PRELIMINARY DEVELOPMENT OF A RELOCATABLE OCEAN MODEL SYSTEM FOR THE WEST COAST OF CANADA: A SUMMARY OF OPP FA5 MODELING

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Preliminary Development of a Relocatable Ocean Model System for the West Coast of Canada: A Summary of OPP FA5 MODELING

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ABSTRACT

Lin, Y., Dunphy, M., Krassovski, M., Blanken, H., Hourston, R. 2022. Preliminary Development of a Relocatable Ocean Model System for the West Coast of Canada: A Summary of OPP FA5 Modeling. Can. Tech. Rep. Hydrogr. Ocean Sci. 343: v + 25 p.

A relocatable ocean model system has the capacity to be easily set up for different geographic regions or scales on demand, with minimal revisions in configuration. Research on a fixed domain on-demand near-shore drift prediction system in Canadian waters is included in the Government of Canada's Ocean Protection Plan (OPP), to contribute to increased marine safety and provide additional expertise in case of hazardous marine conditions. In this report, we describe a relocatable ocean model system developed for the west coast of Canada for demonstration and planning purposes. The implementation of this system has benefited from port models and tools developed by other OPP modelling efforts. Initial and boundary conditions are provided by the operational Coastal Ice Ocean Prediction System for the West coast with $1/36^{\circ}$ horizontal resolution (~2.0 to 2.5 km). At the surface, the operational High-Resolution Deterministic Prediction System provides surface winds, pressure and fluxes with 2.5 km spatial resolution. Case studies have been carried out and the hindcast ocean model results are compared with tidal gauge, acoustic Doppler current profiler, and conductivity-temperature-depth oceanographic data. Preliminary evaluation of the ocean model performance is shown and discussed in this report.

RÉSUMÉ

Lin, Y., Dunphy, M., Krassovski, M., Blanken, H., Hourston, R. 2022. Preliminary Development of a Relocatable Ocean Model System for the West Coast of Canada: A Summary of OPP FA5 Modeling. Can. Tech. Rep. Hydrogr. Ocean Sci. 343: v + 25 p.

Un système de modélisation océanique ad hoc a la capacité d'être configuré facilement pour différentes régions géographiques et différentes échelles, à la demande, avec des révisions minimales de la configuration. La recherche sur un système de prédiction de la dérive côtière sur un domaine fixe et à la demande dans les eaux canadiennes est incluse dans le Plan de Protection des Océans (PPO) du gouvernement du Canada, afin de contribuer à accroître la sécurité maritime et de fournir une expertise supplémentaire en cas de conditions maritimes dangereuses. Dans ce rapport, nous décrivons un système de modélisation océanique ad hoc développé pour la côte ouest du Canada à des fins de démonstration et de planification. La mise en œuvre de ce système a bénéficié des modèles portuaires et des outils développés par d'autres efforts de modélisation du PPO. Les conditions initiales et aux limites sont fournies par le système opérationnel de prévision côtière couplé glace-océan pour la côte ouest avec une résolution horizontale de $1/36^{\circ}$ (~ 2,0 à 2,5 km). En surface, le système opérationnel de prévision déterministe à haute résolution fournit les vents, la pression et les flux de surface avec une résolution spatiale de 2,5 km. Des études de cas ont été réalisées et les résultats du modèle océanique sont comparés à posteriori aux données de marégraphes, de courantomètres acoustiques à effet Doppler et à des profils de température et de salinité. L'évaluation préliminaire de la performance du modèle océanique est présentée et discutée dans ce rapport.

1 INTRODUCTION

1.1 OPP FA5

The Oceans Protection Plan (OPP) is a comprehensive, transformative strategy to build a world-leading marine safety system and protect Canada's marine ecosystems, while enabling inclusive economic growth. It includes a number of initiatives that will enable Canada to compare favorably with some of the best international marine safety regimes in the world and addresses gaps in Canada's current regime. The "improving drift prediction and near-shore modeling" OPP sub-initiative (the oceanography sub-initiative) reflects the reliance of the federal government and external organizations on accurate ocean models to respond to environmental and maritime disasters (e.g., spills and accidents) and to support electronic navigation.

The oceanography sub-initiative has six Functional Areas (FAs):

- FA1&2: Hydrodynamic Modelling for Ports of Importance
- FA3: Drift Prediction and Evaluation
- FA4: Physics Observations
- FA5: Relocatable Modelling and Biological Observations
- FA6: Operationalization
- FA7: DFO-ECCC Service Desk for Operational Oceanography

The modeling component of FA5 is responsible for developing a Fixed Domain On-Demand near-shore drift prediction system (FDOD) that could be deployed in case of emergency in any Canadian waters. It is challenging because Canada has the world's longest coastline which spans three oceans. Hence a relocatable grid for coastal modeling is used to implement the FDOD system, supported by Canadian regional operational ocean forecast systems. This approach will contribute to increased marine safety, enhanced information available on navigational systems, and providing additional expertise in case of hazardous marine conditions. In the observational part of FA5, biological datasets (emphasis may be on the Arctic) have been compiled to develop integrated model layers with oceanographic data. This will provide additional information on the potential impacts of a marine emergency (e.g., oil spill) on biological communities and species at risk.

Within this report, the modeling part of FA5 is summarized. The deliverables include developing and implementing work plans for a relocatable ocean model system. This hydrodynamic modeling system would not be operational 24/7 but could be turned on when needed. The goal of such a system would be to produce additional information to help deal with emergencies or prevent accidents during extreme weather events.

The milestones of the FA5 modeling research and development are listed as the following:

> **December 2021:** A draft workflow of modeling has been presented and discussed at an OPP Oceanography Working Group (OPPWG) meeting; Bligh Island was selected for testing the prototype. Components of the workflow are under development.

February 2022: Preliminary development has been done, including (1) Model grid and bathymetry generation, and (2) Model setup, forcing preparation, and submission. The automated capacity has tested for selected regions in the west coast of Canada and a cursory evaluation of model performance has been conducted.

March 2022: Implementation of modeling workplan complete. The prototype has been tested for Bligh Island and Prince Rupert, BC. Preliminary model performance has been evaluated.

1.2 Relocatable Modeling

A relocatable ocean modeling system (see Figure 1) must have the capacity to be easily set up for different geographic regions or scales on demand, with minimal changes in configuration (Chu and Blain, 2009). The first nested, fully relocatable primitive-equation ocean modeling system is the pioneer Harvard Ocean Predictions System (HOPS, Robinson and Leslie, 1985). The Relocatable Ocean Atmosphere Model (ROAM, Herzfeld, 2009) can be set up anywhere in the Australian region with minimal input by non-expert users. The Naval Research Laboratory (NRL) RELOcatable ocean nowcast/forecast system (RELO) can provide a capability for relocatable ocean forecast modeling and data assimilation to predict the impact of the environment (air, water, land, and ice) on naval operations, training, and support activities (Rowley and Mask, 2014). During the Costa Concordia emergency case (2012), a high resolution, relocatable model, called IRENOM (Interactive RElocatable Nested Ocean Model) was nested in an operational regional model and provided the input to an oil spill model in support of environmental emergencies. More recently, an open-source package called Structured and Unstructured grid Relocatable ocean platform for Forecasting (SURF, Trotta et al., 2016) has been developed. SURF provides a numerical platform, including pre- and post-processing tools for bathymetry, initial and lateral boundary conditions, and atmospheric forcing.

In Canada, Marine Environmental Observation Prediction, and Response (MEOPAR) has been supporting research projects entitled “a Relocatable Coupled Atmosphere-Ocean Prediction System” and “Downscaling atmosphere-ocean forecasts from global to harbor scales with application to the Maritimes”. Chegini et al. (2018) studied the coastal upwelling off Southwest Nova Scotia as part of a larger effort to develop relocatable high-resolution ocean forecasting models by downscaling from global and regional systems.

As a downscaling limited area model, relocatable modeling is made possible by integrating with global and regional operational ocean forecast systems. In Canada, through the development efforts of the Canadian Operational Network of Coupled Environmental PredicTion Systems (CONCEPTS) over the past decade, the operations Regional Ice Ocean Prediction System (RIOPS) can provide 48-hour ice and ocean forecasts four times per day on a 1/12° resolution grid (3-8 km). The domain extends from 26 °N in the Atlantic Ocean over the Arctic Ocean to 44 °N in the Pacific Ocean (Smith et al., 2021). The Coastal Ice Ocean Prediction System for the East and West Coast of Canada (CIOPS-E/W; e.g., Paquin et al., 2021) further improved the horizontal resolution to 1/36° (2-2.5 km) covering the Northwest Atlantic and the Northeast Pacific. Operational analyses and forecasts are available to be incorporated into coastal relocatable models as initial and boundary conditions. As for the atmospheric forcing, the operational High Resolution

Deterministic Prediction System (HRDPS) of ECCC provides a reasonable horizontal grid spacing (e.g., 2.5 km) for the main Pan-Canadian region and a northern region over the Arctic Archipelago and Greenland.

