A Three-dimensional Hydrodynamic Model of Inland Marine Waters of Washington State, United States, for Tidal Resource and Environmental Impact Assessment

M. Kawase[1] and K.M. Thyng[2]

[1] School of Oceanography,
University of Washington,
Box 355351, Seattle, Washington, 98195-5351, USA
E-mail: kawase@u.washington.edu

[2] Department of Mechanical Engineering,
University of Washington,
Box 352600, Seattle, Washington 98195-2600, USA
E-mail: thyngkm@u.washington.edu

Abstract

Inland coastal waters of the State of Washington, United States, are fjord-like in character and feature many passages where substantial tidal currents with speeds up to three meters per second or greater occur. Combined with close proximity to the major metropolitan area of Seattle and easy access to the power grid, the region is a prime candidate within the United States where tidal power generation can play a significant part in the energy portfolio. The Northwest National Marine Renewable Energy Center is developing a three-dimensional model of tidal and sub-tidal circulation of these waters. The model is based on Stanford University's SUNTANS code, is non-hydrostatic, and allows wetting and drying of tidal flats. It covers the eastern Strait of Juan de Fuca, Puget Sound, San Juan and Channel Islands, and the southern Georgia Basin with an unstructured triangular mesh of 250m average resolution. The model is forced with adjusted tidal currents from WebTide along open boundaries in the Straits of Georgia and Juan de Fuca. In this paper the barotropic tidal response of the model is reported. The model is calibrated against compiled tidal data for the region. Tidal currents in the channels are characterized in terms of velocity and energy density, and the system response is characterized in terms of the sea surface height variability. Future plans for the model include incorporation of baroclinic processes and representation of in-stream energy conversion arrays, assessment of the impact of the arrays on barotropic and internal tides, and of mixing and flushing of waters in the basins.

Keywords: fjord estuary, numerical modelling, tidal resource assessment.

Nomenclature

A	=	amplitude, tidal constituent
C_D	=	non-dimensional drag coefficient
t	=	time
$\boldsymbol{u}$	=	velocity vector
η	=	sea surface elevation
ρ	=	sea water density
$\boldsymbol{\tau}$	=	stress
φ	=	relative phase constant, tidal constituent
ω	=	angular frequency, tidal constituent

Subscripts

B	=	value at the bottom
i	=	index for a tidal constituent

1 Introduction

Tidal in-stream energy conversion (TISEC) is a method of renewable energy generation where the kinetic energy of a tidal stream is used to turn an underwater turbine or another type of movable device that in turn drives an electrical generator. Its means of energy harvesting is akin to that of a wind turbine in the atmosphere. Foremost it requires a naturally existing, energetic tidal stream to operate in (here we exclude artificial ways of creating such streams as barrages and constructed channels). Strong tidal currents can occur in places where large tides are driven through constricted channels, or where there is a large difference in sea level across a channel that provides pressure head for driving such a current. They may be found commonly in coastal areas with complex shorelines and in archipelagos.

Promising TISEC resources may be found along a high-latitude coastline that was glaciated during the past ice ages. Fjords – embayments that were carved by coastal glaciers and subsequently filled by sea water –

are natural features of such a shoreline. Many fjords are of comparable size to the largest of the river estuaries, meaning that the volume of water that is exchanged with the adjacent sea on each tidal cycle is substantial. The entrance of a fjord often forms a natural constriction, laterally as well as vertically due to a local bathymetric minimum or a *sill*, through which the exchange flux must pass through. This results in a strong tidal current that TISEC devices may be able to exploit. Moreover, frequently there is a breach in land separating adjacent embayments, again resulting in a strong current through the breach that is driven by the sea level difference between the two embayments.

Assessment of energy harvest potential in such a region would require a model of sufficient complexity that can represent the myriad inlets and multiply connected channels found in such regions (for an example of a relatively simple model capable of doing this, see [1,2].) Typical fjord estuaries are also biologically highly productive, and provide important habitats for diverse organisms, some of which are commercially significant, threatened at the species level, or both. Development of TISEC resources needs be consistent with the existing marine resource usage, and adverse impacts of TISEC development on the environment, if any, must be minimized. These may include reduction in the tidal range within the fjord, resulting in permanent submergence of lower tidal flats and permanent drying of the higher portions, thus impacting shoreline and wetland ecosystems; and reduction in tidal currents resulting in diminished flushing of the basins, which may have impacts on marine water quality within the fjord. Models will again be needed for the assessment of potential impact of TISEC development on the marine and nearshore environment.

