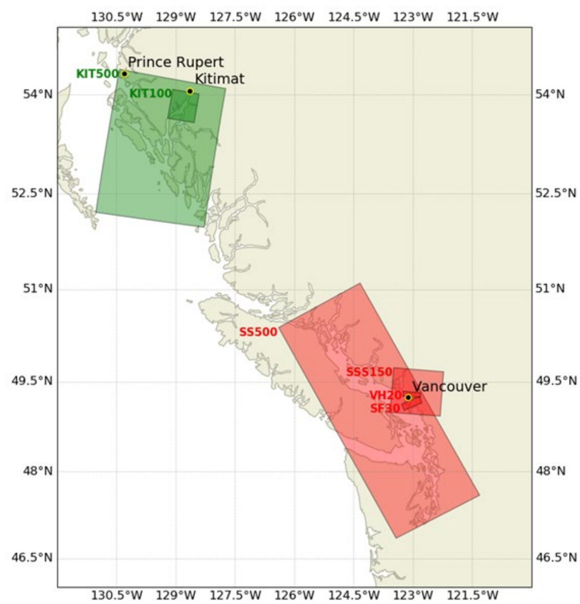
APPLICATION OF HIGH-RESOLUTION HYDRODYNAMIC PREDICTION SYSTEMS TO FORECAST OCEAN CONDITIONS IN CANADIAN PORTS AND APPROACHES



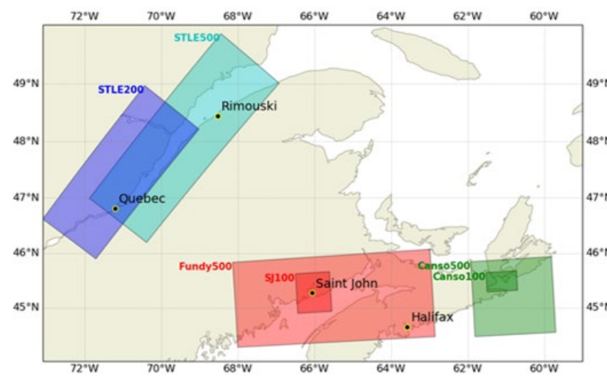


Figure 1. Nested domains of the Port Ocean Prediction Systems on the West and East coasts of Canada.

CONTEXT

The “improving drift prediction and near-shore modelling” sub-initiative of the Oceans Protection Plan (OPP) aims to enhance Government of Canada ocean modelling activities. Under this sub-initiative the Oceans Science Program (OSP) developed six high-resolution Port Ocean Prediction Systems (POPS) intended for forecasting currents, water levels and water properties for specified ports and approaches on Canada’s West and East coasts: Kitimat fjord (B.C.), Port of Vancouver including both Vancouver Harbour and lower Fraser River (B.C.), Strait of Canso Port (N.S.), Port of Saint John (N.B.) and St. Lawrence River (Qc) from the lower St. Lawrence Estuary at Pointe-des-Monts to Trois-Rivières upstream, including also the Saguenay Fjord.

Each POPS includes a domain-specific hydrodynamic ocean model and the related system used to run the model in forecasting mode and to connect and sequence automated data inputs and dependencies. POPS outputs are designed to support delivery of operational services: Canadian Hydrographic Service (CHS) dynamic e-navigation and Environment and Climate Change Canada (ECCC) emergency response to environmental and maritime disasters (e.g., oil spills).

For CHS and ECCC to consider use of the POPS and their outputs, OSP has asked for peer -reviewed advice on scientific validity, stability and robustness within environmental conditions encountered during the period of testing, and fitness for purpose of the POPS for the proposed client applications.

This Science Advisory Report is from the national peer review held on March 14-16 and 21-23, 2023, on the Application of High-Resolution Hydrodynamic Prediction Systems for Forecasting of Ocean Conditions in Canadian Ports and Approaches. Additional publications from this meeting will be posted on the Fisheries and Oceans Canada (DFO) Science Advisory Schedule as they become available.

SUMMARY

- Port-scale Ocean Prediction Systems (POPS) were developed for six high priority ports across Canada (Vancouver Harbour, Fraser River, Kitimat, Saint John Harbour, the St. Lawrence Estuary, and Strait of Canso) for use in support of dynamic electronic navigation and marine emergency response.
- The POPS configurations are based on a common base technical configuration. The design/configuration of each POPS was reviewed and generally considered appropriate for the intended purpose, within limitations noted below.
- Ability of the six POPS in reproducing real-world conditions was assessed against available observational data. The POPS generally show skill in predicting water levels, currents, and water properties at a scale that do not currently exist in available operational models. The models provided coverage for some areas not covered by the current version of the Coastal Ice-Ocean Prediction Systems (CIOPS), and generally matched or outperformed CIOPS in most comparisons against observations considered for areas of overlap between the models.
- Tidal and total water levels comparative statistics are both generally improved relative to CIOPS at water level gauge stations, and performance outside areas of CIOPS coverage is similar to that where comparison with the parent model is possible. Non-tidal water level performance is comparable to that of CIOPS.
- Storm surge was assessed using limited time periods spanning significant storm events in each POPS domain, and surge signals are clearly visible in both CIOPS and POPS. Storm surge comparative statistics in POPS generally match or improve upon those in CIOPS.
- Comparative statistics for currents are generally improved with increasing resolution of the models, particularly where flow around complex topography is present and more accurately resolved. In general, tidal currents are improved more significantly in the POPS than non-tidal currents.
- The seasonal cycle of sea-surface temperature is well captured by the high-resolution models (POPS) with small biases matching or outperforming the larger scale models. Ferry track data generally shows equal or better performance in POPS relative to CIOPS. Regional biases in temperature and salinity are generally reduced, and the POPS skillfully reproduce changes in these water properties, with minor exceptions.
- Currents provided by the POPS yield slightly improved, or equivalent, predictions of drifter trajectories. The accuracy of trajectory predictions may be limited by the accuracy of available wind forecasts and/or limitations in the trajectory model itself.