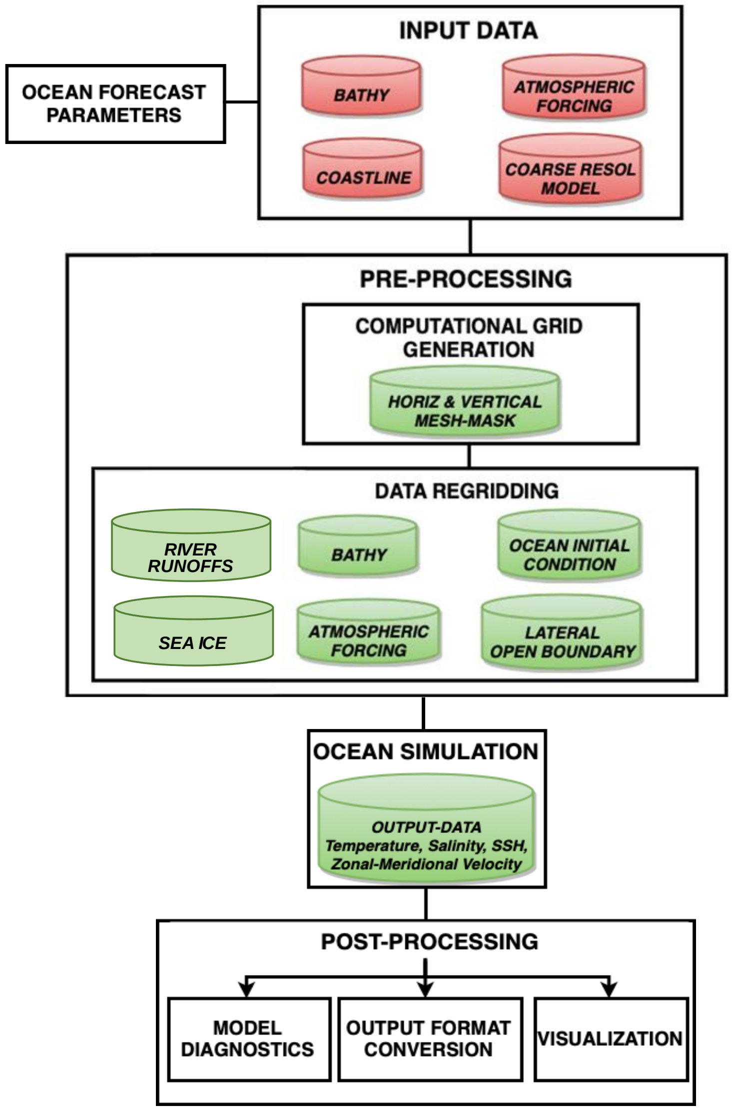

Figure 1. The structure of Fixed Domain On-demand Near-shore Drift Prediction System. Adapted from Trotta et al. (2016).

A fundamental input for a relocatable modeling system is a high-resolution bathymetric database. For example, coastal digital elevation models (DEM) integrating ocean bathymetry and land topography for marine ecological analyses in Pacific Canadian waters (see Figure 2) have become available recently (Davies et al., 2019). The data used to build the series of DEMs (with a horizontal grid spacing of 10 m) were acquired from CHS, Natural Resources Canada, and the National Oceanic and Atmosphere Administration (NOAA). Surface elevations/depths are referenced to mean sea level. Coastline used in this study is the Global Self-consistent, Hierarchical, High-resolution Geography Database (GSHHG).

Figure 2. Canada west coast topo-bathymetric digital elevation model (Davies et al., 2019). Figure adapted from open.canada.ca.

2 WORKFLOW AND IMPLEMENTATION

Development of a relocatable ocean model system for the west coast of Canada is presented in this report for demonstration and planning purposes. The model is not production-ready yet and the activities conducted in this study include requirements analysis, components design, system development, and unit testing.

The implementation of FA5 modeling has benefited from the port models and tools developed by other OPP modelling efforts. Hydrodynamic modelling for hydrographic e-navigation and drift prediction (FA1&2) has been conducted under OPP for Kitimat, Vancouver Harbour, Lower Fraser River, St. Lawrence Estuary, Saint John Harbour, and Strait of Canso. The goal of FA5 modeling is to develop a modeling system that can be configured quickly, and then perform model simulations and predictions automatically with minimal human intervention. Workflow planned for FA5 modeling is shown in Figure 3, where aspects include:

(1) Automated bathymetry interpolation and model grid and mesh mask preparation
(2) Bathymetry refinement via coastline data
(3) Boundary forcing and initial conditions from parent models
(4) Model parameters and configuration using OPP port models as references

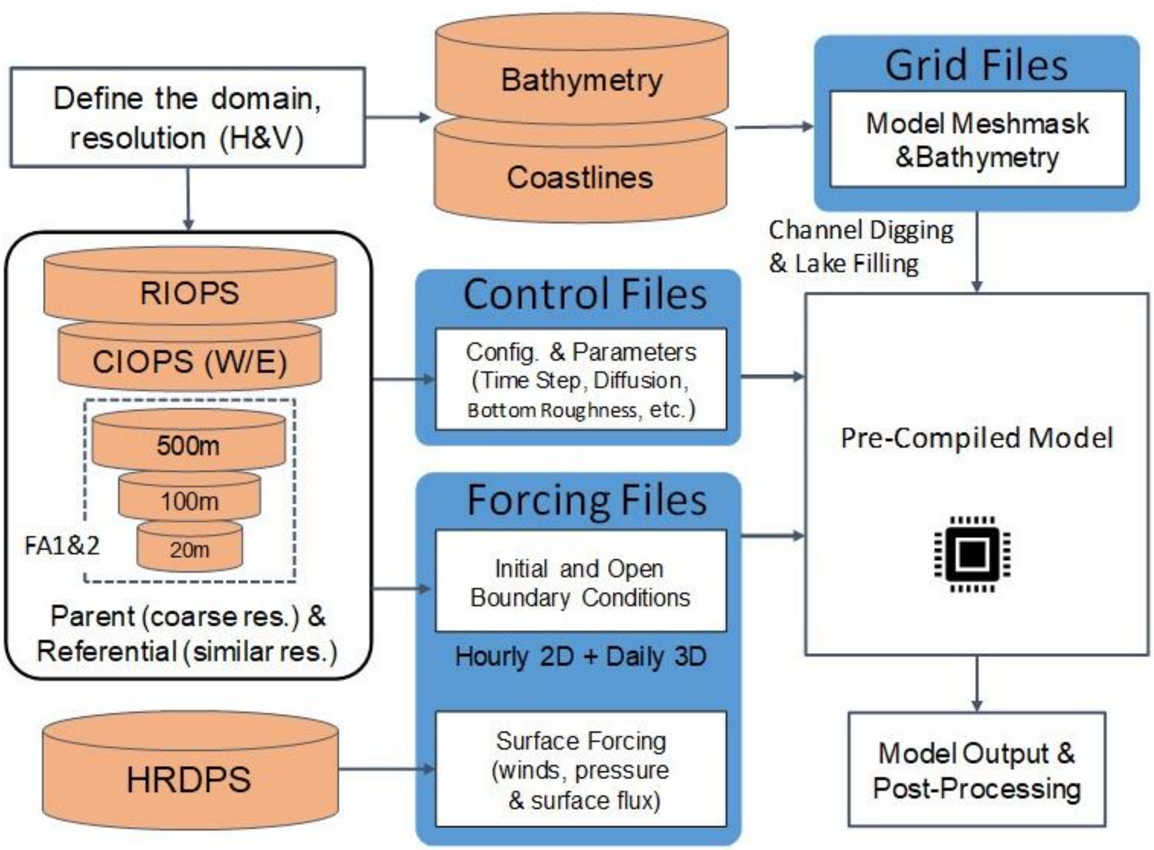

Figure 3. Workflow of the Fixed Domain On-demand Near-shore Drift Prediction System (Phase 1).

The ocean model used in FA5 is the Nucleus for European Modeling of the Ocean (NEMO; Madec et al., 2008) modeling framework; a primitive-equation model on an Arakawa C-grid employing the Boussinesq and hydrostatic approximations.

Initial and boundary conditions, including water temperature (T), salinity (S), Sea Surface Heights (SSH), and ocean currents, are provided by the operational CIOPS-W with 1/36° horizontal resolution (~2.0 to 2.5 km). In the current version, river runoff is only included if the river is represented in the parent model. In this case, the river discharge is implemented through open boundary conditions. Automatic set-up of freshwater discharge not represented in the parent model can be implemented once a river-discharge database is available and associated tools are developed. At the surface, the operational HRDPS provides surface winds, pressure, air temperature, specific humidity, and fluxes (solar radiation, infrared radiation, precipitation, and snow fall rate) with a 2.5 km spatial resolution. The ocean model bathymetry is based on high resolution coastal DEMs for the west coast of Canada.

Port models developed under OPP FA1&2 in the same region (Pacific) were used as the references for setting parameters/configuration and dealing with different resolutions automatically. For example, the hydrodynamic ocean model with a 100 m horizontal resolution for Kitimat BC was selected for the case studies with the similar horizontal resolution in the Bligh Island and Prince Rupert areas in BC. Descriptive parameters, including dimensions, the maximum depth, vertical coordinates, etc., were updated in the model configure file after the generation of model grid. Dynamical parameters, such as the time step, advection and mixing schemes, viscosities and diffusivities, are kept the same as in the similar resolution reference model. This approach has been working flawlessly as to the model stability. In some circumstances, parameters, such as open boundary schemes for narrow channels not well resolved in the coarse resolution parent model, could require human intervention to make a selection.

Shell scripts (Unix/Linux) have been programmed to automate major tasks of the forecast run stream such as initial model setup, forcing data acquisition, model configuration, and post-processing.