Puget Sound (Fig. 1), located in the state of Washington in the United States of America, is the southernmost fjord estuary on the formerly glaciated coast of the Pacific North America, and is the largest such body of water in the United States outside Alaska [3]. Its watershed basin hosts a growing metropolitan region consisting of the cities of Seattle, Tacoma, Everett and others with a combined human population of 3.26 million. Typical for a fjord estuary, Puget Sound features a silled entrance channel called Admiralty Inlet with a sill depth of 50 meters, and other narrow, silled connection channels such as Tacoma Narrows, Deception Pass and the northern Hood Canal. Strong tidal currents occur in these channels: currents up to three meters per second are observed in Admiralty Inlet, and current speeds may reach four meters per second in Deception Pass. In contrast, the deep interior basins have tidal currents of the order of tens of centimetres and depths reaching a maximum of 283 meters off Seattle.

Such strong tidal currents, as well as proximity to a large human population and to existing electrical grids, make Puget Sound an attractive potential tidal energy resource. Already, as of March 2009, two pilot projects are slated to go into the water in Admiralty Inlet within the following two years (Fig. 2): one on the eastern side of the Inlet by the Snohomish Public Utility District (C. Collar, pers. comm.) and the other on the western side of the channel in one of two possible locations by the U.S. Navy (P Havens, pers. comm.)

A recent one-dimensional modelling study of Puget Sound [2] indicates that average 200MW energy generation may be possible in Admiralty Inlet with a Sound-wide reduction in tidal amplitude of approximately 5%, about one-sixth of the current average energy demand of Seattle. Primary constraints on power harvesting come from site size, array interactions, co-existence with other marine resource utilization, and possible environmental impact. The nature of these constraints are as yet poorly known, and research is needed before a sound estimate of the magnitude of harvestable energy resource, coexistent with other marine resource uses and consistent with the need to preserve the marine and the nearshore environment, can be made.

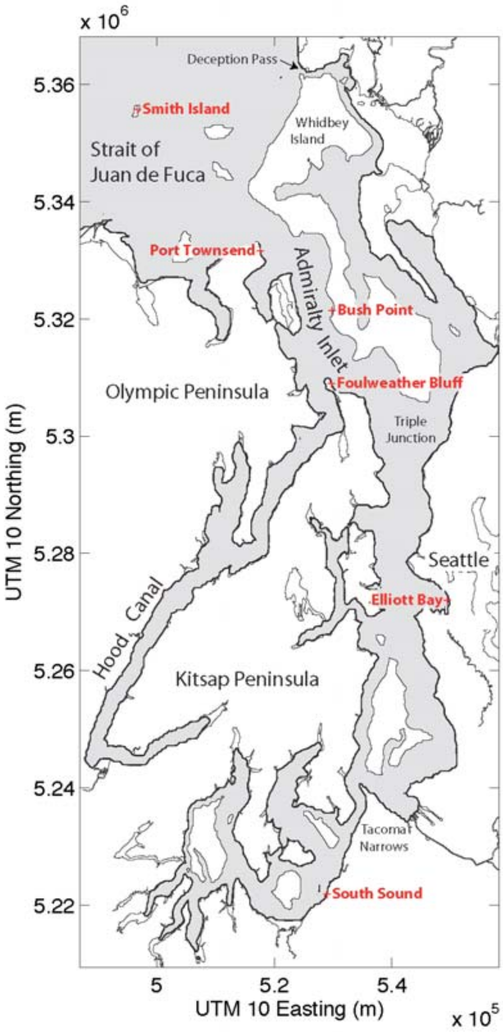

Figure 1: Map of Puget Sound, Washington, U.S.A., with nomenclature used in the paper. Tidal stations used for sensitivity experiments are shown in red.

In order to foster development of understanding of these constraints, as well as of the marine renewable energy in general, in 2008 the U.S. Department of

Energy funded a Northwest National Marine Renewable Energy Center (NNMREC). The Center is a partnership between Oregon State University and the University of Washington; its missions are to conduct research that would close key gaps in understanding of marine renewable energy and to inform the public, regulators, research institutions, and device and site developers of the results of the research. Topics of the research actively pursued at the Center include instrumentation for cost-effective characterization of wave and tidal sites and devices; optimization of device arrays with respect to device orientation and placement; modelling of environmental effects of extraction for both near-field and far-field; and improved reliability and survivability of devices through use of advanced composite materials.

As a part of its mission, the Center is developing a three-dimensional model of tidal and sub-tidal circulation of Puget Sound and inland waters of Washington State. This model will be used for tidal resource and environmental impact assessment. In this paper we describe the model configuration and its initial calibration and validation.

