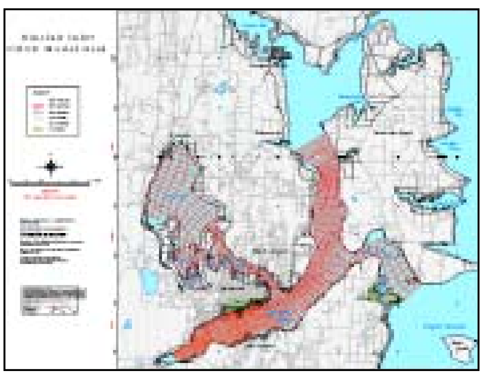
A Hydrodynamic Modeling Study Using CH3D For Sinclair Inlet

November 3, 1999



Prepared For:
Puget Sound Naval Shipyard Project ENVVEST

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ADMINISTRATIVE INFORMATION

A HYDRODYNAMIC MODELING STUDY USING CH3D

FOR SINCLAIR INLET

FINAL REPORT
PREPARED FOR
PUGET SOUND NAVAL SHIPYARD,
BREMERTON, WASHINGTON

BY

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1. Introduction

The Puget Sound Naval Shipyard (PSNS) is located in Bremerton, WA, adjacent to Sinclair Inlet, which is home port to a large fraction of the U.S. Navy's active fleet. The Inlet is primarily a sub-basin of the Puget Sound estuary system (Figure 1). PSNS is a large industrial facility that provides support for ships and service craft and performs construction, conversion, overhaul, repair, alteration, dry docking, decommissioning, and outfitting of ships (SIWMC, 1994). These operations produce wastes, such as metals, and organic materials, which enter the Inlet as runoffs, seepage and fugitive losses.

Compliance with the Non-Point Discharge Elimination System (NPDES) Permit effluent limitations has become increasingly difficult for the shipyard, due to more stringent regulatory requirements. Regulatory guidance encourages a science-based quantitative approach to determining effluent discharge limitations by considering processes, such as contaminant transport and dispersal, bioavailability and assimilative capacity, that govern the fate and transport of contaminants. During the past 10 years, maturity of technology and knowledge in the environmental science has made this approach viable and effective in determining Total Maximum Daily Loads (TMDLs). Adoption of this quantitative approach for TMDL and discharge permit issues has been widely accepted by regulators.

In order to provide technical support for the WaTER Project, SPAWAR Systems Center San Diego (abbreviated as SPAWAR, hereafter) was tasked to develop a risk-based approach to mapping, understanding and estimating cause-and-effect relationships between the quality of the receiving Inlet water and external contaminant loads to the Inlet. This approach was developed using numerical models that simulate fate and transport of contaminants that originate from the watershed (non-point), the shipyard (point source) and other sources to the receiving Inlet water. This modeling approach is, in fact, consistent with EPA's current emphasis on watershed management, ambient monitoring, TMDLs, and ecological risk assessment.

In this approach, a linked watershed management approach including the uses of contaminant fate and transport modeling and ecological risk assessment will be adopted. The linked watershed modeling framework includes integration of the watershed contaminant loading model (HSPF-EPA), the 3-D hydrodynamic model (CH3D-WES) and the water quality model (WASP-EPA model) for the Inlet water (Figure 2). First, contaminant loads from watershed runoff are estimated by HSPF (EPA, 1994). Watershed loads, along with estimated point source loads from the shipyard, Publicly Owned Treatment Works (POTW), and other sources, will be input to the transport (CH3D) and fate (WASP) models. The watershed model, HSPF, and the contaminant kinetic model, WASP, for Sinclair Inlet will be developed and integrated within the next year. The integrated watershed/water quality model will be used to estimate TMDLs for contaminants of concern in the Inlet. The integrated model will be also used to predict and assess impacts of various loading scenarios (e.g., designed load reductions from various sources) on the Inlet water quality conditions.

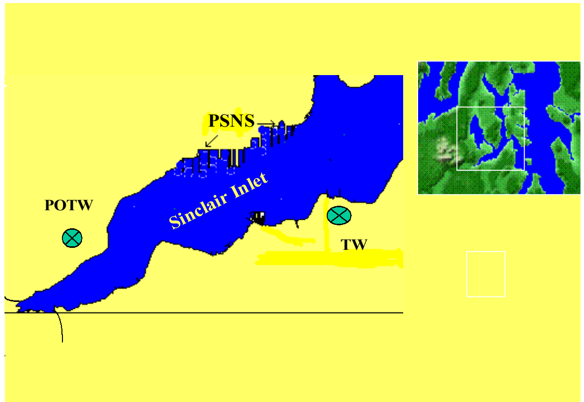

Figure 1. Sinclair Inlet and adjacent water bodies

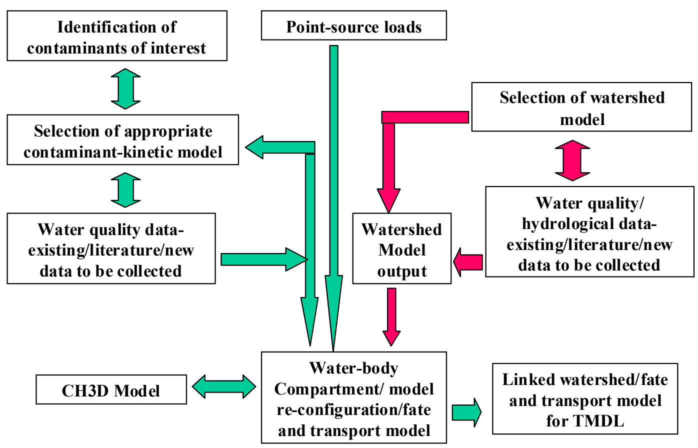

Figure 2. Linked watershed modeling framework of TMDL for Sinclair Inlet

In the same modeling framework, the three-dimensional hydrodynamic model, CH3D, was developed to predict tides and currents of the Inlet. CH3D was calibrated against field hydrodynamic data, including water heights and water column currents measured at fixed locations inside the Inlet. Field-data mapping surveys were conducted by SPAWAR scientists to measure hydrodynamic and water quality parameters inside the Inlet and the adjacent water bodies. Measured tides and currents were used to calibrate and validate CH3D. The calibrated CH3D predicts tides and currents in Sinclair Inlet, Dyes Inlet and portions of the two passages: Port Orchard and Rich Passage. The calibrated CH3D will be linked with the HSPF (watershed) and WASP (water quality) models for TMDLs study of Sinclair Inlet. Development of both HSPF and WASP and their linkage with CH3D for Sinclair Inlet will be conducted during the next fiscal year (2000). This report summarizes results of the development and calibration of CH3D.

2. Study Goals

As part of the linked watershed and water quality modeling framework, a numerical model simulating and predicting fate and transport of contaminants in Sinclair Inlet and the adjacent water bodies needed to be developed. For this, the 3-dimensional hydrodynamic model, CH3D, was developed and calibrated using both historical tides and current data collected by National Oceanic and Atmospheric Administration (NOAA) and U.S. Geological Survey (USGS) prior to 1994 and by SPAWAR during 1997-1998.

3. Study Area

Sinclair Inlet, located in Bremerton, WA, is a semi-enclosed water of ~6 km long in the SW-NE direction and ~2 km wide (Figure 1). To the northwest, the Inlet connects, through a narrow channel, to Dyes Inlet, which is also a semi-enclosed water body with a surface area three times that of the Sinclair Inlet. Further east, Sinclair Inlet connects to Puget Sound through Port Orchard Passage to the north and Rich Passage to the southeast. Compared to Puget Sound, which is a Fjord type of estuary, Sinclair Inlet is relatively shallow; depths in the Inlet vary from over 10 meters in the naval piers near the mouth connecting to Dyes Inlet to 1-4 meters in the southwest regions. Portions of the extreme southwestern regions are subject to wet/dry exposure during tidal cycles. Depths along the two passages increase toward Puget Sound with maximum depths reaching ~25 meters in the two passages.

Sinclair Inlet receives treated sewage discharges from POTWs that serve the cities of Bremerton and Port Orchard. Treated and untreated runoffs enter the Inlet from a number of storm drains distributed around the shoreline. Contaminants from the shipyard operations enter the Inlet by ways of runoffs, seepage and fugitive losses. The impacts on water quality, including bottom sediments and sorbed contaminants, in the Inlet from these external contaminant sources are not well known.

3.1. Hydrodynamics

Flows in Sinclair Inlet are governed primarily by tides that propagate from the Pacific Ocean into Puget Sound and then into the Inlet through two narrow passages, Port Orchard in the north and Rich Passage in the southeast. Tides in the Puget Sound region are semi-diurnal and diurnal mixed modes with two high and two low tides every diurnal cycle (24.8 hours). Once reaching the entrances to the two passages and into the Inlet, the tides are further modulated in a nonlinear fashion by a number of forcing mechanisms, including freshwater inflows, wind, water depth variations and waterbody geometry. Tidal flows in the Inlet are modulated both spatially and temporally, with maximum tidal ranges (from low tide to high tide) reaching 5.5 meters during spring tides.

Freshwater enters into Sinclair Inlet from four small creeks: Gorst Creek, Anderson Creek, Ross Creek and Blackjack Creek (Figure 1). There are several (about 20) smaller creeks discharging freshwater to the Inlet. The Bremerton and Port Orchard POTWs discharge treated sewage effluent into the northern and southwestern near-shore regions. Storm drains distributed around the shores of the Inlet also discharge untreated storm water into the Inlet during rainy seasons.

3.2. Weather

Sinclair Inlet is located at 122.67^0 W and 47.55^0 N, close to the Pacific Ocean. Rainfall concentrate during the months of November-March with an average precipitation of 50 in/yr. The average air temperature ranges between 70-80 degrees Fahrenheit during the day and 40-50 degrees Fahrenheit during the night. The Inlet is surrounded by the Olympic Mountains, the Cascade Range and the mountains of Vancouver Island. Wind in the Inlet region is low, with an average speed less than 5 m/s. Gust winds seldom exceed 10 m/s. Long-term data show that winds are predominantly from the southwest and northeast quadrants. during fall and winter. The spring and summer are characterized by northwesterly wind (Figures 3 and 4).

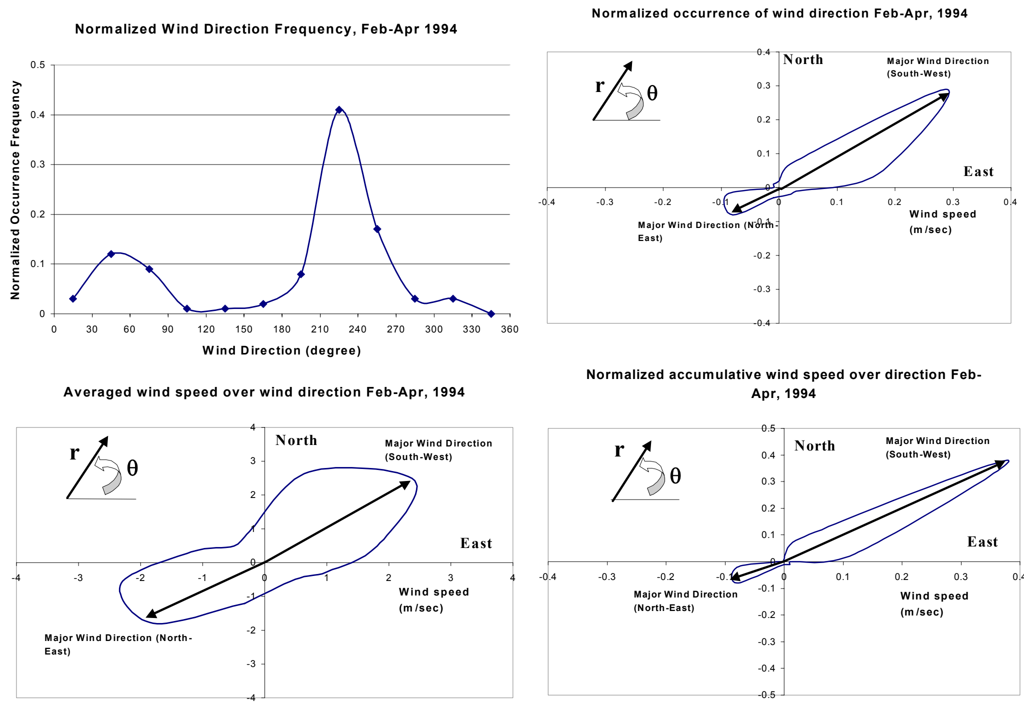

Figure 3. Wind speed and direction for Feb-Apr, 1994

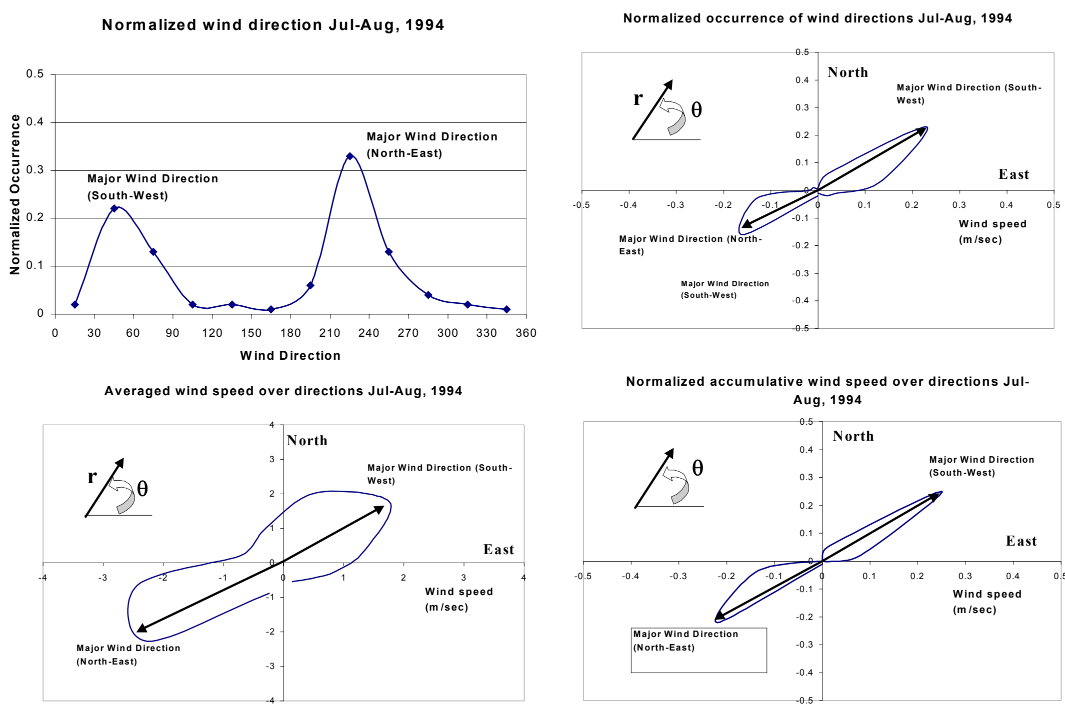

Figure 4. Wind speed and direction for Jul-Aug, 1994

4. External Loading Sources

Potential contaminant loading to Sinclair Inlet can originate from a variety of sources broadly defined as either point source or non-point source.

