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Storm surges in the Strait of Georgia simulated with a regional model

Nancy Soontiens^{1*}, Susan E. Allen¹, Doug Latornell¹, Kate Le Souëf¹, Idalia Machuca¹,

Jean-Philippe Paquin², Youyu Lu³, Keith Thompson², Vasily Korabel²

¹University of British Columbia; ²Dalhousie University; ³Bedford Institute of Oceanography

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The Strait of Georgia is a large, semi-enclosed body of water between Vancouver Island and the mainland of British Columbia connected to the Pacific Ocean via the Strait of Juan de Fuca at the south and Johnstone Strait at the north. During the winter months, coastal communities in the Strait of Georgia are at risk to flooding caused by storm surges, a natural hazard that can occur when a strong storm coincides with high tide. This investigation produces storm surge hindcasts using a three-dimensional numerical ocean model for the Strait of Georgia and the surrounding bodies of water (Strait of Juan de Fuca, Puget Sound, and Johnstone Strait) collectively known as the Salish Sea. The numerical model employs the Nucleus for European Modelling of the Ocean (NEMO) architecture in a regional configuration. The model is evaluated through the comparisons of tidal elevation harmonics and storm surge with observations. Important forcing factors contributing to storm surges have been assessed. It is shown that the surge entering the domain from the Pacific Ocean contributes most significantly to the surge amplitude within the Strait of Georgia. Comparisons between simulations with high resolution and low resolution atmospheric forcing further emphasize that remote forcing is the dominant factor in surge amplitudes of this region. In addition, local wind patterns cause a slight increase in surge amplitude on the mainland side of the Strait of Georgia when compared to the Vancouver Island coastal areas during a major wind storm on Dec 15, 2006. Generally, surge amplitudes are found to be greater within the Strait of Georgia when compared to amplitudes in the Strait of Juan de Fuca.

KEYWORDS: storm surge; Strait of Georgia; Salish Sea; numerical modelling; spatial variation

*Corresponding author's email: nsoontie@eos.ubc.ca

1 Introduction

The Strait of Georgia is a strongly stratified, semi-enclosed body of water located between Vancouver Island and the mainland of British Columbia (Thomson, 1981). It is part of a larger system of waterways collectively known as the Salish Sea and is connected to the Pacific Ocean via the Strait of Juan de Fuca and Johnstone Strait (Figure 1). At its southern end, the Strait of Georgia is connected to the Strait of Juan de Fuca through several passages, the largest being Haro Strait. The San Juan and Gulf Islands are scattered throughout these passages where complex bathymetry and steep topographic slopes induce vigorous tidal mixing (Thomson, 1981). Mixed diurnal and semi-diurnal tides are found throughout most of the Salish Sea but a semi-diurnal amphidrome is present nearby Victoria, where the tides are mainly diurnal (Thomson, 1981). This system is a home to several large coastal communities, such as Vancouver and Victoria, serves as a waterway for commercial traffic and recreational use, and supports a large and active fishing industry.

Many coastal communities in the Strait of Georgia are at risk of flooding and property damage caused by storm surges, a natural hazard arising from the combination of a strong wind storm and high tide. The low atmospheric pressure associated with a storm acts as an inverse barometer elevating the sea level. This effect in combination with strong winds pushing water up against the coast can cause flooding, particularly if the storm occurs during an unusually high tide. There is also a small contribution to increased sea level due to positive sea surface height anomalies propagating northward from the equator along the eastern Pacific coast during El Nino years (Strub & James, 2002). Communities in the Strait of Georgia are particularly susceptible to storm surges in the winter months when there is an increased propensity for storms and a higher sea level caused by southeasterly winds and geostrophic adjustment (Danard, Munro, & Murty, 2003). In the summer months, the wind direction changes to northwesterly and mean sea level is lower. In British Columbia waters, the largest tidal ranges occur in June and December at the summer and winter solstices (Thomson, 1981). The highest water levels are observed in the winter around the perigean spring tide or “King” tide, when the sun and moon are aligned

with the Earth and the moon is at its perigee. Storm surges in the Strait of Georgia are typically observed between November and February (Forseth, 2012). Flooding caused by a storm surge is most likely to occur during a high spring tide (Abeysirigunawardena, Smith, & Taylor, 2011).

Coastal communities can prepare for and respond to storm surge hazards using predictions from storm surge models to determine if flooding conditions are probable. Like coastal ocean models, some of the complexity of a storm surge model depends on the properties of the geographic location of interest. In shallow regions, it is important to include the effects of wetting and drying which allows grid cells to alternate between land and water depending on the modelled sea surface height and depth (Hubbert & McInnes, 1999; Weisberg & Zheng, 2006). Other regions require modelling over a very large domain since non-local effects from the open sea may influence surge propagation (Lane & Walters, 2009; Mercer, Sheng, Greatbatch, & Bobanović, 2002; Weisberg & Zheng, 2006). Such large domains typically use nested or unstructured grids to resolve the details of complicated coastlines. Appropriate treatment of rivers (Flather, 1994), accurate bathymetry and the inclusion of surface waves (Xu, Zhang, Shen, & Li, 2010) have also been identified as important. Most of these models neglect the effects of stratification by treating the ocean as a constant temperature and salinity. An accurate forecast of the meteorological conditions at the ocean surface is of course essential in the generation of useful storm surge forecasts.

Storm surge modelling in the Strait of Georgia dates back to P. Crean, Murty, and Stronach (1988) who used a barotropic finite difference model. Their work is highlighted in reviews of storm surges in Canadian waters (Danard et al., 2003; Murty, Venkatesh, Danard, & El-Sabh, 1995). Compared to eastern Canada (Bernier & Thompson, 2006, 2007, 2010; Bobanović, Thompson, Desjardins, & Ritchie, 2006; Gray et al., 1984; Ma, Han, & de Young, 2015), relatively little has been published on storm surge modelling on the west coast of Canada in recent years. However, a storm surge forecasting program is currently operating over a domain that covers the entire British Columbia coastline (Tinis, 2014). Further, a statistical overview of past surge events in British Columbia waters suggests an increase in extreme water level events during warm El Nino

periods (Abeyasinghe et al., 2011).

The early modelling work of P. Crean et al. (1988), P. B. Crean, Murty, and Stronach (1988) and Stronach, Backhaus, and Murty (1993) developed a series of models covering the Strait of Juan de Fuca, the Strait of Georgia, and Puget Sound using a finite difference discretization of the equations of motion. These models pointed to an important connection between the model's bottom friction parametrization and the location and amplitude of the M_2 amphidrome. They found that a local increase in the bottom friction coefficient, typically from 0.002 to 0.004 in the baroclinic model, especially in the vicinity of Haro Strait, was necessary in order to adequately reproduce the observed M_2 tidal amplitudes and phase lags in the Strait of Georgia (Stronach et al., 1993). Without local adjustments to the bottom friction their M_2 amplitudes were too low and the M_2 tidal phases were too large in the Strait of Georgia (P. Crean et al., 1988). Local adjustments to bottom friction were applied in both their barotropic and baroclinic models. Other studies over a similar domain, such as the barotropic finite element model of Foreman, Walters, Henry, Keller, and Dolling (1995), have avoided local increases in bottom friction although their domain did not include Puget Sound and the northern Strait of Georgia. Foreman, Sutherland, and Cummins (2004) assimilated tide gauge harmonics to study M_2 tidal dissipation without local changes to the bottom friction in a two-dimensional finite element model that did not include baroclinic effects.

More recently, modelling studies have focused on baroclinic features. Masson and Cummins (2004) used the Princeton Ocean Model (POM) in a regional mode to examine the seasonal variability of deep water properties in the Strait of Georgia and noted a strong sensitivity to vertical mixing over the sills. This model employed a sigma or terrain-following vertical coordinate system leading to spurious diapycnal mixing since, numerically, the lateral mixing is computed on sigma levels which may intersect isopycnals in the presence of steep topography. Sutherland, MacCready, Banas, and Smedstad (2011) employed the Regional Ocean Modelling System (ROMS) to study estuarine circulation in the Salish Sea with a model domain that extended outside the Strait of Juan de Fuca into the Pacific Ocean and up to the northern Strait

of Georgia. They noted that their semi-diurnal amplitudes were generally too low. An updated version of this model with added biogeochemical components and an extended domain produced higher than observed surface temperatures in the Strait of Juan de Fuca, suggesting too little mixing within the Salish Sea (Giddings et al., 2014). Smaller domains have also been considered; notably, the passageways through the Discovery Islands north of the Strait of Georgia have been modelled baroclinically by Foreman et al. (2012) with the Finite Volume Coastal Ocean Model (FVCOM) pointing to difficulties in reproducing baroclinic currents on their grid. Accurate reproduction of observed tidal amplitudes and phases and appropriate treatment of mixing is a recurring difficulty in modelling this region.

This article presents the development of a three-dimensional numerical ocean model for the Strait of Georgia and its skill in simulating storm surge hindcasts. The main purposes are to identify the forcing factors that contribute most significantly to storm surges in the Strait of Georgia, to examine the spatial distribution of the storm surge, and to evaluate the performance of a new model of this region. To complement previous barotropic storm surge modelling in this region, this model employs a higher resolution and includes the effect of stratification and rivers. However, wetting and drying is not represented. Model evaluation has focused on regions where the near-coast slopes are steep and so wetting and drying effects are believed to be unimportant. A detailed overview of the model configuration and domain is provided in section 2. That section also describes open and surface boundary conditions as well as choices in grid structure and mixing parametrizations. Next, section 3 presents an evaluation of model performance through comparisons of tidal amplitudes and phases with observations. The model's skill in producing storm surge hindcasts is assessed in section 4. Several simulations comparing the effects of different forcing conditions are also discussed. Finally, a summary and discussion of future research goals is provided in section 5.

2 Model Description

We have used the Nucleus for European Modelling of the Ocean (NEMO) framework in its regional configuration (Madec et al., 2012) to develop an ocean model for the Salish Sea. NEMO is a highly modular tool used for studying ocean physics, ocean-ice interactions, and the biogeochemical properties of the ocean. NEMO's ocean core solves the three-dimensional hydrostatic equations of motion for an incompressible fluid under the Boussinesq approximation on a structured computational grid. **Although these features are not being used in the present work, NEMO's options for grid nesting and bio-geochemical coupling make it a useful tool for studying the complex physics and bio-geochemical interactions within the Strait of Georgia.** This work focuses on the physical configuration of the Salish Sea model, in particular, determining appropriate forcing and boundary conditions for accurate reproduction of tidal amplitudes and phases as well as storm surge elevations. Future work will include bio-geochemical coupling and data assimilation. NEMO version 3.4 was used in this study. **NEMO has been successfully used in other coastal modelling studies in the Northeast Atlantic (Maraldi et al., 2013) and the Mediterranean Sea (Brossier, Béranger, & Drobinski, 2012).**

The modelled domain extends from the Strait of Juan de Fuca to Puget Sound to Johnstone Strait (Figure 1). Bathymetry from the Cascadia physiography data set (Haugerud, 1999) was smoothed to limit large changes in depth across grid cells, so that $\Delta h/\bar{h} \leq 0.8$, where Δh is the difference in depth between two adjacent grid cells and \bar{h} is their average depth. For model stability, additional smoothing at the Strait of Juan de Fuca western boundary was imposed to achieve constant depth across the first ten grid cells **inward from the open boundary. Depths between 0 m and 4 m were set to 4 m and a minimum depth of 4 m was imposed by NEMO.** As depicted in Figure 1, the numerical grid is rotated 29° counter-clockwise of North in order to maintain computational efficiency since currents within the Strait of Georgia are mainly aligned with this rotated axis. **A magnified image of the complex passages through the San Juan and Gulf Islands is provided in Figure 2.**

The curvilinear orthogonal numerical grid has been divided into 398 by 898 by 40 grid

cells, which results in an almost uniform horizontal resolution with grid spacing approximately 440 m by 500 m. The 40 vertical z -levels were stretched gradually in order to achieve higher resolution in the surface layer, with 1 m vertical grid spacing down to about 10 m in depth. Below 10 m the grid was stretched to a maximum grid spacing of 27 m in the lowest layer. At the bottom boundary, partial z -levels were used in order to limit large changes in bathymetry across grid cells (Madec et al., 2012). Model constraints require that all passages be at least two grid points wide. This restriction required choices in either widening or closing narrow straits. In particular, Active Pass was closed and Porlier Pass was widened (Figure 2). Shallow regions were represented by constant depth of 4 m. All of these compromises are expected to have significant effects locally but minimal effects on the large scale.

