Numerical Simulation of Storm Surge in the Boundary Bay Region of the Southern Strait of Georgia, British Columbia

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2023

Canadian Technical Report of Hydrography and Ocean Sciences 365

Fisheries and Oceans Canada Pêches et Océans Canada

Canada

Canadian Technical Report of Hydrography and Ocean Sciences

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NUMERICAL SIMULATION OF STORM SURGE IN THE BOUNDARY BAY REGION OF THE SOUTHERN STRAIT OF GEORGIA, BRITISH COLUMBIA

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Cat. No. Fs97-18/365E-PDF ISBN 978-0-660-68511-3 ISSN 1488-5417

Correct citation for this publication:

Fine, I., Thomson, R., and Hastings, N., 2023. Numerical simulation of storm surge in the Boundary Bay region of the southern Strait of Georgia, British Columbia. Can. Tech. Rep. Hydrogr. Ocean Sci. 365: v + 44 p.

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ABSTRACT

Fine, I., Thomson, R., and Hastings, N., 2023. Numerical simulation of storm surge in the Boundary Bay region of the southern Strait of Georgia, British Columbia. Can. Tech. Rep. Hydrogr. Ocean Sci. 365: v + 44 p.

A two-dimensional (2-D) wetting-and-drying (WAD) version of the Princeton Ocean Model (POM) has been used to examine storm-induced sea levels (storm surge) in the Boundary Bay region of the southern Strait of Georgia. The model uses a two-stage nested grid system, with high-resolution (3 m) bathymetric and topographic data in Boundary Bay and is driven at the outer coastal boundary by hourly atmospheric reanalysis time series. Daily mean steric sea level data are applied at the outer boundary to take into account large-scale open ocean effects on the coastal model. We test the model's hindcasting capability by comparing gridded sea level time series – generated through forcing by both European and Canadian reanalysis datasets – with tide gauge records at Point Atkinson, Vancouver and Cherry Point during the storm surge of 20 December 2018. According to the model, the storm surge lasted for roughly one day and reached maximum heights (independent of the tide) of 0.6 m in the northwest corner of Boundary Bay. Lower storm surge heights of around 0.5 m were generated at the Semiahmoo First Nations region. The highest simulated storm surge of over 0.6 m occurred in the northern Strait of Georgia. These heights are to be added to the local tide height when estimating the total water depth during a storm surge. Based on these results, the model POM2D-WAD is able to accurately reproduce storm surge events in the Strait of Georgia and on the west coast of Vancouver Island provided it is forced on its outer boundary by accurate, high-resolution atmospheric pressure and winds and has a nested-grid formulation founded on high-resolution bathymetric and topographic data in shallow coastal areas.

RÉSUMÉ

Fine, I., Thomson, R., and Hastings, N., 2023. Numerical simulation of storm surge in the Boundary Bay region of the southern Strait of Georgia, British Columbia. Can. Tech. Rep. Hydrogr. Ocean Sci. 365: v + 44 p.

Une version bidimensionnelle (2D) de mouillage et de séchage (WAD) du modèle océanique de Princeton (POM) a été utilisée pour examiner les niveaux de la mer induits par les tempêtes (onde de tempête) dans la région de Boundary Bay, dans le sud du détroit de Géorgie. Le modèle utilise un système de grille imbriquée à deux étages, avec des données bathymétriques et topographiques à haute résolution (3 m) dans Boundary Bay et est piloté à la limite côtière extérieure par des séries chronologiques horaires de réanalyse atmosphérique. Les données quotidiennes du niveau stérique moyen de la mer sont appliquées à la limite extérieure pour prendre en compte les effets de l'océan ouvert à grande échelle sur le modèle côtier. Nous testons la capacité de prévision rétrospective du modèle en comparant des séries temporelles maillées sur le niveau de la mer – générées par le forçage des ensembles de données de réanalyse européennes et canadiennes – avec les enregistrements des marégraphes à Point Atkinson, Vancouver et Cherry Point lors de l'onde de tempête du 20 décembre 2018. D'après le modèle, l'onde de tempête a duré environ une journée et a atteint une hauteur maximale (indépendamment de la marée) de 0,6 m dans le coin nord-ouest de Boundary Bay. Des ondes de tempête plus faibles, d'environ 0,5 m, ont été générées dans la région des Premières Nations de Semiahmoo. La plus forte onde de tempête simulée, de plus de 0,6 m, s'est produite dans le nord du détroit de Géorgie. Ces hauteurs doivent être ajoutées à la hauteur de la marée locale lors de l'estimation de la profondeur totale de l'eau lors d'une onde de tempête. Sur la base de ces résultats, le modèle POM2D-WAD est capable de reproduire avec précision les événements d'ondes de tempête dans le détroit de Géorgie et sur la côte ouest de l'île de Vancouver, à condition qu'il soit forcé sur sa limite extérieure par la pression atmosphérique et les vents précis et à haute résolution. a une formulation de grille imbriquée fondée sur des données bathymétriques et topographiques à haute résolution dans les zones côtières peu profondes.

1. INTRODUCTION

Many coastal communities in the Strait of Georgia are at risk of flooding and property damage caused by storm-induced surges. During a passing storm, the low atmospheric pressure has an inverse barometer effect, elevating the sea level by roughly 1 cm for every fall in air pressure by 1 mb. This effect, in combination with strong winds that push water up against the coast, can result in flooding, particularly if the storm occurs during a high spring tide. Forseth (2012) used tide gauge data from Point Atkinson in West Vancouver to compute dates of potential flooding for twenty-one events in the southern Strait of Georgia based on highest measured sea levels. Eight of these flooding events occurred between 1960 and 2011. Three of the events resulted in significant damage, with the surges of 16 December 1982 and 4 February 2006 responsible for damage greater than approximately $2,000,000 (in 2011 Canadian Dollars). Given its low elevation and exposure to the sea, the Corporation of Delta experienced the greatest flooding and accounted for a majority of the damage reported (Forseth, 2012).

There are presently two storm surge models available for the southern Strait of Georgia. The first, the Salish Sea storm surge model (Soontiens at al., 2015; https://salishsea.eos.ubc.ca/), produces a 48-hour forecast of marine conditions in the Strait of Georgia and Juan de Fuca Strait. (The latter two straits, together with Puget Sound, form the Salish Sea.) The model uses a regional version of the 3-dimensional NEMO circulation model to estimate a storm surge hindcast, with a regular curve-linear mesh of 398 by 898 grid cells, corresponding to horizontal grid sizes of approximately 440 m by 500 m, and 40 vertical levels. The depth array of the model is smoothed to limit large changes in depth across grid cells, such that $\Delta h/h \leq 0.8$, where Δh is the difference in depth between two adjacent grid cells, and h is their average depth. As a result, the effective bathymetric resolution is lower than specified in the model. In addition, bathymetric depths between 0 and 4 m are set to 4 m. The model uses the high-resolution Canadian atmospheric forecasting model (HRDPS; see section 2.3.2 below) and includes forcing by Fraser River discharge (as measured at Hope) and sea level changes associated with the astronomical tide (through boundary conditions) based on the northeast Pacific tidal model of Foreman et al. (2000).

A second model, the British Columbia storm surge forecasting system (http://stormsurgebc.ca), has been operating since 2007 using a 2D nonlinear barotropic Princeton Ocean Model (POM) with a roughly 7 km spatial resolution. Originally developed through funding by Fisheries and Oceans Canada and the British Columbia Ministry of the Environment, this operational model provides online predictions out to seven days to emergency managers and public stakeholders, including the cities of Surrey, Richmond, and Delta. Zhai et al. (2019) used the POM forecasting system to generate a 37-yr storm surge hindcast for southern British Columbia (BC) from 1980 to 2016. Because barotropic models cannot determine baroclinic processes that affect seasonal and interannual sea level variability, they presented a procedure to account for these processes. The computed residual seal level variations were passed through a 40-hour low-pass filter to compare with observations at BC tide gauges.

Here, we use a two-dimensional version of the Princeton Ocean Model that allows for wetting-and-drying of low-lying coastal areas to simulate storm surge in the southern Strait of Georgia. Focus is on Boundary Bay, which was selected as a "Case Study" region for the Flood Mitigation Canada Program funded by Defence Research and Development Canada's Centre for Security Science (DRDC CSS) Program CSSP-2018-CP-2352. The Princeton Ocean Model (Mellor, 2002) is a widely used ocean model with a terrain-following sigma-coordinate system in the vertical and an orthogonal curvilinear coordinate system in the horizontal. Because of these features, and the fact that the model solves for the sea-level directly, POM is particularly suited for coastal ocean simulations. Indeed, one of the earliest applications of POM was to simulate tides and their interaction with (river) buoyancy-driven flows in a bay (Oey et al., 1985).

2. STORM SURGE MODEL

2.1. MODELING STORM SURGE USING THE 2D POM WITH A WETTING-DRYING SCHEME

As noted previously, this study uses a version of the 2D POM model with the wetting and drying (WAD) option. Wetting and drying are common and important phenomena occurring in low-lying coastal zones as well as coastal embayments and inlets. Falling air pressure and strong winds, combined with large astronomical tides, can lead to flooding and subsequent drying. The WAD algorithm in POM, developed by Oey et al. (2005), divides the computational domain into two zones:

1. Absolute dry area (typically at higher elevation), where cells never become wet. This area is bounded by an absolute land boundary (ALB);
2. Wet and dry areas seaward from the ALB, where cells can be wet or dry, depending on the state of the surge and tide. In this area initially some cells are wet, and some are dry. For modeling purposes, the dry cells are covered with a very thin (order of a few centimeters) layer of water.

During numerical simulations, water can fill dry cells, which become wet, and wet calls can be drained and become dry. Although dry cells can accept water from wet cells, water cannot leave dry cells. If the water level in a dry cell exceeds some small threshold, it becomes wet. A WAD version of POM not only allows for inundation in storm surge models, it also removes the minimum depth limitation that exists in many circulation models. The absence of such limitations is critical for tidal marsh areas such as Boundary Bay. In this study, storm surge heights are determined relative to Mean Sea Level (MSL).

2.2. MODEL SET-UP: NESTED GRID FORMULATION

Accurate numerical simulation of storm surge in the rapidly shoaling regions of British Columbia requires setting up the model domain as a series of nested grids of ever finer spatial and temporal resolution. The use of nested grids of smaller cell dimensions and time steps makes it possible to resolve waves as they propagate into the shallow coastal regions. Also, near-coast shallow areas are strongly affected by wind and need special consideration. The principal requirements for numerical models using nested grids are as follows:

- Nested grid cell sizes are generally obtained by dividing the initial, large-scale coarse numerical grid by an integer, typically 3 to 5. Integers larger than this can lead to grid interface problems.

- Nested grids are needed in near-coastal areas; the coarse “parent” grid should be of sufficient extent to resolve possible feed-back effects that the nested grid may have on the parent grid during the simulation.
- A good interface between the inner and outer domains is required to avoid errors and model instability associated with point matching between the different grids. This should allow two-way fluxes without trapping shorter oscillations at the inner domain boundaries.

Because storm surges have relatively long periods of about a day, it is less important to have high resolution bathymetry than for other natural hazards, like tsunamis. Consequently, we have limited our nested grid approach to outer and inner grid levels only. Parameters for the grids are listed in Table 1.

Table 1. Parameters of the numerical grids used in the storm surge model. Grid extent is along the *x* (eastward) and *y* (northward) coordinate directions and is presented in degrees (°). Numerical grid cell sizes for Grids 1 and 2 are roughly 370 m and 60 m, respectively. Columns 2,3 and 4 are presented as *x*, *y* values.

Grid No.	Extent (*x*, *y*) (degrees)	Array (number of grid points)	Cell size (degrees)	Data source	Processing type
1	7.595; 4.2	1520; 1261	0.00500; 0.00333	BC 3 arc-sec bathymetric DEM	Filtering and bilinear interpolation
2	0.875; 0.750	1050; 1350	0.0008333; 0.0005555	BB 1/9 arc-second DEM	Filtering and interpolation

2.2.1. Outer grid (Grid 1)

Grid 1 covers the waters surrounding Vancouver Island and the northwest US coast (Figure 1). The location and coverage of the grid were chosen so that they covered all passes into the Strait of Georgia. This grid is also important for long waves and surge penetrating into the Strait of Georgia through narrow straits, capturing the energy exchange between the deeper shelf waters and the much shallower coastal zone. The grid was created using the British Columbia 3 arc-second bathymetric

Digital Elevation Model (DEM), (NOAA, 2017). Grid 1 has a resolution of 18 arc-seconds in the east-west direction and 12 arc-seconds in the north-south direction, corresponding to spatial scales (*x*,*y*) of approximately 370 m in both directions (Table 1). The grid boundaries span 47.2°– 51.4°N, 129.8° – 122.2°W.

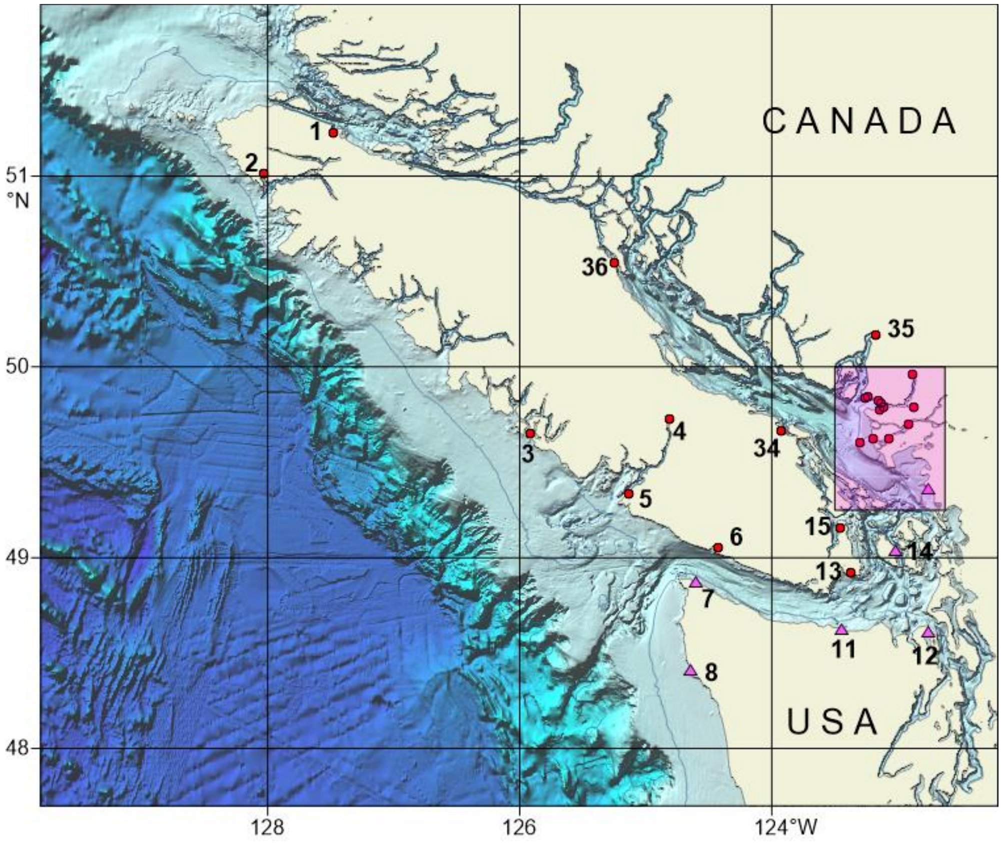

Figure 1. The region covered by the regional-scale coarse grid numerical model, which includes the coast of Vancouver Island, British Columbia and northwest Washington State (Grid 1). The insert shows the location of the nested grid (Grid 2), covering the coast of Metro Vancouver and Boundary Bay in the southern Strait of Georgia. Also shown are the locations of tide gauges that were in operation during the December 2018 event (see Tables 2 and 3 for the tide gauge names and locations).

To comply with the Grid 2 bathymetry (see Section 2.1.2), we replaced the bathymetric data in the Boundary Bay area for Grid 1 with data computed with a high-resolution digital bathymetric model for Boundary Bay; the original 3arc-second bathymetric data are too inaccurate for storm surge modeling for the Boundary Bay region.

2.2.2. Inner grid (Grid 2)

The second numerical grid covers the waters surrounding Metro Vancouver (Figure 2). This grid is of prime importance because it determines wave transformation in the vicinity of Boundary Bay. Model grid cells were created using the 1/9 arc-second Boundary Bay digital Elevation Model (BBDEM, 2020). The gridded data were subsequently re-interpolated to a geographical coordinate system (NAD83 standard) with a rectangular grid cell size of 3 arc-seconds by 2 arc-seconds (approximately 61 m by 62 m) in the east-west and north-south directions, respectively.