4.1. Point Source Loading

- Bremerton Publicly Owned Treatment Work (POTW)- Located on the north shore of Sinclair Inlet, the Bremerton POTW discharges approximately 6.5 million gallons per day (MGD) of treated effluent based on daily flow rates obtained by SSC SD (1997-1998 flow data).
- Port Orchard Waste Water Treatment Plant- Located on the south shore of Sinclair Inlet, the Port Orchard POTW discharges approximately 1.9 MGD of treated effluent based on daily flow rates obtained by SSCSD (1997-1998 flow data).
- Puget Sound Naval Shipyard (PSNS) Drydocks- There are six drydocks at PSNSY that are cross connected to four outlets. Average Jan 1997-Sep 1998 de-watering flows are presented in Table 1. Drydock de-watering is an episodic event depending on operational requirements.

Table 1. PSNSY Drydock flow.

	Drydock 1-5			Drydock 6
	018A	**018B**	**096A**	**19A**
Averaged flow (MGD)	0.7	2.1	0.1	4.8
Days operated during this period *(out of 93 days from Jan 97-Sep98)*	67	79	32	92

- Naval Vessel Sources A number of contaminants have been identified as resulting from naval vessel operation by the Uniform National Discharge Standards (UNDS) program. SSC SD has reviewed the discharges below with the greatest potential for environmental impact based on passive leaching or large system flow rates:

-Vessel Hull Anti-Fouling Paint Leachate
-Vessel Seawater Cooling Discharge
-Vessel Firemain Discharge

Copper, a dominant contaminant in these discharges, has been reported by SSC SD as a significant loading term in U.S. Navy homeport harbors primarily from anti-fouling paint leachate and seawater cooling (Johnson et al, 1998). The Shipbuilding Support Office, Naval Sea Systems Command identified seven active surface vessels and 22 inactive surface vessels that berth at the PSNSY. Table 2 contains the results of the preliminary analysis for naval vessels homeported at Bremerton.

Table 2. Preliminary SSC SD copper loading estimates for naval vessels homeported in Bremerton, WA.

	Annual Cu load (kg/yr)		
Source	Hull Coating leachate *	Seawater Cooling Discharge **	Firemain Discharge **
Active Surface Vessels	1,405	613	60
Inactive Surface Vessels	341	n/a	n/a

* Leach rate of 17 μg/cm^2/day used for active vessels and 1 μg/cm^2/day used for inactive vessel.

** These systems are not operational on inactive vessels.

Further contaminant analysis on a vessel class by vessel class basis is ongoing.

- <u>Civilian Small Boat Hull Leachate</u> Leachate from anti-fouling paint applied to the hull bottoms of civilian small boats is another copper source common to many harbors. Currently, SSC SD is working on obtaining exact boat counts for in-water pleasure craft in Sinclair Inlet.

4.2. Non-point Source Loading

- PSNS Stormwater runoff- Stormwater
- Non-Navy Stormwater runoff-
- Runoff and seepage flows from PSNS- Runoff and seepage are those flows that enter Sinclair Inlet from U.S. Navy property via sheet flow or direct seepage vice stormwater outlets.
- Runoff and seepage flows from Non-Navy Property-
- Riverine inflows from three Creeks-
- Atmospheric deposition-
- Sediment Flux- There is no current loading term for copper flux into or out of marine sediments. Sediments may act as a sink for copper in many urbanized harbors, and have been shown to release previously bound copper back into the water column depending on sediment conditions (Chadwick et al, 1993). However, there are little data regarding overall harbor-wide copper budgets. Chadwick et al (1993) found that while some sediment sites serve as copper sinks others act as copper sources. This observed effect was a site-specific feature and would require detailed harbor sediment sampling to accurately estimate harbor-wide contributions.

5. Hydrodynamic Field Data and Data Collection

At mid-latitude (~47^{o} N), tides in Sinclair Inlet are mixed diurnal and semi-diurnal types. To account for spring-neap tidal variations, time series data collection should cover at least 15 days, preferably 30 days. Harmonic analysis was used to extract the harmonic constants (amplitude and phase of tidal constituents) from sufficiently long time series. Harmonic analysis is based on the assumption that tides and currents are driven by, and therefore, composed of astronomical tidal constituents, which have known tidal frequencies. Amplitudes and phases of these tidal constituents, extracted from the time series using harmonic analysis, are the harmonic constants for the corresponding tides. These harmonic constants were used to estimate variations of tides and tidal currents in Sinclair Inlet for any specified time (Foreman, 1977, 1978, and Cheng and Gartner, 1985).

5.1. USGS Historical Data, 1994

Historical hydrodynamic data in Sinclair Inlet were scarce before 1994. NOAA has a tide gauge at Bremerton gathering tide data over several time periods since 1969. In 1994, USGS conducted two deployments using Acoustic Doppler Current Profilers (ADCPs) to measure water-column currents at three locations in the Inlet. The first deployment spanned February 16 – April 4 and the second deployment was July 28-August 29, 1994 (Figure 5, Table 3). During the first deployment, a broadband ADCP was deployed at the east station (EAST1, depth = 17 meters); one narrow-band ADCP was deployed at the west station (WEST1, depth = 13 meters) and the central station (CENT1, depth = 14 meters). At each station, a upward-looking ADCP sat on the bottom and took measurements throughout the water column. The broadband ADCP at EAST1 measured currents every 0.5 meter in depth, with the first bin at 1.9 meter above the bottom and the last bin at 1 meter below the surface. The narrow-band ADCPs at the west (WEST1) and central (CENT1) stations measured currents every 1 meter in depth, with the first bin at 2.2 meters above the bottom and the last bin at 1 meter below the surface. Water column currents at these 3 stations were measured at every 10 minutes.

The second deployment (July 28-August 29) was conducted at the same three sites as the February-April deployment. However, the two narrow-band ADCPs at the west (WEST2) and central (CENT2) stations were replaced by two broad-band ADCPs, whereas the ADCP at the east station (EAST2) remained unchanged. Currents were measured every 0.5 meters in the water column at a frequency of 15 minutes. Besides the current data, tides in Sinclair Inlet were also measured during each of the two 1994 deployments. Both the tide data and the 3-dimensional current data were used for model calibration and verification, to be discussed later.

5.2. SPAWAR recent data collection 1997-1998

Both water quality parameters and hydrodynamic data were measured during three surveys. The details of these three measurements and results are discussed in a separate report (field study) and will not be repeated here.

The comprehensive data collection program, conducted by SPAWAR during 1997-1998, consisted of a series of surveys employing a ship-mounted, downward-looking ADCP, a fixed tide gauge and stationed upward-looking ADCPs. The mapping surveys were conducted during three periods: September, 1997; March and July of 1998. During each survey, a ship mounted downward-looking ADCP measured current velocities at 1 meter depth interval every 10 seconds. These current data were measured along the track of the moving boat, such as the one shown in Figure 6.

During the fall survey of 1997, SPAWAR deployed a upward-looking broad band ADCP at Station SPA-1 (Figure 5), measuring currents at every 0.5 meter in the water column every 15 minutes during September 17-October 15. The same ADCP was deployed at Station SPA-2, measuring water-column currents between November 25 and December 31. The latest ADCP-deployment was conducted at Station SPA-3 during

June 11-July 19, 1998. These ADCP current data, measured at fixed locations for periods over 30 days, were used for model calibration and verification. The boat-tracking ADCP data were used for further comparison with model results.

Table 3. Currents measurement deployments from 1994-1998

Deployments	Periods	Conducted By	Depths
East Station	2/4-4/4, 7/28-8/29, '94	USGS	17 meters
Central Station	2/16-4/4, 7/28-8/29, '94	USGS	14 meters
West Station	2/16-4/4, 7/28-8/29, '94	USGS	14 meters
SPA1	9/15-11/20, '97	SPAWAR	13 meters
SPA2	6/11-7/19, '98	SPAWAR	23meters

6. Numerical Model and Model Configuration

The numerical model, CH3D, standing for Curvilinear Hydrodynamics in Three Dimensions, was chosen for the test-bed modeling study of Sinclair Inlet. CH3D is a mathematical 3D time-varying hydrodynamic model, which was developed by the Waterways Experiment Station, ACOE, Vicksburg, MS, for the Chesapeake Bay study (Johnson et al., 1991). The Chesapeake Bay Program, established in 1983, aimed to develop strategies to reverse the decline of the quality of the Bay water. Over the past decade, CH3D, along with a water quality sub-model, was used to predict flow and transport in the Bay, providing a detailed assessment of the system's response to nutrient inputs and other parameters over time and space.

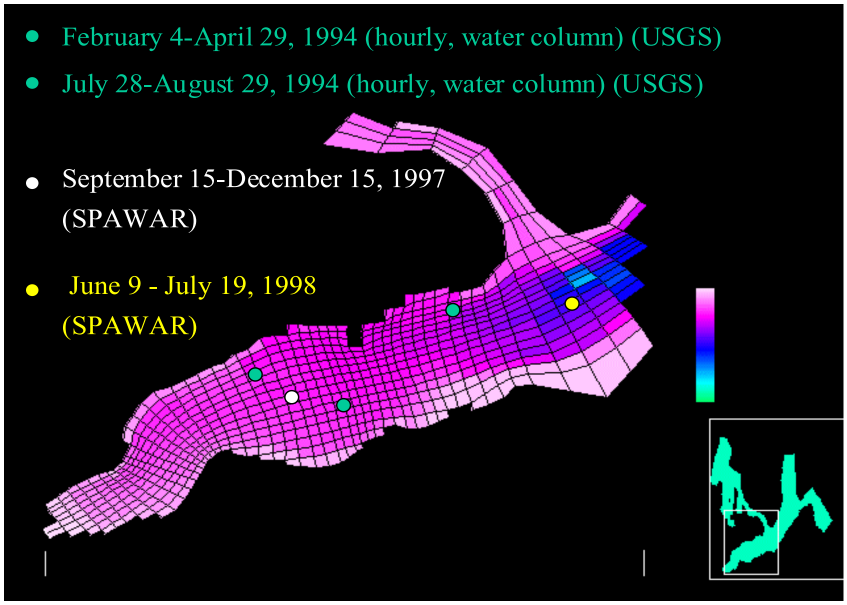

Figure 5. Tide and current measurement locations from 1994-1998

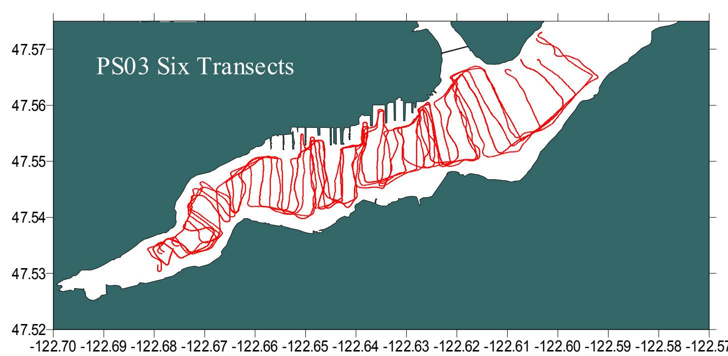

Figure 6. Typical trajectory of boat measuring water-column currents

The governing equations in CH3D are the shallow-water equations transformed into the curvilinear plane. Several assumptions are made in the model formulation, including the hydrostatic (shallow water) approximation, the Boussinesq approximation, and incompressibility. As with any numerical model, the model domain is divided into many small numerical grid cells. It is assumed that hydrodynamic properties (velocity, density) are constant within each cell. Horizontal density gradients in the momentum equations are treated explicitly. Bottom shear stress is approximated using a Manning-Chezy formulation with Manning's n coefficient assigned as a function of local water depth. It is further assumed that the direction of bottom shear stress is exactly opposite to the depth-averaged velocity.

For transport of conservative solutes, a transport equation is solved for each additional conservative species, C_i. Solutes are assumed to be dilute, thus the solute transport equations are uncoupled from hydrodynamics. Furthermore, the transport equation is solved at one time step behind the continuity and momentum equations, effectively uncoupling the transport equation (Wang et al., 1998). This approach is valid because baroclinic forcing changes less rapidly than barotropic forcing.

All variables in CH3D are defined on a staggered grid. Water surface elevation, salinity and solute concentrations are defined at the center of a grid stencil (i,j), while the *U* velocity is defined at (i+1/2, j), the *V* velocity at (i, j+1/2), and water depths at (i+1/2,j) and (i,j+1/2).

CH3D uses curvilinear boundary-fitted numerical grids in the horizontal plane. In the vertical direction, the water column is divided into multiple layers of equal thickness, with the number of layers varying from over 10 layers for deeper regions to one layer for extremely shallow regions (depth < 3 meters). CH3D solves the time-dependent differential equations for water surface displacement ($\varsigma(x,y,t)$), and 3-D velocities ($u(x,y,z,t)$, $v(x,y,z,t)$), temperature, salinity and density. CH3D is capable of handling a variety of external forcing, including tides, winds, tributary flows, point and non-point sources, as well as baroclinic effect due to density differences between freshwater inflows and saline Inlet water. CH3D accounts for the wind field, which introduces shears over the water surface, driving water mass transport in addition to tidal forcing. Flows in the Inlet are driven at the model boundaries. The k-ε turbulence closure scheme is used to estimate the vertical diffusivity, a parameter governing the mixing in the water column.

We obtained historical tide data at Clam Bay and Brownsville from NOAA. These NOAA tide data were collected during early 1970s and were recorded in hard copy only, there is no background descriptions about how these data were collected. We analyzed these data and found that these tide data contained large phase errors. Therefore, these data were discarded and not used for our study. Instead, tides at Clam Bay and Brownsville were generated using the software TIDE1, which is a commercial product capable of predicting tides at several locations inside Puget Sound, including Clam Bay and Brownsville. Generated tides were processed and harmonic constants of 16 major tidal constituents were extracted. The extracted tidal harmonic constants were modified to reproduce tides for two periods, February-April, and July-August, 1994, during which tides and currents were measured inside Sinclair Inlet. Hourly, winds measured inside the Inlet, were applied over the entire model water domain.

Using a grid-generation program, we generated curvilinear model grids with grid cells of different sizes, ranging from 40-100 meters inside the Inlet to over 200 meters in Port Orchard and Rich Passage (Figure 7). Model results based on such variable grid cells provide currents and contaminant transport with finer resolutions inside the Inlet. Resolutions, and thus model accuracy, outside the Inlet are sacrificed, due to the coarser grid cells in those areas. Model time-step is partially limited by the small grid cells inside Sinclair Inlet and a time step of 60 seconds was used in the model, which produces stable results over all the simulation periods.

While grid cells vary in the horizontal direction, grid size (Δz) in the vertical direction (water column) is fixed with $\Delta z=3$ meters. Such grid size was chosen based on model experiment results and the fact that tidal amplitudes in the Inlet are large, reaching 2.8 meters during Spring tides. For $\Delta z < 3$, model runs would become unstable for periods of very low tides when surface grid cells become exposed. The grid size of 3 meters was chosen to always keep the surface layers wet even during the lowest Spring tides.

