Use of Oceanic Reanalysis to Improve Estimates of Extreme Storm Surge

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ABSTRACT

A storm surge hindcast for the west coast of Canada was generated for the period 1980–2016 using a 2D nonlinear barotropic Princeton Ocean Model forced by hourly Climate Forecast System Reanalysis wind and sea level pressure. Validation of the modeled storm surges using tide gauge records has indicated that there are extensive areas of the British Columbia coast where the model does not capture the processes that determine the sea level variability on intraseasonal and interannual time scales. Some of the discrepancies are linked to large-scale fluctuations, such as those arising from major El Niño and La Niña events. By applying an adjustment to the hindcast using an ocean reanalysis product that incorporates large-scale sea level variability and steric effects, the variance of the error of the adjusted surges is significantly reduced (by up to 50%) compared to that of surges from the barotropic model. The importance of baroclinic dynamics and steric effects to accurate storm surge forecasting in this coastal region is demonstrated, as is the need to incorporate decadal-scale, basin-specific oceanic variability into the estimation of extreme coastal sea levels. The results improve long-term extreme water level estimates and allowances for the west coast of Canada in the absence of long-term tide gauge records data.

1. Introduction

Satellite altimeter data reveal that the global mean sea level has been rising at an average rate of 3 mm yr^{-1} over the past several decades (Church et al. 2013; Dieng et al. 2017; Chen et al. 2017). The future rate of global mean sea level rise is projected to exceed the average observed rate under all Intergovernmental Panel on Climate Change (IPCC) scenarios (IPCC 2013). Relative sea level rise across Canada and along the East Coast of the United States show significant deviations from the global mean sea level rise, primarily due to large spatial variations of vertical land motion (James et al. 2015; Lemmen et al. 2016; Piecuch et al. 2018;

Greenan et al. 2019). Hunter (2012) used tide gauge data to show that frequencies of flooding events around the world could increase by a factor of 16 to 1600 with a global mean sea level rise of 0.5 m. Vitousek et al. (2017) found that regions with low variability in extreme water levels (e.g., the tropics) are expected to experience the largest increases in flooding frequency due to sea level rise. For Atlantic Canada, Greenan et al. (2013) showed that the number of flooding events will increase by a factor of up to about 12 000 in some cases over the period of 1990–2100 for the RCP8.5 scenario, which corresponds to the pathway with the highest greenhouse gas emissions. These results suggest that coastlines that are not commonly affected by extremes will be at increased risk in the future. More frequent flooding caused by rising sea level presents challenges to many coastal communities and adaptation actions are under way in light of regional sea level projections and characteristics of storm history (Zhai et al. 2015; Witze 2018).

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Hunter (2012) developed a sea level allowance method to aid in the adaptation planning for sea level rise. A sea level allowance is the additional vertical elevation required for coastal infrastructure if it is to maintain (relative to the recent past) the same frequency of extreme sea level events in a future scenario of sea level rise. The allowance incorporates regional sea level projections and the uncertainty estimates, as well as the statistics of sea level extremes specific to the coastal location. Extreme sea level results from the combined effects of waves, tides, storm surge and large-scale climate variability (Bromirski et al. 2003; Marcos et al. 2015). Statistics on extreme sea levels can be derived from long historical records of hourly measurements at tide gauge locations (Menéndez and Woodworth 2010; Bromirski et al. 2017). In areas where long water level records are not available, multidecadal hindcasts of storm surge, tides and waves obtained from barotropic ocean models can be used to estimate sea level extremes at both global (Carrère and Lyard 2003; Muis et al. 2016) and regional scales (Bernier and Thompson 2006; Zhang and Sheng 2013; Zhang and Sheng 2015; Marsooli and Lin 2018).

In general, use of barotropic models is only valid in regions for which the shelf width is much greater than the internal radius of deformation (Huthnance 1992). Greatbatch et al. (1996) showed that barotropic models have skill in accounting for sea level variability at time scales from a few days to a few months in the northwest Atlantic. A combination of storm surge hindcasts and tidal predictions (Bernier and Thompson 2006; Zhang and Sheng 2013) has been used to improve estimates of sea level allowances for locations where there are no tide gauge observations (<http://www.bio.gc.ca/science/data-donnees/can-ewlat/index-en.php>). Greatbatch et al. (1996) pointed out that the barotropic model is unlikely to be valid for the shelves around the eastern Pacific, where the two length scales are of similar order. Pares-Sierra and O'Brien (1989) used a reduced gravity model to demonstrate the importance of baroclinic effects on the seasonal and interannual sea level variability along the West Coast of the United States. Recently, Soontiens et al. (2015) successfully simulated storm surges in 2006 in the Strait of Georgia using the baroclinic Nucleus for European Modeling of the Ocean (NEMO) and showed that remote forcing is the dominant factor affecting surge amplitudes in this region. Kodaira et al. (2016) demonstrated that the inclusion of density stratification increases the overall predictive skill of global storm surges for fall 2014 using a simplified baroclinic NEMO model. Because of the computational cost of these models, there has been no simulation of multidecadal storm surges along the

coast of the northeast Pacific that includes baroclinic dynamics.

