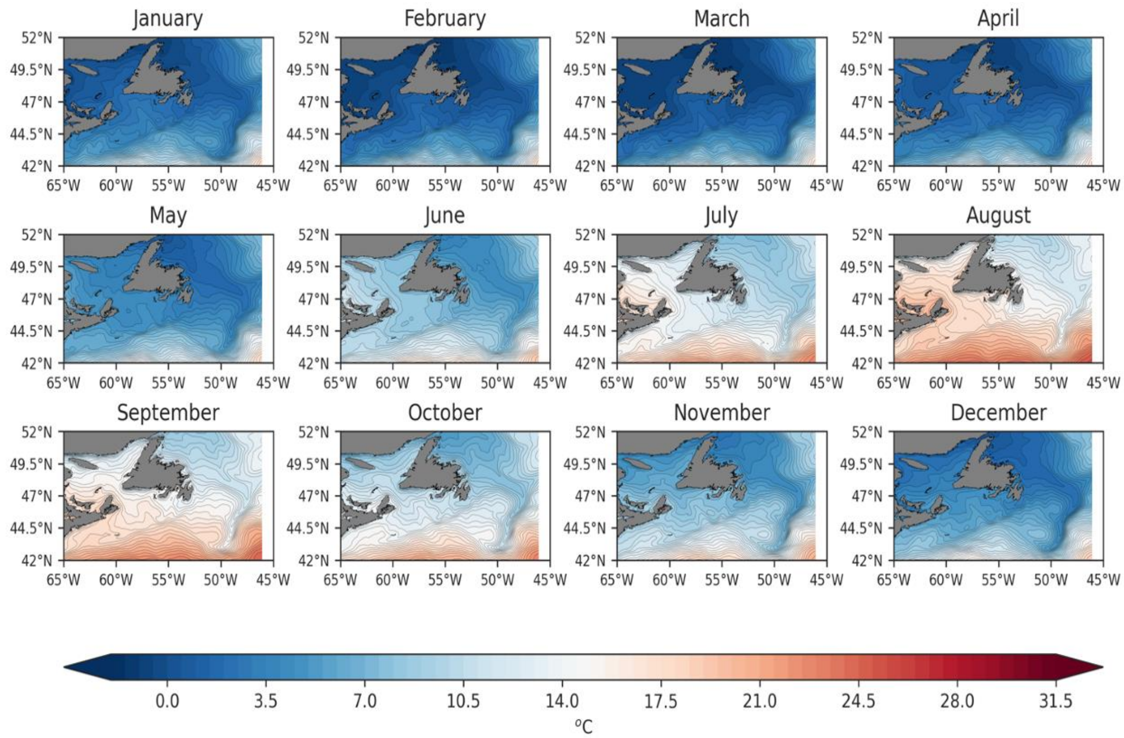

Figure 10 | Sea Surface Temperature (5 m) averaged monthly ensembled output for the period 2021-2040 under SSP5-8.5 for Newfoundland and surrounding waters. Ensemble models: MIROC-ES2L, MPI-ESM1-2-LR, CMCC-ESM2, IPSLCM6A-LR, CMCC-CM2-SR5, CanESM5-CanOE, UKESM1-0-LL, GFDL-ESM4. Modified from Kristiansen et al. 2022.

4.2.3 CMCC - Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici – Italy

Institution: Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, Italy (CMCC)

Abstract: modified from CMCC (2024)

The models were generated as part of the internationally coordinated Coupled Model Intercomparison Project Phase 6 (CMIP6) by the Fondazione Centro Euro-Mediterraneo sui Cambiamenti Climatici, in Italy (CMCC). The following ensembled models were statistically downscaled (1/12°) and interpolated with other models to achieve the fine-resolution scale necessary for a regional study (see Kristiansen et al., 2022) (**Figure 10** and **Figure 11**).

