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Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate-Scale Hydrodynamic Model

Z Yang
T Khangaonkar
R Labiosa
T Kim

November 2010

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Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate-Scale Hydrodynamic Model

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November 2010

Prepared for
The Washington State Department of Ecology

Battelle—Pacific Northwest Division
Richland, Washington 99352

Executive Summary

Puget Sound is a large estuarine system bounded by 2,597 miles of complex shorelines and consists of several subbasins and many large estuaries with distinct properties. Pacific Ocean water enters Puget Sound and the Georgia Strait through the Strait of Juan de Fuca. Freshwater inflows to Puget Sound include 19 major rivers and multiple point and nonpoint sources including effluent discharges from industrial and municipal outfalls, agricultural runoff, and natural watershed runoff. Nutrient pollution is considered one of the largest threats to Puget Sound. There is considerable interest in understanding the effect of nutrient loads entering Puget Sound. The Washington State Department of Ecology contracted with Pacific Northwest National Laboratory to develop an intermediate-scale hydrodynamic and water quality model to study dissolved oxygen and nutrient dynamics in Puget Sound and to help define potential Puget Sound-wide nutrient management strategies and decisions. Specifically, the project is expected to help determine 1) if current and potential future nitrogen loadings from point and non-point sources are significantly impairing water quality at a large scale and 2) what level of nutrient reductions are necessary to reduce or control human impacts to dissolved oxygen levels in the sensitive areas.

The development of a predictive nutrients and dissolved oxygen model of Puget Sound consists of two major components: 1) a three-dimensional coastal hydrodynamic model and 2) an off-line water quality model of Puget Sound. In this study, an intermediate-scale hydrodynamic model of Puget Sound was developed to simulate the hydrodynamics of Puget Sound and the Northwest Straits for the year 2006. The model was constructed using the unstructured Finite Volume Coastal Ocean Model - FVCOM. The average horizontal model grid resolution within Puget Sound in its present configuration is about 880 m. The model is driven by tides, river inflows, and meteorological forcing (wind and net heat flux) and simulates tidal circulation, temperature, and salinity distributions in Puget Sound. The model was calibrated against observed data of water surface elevation, velocity, temperature, and salinity at various stations within the study domain. Model calibration indicated that the model simulates tidal elevations and currents in Puget Sound reasonably well and reproduces the general patterns of the temperature and salinity distributions satisfactorily. The hydrodynamic model solutions have been generated for the year 2006 such that they may be used to drive the off-line water quality model based on CE-QUAL-ICM. One full-year model simulation requires about 34 hours in real time with 48 cores running in parallel mode on a 184-core computer cluster.

Acronyms

2-D	two-dimensional
3-D	three-dimensional
MAE	mean absolute errors
DFO	Department of Fisheries and Oceans Canada
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
FVCOM	Finite Volume Coastal Ocean Model
LIDAR	light detection and ranging
NARR	North American Regional Analysis
NAVD88	North American Vertical Datum of 1988
NCEP	National Center for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
PSDEM	Puget Sound Digital Elevation Model
RME	relative mean error
RMSE	root mean square error
USGS	U.S. Geological Survey
UW	University of Washington
WSE	water surface elevation
XTide	harmonic tide clock and tide predictor based on NOAA's National Oceanic Service algorithms

Contents

Figures

Tables

1.0 Introduction

Puget Sound is a large estuarine system bounded by 2,597 miles of complex shorelines and consists of several subbasins and many large estuaries with distinct properties (Figure 1-1). Pacific Ocean water enters Puget Sound estuary system and the Georgia Strait through the Strait of Juan de Fuca. The Strait of Juan de Fuca is also the outlet for most of the freshwater discharged to the Puget Sound and from the Fraser River in British Columbia. Geographically, Puget Sound is defined by the water body that is southeast of Admiralty Inlet, east of Deception Pass, and south of the Swinomish Channel. Nutrient pollution is considered a significant long term threat to the ecological health of Puget Sound. There is considerable interest in understanding the hydrodynamics and the effect of nutrient loads entering Puget Sound. As part of mandates under the Clean Water Act to manage pollutant loading to meet water quality standards, the U.S. Environmental Protection Agency (EPA) and Washington State Department of Ecology (Ecology) initiated this Puget Sound Dissolved Oxygen Model model-development project.

Ecology has contracted with Pacific Northwest National Laboratory (PNNL) to develop an intermediate-scale hydrodynamic and water quality model to study dissolved oxygen (DO) and nutrient dynamics, evaluate the effects of current and potential future nutrient loads on DO levels in Puget Sound, and define potential Puget Sound-wide nutrient management strategies and decisions. The Puget Sound Water Quality model developed through this project will address the following nutrient management questions:

- Are human sources of nutrients in and around Puget Sound significantly impacting water quality?
- How much nutrient reduction is necessary to reduce human impacts in sensitive areas?

The overall objective of this project by Ecology and PNNL is to work collaboratively with the EPA and a scientific advisory committee to conduct DO modeling in Puget Sound, which will complement concurrent management initiatives. PNNL is responsible for the development of the intermediate-scale model (also called the "coarse-grid model") of Puget Sound for the hydrodynamics and water quality, which will be used to evaluate the effects of human-caused nutrient enrichment on DO across Puget Sound. This model will help inform potential Puget Sound-wide management strategies and support site-specific detailed work that may be completed beyond this project.

The development of the hydrodynamic and water quality model of Puget Sound consists of two major components: 1) a 3-D coastal hydrodynamic model and 2) a water quality model that simulates DO dynamics. This study report presents the development of the intermediate-scale hydrodynamic model of Puget Sound. The water quality model development is being addressed through a companion study report.

A key factor in the development of this Puget Sound-wide model is that the effort was limited to existing information only and that no new data were to be collected.

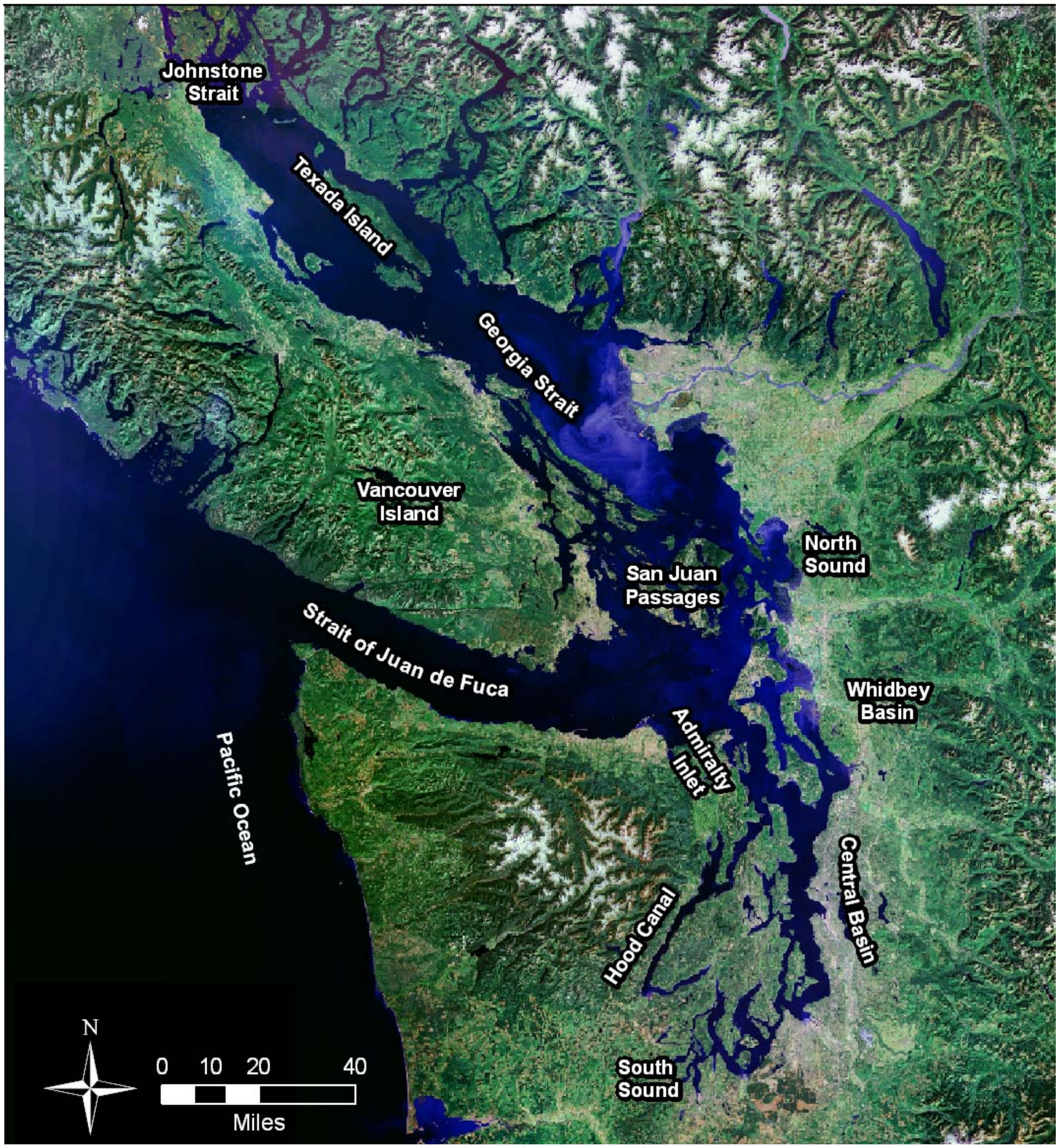

FIGURE 1-1

Study Domain – Puget Sound, the Strait of Juan de Fuca, and Georgia Strait

2.0 Hydrodynamic Model Setup

Puget Sound, the Strait of Juan de Fuca, and Georgia Strait comprise a large and complex estuarine system. The Strait of Juan de Fuca is a high-tidal energy waterway that connects the estuarine system to the eastern Pacific Ocean and is the main outlet of freshwater to the Pacific Ocean. The large freshwater discharge from the Fraser River in Canada is known to affect stratification and currents in the adjacent waters of the Strait of Juan de Fuca and Georgia Strait including waters around the San Juan Islands and the Cherry Point coastline near the United States/Canada border. Therefore, to simulate the circulation in Puget Sound and the Straits properly, there is a need to extend the study domain from the entrance of the Strait of Juan de Fuca to the north end of Georgia Strait near Johnstone Strait in Canada. The circulation in Puget Sound shows distinct fjordal three dimensional (3-D) characteristics with mean outflow in the surface layers and inflow in the lower layers. Near the mouths of estuaries within Puget Sound, there is stratification due to freshwater discharge and complex circulation patterns due to the interaction of river plumes and tidal currents. The currents are also known to be affected by winds and surface heat flux. The hydrodynamic model selected in this study must therefore be capable of simulating 3-D baroclinic circulation, which is induced by density gradients. The model also must simulate the effects of sharp changes in bathymetry from shallow mudflats to the deep fjordal depths of Puget Sound and variable meteorological forcing. The model selection and recommendation for this study was provided by Ecology in consultation with the model Technical Advisory Committee[a] and with input from PNNL as described in the Quality Assurance Project Plan (Sackmann, 2009). Ecology's recommendation was to develop an intermediate scale hydrodynamic model of Puget Sound using the unstructured-grid Finite Volume Coastal Ocean Model (FVCOM) developed by the University of Massachusetts (Chen et al. 2003).

To set up the hydrodynamic model, the following types of data were required:

- Bathymetry and shoreline geometry data
- Tidal elevations at the open boundaries
- Temperature and salinity data at the open boundaries
- River inflows and temperatures
- Meteorology data (surface wind stress and heat flux).

Figure 2-1 shows the stations where various data were obtained for the model setup. The following subsections describe all the components listed above in the model setup.

---

[a] The Model Technical Advisory Committee for the Puget Sound Dissolved Oxygen Modeling Study was formed by Ecology to solicit input on how the study is done and what factors, models, processes, and data needs and limitations need to be considered. The committee includes representatives with modeling expertise from various state and federal agencies, counties, and wastewater treatment plants.

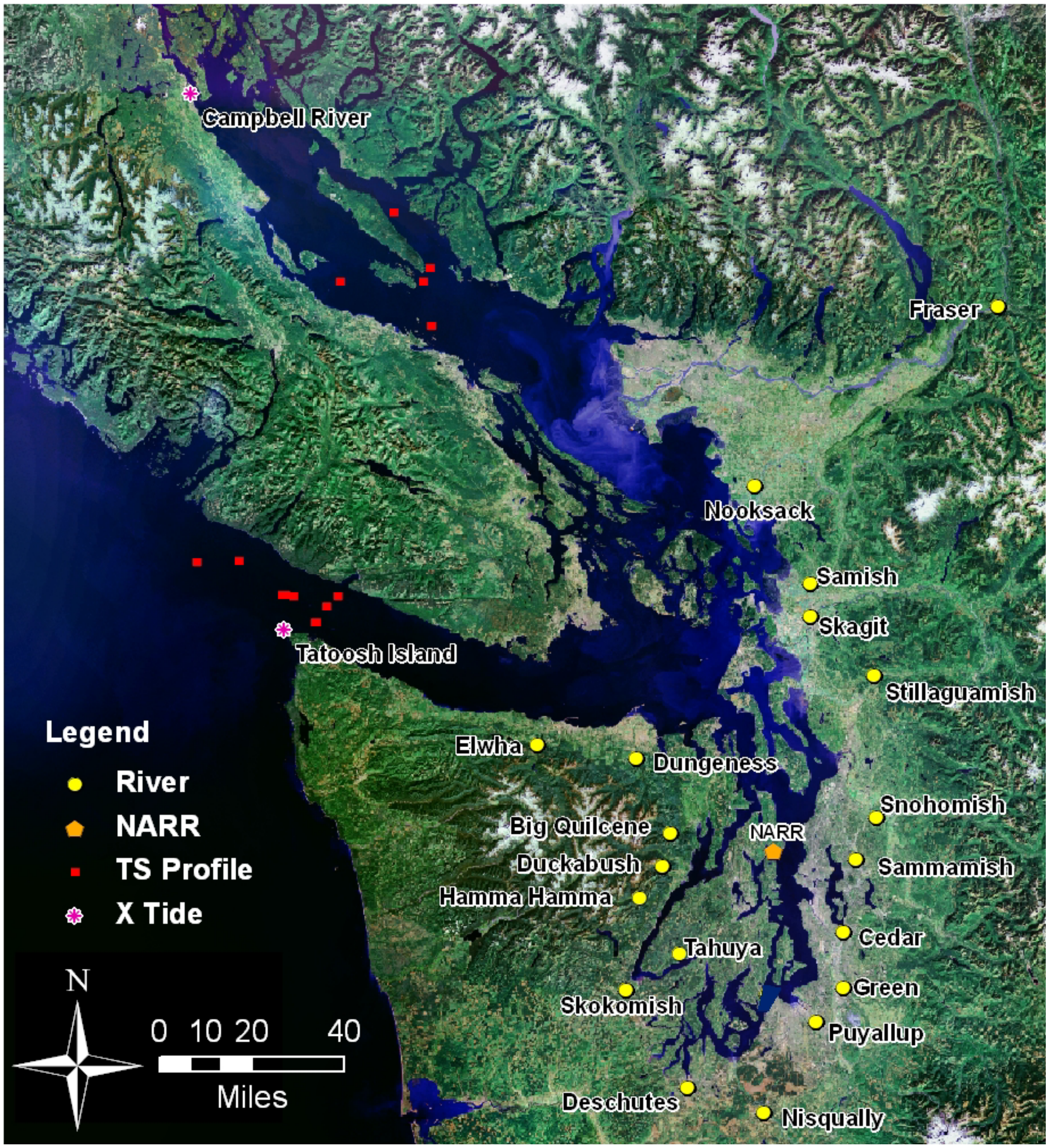

FIGURE 2-1

Data Stations for Model Setup for Puget Sound, the Strait of Juan de Fuca, and Georgia Strait

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2.1 Bathymetry Data

Bathymetry data are one of the most important data sets in the model setup because they define the shape and geometry of the model domain, which controls the circulation dynamics. Bathymetry used for the intermediate-scale Puget Sound model setup primarily consists of data from the following two sources:

1. The University of Washington's Puget Sound Digital Elevation Model (PSDEM) (Finlayson, 2005)
2. Bathymetry data in the Strait of Juan de Fuca and Georgia Strait from the Department of Fisheries and Oceans Canada (DFO). (M. Foreman, personal communication,)

The UW PSDEM bathymetry data cover the main study domain of Puget Sound. These data are at 30-ft by 30-ft horizontal spatial resolution. Detailed information on the PSDEM data of Puget Sound can be found in Finlayson (2005). Other adjacent water bodies including a portion of the Strait of Juan de Fuca, the San Juan Island Passages, North Sound, and the Fraser River were obtained from the DFO. These data are at coarser resolution than the UW PSDEM data but are sufficient for the intermediate-scale Puget Sound model development effort. All bathymetry data used in the model development were referred to the North American Vertical Datum of 1988 (NAVD88).

Tide flats and marshland in the nearshore regions, which can be represented by Light Detection and Ranging (LIDAR) elevation data, generally have a great effect on the circulation and stratification in shallow water estuaries and bays. However, the primary interest of this study is on the larger scale circulation and water quality processes in the major basins of Puget Sound. Therefore, we did not consider shallow tide flat effects in the model and set the minimum water depth as 4.0 m below NAVD88.

2.2 Development of the Model Grid

Two types of models are commonly used in coastal circulation modeling. One is a structured grid model that uses two-dimensional (2-D) quadrilateral elements (hexahedral elements in 3-D) in a computationally rectangular array, and the other is an unstructured grid model that uses triangles or quadrilateral elements with connectivity in an arbitrary order in the 2-D horizontal domain. The advantage of the unstructured grid model is its flexibility to fit the model grid smoothly to complex boundaries such as the Puget Sound shoreline.

FVCOM is a 3-D hydrodynamic model that can simulate tide, density-driven, and meteorological forcing-induced circulation in an unstructured, finite element framework. The unstructured grid model framework of FVCOM is specially suited to Puget Sound, which has complex shoreline geometry, waterways, and islands. FVCOM solves the 3-D momentum, continuity, temperature, salinity, and density equations in an integral form. A sigma-stretched coordinate system was used in the vertical plane to better represent the irregular bathymetry. The model employs the Mellor Yamada level 2.5 turbulent closure scheme for vertical mixing and the Smagorinsky scheme for horizontal mixing. Surface forcing can be directly specified in FVCOM using outputs from an appropriate meteorological model. The model has been successfully applied to simulate hydrodynamics and transport processes in many estuaries, coastal water and open oceans (Zheng and Liu 2003; Chen and Rawson 2005; Zhao et al. 2006; Weisberg and Zheng 2006; Isobe and Beardsley 2006, Aoki and Isobe 2007; Chen et al. 2008; Yang and Khangaonkar 2008; Yang et al. 2009a, b).

An unstructured grid of FVCOM for Puget Sound was generated using bathymetry and shoreline data described in Section 2.1, and the model open boundaries were specified far enough from the entrance of Admiralty Inlet to minimize the effects of the open boundary conditions on Puget Sound. The western extent of the Strait of Juan de Fuca was selected for the western open boundary. On the northern open boundary, because of the presence of the San Juan Islands, the open boundary line was specified north of Texada Island in Georgia Strait.

For model efficiency, the model grid was generated in a way such that coarse grid resolution was used in the areas away from Puget Sound, and a fine grid resolution was specified in the Puget Sound. The model grid resolution gradually decreases away from Puget Sound to the open boundaries to maintain the computational efficiency of the model. Model grid cell sizes vary from 3,000 m at the open boundaries to around 350 m in estuaries and bays. The average cell size is about 1,760 m considering the entire model domain. The average cell size in Puget Sound is 880 m. The total number of nodes and triangular elements in the model are 9,052 and 13,976, respectively, in the horizontal plane. Thirty vertical layers with uniform thickness were specified in the water column in a sigma-stretched coordinate system. The model grid was set up in Universal Transverse Mercator North American Datum 83 (Zone 10) in the horizontal plane with reference to NAVD 88 in the vertical direction. Figure 2-2 shows the unstructured grid of FVCOM for the entire Puget Sound. Close-ups of the model grids in the subbasins including the Whidbey Basin, Hood Canal and Central Basin, and South Puget Sound are shown in Figures 2-3 to 2-5. The model bathymetry is shown in Figure 2-6. Shallow sills at the entrance of Admiralty Inlet and Hood Canal are visible. The deepest region in the model domain is in the north Georgia Strait with water depth over 400m.

2.3 Open Boundary Tides

The Puget Sound hydrodynamic model has two open boundaries: one is located at the entrance of the Strait of Juan de Fuca and the other is north of Texada Island in Georgia Strait. No observed tide data are available at the open boundary in Georgia Strait. Tidal elevations are specified along the open boundaries using XTide (harmonic tide clock and tide predictor: http://tbone.biol.sc.edu/tide/) predictions (Flater 1996) at Tatoosh Island station at the entrance of the Strait of Juan de Fuca and the Campbell River station at the mouth of Johnstone Strait (see locations in Figure 2-1). Tidal elevations were assumed to be the same across the open boundaries and were specified at 15-minute intervals. The radiation condition was specified in the model simulation. The tidal elevations at the open boundary stations for October 2006 are plotted in Figure 2-7. A comparison of the tidal elevations shows that the tidal range and mean elevation at Campbell River are greater than that at Tatoosh Island. This is expected because tides propagate from the Strait of Juan de Fuca into Puget Sound and Georgia Strait where the tidal elevation is amplified due to the effects of the shoreline on the propagating tide.

2.4 Open Boundary Salinity and Temperature Profiles

To simulate salinity and temperature distributions in Puget Sound, time series of salinity and temperature profiles along the open boundaries were used to force the hydrodynamic model. The temperature and salinity profiles were not available at the exact locations of the open boundaries but from various nearby observation stations. In particular, profiles for the northern boundary in Georgia Strait were more scattered and close to mouth of Fraser River. The effort required to interpolate or transform the data accurately to boundary locations would be extensive. The decision to use constant profiles was a first

Note:
- Total Node Number = 9,052
- Total Element Number = 13,976

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FIGURE 2-2

FVCOM Model Grid – Puget Sound, the Strait of Juan de Fuca, and Georgia Strait

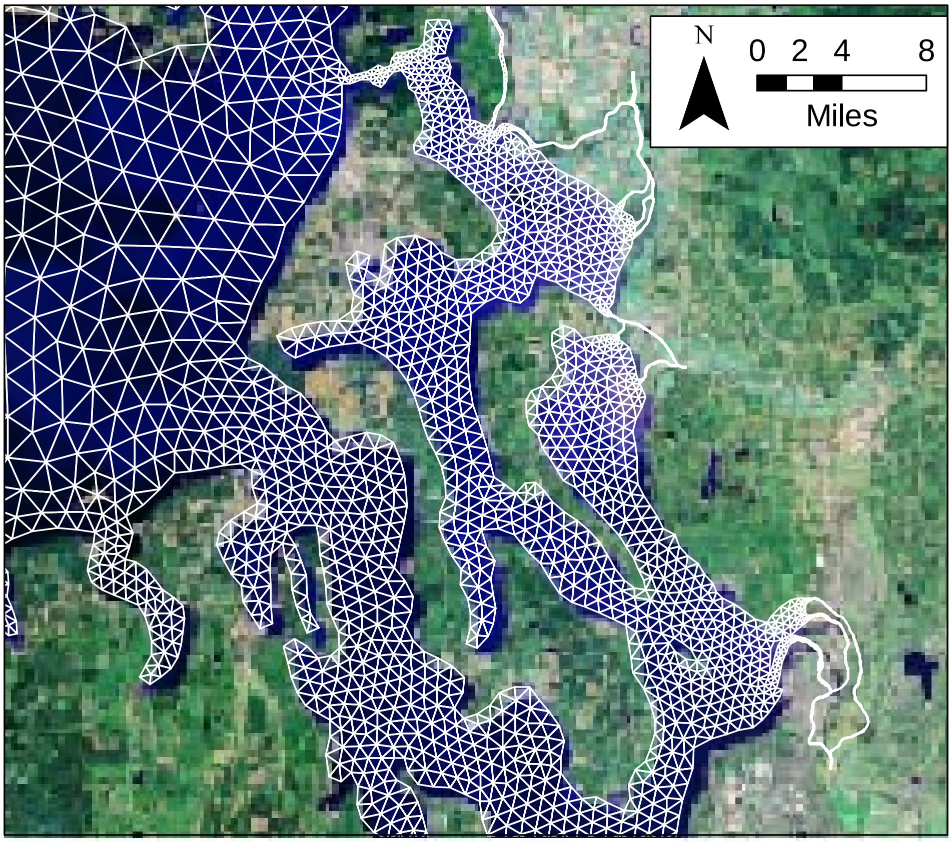

FIGURE 2-3

Model Grid for Admiralty Inlet and Whidbey Basin

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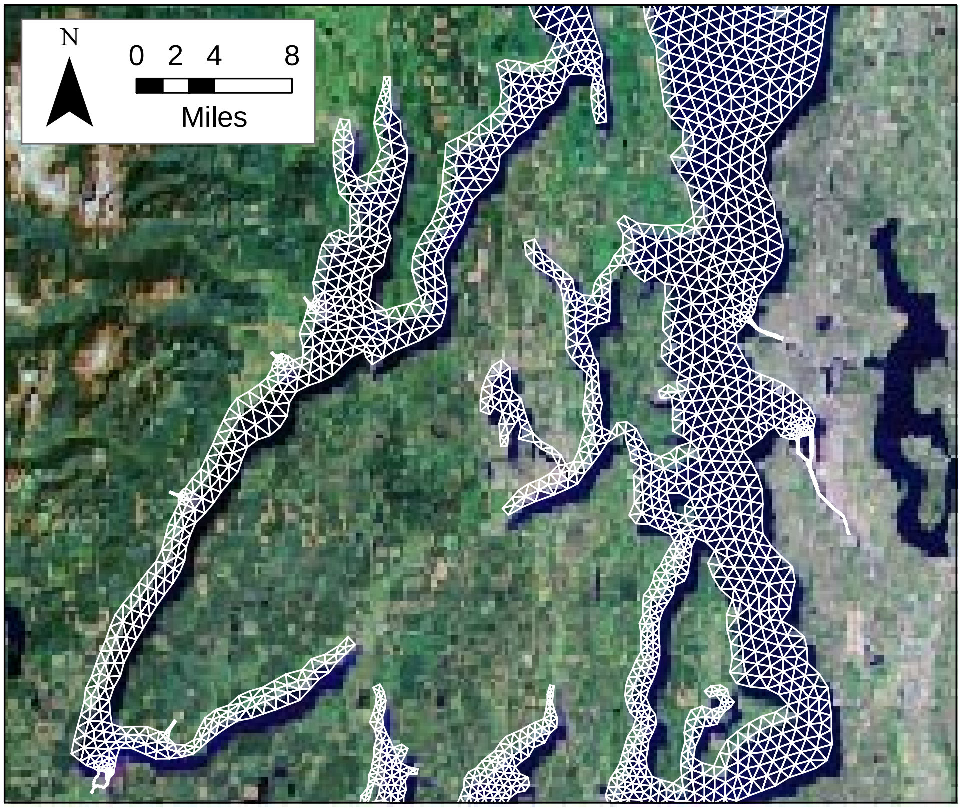