In addition to the equations of motion, a prognostic equation for the sea surface height is solved at each time step. The inclusion of the sea surface height equation requires a fairly restrictive time step due to the presence of high speed surface gravity waves. As such, the split-explicit time stepping algorithm is employed, where the free surface and barotropic equations are solved with a smaller time step than that used for the other variables. The model baroclinic time step and barotropic time step are 10 s and 2 s respectively. Small vertical grid spacing and large vertical velocities in the Boundary Pass and Haro Strait region impose a fairly restrictive baroclinic time step through the vertical Courant-Friedrichs-Lowy (CFL) condition.

The model includes two open boundaries that connect to the Pacific Ocean, the western boundary of the Strait of Juan de Fuca as well as Johnstone Strait at the north, both of which are forced with eight tidal constituents (K_1 , O_1 , P_1 , Q_1 , M_2 , K_2 , N_2 , S_2), temperature and salinity climatologies, and the sea surface height anomaly. Tidal heights and currents at grid points along the Juan de Fuca boundary were extracted from Webtide (Webtide, 2014), an online web prediction model that provides tidal predictions for the northeast Pacific Ocean based on work by Foreman, Crawford, Cherniawsky, Henry, and Tarbotto (2000). The Johnstone Strait boundary was forced with current and elevation tidal harmonics measured and calculated by Thomson and Huggett (1980) for the major M_2 and K_1 constituents. Additionally, O_1 and S_2

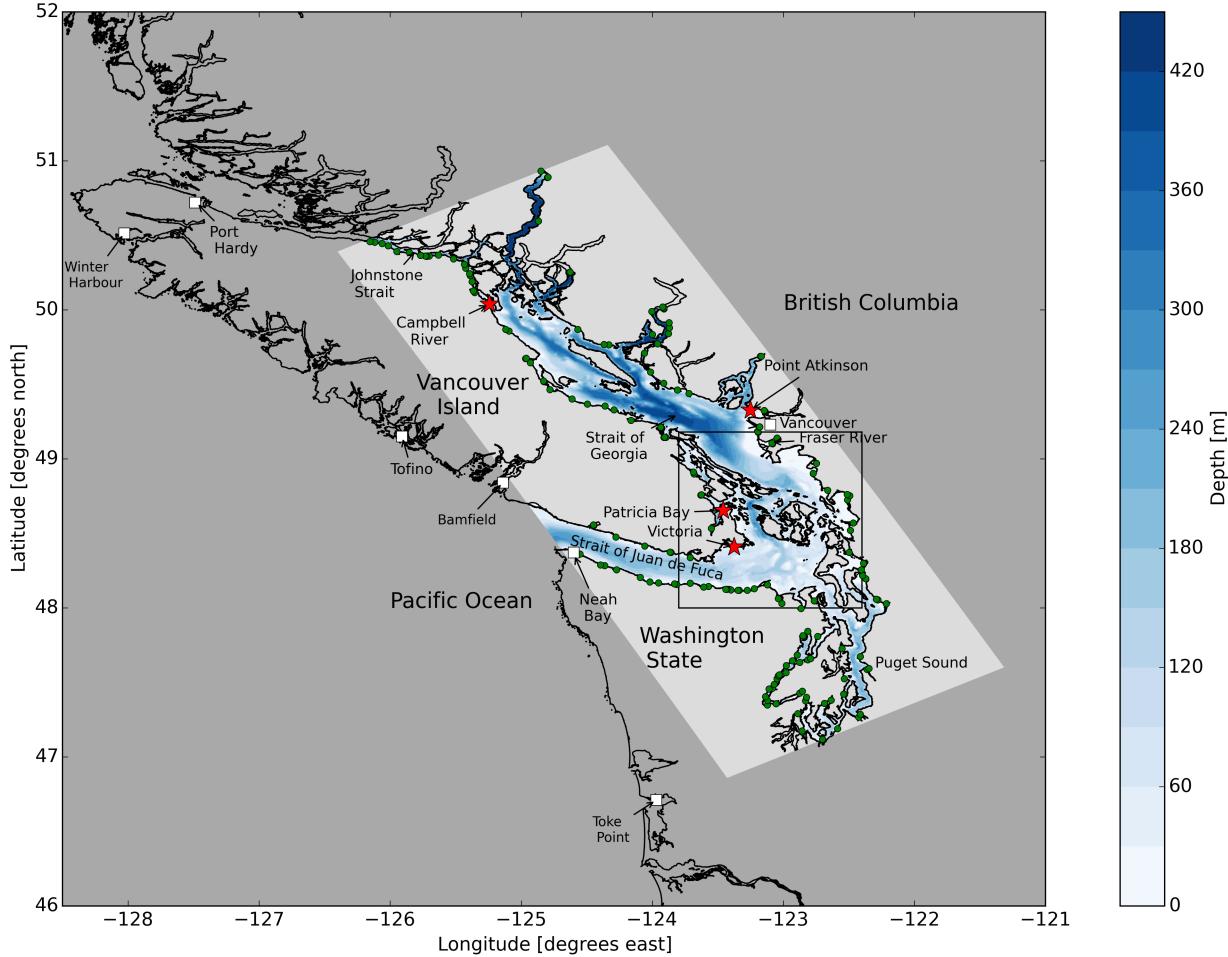


Fig. 1 Model domain (highlighted area) including bathymetry, rivers (green circles), and storm surge locations of interest (red stars). The black rectangle represents the region displayed in Figure 2.

elevation harmonics from their measurements were employed. The remaining constituents were extrapolated from Webtide. At the western boundary, the tidal elevation and currents forcing parameters were tuned for a good match with observations at locations within the Strait of Georgia, including Point Atkinson, Gibsons Landing, Winchelsea and Halfmoon Bay. At the northern boundary, the tides were tuned for good matches at Yorke Island and Kelsey Bay. Further details on the tuning are provided in Appendix A.

Temperature and salinity at the Juan de Fuca boundary were taken from a weekly climatology which was created from results of a model covering the Salish Sea and the west coast of Vancouver Island (Masson & Fine, 2012). Their results, originally on s -levels were interpolated onto z -levels and then onto the NEMO horizontal grid to give a two-dimensional forcing that

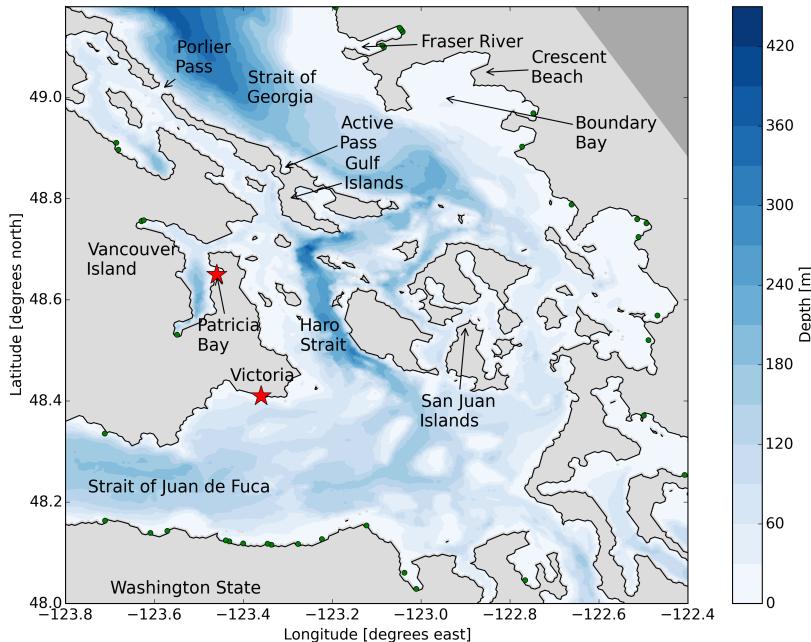


Fig. 2 Model bathymetry and coastlines in the passages between the San Juan and Gulf Islands.

varies with time. To prepare the climatology all years (1995-2008) were averaged and results, approximately every 15 days, were interpolated to a weekly climatology. The model is relaxed to the forced temperature and salinity over the 10 grid points (about 5 km) closest to the open boundaries, using a flow relaxation scheme (Engedahl, 1995). At the north, seasonal climatologies from Thomson (1981) were used.

Sea surface height anomaly (or remote forcing) was set uniformly across the mouth of Juan de Fuca using values from the Tofino tide gauge (Fisheries and Oceans Canada, 2014) which is outside of, but close to, the western boundary of the model domain (Figure 1). A monthly climatology was produced using daily averages from 2000-2010, binning them by month, averaging and setting the yearly mean to zero. For the storm surge simulations, hourly variations in sea surface height were used. These values are the Tofino tide gauge values with the tides removed. Tidal predictions were generated with a tidal analysis package called `t_tide` (Pawlowicz, Beardsley, & Lentz, 2002) using a time series from the year of the storm surge. A harmonic analysis was performed for 67 constituents. In order to prevent over-predicted constituents due to high surge years, the time series was first filtered by applying a Doodson filter (Parker, 2007) and removing periods with large non-tidal amplitudes. Long period constituents such as SA, SSA,

etc were not used in the tidal predictions since these constituents are often contaminated by non-tidal energy from seasonal meteorological trends. Further, constituents with a low signal to noise ratio were neglected. The storm surge simulations also used the sea surface height anomaly from Port Hardy, forced at the northern boundary in Johnstone Strait.

Although Tofino is not the closest tide gauge¹ to the western boundary, we have found that the surge conditions on the western coast of Vancouver Island and near the mouth of the Strait of Juan de Fuca are fairly uniform as summarized in Table 1. Generally, surge amplitudes at Tofino are slightly larger and earlier than Neah Bay and Bamfield. In the future, storm surge forecasts will make use of Neah Bay water level predictions from the National Oceanic and Atmospheric Administration (NOAA).

Table 1. Average surge amplitudes and delay in peak timing from Tofino at several tide gauges on the Pacific coast. Averages obtained over the surge events discussed on this article¹. A negative delay indicates that the peak surge occurred later than at Tofino.

| Location | Mean surge amplitude (m) | Mean delay from Tofino (hrs) |
|----------------|--------------------------|------------------------------|
| Tofino | 0.707 | – |
| Toke Point | 1.17 | -2.83 |
| Neah Bay | 0.658 | -1.83 |
| Bamfield | 0.658 | -0.5 |
| Winter Harbour | 0.572 | 0.333 |
| Port Hardy | 0.491 | -2.67 |

The tidal forcing and remote forcing were applied using the NEMO Flather scheme (Flather, 1994; Madec et al., 2012), a radiation scheme that allows disturbances to propagate out of the domain without reflections off of the open boundary. The barotropic velocity component of the remote forcing was set to zero. At the west, the baroclinic velocities at the boundary were set equal to the values inside the boundary (zero-gradient boundary conditions). This scheme is not part of core NEMO 3.4 (the version used here). Zero gradient conditions were chosen because the baroclinic velocity at the mouth of Juan de Fuca is primarily estuarine and thus set by density variations between inside and outside the domain. No boundary conditions were set on the baroclinic velocities at the north¹.

At coastal boundaries, the partial slip boundary condition, an approximation to no slip, is used. Partial slip allows one to include the frictional effects of lateral boundaries without the restrictive resolution required to represent the lateral boundary layer under no slip conditions. A lateral eddy viscosity of $20 \text{ m}^2 \text{ s}^{-1}$ parametrizes horizontal friction and a lateral eddy diffusivity of $20.5 \text{ m}^2 \text{ s}^{-1}$ is used. Bottom friction is represented by a quadratic law for the bottom momentum flux with drag coefficient $C_D = 5 \times 10^{-3}$. Vertical turbulence and mixing is calculated through the $k - \epsilon$ configuration of the generic length scale (GLS) turbulence closure (Umlauf & Burchard, 2003) with background vertical eddy viscosity and diffusivity set to $1 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ and $1 \times 10^{-5} \text{ m}^2 \text{ s}^{-1}$ respectively. Details on the NEMO implementation of the partial slip lateral boundary condition, quadratic bottom friction law, and GLS turbulence closure scheme are provided by Madec et al. (2012).

The ocean surface is forced with momentum fluxes, solar and non-solar heat fluxes, and precipitation from a 33-km global atmospheric reforecasting model suitable for use in ocean modelling (Smith et al., 2014). Forecasts from the period of 2002-2012 are available. One additional simulation employs the western Canada component of the High Resolution Deterministic Prediction System (HRDPS), a nested 2.5 km resolution atmospheric model provided by Environment Canada (Environment Canada, 2014b). In addition to momentum and heat fluxes, forcing due to the surface atmospheric pressure is also included in the ocean momentum equations (Madec et al., 2012). In the open ocean, the surface atmospheric pressure primarily induces an inverse barometer (IB) sea surface height,

$$\eta_{IB} = -\frac{1}{g\rho_0} (P_s - P_0), \quad (1)$$

where g is the acceleration due to gravity, ρ_0 is a reference density set to 1035 kg m^{-3} , P_s is the sea level atmospheric pressure from the atmospheric model, and P_0 is a reference sea level pressure (set to 101,000 Pa). Since the atmospheric model employs a terrain following vertical coordinate the model surface pressure has been corrected to sea level using (Holton, 1992)

$$P_s = P_1 \left(\gamma \frac{z_1}{T_1} + 1 \right)^{\frac{g}{\gamma R}},$$

where P_1 and T_1 are the model pressure and temperature at height z_1 , R is the ideal gas constant, and γ is a temperature lapse rate set to 0.0098 K m^{-1} . In coastal and shelf seas, the atmospheric pressure forcing can also induce significant non-IB sea surface height, as demonstrated in previous studies of the Hudson Bay and Labrador shelf system (de Young, Lu, & Greatbatch, 1995; Wright, Greenberg, & Majaess, 1987).

