Status of DFO Ocean Modelling: A National Review

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Ocean modelling plays a key role and is essential in research, advice, service, and decision-making within Fisheries and Oceans Canada (DFO). Fostering national coordination and collaboration is the focus of the DFO Ocean Modelling Community (MODCOM), in order to better support DFO needs, priorities, and emerging challenges, as well as needs of external clients. In this report, we review the present status of DFO ocean modelling, including modelling capacity and innovations in model development and applications in DFO over 2018-2020, as well as planned directions for MODCOM. A variety of models from port, shelf, basin, to pan-Canadian scale domains have been developed with applications ranging from forecasts of a few days, to decadal hindcasts, to century long projections covering the areas of climate modelling, ocean forecasting, aquaculture, and acoustics. The model results are being used to address DFO priorities including climate change adaptation, ecosystem management, aquaculture management, and environmental responses. It is anticipated that this review can provide essential information on MODCOM for its members and diverse stakeholders within and outside DFO.

RÉSUMÉ

Han, G., Bianucci, L., Chassé, J., Foreman, M., Holden, J., Horwitz, R., Holdsworth, A., Lambert, N., Lavoie, D., Le Corre, N., Lu, Y., Peña, A., Ratsimandresy, A., Wang, Z., Perrie, W., Steiner, N., Thupaki, P., Zhai L., Brickman, D., Christian, J., Dunphy, M., Soontiens, N., Vagle, S., Guyondet, T., Page, P., Haigh, S., O'Flaherty-Sproul, M. 2022. Status of DFO Ocean Modelling: A National Review. Can. Tech. Rep. Hydrogr. Ocean Sci. 338: viii + 58 p.

La modélisation des océans joue un rôle essentiel dans la recherche, les avis, les services et la prise de décision au sein du Ministère des Pêches et Océans (MPO) du Canada. Favoriser la coordination nationale et la collaboration est l'objectif principale de la Communauté de la Modélisation du MPO (COMMOD) afin de mieux supporter les besoins du MPO, ses priorités, ses défis émergeants ainsi que les besoins des clients externes. Dans ce rapport, nous présentons l'état de la modélisation de l'océan au MPO, incluant la capacité de modélisation et d'innovation dans le développement des modèles et applications couvrant la période 2018-2020 ainsi que les directions planifiées pour COMMOD. Une variété de modèles à l'échelle des ports, plateaux, basins, jusqu'à des domaines pancanadiens ont été développées avec des applications variant des prévisions à court terme, aux modélisations rétrospectives décennales, aux projections sur le siècle et couvrants les domaines de recherche de la modélisation du climat, de la prévision océanique et de l'acoustique marine. Les résultats des modèles sont utilisés pour adresser les priorités du MPO incluant l'adaptation aux changements climatique, la gestion des écosystèmes, la gestion de l'aquaculture et les réponses environnementales. Il est anticipé que cette revue fournira de l'information essentielle pour les membres de COMMOD et pour d'autres intervenants à l'intérieur et à l'extérieur du MPO.

1. Introduction

Ocean modelling plays a key role and is essential in research, advice, service, and decision-making within Fisheries and Oceans Canada (DFO). The DFO Ocean Modelling Community (MODCOM) was established in 2020, as a community of practice for DFO ocean modellers in fields including physical oceanography, biogeochemical oceanography, aquaculture, and acoustics.

The mandate of MODCOM is to facilitate knowledge exchange, collaboration, and strategic alignment related to the research, development, application, and improvement of ocean models in DFO. The specific goals of MODCOM are to support DFO's mandate by (1) Advancing ocean modelling capacity and innovation within DFO, (2) Developing and maintaining state-of-the-art models, (3) Improving efficiency in developing new model configurations and domains, and (4) Ensuring models clearly support DFO needs, priorities, and emerging challenges.

This article reviews the status in model development and applications over 2018-2020, and planned directions for MODCOM. It is recognized that while it endeavours to be full and complete, this review may not capture all MODCOM modelling activities.

Section 2 reviews the development of ocean model capacity within the programs represented by MODCOM. Innovations in advancing ocean sciences, modelling techniques, and applying models in support of DFO priorities are highlighted in Section 3. Section 4 presents planned directions. Information on model configurations and products is included in the Appendix A. A list of acronyms is provided in Appendix B.

2. Model Capacity Development

DFO ocean modelling activities in the past three years have focused on the following themes: ocean climate modeling including physics and biogeochemistry, short-term forecasting, aquaculture-related modelling, and marine environmental quality (acoustic noise) modelling. This section reviews the model development within each of these themes. Table 1 summarizes models and sub-sections presenting them.

2.1. Ocean Climate Modelling

Ocean climate modelling activities are mainly on refinement of applied ocean models to improve hindcasts and projections of ocean conditions under a changing climate, including physical and biogeochemical state of the oceans. These models are to help address vulnerability of fisheries, ecosystems and coastal infrastructure to climate change. A number of models have been developed for Canada's three oceans. Some models have not yet incorporated biogeochemistry but are in the process of doing so.

2.1.1 The North Atlantic

2.1.1.1 The Bedford Institute of Oceanography North Atlantic Model

The Bedford Institute of Oceanography started the development of a 1/12 degree North Atlantic Model (BNAM) about a decade ago. In the past three years, BNAM has been improved continuously in its capacity and performance. BNAM has two products: hindcasts from 1990 to present, and climate projections for two future periods. The BNAM model results have been used to understand deep ocean circulation in the North Atlantic and ocean climate variability on the northwest Atlantic shelf and slope (e.g. Wang et al., 2019). The model products have also found many applications in ecosystem sciences and management (e.g. Beazley et al., 2020).

2.1.1.2 The Gulf of St. Lawrence, Scotian Shelf and Gulf of Maine modelling system

In 2008 the Bedford Institute of Oceanography and the Gulf Fisheries Centre initiated the development of the Gulf of St. Lawrence, Scotian Shelf and Gulf of Maine modelling system, CANadian Ocean PArallelise (CANOPA), for climate variability research and climate change projection (Figure 2). There has been ongoing development of hindcasting to support ecosystem science and study the ecological linkages between fish and the environment in the Quebec and Gulf Regions (Benkort et al., 2020, Brennan et al., 2019, 2021). At present, the grid horizontal resolution varies from 1/4° to 1/108°. Ocean hindcasts are updated annually and provided to aid research in biophysical modelling, aquatic ecosystems, invasive species, and connectivity of marine populations.

The 1/12° CANOPA has been coupled with an atmospheric Canadian Regional Climate Model (CRCM), a hydrology model, and a biogeochemical model (the Gulf of St. Lawrence Biogeochemical Model (GSBM); Lavoie et al., 2021) for regional climate change downscaling (Lavoie et al. 2019; 2020; Siedlecki et al. 2020). GSBM simulates the lower trophic levels (phytoplankton, zooplankton) of the ecosystem, as well as the cycles of nitrate, ammonium, dissolved oxygen, and dissolved inorganic carbon. The coupled model is run in hindcast (1998 to 2020) and projection (1970-2100) modes, to study seasonal and inter-annual variability of the physical and biogeochemical environment as well as future changes resulting from climate change.

2.1.1.3 The Newfoundland and Labrador Regional Ocean-ice Model

To fill climate modelling gaps for the Newfoundland and Labrador Shelf, the Northwest Atlantic Fisheries Centre and the Gulf Fisheries Centre in 2014 started to develop a 7-km Newfoundland and Labrador Regional Ocean-ice Model (NROM, Figure 3) (Han et al., 2019a; Han et al., 2019b), based on the Nucleus for European Modelling of the Ocean (NEMO). The model was refined and several projection runs were completed. The NROM has hindcast products from 1979 to 2010 (Han et al., 2019a). Projection runs have been carried out for climate change scenarios such as A1B over 2011-2069 (Han et al., 2019b) and Representative Concentration Pathway (RCP) 4.5 over 2006-2099 (Le Corre et al., 2020). RCP4.5 is a “moderate mitigation” scenario, whereas RCP2.6 is a “strong mitigation” scenario and RCP8.5 is a “no mitigation” scenario (Moss et al., 2010). The model results have been applied to understand interannual and decadal circulation changes (Han et al., 2019a) and impacts of circulation changes on northern shrimp distribution and abundance (Le Corre et al., 2018). The development of NROM was discontinued in 2020 as it is being replaced by a new DFO North Atlantic ocean-ice downscaling system (see the following subsection).

2.1.1.4 The DFO North Atlantic Ocean-ice Downscaling System

The DFO North Atlantic Ocean-ice Downscaling System (DNAODS, Han et al., 2021) has been under development since 2018, by the Northwest Atlantic Fisheries Centre, the Gulf Fisheries Centre, the Bedford Institute of Oceanography, and the Institute of Ocean Sciences, to provide a consistent downscaling system for all Canadian Atlantic waters. The system consists of a higher resolution (1/12^o) model for the northwest Atlantic region (the focal domain), two-way nested to a lower (1/4^o) resolution model for the North Atlantic (Figure 4). Hindcast runs were carried out for the period from 1980 to 2020. 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 for RCPs 4.5 and 8.5 from 1980-2099 are completed. This model does not include biogeochemistry yet, but addition of a biogeochemical model is being carried out under a current Competitive Science Research Fund (CSRF) project.

During 2019-20, the modelling team in Gulf Region focused their efforts on developing a new ocean model covering the whole GSL at a spatial resolution of 1/36 ° (~2 km), which is to be part of the DNAODS (Figure 4). By forcing the model with potential future climatic conditions, it is possible to estimate how the GSL waters would respond to new climate. Preliminary results have been obtained with this new high resolution model and a complete simulation covering 1980 to 2099 is under way.

2.1.1.5 Regional atmospheric downscaling

A downscaling model formulation was developed for atmospheric fields that are essential for future climate projections over waters off eastern Canada, including the Gulf of Maine, Gulf of St. Lawrence, Grand Banks, Labrador Sea, and Baffin Bay (Figure 5). This regional climate model is based on the Weather and Research Forecast (WRF) model. The simulation period is 1970 to 2099, thereby simulating present climate as well as future climate change scenarios following RCPs 2.6, 4.5, and 8.5.

Outputs from this work define atmospheric forcing fields which are used for climate and marine forecasting projects related to a number of ocean modelling programs in waters off the east coast of Canada, related to sea ice, ocean currents, ocean surface waves, biogeochemical modelling, coastal hazards, and studies related to endangered species like the North Atlantic Right Whale.

2.1.2 The Pacific

2.1.2.1 The Northeastern Pacific Canadian Ocean Ecosystem Model

In the Northeastern Pacific Canadian Ocean Ecosystem Model (NEP36-CanOE), a multi-stage downscaling approach was developed to dynamically downscale global climate projections using a high-resolution (1/36º) regional ocean model (Figure 6; Holdsworth et al., 2021). Rather than generating interannual outputs, a "time-slice" was produced for historical (1986-2005) and future (2046-2065) periods. Each simulation is forced by a climatology of atmospheric forcing fields calculated over these 20 year periods. The winds are augmented with high frequency variability, which introduces a small amount of interannual variability. These simulations were used to estimate changes in the future ocean state for the Northeastern Pacific Continental Margin and explore the mechanisms responsible for these changes using RCPs 4.5 and 8.5. A hindcast from 1996-2019 is in progress. Model outputs have been used to assess the physical impacts of climate change on Pacific bioregions (Friesen et al., 2021b), and are currently being used to project habitat changes for Pacific ground fish species (Thompson et al. 2021b).

2.1.2.2 The British Columbia Continental Margin Model

A coupled ocean-biogeochemical model, the British Columbia Continental Margin Model (BCCM), has been developed to examine seasonal and interannual variability of the physical and biogeochemical environment as well as effects of climate change. The model domain includes the entire Pacific coast of Canada and extends from the Alaska Border (~55.5 °N) to south of the Columbia River (~47 °N) and about 400 km in the offshore direction (Figure 7). The model grid has a horizontal resolution of 3 km and 42 non-uniform vertical levels, with clustering near the surface. Model results have been compared against observations (tide gauge data, altimetry, temperature, salinity, nutrient profiles, and geostrophic currents) over 1981 and 2010 period showing the model is successful in reproducing the main features of the region.

The model results have been analyzed to study seasonal and inter-annual variability of the physical and biogeochemical environment (Peña et al. 2019), potential future changes resulting from climate change (Peña et al., 2018), present-day and potential future hotspots of invasive species (Lyons et al., 2020), ecological connectivity among marine protected areas (Friesen et al., 2021a), and physical impacts of Pacific Region marine protected areas due to projected climate changes (Friesen et al., 2021b).

2.1.3 The Arctic

A regional coupled ocean-sea ice-biogeochemistry model has been developed to study climate change impacts on marine ecosystems in the Canadian Arctic. The model covers the entire Arctic Ocean with some coverage of the Atlantic and Pacific inflow and outflow regions and is referred to as the North Atlantic Arctic (NAA) domain (Figure 8) (Hayashida et al, 2019). The horizontal resolution is highest in the Canadian Arctic and varies from 11 to 15km over the domain. The model is run for past (1969-2015) and future (2015-2086) scenarios to help understand past changes and assess potential future changes in Arctic marine primary production and acidification.

2.2 Short-Term Ocean Forecasting

Short-term ocean forecasting activities are focused on research and implementation of ocean models mainly for forecasting oceanographic conditions in a few days. They are used by MODCOM and clients in support of activities such as emergency responses and marine navigation.

2.2.1 Models covering Canada's three oceans

DFO researchers contributed to the development of various versions of the ocean and sea-ice models covering Canada's three oceans, based on NEMO. Earlier work has been absorbed into short-term operational Regional Ice-Ocean Prediction System (RIOPS, including data assimilation) by the Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS). The current version, RIOPSv2, documented in Smith et al. (2021), has the Pacific boundary at 44°N and Atlantic boundary at 27°N, with a nominal horizontal resolution of 1/12° in latitude/longitude and 75 vertical levels. The ocean component of RIOPSv2 is NEMO3.6, while the sea-ice component in RIOPSv2 is the Los Alamos Community Ice CodE (CICE) version 4.0. DFO researchers maintain two versions of the three oceans model based on NEMO3.6 and the sea-ice component LIM2 and LIM3: 1) an 1/4° version with the same spatial coverage of RIOPSv2, and 2) an 1/12° version with the Atlantic boundary extended further south to 7°N (Figure 9). Currently, the 1/4° version is extensively used for hindcast simulation and analyses (Zhang et al., 2020; Luo et al., 2020), climate projection (Xianmin Hu and Eric Oliver at Dalhousie University) and also for biogeochemical modelling development at DFO Pacific and also by university collaborators (e.g., Wei et al., 2019). The 1/12° version has been tested for hindcast simulations over a few years, but no active research and applications have been carried out yet (Luo et al., 2019).

2.2.2 Northeast Pacific High Resolution Regional Model

A high resolution regional model for the northeast Pacific with a resolution of 1/36 degree (NEP36) was developed with the support of the World Class Tanker Safety System (WCTSS) Initiative (Lu et al., 2017) and updated during the Ocean Protection Plan (OPP) (Figure 6). A hindcast simulation was conducted for the period of 2007 to 2016. The model has been adopted by CONCEPTS for short-term forecasting, running operationally in the Environment and Climate Change Canada (ECCC), and referred to as the Coastal Ice Ocean Prediction System - West (CIOPS-west). Recently the model has been coupled to a biogeochemical model (CanOE) to examine potential future changes in oceanography and biogeochemistry along the Canadian Pacific continental margin (Holdsworth et al., 2021).

2.2.3 OPP port models

The Ocean Protection Plan sub-initiative on "improving drift prediction and nearshore modelling", initiated in 2017 and reaching the end of its first five-year phase in March 2022, aims to implements NEMO-based port-scale models to produce short-term forecasts for operational implementation by Canadian Hydrographic Service and Environment and Climate Change Canada partners in support of electronic navigation and emergency response (oil spill / trajectory modelling) in high-risk areas. The ports are: Kitimat, Port of Vancouver, Fraser River Port, Strait of Canso Port, Port of Saint John, and the St. Lawrence River (Figure 10).

]High resolution models for these areas have been developed with NEMO 3.6. Each model is forced by ECCC's operational atmosphere and ocean models, tuned tides and gauged river runoff data. Recent work has focused on preparing the models for operationalization. Porting all the models into "Maestro", ECCC's sequencer system for operational forecast modelling, was a major accomplishment. At the end of 2020, the most complete system was the Saint John Harbour model, which ran in forecast mode with downscaling from the 500m to 100m resolution domains. More recently, for all six port models, hindcast and forecast capacity has been established for one-way nested 500m and 100-200m domains, with a third level of downscaling to 20 m and 30 m for Vancouver Harbour and the Fraser River, respectively.

The output from the port models has been used for the drift modelling evaluation initiative under OPP. In addition, output from the Saint John Harbour 100m model has been used for: (1) An analysis of flow over Reversing Falls showed form drag was the dominant control of tidal propagation up the Saint John River; (2) Offline Lagrangian experiments indicate surface trapped particles accumulate along fronts generated by the Saint John River plume and analysis is ongoing to better understand the phenomenon.