FIGURE 2-4

Model Grid for Hood Canal and Central Sound

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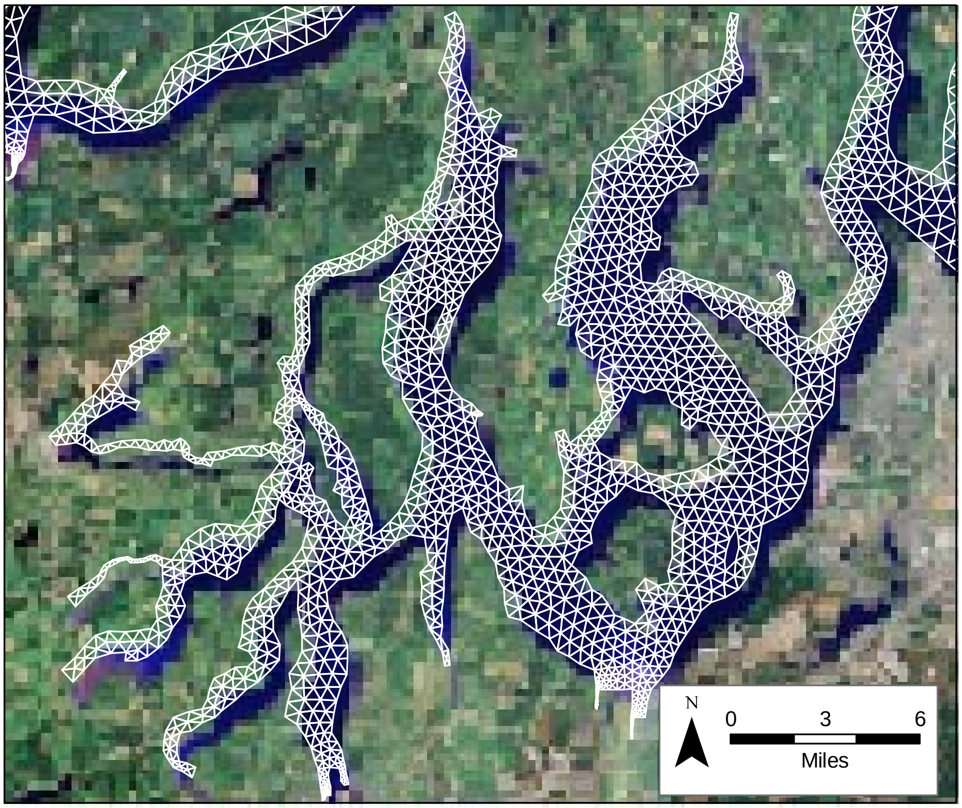

FIGURE 2-5

Model Grid for South Puget Sound

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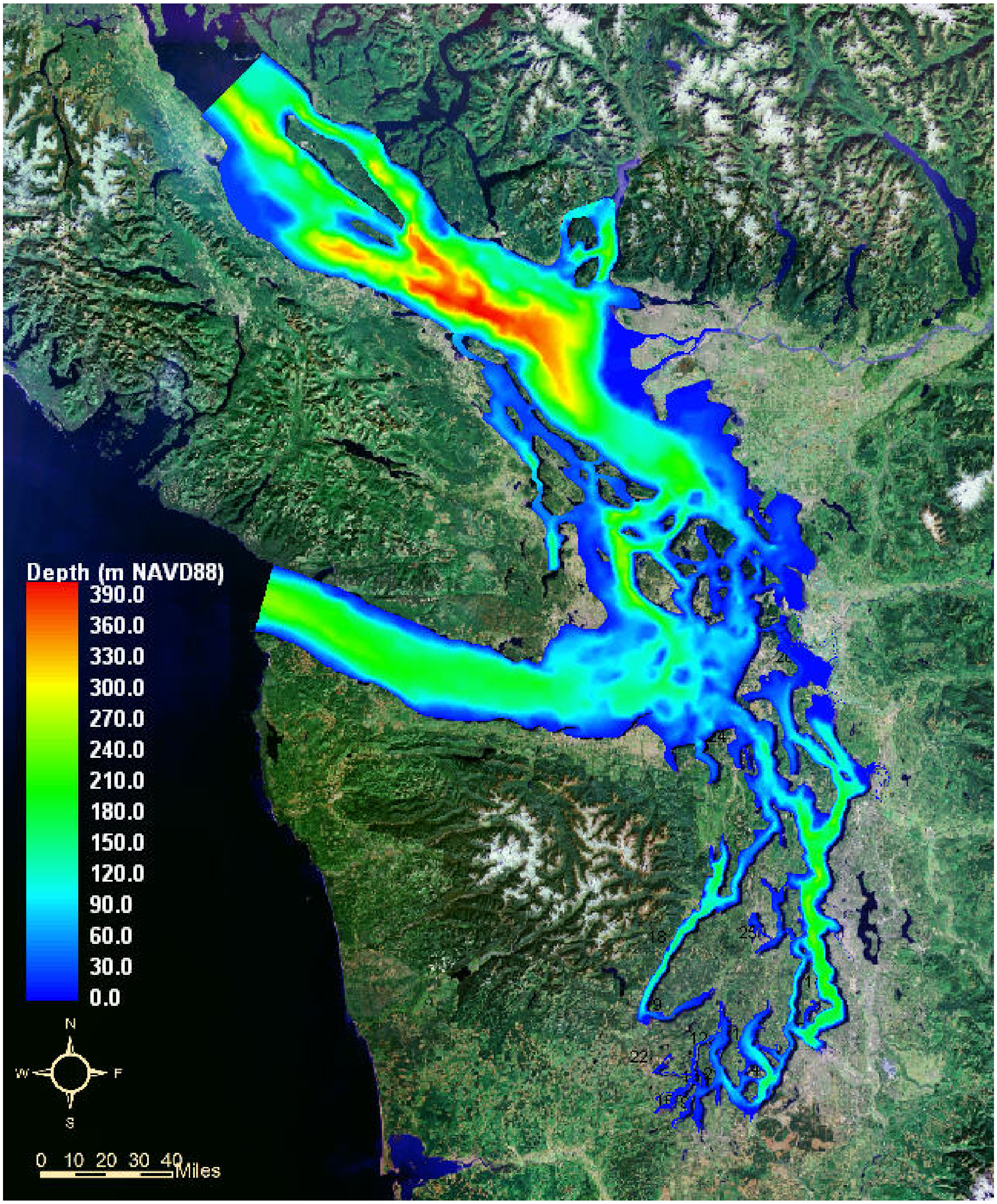
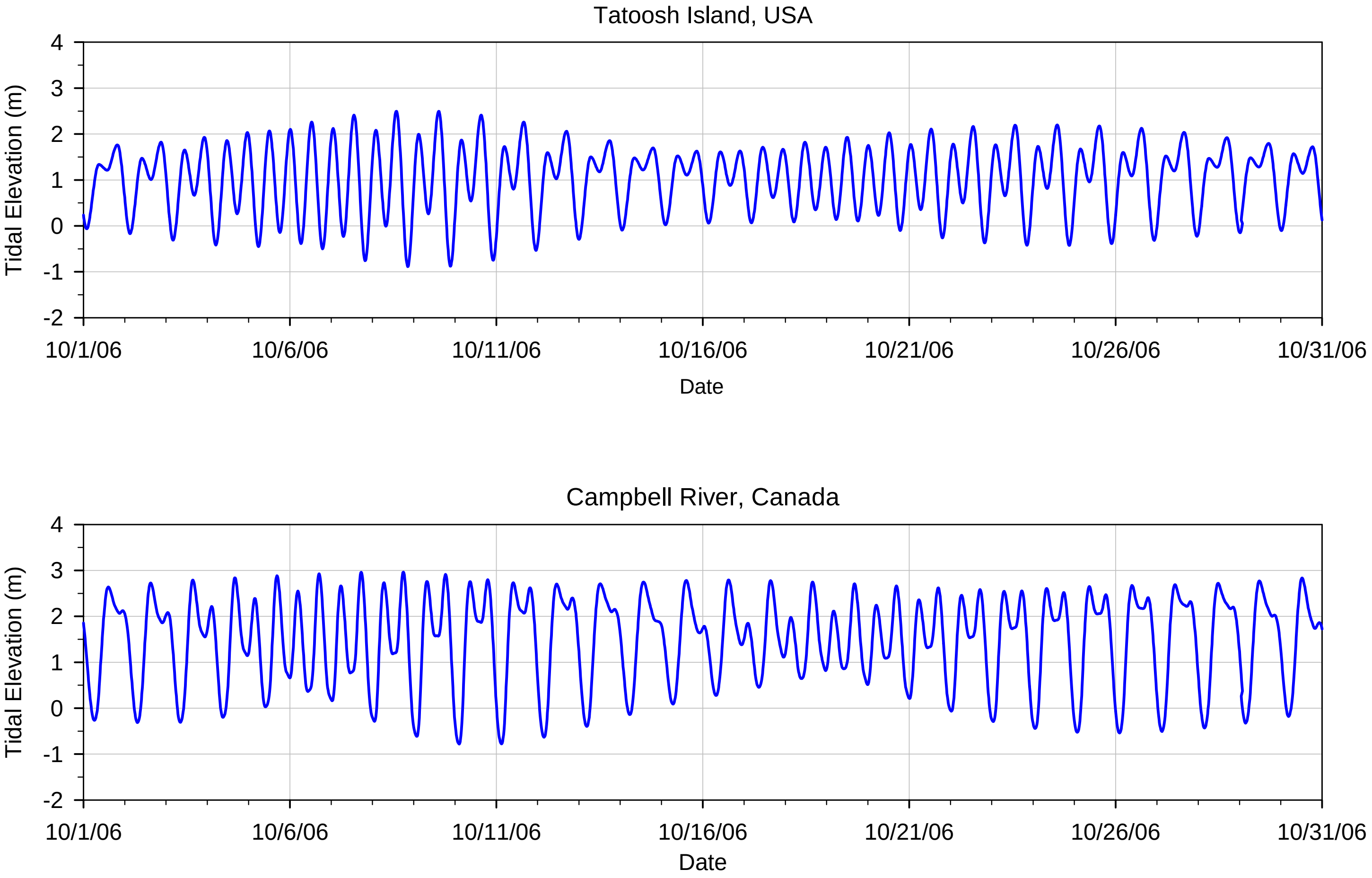


FIGURE 2-6

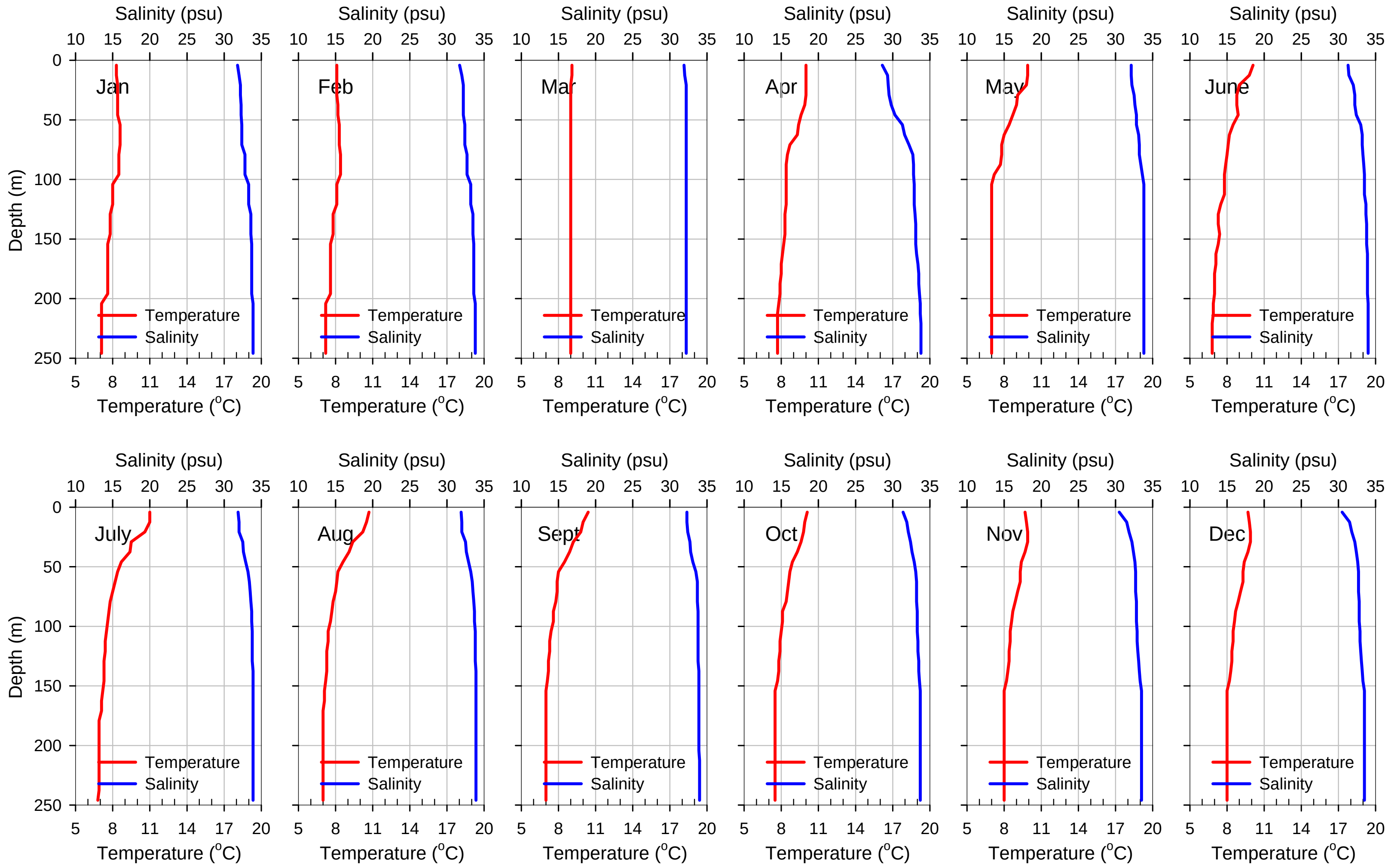
Model Bathymetry – Puget Sound, the Strait of Juan de Fuca, and Georgia Strait



Note:
- Vertical Datum: NAVD88 (m)
- XTIDE prediction

FIGURE 2-7

Tidal Elevations at Open Boundaries Predicted by XTIDE

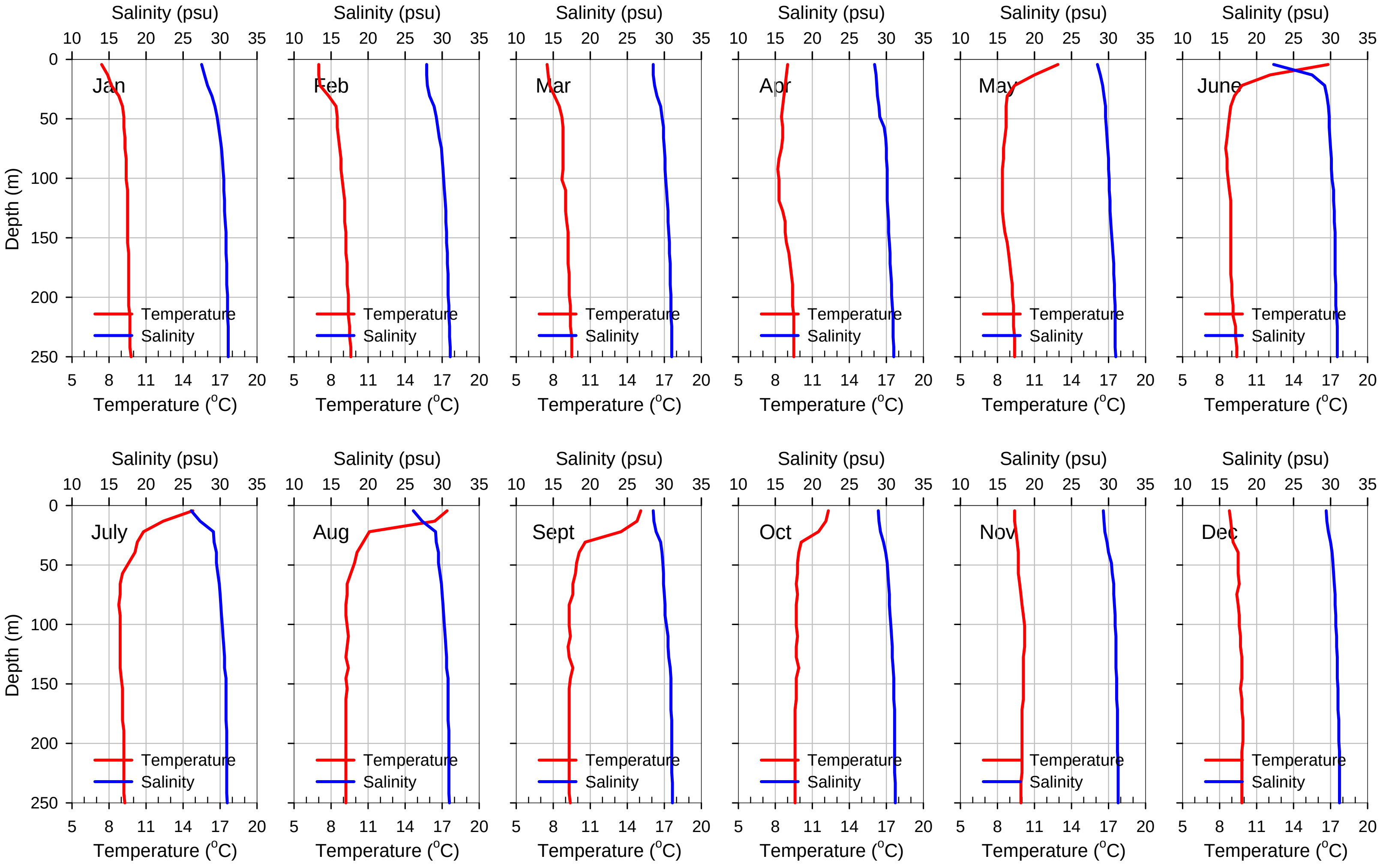


Note:

- Data source: DFO Canada
- Profiles are composite views across multiple points locations

FIGURE 2-8

Temperature and Salinity Profiles at the Strait of Juan de Fuca Open Boundary



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Note:

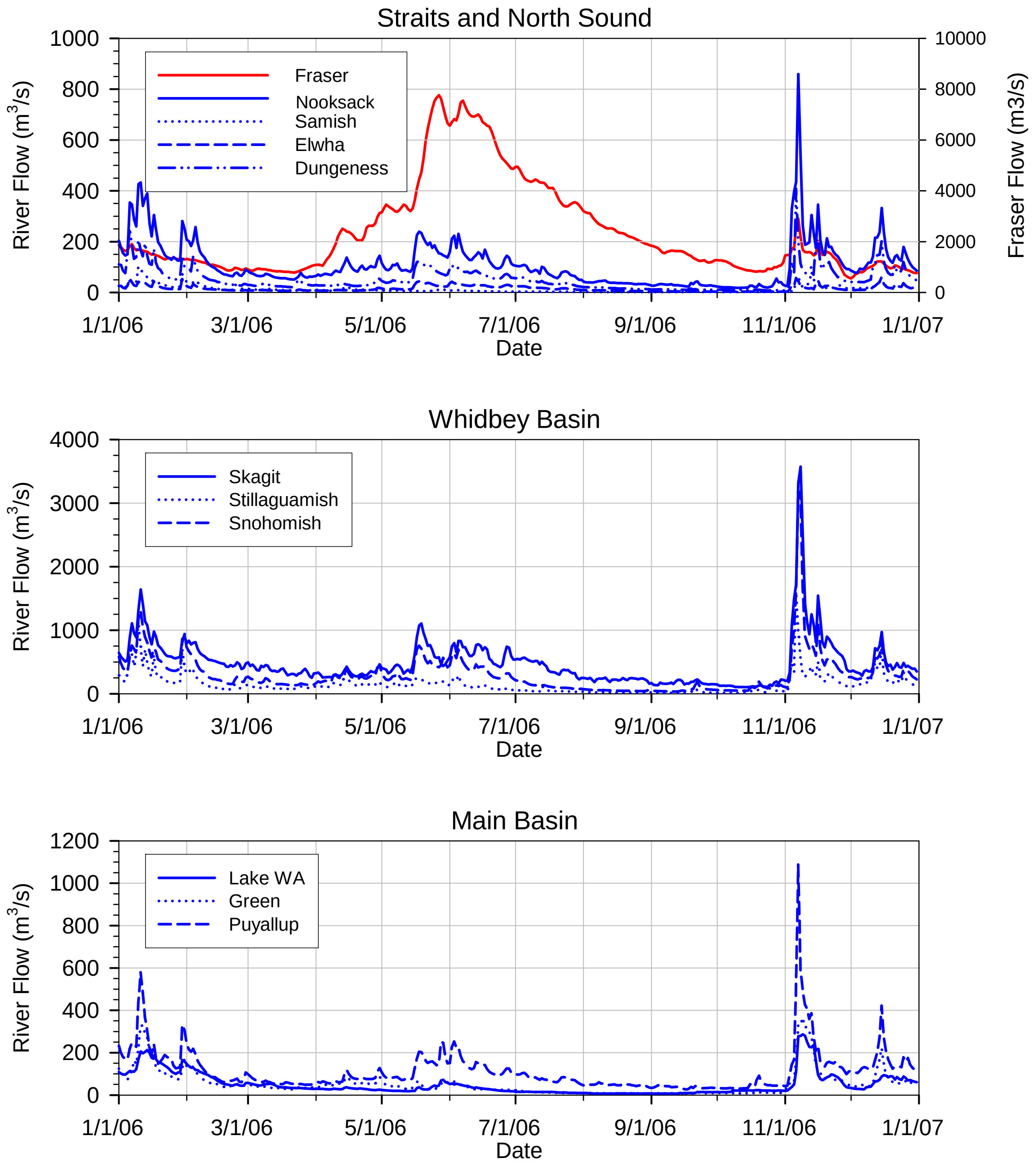
- Data source: DFO Canada
- Profiles are composite views across multiple points locations

FIGURE 2-9

Temperature and Salinity Profiles at Georgia Strait Open Boundary order approximation as a simple approach to specify open boundary conditions in this study. We anticipate that the open boundary conditions will be specified using temporally and spatially dependent data in the future. Monthly salinity and temperature profiles sampled by DFO near the mouth of the Strait of Juan de Fuca and north Georgia Strait for the year 2006 were used to specify the open boundary salinity and temperature conditions (see locations in Figure 2-1). Salinity and temperature profiles were also assumed to be the same at all the grid nodes along each open boundary. Monthly salinity and temperature profiles at the entrance of the Strait of Juan de Fuca and northern Georgia Strait are presented in Figures 2-8 and 2-9, respectively. We can see from the temperature and salinity profiles that Strait of Juan de Fuca waters are partially stratified, seasonally. The bottom temperature remains around 7 to 8 °C over the entire year, and the surface temperature varies from 8 °C in the winter to 11 °C in the summer. Salinity remains around 33 to 34 ppt at the bottom and varies from 28 to 32 ppt, seasonally at the surface. In contrast, temperature and salinity profiles at the northern open boundary in Georgia Strait show strong seasonal stratification. The temperature remains almost constant between 9 to 10 °C at the bottom and changes significantly at the surface, from 7 °C in the winter to 30 °C in the summer. Salinity shows similar variations over the year, with a nearly constant salinity value around 31 ppt at the bottom and 29 ppt at the surface in the winter and less than 25 ppt in the summer. Salinity and temperature values at each model time step were linearly interpolated between profiles for each month.

2.5 River Flows and Temperatures

Nineteen major rivers that discharge into Puget Sound and the Straits were considered in the model. Daily river inflow data were provided by Ecology for the period of 2004 to 2006. Most of the river inflows were obtained from the U.S. Geological Survey (USGS) real-time stream flow gauges. For rivers that had no real-time measurements, river inflows were estimated using a scaling method based on watershed areas. The 19 river inflow stations are shown in Figure 2-1. Figures 2-10 to 2-11 show the river flows for each basin, including the Fraser River in Canada. All river inflows in the United States show similar patterns with high flood events occurring in the late fall and winter periods and relatively low flow in the late spring and early summer. The Puget Sound region experienced a significant flood event in November 2006, which is reflected in the river discharge time series. In contrast, the Fraser River inflow, which is significantly higher than the rest of the inflows into Puget Sound and the Straits, shows a very different seasonal distribution pattern with high flow in the late spring and summer and low flow in the fall and winter. The basin-wide freshwater discharges are plotted in Figure 2-12. River flows are grouped by their discharge basins, and the annual mean flows are summarized in Table 2-1. The Skagit River is the largest river discharging to Puget Sound. The Whidbey Basin consists of the three largest rivers (Skagit River, Snohomish River, and Stillaguamish River) in Puget Sound and accounts for almost 70% of the total freshwater flow into Puget Sound. River temperatures are only available for a limited number of major rivers (including the Fraser (Water Survey of Canada)) and often do not cover the entire year. Comparisons of river temperatures from different rivers (Ecology's Ambient Monitoring Program) indicated that the temperatures of rivers entering Puget Sound are relatively similar (upper panel in Figure 2-13, from Ecology). Therefore, as an approximation, river inflow temperatures for all the rivers, except the Fraser River, were represented by the USGS Cedar River temperature in the model setup. Figure 2-13 shows the temperature distributions for the Cedar River in the United States and the Fraser River in Canada for 2006.