River input provides a significant volume of fresh water to the Salish Sea and can influence stratification, circulation, and primary productivity. However, most rivers in the domain are not gauged so parametrizations were required to represent river flow. Morrison, Foreman, and Masson (2011) provides a method for estimating freshwater runoff in the Salish Sea region based on precipitation. Monthly runoff volumes for each watershed for each year from 1970 to 2012 were acquired from Morrison et al. (2011), as well as monthly averages. Freshwater runoff from each watershed was divided among the rivers in that watershed. The area drained by each river was estimated from Toporama maps by the Atlas of Canada and watershed maps available on the Washington State government website. The watersheds included in our model were Fraser (which represents approximately 44% of the freshwater input into our domain), Skagit (12%), East Vancouver Island (North and South) (12%), Howe (7%), Bute (7%), Puget (6%), Juan de Fuca (5%), Jervis (4%) and Toba (3%). The monthly flow from each river was input as a point source from 0 to 3 metres at the model point closest to the mouth of each river. Incoming water was assumed to be fresh and at surface ocean temperature. A total of 150 rivers were parametrized by this method and their locations are indicated by the green dots in Figure 1.

Initial conditions for temperature and salinity came from a CTD cast in the middle Strait of Georgia taken in Sept 2002 (Pawlowicz, Riche, & Halverson, 2007). Conditions were initially uniform horizontally and velocity was initialized at zero. The model was spun up for 15.5 months from the initial conditions above, starting Sept 16, 2002, using atmospheric forcing from 2002-2003, climatological temperature and salinity and sea surface height at the boundaries, with tides and climatological river output. All storm surge runs were started at least three days prior to the event of interest with zero initial velocities and sea surface height and a stratification

profile from model spin up. The modelled sea surface height adjusted to forcing in less than one day as determined by comparing a simulation with restart conditions to one with velocities and sea surface height initialized to zero.

3 Tidal Evaluation

The model was initially evaluated qualitatively by comparing patterns of tidal amplitude and phase to results from Foreman et al. (1995), focusing on the major M_2 and K_1 constituents. For example, the M_2 amphidrome around Victoria was reproduced as well as the monotonic increase in K_1 amplitude moving northwards along the Strait of Georgia. As the model was reproducing observed tidal patterns, model results were quantitatively evaluated by comparing modelled harmonic constituents to measured harmonic constituents at tidal measuring stations throughout the domain. Comparisons were made using the complex difference (D), defined as (Foreman et al., 1995):

$$D = [(A_0 \cos g_0 - A_m \cos g_m)^2 + (A_0 \sin g_0 - A_m \sin g_m)^2]^{1/2} \quad (1)$$

where A_0 , A_m , g_0 and g_m are the observed and modelled amplitudes and phases. Figure 3 compares modelled and observed amplitude, phase, and complex differences for the M_2 and K_1 tidal constituents for stations along a transect from the Strait of Juan de Fuca through to the Strait of Georgia and Johnstone Strait. Comparisons have been made with data from Foreman et al. (1995), Foreman et al. (2004) and Foreman et al. (2012). Station names and numbers are listed in Table A1 in Appendix A.

In general, the K_1 tidal harmonics are well-represented by the model with complex differences below 5 cm at all stations except Seymour Narrows (station 27). Seymour Narrows is a very constricted region in Johnstone Strait and is not well resolved by the model. As such, the M_2 amplitude and phase are also poorly reproduced here. The model's M_2 amphidrome, indicated by the drop in amplitude around station 5 (Victoria), is too strong resulting in lower than

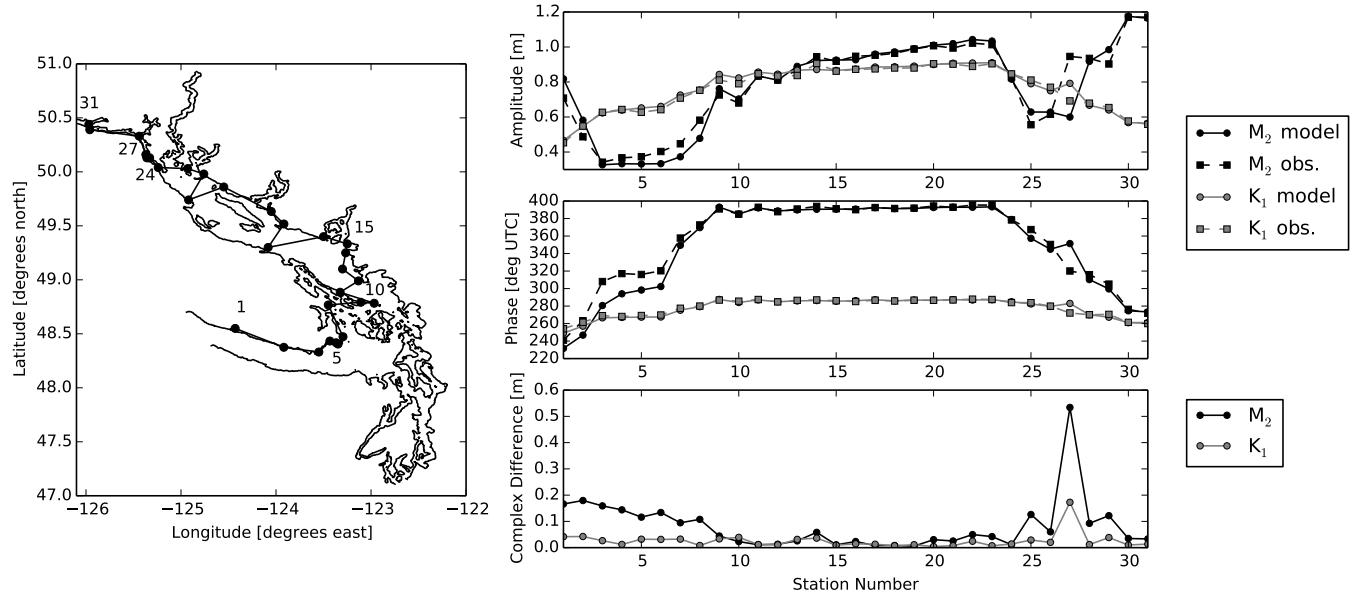


Fig. 3 Evaluation of model tidal amplitude and phases for the M_2 and K_1 constituents. On the left, a transect through the stations used for comparison. On the right, modelled M_2 (black) and K_1 (grey) amplitude (top) and phase (middle) compared with observations in the dashed curves of the same colour. The bottom plot displays the M_2 and K_1 complex differences. Station names and numbers are listed Appendix A in Table A1.

observed M_2 amplitudes in this region. The model also represents the dip in M_2 amplitude around stations 25 and 26 reasonably well. Additionally, the M_2 phase errors in the Strait of Juan de Fuca (stations 1-7) are quite large, leading to large complex differences in this region. The match in the Strait of Georgia (stations 10-24) is very good, with complex differences less than 6 cm, in part due to tidal tuning for highly accurate tides in the main region of interest. Because the tides were tuned for a good match in the Strait of Georgia, the match in the Strait of Juan de Fuca has suffered, particularly noticeable at the station closest to the open boundary (Port Renfrew, 1). Details on the tidal tuning procedure are provided in Appendix A.

4 Storm Surge Hindcasts

A series of five storm surge hindcasts is presented next. Storm surge simulations were started from rest at least three days prior to the event of interest to allow for adjustment of model currents. Stratification conditions from model spin up at a time close to the event (within five days) were chosen to initialize the temperature and salinity fields. Boundary conditions include

atmospheric forcing (momentum and heat fluxes and precipitation) and fresh water input from rivers at the surface, sea surface height anomaly from observations at the open boundary, and tidal forcing with eight tidal constituents.

Forcing the model with only eight tidal constituents leads to an error in modelled sea surface height due to the omission of the next leading order tidal constituents such as J_1 . Comparisons between full tidal predictions and tidal predictions using eight constituents suggest that this error can approach 20 cm during times of high tidal range. As such, model water level predictions were corrected by accounting for this error. Note that the model will contain tidal energy from shallow water constituents due nonlinear interactions in the model equations. As such, the correction is calculated in the following way: For each storm surge location of interest, two tidal predictions are calculated: 1) A tidal prediction with all constituents excluding long period constituents (SA, SSA, etc), shallow water constituents, and constituents with signal to noise ratio less than two, and 2) a tidal prediction with only the eight constituents used to force the model. The difference between these two predictions is added to the model sea surface height as a correction. Note that the harmonic analysis used to generate the constituents is applied in the same manner as that used in the forcing. That is, the time series from the year of the storm surge is filtered to remove periods of large non-tidal energy and then the harmonic analysis is performed. The total modelled water level is determined by adding the mean sea level from the tide gauge record over 1983-2001 to the corrected model sea surface height. This correction is only applied to the modelled water level and not the modelled residuals. All times are reported in UTC.

Model results have been compared with observations by calculating both the total modelled water level and the modelled residual at four permanent tidal measuring stations: Point Atkinson, Victoria, Patricia Bay, and Campbell River (locations indicated in Figure 1). The modelled residual is calculated as the difference in model output between a simulation with all forcing conditions and a simulation forced only with tides and rivers. Water level observations are taken from the Canadian Tides and Water Level Data Archive (Fisheries and Oceans Canada, 2014) and are used to calculate the observed residual, defined as the observed water level minus tidal

predictions. Tidal predictions are calculated using t_tide (Pawlowicz et al., 2002), a MATLAB tool that calculates tidal harmonics from a given time series. **The same method for calculating forcing residuals described in section 2 is used to calculate the observed residuals.**

The model's skill is reported ~~through a few~~ statistical measures of the total water level η and the residual δ . First, the mean absolute error (\bar{e}), defined as

$$\bar{e} = \text{mean}(|M - O|), \quad (1)$$

where M and O are the modelled and observed quantities of interest, is a common measure that estimates the average error in the model. Next, a measure comparing the variance of the error to the variance of the observations defined as (Thompson, Sheng, Smith, & Cong, 2003),

$$\gamma^2 = \frac{\text{var}(M - O)}{\text{var}(O)}, \quad (2)$$

is also calculated. Smaller values of γ^2 indicate better model skill. This quantity was used by Bernier and Thompson (2006) and Bernier and Thompson (2010) in storm surge predictions in Eastern Canada and is calculated here as a point of comparison. A third measure, called the Willmott skill score (Willmott, 1982), is also used to assess overall model skill in predicting the water level and residual. This quantity is defined as

$$WS = 1 - \frac{\sum_{i=1}^N (M_i - O_i)^2}{\sum_{i=1}^N (|M'_i| + |O'_i|)^2}, \quad (3)$$

where $M'_i = M_i - \bar{O}$ and $O'_i = O_i - \bar{O}$ and \bar{O} is the mean of the observations. This score is bounded by zero and one and values close to one indicate good model skill. Since the Willmott skill score is nondimensional, it is an appropriate statistic to report when comparing skills of different variables, in this case, the total water level and the residuals. Since the total water level has a larger variability than the residuals, the γ^2 measure should be much lower for the total water levels; hence, the Willmott skill score provides an additional point of comparison. These three statistics, along with the mean observed values and mean modelled values (which indicate the model's bias) are reported in Table 2 for each hindcast. **Observed and modelled maximum**

water levels and surge values as well as differences in their timing are reported in Table 3.

The five hindcast simulations have been used to assess the model's skill and to learn more about how the storm surge propagates through the Salish Sea domain. First, a general assessment of the model's skill is presented in two hindcasts during Feb 2006 and Nov 2006 in section 4.a. Second, the contribution to the surge due to several forcing conditions, such as atmospheric forcing and open boundary forcing, has been assessed for the Feb 2006 case in section 4.b. This case is also used to determine the importance of modelling tidal forcing with the surge propagation. Third, the spatial variability of the surge as it propagates through the domain is examined for a Dec 2006 storm surge in section 4.c. Fourth, a high wind event that did not result in a large surge or flooding for a Nov 2009 case is discussed in section 4.d. Finally, comparisons between hindcasts using high resolution (HRDPS) and low resolution (CGRF) atmospheric forcing is provided for the Dec 2012 case in section 4.e.