CH3D was set up to simulate tides and currents measured by USGS during February-April and July-August, 1994. Model results were compared with the measured data for the first period (February-April) for model calibration. Field data of July-August were used for model verification. The calibrated CH3D provides flow transport (currents) for contaminants entering into the Inlet from the multiple external sources.

6.1. Model Calibration

Tides collected at the three stations in Sinclair Inlet during February-April 1994 were used for CH3D model calibration. Model simulations were conducted for February 16-April 4, 1994, during which tide and currents were measured at three locations in Sinclair Inlet. After a 2-day model "spin-up", 47-days of time-series of simulated tides and currents at the three USGS stations were saved for harmonic analysis. Amplitudes and phases of four major tidal constituents (M_2, K_1, O_1, and S_2) from harmonic analysis of model results are tabulated and compared with the respective values from field data (Table 4). Differences between measured tides and model results are less than 5 cm for M2 and 3 cm for K1 amplitudes; and less than 2^o for tidal phases for both tidal constituents. A phase of 1^o is equivalent to about 2 minutes for semi-diurnal (e.g., M2) tides and about 4 minutes for diurnal (e.g., K1) tides. Figures 8a and 8b show the time-series comparisons of tides between model and measurement. They show mixed diurnal and semi-diurnal tides and the spring-neap tidal cycle, which typically has a period of about 2 weeks.

The harmonic constants of the measured tides at the three stations which are physically close to each other, are different, although the differences are small. These differences may be attributed to measurement errors and the interpolation approximation embedded in the harmonics analysis program.

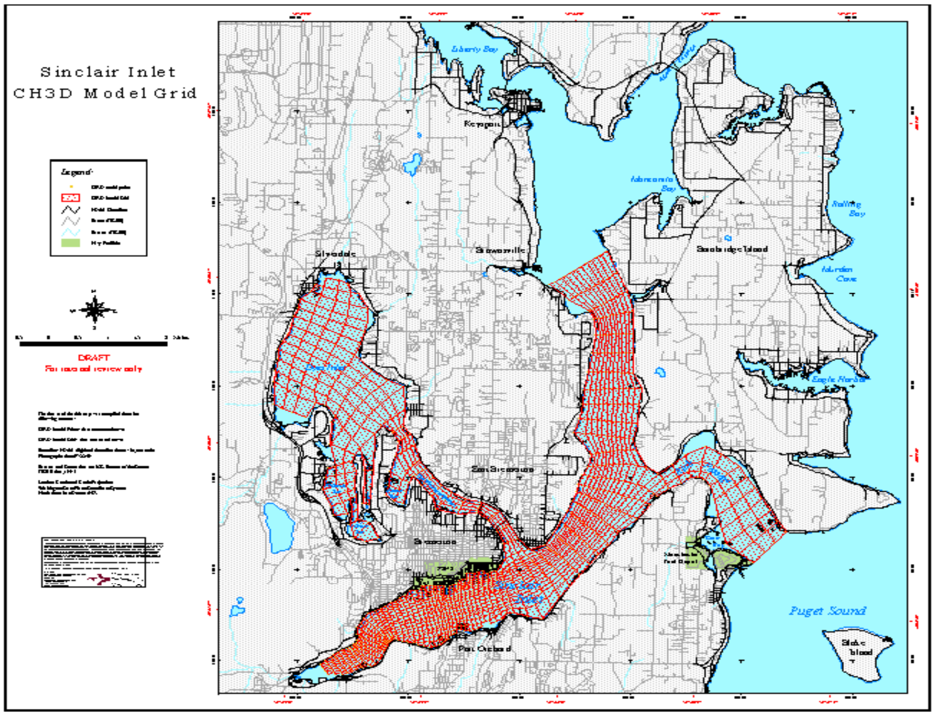

Figure 7. Numerical grids in Sinclair Inlet

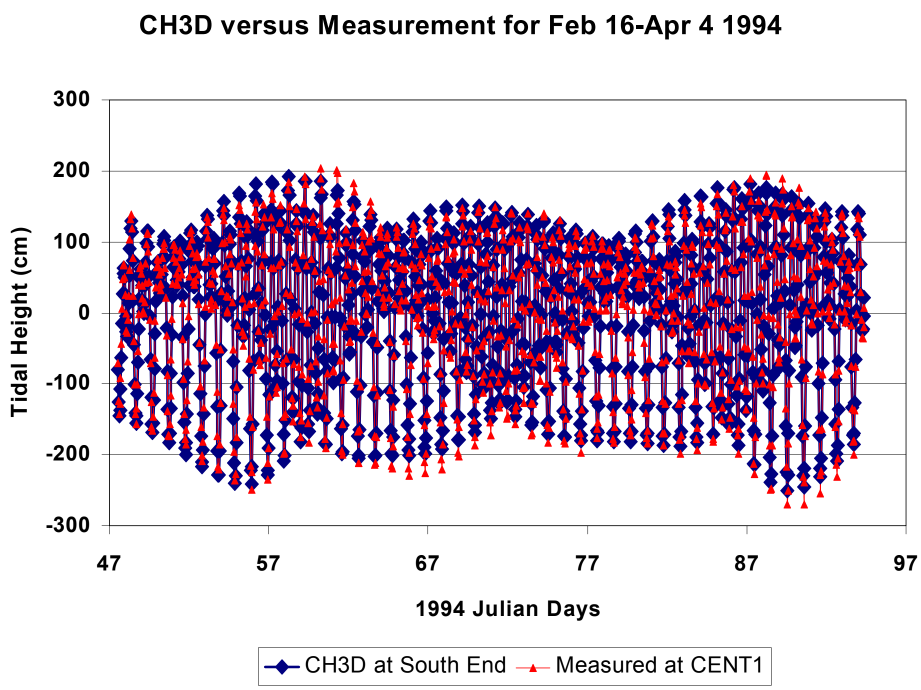

Figure 8a. Comparison of tides between CH3D-prediction and measurement

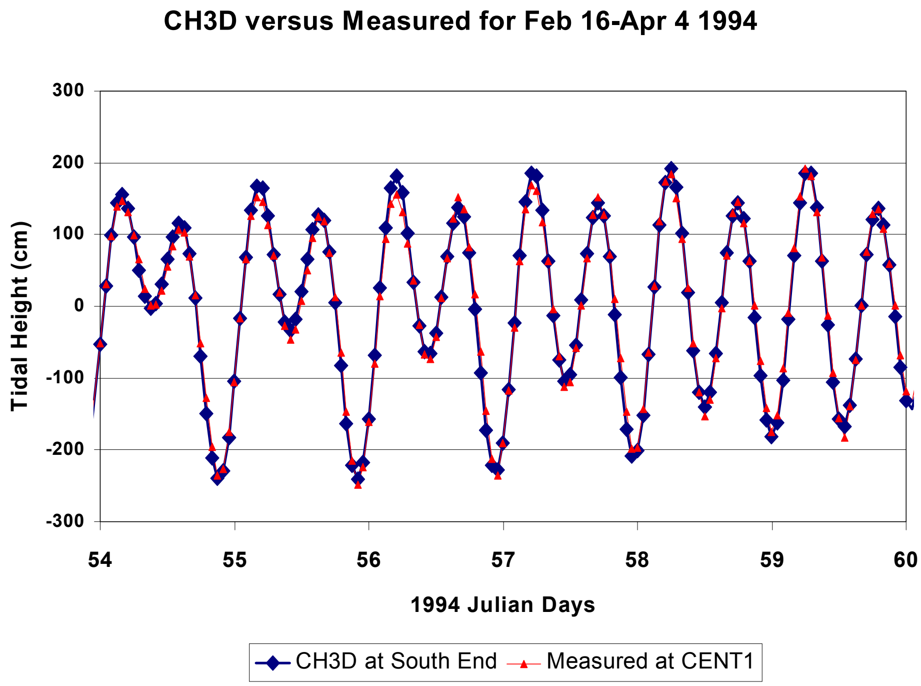

Figure 8b. Comparison of tides between CH3D-prediction and measurement

Table 4. CH3D-Model Calibration of Water Surface Elevation (February, 1994)

	M2		S2		K1		O1	
	Amp (cm)	Phase (degree)	Amp (cm)	Phase (degree)	Amp (cm)	Phase (degree)	Amp (cm)	Phase (degree)
Calibration: Feb 1994								
Model	116.3	144.2	26.7	166.3	93.0	157.8	47.8	145.7
Field Data: West	112.1	145.6	26.9	169.7	93.6	157.8	48.1	143.1
Central	114.7	145.5	27.6	168.8	96.2	157.1	49.5	149.9
East	112.2	145.5	26.9	169.9	94.2	157.9	48.8	143.0
Difference*	3.3	-1.3	-0.4	-3.1	-1.6	0.2	-1.0	0.4
Verification: Jul, 1994								
Model	114.7	143.9	25.0	163.6	79.1	158.7	48.1	145.3
Field Data: West	114.9	145.3	25.6	165.7	80.1	159.9	50.6	149.1
Central	115.1	145.8	25.7	165.2	80.4	159.2	50.9	149.5
East	115.6	144.9	26.0	164.9	80.7	159.6	50.9	148.8
Difference*	-0.5	-1.4	-0.7	-1.6	-1.3	-0.8	-2.7	-0.4

Difference* = Model – Average of Field Data (Average of West, Central and East Stations)

CH3D predicts currents at every 3 meters in the water column. ADCP current data are averaged every 3 meters in the water column for comparison with model results. Model-predicted currents are compared with measured values at the top, middle and bottom layers in the water column. Vertically-averaged currents are also compared between model and measurements at the three stations, CENT1 (the central station), WEST1 (west station), and EAST1 (east station), for the period of Feburary-April, 1994 (Figures 9-11).

On average, both model and measurements show that currents in Sinclair Inlet are low, seldom exceeding 15 cm/s. While model predictions are in agreement with measurements, model-measurement comparison is best at the central station, CENT1, followed by EAST1 and WEST1. Predictions underestimated currents by 2 cm/s at stations EAST1 and WEST1. Both these two stations, WEST1 and EAST1, where model under-predicted currents by about 2 cm/s, are close to the shore, whereas the central station, CENT1, is located in the midst of water. The reason for the model's under-prediction by a constant current of 2 cm/s needs to be further investigated. Based on the fact that the model-measurement difference is almost constant, it should be caused by processes other than tidal forcing. The time-invariant model-measurement difference is probably due to the negligence of external freshwater inflows in the model, including the riverine inflows, that presumably have relatively larger impacts on residual currents in the region. Effects of freshwater inflows to the local circulation patterns as well as transport patterns will be accounted for in CH3D, once the estimation of riverine inflows becomes available from the watershed modeling study using HSPF, which is to be completed for the year of 2000.