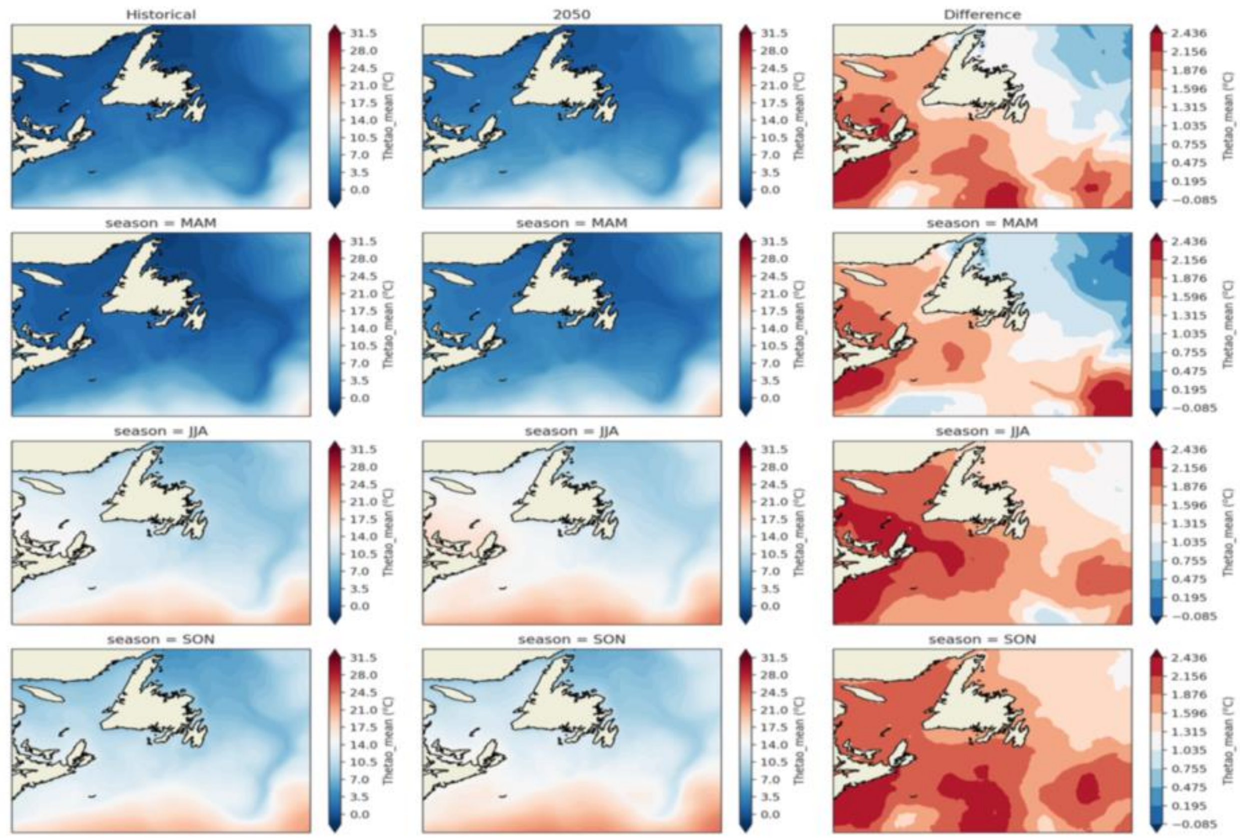

Figure 11 | Seasonal averaged sea surface temperature (at 5 m depth) under SSP5-8.5, based on ensemble average of CMIP6 models for year 2050 and difference from historical. Ensemble models: MIROC-ES2L, MPI-ESM1-2-LR, CMCC-ESM2, IPSLCM6A-LR, CMCC-CM2-SR5, CanESM56-CanOE, UKESM1-0-LL, GFDL-ESM4. Modified from Kristiansen et al. (2022)

CMCC-CM2-SR5 (Lovato and Peano, 2020)

CCMC-CM2-SR5 was released in 2016, and presents the following components: Modal Aerosol Modules with three lognormal modes (MAM3) for aerosol; Community Atmosphere Model (CAM) 5.3 (1°; 288 Long. x 192 Lat.; 30 vertical levels; top at ~2 hPa); land CLM4.5 (BGC mode); ocean NEMO3.6 (ORCA1 tripolar primarily 1° grid with meridional refinement down to 1/3° in the tropics; 362 Long. x 292 Lat.; 50 vertical levels; top grid cell 0-1 m); and Community Ice CodE (CICE4.0) for the sea-ice model. The native nominal resolution for aerosol, atmosphere, land, ocean, and sea-ice is 100 km. The CCMC-CM2-SR5 used in the Atlantic Canada (Kristiansen et al., 2022) was downscaled (statistical) and interpolated with other models to generate future projections with high-resolution (1/12°) output (**Figure 11**).

CMCC-ESM2 (modified from CMCC Foundation)

CMCC-ESM2, released in 2017, is an integration between the climate coupled model CMCC-CM2, encompassing the interactive dynamics of atmosphere, ocean, sea-ice, and land components, with the inclusion of marine biogeochemistry to fully represent the global carbon cycles. The main modules are atmosphere CAM5.4 (1°; 288 Long. x 192 Lat.; 30 levels; top at ~2 hPa), ocean NEMO3.6 (ORCA1 tripolar primarily 1° Lat./Long. with meridional refinement down to 1/3° in the tropics; 362 Long. x 292 Lat.; 50 vertical levels; top grid cell 0-1 m), sea-ice CICE4.0, land surface CLM4.5 (BGC mode), and ocean biogeochemistry model, BFM5.1. The native nominal resolution of all components is 100 km. This model was applied to Newfoundland coastline downscaled and interpolated to achieve fine resolution (1/12°) by (Kristiansen et al., 2022) (**Figure 11**).

4.2.4 GFDL-ESM4 - GFDL Earth System Models version 4.1 (Dunne et al., 2020)

Institution: National Oceanic and Atmospheric Administration (NOAA), Geophysical Fluid Dynamics Laboratory Model (GFDL), the United States of America.

Abstract: see GFDL-NOAA (2024)

The NOAA Geophysical Fluid Dynamics Laboratory Model (GFDL) has been improving their models based on the CMIP6. However, the CMIP5 suites are still supported by the group (GFDL-NOAA). The ESM4.1 is a model with fully coupled chemistry-carbon-climate Earth System Model with representation of both the stratosphere and biosphere developed to improve the carbon-chemistry-climate simulations for the CMIP6. It is composed of AM4.0 atmosphere component at approximately 1° resolution with 49 vertical levels of comprehensive, interactive chemistry and aerosols (including aerosol indirect effect) from precursor emissions. The ocean component is termed OM4 MOM6, having a ½° resolution with 75 levels, using hybrid pressure/isopycnal vertical coordinates. The sea ice component, SIS2, has radiative transfer and C-grid dynamics. Land model LM4.1, has a vegetation dynamics model with explicit treatment of plant age, height structure and soil microbes, with daily fire, crops, pasture, and grazing tiles; COBALTv2 ocean biogeochemical component representing ocean ecological and biogeochemical interactions; and fully interactive dust and iron cycling between land-atmosphere and ocean (GFDL, 2023).

