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Assessment of Energy Removal Impacts on Physical Systems: Hydrodynamic Model Domain Expansion, Refinement, and Online Dissemination of Model Results

Environmental Effects of Marine and Hydrokinetic Energy – Fiscal Year 2010

Z Yang
T Khangaonkar
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August 2010

Pacific Northwest NATIONAL LABORATORY

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Richland, Washington 99352

Abstract

In this report we describe 1) the expansion of the PNNL hydrodynamic model domain to include the continental shelf along the coasts of Washington, Oregon, and Vancouver Island and model refinement in neashore regions; and 2) the approach and progress in developing the online/Internet disseminations of model results and outreach efforts in support of the Puget Sound Operational Forecast System (PS-OPF). Submittal of this report completes the work on Task 2.1.2, Effects of Physical Systems, Subtask 2.1.2.1, Hydrodynamics, for fiscal year 2010 of the Environmental Effects of Marine and Hydrokinetic Energy project.

Project Overview

Energy generated from the world's oceans and rivers offers the potential to make substantial contributions to the domestic and global renewable energy supply. The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Wind and Water Power Program supports the emerging marine and hydrokinetic (MHK) energy industry. As an emerging industry, MHK project developers face challenges with siting, permitting, construction, and operation of pilot- and commercial-scale facilities, as well as the need to develop robust technologies, secure financing, and gain public acceptance.

In many cases, little is known about the potential effects of MHK energy generation on the aquatic environment from a small number of devices or a large-scale commercial array. Nor do we understand potential effects that may occur after years or decades of operation. This lack of knowledge affects the solvency of the industry, the actions of regulatory agencies, the opinions and concerns of stakeholder groups, and the commitment of energy project developers and investors.

To unravel and address the complexity of environmental issues associated with MHK energy, Pacific Northwest National Laboratory (PNNL) is developing a program of research and development that draws on the knowledge of the industry, regulators, and stakeholders and builds on investments made by the EERE Wind and Water Power Program. The PNNL program of research and development—together with complementary efforts of other national laboratories, national marine renewable energy centers, universities, and industry—supports DOE's market acceleration activities through focused research and development on environmental effects and siting issues. Research areas addressed include

- **categorizing and evaluating effects of stressors** – Information on the environmental risks from MHK devices, including data obtained from in situ testing and laboratory experiments (see other tasks below) will be compiled in a knowledge management system known as Tethys to facilitate the creation, annotation, and exchange of information on environmental effects of MHK technologies. Tethys will support the Environmental Risk Evaluation System (ERES) that can be used by developers, regulators, and other stakeholders to assess relative risks associated with MHK technologies, site characteristics, waterbody characteristics, and receptors (i.e., habitat, marine mammals, and fish). Development of Tethys and the ERES will require focused input from various stakeholders to ensure accuracy and alignment with other needs.
- **effects on physical systems** – Computational numerical modeling will be used to understand the effects of energy removal on water bodies from the short- and long-term operation of MHK devices and arrays. Initially, PNNL's three-dimensional coastal circulation and transport model of Puget Sound will be adapted to test and optimize simulated tidal technologies that resemble those currently in proposal, laboratory trial, or pilot study test stages. This task includes assessing changes to the physical environment (currents, waves, sediments, and water quality) and the potential effects of these changes on the aquatic food webs) resulting from operation of MHK devices at both pilot- and commercial-scale in river and ocean settings.
- **effects on aquatic organisms** – Testing protocols and laboratory exposure experiments will be developed and implemented to evaluate the potential for adverse effects from operation of MHK devices in the aquatic environment. Initial studies will focus on electromagnetic field effects, noise associated with construction and operation of MHK devices, and assessment of the potential risk of

physical interaction of aquatic organisms with devices. A variety of fish species and invertebrates will be used as test animals, chosen due to their proximity to and potential susceptibility to MHK devices.

- **permitting and planning** – Structured stakeholder communication and outreach activities will provide critical information to the project team to support execution of other project tasks. Input from MHK technology and project developers, regulators and natural resource management agencies, environmental groups, and other stakeholder groups will be used to develop the user interface of Tethys, populate the database, define the risk attributes of the ERES, and communicate results of numerical modeling and laboratory studies of exposure of test animals to MHK stressors. This task will also include activities to promote consideration of renewable ocean energy in national and local Coastal and Marine Spatial Planning activities.

The team for the Environmental Effects of MHK Energy development project is made up of staff, faculty, and students from

- Pacific Northwest National Laboratory
  - Marine Sciences Laboratory (Sequim and Seattle, Washington)
  - Risk and Decision Sciences (Richland, Washington)
  - Knowledge Systems (Richland, Washington)
- Oak Ridge National Laboratory (Oak Ridge, Tennessee)
- Sandia National Laboratories (Albuquerque, New Mexico; Carlsbad, California)
- Oregon State University, Northwest National Marine Renewable Energy Center (Newport, Oregon)
- University of Washington, Northwest National Marine Renewable Energy Center (Seattle, Washington)
- Pacific Energy Ventures (Portland, Oregon).

Acronyms and Abbreviations

ADCIRC	Advanced Circulation (model)
DOE	U.S. Department of Energy
EERE	DOE Office of Energy Efficiency and Renewable Energy
ERES	Environmental Risk Evaluation System
FVCOM	Finite Volume Coastal Ocean Model
MHK	marine and hydrokinetic
NAM-WRF	North American Mesoscale – Weather Research and Forecasting (model)
NCEP	National Centers for Environmental Protection
NCOM	Navy Coastal Ocean Model
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service
NRL	Naval Research Laboratory
NWS	National Weather Service
PS-CTM	Puget Sound Circulation and Transport Model
PNNL	Pacific Northwest National Laboratory
PS-OFS	Puget Sound Operational Forecast System
USGS	U.S. Geological Survey

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1.0 Introduction

The task described in this report included two components: 1) expansion of the Puget Sound Operational Forecast System (PS-OPF) model domain to include the continental shelf along the coasts of Washington, Oregon, and Vancouver Island and 2) online/Internet disseminations of model results and outreach efforts, including continued development of the PS-OPF. The modeling effort and results of the dissemination subtask are summarized in the following sections.

2.0 Expansion of the Model Domain

To consider the effects of tidal energy propagating from the open ocean and upwelling, the existing Puget Sound model developed based on the Finite Volume Coastal Ocean Model (FVCOM) needed to be extended further out to the continental shelf. The hydrodynamic model of the Salish Sea was expanded to the continental shelf with inclusion of the coasts of Vancouver Island, Washington and Oregon. A new model grid with coverage of the northeastern Pacific Ocean was constructed using the University of Washington digital elevation model data as well as bathymetry data obtained from the National Oceanic and Atmospheric Administration (NOAA) (Figure 1). The model is driven by eight major tidal harmonics extracted from the Advanced Circulation (ADCIRC) model tide predictions in the Pacific Ocean.

The modeling effort also included refinement of nearshore regions and improvement of temperature simulation. Key regions such as Bellingham Bay and the Nisqually Estuary have been further refined in the updated model to better simulate the nearshore process in those important estuaries and bays. Examples of tidal elevations at the southern and northern open boundaries are shown in Figure 2. Model runs were conducted to simulate tidal propagation along the Pacific Northwest coast and in Puget Sound. Time series plots of tidal elevations at the entrances to the Strait of Juan de Fuca, Admiralty Inlet, and Seattle harbor are shown in Figure 3. Water surface contours at high tide (with respect to Seattle) and low tide are presented in Figure 4. Velocity contours/vectors at flood tide and ebb tide are shown in Figure 5.

3.0 Online/Internet Dissemination of Model Results and Outreach

This component was completed and model results were presented to the 11th International Conference of Estuarine and Coastal Modeling (ECM11) in November 2009 in Seattle, Washington. The model now contains new components such as a linkage of hydrodynamic solution files to NOAA's oil spill trajectory model GNOME and real-time model validation to NOAA's Physical Oceanographic Real-Time System (PORTS) datasets. A peer-reviewed paper was accepted for publication in the conference proceedings.[1] A copy of the paper is provided in Appendix A. This subtask also included continued development of the PS-OFS, such as using NOAA Nation Centers for Environmental Protection (NCEP)

[1] Yang Z, T Khangaonkar, J Chase, and T Wang. Puget Sound Operational Forecast System - A Real-time Predictive Tool for Marine Resource Management and Emergency Responses. Tobe published by the American Society of Civil Engineers in the proceedings for the 11th International Conference on Estuarine and Coastal Modeling.

meteorological outputs to drive sea temperate simulation in PS-OFS. A peer-reviewed manuscript describing this work was submitted for publication in the *International Journal of Ocean and Climate Systems*.[2] Appendix B provides a copy of the manuscript submitted for review. The architecture of the PS-OFS is shown in Figure 6.