The SURF platform (Trotta et al., 2016) was used to prepare the model grid, bathymetry, and mesh mask through the following steps: (1) Parameters Initialization, (2) Check/Download/Cut Input Coastline, (3) Check/Download/Cut Input Bathymetry, (4) Generate 2d Child Mesh File, (5) Define Bathy Regridded-datasets, and (6) Re-generate 3d Child-meshmask File. We have customized and modified the Surf-Nemo platform to meet our requirement. Surf platform was transferred from its Virtual Machine environment to the General-Purpose Science Cluster (GPSC) interactive cluster. The Python package, Gridtools, was incorporated to conduct the automated coastline improvement including channel digging & lake/hole filling.

The Python package bdytools provides the tooling for producing initial and boundary condition files for one-way offline NEMO downscaling. Only 2D fields (e.g., SSH and depth-averaged currents) are available with an hourly interval from the operational CIOPS-W system and three-dimensional fields (temperature, salinity, and velocities) are saved every 24 hours as daily averages. Barotropic flow is imposed at open boundaries (by Flather radiation open boundary scheme) using hourly sea-surface height and barotropic flow (SSH, ubar & vbar). Temperature, salinity and baroclinic currents are imposed using the Flow Relaxation Scheme. In the future, open boundary elevations can be generated as a combination of detided sea surface heights from parent model results, and reimposed tides from a tidal database.

3 CASE STUDIES

3.1 Bligh Island

Case studies have been carried out at Bligh Island, BC, where a sunken vessel was leaking oil and became the source of visible sheen on the surface of the water in 2020. This site was selected for testing FA5 also because:

- It has not been covered by existing port models (FA1&2 under OPP)
- It is dynamically representative of many regions along the BC coast (with Gold River to the east)
- Data availability including tidal gauge, Acoustic Doppler Current Profiler (ADCP), and Conductivity-Temperature-Depth (CTD) oceanographic data

The relocatable model domain is shown as in Figure 4, with a horizontal resolution in both latitude and longitude of 1/720° (~150 m). It has 289×225 grid points in the horizontal and 50 z-levels in the vertical. The relocatable grid is generated by the SURF platform (Trotta et al., 2016), which is not constrained by the orientation of the parent model grid. Higher resolution was used near the surface with inter-layer spacing ranging from 1.1 to 10.8 m. Maximum water depth in the domain is 290 m. Automated coastline improvement was carried out based on GSHHG coastlines using Gridtools. The difference in relocatable model grid is shown in Figure 5.

The mouth of the Gold River is not inside in the relocatable model domain (Figure 4) , so the river influence has to be through the eastern open boundary in the middle of the inlet (as the river is included in the parent model, CIOPS-W). Various open boundary schemes were tested in this case study. Daily averages of 3-D fields (T and S) from the parent model (CIOPS-W) were used for the open boundary conditions.

There were two model runs carried out as shown in Table 1. Model results were saved hourly and were examined after five days for spin-up, i.e., for Dec 04, 2015 - Feb 01, 2016, and Aug 18, 2017 - Aug 17, 2018. Preliminary evaluation of the ocean model performance has been conducted. Hindcast ocean model results have been compared with tidal constituents observed at Saavedra Islands (station #8645, see Table 2). Compared with observed data from ADCP at cook1 and zuc1 sites in Cook and Zuciarte channels separately (as marked in Figure 6), Figure 7 to Figure 9 show the model eastward and northward components of the ocean currents. Relocatable model produced water temperature and salinity (Figure 10 and Figure 11) were compared with CIOPS-W results and CTD data at subsurface (~40 m) and near bottom (~150 m) at the Cook Channel site (2017-2018). The root mean square error (RMSE) scores for relocatable model runs in the Bligh Island area are summarized in Table 3. Overall, the high resolution 3-D relocatable model demonstrated the capability for simulating both tidal and non-tidal flow regimes. Relevant discussion including the likely source of error is presented in Section 4.

Table 1. Relocatable model runs for Bligh Island.

Relocatable Model Runs	Simulation Period	Boundary SSH	Boundary TS	ADCP	CTD
1	2015 Nov 29-2016 Feb 01	hourly	daily	Yes	
2	2017 Aug 13-2018 Aug 17	hourly	daily	Yes	Yes

Table 2. Tidal constituent comparison between relocatable model results and observational tidal gauge data (Saavedra Islands).

Tidal Constituent	Amplitude (m)			Phase (°)			Difference in Complex Plane	
	OBS	MOD	DIFF	OBS	MOD	DIFF	(m)	(%)
M2	1.00	0.97	-0.02	240.01	239.61	-0.40	0.02	2.42
K1	0.46	0.46	0.01	238.15	234.82	-3.33	0.03	6.01
S2	0.29	0.28	-0.01	268.21	267.58	-0.63	0.01	2.95
O1	0.27	0.28	0.01	223.47	223.18	-0.29	0.01	3.02
N2	0.21	0.20	0.00	215.41	215.37	-0.04	0.00	2.07

Table 3. Summary of the RMSE scores for the relocatable model runs in the Bligh Island area.

Items	RMSE	Sites	Depths	Relocatable Model Runs	Figures
U compared with ADCP	4.0-6.9 cm/s	zuc1	Surface to Subsurface	1	Figure 7
	2.6 - 4.5 cm/s	zuc1	Subsurface to Near bottom	1	Figure 8
	2.8 - 4.3 cm/s	cook1	Surface to Subsurface	2	Figure 9
V compared with ADCP	7.0-12.6 cm/s	zuc1	Surface to Subsurface	1	Figure 7
	4.0-10.8 cm/s	zuc1	Subsurface to Near bottom	1	Figure 8
	7.1-13.5 cm/s	cook1	Surface to Subsurface	2	Figure 9
T compared with CTD	0.70 °C	cook1	Subsurface	2	Figure 10
	0.99 °C	cook1	Near-bottom	2	Figure 10
S compared with CTD	0.46	cook1	Subsurface	2	Figure 11
	0.12	cook1	Near-bottom	2	Figure 11

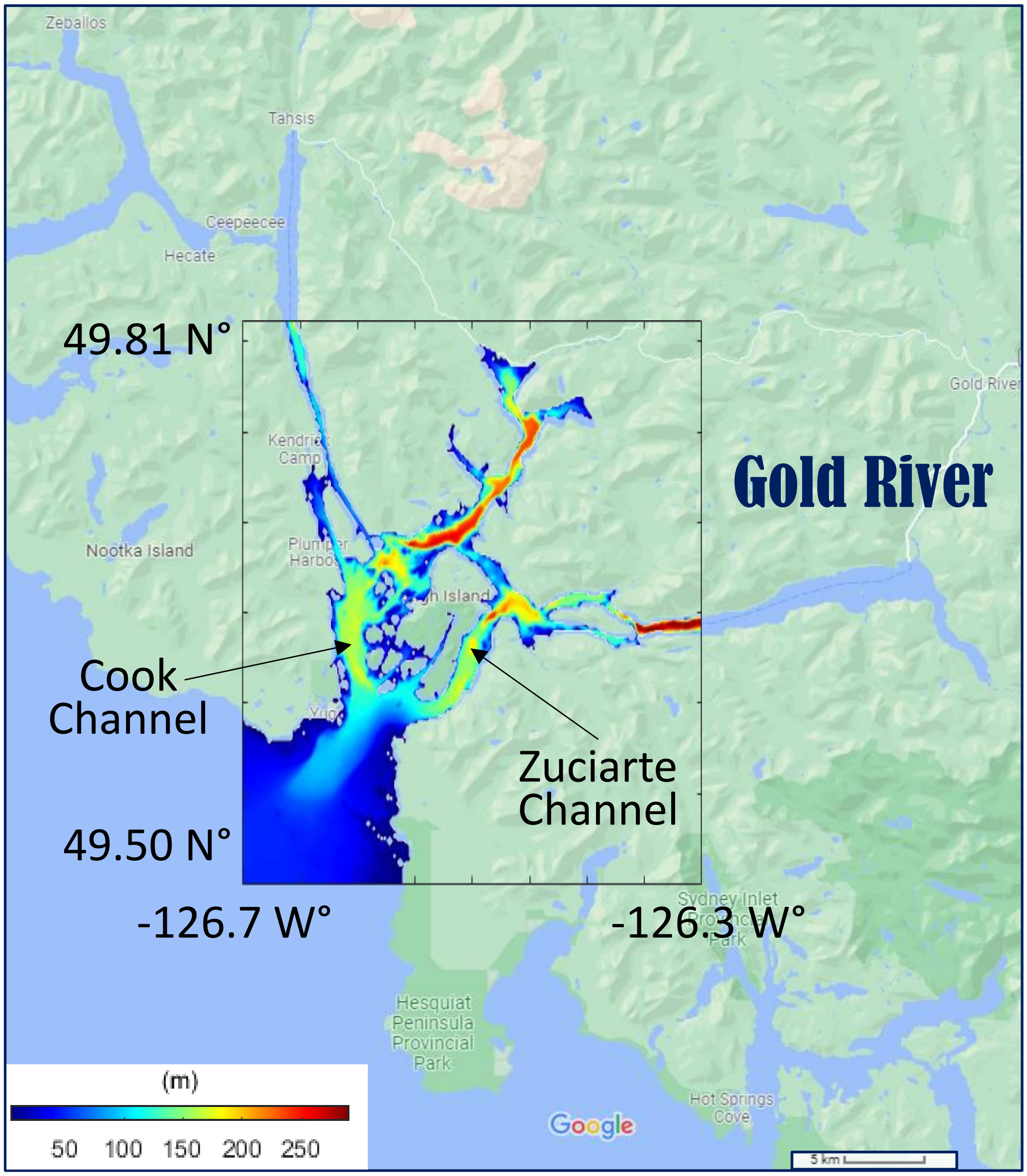

Figure 4. Relocatable model domain and bathymetry in the Bligh Island area of west Vancouver Island.