2 Methods

The model is based on the Stanford Unstructured Nonhydrostatic Terrain-following Adaptive Navier-Stokes Simulator (SUNTANS, see [4]), written in the C programming language. The model predicts sea surface height variation (tidal level) and tidal currents in three dimensions; in future, prediction of salinity and water density will also be incorporated. SUNTANS is non-hydrostatic and resolves vertical fluid accelerations that would be ignored in traditional models of tidal circulation. It is also parallelized with automatic partitioning and load-balancing of the domain. SUNTANS uses an unstructured numerical grid in the horizontal and a z-level vertical coordinate suited to estimating pressure gradients in steep terrain encountered in fjord estuaries.

The model domain (Fig. 2) covers the entire Puget Sound as well as the eastern Strait of Juan de Fuca, the San Juan and the Gulf Islands, and the southern Georgia Basin. The domain is discretized into an unstructured triangular grid of average 250 meters horizontal resolution, and twenty-six vertical levels with 14.5m vertical resolution. The PSDEM 2000 digitized bathymetry [5] is used for depth, with some supplementary sounding data in the Canadian waters. The grid has two open boundaries, one in the Strait of Juan de Fuca and the other in the Georgia Basin. Dirichlet boundary conditions in depth-averaged tidal velocity, taken from WebTide [6] and adjusted to ensure zero net mass flux, are applied along the two open boundaries. The sea water density is held constant and uniform; only barotropic tidal response is considered at this point. Temperature and salinity open boundary conditions as well as river input and atmospheric forcing will be incorporated into the model in the future.

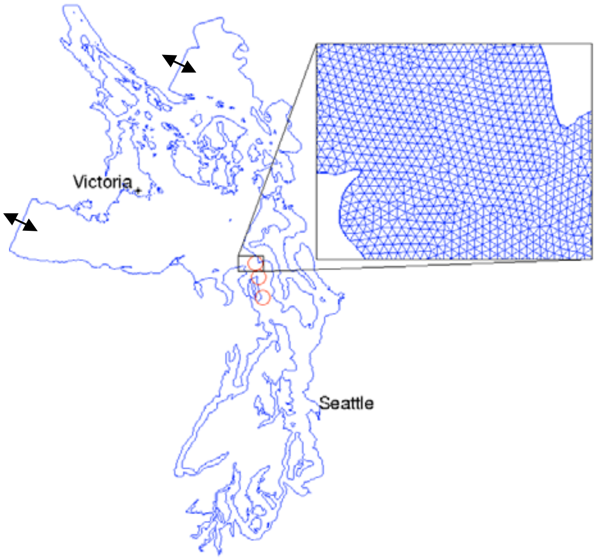

Figure 2: Model domain with enlargement of the Admiralty Inlet area (insert) showing the unstructured grid. Bidirectional arrows indicate open boundaries. Red circles indicate locations of proposed pilot TISEC projects.

The only dissipative process in the model is a quadratic bottom drag of the form

$$\boldsymbol{\tau}_B = \rho C_D |\boldsymbol{u}_B| \boldsymbol{u}_B$$

It is customary to represent tidal variability of sea surface elevation and currents as a sum of sinusoidal oscillations, or constituents, with discrete frequencies corresponding to periodicities in the astronomical forcing that gives rise to the tides:

$$\eta(t) = \sum_i A_i \cos(\omega_i t - \varphi_i)$$

In Puget Sound, the important constituents are the lunar (M_2), the solar (S_2), and the larger Lunar elliptic (N_2) semi-diurnal tides; and the lunisolar (K_1), the lunar (O_1) and the solar (P_1) diurnal tides [7,8]. Each constituent is characterized by its amplitude A_i and the phase offset relative to a standard time base φ_i. In order to validate the modelled tide against observations in a global and holistic manner throughout the model domain, the modelled sea surface height is sampled at locations where the amplitude and phase constants from historical measurements are available [7–9]. The resultant time series are harmonically analyzed with the Matlab programming package T-Tide [10], and the model's tidal constants are compared with the observations in plots against each other. We are particularly interested in an accurate calibration of the relative phase constant φ_i, for its variation through the embayment (phase propagation of tidal oscillation) is a measure of dissipation of tidal mechanical energy in the embayment [11]. The greater the energy dissipation, the more pronounced the phase propagation and the *slower* the phase speed of the tide. (Conversely, in a frictionless embayment the tidal response becomes a standing oscillation – in other words, phase propagation becomes instantaneous.) In order to assess the energy extraction potential and other aspects of tidal energetics of an embayment, the model must represent the energetic dynamics of the natural system correctly.

