Storm Surges

April 24, 2014

Abstract

Abstract to be completed

1 Introduction

(Masson and Cummins, 2004)

2 Model Configuration

We have used the Nucleus for European Modelling of the Ocean (NEMO) framework in its regional configuration to develop an ocean model for the Strait of Georgia and Salish Sea. NEMO is a highly modularized 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 not used in the present work, NEMO's options for grid nesting and biogeochemical coupling make it a useful tool for studying the complex physics and biogeochemical interactions within the Strait of Georgia. This work focuses on validating the physical set up 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 biogeochemical coupling and data assimilation.

2.1 Model domain

The modelled domain extends from the Strait of Juan de Fuca to Puget Sound to Johnstone Strait as shown in Figure 1. Bathymetry from the Cascadia physiography dataset (Haugerud, 1999) was smoothed to limit the difference in depth across grid cells. 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. As depicted in Figure 1, the numerical grid is rotated 29° counter-clockwise of North in order to maintain computational efficency since currents within the Strait of Georgia are mainly aligned with this rotated axis.

The curvilinear orthogonal numerical grid is divided into 400 by 900 by 40 grid cells, which results in an almost uniform horizontal resolution with grid spacing approximately 400 m by 500 m. The 40 vertical z-levels are 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 10m the grid is stretched gradually with a maxmimum grid spacing of 27 m at the lowest layer. At the bottom boundary, partial z-levels are utilized in order to limit large changes in bathymetry across grid cells (Madec, 2008).

2.2 Boundary conditions and subgrid scale processes

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, temperature and salinity climatologies, and the sea surface height anomaly. The details of

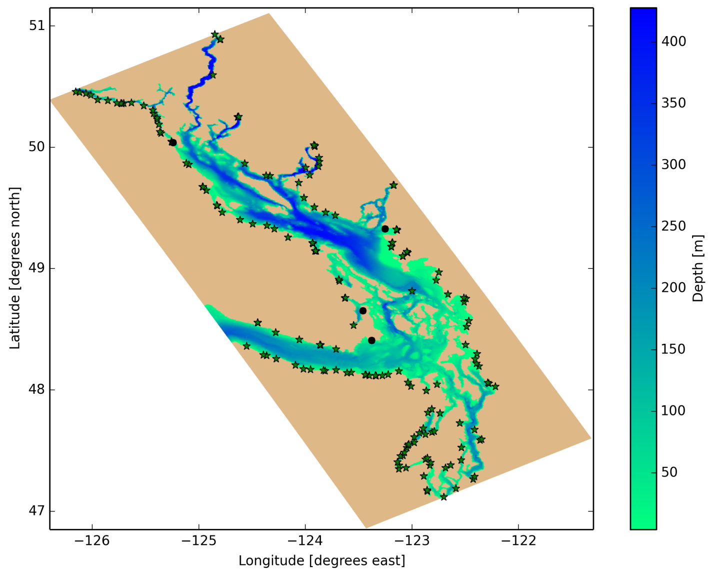

Figure 1: Model domain including bathymetry, rivers (*), and storm surge locations (o) of interest.

these forcing conditions are described below. At coastal boundaries, the partial slip boundary condition, an approximation of the no slip boundary condition, is used. The partial slip boundary condition allows one to include the frictional effects of lateral boundaries without the restricitve resolution required to represent the lateral boundary layer under no slip conditions. A lateral eddy viscosity of 20 m ^{2} s $^{-1}$ parameterizes horizontal friction and the lateral eddy diffusivity is 20.5 m ^{2} s $^{-1}$. At the ocean surface, meterological conditions and fresh water input from rivers are included and described in more detail below. 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 and Burchard, 2003) with background vertical eddy viscosity and diffusivity set to 1×10^{-4} and 1×10^{-5} m^2 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, 2008).

In addition to the equations of motion, a prognostic equation for the sea surface height is solved at each time step. The inclusion 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 time step and barotropic time step are 10 s and 2 s respectively.

2.2.1 Tidal forcing

The model was forced by tidal elevations and currents at the Juan de Fuca and Johnstone Strait boundaries. Tidal heights and currents for eight tidal constituents (K1 ,O1, P1, Q1, M2, K2, N2, S2) at grid points along the Juan de Fuca boundary were extracted from Webtide, an online web prediction model for the northeast Pacific Ocean, which is based on work by Foreman et al. (2000). The Johnstone Strait boundary was forced with current and elevation tidal harmonics measured and calculated by Thomson and Huggett (1980) for the major M2 and K1 constituents. Additionally, O1 and S2 elevation harmonics from their measuresments were employed. The remaining consituents were extrapolated from Webtide.

2.2.2 Temperature and salinity

Temperature and salinity at the Juan de Fuca boundary were taken from a weekly climatology which was created from results from a model covering the Salish Sea and the west coast of Vancouver Island (Masson and Fine, 2012). Their results, originally on s-levels were interpolated onto z-levels and then onto the NEMO horizontal grid. To prepare the climatology all years (1995-2008) were averaged and results, approximately every 15 days, were interpolated to a weekly climatology.

2.2.3 Sea Surface Height

Sea surface height at the mouth of Juan de Fuca was set using values from the Tofino tide guage. 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 guage values, de-tided and with the zero reset as for the climatology.

2.2.4 Open Boundary Conditions

The model relaxed to the forced temperature and salinity over the 10 grid points (about 5km) closest to the open boundaries, using the NEMO FRS scheme (Madec, 2008). The tidal forcing and sea surface height was used in the barotropic velocity forcing which used the NEMO Flather scheme Madec (2008). The baroclinic velocities at the boundary were set to be equal to the values inside the boundary (zero-gradient boundary conditions). This scheme is not part of core NEMO. 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.

2.3 River forcing

River input provides a significant volume of freshwater to the Salish Sea and can influence stratification, circulation and primary productivity. However, most rivers in the domain are not gauged so parameterisations were required to represent river flow. Morrison et al. (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 between 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 in the three grid points closest to the surface at the model point closest to the mouth of each river. Incoming water was assumed to be fresh and at surface temperatyre. A total of 150 rivers were parameterised by this method.

2.4 Atmospheric forcing

2.5 Initial conditions

Initial conditions for temperature and salinity were taken from a CTD cast in the middle Strait of Georgia taken in Sept 2002 (Pawlowicz et al., 2007). Conditions were initially uniform horizontally. Velocity was initialized at zero.

2.6 Spin-up

The model was spun up for a 15.5 months from the initial conditions above, starting Sep 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 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.

3 Model Evaluation

3.1 Tidal evaluation

The model was initially evaluated qualitatively by comparing patterns of tidal amplitude and phase to results from (Foreman et al., 1995). For example, the amphidromic dome around Victoria was produced in the M_2 results, as well as the monotonic decrease in M_2 amplitude moving northwards along the Strait of Georgia. Initially, the Johnstone Strait boundary was closed, but modelled M_2 amplitudes were too small compared to measured amplitudes... TBC

Once our 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 by (Foreman et al., 1995) as:

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

where A_0, A_m, g_0 and g_m are observed and modelled amplitudes and phases.

Complex differences were less than ??cm at all stations in our domain, which was assumed to be acceptable for our purposes.

4 Storm Surge Hindcasts

5 Conclusions

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