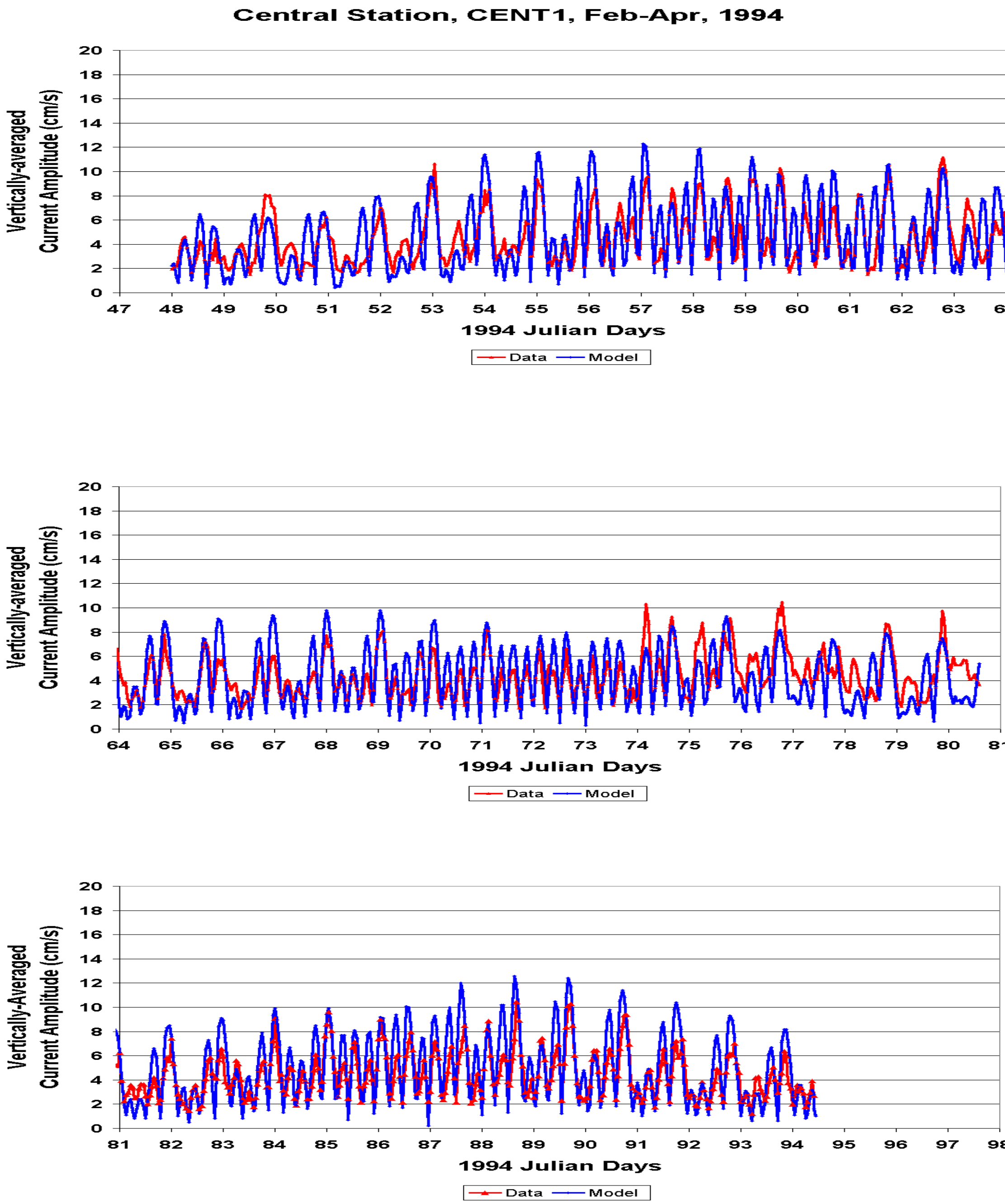

Figure 9a. Comparison of predicted and measured current amplitudes at CENT1

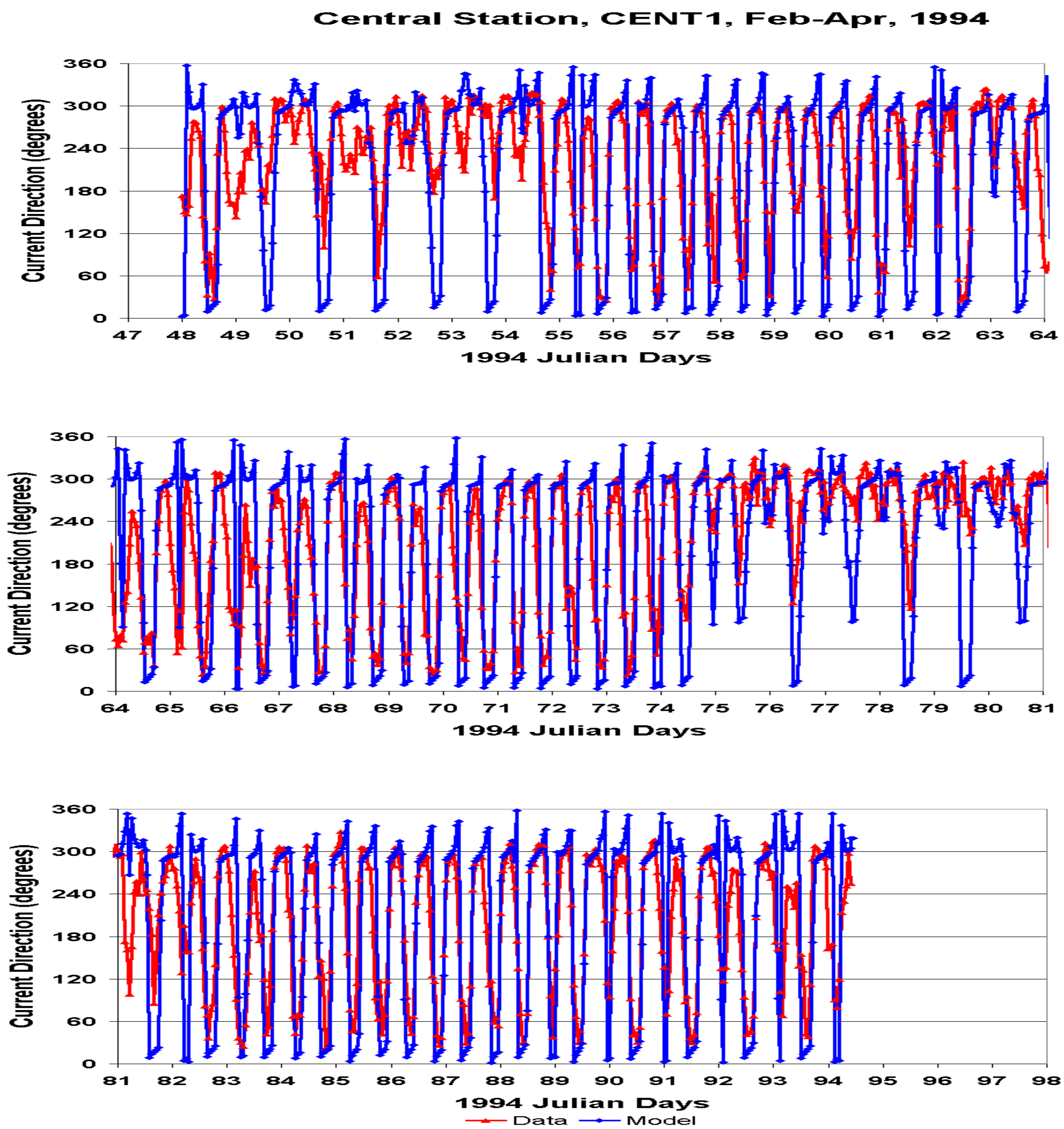

Figure 9b. Comparison of predicted and measured current directions at CENT1

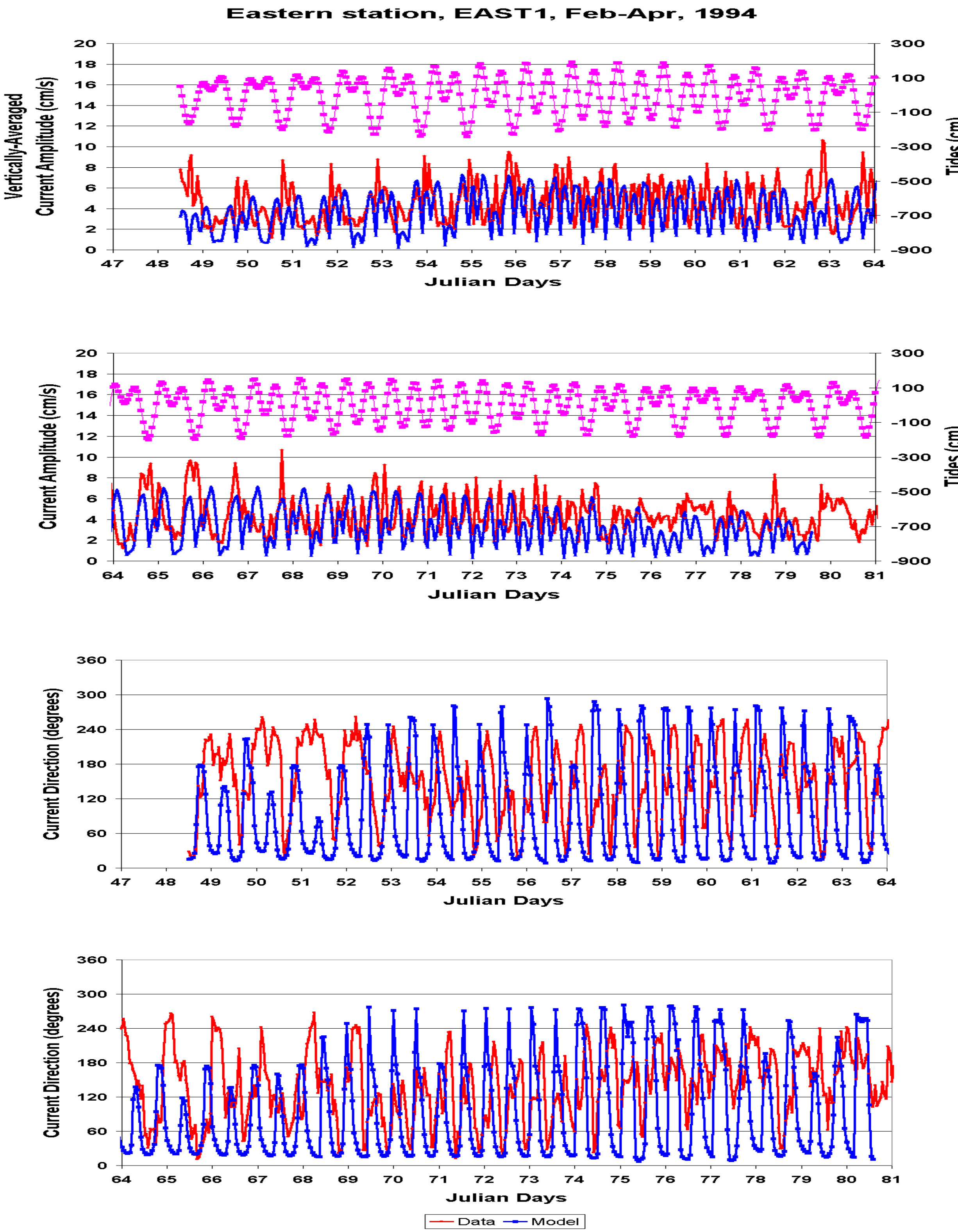

Figure 10. Comparison of predicted and measured current amplitudes and directions at EAST1

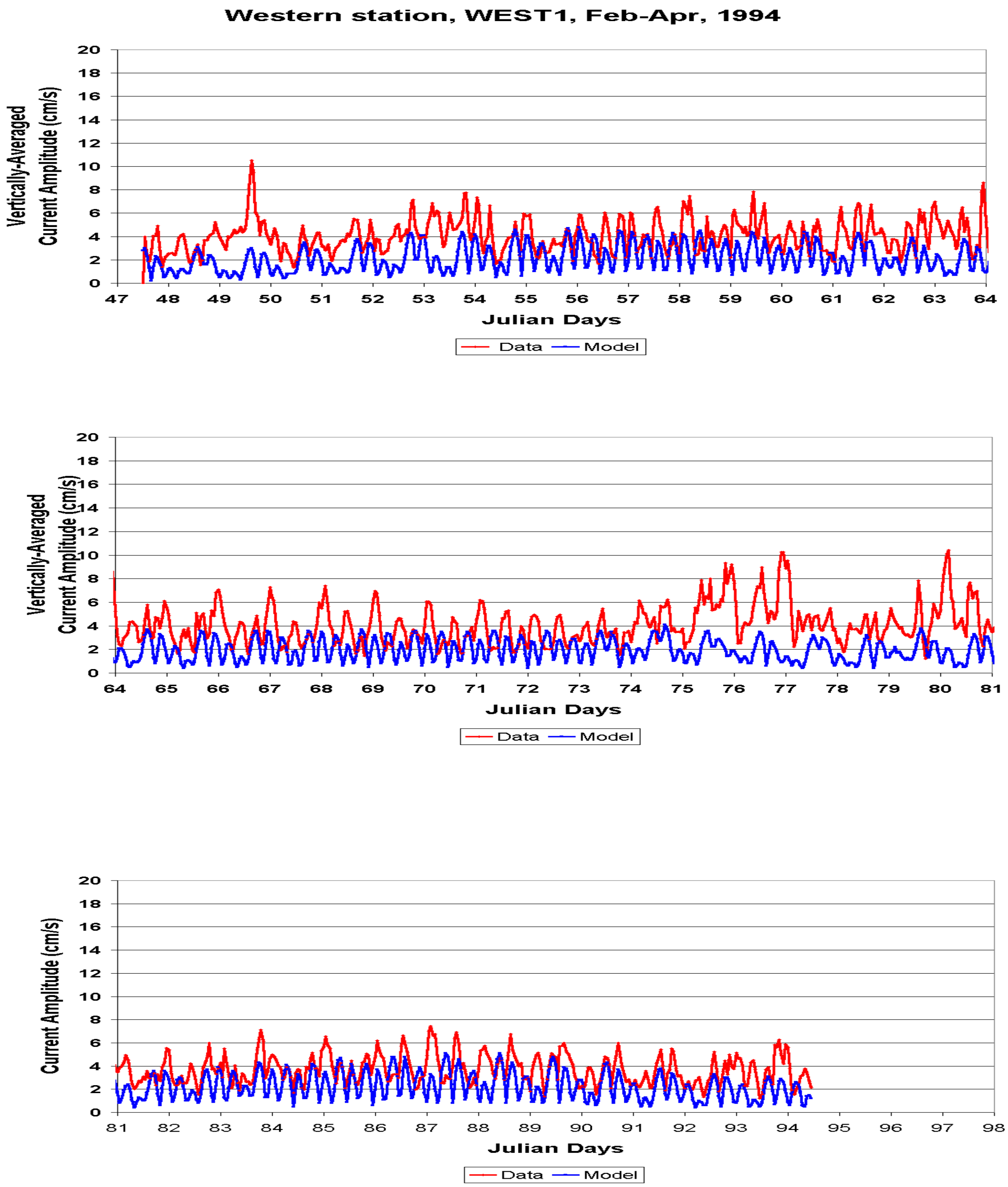

Figure 11a. Comparison of predicted and measured current amplitudes at WEST1

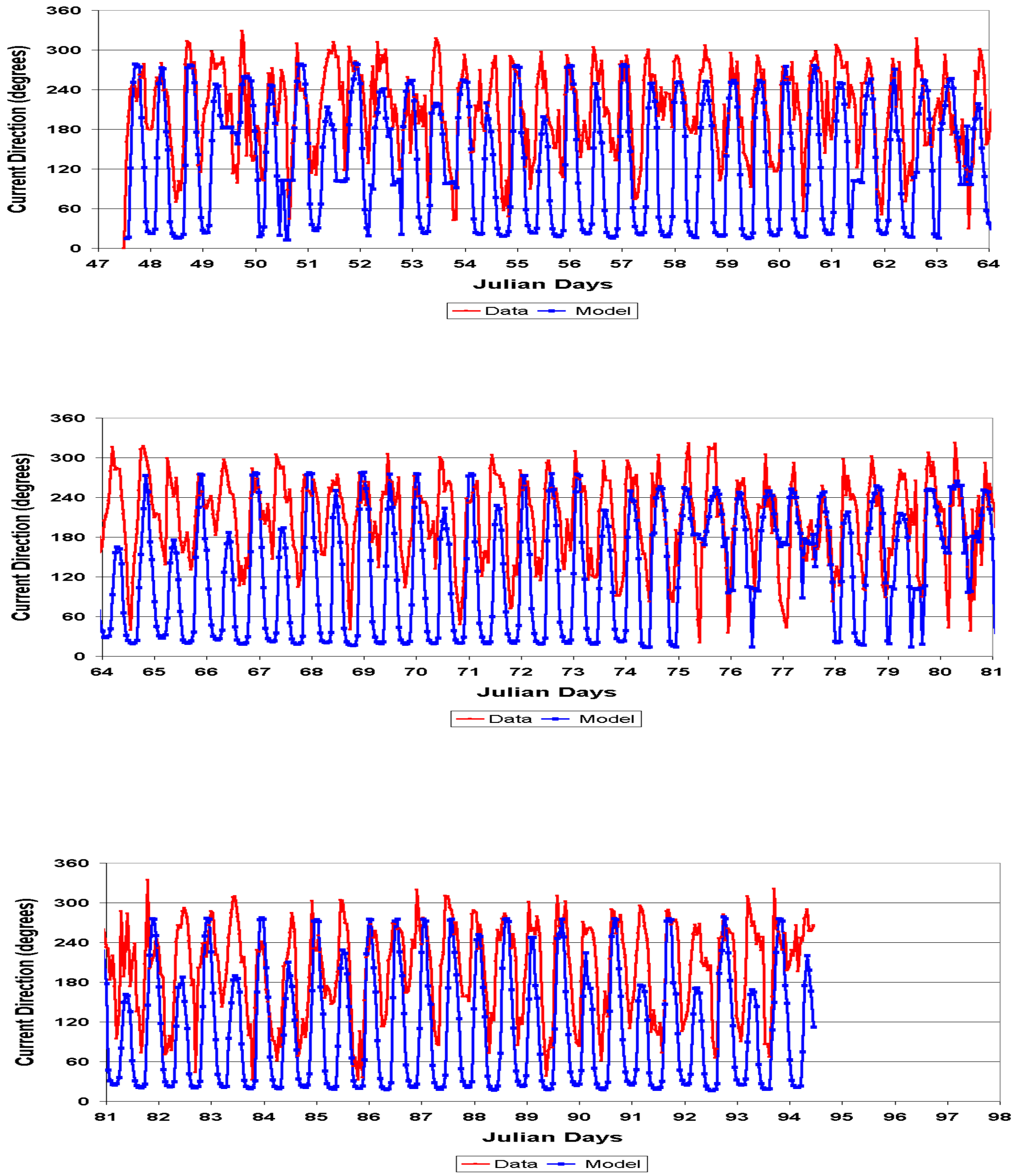

Figure 11b. Comparison of predicted and measured current directions at WEST1

6.2. Model Verification

In model verification, the calibrated CH3D, with model parameters remaining unchanged, was used for further simulations. Simulations for model verification would test accuracy, consistency and predictability of CH3D. Simulations were carried out for model verification against three independent field data sets: USGS's tide and current data collected at the three stations, CENT2, EAST2, and WEST2, during the summer of 1994; and SPAWAR's two sets of current data collected during 1997-1998. Tides at the three stations in this period are well predicted by the model (Table 4), as expected. Results for the summer (Jul-Aug) of 1994 are similar to those of the Feb-Apr 1994 period. For the summer of 1994, the central station, CENT2, gives the best comparison between predicted and measured currents (Figure 12), with mean and peak current amplitudes about 6 and 11 cm/s, respectively. Currents at CENT2 are predominantly influenced by tides. Because of the enclosed configuration of the Inlet, tidal currents can be described by modified standing wave modes in the region, and are bi-directional, switching directions between 300^0 and 15^0 during flood and ebb tides (Figure 12). Influence of spring and neap tides are also reflected in both model results and measurements.