A number of runs have been performed with the quadratic bottom drag coefficient C_D ranging from 3×10^{-4} to 3×10^{-2} (non-dimensional) to explore sensitivity of the modelled tides to dissipation. A standard value for C_D is set at 3×10^{-3}. Further experiments in which amplitudes and phases of the tidal constituents making up the forcing were adjusted, were also performed to explore sensitivity of the model to the boundary conditions.

3 Results

Strong tidal currents with peak velocities exceeding two meters per second are generated in two areas within Puget Sound: north Admiralty Inlet and Tacoma Narrows (Fig. 3). Similar tidal currents are also generated in Deception Pass, connecting the northern Puget Sound and the eastern Strait of Juan de Fuca; and in several channels through the San Juan Islands east of Victoria, British Columbia (Fig. 2). The Victoria Sill region, south of Victoria in the Strait of Juan de Fuca, also has substantial currents. In terms of the current strength and the size of the region, however, the north Admiralty Inlet appears to be the most substantial tidal energy resource in the region, consistent with the developer interest in this region.

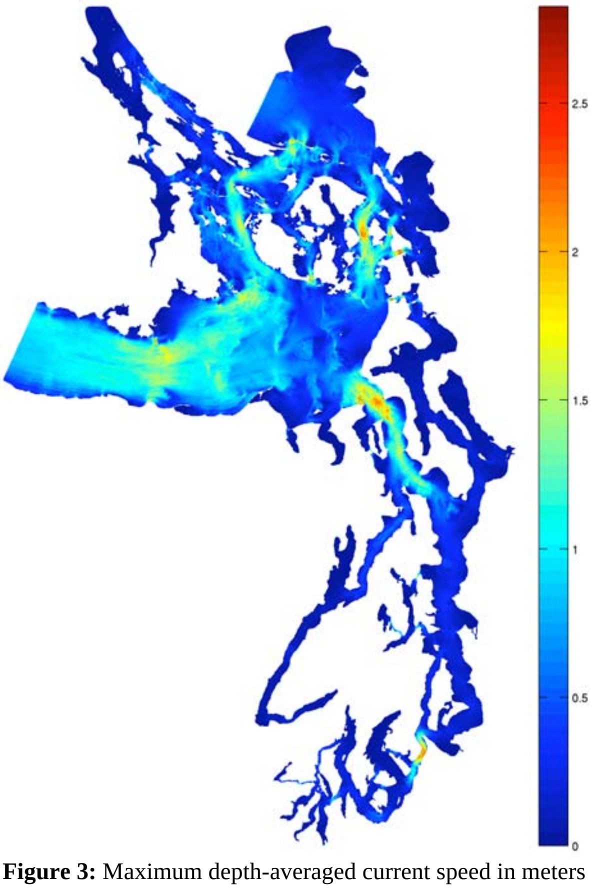

Figure 3: Maximum depth-averaged current speed in meters per second.

The intensity and the extent of the modelled current maximum in north Admiralty Inlet agree well with the results of a current survey performed by our group using a shipboard acoustic Doppler current profiler (ADCP) in August 27 – 28, 2007 (Fig. 4). A broad centre-channel maximum with current speeds near three meters per second lies roughly over the seaward sill of Admiralty Inlet. A second region of high intensity is seen to the west, north of Point Wilson (the sharp promontory on the northeast corner of the western shoreline); however waters here are generally shallow, with depths in the range of 15 – 20 meters, and this may limit developer interest in this area. In addition, a current maximum is indicated in the model and hinted at in the ADCP survey adjacent to Admiralty Head (the triangular head on the north-eastern shoreline). Finally, additional current "hot spots" are seen to the southeast of the main maximum, both in the model and in the survey. The peak intensity of the modelled current maximum is a little less than observed, but this might be due to the fact that the shipboard ADCP measurement omits the bottom ten meters or so of the water column and thus tends to bias the vertical average towards higher values found further up in the water column.