According to Dunne et al. (2020), the GFDL-ESM4 (ESM4.1) is a robust GFDL model is a more comprehensive Earth system interaction (dynamics, physics, and aerosols) than the CM4 (focused on ocean physical components), and has double-resolution for both ocean and atmosphere as compared to the previous CM3 (biochemistry model) and ESM2 (carbon model) (**Figure 12**). An integrated ensemble of the GFDL-ESM4 and other models was applied by Kristiansen et al. (2022) to Newfoundland waters, to achieve high-resolution regional climate projection for scenarios SSP1-2.6, SSP2-4.5, and SSP5-8.5 (**Figure 10**).

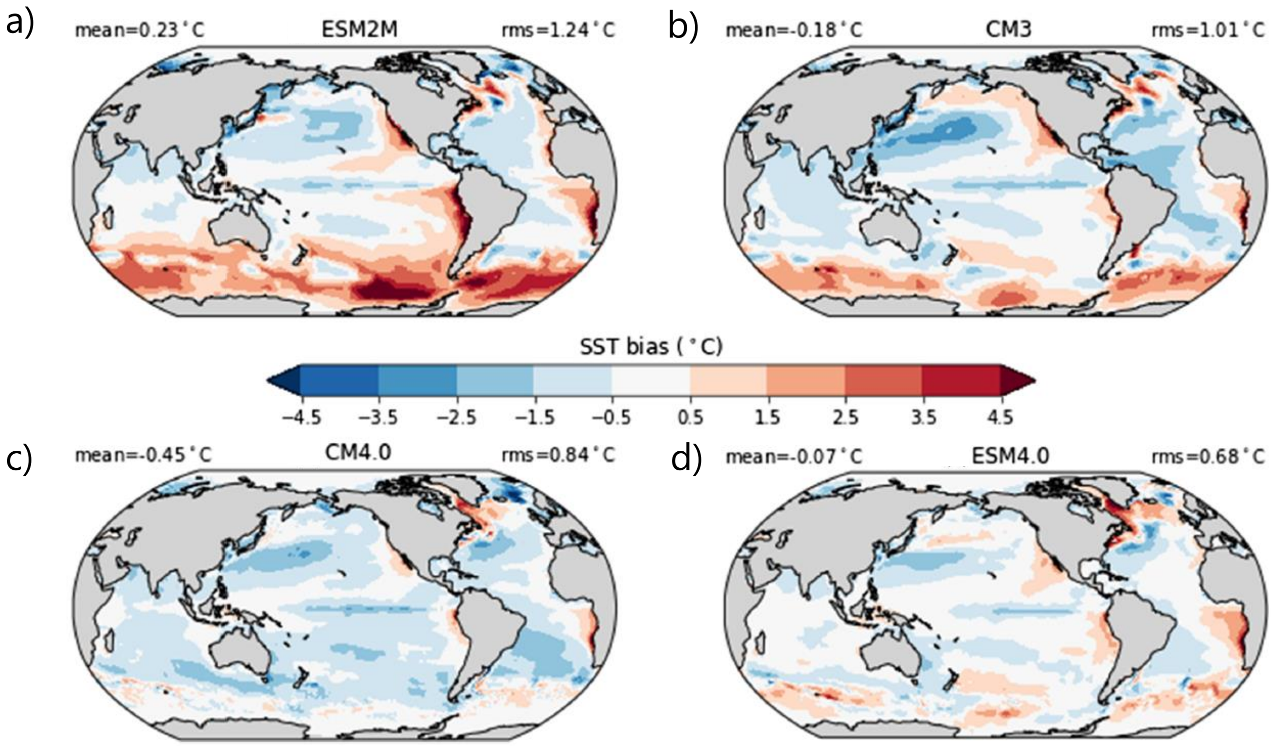

Figure 12 | Output of bias in sea surface temperature (°C) in a: ESM2M; b: CM3; c: CM4.0; d: ESM4.1. Modified from Dunne et al. (2020).

4.2.5 IPSLCM6A-LR - IPSL Climate Model version 5 (Low Resolution) (Hourdin et al., 2020)

Institution: Institut Pierre Simon Laplace (IPSL)

Abstract: modified from Hourdin et al. (2020)

The Institut Pierre Simon Laplace (IPSL) is a French climate modelling center (CMC) which develops Climate Models (CM) that contribute to the CMIP5 and CMIP6. The latest IPSL model version is CM6, with CM5 is no longer supported. The IPSL-CM6A-LR is part of CMIP6, focused on the representation of the physical climate, along with the global carbon cycle. This model's climatology was strongly improved, compared to previous models (Boucher et al., 2020). The equilibrium climate sensitivity and transient climate response have both increased from the previous climate model, IPSL-CM5A-LR. IPSL-CM6A-LR is composed of the atmospheric model LMDZ Version 6A-LR (resolution of 2.5° × 1.3° and 79 vertical layers); the oceanic model NEMO3.6 – OPA (1° nominal resolution, with latitudinal grid refinement of 1/3° in the equatorial region; and 75 vertical levels); the sea ice dynamics and thermodynamics NEMO-LIM3.6; the ocean biogeochemistry NEMO-PISCES; and the land surface model ORCHIDEE2.0. This model was applied as a downscaled ensemble climate projection for Newfoundland waters by Kristiansen et al. (2022) (**Figure 10**).

