Use of Oceanic Reanalysis to Improve Estimates of Extreme Storm Surge

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1. Introduction

- **Rising sea level leads to more frequent flooding and infrastructure damage for coastal communities in Canada.**
- **Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT) has been developed for DFO Small Craft Harbours to provide science advice on vertical allowances. This tool depends on having a water level record at the sites where there are no tide gauge observations.**

2. Objectives

- **Develop a method to incorporate baroclinic effects into the estimation of storm surges on the west coast of Canada.**
- **Demonstrate that basin-scale oceanic processes play an important role in accurate simulation of extreme sea levels.**

3. Methods

3.1 Storm Surge Model

- **The British Columbia storm surge forecasting system (https://www.stormsurgebc.ca/) is based on a 2-D nonlinear barotropic Princeton Ocean Model (POM) and is forced by wind and sea-level pressure.**
- **We use the POM forecasting system to generate a storm surge hindcast from 1980 to 2016.**
- **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 variations (η_{bc}), captured by the ORAS5 ensemble global oceanic reanalysis, where $\eta_{POM} = \eta_{total} - \eta_{tide} - \eta_{bc}$.**

3.2 Tide Gauge Observations

- **Observed hourly water levels, η_{total}, at 13 tide gauges were obtained from the Canadian Hydrographic Service (CHS) and the U.S. Center for Operational Oceanographic Products and Services (COOPS).**
- **Residuals are calculated by removing linear trends, predicted tides and variability at periods shorter than 40 hours.**

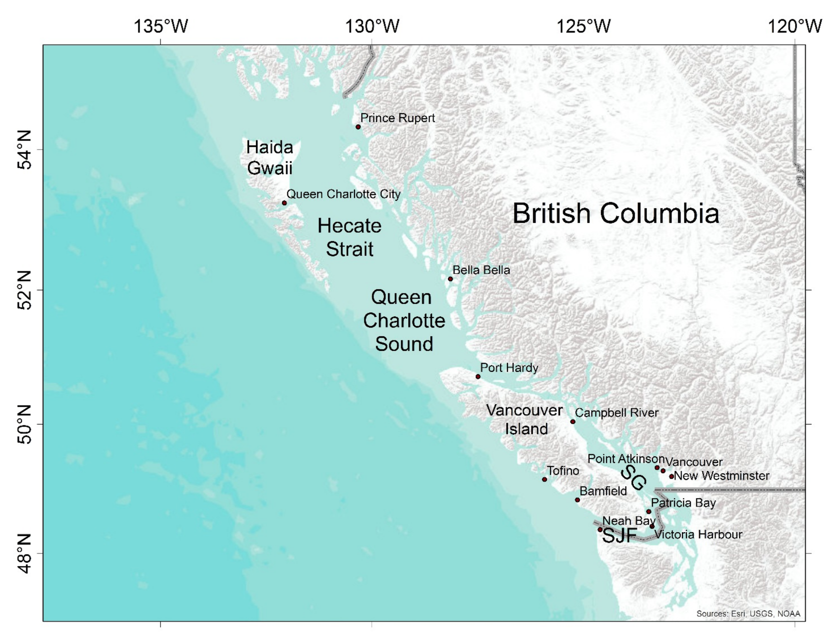

Figure 1: Map showing tide gauge stations along the coast of British Columbia, Canada. SG is the Strait of Georgia. SJF is the Strait of Juan de Fuca.

3.3 Adjusting Modeled Surge Heights Using Oceanic Reanalysis

- **ORAS5 (Zuo et al., 2019) is the oceanic reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF)**
- **ORAS5 water levels include both barotropic and baroclinic effects, but not inverse barometer height.**
- **Sea level associated with baroclinic processes is defined as $<\eta_{bc}> = \eta_{ORAS5} - <\eta_{POM} - \eta_{ib}>$, where η_{ib} is the inverse barometer height, and η_{ORAS5} is the monthly ORAS5 sea levels, and <> denotes the monthly mean.**
- **Adjusted storm surge height, $\eta_a = \eta_{POM} + \eta_{bc}$.**

4. Results

4.1 Comparison of Monthly Water Levels

- **Inverse barometer height dominates the modeled storm surge.**
- **The storm surge model significantly underestimates the monthly observed variability.**
- **Monthly means of ORAS5 water levels capture the seasonal and interannual variations of observations.**
- **Adjusted surge heights show major improvement, compared with modeled surge height.**