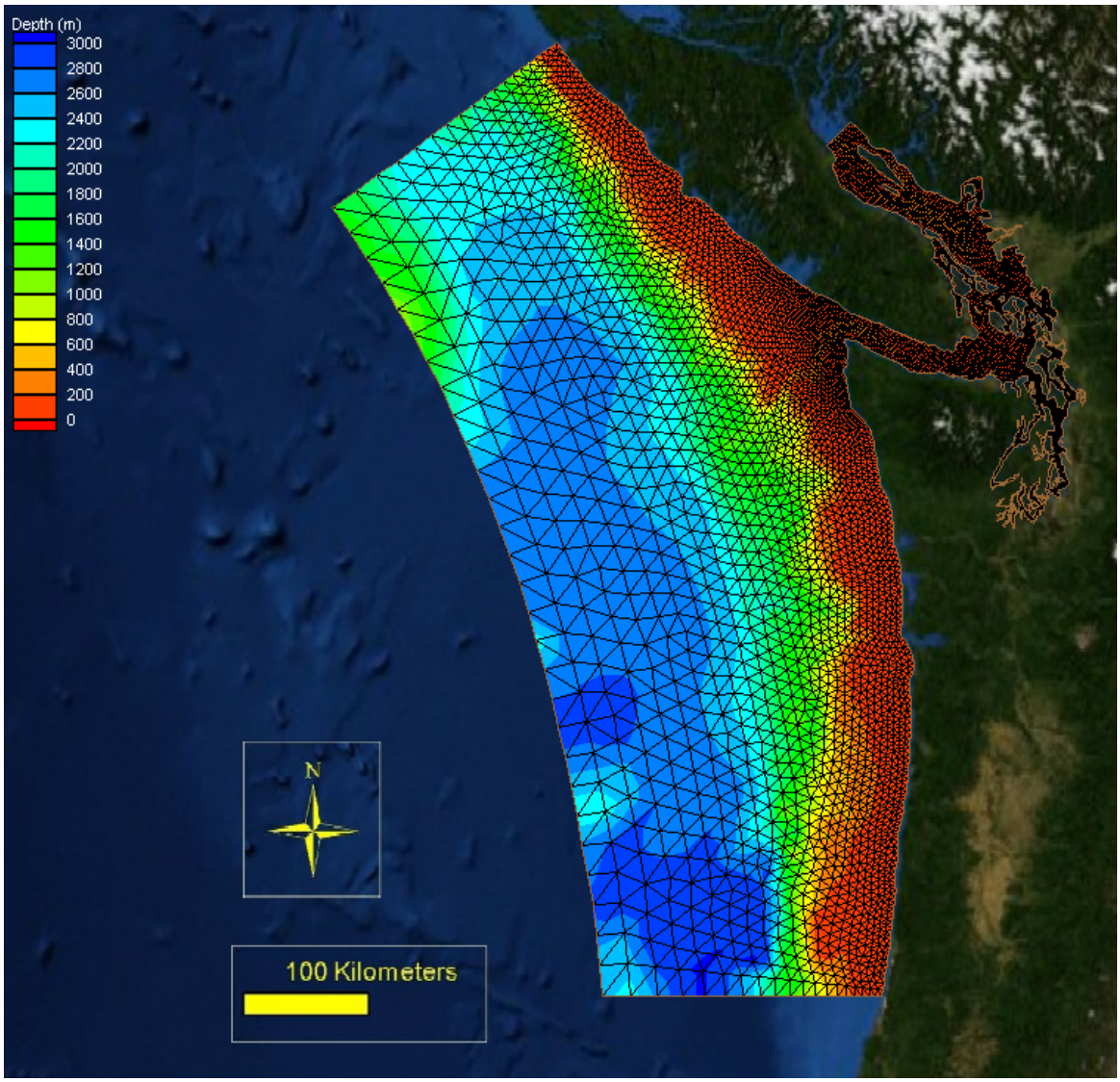

Figure 1. Model Grid and Bathymetry

[2] Yang Z, T Khangaonkar, and T Wang. Use of advanced meteorological model output for coastal ocean modeling in Puget Sound. *International Journal of Ocean and Climate Systems*; in review.

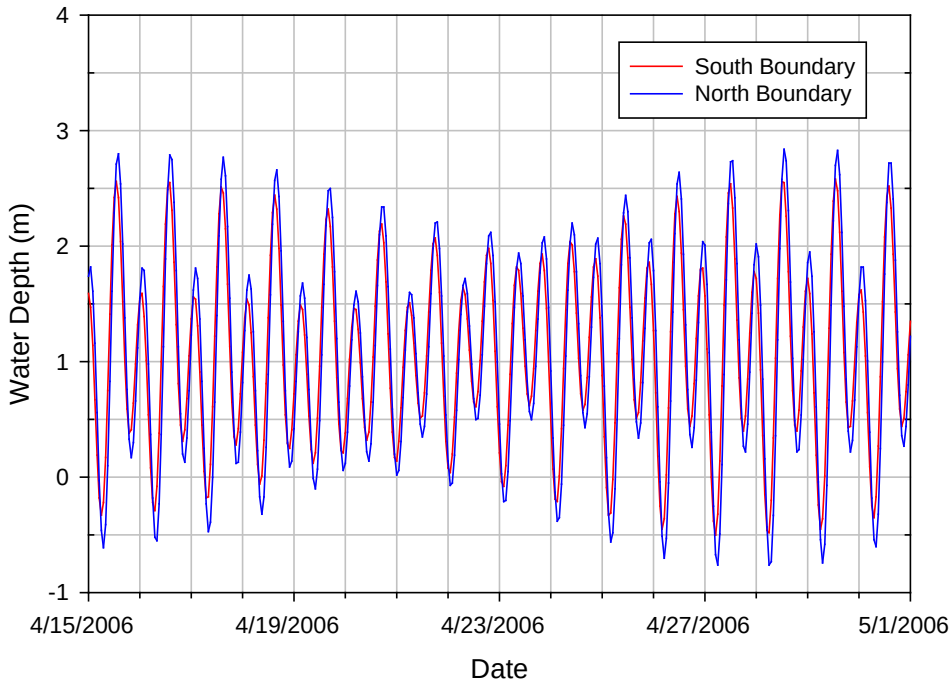

Figure 2. Tidal Boundary Conditions

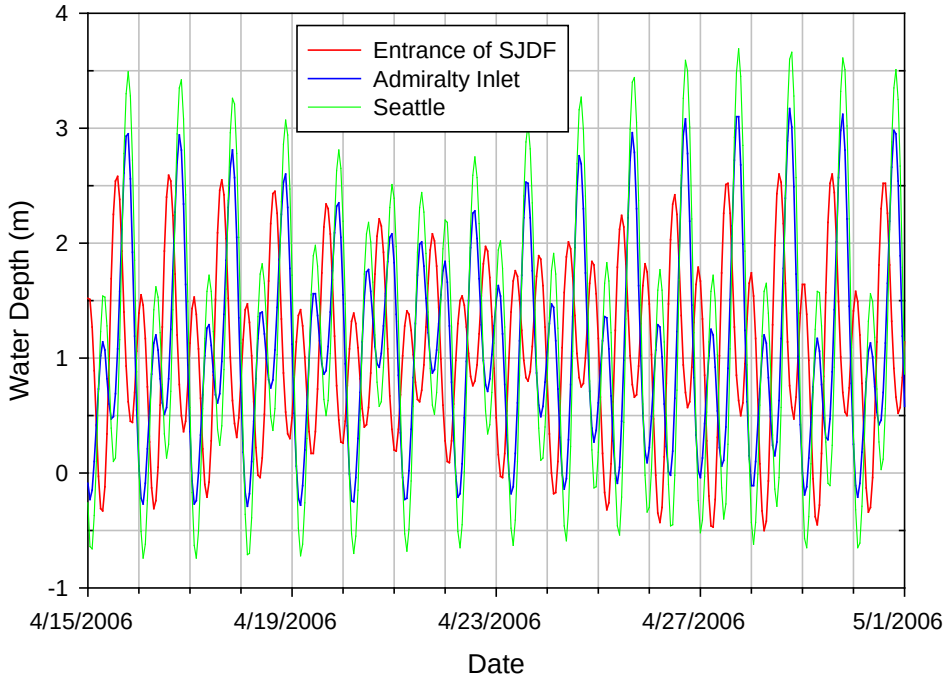

Figure 3. Predicted Tidal Elevations in Puget Sound

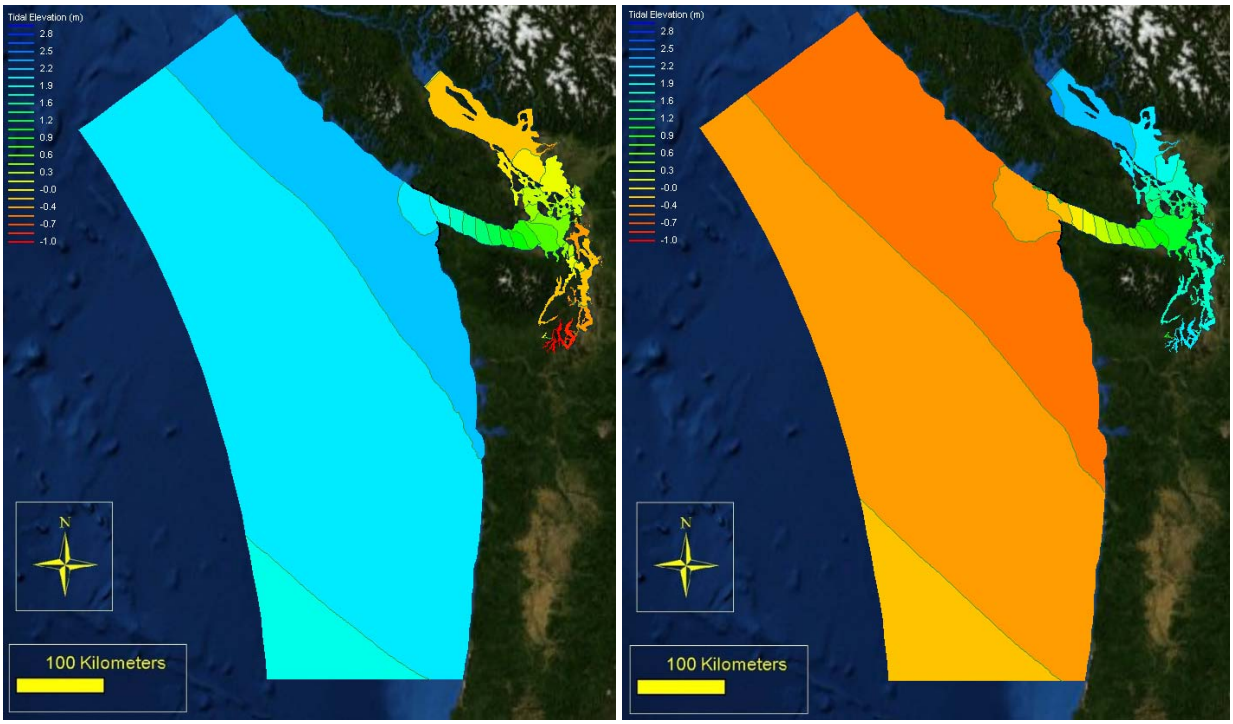

Figure 4. Tidal Elevations at Low Tide (Left Panel) and High Tide (Right Panel) with Respect to South Sound