4.2.6 MIROC-ES2L - Model for Interdisciplinary Research on Climate, Earth System Version 2 for long-term simulations (Hajima et al., 2020)

Institution: Model for Interdisciplinary Research on Climate (MIROC), Japan.

Abstract: Hajima et al. (2020)

MIROC-ES2L embeds a terrestrial biogeochemical component with explicit carbon-nitrogen interaction to account for soil nutrient control on plant growth and the land carbon sink. The ocean biogeochemical component of the model simulates the biogeochemical cycles of carbon, nitrogen, phosphorus, iron, and oxygen such that oceanic primary productivity can be controlled by multiple nutrient limitations. The ocean nitrogen cycle is coupled with the land component via river discharge processes, and external inputs of iron from pyrogenic and lithogenic sources are considered. The physical core comprises the MIROC5.2 component models of the atmosphere (CCSR-NIES AGCM coupled with the aerosol SPRINTARS) with resolution of 2.8° and 40 layers; ocean CCSR-COCO with 1° (finer at the Equator) and 62 vertical levels; and land MATSIRO. The MIROC-ES2L was utilized as an integrated forcing to project climate changes in Newfoundland waters by Kristiansen et al. (2022) (**Figure 10**).

4.2.7 MPI-ESM1.2-LR - Max Planck Institute Earth System Model Low Resolution version (Mauritsen et al., 2019)

Institution: Max Planck Institute for Meteorology, Germany.

Abstract: modified from Mauritsen et al. (2019)

The Max Planck Institute for Biogeochemistry and the Max Planck Institute for Chemistry partnered to provide a better understanding of the factors that influence concentrations of greenhouse gases in the atmosphere, and their interaction with the terrestrial and marine biospheres. As a result, the MPI-ESM models reflect the characteristics of climate change under idealized forcing as well as complex forcing. MPI-ESM1.2_LR is a low-resolution Earth System Model (version 1.2) released in 2017 for CMIP6. As an upgrade, it conserves energy and moisture developed to focus on instrumental record warming and have statistical consistency with observed temperature data. The model has a high climate sensitivity (about 7 K) to a doubling of atmospheric CO_2. The climate model components include the second version of Max Planck Institute Aerosol Climatology with simple plume implementation (MACv2-SP) as the aerosol component; the GCM from the European Centre for Medium-Range Weather Forecasts developed in Hamburg ECHAM6.3 for the atmosphere (spectral T63; 200 km grid spacing; 47 levels). The model interacts with the Jena Scheme for Biosphere Atmosphere Coupling in Hamburg (JSBACH3.20) as land component. The ocean model is the Max-Planck-Institute Ocean model MPIOM1.6.3 (bipolar GR1.5, approximately 1.5°; 150 km grid spacing; 40 levels). The HAMburg

Ocean Carbon Cycle version 6 (HAMOCC6) is integrated for ocean biogeochemistry. For sea ice, an unnamed thermodynamic sea ice model (thermodynamic Semtner zero-layer; dynamic Hibler 79) was included. The native nominal resolution is 250 km for aerosol, land, ocean biogeochemistry, and sea ice. The model has been statistically downscaled by DFO (Kristiansen et al., 2022) for high-resolution (<0.1°) application in Newfoundland (**Figure 10**).

4.2.8 UKESM1-0-LL - The United Kingdom Earth System Model Low-resolution (UKESM, 2024)

Institution: Meteorological Office (Met Office) of the United Kingdom and Natural Environment Research Council (NERC)

Abstract: modified from Sellar et al. (2019)

The UKESM project is a joint United Kingdom's Met Office and Natural Environment Research Council (NERC) collaboration that developed the UKESM1.0 as a successor to the HadGEM2-ES model. UKESM1 delivers simulations used in CMIP6 for studying past and future climate around the globe. The main focus of the model is the Sulphur cycle and its connection to historical aerosol forcing (UKESM). The model UKESM1-0-LL is composed of HadGEM3-GA7.1 as the physical-dynamical core, including the Global Atmosphere 7.1 (GA7.1; N96; 192 Long. x 144 Lat; 85 levels; top level 85 km) configuration of the Unified Model (UM); the Nucleus for European Modelling of the Ocean (NEMO) model; the Los Alamos Sea Ice Model CICE-HadGEM3-GSI8 (eORCA1 tripolar primarily 1°; 360 Long. x 180 Lat.); and the Joint UK Land Environment Simulator (JULES ES-1.0) land surface model; NEMO-HadGEM3-GO6.0 (eORCA1 tripolar primarily 1° Lat./Long. with meridional refinement down to 1/3° in tropics; 360 Long. x 180 Lat.; 75 levels; top grid cell 0-1 m) ocean model; and Ice sheets model CICE-HadGEM3-GSI8 (eORCA1 tripolar primarily 1°; 360 Long. x 180 Lat.). The additional 140 ES process models include the stratospheric-tropospheric (UKCA-Strat Trop) version of the United Kingdom Chemistry and Aerosol UKCA-GLOMAP-mode model, the Model of Ecosystem Dynamics, nutrient Utilization, Sequestration and Acidification (MEDUSA), and biogeochemistry component of MEDUSA2. The UKESM1-0-LL was utilized to generate a downscaled high-resolution interpolated model for Newfoundland by Kristiansen et al. (2022) (**Figure 10**).