4.a *Example Storm Surge Hindcasts*

A hindcast for a storm surge that occurred on Feb 4, 2006 is presented next. The simulation ran from Feb 1-8, 2006. The model's ability to reproduce this event is demonstrated in Figure 4 which compares observations **with** corrected model output at Point Atkinson, Victoria, Patricia Bay, and Campbell River. First, the timing of maximum water level matches well between the observations and the model at all four locations, the most significant contribution to high water being from the tides which are generally well-represented by the model. There is good agreement in the water level maximum at both Victoria and Patricia Bay, although it is slightly under predicted at these two locations. The maximum water level at Point Atkinson and Campbell River is slightly over predicted and the error is more significant, but the tidal range is also larger. It is surprising that Victoria and Patricia Bay agree so closely with observations because the M₂ tidal amplitudes in the model are known to be too low in this area. **Given that the water levels are over predicted at Point Atkinson and Campbell River, it is likely that one of the forcing factors is overestimated in this example.**

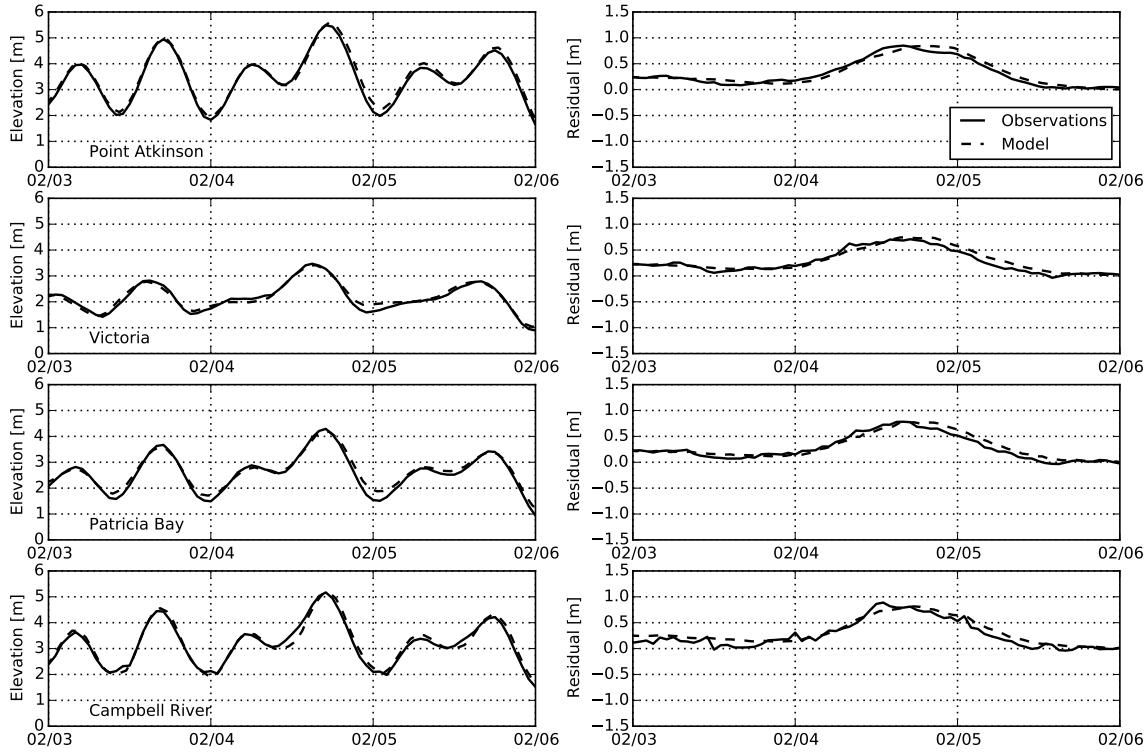


Fig. 4 Comparison of observations and model output for the Feb 4, 2006 storm surge. Left: total water level observation (solid) and corrected model (dashed). Right: observed residuals (solid) and modelled residuals (dashed).

In general, there is also very good agreement between the observed and modelled residuals (Figure 4). The most noticeable difference is a broader peak in the model's surge curve, leading to a delay of a few hours in timing of the peak surge for most of the stations (Table 3). Note that the surge manifests as a broad peak in both the modelled and observed residual leading to a high probability that large residuals coincide with the high tide. As such, it is of minor consequence that the timing of the observed and modelled maximum residuals do not match perfectly.

A more detailed evaluation of the model performance is provided by a group of statistical measures, including the mean absolute error, the observed mean, the modelled mean, γ^2 , and the Willmott skill score for both the water level and residuals (Table 2). The statistics are calculated with hourly output over the three-day period displayed in Figure 4. The mean absolute error in the water level ranges from 8.2 cm at Victoria to 12.2 cm at Campbell River, whereas, the mean absolute error in the residuals is smaller at all stations; however, this measure does not account for the large variability in water levels due to the tides. A statistic that does take into account this variability is γ^2 which suggests very good agreement in both the predicted water levels and

residuals. Good agreement is also reflected in high Willmott skill scores at all locations. Note that the γ^2 measures and Willmott skill scores degrade slightly for the residuals, likely because the well-tuned tidal signal dominates the water level predictions.

An additional storm surge hindcast for a Nov 16, 2006 storm surge is provided as another means of assessing model performance and is mentioned briefly here. The model performs reasonably well in this hindcast; Willmott skill scores are greater than 0.95 (Table 2). Further, the γ^2 statistic suggests that the standard deviation of the error in the modelled residuals is about 40% ($\sqrt{0.16}$) of the standard deviation of the observed residuals. The best match in maximum surge occurred at Campbell River with a 4.3 cm underestimate by the model. **The timing of the maximum surge was too early at all stations except Campbell River.**

This case was also used to assess the importance of the northern boundary residual forcing and ~~was used to briefly examine stratified effects.~~ When the northern boundary forcing is excluded the surge amplitude at Campbell River drops by about 10 cm. The other stations were not very much affected. This was also observed in another hindcast (Dec 2006). The effect of stratification was examined by considering a case with an initially horizontally uniform stratification and comparing to the fully stratified case. The largest differences were observed at Victoria, with an average 5 cm increase in sea surface height after an initial adjustment period. Other studies have seen an improvement in modelled surge amplitudes when using a baroclinic model as opposed to a three-dimensional barotropic model (Ma et al., 2015). We plan to investigate stratified effects in more detail in a future study.

4.b *Factors Contributing to Storm Surges*

Next, an assessment of the factors that are most important in the storm surge forcing conditions is presented for the Feb 2006 storm surge (Figure 5). Several simulations were done: First, a simulation with all the forcing conditions, including tides, local atmospheric forcing (both local winds and local atmospheric pressure), and sea surface height anomaly at the open boundary (also called remote forcing) in the black curve. Second, a simulation with all forcing except the

local atmospheric forcing in the dashed green curve. Third, a simulation with all forcing except the remote forcing in the red curve. Fourth, a simulation with only tides and local wind forcing, that is, excluding remote forcing and local atmospheric pressure forcing in the dashed blue curve.

Comparisons between these simulations will determine the contributions from the remote forcing, the local wind forcing, and the local atmospheric pressure forcing. Finally, a simulation without tidal forcing was performed to study the importance of the tide-surge interaction (Figure 6).

First, it is clear that remote forcing at the open boundary contributes most significantly to the surge at each of these locations (Figure 5). When the remote forcing is not included as a forcing condition, the surge drops from a maximum **84 cm** to 11 cm at Point Atkinson and its maximum occurs eight hours later. A similar drop in the maximum surge and delay in timing of the maximum surge is observed at the other locations. When local atmospheric forcing is neglected, almost all of the surge amplitude is accounted for in the remote forcing.

The contribution to the surge due to local atmospheric forcing is small and appears to be geographically dependent, most likely due to the effects of the local winds. Removal of the local atmospheric forcing leads to a drop of about **2 cm** in the maximum surge at Point Atkinson and **2.5 cm** at Campbell River. By contrast, the surge amplitude increases by **4.5 cm** at Victoria and 3.6 cm at Patricia Bay. The southeasterly winds over the Strait of Georgia could be acting to push water away from the southern tip of Vancouver Island, resulting in a slight decrease in the surge amplitude at Victoria and Patricia Bay when wind effects are included in the model. A simulation with only tides and local wind forcing produces a surge of 7.8 cm at Point Atkinson, a small fraction of the total observed surge, and only centimetres at the other locations. Note that this wind-induced surge occurs well after the peak surge occurred in both the observations and simulations with full forcing.

A simple steady state argument balancing the wind stress with the pressure gradient can be used to calculate the slope of the sea surface in a body of water with a constant depth D (Pugh, 2004):

$$\text{slope} = \frac{C\rho_{air}U^2}{g\rho D}, \quad (4)$$

where C is the coefficient of friction, ρ_{air} is the density of air, g is the acceleration due to gravity, U is the wind speed, and ρ is the density of water. Given $C = 10^{-3}$, $\rho_{air} = 1.23 \text{ kg m}^{-3}$, $\rho = 1035 \text{ kg m}^{-3}$, wind speed $U = 20 \text{ m s}^{-1}$, and depth $D = 100 \text{ m}$, the slope of the sea surface is approximately 5×10^{-7} . At Point Atkinson, a westerly wind can act over a small distance of approximately 50 km, giving a sea surface elevation on the order of centimetres in agreement with the model findings. Since the Strait of Georgia is not a constant depth and is up to 400 m deep, this calculation is only an approximation. Choosing a larger depth would result in an even smaller estimate for the sea surface elevation caused by wind stresses. Further, northwesterly winds would induce the largest elevations at Point Atkinson due to the large distance over which the winds can act.

Next, the surge amplitude decreases by a few centimetres at all four locations if local atmospheric pressure is not included in the surface forcing. This drop is smaller than the IB sea level change calculated by equation (1), approximately 1 cm rise in sea level associated with 1 hPa drop in atmospheric pressure. In this event, the pressure at the Vancouver International Airport dropped to about 99 000 Pa (Environment Canada, 2014a), corresponding to a 20 cm rise in sea level. This magnitude is in line with the findings of Murty et al. (1995) that the IB contributes up to $\frac{1}{3}$ of the total surge amplitude. In our model, including the influence of remote atmospheric pressure forcing (in the sea level at the open boundary) produces realistic surge amplitudes compared with the runs only including local atmospheric forcing. Our results suggest that the local atmospheric pressure generates a sea level change that is smaller than the IB response. **It is the atmospheric pressure gradient that drives changes in the sea surface height. Since our domain is relatively small, so is the atmospheric pressure gradient, and hence, we see only a small contribution from local atmospheric pressure.**

These comparisons point to the importance of including, as a forcing condition at the open boundary, the surge entering the domain from the Pacific Ocean. Storms travelling over the Pacific Ocean towards the west coast of the northern United States and Canada can induce elevated sea levels along the coastline which then enter the Salish Sea system through the Strait

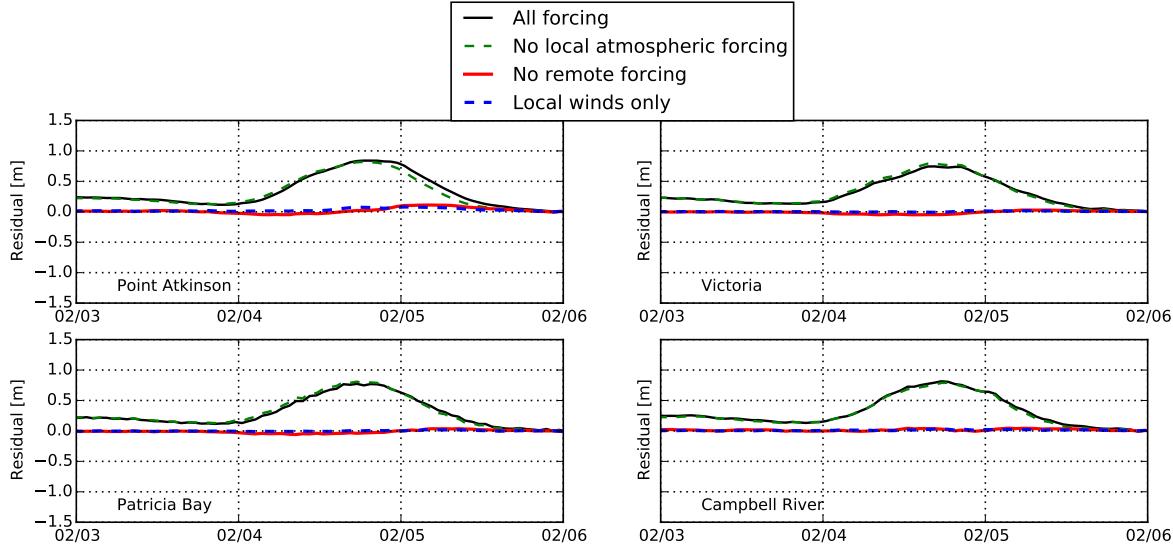


Fig. 5 Comparison of the modelled residual for four simulations in Feb 2006: A simulation with all forcing (solid black), a simulation without local atmospheric forcing (dashed green), a simulation without remote forcing (solid red), and a simulation with only tides and local wind forcing, i.e. no remote forcing or local atmospheric pressure (dashed blue).

of Juan de Fuca. Previous simulations by Murty et al. (1995) suggest that the surge entering the system through the Strait of Juan de Fuca contribute most significantly to storm surges in this domain. **Our study is consistent with these findings.**

Next, an assessment of the importance of including the tide-surge interaction, which is important in shallow regions due to nonlinear effects and bottom friction (Bernier & Thompson, 2007), is presented for this hindcast (Figure 6). The most significant differences occur at Point Atkinson where the maximum of the surge-only case is 8.4 cm higher than maximum modelled residual, about 10% of the total surge amplitude. In contrast, the tide-surge interaction at Victoria is hardly noticeable. Indeed, a spatial map of the difference between the modelled residual and surge-only simulation (Figure 7) indicates that the tide-surge interaction is more pronounced north of the San Juan and Gulf Islands. The passages between these islands are known for vigorous tidal mixing, which may have a nonlinear effect on the surge propagation. However, the effect is a relatively small overestimate of the surge elevation and no changes to the timing of the surge. So, in operational settings, performing a surge-only simulation and adding the predicted tides *a posteriori* could be more computationally efficient with only a small decrease in the accuracy of the prediction.