Note:

- River inflow data were obtained from Ecology

FIGURE 2-10

Individual River Inflow in the Straits and North Sound, Whidbey Basin, and the Main Basin

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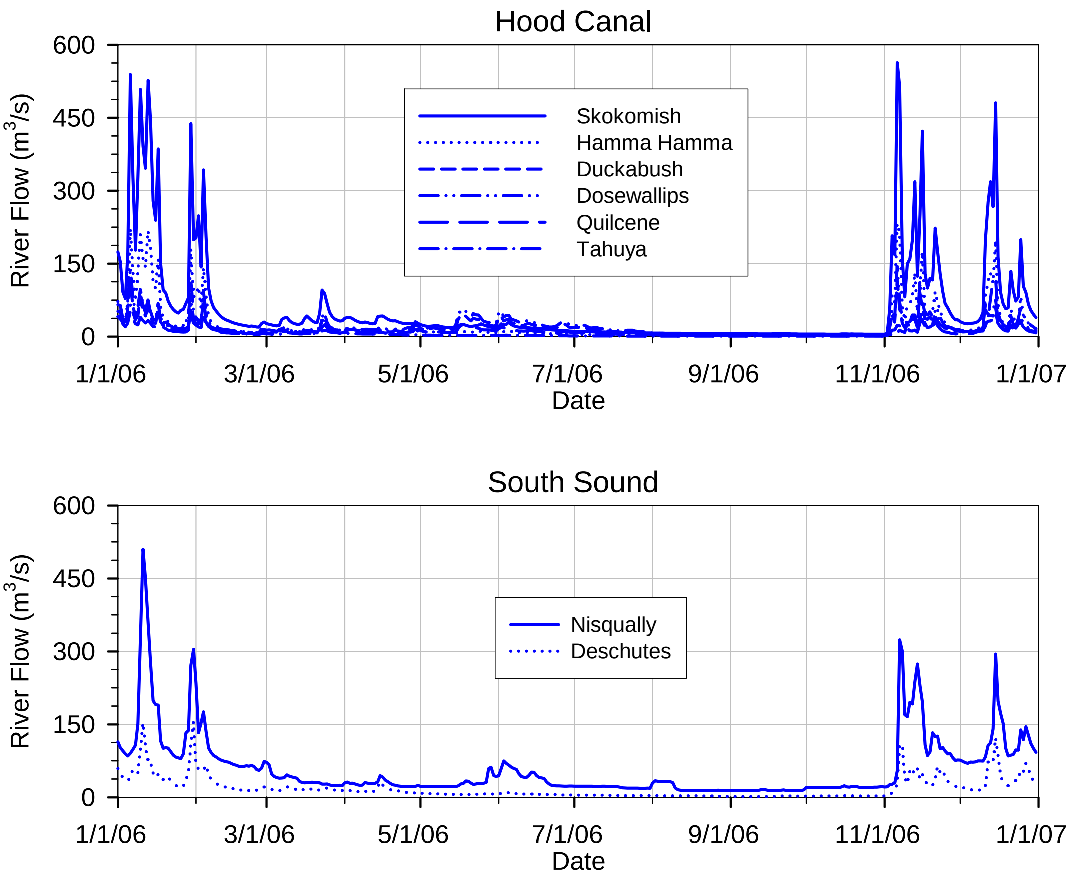

Note:
- River inflow data were obtained from Ecology

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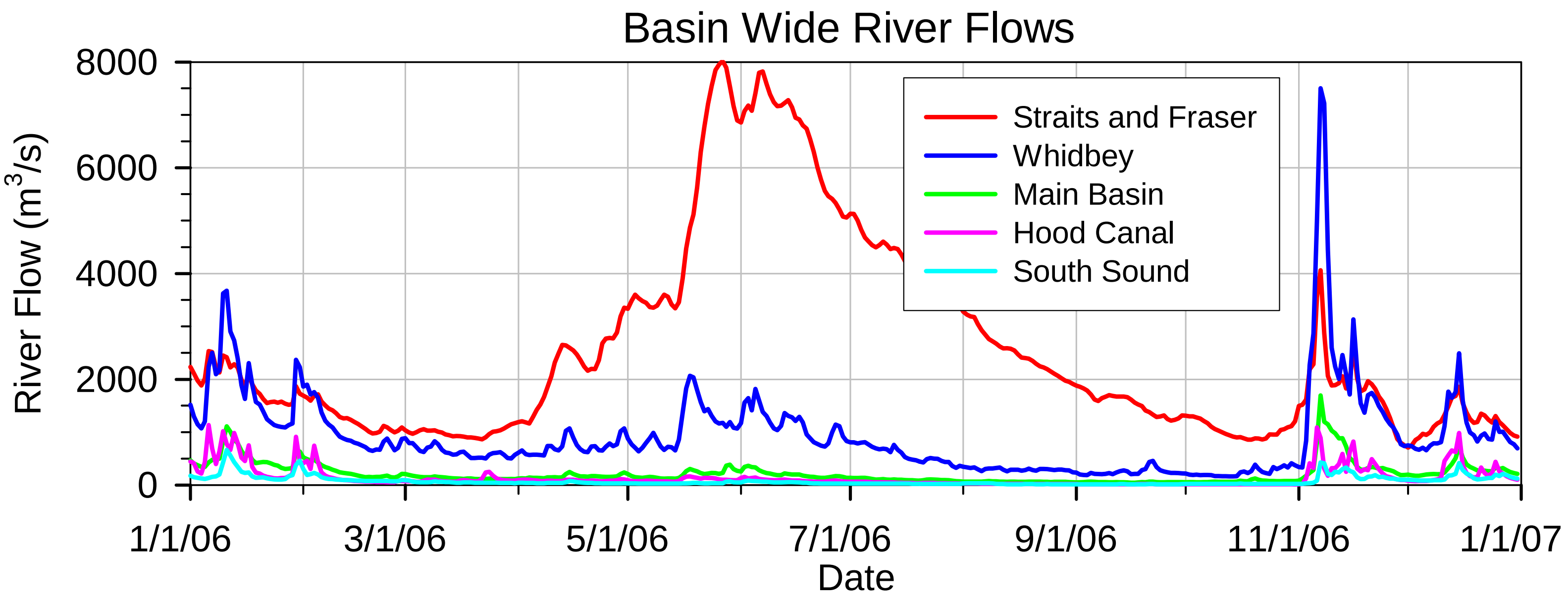
FIGURE 2-11

Individual River Inflow in Hood Canal and South Sound



Note:

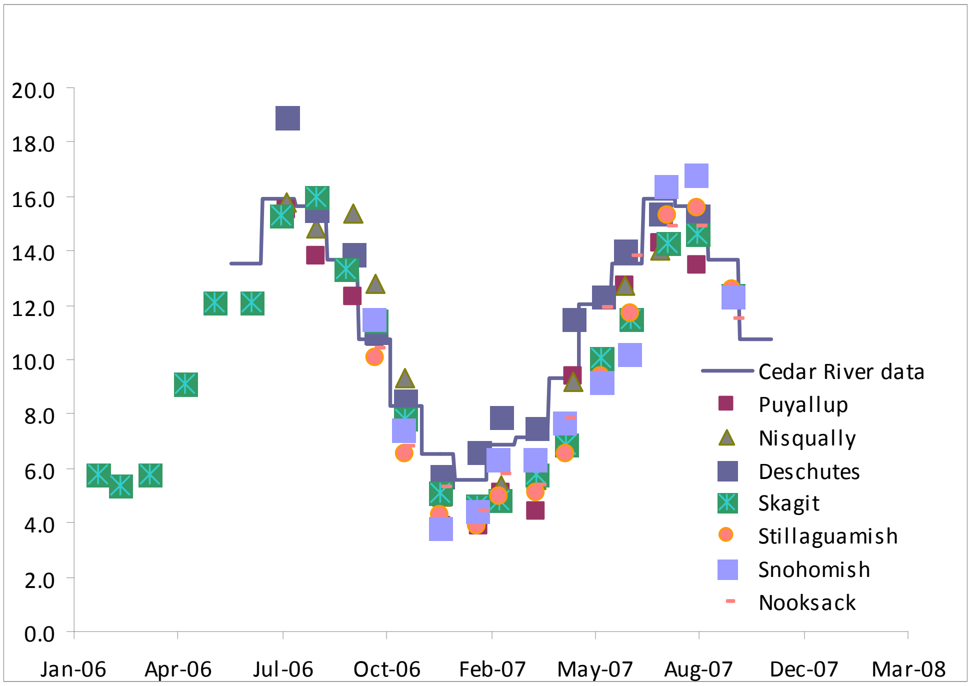
- River inflow data were obtained from Ecology

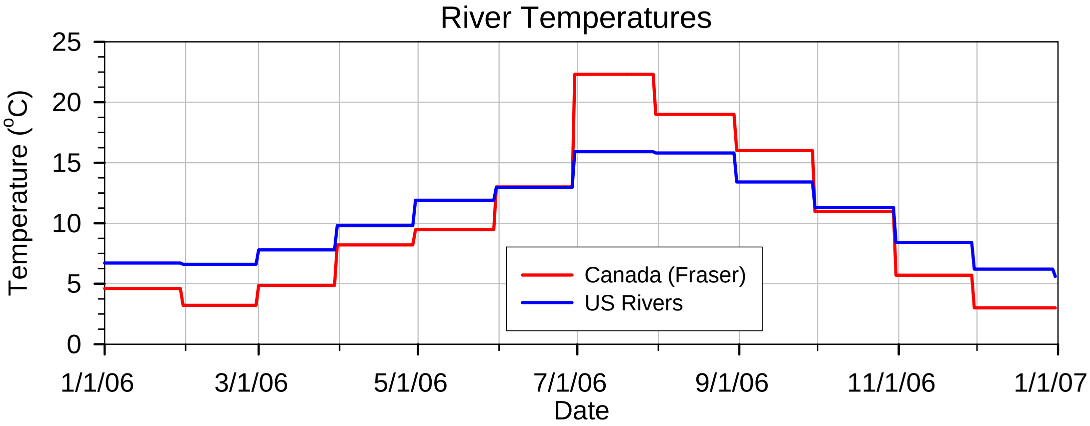
FIGURE 2-12

Basin-wide River Inflows – Puget Sound, the Strait of Juan de Fuca, and Georgia Strait

Table 2-1. Summary of River Inflows (* Percentage is relative to the total inflows in Puget Sound)

River/Basin Name	Annual Mean Flow (m^3/s)	Station ID
Straits and North Sound	**2541**	
Fraser (Canada)	2351.6	WSC08MF005
Dungeness	14.8	USGS12048000
Elwha	52.1	USGS12045500
Nooksack	109.8	USGS12213100
Samish	12.5	USGS12201500
Whidbey Basin	**919 (68%)***	
Skagit	475.5	USGS12200500
Stillaguamish	144.6	USGS12167000
Snohomish	298.8	USGS12150800
Main Basin	**214 (16%)***	
Lake Washington	48.8	USGS12119000 & USGS12125200
Green/Duwamish	52.3	USGS12113000
Puyallup	112.7	USGS12101500
Hood Canal	**139 (10%)***	
Tahuya	10.6	
Skokomish	56.9	USGS12061500
Duckabush	16.7	USGS12054000
Dosewallips	20.9	
Hamma Hamma	23.5	
Big Quilcene	10.0	USGS12052210
South Sound	**76 (6%)***	
Nisqually	58.3	USGS12089500
Deschutes	17.8	USGS12080010





Note:

- River temperature data were obtained from Ecology

FIGURE 2-13

Puget Sound River Inflow Temperature Distributions

2.6 Initial Conditions

Initial conditions representing the start of year 2006 for water surface elevation, velocity, temperature, and salinity were required for setting up the simulation. Typically, in tidal circulation modeling, initial conditions for water surface elevation and velocity fields are set to zero because the spin-up time for tidal elevation and velocity is quite short (a couple of days). For salinity and temperature initial conditions, either constant or spatially varying profiles can be specified. Spatially varying salinity and temperature profiles can be obtained through interpolation of observation data or generated by the model using the restart option for a continuous model run. In this study, we chose the approach of simulating the year 2005 condition with boundary forcings of 2005 (tidal open boundary conditions, meteorological forcing, and river inflows) and the same model parameters as 2006. Model results were saved at the end of 2005. The saved model results were read as the initial condition to conduct the 2006 model simulation using the restart option in the model.

2.7 Meteorology Data

To simulate wind-induced currents and temperature distribution in Puget Sound, meteorological forcing is specified in the model setup. FVCOM v2.6 used in this study does not have the full internal thermal formulation. It only accepts pre-calculated net heat flux (in or out of water) from atmosphere. We anticipate using the full internal thermal formation which is available in the newer version of FVCOM v2.7.1 in the future. The meteorological input parameters for FVCOM v2.6 include 1) wind speed and direction, 2) shortwave and longwave radiation (downward and upward), and 3) latent heat flux and sensible heat flux. There are two approaches to specifying the meteorological forcing in this study. The first approach is based on observed data at various meteorological stations around the Sound to obtain the wind forcing and calculate the net heat flux. Although there are several National Oceanic and Atmospheric Administration (NOAA) real-time meteorological stations around Puget Sound, meteorological parameters (such as solar radiation, humidity, air temperature, dew point temperature, cloud cover etc.) are not always measured at each of the meteorological stations. Furthermore, data gaps often exist in measured data. The second approach to specifying meteorological forcing is to use meteorological model outputs. The North American Regional Reanalysis (NARR) data sets (http://www.emc.ncep.noaa.gov/mmb/rreanl/) were used in this study. These data are generated by the NOAA National Center for Environmental Prediction (NCEP) based on the regional meteorological model (Eta Model) at 32 km resolution. NARR data sets provide all the meteorological parameters required in FVCOM as model inputs at 3-hour intervals.

All the meteorological input parameters for the model are plotted in Figures 2-14 to 2-18. Figure 2-14 shows wind speed is below 10 m/s most of the year. Wind is low during summer (around 5 m/s) and high during winter (as high as 15 m/s). Shortwave solar radiation shows distinct seasonal variation with daily peaks ranging from 100 W/m^2 in the winter to nearly 1000 W/m^2 in the summer (Figure 2-15). Upward shortwave solar radiation is quite constant with a value of around 100 W/m^2 throughout the year. Downward and upward longwave radiations vary and are in the range of 280 W/m^2 to 550 W/m^2 with little seasonal variation. Both sensible and latent heat fluxes show strong seasonal variation with high values in the summer and low values in the winter. It is noted that sea surface temperature is one of the parameters in NARR data set and its effect on meteorological parameters is considered. However the NARR sea surface temperature is not identical to the sea surface temperature calculated in the Puget Sound model. The difference in sea surface temperatures between NARR and

FVCOM could affect estimates of final net heat flux. However, the good match with observed data confirms that the differences are likely small and that this approach is reasonable. The net heat flux HF_{net}, which is a model input parameter in FVCOM, is calculated based on the following formula:

$$HF_{net} = SW_{down} + LW_{down} - SW_{up} - LW_{up} - HF_{sensible} - HF_{Latent}$$

Net heat flux is plotted in Figure 2-18, which shows that the maximum net heat flux is in August and the minimum occurs in January.