The British Columbia storm surge forecasting system (<http://stormsurgebc.ca>) has been operating since 2007 using a 2D nonlinear barotropic Princeton Ocean Model (POM). Model predictions out to 7 days are provided online to emergency managers and public stakeholders including the cities of Surrey, Richmond, and Delta. In this study, we use the POM forecasting system to generate a 37-yr storm surge hindcast from 1980 to 2016. Because barotropic models cannot determine baroclinic processes that affect seasonal and interannual sea level variability such as those described in the northeast Pacific by L. Zhai et al. (2019, unpublished manuscript), we present a procedure to account for these processes. We further demonstrate that basin-scale oceanic processes in the Pacific Ocean play an important role in estimation of extreme sea levels.

This paper is structured as follows. Section 2 describes the storm surge model, tide gauge observations, and oceanic reanalysis data. Comparisons of surge hindcast, adjusted surge, and tide gauge observations are presented in section 3. Discussion and conclusions are presented in section 4.

2. Methods and data

a. Storm surge model

The storm surge model is based on a two-dimensional implementation of the Princeton Ocean Model (Blumberg and Mellor 1987; Mellor 2004). Sea level η , including the inverted barometer effect, is solved using the depth-averaged barotropic momentum and continuity equations:

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + \mathbf{f} \times \mathbf{u} = -g \nabla \eta - \frac{1}{\rho_0} \nabla P_a + \frac{\boldsymbol{\tau}_s - \boldsymbol{\tau}_b}{\rho_0 H} + \nabla \cdot A \nabla \mathbf{u}, \quad (1)$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial(Hu)}{\partial x} + \frac{\partial(Hv)}{\partial y} = 0, \quad (2)$$

where $\mathbf{u} = (u, v)$ represents the depth-averaged horizontal velocity vector; $\mathbf{f}$ is the upward-pointing vector of the Coriolis parameter; g is the acceleration due to gravity; $\boldsymbol{\tau}_s$ and $\boldsymbol{\tau}_b$ are the surface and bottom stress vectors, respectively; A is the horizontal viscosity coefficient; H is the total water depth ($H = \eta + h$); h is the mean water depth; P_a is the atmospheric pressure at the sea level; and ρ_0 is the reference (constant) water density. Wind stress $\boldsymbol{\tau}_s$ is computed from the wind velocity at 10 m above the sea surface using the bulk formula of Large and Pond (1981). The bottom friction

is parameterized using a quadratic law, with a fixed drag coefficient of 0.0025, except in specific limited regions in Juan de Fuca Strait where larger bottom friction coefficients were used to dampen reflection of waves entering the Strait of Georgia (Fig. 1). The horizontal viscosity is parameterized according to Smagorinsky (1963).

The model domain extends from 30° to 61.4°N and from 122°W to 180°. The model resolution is 1/16°, corresponding to a resolution of about 7 km. The bathymetry was derived from the GEBCO 1-arc-min grid. At open boundaries, the radiation condition of Flather (1976) is applied to the normal velocity.

At the ocean surface, the surge model is driven by hourly winds and sea level pressures taken from two products of the U.S. National Center for Environmental Prediction (NCEP). The surface forcing data are obtained from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) during 1980–2010 and from the Climate Forecast System, version 2 (CFSv2; Saha et al. 2011), during 2011–16. CFSv2 can be considered as a seamless extension of CFSR (Saha et al. 2014).

The model is integrated for 37 years, from 1980 to 2016, and hourly sea levels are extracted for grid points nearest to tide gauge locations. To compare the model results with the tide gauge observations, we removed the long-term mean and applied a 40-h low-pass filter to the hourly modeled surge. The filter cutoff period takes into account the characteristic time scale for storm surge along the coast of British Columbia of approximately 3 days.

Assuming that the non-isostatic pressure effect is small, the hourly storm surge heights η_{POM} modeled by the barotropic POM can be written as the sum of a wind-driven component η_{wind} and an inverse barometer component η_{ib} :

$$\eta_{\text{POM}} \equiv \eta_{\text{wind}} + \eta_{\text{ib}}. \quad (3)$$

The goal of the study is to show that the modeled storm surge heights η_{POM} closely simulate actual storm surge heights within the tide gauge water level records η_{total} , provided we accurately account for contributions from the tides η_{tide} , and baroclinic intraseasonal and inter-annual variations η_{bc} , captured by the ensemble global oceanic reanalysis ORAS5, where

$$\eta_{\text{POM}} = \eta_{\text{total}} - \eta_{\text{tide}} - \eta_{\text{bc}}. \quad (4)$$

b. Tide gauge observations

Observed hourly water levels at 12 permanent operating tide gauge stations (Fig. 1) were obtained for all available periods from the Integrated Science Data

FIG. 1. Map showing tide gauge stations along the coast of British Columbia, Canada. Gray line is the boundary between the United States and Canada. SG is the Strait of Georgia. SJF is the Strait of Juan de Fuca.