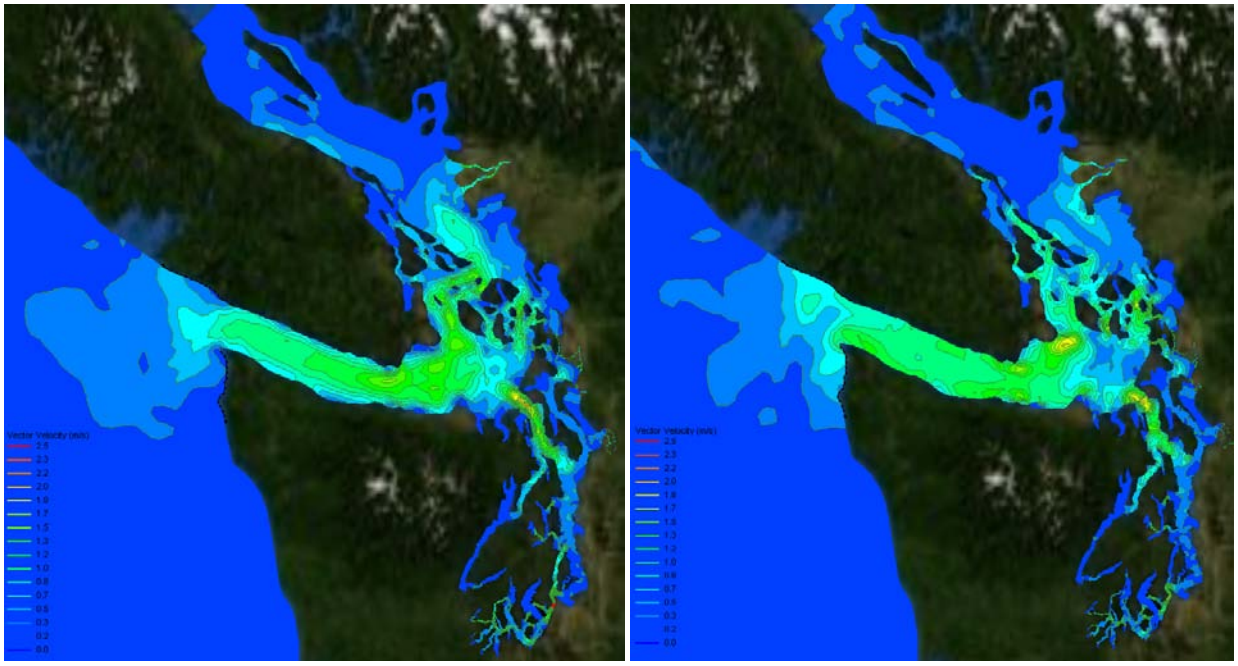

Figure 5. Tidal Currents at Ebb Tide (Left Panel) and Flood Tide (Right Panel) in the Salish Sea and Northwest Coast

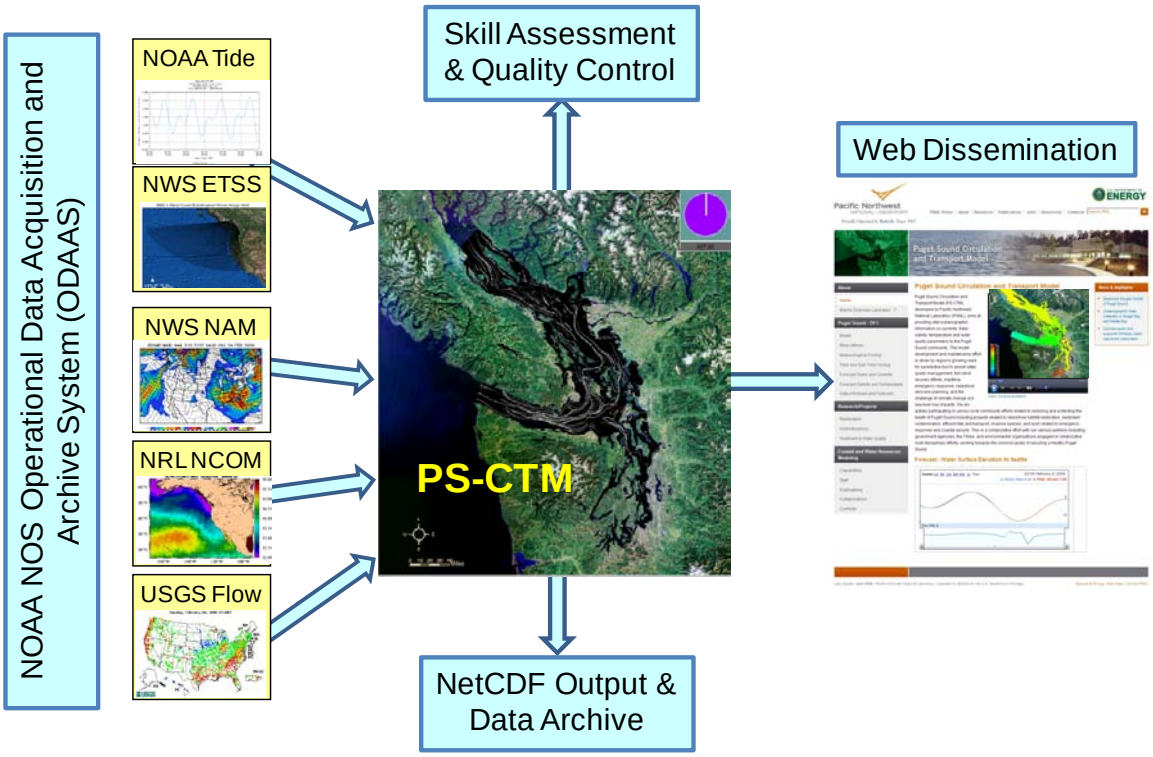

Figure 6. Architecture of the Puget Sound Operational Forecast System

Appendix A

Conference Proceedings Paper

Appendix A
Conference Proceedings Paper

Proceedings of the 11th International Conference on Estuarine and Coastal Modeling, edited by M. L. Spaulding, American Society of Civil Engineers, Seattle, WA

Puget Sound Operational Forecast System - A Real-time Predictive Tool for Marine Resource Management and Emergency Responses

Zhaoqing Yang[1], Tarang Khangaonkar[1]
Jared Chase[1], and Taiping Wang[1]

Abstract

To support marine ecological resource management and emergency response and to enhance scientific understanding of physical and biogeochemical processes in Puget Sound, a real-time Puget Sound Operational Forecast System (PS-OFS) was developed by the Integrated Coastal Ocean Modeling group (ICOM) of Pacific Northwest National Laboratory (PNNL). PS-OFS employs the state-of-the-art three-dimensional coastal ocean model and closely follows the standards and procedures established by National Oceanic and Atmospheric Administration (NOAA) National Ocean Service (NOS). PS-OFS consists of four key components supporting the Puget Sound Circulation and Transport Model (PS-CTM): data acquisition, model execution and product archive, model skill assessment, and model results dissemination. This paper provides an overview of PS-OFS and its ability to provide vital real-time oceanographic information to the Puget Sound community. PS-OFS supports Pacific Northwest region's growing need for a predictive tool to assist water quality management, fish stock recovery efforts, maritime emergency response, nearshore land-use planning, and the challenge of climate change and sea level rise impacts. The structure of PS-OFS and examples of the system inputs and outputs, forecast results are presented in details.

[1]Integrated Coastal Ocean Modeling (ICOM), Marine Sciences Laboratory, PNNL, Battelle Seattle Research Center. 1100 Dexter Avenue North, Suite 400, Seattle, WA 98109

Introduction

Puget Sound is a large fjordal estuary located on the northwest coast of United States. It has several large sub-basins and is bounded by approximately 4,180 km of complex shorelines. Puget Sound connects the Pacific Ocean via Strait of Juan de Fuca and the Strait of Georgia from British Columbia, Canada. A high resolution three-dimensional Puget Sound circulation and transport model (PS-CTM) has been developed by the Coastal Ocean Dynamics & Ecosystem Modeling group (CODEM) of Pacific Northwest National Laboratory (PNNL) to assist nearshore habitat restoration design, juvenile fish migration and water quality management in Puget Sound. PS-CTM is built using the unstructured-grid Finite Volume Coastal Ocean Model (FVCOM) (Chen et al., 2003) and it has been validated to various data sets of water level, current, salinity and temperature in various sub-basins of the Puget Sound (Yang and Khangaonkar, 2007 & 2008). As the model becomes more robust through continuous improvements, demand of key oceanographic information generated from the model, such as water levels, currents, salinity and temperature, has been increased significantly. Therefore, it is important that model results are made available to the general public in the Puget Sound community through a real-time operational forecast system.

An operational forecast system (OFS) is defined as a system that is created in response to specific needs, implemented according to well-defined standards, and runs stably, regularly and automatically with quality control (NOAA, 1999, Vincent et al., 2003, Aikman et al., 2008). OFS have been developed in various water bodies in the United States in support of safe and efficient marine navigation, emergency response and ecosystem management (Aikman et al., 2008). These OFSs include five Great Lakes (Erie, Huron, Michigan, Ontario and Superior) and four estuarine and bays (Chesapeake Bay, Galveston Bay, Port of New York and New Jersey, St John's River). The Coastal Survey Development Laboratory (CSDL) of National Ocean Service (NOS) have established a standardized Coastal Ocean Modeling Framework (COMF) to increase the efficiency of the development, transition and operation of real-time coastal and estuarine OFS (Gross et al., 2006; Aikman et al., 2008).

The Puget Sound operational forecast system (PS-OFS) is a real-time operational forecast system which predicts key oceanographic parameters and disseminates model results online in real-time. PS-OFS aims at providing vital oceanographic information to the community in Puget Sound on a continuous and efficient basis. In addition, development of PS-OFS will further enhance our research and understanding of the physical and biogeochemical processes in Puget Sound, as well as the challenge of climate change and sea level rise impacts in Pacific Northwest region. Development of the Puget Sound Operational Forecast System

(PS-OFS) closely followed the procedures and standards established by NOAA NOS through the development of various OFS in the United States.

Structure of PS-OFS

PS-OFS primarily consists of four key components around the core of PS-CTM (Figure 1): 1) Data acquisition from NOAA's operational data acquisition and achieve system (ODAAS); 2) Model execution for daily cycle forecast; 3) Model skill assessment; and 4) Dissemination of model results. These four components are executed through the following processes in each cycle of forecast:

- Set environment variables and date module
- Get forecast data from ODAAS
- Reformat data for model input
- Run Puget Sound forecast model
- Conduct model skill assessment
- Extract model results and generate graphics
- Archive model products
- Produce PS-OFS status flags

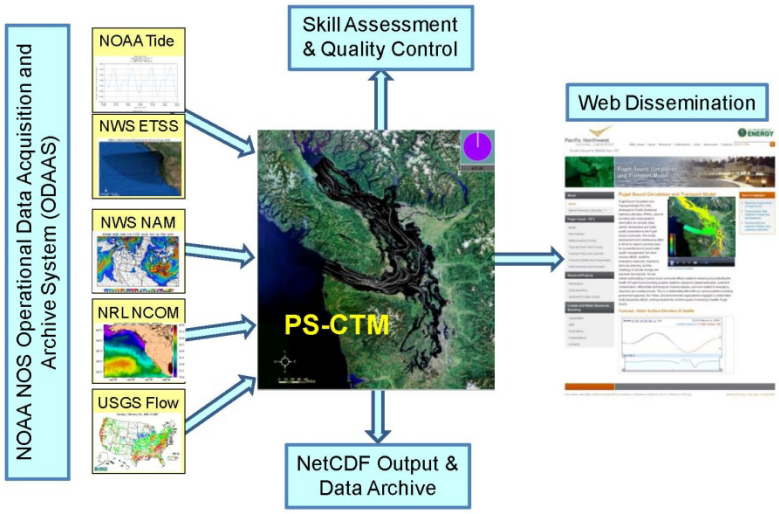

Figure 1 Structure of Puget Sound Operational Forecast System (PS-OFS)

The core of PS-OFS is the three-dimensional Puget Sound circulation and transport model (PS-CTM). Because of presences of complex coastlines, large tide flats and the density-stratified fjordal circulation in Puget Sound, PS-CTM should be constructed in an unstructured-grid or boundary-fitted-grid framework and have the capability to simulate the wetting/drying processes over tide flats and the baroclinic motion induced by density-stratification. While a number of open-source advanced coastal ocean models are available for this purpose, the Finite Volume Coastal Ocean Model (Chen et al., 2003) is currently selected as the main model for the PS-OFS. FVCOM has been widely used in simulations of circulations in many estuarine and coastal systems (Chen and Rawson, 2005; Weisberg and Zheng, 2006; Isobe and Beardsley, 2006; Aoki and Isobe, 2007; Chen et al., 2008; Yang and Khangaonkar, 2008, 2009, Khangaonkar and Yang, 2009). Figure 2 shows the unstructured-grid of PS-CTM for the entire Puget Sound and the Northwest Straits.