- The POPS model simulations were stable for 5-6 year hindcast periods, which included extreme events in several domains. Fallback mechanisms for missing observational input data are used where relevant.
- Forecast evaluation focused on measuring the degradation of model skill as a function of forecast lead time. Model skill was not found to degrade substantially over the 48-hour forecasts, as error growth trends for water level and sea surface temperature were typically small.
- It is recognized that the POPS have certain limitations:
  - Model accuracy is impacted by limits of the model inputs.
  - Quantitative assessments of skill are limited to regions of the POPS domains where observations are available. Observational data are focused on the inner (port) domain and are typically sparser in the coarser outer domain. Current data are also more limited than water property and water height data.
  - The ocean model version used in all POPS does not correctly represent intertidal areas, and consequently the model results are not considered usable in intertidal areas.
  - Biases in temperature and salinity observed in specific locations could lead to errors in surface currents that could not be assessed with available data.
  - The POPS are not coupled to a complete ice model, which could impact surface currents and potentially other variables for regions that experience ice cover.
  - Port systems include region-specific features that are under-resolved and/or not reproduced in the models and may include portions of the domain that are not reliable.

BACKGROUND

Over the past decade, major efforts have been made by the Government of Canada, including under the Canadian Operational Network of Coupled Environmental Prediction Systems (CONCEPTS) interdepartmental collaboration, to develop ocean-sea-ice systems based on NEMO models (Nucleus of European Modelling of the Ocean) for operational ocean and sea ice forecasting from global to regional scales. Two Coastal Ice-Ocean Prediction Systems for the East and West coasts of Canada (respectively CIOPS-E and CIOPS-W) have been developed and implemented in operation for short-term forecasts (48-h) at the Canadian Center for Meteorological and Environmental Prediction (CCMEP) of ECCC since December 1st, 2021. Those coastal systems are linked using a one-way nesting approach to the operational largest scale Regional Ice-Ocean Prediction System (RIOPS), forming the backbone for downscaling to nearshore areas.

Under the “improving drift prediction and near-shore modelling” sub-initiative of the Oceans Protection Plan (OPP), high-resolution Port Ocean Prediction Systems (POPS) have been developed for forecasting water levels, currents, and water properties in six ports and approaches on Canada’s West and East coasts: Kitimat fjord, Vancouver Harbour, lower Fraser River, Port of Saint John, Strait of Canso Port, and St. Lawrence River estuary, with the intention of supporting dynamic e-navigation and marine emergency response. The POPS are driven by and build upon existing operational models, using the following technical configuration:

- Each POPS uses the CONCEPTS NEMO codebase (a customized version of NEMO 3.6 that is used in operations at ECCC and thus chosen to ease collaboration between DFO and ECCC) as hydrodynamic model driver running on structured horizontal grids with horizontal resolution from 500 m at its coarsest to 20 m at its finest, depending on the port (Figure 1).

POPS are configured with two levels of offline one-way nesting to downscale from the parent model. The outermost grids are driven using open boundary conditions derived from the operational ECCC CIOPS-E/W systems (version 2), with CIOPS-W already including a 500m sub-domain for the Salish Sea (SS500; Figure 1). The models are run without data assimilation or nudging employed.

- Freshwater river inputs are included by using real-time river gauge data where available, or climatology otherwise. Fallback mechanisms for all real-time gauge data were implemented to mitigate the scenario of missing or bad gauge data such that the POPS continue to run in a gracefully degraded mode in those scenarios.
- Atmospheric forcing is provided by ECCC's High Resolution Deterministic Prediction System (HRDPS) which has 2.5 km horizontal resolution.
- For the POPS of the St Lawrence River, sea ice is handled within NEMO using a simple parameterization (when local freezing point is hit, temperature and heat flux are clamped) rather than through a dynamic ice model.
- The six POPS run at DFO in a standardized and automated environment framework (suite governed by the Maestro sequencer developed at ECCC's CCMEP) to produce one day of pseudo-analysis and four 48-h forecasts (real-time mode) on a regular daily basis. The automation suite is also used to run the POPS in hindcast mode, after adjustment mainly in the handling of different sources of forcing data. This consistent unified approach to build and run all the POPS is similar to that used in operations at ECCC's CCMEP and is key to facilitate technological transfer and portability of the prediction systems to operations, and ultimately their maintenance.