2.2.4 OPP drift models

As a complementary activity to the port model development described in the previous section, the "drift methodology and tool development" functional area is tasked with developing drift prediction and verification tools for surface and subsurface drifting objects. This includes developing and refining evaluation metrics for drifting objects and establishing a means of providing automated verification capacity. A drift characterization and verification toolbox is being developed to meet this need. The drift tool is a modular, open source Python application running on the Government of Canada's General Purpose Science Cluster (GPSC). It provides a streamlined and robust means of incorporating observed drifter data, modelled ocean and atmosphere data, as well as multiple drift prediction methods to create a standardized set of output. The analysis can be further customized to better represent location and drifting object type by using tailored correction factors and post-processing. Additional analysis can then be performed to provide comparisons between prediction systems, drift methodologies, drifter types, regions, etc.

Drift evaluations of the Global Ice Ocean Prediction System (GIOPS, the Regional Ice Ocean Prediction System (RIOPS), CIOPS-East, CIOPS-West and the SalishSeaCast model have been completed using various observed drifter types from targeted projects as well as from the Global Drifter program (Figure 11, Figure 12). The results of these evaluations have gbeen used to provide supporting analysis for multiple ECCC Comité des passes opérationnelles et parallèles (CPOP) processes. Several studies to assess the impact of spatial and temporal interpolation and ocean model resolution on drift predictions have also been performed. These include an analysis of spatial filtering of the model velocity fields as well as an analysis of windage/correction factors. Additionally, the drift characterization tool was run in an automated demo mode for approximately one year using RIOPS output to provide daily drift calculations. Daily downloads from the Copernicus Marine Environment Monitoring Service (CMEMS) global drifter database were also performed during that time to support delayed mode drift evaluations where needed.

2.2.5 The Eastern Newfoundland Shelf Model

A high-resolution coastal ocean model was established for the eastern Newfoundland Shelf in the northwest Atlantic (Figure 13), based on the Finite Volume Community Ocean Model (FVCOM) (Ma and Han, 2019). The model was initially developed in support of Canadian Coast Guard Manolis-L operations and then refined in support of the Surface Water and Ocean Topography – Canada (SWOT-C) program. For the SWOT-C application, the model results were evaluated against tide-gauge data, current meter data, and satellite altimetry data in May-October, 2010. A deterministic ensemble Kalman filter (DEnKF) was implemented for assimilating sea surface height data.

2.3 Aquaculture-related Modelling

Aquaculture-related modelling activities mainly address priorities of DFO aquaculture regulatory programs. They support the establishment and implementation of scientifically validated environmental and disease management policies and for site licensing, production planning and sustainable development of aquaculture. Furthermore, these modelling activities can also support management and operations at the farm level through collaborative programs involving DFO and the industry. The unstructured grid FVCOM is adopted as it allows a better representation of the complex coastline and steep and complex bathymetry in the vicinity of aquaculture sites.

2.3.1 The south coast of Newfoundland

The Coast of Bays region of the south coast of Newfoundland is where most of the finfish aquaculture activities in Newfoundland and Labrador take place. High resolution circulation models of different configurations are developed to help understand the oceanography of the region which will provide the knowledge to assess interaction between the aquaculture activity and the environment. Observation data have been collected to help understand the physical processes occurring in the region and to validate and initialize the models.

2.3.2 The Pacific coastal waters

2.3.2.1 The Discovery Island Model

In Discovery Island, an existing model (Foreman et al., 2012) was updated from FVCOM v2.7 to v4.1 and coupled to a biogeochemical module known as FVCOM-Integrated Compartment Model (FVCOM-ICM) (Bianucci et al., 2018) (Figure 14). The goal was (and still is) to provide a more complete tool to evaluate the effect of aquaculture on the environment as well as to predict effects of climate change in regions with aquaculture interests. Evaluation of the coupled model is currently ongoing for a 2017 spring simulation.

2.3.2.2 The Queen Charlotte Strait Model

In the Queen Charlotte Strait, the goal was to provide FVCOM high resolution hydrodynamic modelling in the region around Port Hardy, which could be used later for farm siting or other aquaculture applications (Figure 14). Current simulations are for summer and winter 2019.

2.3.2.3 The Baynes Sound Circulation Model

Baynes Sound is one of the most prolific shellfish regions in British Columbia, significantly contributing to the province's total production of clams and oysters. As part of a project to assess the ecological carrying capacity of the region and provide guidance on future expansion of the bivalve industry, coupled physical and biogeochemical models were developed and applied to simulate the present and planned future ecosystems. The physical circulation model was an application of FVCOM to the central Strait of Georgia (SOG) with varying horizontal resolution that is as fine as 40m in Baynes Sound. Though the predominant circulation was found to be estuarine, tidal mixing at the two entrances to the Sound and seasonal variability in the winds, river discharges, and inputs from the SOG were found to play important roles.

2.3.2.4 The West Coast Vancouver Island Model

A FVCOM-based model was developed for the region. A simulation was carried out for the period of March 1 to June 30, 2016. Model resolution varies from 9 km along the continental shelf to 60 m in the coastal inlets. Model output was shown to compare favourably with velocity, temperature, salinity, and sea surface height observations. Passive buoyant particles were also released from all salmon farm leases in the region and a farm-to-farm connectivity table was constructed as part of an upcoming Canadian Science Advisory Secretariat (CSAS) request.

2.3.3 The coastal models in the southern Gulf of St. Lawrence

In the Gulf Region, scientists supporting the Aquaculture Monitoring and Modelling Program (AMMP) have developed several coastal models in the southern GSL (Figure 15). These AMMP activities focused on highly productive bays in Nova Scotia, New Brunswick, and PEI. Hydrodynamic and biogeochemical models are used to better understand aquaculture productivity and inform management about aquaculture-environment interactions at the ecosystem scale. The FVCOM is used at different spatial resolutions.

2.3.4 Southwest New Brunswick

Finfish aquaculture in southwest New Brunswick is located in three regions of the Bay of Fundy: Passamaquoddy Bay, Grand Manan, and along the northern coast of the Bay of Fundy between Beaver Harbour and Haleys Cove (Figure 16). A FVCOM model of the Bay of Fundy and Gulf of Maine with high resolution in the three aquaculture regions is under development to update an older model of the region (Greenberg, Shore, Page, & Dowd, 2005; Page, et al., 2005). The model is, and will be, used in the following applications: advice for aquaculture site assessment CSAS Science Responses; transport and dispersal of bath pesticides used in the treatment of sea lice; deposition of organics and in-feed drugs released from net-pen fish farms; wild salmon migration (Quinn, et al., 2021 submitted); and disease spread between farms. Non-aquaculture applications of this model include input to search and rescue operations, Transport Safety Board navigational investigations, and selection of instrument deployment locations.

2.4 Acoustic Modelling

2.4.1 The Acoustic Model for the Salish Sea

One of the MODCOM modelling themes is to numerically model large vessel noise levels due to actual and expected shipping traffic. A project under this theme is to set up a vessel noise model to simulate large vessel noise levels in the Salish Sea (e.g., Straits of Georgia and Juan de Fuca) (Figure 17). This work involved creating required environmental input data sets for the acoustic model, formatting available Automatic Identification System (AIS) vessel data, creating synthetic AIS records that simulate vessel scenarios of interest and running the model. The first vessel scenario tested was a possible future scenario with additional tankers transiting the Salish Sea shipping lanes. The model results were verified against observations from 6 moorings deployed in 2018 and 2019.

3. Research and Applications

This section presents research on physical and biogeochemical processes and on applications to ecosystem and fisheries management using some of the models described in Section 2. Research findings are briefly summarized below. For details, refer to papers cited.

3.1. Climate and Biogeochemical Modelling

3.1.1 The North Atlantic

3.1.1.1 The Bedford Institute of Oceanography North Atlantic Model

The North Atlantic Ocean plays an important role in the global climate system due to the presence of the Atlantic Meridional Overturning Circulation (AMOC), and the AMOC is of great interest to oceanographers. The AMOC exhibits significant natural variability as well as potential long-term trends due to anthropogenic climate change. Furthermore, these changes can impact the ecosystems of the North Atlantic Ocean. Wang et al. (2019) interpreted variations of the AMOC using results from BNAM (introduced in Section 2.1.1.1). This study revealed that the AMOC can be decomposed into two distinct modes, one associated with Labrador Sea winter convection and the other related to the wind-driven Ekman transport (Figure 18 and 19). For the first time, this study reported that the downward movement of dense water in high latitudes leads to the weakening of the AMOC, and provided an explanation for the strong and weak AMOC regimes. Consequently, a new index of AMOC was introduced for the annual reporting of the North Atlantic Fisheries Organization (NAFO). Changes in the AMOC can also impact the hydrographic conditions on the Scotian Shelf, where warming in recent years has been observed, raising concerns over climate change impacts. Using model results from BNAM, Brickman et al. (2018) revealed that the interaction between the Gulf Stream and the Labrador Current at the tip of Grand Bank is the mechanism behind this warming. Furthermore, a feature of the AMOC reported in Wang et al. (2019) helped interpret a pattern of the distribution of the glass sponge, a sensitive benthic species protected by DFO and has assisted in its long-term conservation management (Beazley et al., 2020).

DFO considers deep-sea sponges/corals as ecologically significant species, and their habitats can qualify as sensitive benthic areas (SBAs). Data from the BNAM were used with species distribution models (SDMs) to predict the distribution of key species/habitats (Kenchington et al., 2018; Beazley et al., 2018; 2020; Wang et al., 2020). Ocean model data enabled for the first time the application of SDMs to predict the distribution of SBAs in eastern Canada. Using BNAM outputs, Beazley et al. (2018) reported that a warm and saline water mass was associated with the sponge grounds. This innovation led to further collaborative work on the impacts of climate change on the distribution of this SBA type (Beazley et al., 2020) in support of marine spatial planning. Beazley et al. (2020) found that suitable habitat may potentially increase up to 4 times the present-day size of the sponge grounds in this novel study, and suggested new locations for monitoring changes to distribution. Model results from the BNAM fill data gaps in the distribution of SBAs, particularly in poorly sampled areas on the continental slope, which helped lead to the establishment of 34 marine refuges. BNAM results were also used in the investigation of the connectivity of the 14 closed areas around the high-seas portion of Grand Bank and Flemish Cap (Kenchington et al., 2018; Wang et al., 2020) in support of Canadian contributions to the NAFO. These were the first studies in NAFO and Canada to use particle tracking algorithms to examine biophysical connectivity among areas closed to protect key species and habitats. Wang et al. (2020) was the first study to apply a novel 3-D passive particle tracking model which used current data from BNAM to investigate this connectivity. This study discovered that source populations for sponges in the upstream closure are likely in adjacent waters of the Canadian continental shelf. The work on connectivity modeling of the closed areas in the NAFO regulatory area of Flemish Cap and the Tail of Grand Bank has been accepted as formal scientific advice by the 2020 NAFO Scientific Council for their review of closed areas.

Knowledge on linkages between the ocean environment and biology can help predict behavioral changes of marine species and explain changes in their productivity. BNAM results were applied to investigate the distribution and spawning behavior of commercial species such as lobster, snow crab, shrimp, halibut, and mackerel under current and future climates (Stanley et al. 2018; Shackell et al., 2019; Greenan et al., 2019; Lyons et al., 2020; Mbaye et al., 2020; Camille et al., 2021) in order to improve sustainable management. These were to envisage new ways in which ocean variables might be useful in predicting behavioral changes of marine species and possibly explain changes in their productivity. These studies have improved the understanding of the distribution and behaviour of important commercial species, species at risk, invasive species, and sensitive benthic species.

Northern shrimp (*Pandalus borealis*) represents one of the most important fisheries in the Northwest Atlantic Ocean, but few studies have considered connectivity among different management units (i.e., stocks). Building on the work of Le Corre et al. (2019), a northern shrimp larvae biophysical model was developed using the large-scale BNAM ice-ocean model to study potential larval dispersal of northern shrimp larvae at the scale of the Northwest Atlantic (Le Corre et al., 2020). A largely stable larval connectivity system was identified, driven by the main currents that flow over both the Greenland and Canadian continental shelves (Figure 20). A relatively low but consistent exchange of larvae between Greenland and Canada across the Baffin Island continental shelf was observed. The highest potential settlement densities were noticed on the northwestern Greenland and Newfoundland shelves, representing retention areas that correspond to the highest abundances of adult shrimp. This study helped to determine the appropriate spatial scale at which to evaluate northern shrimp management strategies.

3.1.1.2 The Gulf of St. Lawrence, Scotian Shelf and Gulf of Maine modelling system

In Lavoie et al. (2021), the CANOPA-GSBM model (Section 2.1.1.2) is used to revisit previous estimates of the riverine nutrient contribution to surface nitrate in the Lower St. Lawrence Estuary (average of 25% in summer (June to September) and 36% from late fall to early spring). The model is also used to explain the mechanisms that lead to high ammonium concentrations, low dissolved oxygen, and undersaturated calcium carbonate conditions on the Magdalen Shallows (a combination or organic matter transport from upstream regions combined with strong stratification). The coupled model was also used in conjunction with individual-based models to investigate the spatio-temporal production dynamics of two krill species in the GSL (Benkort et al., 2020), as well as changes in *Calanus* sp. spatial distribution and how it changes with environmental variability (Brennan et al., 2019; 2021). These studies on Calanus distribution are part of a larger study that aims to understand the distribution of endangered North Atlantic right whales in recent years.

The model was also used to project future biogeochemical and physical conditions in the Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine (Lavoie et al., 2020; Siedlecki et al., 2021). The results show a decrease in sea ice, a general warming, a decrease in salinity in the upper layers and an increase at depth, as well as an increase in stratification. Projected future changes in nitrogenous nutrients were variable and generally not significant. The chlorophyll a biomass decreases in the GSL and on the eastern Scotian Shelf but increases elsewhere. All the simulations show acidification over the model domain with a decrease in pH and carbonate saturation at all depths. By 2090 a mean aragonite saturation level of 1 is reached over most of the domain on the bottom and at the surface of the GSL and Scotian Shelf. Calcite saturation also reaches this critical level at the bottom of the Magdalen Shallows and the eastern Scotian Shelf.

3.1.1.3 The Newfoundland and Labrador Regional Ocean-ice Model

The result from the NROM model (Section 2.1.1.3) at a long-term ocean monitoring station off St. John's over the inner Newfoundland Shelf showed substantial interannual variability in the surface temperature and salinity, a warming trend in the surface temperature, and no trend in the surface salinity over 1979-2010, consistent with observations (Han et al., 2019a). The model sea ice extent south of 55ºN shows significant interannual and decadal variability and a declining trend consistent with observations. The model results reveal that the inshore Labrador Current has a positive trend while the offshore Labrador Current does not. The freshwater transport in the inshore

Labrador Current increases as the volume transport increases due to large-scale baroclinic forcing; while the freshwater transport in the offshore Labrador Current decreases as the salinity increases.

As connectivity through larval dispersal is a key driver of the northern shrimp stock-recruitment relationships and can strongly influence population dynamics, a NROM-based biophysical model was used to investigate northern shrimp connectivity and its spatiotemporal variability in the Newfoundland and Labrador shelf region (Le Corre et al., 2019). Overall, the model showed that populations located on the northern Newfoundland and Labrador shelf supplied potential settlers to southern populations because of the dominant Labrador Current (Figure 21). This study improved understanding of northern shrimp population dynamics and their sensitivity to changing environmental conditions, which helped improve management strategies.

Over the 21st century, the projected results using NROM show general trends of warming, freshening, and decreasing ice over the Newfoundland and Labrador Shelf (Han et al., 2019b). In Le Corre et al. (2021), projections from NROM (RCP8.5 scenario) were used to investigate spatial variability of northern shrimp preferred depth and thermal habitat, and larval settlement patterns over the Newfoundland and Labrador shelf and slope, throughout the 21st century. They found a likely expansion of the potentially suitable habitat for northern shrimp from 2010 to 2050 prior to a decline and shift towards more coastal and southern areas from 2060 to 2090. By end of the 21st century, historically important areas are likely to be negatively impacted in terms of suitable habitat and settlement potential, whereas previously less important areas may see an increase in abundance.

3.1.2 The North Pacific

3.1.2.1 The Northeastern Pacific Canadian Ocean Ecosystem Model

Projections from NEP36-CanOE (Section 2.1.2.1) suggest that the NEP region is becoming warmer and fresher with increases in stratification, primary production and phytoplankton biomass (Holdsworth et al., 2021). Density surfaces move deeper in the water column, and this change is mainly driven by surface heating and freshening. Changes in saturation state are mainly due to anthropogenic CO_2 with minor contributions from solubility, remineralization and advection. The depths of the aragonite saturation horizon and the oxygen minimum zone are projected to become shallower by 100 m and 75 m respectively. Extreme states of temperature, oxygen, and acidification along the continental slope are projected to become more frequent and more extreme, with the frequency of occurrence of $[O_2] < 60$ mmol m^{-3} expected to approximately double under either scenario.