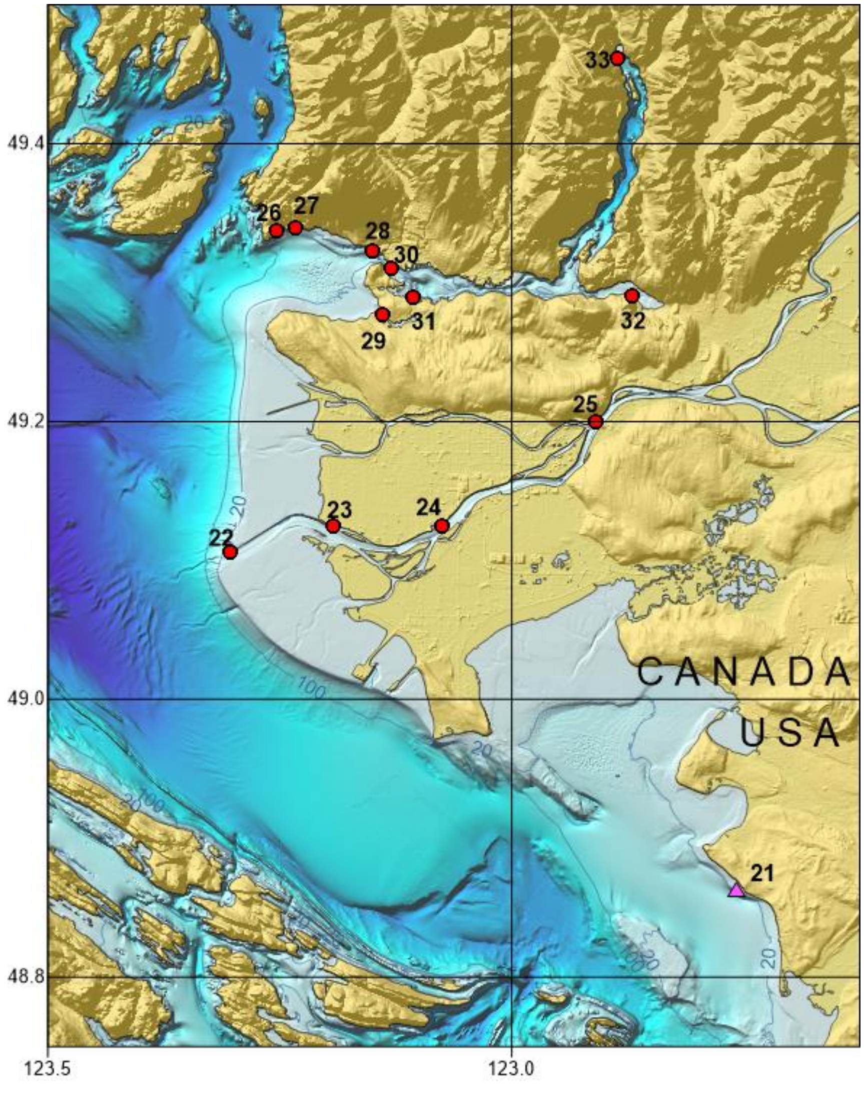

Figure 2. The coastal region covered by Grid 2, including the waters surrounding Greater (Metro) Vancouver. The *x*, *y* grid scales for this region are approximately 61 m and 62 m, respectively. Shown are the locations of the CHS tide gauges (solid dots) and NOAA tide gauge (triangle). The area above mean sea level is shaded yellow. (See Tables 2 and 3 for the tide gauge names and locations.)

Table 2. Canadian Hydrographic Service (CHS) tide gauge coordinates for sites used in the storm surge modeling.

Site No.	Station ID No.	Station Location	Latitude (degrees N)	Longitude (degrees W)
1	8408	**Port Hardy**	50.72250	127.48330
2	8735	**Winter Harbour**	50.51306	128.02889
3	8615	**Tofino**	49.15361	125.91250
4	8575	**Port Alberni**	49.22556	124.81389
5	8545	**Bamfield**	48.83611	125.13583
6	8525	Port Renfrew	48.55510	124.42075
13	7120	**Victoria**	48.42417	123.37083
15	7277	**Patricia Bay**	48.65361	123.45167
22	7594	Sand Heads	49.10583	123.30333
23	7607	**Steveston**	49.12444	123.19222
24	7610	Woodwards Landing	49.12500	123.07528
25	7654	**New Westminster**	49.20000	122.91028
26	7795	**Point Atkinson**	49.33722	123.25389
27	7786	**Sandy Cove**	49.33989	123.23289
28	7780	Ambleside	49.32270	123.15091
29	7707	Kitsilano	49.27660	123.13930
30	7724	Calamity Point	49.31000	123.13000
31	7735	**Vancouver**	49.28972	123.10667
32	7755	Port Moody	49.29000	122.87000
33	7774	Indian Arm	49.46186	122.88601
34	7917	Nanaimo Harbour	49.16276	123.92352
35	7808	Darrel Bay	49.66840	123.16917

Comment: The names of permanent CHS tide gauges are in bold.

Table 3. National Oceanic and Atmospheric Administration (NOAA) tide gauge coordinates for US sites used in the storm surge modeling.

Site No.	Station ID No.	Station Location	Latitude (degrees N)	Longitude (degrees W)
7	9443090	Neah Bay	48.36666	124.61166
8	9442396	La Push	47.91329	124.6370
11	9444090	Port Angeles	48.125	123.44
12	9444900	Port Townsend	48.11169	122.758
14	9449880	Friday Harbor	48.54666	123.015
15	9449424	Cherry Point	48.8633	122.7583

2.3. ATMOSPHERIC FORCING

Storm surge events in the Salish Sea can be forced using hourly time series of atmospheric pressure, wind velocity and other variables along the outer boundary of Grid 1. The two reanalysis datasets we applied to the model are the ERA5 data provided by the European Centre for Medium Range Weather Forecasts and the corresponding data from Environment Canada's High Resolution Deterministic Prediction System (HRDPS). We also examined forcing by the North American Regional Reanalysis (NARR) data produced by the National Center for Atmospheric Research (NCAR) (Kalnay et al., 1996; Kistler et al., 2001) but found that the wind velocities on the outer coast and in Juan de Fuca Strait differed markedly from those provided by ERA5 and HRDPS. Thus, the focus here is on the first two datasets, which produced numerical simulations of storm surge that agreed closely with those derived from tide gauge records.

2.3.1. ERA5- Europe's global high-resolution atmospheric reanalysis

In 2019, the European Centre for Medium Range Weather Forecasts (ECMWF) released a new, fifth generation global high-resolution dataset named ERA5. The dataset provides hourly estimates of a large number of atmospheric, land and oceanic climate variables from 1979 to the present, covering the Earth on a 30-km grid and resolving the atmosphere using 137 levels from the surface up to a height of 80 km. ERA5 includes information on uncertainties for all variables at reduced spatial and temporal resolutions. ERA5 combines vast amounts of historical observations into global estimates using advanced modeling and data assimilation systems, and replaces the ERA-Interim reanalysis, which stopped being produced on 31 August 2019.

2.3.2. HRDPS –Canada’s High Resolution Deterministic Prediction System

The High Resolution Deterministic Prediction System (HRDPS) is a set of nested, limited-area model (LAM) forecast grids from the non-hydrostatic version of Environment Canada’s Global Environmental Multiscale (GEM) model. The model data have a 2.5 km horizontal grid spacing for the inner domain over one main Pan-Canadian region and a northern region over the Arctic Archipelago and Greenland. The pilot model of the HRDPS is the Regional Deterministic Prediction System or RDPS (GEM Regional model). The HRDPS is operational except for the northern domain, which remains experimental. The hourly fields in the HRDPS high resolution GRIB2 dataset are made available four times a day for the Pan-Canadian domain for a 48-hour forecast period (except the northern domain).

In the case of short-term forecasts in the presence of complex terrain or along coastal shores, the influence of changes in the altitude, topography and nature of the terrain are better described for phenomena at this scale. This includes phenomena such as lake or sea breezes, local valley flows, and phase changes. Even over less rugged terrain, or over water away from shore, these more precise forecasts can be useful over a long period. As well, for hydrological forecasts on smaller basins, consideration should be given to using the HRDPS.

2.4. LATERAL BOUNDARY CONDITIONS

Specification of the prevailing oceanic conditions at the open ocean boundaries are important part of the model setup. For hindcasting cases, we can use observed data or reanalysis data that are based on the observations. Here, we have used daily mean sea level anomalies provided through the ECMWF Copernicus portal https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=overview. These conditions, in addition to the atmospheric forcing, are needed to accurately determine the storm surge component of the sea level response. The Copernicus dataset is mainly based on altimetry observations and provides gridded global data at a 0.25-degree resolution. The dataset does not include the inverse barometer effect or tides but does include oceanic steric effects. We have added the inverse barometer values at the boundary of the model to satisfy the simulation requirements, which use the full barometric effect. To dampen imperfect reflection of barotropic waves at the outer boundaries, enhanced horizontal mixing was introduced along the boundaries (corresponding to a so-called “sponge layer”) in addition to the usual outward radiation conditions. Introducing a sponge layer along the boundaries is standard numerical modeling methodology and is required to decrease incompatibilities in the boundary conditions arising from sea level variations within the inner domain of the model. The sponge layer decreases artificial intensification of processes along the boundaries.

3. THE STORM SURGE OF DECEMBER 20, 2018

We have used our model to examine the storm surge of December 20, 2018, and to compare the model results against observations from tide gauges in the Strait of Georgia. Although there is no documental evidence for flooding from this event – the peak of the event did not coincide with high tide – the residual sea level record shows that the storm surge itself was one of the highest in a decade.

Figure 3 shows snapshots of the pressure and wind speed derived from the ERA5 reanalysis data. As the figures indicate, the cyclone responsible for the 2018 storm surge intensified as it moved toward Vancouver Island from the southwest, reaching the coast at approximately 18:00 UTC on December 20. The storm then weakened significantly after crossing the coastline. Based on the path of cyclone corecentre (Figure 4), the cyclone was moving with an average speed of roughly 60 km/h.

The series of atmosphere pressure and wind speed records at the shelf break and in Boundary Bay during December 2018 are shown in Figures 5 and 6. In Boundary Bay, the local effect of the atmospheric depression was clearly weaker than at the shelf break. Specifically, the deepest trough in air pressure at the coast decreased by 10 mb upon reaching the bay, while the peak wind weakened from about 18 m/s to below 13 m/s within the bay. Time series of the residual sea level for the individual sites listed in Table 4 are presented in the Appendix.

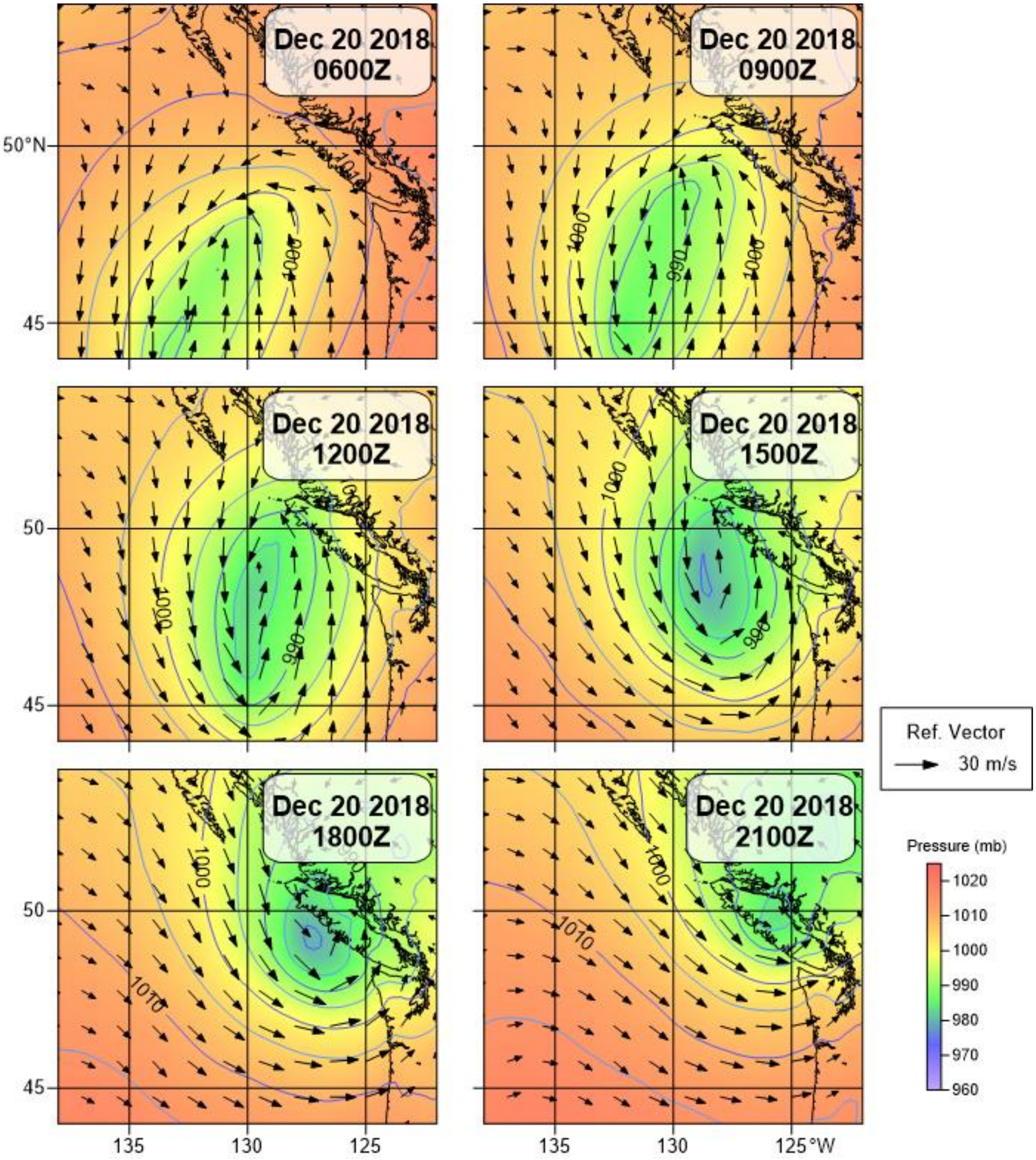

Figure 3. Weather maps over the study region on December 20, 2018. Times are in UTC (Universal Coordinated Time, Z).

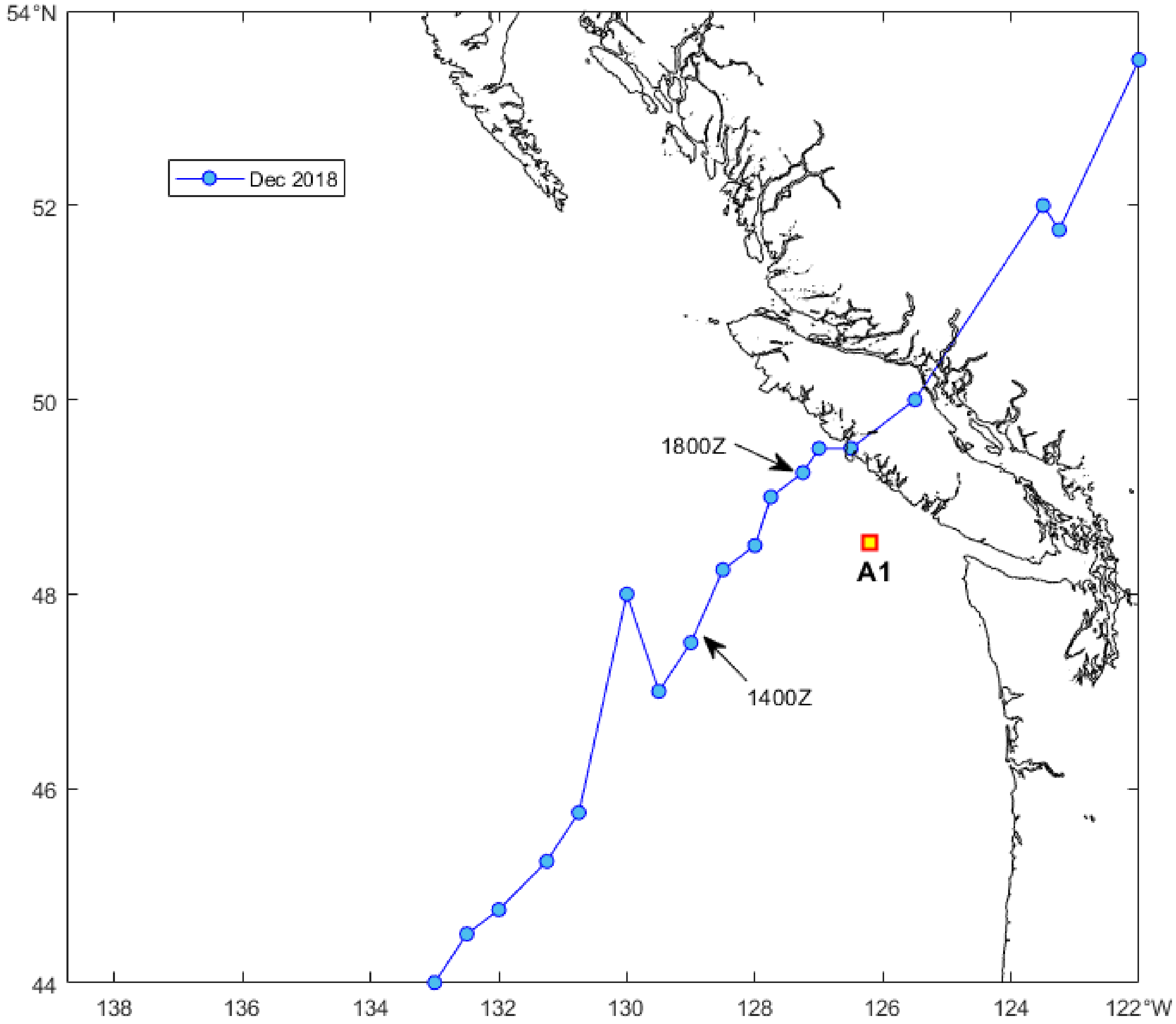

Figure 4. Trace of the centre (core) of the cyclone of December 20, 2018, off the British Columbia-Washington coast. The small red square labelled "A1" denotes the Department of Fisheries and Oceans permanent mooring site near the shelf break. Times are in UTC (Universal Coordinated Time, Z).