5 Conclusion

The Atlantic Canadian Ocean has been relatively well modeled under various climate change projections, with emphasis on the Gulf of Saint Lawrence and the Gulf of Maine, where RCMs were used to better understand local oceanic drivers and forcings, due to their ecological and economic importance. These high-resolution RCMs aim to resolve local phenomena and project sea temperature variation along coastal areas, which has application to seafood industries such as fisheries and aquaculture. However, the finest resolution currently applied by the RCMs is about 7 km which is not fully adequate to capture smaller scale phenomena, such as eddies and precipitation extremes. The ongoing development of downscaled (bias adjusted) models is important to support climate change mitigation/adaptation plans for coastal industries and communities in the Atlantic provinces.

6 References

Arora, V. K., Matthews, H. D. (2009). Characterizing uncertainty in modeling primary terrestrial ecosystem processes. *Global Biogeochemical Cycles, 23*(2). doi:https://doi.org/10.1029/2008GB003398

Arora, V. K. et al. (2011). Carbon emission limits required to satisfy future representative concentration pathways of greenhouse gases. *Geophysical Research Letters, 38*(5). doi:https://doi.org/10.1029/2010GL046270

Boucher, O. et al. (2020). Presentation and Evaluation of the IPSL-CM6A-LR Climate Model. *Journal of Advances in Modeling Earth Systems, 12*(7), e2019MS002010. doi:https://doi.org/10.1029/2019MS002010

Brennan, C. E. et al. (2016). Sensitivity of Northwest North Atlantic Shelf Circulation to Surface and Boundary Forcing: A Regional Model Assessment. *Atmosphere-Ocean, 54*(3), 230-247. doi:10.1080/07055900.2016.1147416

Brickman, D. et al. (2021). Projections of physical conditions in the Gulf of Maine in 2050. *Elem. Sci. Anth., 9*, 1-15.

Brickman, D., Drozdowski, A. (2012). Development and Validation of a Regional Shelf Model for Maritime Canada based on the NEMO-OPA Circulation Model. Fisheries and Oceans Canada.

Brickman, D. et al. (2018). Mechanism for the recent ocean warming events on the Scotian Shelf of eastern Canada. *Continental Shelf Research, 156*, 11-22. doi:https://doi.org/10.1016/j.csr.2018.01.001

Brickman, D. et al. (2016a). High resolution future climate ocean model simulations for the Northwest Atlantic Shelf region. Fisheries and Oceans canada (DFO), Bedford Institute of Oceanography, Dartmouth, Nova Scotia. https://waves-vagues.dfo-mpo.gc.ca/Library/365880.pdf

Brickman, D. et al. (2016b). Variability of Current Streams in Atlantic Canadian Waters: A Model Study. *Atmosphere-Ocean, 54*(3), 218-229. doi:10.1080/07055900.2015.1094026

Canadell, J. G. et al. (2021). Global Carbon and Other Biogeochemical Cycles and Feedbacks. In C. Intergovernmental Panel on Climate (Ed.), *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 673-816). Cambridge: Cambridge University Press.

Chen, D. et al. (2023). Framing, Context, and Methods. In C. Intergovernmental Panel on Climate (Ed.), *Climate Change 2021 – The Physical Science Basis: Working Group I Contribution to the Sixth*

Assessment Report of the Intergovernmental Panel on Climate Change (pp. 147-286). Cambridge: Cambridge University Press.

Christian, J. R. et al. (2010). The global carbon cycle in the Canadian Earth system model (CanESM1): Preindustrial control simulation. *Journal of Geophysical Research: Biogeosciences, 115*(G3). doi:https://doi.org/10.1029/2008JG000920

Christian, J. R. et al. (2022). Ocean biogeochemistry in the Canadian Earth System Model version 5.0.3: CanESM5 and CanESM5-CanOE. *Geosci. Model Dev., 15*(11), 4393-4424. doi:10.5194/gmd-15-4393-2022

CMCC. (2024). Data. https://www.cmcc.it/research/data-services-and-products/data-list

Delworth, T. L. et al. (2006). GFDL's CM2 Global Coupled Climate Models. Part I: Formulation and Simulation Characteristics. *Journal of Climate, 19*(5), 643-674. doi:https://doi.org/10.1175/JCLI3629.1

Delworth, T. L. et al. (2012). Simulated Climate and Climate Change in the GFDL CM2.5 High-Resolution Coupled Climate Model. *Journal of Climate, 25*(8), 2755-2781. doi:10.1175/JCLI-D-11-00316.1

Dixon, K. W. et al. (2016). Evaluating the stationarity assumption in statistically downscaled climate projections: is past performance an indicator of future results? *Climatic Change, 135*(3), 395-408. doi:10.1007/s10584-016-1598-0

Dufresne, J. L. (2013). Climate change projections using the IPSL-CM5 Earth System Model: from CMIP3 to CMIP5. *Clim. Dyn., 40*.