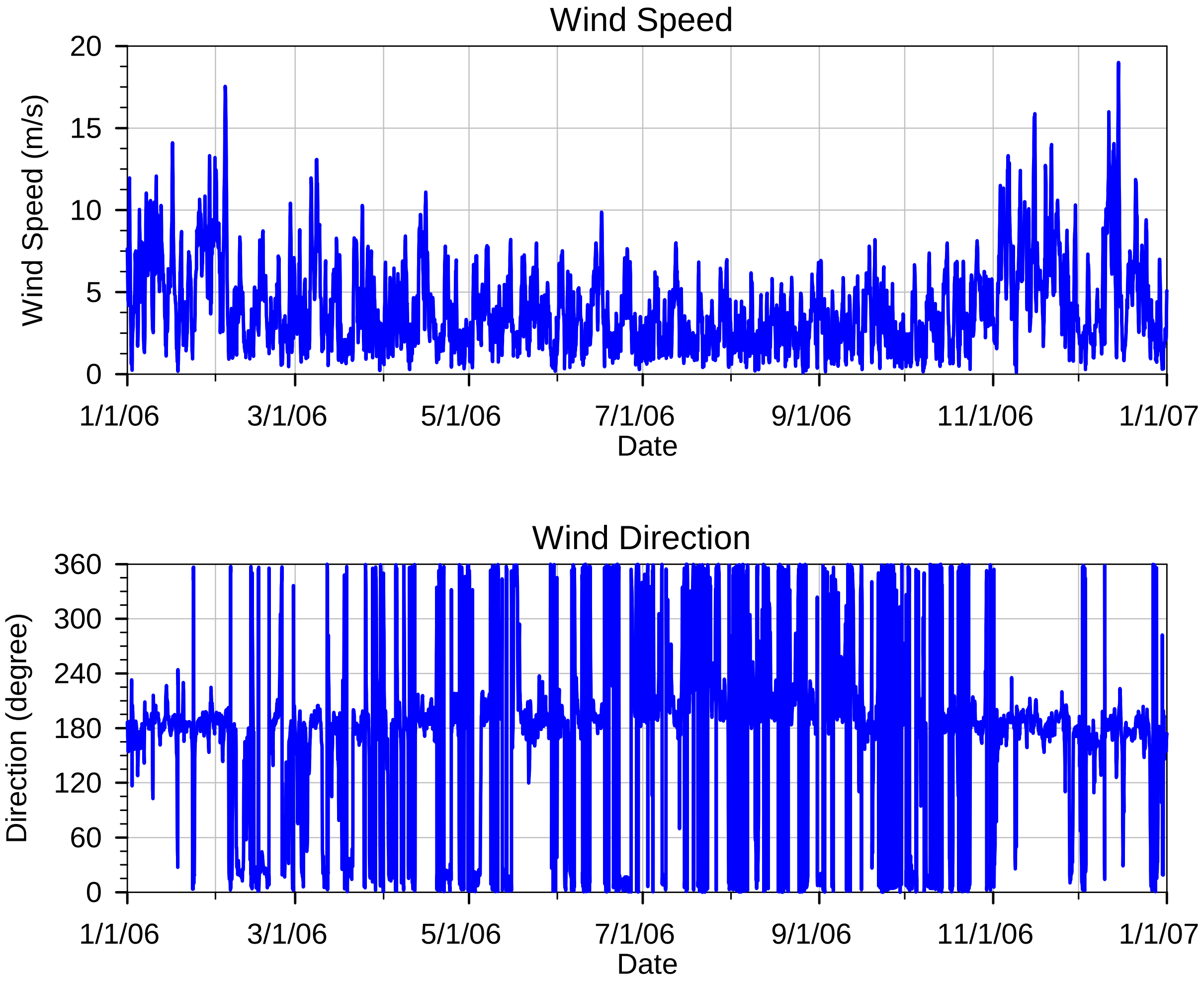


FIGURE 2-14

Wind Speed and Direction Data from NARR Dataset near Seattle

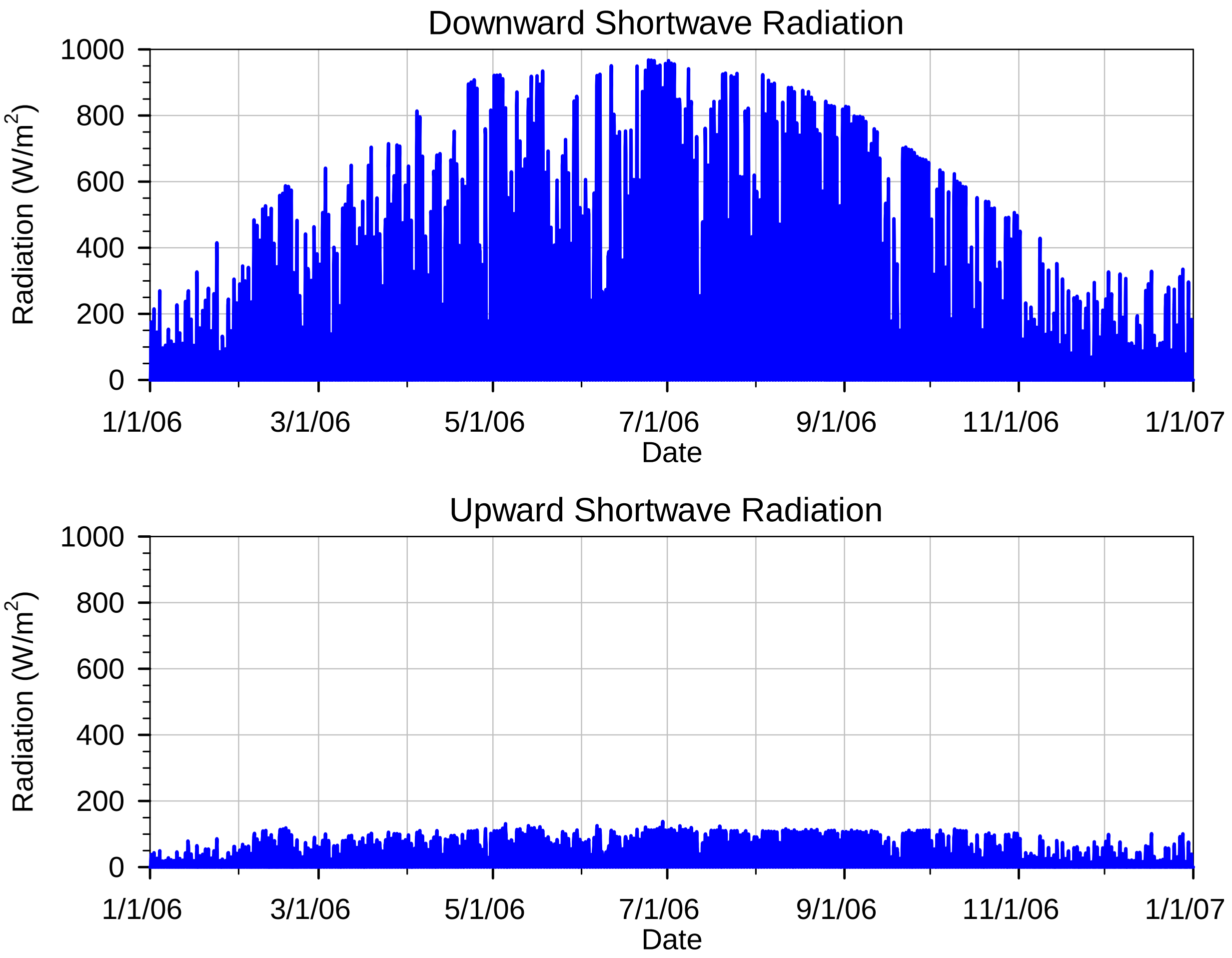


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FIGURE 2-15

Downward and Upward Shortwave Radiation from NARR Dataset near Seattle

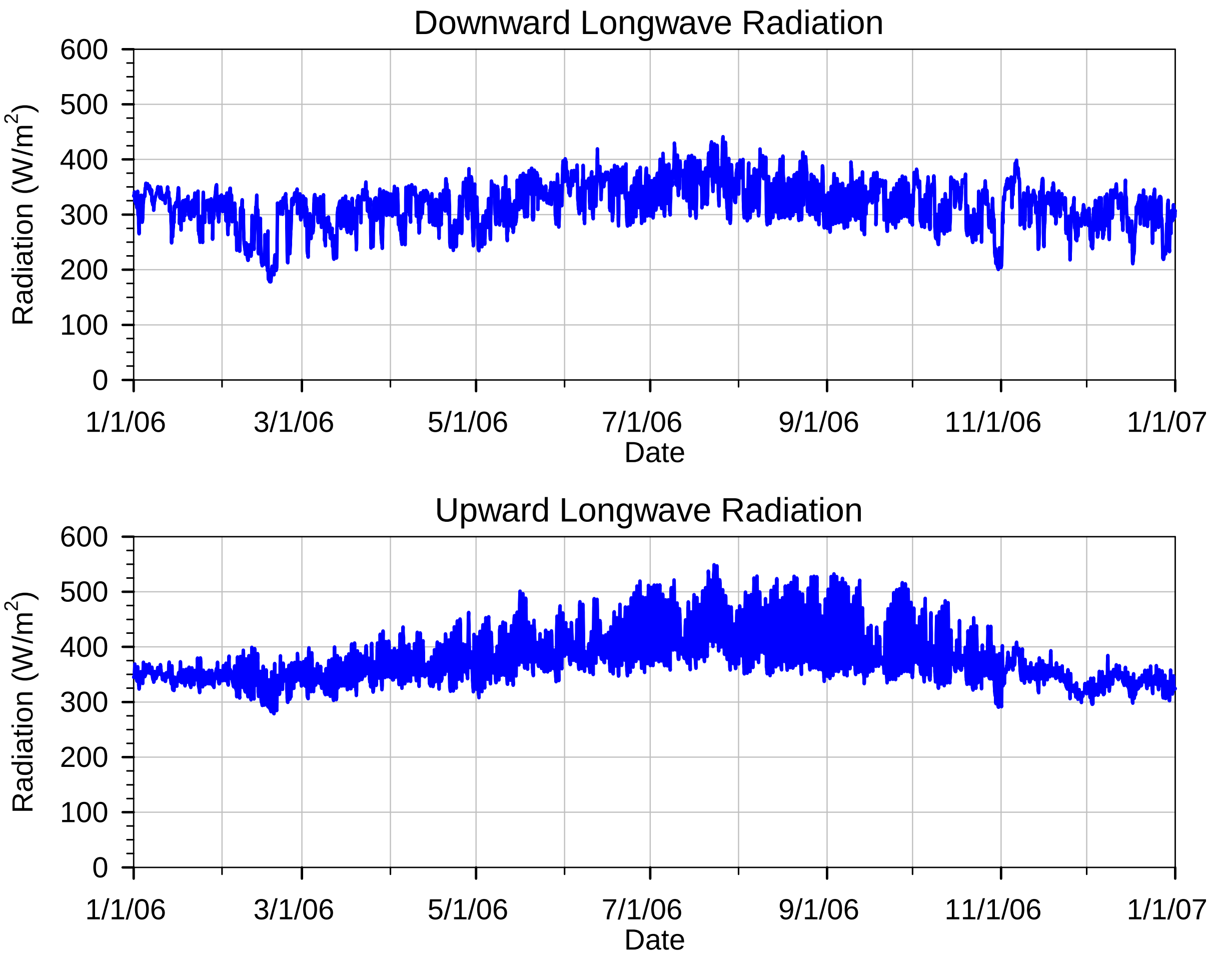

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FIGURE 2-16

Downward and Upward Longwave Radiation from NARR Dataset near Seattle

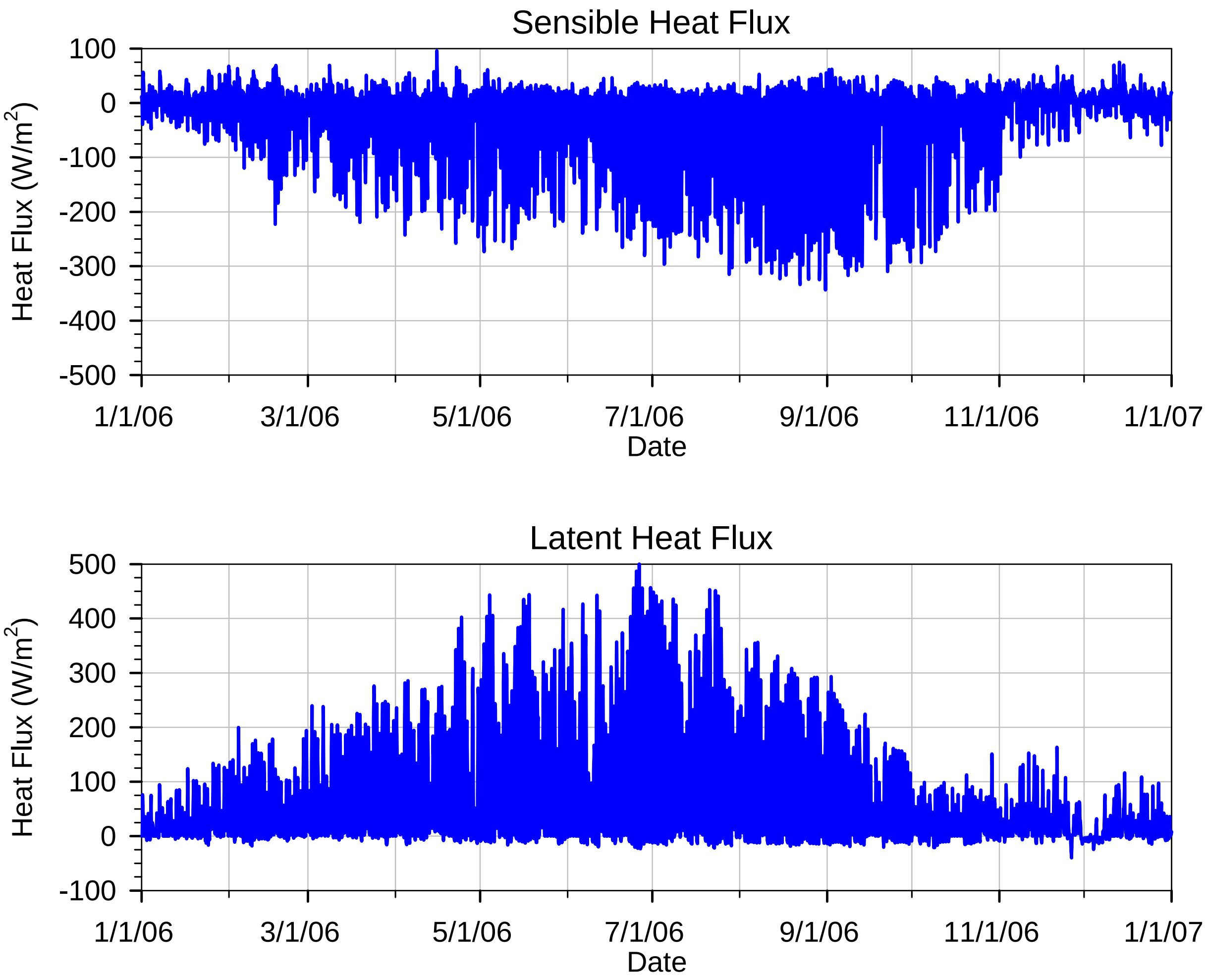
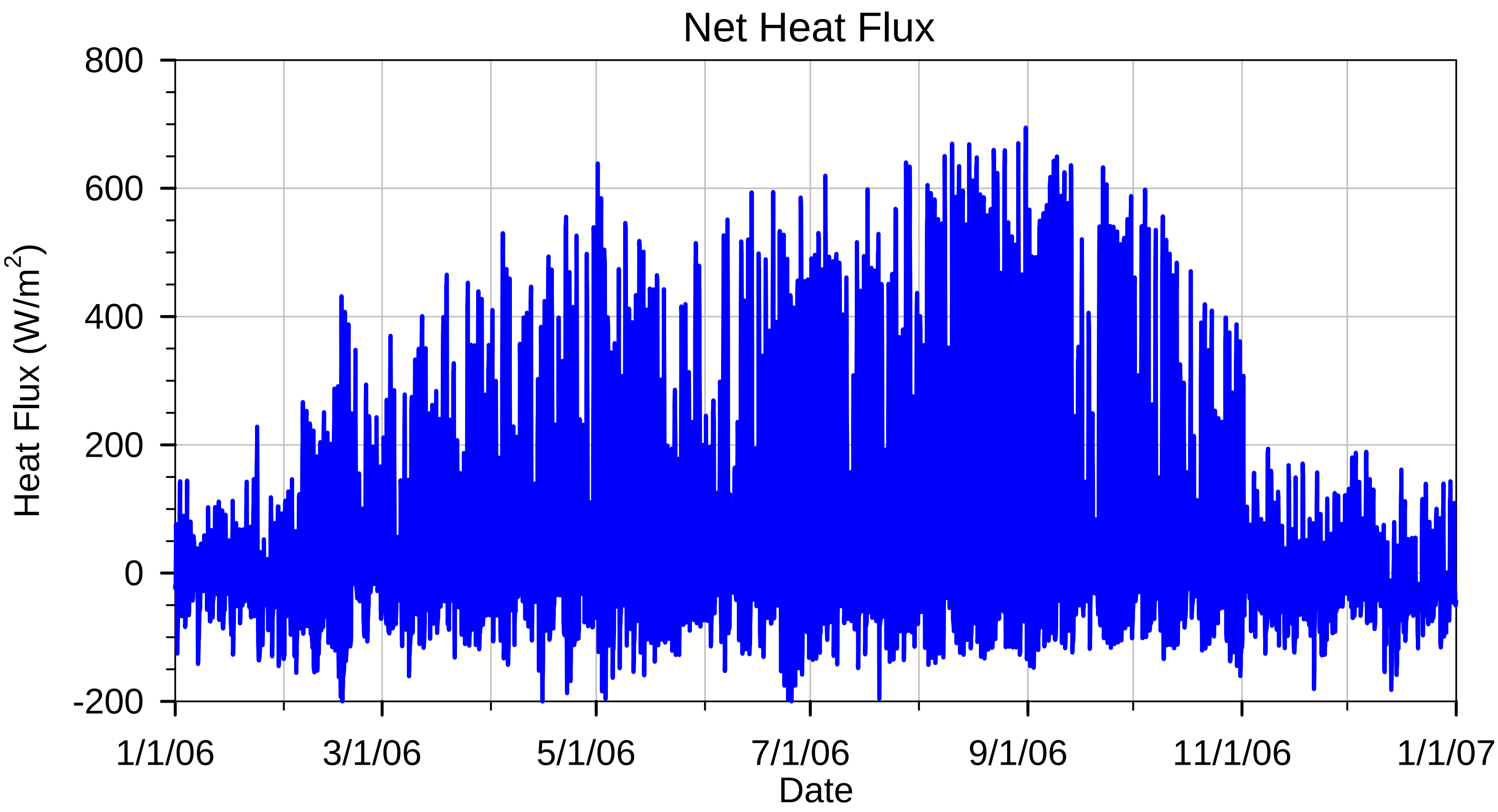


FIGURE 2-17

Sensible and Latent Heat Flux from NARR Dataset near Seattle



Note:

- Net Heat Flux = $SW_{down} + LW_{down} - SW_{up} - LW_{up} - HF_{sensible} - HF_{Latent}$

FIGURE 2-18

Estimated Net Heat Flux based on NARR Dataset near Seattle

3.0 Model Calibration

3.1 Introduction

Following the completion of model setup as described in Section 2.0, model calibration was conducted for the entire year 2006. The year 2006 was selected for model calibration because it is the most data-rich period for salinity, temperature, and water quality data in Puget Sound collected by Ecology as part of the South Puget Sound Dissolved Oxygen Study (Roberts et al., 2008). Model calibration was achieved through matching the predicted water surface elevation (WSE), velocity, salinity, and temperature to observed data at selected stations in Puget Sound. To accomplish this task, model parameters such as friction coefficients, model grid, bathymetry, and boundary condition were adjusted until best match with observed data was obtained. Key model parameters used in this calibration effort are listed in Table 3-1.

Table 3-1. Key Hydrodynamic Model Parameters and Configuration

Model Parameter	Value	Comment
External Time Step	2.0 (sec)	
Internal Time Step	10.0 (sec)	
Bottom Friction Coefficient	0.005	Quadratic Bottom Stress
Bottom Roughness	0.005 (m)	Log Boundary Layer Theory
Horizontal Diffusion	Smagorinsky Scheme	Multiplicative Coefficient = 0.2
Vertical Eddy Viscosity	MY 2.5 Turbulent Closure	
Vertical Layer	30	Uniform Sigma Layers
Minimum Depth	4 (m)	Relative to NAVD88
Tidal Open Boundary Condition	Water Surface Time Series	Radiative Boundary Condition
Salinity and Temperature Open Boundary Conditions	Constant	Based on Monthly Observed Profiles
Meteorological Forcing	Wind Speed/Direction and Net Heat Flux	Directly Provided by NOAA/NCEP NARR Outputs
Water Column – Bed Coupling	Inactive	No Groundwater or Thermal Effect

There are six real-time tidal stations maintained by NOAA throughout the Straits and Puget Sound. Additional tidal elevation data at three XTide stations were obtained for model calibration in Whidbey Basin, Hood Canal, and South Puget Sound. Velocity data are very limited in Puget Sound. Acoustic Doppler Current Profiler (ADCP) data in South Puget Sound (Roberts et al., 2008), Skagit Bay, and Swinomish Channel were used for model calibration (Yang and Khangaonkar, 2008). Ecology has also collected many monthly salinity and temperature profiles throughout Puget Sound. In this study, selected profiles in the major subbasins were used for salinity and temperature model calibration (http://www.ecy.wa.gov/apps/eap/marinewq/mwdataset.asp).

The intermediate-scale hydrodynamic model of Puget Sound was run on a 184-core cluster computer. A 10-second time step was used for the model simulation. All model input files were interpolated linearly into the 10-second intervals in the model during the model runs. A one-year model run with 64 computational cores requires about 34 hours in real time. Although the cluster has 184 cores the intermediate-scale model could not fully use all the computational cores because of the relatively small size of the model grid. Sensitivity tests with respect to number of computational cores indicated that the speed of model run reached the maximum with 64 cores. A separate sensitivity test showed that the high resolution Puget Sound model (Yang and Khangaonkar 2008) which grid size is an order of magnitude greater than the current intermediate-scale model could fully use all the computational cores to speed up the model run time

Comparisons of model results and observed data for WSE, velocity, salinity, and temperature are discussed in the following three sections. The observed data locations for model calibration are presented in Figure 3-1.

3.2 Model Calibration – Water Surface Elevation

Comparisons of predicted WSE and NOAA real-time observations at stations in the Straits and Puget Sound are presented in Figures 3-2 and 3-3, respectively. Overall, model predictions match the data reasonably well. The spring-neap tidal cycle and the diurnal inequality were reproduced well in the model simulations. Predicted tidal phases were also in good agreement with observed data. In the Strait of Juan de Fuca, diurnal tides are dominant (e.g., Port Angeles Station, Figure 3-2). As tides propagate from the Strait of Juan de Fuca to Puget Sound, tidal amplitudes are increased and semi-diurnal tides become more dominant. To further calibrate the model in the subbasins of Puget Sound, model predictions were also compared to XTide predictions at Bangor in Hood Canal, Budd Inlet in South Puget Sound, and Green Bank in Whidbey Basin (Figure 3-4). Tidal ranges were largest at Budd Inlet Station in South Puget Sound (Figure 3-4). To quantify the accuracy of model calibration for WSE, error statistics which quantify the differences between model results and observations were calculated. Mean absolute errors (MAE) and root mean square errors (RMSE) at all the stations for 2006 are calculated based on following equations and shown in Table 3-2.

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|\eta_i^m - \eta_i^o\right|$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\eta_i^m - \eta_i^o\right)^2}$$

where where *N* is the total data points of field observations; η_i^m is modeled WSE and η_i^o is observed WSE.

The mean MAEs and RMSEs of all the stations are 0.22 m and 0.27 m, respectively. This is likely due to errors introduced from the XTide open boundary conditions and neglecting the tide flats in the nearshore regions. To further quantify the errors, relative mean errors (RME) were calculated. RME is defined as the ratio of MAE to the mean of daily tidal ranges. All RMEs are within 10% except at Cherry Point, which has a RME of 10.6%. The spatial distribution of the error statistics also showed that errors did not grow as tides propagated into Puget Sound. Instead, the three stations in the Straits (Port Angeles, Friday Harbor, and Cherry Point) have the highest relative mean errors. This indicates that the main source of error in WSE predictions might be error associated with the open boundary conditions, especially from the northern boundary at Georgia Strait.

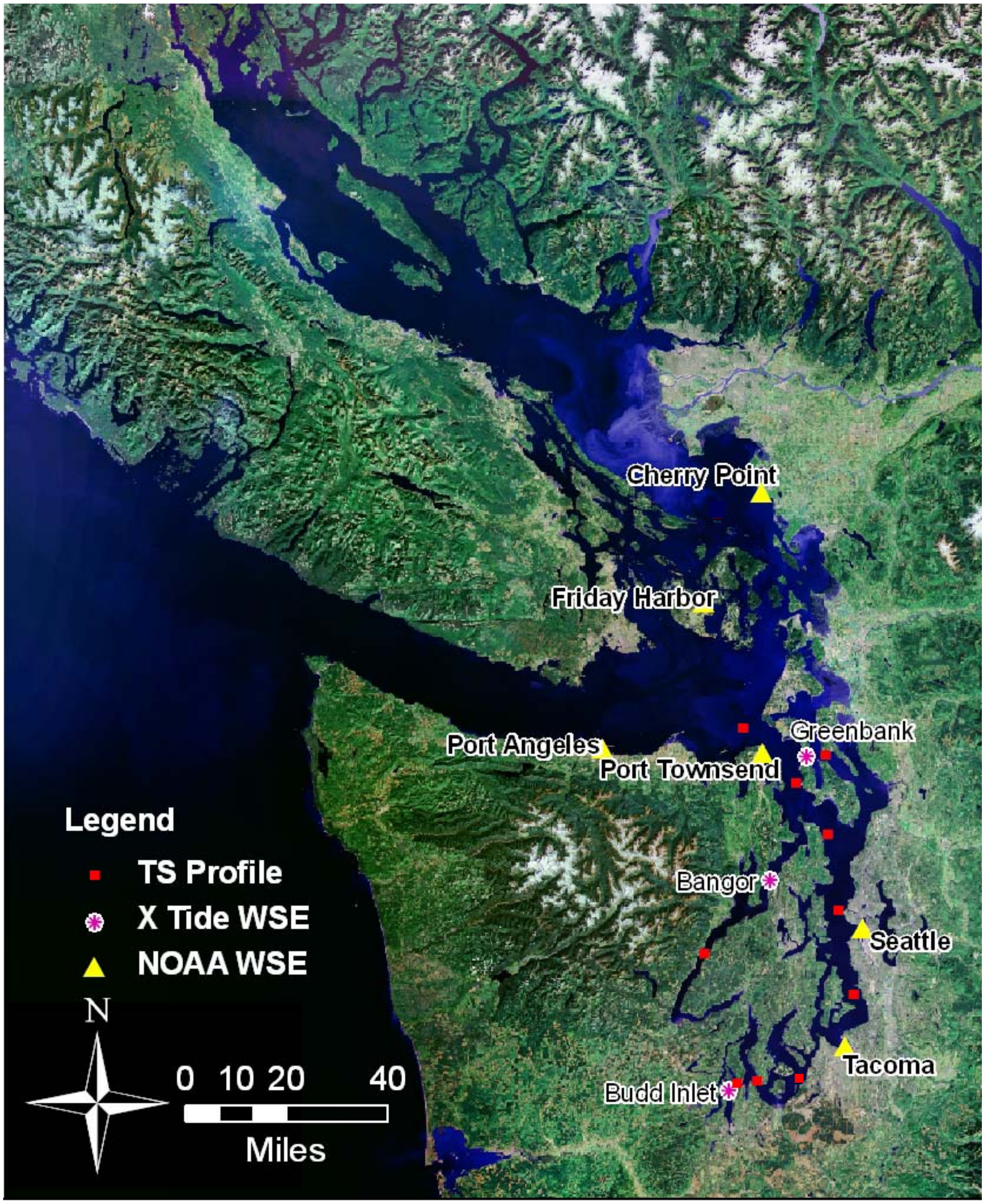
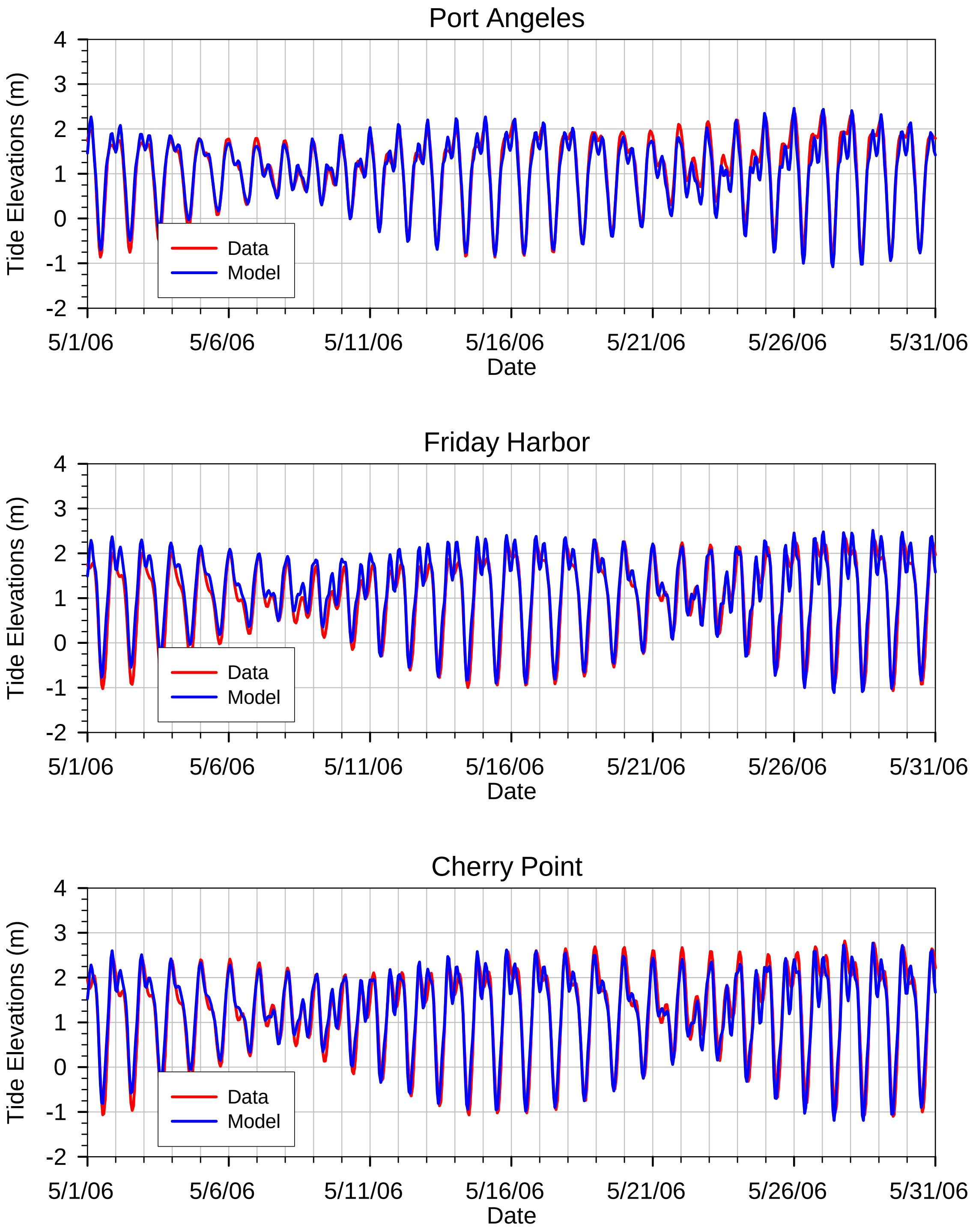


FIGURE 3-1

Data Locations for Model Calibration



Note:

- Observed data are obtained from NOAA real-time stations

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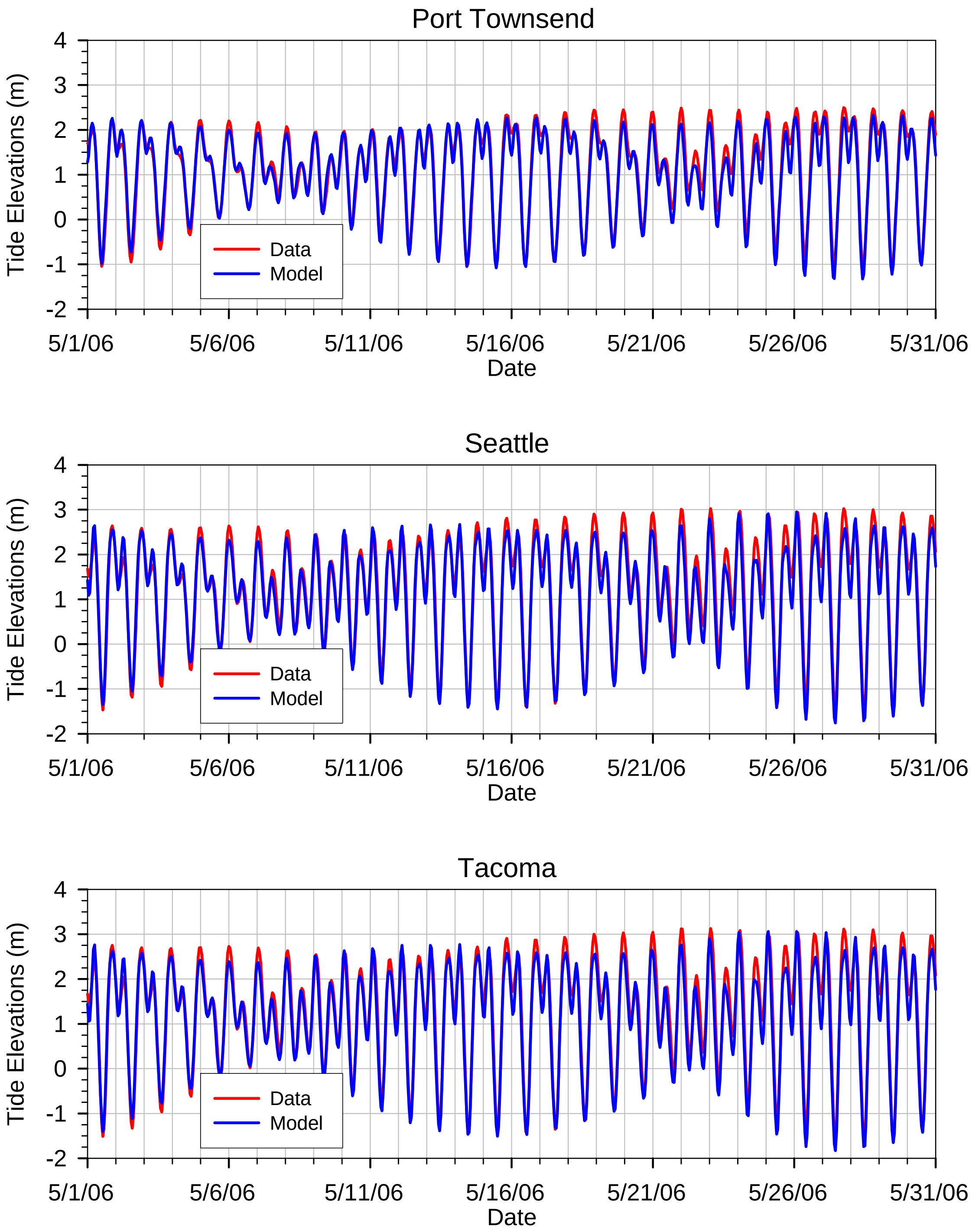
FIGURE 3-2

Comparisons of Predicted and Observed WSE at Port Angeles, Friday Harbor, and Cherry Point

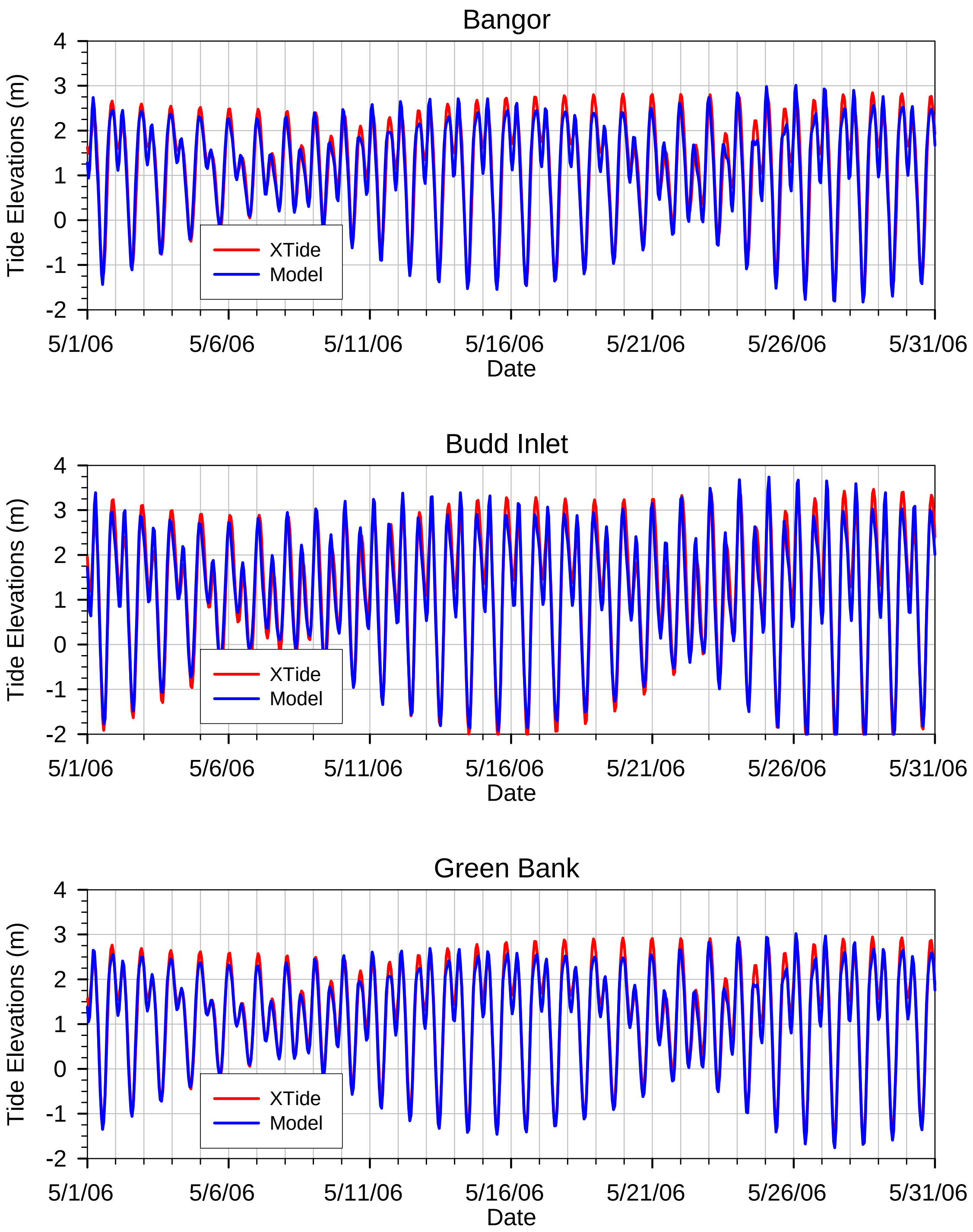


Note:

- Observed data are obtained from NOAA real-time stations

FIGURE 3-3

Comparisons of Predicted and Observed WSE at Port Townsend, Seattle, and Tacoma



Note:

- Observed data are obtained from XTide prediction

FIGURE 3-4

Comparisons of Predicted and Observed WSE at Bangor, Budd Inlet, and Greenbank

Table 3-2. Model Calibration Error Statistics for Water Surface Elevation (2006)

Station	MAE (m)	RMSE (m)	RME (%)
Port Angeles	0.17	0.22	7.6
Friday Harbor	0.24	0.31	9.7
Cherry Point	0.25	0.31	10.6
Port Townsend	0.18	0.23	6.7
Seattle	0.22	0.27	6.3
Tacoma	0.23	0.28	6.3
Bangor	0.24	0.29	7.1
Budd Inlet	0.28	0.34	6.2
Green Bank	0.16	0.20	4.6
Mean	**0.22**	**0.27**	**7.2**

Predicted horizontal 2-D distributions of WSE (high tide and low tide with respect to Seattle) on May 15, 2006 are presented in Figures 3-5 and 3-6. Tidal elevations show the greatest gradient in the Strait of Juan de Fuca and the smallest gradient in Georgia Strait. Figures 3-5 and 3-6 also show that South Puget Sound has the largest tidal range in the study domain.