ASSESSMENT

Evaluation methodology

Model performance for each POPS was assessed through the analysis of a 5 to 6-year hindcast (2016/17-2021) and a set of 48-h forecasts during a two-month period (winter 2021-2022). All systems were stable during the long hindcast period, which samples some extreme events. The POPS hindcasts were compared against a variety of observations in a systemic fashion using an in-house analysis package. Results (comparative statistics against observations) were also systematically compared with the results obtained with the parent models CIOPS-E/W in areas of overlap between the models. Not all types or sources of observations were available for all ports, but evaluation was done with the widest-feasible range of observations for each port to ensure that the assessment is as complete as possible. Sources of observations include, but are not limited to:

- Water level from water level gauges and constituent stations
- Sea surface temperature (SST) from moored weather buoys
- Temperature and salinity from vertical CTD profiles (Conductivity-Temperature-Depth probe), moored CTDs (MCTD) and ferry thermosalinographs
- Currents from Acoustic Doppler Current Profiler (moored, floating, towed, and horizontally mounted ADCPs) and current meters
- A variety of types of drifters

Model data was extracted to match the temporal and spatial extent of the observations, and any further manipulation (e.g., tidal analysis) was done consistently on both model results and observations. Comparative statistics were calculated per-observation and, when useful, aggregated to provide a succinct assessment of model skill. Those include basic statistics like bias and errors (Centered Root Mean Square Errors, CRMSE), as well as more specialized quantities. Evaluation was largely done in yearly intervals, with results reported for all years of the hindcasts where observations are available. Storm surge was evaluated by selecting a set of the largest storms that passed near or through the POPS domain and evaluating non-tidal water level over these short intervals. Drift evaluations used the outputs of Lagrangian particle tracking simulations that included windage and wave parameters, but that were not derived for coastal settings.

Based on the two months of forecasts run for each POPS, sets of 48-h forecasts starting at a nominal time of 0:00 UTC were analyzed as a function of lead time (i.e., time elapsed since the start of the 48-h forecast period). Forecast performance was evaluated as the discrepancy (bias and CRMSE) between the model values and the observed values available (tide gauge, sea surface temperature, and horizontal ADCP records) as a function of forecast lead time. The error growth curves represent the discrepancy averaged over the set of evaluated forecasts.

POPS were also run in best-effort demonstration mode for one year to validate the reliability of the automation system and associated logistics for an operational use.

Port-specific results

The Summary section above provides a general assessment across all six POPS. Additional results specific to each port are outlined in the sections below.

Saint John Harbour

The oceanography of the Bay of Fundy and the port of Saint John is dominated by large diurnal tides and key observations used to evaluate the systems are found in Figure 2. The Saint John River is explicitly included in both ocean model domains (Fundy500 for the Bay of Fundy 500 m grid and SJ100 for the Port of Saint John 100 m grid). This leads to significantly improved results for near-surface currents in the Saint John harbour area relative to CIOPS-E, which uses a climatological runoff to account for the Saint John River. The improvement in currents in SJ100 relative to CIOPS-E is most stark for the non-tidal circulation, though the tidal and total are also consistently improved. Water temperature has a slightly warm bias, which in some regions is slightly larger than the bias in CIOPS-E. However, salinity biases are consistently reduced in both Fundy500 and SJ100.

The port model system of Fundy500 and SJ100 is an improvement over the existing CIOPS-E system with better representation of water levels, near surface currents, and the variability of the river plume. SJ100 is the most skillful of the three domains at reproducing water levels, currents, and water properties, and has the most accurate representation of the Saint John River plume of the three domains considered. Since the NEMO 3.6 codebase does not include wetting/drying physics, the extensive intertidal flats in the upper Bay of Fundy are not well represented in Fundy500, and care should be taken when considering applications near these areas. The river system is included in both Fundy500 and SJ100 primarily to facilitate proper river outflow, however, the details of the circulation in the river are not well validated due to lack of data and the imposed minimum water depth.

Strait of Canso

The bathymetry and the limits of the ocean model domains for the 500 m grid (STC500) and the 100 m grid (STC100) of the Strait of Canso POPS are shown on Figure 3. STC100 has 10-20% lower water level error (CRMSE) than STC500 or CIOPS-E for both tidal and non-tidal water levels. There were no POPS improvements over CIOPS-E performance for storm surge water level. Comparative statistics for currents are improved with increasing model resolution at inshore sites, particularly where topographic steering is present. The POPS showed no improvement over CIOPS-E for currents on the open shelf. STC500 did not show statistically significant improvement over CIOPS-E performance for drift trajectories. Drift was not evaluated for the finest 100 m grid since no drifters were available in the STC100 domain. The Strait of Canso POPS improves salinity representation at depth, where topography is likely relevant. POPS did not improve over CIOPS-E for surface salinity, or for temperature. Deep water intrusion/renewal over the sill of the Strait of Canso is reasonably represented in the highest resolution model, while this feature was not resolved by CIOPS-E. For some storms in the Strait of Canso, an unresolved seiche at all model resolutions contributes to the water level error.

St. Lawrence Estuary

The bathymetry and the limits of the ocean model domains for the 500 m grid (STLE500) and the 200 m grid (STLE200) of the St Lawrence Estuary POPS, and key observations used to validate the systems are shown on Figure 4. With respect to the evaluation of water levels and storm surge, all comparative statistics are generally improved with increased model resolution (from CIOPS-E to STLE500 to STLE200). This improvement is more important in the Quebec region for STLE200 since the western border is pushed back by approximately 130 km, which improves the tides and mean sea level in this region. Surface currents near Québec are also improved with increased resolution. The inclusion of the Saguenay Fjord in STLE200 also seems to improve the surface currents at the head of the Laurentian Channel. Water masses are significantly improved for the POPS compared to CIOPS-E in the Middle Estuary: near surface salinity bias in the Middle Estuary is of the order of –12 PSU for the parent model, compared to less than 1 PSU for the POPS. Drift trajectories are significantly improved in the upper part of the Middle Estuary for the POPS compared to CIOPS-E. No bottom friction tuning was done in the Saguenay Fjord, unlike the rest of the 200 m domain. As a result, tidal error is higher in this region than in surrounding areas. Finally, no complete ice model is coupled to the NEMO model. The impact of this gap on surface currents is possibly more important for the Fluvial Estuary and the Saguenay Fjord from January until March, the ice being mainly mobile for the rest of the area.