Management (ISDM) digital archives of Fisheries and Oceans Canada (<http://www.isdm-gdsi.gc.ca/isdm-gdsi/twl-mne/maps-cartes/inventory-inventaire-eng.asp>). We also include Neah Bay in Washington State (<https://tidesandcurrents.noaa.gov/waterlevels.html?id=9443090>) because it sits at the entrance to the Salish Sea and may inform the accuracy of the stations within the inner coastal waters. To compare the modeled surge with the water level observations, the steps in deriving the tidal residual, $\eta_o \equiv \eta_{\text{total}} - \eta_{\text{tide}}$, from each tide gauge record are to 1) remove physically unlikely outliers identified as large tidal elevations or by a clear vertical offset; 2) linearly detrend the hourly water levels using the full record; 3) select data for the study period from 1980 to 2016; 4) perform harmonic tidal analyses on 18.6-yr record lengths; 5) perform additional harmonic tidal analyses on the residual water levels obtained in step 4 on a year-by-year basis; 6) apply a 40-h low-pass filter to the residual water levels obtained in step 5; and 7) remove the long-term mean.

Step 2 is necessary, as extreme analysis requires stationary time series with no long-term trend. The tidal analysis performed in step 4 is based on fitting 45 astronomical constituents and 24 of the most important shallow-water constituents to the observations using the tidal analysis package, t_{tide} , of Pawlowicz et al. (2002) with nodal corrections. Several studies (Eliot 2010; Menéndez and Woodworth 2010; Talke et al. 2018) have demonstrated that the 18.6-yr nodal cycle affects the estimation of extreme storm tides and needs to be removed. The nodal correction in t_{tide} takes into account the latitude of tide gauge locations. Step 4 also ensures sufficient record lengths to permit accurate separation

of neighboring tidal frequencies. For example, the frequencies of the main constituents in the fortnightly (MSf and Mf) and monthly (MSm and Mm) bands are too close together to be resolved by a 1-yr time series (Crawford 1982). Following removal of the tidal constituents from the water level records, a spectral analysis was used to confirm that the 18.6-yr time series were long enough to remove most of the fortnightly and monthly tidal energy. The spectral analysis also revealed that step 4 failed to remove all of the tidal energy at diurnal and semidiurnal frequencies due to annual variations in baroclinic tidal dynamics associated with changes in water density. We subsequently performed steps 5 and 6 to effectively remove all diurnal and semidiurnal tidal variability. Step 7 allows direct comparisons between the observations and model results.

c. Adjusting modeled surge estimates using oceanic reanalysis data

Barotropic storm surge models do not include processes related to large-scale sea level variability arising from El Niño and La Niña events or from the effects of steric water level changes due to variations in water density (L. Zhai et al. 2019, unpublished manuscript). These processes have been identified as major drivers of changes in extreme sea levels (Marcos et al. 2015; Muis et al. 2018). Contributions from these processes can be derived using ORAS5 (Zuo et al. 2017, 2019) produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ORAS5, which is based on version 3.4.1 of the NEMO model (Madec 2008), has 75 vertical levels and a horizontal resolution of 0.25°. ORAS5 assimilates temperature, salinity, sea ice concentration, and sea surface temperature. The filtered along-track sea level anomalies (SLA) produced by Archiving Validation and Interpretation of Satellite Oceanographic data (AVISO) have also been assimilated in ORAS5 using a variational data assimilation scheme (Weaver et al. 2005). ORAS5 is forced at the surface by wind and by heat and freshwater fluxes from ERA-Interim (Dee et al. 2011). Note that the surface forcing of ORAS5 does not include sea level pressure. For this study, we have extracted monthly mean ORAS5 sea levels for the northeast Pacific for the period 1980–2016 from the full ORAS5 dataset (1979–2017) published through the Integrated Climate Data Center at University of Hamburg (<http://icdc.cen.uni-hamburg.de/projekte/easy-init/easy-init-ocean.html>). For inlets and bays that are not resolved by the 1/4° ORAS5 model, small subsets of the model domain, covering oceanic grids at the entrances to the regions, were selected and a nearest neighbor method then used to extrapolate data to the query points.

The storm surge model simulates sea level, for which the density of the ocean is assumed to be constant. On the other hand, the ORAS5 sea levels are composed of both barotropic and baroclinic parts, for which the density of the ocean is determined by temperature, salinity, and pressure. Here, we are only interested in adjusting the storm surge model for the baroclinic contribution available through ORAS5. If we simply add ORAS5 values to modeled surge to account for the large-scale sea level variability, we would add the contribution from the monthly barotropic wind-induced component of sea level in ORAS5 to the wind-induced component already present in the model. To avoid this problem of double-counting, we need to remove the monthly barotropic wind-driven component from the surge hindcast and limit the adjustment to the baroclinic component. To do this, we define the sea level component associated with baroclinic processes as

$$\langle \eta_{bc} \rangle = \langle \eta_{ORAS5} \rangle - \langle \eta_{POM} - \eta_{ib} \rangle, \quad (5)$$

where $\eta_{ib} = -(P_a - P_0)/g\rho_0$, P_0 is the reference sea level pressure, and η_{ORAS5} is the sea level derived from monthly ORAS5 data, and the angle brackets denote the monthly mean. To include the effects of baroclinicity, we add the hourly interpolated values of $\langle \eta_{bc} \rangle$, denoted as η_{bc} , to η_{POM} . The combined time series is referred to as the adjusted storm surge height, $\eta_a = \eta_{POM} + \eta_{bc}$.

