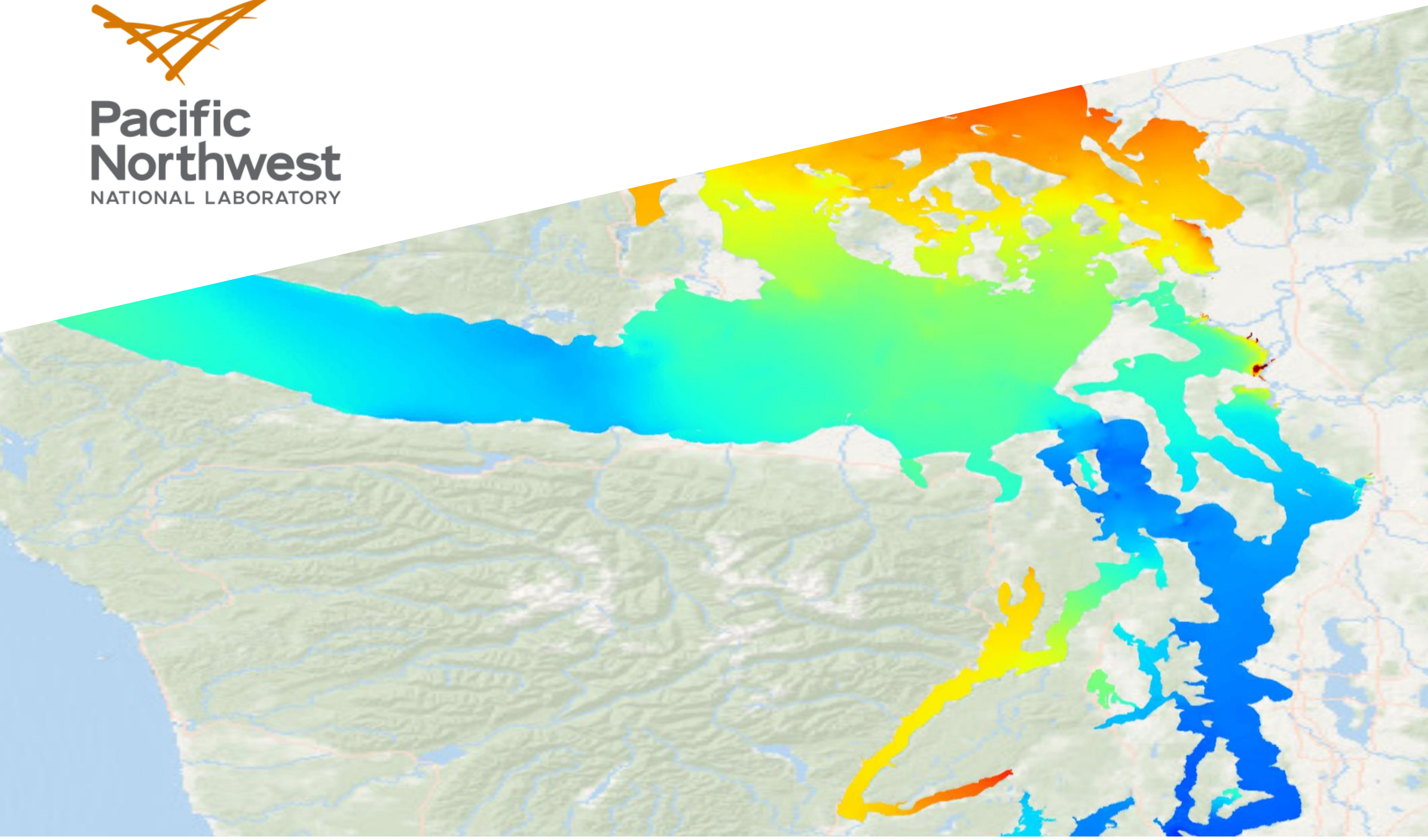

PNNL-28685

Storm Surge Modeling in Puget Sound

May 2019

Z Yang
T Wang
L Castrucci

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Summary

In this study, a storm surge model of the Salish Sea was developed to simulate storm surge in Puget Sound using the unstructured-grid, finite-volume community ocean model (FVCOM). The model was based on Pacific Northwest National Laboratory's existing Puget Sound hydrodynamic model that has been validated extensively in previous studies. To identify representative historical storm events, a systematic approach was developed based on the non-tidal residual (NTR) method. A total of 34 storm surge events between 1980 and 2016 were identified and simulated. To accurately simulate storm surge inside Puget Sound, the model was driven by reanalyzed Climate Forecast System Reanalysis meteorological forcing and observed water levels at the entrance of Strait of Juan de Fuca and southern entrance of Johnstone Strait. Model results for total water level, storm surge, and currents were compared with field measurements. A series of error statistics parameters were also calculated to quantify the model's skills in simulating storm surge in the Salish Sea.

Error statistics of model performance metrics demonstrated that the Salish Sea storm surge model was able to simulate storm surge inside Puget Sound with high accuracy. Storm surge propagation into Puget Sound is a nonlinear process that cannot be simply determined by a static approach for the entire domain. The maximum NTR distribution inside Puget Sound suggests that storm surge tends to be amplified in several sub-basins and inlets of the Puget Sound, such as Bellingham Bay, Hood Canal, south Puget Sound, and the multi-inlet basin behind Agate and Rich Passages. Therefore, future study is necessary to further quantify the storm surge level in these high-risk areas through field measurements and refined model simulations.

Acknowledgments

The project is primarily funded by a grant from the NOAA Regional Coastal Resilience Grants Program (grant #NA16NOS4730015). Additional funds were provided by the State of Washington as well as the Pacific Northwest Climate Impacts Research Consortium (CIRC), which is partially funded by the Regional Integrated Sciences and Assessments program under NOAA grant #NA15OAR4310145. The Puget Sound storm surge model simulation was performed using resources available through Research Computing at Pacific Northwest National Laboratory (PNNL). PNNL is operated by Battelle for the U.S. Department of Energy under Contract DE-AC05-76RL01830.

Acronyms and Abbreviations

ADCP	acoustic Doppler current profiler
CFSR	Climate Forecast System Reanalysis
DFO	Fisheries and Oceans Canada (Department of Fisheries and Oceans)
FVCOM	finite-volume community ocean model
NCEP	National Centers for Environmental Prediction
NOAA	National Oceanic and Atmospheric Administration
NTR	non-tidal residual
PNNL	Pacific Northwest National Laboratory
PNW	Pacific Northwest
RMSE	root mean square error
SI	scatter index
SJDF	Strait of Juan de Fuca
WSG	Washington Sea Grant

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1.0 Introduction

Storm surge and coastal inundation induced by extreme weather events such as tropical cyclones (e.g., hurricanes) and extratropical cyclones (e.g., nor'easters) pose a great threat to coastal communities around the world (Hauer et al. 2016; Mousavi et al. 2011). The Pacific Northwest (PNW) coast of United States is subject to frequent extratropical cyclone activities, which bring in severe weather conditions such as high winds and rainfalls to the region. Figure 1.1 shows the historical winter season (November–March, 1871–2010) extratropical cyclone intensity distribution for North America. In the Puget Sound region, on average, each year roughly one notable historical extratropical cyclone track passed through each 0.5 degree × 0.5 degree raster grid cell.

During the storm events, strong wind combined with lower atmospheric pressure often leads to increased water level and inundation in Puget Sound. However, based on literature review, no detailed modeling studies have been conducted to simulate storm surge and to map the spatial distribution of the surge risk in Puget Sound. Therefore, there is a strong need to conduct a high-resolution storm surge modeling to understand how storm surge propagates inside Puget Sound as well as its temporal and spatial distributions, especially within the complex sub-basins.