Figure 2 Model Grid for Puget Sound, Strait of Juan de Fuca and Georgia Strait

The model grid of Puget Sound consists of around 110,000 nodes and 210,000 triangular elements with element sizes varying from around 2,500 meters at the open boundaries to the order of 10 meters within estuaries and river channels. Twenty uniform vertical layers were specified in the water column in a sigma-stretched coordinate system. PS-CTM simulates water levels, three dimensional currents, salinities and temperatures with forcing of water levels at the open boundaries, meteorological forcing (wind and net heat flux) at the water surface and river inflows at river heads. Details on the development of PS-CTM and its applications are described in Yang and Khangaonkar (2008) and Khangaonkar and Yang (2009).

Data Acquisition for PS-OFS

Data acquisition for PS-OFS includes four types of data: 1) open boundary water level; 2) open boundary temperature and salinity; 3) meteorological forcing; 4) river inflows. The first three types of data can be obtained from NOAA NOS's Operational Data Acquisition and Archive System. River inflow data are obtained from United States Geological Survey (USGS) real-time stream gages in the Puget Sound region.

Tide and Subtidal Water Levels

Open boundary water levels consist of tidal and sub-tidal components. Tide is the dominant forcing mechanism for circulation in Puget Sound and the Northwest Straits. Tidal surface elevations along the open boundaries can be specified by either tidal constituents at NOAA real-time water level stations or harmonic tide clock and tide predictor (XTide) based on NOAA tidal prediction algorithms (Flater, 1996). Because there are no NOAA tide stations (and harmonic constituents) on the northern open boundary in British Columbia, in current PS-OFS configuration tidal elevations at open boundaries are specified by XTide predictions at Neah Bay at the entrance of the Strait of Juan de Fuca and at Campbell River at the north end of Strait of Georgia (Figure 3). Subtidal water levels at the open boundaries are specified by NOAA National Weather Service's Extra-Tropical Storm Surge (ETSS) model predictions in the US West Coast region. ETSS forecasts sub-tidal water levels every three hours out to 84 hours.

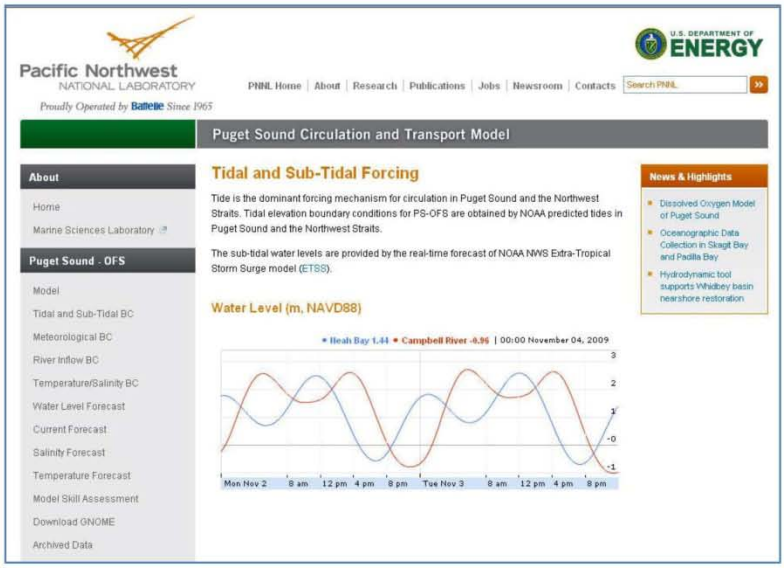

Figure 3 Tidal Elevations (from XTide) at Neah Bay and Campbell River Stations

Salinity and Temperature Open Boundary Conditions

Temperature and salinity values at the model open boundaries of PS-OFS are specified by The Naval Research Laboratory's global Navy Coastal Ocean Model (NCOM) forecast in the Pacific region. NCOM runs daily and forecasts every 3 hours out to 72 hours for water level, current, salinity and temperature at $1/8^{o}$ (14 km) resolution (Figure 4) and outputs in NetCDF format. In current PS-OFS configuration, temperature and salinity values at two grid points near PS-CTM open boundaries are obtained from NCOM and used to drive PS-OFS (Figure 4). Time series of NCOM temperature forecast near the surface at model open boundaries are shown in Figure 5.

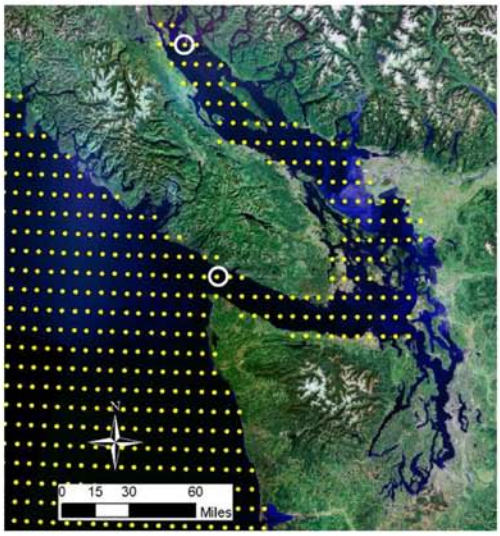

Figure 4 NCOM Grid and for PS-OFS Open Boundary Points (Circled)

Figure 5 NCOM Temperatures Forecast at PS-OFS Open Boundaries

Wind and Surface Heat Flux

Meteorological forcing parameters are required as model input in PS-OFS. NOAA National Weather Service (NWS) North American Model Weather Research Forecast (NAM-WRF) generates real-time meteorological forecast every 3 hours out to 84 hours at 12 km resolution. The meteorological parameters obtained from NAM-WRF include: 1) wind speed and direction, 2) shortwave and longwave radiations (downward and upward), 3) latent heat flux and 4) sensible heat flux. The surface net heat flux which is required as an input to FVCOM can be directly calculated using shortwave and longwave radiations, latent heat flux and sensible heat flux. Figure 6 shows the wind vector distribution over the Pacific Northwest region at 12:00 pm on November 3, 2009.

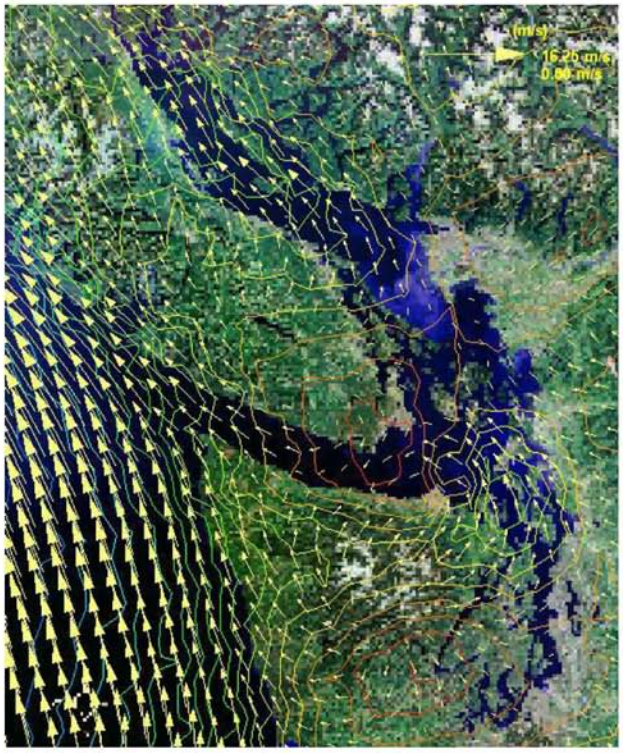

Figure 6 NOAA/NECP NAM-WRF Forecast Wind in Pacific Northwest Region

River Inflows

A total of 19 rivers, including the Fraser River from British Columbia of Canada, are currently considered in PS-OFS (Figure 7). Real-time forecasts of river discharges are currently not available or very limited to specific rivers. In current PS-OFS configuration, daily average river inflows based on real-time data for the day before forecast are used as model input. Real-time USGS stream flow gauges exist in 13 major rivers in Puget Sound. Five small rivers in Hood Canal (Big Quilcene, Duckabush, Dosewallips, Hamma Hamm and Tahuya) do not have real-time data and inflows of these rivers are estimated using scaling method based on watershed areas and nearby real-time stream gage data. Real-time data for Fraser River are obtained from Environmental Canada real-time station #08MF005 at Hope, British Columbia. River inflows in the Whidbey Basin, which receives freshwater discharge from three largest rivers in Puget Sound (Skagit River, Snohomish River and Stillaguamish River) are shown in Figure 8.