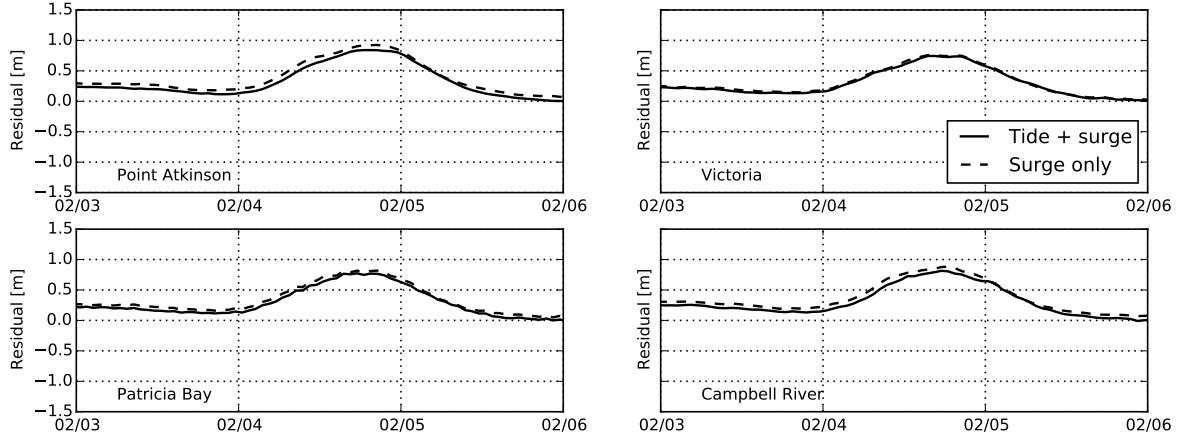


Fig. 6 Modelled residuals (solid) compared with a simulation of the surge propagation without tidal forcing (dashed) for the Feb 2006 hindcast.

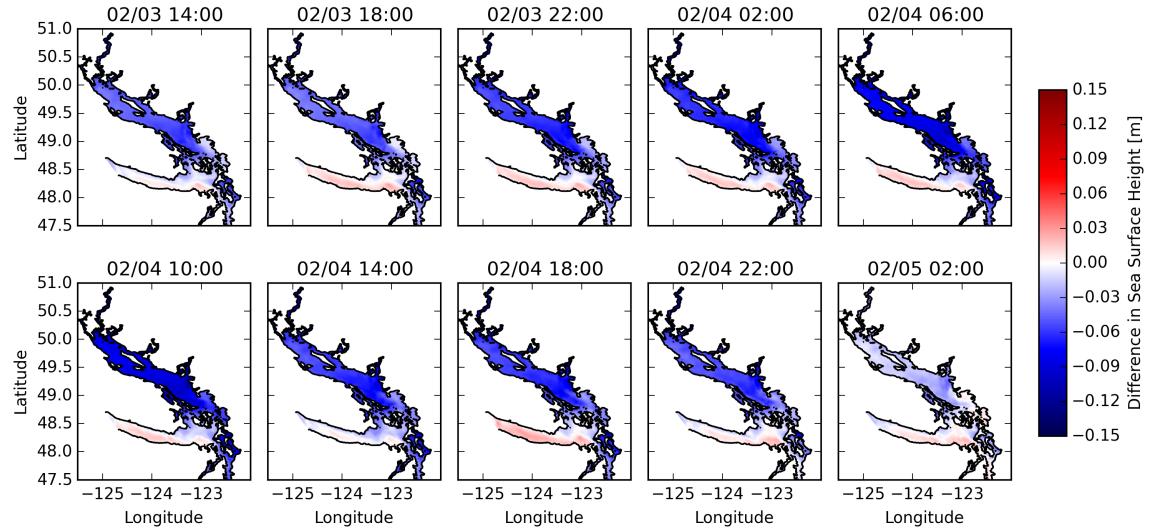


Fig. 7 Spatial dependency of tide-surge interaction in Feb 2006 hindcast. Difference in sea surface height between simulations with tidal forcing and without tidal forcing. Each plot is an average over 4 hours.

4.c Spatial Extent of Surge

A major wind storm on Dec 15, 2006 is hindcasted next. Although the storm was very strong (gusts over 120 km hr^{-1}) and the observed residual at Point Atkinson reached 94 cm, this event did not coincide with high tide and so no significant or reported flooding occurred in the Vancouver area (Forseth, 2012). Because of the high winds, this event has been used to examine the propagation of the surge throughout the domain and spatial variations in the surge amplitude. First, an assessment of the accuracy of the hindcast is provided.

Modelled residuals are generally too low in this hindcast (Figure 8), however, the timing of

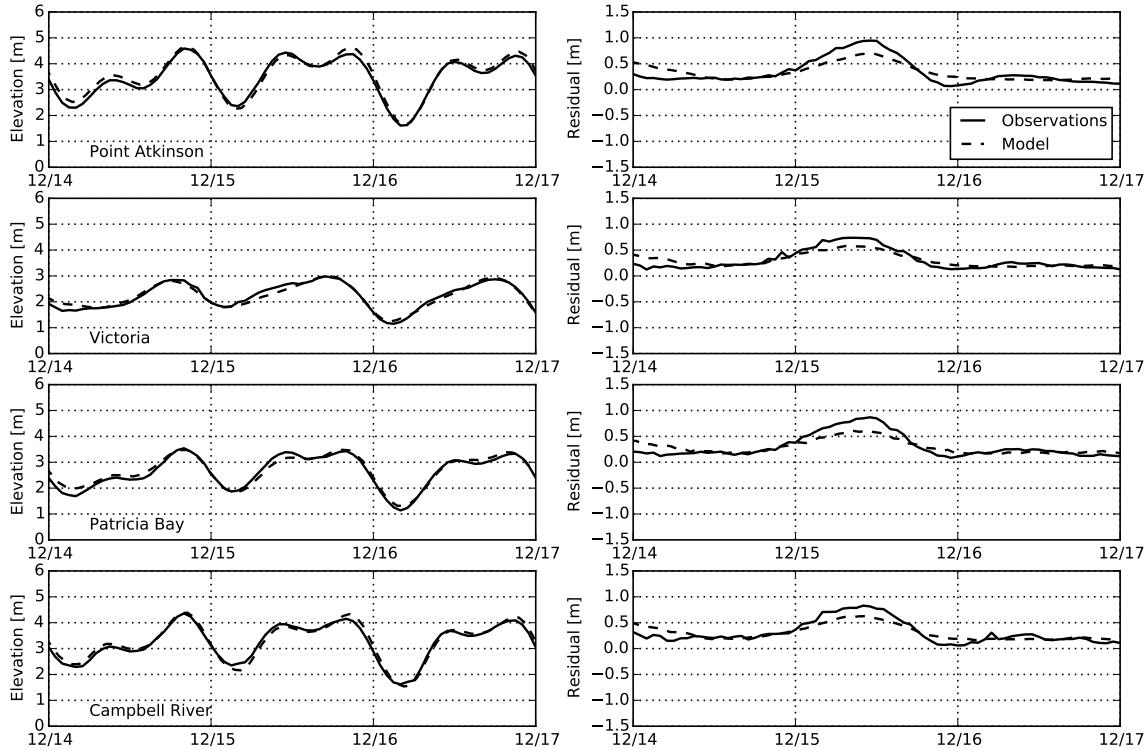


Fig. 8 Comparison of observed and modelled water level and residuals during the Dec 15, 2006 storm surge simulation.

the surge agrees well. All Willmott skill scores rank above **0.89** and the γ^2 measure also indicates good agreement between model and observations (Table 2). The γ^2 measure suggests that the standard deviation of the error in the modelled residuals is roughly half of the standard deviation of the observed residuals. Note that the performance has degraded when compared to the Feb 2006 and Nov 2006 cases. This could be due to a number of factors. First, the very large wind speeds observed during this storm are significantly underrepresented by the atmospheric model leading to lower wind stress and less piling of water against the coast. Second, the anomaly forcing at the open boundaries could be too low. The observed residual at Tofino, BC (a point nearby but outside of the domain) is up to 10 cm lower than the observed residual at Neah Bay, WA (a point nearby but inside of the domain). Since the storm surge is less sensitive to wind forcing at the surface than anomaly forcing at the open boundaries, the latter is likely the cause, although it still does not account for all of the error.

The evolution and spatial distribution of the surge is highlighted in Figure 9 where the modelled residual is plotted every hour beginning on Dec 15 at 05:30 UTC through to Dec 15

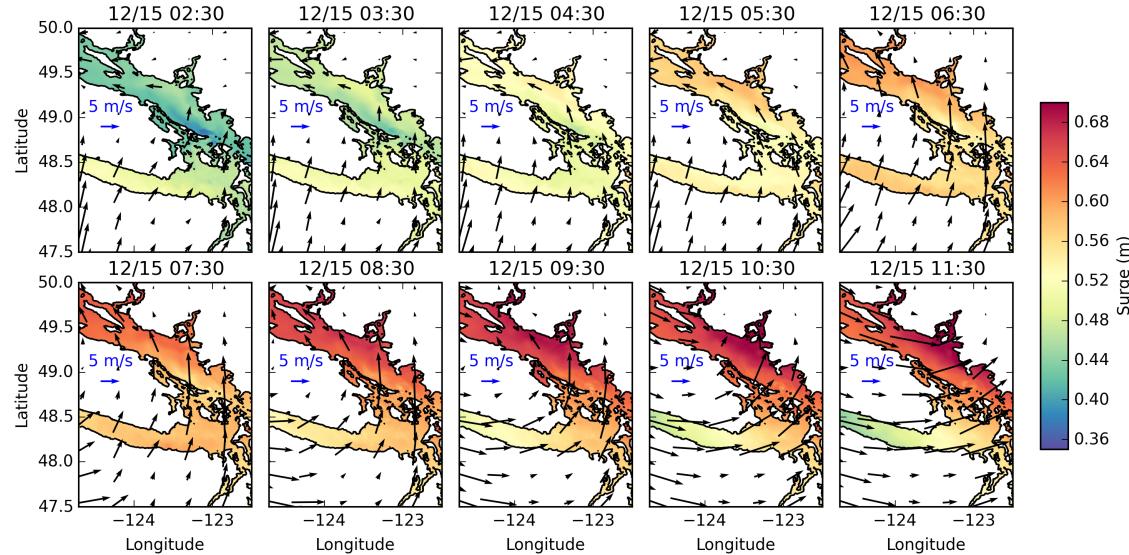


Fig. 9 Propagation of the storm surge on Dec 15, 2006. Modelled residual every hour starting on Dec 15 at 05:30 UTC. Time advances from top left to bottom right. Wind vectors from the atmospheric forcing are overlaid in black.

at 14:30 UTC. The surge enters the system from the Strait of Juan de Fuca, peaking between Dec 15 at 9:30 UTC and Dec 15 at 11:30 UTC and then begins to subside throughout the entire domain. Notably, the Strait of Georgia experiences the largest surge values, upwards of 70 cm, whereas the Juan de Fuca region experiences a maximum surge around 60 cm (Figure 9). Additionally, the coastal areas on the mainland side of the Strait of Georgia experience slightly higher surges (~ 10 cm) than the Vancouver Island side, likely due to the southerly wind in the atmospheric model pushing water against the mainland coast. At about 11:30 UTC, the winds at Point Atkinson switch to northwesterly and then westerly, further amplifying the surge along the mainland coast.