The Washington Coastal Resilience Project is a 3-year effort by 15 institutional partners to rapidly increase the state’s capacity to prepare for coastal hazards, such as flooding and erosion, that are related to sea level rise. Funded by the National Oceanic and Atmospheric Administration (NOAA) Regional Coastal Resilience Grants Program and the Regional Integrated Sciences and Assessments Program, the project seeks to improve risk projections, provide better guidance for land use planners, and strengthen capital investment programs for coastal restoration and infrastructure. The Washington Sea Grant is leading the multi-institution research effort to assess the extreme coastal water level during storm events to support sea level rise planning in Washington State. PNNL was contracted by the Washington Sea Grant to support the project by conducting storm surge modeling and analysis in Puget Sound. This report summarizes the storm surge modeling effort in Puget Sound, including the modeling approach, data used for model validation, results analysis and conclusions.

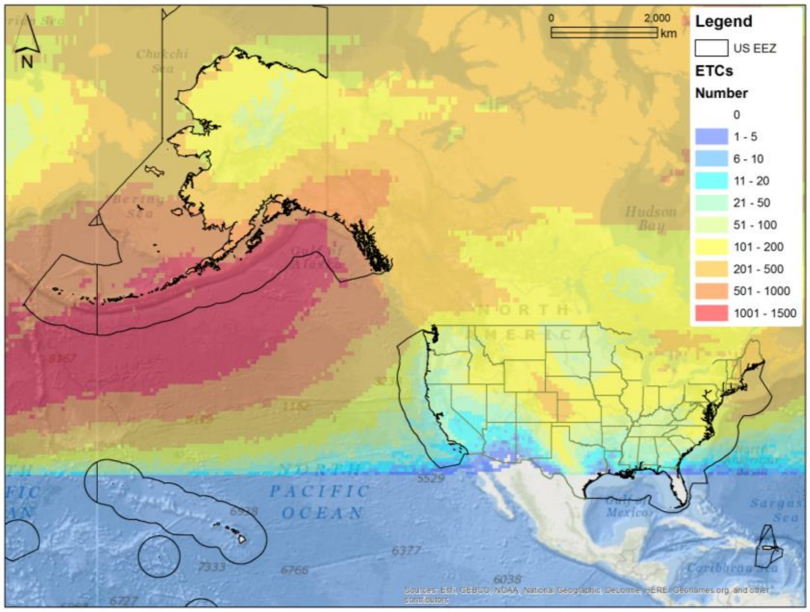

Figure 1.1. Number of extratropical cyclone tracks passing through each 0.5 degree × 0.5 degree raster grid cell for the North America during 1871–2010 winter seasons based on the 20th Century Reanalysis data set (Compo et al. 2011).

2.0 Methodology

The selected storm surge events studied, associated model setup, and model performance metrics are described in the following sections.

2.1 Selection of Historical Storm Surge Events

Unlike the U.S. East Coast and the northern Gulf of Mexico that are mostly impacted by tropical cyclones, storm surge in Puget Sound is small and the associated water level anomaly is often buried by large astronomical tides. Therefore, it is important to develop a systematic approach to detecting storm surge signals and identifying associated individual storm surge events. This section describes the detailed procedures for identifying storm surge events for model simulation based on historical data at NOAA tide gauges in Puget Sound.

The long-term, hourly water level records over the past 38 years (1980–2016) at four NOAA tidal stations—Neah Bay Seattle, Port Townsend, and Tacoma (Figure 2.2)—were used to determine the storm events that occurred in the Puget Sound during that time period. The Neah Bay gauge was chosen because it represents the incoming storm surge entering the Salish Sea from the open coastal ocean. The Seattle, Port Townsend, and Tacoma stations were selected because they are located inside Puget Sound. Tide gauges at Port Angeles, Friday Harbor, and Port Atkinson were used for model validation. The time period of 1980–2016 was determined based on the availability of the meteorological forcing data from Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010) used to drive the storm surge model.

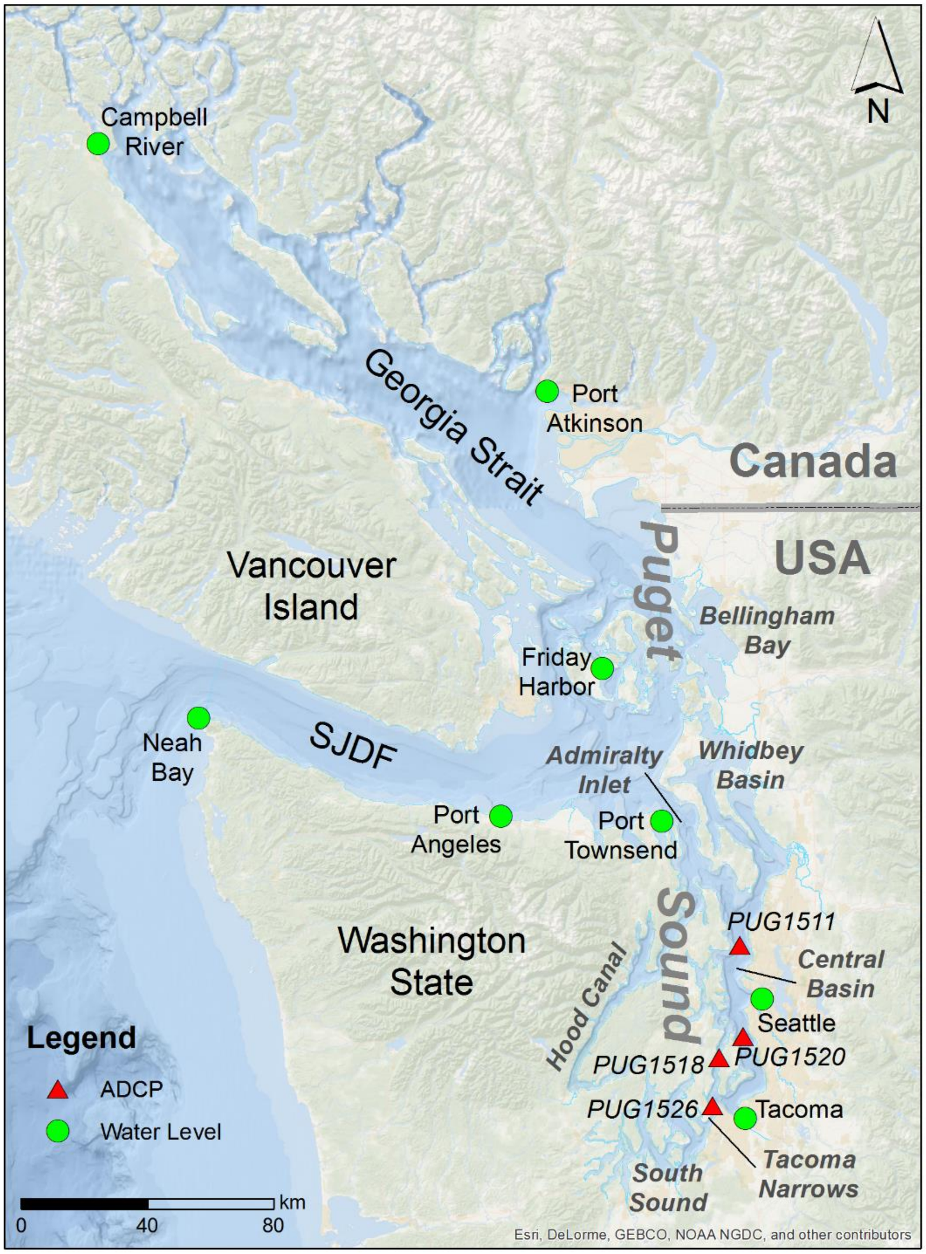

Figure 2.2. Distribution of representative NOAA real-time tidal stations (green circles) and selected historical current stations (red triangles) within the Salish Sea, which consists of the Strait of Juan de Fuca (SJDF), Georgia Strait, and Puget Sound.