3.3 Model Calibration – Tidal Currents

Velocity data available for model calibration are very limited. ADCP data obtained at four stations in Puget Sound in 2006 were used for model calibration. These stations include Dana Passage and Pickering Passage data in South Puget Sound obtained from Ecology and Skagit Bay and Swinomish Channel data obtained from Skagit River System Cooperative (Figure 3-1). For simplicity, comparisons were made between the model results and observed data along the major-axis of tidal currents at the surface, middle, and bottom layers of the water column.

The Pickering Passage data set covered a three-month period from September 21, 2006 to December 21, 2006. As an example, velocity comparisons for October 2006, shown in Figure 3-7, indicate that predicted velocities at Pickering Passage match the data, both in magnitude and phase. Velocities in Pickering Passage are relatively small and dominated by a semi-diurnal tide. Baroclinic motion is minimal because of little freshwater discharge to that portion of the South Sound.

Dana Passage data covered a period of more than four months from September 21, 2006 to January 28, 2007. A comparison of predicted and observed velocities at Dana Passage is shown in Figure 3-8. Although the Dana Passage station is also located in South Puget Sound, tidal currents at Dana Passage station are much stronger than those at Pickering Passage station. Similar to the Pickering Passage station, Figure 3-8 shows that predicted velocities match the observed data well. The spring-neap tidal cycle was clearly shown in the model predictions.

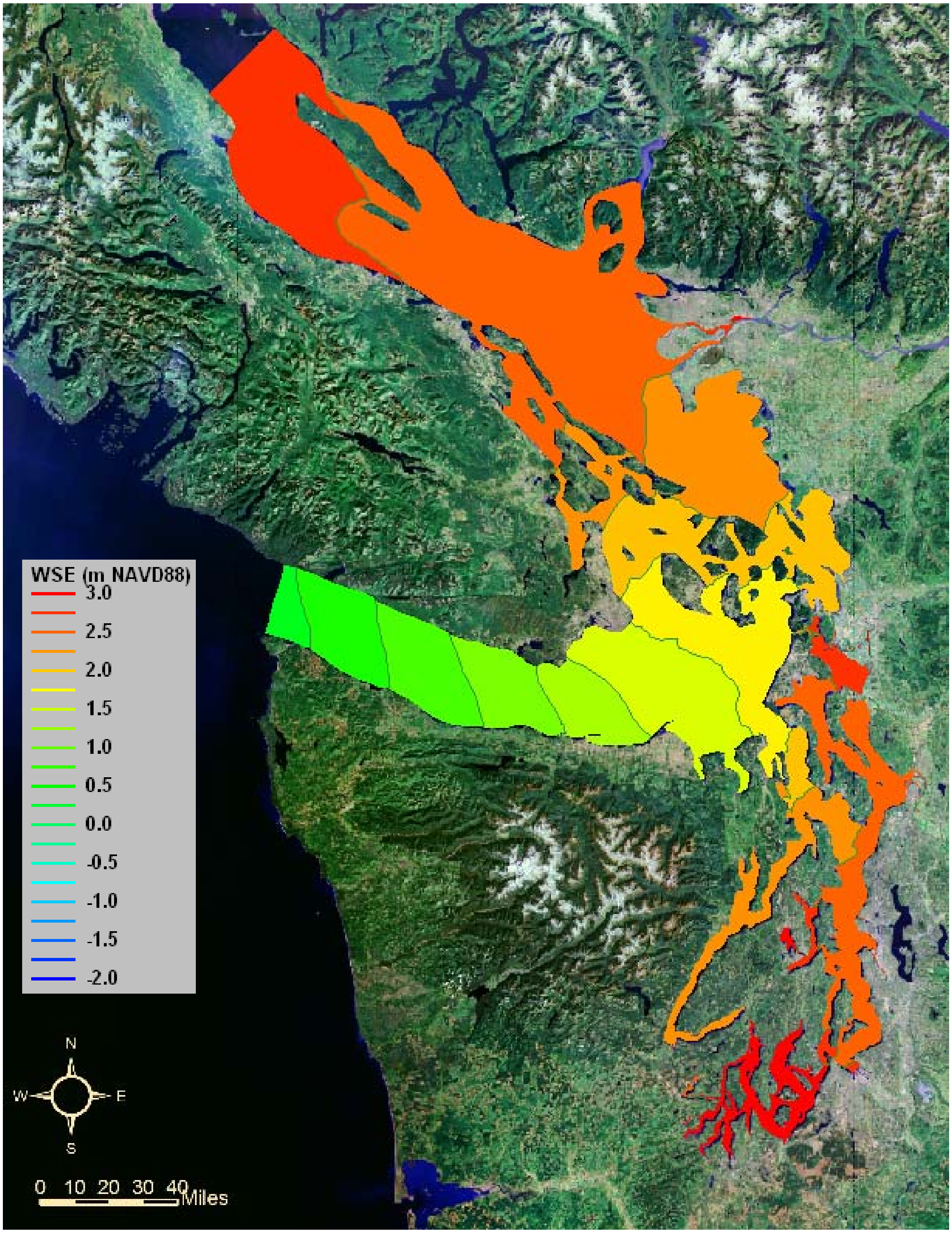


FIGURE 3-5

Water Surface Elevation at High Tide in Puget Sound (5/15/2006, 1:00 PM)

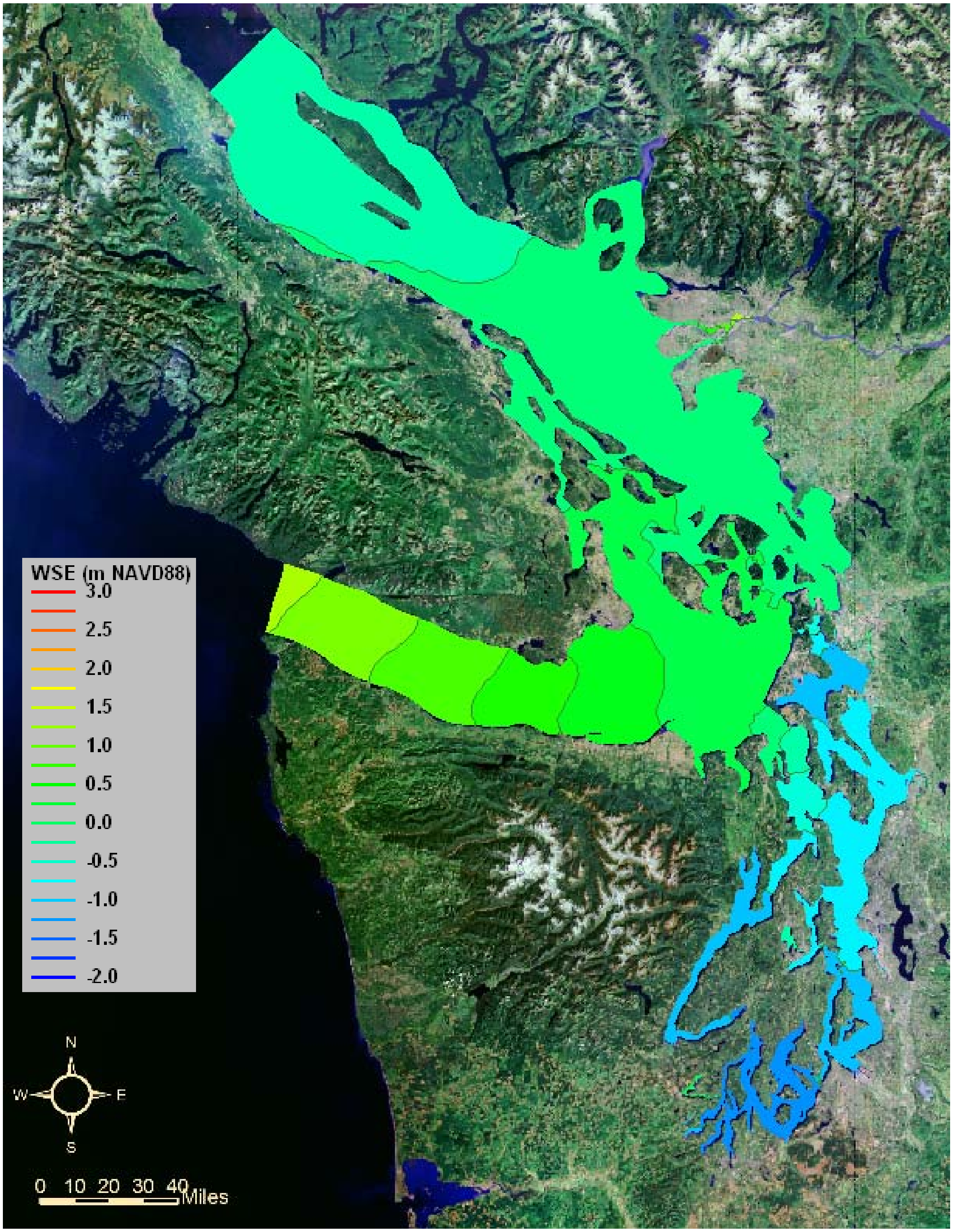


FIGURE 3-6

Water Surface Elevation at Low Tide in Puget Sound
(5/15/2006, 8:00 PM)

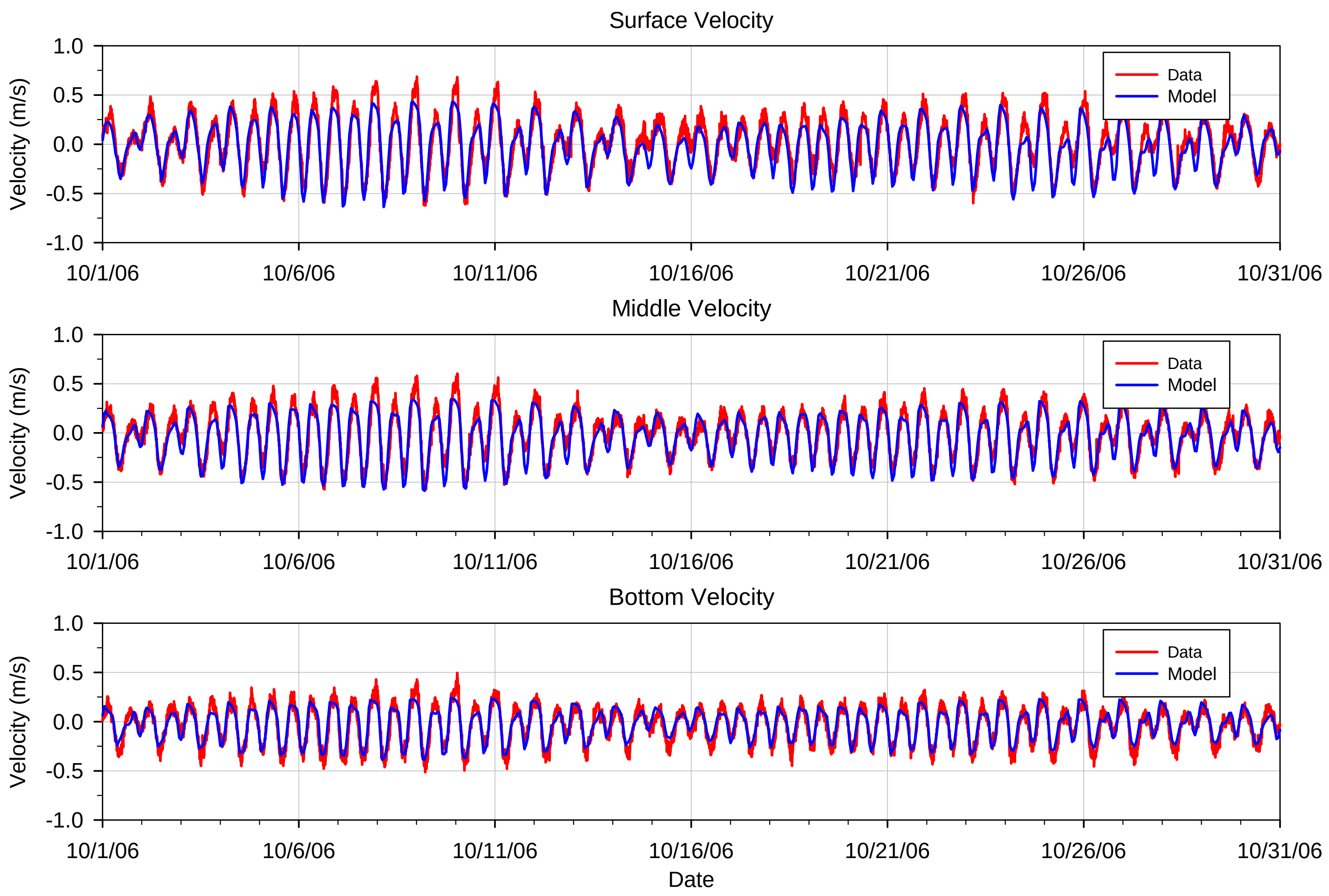


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Figure 3-7

Velocity Comparison at Pickering Passage, South Puget Sound

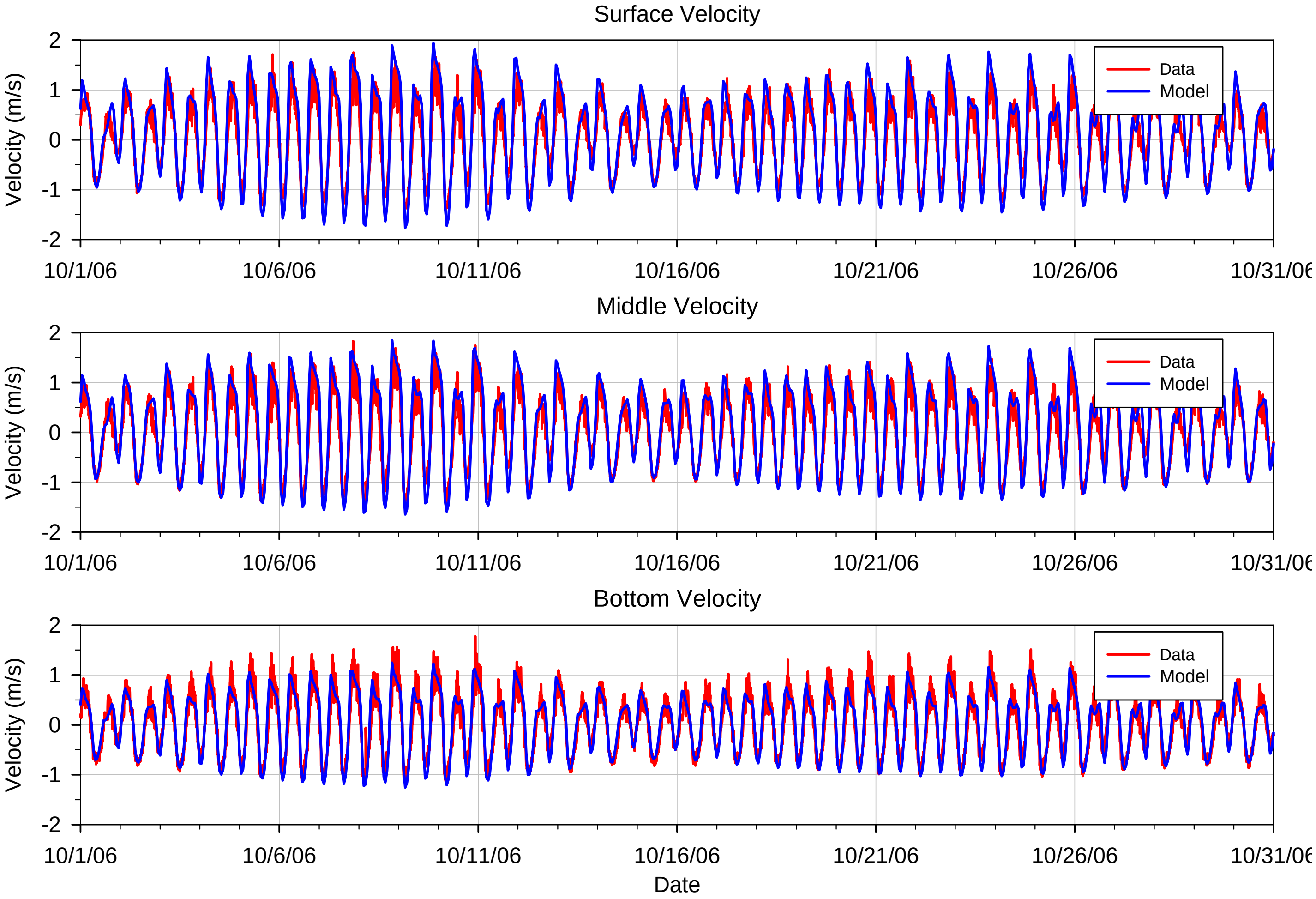

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FIGURE 3-8

Velocity Comparison at Dana Passage, South Puget Sound

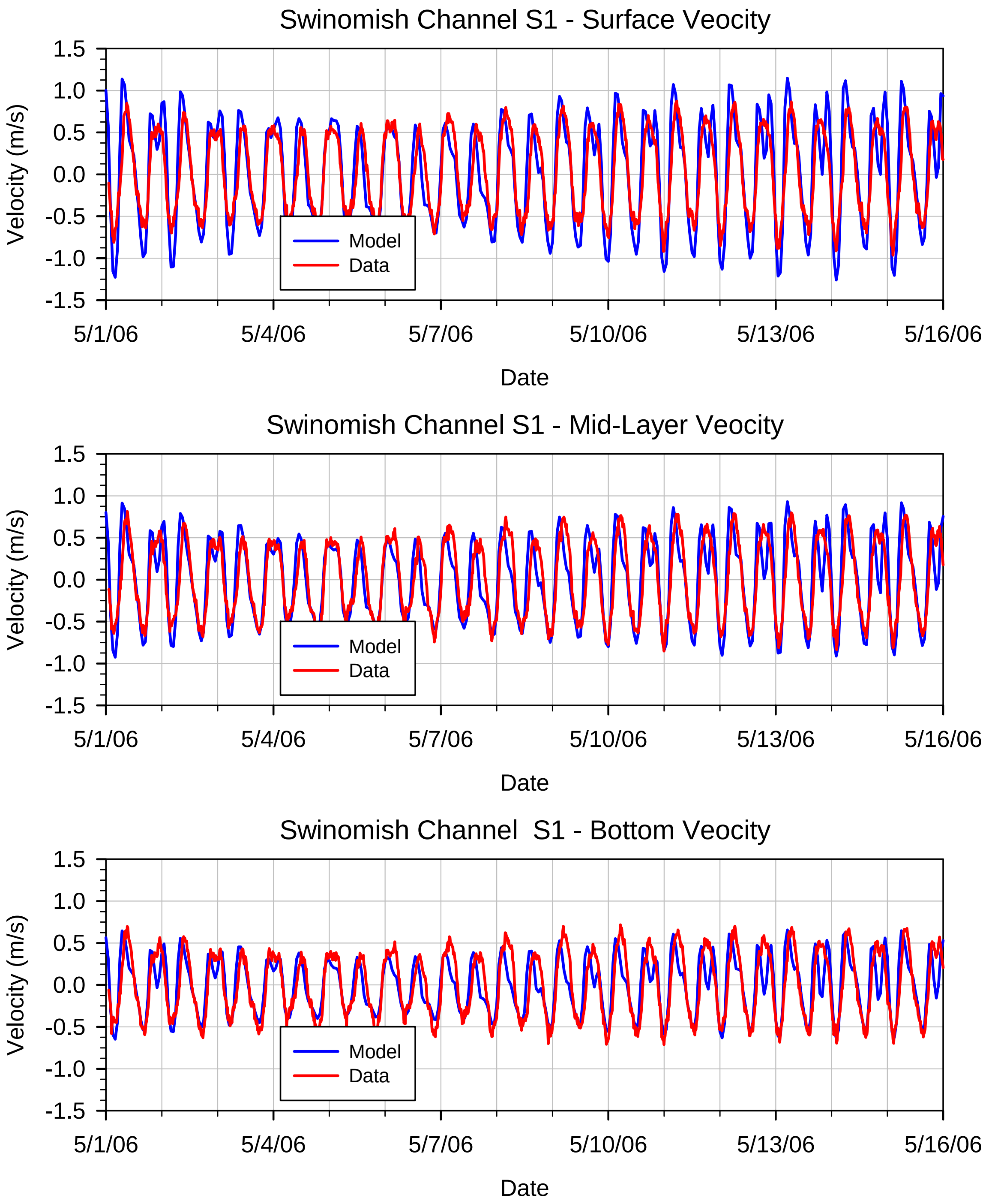
The Swinomish Channel station is located at the Padilla Bay entrance of the Channel. It is the smallest of the three connections between Puget Sound and the Strait of Juan de Fuca (the other two connections are Deception Pass and Admiralty Inlet). Tidal elevations and currents in Swinomish Channel are strongly affected by tides propagating from the Strait of Juan de Fuca (through Padilla Bay) and from Puget Sound (through Skagit Bay). A comparison of predicted and observed velocities in Swinomish Channel Station from May 1 to May 16, 2006 is shown in Figure 3-9. Figure 3-9 shows that the model results are in good agreement with the data. In particular, predicted phases of tidal currents matched the data very well, which indicated that the model predicted the tidal waves in the Northwest Straits and Puget Sound well.

A comparison of predicted and observed velocities at Skagit Bay station is shown in Figure 3-10. Although the accuracy of model predictions at the Skagit Bay station is not as high as at other stations, especially during ebb tides, the model prediction reproduced the general shape and pattern of the velocity time series. The main reason that predicted velocities in Skagit Bay is not as good as at other locations is that the bathymetry in the model was simplified in the nearshore region, and the effect of tide flats was not considered in the model.

The error statistics between predicted and observed velocities at all stations are shown in Table 3-3. Model predictions show the largest errors in the surface layer and smallest errors in the bottom layer. The overall mean MAE and RMSE for all four stations are 0.19 m/s and 0.24 m/s, respectively.

To provide a more thorough evaluation of the model, predicted velocities in other basins of Puget Sound including the Main Basin, Admiralty Inlet, Whidbey Basin, and Hood Canal should be compared to the observed data. While some velocity data are available in other subbasins of Puget Sound, they do not fall in the 2006 model calibration period selected for this study.

To visualize the tidal current distributions in Puget Sound and the Straits, predicted surface and bottom velocities were generated at flood and ebb tides. Figures 3-11 and 3-12 show the velocity distributions in Puget Sound during large flood and ebb tides on May 15, 2006. High velocities are observed in Admiralty Inlet and South Puget Sound. Hood Canal has the weakest currents in Puget Sound.


Swinomish Channel S1 - Surface Veocity

Swinomish Channel S1 - Mid-Layer Veocity

Swinomish Channel S1 - Bottom Veocity

FIGURE 3-9

Velocity Comparison at Swinomish Channel – Padilla Bay Entrance, Whidbey Basin

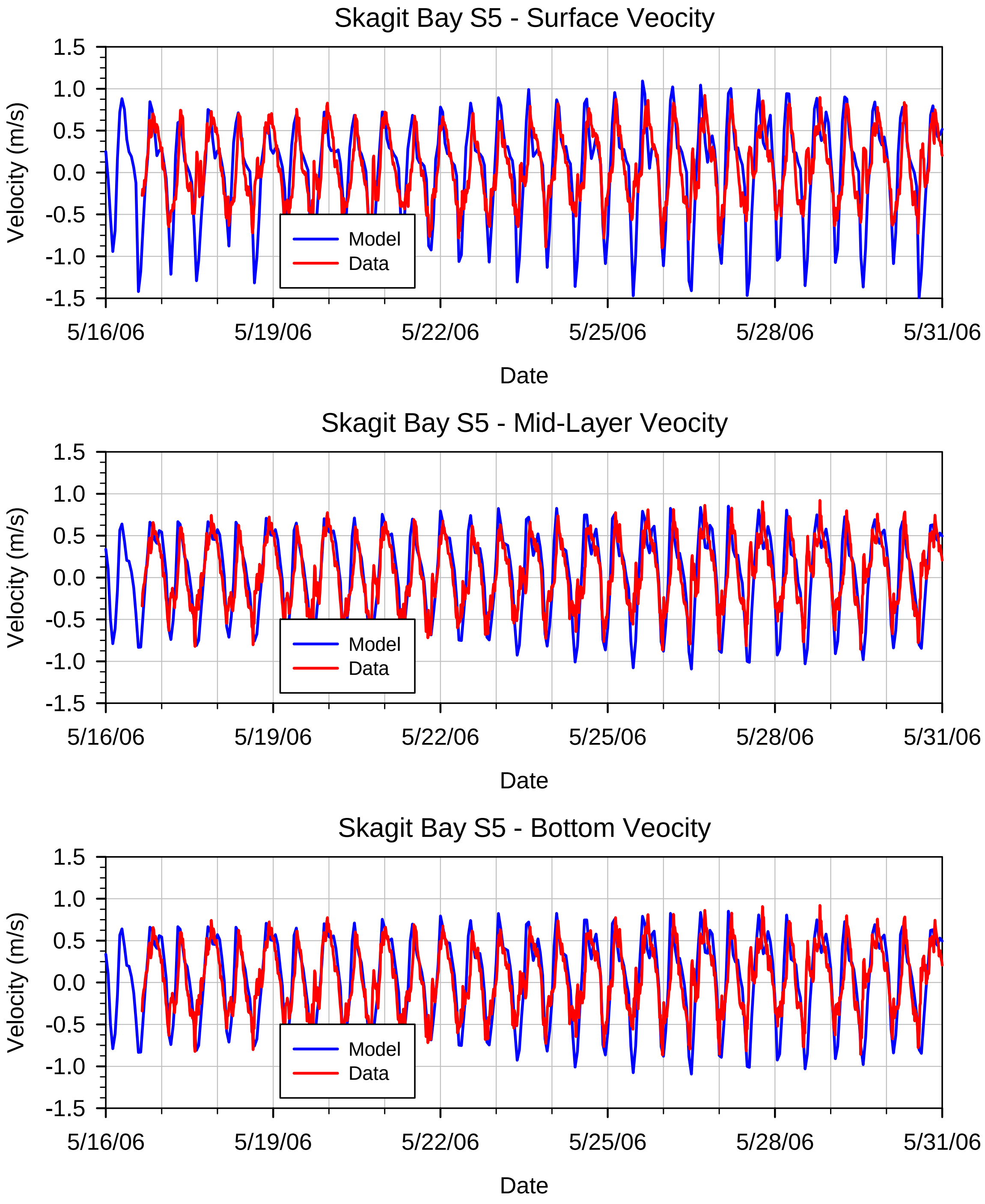


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FIGURE 3-10

Velocity Comparison at Skagit Bay, Whidbey Basin

Table 3-3. Model Calibration Error Statistics for Velocity

Station	MAE (m/s)			RMSE (m/s)		
	Surface	Middle	Bottom	Surface	Middle	Bottom
Pickering Passage	0.10	0.07	0.06	0.12	0.09	0.08
Dana Passage	0.27	0.26	0.20	0.34	0.34	0.25
Swinomish Channel	0.24	0.20	0.17	0.30	0.26	0.22
Skagit Bay	0.29	0.23	0.17	0.39	0.30	0.22
Mean		**0.19**			**0.24**	

3.4 Model Calibration – Temperature and Salinity

Simulating temperature and salinity distributions in Puget Sound is a greater challenge compared to simulating tidal elevation and currents because of the uncertainty associated with meteorological forcing and open boundary conditions and the complexity of density-induced baroclinic motion. Initial model calibration indicated that salinity (and temperature) open boundary conditions had a strong effect on the salinity distribution in Puget Sound. Using the available monthly salinity profiles (Figures 2-8 and 2-9) as open boundary conditions tended to produce low salinity values in Puget Sound. The surface water with warmer temperature and lower salinity near the open boundaries (Figures 2-8 and 2-9) generally reflects the influence of freshwater discharged from Puget Sound and the Fraser River, particularly if the profiles were recorded during tides propagating out of the model domain. The open boundary conditions should be free of these effects to avoid double counting. Furthermore, the instantaneous temperature and salinity profiles in the Strait of Juan de Fuca (Figure 2-8) and Georgia Strait (Figure 2-9) were not taken at the same time and day for each month. To reduce the variabilities and uncertainties of the open boundary condition, constant temperature and salinity values were used to specify the open boundary temperature and salinity conditions. The constant values were estimated based on mean values of the profile distribution below 50 m water depth. The estimated open boundary temperature and salinity values are 7.4 °C and 33.5 in the Strait of Juan de Fuca and 9.3 °C and 30.6 ppt in Georgia Strait. This assumption avoids double-counting the freshwater sources to the model domain, since the freshwater influence reflected in the surface profiles likely originated within the model domain.