Figure 7 River Locations in Puget Sound and the Northwest Straits

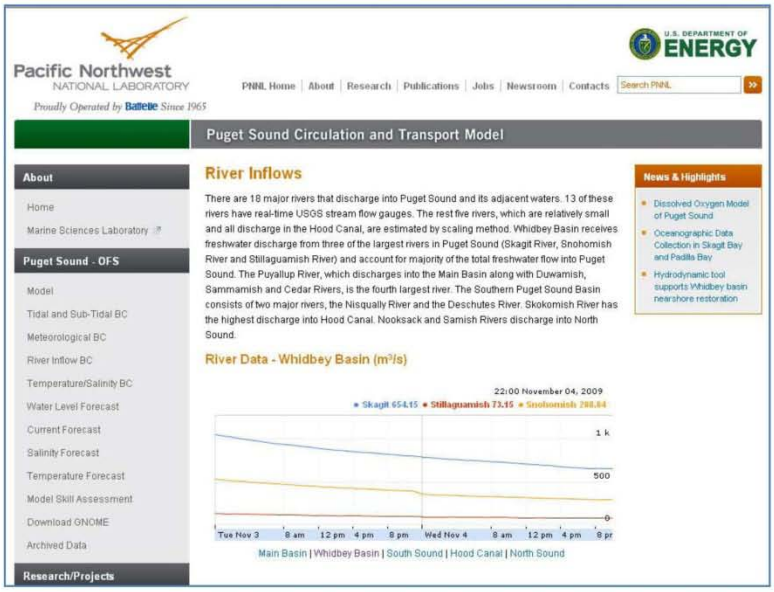

Figure 8 River Inflows in Whidbey Basin of Puget Sound

Forecast Results and Web Dissemination

PS-OFS currently operates daily and forecasts every hour out to 48 hours. A status message with quality control flags and product links is generated automatically everyday at the end of each forecast cycle. Forecast results, such as water level, current, temperature and salinity, are displayed online at selected locations in Puget Sound. These locations include all the real-time stations at NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) and NOAA's Physical Oceanographic Real-Time System (PORTS) stations in Puget Sound. Forecast water levels are compared to six NOAA CO-OPS real-time stations at Port Angeles, Friday Harbor, Cherry Point, Port Townsend, Seattle and Tacoma. Example of water level forecast with comparison to NOAA real-time data from November 2 to 3, 2009 at Seattle Station is shown in Figure 9.

Figure 9 Water Level Forecast at Seattle

Currently, there are no NOAA real-time current and salinity data available in Puget Sound. However, two NOAA PORTS stations, Tacoma and Cherry Point, have real-time water temperature data. Examples of current forecast at Elliott Bay, salinity forecast at Skagit Bay and temperature forecast at Tacoma from November 2 to 3, 2009 are shown in Figures 10, 11 and 12 respectively.

Model skill assessment is also conducted for PS-OFS based on observed water level data. NOAA NOS has established a set of criteria for model skill assessment (NOAA, 2003; Zhang et al.,, 2006; Patchen, 2008). Various criteria can be selected and used to evaluate the performance of a coastal hydrodynamic model based on the objective of the modeling system and user requirements. Due to the limitation of observation in Puget Sound, only root mean square error (RMSE) for water levels is conducted for PS-OFS (Figure 13). The overall RMSEs are in the range of 0.1 to 0.2 m. Harmonic analysis indicated errors for mean water surface elevations have significant contribution to the total RMSEs. Therefore, model skills for water levels can be further improved through improvement of sub-tidal water levels at open boundaries.

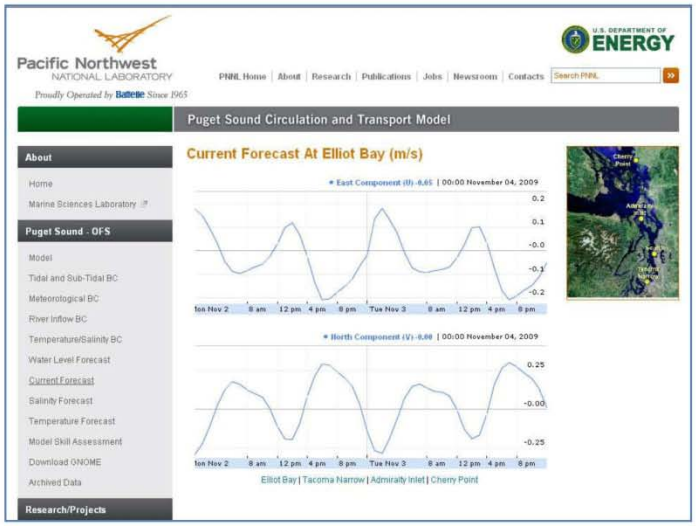

Figure 10 Current Forecast at Elliott Bay Station

Figure 11 Salinity Forecast at Skagit Bay Station

Figure 12 Temperature Forecast at Tacoma Station

Figure 13 Model Skill Assessment of PS-OFS - Water Level

Summary

A real-time Puget Sound Operational Forecast System (PS-OFS) has been developed using the unstructured-grid Puget Sound Circulation and Transport Model (PS-CTM). PS-OFS is driven by XTides and NOAA ETSS sub-tidal water levels on the open boundaries. Salinity and temperature open boundary conditions are provided by the Office of Naval Research's Navy Coastal Ocean Model (NCOM). The meteorological inputs are obtained from the real-time forecast of NOAA/NCEP NAM-WRF. River inflows are provided by the USGS real-time stream gage data. Model open boundaries are specified at the entrance of Strait of Juan de Fuca and the north end of Strait of Georgia. The development of PS-OFS closely follows NOAA's operational forecast standards and procedures such as model inputs, quality control, model skill assessment, data archive and web dissemination. PS-OFS is currently under real-time testing and continuous improvement. The performance of PS-OFS demonstrates its ability to provide vital real-time oceanographic information to the Puget Sound community, in response to the region's growing need for a predictive tool to assist marine resources management, emergency response, and enhance fundamental oceanographic research in Puget Sound.

While the PS-OFS is up and running in real-time operation, further improvements of PS-OFS are possible. Future work for the system improvements includes:

- Inclusion of skill assessments for currents, salinity and temperature and expansion of the skill metrics such CF, POF and NOF.
- Generation of skill assessment on a monthly basis
- Inclusion more real-time observations from The Northwest Association of Networked Ocean Observing Systems (NANOOS).
- Improvement of meteorological forcing by including the effects of atmospheric pressure anomaly and feedback of water temperature.
- Inclusion of nowcast at six-hour cycle as needed.

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Appendix B

Submitted Journal Article

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Submitted Journal Article

For Submission to International Journal of Climate and Ocean Systems

Use of Advanced Meteorological Model Output for Coastal Ocean Modeling in Puget Sound

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Abstract

It is a great challenge to specify meteorological forcing in estuarine and coastal circulation modeling using observed data because of the lack of complete datasets. As a result of this limitation, water temperature is often not simulated in estuarine and coastal modeling, with the assumption that density-induced currents are generally dominated by salinity gradients. However, in many situations, temperature gradients could be sufficiently large to influence the baroclinic motion. In this paper, we present an approach to simulate water temperature using outputs from advanced meteorological models. This modeling approach was applied to simulate annual variations of water temperatures of Puget Sound, a fjordal estuary in the Pacific Northwest of USA. Meteorological parameters from North American Region Re-analysis (NARR) model outputs were evaluated with comparisons to observed data at real-time meteorological stations. Model results demonstrated that NARR outputs can be used to drive coastal ocean models for realistic simulations of long-term water-temperature distributions in Puget Sound. Model results indicated that the net flux from NARR can be further improved with the additional information from real-time observations.

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1 Introduction

Estuarine and coastal circulation is primarily subject to three types of forcing: tides, river inflows, and meteorological conditions that include surface wind stress and heat exchanges. Tidal forcing is generally well defined in coastal modeling. Many observations and accurate predictions are available to specify open boundary conditions (Foreman, 1978; Flater, 1996; Mark et al., 2004). In the United States, river inflow data are also well established by the United States Geological Survey (USGS) stream flow network in all the major rivers. However, meteorological forcing data are often limited and have high uncertainties in coastal and estuarine modeling, in comparison to tides and river inflows. In many research and practical modeling applications, meteorological forcing mechanisms are either specified with limited data sets or even neglected. In particular, simulating water temperatures in estuarine and coastal waters remains a big challenge, especially when seasonal and annual long-term simulations are required for large coastal and estuarine water bodies. Over the last decade, rapid development of advanced meteorological models has greatly improved the accuracy of predicted meteorological parameters. The most widely used comprehensive meteorological models include 1) fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) (Dudhia, 1993; Grell et al., 1995, Charles and Colle, 2009); 2) National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) Weather Research and Forecasting North American Model (WRF-NAM) (Black, 1994; Rogers et al., 1996; Michalakes et al., 2004); and 3) NOAA NCEP North American Regional Analysis (NARR) (Lin et al., 1999; Mesinger et al., 2003, 2006).

The availability of the continuous and systematic meteorological data from the advanced meteorological model outputs is of major benefit to the estuarine and coastal ocean modeling community. Many studies have used meteorological model outputs to drive the coastal ocean and estuarine models for coastal environmental predictions. Gomez-Gesteira et al. (2006) used long-term forecast of winds to calculate the Ekman transport along the Galician coast northwest of Spain from November 1999 to October 2005. Chen et al. (2005) applied MM5 data to hindcast the ocean surface forcing fields over the Gulf of Main and Georges Bank region. WRF-NAM is a state-of-the-art next-generation mesoscale numerical weather prediction system that serves both the atmospheric research and operational forecasting communities. Lopes et al. (2009) coupled WRF output to model the temperature and the phytoplankton distributions at the Aveiro near the coastal zone in Portugal. Koracin et al. (2004) used the month-long MM5 outputs to investigate perturbations of topographically forced wind stress and wind stress curl during upwelling-favorable winds along the California and Baja California coasts during June 1999. Qi et al. (2009) applied WRF wind fields to drive the unstructured finite-volume surface wave model FVCOM-SWAVE to simulate wind-induced surface waves on the U.S. northeast shelf with a central focus in the Gulf of Maine and the New England Shelf. Surface winds are a major forcing mechanism of circulation of the coastal oceans and estuaries. Otero and Ruiz-Villarreal (2008) compared winds from NARR (NCEP Reanalysis 1 and 2) and MM5 to observations for the coastal region around northwest and north Iberia during a typical autumn downwelling period. Signell et al. (2004) evaluated the quality of wind outputs from four meteorological models for oceanographic modeling in semi-enclosed basins and concluded that high-resolution, non-hydrostatic meteorological models offer significant advantages for driving oceanographic modeling. Capet et al. (2004) also showed that the spatial structure of nearshore wind analyzed

from high-resolution atmospheric model COAMPS has a strong influence on the patterns of upwelling circulation and biogeochemical processes in the coastal regions. More recently, Huang et al. (2010) demonstrated that a three-dimensional (3-D) hydrodynamic model of Lake Ontario can successfully reproduce the lake surface temperature and stratification using observed and atmospheric forecast forcing.

In this paper, we present an approach of linking meteorological model outputs such as NARR to a costal ocean model to simulate water temperatures. This was accomplished over Puget Sound, a large fjordal estuary in the Pacific Northwest coast. Comparisons of model results to observed data at locations in the main stem of the estuary are presented. This study demonstrated that while there is room for improvement, advanced meteorological model outputs from NARR (wind, solar radiation and surface heat fluxes) can be used to drive coastal ocean modeling to simulate water temperature diurnal to seasonal variations in Puget Sound.