To identify individual historical storms, the non-tidal residual (NTR) analysis method was used. In this study, the NTR is defined as the instantaneous difference between the measured water level and predicted astronomical tide. A positive NTR value of 0.5 m was used as a criterion to identify a storm surge event. Based on this criterion, a total number of 108 storm surge events were identified at Neah Bay, 123 at Port Townsend, 118 at Seattle, and 79 at Tacoma (see Table 2.1). The number of storm surge events at the Tacoma station is much less than the rest of the stations, partially because the data only became available after 1997.

Table 2.1. Number of identified storm surge events that had NTR values greater than 0.5 m at four NOAA real-time tide stations in Puget Sound.

Station	Number of Events (1980 – 2016)	Data Period
Neah Bay	108	1934–ongoing
Port Townsend	123	1972–1976 1979–ongoing
Seattle	118	1899–ongoing
Tacoma	79	1997–ongoing

Clearly, there are a lot of events to analyze and simulate if considering all the events listed in Table 2.1, because many of these events are not common for all the stations. To reduce the number of storm surge events for model simulation, the following two additional criteria (in addition to NTR >0.5 m) were applied to further select a subset of storm surge events from those listed in Table 2.1:

- All top 20 events based on NTR ranking at each of the four stations.
- All common events that make the top 50 among Neah Bay, Port Townsend, and Seattle. Tacoma station was not considered in this criterion because its data period is significantly shorter than that of the other three stations.

Figure 2.3 shows the top 50 NTR events at the Neah Bay, Port Townsend, and Seattle stations and the top 20 NTR events at the Tacoma station. The uncommon events below rank 20 at Neah Bay, Port Townsend, and Seattle were not considered for simulations. Based on the above selection criteria, a final set of 34 storm surge events were identified and are listed in Table 2.2. The NTR values associated with each storm surge event at each station are also provided.

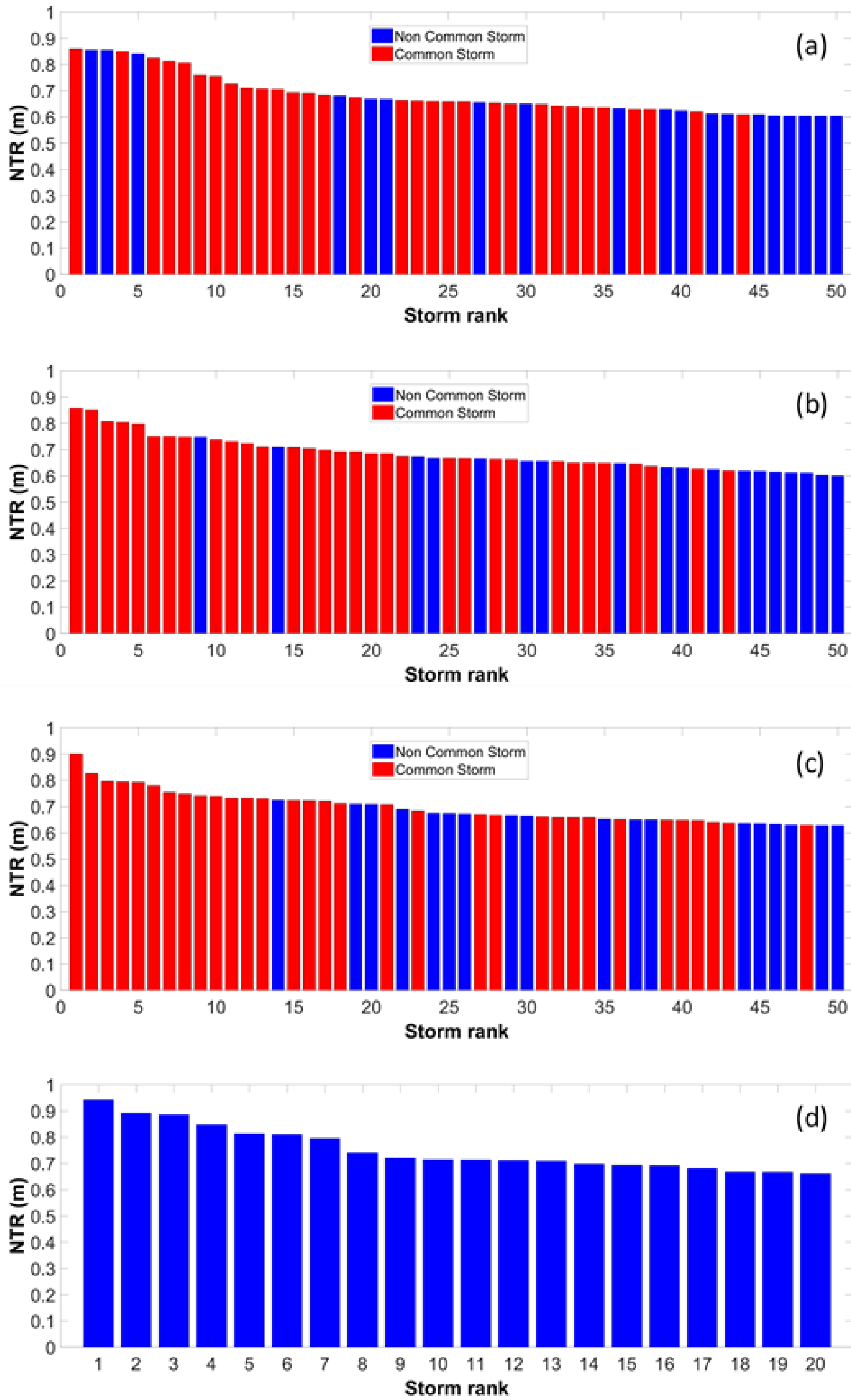

Figure 2.3. Top 50 NTR storm surge events in (a) Neah Bay, (b) Port Townsend, (c) Seattle, and top 20 events in (d) Tacoma. Red indicates common events for the Seattle, Port Townsend, and Neah Bay stations and blue represents uncommon events. The Tacoma station is not considered in the common events analysis because of its shorter data period.

Table 2.2. Selected storm surge events in the Salish Sea for model simulations.

	NTR (m)			
Event Date	Neah Bay	Port Townsend	Seattle	Tacoma
2016 - 10 - 16	0.684	0.663	0.712	0.711
2016 - 03 - 10	0.621	0.738	0.723	0.681
2016 - 03 - 06	0.518	0.749	0.709	0.72
2015 - 12 - 13	0.641	0.804	0.826	0.811
2014 - 12 - 11	0.707	0.698	0.739	0.714
2012 - 12 - 02	0.675	0.646	0.647	0.598
2010 - 01 - 18	0.66	0.751	0.76	0.796
2008 - 01 - 05	0.693	0.667	0.64	0.662
2007 - 12 - 03	0.71	0.711	0.73	0.741
2007 - 11 - 12	0.529	0.532	0.675	0.709
2006 - 12 - 15	0.651	0.797	0.901	0.886
2006 - 11 - 16	0.629	0.676	0.78	0.713
2006 - 02 - 04	0.635	0.691	0.732	0.639
2006 - 02 - 01	0.635	0.691	0.732	0.639
2002 - 12 - 16	0.814	0.804	0.794	0.848
1999 - 03 - 03	0.654	0.709	0.661	0.643
1998 - 11 - 25	0.629	0.705	0.741	0.667
1998 - 02 - 21	0.598	0.71	0.71	0.694
1998 - 02 - 12	0.659	0.637	0.637	0.627
1998 - 02 - 07	0.61	0.685	0.667	0.658
1997 - 10 - 04	0.639	0.62	0.629	0.597
1997 - 01 - 01	0.85	0.852	0.792	N/A
1996 - 02 - 21	0.669	0.53	0.551	N/A
1992 - 01 - 31	0.691	0.662	0.658	N/A
1992 - 01 - 28	0.664	0.65	0.658	N/A
1987 - 12 - 09	0.662	0.626	0.658	N/A
1987 - 12 - 01	0.654	0.685	0.722	N/A
1983 - 11 - 17	0.727	0.73	0.67	N/A
1983 - 11 - 11	0.756	0.655	0.648	N/A
1983 - 02 - 12	0.668	0.582	0.583	N/A
1983 - 01 - 27	0.86	0.858	0.754	N/A
1982 - 12 - 19	0.826	0.749	0.72	N/A
1981 - 11 - 15	0.76	0.666	0.683	N/A
1980 - 01 - 12	0.649	0.723	0.651	N/A

2.2 Model Setup

The Salish Sea storm surge model is mainly based on PNNL's existing Salish Sea hydrodynamic model (Yang and Khangaonkar 2010; Yang and Wang 2013, Yang et al. 2014) implemented using the finite-volume, community ocean model (FVCOM; Chen et al. 2003). Figure 2.4 shows the unstructured model grid and the associated bathymetric features. The model grid consists of approximately 120,000 nodes and 215,000 elements, and has a grid cell resolution of about 8 km along the open boundary to an average of 200 m inside Puget Sound.