3.1.2.2 The British Columbia Continental Margin Model

Pena et al.'s (2019) hindcast results from BCCM (Section 2.1.2.2) over 1979-2011 off the British Columbia coast indicate that the dominant large-scale pattern of nutrient and primary production variability correlates with the North Pacific Gyre Oscillation (NPGO), whereas near the coast local processes such as upwelling and river input play an important role. Projected results for the 2041-2071 period under RCP 4.5 and RCP 8.5 climate change scenarios show general warming, moderate increases in primary production, and changes in stratification and circulation that contribute to increasing ocean acidification and decreasing oxygen. The model has also been applied to assess: 1) how ecological connectivity between MPAs may shift with projected ocean temperature changes in the Northern Shelf Bioregion in British Columbia (Friesen et al., 2021a), 2) the environmental impacts of climate change on Pacific bioregions (Friesen et al., 2021b), 3) how demersal fish biodiversity in Canadian Pacific waters has changed since 2003 and assess the degree to which these changes can be explained by environmental change and commercial fishing (Thompson et al. 2021a), and 4) changes in NE Pacific groundfish biodiversity under projected warming and deoxygenation (Thomson et al., 2021b).

3.1.3 The Arctic

The NAA model (Section 2.1.3) has been applied to help understand past variations and assess potential future changes in Arctic marine primary production and acidification. Specific applications include: 1) Assessment of recent climate change related changes in marine ecosystems in the Canadian Arctic with focus on the Inuvialuit Settlement region to help understand recent changes in mammal distributions (e.g., beluga whales); 2) Assessment of potential future changes in environmental conditions (temperature, salinity, sea-ice cover, ocean acidification) and marine ecosystems (nutrients, ice algae, phytoplankon and zooplankton distributions, and total primary production in ocean and sea-ice ecosystems) with contributions to the Arctic Council's Arctic Monitoring and Assessment Program (AMAP) (Mortenson et al. 2020, Steiner et al. 2019); 3) Linking of climate model simulations of the past and future to distributions of forage species such as Arctic cod (*Boreogadus saida*) to understand potential impacts on subsistence fisheries in the Western Canadian Arctic (AMAP, 2018, Steiner et al. 2019); 4) Assessment of changes in marine sulphur sulfate aerosol emissions by simulating the production of dimethylsulfide (DMS) in oceanic phytoplankton and sea-ice algae (Hayashida et al. 2020); and 5) Improvement of model parameterizations for Arctic ocean biogeochemistry models via multi-model intercomparisons (Watanabe et al. 2019, Hayashida et al. 2019).

The model results indicate that sea-ice primary production provides an important source of carbon to the food chain before open water production becomes available, and that substantial interannual variability in ice-algal production can be linked to variations in Arctic cod abundance (Steiner et al. 2019). The acidification study indicated that minima in saturation state occur in winter (due to colder waters and limited primary production) and are exacerbated by the sea-ice carbon pump. Hence, summer observations do not reflect the minima in saturation states organisms are experiencing. the results further showed that regional and seasonal undersaturation of aragonite are occurring with increasing frequency, indicating an imminent threat to Canadian Arctic ecosystems (Mortenson et al, 2020). Hayashida et al. (2020) highlighted the importance of spring DMS fluxes from ice algae in Arctic environments. The results suggested that DMS climatologies commonly used in Earth system models lack data in the Arctic and are biased towards subpolar values and misrepresent both timing and magnitude of DMS emissions in the Arctic."

3.2 Short-term Ocean Forecasting

3.2.1 OPP port models

Under OPP, a NEMO-based ocean forecasting system was developed for Saint John Harbour (Section 2.2.3). The harbour is characterized by large tides, significant river runoff, and complicated geometry. There is no data product available for total Saint John River volume flux, so the model's open boundary condition was modified to apply boundary forcing via river water level rather than volume flux. Paquin et al. (2019) demonstrated the capability of this framework to provide port-scale modelling for Saint John Harbour.

The output from the OPP Saint John Harbour model has been used for an analysis of flow over Reversing Falls. Reversing Falls blocks most of the large tides from the harbour from propagating up the Saint John River. Horwitz et al. (2021) showed that form drag is the primary control of flow over Reversing Falls and that a steady balance between drag and the surface pressure gradient dominates the dynamics. Despite the presence of strong stratification, estuarine processes are secondary to the dynamics of a gravitationally driven flow. This river-like dynamic has the unusual feature that the pressure gradient and flow direction change sign on a semi-diurnal cycle.

3.2.2 The Eastern Newfoundland Shelf Model

Ma and Han (2019) used the hourly sea surface height (SSH) from the eastern Newfoundland coastal model (Section 2.2.5) to generate simulated surface water and ocean topography (SWOT) SSH data by applying a SWOT simulator. They then used the simulated SWOT data to reproduce SSH and geostrophic currents associated with the inshore Labrador Current, by applying optimal interpolation (OI) in time and space. It was found that the inshore Labrador Current is reconstructed fairly well at the weekly scale. In a subsequent study, the simulated SWOT data were assimilated into the Newfoundland coastal ocean model by using a deterministic ensemble Kalman filter (DEnKF). The DEnKF assimilation does a good job at not only the weekly but also daily scales.

3.3 Aquaculture-related Modelling

3.3.1 Pacific coastal waters

Simulations for the west coast of Vancouver Island using FVCOM (see Section 2.3.2) have demonstrated that river discharges, atmospheric forcing, and interactions with the nearby continental shelf all play important roles in the temporally and spatially varying currents, salinities, and temperatures at salmon farms in the region. Although the limited availability of river discharge data, the relatively coarse spatial resolution of the weather models providing the atmospheric forcing, and excessive mixing within FVCOM were identified as the major limitations to model accuracy, the simulations were generally in reasonable agreement with observations (see Figure 22), and were able to identify mechanisms leading to some of the low oxygen events on the farms and support the tracking and removal of oil from the wreck of the MV Schiedyk near Bligh Island in Nootka Sound.

Furthermore, available FVCOM simulations for the west coast of Vancouver Island, Discovery Islands, and Broughton Archipelago were used to study the potential hydrodynamic connectivity among finfish farms in each of the regions (DFO, 2021). The objective was to further understand how neutral, passive particles disperse from farms and reach other aquaculture sites given only the flow fields in their surrounding environment. In this study, 30 virtual particles were released every two hours from each farm and each particle was tracked for up to 14 days, recording whenever a particle reached another farm. The particles were neutral (i.e., following the three-dimensional currents, without sinking by their own weight) and passive (i.e., not interacting with the environment nor decaying with time) to estimate the farthest possible reach of the particles (example of particle dispersal during the last day of tracking shown in Figure 23). The results highlighted the importance of moving towards area-based management, since seemingly distant farms can be tightly connected by flow fields. Furthermore, connectivity among farms increased considerably as more time elapsed since the particle release, implying that the nature of the particle and the ability to survive in seawater is also key to management.

3.3.2 Coastal waters of the southern Gulf of St. Lawrence

The modelling framework developed in the Gulf region over the past 10 years (Guyondet et al. 2015) to study nearshore ecosystems at the local scale (estuary, bay) and their interactions with shellfish aquaculture was recently transferred to a new modelling suite based on the FVCOM (see Section 2.3.3). The method relies on the coupling of a hydrodynamic (FVCOM), a biogeochemical (Integrated-Compartment Model (ICM)), and a shellfish ecophysiological model. The FVCOM-ICM coupling developed at the Pacific Northwest National Laboratory (Khangaonkar et al. 2012) was further refined to include the shellfish component and its interactions with the rest of the biogeochemical variables. The first application of this fully coupled model was conducted in Baynes Sound, BC (see section 2.3.2.3 for the circulation component) to evaluate the pressure of current shellfish farming activities on pelagic resources (nutrient availability, phytoplankton biomass and productivity) and advise on the ecological carrying capacity of the sound for future expansion of this industry (DFO, 2021b).

Further refinement of this modelling framework is underway to address questions related to other ecosystem stressors such as eutrophication. A first step was recently completed with the development and testing of an opportunistic macro-alga (*Ulva lactuca*) sub-model (Lavaud et al., 2020). This new component is currently being incorporated, as well as an eelgrass sub-model, into the overall modelling structure, which will ultimately aim at assessing the response of nearshore ecosystems to the cumulative impact from multiple stressors in the southern Gulf of St. Lawrence.

3.3.3 Southwest New Brunswick

As introduced in Section 2.3.4, FVCOM has been used to examine the suitability of the 30-day single current meter record frequently used in predicting deposition footprints associated with aquaculture activities. In particular, model results have been used to examine the sensitivity of transport and dispersal estimates of aquaculture discharges to the estimated spatio-temporal variability of current fields in the vicinity of fish farms. It was determined that a single current meter record is typically only representative of limited spatial and temporal window.

Due to the computational intensive nature of the aquaculture model for southwest New Brunswick, it is an inefficient platform for testing innovative improvements. For this reason we are using a modified version of the FVCOM grid from the NEMO-FVCOM model comparison (Nudds et al., 2020) as a testbed for improvements to aquaculture modeling. To date, several aspects have been explored including: open boundary placement, river forcing, wetting and drying, and grid resolution. Impacts of the placement of the open boundary were examined and it was determined that, for the model forcing used, an on-shelf placement of the open boundary resulted in better agreement between measured and modeled temperature and salinity. Comparison of model runs where forcing the Saint John River with river level data and river discharge data, have indicated that either method is suitable for modeling river input.

4. Planned Directions for MODCOM

While the modelling activities described in Section 2 and 3 will continue to address diverse needs for hindcasts, predictions and projections of ocean conditions within DFO and its partners and clients, the focus of MODCOM will continue to strengthen our coordination and collaboration in model development, product development and dissemination, as well as knowledge exchanges, significantly enhancing our ability to address priority and emerging issues in an effective and efficient way. We will further strength and expand our coordination and collaboration with other government agencies, academia, and international communities.

MODCOM has been organizing regular scientific and technical seminars since July 2020. These seminars provide a forum for the MODCOM members to share progress and lessons learned, discuss scientific ideas, exchange model development experiences, and foster collaborations among themselves and with external scientific communities.

We are working towards enhancing a MODCOM repository system including common model codes, pre- and post-processing tools, atmospheric forcing fields, bathymetry files and core verification datasets. A group account on Gitlab has been created as a way to maintain and improve the code of the ocean circulation models NEMO and FVCOM and their associated biogeochemistry modules, and to share code among different groups. On the Gitlab page, instructions and guides are provided to help new users to install and run the model from their own workspace on the GPSC cluster. Any MODCOM member can be part of the group on gitlab.com, with full access for use and contribution.

We are initiating model-based state of the oceans reporting to complement existing state of the oceans reporting for Canada's three oceans. Within the Atlantic Zone Monitoring Program some model output has been integrated into the traditionally observation-based state of the oceans report. A model-based state of the ocean report for 2021 is being completed for the northwest Atlantic (Chassé et al., 2022). By expanding this work, we plan to start working on a model-based state of the oceans report for the northeast Pacific as well.

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Appendix A: Additional Information on Model Configuration and Output

A.1 Climate and Biogeochemical Models

A.1.1 The North Atlantic

A.1.1.1 The Bedford Institute of Oceanography North Atlantic Model

The BNAM was developed at the Bedford Institute of Oceanography (BIO). The purpose of the development of this model was to support ongoing DFO monitoring programs such as AZOMP (Atlantic Zone Off-Shelf Monitoring Program) and AZMP (Atlantic Zone Monitoring Program). Results from this model are contributed annually to AZOMP and AZMP reports for NAFO (Northwest Atlantic Fisheries Organization) and CSAS (Canadian Science Advisory Secretariat).

The model is based on version 2.3 of NEMO (Nucleus for European Modelling of the Ocean), a modeling framework of ocean modelling. The physical core consists of OPA (ocean) and LIM (sea-ice). Details about the NEMO modeling system can be found at https://www.nemo-ocean.eu/.

The BNAM grid dimension is 1435×1122 (X×Y). The southern and northern boundaries are located at 7°N and roughly 67°N (Figure 1), respectively. The BNAM domain includes a large portion of the Mediterranean Sea, a source of dense, warm, and salty water that has significant influnces on watermass properties of North Atlantic. Major portions of the Greenland, Iceland, and Norwegian (GIN) Seas, and Hudson Bay occupy the northern part of the model domain, hence wintertime dense water formation processes in the GIN Seas and fresh water outflow from the Hudson Bay are included. The domain covers the entire subtropical gyre including the Gulf Stream. The inclusion of the Labrador Current and Gulf Stream enables the simulation of the interactions of the two currents that contribute to changes in watermass properties on the Scotian Shelf.

The minima of the grid sizes are 2.7 km (zonal direction) and 2.1 km (meridional direction) in the northern part of the domain (Figure 1). The maximum is 9.17 km, along the southern boundary (Figure 1). BNAM has two products. One is the BNAM hindcast (1990 to present), and the other is climate projections (RCP4.5 and RCP8.5).

(1) BNAM hindcast climatology datasets

Monthly climatology of the temperature, salinity, and currents has been approved and published on the Federal Geospatial Platform (FGP) and Open Data:

Open Data:

https://search.open.canada.ca/en/od/?search_text=BNAM

FGP (visible only through VPN, inside government only):

Temperature: https://gcgeo.gc.ca/geonetwork/metadata/eng/5577393c-5eb2-4d07-a64e-d2a1b675a242

Salinity: https://gcgeo.gc.ca/geonetwork/metadata/eng/c44a8574-9f7d-45b7-afda-27802353a04c

Currents: https://gcgeo.gc.ca/geonetwork/metadata/eng/dd5ef0d6-d588-4f4f-99e5-27c4bdfddf6a

Web maps (surface and bottom):

Temperature:

https://www.arcgis.com/home/webmap/viewer.html?url=https%3A%2F%2Fgisp.dfo-mpo.gc.ca%2Farcgis%2Frest%2Fservices%2FFGP%2FMonthly_Temperature_NorthwestAtlanticOcean_19902015_EN%2FMapServer&source=sd

Salinity:

https://www.arcgis.com/home/webmap/viewer.html?url=https%3A%2F%2Fgisp.dfo-mpo.gc.ca%2Farcgis%2Frest%2Fservices%2FFGP%2FMonthly_Salinity_NorthwestAtlanticOcean_19902015_EN%2FMapServer&source=sd

Currents:

https://www.arcgis.com/home/webmap/viewer.html?url=https%3A%2F%2Fgisp.dfo-mpo.gc.ca%2Farcgis%2Frest%2Fservices%2FFGP%2FMonthly_Currents_NorthwestAtlanticOcean_19902015_EN%2FMapServer&source=sd

(2) BNAM future climate scenarios

4 future climate scenarios:

RCP 8.5: 2055 & 2075 climatologies

RCP 4.5: 2055 & 2075 climatologies

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A.1.1.2 The Gulf of St. Lawrence, Scotian Shelf, and Gulf of Maine modelling system

The CRCM is based on the dynamical formulation of the Canadian Mesoscale Compressible Community (MC2) model and the simulations were performed at a horizontal resolution of 25 km, with 29 levels in the vertical direction. The hydrology model provides the freshwater runoff for the main rivers (80) entering the ocean domain. The NEMO ice-ocean coupled model (with a horizontal resolution of 1/12°, Figure 2, and 46 levels in the vertical), and a biogeochemical model (GSBM). GSBM simulates the lower trophic levels (phytoplankton, zooplankton) of the ecosystem, as well as the cycles of nitrate, ammonium, dissolved oxygen, and dissolved inorganic carbon. Using the A1B, RCP4.5 and RCP8.5 IPCC scenarios, eleven 100-year-long high-resolution simulations of ocean dynamics (1970-2100) were downscaled. The results are relevant to ecosystem research, fishery management, species at risk, invasive species, International Governance, and climate change risk assessments. This ensemble of downscaled climate simulations helps to improve statistical confidence in the robustness of the results with better quantification and mapping of the potential changes in environmental conditions for the Gulf of St. Lawrence, the Scotian Shelf, and the Gulf of Maine.

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A.1.1.3 The Newfoundland and Labrador Regional Ocean Model (NROM)

The ocean model in the NROM is based on the version 2.3 of the Nucleus for European Modelling of the Ocean (NEMO) modelling system, using version 9 of the Ocean Parallelise

System (NEMO-OPA9) and version 2 of the Louvain-la-Neuve Ice Model (NEMO-LIM2) as the sea ice component. NEMO-OPA9 is a primitive equation, finite difference ocean circulation model with a free sea surface and z-level vertical coordinate. NEMO-LIM2 is a two-category thermodynamic-dynamic sea ice model. The model domain covers the Newfoundland Shelf including the Grand Banks, Labrador Shelf, their adjacent deep Northwest Atlantic Ocean and parts of the Labrador Sea (Figure 3). The model uses bathymetry from the Canadian Hydrographic Service at 7 km resolution for the shelf and the ETOPO5 bathymetry for the deep oceans. For the projection period, the surface atmospheric forcing fields are from the Canadian Regional Climate Model over the North Atlantic. The open boundary conditions are from the Canadian Global Climate Model Version 3, with a bias correction for the 1981-2010 mean.

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A.1.1.4 The DFO North Atlantic Ocean-ice Downscaling System (DNAODS)

The numerical ocean-ice model used in the DNOADS is based on the NEMO, version 3.6 stable (Madec, 2016) modelling system and version 2 of the Louvain-la-Neuve Ice model (LIM2). NEMO 3.6 is a primitive equation, finite difference, ocean circulation model. The z-coordinate used allows the free surface and the bottom layer to vary as a function of geographical locations. DNAODS has two grid domains at present (Figure 4). The North Atlantic domain is from 7ºN in the south to 66ºN in the north, with a horizontal resolution of 1/4º. The Northwest Atlantic domain is from 35ºN to 64ºN in the north, and west of 35ºW, with a horizontal resolution of 1/12º (Figure 4). In the vertical there are 50 layers, with the first grid at 1.5 m below surface and a maximum spacing of 215 m. Model bathymetry is from ETOPO1.