In a simulation without atmospheric forcing, the surge amplitude across the Strait of Georgia is uniform with no pronounced difference between the mainland side and Vancouver Island side (Figure 10). While the surge entering the domain from the Pacific Ocean is the leading order contribution, the winds may induce localized changes to the surge amplitude. Interestingly, the winds over the Strait of Juan de Fuca cause a decrease in surge amplitude in this region as the winds are acting to push the water towards the mainland (Figure 9). Even without atmospheric forcing, there is still a significant difference in surge amplitude between the Strait of Georgia and the Strait of Juan de Fuca, ¹ perhaps the incoming surge wave is partially reflected from

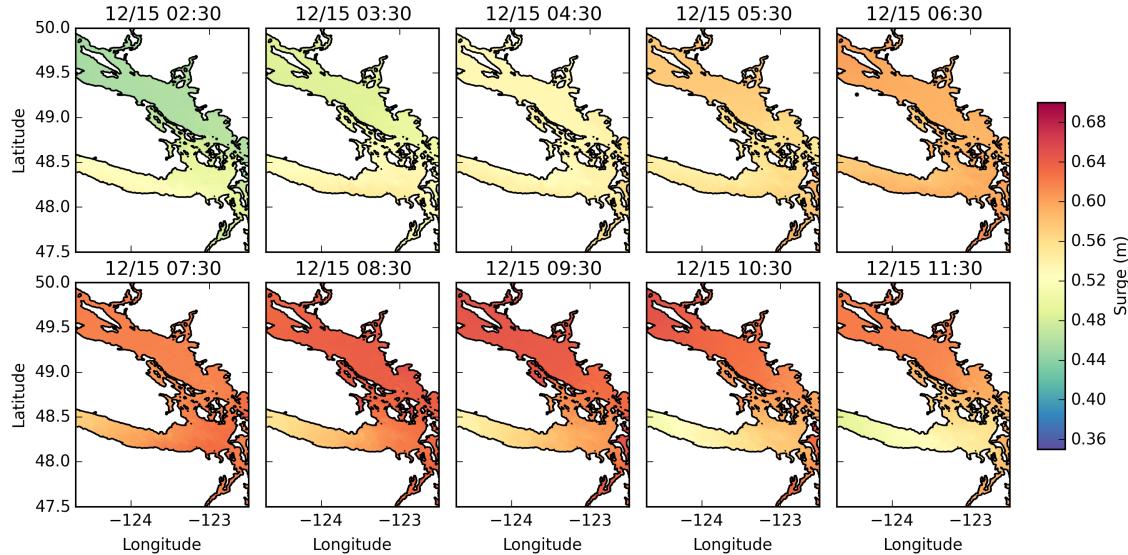


Fig. 10 As in Figure 9 but for a simulation that does not include atmospheric forcing.

the mainland coast in the Strait of Georgia. Since local winds are stronger in this case, their contribution to the surge amplitude of about 6 cm at Point Atkinson is more significant than in the Feb 2006 case. However, this is still less than 10 % of the total surge amplitude.

4.d Strong Wind Event

Next, a relatively strong wind event recorded at Point Atkinson on Nov 19, 2009 is considered. Wind speeds at Point Atkinson reached up to 18 m s^{-1} which is approximately the same magnitude to that observed on Feb 4, 2006. Although large wind speeds were observed, the surge associated with this event is rather small when compared to the previous cases (Figure 11). Two significant surge events are noted, the first occurring on Nov 19 with an observed amplitude of about 55 cm at Point Atkinson, and a second, larger surge of 70 cm on Nov 20. The strong wind event of Nov 19 was associated with the smaller of the two surges, supporting the fact that local winds do not contribute significantly to surge amplitudes. Neither of the surges occurred during a high tide and so no high water level events were recorded. Although the sea surface height plots are not shown here, the other three locations also observed a maximum surge on Nov 20, which appears to be linked to a secondary high wind event and another surge entering the system at Tofino and Port Hardy.

Danard et al. (2003) discuss the role of wind fetch, the distance over which wind acts on the surface of a water basin, in setting up seiche motion in lakes and its contribution to storm surges. As wind blows over the surface of a lake, the water level becomes elevated on the downwind side and depressed on the upwind side in response to the wind-induced currents. The longer the fetch, the more significant the tilting of the water surface. These changes in water level can also contribute to storm surges. During the high wind events on Nov 19 and Nov 20, the winds at Point Atkinson were directed to the west, explaining the lack of strong surge observed during this event since wind stresses would act to depress the water on the east side of the basin. In fact, the surge amplitude at Victoria on Nov 20 was **71.8 cm** which is slightly higher than that observed at Point Atkinson (**70 cm**). Of the cases considered so far, this is the only example where the surge amplitude at Victoria was higher than that at Point Atkinson. The model results do not reflect a higher surge at Victoria (**54 cm versus 58.7 cm at Point Atkinson**), perhaps due to an underestimate in the wind speed and some discrepancies in the wind direction of the atmospheric forcing. **There is a fairly significant delay in the timing of the maximum surge at most stations (Table 3). The model's surge curve is much broader and does not contain the narrow peak on Nov 20 as seen in the observations.**

The modelled water levels and residuals are, **on average**, too high for this hindcast, except at Victoria (Table 2). Generally, the skills scores are very good, scoring above **0.89** at all stations.

4.e High Resolution Atmospheric Forcing

The above comparison between the modelled and observed winds at Point Atkinson suggests that the atmospheric forcing product (CGRF) may not be adequate to produce accurate storm surge hindcasts since the wind speeds are substantially lower than observed. CGRF is a global atmospheric reforecasting model with horizontal resolution approximately 33 km over the Salish Sea domain, which is problematic since the Strait of Georgia itself is only about 30 km wide. As such, there are only one or two grid cells that are entirely over water in our domain, resulting in overly damped wind speeds at grid points close to land such as Point Atkinson. To determine

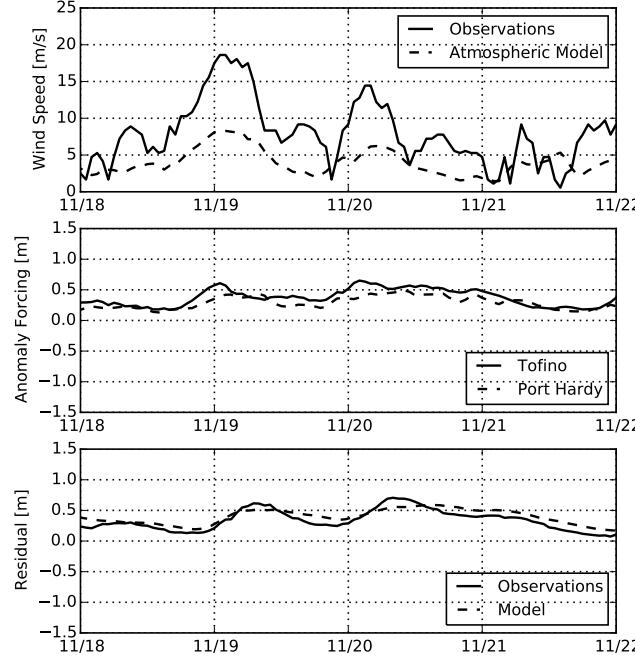


Fig. 11 Wind and storm surge conditions at Point Atkinson for a strong wind event on Nov 19, 2009. Top: Wind speed from Environment Canada observations (Environment Canada, 2014a) at Point Atkinson (solid) and from the atmospheric model (CGRF) at a grid point near Point Atkinson (dashed). Middle: Sea surface height anomaly at Tofino (solid) and Port Hardy (dashed) used as forcing conditions at the western and northern open boundaries. Bottom: Observed (solid) and modelled (dashed) residuals at Point Atkinson.

the effect of under-resolved wind forcing on the storm surge hindcasts we compare simulations that have been forced with 1) the low resolution CGRF model and 2) a high resolution (2.5 km) HRDPS model from Environment Canada. These simulations are performed for a storm surge that occurred on Dec 17, 2012 and cover the time period Dec 14-19, 2012. The high resolution product is not available for the hindcasts already discussed.

First, a comparison of the wind speed and direction for the two models and observations is provided in Figure 12 at Point Atkinson, Sandheads and a NOAA Neah Bay buoy. Sandheads is a lighthouse station in the southern Strait of Georgia. For each of the models, the wind speed and direction ~~the wind is heading~~ at the closest grid point to the longitude/latitude of Point Atkinson and Sandheads is used for comparison. Although the low resolution CGRF model has a grid spacing of 33 km, grid points align closely with these locations. At Point Atkinson, the high resolution model is in very good agreement with observations for both the wind speed and direction, however, the low resolution CGRF model significantly underestimates the wind

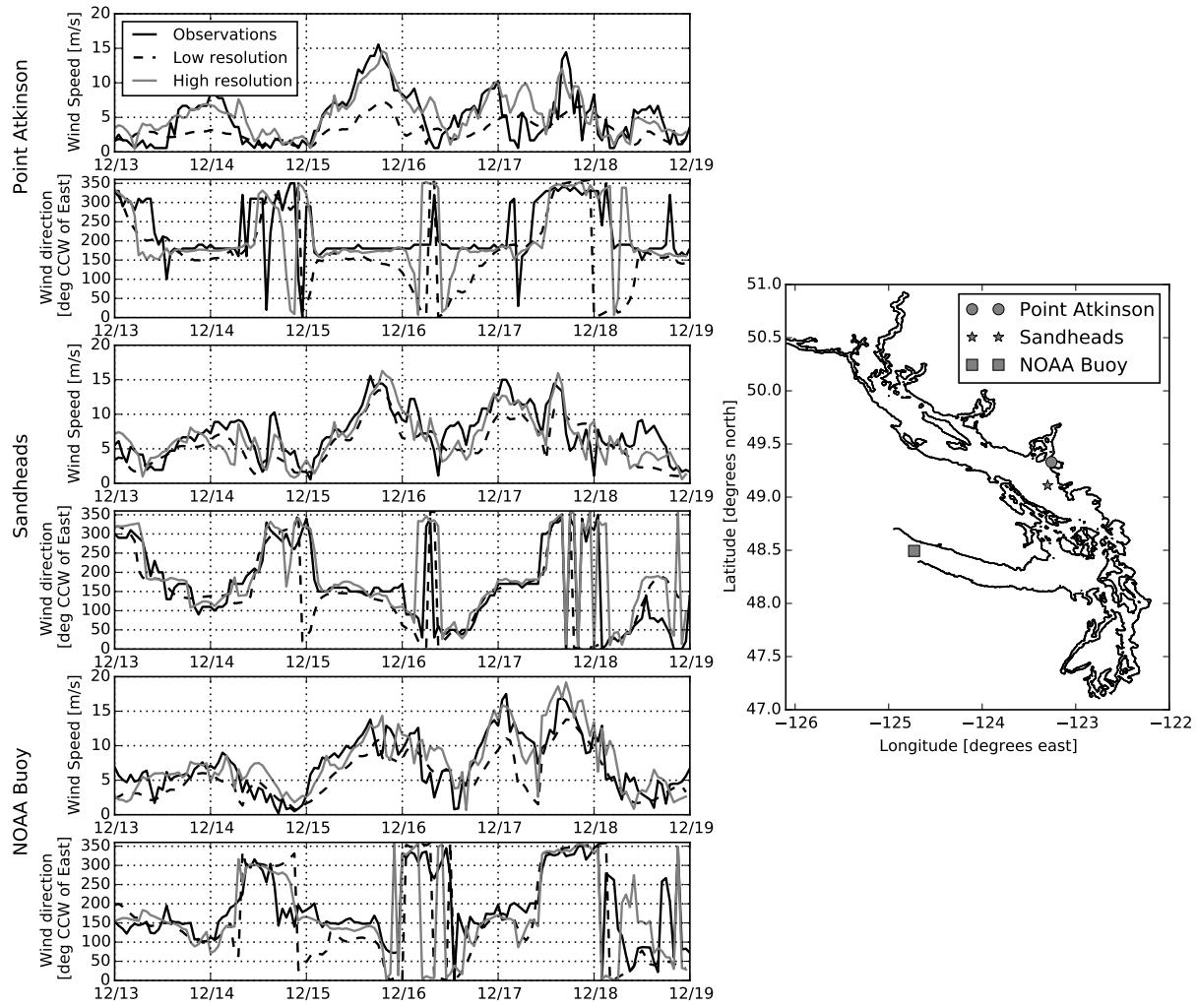


Fig. 12 Comparison of observed and modelled winds during Dec 2012 storm surge simulation at Point Atkinson (top), Sandheads (middle) and NOAA Buoy 46087 (bottom). Observed winds shown in solid black, low resolution CGRF model in dashed black and high resolution model in grey. Observations from Sandheads and Point Atkinson are from the Environment Canada Climate Data archives (Environment Canada, 2014a). Observations at the NOAA Buoy are found at this url: http://www.ndbc.noaa.gov/station_page.php?station=46087. Wind direction represents the direction that the wind is headed.

speed during high wind periods on Dec 15, 2012 and Dec 17, 2012. At Sandheads, both the low resolution and high resolution models have good agreement with observations. The low resolution model has a very good match at Sandheads likely because this grid cell happens to be mostly over water. Although not shown here, both models have a similar sea level atmospheric pressure at these locations. Note that data assimilation is used in the parent model of the nested HRDPS product.