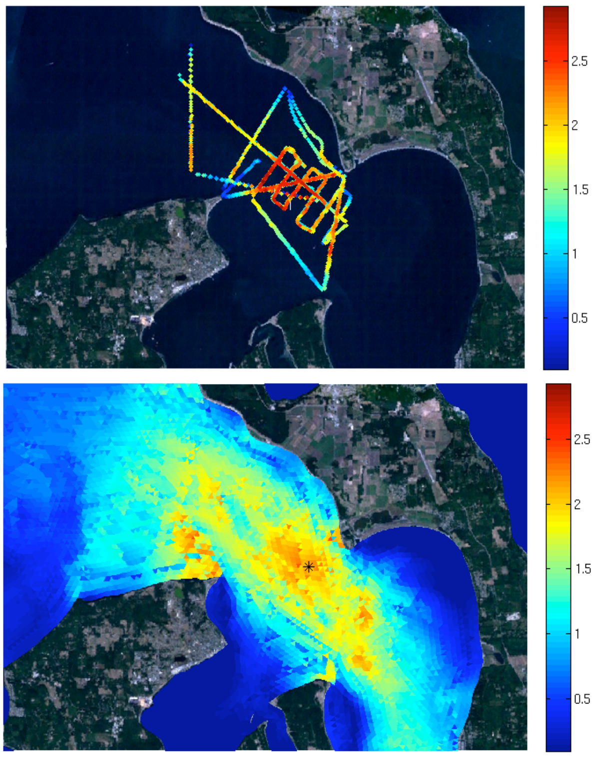

Figure 4: Comparison of depth averaged current speed (m/s) in Admiralty Inlet from ADCP survey transects of August 27-28, 2007 (top) and from the model over the same period (bottom). Asterisk indicates the location of the bottom-mounted ADCP whose data is shown in Fig. 5.

The modelled current is further compared with a current observation from a bottom-mounted stationary ADCP that was placed within the survey area for the period of August 18 through September 19, 2007 (Fig. 5; see Fig. 4 for the location of the current profiler). The model predicts timings of high and low waters and flood and ebb tides accurately. However, the dip in the