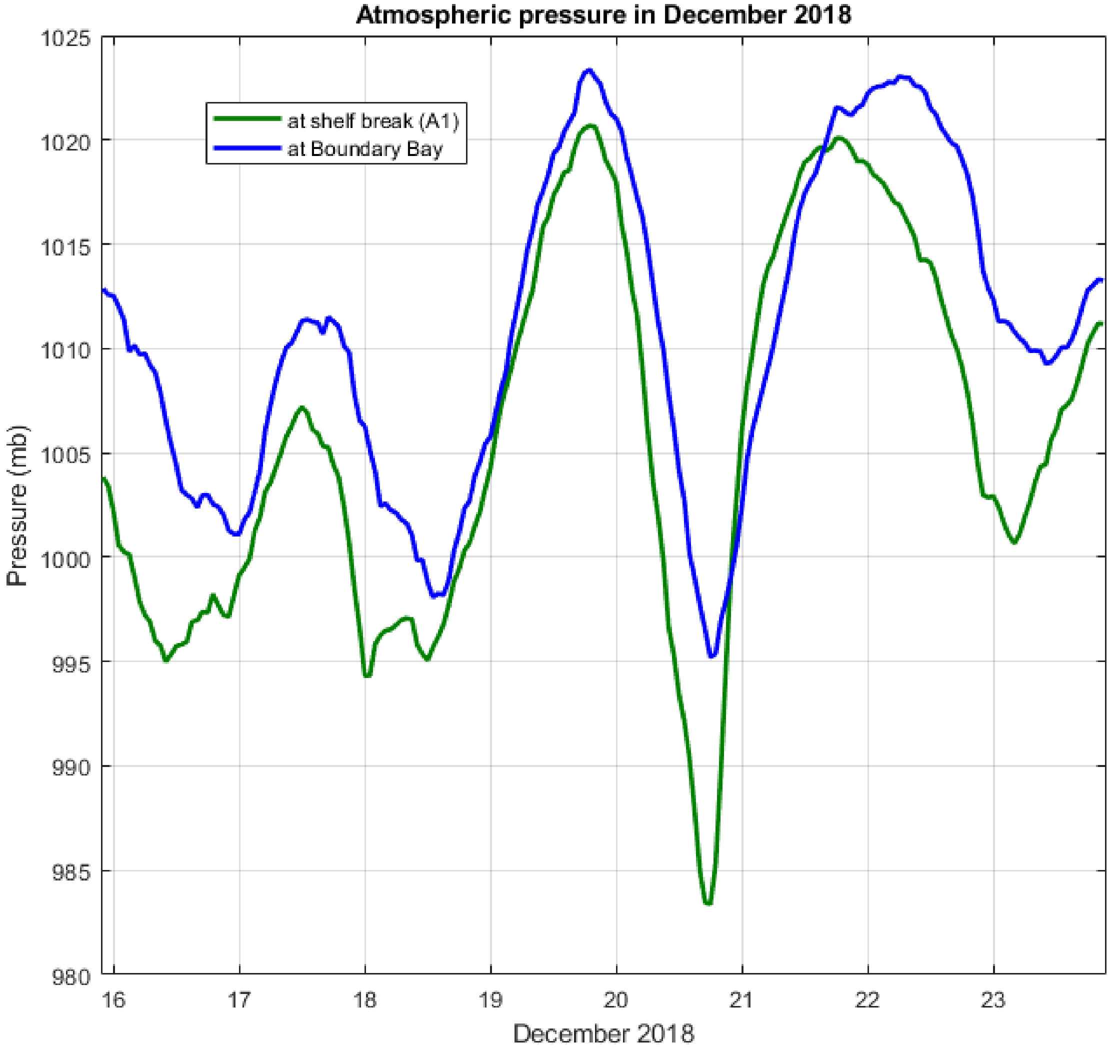

Figure 5. Time series of atmospheric pressure over the shelf break (green line) at current meter mooring Site A1 (see Figure 3.2) and in Boundary Bay (blue line) during December 16-23, 2018, based on the ERA5 reanalysis data.

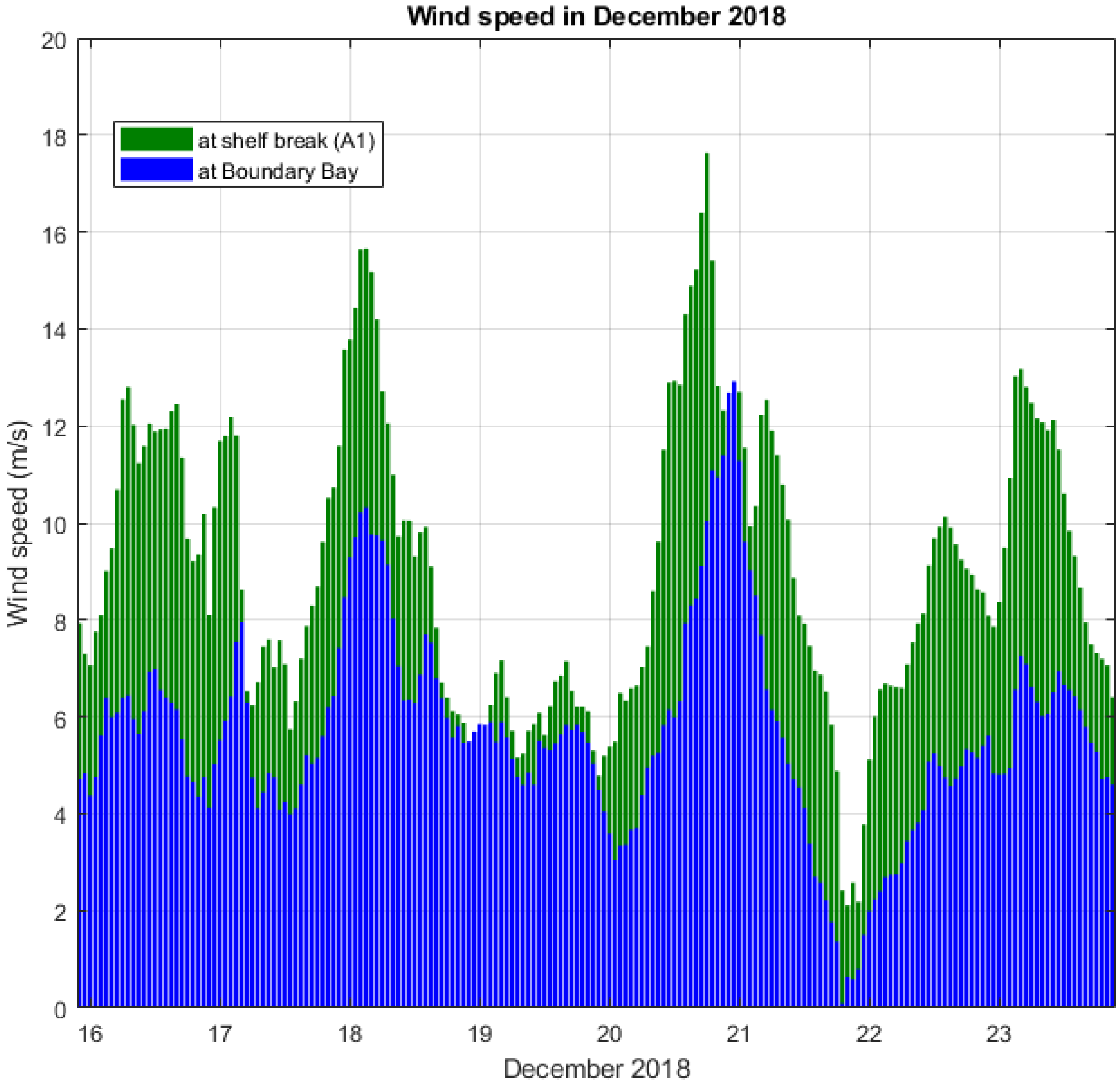

Figure 6. Time series of wind speed over the shelf break at current meter mooring Site A1 (green lines) and in Boundary Bay (blue lines) during December 16-23, 2018, based on ERA5 reanalysis data.

Figures 7 to 9 present maps of the numerically simulated maximum sea level elevation during the event. As the figures indicate, the storm surge was higher in the open Strait of Georgia than in Boundary Bay, especially its northern part of the strait. Juan de Fuca Strait and the northern coast Vancouver Island were less affected. The shallow waters off Metro Vancouver (Figure 8), which includes the Fraser River delta and Boundary Bay, were more affected by the storm surge than the deep-water areas. In Boundary Bay (Figure 9), the storm surge reached its highest values in the northern and northeastern sectors (Figure 9).

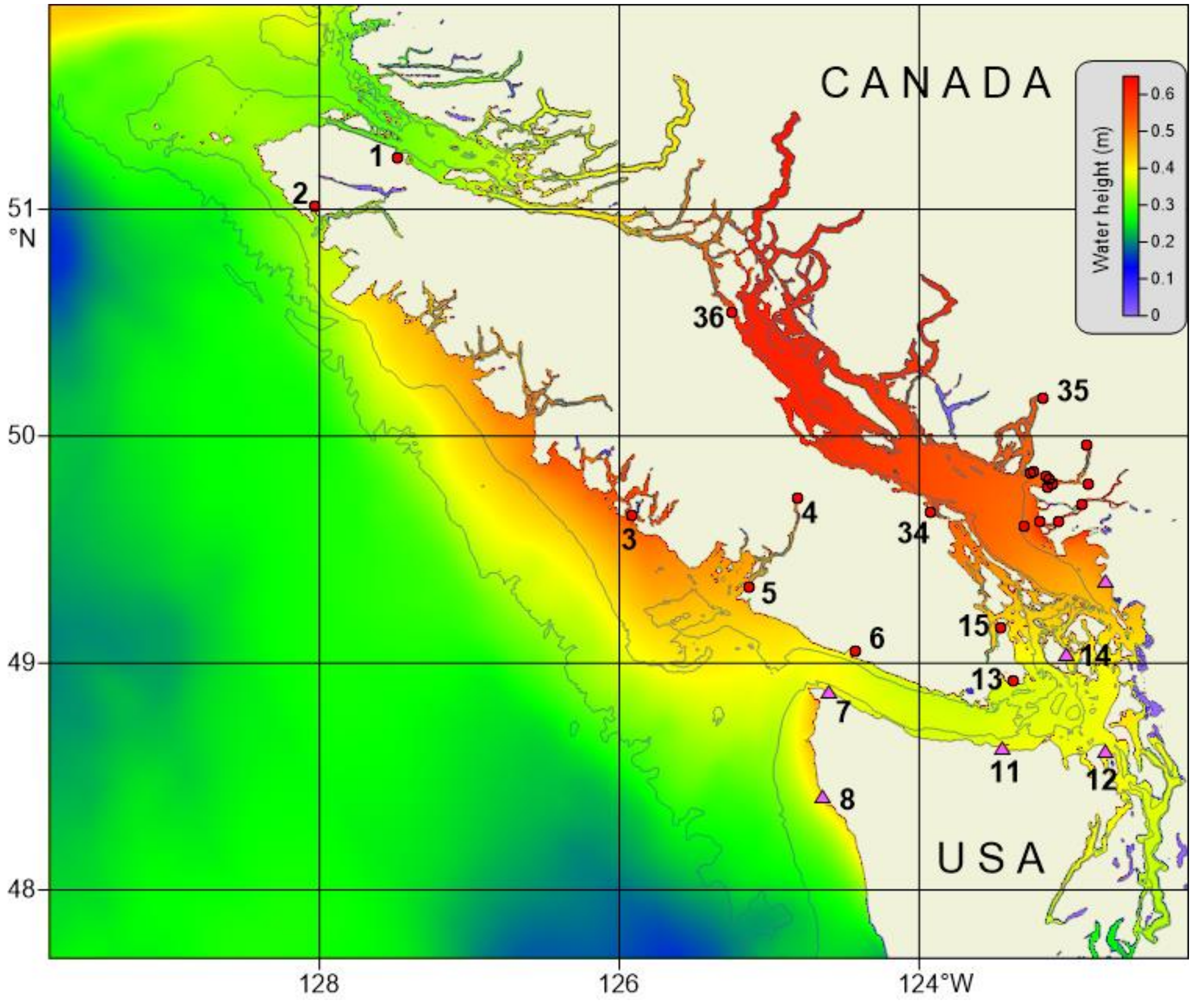

Figure 7. Map of the maximum modeled residual (detided) sea level during the storm surge of December 20, 2018. Shown are the locations of the Canadian and US tide gauges (see Tables 2 and 3 for the tide gauge names and coordinates).

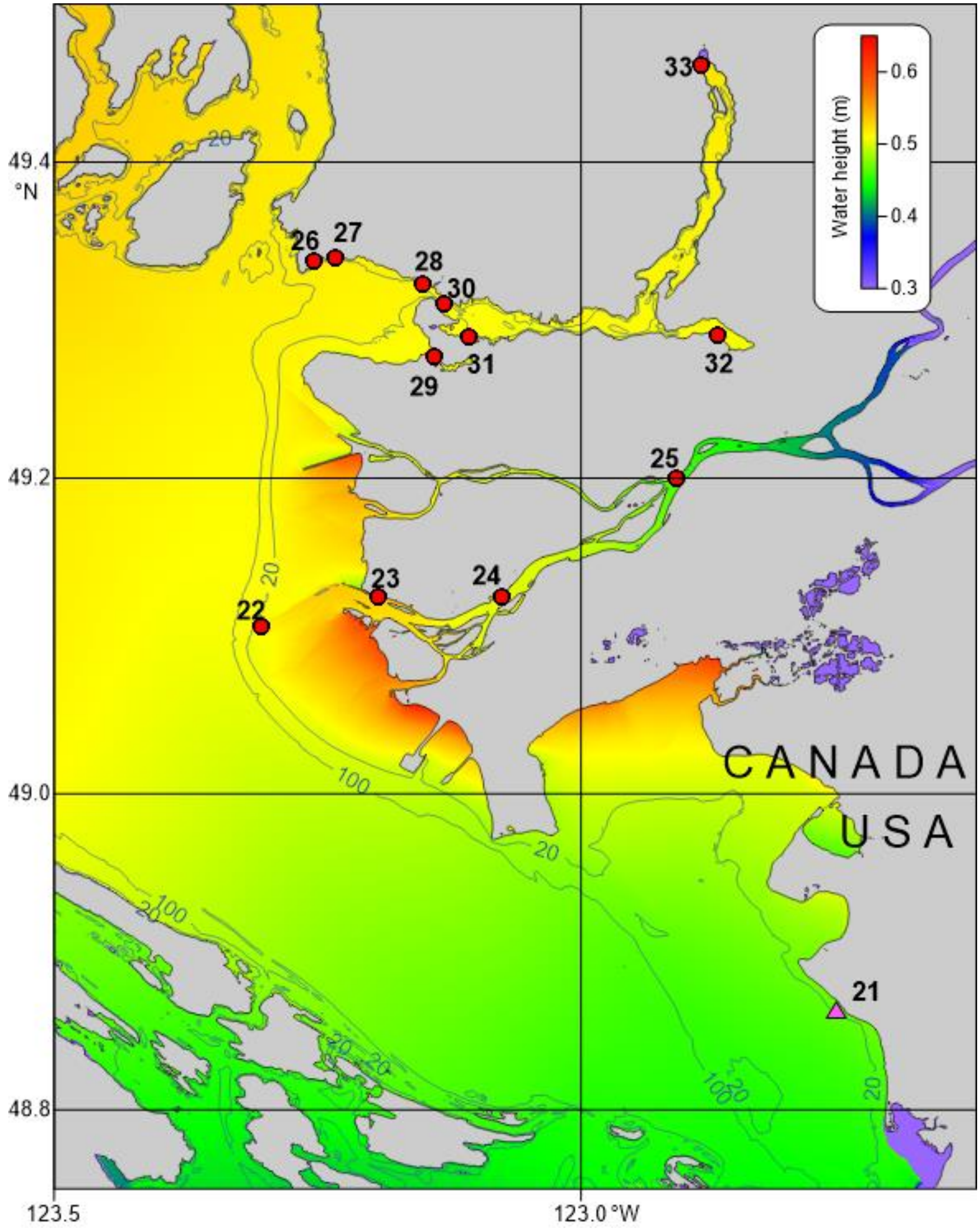

Figure 8. Map of the maximum modeled residual (detided) sea levels during the storm surge of December 20, 2018, over the Grid 2 domain. Also shown are the locations of the Canadian and US tide gauges (see Tables 2 and 3 for the tide gauges names and coordinates).

Table 4. Sites for the storm surge model output.

Site No.	Latitude (degrees N)	Longitude (degrees W)
S1	49.08257	122.864
S2	49.08369	122.896
S3	49.06912	122.938
S4	49.06351	122.979
S5	49.05455	123.017
S6	49.03101	123.051
S7	49.00635	123.030
S8	49.03998	122.889
S9	49.01756	122.867
S10	49.01308	122.806
S11	48.97049	122.748
S12	48.9548	122.825

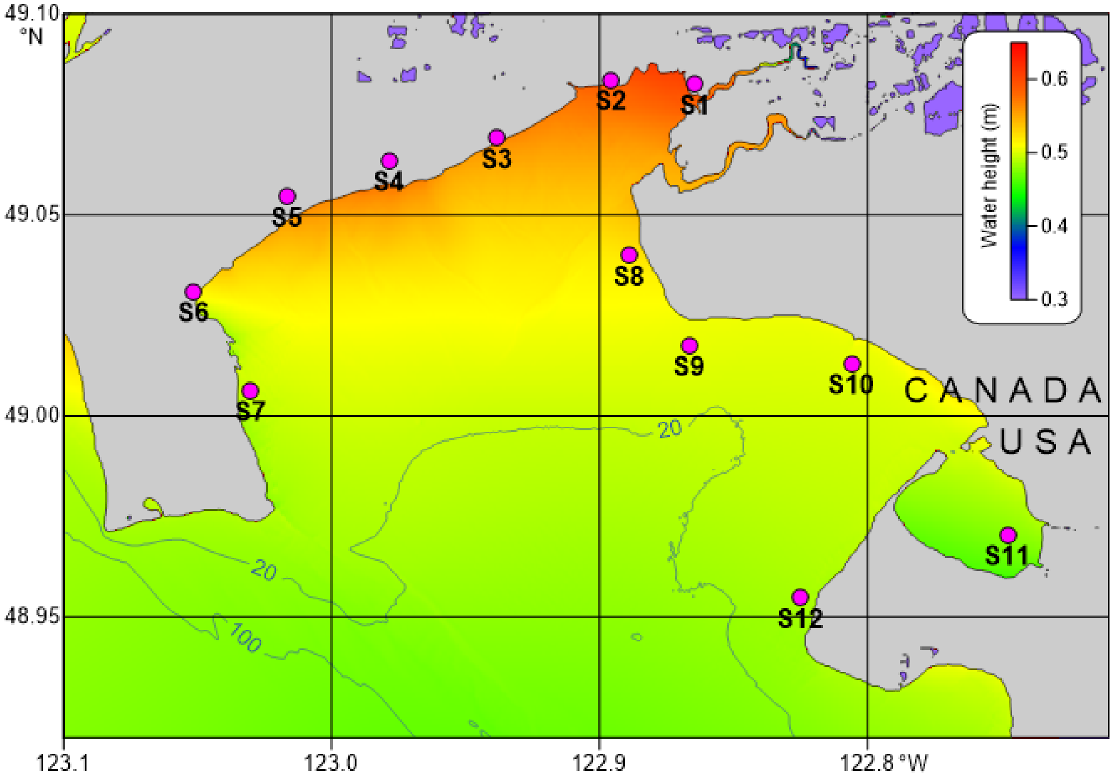

Figure 9. Expanded map of the maximum modeled residual (detided) sea level during the storm surge of December 20, 2018 in Boundary Bay. Also shown are the locations of Sites S1 to S12 for the modeled output.