Hindcasts with both atmospheric forcing products agree well with the observations (Figure

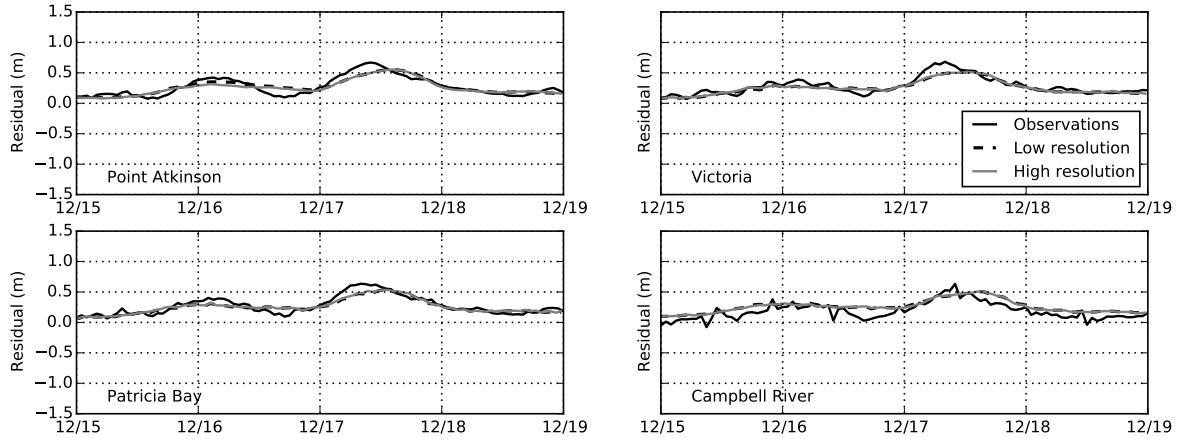


Fig. 13 Comparison of observed (solid black) and modelled residuals for the Dec 2012 storm surge simulation. Modelled residuals from two simulations using a low resolution (dashed) and high resolution (grey) atmospheric products are shown.

13). Willmott skill scores for both modelled residuals are above 0.84 at these four locations. There is considerable noise in the observed Campbell River residual, which could explain its low skill score (Table 2). The modelled residuals in each simulation deviate only slightly from each other, most noticeable at Point Atkinson during the strong wind event on Dec 15, 2012 where simulation with the low resolution atmospheric forcing has a residual that is 5 cm higher. The maximum residuals on Dec 17, 2012 are almost identical at each station (Table 3). Although the wind speeds on Dec 15, 2012 are quite high, this event did not result in any flooding or residuals greater than 50 cm. Significant flooding occurred later, on Dec 17, 2012, where the observed surge amplitude at Point Atkinson was 66.3 cm. Even though the low resolution model significantly under predicts the wind speed at some locations, it performs comparably to forcing with high resolution products. Much of the fine scale detail offered by the high resolution atmospheric model is averaged out since, to first order, the storm surge is a spatial integral of the wind. This result further demonstrates that the local wind is not the most important factor for setting up storm surges over this domain; however, local wind patterns contribute to wave conditions which can impact flooding and are not accounted for in this model.

5 Conclusion and discussion

In this article, we describe a three-dimensional numerical ocean model of the Salish Sea for accurate hindcasts of storm surges in the Strait of Georgia. The model is forced with eight tidal constituents at the western and northern open boundaries, as well as sea surface height anomaly from de-tided observations at Tofino and Port Hardy. Additionally, wind stress and local atmospheric pressure forcing were used at the ocean surface using an atmospheric reforecasting product called CGRF (Smith et al., 2014). Storm surge simulations began with zero initial conditions for the currents and sea surface height and were commenced several days prior to the event of interest to spin up the velocity fields.

Hindcasts of five significant events in February 2006, November 2006, December 2006, November 2009, and December 2012 were simulated. In general, the model performs well at reproducing the observed water level heights and residuals, with Willmott skill scores greater than 0.84 in all cases and generally higher skill scores for the water level heights. Further, in a single simulation, the skill scores are fairly consistent between the four stations examined. We have also assessed the relative importance of different forcing factors contributing to the storm surge. The sea surface height anomaly entering the system from the Pacific Ocean, or remote forcing, contributes most significantly to the surge amplitude, in agreement with previous studies in this region (Murty et al., 1995). Although the large scale wind patterns and atmospheric conditions are important in setting up the surge on the Pacific Ocean boundaries, the local winds within the Strait of Georgia are not the leading order contribution to surge amplitude. However, the local wind patterns can set up small spatial differences in the surge, resulting in higher surges on the mainland side of the Strait of Georgia due to the usually southerly winds during storm surge season. Additionally, surge amplitudes in the Strait of Georgia are typically higher than those in the Strait of Juan de Fuca, perhaps due a partial reflection of the surge from the mainland coast. Results from an additional simulation with no tidal forcing but only surge propagation and atmospheric forcing found that nonlinear effects due to the tide-surge interaction were most important north of the San Juan and Gulf Islands. The modelled surge amplitude increased by

about 10% at Point Atkinson when the tide-surge interaction was neglected in one example.

Comparisons between high resolution and low resolution atmospheric forcing further suggest that local winds are not the leading order factor in setting up large surge amplitudes. The low resolution model significantly underestimated wind speeds in certain areas of the domain, however, it performed just as accurately in reproducing surge amplitudes as the high resolution product. Although the high resolution model delivers fine scale detail and more accurate local wind patterns, it did not provide any improvement to the surge hindcast. Since both of these products provide the same level of accuracy for storm surge hindcasts, in the future we will use the high resolution atmospheric model to produce real-time storm surge predictions, even though most of our testing was performed with the low resolution model. Additionally, the sea surface height anomaly from Neah Bay, forecasted by the National Oceanic and Atmospheric Administration (NOAA), will be used in future real-time water level predictions during the storm surge season.

Several factors considered in other storm surge modelling studies have been neglected in these simulations. Primarily, effects due to wetting and drying have not been included. This is an important factor to consider in shallow, low lying areas where water levels retreat significantly to reveal land. In this article, the four locations used to assess storm surge accuracy are not in shallow regions and so wetting and drying is not considered to be important. However, several communities in the Strait of Georgia, such as Boundary Bay and Crescent Beach, are in shallow regions and are typically most affected by storm surge during the winter season. As such, efforts to include wetting and drying will be considered in the future. Additionally, flooding effects due to wave run up is left for a more detailed inundation study with higher resolution in the near-shore areas. Local winds have a significant impact on wave action which is a primary concern for flooding management. Further, the remote forcing is applied uniformly across the open boundary and so any spatial variability in the incoming surge are not accounted for in the model. Since the remote forcing is an important contributing factor, any forecasting with this regional model must make use of results from a larger scale prediction system.

Since the Strait of Georgia is a large, semi-enclosed body of water storm surges can behave and evolve differently than in other coastal regions. For instance, the complicated coastlines and local wind patterns result in important spatial variations in the surge amplitude. As such, the strong wind caused by a large storm is not the only factor to be considered in community preparedness for surge conditions. The geometry of the Strait and local wind patterns render communities on the mainland side of the southern Strait of Georgia more susceptible to surges. Additionally, communities such as Campbell River are at risk due to the long fetch and predominately southerly winds during the winter months.

Finally, difficulties in reproducing accurate M_2 tidal harmonics in both the Strait of Georgia and the Strait of Juan de Fuca have been highlighted in this study among others (Foreman et al., 2004; Stronach et al., 1993). Future work will attempt to improve model accuracy by examining mixing parametrizations and energy dissipation due to bottom friction and their effect on tidal harmonics **and investigating stratified effects on surge amplitudes**. Additionally, a biological-chemical modelling component will be added.

Appendix A. Details on tidal tuning

This section details the procedure used to tune the tidal forcing for a good match with observations in the Strait of Georgia. Originally, the eight most important tidal constituents were extracted from a tide prediction tool called Webtide (Webtide, 2014) at the western Juan de Fuca boundary based on work by Foreman et al. (2000). At the northern boundary, M_2 and K_1 tidal harmonics for both elevation and currents were taken from Thomson and Huggett (1980), as well as elevation harmonics for O_1 and S_2 . The remaining constituents were extrapolated from Webtide based on the ratio between S_2/M_2 amplitudes and phase differences for the semi-diurnal constituents and O_1/K_1 for the diurnal constituents. However, these forcing conditions did not result in a good match between observed and modelled tidal elevation harmonics in the Strait of Georgia, the main region of interest (although the matches in the Strait of Juan de Fuca were adequate). As such, tidal forcing was tuned, by first adjusting the western boundary

M_2 and K_1 phase and K_1 amplitude for a good match in the Strait of Georgia (specifically at Point Atkinson, Gibsons Landing, Winchelsea and Halfmoon Bay). This tuning was performed on simulations that used only M_2 and K_1 forcing. Next, the M_2 and K_1 fluxes at the northern boundary were adjusted because the cross-sectional area of transect used by Thomson and Huggett (1980) to measure tidal currents in Johnstone Strait is smaller than the cross-sectional area of our northern boundary. **The northern boundary tides were tuned for good matches at Yorke Island and Kelsey Bay.** Finally, the remaining constituents were added, starting with O_1 , then S_2 , and then in pairs P_1/N_2 and Q_1/K_2 . Final adjustments were made by slightly varying amplitude and phase, evaluating the changes to M_2 , K_1 and the ratios S_2/M_2 , N_2/M_2 , K_2/M_2 , O_1/K_1 , P_1/K_1 , Q_1/K_1 and then choosing new values to move closer to observations by linear interpolation.

Below, Table A1 compares the M_2 and K_1 elevation harmonics with data from Foreman et al. (1995), Foreman et al. (2004) and Foreman et al. (2012). Overall, the average complex difference for M_2 is 8.05 cm and for K_1 is 2.58 cm, but both constituents perform very well in the Strait of Georgia region.

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Table 2. Evaluation of model performance for all hindcasts presented. Mean absolute error (\bar{e}), observed mean (subscript o), modelled mean (subscript m), γ^2 , and the Willmott skill score (WS) are provided for water level predictions (η) and residuals (δ). Statistics are calculated over the time period displayed in each simulation's corresponding figure (three or four days). For the Nov 2006 case, the statistics were calculated over a three day period.