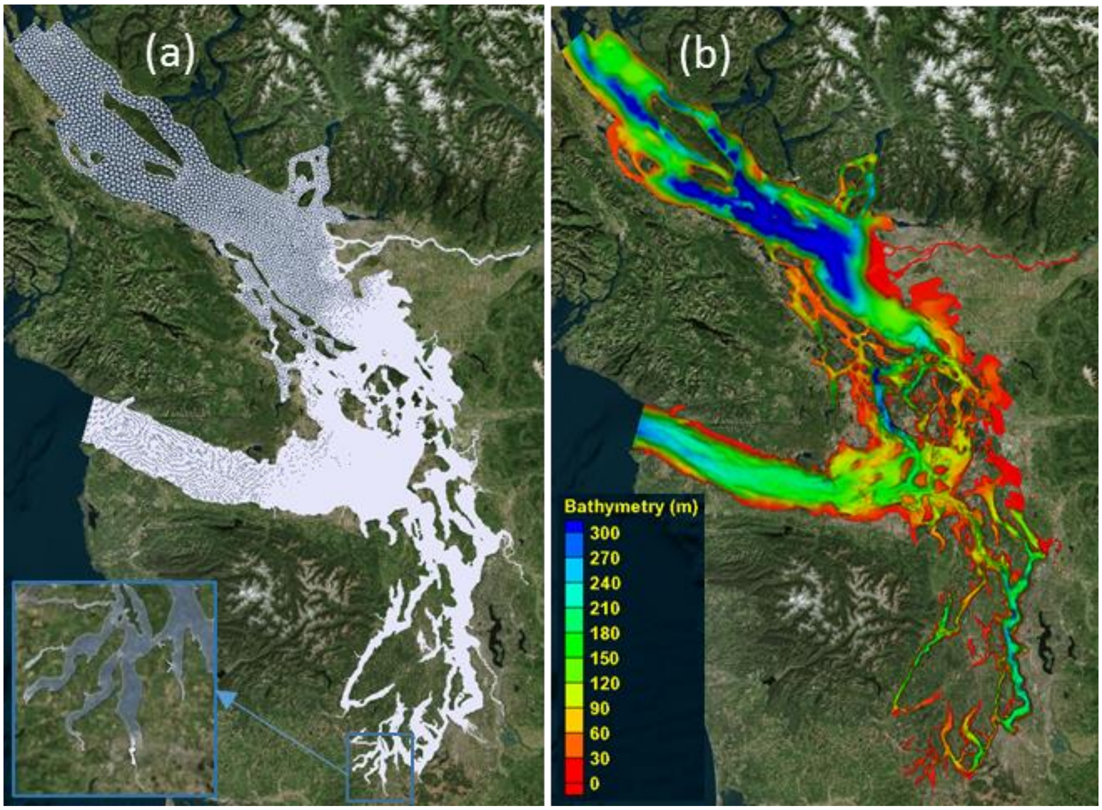

Figure 2.4. Salish Sea storm surge model: (a) model grid and (b) bathymetry.

There are two open boundaries in the Salish Sea model; one is at the entrance of the Strait of Juan de Fuca and the other is at the north end of the Strait of Georgia. Open boundary conditions were specified by observed water levels at two tidal stations—Neah Bay, Washington and Campbell River, British Columbia (Figure 2.2). It is widely recognized that storm surge inside an estuary is caused by the combination of remote surge that propagates into the estuary through the open boundary and local surge generated by meteorological forcing inside the system. Therefore, by directly forcing the model with observed water levels at the open boundaries, the contribution from the remote surge can be accurately captured. In addition, to calculate the storm surge level (i.e., NTR) for each storm event, a separate baseline run was conducted for the same storm period by forcing the model with astronomical tides only at both open boundaries.

Meteorological forcing, such as wind and atmospheric pressure field, is important for local surge induced by a storm event. In this study, the NOAA National Centers for Environmental Prediction (NCEP) CFSR wind and atmospheric pressure field was used to drive the storm surge model. The CFSR wind has a spatial resolution of 0.5 degree and an hourly temporal resolution. While this spatial resolution is relatively coarse compared to the size of the storm surge model domain, the CFSR data set is still one of the best publicly available meteorological products, considering its temporal resolution (hourly) and duration (1979–present) (e.g., Wang et al. 2018).

Model configurations and parameterizations are summarized below:

- Open boundary condition: hourly water levels at Neah Bay, Washington, and Campbell River, British Columbia
- Meteorological forcing: hourly, 0.5-degree CFSR wind (10 m above the sea surface) and atmospheric pressure (at the sea surface)
- Simulation period: a 7-day window centering each storm event
- Model time step: 0.4 second for the barotropic mode
- Number of vertical layers: 4 uniform sigma layers
- Bottom drag coefficient: C_d = 0.0025
- Model output frequency: hourly.

All model runs were conducted in the barotropic mode without considering the effect of water density variation caused by salinity and temperature. River discharge was not included either. This is a common practice in storm surge simulation because the effect of river discharge on water level variation is generally much more localized (upstream of estuaries) and smaller compared to that of meteorological forcing.

Lastly, in addition to model simulations corresponding to the historical 34 storm events, a separate model run was conducted to evaluate the model's performance in simulating currents using acoustic Doppler current profiler (ADCP) measurements. NOAA conducted extensive ADCP measurements in Puget Sound during the period of 2015–2017. Unfortunately, none of the storm surge event identified in Table 2.2 fell within any of the ADCP measurement periods. For the purpose of model validation for tidal current prediction, a 20-day model run was conducted for the period of 8/20/2015–9/9/2015, which corresponds to ADCP measurement periods at four stations in the Central Basin and South Sound (Figure 2.2). Locations, water depth, and data periods for these ADCP data are provided in Table 2.3.

Table 2.3. ADCP stations selected for model validation in Puget Sound

Station Name	Latitude	Longitude	Water Depth (m)	Layers	Start Date	End Date
PUG1511	47.76	-122.43	169.78	38	2015-05-29	2015-09-11
PUG1520	47.50	-122.42	150.50	35	2015-07-24	2015-09-14
PUG1518	47.44	-122.52	82.82	19	2015-07-23	2015-09-12
PUG1526	47.304	-122.55	66.90	31	2015-07-24	2015-09-14

2.3 Model Performance Metrics

As mentioned in Section 2.2, for each of the 34 storm events, two separate model runs were conducted: one driven by astronomical tides (baseline) and one driven by observed water levels (storm surge). For each storm event, the NTR time series at each grid point can be obtained by calculating the instantaneous differences in water level between the baseline run and the storm surge run. A series of model performance metrics were calculated to quantitatively evaluate model performance in simulating water level and storm surge (NTR).

The root mean square error ($RMSE$) is defined as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - M_i)^2}{N}}$$

where N is the number of observations, M_i is the measured value, and P_i is the model generated value.