3. Results

a. Model validation

The hourly modeled surge η_m and adjusted surge η_a were evaluated using observed tidal residuals η_o at the 12 tide gauge sites listed in Table 1. To provide a quantitative comparison, we followed Bernier and Thompson (2006) and calculated three parameters, specifically, the standard deviations of η_o , η_{POM} , and η_a , the standard deviations of $\eta_o - \eta_{POM}$ and $\eta_o - \eta_a$, and the γ^2 values of $\eta_o - \eta_{POM}$ and $\eta_o - \eta_a$, defined as the ratios of the variance of $\eta_o - \eta_{POM}$ and $\eta_o - \eta_a$ to the variance of η_o , respectively. The standard deviation of η_o (Table 1) ranges from 0.129 to 0.171 m at the oceanic stations, defined as all tide gauge sites except New Westminster, which is situated on the Fraser River. The standard deviation of η_{POM} (Table 1) ranges from 0.099 to 0.132 m. Thus, the surge model underestimates the observed variability by about 0.04 m. The standard deviation of adjusted surge η_a ranges from 0.115 to 0.158 m, corresponding to an improvement of about

TABLE 1. Standard deviation (m) of hourly observed tidal residual (column 2), numerically modeled storm surge (column 3), adjusted storm surge using ORAS5 (column 4), and adjusted storm surge using weekly tide gauge (TG) data (column 5), biweekly tide gauge data (column 6), and monthly tide gauge data (column 7). The last three columns are discussed in [section 3c](#).

Station	TG	Modeled	ORAS5 adjusted	TG adjusted		
				Weekly	Biweekly	Monthly
Neah Bay	0.171	0.102	0.121	0.162	0.156	0.149
Tofino	0.167	0.114	0.133	0.163	0.159	0.155
Bamfield	0.157	0.107	0.123	0.153	0.150	0.146
Victoria Harbour	0.140	0.099	0.115	0.135	0.131	0.127
Patricia Bay	0.139	0.101	0.120	0.133	0.130	0.126
New Westminster	0.279	0.102	0.123	0.268	0.259	0.240
Vancouver	0.141	0.103	0.125	0.134	0.130	0.126
Point Atkinson	0.140	0.103	0.125	0.132	0.128	0.123
Campbell River	0.149	0.111	0.139	0.145	0.141	0.137
Port Hardy	0.149	0.103	0.127	0.146	0.143	0.139
Bella Bella	0.161	0.114	0.138	0.158	0.155	0.150
Queen Charlotte City	0.129	0.112	0.123	0.132	0.131	0.129
Prince Rupert	0.164	0.132	0.158	0.164	0.162	0.158

0.02 m compared to the modeled surge at all tide gauge sites. Observed sea level variability at New Westminster is twice that at oceanic stations, because it measures the highly variable volume transport of the Fraser River. Because the horizontal resolution of all models (including the surge model and ORAS5) are too coarse to resolve the coastline and bathymetry of the river, the modeled variability at New Westminster is partly indicative of oceanic conditions and comparable to that at neighboring stations.

To further demonstrate the effect of baroclinic dynamics on storm surge estimates, we generated maps of the standard deviations of hourly modeled and adjusted surge ([Fig. 2](#)). Overall, the baroclinicity has its greatest effect on the shelf and along the coast. Also, both modeled and adjusted surges show large spatial variations. Stronger variability occurs in regions to the east of Hecate Strait and north of Haida Gwaii. [Figure 3](#) shows monthly means of hourly modeled and adjusted surges compared to observations at Victoria Harbour. The figure illustrates the pronounced differences between barotropic and baroclinic dynamics, and is generally representative of the other tide gauge locations in this study. The monthly means of observed surge have ranges (maximum minus minimum) of 0.51 m at Victoria Harbour. This is well captured by the adjusted surge, but is underestimated by 0.2 m by the modeled surge. During the El Niño years of 1982–83, 1997–98, 2009–10, and 2014–16, the monthly mean values of adjusted surge are elevated by up to 0.2 m relative to the modeled surge. [Figure 3](#) (top) shows that the IB height dominates the modeled surge. The γ^2 values of hourly $\eta_o - \eta_{ib}$ ([Table 3](#)) increases from 0.289 at stations to the north to 0.559 at stations to the south, suggesting that the IB effect generally decreases to the south, consistent

with the finding of [Chelton and Davis \(1982\)](#) and [Bromirski et al. \(2017\)](#).

The standard deviation of modeled error ($\eta_o - \eta_{POM}$) varies from 0.075 to 0.107 m at oceanic stations ([Table 2](#)). The error of the adjusted surge is between 0.052 and 0.081 m and is reduced by 0.03 m at all oceanic stations compared to that of the modeled surge. The γ^2 values of $\eta_o - \eta_{POM}$ range from 0.248 to 0.393, whereas the γ^2 values of $\eta_o - \eta_a$ are reduced significantly by $\sim 50\%$ ([Table 3](#)). We note that the γ^2 values of $\eta_o - \eta_a$ lie below or close to the lower bound of the surge hindcast error ([Table 1](#) in [Bernier and Thompson 2006](#)) and the operational forecasting system for the northwest Atlantic ([Fig. 5](#) in [Bernier and Thompson 2015](#)). The γ^2 values of $\eta_o - \eta_a$ are also similar to those in [Table 2](#) of [Soontiens et al. \(2015\)](#). The above comparison highlights that, in some situations, there is a need to include basin-scale baroclinic dynamics to improve the simulation of storm surge relying on barotropic models.