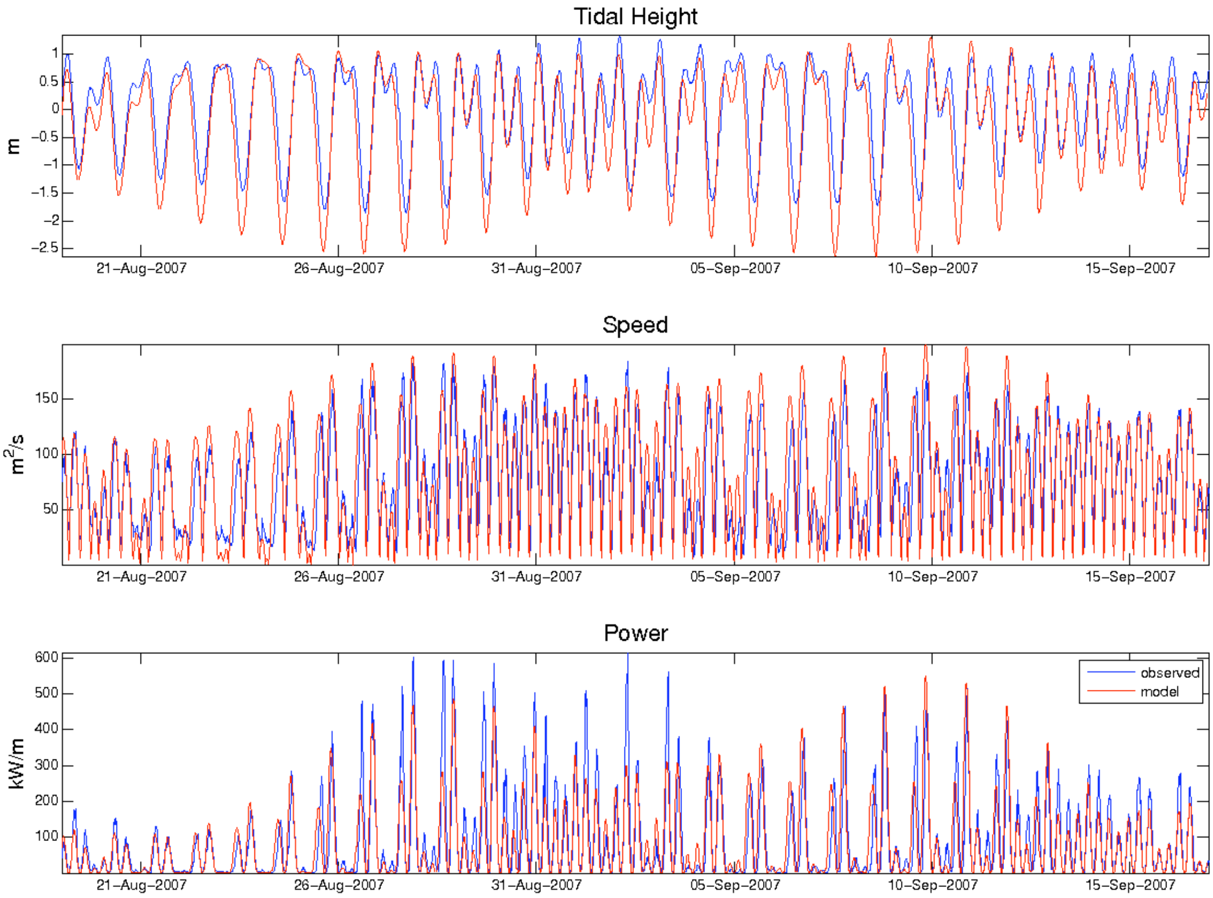

Figure 5: Comparison of observed and modelled tidal variability at the bottom-mounted ADCP location (see Fig.4) in Admiralty Inlet. Top: sea surface height (m). Middle: depth-averaged speed (m/s). Bottom: depth-averaged power density ($\rho|\boldsymbol{u}|^2/2$, in W/m^2). Blue lines represent observations; red lines, model output.

water level during the lower low tide is consistently overestimated in the model, while the peak current is at times underestimated; the latter is particularly evident in the depth-averaged power density, which, being proportional to the cube of the current speed, is sensitive to error at the time of maximum power. Nevertheless the predicted current speed and power outside the peak periods agree quantitatively with the observation.

For a more global validation of the model's performance, amplitudes and phase constants of tidal constituents were calculated at locations reported in [8] and [9] and compared with values calculated from observations at these locations (Fig. 6). Focus is on the largest semi-diurnal (M_2) and diurnal (K_1) constituents in the sound. The overall range of values for the predicted amplitude agrees with the observations. For both semi-diurnal and diurnal tides, however, the model has a tendency to over-predict tidal amplitude in areas characterized by lower amplitudes, mostly in the Strait of Juan de Fuca. Particularly noticeable is a gap, or a jump, in the observed M_2 amplitude from 75.1 cm to 89.5 cm (indicated in Fig. 6 with a red arrow). This occurs in the southern Admiralty Inlet between Bush Point and Foulweather Bluff (see Fig. 1) over a relatively short distance. The modelled M_2 amplitude does not show such a large amplitude change from Bush Point to Foulweather Bluff; the model response seems to divide itself into two regimes, one for Puget Sound inward of this gap and the other for all points outside, with the latter showing consistent over-prediction.

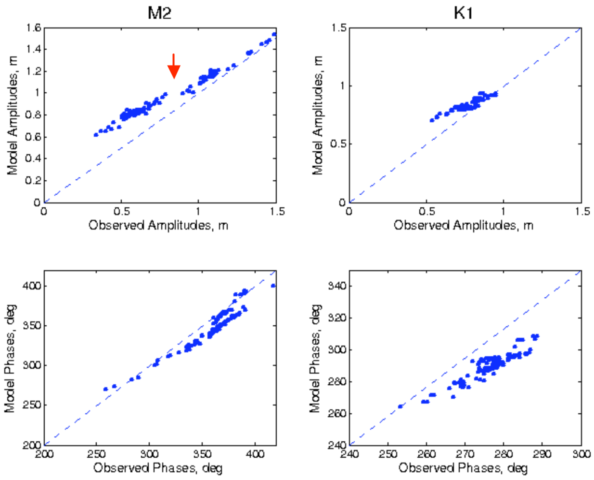

Figure 6: Comparison and M_2 (left) and K_1 (right) amplitude (top) and phase (bottom): observed (x) vs. modelled (y). Dashed diagonal corresponds to a perfect observation- model match. Red arrow indicates the observed jump in the M_2 amplitude from Bush Point to Foulweather Bluff (see Fig. 1).

No similar gap in the K_1 amplitude is seen, although the over-prediction of low amplitudes is still noticeable. The M_2 phase range is accurately predicted overall, while the K_1 phase shows an offset error and a small under-prediction in range.

Sensitivity of the modelled tides to the magnitude of bottom friction was explored with runs with different values for the bottom drag coefficient C_D (Figs. 7 and 8). Tidal amplitude and phase constants from selected locations around Puget Sound (indicated in Fig. 1) are plotted as functions of C_D and compared with the observed amplitude and phase. The focus is on the M_2 tidal response: because of its large amplitude and high frequency, M_2 tidal constants can be determined accurately from a relatively short model run. In order to focus on the sensitivity of tidal phase propagation, the difference in the phase constant between each location and a reference point at Smith Island in the middle of the eastern Strait of Juan de Fuca (Fig. 1) is plotted.