2 Methodology

2.1 Study Domain – Puget Sound

Puget Sound is a large fjordal estuary located in the Pacific Northwest coast of North America (Figure 1). Circulation in Puget Sound is dominated by tides that propagate into Puget Sound and further north to the Strait of Georgia from the Pacific Ocean through the Strait of Juan de Fuca. 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 the Strait of Georgia in British Columbia affects stratification and currents in the adjacent waters of the Strait of Juan de Fuca and Puget Sound

(Moore et al., 2008; Newton, 1995; Ebbesmeyer et al., 1989). The circulation in Puget Sound shows distinct fjordal characteristics with mean outflow in the thin surface layers and inflow right below the pycnocline. This is caused by the strong influence of numerous freshwater discharges from rivers in the sub-basins of Puget Sound. The circulation in Puget Sound is also known to be affected by winds and surface heat flux (Thomson et al., 2007; Tinis et al., 2006; Holbrook and Halpern 1982).

2.2 Hydrodynamic Model (FVCOM)

Puget Sound consists of over 4,100 km of complex shoreline, many islands, interconnected water waterways, and sub-basins. To represent these complex geometric features accurately and efficiently, we selected a 3-D unstructured-grid, finite-volume coastal ocean model (FVCOM) developed by Chen et al. (2003). FVCOM is a 3-D hydrodynamic model that can simulate tide, density-driven, and meteorological forcing-induced circulation in an unstructured, finite-element framework. 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. One advanced feature in FVCOM is that meteorological forcing can be directly specified using outputs from meteorological models.

The governing equations for continuity and momentum in FVCOM are in the following forms:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-\frac{1}{\rho_0}\frac{\partial P}{\partial x}+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right)+F_u \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1}{\rho_0}\frac{\partial P}{\partial y}+\frac{\partial}{\partial z}\left(K_m\frac{\partial u}{\partial z}\right)+F_v \tag{3}$$

$$\frac{\partial P}{\partial z}=-\rho g \tag{4}$$

where (x, y, z) are the east, north, and vertical axes in the Cartesian coordinates; (u, v, w) are the three velocity components in the x, y, and z directions; (F_u, F_v) are the horizontal momentum diffusivity terms in the x and y directions; K_m is the vertical eddy viscosity coefficient; ρ is density; P is pressure; and f is the Coriolis parameter.

The 3-D transport equations for temperature and salinity are:

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\frac{\partial}{\partial z}\left(K_h\frac{\partial T}{\partial z}\right)+F_T \tag{5}$$

$$\frac{\partial S}{\partial t}+u\frac{\partial S}{\partial x}+v\frac{\partial S}{\partial y}+w\frac{\partial S}{\partial z}=\frac{\partial}{\partial z}\left(K_h\frac{\partial S}{\partial z}\right)+F_S \tag{6}$$

where T and S are temperature and salinity, K_h is the vertical eddy diffusivity coefficient, and (F_T, F_S) are the horizontal thermal and salt diffusivity terms.

Temperature and salinity are related to density through the equation of state:

$$\rho = \rho(T, S) \tag{7}$$

The bottom friction is described by the quadratic law. FVCOM has been applied to study various physical processes in estuarine and coastal waters (Chen et al., 2006; Weisberg and Zheng, 2006; Isobe and Beardsley, 2006; Frick et al., 2007; Huang et al., 2008; Chen et al., 2008; Yang and Khangaonkar, 2008, 2009; Yang et al., 2010, Foremen et al., 2009; Shore, 2009).

2.3 Model Grid

An unstructured grid of FVCOM for Puget Sound was generated using bathymetric data from Puget Sound Digital Elevation Model (Finlayson et al., 2000). To simulate the circulation in Puget Sound and the northwest 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 in Canada. 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. Because of the presence of the San Juan Islands and waterways, the northern open boundary line was specified at the north end of Georgia Strait. While tide flats play important role in the estuarine circulation dynamics near the estuarine mouth, the primary objective of this modeling study was to investigate the performance of meteorological model outputs as surface forcing in a coastal ocean model for water temperature simulations. Therefore, the effects of shallow tide flats were not included in this model configuration, and the minimum water depth was set to 4.0 m below NAVD88. For modeling efficiency, 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 1,600 m considering that the entire

model domain and the average cell size in Puget Sound is 800 m. Thirty vertical layers with uniform thickness were specified in the water column in a sigma-stretched coordinate system.

2.4 Model Open Boundary Conditions

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 at north end of Georgia Strait. Tidal elevations are specified along the open boundaries using XTide predictions (Flater, 1996). Tidal elevations were assumed to be the same across the open boundaries and were specified at 15-minute intervals. Tidal range and mean elevation at the north end of Georgia Strait are greater than that at the entrance of Strait of Juan de Fuca because tides are amplified as the tides propagate from the Strait of Juan de Fuca into Puget Sound and Georgia Strait. Salinity and temperature open boundary conditions were specified based on the monthly profiles collected by the Department of Fisheries and Oceans, Canada, near the entrance of the Strait of Juan de Fuca and north Georgia Strait for year 2006. Salinity and temperature profiles were assumed to be the same at all the grid nodes along each open boundary.

Nineteen major rivers (including the Fraser River) that discharge into Puget Sound and the Straits were considered in the model. Most of the river inflow data were obtained from the USGS real-time stream flow gauges. For rivers that had no real-time measurements, river inflows were estimated by the Washington Department of Ecology using a scaling method based on watershed areas. All river inflows inside Puget Sound 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. In contrast, the Fraser River inflow, which is significantly higher than the rest of river

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.

3 Model Simulations

3.1 Simulations with Direct NARR Forcing

The focus of this paper is on the water temperature simulations using forcing from meteorological model outputs as opposed to relying on measured data from meteorological stations. Model results for tide, current, and salinity predictions have been presented in Yang et al. (2010) and are not repeated here. It is a great challenge to simulate the temperature distributions in estuaries and coastal waters such as Puget Sound compared to tide and current simulations because of the uncertainty associated with meteorological forcing and the complexity of density-induced baroclinic motion.

To simulate the temperature distribution in Puget Sound, wind stress and net heat flux are required to specify surface boundary conditions at the water surface. The meteorological input parameters for FVCOM 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 generally two approaches to specifying the meteorological forcing for temperature simulations in a coastal ocean model. The first approach is based on observed data at meteorological stations to obtain data on wind and other parameters to calculate the net heat flux. However, not all the meteorological parameters (such as solar radiation, humidity, air temperature, dew point temperature, cloud cover, etc.) are consistently measured at meteorological stations. Furthermore, there are often gaps in measured data. Therefore, it is problematic to reply only on

observed data for meteorological forcing in coastal ocean models for long-term simulations. The second approach to specifying meteorological forcing is to use advanced meteorological forecast model outputs that are available continuously over long time periods, such as MM5, NAM-WRF, and NARR. In this study, NARR data are used for meteorological forcing in the FVCOM model for temperature simulations.

NARR data are generated by the NOAA NCEP based on the regional meteorological model at a 32-km resolution. For simplicity, we selected NARR output at one single grid point close to the center of the model domain and applied the forcing uniformly to the entire model domain. The selected NARR data location is near Seattle, WA (see Figure 1). NARR data sets provide all the meteorological parameters required to calculate the net heat flux as model input in FVCOM. The total net heat flux H_{NET} is calculated based on the following formula:

$$H_{NET} = H_{SW} + H_{LW} - H_{SH} - H_{LH} \qquad (7)$$

where H_{SW} is the net shortwave solar radiation; H_{LW} is the net longwave solar radiation (including the longwave back radiation); H_{SH} is the sensible heat flux, and H_{LH} is the latent heat flux. Figure 2 shows the distributions of net shortwave and longwave solar radiation, the sensible heat flux and latent heat flux for the year 2006. The net shortwave radiation, the sensible and latent heat fluxes, shows strong seasonal variation with large values in the summer and low values in the winter. It should be noted that the negative values in sensible heat flux from NARR data represent heat transfer from the atmosphere to the water. The total net heat flux calculated based on Eq. (7) is plotted in Figure 3. We can see that in general, the net heat flux is the highest in the summer and the lowest in winter.

The hydrodynamic model of Puget Sound was run with a 10-second time step for the entire year of 2006 using the net heat flux calculated by Eq. (7) based on NARR outputs. All model input files were interpolated linearly into the 10-second intervals in the model during model simulations. A 1-year model run with 64 computational cores requires about 34 hours in real time. Due to the lack of long-term series temperature data, we compared model results to the monthly datasets collected by the Washington Department of Ecology. Model results at surface and bottom layers in the model were extracted for comparisons in three observation stations along the mains stem of Puget Sound: Admiralty Inlet (ADM), Central Puget Sound (PSB), and Nisqually at South Puget Sound (NSQ). Figure 4 shows the comparisons of surface and bottom temperatures between model results and observed data for year 2006. Data for January, July, November, and December were not available at Station ADM and PSB. The model was able to capture the seasonal variations from cooling in the winter and warming in the summer. In general, seasonal variations in temperature are small near the entrance of Puget Sound at Admiralty Inlet and increase gradually towards the south end of Puget Sound. However, it is noticed that the ranges of seasonal variations were under-predicted at all stations.