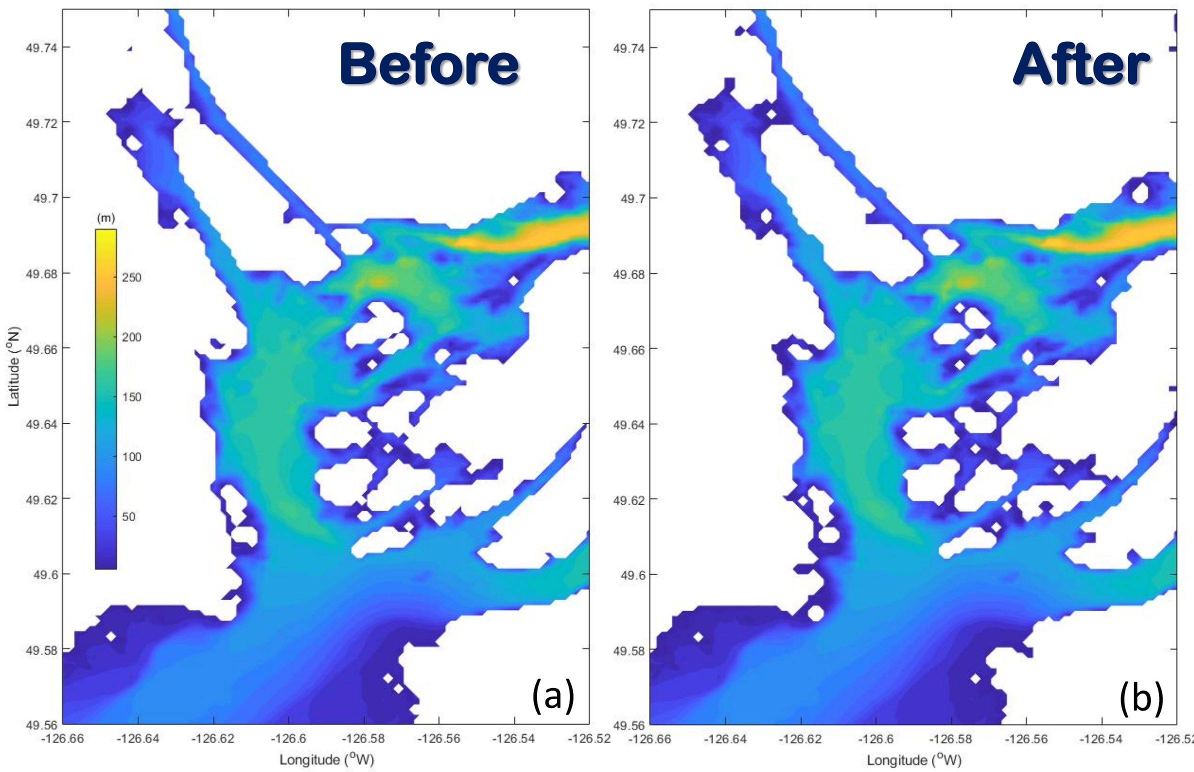

Figure 5. Automated coastline improvement in relocatable model grid over the Cook Channel area based on GSHHG coastlines using Gridtools. (a) pre-processing; (b) post-processing.

Figure 6. Locations of the ADCP data (Cook and Zuciarte channels) and the CTD data (Cook Channel).

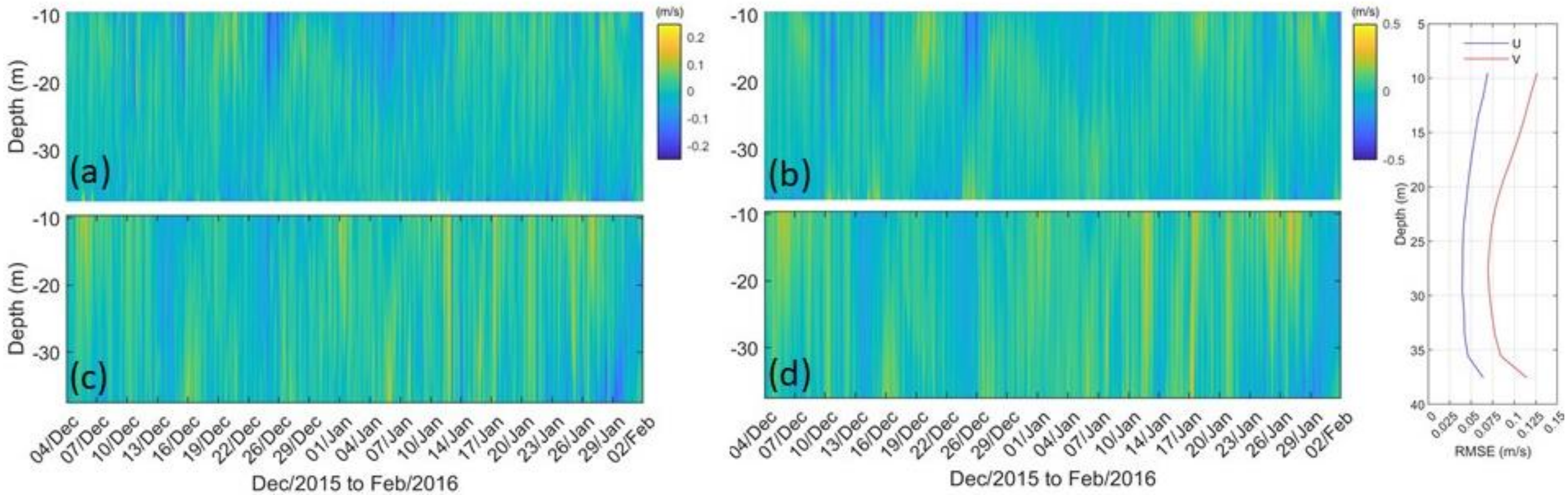

Figure 7. (a) U and (b) V components of ocean currents of subsurface ADCP data in Zuciarte Channel. Relocatable model produced results are shown in (c) U and (d) V components for comparison. Root mean square error (RMSE) of modeled U and V components is plotted in the right panel.

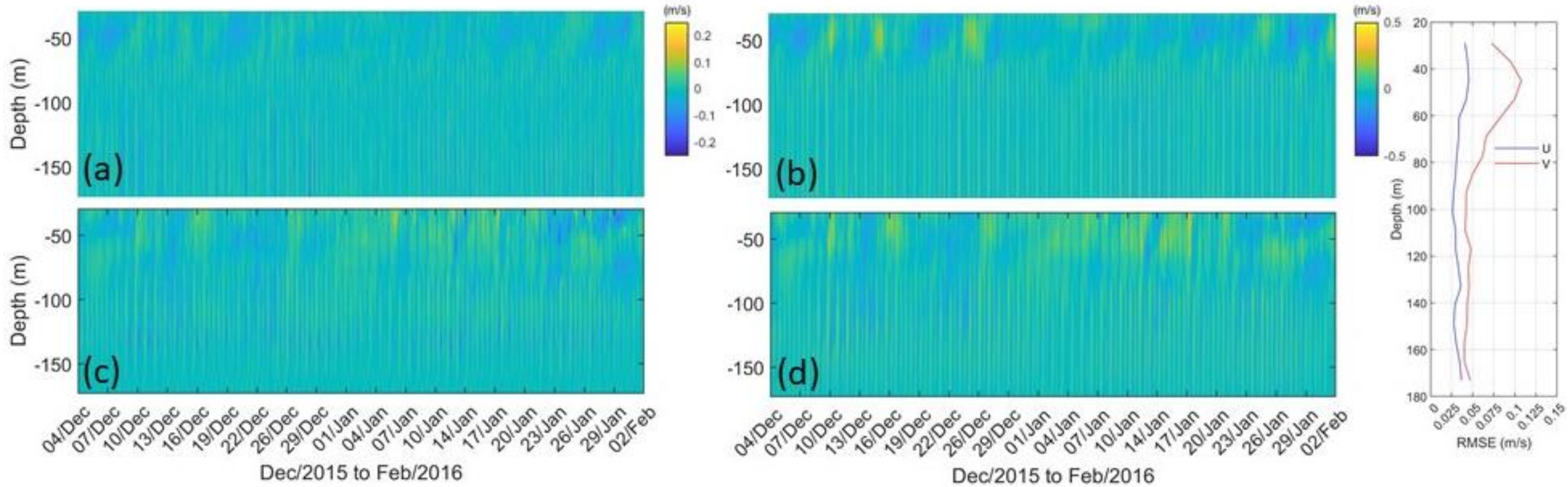

Figure 8. (a) U and (b) V components of ocean currents of near-bottom ADCP data in Zuciarte Channel. Relocatable model produced results are shown in (c) U and (d) V components for comparison. Root mean square error (RMSE) of modeled U and V components is plotted in the right panel.