The 6-hourly ECMWF Reanalysis Interim product is used as atmospheric forcing at the sea surface. The SODA 3.4.2 monthly mean product (Carton and Giese, 2008) and major tides are used as lateral open boundary conditions. For the open boundary conditions, sea level and vertically averaged velocity were applied by using the Flather boundary condition, while three-dimensional temperature, salinity and velocity were specified with a sponge layer relaxing from the open boundary towards the ocean interior. Relaxation was also applied for the sea ice boundary condition. Climatological monthly river runoffs were specified as surface precipitation (Bordeau et al., 2010).

The model products are available from 1980 to 2020. For more detail, contact Guoqi Han at Guoqi.Han@dfo-mpo.gc.ca.

A.1.1.5 Regional atmospheric downscaling

The regional atmospheric downscaling used the WRF model version 3.6 with 250x175 grid points on polar steorographic projection, 45km horizontal projection and 38 vertical levels, up to 20hPa (Figure 5). Spectral nudging, SST correction lake module and CO2 scenarios are applied in the scenarios. For future projections, earth system model outputs are used, such as HadGEM2-ES, with resolution 1.5º x 1.2º, following RCP 8.5 / 4.5. Physics schemes include RRTM for longwave and shortwave radiation, NOAP-MP(4) land scheme, MYNN planetary boundary layer, Morrison 2-monent could microphysics scheme, and Kain-Fritsch cumulus parameterization scheme.

For data access and other details contact Will Perrie at william.perrie@dfo-mpo.gc.ca.

A.1.2 The Pacific

A.1.2.1 NEP36-CANOE

The Northeastern Pacific Canadian Ocean Ecosystem Model (NEP36-CanOE) is a configuration of the Nucleus for European Modelling of the Ocean (NEMO) v3.6 with a 1/36° (1.5 − 2.25 km) spatial resolution and 50 vertical levels (Figure 6). The CanOE biogeochemistry model was developed for the Canadian Earth System Model and is described in Swart et al. (2019) and Christian et al. (2021). Our published climate downscaling simulations (Holdsworth et al., 2021) used the second-generation Canadian Earth System model (CanESM2), for which high-resolution downscaled projections of the atmosphere over the region were available from the Canadian Regional Climate Model version 4 (CanRCM4) (Scinocca et al., 2016). CanRCM4 is an atmosphere only model with a 0.22° resolution and was used to downscale climate projections from CanESM2 over North America and its adjacent oceans. We used anomalies from CanRCM4 for the surface boundary conditions and from CanESM2 for open ocean boundary conditions.

In addition to saving mean values over each 5-day averaging period, we also save maximum and minimum values over the same period to investigate extreme values.

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A.1.2.2 BCCM

The BCCM (Figure 7) consists of an ocean circulation model and a biogeochemical model. The ocean circulation model is an implementation of version 3.5 of ROMS (Regional Ocean Modelling System), a terrain following, primitive equation model, which has been used extensively to model various regions of the world's oceans. The biogeochemical model is a nitrogen based NPZD-type lower trophic levels model that includes two types of phytoplankton, zooplankton and detritus, nitrate, ammonium, silicate, and biogeochemistry modules describing the oxygen and carbon cycles. The model employs Earth Topography 2-arc-min (ETOPO2) bathymetry and is forced by atmospheric forcing fields, tidal boundary forcing (amplitude and phase) for 8 main tidal constituents (M2, K1, O1, S2, N2, P1, K2 and Q1), boundary conditions for temperature, salinity, u, v, nutrients, oxygen and carbon, and freshwater discharges from 154 rivers affecting the study area, derived as in Morrison et al. (2012).

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A.1.3 The Arctic

The Arctic model (Figure 8) contains a physical ocean model which is based on the NEMO, a sea-ice model (LIM), options for two ocean biogeochemistry models, the simpler Canadian Model for Ocean Carbon (CMOC) and the more complex Canadian Model for Ocean Ecosystems (CanOE). The model also includes a sea-ice biogeochemistry component, the Canadian Sea-Ice Biogeochemistry model (CSIB). The biogeochemistry models also include representations of carbon and sulphur cycles which allow to assess changes in ocean acidification and the production of marine sulphur aerosols. The models have been developed in close collaboration with the Canadian Center for Climate Modelling and Analysis (CCCma), Environment and Climate Change Canada (ECCC). The models are referred to as NAA-CanOE-CSIB and NAA-CMOC.

CMOC represents one class for each of nutrients, phytoplankton, zooplankton and detritus as well as oxygen and carbon biogeochemistry and constant elementary carbon to nitrogen ratios. CanOE represents two classes for each of nutrients, phytoplankton, zooplankton and detritus as well as oxygen, carbon and sulphur biogeochemistry. CSIB represents ice algae, nutrient supply as well as sulphur and carbon biogeochemistry.

The models have been forced for past time periods using reanalyses data and for future projections using output from the Canadian regional Climate Model (CanRCM) and the Canadian Earth System Model (CanRCM).

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A.2 Short-term Ocean Forecasting Models

A.2.1 Models covering Canada's three oceans

DFO currently maintains two versions of the three oceans model based on NEMO3.6 and the sea-ice component LIM2 and LIM3: 1) an 1/4° version with the Pacific boundary at 44°N and Atlantic boundary at 27°N, and 2) an 1/12° version with the Atlantic boundary extended further south to 7°N. The horizontal grids all follow the tri-polar ORCA configuration. There are 75 levels in the vertical. High vertical resolution is applied in the upper ocean with 18, 24 and 31 levels for the top 50 m,100 m and 200 m, respectively. The vertical cell thickness is ~ 1 m close to the surface and increases smoothly to ~ 200 m at the depth of 6000 m. Model bathymetry is derived from 1-minute resolution ETOPO data and GEBCO data with a minimum water depth of 12 m. Partial cells are used near the bottom to better represent the seafloor. To account for the temporal changes in sea surface elevation, the "variable volume level" scheme is used to allow the stretching/compression of the vertical cell thickness according to the ratio of $(\zeta + H)/H$, where ζ is the sea surface height and H is the total water depth when $\zeta = 0$. Although LIM2 is still an option, LIM3 is used as the sea-ice component for most simulations. LIM3 includes both the thermodynamic and dynamic components with elastic-viscous-plastic (EVP) rheology, and supports multiple ice thickness categories and can better simulate thin ice with intense growth and melting processes and thickness redistribution caused by ridging and rafting. In our simulations, the default five thickness categories (lower thickness boundaries: 0.00, 0.45,1.13, 2.14 and 3.67 m) are used. In the ocean module, the subgrid-scale parameterizations include 1) a rotated Laplacian isopycnal scheme for lateral tracer diffusion; 2) a bi-Laplacian scheme for lateral momentum mixing; 3) a $k-\varepsilon$ based on Generic Length Scale (GLS) turbulence scheme for vertical mixing. In addition, the 1/4° version includes the parameterization of eddy induced tracer advection. Five major constitutes (M2, S2, N2, K1 and O1) of tides are introduced through models' open boundaries.

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A.2.2 Northeast Pacific High Resolution Regional Model

The current version of NEP36 is based on the ocean component of version 3.6 of the Nucleus European Modelling of the Ocean (NEMO, https://www.nemo-ocean.eu). The sea-ice module is turned off because of the minimum presence of sea-ice in the model domain. Sea surface temperature (SST) below freezing point is set to be the freezing temperature. The model domain covers the northeast Pacific roughly to the east of 140°W and to the north of 45°N (Figure 6). The horizontal grids follow the tri-polar ORCA configuration with a nominal resolution of 1/36° in longitude/latitude, corresponding to an average grid spacing of 1.7 km. The vertical grid has 50 z-levels, with full cell sizes in the water column and partial cell sizes near the bottom. The minimum thickness of partial cells at a particular location is set to be the minimum of 6 m or 20% of the full size of the cell near the bottom. The sizes of the full vertical cells vary from 1 m at the surface to 450 m at 5000 m. There are 23, 27, and 32 levels for the upper 100 m, 200 m, and 500 m, respectively. Further, the use of "variable volume level" allows the thickness of the vertical levels to vary with changes in sea surface elevation. The bathymetry is the same as that described by Lu et al. (2017). The maximum and minimum water depths are set to be 4557 m and 8 m, respectively.

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A.2.3 The OPP port models

The OPP high resolution models (Figure 10) are developed with NEMO 3.6. They are forced at the open boundaries by ECCC's Coastal Ice Ocean Prediction Systems on both coasts (CIOPS-East and CIOPS-West, to be fully operational in late 2021), at the surface by ECCC's High Resolution Deterministic Prediction System (HRDPS), and with tuned tides from WebTide. All ports have a first level downscaling at 500 m resolution, which enables 100/150 m and 20 m resolution subdomains. The models have z-levels, partial steps, a variable volume formulation, time sub-stepping for vertical advection, and one-way nesting without AGRIF. River forcings includes gauged flows and runoff climatologies. All areas have complete hindcast capabilities at 500m resolution, and complete or nearly complete 100m development.

Once fully operational, CHS will provide electronic navigation products via S-100 series files. Full model output available from developers upon request. Contact Rachel Horwitz at Rachel.Horwitz@dfo-mpo.gc.ca or Michael Dunphy at Michael.Dunphy@dfo-mpo.gc.ca.

A.2.4 The OPP drift models

Currently, the drift-tool is able to incorporate output from ocean models that have been developed using NEMO as well as wind outputs from atmospheric models. It can provide predictions using three separate Lagrangian particle tracking methodologies - Ariane, OpenDrift, and Modèle Lagrangien de Dispersion des Particules d'ordre n (MLDPn-DRIFTER). It operates with three main run modes as follows:

The Drift Characterization module uses a seeded grid of simulated drifters to produce maps of particle transport (Figure 11). This mode has the potential to be adapted/leveraged for automated real-time applications such as instantaneous estimates of drift at a given location including statistics of expected transport distance. It could also be used to characterize drift for various drift categories (PIW, Dead Whales, larvae….) or to create daily safest navigation routes around MPAs (help minimize drift of dangerous substances into protected areas during potential event of along route incidents).

The Drift Evaluation module evaluates drift predictions against observed drifter observations (Figure 12). It allows for easy comparisons between multiple ocean model inputs, windages, and drift prediction methods. The output is cropped to a common spatial and temporal domain and stored in per drifter output files for convenient storage and analysis. The resultant analysis includes both mapped and time series representations of skill scores and drifter tracks, as well as output files containing all the data required for a user to perform further independent analysis. The results can be analyzed per drifter, per user defined region or for the entire data set.

The Drift Correction Factor module enables estimation of the best windage coefficients (aka correction factors) for given drifter types. Observed drifter data, along with modelled ocean and atmospheric data are used to determine the modelled currents and winds along an observed trajectory. This information is then used to determine the correction factor needed to produce a perfect drift prediction (Sutherland et al, 2020). When this module is run prior to an experiment, these correction factors can then be used as parameters in the drift characterization and evaluation modules to create a better overall prediction of drift.

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A.2.5 The Eastern Newfoundland Shelf Model

The eastern Newfoundland Shelf model uses FVCOM version 4.0. The model has uniform 2 km unstructured grids in the horizontal, covering the inner Newfoundland Shelf (Figure 17). Vertically, a hybrid coordinate is selected with 40 levels in total. The revised Mellor and Yamada level 2.5 turbulence scheme is used for the vertical mixing. For the horizontal mixing of momentum and tracers, the Smargorinsky method is used. The model was integrated for six months from May 2010 to October 2010 and the hourly results in the last five months are used for generating synthetic Surface Water and Ocean Topography data.

The model is initialized with the output of a Newfoundland shelf model on May 1, 2010 and is forced by hourly wind, shortwave and longwave flux, air temperature, humidity, and air pressure data of the National Centers of Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR) product.

Non-tidal sea surface heights are specified along the open boundary from the Newfoundland shelf model results. The tidal heights from the Oregon State University TOPEX/Poseidon Global Inverse Solution (http://volkov.oce.orst.edu/tides/TPXO7.2.html) are added to the non-tidal heights. Temperature and salinity extracted from the Newfoundland shelf model are specified at the open boundary where flow enters the model domain. Where flow exits the domain, temperature and salinity values are computed from a gravity-wave radiation boundary condition. The 2-D external boundary velocities and 3-D velocities are calculated through the linear momentum equations without inclusion of vertical and horizontal diffusion terms. A 10 km sponge layer is applied along the open boundary to filter out high frequency noise reflected by the open boundary.

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A.3 Aquaculture-related Models

A.3.1 The Pacific coastal waters

A.3.1.1 The Discovery Island Model and The Queen Charlotte Strait Model

These two models (Figure 13) are based on the FVCOM model. Horizontal resolution in both DI and QCS model domains goes from ~50 m to ~2 km, with 20 terrain-following vertical levels in DI and 16 in QCS (vertical resolution is always higher near the surface). The initial and boundary conditions of the DI model were taken from the SalishSeaCast model (Soontiens et al., 2016); for the QCS model, the initial and open boundary conditions were taken from the Coastal Ice Ocean Prediction System for the West coast (CIOPS-West). For both models, the High Resolution Deterministic Prediction System (HRDPS) from Environment and Climate Change Canada (ECCC) provided surface forcing at 2.5 km horizontal resolution (and some preliminary results were obtained using a beta-version HRDPS at 1 km resolution).

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A.3.1.2 The Baynes Sound Circulation Model

A FVCOM simulation was carried out for May 2016 to April 2017 with the wetting-drying option activated in order to capture the impact of extensive mudflats in the region (Figure 14). Atmospheric forcing was taken from the High Resolution Deterministic Predictive System model for western Canada, a product of Environment and Climate Change Canada (ECCC), with 2.5km horizontal resolution. Temperature, salinity, and sea surface heights along the open boundaries were taken from a combination of observations and other models while river discharges were based on observations taken by Water Survey of Canada (ECCC) for Courtenay River and estimated for three other smaller rivers. All discharge temperatures were set to an annual cycle computed by earlier studies for the Courtenay River. The FVCOM results compared favourably with limited temperature, salinity, velocity, and sea surface height observations.

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A.3.1.3 The West Coast Vancouver Island Model

The FVCOM-based model has resolution varying from 9km along the continental shelf to 60m in the coastal inlets. Temperature, salinity, sea surface height forcing along the outer boundary, and temperature and salinity initial conditions were taken from a pre-operational run of the Coastal Ice-Ocean Prediction System for the northeast Pacific (CIOPS-W) conducted by Environment and Climate Change Canada (ECCC). Atmospheric forcing was taken from the High Resolution Deterministic Prediction System (HRDPS), also run at ECCC. River discharge volumes were either taken directly from observations made by Water Survey of Canada (ECCC), or estimated from historical observations and/or watershed area ratios. Similarly, associated river temperatures were either based on direct measurements by organizations like PacFish or estimated from observations in watersheds with similar characteristics.

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A.3.2 The Coastal waters of the southern Gulf of St. Lawrence

Several local-scale, high resolution (typically 5 – 50m) models have been developed through the years in the Gulf region (Figure 15). Earlier applications were using the RMA10–11 finite element suite of models in 2D vertically averaged configurations, while more recent applications are full 3D and based on FVCOM4.1. For coupled hydrodynamic-biogeochemical (BGC) models, the level of detail in the BGC structure is commensurate to the objectives of each specific application but all rely on a classical NPZD (Nutrient-Phytoplankton-Zooplankton-Detritus) representation of the nitrogen cycle. All applications are built on direct observations for forcing and validation. Atmospheric and river forcing is usually provided by ECCC monitoring stations, while open boundary forcing and validation data (tides, currents, temperature, salinity) are collected by direct deployments of oceanographic instruments by Gulf region's personnel. Simulations are typically limited to the ice-free period (May – November), most relevant for biological activity, with the exception of StPeter's Bay where a full annual cycle was covered and sea-ice dynamics were included.

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A.3.3 Southwest New Brunswick

Using FVCOM 4.1, three preliminary one-year runs were conducted for 2016, 2017, and 2018. The model horizontal grid resolution ranges from ~30 m to 9.9 km (Figure 16). Typical horizontal grid cell side length is approximately 100 m in the coastal waters where finfish aquaculture occurs. In the vertical, 21 sigma levels were used. The model was run with wetting and drying. Output of the 2.5 km High Resolution Deterministic Predictive System model (HRDPS) continental grid from Environment and Climate Change Canada (ECCC) was used for atmospheric forcing. Lateral open boundaries were forced with temperature, salinity, and de-tided sea-surface height data from ECCC's Regional Ice Ocean Predictive System (RIOPS) and tides from the OSU tidal prediction software OTPS (https://www.tpxo.net/otps). Discharge from 9 rivers was included with data obtained from ECCC, NB Power, and JD Irving. The model grid is presently under revision to improve the horizontal grid and bathymetry in coastal areas of interest.