Fraser River

The Fraser River POPS (Figure 5) resolves the South Arm of the lower Fraser River up to the Port Mann bridge at considerably higher resolution than the parent model. It also resolves the river up to Mission and to Pitt Lake, covering area not resolved in the parent model. Total water level error (CRMSE) in the POPS is somewhat smaller than in the parent model near the mouth of the Fraser. The improvements in the POPS relative to the parent model are more stark as one progresses up the river due to an improved representation of the freshet water level in the POPS. Current velocity in the river is well captured at one horizontal ADCP location within the South Fraser 30 m domain (SF30). Temperature and salinity performance is generally comparable with the parent model, with some improvement in surface salinity near the Tsawwassen terminal. Drift performance is significantly improved in the high-resolution models relative to Salish Sea 500 parent model (SS500). Minor regressions in water level performance at the upstream extent of the 30 m model relative to the South Salish Sea 150 m (SSS150) model are considered an acceptable trade-off for the improved resolution that better resolves the river velocities. Circulation around mudflats (parts of Sturgeon and Roberts Banks and several places in the river) may not be represented well due to lack of wetting and drying capability in the model.

Vancouver Harbour

The Vancouver Harbour POPS (Figure 6) resolves Burrard Inlet, an area not resolved by the parent model Salish Sea 500. In areas covered by the parent models and the POPS (west of First Narrows), comparative statistics show that total water level error is about 30% smaller (CRMSE) in the POPS, and the absolute error level is largely maintained within the inlet. Non-tidal and storm surge water level performance is comparable to that of the parent model. Currents, in particular the jets at First and Second Narrows, are marginally resolved in the outer model (SSS150) and significantly better resolved in the higher-resolution inner Vancouver Harbour model (VH20). The high-resolution models match or outperform the larger scale models in representing the vertical temperature and salinity distribution. Preliminary drift evaluation indicates that VH20 marginally outperforms SSS150. Circulation around intertidal areas (such as near Maplewood Flats) may not be well-represented due to the lack of wetting and drying in the current version of the model.

Kitimat

In the Kitimat POPS (Figure 7), representation of water levels at Kitimat is improved by approximately 30% in CRMSE over CIOPS-W, primarily through improvement of the tidal water level. Storm surges, which are likely to be remotely forced, were well represented in the POPS and CIOPS-W. Representation of currents improves with model resolution, especially in the upper 100 m of the ocean. In the port and approaches, tidal currents are well represented. Major non-tidal flow features are captured qualitatively, but not always quantitatively. Modelled temperatures and salinities are also improved, especially within 100 m of the ocean surface. The low salinity surface layer present throughout the fjord system is well represented. At depth a slight salty bias is present in the model solutions. Under non-storm conditions, modelled drift trajectories in the port were found to be more accurate when using currents from higher resolution models.

The heavily trafficked ferry route through Princess Royal and Grenville Channel is only marginally resolved in the POPS. Results from this region should be interpreted with appropriate caution. Similarly, the model was tuned for optimal performance at Kitimat. Model performance is not as good near the boundaries, and therefore the model results should not be used to provide advice in the vicinity of Prince Rupert and Klemtu.

Sources of Uncertainty

The circulation models assessed here aim to reproduce/forecast real-world ocean conditions as best as possible, but like all numerical ocean models, the accuracy is limited by the model grid resolution, the representation of the physical processes implemented in the model, and the accuracy and resolution of the input data. In particular, these models do not well represent intertidal areas owing to the lack of a wetting and drying scheme in NEMO 3.6, and do not use a complete dynamic ice model which may impact results in areas that form ice. Additionally, the coarse resolution of the atmospheric product available to drive these models can lead to poor performance in topographic channeling features, such as in fjords.

Quantitative assessment of the models was conducted with available data, which is not uniform across variables, time, or spatial extent. Generally, data availability is sparse and insufficient to assess the representation of the spatial scales resolved in the models. The assessment is limited to the range of conditions sampled by observations within the hindcast period, and so may not capture super-extreme events, and are expected to under-sample adverse weather conditions that prevent ship-based fieldwork or cause instrument or communications failures for shore-based systems. The drift evaluation is limited both by a paucity of drift tracks and by considerable uncertainty in the appropriate application of windage and wave contributions to drift simulations in coastal places and for high resolution models.

The intrinsic variability of each system and the relative contribution of this unconstrained variability to the total error has not been characterized.

CONCLUSION

In collaboration with ECCC through CONCEPTS, DFO has developed high-resolution Port Ocean Prediction Systems (POPS) for 48-h forecasting of water levels, currents and water properties in six high priority ports and approaches across Canada: Kitimat fjord, Vancouver Harbour, lower Fraser River, Port of Saint John, Strait of Canso Port, and St. Lawrence River estuary. These POPS are designed to run on a daily basis in an automated environment framework, similar to that used in operations at ECCC, and are forced by the operational ocean model CIOPS (open ocean boundary conditions) and atmospheric model HRDPS (surface forcing), as well as real-time runoff observations (or climatology when not available).

During this science advisory meeting, each POPS was assessed through the analysis of a long hindcast (5 to 6-years), which samples some extreme events, and a set of 48-h forecasts. All systems demonstrate stability and robustness within environmental conditions encountered during the period of testing both in hindcast mode and in forecast mode (no substantial degradation of model skill as a function of forecast lead time). Based on comparative statistics against available observations, POPS generally show skill in predicting tidal and total water levels (including storm surge), surface currents and drifts, and water properties at a scale that do not currently exist in available operational ocean models. They also generally matched or outperformed parent models CIOPS in areas of overlap between the models.