In this study, no time series data for temperature and salinity were available for model calibration for the 2006 time period. However, there are a total of 25 monitoring stations within Puget Sound where temperature, salinity, and water quality data are collected monthly by Ecology . In this study, we selected 11 stations representing the subbasins in Puget Sound for temperature and salinity profiles comparisons (Figure 3-1).

Comparisons of predicted and observed temperature and salinity profiles at Station ADM2 in the Strait Juan de Fuca Strait near the entrance of Admiralty Inlet are presented in Figure 3-13. Model results were in good agreement with observed data most of the time. No significant variations over time and through the water column were observed in both modeled and observed temperature and salinity distributions. The largest difference in salinity comparison occurred in January, which was mainly caused by the initial conditions.

Comparisons of predicted and observed temperature and salinity profiles at Station ADM1 in Admiralty Inlet are presented in Figure 3-14. Similar to Station ADM2, predicted temperature and salinity profiles followed the general trend of observed profiles. Strong stratifications and temporal variations were not observed in salinity and temperature distributions.

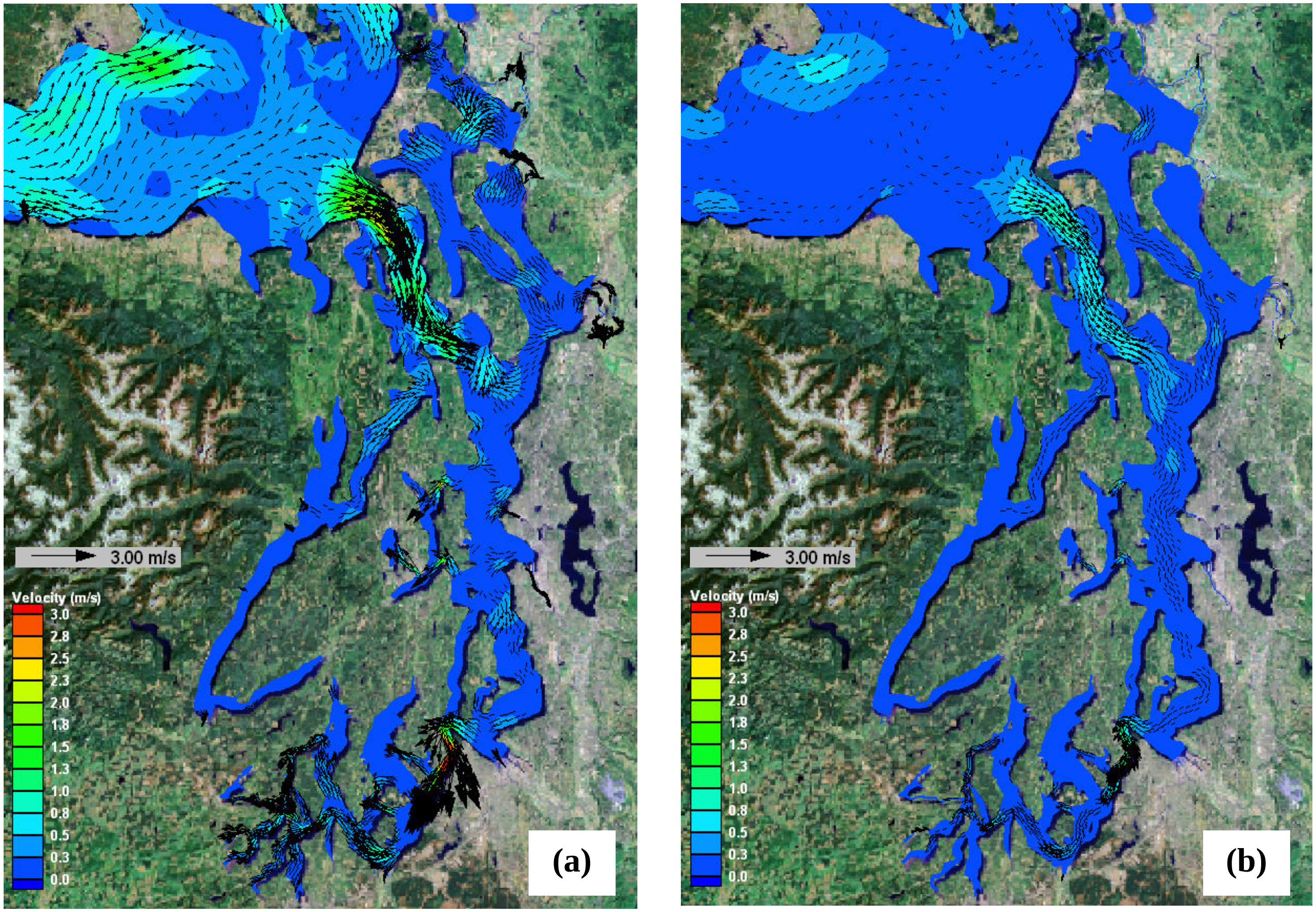

FIGURE 3-11

Surface (a) and Bottom (b) Velocity at Flood Tide in Puget Sound (5/15/2006, 5:00 PM)

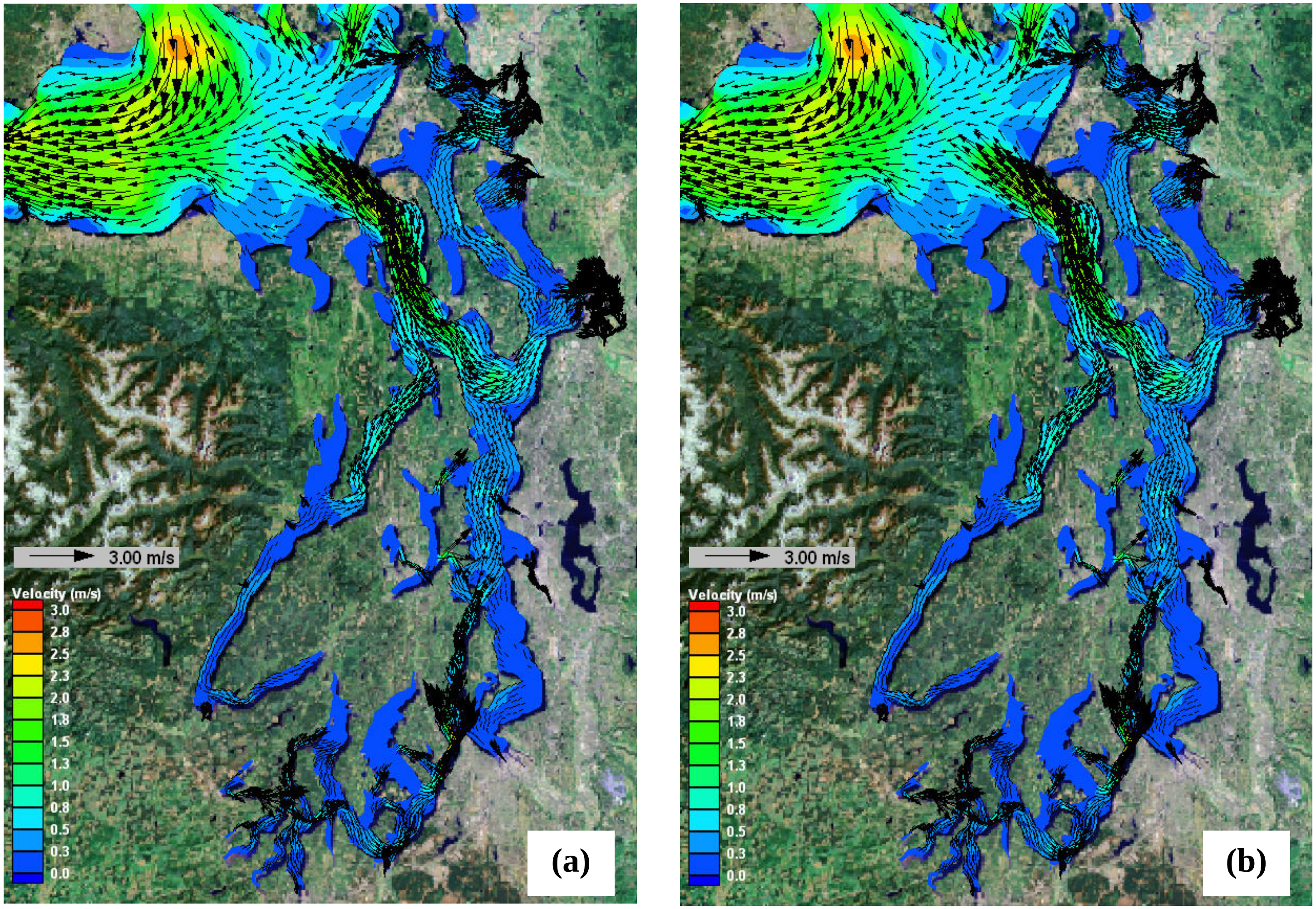

FIGURE 3-12

Surface (a) and Bottom (b) Velocity at Ebb Tide in Puget Sound (5/15/2006, 11:00 PM)

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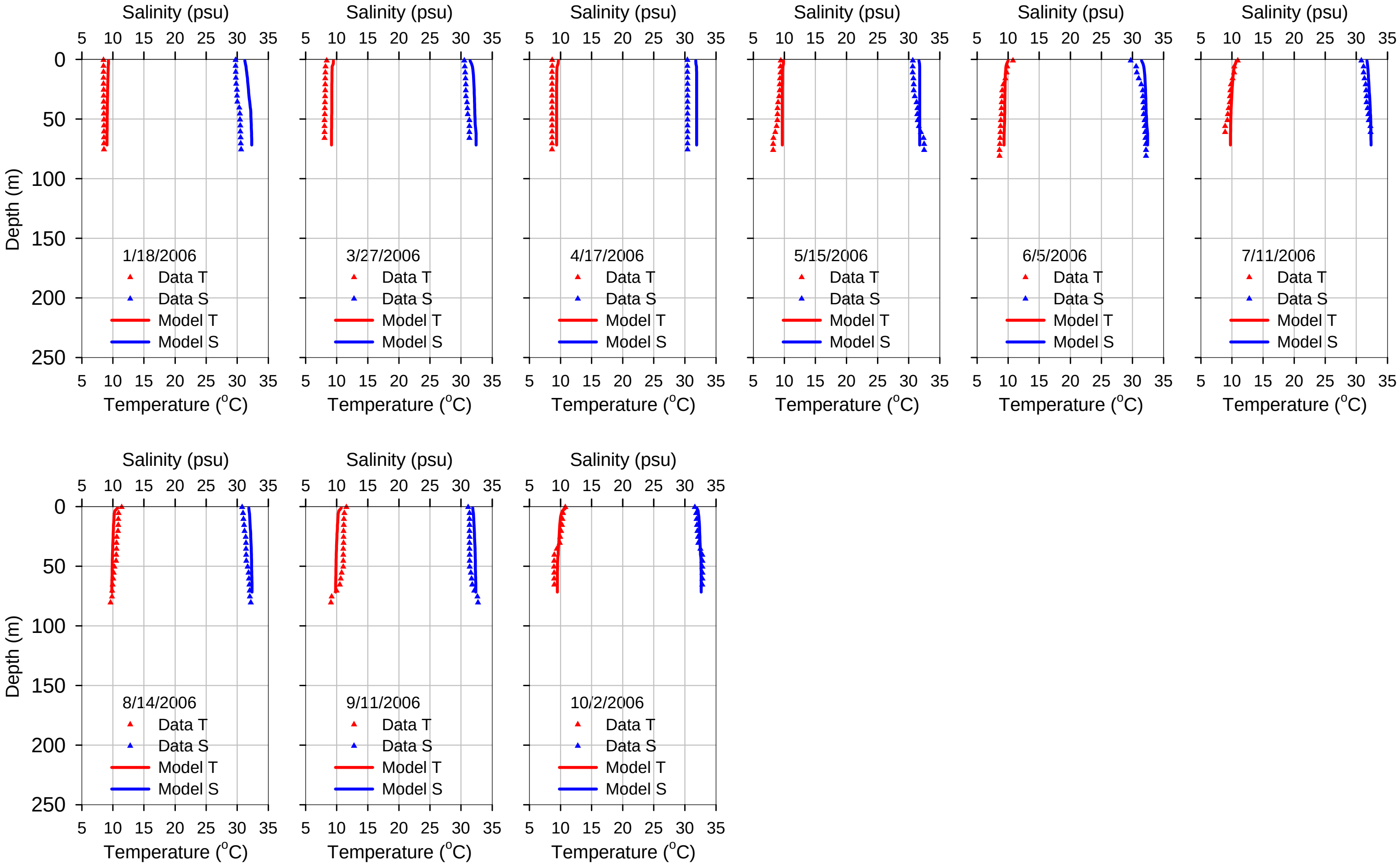

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FIGURE 3-13

Comparisons of Temperature and Salinity Profiles at ADM2 (Admiralty Inlet Entrance)

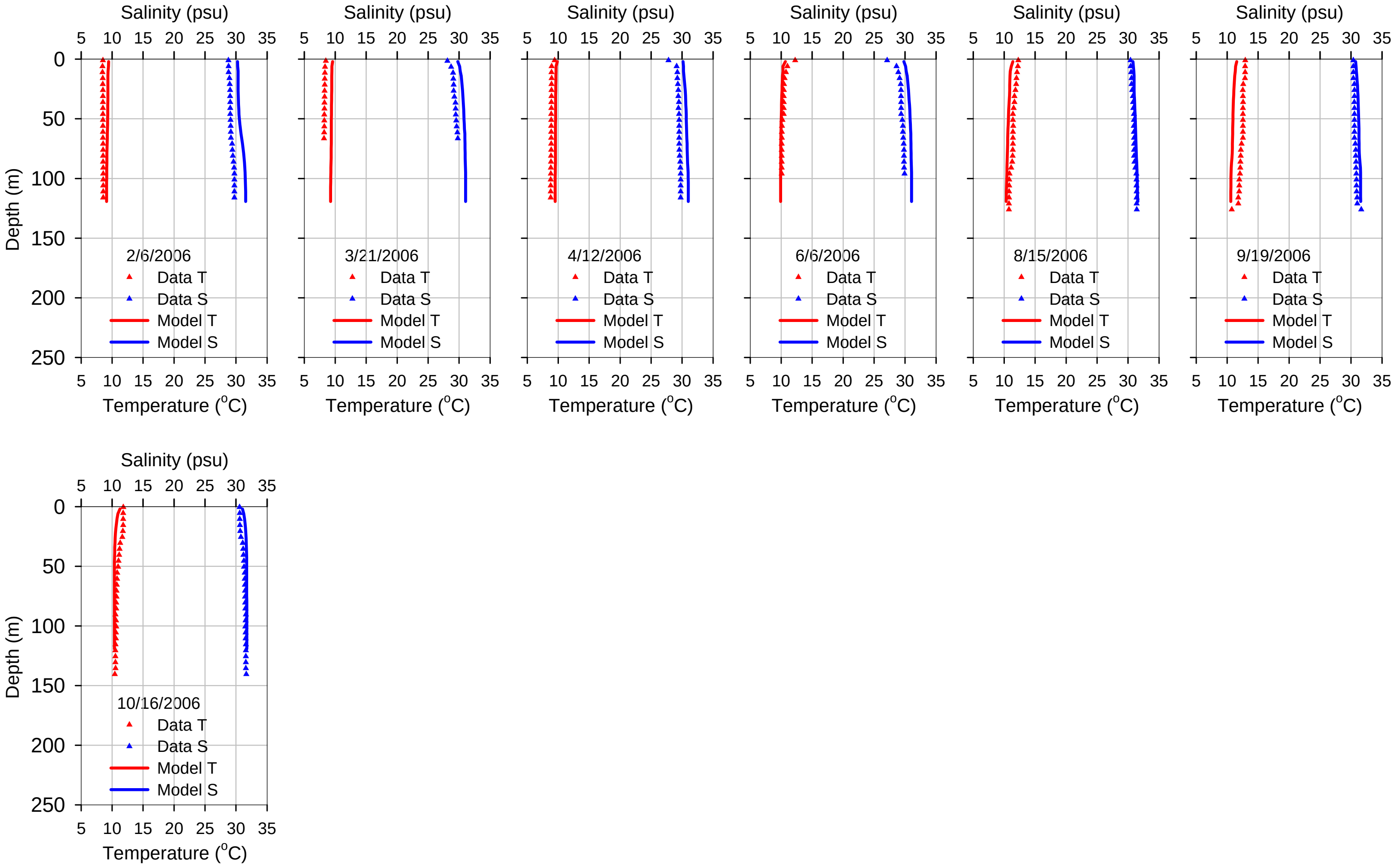

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FIGURE 3-14

Comparisons of Temperature and Salinity Profiles at ADM1 (Admiralty Inlet North)

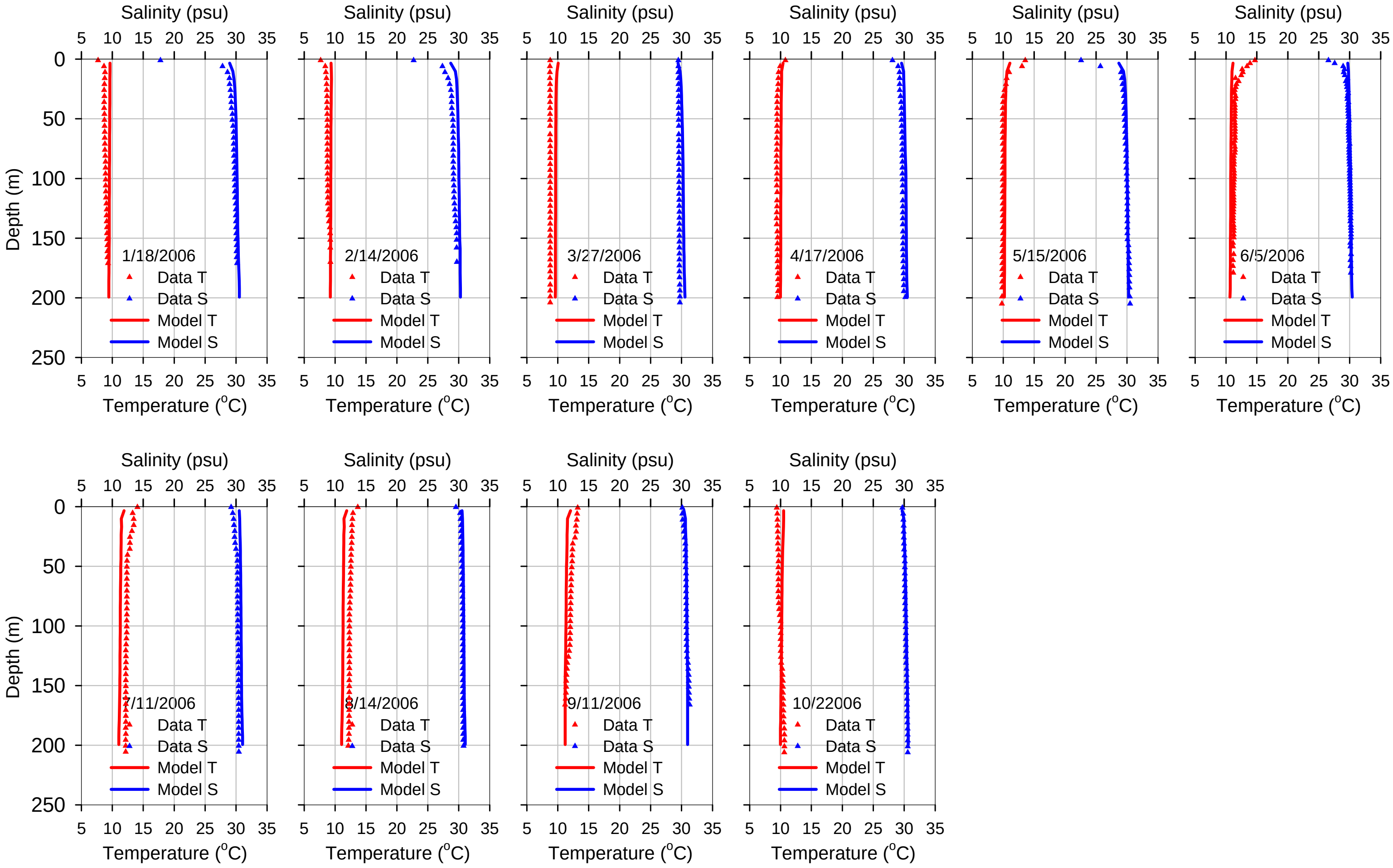

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FIGURE 3-15

Comparisons of Temperature and Salinity Profiles at ADM3 (Admiralty Inlet South)

Figure 3-15 shows the comparisons of predicted and observed temperature and salinity profiles at Station ADM3 in the south part of Admiralty Inlet. Predicted temperature and salinity matched the data reasonably well. However, the model under-predicted the temperature salinity stratifications in the surface layer (<20 m) observed in January, February, May, and June. While there are a number of factors that may cause such under-prediction (see Section 4), all model profiles were consistently extracted at noon each day; however, data were collected at different times of the day that were not reported.

Figure 3-16 shows the comparisons of predicted and observed temperature and salinity profiles at Station PSB in the main basin of Puget Sound. The water depth at this location seems to be much shallower than that in the model. It is likely that the sample location was much closer to the shore. Predicted temperature and salinity below the surface stratification layer matched the data well.

Comparisons of predicted and observed temperature and salinity profiles at Station EAP in East Passage (Figure 3-17) are very similar to that at Station ADM3 (Figure 3-15). Predicted temperature and salinity generally matched the data well. Temperature and salinity distributions below the surface layer closely followed the data profiles over the entire year.

Comparisons of predicted and observed temperature and salinity profiles at Station GOR1 near Tacoma Narrows of South Puget Sound are presented in Figure 3-18**.** In contrast with other stations in the main basin, temperature and salinity in the water column at Station GOR1 was quite well mixed for throughout the year. Model results showed good agreement with the data at this station as well.

Figure 3-19 shows the comparisons of predicted and observed temperature and salinity profiles at Station HCB003 in Hood Canal. The data show strong temperature and salinity stratifications in the upper 50 m of the water column most of the year. This is because Hood Canal is a low-tidal energy water body in Puget Sound, and vertical mixing is very weak such that stratification develops and persists throughout the year. The predicted temperature and salinity distributions and stratification levels in the water column were lower than observed data. It is noted that predicted salinity seemed to be strongly affected by the initial condition. As shown in Figure 3-19, predicted salinity profiles slowly moved towards the data differences between predicted and observed profiles, which were reduced by the end of the year.

Figure 3-20 shows the comparisons of predicted and observed temperature and salinity profiles at Station SAR003 in the Saratoga Passage of Whidbey Basin. Whidbey Basin provides nearly 70% of freshwater input into Puget Sound (Table 2-1). Therefore, temperature and salinity in the water column were highly stratified, as shown in the data. While the model-predicted temperature and salinity distributions compared well to data below the surface layer, the level of stratification in the surface layer was not as strong as observed in the data. One of the possibilities for this is that bathymetric detail associated with tidal channels during low tides and the wetting and drying process in the tide flats is not included in this effort. Although simulated stratification is not as high as observed in the data, especially near the river mouths and tide flats, the match to observed currents and tides indicates that error associated with overall flushing and transport of water on a Puget Sound-wide scale is likely small and will not affect the ability to provide reasonable hydrodynamics for conducting water quality modeling.

Figures 3-21 and 3-22 show comparisons of predicted and observed temperature and salinity profiles at Stations NSQ and DNA in South Puget Sound. Both stations show a partially to well-mixed water column except during January and February. Predicted temperature and salinity matched the data reasonably well in terms of vertical means and variations of the profiles, and the bias (≈ 2˚C at the most) during the winter is likely due to the use of NARR data from Seattle area and is not considered critical.

To evaluate the overall performance of the model for temperature and salinity predictions, average absolute errors of predicted mean values of temperature and salinity profiles were calculated. The average absolute error of a temperature/salinity profile is defined as the absolute difference between the mean values of model results and observed data averaged over the water column. Table 3-4 shows that average absolute errors for temperature and salinity profiles in all stations were below 1.0 °C and 1.0 ppt respectively, except at Station HCB003 in Hood Canal.

Table 3-4. Model Calibration Error Statistics for Temperature and Salinity

Station	Temperature Absolute Error (°C)	Salinity Absolute Error (ppt)
Admiralty Inlet Entrance (ADM2)	0.57	0.78
Admiralty Inlet North (ADM1)	0.77	0.94
Admiralty Inlet South (ADM3)	0.76	0.51
Puget Sound Main Basin (PSB)	0.98	0.71
East Passage (EAP)	0.67	0.33
Gordon Point/Tacoma Narrows (GOR1)	0.87	0.24
Hood Canal (HCB003)	1.05	1.36
Saratoga Passage (SAR003)	0.67	0.27
Nisqually Reach (NSQ)	0.87	0.24
Dana Passage (DNA)	0.88	0.25
Mean	**0.81**	**0.56**

In summary, the model reproduced the seasonal distributions of temperature and salinity well although at some stations (such as HCB003 in Hood Canal and SAR003 in Saratoga Passage) the model under-predicted the level of stratifications in the surface layer of the water column. Horizontal 2-D distributions of surface and bottom temperatures and salinities at high tide and low tide are shown in Figures 3-23 to 3-26. Freshwater plumes and stratifications near the regions of estuarine mouths were clearly seen in the model predictions with comparisons of surface and bottom temperature and salinity distributions.