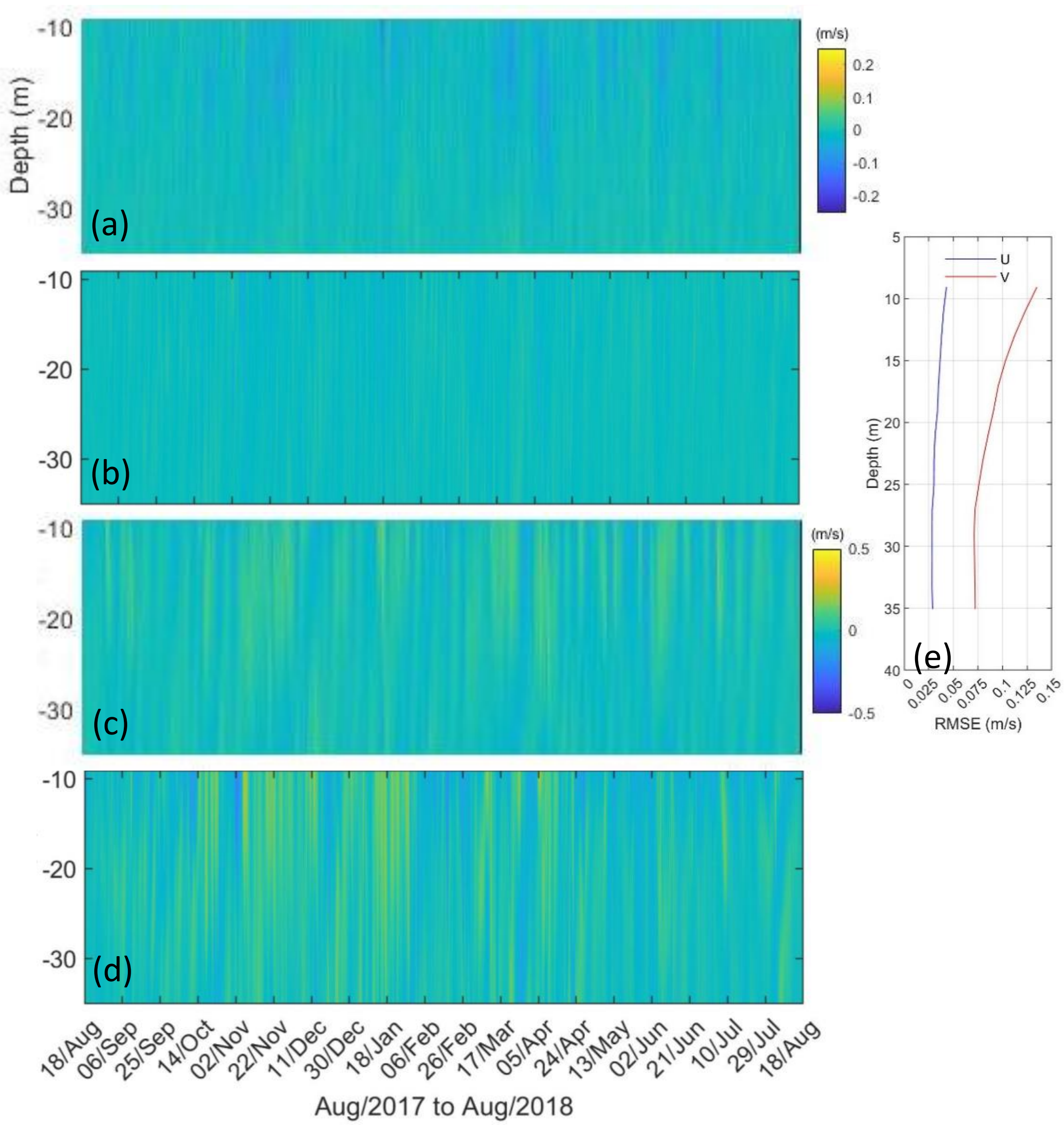

Figure 9. (a) U and (c) V components in ADCP data compared with relocatable model produced (b) U and (d) V components of ocean currents in Cook Channel. Root mean square error (RMSE) of modeled U and V components is plotted in (e).

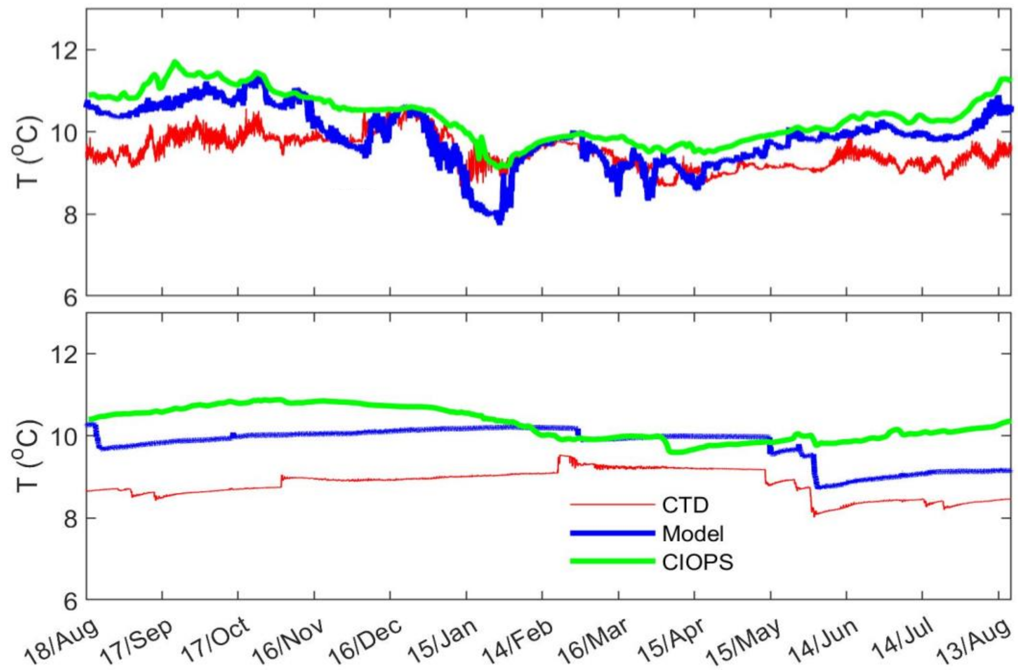

Figure 10. Relocatable model produced water temperature (blue lines) compared with daily CIOPS-W results (green lines) and CTD data (red lines) at subsurface (~40 m, upper panel) and near bottom (~150 m, lower panel) in Cook Channel. RMSE values for the relocatable model are 0.70 °C subsurface and 0.99 °C near bottom.

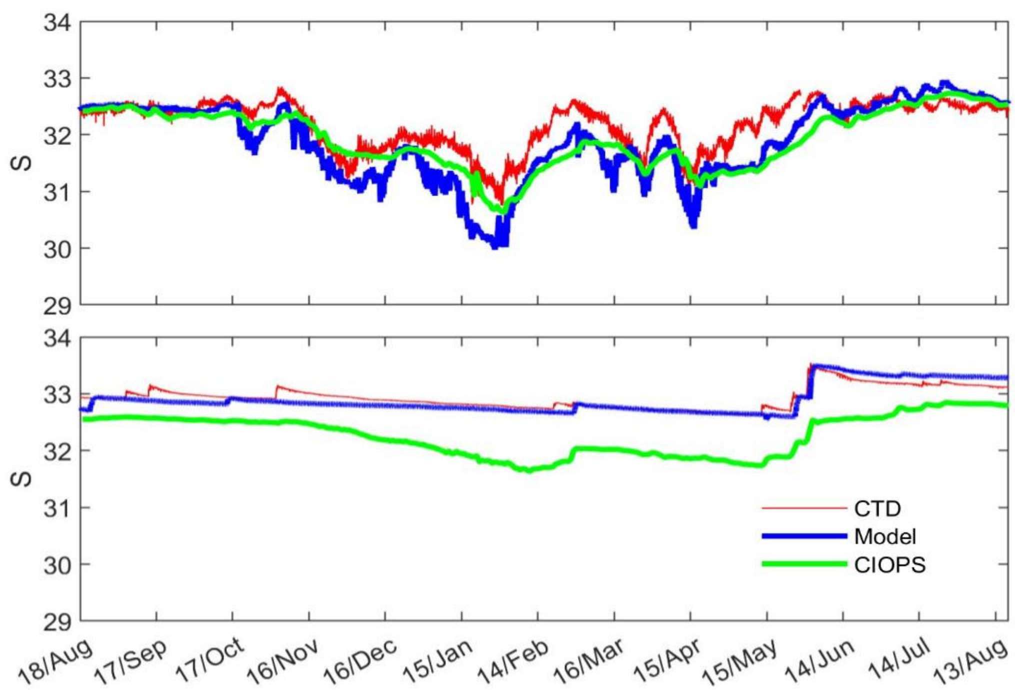

Figure 11. Relocatable model produced water salinity (blue lines) compared with daily CIOPS-W results (green lines) and CTD data (red lines) at subsurface (~40 m, upper panel) and near bottom (~150 m, lower panel) in Cook Channel. RMSE values of the relocatable model are 0.46 at subsurface and 0.12 near bottom.

3.2 Prince Rupert (Nested Grid)

The second case study was carried out for the Prince Rupert area (Figure 12). This site was selected to test

- open boundary schemes (without real-time Skeena River runoffs included in the relocatable model)
- daily 3-D CIOPS-W T/S fields as open boundary conditions for a further inland area
- nested-grid capacity (multi-layer downscaling, e.g., from CIOPS-W to 60 m).

The relocatable model domains are shown as in Figure 12. The Level-1 domain (outer model) has a horizontal resolution in both latitude and longitude of 1/360° (~300 m), while the Level-2 nested domain (inner model) has a horizontal resolution in both latitude and longitude of 2 arc second (~60m).

Maximum water depth in the domain is 389 m (outer model) and 181 m (inner model). Both models have 120 z-levels in the vertical with the higher resolution (1.1 m for the outer model and 1.0 m for the inner model) near the surface and 4.1 m (outer model) and 1.7 m (inner model) resolutions at the bottom. Automated coastline improvement was carried out based on GSHHG coastlines and Gridtools.