All POPS were found to be generally suitable to support dynamic e-navigation applications and marine emergency response, subject to requirements of specific applications. The meeting also identified and recognized some current limitations in the port systems. Notably, POPS should not be used for navigation purposes in intertidal areas, and POPS domains include region -specific features that are under-resolved and/or not reproduced (such as sea ice) in the models.

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APPENDIX—FIGURES

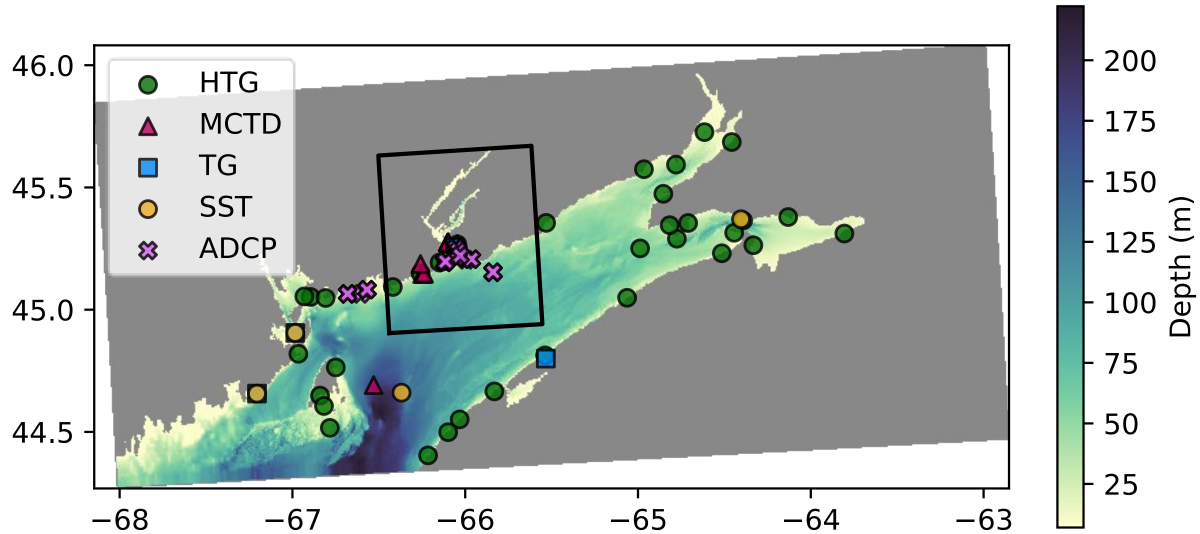
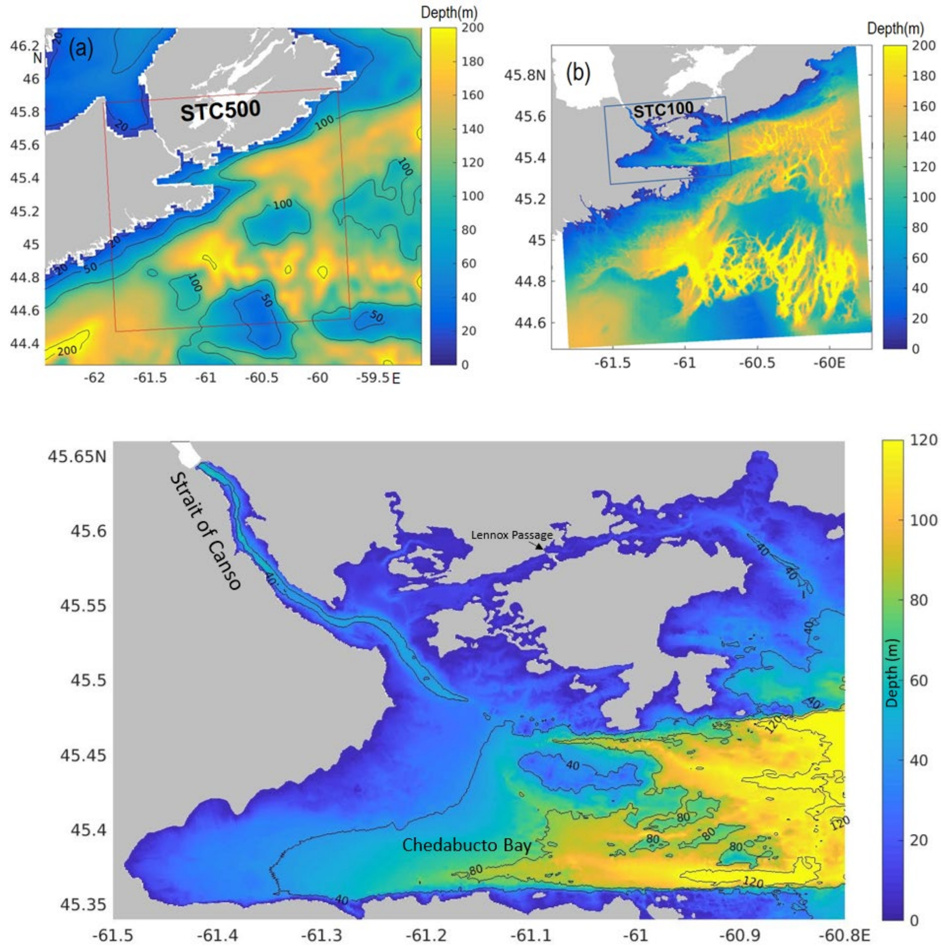


Figure 2. Bathymetry and ocean model domain for the Bay of Fundy 500 m grid (Fundy500), with locations of key observations plotted (HTG for historical tide gauge; MCTD for moored Conductivity-Temperature-Depth probe; TG for tide gauges; SST for sea surface temperature sensor; ADCP for Acoustic-Doppler-Current-Profiler observation). The black box indicates the extent of the ocean model domain for the Saint John Harbour 100 m grid (SJ100).