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A.4 ACOUSTIC MODELS

A.4.1 The Acoustic Model for the Salish Sea

An acoustic model based on Aulanier et al.s (2017) modelling suite was implemented for the Salish Sea between Vancouver and Swiftsure Bank. The bathymetry for the model was interpolated from Canadian Hydrographic Services (CHS) soundings to a 15 arc second (~300 m) resolution grid. The model domain along with the bathymetry included in the model are shown in Figure 16. The figure also shows the locations of the hydrophones that were used to verify the acoustic model. AIS data of ships transiting the domain, along with available vessel source levels for different ship types and ship dimensions and ship speed were used to model vessel specific source levels. The following ship types were considered: 1) Bulk carriers, 2) Container ships, 3) Ferries, 4) Fishing vessels, 5) Government/Research, 6) Naval vessels, 7) Passenger vessels, 8) Recreational vessels, 9) Tankers, 10) Tugs, 11) Vehicle carriers, 12) Registered whale watching vessels, and 13) Others (which included vessels of unknown type).

Sound speed profiles used in the modelling domain were calculated using temperature, salinity and depth data from a three-dimensional hydrodynamic model (SalishSeaCast) [Soontiens and Allen, 2017; Soontiens et al. 2016]that covers this region. The acoustic model was used to simulate shipping noise at 63 Hz, 125 Hz, and 250 Hz as these frequencies cover the range where noise from large ships is typically greatest. The present model is only capable of modeling frequencies up to 500 Hz. The model was verified using observations from 6 hydrophones deployed near the shipping route in parts of the Salish Sea (Figure 16). The simulation period used for model verification was May - October in 2018 and this period was chosen based on availability of AIS data.

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Appendix B: Abbreviations

ACCASP	Aquatic Climate Change Adaptation Services Program
AIS	Automatic Identification System
AMAP	Arctic Monitoring and Assessment Program
AMMP	Aquaculture Monitoring and Modelling Program
AMOC	Atlantic Meridional Overturning Circulation
AR5	Fifth Assessment Report
AZMP	Atlantic Zone Monitoring Program
AZOMP	Atlantic Zone Off-shelf Monitoring Program
BCCM	British Columbia Continental Margin Model
BNAM	Bedford Institute of Oceanography North Atlantic Model
CanESM	Canadian Earth System Model
CanOE	Canadian Ocean Ecosystem Model
CANOPA	CANadian OPA
CANOPA-GSBM	CANadian OPA-Gulf of St. Lawrence Biogeochemical Model
CanRCM4	Canadian Regional Climate Model version 4
CCCma	Canadian Center for Climate Modelling and Analysis
CFSR	Climate Forecast System Reanalysis
CHS	Canadian Hydrographic Service
CIOPS	Canadian Ice-Ocean Prediction System
CMEMS	Copernicus Marine Environmental Monitoring Service
CMOC	Canadian Model of Ocean Carbon
COMDA	Centre for Ocean Model Development and Applications
CONCEPTS	Canadian Operational Network for Coupled Environmental Prediction Systems
CPOP	Comité des Passes Opérationnelles et Parallèlles
CRCM	Canadian Regional Climate Model
CSAS	Canadian Science Advisory Secretariat
CSIB	Canadian Sea-Ice Biogeochemistry Model
CTD	Conductivity Temperature Depth
DMS	Dimethylsulfide
DNAODS	DFO North Atlantic Ocean-ice Downscaling System
ECCC	Environment and Climate Change Canada
ECMWF	European Centre for Medium-Range Weather Forecasting
ETOPO2	Earth Topography 2-arc-min
FGP	Federal Geospatial Platform
FVCOM	Finite-Volume Community Ocean Model
FVCOM-ICM	FVCOM-Integrated Compartment Model
GIN	Greenland, Iceland and Norwegian
GIOPS	Global Ice-Ocean Prediction System
GPSC	General Purpose Science Cluster

GSBM	Gulf of St. Lawrence Biogeochemical Model
GSL	Gulf of St. Lawrence
HRDPS	High Resolution Deterministic Prediction System
IBM	Individual-Based Model
IPCC	Intergovernmental Panel on Climate Change
LIM	Louvain sea-Ice Model
MC2	Canadian Mesoscale Compressible Community
MLDPn	Modele Lagrangien de Dispersion des Particules d'ordre n
MODCOM	DFO Ocean Modelling Community
MSC	Meteorological Service Canada
MYNN	Mellor–Yamada–Nakanishi–Niino
NAA	North Atlantic Arctic
NAFO	Northwest Atlantic Fisheries Organization
NCEP	National Centers of Environmental Prediction
NEMO	Nucleus for European Modelling of the Ocean
NEMO-LIM2	Nucleus for European Modelling of the Ocean-Louvain-la-Neuve Ice Model
NEP36-CanOE	Northeastern Pacific Canadian Ocean Ecosystem Model
NOAP-MP	
NPGO	North Pacific Gyre Oscillation
NPZD	Nutrient-Phytoplankton-Zooplankton-Detritus
NROM	Newfoundland and Labrador Regional Ocean Model
OI	Optimal Interpolation
OPP	Oceans Protection Program
OSF	Ocean Sciences Framework
PEI	Prince Edward Island
RIOPS	Regional Ice-Ocean Prediction System
ROMS	Regional Ocean Modelling System
RRTM	Rapid Radiative Transfer Model
SBAs	Sensitive Benthic Areas
SDMs	Species Distribution Models
SOG	Strait of Georgia
SSH	Sea Surface Height
SST	Sea Surface Temperature
SWOT	Surface Water and Ocean Topography
WRF	Weather and Research Forecast
WCTSS	World Class Tanker Safety System

Figures

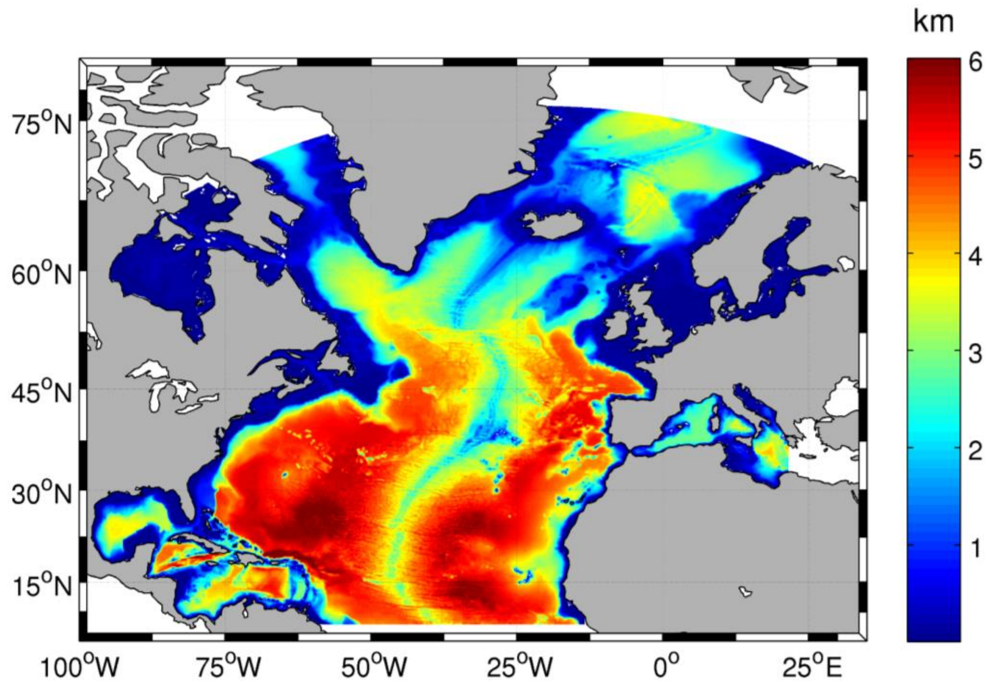

Figure 1*:* The BNAM model domain, with bathymetry (in km) denoted by color shading.

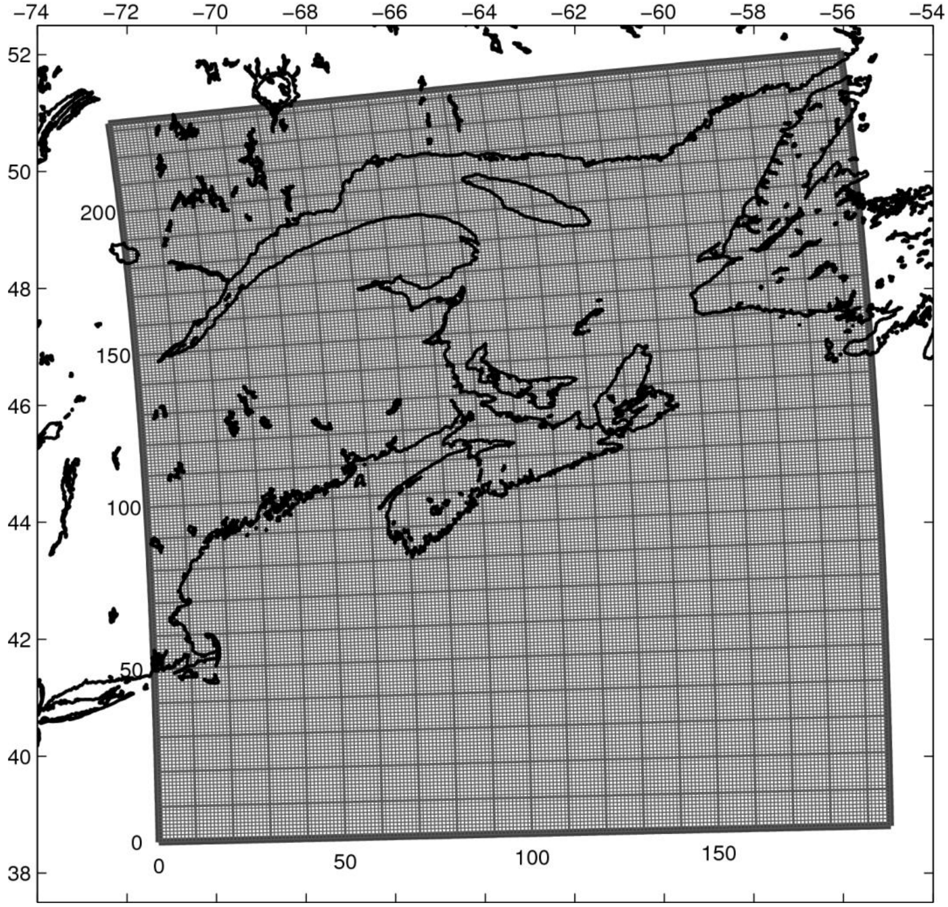

Figure 2: The CANOPA model domain.

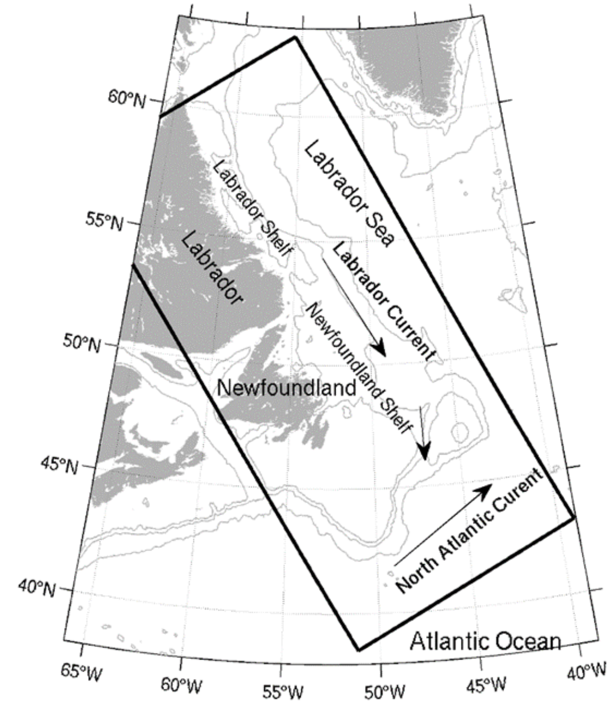

Figure 3*:* Map showing the Labrador and Newfoundland Shelf and adjacent Northwest Atlantic Ocean as well as the NROM open boundaries (thick solid lines). The isobaths displayed are 200, 1000, and 3000 m respectively.

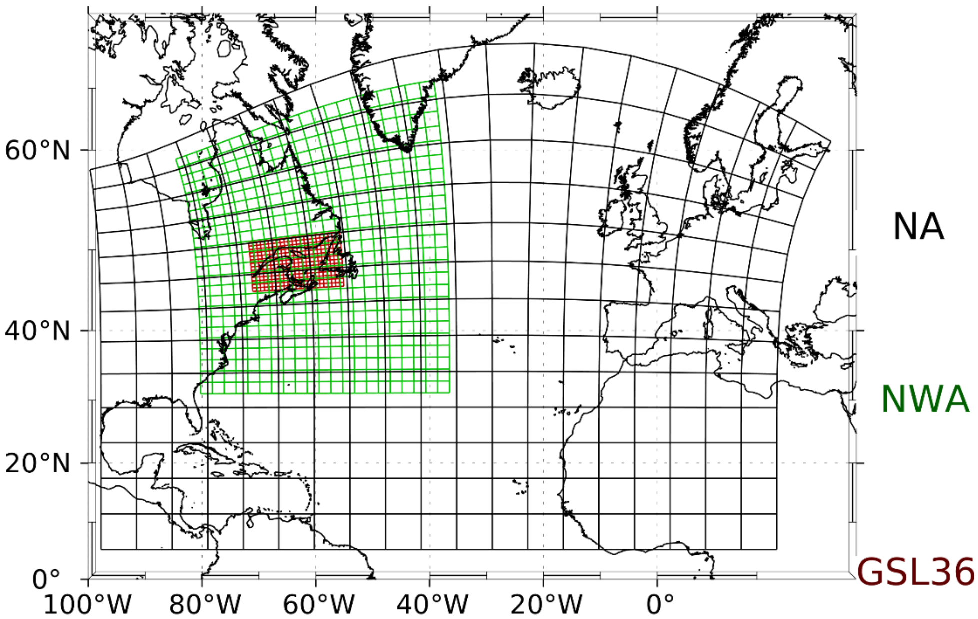

Figure 4: Map showing the North Atlantic (NA, black) as well as the DNAODS model domains with different horizontal resolutions. The horizontal resolutions are 1/4°, 1/12°, and 1/36° for the NA, the northwest Atlantic (NWA, green), and the Gulf of St. Lawrence (GSL, red) domains, respectively.

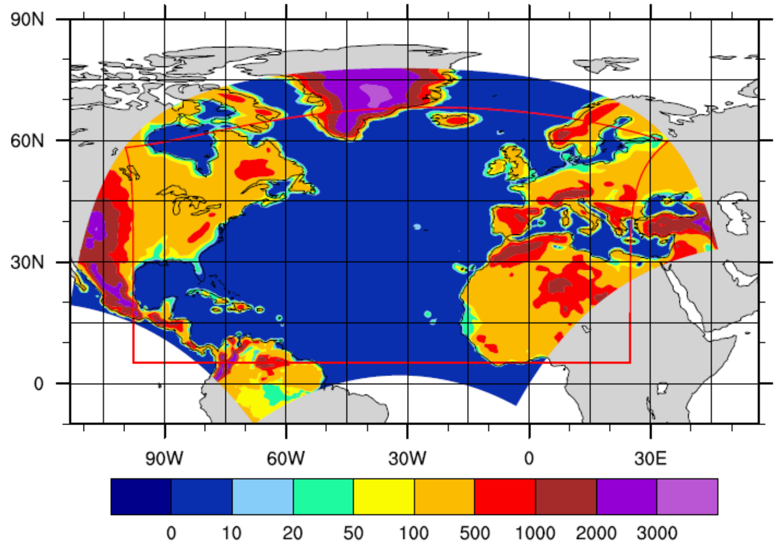

Figure 5: Domain for WRF simulations for the North Atlantic.