While both predicted and measured current amplitudes at EAST2 and WEST2 are in the same oscillatory modes, which are driven by tides, model-predicted current amplitudes were less than measured values by 2 cm/s throughout the simulation period, a phenomenon observed for the Feb-Apr 1994 period. This phenomenon can be verified by adding 2 cm/s to the model-predicted current amplitudes and comparing with measured values (Figure 14b for WEST2). As discussed earlier, there are several possible reasons for the underprediction of ~2 cm/s by the model: local freshwater inflows, complex pier configurations and effect of shorelines, all of which were not included or well resolved in the model for the same reasons mentioned earlier. It is also observed that, for EAST2 and WEST2, current directions are quite different between model and measurement.

The central station, CENT1 and CENT2, was located in the relatively open water, several hundred yards away from the shores. Both the eastern and western stations, EAST1, EAST2 , WEST1 and WEST2 were near the shorelines and close to the pier pilings (especially for EAST2). The pier pilings would cause change of flow field, especially in the wake of the pilings. In CH3D, such piling effects were not considered due to the complexities associated with such wake processes. Nevertheless, the fact that model-measurement comparisons are consistently better at the central station versus the eastern and western stations provides reasonable support to shore effects for model-measurement discrepancies in the near-shore regions.

Model-measurement comparisons were also conducted for the two stations, SPA1 and SPA2, where currents were measured by SPAWAR for two periods, Sep-Dec 1997 and Jul-Aug, 1998, with each period over 35 days. SPA1 was located inside the Inlet and was close to CENT1 and CENT2. As expected, both current amplitudes and directions were adequately predicted by the model throughout the 67-day period (Figures 15a and 15b).

SPA2 is located in the mouth of the Inlet, outside the connection channel with the Dyes Inlet, where flow regimes are most complicated. Predicted current amplitudes are generally in agreement with measured values throughout the 36-day spring-neap tidal period (Figures 16a and 16b). Currents can reach over 65 cm/s, in contrast to the low currents (~10 cm/s) further inside the Inlet. Principle current directions at this station vary within an angle of 280^0 and 340^0 (south-east direction) during tidal variations. This is uncharacteristic of bi-directional tidal current patterns for tidally-dominated flows. In fact, as to be discussed in the next section, currents in this regions result from simultaneous actions of several processes, including incoming tides from Puget Sound, outgoing tides from Sinclair Inlet, time-lagged flux out of and into the Dyes Inlet, local geometry and depth variations in the region.

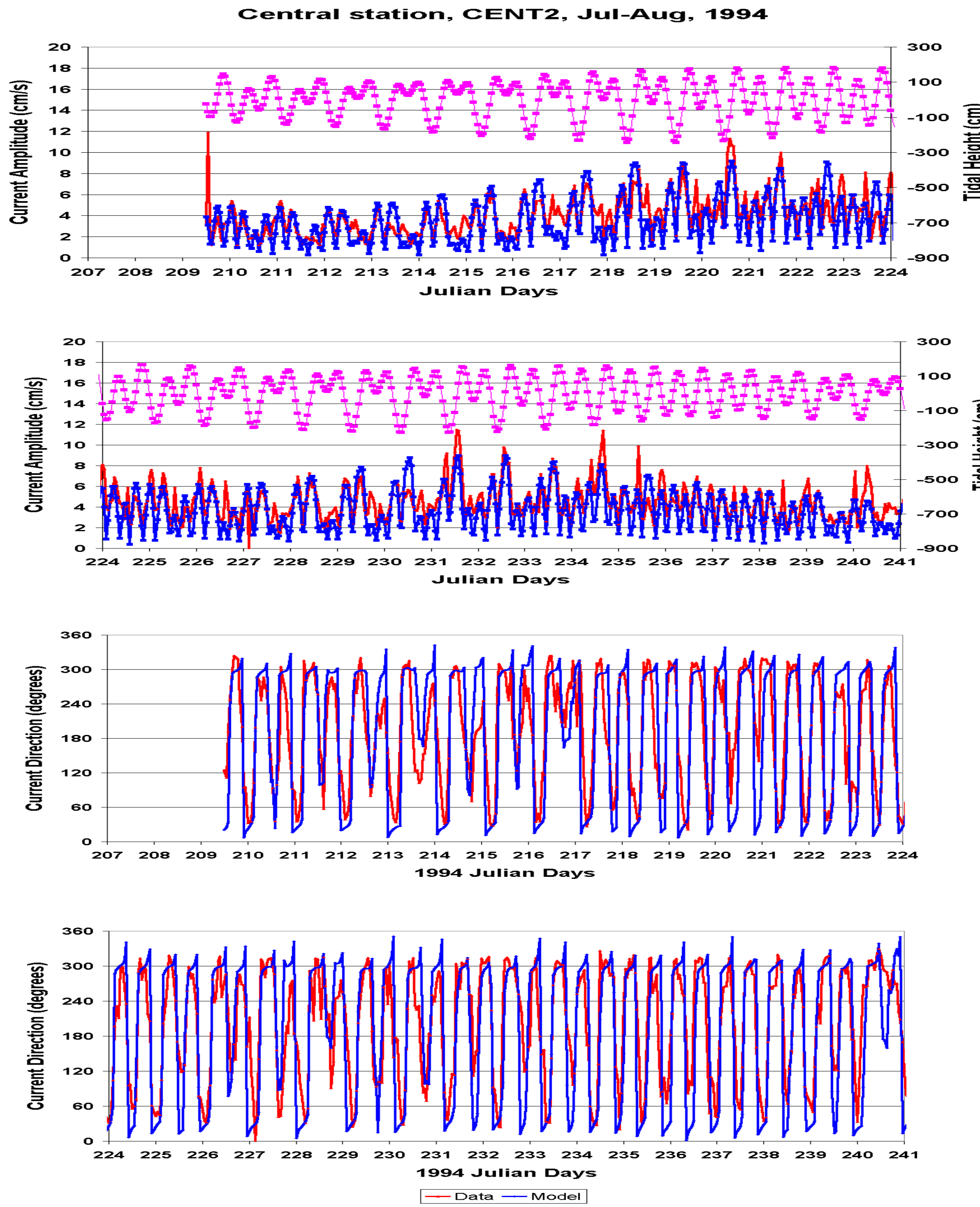

Figure 12. Comparisons of predicted and measured current amplitudes and directions at CENT2

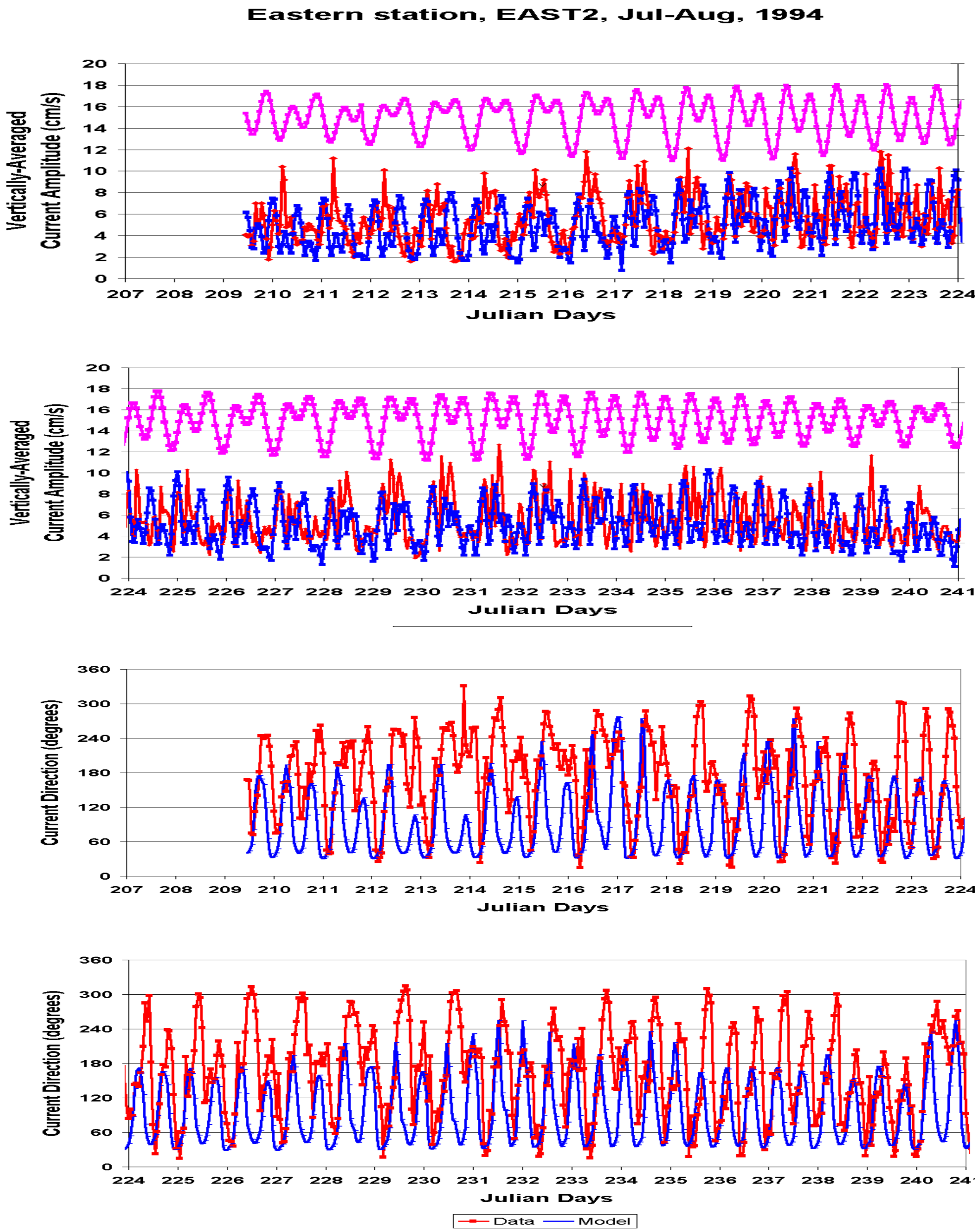

Figure 13. Comparisons of predicted and measured current amplitudes and directions at EAST2

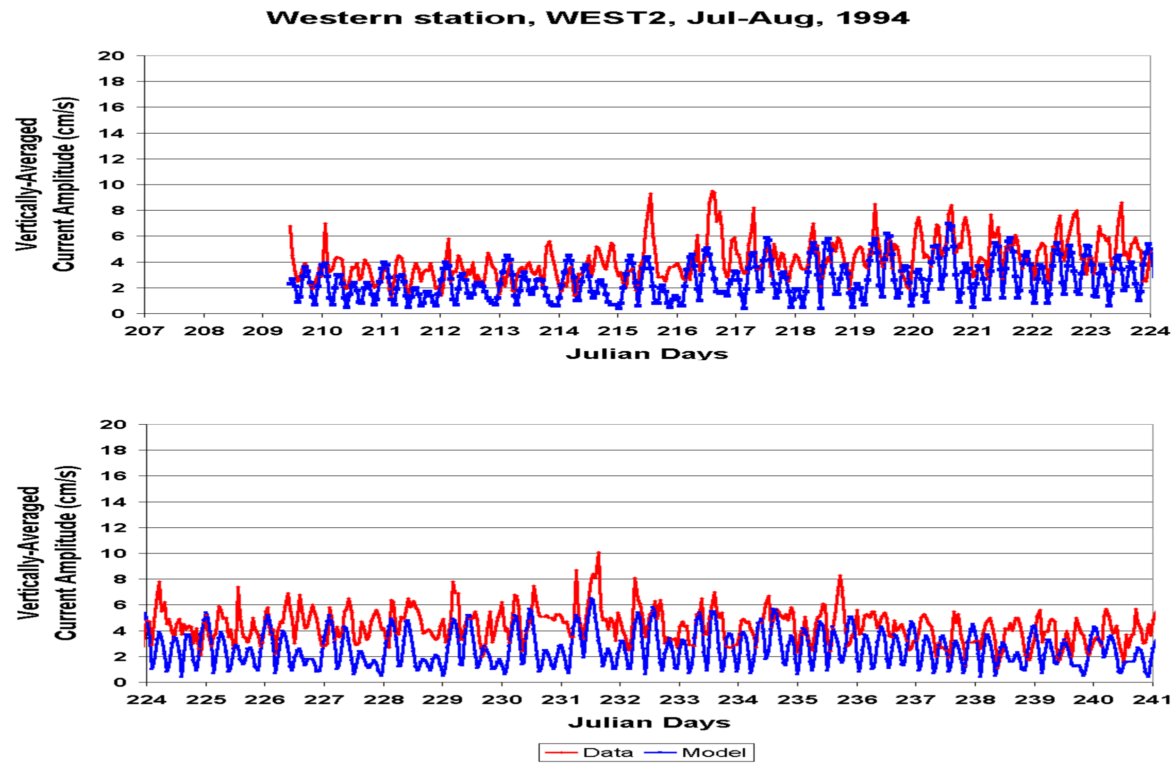

Figure 14a. Comparisons of predicted and measured current amplitudes at WEST2

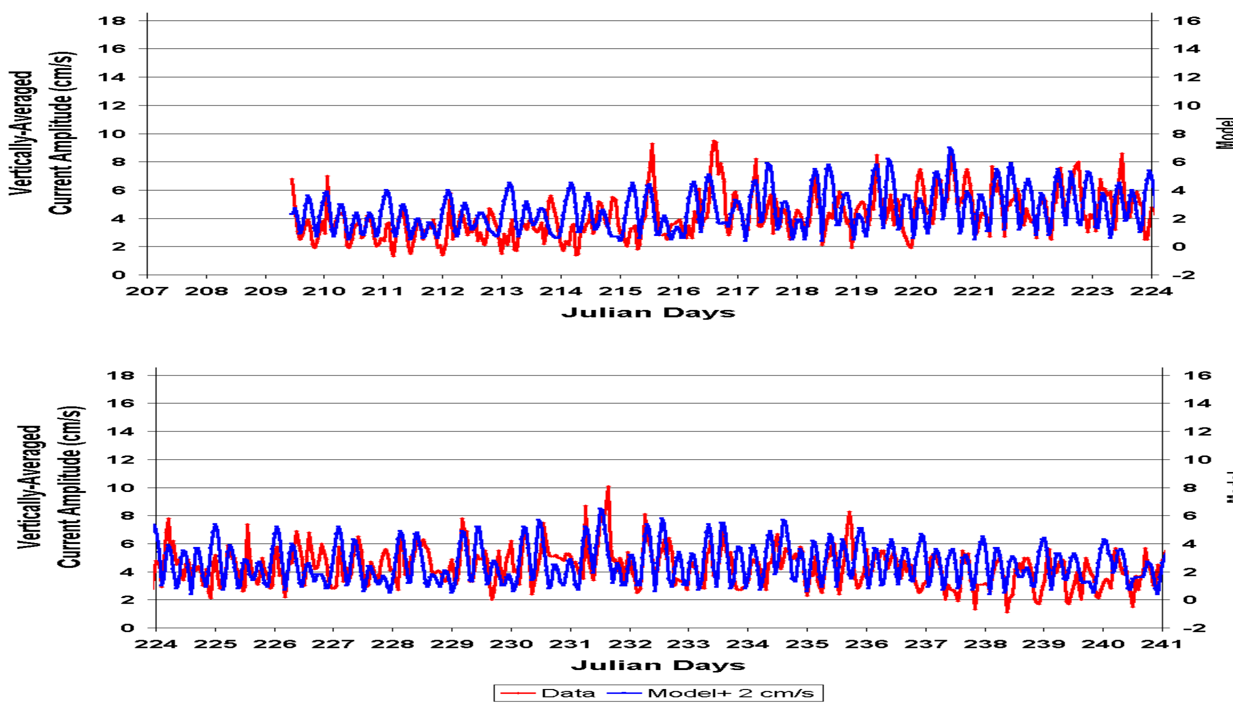

Figure 14b. Comparisons of measured and (predicted + 2 cm/s) current amplitudes at WEST2