(c)

Figure 3. (a) CIOPS-E bathymetry with the ocean model domain outlined (red line) for the Strait of Canso 500 m grid (STC500). (b) STC500 bathymetry with the ocean model domain outlined (blue line) for the Strait of Canso 100 m grid (STC100). (c) STC100 bathymetry.

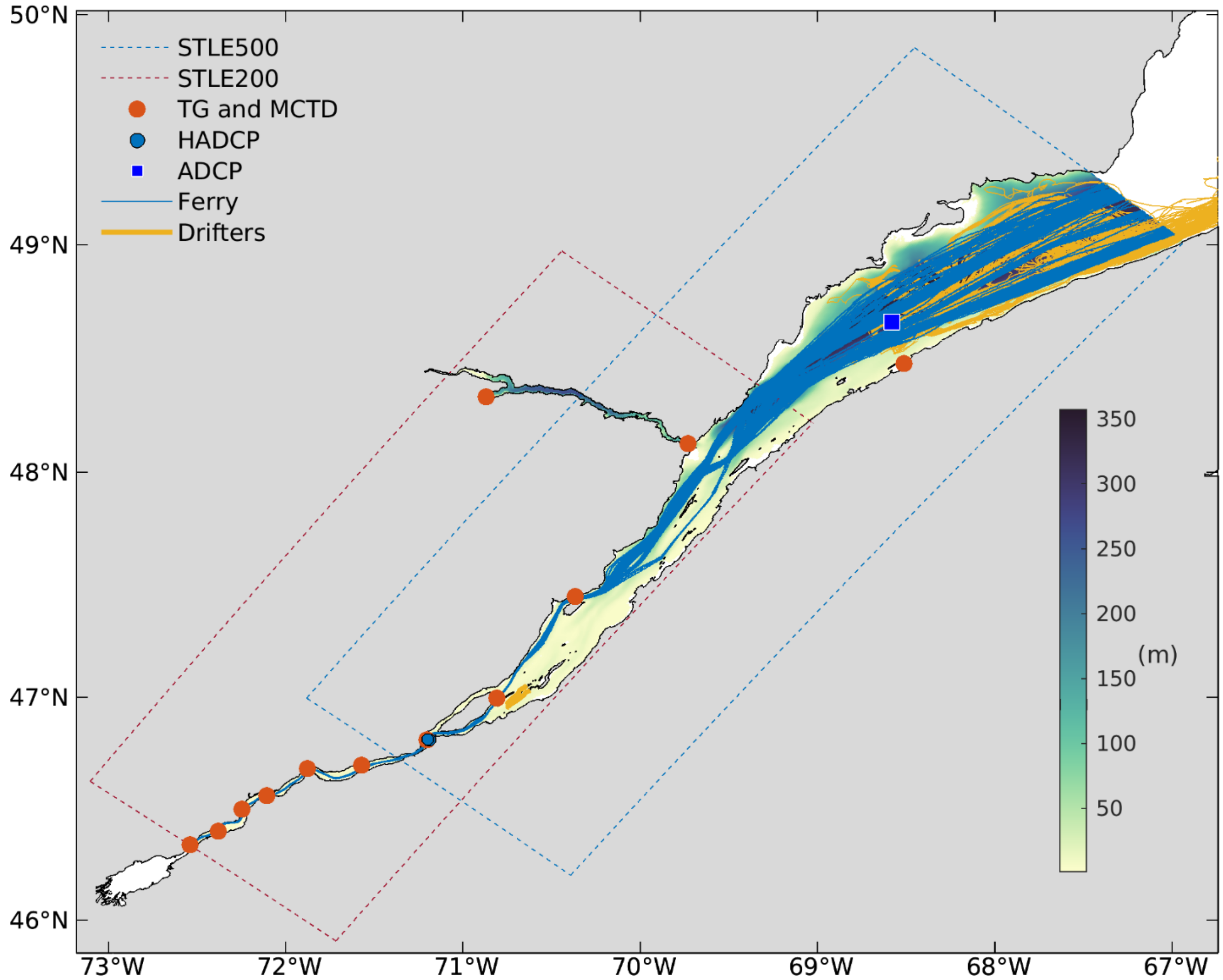


Figure 4. Bathymetry and limits of the ocean model domain for the Saint-Lawrence Estuary 500 m grid (blue dashed line; STLE500) and 200 m grid (red dashed line; STLE200), including location of data used for validation (TG for tide gauges; MCTD for or moored Conductivity-Temperature-Depth probes; HADCP and ADCP for horizontal and vertical Acoustic-Doppler-Current-Profiler measurements; Ferry for thermosalinograph on board of ferries; Drifters for surface drifter buoys). The locations of temperature and salinity vertical profiles from CTD casts are not plotted on this figure.