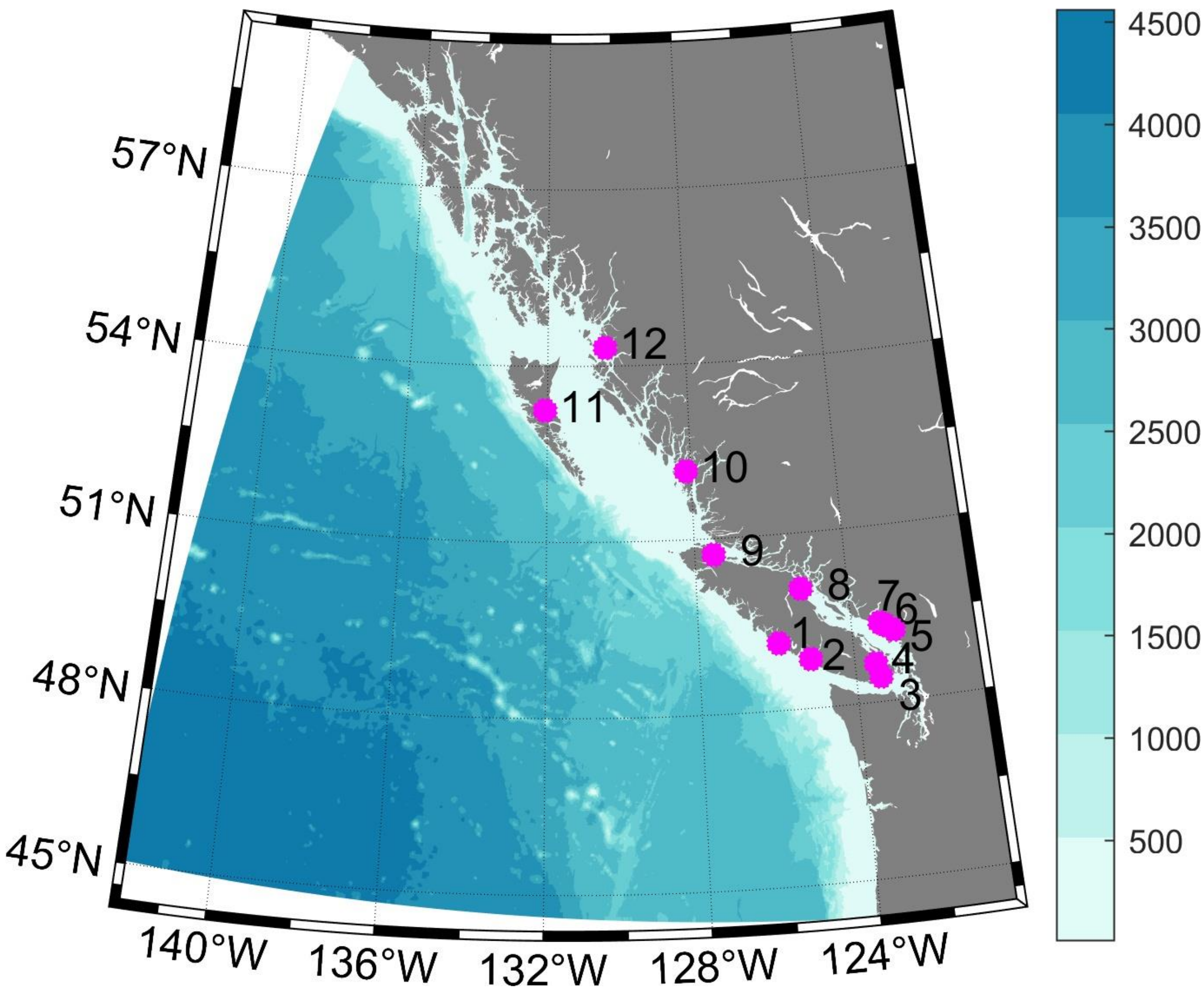

Figure 6: Model domain and bathymetry (m) for NEP36, as well as tide-gauge locations (dots).

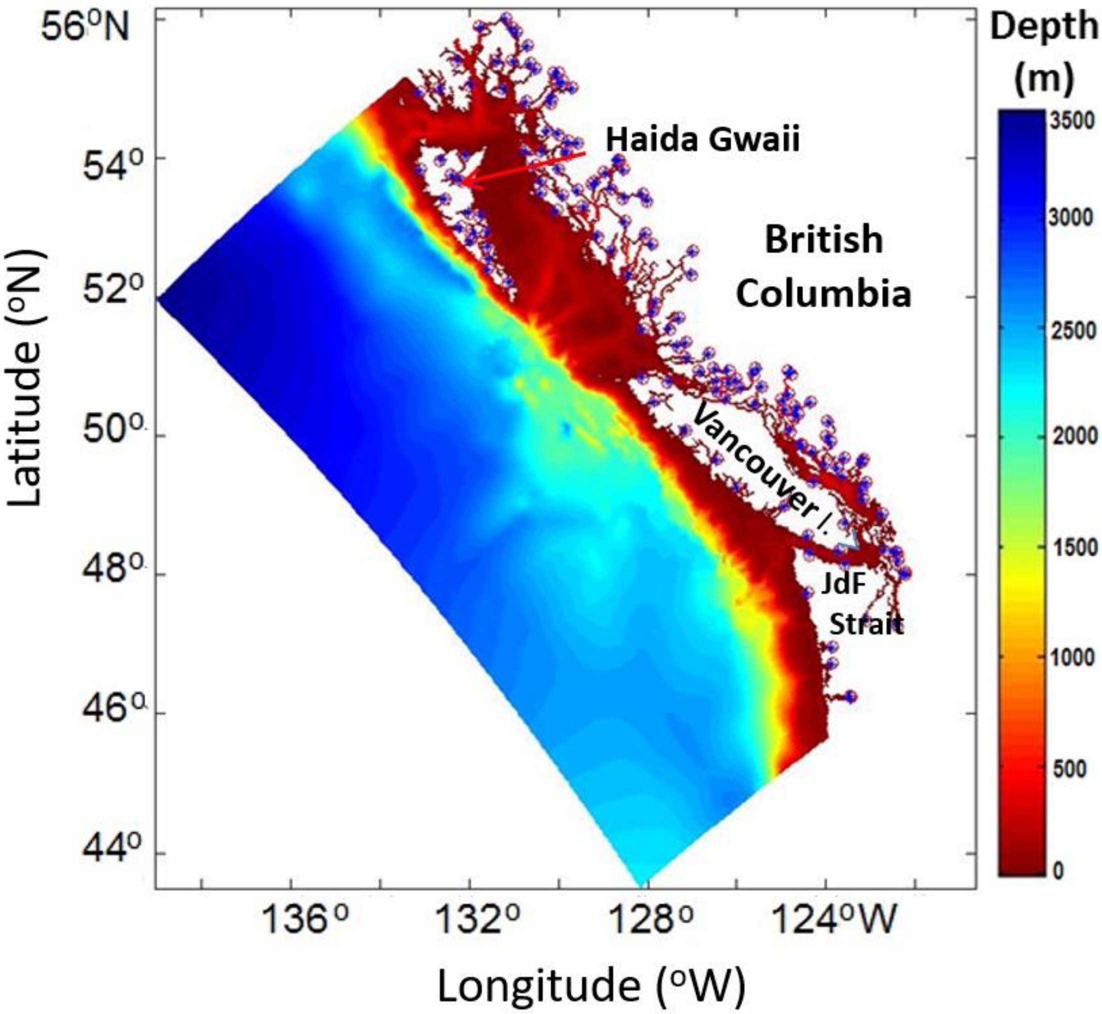

Figure 7: Model domain and bathymetry (m) for BCCM. River input locations (blue dots) are also depicted.

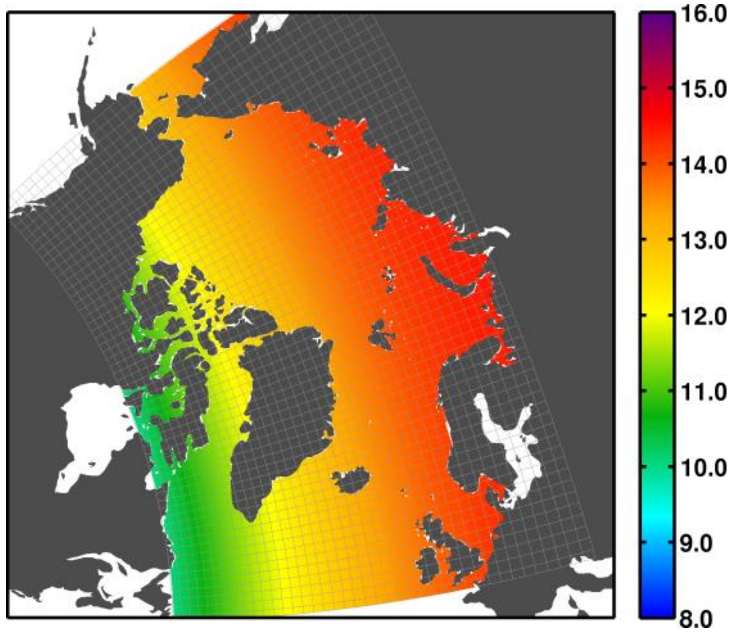

Figure 8: NAA model domain. Colors indicate the resolution in km.

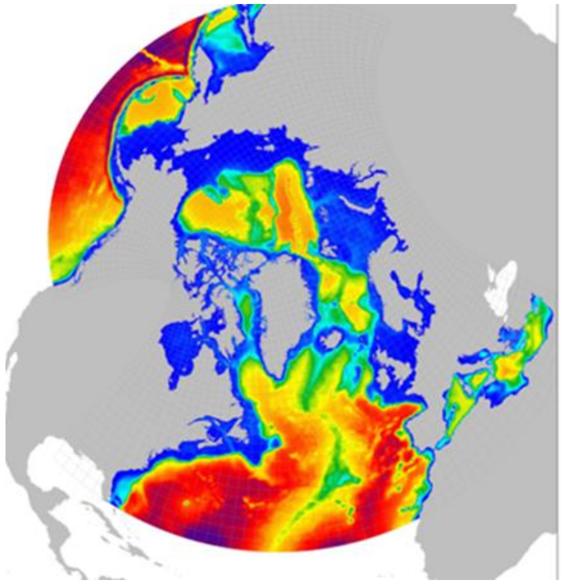

Figure 9: Model domain and bathymetry used for the 1/12^{o} and 1/4^{o} models covering Canada's three oceans.

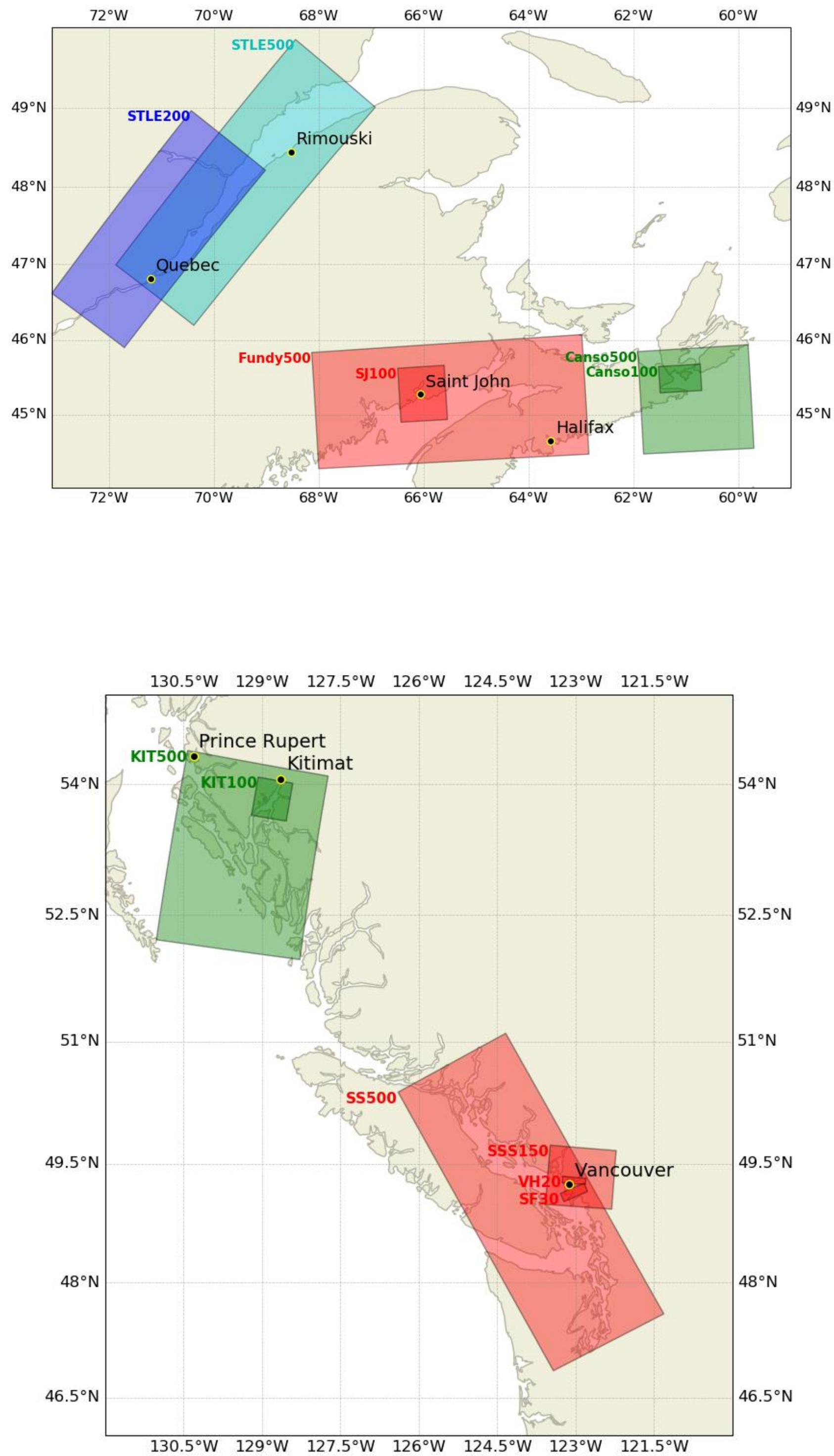

Figure 10: Maps of the six OPP model domains.

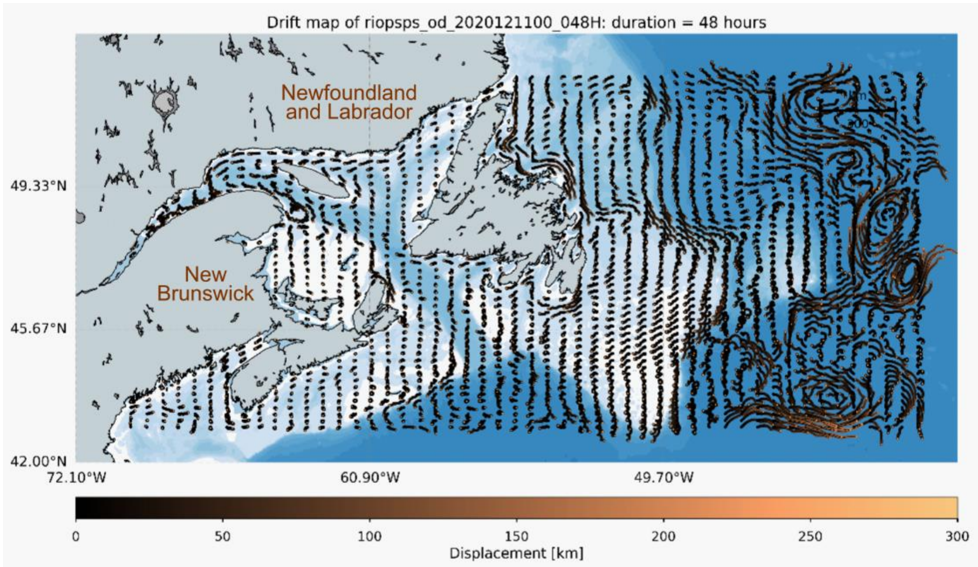

Figure 11: Visualization output from the drift characterization module. Here, the ocean is seeded with a grid of particles, which are allowed to propagate freely for 48 hours while being forced by ocean currents from ECCC's Regional Ice Ocean Prediction System (RIOPS).

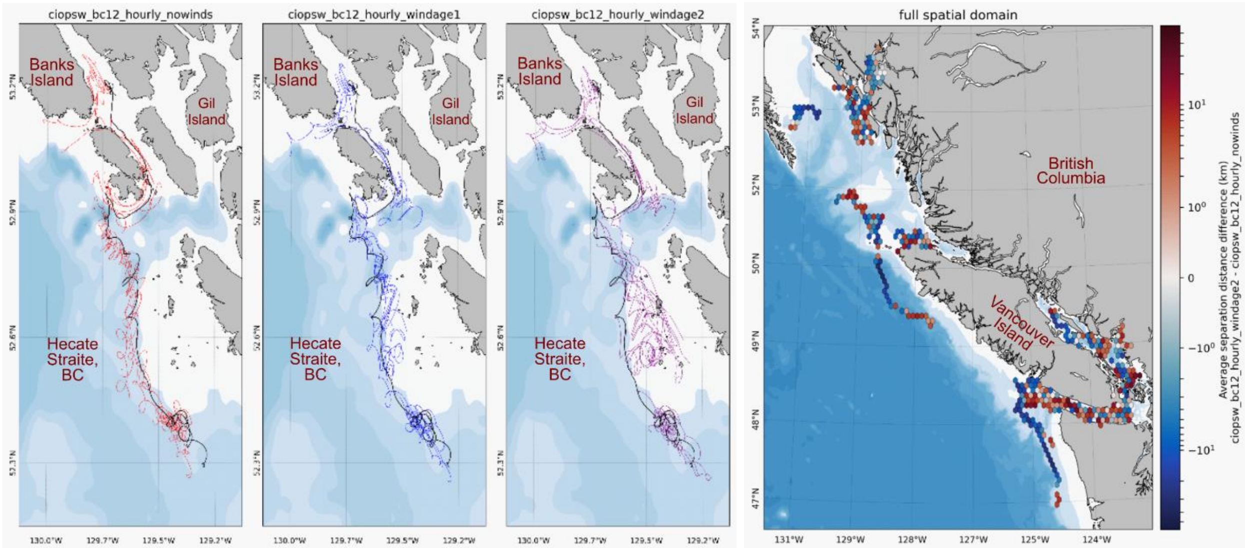

Figure 12: Sample visualization output from the drift evaluation module. For all panels, ocean forcing was provided by ECCC's Coastal Ice Ocean Prediction System for the West Coast of Canada (CIOPS-W) and wind forcing was provided by the High Resolution Deterministic Prediction System (HRDPS). (Left three panels) In this example, modelled drifters are released at consistent time intervals along an observed drifter track (in black). The experiment was repeated three times using windage values of 0% (red), 1% (blue) and 2% (purple). (Right panel) Difference in the modelled-observed separation distance between two experiments performed using differing windage parameters. Blue (red) colours indicate that the experiment with windage 2% (0%) performs better.