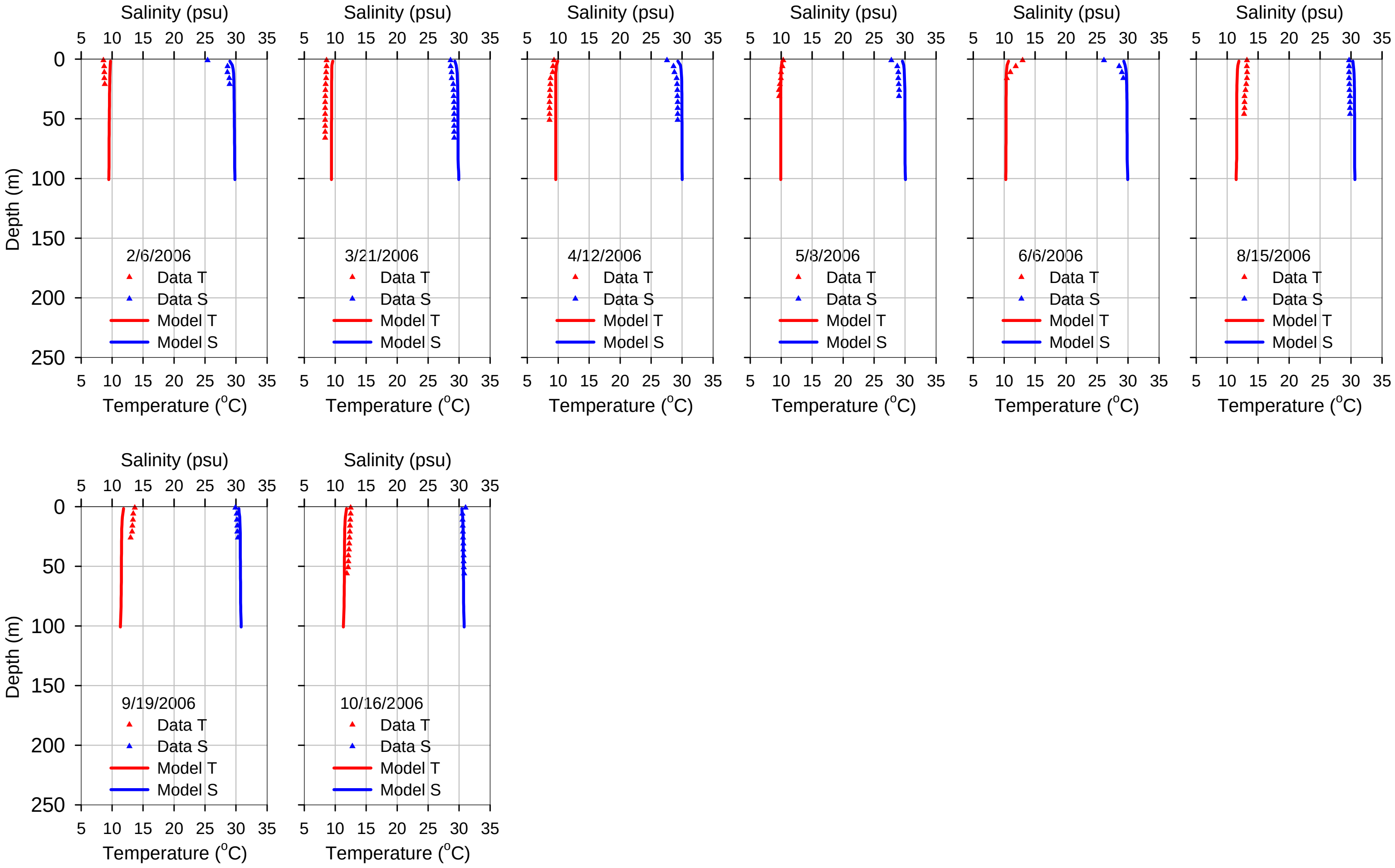

FIGURE 3-16

Comparisons of Temperature and Salinity Profiles at PSB (Main Basin)

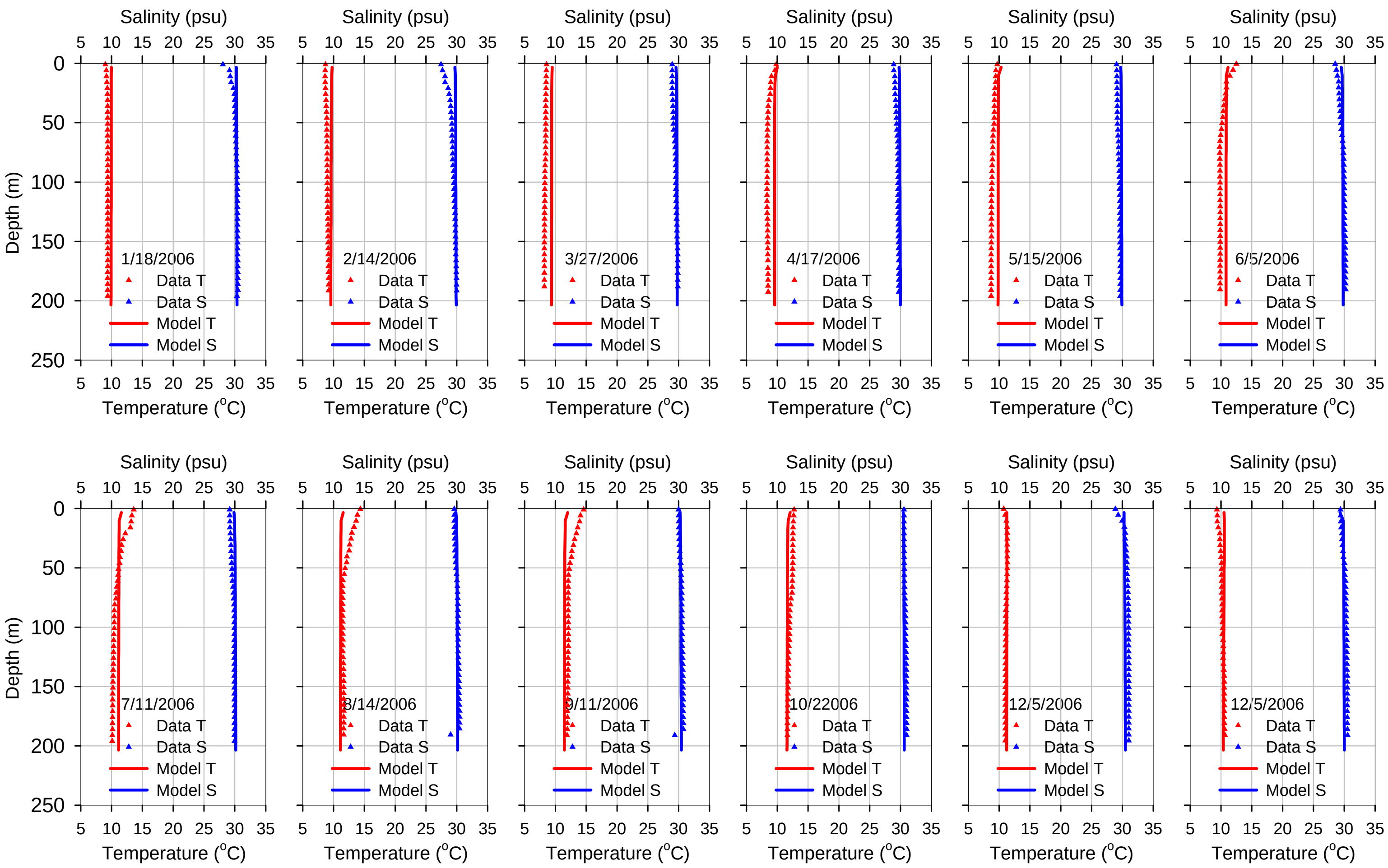

FIGURE 3-17

Comparisons of Temperature and Salinity Profiles at EAP (East Passage)

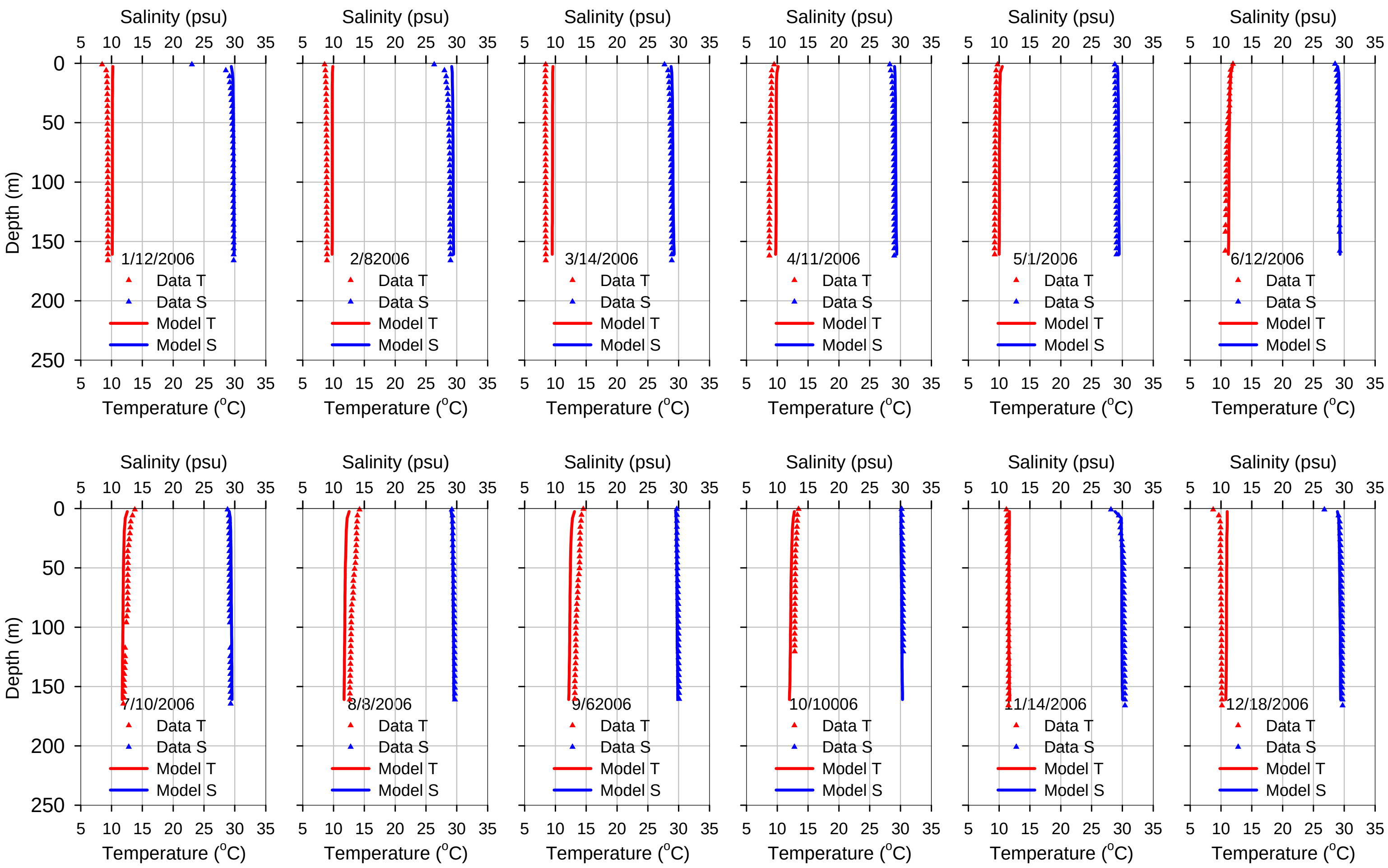

FIGURE 3-18

Comparisons of Temperature and Salinity Profiles at GOR1 (Gordon Point)

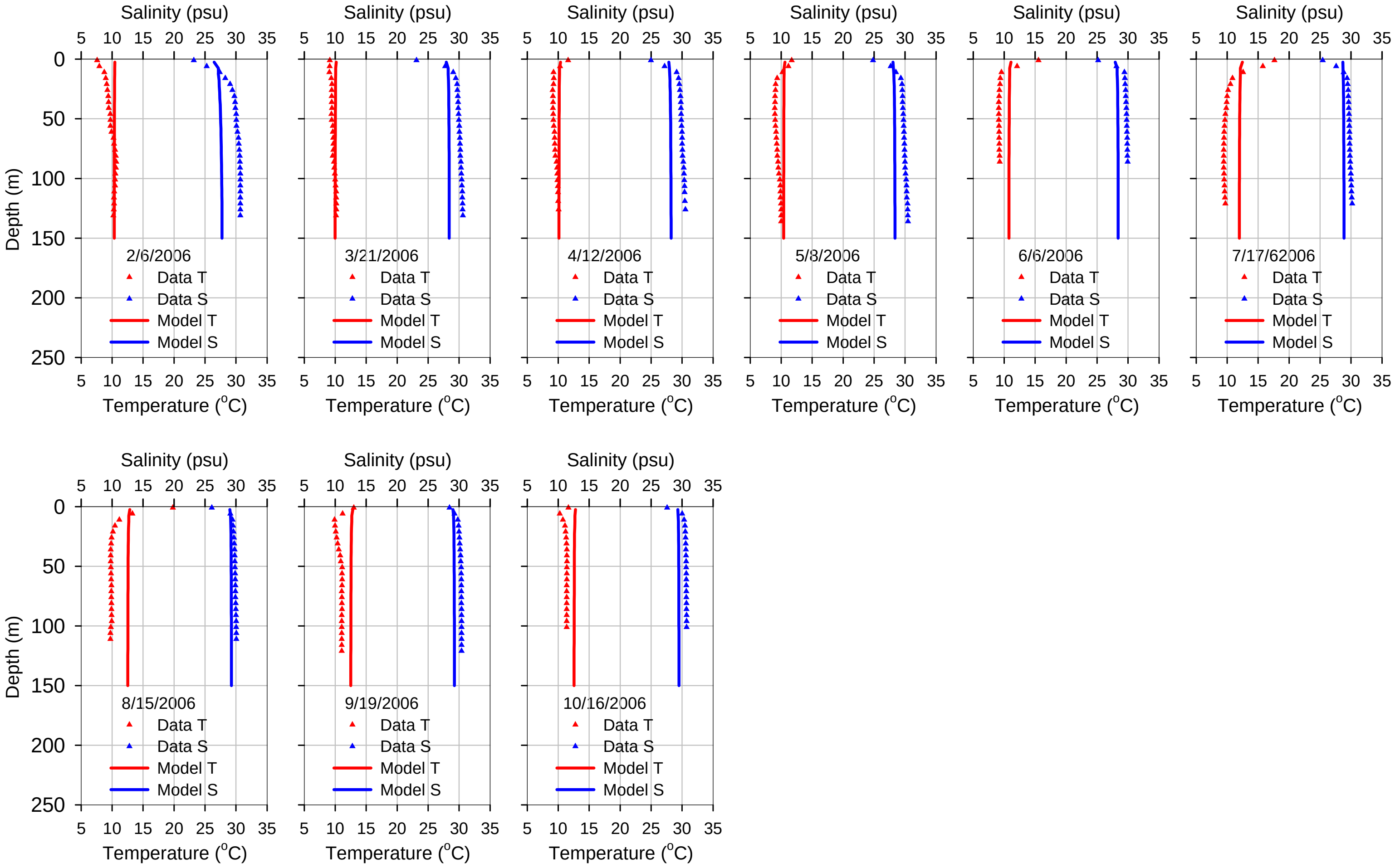

FIGURE 3-19

Comparisons of Temperature and Salinity Profiles at HCB003 (Hood Canal)

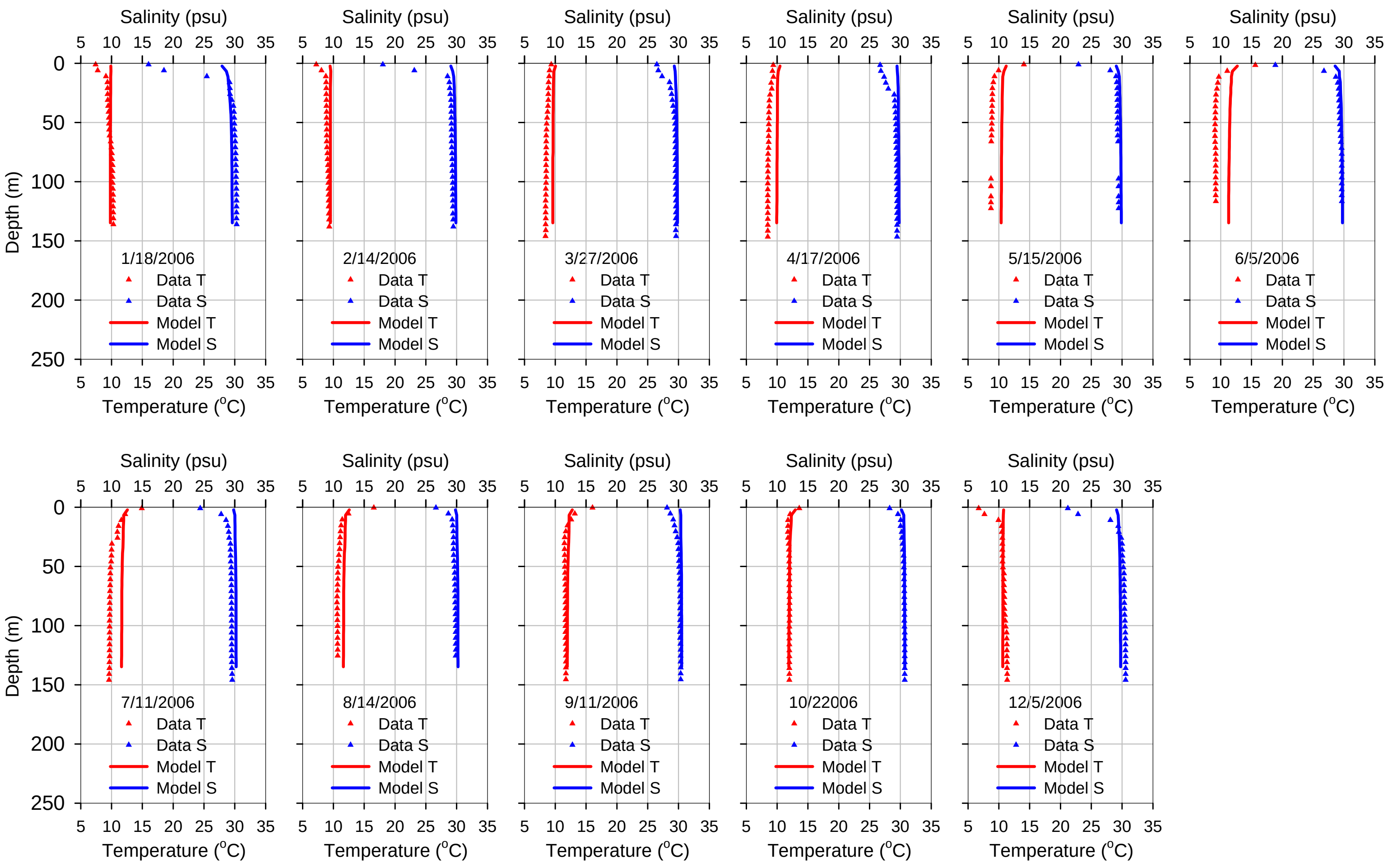

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FIGURE 3-20

Comparisons of Temperature and Salinity Profiles at SAR003 (Saratoga Passage)

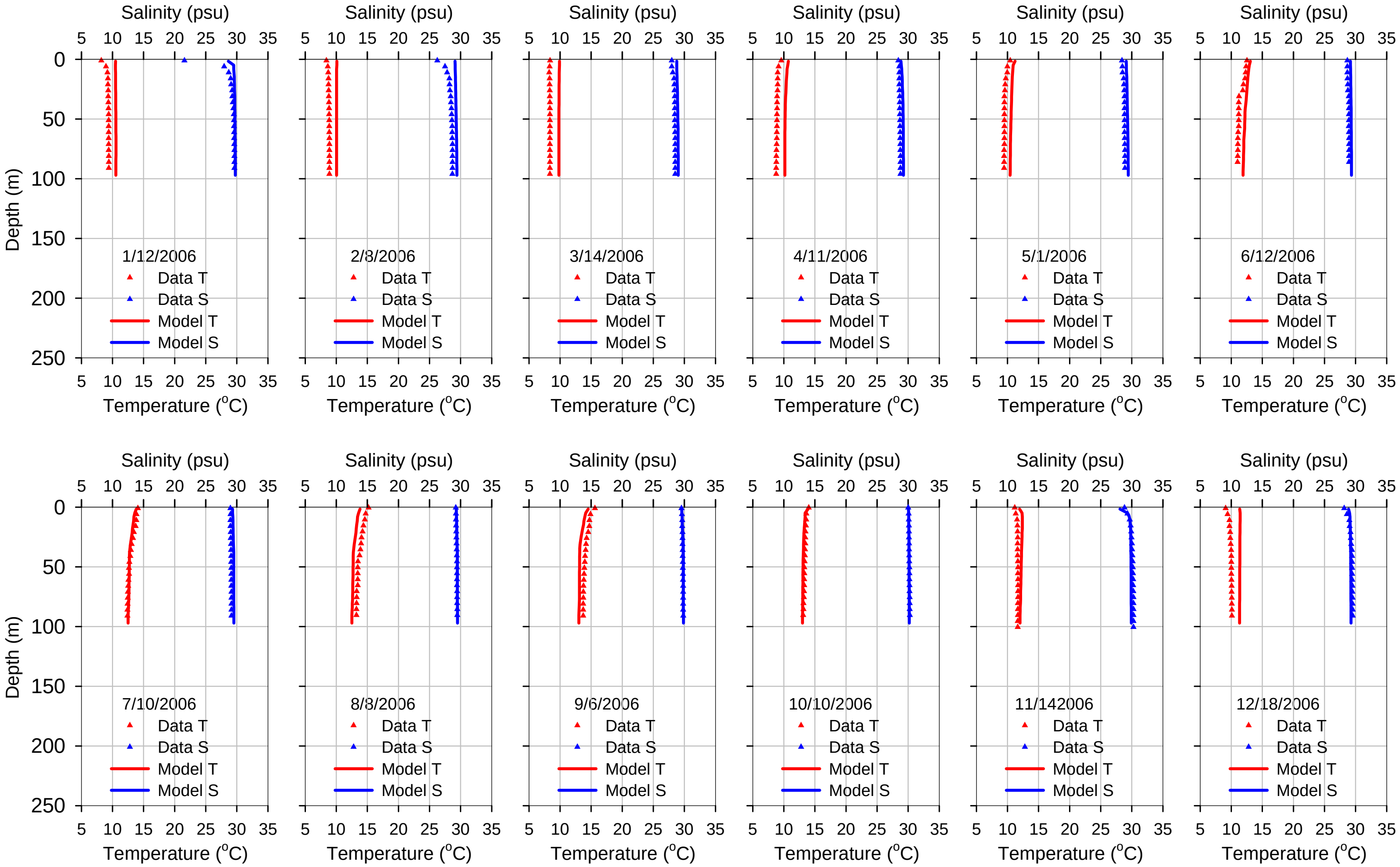

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FIGURE 3-21

Comparisons of Temperature and Salinity Profiles at NSQ (Nisqually Reach)

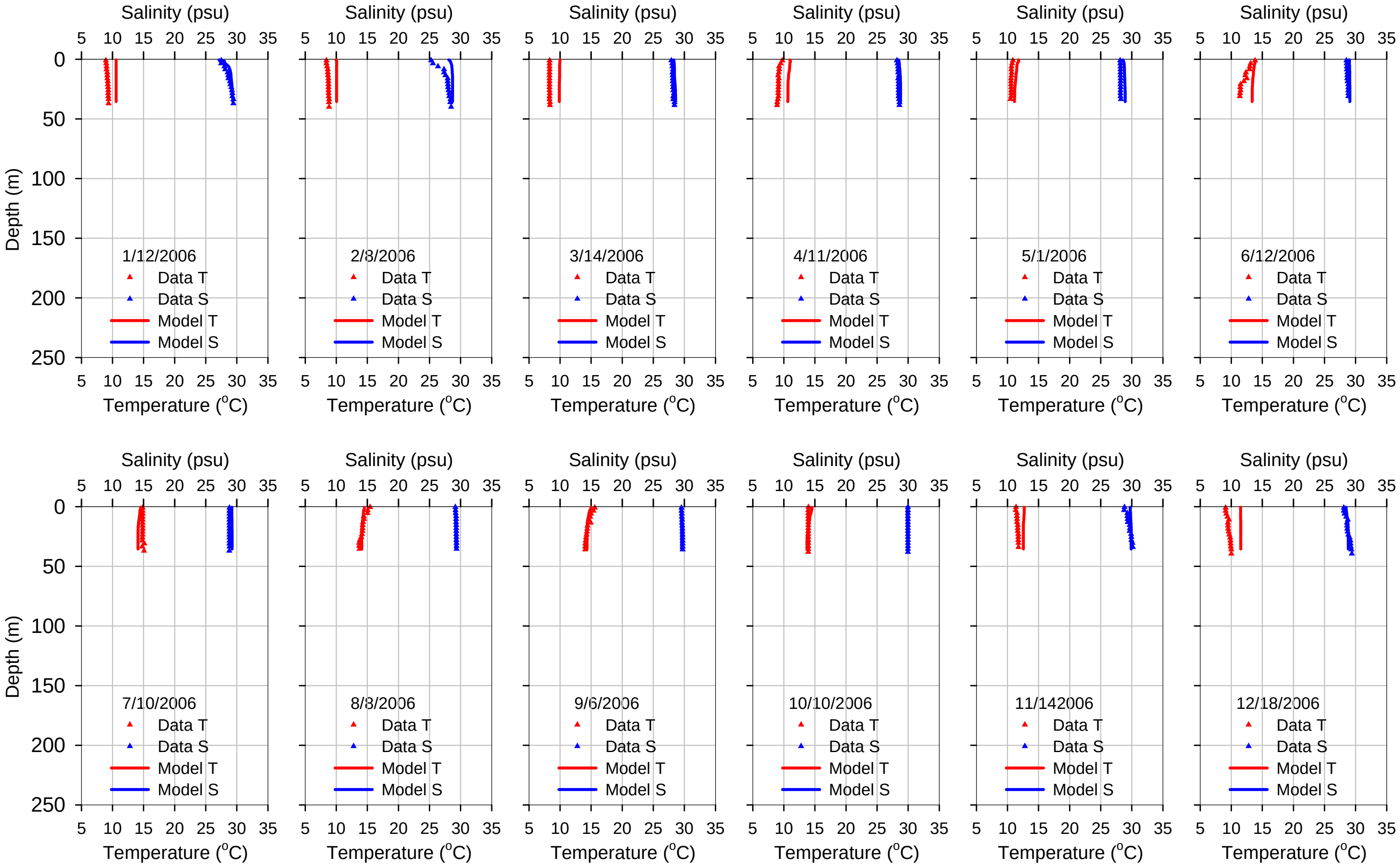

FIGURE 3-22

Comparisons of Temperature and Salinity Profiles at DNA (Dana Passage)