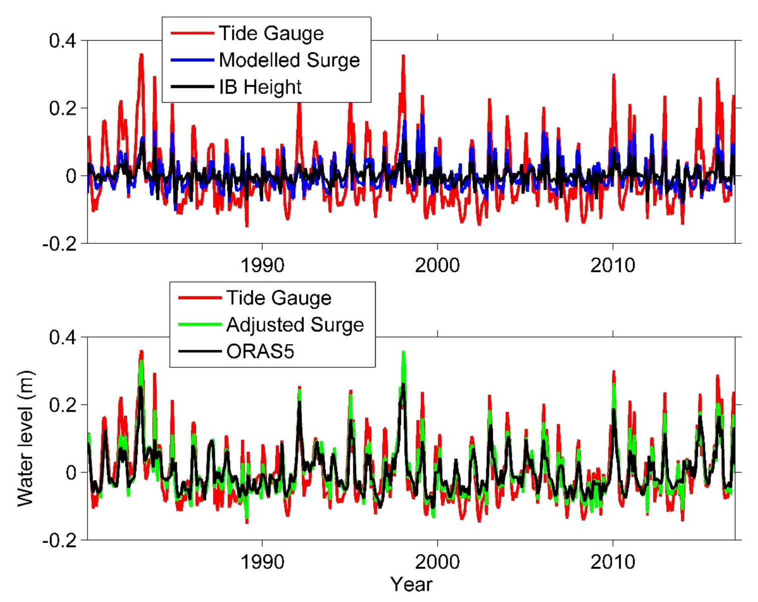

Figure 2. Monthly means (m) of hourly observed (red line), modeled (blue line in top panel) and adjusted (green line in bottom panel) storm surge, IB height (black line in top panel) and ORAS5 water levels (black line in bottom panel) for Victoria Harbour.

4.2 Spatial Variability of Storm Surge

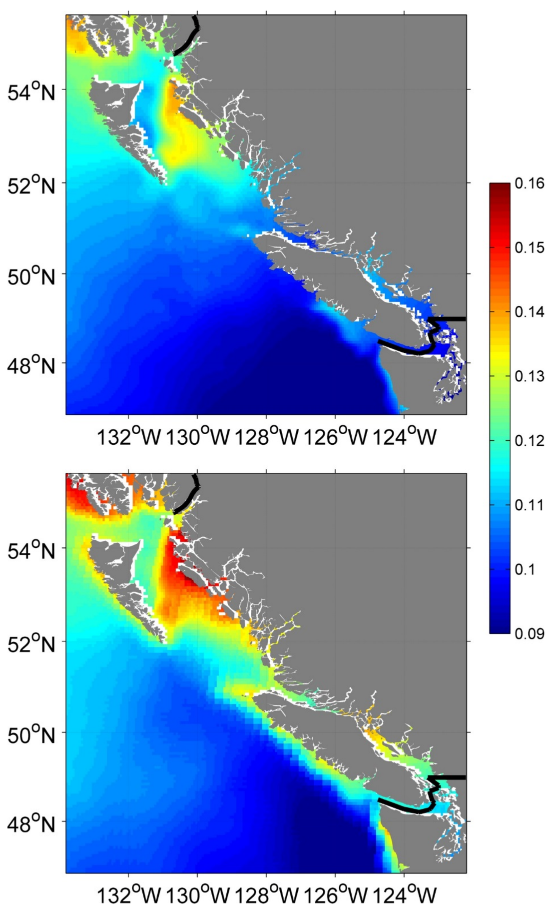

Figure 3. Standard deviation (m) of the hourly, modeled (top) and adjusted (bottom) surge.

- **Baroclinicity has greatest effect on the shelf and along the coast.**
- **Stronger variations occur to the east of Hecate Strait and north of Haida Gwaii.**