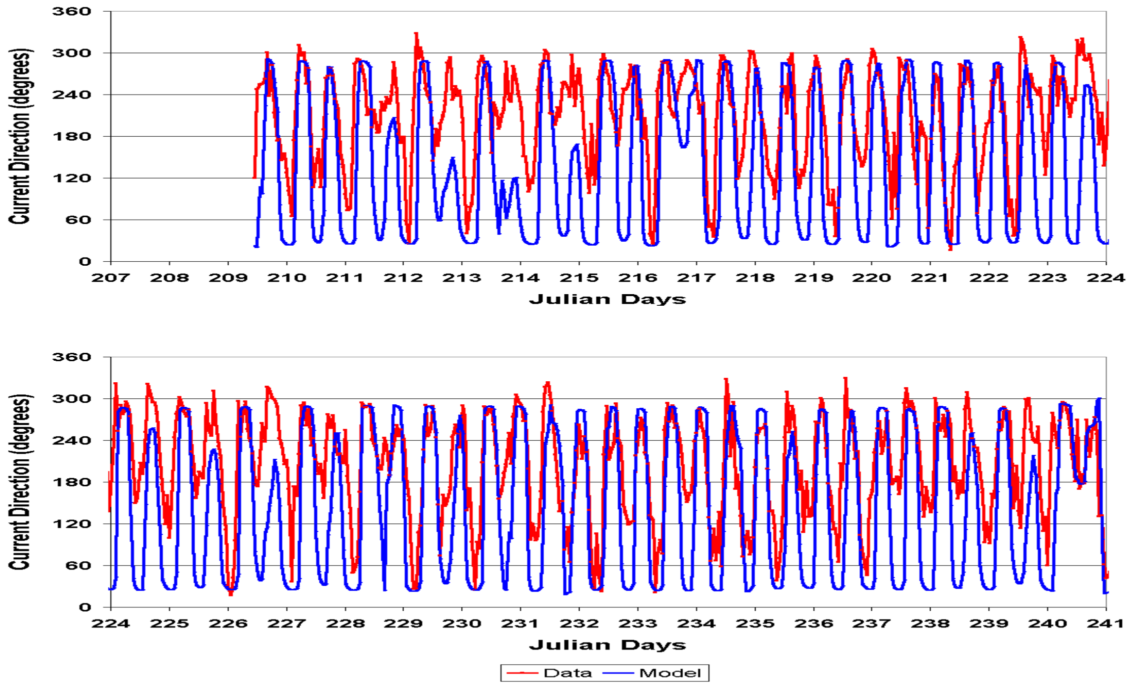

Figure 14c. Comparisons of predicted and measured current directions at WEST2

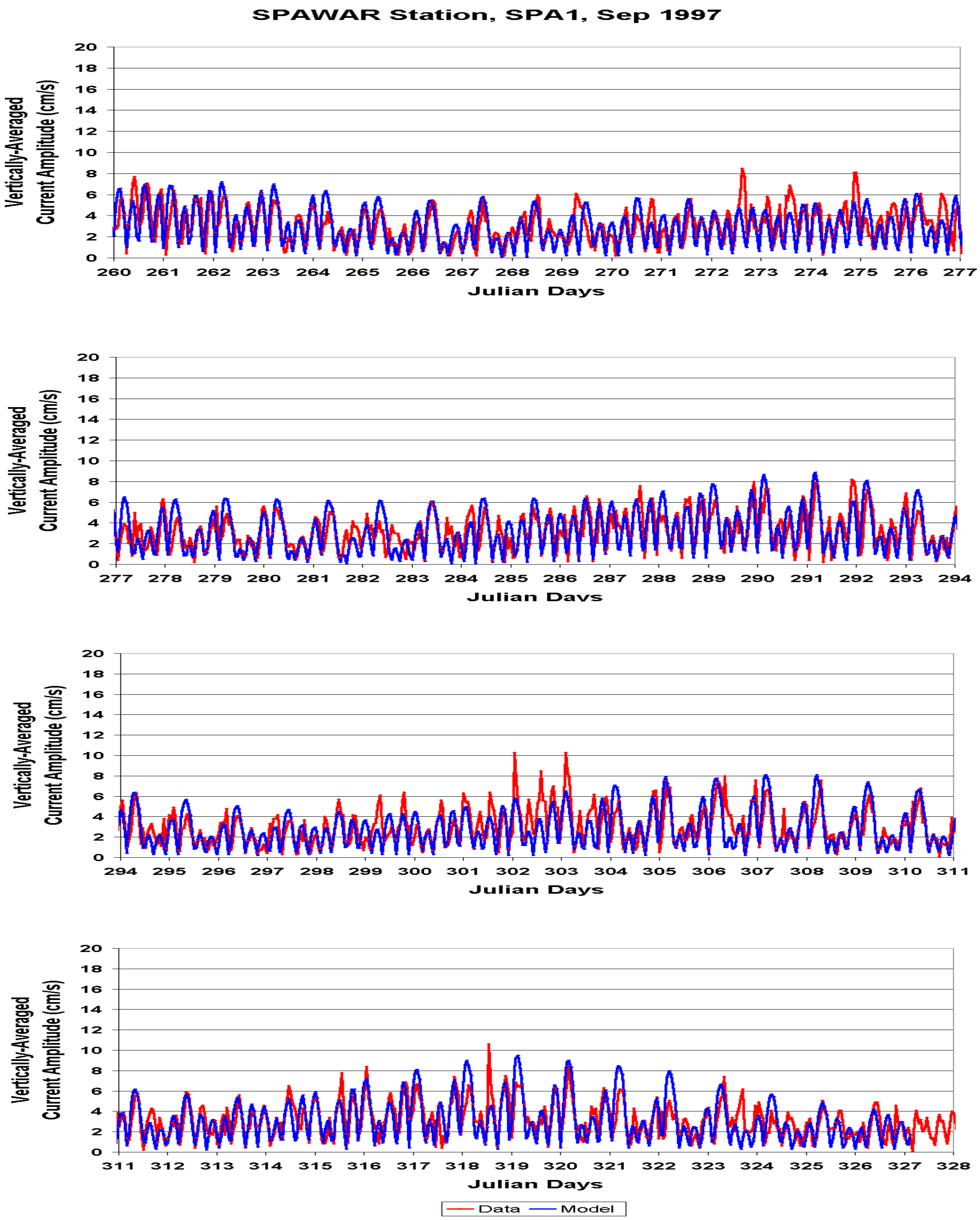

Figure 15a. Comparisons of predicted and measured current amplitudes at SPA1

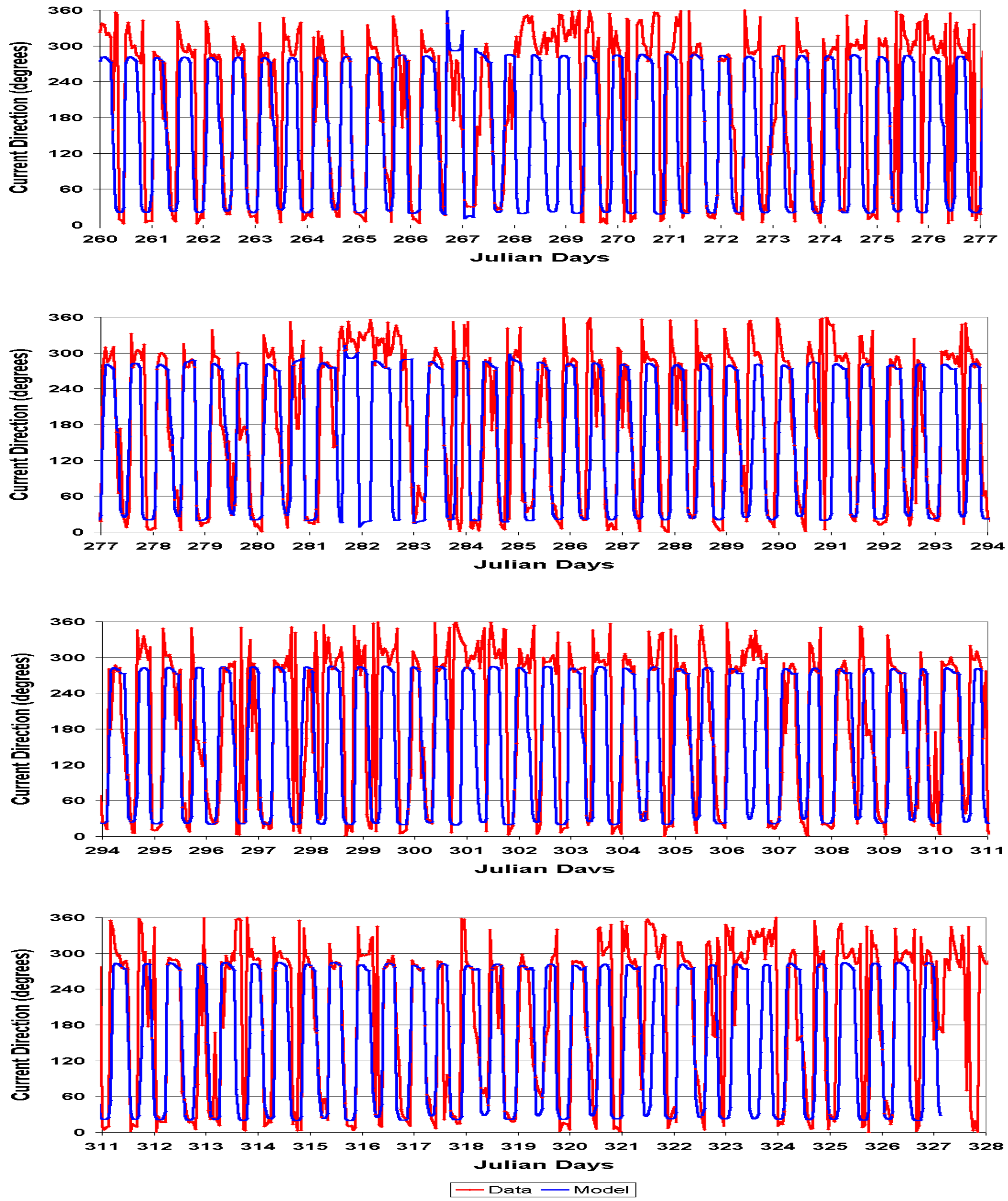

Figure 15b. Comparisons of predicted and measured current directions at SPA1

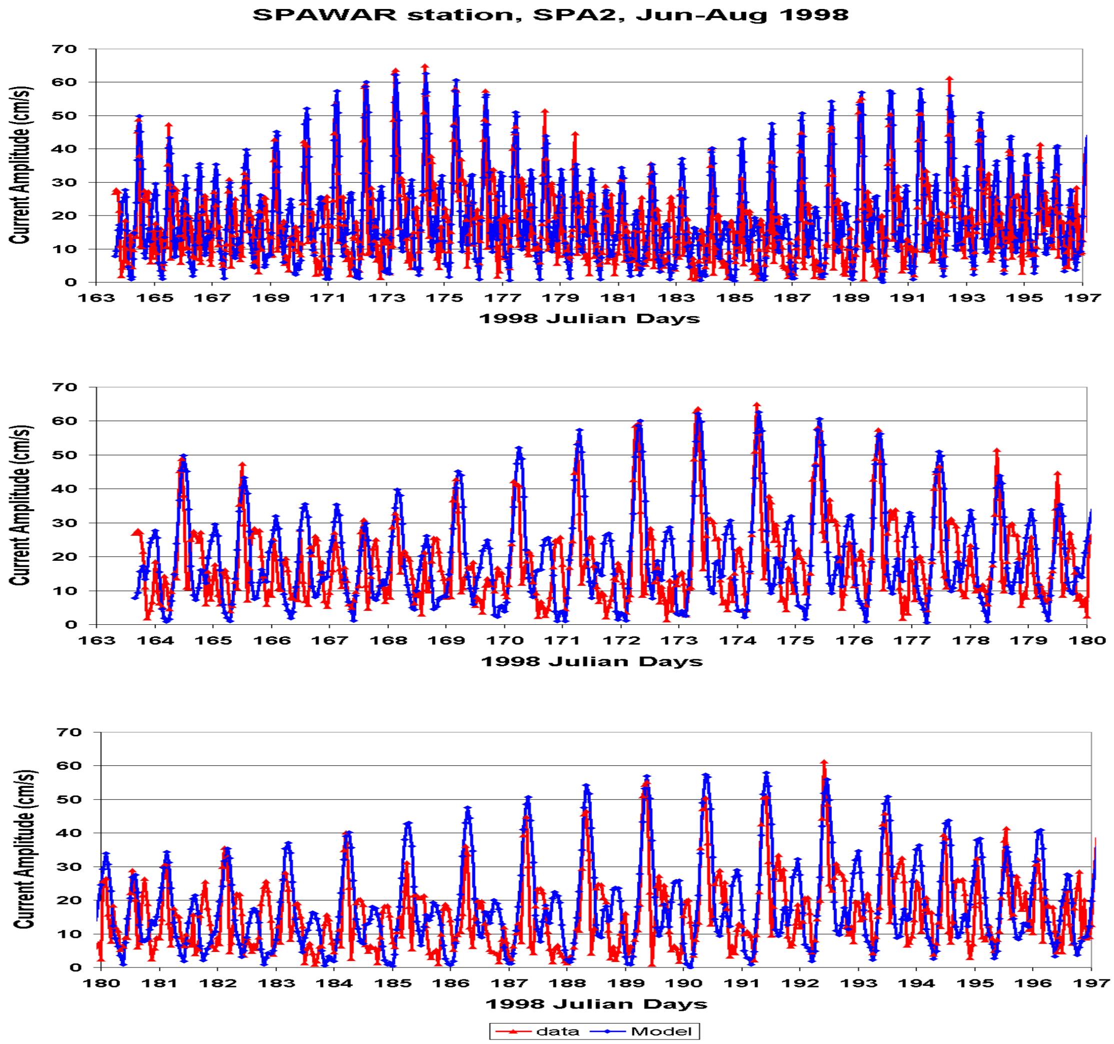

Figure 16a. Comparisons of predicted and measured current amplitudes at SPA2

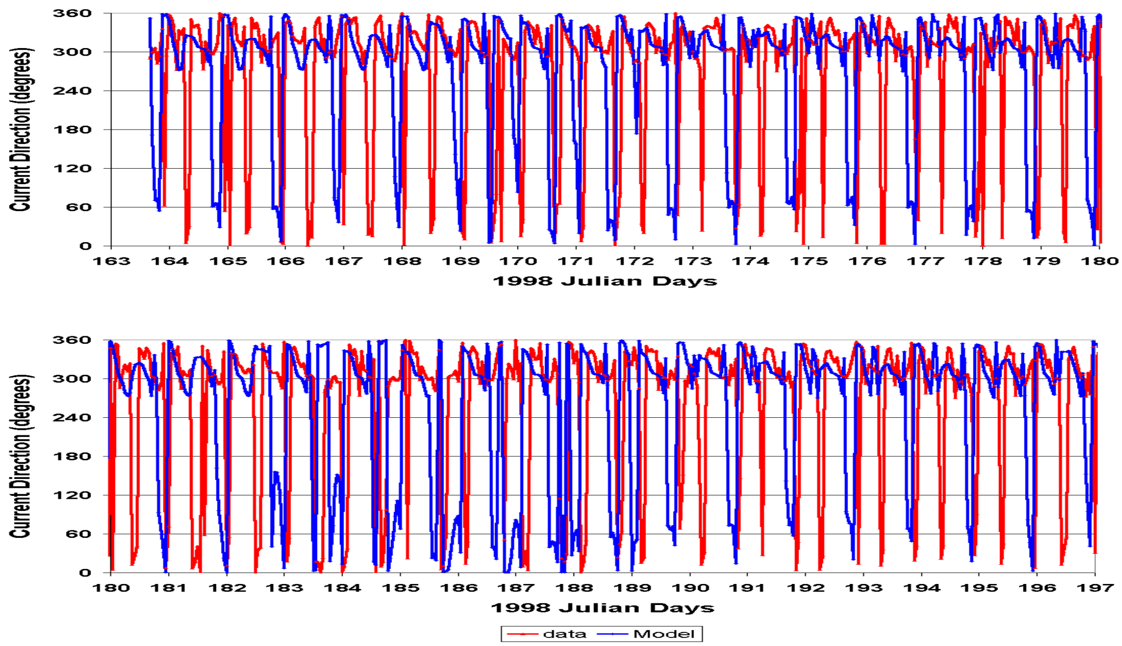

Figure 16b. Comparisons of predicted and measured current directions at SPA2

6.3. Ship-Mounted ADCP currents

During three SPAWAR surveys in September, 1997; March, 1998; and July, 1998, water current data throughout Sinclair Inlet were collected from a hull-mounted ADCP pointing down. Approximately 2,000,000 measurements were compared to model results for the same time and spatial location. Time was matched between measurements and model predictions to the closest 10 minute interval. Horizontal spatial location was matched to the nearest model node (typically within 100m). Depth was matched to the nearest 3m model bin, correcting for tidal height.

Figures 17a-17c plot contours of the root mean square (rms) error between measurements and model predictions at all model nodes with at least 15 measurements. The locations of the model nodes are shown as black dots in the figure. Since the measurements are pooled into 10 minute bins for model comparison and since the boat was underway when measurements were taken, these 15 or more measurements tend to be collected widely spaced in time and are relatively independent of each other. The rms error shown in Figure 17a is calculated from water column mean velocity measurements and model predictions over all tidal conditions

Figure 17a shows that model predictions agreed with current measurements to within 15 cm/sec over large areas of the Inlet. The larger error near the channel to Dyes Inlet (to the north) tended to be caused by the model over-predicting water speed. It should be noted, however, that current amplitudes in the channel exceed 110 cm/s. Meanwhile, model grids in the channel are coarse and predicted currents may not be representative of local phenomenon with adequate resolution. The error near the Inlet mouth (to the east) tended to be caused by the model under-predicting water speed. Rms error in the mouth region is also in the same range (<15 cm/s), measured and predicted current amplitudes are over 75 cm/s.

Figures 17b and 17c show the mean water column ADCP-model prediction speed difference on strong incoming and outgoing tides respectively. The plots include data collected only during tides when water levels were changing at greater than 66 cm/hour. Rms error by depth will be presented in the future, as well as error as a function of tidal flow.

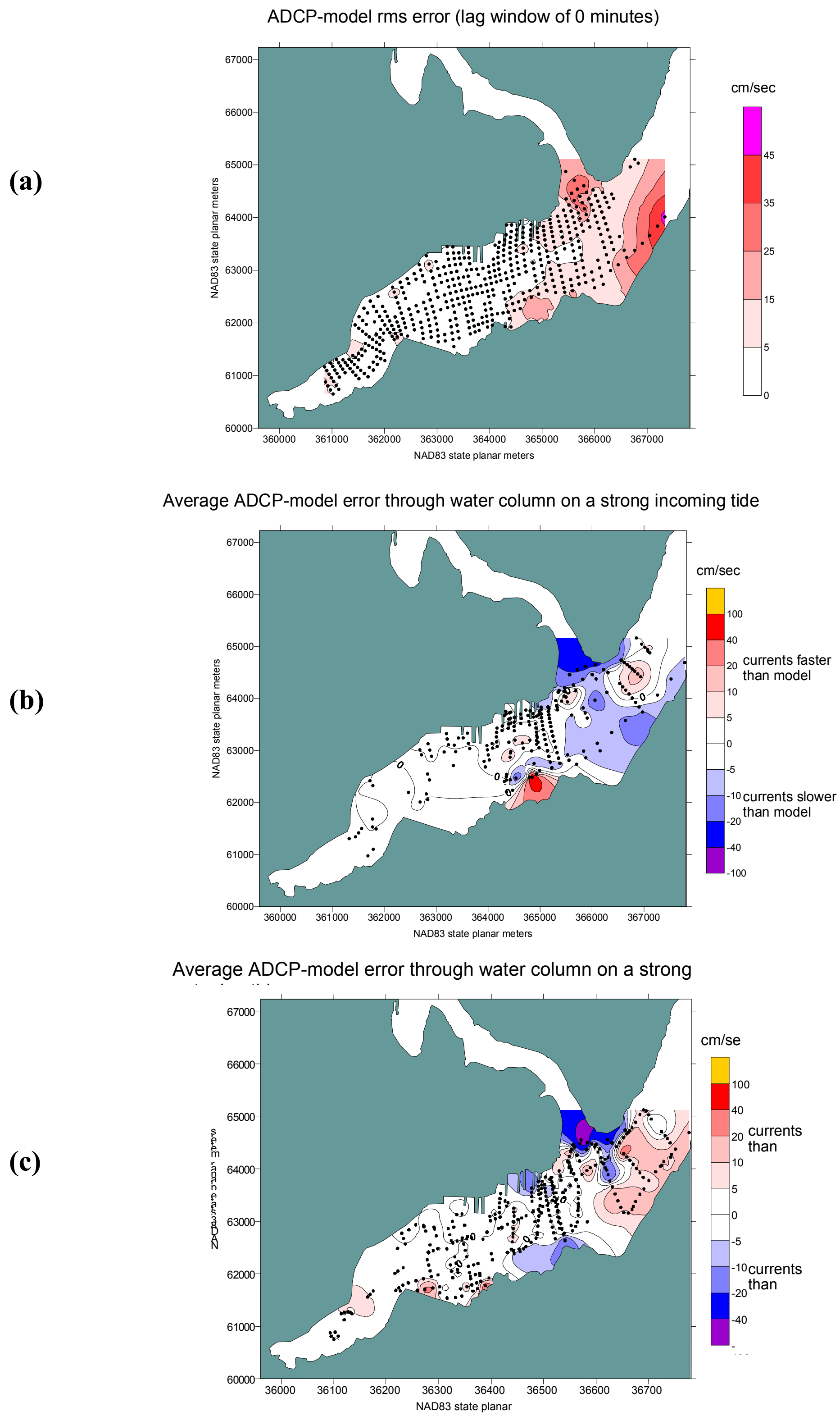

Figure 17. Root-Mean-Square errors of currents between measurement and model for (a) average tidal condition, (b) flood tides and (c) ebb tides

6.4. General Circulation and Flow Exchange Patterns in Sinclair Inlet

Sinclair Inlet is a sub-estuary of Puget Sound, which connects to the Pacific Ocean. Tidal ranges in Puget Sound are large, reaching over 5 meters in different parts of the Sound. In general, such large tidal ranges would generally result in large tidal currents. For examples, Figure 18 shows the relationships between tides (ranges) and currents for 4 navy harbors: May Port, San Diego Bay, Sinclair Inlet and Norfolk. In these figures, large currents are associated with large tidal ranges. For Puget Sound, the current-tide relationship is true for most regions of the Sound. However, currents inside Sinclair Inlet are low (~10 cm/s), uncharacteristic of large tidal regimes. To fully understand and explain flow patterns in the Inlet, this interesting phenomenon (low currents) needs to be considered in conjunction with other evidence reflected in both limited measurements and model results.