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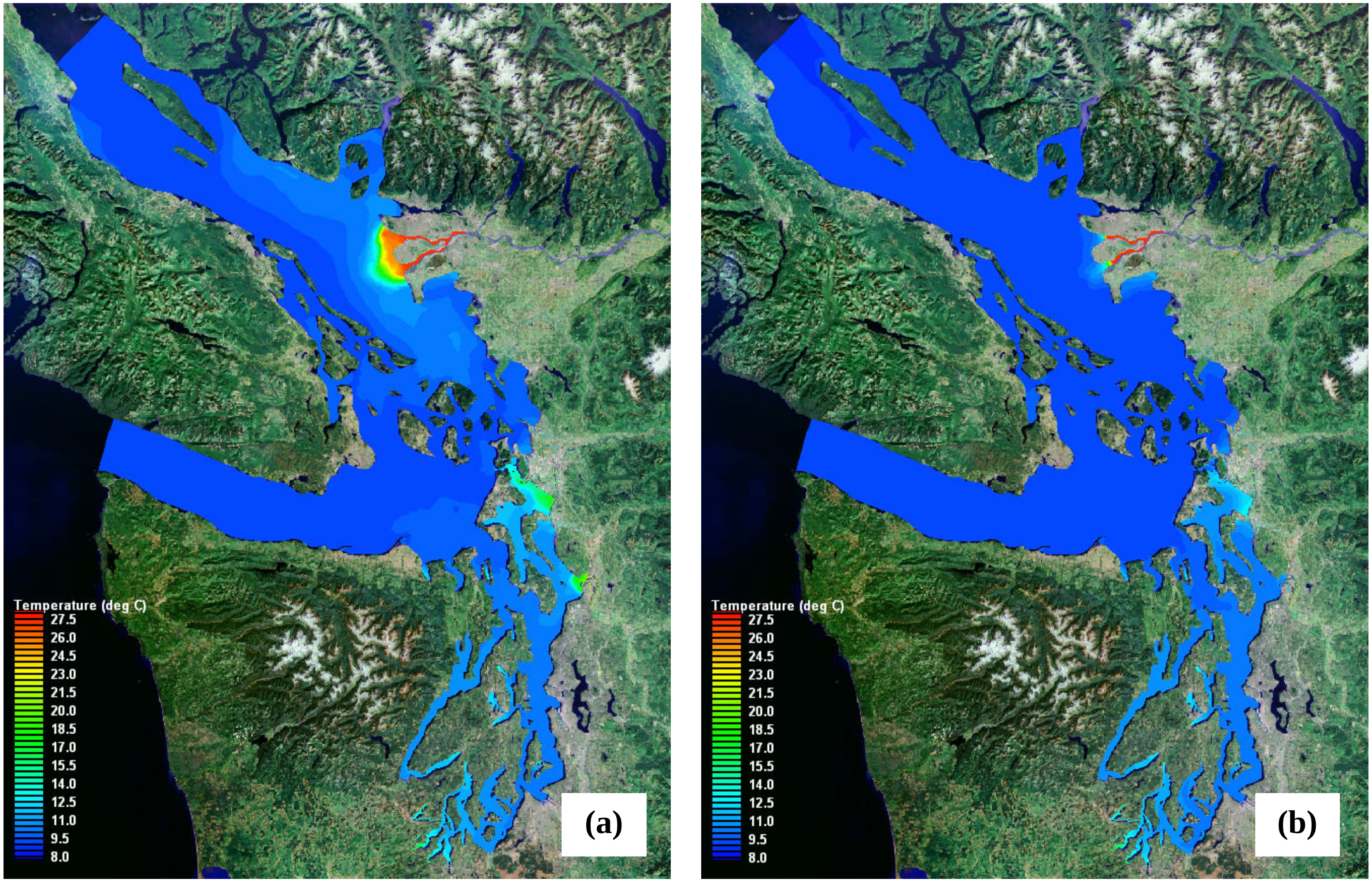

FIGURE 3-23

Surface (a) and Bottom (b) Temperature at High Tide in Puget Sound (5/15/2006, 1:00 PM)

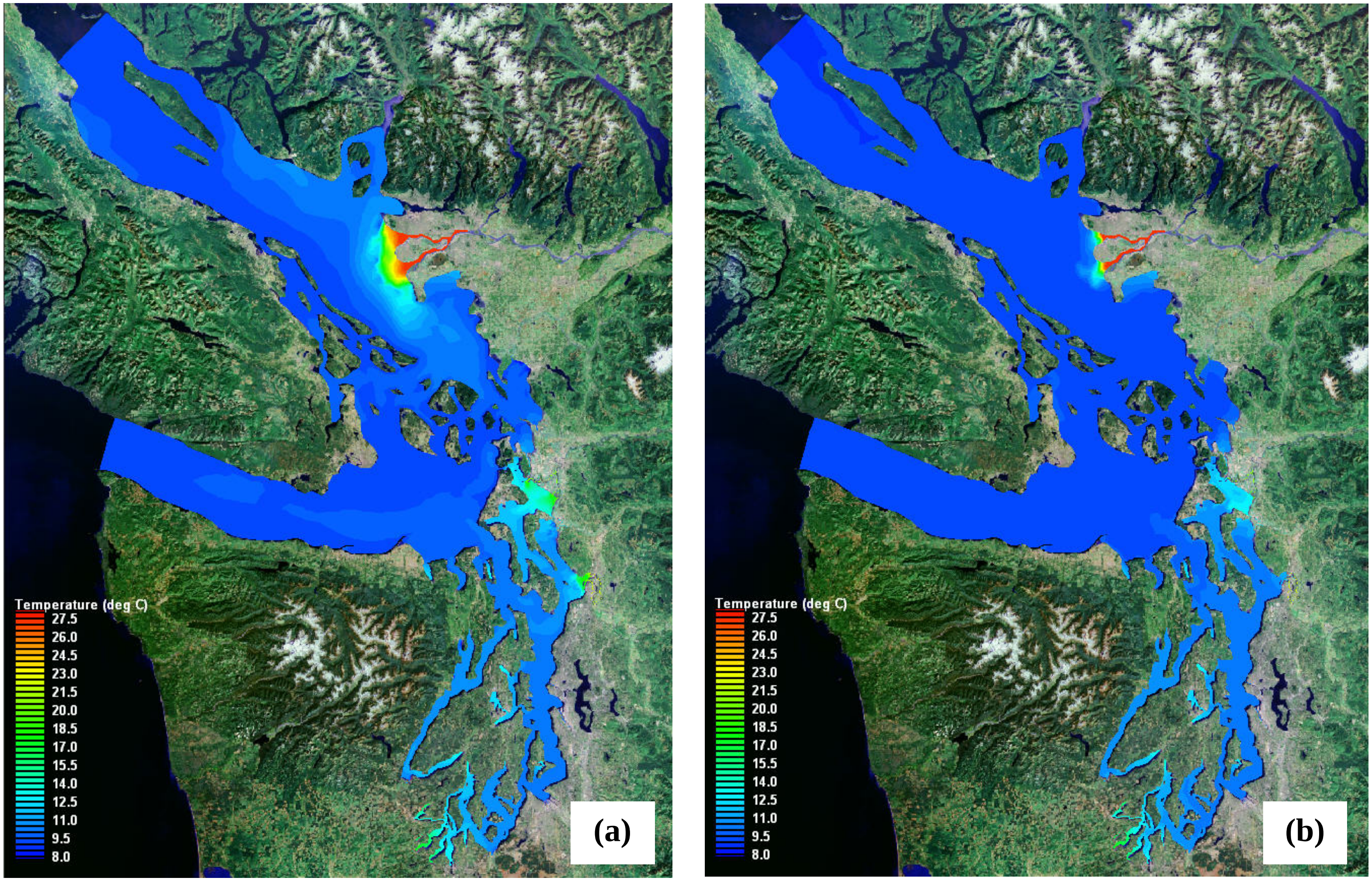

FIGURE 3-24

Surface (a) and Bottom (b) Temperature at Low Tide in Puget Sound (5/15/2006, 8:00 PM)

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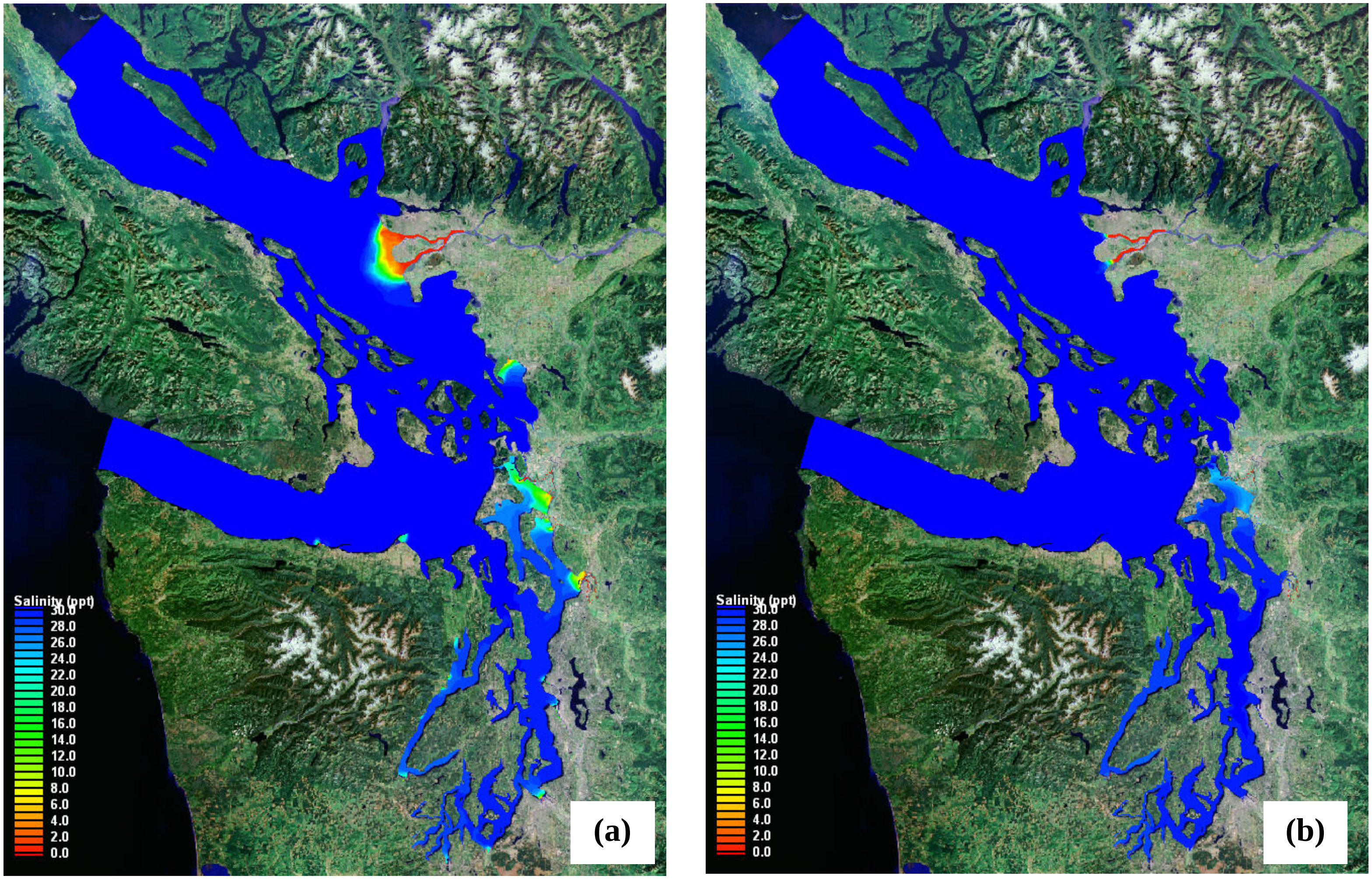

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FIGURE 3-25

Surface (a) and Bottom (b) Salinity at High Tide in Puget Sound (5/15/2006, 1:00 PM)

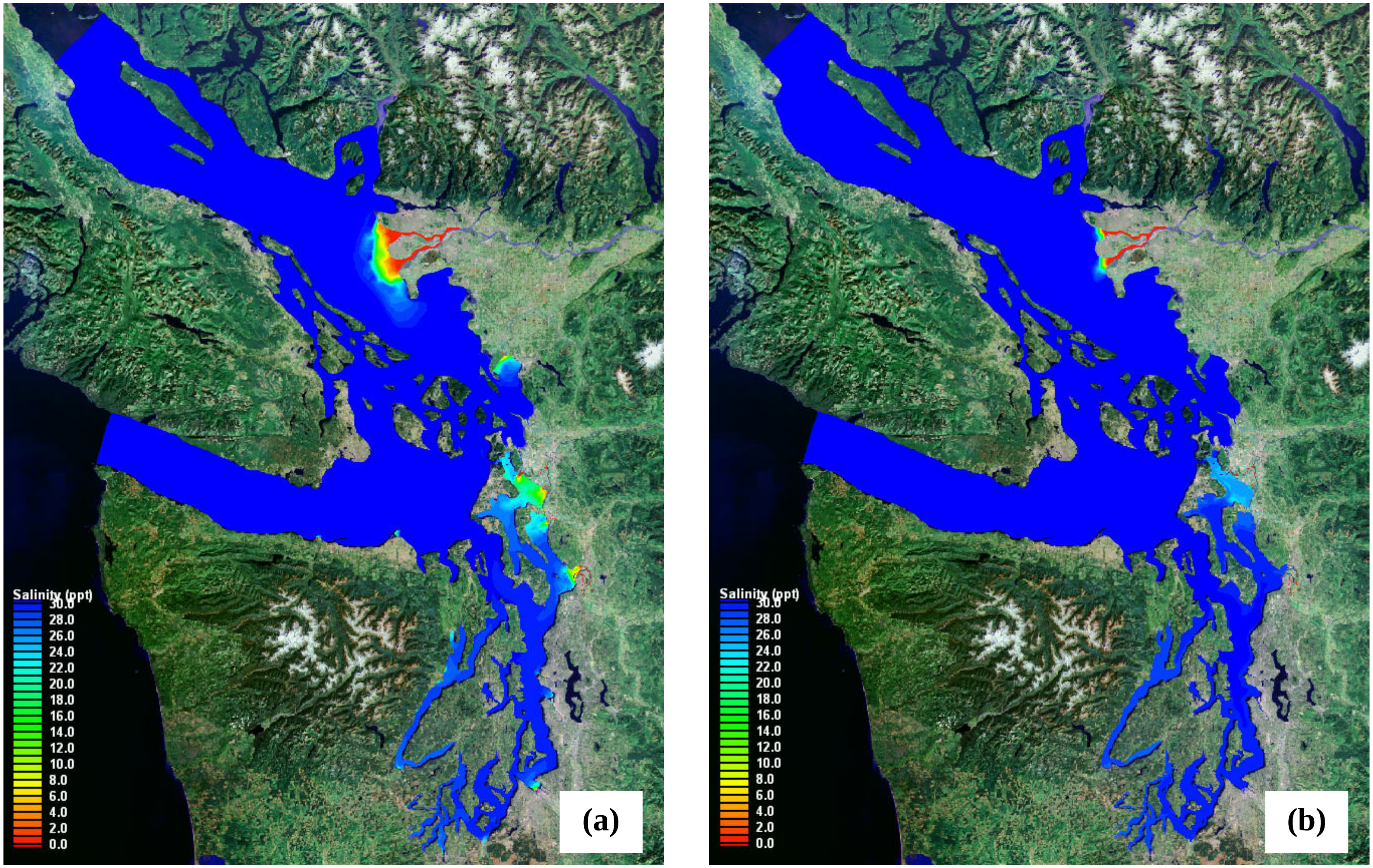

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FIGURE 3-26

Surface (a) and Bottom (b) Salinity at Low Tide in Puget Sound (5/15/2006, 8:00 PM)

4.0 Summary and Next Steps

4.1 Summary

In this study, an intermediate-scale 3-D hydrodynamic model for Puget Sound and the Northwest Straits was developed using the unstructured grid coastal ocean circulation modeling tool FVCOM. The model simulates tidal circulation, temperature, and salinity distributions in Puget Sound and provides hydrodynamic solutions to drive the off-line water quality model, which is under development as part of the project. The model was calibrated using observed tides, currents, salinity, and temperature data for 2006. Comparisons of model results to observed data demonstrated that the model is able to simulate tidal circulation and the general distribution patterns of salinity and temperature in Puget Sound.

The salient features and characteristics of the Puget Sound hydrodynamic model developed in this study are as follows.

- The model consists of 9,052 grid nodes and 13,976 elements in the horizontal plane and 30 uniform sigma-stretched layers in the vertical direction. The average element size is 1,760 m.
- The model is driven by tides, river inflows, and meteorological forcing (wind and net heat flux).
- The model has two open boundaries: one at the entrance of the Strait of Juan de Fuca and the other at the north end of Georgia Strait.
- Tidal elevations at the open boundaries were specified using XTide prediction. River inflows were obtained from USGS and DFO stream gauge records or estimated using the scaling method based on watershed areas. Meteorological forcing was obtained from NCEP's NARR data sets.
- Constant salinity and temperature open boundary conditions were specified based on salinity, and temperature profiles obtained from the DFO.
- The model was run in parallel mode on a 184-cores cluster computer. A one-year model run with 64 computation cores requires 34 hours in real time.
- Model results can be output in NetCFD format to provide hydrodynamic information and drive the off-line water quality model FVCOM-ICM.

4.2 Model and Data Uncertainty

The intermediate-scale model of Puget Sound simulates the hydrodynamics in Puget Sound and the Straits well and is sufficient for the project objectives. For completeness, we describe factors contributing to uncertainty in the model predictions. Factors include uncertainty in the data used for model input and output comparison. The model predicted water surface elevations and velocities very well, but temperature and salinity comparisons found somewhat higher errors. The following factors may contribute to errors in model predictions of WSE, velocities, temperatures, and salinities:

- <u>Simplification of model bathymetry in the nearshore and estuarine regions:</u> In the intermediate-scale model, the effect of wetting and drying is not considered. Therefore, a minimum water depth of 4 meters (NAVD 88) was specified in the entire model domain to avoid the model cells becoming dry during low tides in the nearshore shallow water regions. This simplification increases the tidal prism and mixing processes in the nearshore region, which in turn affects the prediction of the stratification level in the nearshore region and influences the main basin and subbasins of Puget Sound. However, given the focus on optimizing circulation in the larger Puget Sound region and that output data were compared with data collected away from nearshore regions, we do not expect this assumption to influence model performance.

- Uncertainty of XTide predictions at the open boundaries: Comparisons of model results and observed data for WSE indicated that larger errors exist in the Strait of Juan de Fuca and Georgia Strait, which are likely induced by the errors in open boundary tides specified using XTide prediction software. However, no other source of water surface elevations currently available would improve predictions in this area.
- Uncertainty in meteorological model outputs for net heat flux forcing: In this study, meteorological forcing was obtained from NARR data, which were pre-calculated from the meteorological model. Therefore, heat flux was not directly coupled to the water surface temperatures calculated in the model. This may result in overheating or cooling in shallow areas in the model domain.
- Uncertainty of river temperatures (same river temperature for all rivers in U.S, waters): Due to the lack of river temperature measurements in every individual river, all river temperatures in U.S. waters were assumed to be the same as that of the Cedar River. This approximation could result in an error as high as 3°C in river temperature inputs (Figure 2-13). The errors in river temperatures would affect the accuracy of surface temperatures, especially in estuaries and bays. However, given that density is dominated by salinity effects in Puget Sound, this assumption will not affect larger Puget Sound circulation patterns.
- Uncertainty of temperature and salinity open boundary conditions: The temperature and salinity open boundary conditions were specified based on the temperature and salinity profiles obtained from the DFO. These profiles were not located exactly at the open boundaries, and boundary values at every time step (10 seconds) were interpolated from the instantaneous profiles measured monthly. Furthermore, profiles collected in the Strait of Juan de Fuca and Georgia Strait each month did not occur in the same day. Because salinity and temperature profiles show low seasonal variability, the use of a single annual value is appropriate and eliminates a freshwater bias.

Model uncertainty may be reduced through further evaluation of factors listed above and model iterations to improve the fit to the existing information. The model is sufficiently calibrated to describe Puget Sound circulation and to meet the overall project objectives. A much more comprehensive model calibration/calibration exercise conducted with extensive synoptic observed data sets (time series and profiles) for each subbasin and estuary would optimize model fit to that area and would improve error statistics. This higher level of effort is beyond the current scope of work of this study.

4.3 Next Steps and Recommendations

The circulation model output will provide input to the next phase of the project. The water quality model will simulate nutrients, DO, and phytoplankton using 2006 circulation model output. One of the advantages of the off-line water quality model is that hydrodynamic calculations do not have to be repeated for each iteration of water quality model during model development, calibration and application. In this study, hydrodynamic model solutions will be saved at 100 seconds or longer intervals for the year 2006.

Among all the factors that affect the model uncertainty, improvement of model open boundary conditions for tidal elevations and modification of model bathymetry may have the strongest effect on improving WSE and temperature and salinity predictions. We recommend a review and testing of model predictions using different sources of tidal elevations along the open boundary. We also recommend that as part of this effort, water depths in the tide flats be manually adjusted to the minimum level such that the model operates just outside the range of wetting and drying process or be regenerated to incorporate the effect of tide flats (Yang and Khangaonkar 2007). The above recommendations are provided in the spirit of trying to continually improve the overall quality and accuracy of the model. As demonstrated in the model calibration section, the calibration achieved despite the discussed data limitations is considered reasonably good for the water quality modeling project objective

Lastly, we recommend that sensitivity analysis be conducted to investigate how the model responds to various parameters, forcing, boundary, and initial conditions and thus better understand the level of uncertainty. Sensitivity analysis of model parameters may include bottom friction, vertical mixing coefficient, and vertical distribution of sigma layers. Wind is an important forcing mechanism to the circulation and mixing process. The effect of wind and it spatial variation on the hydrodynamics of Puget Sound merits further investigation. Salinity and temperature open boundary conditions should be assessed in the sensitivity analysis. Finally, we recommend that the effect of river temperature variations on the temperature distributions in Puget Sound be also investigated.

5.0 References

Aoki K, and A. Isobe. 2007. "Application of Finite Volume Coastal Ocean Model to Hindcasting the Wind-Induced Sea-Level Variation in Fukuoka Bay." *J. of Oceanography*, 63 (2), pp. 333-339.

Chen C, H Liu, and RC Beardsley. 2003. "An Unstructured, Finite-Volume, Three-Dimensional, Primitive Equation Ocean Model: Application to Coastal Ocean and Estuaries." *J. Atm. & Oceanic Tech*. 20:159-186.

Chen C, and M. Rawson. 2005. "An ecosystem management model system for the Satilla River Estuary, Georgia." Oceans, 2005. Proceedings of MTS/IEEE, Vol. 1, pp. 622–632.

Chen C, P Xue, P Ding, RC Beardsley, Q Xu, X Mao, G Gao, J Qi, C Li, and H Lin. Cowles, G., Shi, M., 2008. "Physical Mechanisms for the Offshore Detachment of the Chanjiang Diluted Water in the East China Sea." *J. Geophys. Res*., 113, C02002, doi: 10.1029/2006JC003994.

Ecology Freshwater Ambient Monitoring Program: http://www.ecy.wa.gov/programs/eap/fw_riv/rv_main.html#

Ecology Marine Ambient Monitoring Program: http://www.ecy.wa.gov/apps/eap/marinewq/mwdataset.asp

Finlayson DP. 2005. *Combined Bathymetry and Topography of the Puget Lowland, Washington State. University of Washington*, (http://www.ocean.washington.edu/data/pugetsound/)

Flater D. 1996. "A Brief Introduction to XTide." *Linux Journal*, 32, 51-57.

Isobe A, and RC Beardsley. 2006. "An Estimate of the Cross-Frontal Transport at the Shelf Break of the East China Sea with the Finite Volume Coastal Ocean Model." *J. Geophys. Res*., 111, C03012, doi:10.1029/2005JC003290.

Roberts, M., J. Bos, and S. Albertson. 2008. South Puget Sound Dissolved Oxygen Study, Interim Data Report. Washington State Department of Ecology Publication No. 08-03-037. Available from www.ecy.wa.gov/biblio/0803037.html.

Sackmann, B. 2009. Quality Assurance Project Plan: Puget Sound Dissolved Oxygen Modeling Study: Intermediate-scale Model Development. Washington State Department of Ecology Publication No. 09-03-110. Available from www.ecy.wa.gov/biblio/0903110.html.

Water Survey of Canada. http://www.wsc.ec.gc.ca/products/main_e.cfm?cname=archive_e.cfm

Weisberg RH, and L Zheng. 2006a. "Circulation of Tampa Bay driven by buoyancy, tides, and winds, as simulated using a finite volume coastal ocean model." *J. Geophys. Res*., 111, C01005, doi:10.1029/2005JC003067

Yang Z, and T Khangaonkar. 2008. "Modeling Tidal Circulation and Stratification in Skagit River Estuary Using an Unstructured Grid Ocean Model." *Ocean Modelling*, doi:10.1016/j.ocemod.2008.07.004

Yang Z, and T Khangaonkar. 2007. *Development of a Hydrodynamic Model of Puget Sound and Validation and Application for the Northwest Straits*. PNNL-17161, Pacific Northwest National Laboratory, Richland, WA.

Yang Z, T Khangaonkar, M Calvi, and K Nelson. 2009a. "Simulation of Cumulative Effects of Nearshore Restoration Projects on Estuarine Hydrodynamics." *Ecol. Model*. doi:10.1016/j.ecolmodel.2008.12.006

Yang Z, KL Sobocinski, D Heatwole, T Khangaonkar, R Thom, and R Fuller. 2009b. "Hydrodynamic and Ecological Assessment of Nearshore Restoration: A Modeling Study." *Ecol. Model*. doi:10.1016/j.ecolmodel.2009.07.011.

Zhao L, C Chen, and G Cowles. 2006. "Tidal Flushing and Eddy Formation in Mount Hope Bay and Narragansett Bay: An Application of FVCOM." *J. Geophys. Res*., 111, C10015, doi:10.1029/2005JC003135.

Zheng L, C Chen, and H Liu. 2003. "A Modeling Study of the Satilla River Estuary, Georgia. Part I: Flooding/Drying Process and Water Exchange over the Salt Marsh-Estuary-Shelf Complex." *Estuaries*, 26 (3), pp. 651–669.