Time series of the simulated residual sea level variations during the period 16-24 December 2018 are shown in Figures 10-12. It is clear that Site S4, located 0.7 m above the initial sea level elevation, remained dry, while Sites S1-S3 and S5-S6 changed from dry to wet and back. Sites S7-S12 were wet throughout the simulation. The maximum storm surge and the shape of the records varied only slightly from the site to site.

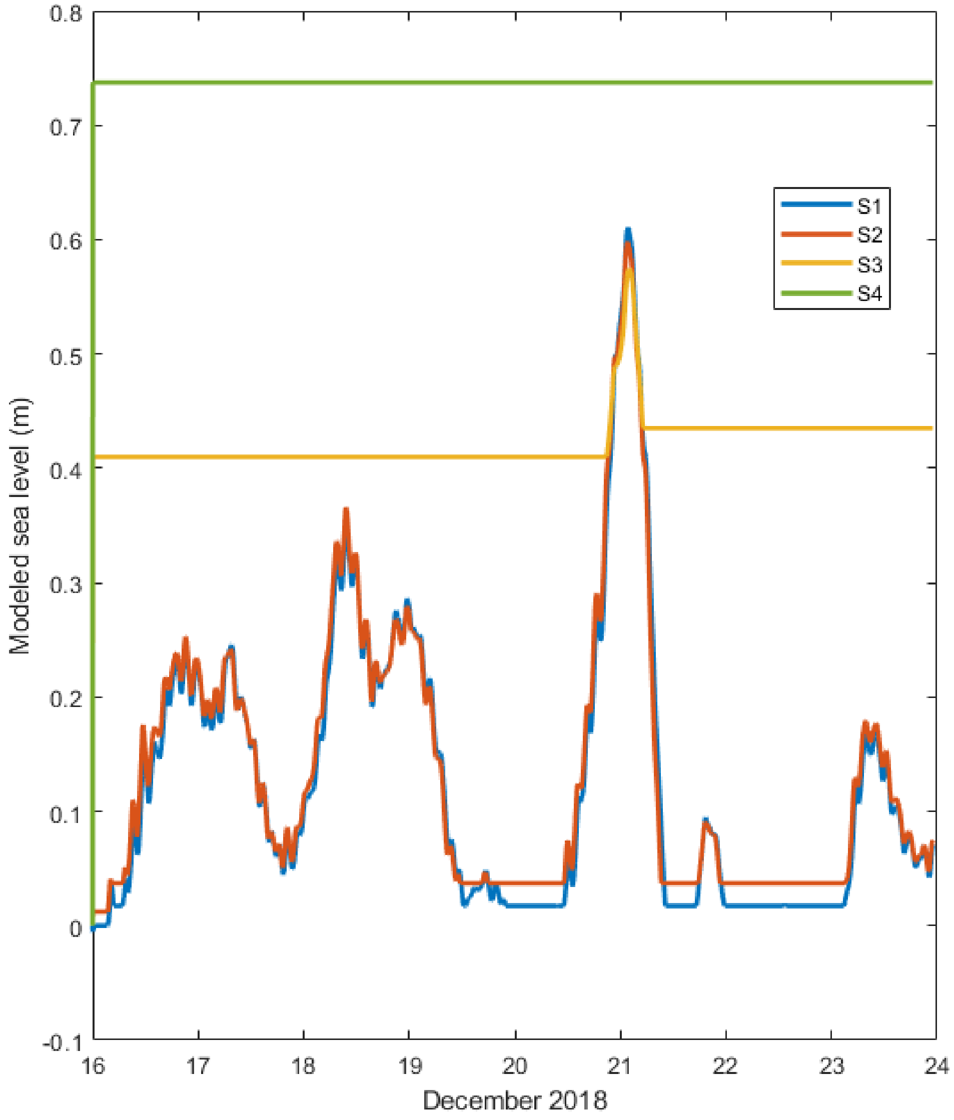

Figure 10. Modeled residual (detided) sea level records in December 16-24, 2018, for Sites S1-S4.

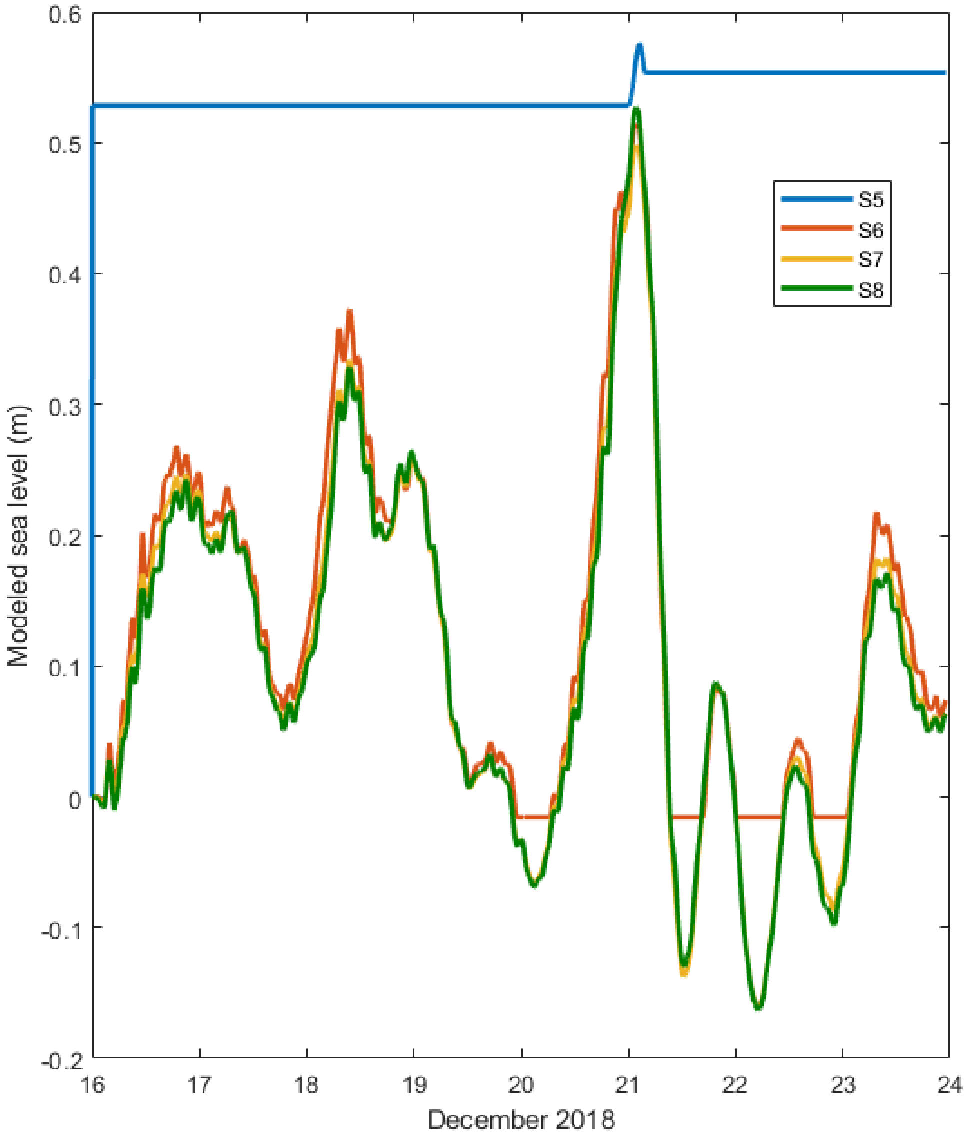

Figure 11. Modeled residual sea level records in December 16-24, 2018 for Sites S5-S8.

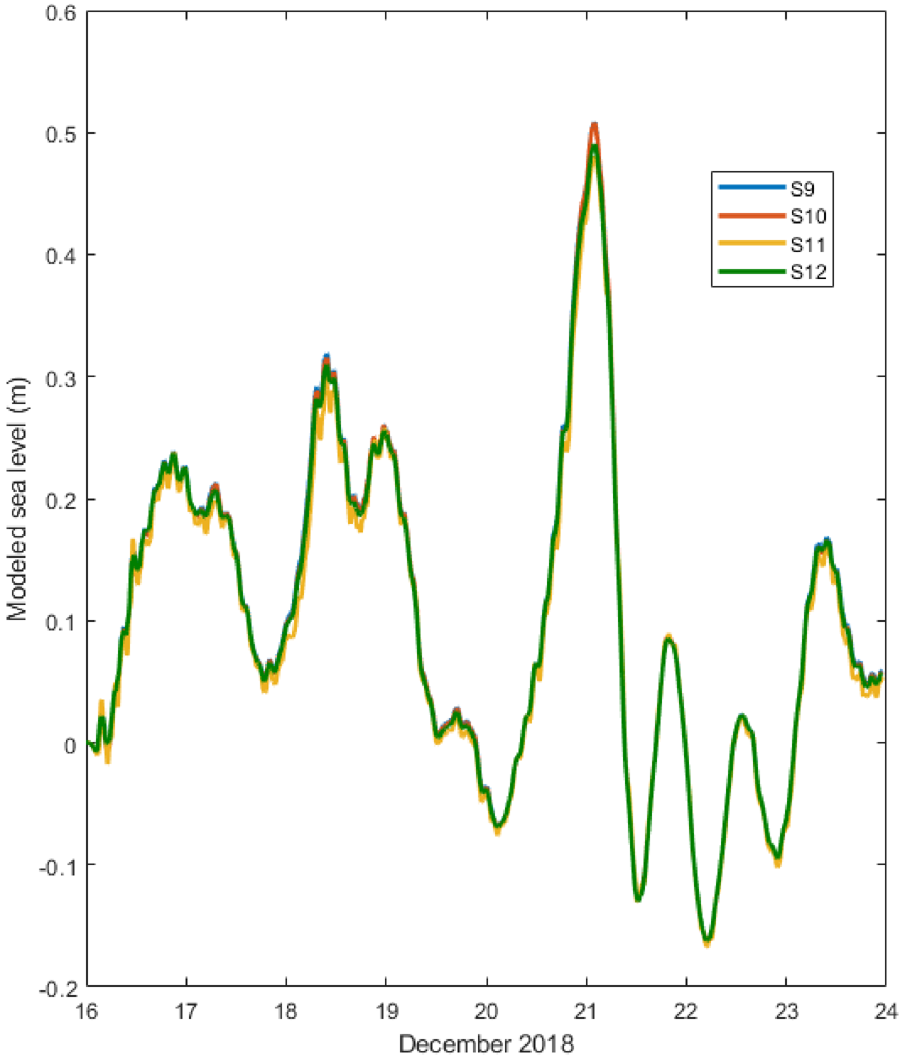

Figure 12. Modeled residual sea level records in December 16-24, 2018 for Sites S9-S12.

To estimate the validity of our model, we computed the correlation and skill number of the model with different parameters against observations at the tide gauge locations. The skill number S is defined as

$$S = 1 - \frac{\sum(\varsigma_{obs} - \varsigma_{mod})^2}{\sum \varsigma_{obs}{}^2},$$

where ς_{obs} and ς_{mod} are the observed and modeled sea level records (with mean removed), respectively. Comparisons of the observed and modelled sea level records are presented in Table 5. It is evident that the 2D-POM out-performed the UBC model (https://salishsea.eos.ubc.ca/), probably because of its much higher effective resolution and because it includes critical waterways (Discovery Channel and Johnstone Strait) in the northern part of the model domain. The model based on the High-resolution Canadian HRDPS atmospheric data provided better results than the model with ERA5 forcing, although the results for both forms of forcing are acceptable.

Table 5. Comparison of residual water levels produced by the three storm surge models against observed residual water levels at 19 CHS tide gauges for the period December 17-24, 2018. The column "UBC" is based on data from the "BC Salish Sea Model Project": https://salishsea.eos.ubc.ca/storm-surge/forecast#tide-gauge-station-sea-surface-heights. The UBC model is three-dimensional and includes the astronomical tides and forcing from the Fraser River runoff.

No	Station ID	Station name	Correlation coefficient, *r*			Skill, *S*		
			HRDPS	ERA5	UBC	HRDPS	ERA5	UBC
1	8408	Port Hardy	0.95	0.95		0.91	0.91	
2	8735	Winter Harbour	0.97	0.96		0.90	0.88	
3	8615	Tofino	0.95	0.94		0.90	0.87	
5	8545	Bamfield	0.94	0.94		0.88	0.86	
6	8525	Port Renfrew	0.95	0.94	0.83	0.86	0.85	0.69
13	7120	Victoria	0.91	0.90	0.83	0.83	0.80	0.68
14	7277	Patricia Bay	0.90	0.89	0.84	0.81	0.78	0.70
22	7594	Sand Heads	0.80	0.78	0.73	0.63	0.59	0.54
23	7607	Steveston	0.86	0.85		0.73	0.69	
25	7654	New Westminster	0.74	0.72	0.72	0.55	0.52	0.46
26	7795	Point Atkinson	0.89	0.88	0.85	0.80	0.77	0.72
27	7786	Sandy Cove	0.90	0.89	0.84	0.80	0.77	0.69
28	7780	Ambleside	0.82	0.81		0.68	0.65	
30	7724	Calamity Point	0.76	0.75		0.57	0.55	
31	7735	Vancouver	0.88	0.87		0.78	0.74	
33	7774	Indian Arm	0.73	0.70		0.53	0.49	
34	7917	Nanaimo Harbour	0.91	0.89	0.83	0.83	0.80	0.69
35	7808	Darrell Bay	0.85	0.83		0.71	0.68	
36	8074	Campbell River	0.91	0.90	0.81	0.82	0.80	0.63

The modeled records of the storm surge in Boundary Bay (see Figure 9 and Table 6 for the locations) appear in Figures 10-12. It is clear that the records are similar, which means that the sea level change over Boundary Bay has a smooth spatial distribution.

Table 6. Maximum modeled residual storm-induced sea level computed for sites in Boundary Bay. See Figures 10-12 for time series of residual sea level for selected sites in the bay.

Site No	Sea level
S1	0.61
S2	0.60
S3	0.58
S4	-
S5	0.58
S6	0.52
S7	0.50
S8	0.53
S9	0.51
S10	0.51
S11	0.48
S12	0.49

4. CONCLUSIONS

A high-resolution, nested-grid 2D Princeton Ocean Model with wetting-drying option (POM2D-WAD) has been used to simulate the distribution of storm surge of December 20, 2018 that was generated in the southern Strait of Georgia and adjoining Boundary Bay. The model uses high-resolution bathymetry and topography of the area and two versions of atmospheric forcing: the European high-resolution global reanalysis ERAS5 and the Canadian High Resolution Deterministic Prediction System (HRDPS). The main results of the modelling are:

- Both versions of the atmospheric forcing simulate the storm surge well; the results closely match the observations at 21 CHS tide gauges located around Vancouver Island.

- The spatial distribution of maximum storm surge amplitudes within Boundary Bay changes gradually, with highest values of around 0.6 m occurring toward the northern head of the bay. The distribution of maximum storm surge amplitude along the Semiahmoo coast is nearly uniform, with values are around 0.5 m.
- The model POM2D-WAD is able to accurately reproduce storm surge events in the Strait of Georgia and on the west coast of Vancouver Island provided it is forced on its outer boundary by accurate, high-resolution atmospheric pressure and winds and has a nested-grid formulation founded on high-resolution bathymetric and topographic data in shallow coastal areas. The model is further improved by adjusting the outer oceanic boundary to match low-frequency steric sea level variations, such as those associated with decadal scale El Niño-La Niña events in the open ocean.

Because storm surges caused by strong atmospheric depressions are different owing to differences in individual cyclonic parameters (e.g., wind speed and direction, pressure distribution, and spatial extent), it would be informative to model several other intense historical events to estimate the common and specific features of the storm surge distribution in the southern Strait of Georgia and Boundary Bay and estimate possible risk of storm surge to the areas. The future effects of global sea level rise should be also taken into account.

ACKNOWLEDGEMENTS

This project was funded through “Coastal Flood Mitigation Canada” within the Defence Research and Development Canada’s Centre for Security Science (DRDC CSS) Program (CSSP), led on the Pacific Coast by the Geological Survey of Canada, Natural Resources Canada. The support of our colleagues throughout the program is gratefully acknowledged. We thank Marlene Jeffries (Canadian Hydrographic Service, CHS) and Mark Ranking (Ocean Networks Canada, ONC) for providing us with the high-resolution bathymetric and topographic data for the Boundary Bay region and for helping with the vertical datum adjustment and Anne Ballantyne (Canadian Hydrographic Service) for providing the tidal constituents for the Canadian tide gauges. Maxim Krassovski of the Institute of Ocean Sciences assisted us with the data and provided valuable information on storm surge modeling.

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APPENDIX

Time series of observed and numerically simulated residual (detided) sea level for selected tide gauges sites on the west coast of British Columbia and Washington State (See Figures 7-9 for locations). The red and blue lines denote time series derived using the reanalysis data from the Canadian High Resolution Deterministic Prediction System (HRDPS) and the European Centre for Medium Range Weather Forecasts (ERA5), respectively.