Sinclair Inlet connects to Puget through two passages, the Clam Bay in the southeast and Brownsville in the north. Tides, traveling from the ocean along Puget Sound, pass through these two passages with strong energy: tides over 5 meter range at both openings. Entering Rich Passage and Port Orchard passages, tidal currents are strong, reaching over 50 cm/s in these regions. As incoming tides reach the mouth, a northward channel passage connects to Dyes Inlet to the north. Total surface area and volume of Dyes Inlet is about three times those of Sinclair Inlet. As incoming ocean tides reaches the mouth, a large fraction (~ 75 %) of the tidal flow enters Dyes Inlet, while only a small portion (roughly 25%) enters Sinclair Inlet. Figure 19 shows three time series of water mass flux across three cross sections : incoming tides, tidal exchange in Dyes Inlet and tidal exchange in Sinclair Inlet. The amplitudes of mass flux for Dyes Inlet is about 3 times that for Sinclair Inlet, which is in proportion to ratios of the surface area and volume between these two water bodies.

The dominant driving mechanism for the flow in Sinclair Inlet is tidal forcing. Circulation patterns inside Sinclair Inlet are relatively uniform and consist of bi-directional low speed currents (< 15 cm/s). However, circulation patterns are very complicated at the mouth where incoming tides, fluxes from Dyes Inlet and from Sinclair Inlet interact with one another simultaneously. Moreover, the large variations of water depths compound complexities of circulation in the region. As incoming tides enter into Dyes Inlet, the narrow channel passage in Dyes Inlet dampens flow into Dyes Inlet and water accumulates in Sinclair Inlet. At the end of flood tide (high slack tide), influx of water from Sinclair Inlet into Dyes Inlet persists for another 1-2 hours before static pressure in these two water bodies are balanced. During ebbing tides, the narrow channel passage works equally effectively in preventing water from flowing out of Dyes Inlet into Puget Sound. As the tidal stage reaches slack low water, water in Dyes Inlet continues to flow out for another ~ 1 hour. This phase difference of water surface elevation can be seen in Figure 20, where water surface elevations in Dyes Inlet lag those in Sinclair Inlet by ~ 1 hour over tidal cycles.

During flood tides, currents flowing into Dyes Inlet induce clockwise currents near the shipyard and water flows from Sinclair Inlet into Dyes Inlet (Figures 21a-21c). Incoming tides flow into Sinclair Inlet along southern shore regions, which combines with the clockwise flows near the shipyard to form a large clockwise gyre at the mouth. During ebb tides, the Dyes Inlet channel passage works as a plume ejecting water from Dyes Inlet into Sinclair Inlet. This jet plume is then deflected along the northern shores to the east of the entrance by tides ebbing from Sinclair Inlet, thus forming a clockwise flows in region to the east of the entrance. Such phenomenon is further enhanced by the relatively large depth in the center of the mouth, and a local clockwise gyre is formed. Therefore, clockwise gyres are produced during both flood and ebb tides, and the shapes of these two gyres are different.