3.2 Evaluation of NARR Forcing

The results of water-temperature predictions with direct use of the original NARR outputs indicated that NARR meteorological forcing may under-estimate the net flux in Puget Sound for the period of 2006. This may be due to the relatively coarse resolution of the NARR outputs (32 km), and net heat flux calculated based on NARR outputs do not take into account the dynamic feedback of the water-surface temperature simulated in the hydrodynamic model. To evaluate this, we compared the NARR heat flux to the estimated net heat flux using real

observed data based on heat-exchange equations. The formulas used for the heat-exchange calculation between water and atmosphere are similar to those in the CE-QUAL-W2 model (Cole and Wells, 2009). In general, the net heat flux can be calculated based on the following formula:

$$\phi_n = \phi_{sn} + (\phi_{an} - \phi_{br}) - \phi_e - \phi_c \qquad (8)$$

The first term ϕ_{sn} in Eq. (8) is the net shortwave solar radiation defined as (Wunderlich, 1972):

$$\phi_{sn} = \left(2.044 \times A_0 + 0.1296 \times {A_0}^2 - 1.941 \times 10^{-3} \times {A_0}^3 + 7.591 \times 10^{-6} \times {A_0}^4\right) \times (1.0 - 0.0065C^2) \times 24 \times B_0 \qquad (9)$$

where C is the cloud cover ratio; A_0 is the solar altitude as a function of time and latitude; B_0 is the unit conversion factor. The second term ϕ_{an} in Eq. (8) is the incoming longwave radiation minus the reflected longwave radiation:

$$\phi_{an} = 0.97 \times 5.31 \times 10^{-13} \times (T_a + 273.15)^6 \times (1 + kC^2) \qquad (10)$$

where T_a is air temperature at 2 m height above water surface, and k is a constant. The third ϕ_{br} term in Eq. (8) is the longwave back radiation:

$$\phi_{br} = 5.51 \times 10^{-8} \times (T_s + 273.15)^4 \qquad (11)$$

where T_s is the water surface temperature. It should be noted that ($\phi_{an} - \phi_{br}$) is equivalent to the total net longwave radiation flux defined in NARR output. The fourth term, ϕ_e, in Eq. (8) is the latent (evaporation) heat flux:

$$\phi_e = f(W_z)(e_s - e_a) \qquad (12)$$

where $f(W_z)$ is the empirical wind speed function for heat flux; e_s is the saturated vapor pressure at water surface which is a function of dew point temperature; e_a is the vapor pressure of air measured at a distance 2 m above the water surface and is a function water surface temperature. The last term, ϕ_c, in Eq. (8) is the sensible (conductive) heat flux:

$$\phi_c = bf(W_z)(T_s - T_a) \qquad (13)$$

where b is the Bowen Constant, and T_s is the water-surface temperature.

Observed meteorological data at NOAA real-time stations were used to calculate the net heat flux [see Eq. (8) and Eq. (9) to Eq. (13)]. Measured air temperature, dew point temperature, water-surface temperature, and wind speed data at NOAA meteorological stations at Seattle and Tacoma were obtained. No cloud cover data were available at the NOAA meteorological stations, and therefore no cloud cover was assumed in the calculation. This implies that the net heat flux calculation would be over-estimated, especially in the Pacific Northwest region. Some missing data gaps in the datasets were filled with other observed data in the nearby meteorological stations or interpolated. A comparison of measured and NARR air temperatures is shown in Figure 5. It is seen that the NARR forecast air temperatures are in agreement with the NOAA observed temperatures in daily, weekly, and seasonal variations. Comparison of wind sticks between NOAA observed data and NARR outputs are shown in Figure 6. It is seen that the NARR wind speed output is generally in agreement with the observed data.

The calculated net heat flux based on NOAA observed data is compared to NARR outputs for the period of August 2006 (Figure 7). We can see a good correlation between the NOAA data and NARR data in daily variations with warming during the mid-day (positive heat flux) and cooling during the night (negative heat flux). However, it is also noticeable that the NARR outputs are smaller than the calculated net heat flux based on observed data. To further evaluate the range of seasonal variations for NARR net heat flux, we calculated the daily maximum and minimum distributions of net heat fluxes from NARR outputs and NOAA observations. Figure 7 shows that the NARR heat flux is lower than that calculated based on NOAA-observed data from late spring to the end of summer. It should be noted that the net heat flux-based NOAA-observed data are expected to be over-predicted because cloud cover was neglected in the calculation,

which is an important factor to consider in the Pacific Northwest coast. It is also noted the estimated net heat flux becomes lower than the NARR output after October, which may explain the over-prediction of water temperatures in the later part of the year in Station NSQ (Figure 4).

3.3 Simulations with Improved NARR Forcing

Based on the comparisons of NARR and observed net heat flux distributions, we increased NARR heat flux by 15% after trial and error sensitivity tests were conducted. We also replaced the NARR net heat flux values with observed data in October, November, and December. The model then was re-run with the modified meteorological forcing. Figure 9 shows new model results for predicted surface and bottom water temperatures at Stations ADM, PSB, and NSQ. Compared to Figure 4, the level of agreement between model results and observed data was much improved. The model was able to reproduce the seasonal variations in temperature from fully mixing in early spring (February to April), development of stratification in the summer and early fall (June to October), and final turnover in the winter (November and December) where surface temperatures were colder than bottom temperatures. Furthermore, the model also successfully predicted the spatial variations of stratification observed in the data. For example, temperature stratification at the entrance of Puget Sound (Station ADM in Admiralty Inlet) is greater than that at the central Puget Sound (Station PSB). Towards the south end of Puget Sound (Station NSQ), stratification increased again, and seasonal variations became more evident. Model results also showed that temperatures (especially bottom temperatures) increase from the entrance of Puget Sound to the South Puget Sound, consistent with observed data.

4 Summary

In this paper, an approach that uses advanced meteorological forecast model outputs to drive a coastal ocean model for hydrodynamic simulation, including water temperature, was investigated. The simulation of water temperature as part of the hydrodynamics in estuarine and coastal modeling is still not done as routinely as is salinity in actual practice. This is partially because of the assumption that density-induced baroclinic motion is more dominated by the salinity gradient than the temperature gradient. Another important factor that limits the application of water-temperature simulation in estuarine and coastal hydrodynamic modeling is the lack of complete meteorological forcing data, such as wind, solar radiation, and heat fluxes. In large estuarine systems such as Puget Sound and the northwest straits, the effect of temperature on baroclinic circulation could become as significant as salinity when surface heat changes play an important role in temperature variations. The availability of advanced meteorological model outputs has made it possible and practical to conduct long-term simulations of water temperature in coastal modeling. The North American Region Re-analysis (NARR) outputs produced by NOAA on a continuous basis were linked to the Puget Sound hydrodynamic model constructed based on FVCOM in this study to simulate a year-long (2006) water-temperature distribution in Puget Sound. Comparisons of NARR outputs and observed data indicated that some parameters of NARR outputs, such as air temperatures, are quite consistent with the observed data while heat fluxes taken directly from NARR tend to be lower than required for matching observed temperature data for the study period in Puget Sound. Although uncertainties exist in NARR outputs and the outputs are in 3-hour intervals, the hydrodynamic model driven with NARR data showed good agreement of predicted water temperatures with observed data over a full-year cycle in Puget Sound. Additional modeling

analysis also indicated that meteorological model outputs, such as from NARR, can be improved with some guidance from real observation if available to improve the accuracy of model predictions of water temperatures. While this study provides a useful approach to modeling estuarine circulation and water temperature using the meteorological model outputs combined with real observation, more work is needed to further improve the accuracy of the model prediction for coastal water temperatures. For example, heat flux outputs from meteorological models are not directly coupled to the water temperatures in the coastal ocean models in temperature simulations. A potential improvement is the inclusion of feedback of water temperature in the heat-exchange calculations in the coastal ocean model with meteorological parameters instead of heat fluxes from meteorological model outputs. Other potential improvements include using satellite sea surface temperature images to provide more data for model validations and to implement spatial varying meteorological forcing using higher resolution meteorological model outputs such as NAM-WRF (in 12-km resolution).

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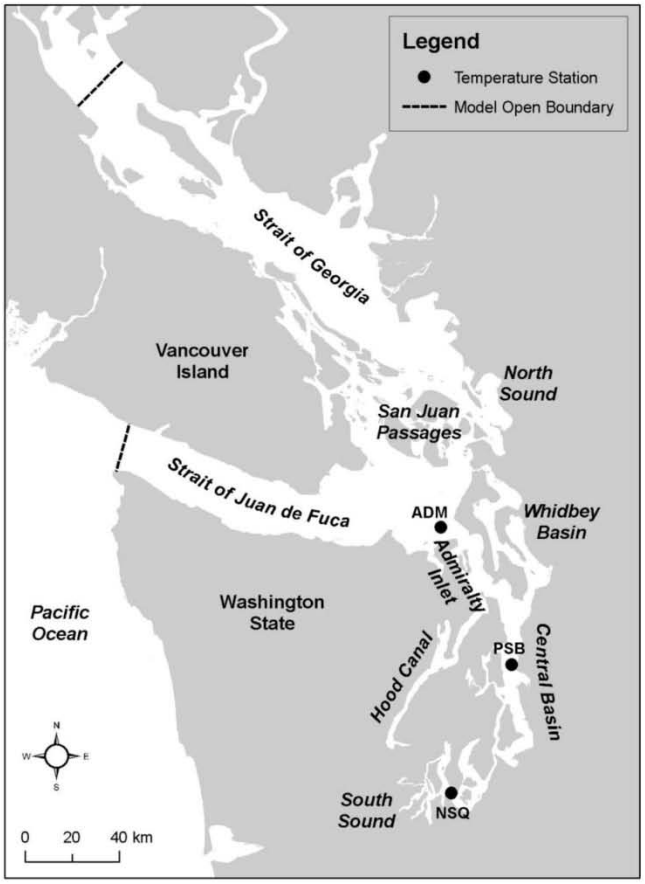

Figure 1. Study Domain - Puget Sound (update with new station – ADM, PSB, NSQ)

