Development of a high-resolution wave and storm surge forecast model for southern British Columbia coastal waters.

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Juan de Fuca Strait (JdF) and the Strait of Georgia (SoG) are the two major coastal waters in southern British Columbia, with great socio-economic importance to all of Canada. These straits form Canada's marine gateway to Asia, and there are more than 10,000 freighters annually that sail JdF and SoG en route to Vancouver or to US ports in Puget Sound. Adding recreational boating, commercial and sport fisheries, navy vessels, and ferry services, makes the area one of the busiest marine areas in the world. Of further importance is the recreational value of these coastal waters with more than 2/3 of British Columbians living within less than 50 km of SoG.

Waves in SoG are generally small, with the median value of the significant wave height H_s=0.3m. However, during winter storms the significant wave height regularly reaches H_s>1.5m in the central SoG and H_s > 2.5m in the northern SoG (Figure 1). These higher sea states have a significant socio-economic impact on the area. For example, (i) frequently, the complete shut-down of the entire BC Ferries services in SoG for the duration of these storms; (ii) flooding of properties along the Fraser delta, especially if the storms coincide with spring tides; (iii) distress of recreational boats, or even commercial vessels, (iv) increased coastal erosion, among others. Generally, sea state will also affect the dispersion of pollutants, nutrients, harmful algae, and the break-up of oil spills.

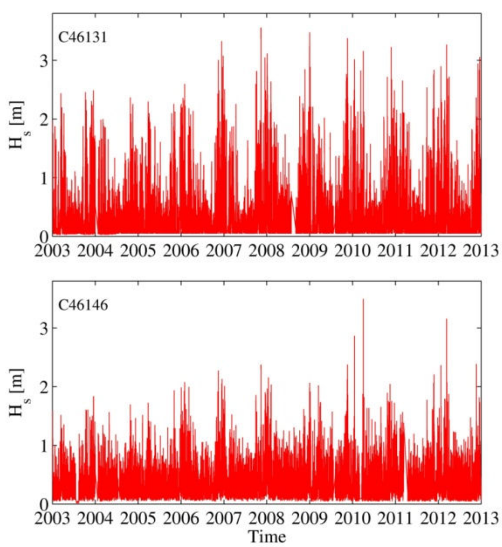

Figure 1: Significant wave height observed at EC wave buoys in northern SoG (top) and central SoG (bottom).

Despite the wide reaching impact of high sea state events, Environment Canada's (EC) operational wave forecast does not include SoG or even JdF. Moreover, the existing model cannot readily be extended to these areas, due to a coarse resolution, and, more important, due to some specific physical processes affecting the local wave field, which are currently not adequately understood and therefore are not included in the operational wave model.

Coastal wave models exist and are run routinely for many areas worldwide. However, the oceanographic setting of SoG and JdF pose some unique challenges regarding wave physics. Wind energy input may be relatively uniform for along-strait wind direction, forming moderate fetch conditions, or spatially variable and extremely fetch limited for strong orographic outflow conditions across the straits. In most of the area the waves are considered deep water waves, except over the mudflats off the Fraser delta. However, the biggest challenge may be the implementation of accurate predictive models for interacting waves and currents. The area features strong tidal currents of up to 5 knots, and a mixture of semi-diurnal and diurnal

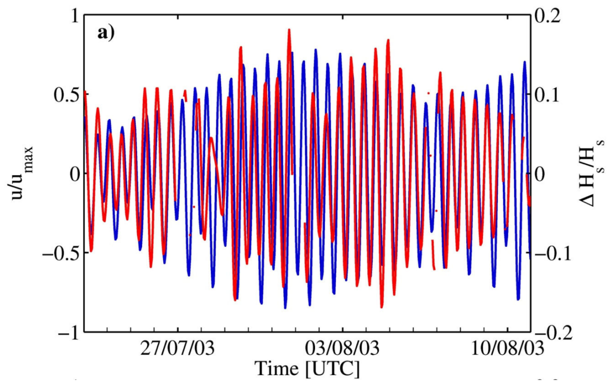

Figure 2 Modulation of significant wave height (red) by tidal currents (blue) in Dixon Entrance (northern BC). Surprisingly, wave heights increase when wave propagation and current are in the same direction, and decreases for opposing currents . (From Gemmrich & Garrett, 2012)

dominant frequencies. In addition, the Fraser outflow generates a strong estuarine circulation with seasonal variability, and is strongly dependent on mixing processes in the strait. Modulation of the wave height by currents is known from observations (*e.g.* Gemmrich & Garrett, 2012), but is not yet explained by state-of-the-art models (Fig. 2). On the other hand, the back-effects of waves on currents due to momentum transfer by breaking waves, and in this case enhanced mixing that will affect the estuarine circulation, are still open questions.

To address these issues, we will need a high resolution operational model for waves coupled to the circulation and the driving wind fields. This coupling is relevant not only to achieving accurate local wave forecasts but to improve the parameterization of physics of operational wave models under *e.g.* changing climate conditions. The associated NEMO-based circulation model is being developed at UBC (Susan Allen) and wind fields at 2.5km resolution (expected to increase to 250m resolution) at EC (Luc Fillion), as part of MEOPAR initial projects. Here, we propose to implement a high resolution wave model, develop and test wave physics modules relevant to the specific settings of SoG and JdF, and provide the end product to EC for operational forecasting. Specific localized settings of the operational model will be decided based on consultation with local stakeholders such as BC Ferries, the West Shore coal port, the local yachting and sailing community, as well as municipal planners such as the Cities of Delta and Richmond. Besides the operational capability of the model we will use it to map out hotspots of wave activity, *i.e.* combinations of environmental parameters that might locally lead to particular rough sea states. This information will be disseminated to mariners.