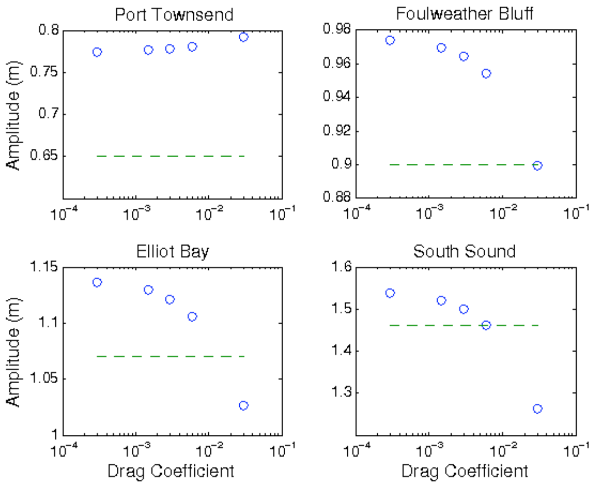

Figure 7: M_2 amplitude at four selected locations in Puget Sound (see Fig. 1) as a function of the drag coefficient C_D. Horizontal bar denotes observed value reported in [8].

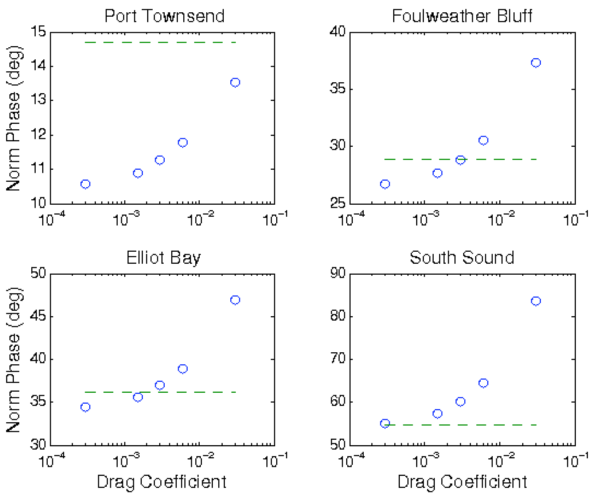

Figure 8: As for Fig.7, but difference in M_2 phase from the phase at Smith Island (see Fig.1 for the location) Positive value indicates M_2 tide propagating from Smith Island to the location.

Amplitude of the M_2 tide within Puget Sound decreases with increasing drag coefficient, while at the mouth of the sound the amplitude increases slightly (Fig.7). This indicates that the increased friction in Admiralty Inlet, where the current is strong and the friction relatively greater because of the quadratic effect, is providing resistance to the exchange between the sound and the Strait of Juan de Fuca. As a result the tide within the sound is reduced, while just outside it is slightly increased due to a pile-up of water that would have entered the sound with a lower friction. Polagye *et al.* [2] found a similar effect in a channel model of Puget Sound as a result of increased energy dissipation due to TISEC in Admiralty Inlet.

Phase difference between each location and the reference point increases with increasing friction, with the magnitude of increase relatively greater the further inland the location is (Fig.8). This indicates greater phase propagation with higher friction, consistent with greater energy dissipation within the sound.

The highest value of C_D tried in this study results in a clearly unrealistic response, but otherwise there is no single value for C_D that gives rise to a perfectly realistic response everywhere. Further improvements in the model response may require improved boundary conditions, improved bathymetry, or incorporation of density contrast between the salty marine water and the fresh water from rivers that drive internal (baroclinic) motions. While at this point we do not yet have a systematic approach towards making such improvements, we sought to investigate aspects of the model's sensitivity to the quality of the boundary conditions by manipulating amplitude and phase constants of the tidal constituents that make up the boundary condition. Specifically, we tried to adjust the tidal condition along the northern open boundary relative to the western boundary (see Fig. 2) by either adding a constant phase offset or multiplying the amplitude with a constant factor.

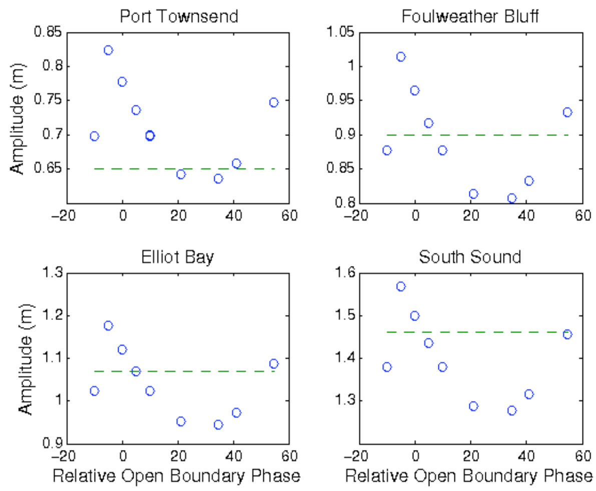

Figure 9: M_2 amplitude at the four selected locations as in Fig. 7 as a function of the additional phase offset added to the northern boundary condition. Horizontal bar denotes observed value as in Fig. 7.