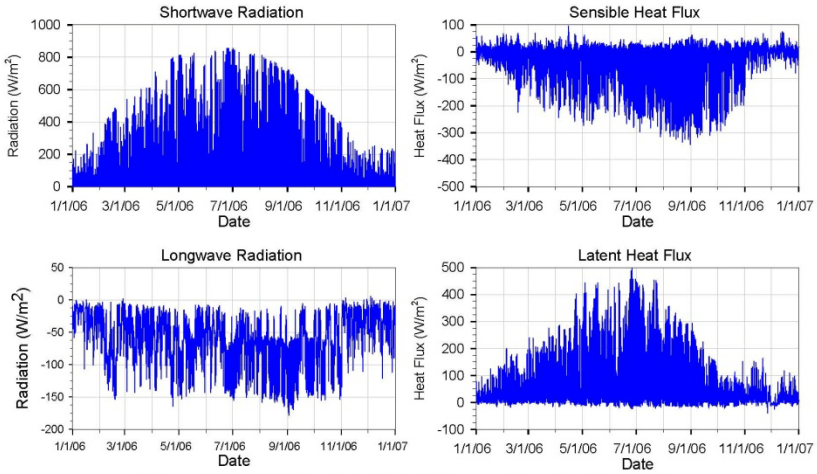

Figure 2. NARR Predicted Heat Fluxes Near Seattle, WA

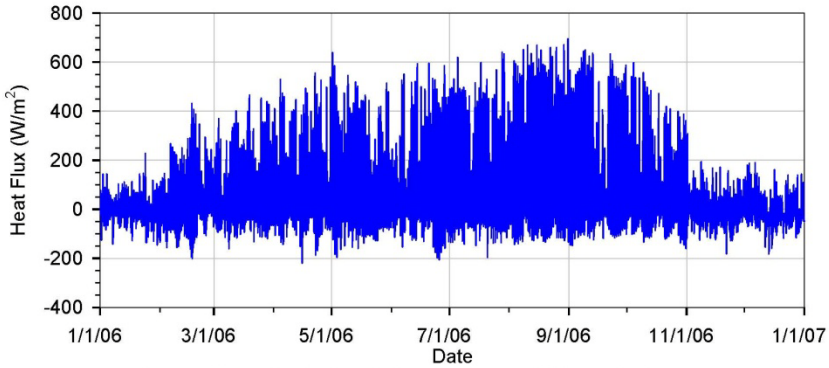

Figure 3. Net Heat Flux Calculated from NARR Outputs

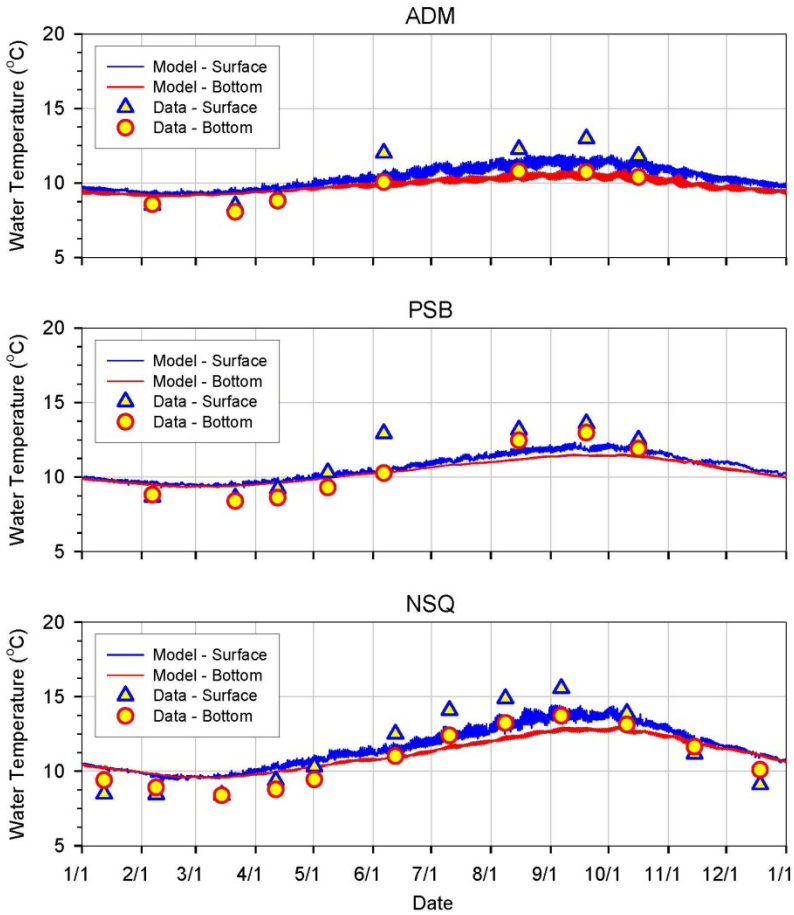

Figure 4. Comparisons of Modeled and Observed Temperatures at three locations in Puget Sound with NARR Forcing

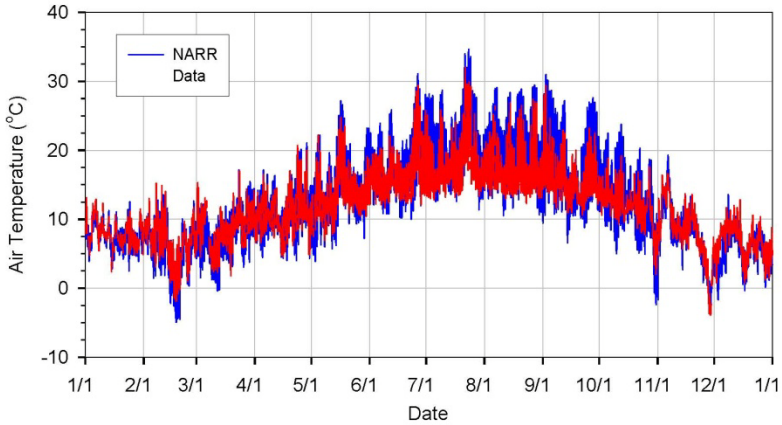

Figure 5. Comparison of NOAA Observed and NARR Air Temperatures at Seattle, WA

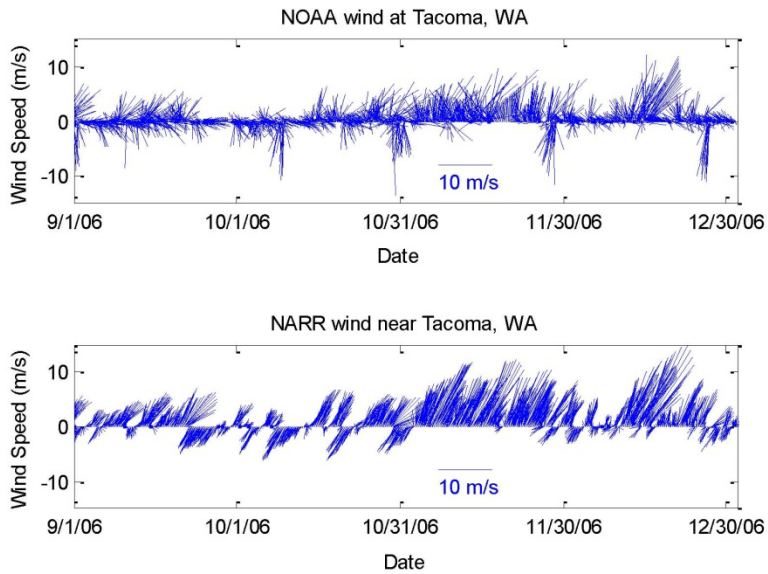

Figure 6. Comparison of NOAA Observed Wind Data and NARR Wind Output

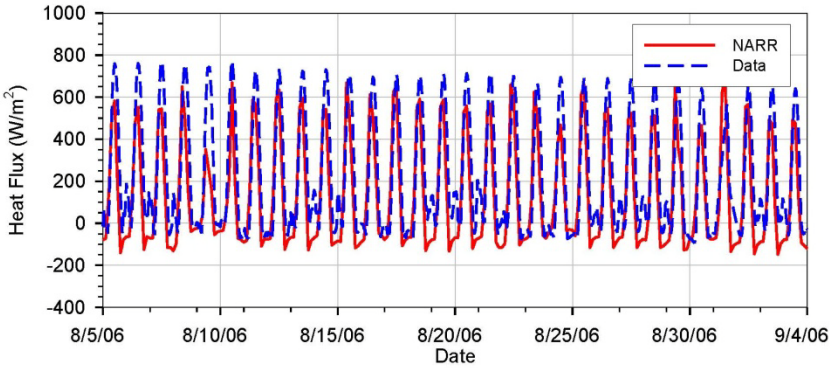

Figure 7. Comparisons of Net Heat Fluxes Calculated from NARR Outputs and Field Observed Data in Seattle Station

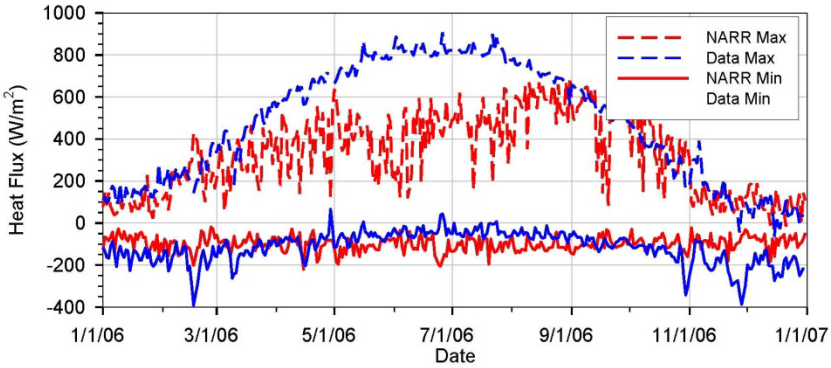

Figure 8. Daily Maximum and Minimum Net Heat Flux

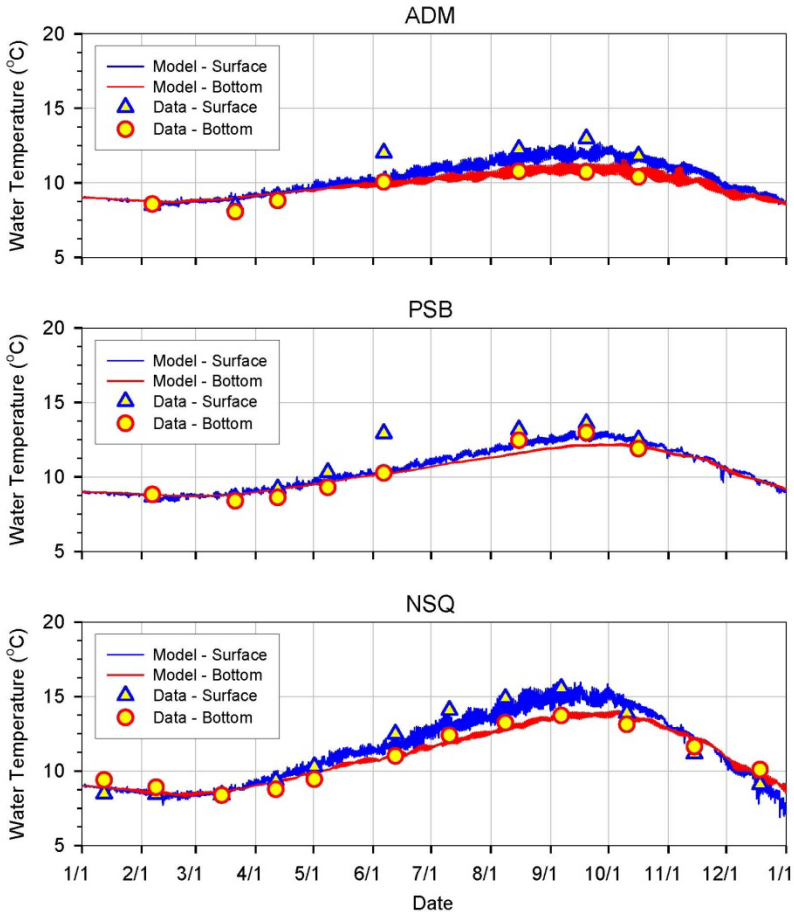

Figure 9. Comparisons of Modeled and Observed Surface and Bottom Water Temperatures in Puget Sound with NARR and Observed

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