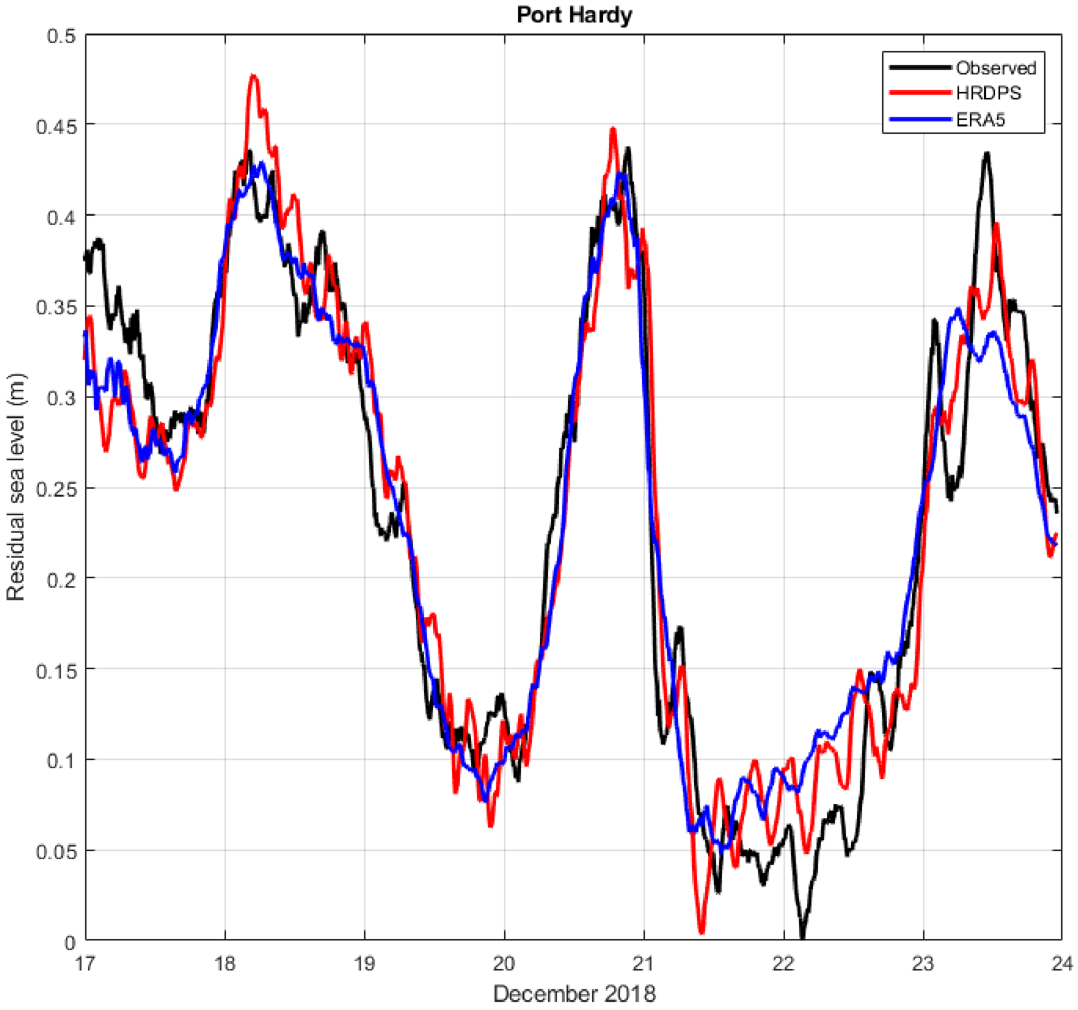

Figure A1. Comparison of the modeled sea level versus the observed records (black curve) at Port Hardy for the HRDPS (red curve) and ERA5 forcing (blue curve).

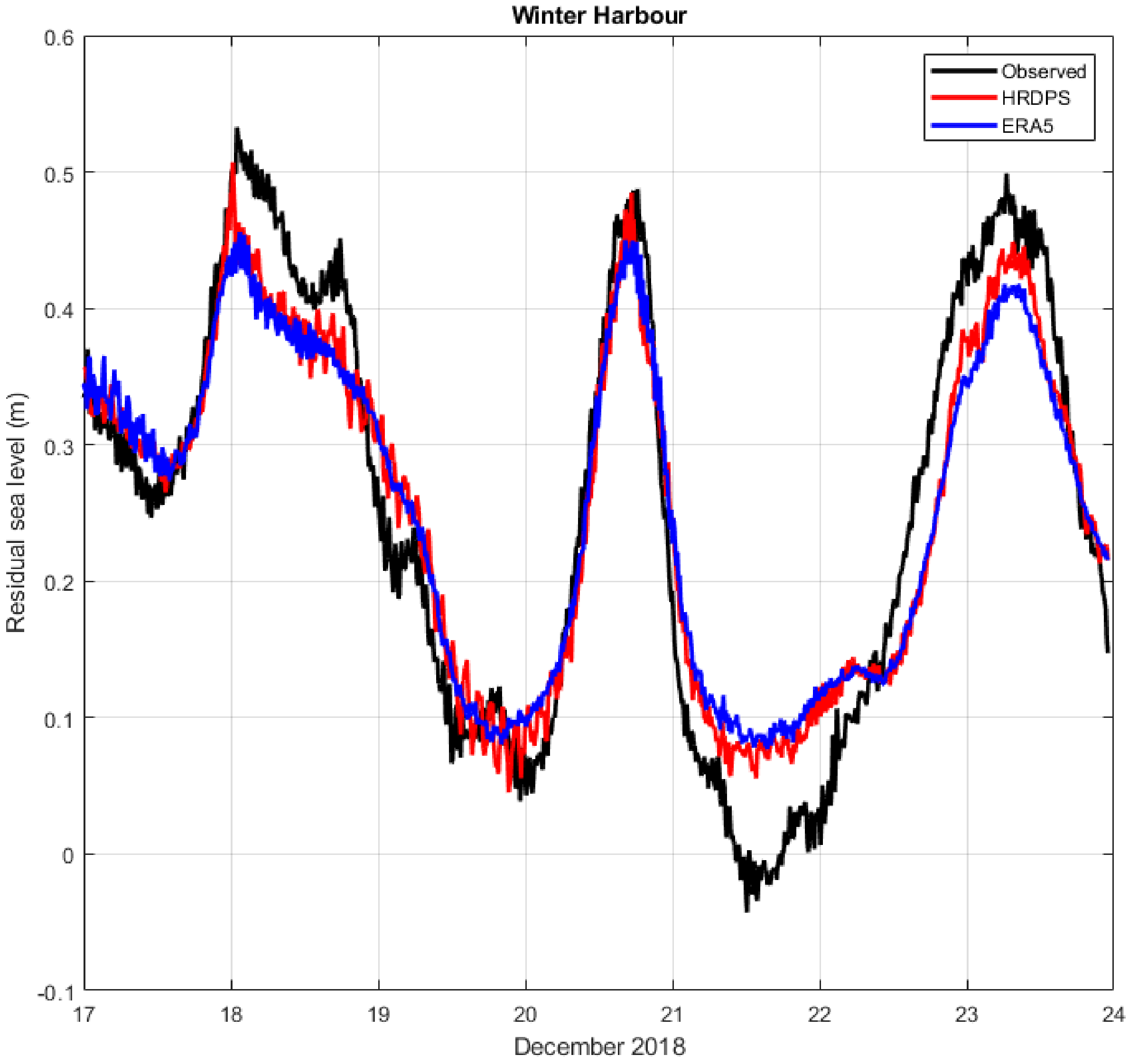

Figure A2. Comparison of the modeled sea level versus the observed records (black curve) at Winter Harbour for the HRDPS (red curve) and ERA5 forcing (blue curve).

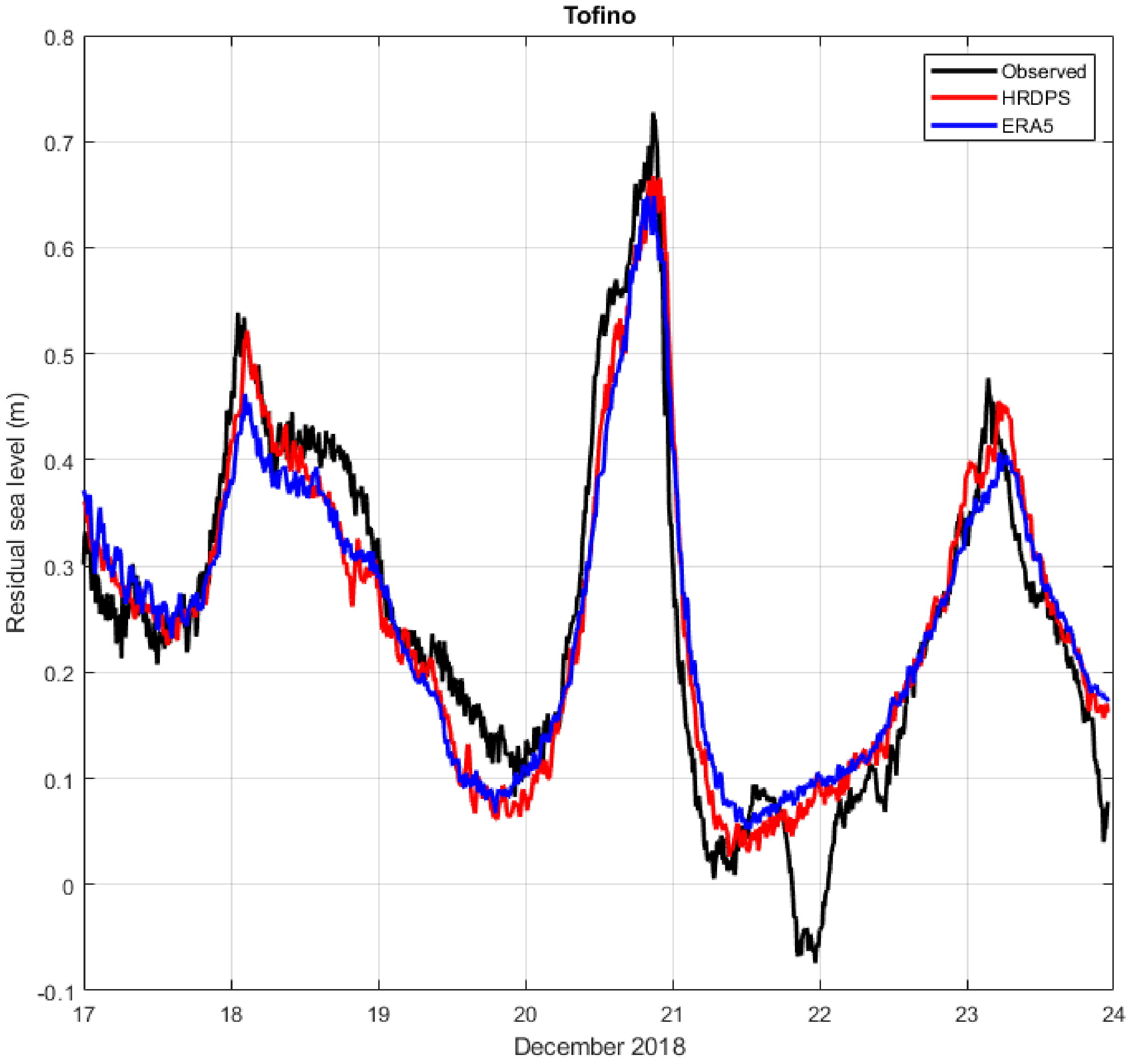

Figure A3. Comparison of the modeled sea level versus the observed records (black curve) at Tofino for the HRDPS (red curve) and ERA5 forcing (blue curve).

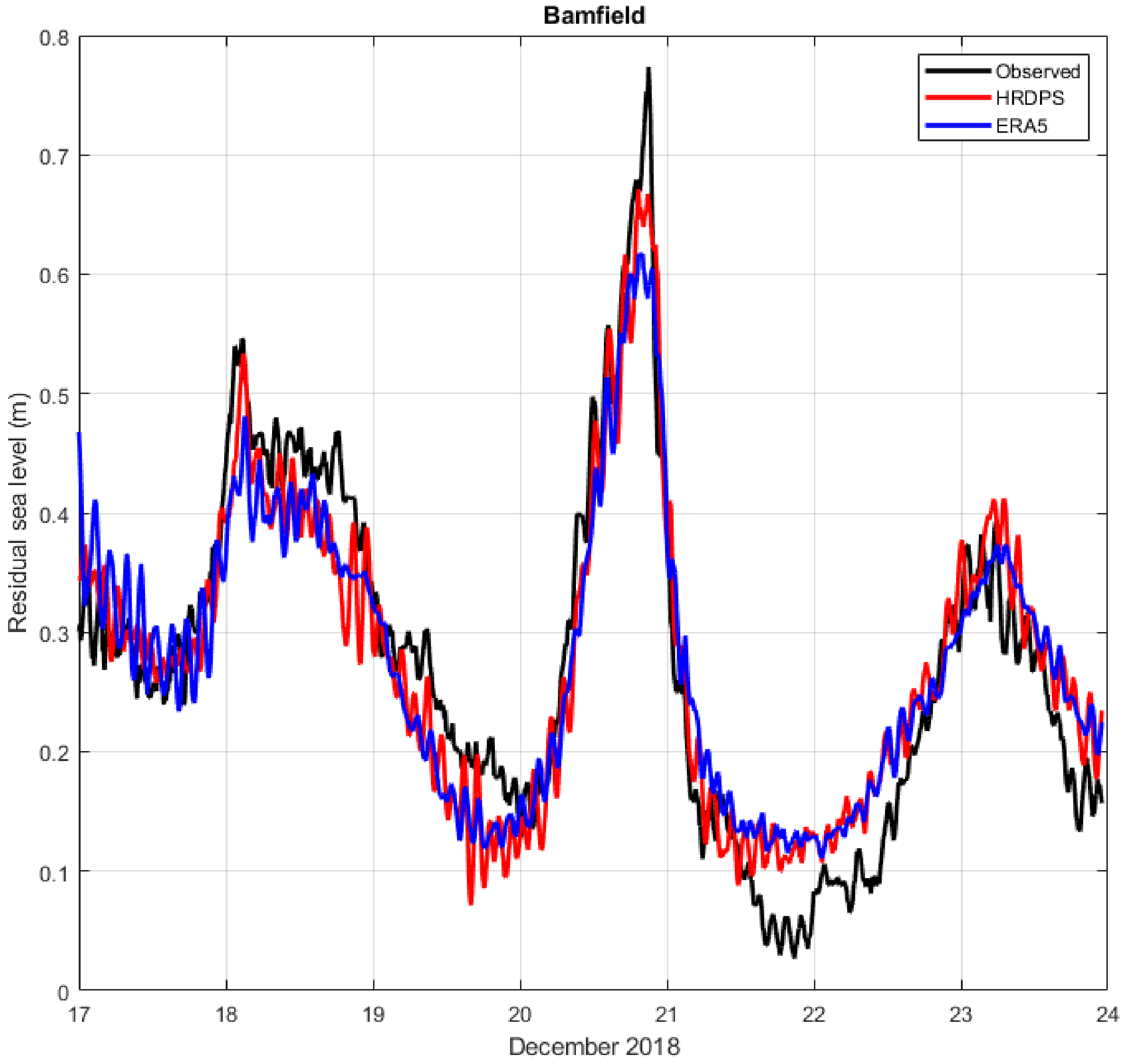

Figure A4. Comparison of the modeled sea level versus the observed records (black curve) at Bamfield for the HRDPS (red curve) and ERA5 forcing (blue curve).

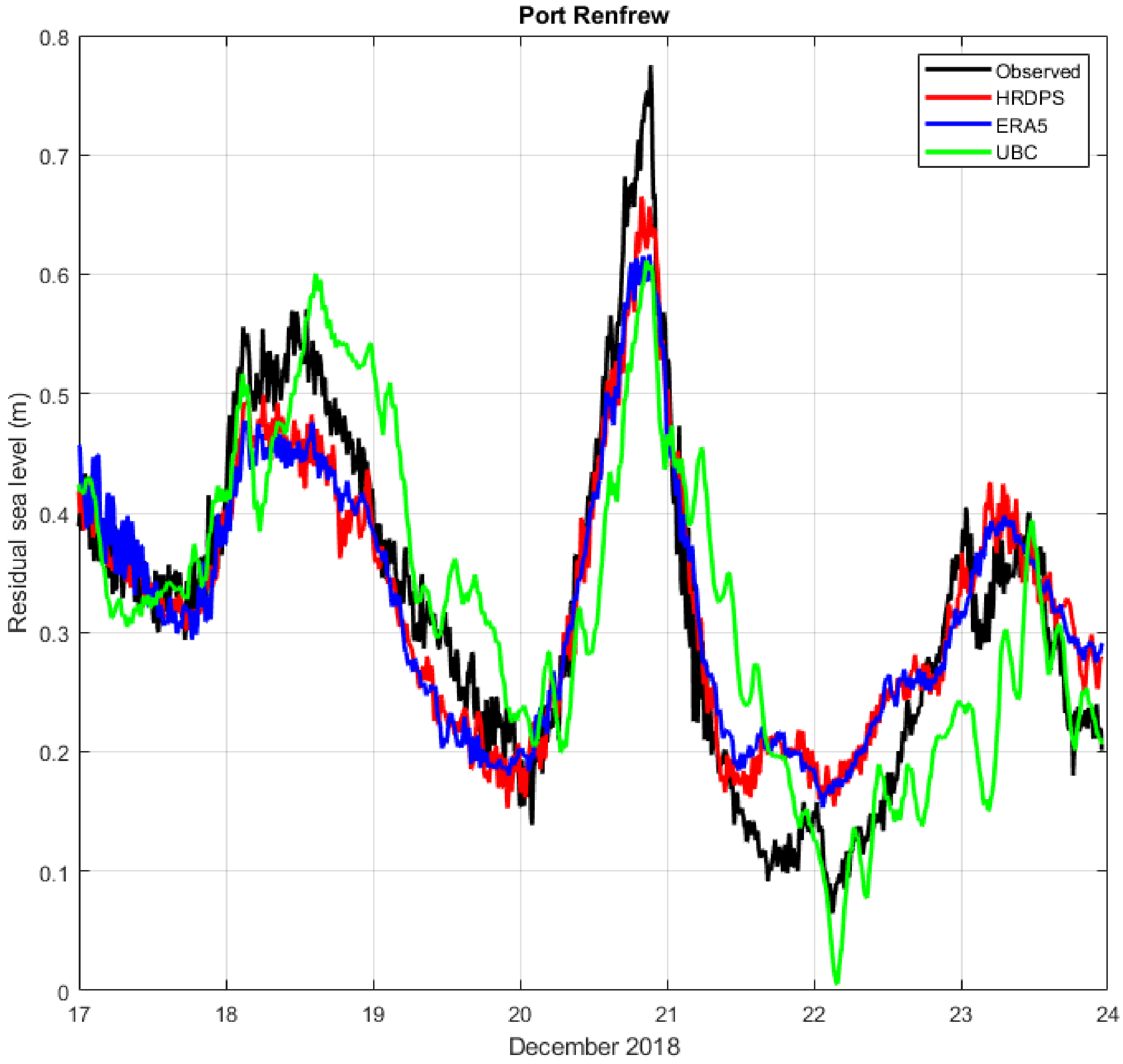

Figure A5. Comparison of the modeled sea level versus the observed records (black curve) at Port Renfrew for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