4.3 Frequency Spectra of Storm Surge

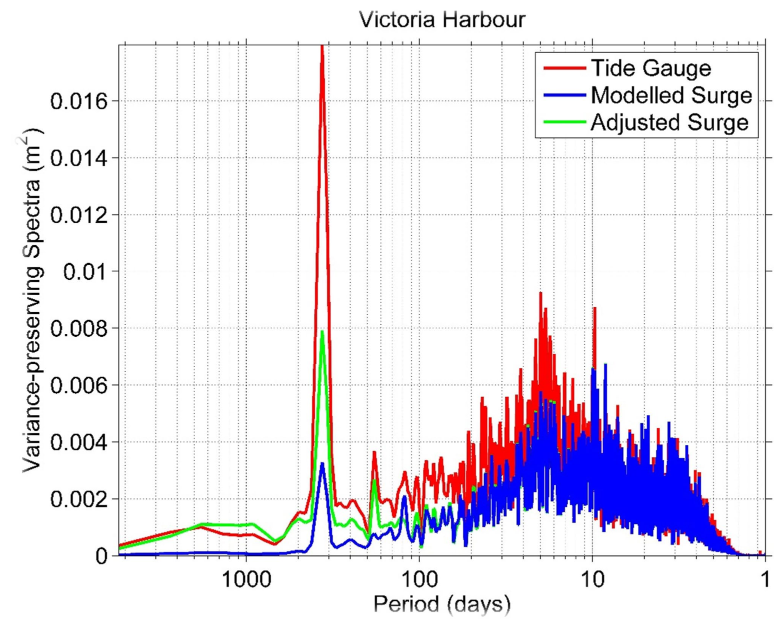

Figure 4. Variance-preserving spectra of hourly observed tidal residual (red), modeled (blue) and adjusted surge (green) for Victoria Harbour.

- **Barotropic surge model captures the observed variability at periods of 2-10 days.**
- **Adjusted surge improves at interannual and seasonal time scales, but not at intra-seasonal time scales.**

4.4 Estimation of Extreme Storm Surges

- **Gumbel distribution is fitted to annual maxima of hourly sea levels**

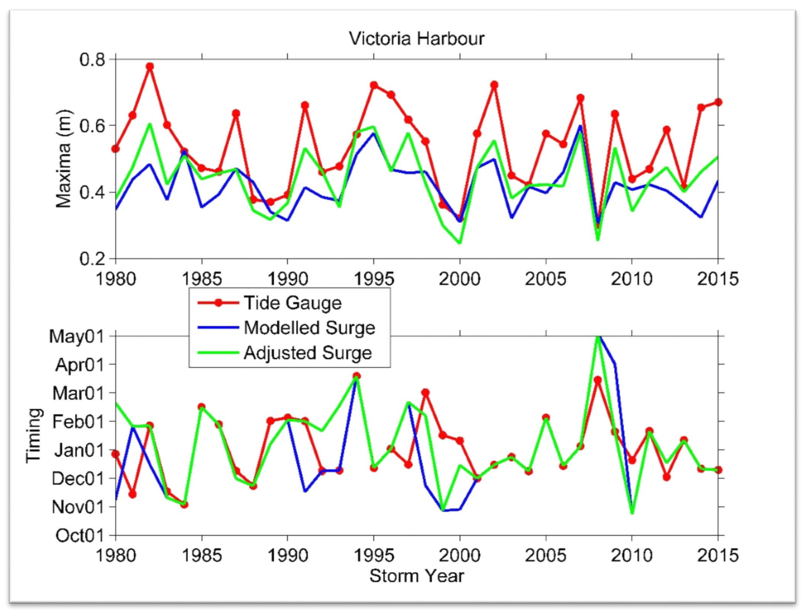

Figure 5. Annual maxima (top) and timing of annual maxima (bottom) of observed tidal residual (red), modeled (blue) and adjusted surge (green).

- **Adjusted surge improves estimates of annual maxima.**
- **Timing of most storm events is captured by modeled and adjusted surge.**