Dunne, J. P. (2012). GFDL's ESM2 global coupled climate-carbon earth system models. Part I: physical formulation and baseline simulation characteristics. *J. Clim., 25*.

Dunne, J. P. et al. (2020). The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics. *Journal of Advances in Modeling Earth Systems, 12*(11), e2019MS002015. doi:https://doi.org/10.1029/2019MS002015

Eyring, V. et al. (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development, 9*, 1937-1958. doi:doi:10.5194/gmd-9-1937-2016

Flato, G. et al. (2019). Modelling Future Climate Change. In E. Bush & D. S. Lemmen (Eds.), *Canada's Changing Climate Report* (pp. 74–111). https://changingclimate.ca/CCCR2019/chapter/3-0/

Gebrechorkos, S. et al. (2023). A high-resolution daily global dataset of statistically downscaled CMIP6 models for climate impact analyses. *Scientific Data, 10*(1), 611. doi:10.1038/s41597-023-02528-x

GFDL-NOAA. GFDL Models. Accessed August 16. https://www.gfdl.noaa.gov/about-models/

GFDL-NOAA. (2024). GFDL Models. Accessed October 21. https://www.gfdl.noaa.gov/about-models/

Giorgetta, M. A. et al. (2013). Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase 5. *Journal of Advances in Modeling Earth Systems, 5*(3), 572-597. doi:https://doi.org/10.1002/jame.20038

Greenan, B. et al. (2019). Climate change vulnerability of American lobster fishing communities in Atlantic Canada. *Frontiers in Marine Science, 6*, 18. doi:10.3389/fmars.2019.00579

Griffies, S. M. et al. (2015). Impacts on Ocean Heat from Transient Mesoscale Eddies in a Hierarchy of Climate Models. *Journal of Climate, 28*(3), 952-977. doi:https://doi.org/10.1175/JCLI-D-14-00353.1

Guo, L. et al. (2013). Dynamical Downscaling over the Gulf of St. Lawrence using the Canadian Regional Climate Model. *Atmosphere-Ocean, 51*(3), 265-283. doi:10.1080/07055900.2013.798778

Hajima, T. et al. (2020). Development of the MIROC-ES2L Earth system model and the evaluation of biogeochemical processes and feedbacks. *Geosci. Model Dev., 13*(5), 2197-2244. doi:10.5194/gmd-13-2197-2020

Han, G. et al. (2022). Status of DFO Ocean Modelling: A National Review. Institute of Ocean Sciences Fisheries and Oceans Canada. Sidney, BC, V8L 4B2 Canada.

Han, G. et al. (2021). Simulated monthly ocean climatology of the northwestern Atlantic : 1980-2018. In *Canadian data report of hydrography and ocean sciences* (pp. vi, 22). Sidney, BC: Institute of Ocean Sciences, Fisheries and Oceans Canada.

Hourdin, F. et al. (2020). LMDZ6A: The Atmospheric Component of the IPSL Climate Model With Improved and Better Tuned Physics. *Journal of Advances in Modeling Earth Systems, 12*(7), e2019MS001892. doi:https://doi.org/10.1029/2019MS001892

IPCC. (2014). Climate change 2014: Synthesis report. Intergovernmental Panel on Climate Change (IPCC), Geneva, Switzerland. https://www.ipcc.ch/reports/?rp=ar5

IPCC. (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press. Cambridge, UK and New York, NY, USA. https://www.ipcc.ch/srocc/

IPCC. (2022). Climate change 2022. Impacts, adaptation and vulnerability. Full Report. Intergovernmental Panel of Climate Change (IPCC), United Nations (UN). https://report.ipcc.ch/ar6wg3/pdf/IPCC_AR6_WGIII_FinalDraft_FullReport.pdf

IPCC. (2023). Synthesis Report (SYR) of the IPCC Sixth Assessment Report (AR6): Summary for Policymakers. https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_SPM.pdf

Kang, D., Curchitser, E. N. (2013). Gulf Stream eddy characteristics in a high-resolution ocean model. *Journal of Geophysical Research: Oceans, 118*(9), 4474-4487. doi:https://doi.org/10.1002/jgrc.20318

Kleisner, K. M. et al. (2017). Marine species distribution shifts on the U.S. Northeast Continental Shelf under continued ocean warming. *Progress in Oceanography, 153*, 24-36. doi:https://doi.org/10.1016/j.pocean.2017.04.001

Kristiansen, T. et al. (2022). Regional downscaling of CMIP6 climate projections for the Newfoundland coastline. Fisheries and Oceans Canada. San Francisco, California -USA.