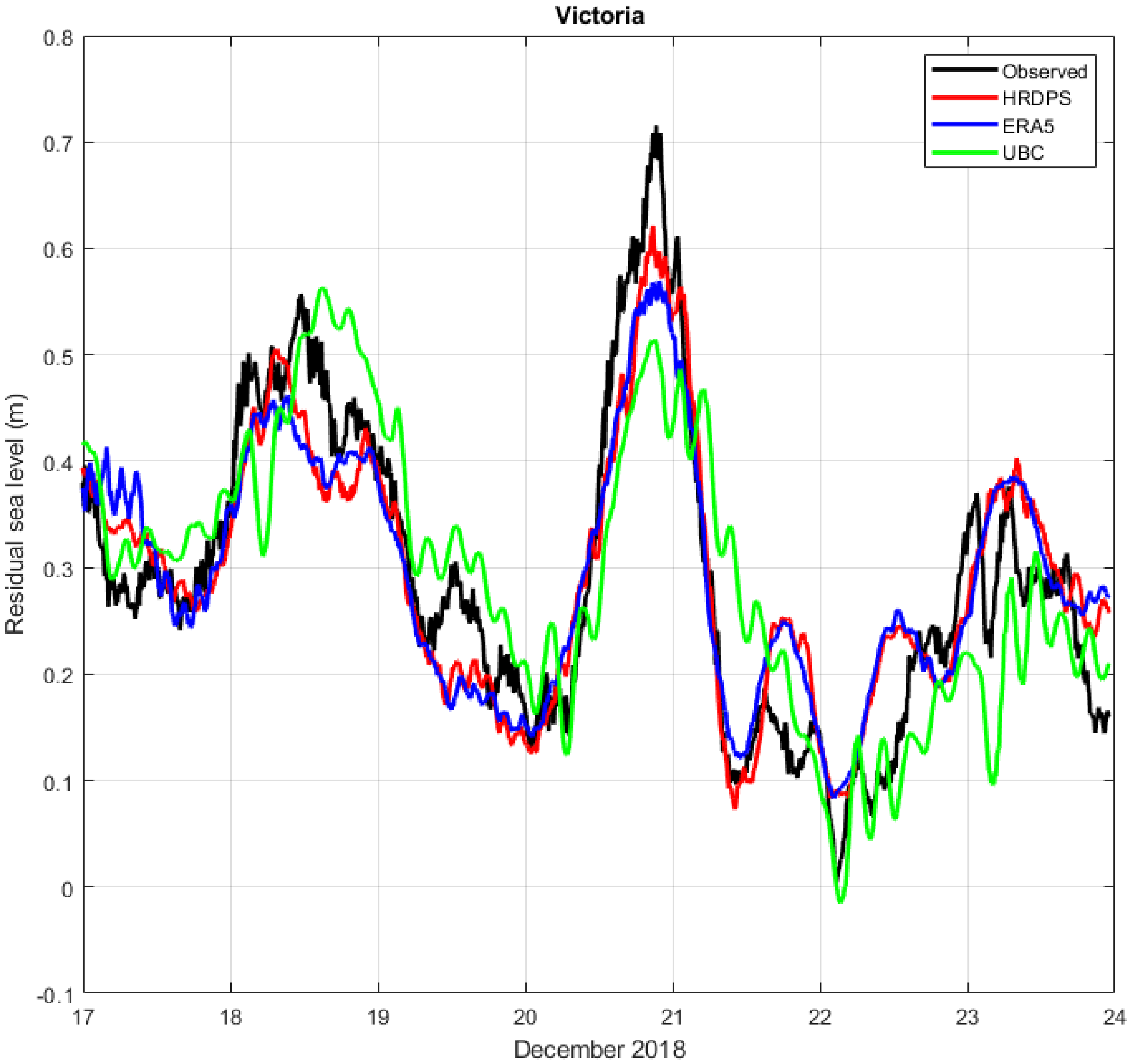

Figure A6. Comparison of the modeled sea level versus the observed records (black curve) at Victoria for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

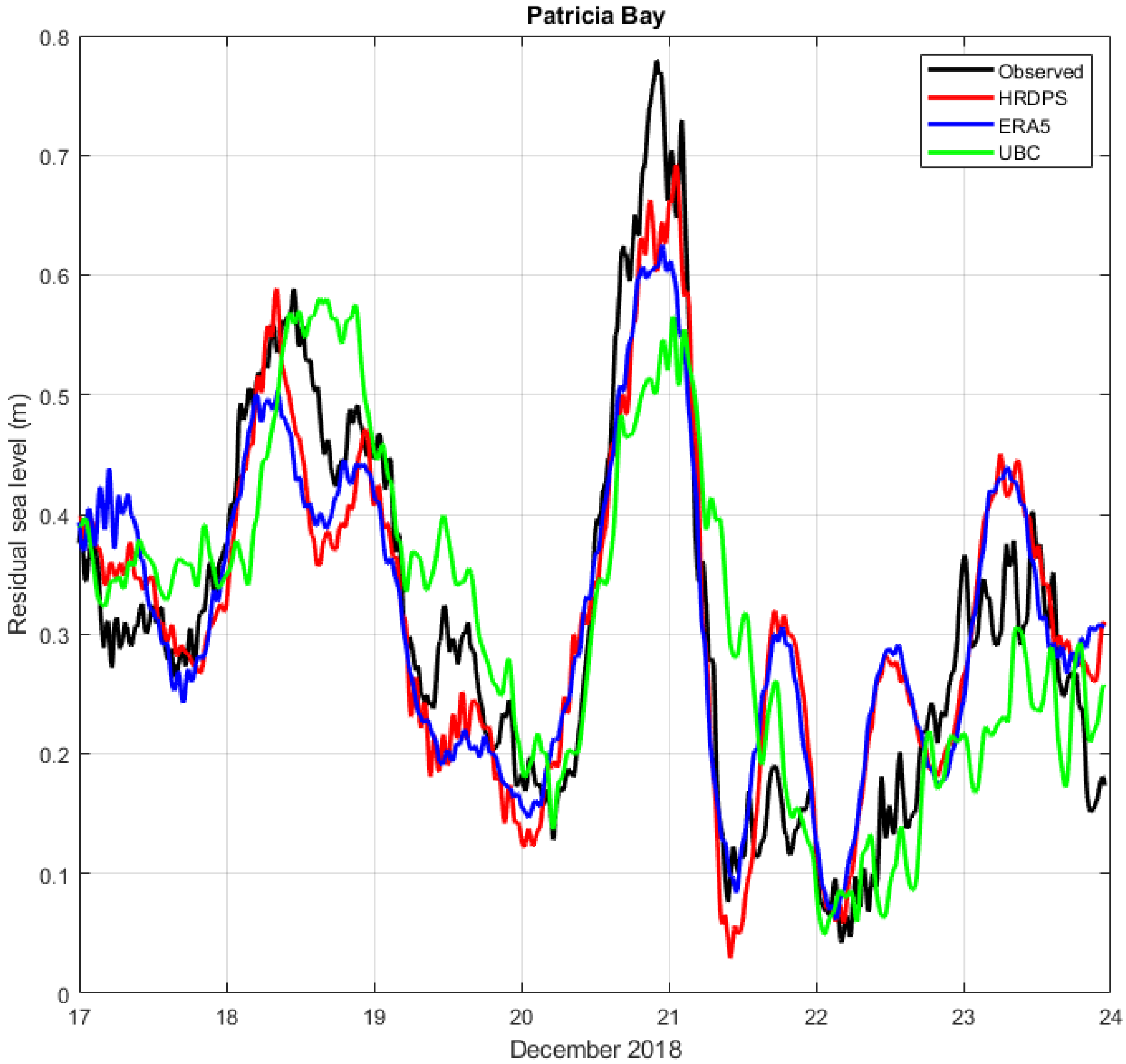

Figure A7. Comparison of the modeled sea level versus the observed records (black curve) at Patricia Bay for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

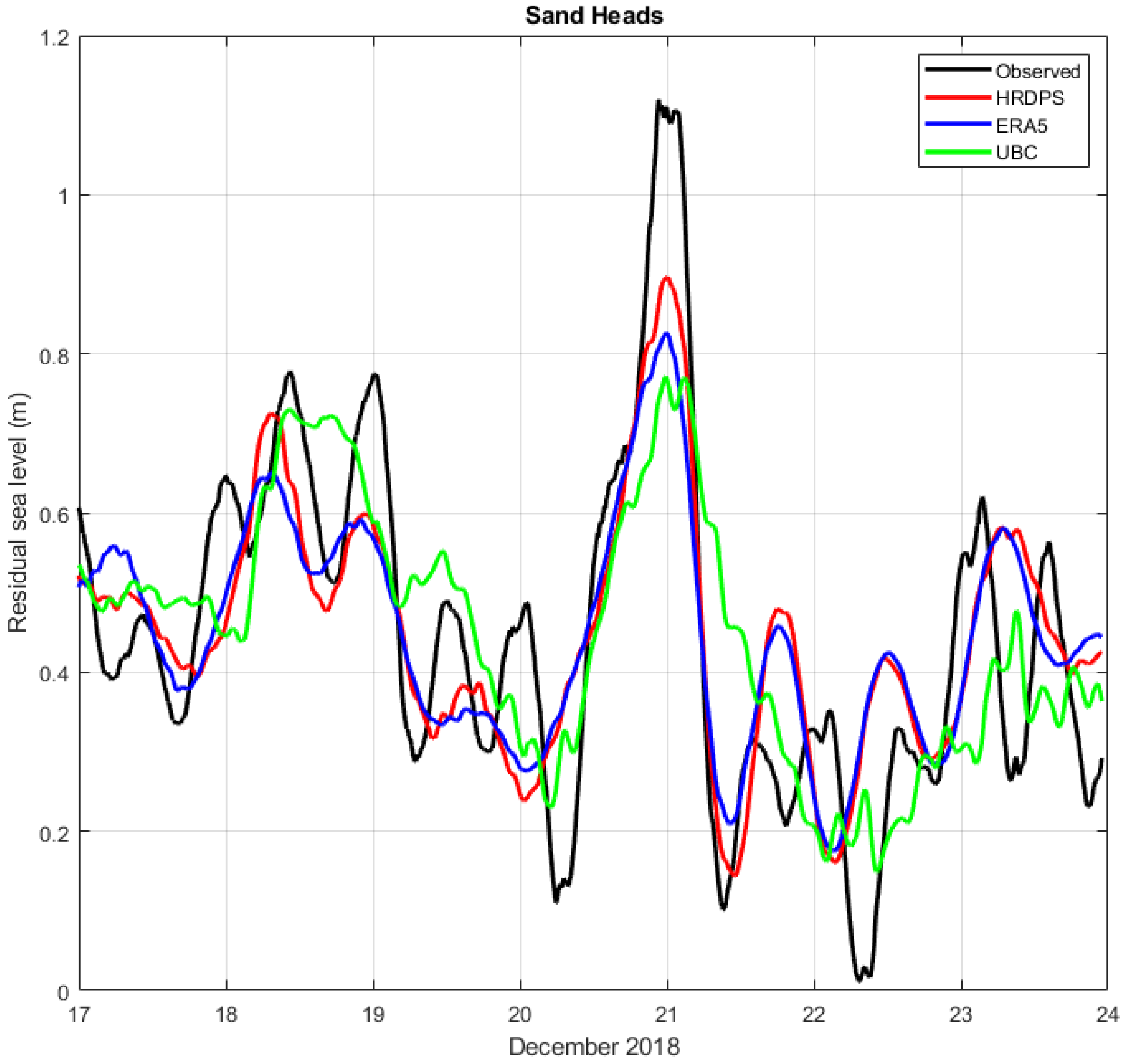

Figure A8. Comparison of the modeled sea level versus the observed records (black curve) at Sand Hands for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

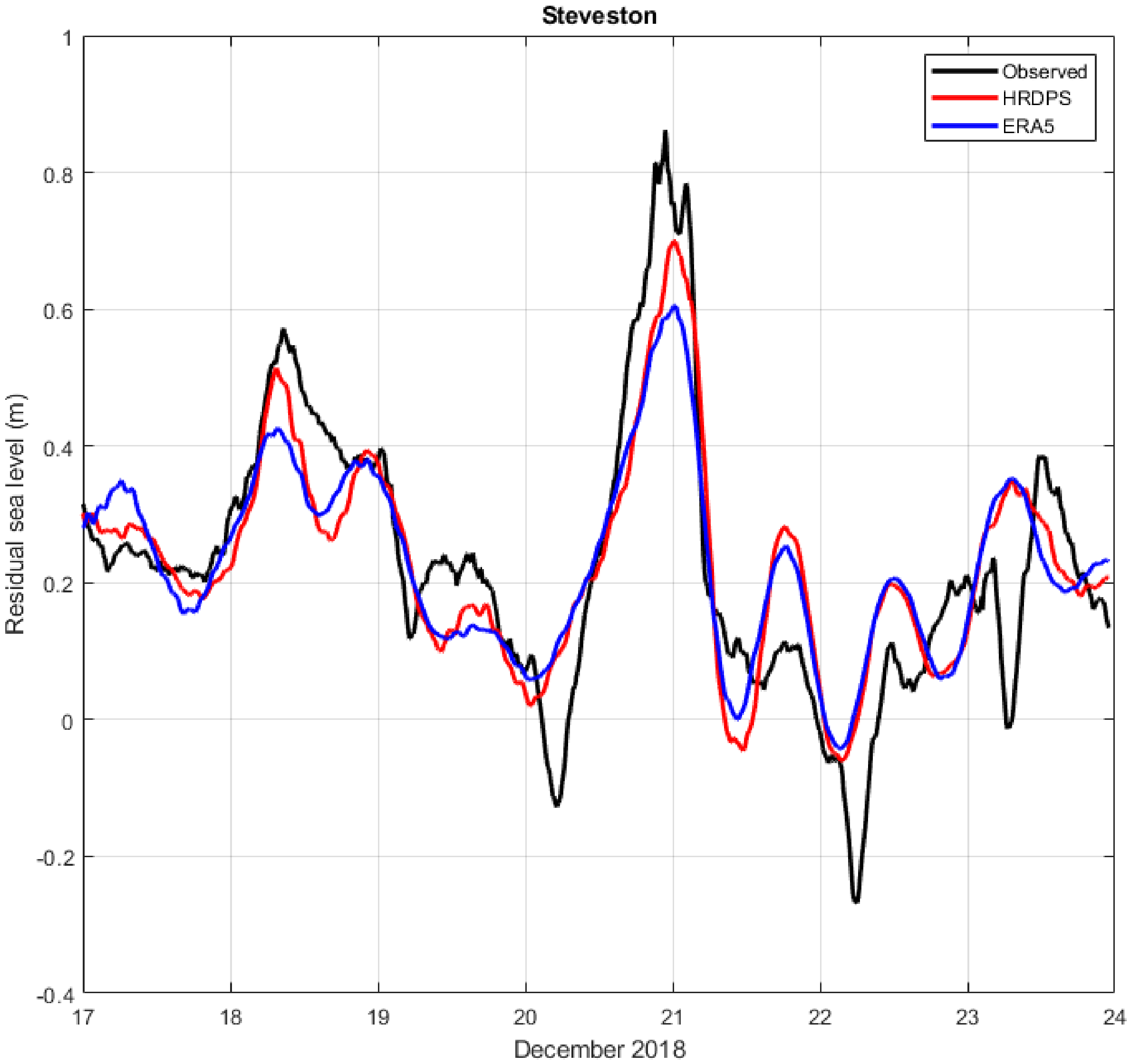

Figure A9. Comparison of the modeled sea level versus the observed records (black curve) at Port Renfrew for HRDPS (red curve) and ERA5 forcing (blue curve).

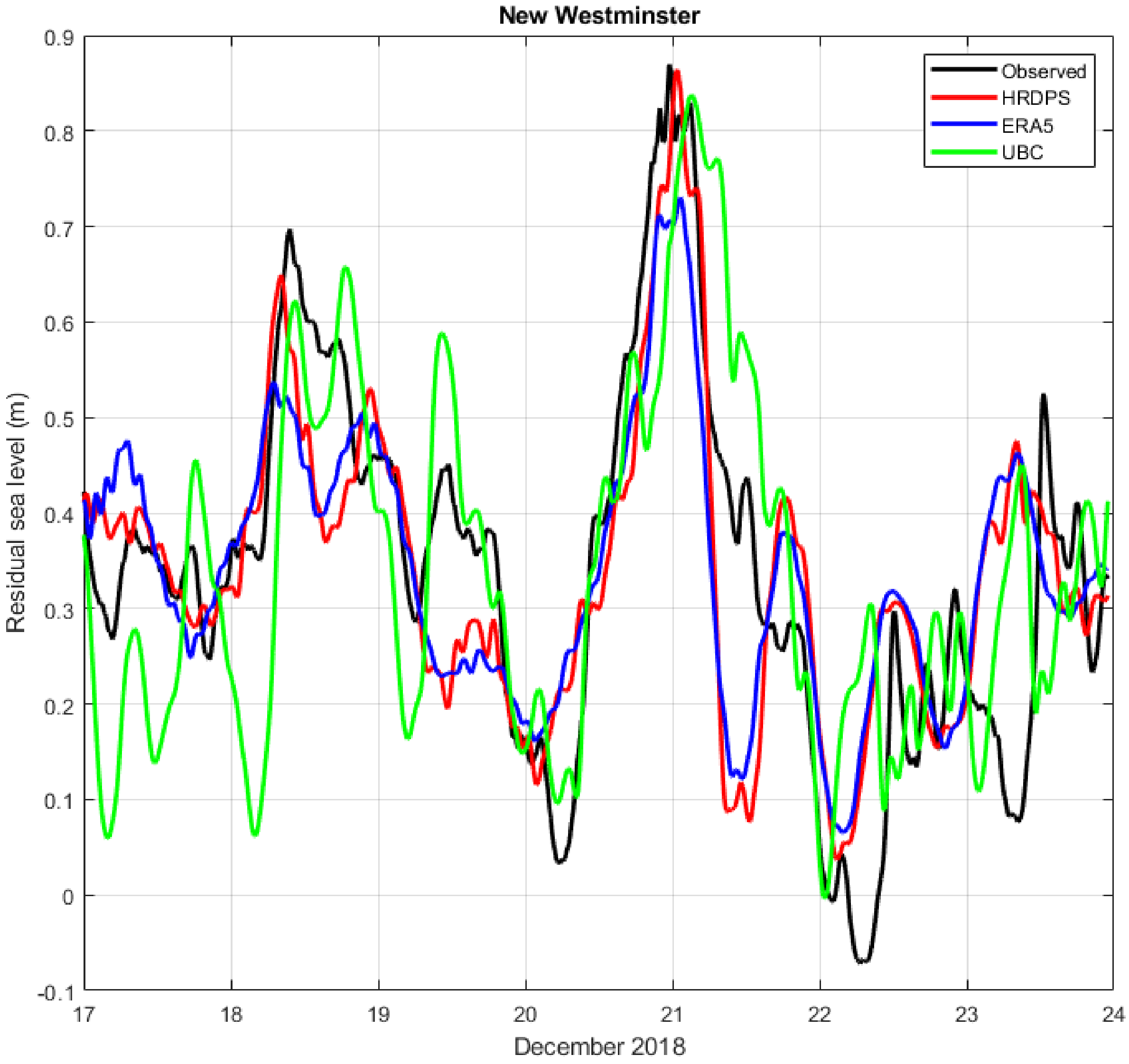

Figure A10. Comparison of the modeled sea level versus the observed records (black curve) at New Westminster for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