The scatter index (SI) is the $RMSE$ normalized by the average magnitude of measurements:

$$SI = \frac{RMSE}{\overline{abs(M)}}$$

The mean absolute error is defined as:

$$MAE = \sum_{i=1}^{N} abs(P_i - M_i)$$

The bias is defined as:

$$Bias = \frac{\sum_{i=1}^{N}(P_i - M_i)}{N}$$

The percentage bias is defined as:

$$Bias(\%) = \frac{\sum_{i=1}^{N} P_i - \sum_{i=1}^{N} M_i}{\sum_{i=1}^{N} abs(M_i)} \cdot 100$$

The linear correlation coefficient (R) is a measure of the linear relationship between the predictions and the measurements from 0 to 1 where 1 is a perfect fit:

$$R = \frac{\sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2 \left(M_i - \overline{M}\right)^2}{\overline{\sqrt{\left(\sum_{i=1}^{N}\left(M_i - \overline{M}\right)^2\right)\left(\sum_{i=1}^{N}\left(P_i - \overline{P}\right)^2\right)}}}$$

3.0 Model Results and Discussion

Model validation relative to water levels and currents, error statistics of model performance metrics, and NTR two-dimensional (2-D) distributions are described in the following sections.

3.1 Model Validation – Water Levels

Model validation is a critical step in storm surge modeling, especially when the storm surge magnitude in Puget Sound is relatively small compared to background astronomical tides. Inside the Salish Sea, water levels have been routinely recorded at several tidal stations by NOAA and Fisheries and Oceans Canada (DFO). To assess the model performance, model-predicted total water level (astronomical tides + surge) time series for each storm event were compared with observed water levels at tide stations. Meanwhile, model-predicted storm surge (NTR) time series for each storm event were calculated and compared with those derived from data. Figure 3.1 through Figure 3.3 show the time series comparisons of total water level and NTR between model predictions and field measurements at six tidal stations inside the model domain for three example storm events, which occurred in 1997-1-1, 2006-12-15, and 2016-10-16. These three events ranked as the top 5, top 1, and top 18 storm surge events, respectively, based on NTR values at the Seattle station (see Table 2.2). The complete plots of modeled and data comparisons for all 34 storm surge events are provided in Appendix A.

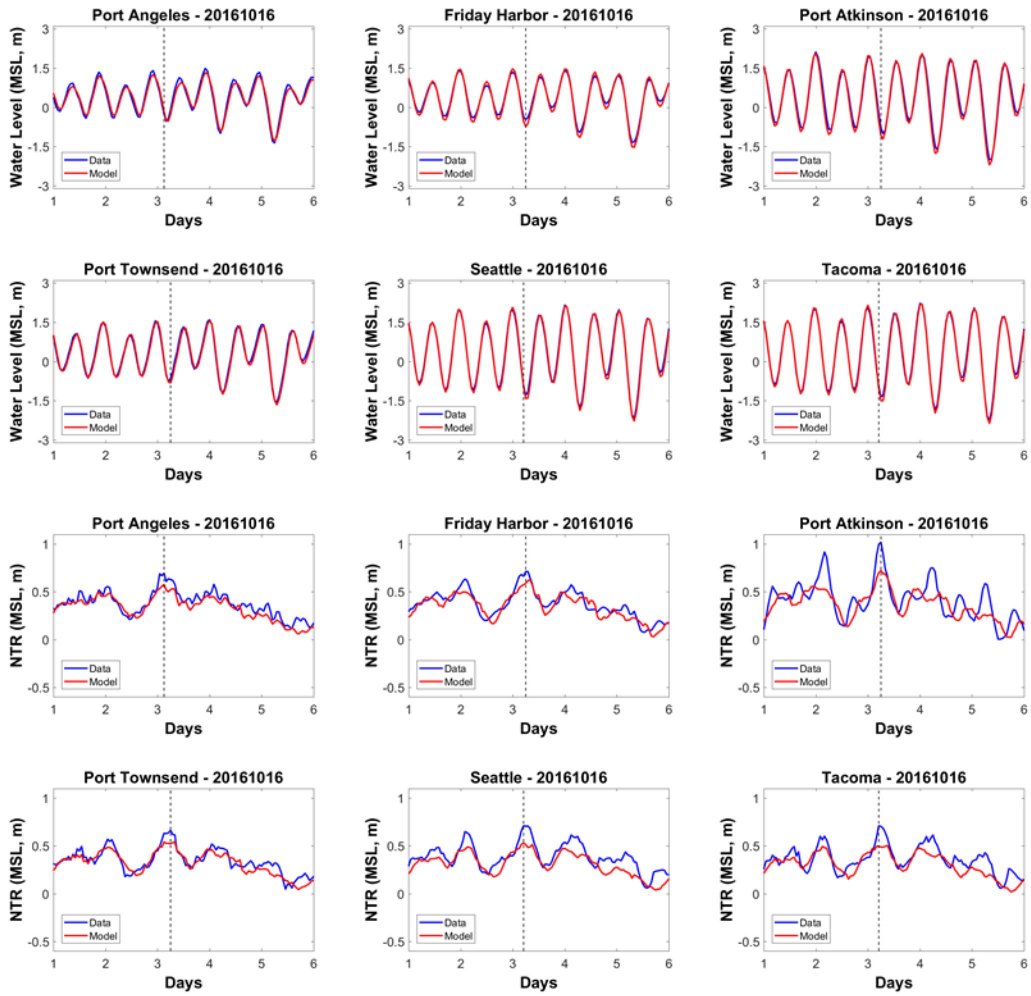

Figure 3.1. Time series comparisons of total water level and NTR for storm event 2016-10-16 at six tidal stations inside the model domain.

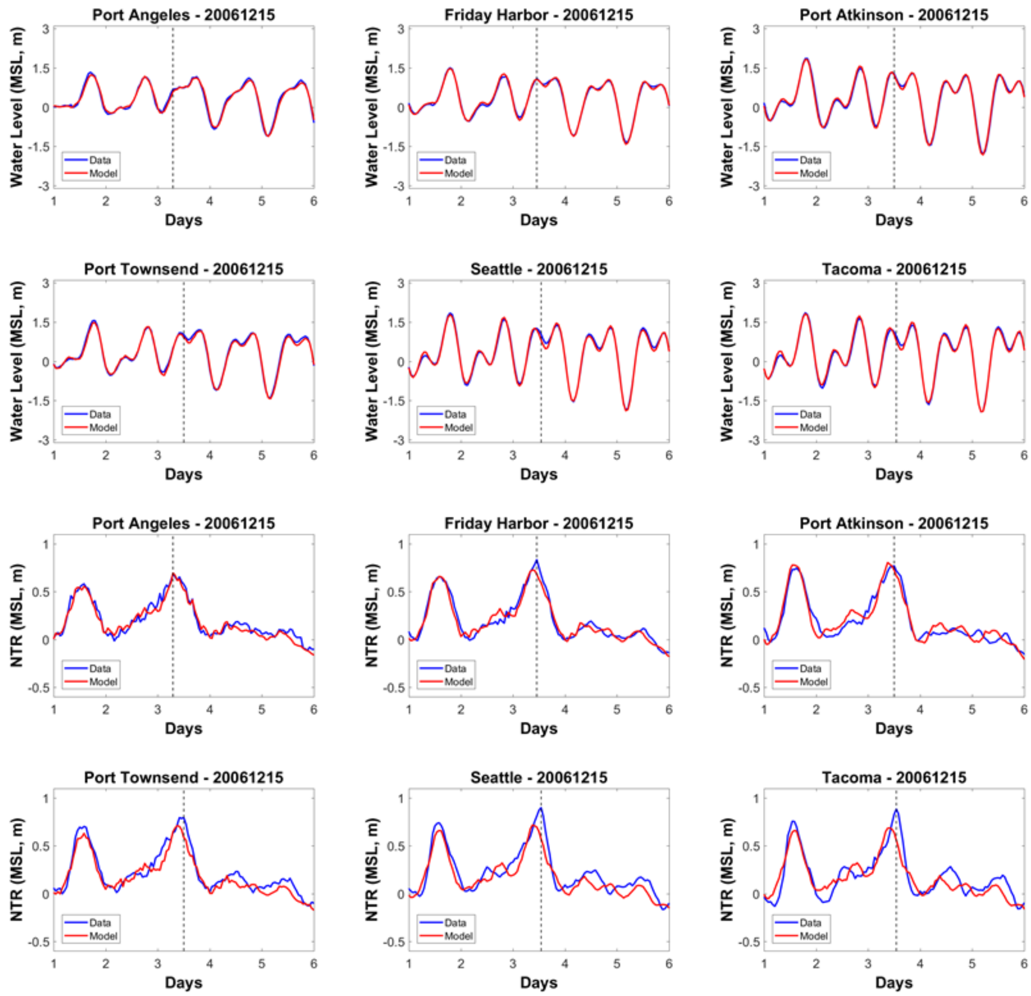

Figure 3.2. Time series comparisons of total water level and NTR for storm event 2006-12-15 at six tidal stations inside the model domain.