A modest (5 ~ 10°) positive phase offset added to the northern boundary condition, corresponding to ten to twenty minute shift in the timing of high and low tides, appears to result in an improvement in the amplitude response throughout Puget Sound (Fig.9), as well as in the phase in the deeper reaches of the sound (Fig.10). Both the amplitude and the relative phase go through an extremum at a higher value of phase offset; the extremal value is closer to the observed value at some locations but not at others. Multiplication of the northern boundary amplitude by a small positive factor (1.1 ~ 1.2) resulted in an improvement of response within Puget Sound, but deterioration elsewhere especially in areas close to the northern boundary (not shown).

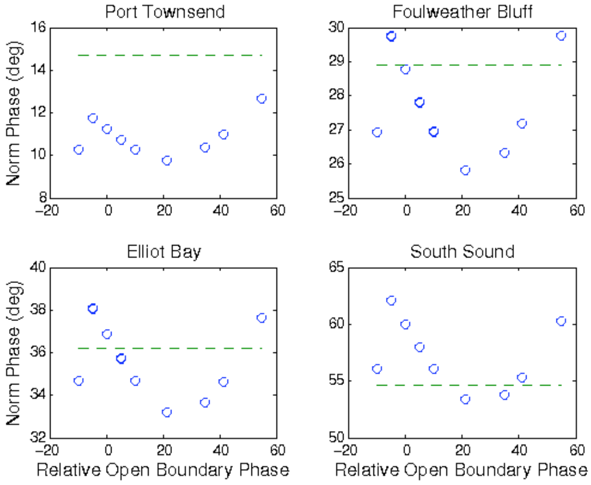

Figure 10: As for Fig.9, but M_2 phase relative to the phase at Smith Island.

4 Discussion

The intial results from the model presented here indicate that this is a highly promising model for the study of tidal dynamics of Puget Sound and the rest of Washington inland marine waters and for use in assessment of tidal energy resources and of environmental impacts of TISEC development. Immediate future plans for the model include quantitative analysis of tidal energy dissipation and incorporation of density contrast between marine and river waters for internal (baroclinic) dynamics.

At the same time, there is clearly room for improvement in the model's prediction of tides. For the purpose of tidal energy resource assessment and environmental impact assessment, the most important quantities to be validated against data are the amplitude and the phase of each major tidal constituent throughout the model domain, since these have a direct bearing on the mechanical energy flux into the estuary, and tidal current velocity, or equivalently kinetic energy density. While the Froude number is small throughout the domain and the tidal dynamics can be considered largely that of long gravity waves, the response is highly sensitive to the model geometry, dissipation, and boundary conditions.

Of particular concern is the model's inability to reproduce the M_2 tidal amplitude increase from Bush Point to Foulweather Bluff. This corresponds to the location of the landward sill of Admiralty Inlet [3]. The underestimation of the increase may indicate a tendency of the model to create tidal "choking" – throttling of tidal energy propagation into the fjord interior due to constriction and highly energetic, nonlinear current [12] – at this location. This in turn may indicate that the bottom bathymetry is not accurately represented over the landward sill. Indeed it is possible that, at the moment, accuracy of the model tidal response is limited by the accuracy of the underlying geometric data. While Puget Sound is a well-travelled waterway, many of the bathymetric soundings that went into data sets such as [5] have not been updated in the last half-century. In some ways, the depth of the Sound as a whole has put acquisition of improved bathymetric data into low priority, since bottom features in deeper parts of the Sound do not pose navigational problems. Other modelling studies in Puget Sound (e.g. [13]) have also found that having an accurate bathymetry is important in producing an accurate tidal response in the model. Even simple one-dimensional models such as [2] and [8] require a good coastline and bathymetric data set to base their geometry on. Thus, accurate bathymetric soundings, not only around locations of energy extraction but over the whole estuary, must be considered a high-priority data to acquire for tidal power development in an estuary. This need merits special attention in areas with promising potential tidal resource but with sparse and/or unreliable bathymetric coverage, such as remote fjords.

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