There were two model runs carried out to explore the sensitivity to horizontal resolution (Table 4). Relocatable model results during Aug 28-Nov 30, 2018, were saved and examined after the five days for spin-up. Preliminary evaluation of the ocean model performance has been conducted. Hindcast ocean model results have been compared with tidal constituents observed at Prince Rupert (station #9354, see Table 5).

Relocatable model (Level-2) produced ocean currents (Figure 13) were compared with ADCP current meter data collected in the deep trough (~120 m) to the west of Kinahan Islands (Figure 12, Chat1, deployed on 2018/08/23 at 54.201°N and 130.450°W).

As shown in Figure 14 and Figure 15, water temperature and salinity from nested grid (Level-2) model results are compared with CIOPS-W results and CTD data at subsurface (~50 m) and near bottom (~103 m) at the Chat1 site (as marked in Figure 12). One-month (September 2018) averaged sea surface salinity (SSS) and temperature (SST) from Level-1 model results are compared with CIOPS-W results in Figure 16, which demonstrated comparable patterns with small scale variations. The RMSE scores for relocatable model runs in the Prince Rupert area are summarized in Table 6.

Overall, the high resolution 3-D relocatable model demonstrated the capability for simulating the tidal-dominant flow variations and vertical structure (e.g., the shear in the tidal currents is well simulated as shown in Figure 13) with a reasonable accuracy. Relevant discussion is provided in Section 4.

Table 4. Relocatable model runs for Prince Rupert.

Relocatable Model Runs	**Simulation Period**	**Boundary SSH**	**Boundary TS**	**Nested Grid**	**H-Res.**
1	2018 Aug 23-2018 Nov 30	hourly	daily	Level 1	300m
2	2018 Aug 23-2018 Nov 30	hourly	daily	Level 2	60m

Table 5. Tidal constituent comparison between relocatable model results and observational tidal gauge data (Prince Rupert).

Tidal Constituent	Amplitude (m)			Phase (°)			Difference in Complex Plane	
	OBS	MOD	DIFF	OBS	MOD	DIFF	(m)	(%)
M2	1.95	1.99	0.04	267.21	271.89	4.68	0.17	8.55
S2	0.64	0.73	0.09	298.81	301.60	2.79	0.10	14.90
K1	0.51	0.43	-0.08	259.69	252.11	-7.58	0.10	19.52
O1	0.39	0.40	0.01	243.10	250.17	7.06	0.05	12.51
N2	0.31	0.30	-0.01	243.72	243.71	-0.01	0.01	1.89

Table 6. Summary of the RMSE scores for the nested grid (Level-2) model run (Aug 23-Nov 30, 2018) in the Prince Rupert area.

Items	**RMSE**	**Sites**	**Depths**	**Relocatable Model Runs**	**Figures**
U compared with ADCP	5.2 - 7.8 cm/s	Chat1	Surface to Subsurface	2	Figure 13
V compared with ADCP	3.8 - 8.4 cm/s	Chat1	Surface to Subsurface	2	Figure 13
T compared with CTD	0.36 °C	Chat1	Subsurface	2	Figure 14
	0.64 °C	Chat1	Near-bottom	2	Figure 14
S compared with CTD	0.10	Chat1	Subsurface	2	Figure 15
	0.11	Chat1	Near-bottom	2	Figure 15

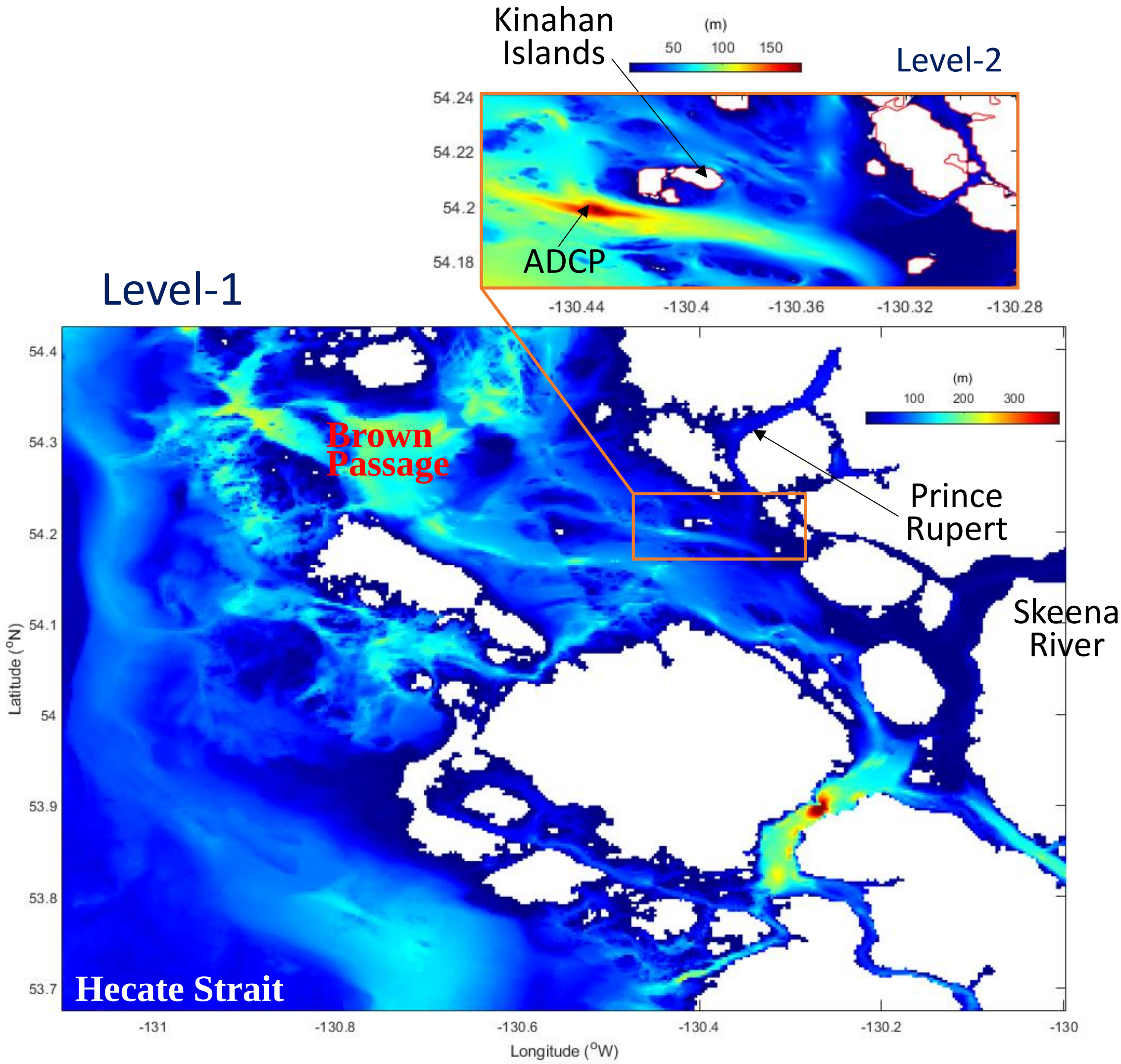

Figure 12. Relocatable model domain and bathymetry (nested grid: Level-1 and Level-2) of the case study for Prince Rupert, BC. Chat1 ADCP site has been marked on the Level-2 domain subplot.