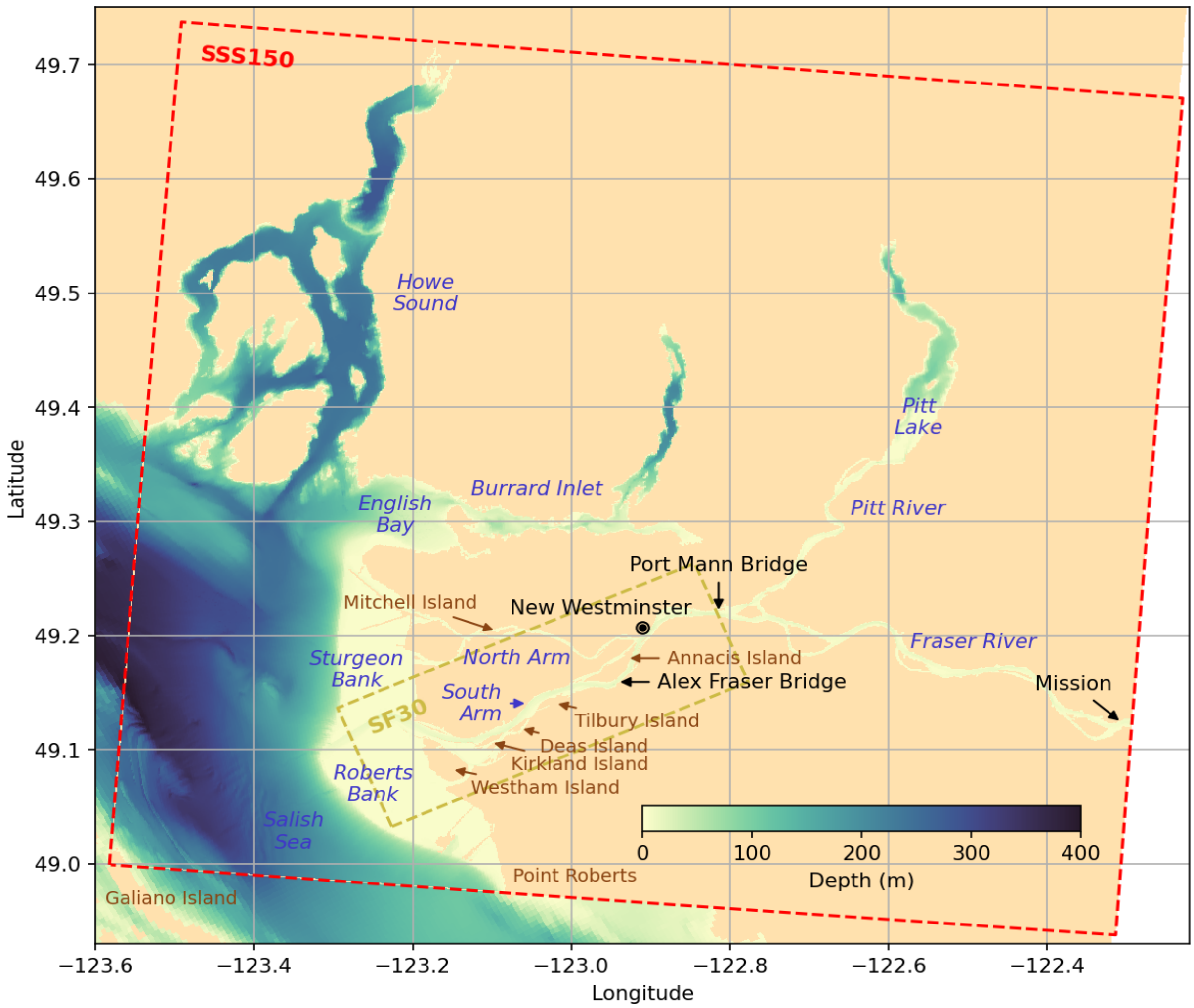


Figure 5. Ocean model domain with bathymetry for the South Salish Sea 150 m grid (red dashed line; SSS150) and South Fraser 30 m grid (dark yellow dashed line; SF30).