Lambert, N. et al. (2013). Projection of future river runoffs in Eastern Atlantic Canada from Global and Regional climate models. DFO. Gulf Fisheries Centre 343 Université Avenue, PO Box 5030 Moncton, New Brunswick, E1C 9B6. https://waves-vagues.dfo-mpo.gc.ca/library-bibliotheque/349262.pdf

Lanzante, J. R. et al. (2018). Some Pitfalls in Statistical Downscaling of Future Climate. *Bulletin of the American Meteorological Society, 99*(4), 791-803. doi:https://doi.org/10.1175/BAMS-D-17-0046.1

Lavoie, D. et al. (2019). Projections of future trends in biogeochemical conditions in the Northwest Atlantic using CMIP5 earth system models. *Atmosphere-Ocean, 57*(1), 18-40. doi:10.1080/07055900.2017.1401973

Lavoie, D. et al. (2020). Projections of future physical and biogeochemical conditions in the Gulf of St. Lawrence, on the Scotian Shelf and in the Gulf of Maine. Fisheries and Oceans Canada (DFO), Pelagic and Ecosystem Science Branch, Quebec. http://www.publications.gc.ca/site/fra/9.892092/publication.html

Lavoie, D. et al. (2021). The Gulf of St. Lawrence Biogeochemical Model: A Modelling Tool for Fisheries and Ocean Management. *Frontiers in Marine Science, 8*(1427). doi:10.3389/fmars.2021.732269

Long, Z. et al. (2016). Impacts of Climate Change in the Gulf of St. Lawrence. *Atmosphere-Ocean, 54*(3), 337-351. doi:10.1080/07055900.2015.1029869

Lovato, T., Peano, D. (2020). *CMCC CMCC-CM2-SR5 model output prepared for CMIP6 ScenarioMIP*. Retrieved from: https://doi.org/10.22033/ESGF/CMIP6.1365

Mauritsen, T. et al. (2019). Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO2. *Journal of Advances in Modeling Earth Systems, 11*(4), 998-1038. doi:https://doi.org/10.1029/2018MS001400

Morris, M. et al. (2022). Statistical Downscaling. In *UTCDW Guidebook*. https://utcdw.physics.utoronto.ca/UTCDW_Guidebook/Chapter4/chapter4.html

Murray, R. J. (1996). Explicit Generation of Orthogonal Grids for Ocean Models. *Journal of Computational Physics, 126*(2), 251-273. doi:https://doi.org/10.1006/jcph.1996.0136

Pozo Buil, M. et al. (2023). Evaluation of Different Bias Correction Methods for Dynamical Downscaled Future Projections of the California Current Upwelling System. *Earth and Space Science, 10*(12), e2023EA003121. doi:https://doi.org/10.1029/2023EA003121

Rutherford, K., Fennel, K. (2018). Diagnosing transit times on the northwestern North Atlantic continental shelf. *Ocean Sci., 14*(5), 1207-1221. doi:10.5194/os-14-1207-2018

Rutherford, K. et al. (2024). Uncertainty in the evolution of northwestern North Atlantic circulation leads to diverging biogeochemical projections. *Biogeosciences, 21*(1), 301-314. doi:10.5194/bg-21-301-2024

Saba, V. S. et al. (2016). Enhanced warming of the Northwest Atlantic Ocean under climate change. *Journal of Geophysical Research: Oceans, 121*(1), 118-132. doi:10.1002/2015JC011346

Sellar, A. A. et al. (2019). UKESM1: Description and Evaluation of the U.K. Earth System Model. *Journal of Advances in Modeling Earth Systems, 11*(12), 4513-4558. doi:https://doi.org/10.1029/2019MS001739

Shchepetkin, A. F., McWilliams, J. C. (2003). A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. *Journal of Geophysical Research: Oceans, 108*(C3). doi:https://doi.org/10.1029/2001JC001047

Shchepetkin, A. F., McWilliams, J. C. (2005). The regional oceanic modeling system (ROMS): a split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean Modelling, 9*(4), 347-404. doi:https://doi.org/10.1016/j.ocemod.2004.08.002

Siedlecki, S. et al. (2021). Projecting ocean acidification impacts for the Gulf of Maine to 2050: New tools and expectations. *Elementa: Science of the Anthropocene, 9*(1). doi:10.1525/elementa.2020.00062

Society, T. R. (2021). Next generation climate models: a step change for net zero and climate adaptation [Policy briefings]. *Climate change: science and solutions,* (1), 11. https://royalsociety.org/-/media/policy/projects/climate-change-science-solutions/climate-science-solutions-modelling.pdf

Srivastava, A. et al. (2020). Evaluation of historical CMIP6 model simulations of extreme precipitation over contiguous US regions. *Weather and climate extremes, 29*, 100268. doi:https://doi.org/10.1016/j.wace.2020.100268

Taylor, K. E. et al. (2012). An Overview of CMIP5 and the Experiment Design. *Bulletin of the American Meteorological Society, 93*(4), 485-498. doi:https://doi.org/10.1175/BAMS-D-11-00094.1

UKESM. Science of UKESM. Accessed August 16. https://ukesm.ac.uk/science-of-ukesm/

UKESM (2024, January 8). UKESM1-0-LL. Available at: https://ukesm.ac.uk/wp-content/uploads/2022/06/UKESM1-0-LL.html

7 Appendix

Appendix A | Overview scores for CMIP5 (left-hand side of table) and CMIP6 (right-hand side of table) Earth system models (ESMs), for multiple benchmarks against different datasets. Scores are relative to other models within each benchmark row, with positive scores indicating a better agreement with observations. Modified from Canadell et al. (2021).