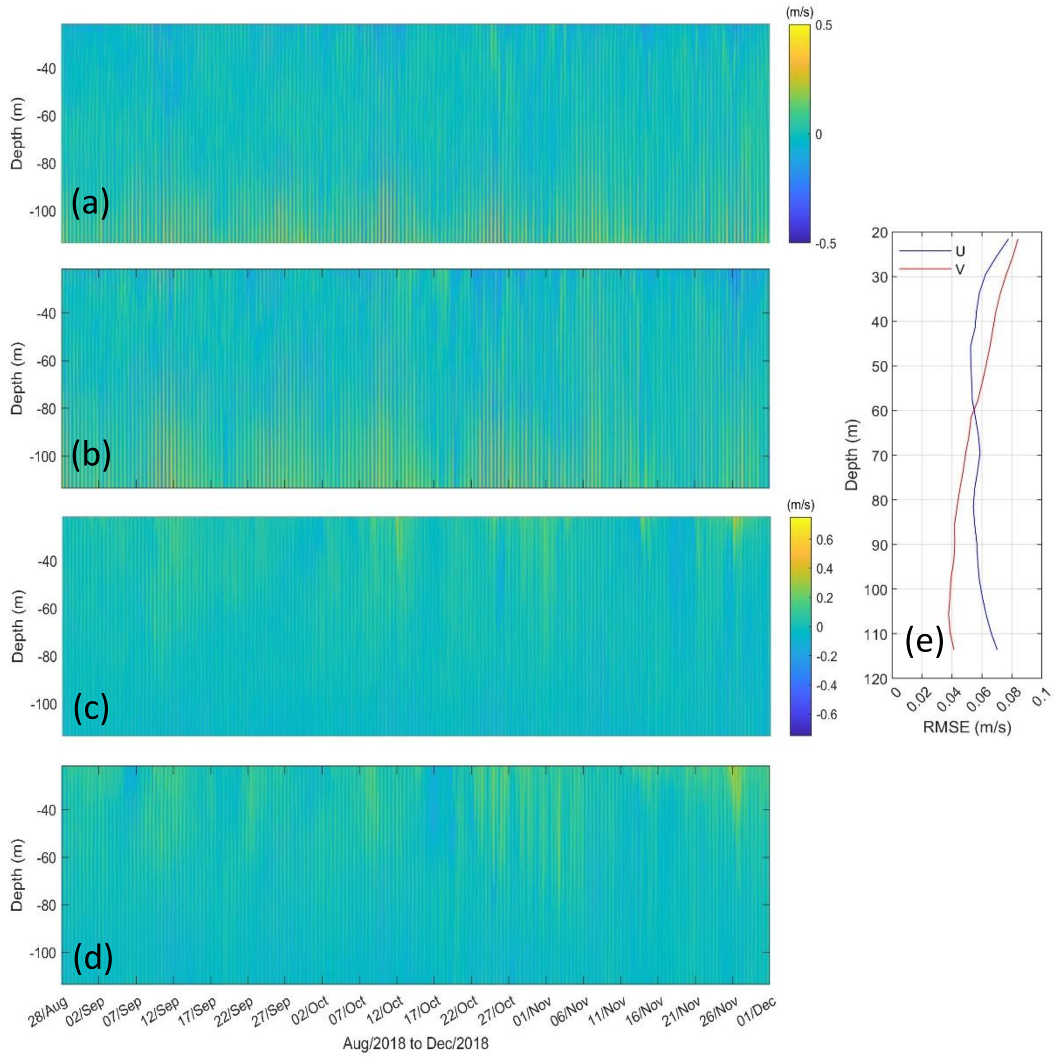

Figure 13. (a) U and (c) V components in ADCP data compared with relocatable model produced (b) U and (d) V components of ocean currents at the Chat1 site (as marked in Figure 12). Root mean square error (RMSE) of modeled U and V components is plotted in (e).

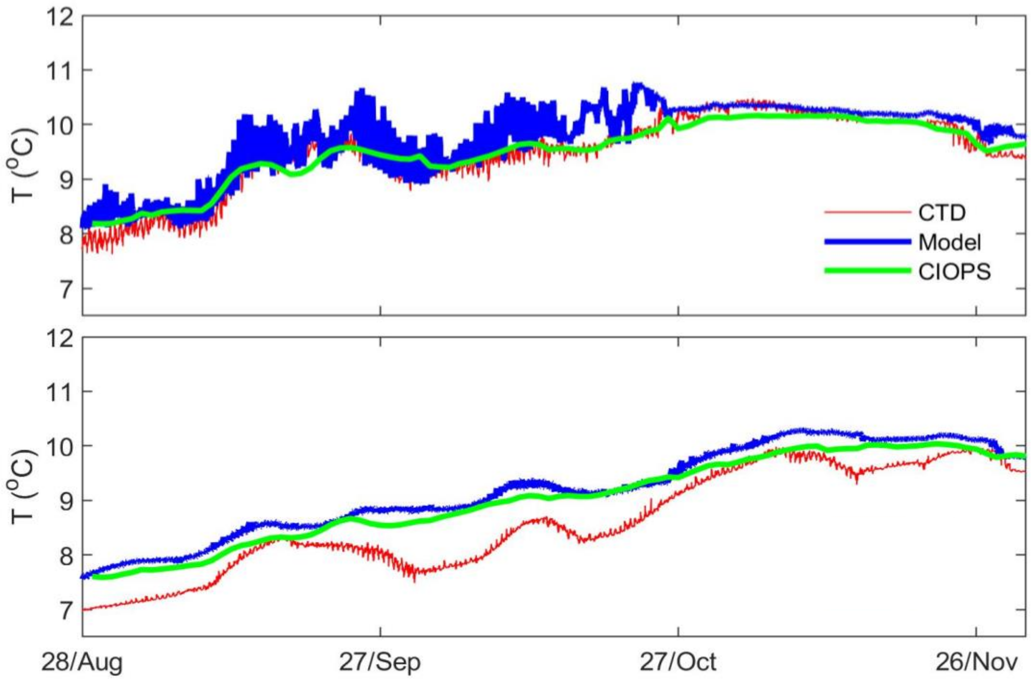

Figure 14. Nested grid model (Level-2) produced water temperature (blue lines) compared with CIOPS-W results (green lines) and CTD data (red lines) at subsurface (~50 m, upper panel) and near bottom (~103 m, lower panel) at the Chat1 site (as marked in Figure 12). RMSE values for the relocatable model are 0.36 °C subsurface and 0.64 °C near bottom.

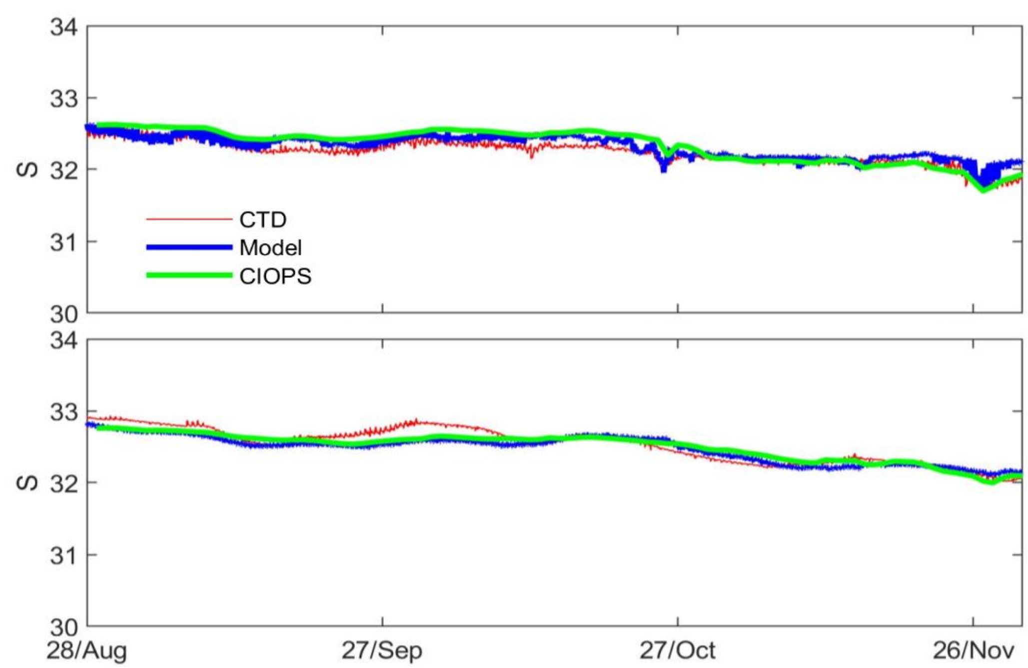

Figure 15. Nested grid model (Level-2) produced water salinity (blue lines) compared with CIOPS-W results (green lines) and CTD data (red lines) at subsurface (~50 m, upper panel) and near bottom (~103 m, lower panel) at the Chat1 site (as marked in Figure 12). RMSE values for the relocatable model are 0.10 subsurface and 0.11 near bottom.

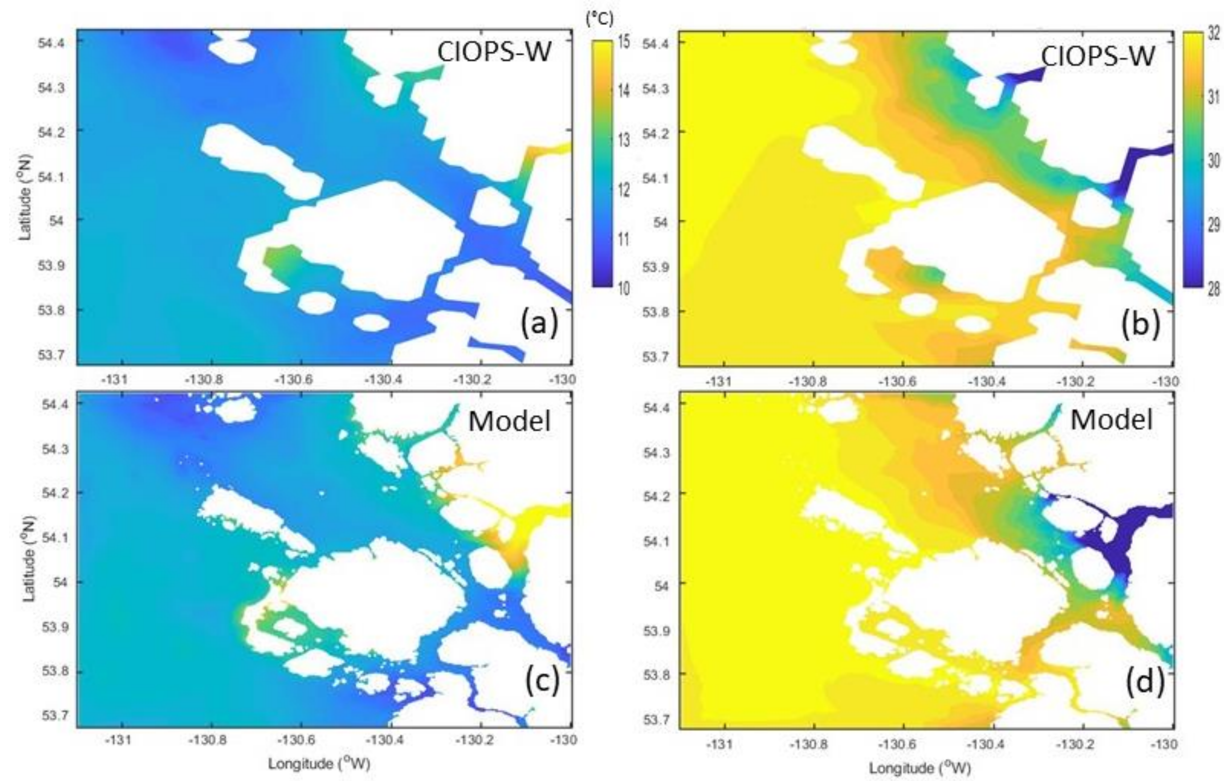

Figure 16. Comparison between the SSS (monthly average of September 2018) fields produced by (a) CIOPS-W and (c) the relocatable model (Level-1). Comparison between the SST (monthly average of September 2018) fields produced by (b) CIOPS-W and (d) the relocatable model (Level-1).