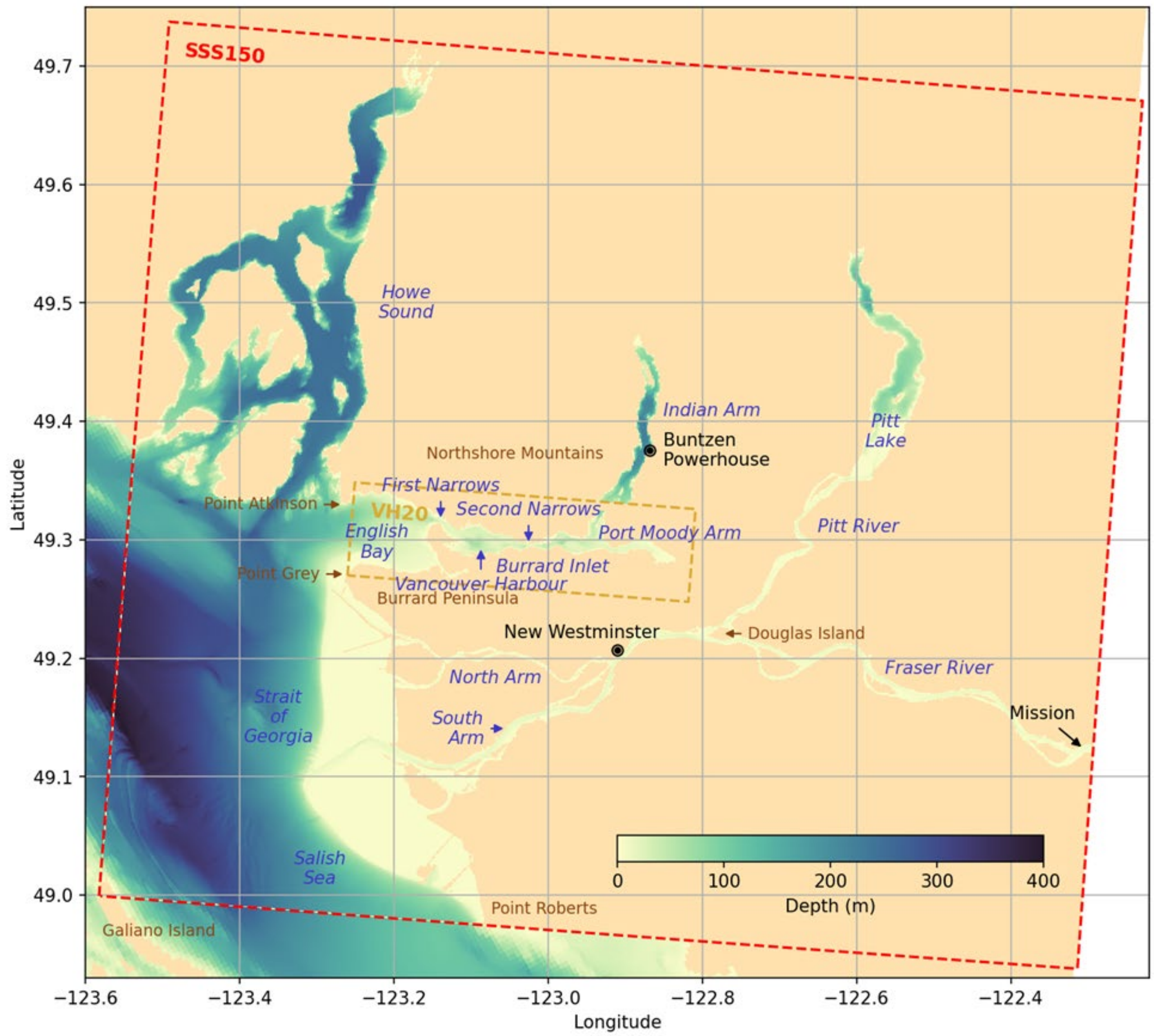


Figure 6. Ocean model domain with bathymetry for the South Salish Sea 150 m grid (red dashed line; SSS150) and Vancouver Harbour 20 m grid (dark yellow dashed line; VH20).

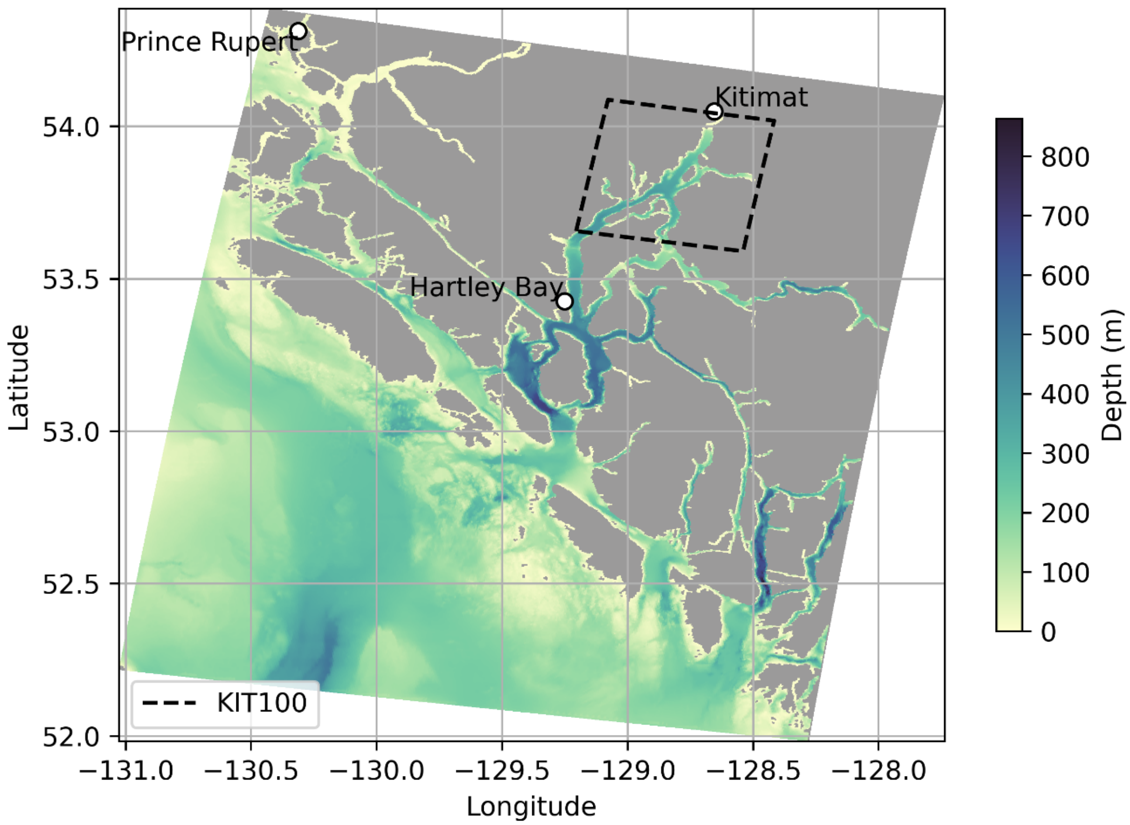


Figure 7. Ocean model domain with bathymetry for the Kitimat 500 m grid (KIT500). The limits of 100 m model domain (KIT100) are shown by the dashed back line.

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