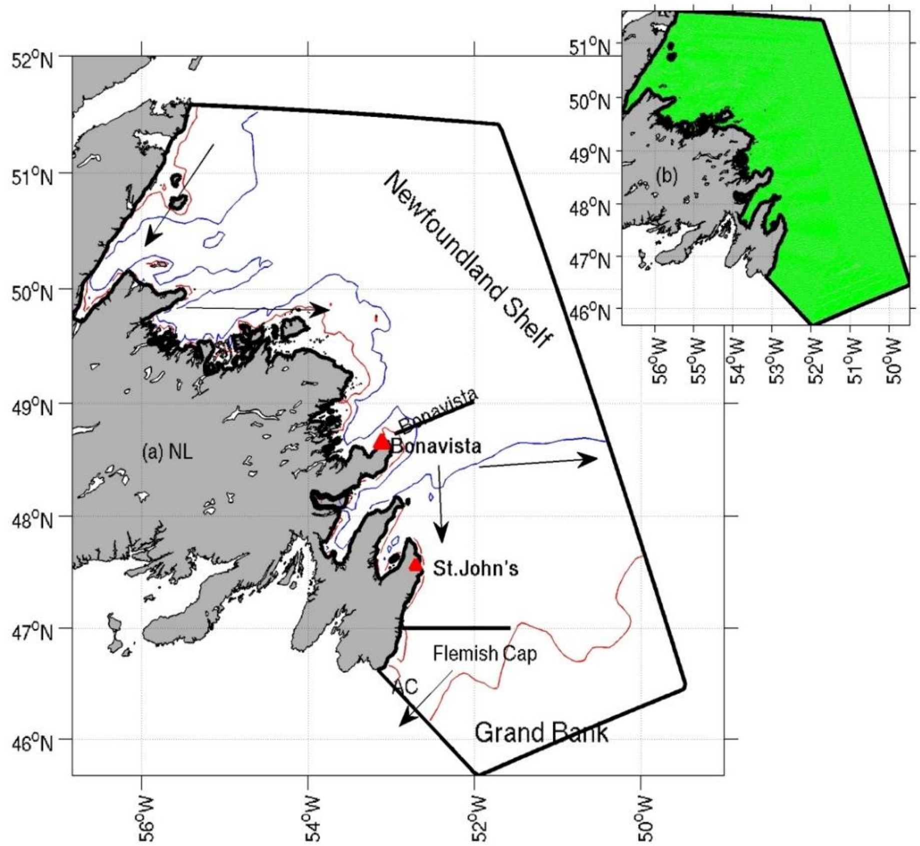

Figure 13: Domain of the Newfoundland coastal ocean model. Arrows indicate the inshore Labrador Current and its bifurcation off Bonavista. Also depicted are selected tide-gauge stations (triangle), cross-shore transects (thick segments) and the 100- and 200-m isobaths.

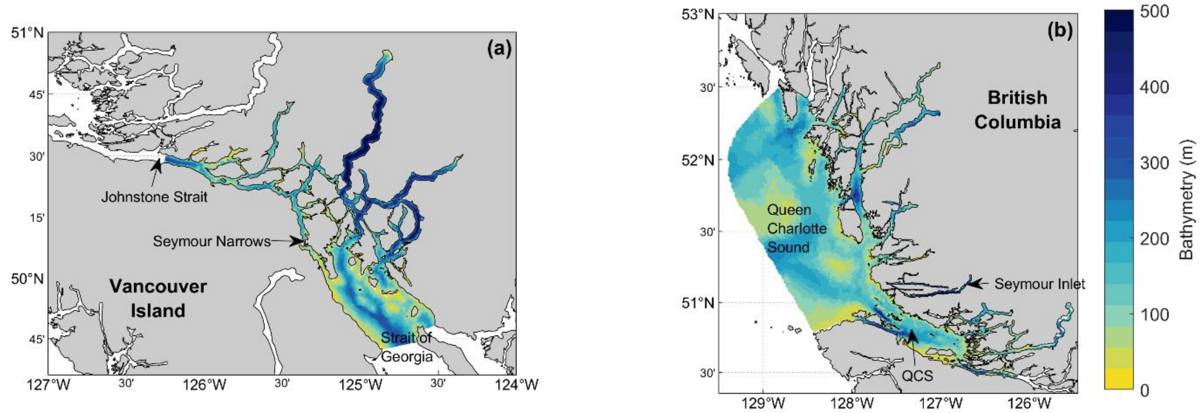

Figure 14: Bathymetry from two high-resolution, coastal model domains developed for aquaculture applications: (a) Discovery Islands and (b) Queen Charlotte Strait (QCS).

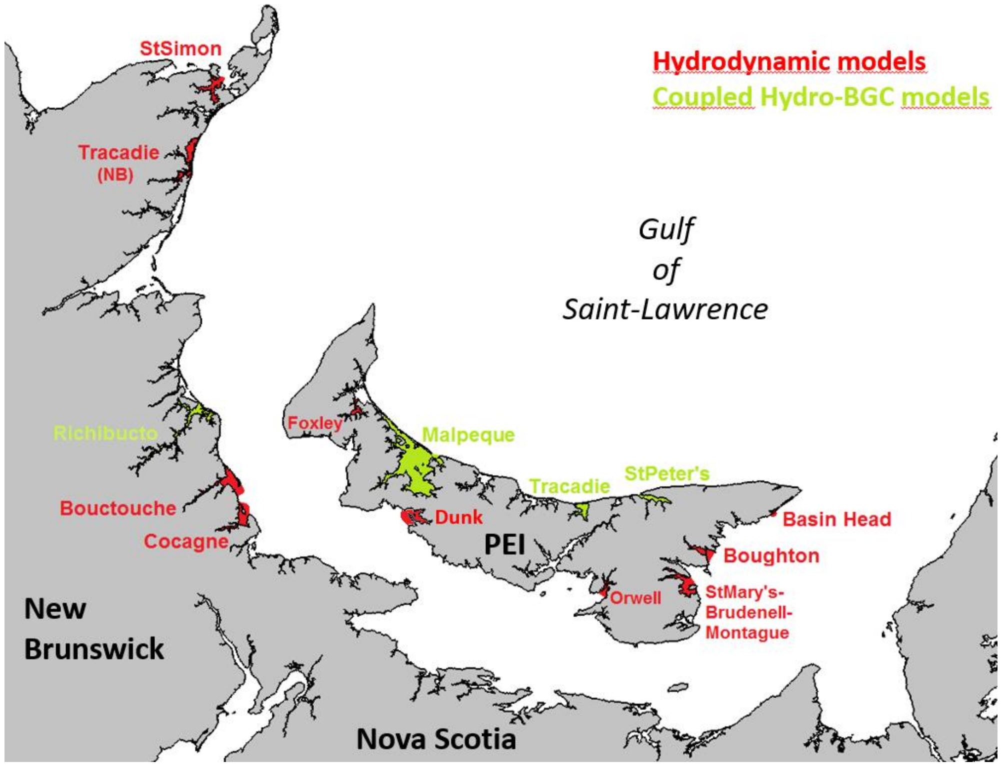

Figure 15: Map of local-scale, high resolution domains covered in the southern Gulf of Saint-Lawrence with hydrodynamic or coupled hydro-biogeochemical models.

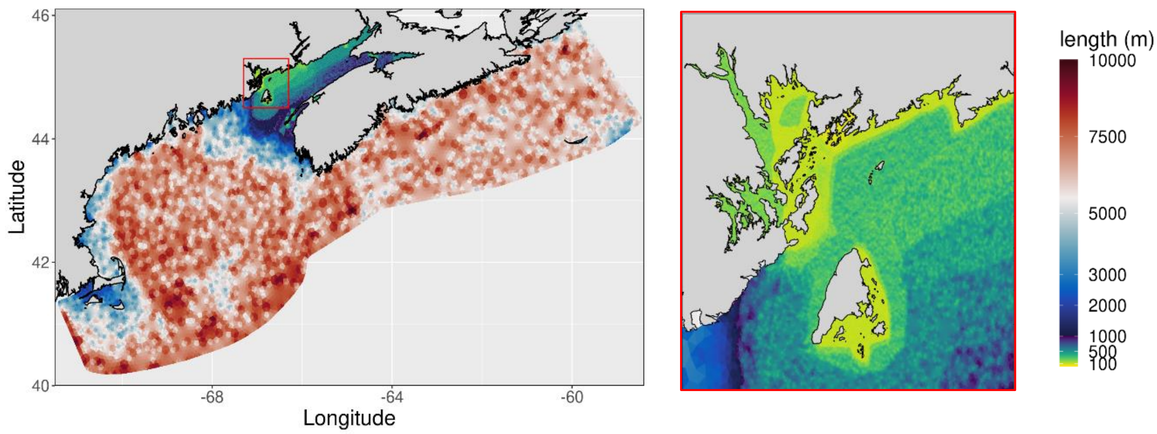

Figure 16: Horizontal grid length scale for coastal model domains developed for aquaculture in southwest New Brunswick. Right figure is an enlargement of region in red box of left figure.

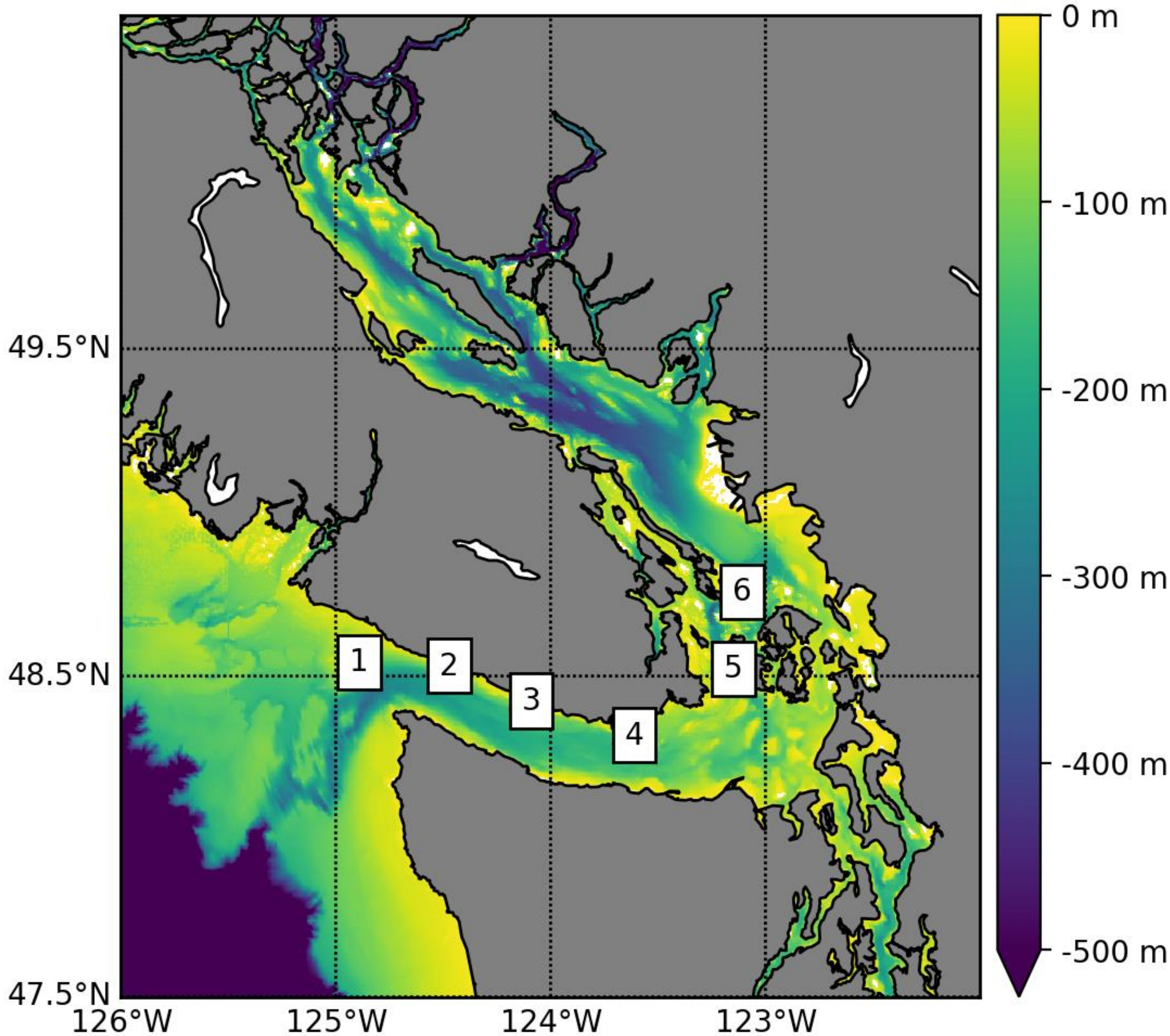

Figure 17: Domain of the acoustic model and location of hydrophone moorings used to evaluate the model. Bathymetry is also shown.

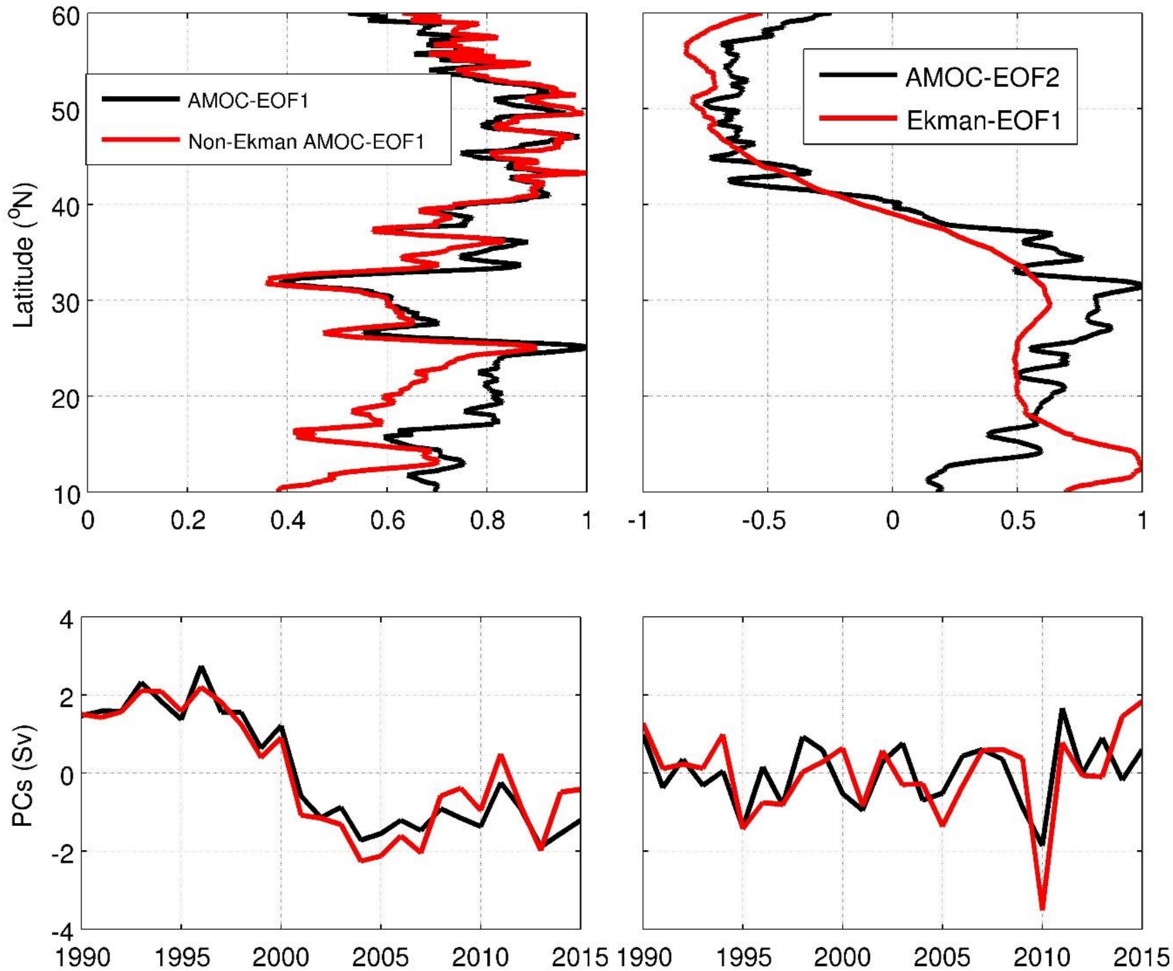

Figure 18: EOF patterns of AMOC , Non-Ekman AMOC (indicated in the plot) and Ekman transport (top panels); Associated PCs of these EOFs (bottom panel).