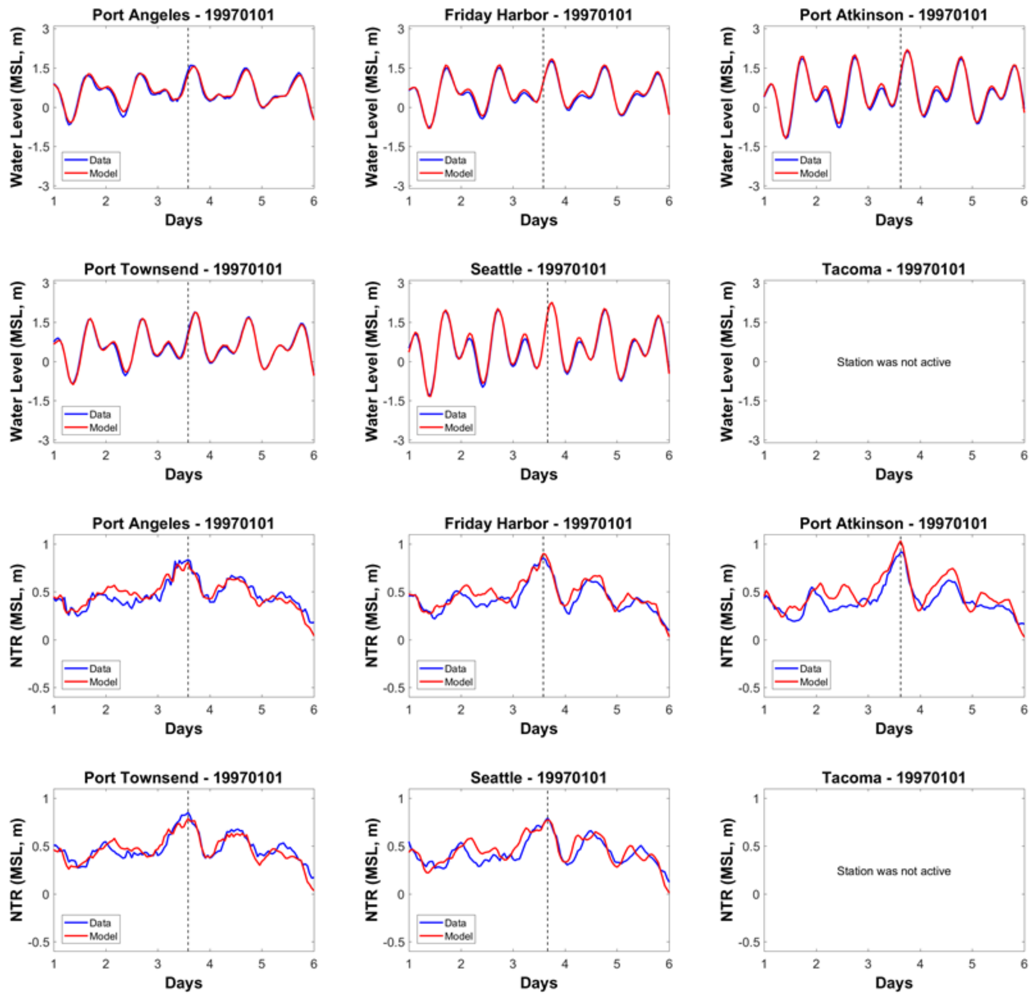

Figure 3.3. Time series comparisons of total water level and NTR for storm event 1997-1-1 at six tidal stations inside the model domain.

Overall, the model predictions match field measurements very well for both total water level and NTR. The maximum storm surge varies spatially across the tidal stations, indicating the surge is not entirely determined by the same surge propagated from the open boundary at Neah Bay. Localized meteorological forcing and nonlinear interaction both contributed to the surge inside Puget Sound.

3.2 Model Validation – Currents

Although the focus of the this study is on the prediction of storm surge distribution in Puget Sound, it is important to evaluate the storm surge model's capability of simulating tidal currents accurately to understand the full hydrodynamic process in the system. Therefore, additional model validation was conducted to compare modeled and observed currents. The 20-day simulation period (8/20/2015–9/9/2015) covers a complete spring-neap tidal cycle. Figure 3.4 through Figure 3.7 show the time series comparisons of depth-averaged currents between model predictions and ADCP measurements at four representative stations inside Puget Sound (Figure 2.2). Good agreement between model results and measurements at all stations confirmed that the storm surge model is able to accurately simulate tidal currents inside Puget

Sound. The model captured the spring-neap tidal cycle and diurnal inequality very well. In comparison, current speeds at the two stations in the Central Basin (PUG1511 and PUG1520) are relatively small (Figure 3.4 and Figure 3.5). A dominant northern current (positive V-component) in the Colvos Passage is observed in both modeled results and measurements (Figure 3.6), as shown in a past study by Yang and Wang (2013). Tidal currents in the Tacoma Narrows are strong; with the maximum depth-average current speed exceeds 2 m/s during spring tide (Figure 3.7).

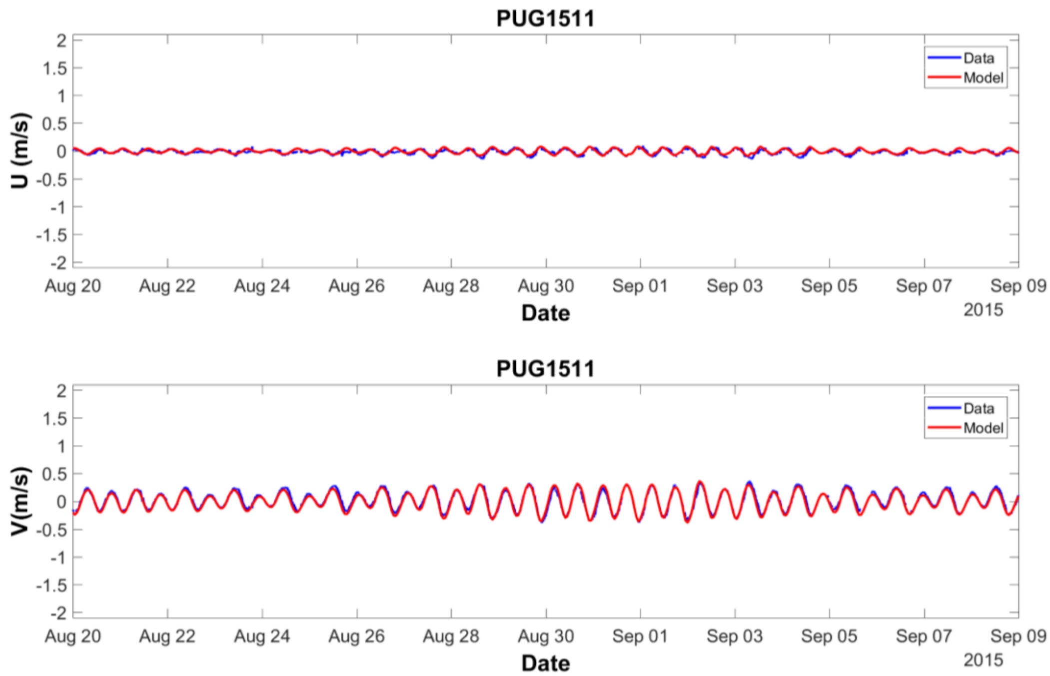

Figure 3.4. Time series comparisons of simulated and observed depth-averaged velocity (Upper – U/East velocity; Lower – V/North velocity) at station PUG1511 in the North Central Basin.