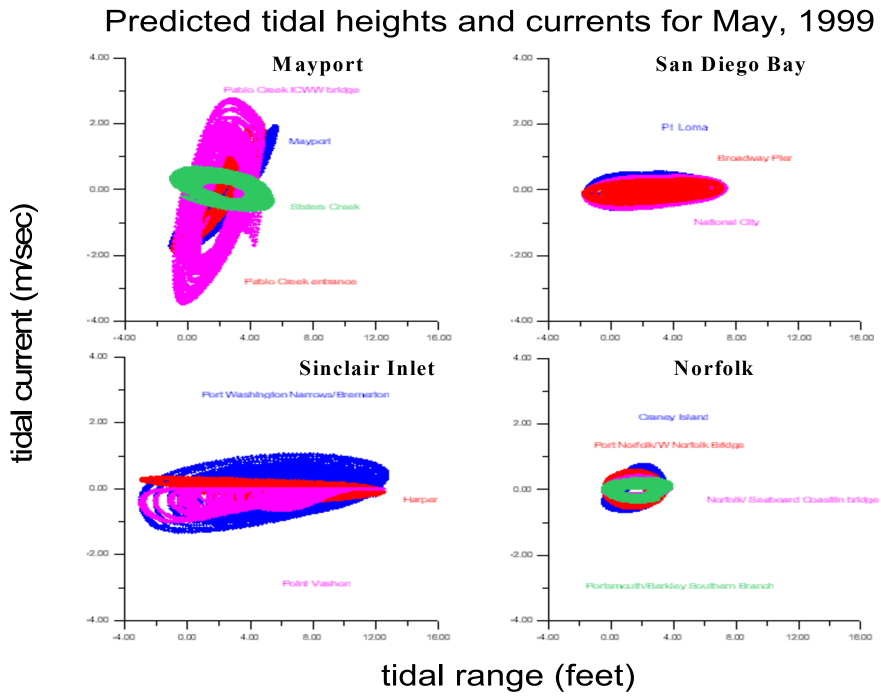

Figure 18. Current-tide relationships for 4 navy harbors

Fluxes of flow across the Inlet

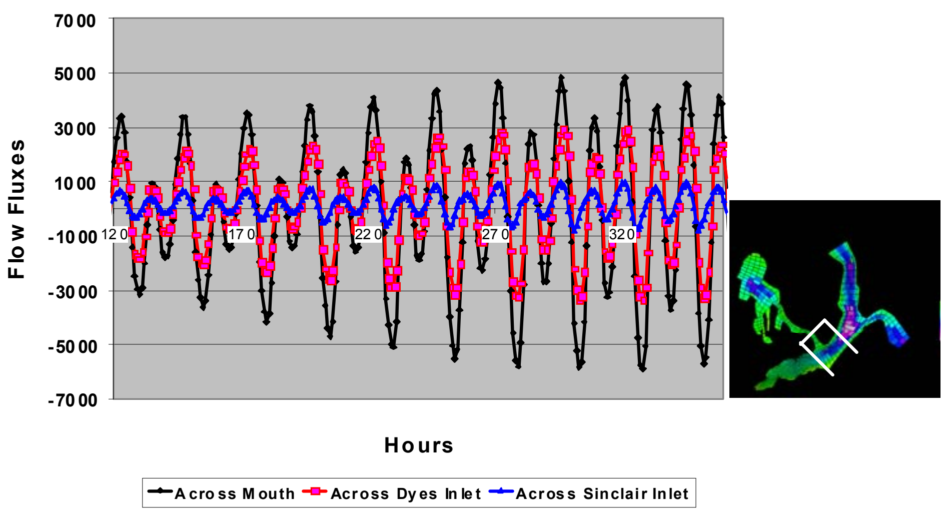

Figure 19. Tidal flow fluxes across Port Orchard Passage, Dyes Inlet and Sinclair Inlet

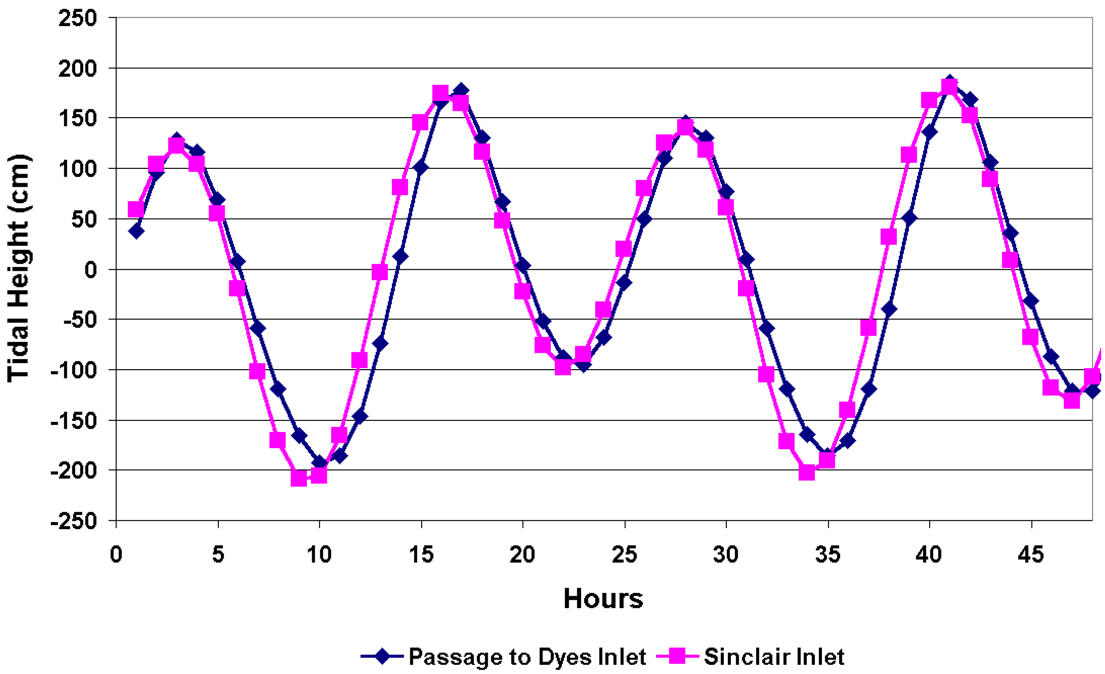

Figure 20. Tides with phase difference between Dyes Inlet and Sinclair Inlet

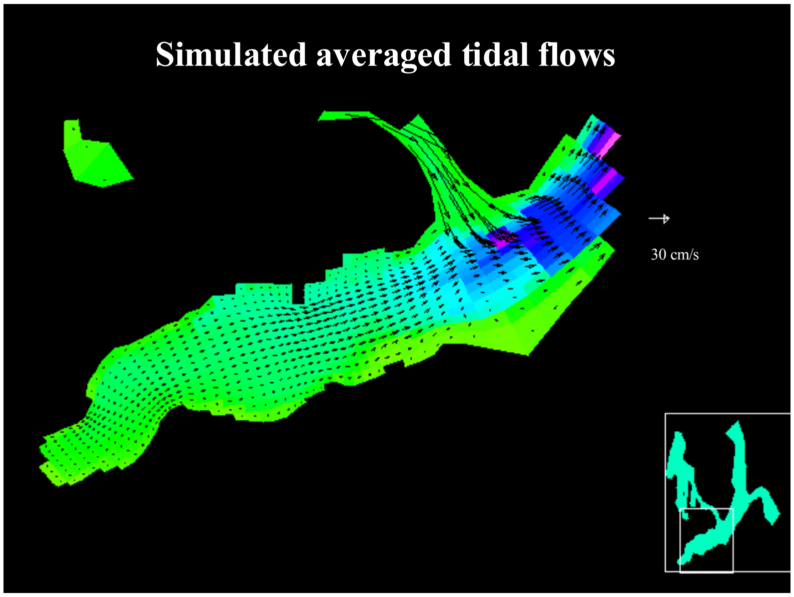

Figure 21a. Gyres at the mouth during ebbing tides

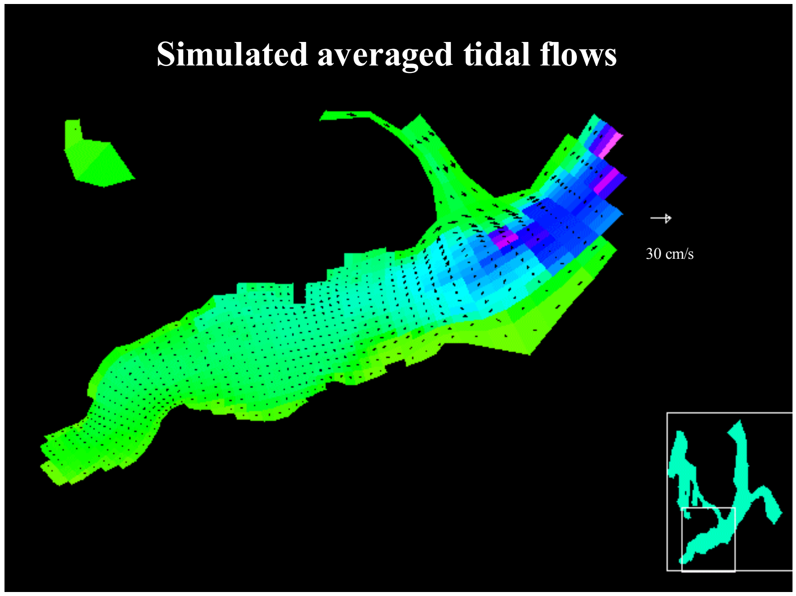

Figure 21b. Gyres at the mouth during slack water

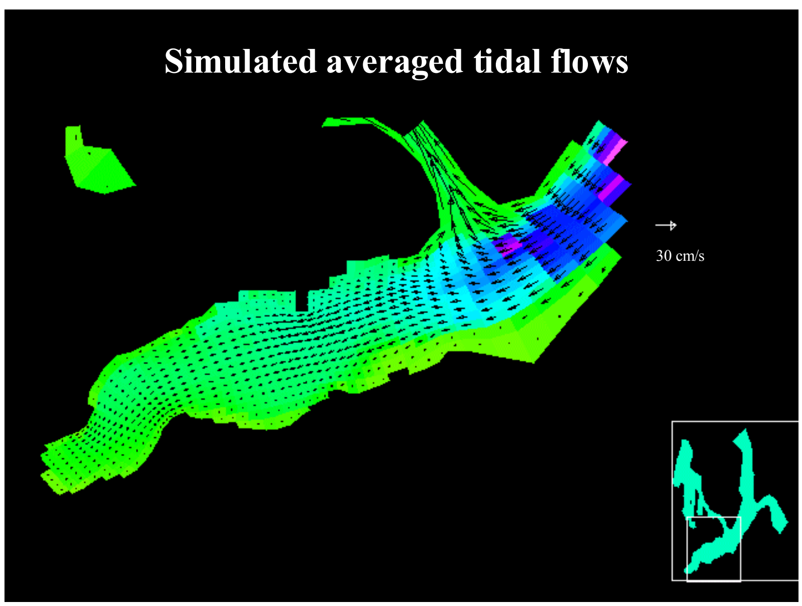

Figure 21c. Gyres at the mouth during flooding water

7. Conclusions and Future Work

Hydrodynamics and circulation patterns in Sinclair Inlet are simulated using CH3D, the 3-D hydrodynamic model. Because of unique geometry and water body configuration of the Inlet, currents inside the Inlet are low, in contrast to the large tidal ranges. Dyes Inlet acts as a reservoir to Sinclair Inlet, taking about 75% of the incoming tidal energy during flood tides and discharging directly out to the outer passages, with influence on flows in the Inlet. Flow exchanges among Dyes Inlet, Sinclair Inlet and flows in outer passages occur at the mouth, causing complex circulation patterns in the region.

Sinclair Inlet is a shallow semi-enclosed water body, flows in the Inlet are most tidally driven. Therefore, flows in the Inlet are mostly 2-D flow regimes. However, water depths at the mouth and in the outer Passage regions are large (over 20 meters). Three dimensional effect in these regions are un-negligible. Three-dimensional effects on flow and transport in Sinclair Inlet primarily result from difference of water density in the water column and wind-driven 2-layer flows. Density-induced effects on mixing and circulations in both horizontal and vertical directions is called “baroclinic” effect. Wind in the Inlet is low and presumably would cause little effects on the three-dimensionality of the flow regimes. Difference of water density in the water column may be caused by several factors:

1) freshwater inflows from external loads
2) exchanges of water with different density from Dyes Inlet and incoming tides; and
3) solar heating in the surface layers of the water column.

The above three sources of baroclinic flows are not included in CH3D because these information are lacking. External freshwater inflows include riverine flow from runoff and baseflows from ground water, effluent discharges from POTW and PSNS and other point sources. Although scattered measurement data are available, information of water density variations from Dyes Inlet is not available. Solar heating cooling cycle in the surface layer water would cause density flows over a diurnal cycle (Wang and Martin, 1991). Meteorological parameters needed to estimate (predict) density stratification from diurnal solar heating process include water and air temperature, air humidity, and cloudiness. With these information, the net heat that the surface layer would receive from solar heating would be estimated. Water temperature (density) stratification can then be predicted.

The above information, especially riverine flows from runoffs, will become available once the watershed modeling study is completed in the next fiscal year. The watershed model, HSPF, would be applied to the entire model domain, including Sinclair Inlet, Dyes Inlet and the two passages. Such an extended coverage for the watershed model domain is essential to adequate and accurate estimation of freshwater inflows to both Sinclair Inlet and Dyes Inlet. With freshwater inflows to the entire model domain, density (salinity and temperature) flows and transport can then be simulated by CH3D. Parameters needed for solar heating estimation would also be needed in the watershed modeling study. Therefore, those parameters would also become available during or after the watershed modeling study is completed. In summary, the task components and their schedules of the integrated watershed model are shown in Figure 22.

COMPONENTS OF THE INTERGRATED WATER QUALITY/WATERSHED MODEL

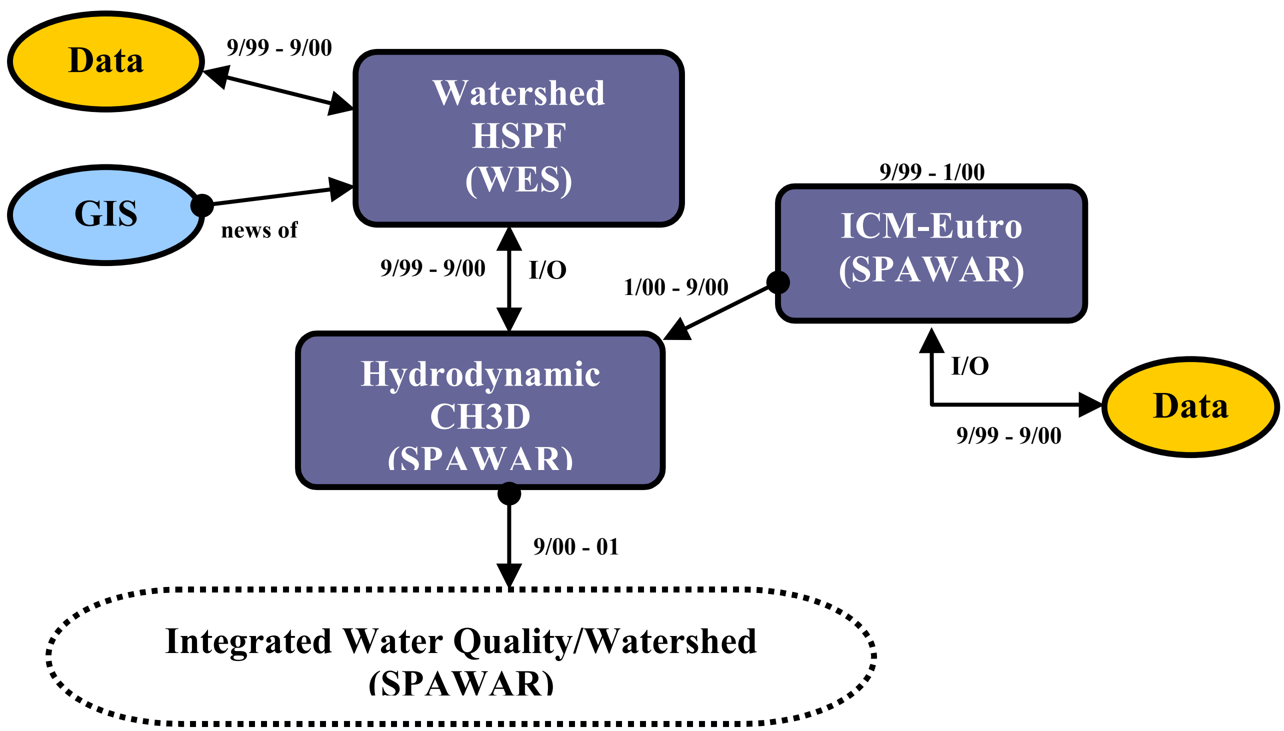

Figure 22. Flow chart and schedules of the linked watershed model for Sinclair Inlet

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