To further evaluate the hourly modeled and adjusted surges, we examined variance-preserving spectra of the data. An example of this for Victoria Harbour is presented in [Fig. 4](#). The barotropic surge model captures the observed variability at periods of 2–10 days, but clearly underestimates the observed variability at periods greater than 10 days, such as those at interannual (>365 days), seasonal (annual and semiannual harmonics), and intraseasonal (10–100 days) time scales. The adjusted storm surge shows better agreement with observations at interannual and seasonal time scales, but shows no improvement at intraseasonal time scales. The possible causes for the underestimation of intraseasonal sea level variability of the adjusted surge are addressed in [section 3c](#).

FIG. 2. Standard deviation (m) of the hourly (top) numerically modeled and (bottom) adjusted surge. Black line is the boundary between the United States and Canada.

b. Estimation of extreme storm surges

Extreme sea levels can be described through either changes in the magnitude of extreme water level events or changes in the occurrence of these events (Menéndez and Woodworth 2010). These two quantities can be quantified by two types of statistical models, including the generalized extreme value (GEV) approach and the generalized Pareto distribution (GPD) approach. The GEV approach, including the Gumbel distribution, examines the highest annual water levels for a given location and models the probabilities of the occurrences of these maxima (Vitousek et al. 2017). The GPD approach incorporates hourly observations above a certain threshold that, for example, could be defined as the 99th percentile and has to be high enough to ensure that exceedances describe real extreme events (Buchanan et al. 2017). Among 20 different extreme-value analysis

FIG. 3. (top) Monthly means (m) of hourly observed (red line), modeled storm surge (blue line), and IB height water levels (black line) for Victoria Harbour. (bottom) Monthly means (m) of hourly observed (red line), adjusted storm surge (green line), and ORAS5 water levels (black line) for Victoria Harbour.

methods, Wahl et al. (2017) demonstrated that the Gumbel approach gives the highest estimate of 100-yr return water levels for the northeast Pacific. Hence, we chose the more conservative Gumbel approach for the current study to meet the engineering application for Small Craft Harbours in Canada, which is to provide allowance estimates in areas where there are no tide gauge measurements.

Because the large-scale Princeton Ocean Model used in this study was designed to provide 3-hourly estimates of coastal storm surge heights on an operational basis, tides, and tide–storm surge interaction (which have high computational needs) were not considered implicitly in this study. Tides can play an important role in coastal flooding at the time of a storm surge event. For example, a moderate storm surge can have a large impact when it coincides with high tides. To simulate this effect, the simple method is to add tidal predictions and nontidal heights. Zhang and Sheng (2015) applied the Monte Carlo (MC) method (Oliver et al. 2012) to generate realizations of total sea levels by randomly changing the time lag between predicted tides and nontidal heights. Both methods assume that tide–surge interactions are small, and give similar return levels for regions where the tidal elevations are dominant (Zhang and Sheng 2015). Moreover, Soontiens et al. (2015) showed that the effect of tide–surge interaction is small and there is no change in the timing of the surge in the Strait of Georgia. On the basis of these studies, we consider the effect of tides and tide–surge interaction of secondary importance on the British Columbia coast.

TABLE 2. Standard deviation (m) of $\eta_o - \eta_m$ (column 2), $\eta_o - \eta_a$ adjusted using ORAS5 (column 3), using weekly tide gauge data (column 4), biweekly tide gauge data (column 5), and monthly tide gauge data (column 6). The last three columns are discussed in section 3c.

Station	Modeled	ORAS5 adjusted	TG adjusted		
			Weekly	Biweekly	Monthly
Neah Bay	0.107	0.081	0.041	0.052	0.0607
Tofino	0.096	0.067	0.030	0.038	0.047
Bamfield	0.091	0.065	0.027	0.035	0.0443
Victoria Harbour	0.081	0.057	0.028	0.036	0.0425
Patricia Bay	0.080	0.054	0.030	0.037	0.0432
New Westminster	0.265	0.270	0.061	0.079	0.1016
Vancouver	0.082	0.057	0.035	0.042	0.0484
Point Atkinson	0.080	0.060	0.035	0.043	0.0492
Campbell River	0.083	0.060	0.033	0.041	0.0481
Port Hardy	0.091	0.057	0.032	0.040	0.0487
Bella Bella	0.091	0.057	0.031	0.039	0.047
Queen Charlotte City	0.075	0.052	0.034	0.041	0.0467
Prince Rupert	0.082	0.052	0.029	0.037	0.0441

Following Hunter [2012, their Eq. (5)], we fitted a Gumbel distribution to the annual maxima of hourly sea levels according to

$$F = \exp \left[-\exp \left(\frac{\mu - z}{\lambda} \right) \right], \quad (6)$$

where F is the probability that the annual maximum is less than a return level z , μ is the location parameter, and λ is the scale parameter. The probability F is related to the return period $R(z)$ according to $F = \exp\{-[1/R(z)]\}$ (Pugh 1996, p. 270). The scale parameter is one of the input quantities used to calculate sea level allowances for adaptation of coastal infrastructure. The fitted Gumbel distribution with two parameters allows us to quantify return periods that are longer than

the observed records. Annual maxima were computed from September of year n to August of year $n + 1$, the period we are defining as storm year n . The reason for this choice of time period is that the largest storm surge events typically occur during the winter period and, therefore, using the calendar year could result in an event in late December–early January being captured in two adjoining years.