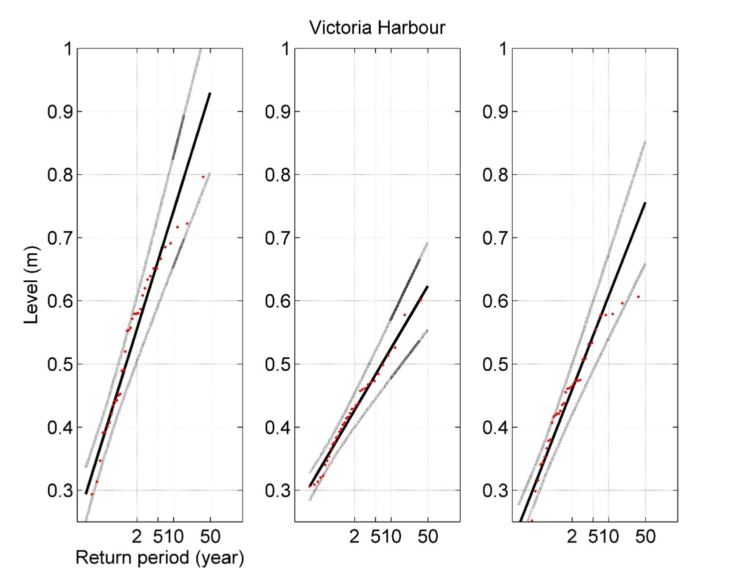

Figure 6. Return levels (m) of observed tidal residuals (left), modeled (middle) and adjusted surge using ORAS5 (right). Red dots are the ranking of annual maximum surge heights. Solid lines are maximum likelihood curves and dashed lines show the 95% confidence bounds.

- **Gumbel fit is good for return levels at shorter return periods.**
- **Modeled surge underestimates the observed 10-year return level.**
- **Adjusted surge level shows a smaller error.**

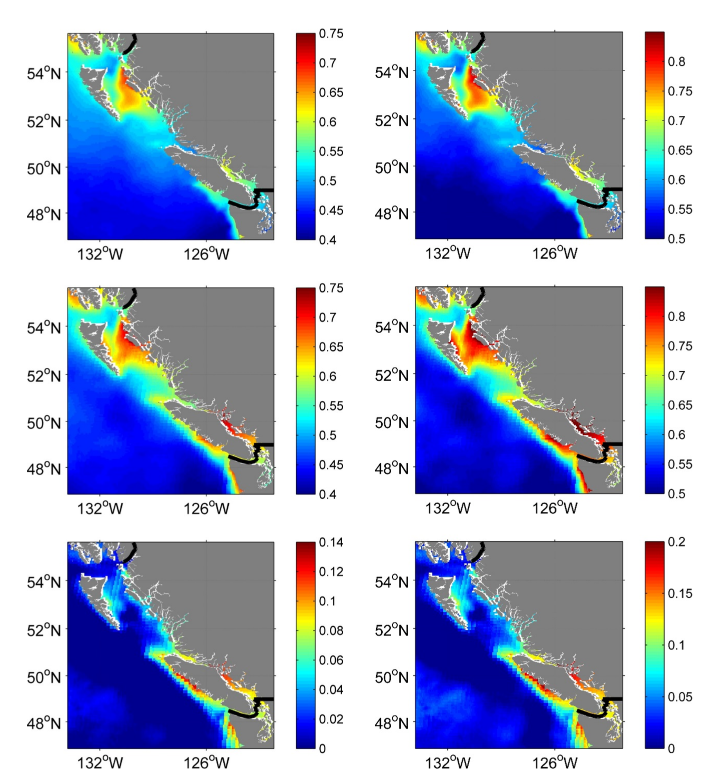

Figure 7: 10-year (left) and 50-year (right) return levels (m) of modeled (top) and adjusted (middle) storm surges. (Bottom left) difference of 10-year return levels between adjusted and modeled storm surge. (Bottom right) difference of 50-year return levels between adjusted and modeled storm surge.

4.5 Influence of Baroclinicity on Return Levels

- **Baroclinic effect is 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, by passing coastal trapped waves originating with wind events off southern Oregon and northern California, and by seasonal changes in the location of the bifurcation region between the poleward-flowing Alaska Current and equatorward-flowing California Current.**

5. Conclusions

- **This research demonstrates the importance of baroclinic dynamics and steric effects to accurate storm surge forecasting for coastal regions.**
- **The results show the need to incorporate decadal-scale, basin-specific oceanic variability into the estimation of extreme coastal sea levels.**
- **This approach improves long-term extreme water level estimates for the west coast of Canada in the absence of long-term tide gauge records data.**

References

Zhai, L., B. J. W. Greenan, R. Thomson and S. Tinis, 2019: Use of oceanic reanalysis to improve estimates of extreme storm surge, Journal of Atmospheric and Oceanic Technology, in review.

Zuo, H., M. A. Balmaseda, S. Tietsche, K. Mogensen, and M. Mayer, 2019: The ECMWF operational ensemble reanalysis-analysis system for ocean and sea-ice: a description of the system and assessment, Ocean Sci. Discuss., https://doi.org/10.5194/os-2018-154, in review.

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