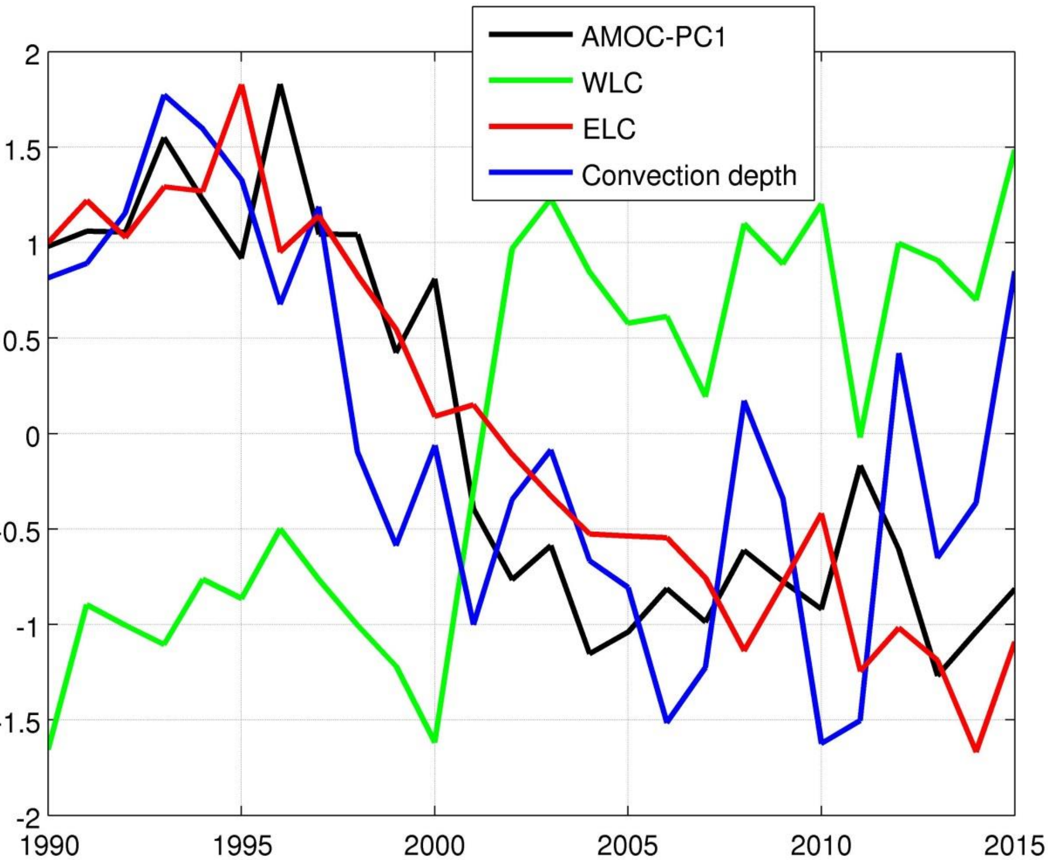

Figure 19: PC1 of the AMOC, Western Labrador Current (WLC), Eastern Labrador Current (ELC) and modelled winter convection depths from 1990 to 2015. Note: They were standardized to unit variance prior to plotting.

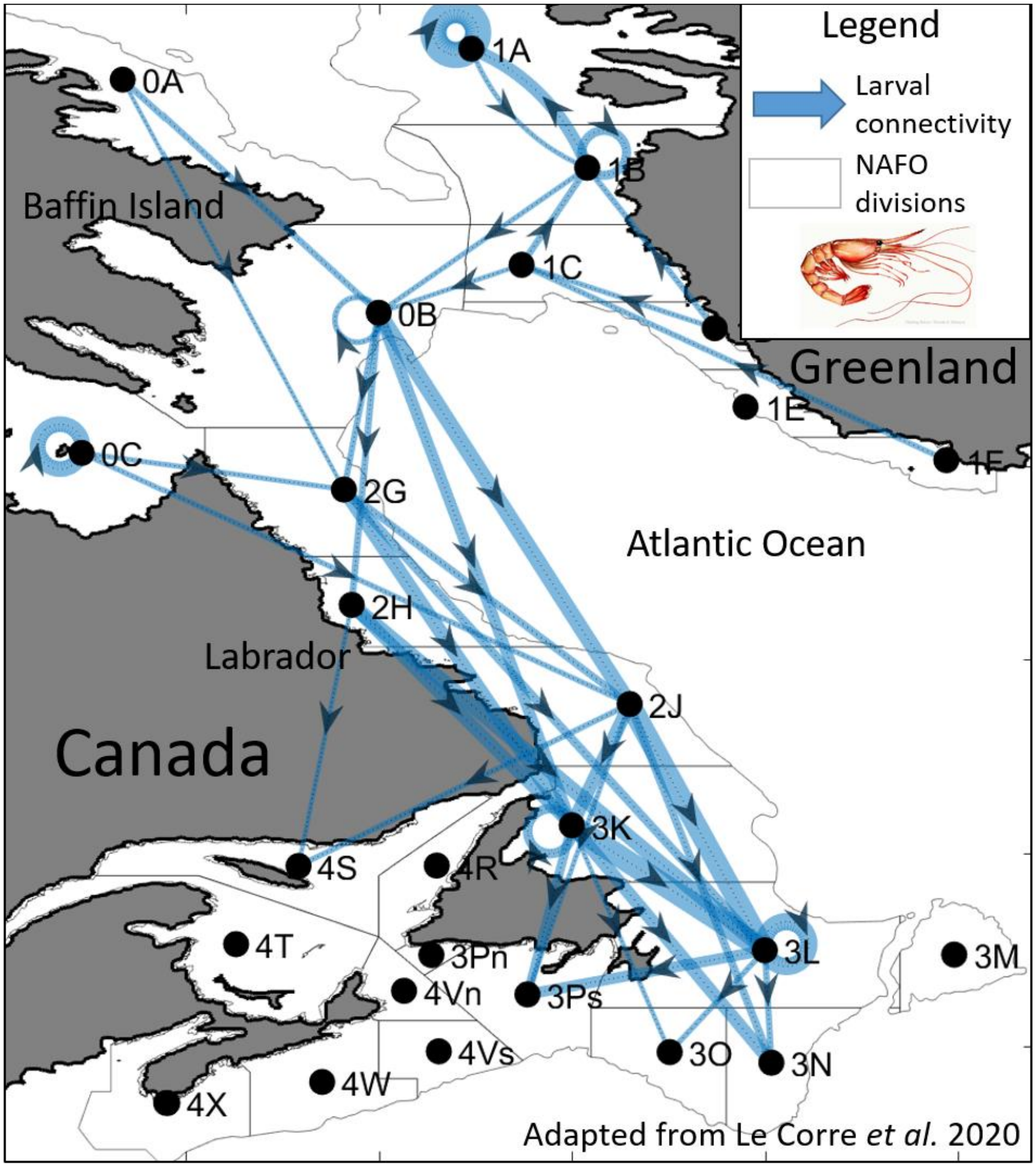

Figure 20: 4-year average northern shrimp larval connectivity across management areas (NAFO divisions) in the northwest Atlantic Ocean. Results are based on the results from a biophysical model (featuring BNAM). For clarity purpose, only the main connections are represented. The figure is adapted from Le Corre et al. 2020.

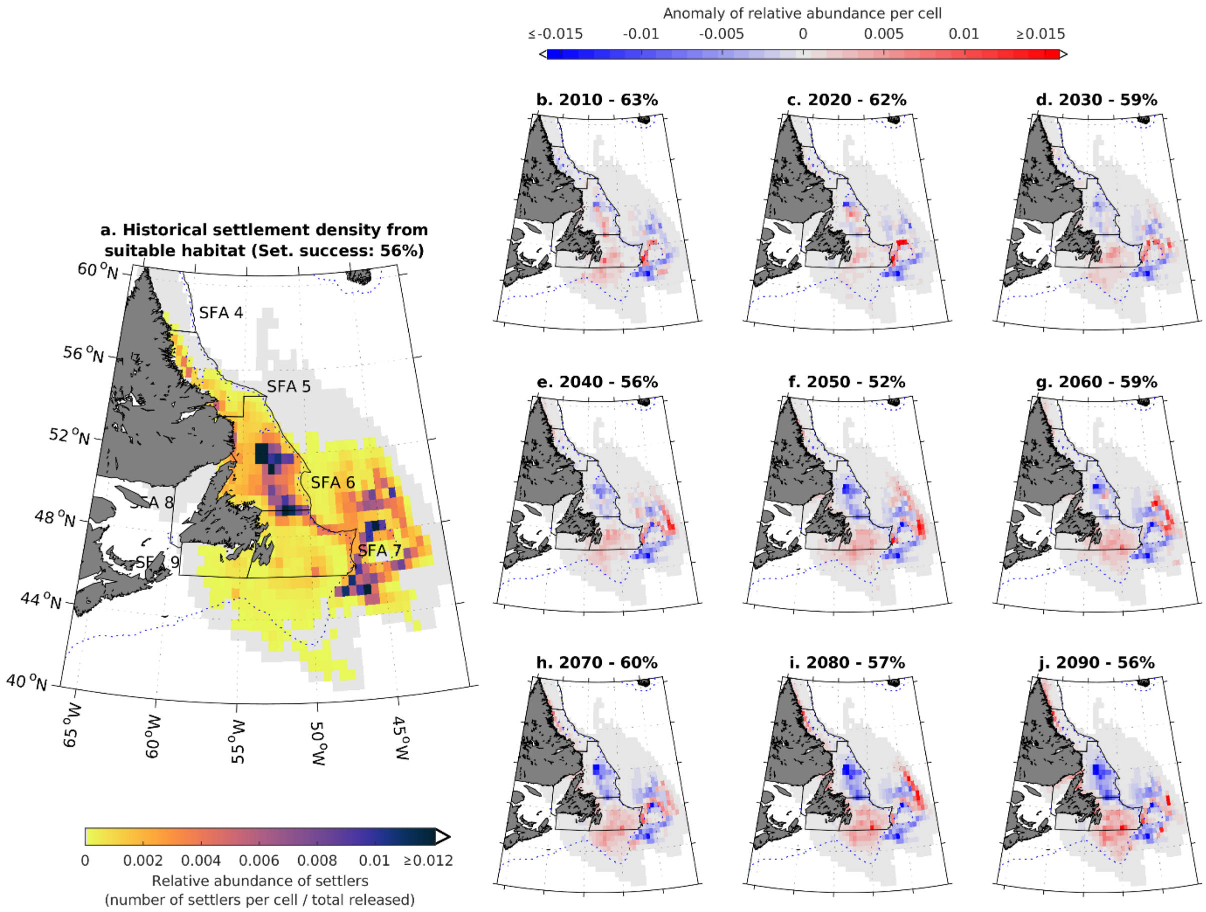

Figure 21: Map of the historical settlement density (a. 1980–2000 mean) and corresponding settlement anomalies from 2010 to 2090 (maps b to j) based on larval dispersal from a northern shrimp NROM-based (RCP8.5 projection) biophysical model. Percentage of settlement success (i.e. larvae remaining on the continental shelf) is indicated beside the studied year. The figure is adapted from Le Corre et al. 2021

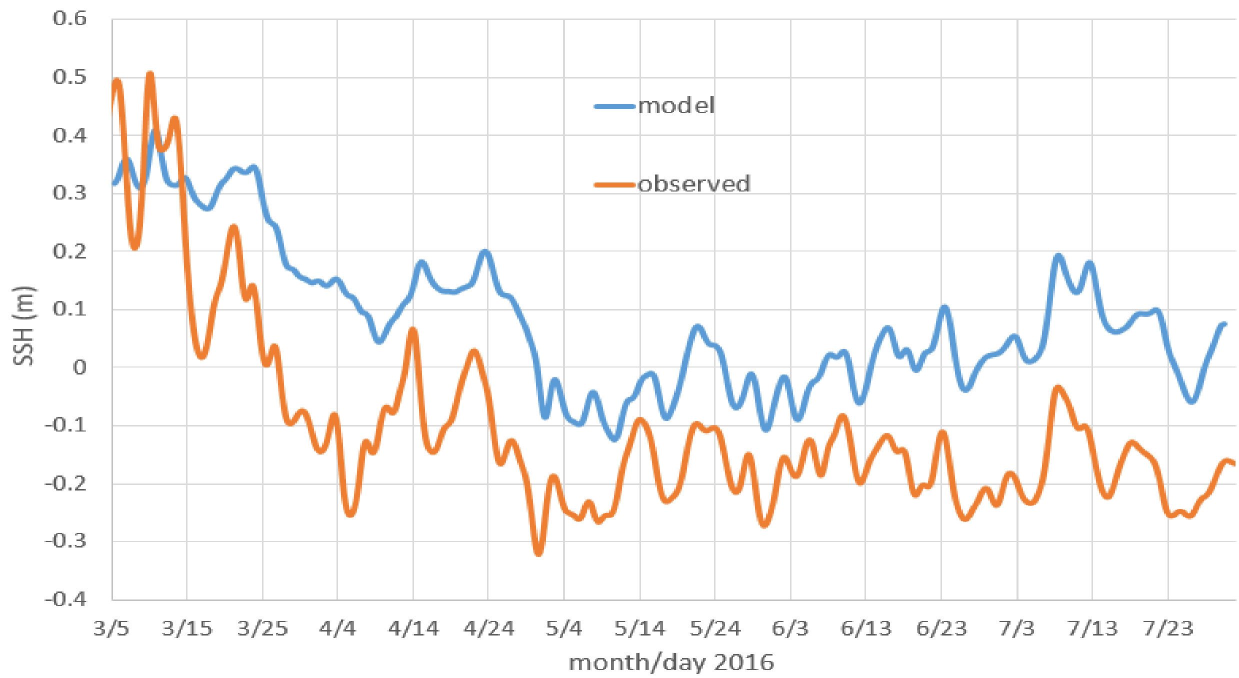

Figure 22: Hourly, low-pass filtered, observed and model sea surface heights (SSHs) at Tofino for March 4 to July 31, 2016. The model time series reference (zero) level is the geoid (as determined by the CIOPS-W model that provides boundary forcing) while for the observations it is the 2016 mean elevation.

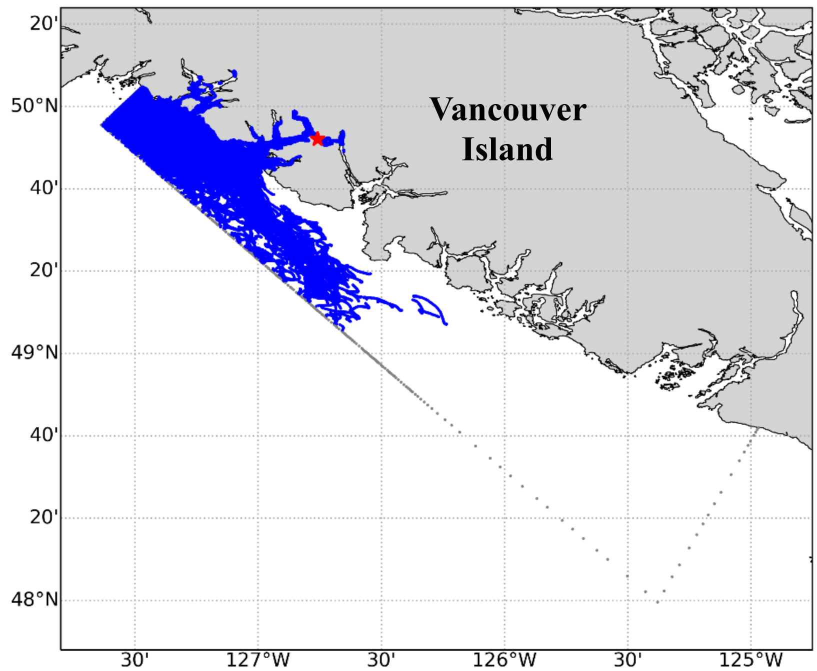

Figure 23: Neutral, passive particles released from a location representative of a farm in Esperanza Inlet (red star). Blue dots show particles in the last day of the 14-day tracking period. Grey dotted line represents the boundary of the WCVI model domain.

Tables

Table 1: Summary of DFO ocean models and sub-sections in which these models are presented.

1	Bedford Institute of Oceanography North Atlantic Model	2.1.1.1, 3.1.1.1, A.1.1.1
2	Gulf of St. Lawrence, Scotian Shelf and Gulf of Maine modelling system	2.1.1.2, 3.1.1.2, A.1.1.2
3	Newfoundland and Labrador Regional Ocean-ice Model	2.1.1.3, 3.1.1.3, A.1.1.3
4	DFO North Atlantic Ocean-ice Downscaling System	2.1.1.4, A.1.1.4
5	Regional atmospheric downscaling model	2.1.1.5, A.1.1.5
6	Northeastern Pacific Canadian Ocean Ecosystem Model	2.1.2.1, 3.1.2.1, A.1.2.1
7	British Columbia Continental Margin Model	2.1.2.2, 3.1.2.2, A.1.2.2
8	North Atlantic Arctic Model	2.1.3, 3.1.3, A.1.3
9	Models covering Canada's three oceans	2.2.1, A.2.1
10	Northeast Pacific High Resolution Regional Model	2.2.2, A.2.2
11	OPP port models	2.2.3, 3.2.1, A.2.3
12	OPP drift models	2.2.4, A.2.4
13	Eastern Newfoundland Shelf Model	2.2.5, 3.2.2, A.2.5
14	Pacific coastal waters models	2.3.2, 3.3.1, A.3.1
15	Southern Gulf of St. Lawrence models	2.3.3, 3.3.2, A.3.2
16	Southwest New Brunswick models	2.3.4, 3.3.3, A.3.3
17	Acoustic Model for the Salish Sea	2.4.1, A.4.1