Figure 5 (top) shows that the observed annual maxima range from 0.30 to 0.78 m. Extreme storm surge events typically take place in late fall or winter (Fig. 5, bottom). The modeled storm surge underestimates large storm events, such as the one in 1982, by 0.3 m. The adjusted surge improves estimates of the annual maxima, as illustrated by the improvement of 0.1 m

TABLE 3. Values of γ^2 , defined as the ratios of the variance of the errors from the numerical model to the variance of the observations. γ^2 values of hourly IB height (column 2), modeled storm surge (column 3), adjusted storm surge using ORAS5 (column 4), and adjusted storm surge using weekly tide gauge data (column 5), biweekly tide gauge data (column 6), and monthly tide-gauge data (column 7). The last three columns are discussed in section 3c.

Station	IB height	Modeled	ORAS5 adjusted	TG adjusted		
				Weekly	Biweekly	Monthly
Neah Bay	0.559	0.393	0.223	0.058	0.093	0.126
Tofino	0.494	0.329	0.159	0.032	0.053	0.079
Bamfield	0.493	0.339	0.173	0.029	0.051	0.080
Victoria Harbour	0.488	0.337	0.164	0.040	0.065	0.093
Patricia Bay	0.467	0.331	0.151	0.046	0.070	0.097
New Westminster	0.867	0.898	0.937	0.048	0.080	0.133
Vancouver	0.469	0.335	0.167	0.063	0.090	0.118
Point Atkinson	0.454	0.323	0.181	0.064	0.093	0.123
Campbell River	0.446	0.309	0.159	0.048	0.077	0.104
Port Hardy	0.421	0.373	0.148	0.045	0.074	0.107
Bella Bella	0.402	0.320	0.123	0.037	0.059	0.085
Queen Charlotte City	0.278	0.341	0.165	0.068	0.099	0.131
Prince Rupert	0.363	0.248	0.100	0.032	0.050	0.073

FIG. 4. Variance-preserving spectra of hourly observed tidal residuals (red), modeled surge (blue), and adjusted surge (green) for Victoria Harbour.

for the 1982 event. The timing of 25 out of 36 storm surge events is captured by both the modeled and adjusted surge. We note that it is challenging to get the timing right when surge amplitudes are small and there are similar amplitudes for several events in a given year.

Figure 6 shows the return level versus return period for extreme sea levels at Victoria Harbour. The Gumbel fit is reasonably good for return levels at shorter return periods as the data lie within the 95% confidence bounds. The confidence range increases with increasing return period because fewer data are available at higher water levels. At coastal oceanic stations, observed 10-yr return levels range from 0.68 to 0.83 m (Table 4). At New Westminster, the 10-yr return level is 1.26 m, much higher than that for nearby oceanic stations, due to the influence of the Fraser River. The modeled surge for oceanic sites underestimates the observed 10-yr return level by 0.06–0.28 m, while the adjusted surge level shows a smaller error of -0.01 to $+0.19$ m relative to observations (Table 4). For many scientific and engineering applications, it is also important to quantify extreme sea levels with low probability but high impact potential. Table 5 shows that the observed 50-yr return level ranges from 0.86 to 1.05 m at oceanic stations, and is increased by 0.2 m compared to the 10-yr return level. At New Westminster, the observed 50-yr return level is 1.7 m and is 0.44 m higher than the observed 10-yr return level. Differences between the modeled and observed 50-yr return level are in the range of 0.1–0.37 m at oceanic stations, while the differences for the adjusted surge shows a reduced range of 0.07–0.26 m.

Figure 7 (top-left panel) highlights the spatial variability in the 10-yr return level of η_{POM} . The largest

FIG. 5. (top) Annual maxima and (bottom) timing of annual maxima of observed tidal residuals (red), modeled surge (blue), and adjusted surge (green).

return level on the east side of Hecate Strait is likely the result of the storm tracks which bring strong westerly and southwesterly winds to the western mainland coast of BC. These also generate strong northward currents along the eastern side of Hecate Strait, causing high setup associated with the Coriolis effect (Hannah and Crawford 1996). The 10-yr return level of the adjusted surge (Fig. 7, middle left) is higher than that of the modeled surge along the entire coast of British Columbia. To further demonstrate the influence of baroclinic dynamics on the 10-yr return level, we computed the difference of the return levels from modeled and adjusted surge heights. The baroclinic contributions (Fig. 7, bottom) are greatest around Vancouver Island and along the coast of Washington State, where coastal sea levels are affected by variations in the poleward-flowing Vancouver Island Coastal Current (Thomson et al. 1989), by passing coastal trapped waves originating with wind events off southern Oregon and northern California (Connolly et al. 2014; Thomson and Krassovski 2015), and by seasonal changes in the location of the bifurcation region between the poleward-flowing Alaska Current and equatorward-flowing California Current (Thomson 1981). The spatial pattern for 50-yr return level (Fig. 7, right) remains similar to that for 10-yr return level.