The average values were calculated over all of the hindcasts, excluding the Dec 2012 HRDPS simulation.

| Location | Water Level (η) | | | | | Residual (δ) | | | | |
|-----------------------|------------------------|--------------------|--------------------|------------|-------|-----------------------|----------------------|----------------------|------------|-------|
| | \bar{e} (cm) | $\bar{\eta}_o$ (m) | $\bar{\eta}_m$ (m) | γ^2 | WS | \bar{e} (cm) | $\bar{\delta}_o$ (m) | $\bar{\delta}_m$ (m) | γ^2 | WS |
| Feb 2006 | | | | | | | | | | |
| Point Atkinson | 11.6 | 3.458 | 3.558 | 0.012 | 0.994 | 5.5 | 0.318 | 0.33 | 0.058 | 0.985 |
| Victoria | 8.2 | 2.182 | 2.205 | 0.035 | 0.99 | 5.3 | 0.276 | 0.298 | 0.075 | 0.979 |
| Patricia Bay | 10.4 | 2.601 | 2.678 | 0.025 | 0.99 | 5.5 | 0.275 | 0.298 | 0.066 | 0.981 |
| Campbell River | 12.2 | 3.202 | 3.235 | 0.034 | 0.991 | 7.0 | 0.27 | 0.317 | 0.066 | 0.973 |
| Nov 2006 | | | | | | | | | | |
| Point Atkinson | 10.2 | 3.422 | 3.499 | 0.026 | 0.99 | 6.7 | 0.32 | 0.305 | 0.128 | 0.96 |
| Victoria | 7.8 | 2.158 | 2.182 | 0.065 | 0.982 | 4.7 | 0.246 | 0.26 | 0.134 | 0.961 |
| Patricia Bay | 9.4 | 2.565 | 2.634 | 0.043 | 0.983 | 5.9 | 0.258 | 0.261 | 0.152 | 0.953 |
| Campbell River | 9.9 | 3.201 | 3.243 | 0.032 | 0.991 | 6.3 | 0.29 | 0.293 | 0.153 | 0.951 |
| Dec 2006 | | | | | | | | | | |
| Point Atkinson | 12.9 | 3.452 | 3.531 | 0.028 | 0.99 | 10.0 | 0.336 | 0.33 | 0.272 | 0.895 |
| Victoria | 8.1 | 2.229 | 2.226 | 0.046 | 0.988 | 7.2 | 0.306 | 0.3 | 0.227 | 0.916 |
| Patricia Bay | 10.2 | 2.628 | 2.674 | 0.035 | 0.989 | 8.8 | 0.308 | 0.293 | 0.255 | 0.896 |
| Campbell River | 11.3 | 3.234 | 3.265 | 0.034 | 0.991 | 8.2 | 0.311 | 0.304 | 0.235 | 0.912 |
| Nov 2009 | | | | | | | | | | |
| Point Atkinson | 14.5 | 3.426 | 3.55 | 0.01 | 0.995 | 8.3 | 0.344 | 0.397 | 0.204 | 0.897 |
| Victoria | 10.9 | 2.249 | 2.24 | 0.029 | 0.992 | 4.4 | 0.365 | 0.361 | 0.201 | 0.933 |
| Patricia Bay | 12.0 | 2.589 | 2.685 | 0.021 | 0.991 | 7.4 | 0.307 | 0.356 | 0.216 | 0.894 |
| Campbell River | 11.6 | 3.219 | 3.247 | 0.016 | 0.996 | 6.9 | 0.341 | 0.38 | 0.188 | 0.915 |
| Dec 2012-CGRF | | | | | | | | | | |
| Point Atkinson | 11.0 | 3.362 | 3.432 | 0.007 | 0.997 | 5.7 | 0.274 | 0.273 | 0.219 | 0.929 |
| Victoria | 12.9 | 2.146 | 2.111 | 0.036 | 0.99 | 4.7 | 0.282 | 0.256 | 0.175 | 0.934 |
| Patricia Bay | 12.8 | 2.551 | 2.571 | 0.024 | 0.993 | 5.2 | 0.275 | 0.255 | 0.185 | 0.934 |
| Campbell River | 12.1 | 3.064 | 3.106 | 0.013 | 0.996 | 8.4 | 0.188 | 0.263 | 0.216 | 0.849 |
| Dec 2012-HRDPS | | | | | | | | | | |
| Point Atkinson | 10.5 | 3.362 | 3.42 | 0.007 | 0.998 | 6.2 | 0.274 | 0.26 | 0.231 | 0.921 |
| Victoria | 12.6 | 2.146 | 2.113 | 0.035 | 0.99 | 4.6 | 0.282 | 0.258 | 0.171 | 0.937 |
| Patricia Bay | 12.6 | 2.551 | 2.575 | 0.024 | 0.993 | 5.0 | 0.275 | 0.26 | 0.175 | 0.94 |
| Campbell River | 12.1 | 3.064 | 3.104 | 0.014 | 0.996 | 8.1 | 0.188 | 0.26 | 0.218 | 0.854 |
| Averages | | | | | | | | | | |
| Point Atkinson | 11.6 | 3.401 | 3.483 | 0.013 | 0.995 | 6.7 | 0.302 | 0.307 | 0.192 | 0.932 |
| Victoria | 10.8 | 2.175 | 2.162 | 0.04 | 0.989 | 5.1 | 0.29 | 0.28 | 0.167 | 0.94 |
| Patricia Bay | 11.6 | 2.573 | 2.619 | 0.028 | 0.991 | 6.0 | 0.281 | 0.279 | 0.179 | 0.932 |
| Campbell River | 11.6 | 3.139 | 3.177 | 0.021 | 0.994 | 7.8 | 0.246 | 0.293 | 0.188 | 0.893 |

Table 3. Summary of maximum water level, maximum surge amplitude and model delay for all simulations. The model time delay is the number of hours between the maximum in the observations and the maximum in the model. A negative number means the model's maximum was later than the observations. Values calculated over the same periods discussed in

Table 2.

| Location | Water Level (η) | | | Residual (δ) | | |
|----------------|------------------------|-------------|---------------|-----------------------|-------------|---------------|
| | Max obs (m) | Max mod (m) | Delay (hours) | Max obs (m) | Max mod (m) | Delay (hours) |
| Feb 2006 | | | | | | |
| Point Atkinson | 5.460 | 5.588 | 0 | 0.844 | 0.841 | -3 |
| Victoria | 3.440 | 3.415 | -1 | 0.700 | 0.745 | 1 |
| Patricia Bay | 4.250 | 4.179 | -1 | 0.781 | 0.773 | -2 |
| Campbell River | 5.100 | 5.170 | -1 | 0.876 | 0.815 | -5 |
| Nov 2006 | | | | | | |
| Point Atkinson | 5.010 | 5.040 | 0 | 0.880 | 0.725 | 1 |
| Victoria | 2.995 | 2.968 | 1 | 0.664 | 0.563 | 5 |
| Patricia Bay | 3.840 | 3.743 | 0 | 0.709 | 0.607 | 2 |
| Campbell River | 4.750 | 4.739 | 0 | 0.709 | 0.666 | -1 |
| Dec 2006 | | | | | | |
| Point Atkinson | 4.565 | 4.654 | 0 | 0.944 | 0.699 | 0 |
| Victoria | 2.965 | 3.005 | -1 | 0.737 | 0.580 | 1 |
| Patricia Bay | 3.505 | 3.480 | 0 | 0.859 | 0.613 | 1 |
| Campbell River | 4.295 | 4.389 | -1 | 0.823 | 0.626 | 0 |
| Nov 2009 | | | | | | |
| Point Atkinson | 5.150 | 5.272 | 0 | 0.699 | 0.587 | -7 |
| Victoria | 3.195 | 3.144 | -4 | 0.718 | 0.540 | -8 |
| Patricia Bay | 3.985 | 3.902 | 0 | 0.637 | 0.541 | -8 |
| Campbell River | 4.680 | 4.782 | 0 | 0.664 | 0.588 | -1 |
| Dec 2012-CGRF | | | | | | |
| Point Atkinson | 5.345 | 5.416 | 0 | 0.663 | 0.555 | -4 |
| Victoria | 3.145 | 3.117 | 0 | 0.663 | 0.518 | -4 |
| Patricia Bay | 4.115 | 3.975 | 0 | 0.632 | 0.533 | -4 |
| Campbell River | 4.805 | 4.900 | 0 | 0.578 | 0.507 | -6 |
| Dec 2012-HRDPS | | | | | | |
| Point Atkinson | 5.345 | 5.414 | 0 | 0.663 | 0.555 | -4 |
| Victoria | 3.145 | 3.123 | 0 | 0.663 | 0.518 | -4 |
| Patricia Bay | 4.115 | 3.984 | 0 | 0.632 | 0.533 | -4 |
| Campbell River | 4.805 | 4.905 | 0 | 0.578 | 0.511 | -6 |
| Averages | | | | | | |
| Point Atkinson | 5.196 | 5.277 | 0 | 0.752 | 0.634 | -3.125 |
| Victoria | 3.147 | 3.125 | -0.625 | 0.684 | 0.563 | -2.125 |
| Patricia Bay | 4.005 | 3.901 | -0.125 | 0.689 | 0.584 | -2.875 |
| Campbell River | 4.756 | 4.835 | -0.250 | 0.673 | 0.590 | -3.875 |

Table A1. Comparisons of modelled and observed amplitudes and phases. R is the ratio of modelled to observed amplitude. $\Delta\phi$ is the difference between modelled and observed phase. D is amplitude of the complex difference. The mean error and root mean square (RMS) error are calculated as the difference between the modelled quantity and observed quantity.

| | Station name | Longitude | Latitude | M ₂ | | K ₁ | | |
|---------------------|------------------|-----------|----------|----------------|--------------------|----------------|------|--------------------|
| | | | | R | $\Delta\phi$ (deg) | D (cm) | R | $\Delta\phi$ (deg) |
| 1 | Port Renfrew | -124.43 | 48.55 | 1.16 | -9.4 | 16.63 | 1.03 | -4.94 |
| 2 | Sheringham Point | -123.92 | 48.38 | 1.19 | -16.47 | 17.95 | 1 | -4.44 |
| 3 | Pedder Bay | -123.55 | 48.33 | 0.96 | -27.39 | 15.91 | 0.99 | -2.41 |
| 4 | Esquimalt | -123.43 | 48.43 | 0.91 | -23.09 | 14.40 | 0.99 | -1.04 |
| 5 | Victoria | -123.37 | 48.42 | 0.89 | -17.77 | 11.62 | 1.04 | -1.83 |
| 6 | Clover Point | -123.35 | 48.41 | 0.83 | -17.95 | 13.39 | 1.03 | -2.23 |
| 7 | Finnerty Cove | -123.3 | 48.47 | 0.83 | -8.24 | 9.47 | 1.02 | -2.19 |
| 8 | Fulford Harbour | -123.45 | 48.77 | 0.82 | -3.08 | 10.78 | 1 | -0.63 |
| 9 | Tumbo Channel | -123.11 | 48.79 | 1.05 | 2.03 | 4.43 | 1.04 | 0.66 |
| 10 | Patos Island | -122.97 | 48.78 | 1.03 | 0.26 | 2.32 | 1.04 | -1.5 |
| 11 | Whaler Bay | -123.33 | 48.89 | 1 | -0.76 | 1.10 | 1.01 | -0.48 |
| 12 | Tsawwassen | -123.13 | 48.99 | 1 | 0.92 | 1.31 | 1.01 | 0.19 |
| 13 | Sandheads | -123.3 | 49.1 | 1.02 | -1.05 | 2.58 | 1.04 | -0.59 |
| 14 | Point Grey | -123.27 | 49.25 | 0.98 | -3.31 | 5.83 | 0.96 | -0.68 |
| 15 | Point Atkinson | -123.25 | 49.33 | 1.01 | -0.48 | 1.07 | 1 | -0.56 |
| 16 | Gibsons Landing | -123.5 | 49.4 | 0.98 | 0.75 | 2.34 | 1 | 0.96 |
| 17 | Winchelsea | -124.08 | 49.3 | 1.01 | -0.19 | 0.78 | 1.01 | 0.51 |
| 18 | Halfmoon Bay | -123.92 | 49.52 | 1.01 | -0.15 | 0.83 | 1.01 | 0.15 |
| 19 | Irvines Landing | -124.05 | 49.63 | 1 | -0.32 | 0.59 | 1.01 | 0.24 |
| 20 | Powell River | -124.55 | 49.86 | 1 | -1.72 | 3.05 | 1 | -0.01 |
| 21 | Little River | -124.92 | 49.74 | 1.03 | 0.07 | 2.54 | 1.01 | 0.33 |
| 22 | Lund | -124.76 | 49.98 | 1.02 | -2.52 | 4.98 | 1.02 | -0.95 |
| 23 | Twin Islets | -124.93 | 50.03 | 1.02 | -2.05 | 4.22 | 1.01 | -0.24 |
| 24 | Campbell River | -125.24 | 50.04 | 0.99 | 0.51 | 1.12 | 1 | 0.94 |
| 25 | Maude Island E | -125.33 | 50.13 | 1.13 | -10.02 | 12.62 | 0.97 | -1.44 |
| 26 | Nymph Cove | -125.36 | 50.13 | 1.02 | -5.43 | 6.04 | 0.97 | -0.29 |
| 27 | Seymour Narrows | -125.34 | 50.13 | 0.63 | 31.31 | 53.40 | 1.14 | 10.91 |
| 28 | Brown Bay | -125.37 | 50.16 | 0.98 | -5.63 | 9.26 | 0.98 | -0.04 |
| 29 | Chatham Point | -125.44 | 50.33 | 1.09 | -5.49 | 12.18 | 0.98 | -3.18 |
| 30 | Kelsey Bay | -125.96 | 50.39 | 1 | -1.69 | 3.50 | 0.98 | -0.39 |
| 31 | Yorke Island | -125.97 | 50.44 | 0.99 | 1.59 | 3.32 | 1.01 | 1.37 |
| Mean Error (cm/deg) | | | | 4.23 | 6.5 | 8.05 | 1.56 | 1.49 |
| RMS Error (cm/deg) | | | | 7.67 | 10.73 | 12.73 | 2.41 | 2.57 |
| | | | | | | | | 3.91 |