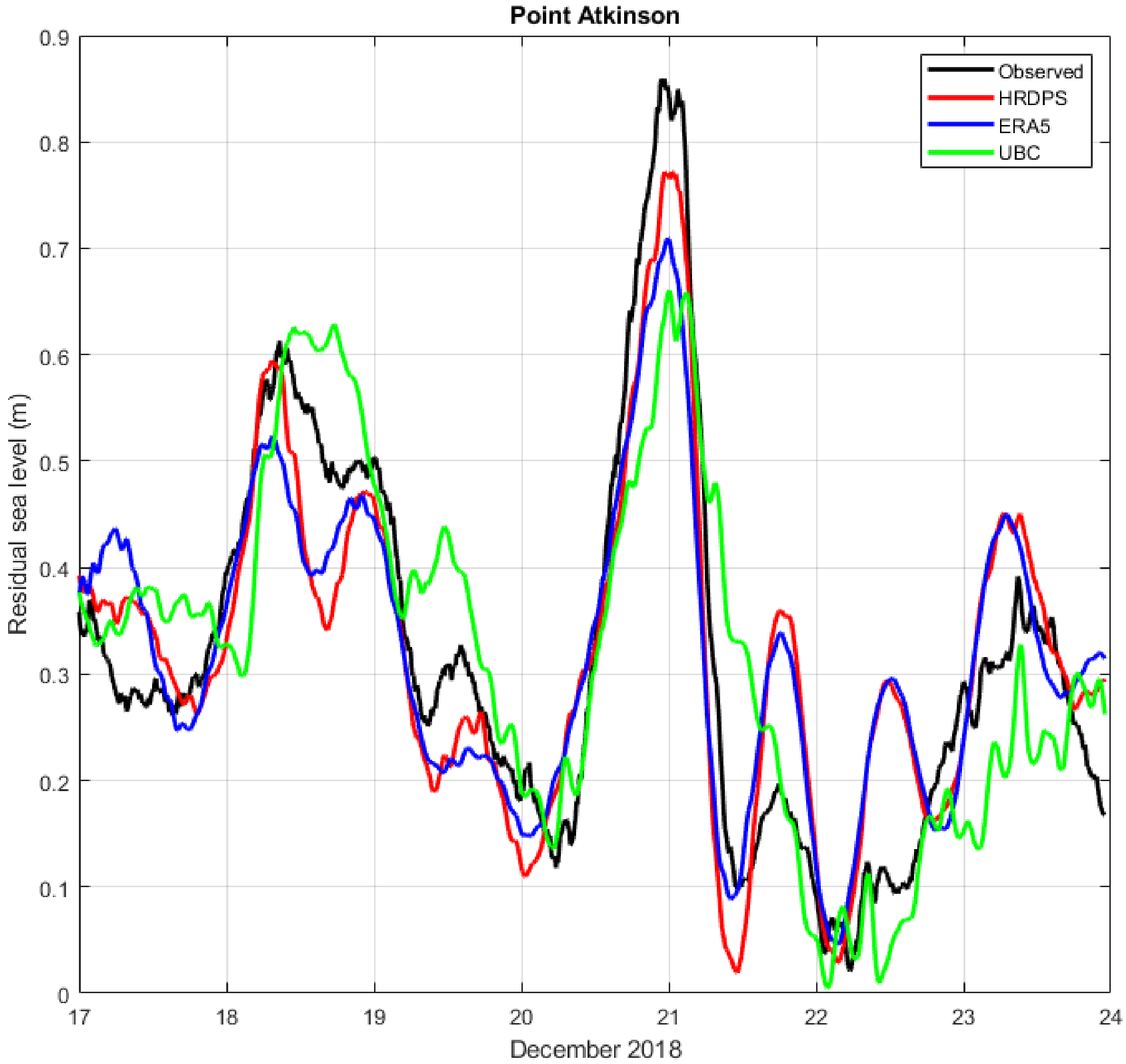

Figure A11. Comparison of the modeled sea level versus the observed records (black curve) at Point Atkinson for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

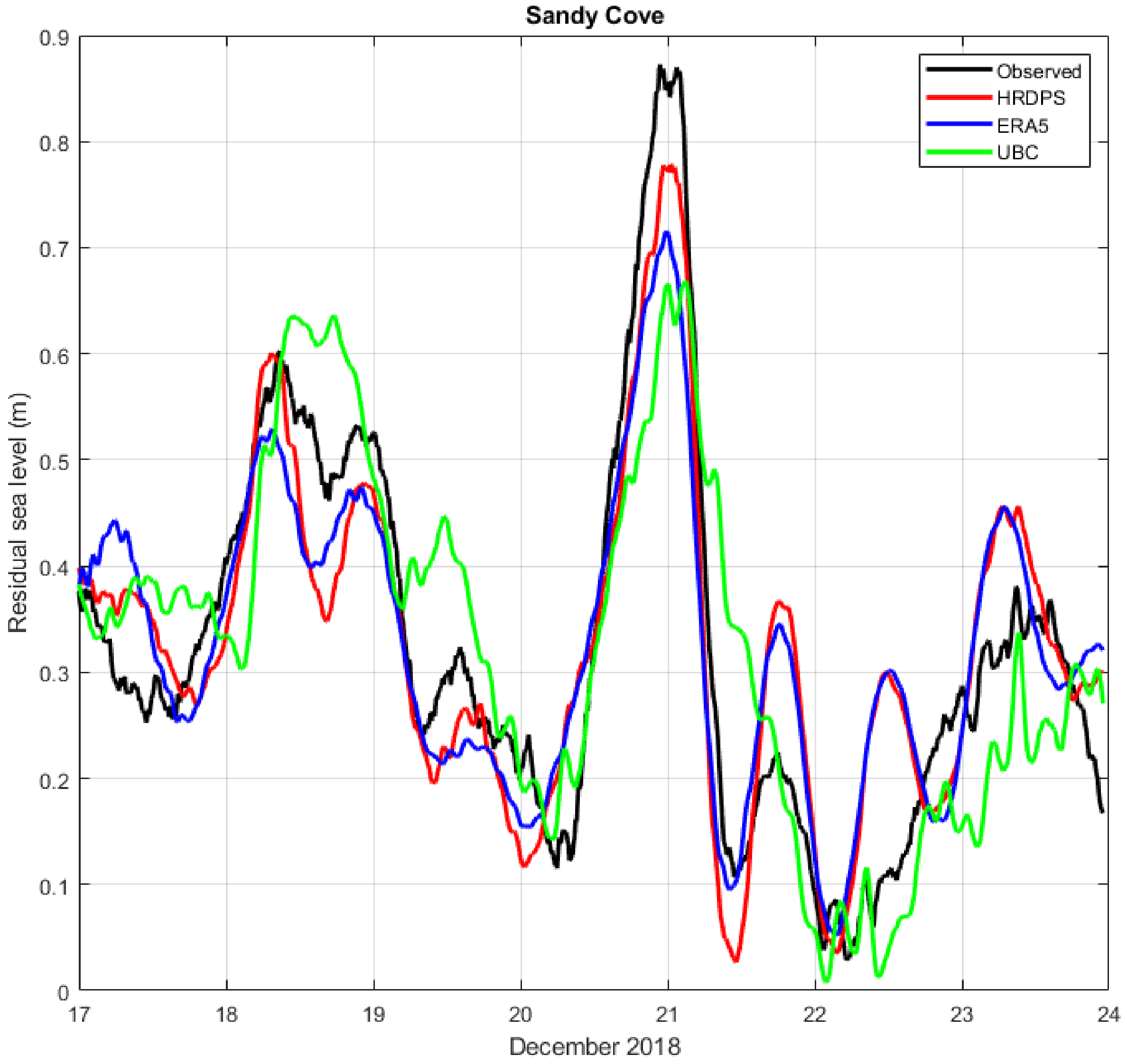

Figure A12. Comparison of the modeled sea level versus the observed records (black curve) at Sandy Cove for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

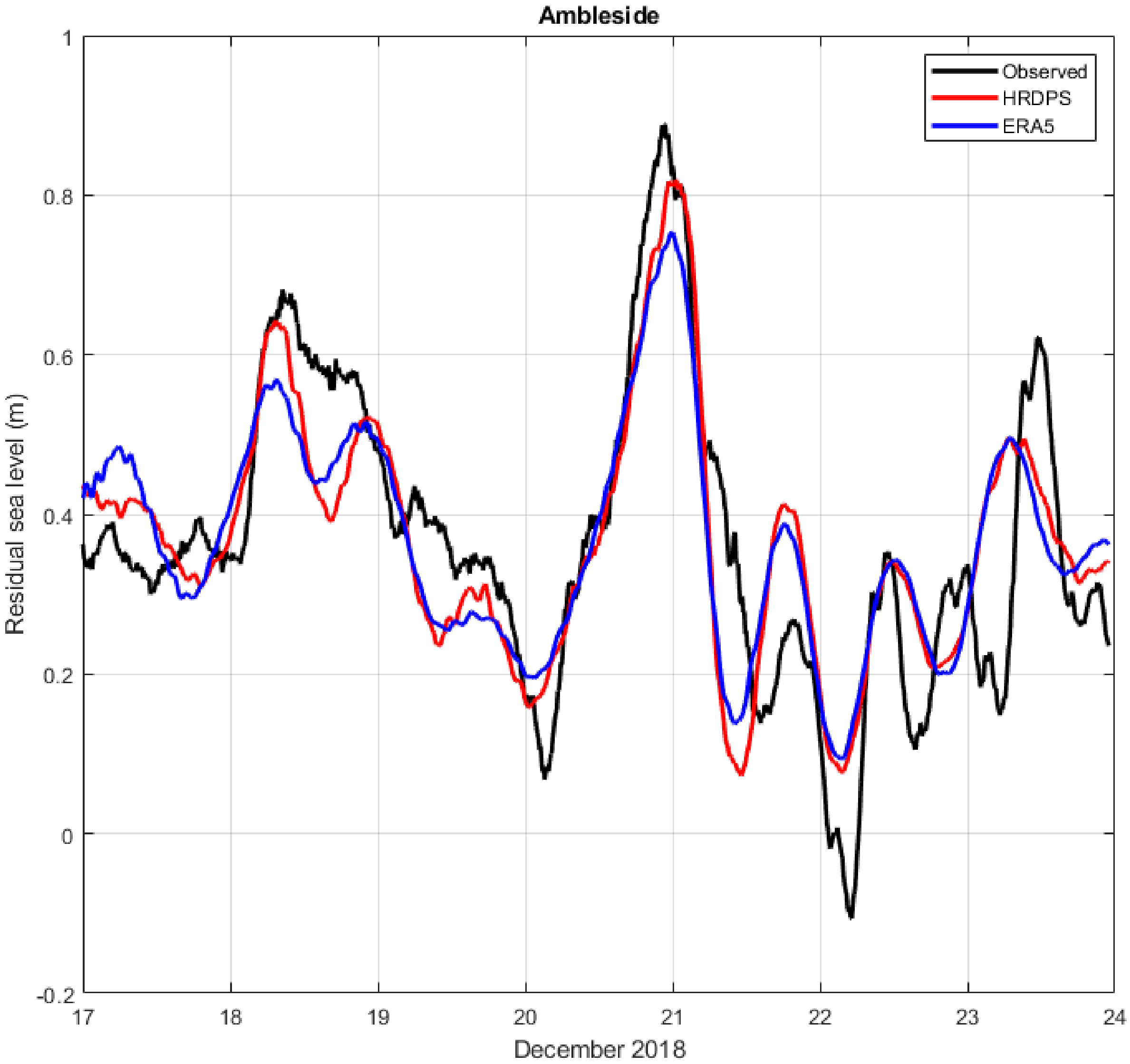

Figure A13. Comparison of the modeled sea level versus the observed records (black curve) at Ambleside for the HRDPS (red curve) and ERA5 forcing (blue curve).

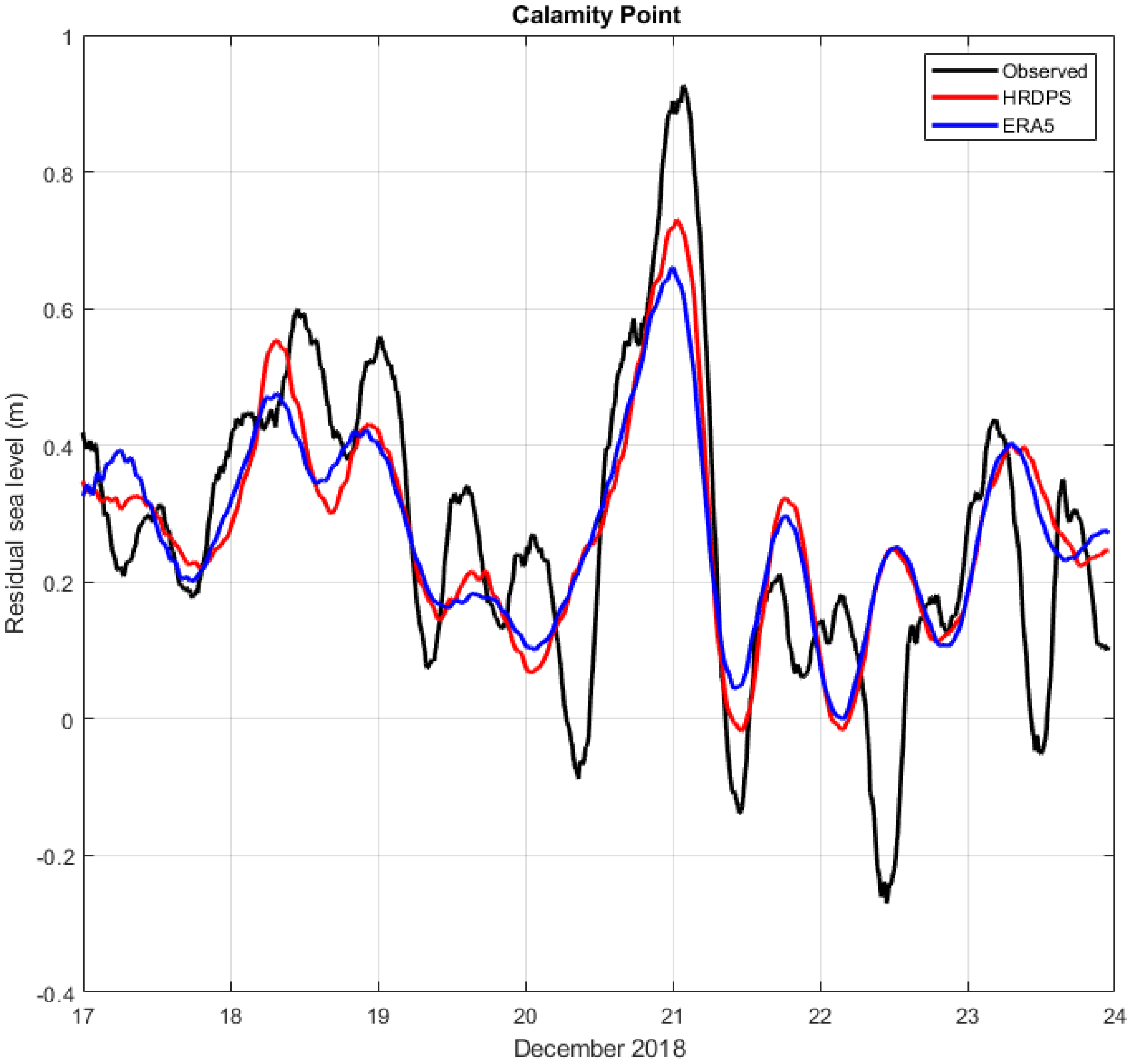

Figure A14. Comparison of the modeled sea level versus the observed records (black curve) at Calamaty Point for the HRDPS (red curve) and ERA5 forcing (blue curve).