Gumbel scale parameters derived from observed tidal residuals (Table 6) range from 0.10 to 0.133 m at oceanic stations. The ratio of modeled and observed scale parameter is between 48% and 77%, whereas the ratio of adjusted and observed scale parameter is between 67% and 99%. Overall, the adjusted surge improves estimation of the Gumbel scale parameters by

FIG. 6. Return levels (m) of (left) observed tidal residuals, (center) modeled surge, and (right) adjusted surge using ORAS5. Red dots are the ranking of annual maximum surge heights. Solid lines are maximum likelihood curves, and dashed lines show the 95% confidence bounds.

20%, which is significant when trying to characterize extreme water level events as best possible.

c. Sensitivity tests

Comparison of frequency spectra derived from the adjusted surge and observed tidal residuals (Fig. 4)

reveals that the adjusted surge contains less variability over periods of 10–100 days. There are baroclinic effects on time scales shorter than 1 month that may impact water levels in this region, such as propagation of coastal trapped waves (Connolly et al. 2014; Thomson and Krassovski 2015). These effects are not accounted for

TABLE 4. The 10-yr return levels (m) derived from hourly observed sea level (column 2), numerically modeled sea level (column 3), adjusted sea level using ORAS5 (column 4), and adjusted sea level using weekly tide gauge data (column 5), biweekly tide gauge data (column 6), and monthly tide gauge data (column 7). The last three columns are discussed in section 3c.

Station	TG	Modeled	ORAS5 adjusted	TG adjusted		
				Weekly	Biweekly	Monthly
Neah Bay	0.81	0.53	0.62	0.75	0.73	0.71
Tofino	0.83	0.60	0.67	0.79	0.77	0.74
Bamfield	0.81	0.56	0.62	0.78	0.76	0.74
Victoria Harbour	0.74	0.52	0.60	0.70	0.68	0.65
Patricia Bay	0.76	0.54	0.63	0.70	0.68	0.67
New Westminster	1.26	0.55	0.65	1.15	1.05	0.96
Vancouver	0.78	0.55	0.66	0.71	0.69	0.67
Point Atkinson	0.78	0.56	0.66	0.70	0.69	0.67
Campbell River	0.79	0.60	0.72	0.74	0.73	0.72
Port Hardy	0.70	0.50	0.59	0.67	0.64	0.63
Bella Bella	0.75	0.54	0.61	0.72	0.69	0.67
Queen Charlotte City	0.68	0.62	0.69	0.72	0.73	0.70
Prince Rupert	0.72	0.60	0.67	0.71	0.70	0.71

TABLE 5. The 50-yr return levels (m) derived from hourly observed sea level (column 2), numerically modeled sea level (column 3), adjusted sea level using ORAS5 (column 4), and adjusted sea level using weekly tide gauge data (column 5), biweekly tide gauge data (column 6), and monthly tide gauge data (column 7). The last three columns are discussed in section 3c.

Station	TG	Modeled	ORAS5 adjusted	TG adjusted		
				Weekly	Biweekly	Monthly
Neah Bay	1.00	0.63	0.77	0.94	0.91	0.90
Tofino	1.05	0.71	0.82	0.99	0.96	0.92
Bamfield	1.03	0.66	0.77	0.99	0.96	0.93
Victoria Harbour	0.93	0.62	0.76	0.89	0.85	0.82
Patricia Bay	0.96	0.64	0.79	0.89	0.86	0.84
New Westminster	1.70	0.66	0.81	1.56	1.41	1.31
Vancouver	0.99	0.66	0.82	0.90	0.88	0.85
Point Atkinson	0.98	0.67	0.82	0.88	0.87	0.85
Campbell River	1.00	0.71	0.88	0.92	0.91	0.90
Port Hardy	0.87	0.59	0.71	0.82	0.78	0.76
Bella Bella	0.92	0.63	0.73	0.87	0.83	0.81
Queen Charlotte City	0.86	0.76	0.86	0.90	0.91	0.87
Prince Rupert	0.87	0.71	0.80	0.85	0.84	0.85

in the monthly means from the ORAS5 product. In this section, to quantify the influences of different time scales of these missing processes, we created weekly, biweekly, and monthly averages of tidal residuals and define the corresponding baroclinic processes as

$$\langle \eta_{bc} \rangle_m = \langle \eta_o - \eta_{POM} \rangle_m, \quad (7)$$

where m indicates the weekly, biweekly, or monthly averaging period. Then the hourly interpolated values of $\langle \eta_{bc} \rangle_m$ were added to η_{POM} , and the combined time series referred to as the adjusted surge using tide gauge data. Overall, shortening of the averaging period causes the adjusted surge to agree more closely with the observed tidal residuals. For New Westminster, the standard deviation of the adjusted surge using ORAS5 is half that derived from the tide gauge record (Table 1); the standard deviation of the error of weekly adjusted surge (Table 2) is significantly reduced by 0.2 m. The γ^2 values of the weekly adjusted surge (Table 3) range from 3% to 7%, which is half the value of the monthly adjusted surge. When the averaging periods are decreased from 1 month to 1 week, the amplitudes of large surge are also improved (Fig. 8). The Gumbel scale parameters of weekly adjusted surge (Table 6) reproduce greater than 88% of the scale parameters derived from observations. The 10-yr return levels of weekly adjusted surges (Table 4) have errors of less than 0.11 m.