Ocean Benchmarking Results	CMIP5 ESMs									CMIP6 ESMs										
	bcc-csm1-1	CanESM2	CESM1-BGC	GFDL-ESM2G	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR	NorESM1-ME	HadGEM2-ES	BCC-CSM2-MR	CanESM5	CESM2	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL	Mean CMIP5	Mean CMIP6
Ocean Ecosystems			2.18	0.20	-0.20		0.04		0.22		-0.37	0.83	-0.37	-0.26	-0.91	-0.67	-1.93	0.27	0.30	0.67
Chlorophyll		-1.50	2.15	0.44	1.02		0.49		0.56		-0.67	0.88	-0.21	0.10	-1.02	-0.41	-2.19	0.18	0.13	0.04
Oxygen, surface			0.73	-0.13	-1.98		-0.53	-1.53	-0.29		0.73	0.34	-0.09	-0.41	0.35	-0.30	0.40	0.49	0.64	1.57
Ocean Nutrients			-0.84	-0.10	0.91		-0.80	-1.25				-0.02	1.00	1.88		-0.90	-1.14	-0.17	-0.16	1.60
Nitrate, surface		0.21	-1.63	0.67	1.22		-0.18	-1.70	0.82		1.21	-0.90	0.29	1.21	1.02	0.39	-1.78	-0.56	-0.47	0.18
Phosphate, surface			-0.69	-0.04	0.04		-0.45	-0.43				0.39	-0.14	0.17	-0.41	-0.98	0.00	0.02	0.88	1.63
Silicate, surface			0.44	-0.71	0.24		-0.81	-0.20	-2.16			0.50	1.24	1.60		-1.21	-0.19	0.18	-0.29	1.37
Ocean Carbon											1.24	-0.23	-0.62	-0.69	-1.08	-1.12	1.31			1.19
TAlk, surface		-0.27	1.01	0.12	0.19		0.32	-2.31	-0.22		0.06	-0.36	0.85	-0.42	0.29	-2.40	1.27	0.06	1.27	0.54
DIC, surface		0.60	-0.14	-0.31	-0.40		-0.34	-2.85	-0.96		0.41	-0.73	0.07	1.01	0.42	0.19	1.20	0.82	0.43	0.60
Anthropogenic											1.35	-0.06	-0.77	-0.78	-1.23	-0.84	1.14			1.19
Ocean Physical Drivers	-0.22	0.02	0.29	-1.11	0.14	-0.23	-1.36	-0.70	-0.79	-0.37	0.51	0.76	0.22	0.34	-0.14	-0.23	-1.22	0.65	1.20	2.25
Mixed Layer Depth			0.39	-1.38			-1.95	0.25		-0.71	0.81	1.50	0.21	0.51	-0.82	0.61	-1.28	0.66	-0.29	1.48
Temperature, surface	-0.26	0.38	0.13	-1.30	-1.52	-0.29	-0.20	-0.48	-0.60	0.14	0.21	0.52	0.16	-0.36	-0.23	-0.29	-0.58	1.19	1.54	1.82
Temperature, 200m	-0.26	0.22	0.43	-0.87	-0.03	-0.21	-0.93	-1.14	-1.30	-0.29	0.35	0.51	-0.67	0.30	0.46	-0.34	-1.03	1.04	1.69	2.09
Temperature, 700m	-0.65	0.94	0.62	-0.19	0.79	-0.83	-2.03	0.27	0.50	-0.77	-0.97	0.35	-0.44	0.33	-0.55	-1.95	0.32	1.29	1.59	1.37
Vertical temperature gradient	-0.49	0.04	0.91	0.08	-0.11	0.08	-0.22	-1.85	-2.03	-0.57	0.66	0.89	0.62	-0.52	0.82	-0.53	-1.68	1.04	1.22	1.66
Salinity, surface	-0.08	-1.22	0.01	-0.69	0.23	-0.67	0.04	-1.42	-1.78	0.93	0.34	0.29	1.62	0.13	0.16	-0.30	-0.22	-0.99	1.43	2.19
Salinity, 200m	-0.62	-0.29	-0.07	-0.57	0.54	-0.57	-0.26	-0.75	-0.76	-0.25	0.49	-0.47	0.15	0.65	0.58	0.01	-0.98	-0.22	1.41	1.99
Salinity, 700m	0.44	-0.35	-1.06	-0.54	0.70	0.46	-0.46	-0.80	0.32	0.36	0.25	-1.16	-0.47	0.54	0.33	-0.39	-0.87	-0.54	1.58	1.64
Ocean Relationships			-1.86	-0.36	-0.29		1.50	-0.43	0.68		-0.02	0.72	1.20	0.17	-1.86	0.02		-1.12	0.39	1.25
Oxygen, surface/WOA2018			0.27	0.23	-0.63		-0.26	-0.12	-0.38		0.29	-0.21	0.19	0.18	0.14	-0.07		0.03	-0.23	0.53
Nitrate, surface/WOA2018		-2.41	-1.38	-0.18	0.06		1.41	-0.16	0.78		0.09	0.79	1.07	0.26	-1.35	0.20		-0.74	0.52	1.04

Relative Scale

Worse Value — Better Value — Missing Data or Error