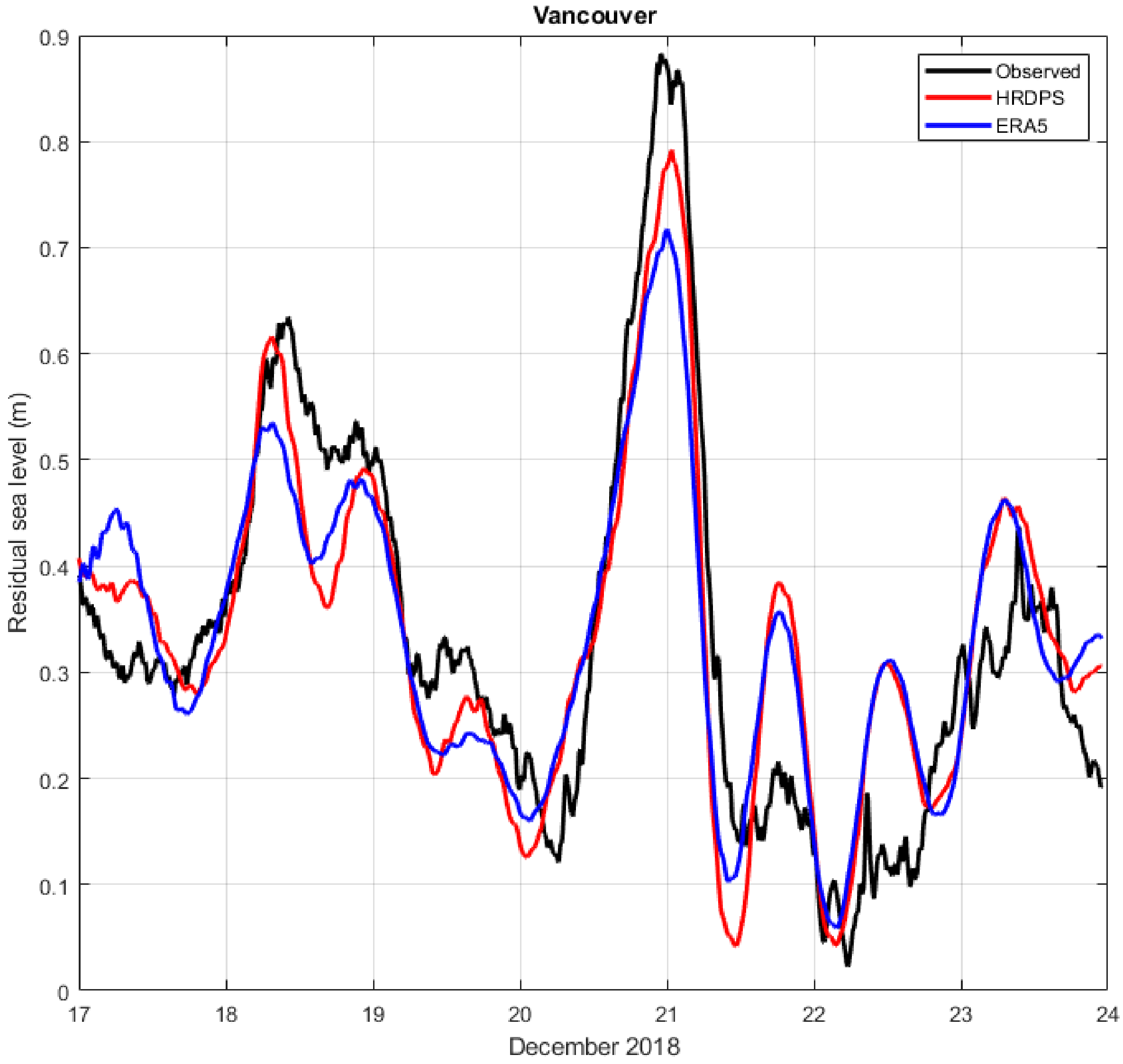

Figure A15. Comparison of the modeled sea level versus the observed records (black curve) at Vancouver for the HRDPS (red curve) and ERA5 forcing (blue curve).

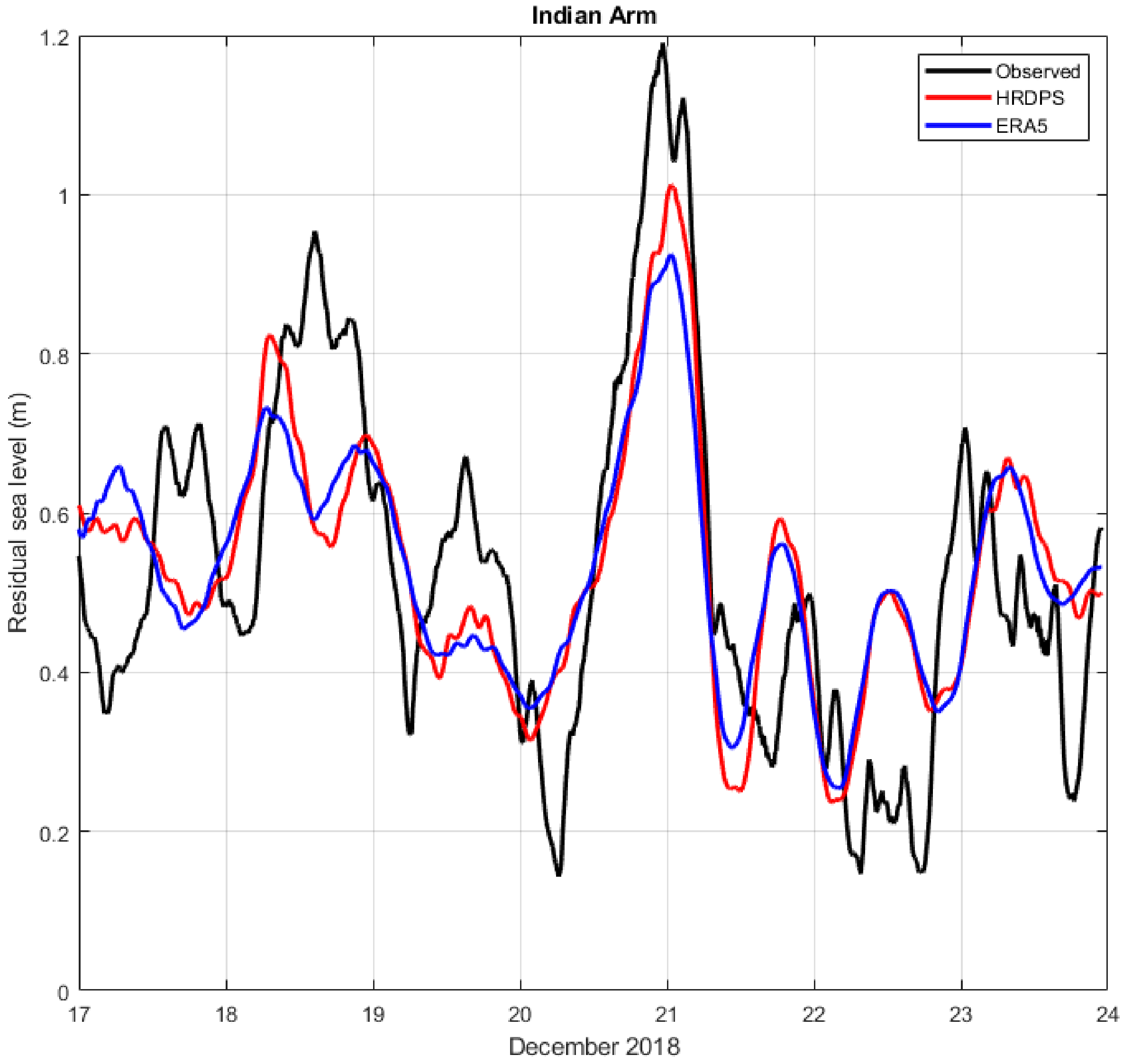

Figure A16. Comparison of the modeled sea level versus the observed records (black curve) at Indian Arm for the HRDPS (red curve) and ERA5 forcing (blue curve).

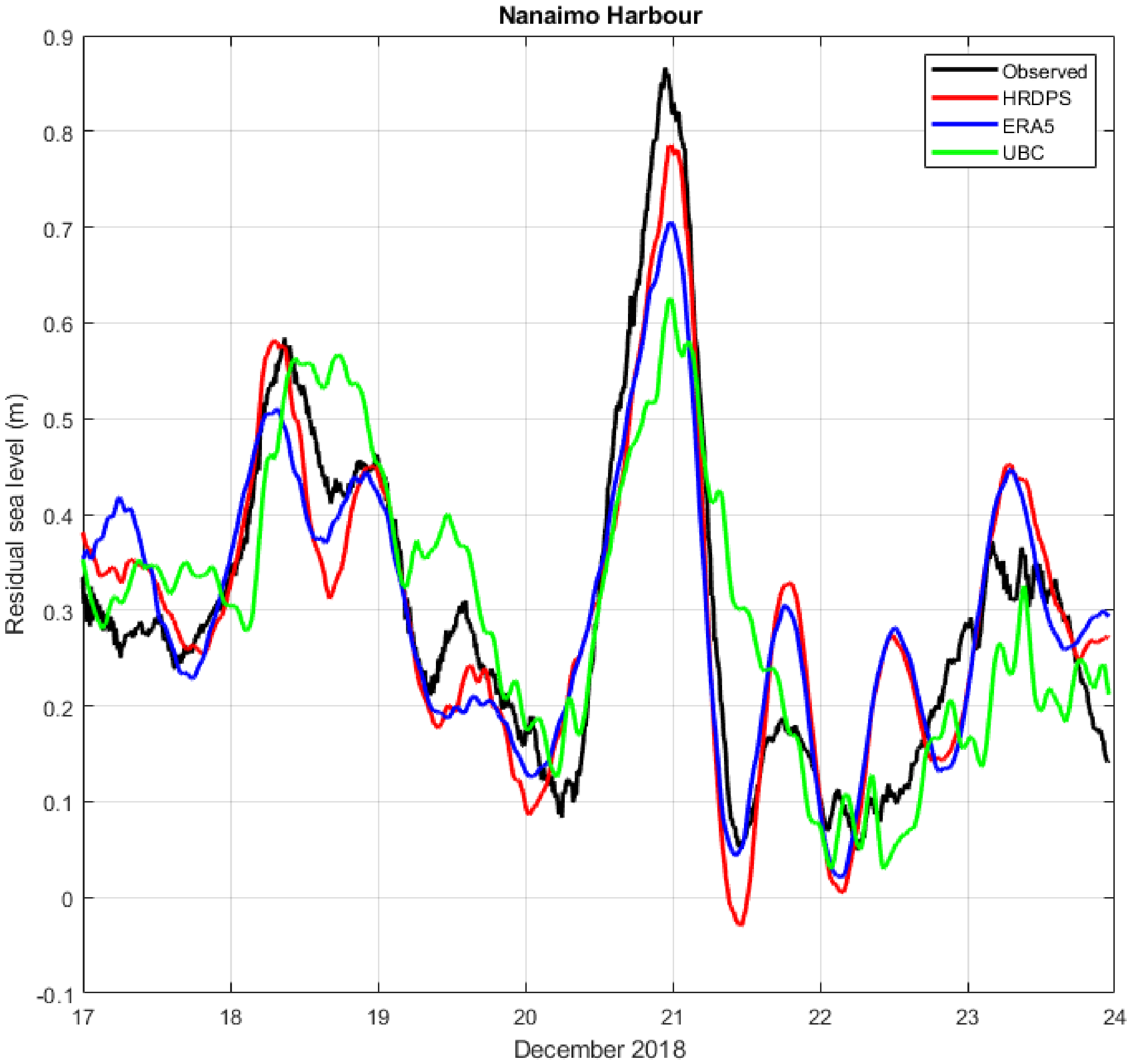

Figure A17. Comparison of the modeled sea level versus the observed records (black curve) at Nanaimo Harbour for HRDPS forcing (red curve), ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).

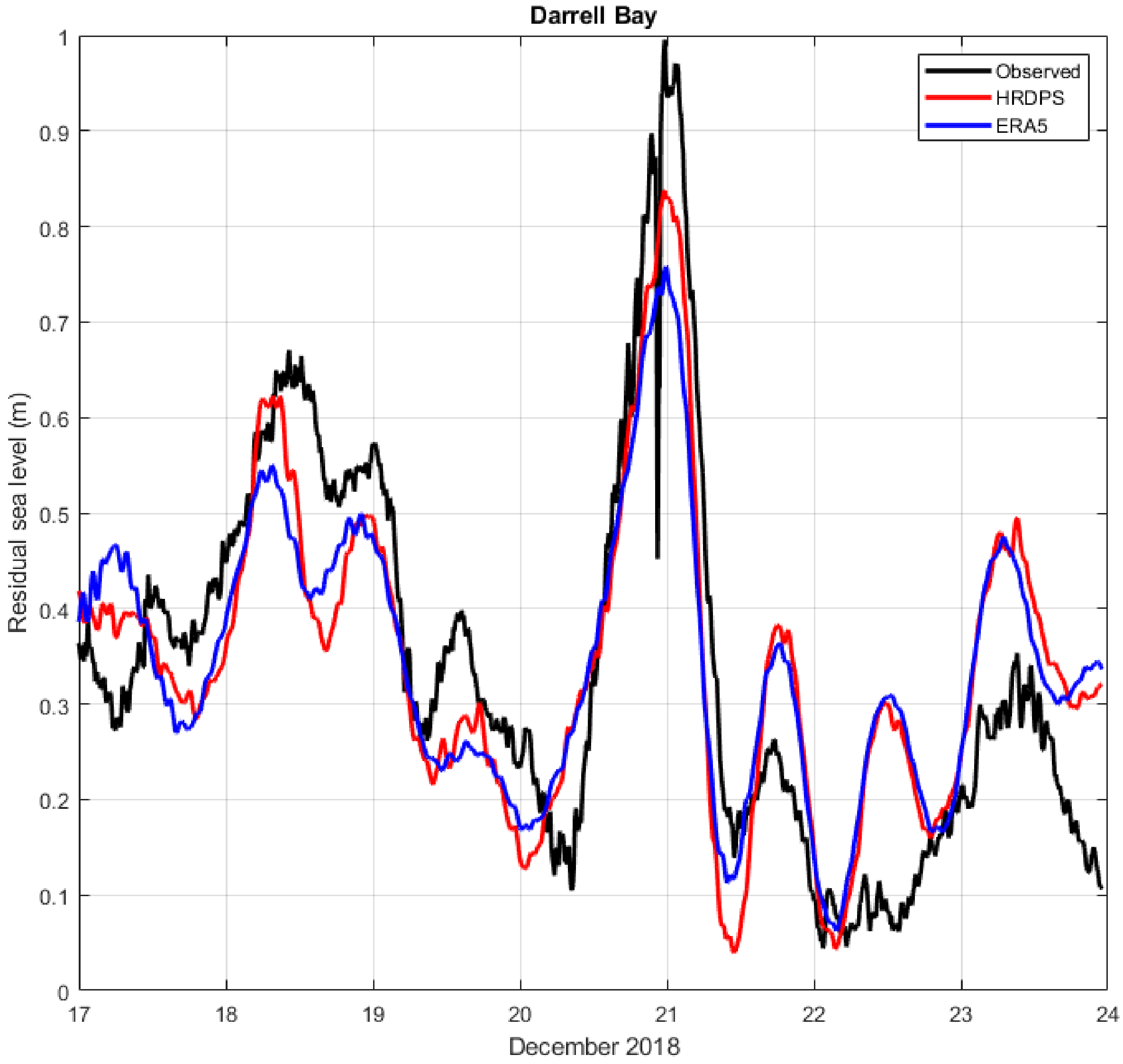

Figure A18. Comparison of the modeled sea level versus the observed records (black curve) at Darrel Bay for the HRDPS (red curve) and ERA5 forcing (blue curve).

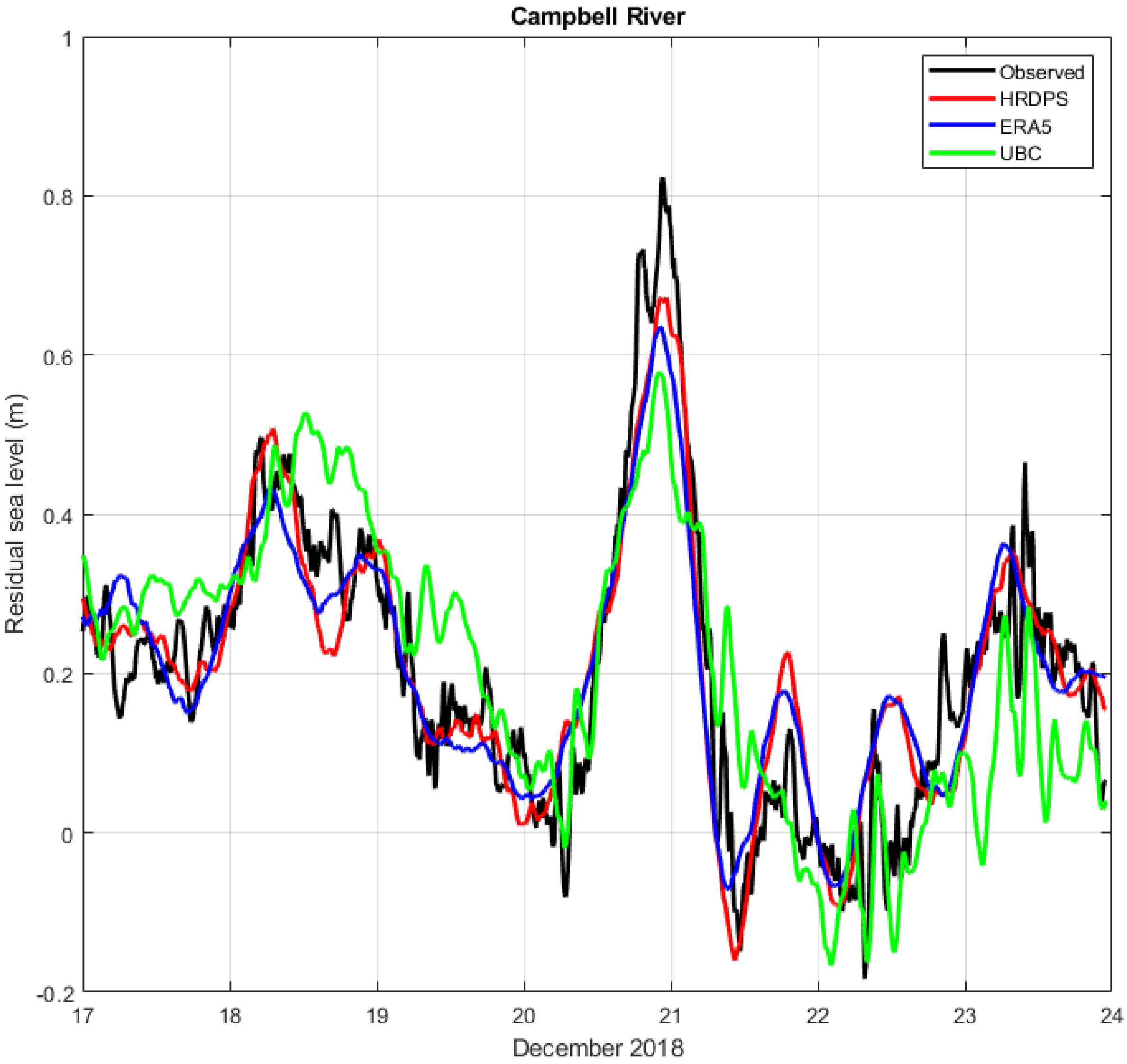

Figure A19. Comparison of the modeled sea level versus the observed records (black curve) at Port Renfrew for HRDPS (red curve) forcing, ERA5 forcing (blue curve), and the UBC Salish Sea Storm Surge model (green curve).