4. Discussion and conclusions

This study provides a dynamics-based approach to the computation of extreme storm surges by combining

storm surge simulated by a barotropic numerical model with large-scale processes derived from oceanic reanalysis data. Our approach complements statistical reconstruction of extreme water levels using climate indices and atmospheric/oceanic variables (Wahl and Chambers 2016; Cid et al. 2018). We show that hourly storm surge simulations that are adjusted using monthly reanalysis data reproduce the standard deviation of tide gauge observations reasonably well. Specifically, the reanalysis adjustments reduce the standard deviation of surge errors by 0.03 m, reduce γ^2 values by 50%, and improve Gumbel scale parameters by ~20% compared to the modeled surges. Sensitivity tests using tide gauge data with different averaging periods show that shortening the averaging period from a month to a week further improves adjustment of the modeled surge. These improvements likely arise from inclusion of local and regional baroclinic effects on time scales of days to weeks, such as those associated with the fortnightly cycle in tidal mixing intensity in coastal waters (e.g., Griffin and LeBlond 1990), from variations in discharge from major rivers (specifically, the Fraser River; Thomson 1981), and from variations in upwelling along the outer coast (Thomson et al. 2014).

The adjusted surge produced by this study provides an improvement for the Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT; <http://www.bio.gc.ca/science/data-donnees/can-ewlat/index-en.php>). For the BC coast, the CAN-EWLAT tool currently relies on data from the nearest tide gauge site to characterize the water level history, which can be problematic when a coastal site is located a considerable distance from the tide gauge (Zhai et al. 2014). CAN-EWLAT is being used by Fisheries and Oceans Canada Small Craft

FIG. 7. The (left) 10- and (right) 50-yr return levels (m) of (top) modeled and (middle) adjusted storm surges. (bottom) Differences between adjusted and modeled storm surges.

Harbours for climate change adaptation planning for coastal infrastructure (wharves and breakwaters) to support the fishing industry in Canada. At global scales, our study will help reduce uncertainties in present-day estimates of extreme sea levels, which were found to be more important than future regional sea level rise uncertainties in the northwestern United States (Wahl et al. 2017).

The British Columbia Storm Surge Forecasting System currently provides 6-day total water level forecast only at tide gauge locations, where information on baroclinic water levels is available. The dynamics-based

approach developed in this study, combined with global forecasts of baroclinic water levels (<http://cmems-resources.cls.fr/documents/QUID/CMEMS-GLO-QUID-001-024.pdf>), can be easily adopted to improve storm surge forecasts along the entire coast of British Columbia without additional computational cost.

Recently, L. Zhai et al. (2019, unpublished manuscript) demonstrated that the seasonal and interannual sea level variability along the coast of the northeast Pacific can be mostly accounted for by including steric-height variations. Changes in steric height are strongly influenced by remote winds offshore near 38°N and in

TABLE 6. Gumbel scale parameters (m) derived from hourly observed sea level (column 2), numerically modeled sea level (column 3), adjusted sea level using ORAS5 (column 4), and adjusted sea level using weekly tide gauge data (column 5), biweekly tide gauge data (column 6), and monthly tide gauge data (column 7). The last three columns are discussed in [section 3c](#).

Station	TG	Modeled	ORAS5 adjusted	TG adjusted		
				Weekly	Biweekly	Monthly
Neah Bay	0.115	0.061	0.092	0.111	0.108	0.110
Tofino	0.133	0.068	0.093	0.124	0.116	0.109
Bamfield	0.132	0.063	0.088	0.128	0.123	0.119
Victoria Harbour	0.117	0.061	0.092	0.113	0.107	0.101
Patricia Bay	0.122	0.064	0.096	0.112	0.108	0.104
New Westminster	0.265	0.066	0.098	0.246	0.220	0.212
Vancouver	0.127	0.066	0.099	0.114	0.111	0.106
Point Atkinson	0.124	0.066	0.099	0.109	0.109	0.106
Campbell River	0.122	0.067	0.103	0.111	0.109	0.109
Port Hardy	0.102	0.052	0.074	0.093	0.084	0.081
Bella Bella	0.100	0.056	0.072	0.093	0.086	0.084
Queen Charlotte City	0.105	0.081	0.104	0.109	0.110	0.102

the central tropical Pacific Ocean. [Bromirski et al. \(2017\)](#) demonstrated that extreme storm surge and extreme waves both occur during extreme events about 30% of the time in the northeast Pacific. A fully baroclinic model with high spatial resolution, such as the NEP36 configuration ([Lu et al. 2017](#); L. Zhai et al. 2019,

unpublished manuscript) coupled with a wave model ([Wang and Sheng 2016](#)), may allow us to further improve the simulation of storm surges and the estimation of extreme water levels. However, this is more computationally intensive than the method demonstrated in this study.

FIG. 8. Return levels (m) of adjusted storm surge using (left) monthly, (center) biweekly, and (right) weekly tide gauge data. Red dots are the ranking of annual maximum surge heights. Solid lines are maximum likelihood curves, and dashed lines show the 95% confidence bounds.

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