4 DISCUSSION

In this report, we described an experimental relocatable ocean model system developed under OPP FA5 modeling for the west coast of Canada. Initial and boundary conditions are provided by the operational Coastal Ice Ocean Prediction System for the West coast with 1/36° horizontal resolution (~2.0 to 2.5 km). At the surface, the operational High-Resolution Deterministic Prediction System provides surface winds, pressure and inputs for calculating heat fluxes with 2.5 km spatial resolution.

The preliminary development has been tested with two case studies for Bligh Island, and Prince Rupert, BC. Hindcast ocean model results were compared with tidal gauge, ADCP, and CTD data. Difference in quality of solution at Bligh Island and Prince Rupert is found. It indicates that the vertical structure of the currents (e.g., the shear in the tidal currents) was better simulated in Prince Rupert than Bligh Island. It would be related to the relatively better T,S simulation in Prince Rupert was obtained than in Bligh Island. With 120 layers in the vertical, the relocatable model captures the flow structure better in Prince Rupert (compared with 50 layers at Bligh Island). A nested grid with higher horizontal resolution (~60m) in the Prince Rupert area should solve small scale dynamics better than the Bligh Island model grid (with a resolution of ~150 m). It requires further investigations including using more moored T, S, and current meter data that available in the Chatham Sound area.

The tests indicate that this relocatable modeling system can be configured in a time scale of hours with minimal human intervention before a model run submission. It can perform reasonable model simulations and predictions. However, the challenges exist in model domain/ resolution selection and optimization, which may require a couple of iterations before finding an adequate configuration. Local oceanography understanding is essential to minimize the model set up time and potential iterations. For example, a fine vertical resolution (near bottom) is needed to solve the baroclinic tidal currents in the Prince Rupert study case. Brown Passage (Figure 12) in central western Chatham Sound is an important channel for water exchange with the larger water bodies to the west, and the open boundary of the relocatable model should not be placed in this area.

Referential port models developed under OPP FA1&2 (e.g., Kitimat models with a similar horizontal resolution) were able to provide parameters/configuration automatically and effectively. High resolution (horizontal and vertical) is found to be important for coastal ocean modeling. For example, significant improvement on the deep water T and S was found in the Bligh Island study case as shown in Figure 10 and Figure 11, and the Prince Rupert study case as shown in Figure 14.

The parent model used in this study is the operational CIOPS-W model, providing initial condition and open boundary conditions (hourly SSH and 2D currents, daily vertical profiles of currents, and T/S). Open boundary conditions incorporate the hourly 2D depth averaged currents and combined with daily-averaged 3D currents from CIOPS-W results.

The major improvement by the high resolution (horizontal and vertical) relocatable model is more realistic T/S profiles near bottom (Figure 10, Figure 11, and Figure 14) compared with the CTD data. On the surface, the coarse resolution surface atmospheric forcing (e.g., heat flux based on 2.5 km resolution HRDPS data) could be improved in the future.

Open boundary conditions of 3D T and S are obtained from daily averaged values. There is no systematic bias found at CTD sites for using daily T and S profiles at open boundaries. Due to the daily averaging, tidal variations of 3D currents, T/S, and the daily cycle of water temperature in the near surface layer are not included in the open boundary files. However, the test runs demonstrated that the relocatable model was able to reasonably reproduce the observed T and S inside the model domain (e.g., Figure 10 and Figure 11). The study area should be set far from the open boundaries, to decrease the effect of using daily averaged fields. If the required horizontal resolution for the relocatable model is very high (i.e., resolution ratio between the relocatable and parent models is too large), adding intermediate nesting level(s) is necessary. With one-way nesting, model results from the bridging nesting level(s) will provide hourly open boundary condition files including T and S for the inland study areas. Thus intermediate nesting level(s) can help the modeling not only for spatial resolution but also for the temporal resolution of open boundary conditions.

A spin-up period is necessary to eliminate dynamic inconsistency in the initial condition files due to the interpolation. Using the parent model currents (U, V) and SSH as the starting point can help speed up this adjustment in the relocatable model. The duration of the model spin up depends on multiple factors such as the domain size, maximum water depths, dominant dynamics, and stratification. As a relocatable coastal model will be used to assist emergency responses, the model grid size should be small for efficiency consideration. The maximum water depth is normally less than 200 m (within continental shelf) except in deep fjords. For applications such as oil spills, the spin up time is determined by the state when the model reasonably simulates surface currents. The total kinetic energy may not be a good indicator if there is no need for the deep motions to be fully spun up. A couple of tidal cycles could have mixed away any dynamic inconsistency in initial fields that were interpolated/extrapolated from coarse parent models. However, impacts of river runoff may not be well resolved inside the domain of the relocatable model. Spin up time for the relocatable modeling will have to be extended for river runoff effect to reach oceanic waters. Currently, the spin up period is set up for 5 days, which has been tested with the case studies for Bligh Island and Prince Rupert areas based on T, S and current velocity profiles at inner sites. The spin up duration will be re-examined and potential metrics (e.g., surface kinetic energy) will be tested and selected in the future when examining the model solution where the influence of river forcing is important.

Cutting off river channels (e.g., Gold River in the Bligh Island case, and Skeena River in the Prince Rupert area) was also tested. It worked well for downstream river areas by using the Flather radiation open boundary scheme incorporated in the NEMO model. However, it is required that parent models (e.g., CIOPS-W) should have the river incorporated and there are sufficient grids crossing the river channel. That means that this configuration may not work well for small rivers (if not included in the parent model), and open boundaries of the relocatable model domain should avoid the narrow part of the river. On the other hand, the Flow Relaxation Scheme (FRS) could be considered for open boundaries where the narrow channels were not resolved by the coarse resolution parent model (i.e., velocities and sea surface heights are zeros). It requires further investigation if flow through the narrow channel is not zero, e.g., a river channel if not included in the parent model. A river database needs to be developed and then incorporated for the relocatable system. Associated tools will be developed in the future.

5 FUTURE WORK

The research and development summarized in this report are ongoing, and presently focusing on the west coast of Canada. Long-term efforts on development are expected before such system can be deployed in case of emergency in any Canadian waters. Cross-department collaborations are required for data inputs (bathymetry, rivers, atmospheric forcing, etc.) and the Fixed Domain On-Demand near-shore drift prediction system (FDOD) operations (e.g., with a heat map of risk).

It is also notable there are limitations to be understood and caution is required for the current version, which is only for demonstration and planning purposes as the research program under the OPP. For example, the relocatable ocean model won't handle the case if the study area spans multiple parent/atmospheric model domains. If the study area is too close to the edge of the parent/atmospheric model domain (e.g., CIOPS-W), a larger (but coarser) parent/atmospheric model would be used (e.g., RIOPS). The current version is also constrained by the availability of the DEM extent as shown in Figure 2. Also, until a river database is developed and incorporated, the current version will have problems in areas near the coast (or long inlets) where the freshwater inputs can be dominated by runoff from numerous small rivers and streams rather than a few big rivers. Details of the limitations would be identified and solved/mitigated where possible, with further development in the future work.

One of the high priority action items would be to improve the tidal comparison as shown in Table 5. Tidal databases such as:

(1) WebTide, https://www.bio.gc.ca/science/research-recherche/ocean/webtide/index-en.php
(2) FES2014, https://www.aviso.altimetry.fr/es/data/products/auxiliary-products/global-tide-fes.html
(3) OSU, http://g.hyyb.org/archive/Tide/TPXO/TPXO_WEB/global.html

would be used for improved tidal elevations at open boundaries. Accordingly, total open boundary elevations will be automatically generated as a combination of detided sea surface heights from parent model results and reimposed tides (amplitude and phase) from the tidal database.

Improvement plan and further areas of development may include the following:

(1) Developing Version 1 of the relocatable ocean modeling system
(2) Automating the detiding & reimposing tides from a tidal database
(3) Using higher resolution HRDPS atmospheric model data where available (e.g., 1 km HRDPS)
(4) Upgrading to NEMO v4.2; Future work could also involve auto-configuring the Adaptive Grid Refinement In Fortran (AGRIF) package for multi-level nesting in NEMO
(5) Incorporating a river database and developing the tools for both climatological runoff inputs and gauged rivers
(6) Incorporating bathymetry covering all Canadian waters
(7) Adding other components (e.g., sea-ice)
(8) Graphical User Interface (GUI) and system integration

The automated system with minimal human intervention needs to be tested and evaluated for historical marine emergency events. The system should be able to provide prompt near-shore predictions up to 48 hours (constrained by parent ocean forecast systems). The model and tools also need to be updated and maintained to be consistent with operational parent models and port models.

In addition to the modeling, improving our understanding of regional and local oceanography is fundamental to minimize iterations in the relocatable modeling. Pre-set domains (based on a heat map of risk) could significantly decrease the emergency response time in the future.

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