The wave model will be based on WAVEWATCHIII®, a constantly updated 3rd generation wave model (Tolman, 2009), involving new technology in terms of software for wave-propagation, specification of two-way nested high-resolution grids, and extra physics. The model has a modular construction which allows experimentation with new formulations for the wind input parameterizations, wave dissipation parameterizations, nonlinear wave-wave interactions (Tolman, 2013) and other previously unresolved physics, *e.g.* physics of local wave fields. In regions where physics specific to shallow water waves has to be considered waves will be modelled with SWAN (Simulating WAves Nearshore; 2013), nested within WAVEWATCHIII®. The model will be implemented on a computer platform at UVic, with settings for automatic operational forecasting, using latest technology for nested grids and high resolutions for areas of specific interest, (Mulligan et al., 2011; Xu et al., 2012) including:

- for relatively coarse-resolution large domain, *e.g.* essentially all the Pacific in order to capture distant swell energy, nesting to higher resolution for
- selected fine-resolution domains, for the outer waters approaching JdF as well as areas of interest such as waters around Queen Charlotte Sound, Hecate Strait, Dixon Entrance, or the west coast off Vancouver Island,
- high resolution, unstructured sub-grid inner waters of JdF to SoG

It is anticipated that experimental forecasts will be broadcast on the VENUS webpage, and operational forecasts will be performed by EC once the model is ready to be transferred.

Such a model development will need substantial model validation. For this, we will partner with AXYS Technologies Inc. (Sidney, BC) to temporarily retrofit the two SoG EC wave buoys (C46131, C46146) with directional wave sensors, and to get access to the full set of raw wave data. In addition, the deployment of an additional wave buoy in the southern SoG is planned for, with variable duration periods, subject to permitting issues. The spatial variability of the wave field will be evaluated with high resolution satellite-based SAR (synthetic aperture radar) images (TerraSAR-X), in collaboration with the German Aerospace Centre (Susanne Lehner, DLR). Current observations from the VENUS CODAR system will be included in the wave analysis. In turn, wave information will be used to help improve the wave mode of HF Radars (*e.g.* Barrick & Lipa, 1979), in collaboration with MUN (Eric Gill). Verification of EC winds for specific storm test case events will be performed with state-of-the-art algorithms using satellite SAR imagery from Canada's RADARSAT-2 (Zhang and Perrie, 2012).

Anticipate budget:

Category	Year 1	Year 2	Year 3	Total
Personnel	$115,000	$120,000	$125,000	$360,000
Materials, supplies, dissemination	$1,000	$4,000	$5,000	$10,000
Travel	$9,000	$9,000	$10,000	$27,000
Equipment	$15,000	$65,000		$80,000
Total	**$140,000**	**$198,000**	**$139,000**	**$477,000**

Personnel: salary for a post doctoral fellow (sharing time between BIO and UVic) and partial salary support for research associate Dr. J. Gemmrich (UVic).
Equipment: purchase of a 24 core computer cluster ($15k), and a relocatable wave buoy (65k, incl. mooring)
Travel: for planning and collaboration UVic-BIO-UBC. Conference travel for PDF and RA in year 2 and 3.

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Qualification of research team:

Johannes Gemmrich is physical oceanographer working as a senior research associate at the University of Victoria. His main interests are in the areas of air-sea interactions, wave processes and turbulence. His publications include an extensive list on the physical processes associated with large and/or breaking waves, and he has been an invited speaker at international symposia and colloquia on surface wave processes. He holds a Ph.D. in Physics and a M.Sc. in Marine Meteorology.

William Perrie is an adjunct professor at Dalhousie University. He is also a senior Research Scientist with DFO at the Bedford Institute of Oceanography. Research interests include forecasting air-sea variables related to storms (*e.g.* waves, winds, and currents). He is actively involved in national and international forums, and programs that have built strong collaborations with scientists within DFO as well as throughout Canada and the world. He is the Editor-in-Chief of *Ocean Modelling*. His activities address some of the major issues facing DFO, national and international programs, in marine weather, climate and sea conditions.

Jody Klymak is an Associate Professor at UVic in the School of Earth and Ocean Sciences and the Department of Physics. His background is observational and numerical physical oceanography, with particular emphasis on small scale flow over topography, turbulence, and coastal processes. He has extensive experience in analyzing unique data sets, and interpreting them to develop new physical parameterizations.

Chris Garrett is Professor Emeritus at UVic, having been Lansdowne Professor of Ocean Physics until his retirement in 2010. He has a background and extensive publications in many areas of physical oceanography, with an emphasis on theoretical aspects of small-scale processes, including surface waves and their effects. He is still active on various topics, including surface waves with Johannes Gemmrich and marine renewable energy with Patrick Cummins of the Institute of Ocean Sciences. For the latter topic, which includes wave energy, he recently served on a US NRC committee.