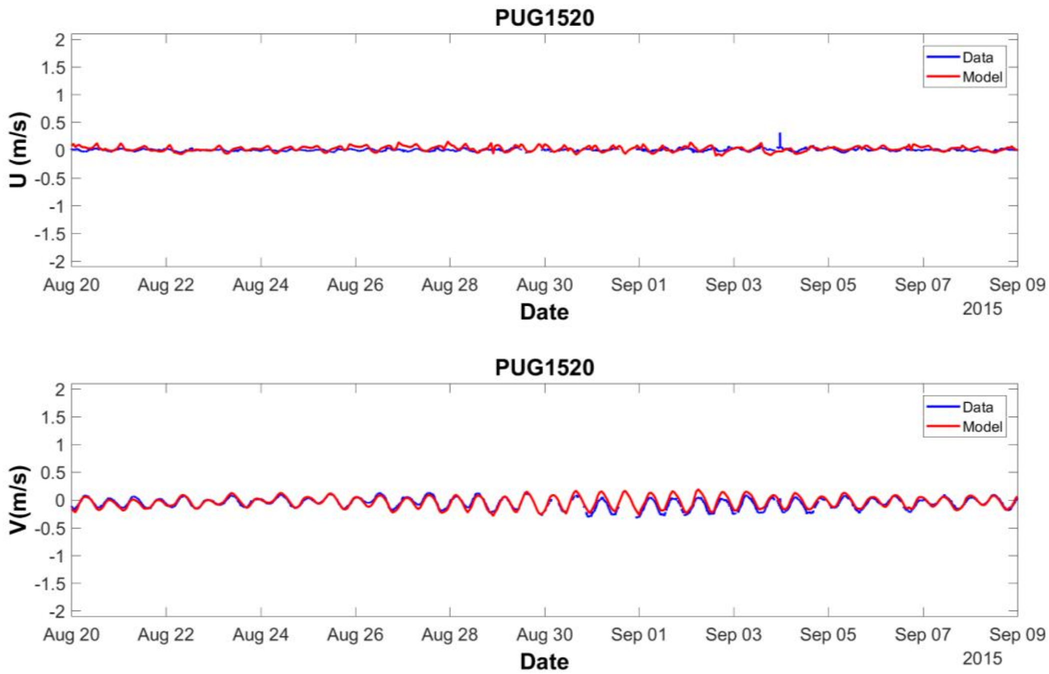

Figure 3.5. Time series comparisons of simulated and observed depth-averaged velocity (Upper – U/East velocity; Lower – V/North velocity) at station PUG1520 in the South Central Basin.

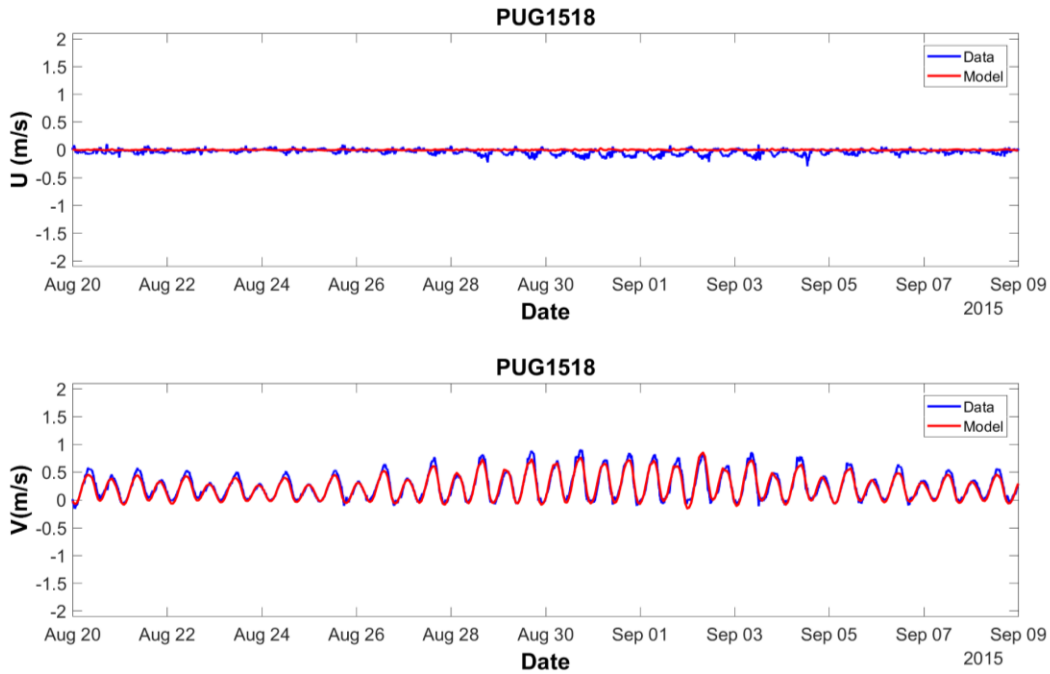

Figure 3.6. Time series comparisons of simulated and observed depth-averaged (Upper – U/East velocity; Lower – V/North velocity) at station PUG1518 Colvos Passage.

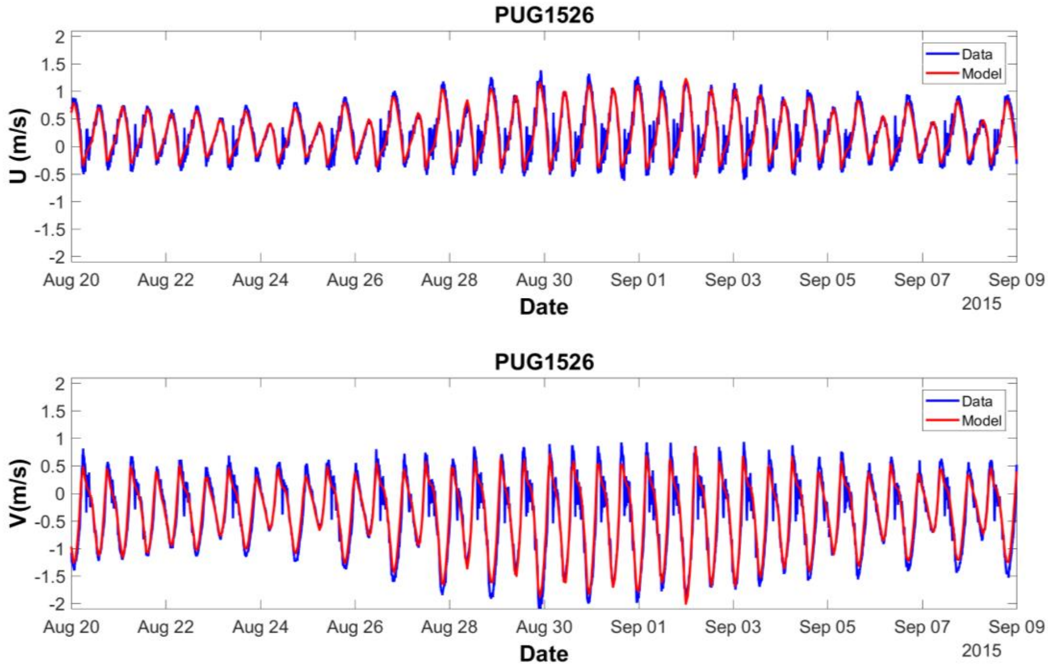

Figure 3.7. Time series comparisons of simulated and observed depth-averaged velocity (Upper – U/East velocity; Lower – V/North velocity) at station PUG1526 in the Tacoma Narrows.

3.3 Error Statistics of Model Performance Metrics

Six widely used error statistics parameters were calculated to further quantify the model's performance in reproducing the observed water level and NTR inside the model domain. These parameters include $RMSE$, MAE, SI, bias, *bias%*, and R, as described in Section 2.3.
The error statistics for simulated total water level and NTR for the three example storm events discussed in Section 3.1 are summarized in Table 3.1. and Table 3.2, respectively. Error statistics in Table 3.1 confirmed that the model successfully reproduced the total water level with very high model skills. For example, the linear correlation coefficient R is equal to 0.99 and RMSE is on the order of 0.1 m with all percentage bias within 10%. The model skill in reproducing NTR is slightly reduced, especially for SI, bias%, and R. However, the overall errors are still within acceptable ranges (Table 3.2). To assess the model's skill in capturing the maximum storm surge height, error statistics for the maximum NTR values at each tidal station were also calculated for all 34 storm events (i.e., only 34 pairs of values). As shown in Table 3.3, the model is capable of reproducing the maximum NTRs, although the error statistic values are not as good as those shown in Table 3.1 and Table 3.2, which is to be expected because it is more challenging to reproduce instantaneous maximum storm surge height. The error statistics for all 34 storm events are provided in Appendix B.

Table 3.1. Error statistics of total water level predictions for three example storm events.

Station	Event	*RMSE* (m)	*MAE* (m)	*SI*	*Bias* (m)	*Bias* (%)	*R*
Port Angeles	20161016	0.13	0.12	0.23	-0.03	-4.39	0.98
	20061215	0.09	0.06	0.14	-0.01	-2.13	0.99
	19970101	0.09	0.07	0.13	0.02	3.14	0.99
Friday Harbor	20161016	0.10	0.09	0.15	-0.04	-6.58	0.99
	20061215	0.05	0.04	0.08	0.01	0.93	0.99
	19970101	0.08	0.07	0.12	0.06	9.85	0.99
Port Townsend	20161016	0.11	0.09	0.16	-0.05	-6.73	0.99
	20061215	0.07	0.06	0.12	-0.03	-5.15	0.99
	19970101	0.07	0.05	0.10	0	0.64	0.99
Seattle	20161016	0.09	0.07	0.09	-0.04	-3.59	0.99
	20061215	0.07	0.06	0.10	-0.01	-2.02	0.99
	19970101	0.09	0.07	0.11	0.05	5.70	0.99
Tacoma	20161016	0.09	0.07	0.08	-0.04	-3.44	0.99
	20061215	0.08	0.07	0.11	0.02	2.06	0.99
	19970101	N/A	N/A	N/A	N/A	N/A	N/A
Port Atkinson	20161016	0.15	0.12	0.16	-0.06	-6.03	0.99
	20061215	0.07	0.06	0.10	0	0.66	0.99
	19970101	0.11	0.09	0.14	0.06	8.71	0.99

Table 3.2. Error statistics of NTR predictions for three example storm events.

Station	Event	RMSE (m)	MAE (m)	SI	Bias (m)	Bias (%)	R
Port Angeles	20161016	0.07	0.06	0.20	-0.05	-12.20	0.92
	20061215	0.06	0.04	0.30	-0.02	-7.29	0.96
	19970101	0.07	0.06	0.15	0.01	2.33	0.88
Friday Harbor	20161016	0.07	0.06	0.21	-0.03	-8.20	0.89
	20061215	0.05	0.04	0.29	-0.01	-4.53	0.97
	19970101	0.07	0.06	0.15	0.04	8.86	0.93
Port Townsend	20161016	0.06	0.05	0.20	-0.03	-8.50	0.90
	20061215	0.08	0.07	0.47	-0.05	-19.16	0.95
	19970101	0.07	0.06	0.15	-0.01	-2.51	0.88
Seattle	20161016	0.10	0.09	0.34	-0.08	-19.76	0.85
	20061215	0.10	0.08	0.59	-0.05	-21.54	0.93
	19970101	0.09	0.07	0.19	0.02	4.88	0.83
Tacoma	20161016	0.10	0.08	0.34	-0.06	-16.44	0.80
	20061215	0.11	0.09	0.69	-0.02	-7.73	0.88
	19970101	N/A	N/A	N/A	N/A	N/A	N/A
Port Atkinson	20161016	0.09	0.07	0.25	-0.04	-10.04	0.87
	20061215	0.10	0.08	0.44	-0.04	-15.88	0.93
	19970101	0.08	0.06	0.17	0	0.55	0.91

Table 3.3. Error statistics of maximum NTR predictions for the 34 storm events.

Station	RMSE (m)	MAE (m)	SI	Bias (m)	Bias (%)	R
Port Angeles	0.09	0.07	0.14	-0.05	-7.76	0.64
Friday Harbor	0.09	0.07	0.13	-0.03	-4.15	0.56
Port Townsend	0.09	0.08	0.15	-0.06	-8.59	0.59
Seattle	0.10	0.08	0.16	-0.07	-9.62	0.46
Tacoma	0.12	0.09	0.19	-0.08	-12.01	0.44
Port Atkinson	0.11	0.10	0.16	-0.06	-7.31	0.56

Model skill for simulating tidal currents at the four ADCP stations was also evaluated. Only error statistics for current speed are calculated because Figure 3.4 through Figure 3.7 indicate the simulated directionalities are generally in good agreement with the observations. Table 3.4 shows the error statistics for simulated tidal currents at the four ADCP stations. Error statistics at PUG1511 and PUG1520 are not as good as at PUG1518 and PUG 1526 because tidal currents in the Central Basin are generally small. Overall the model skill is good at reproducing tidal currents in Puget Sound.

Table 3.4. Error statistics for modeled tidal currents.

Station	RMSE (m/s)	MAE (m/s)	SI	Bias (m/s)	Bias%	R
PUG1511	0.04	0.03	0.25	0.00	17.24	0.84
PUG1520	0.05	0.04	0.44	0.01	24.39	0.75
PUG1518	0.06	0.05	0.24	-0.02	-7.83	0.97
PUG1526	0.14	0.11	0.22	-0.09	-12.37	0.98

3.4 NTR 2-D Distributions

One of the advantages of using high-resolution numerical models for storm surge simulation is the ability to assess the detailed spatial distribution of high water level induced by storm surge. Figure 3.9 shows the maximum NTR distribution during a single storm event (1/1/1997) for the entire model domain. This storm event is ranked as one of the top storms, as shown in Table 2.2. The 2-D map shows that storm surge varies substantially throughout the Salish Sea. Higher NTR occurs mostly in the northern Puget Sound and Georgia Strait as well as in several sub-basins, such as Bellingham Bay, Hood Canal and the multi-inlet West Sound behind Agate and Rich Passages. The large spatial variation of NTR suggests that storm surge inside the Salish Sea is a nonlinear process that is determined by the combination of remote surge, meteorological forcing, and coastal geometry. Fetch also plays an important role in high storm surge in the Strait of Georgia.

The spatial distribution of the maximum and mean NTR values among all 34 storm events is presented in Figure 3.9 and Figure 3.10, respectively. The maximum storm surge exceeds 0.8 m nearly throughout Puget Sound and the mean NTR is generally within the range of 0.6 to 0.7 m. There is also a very distinct spatial variability similar to that shown in Figure 3.8. Depending on specific locations, the surge inside Puget Sound could be amplified or dissipated as it propagates into the Salish Sea from the PNW coast. The high-resolution 2-D distribution of NTR provides valuable information for coastal flood risk assessment in Puget Sound.

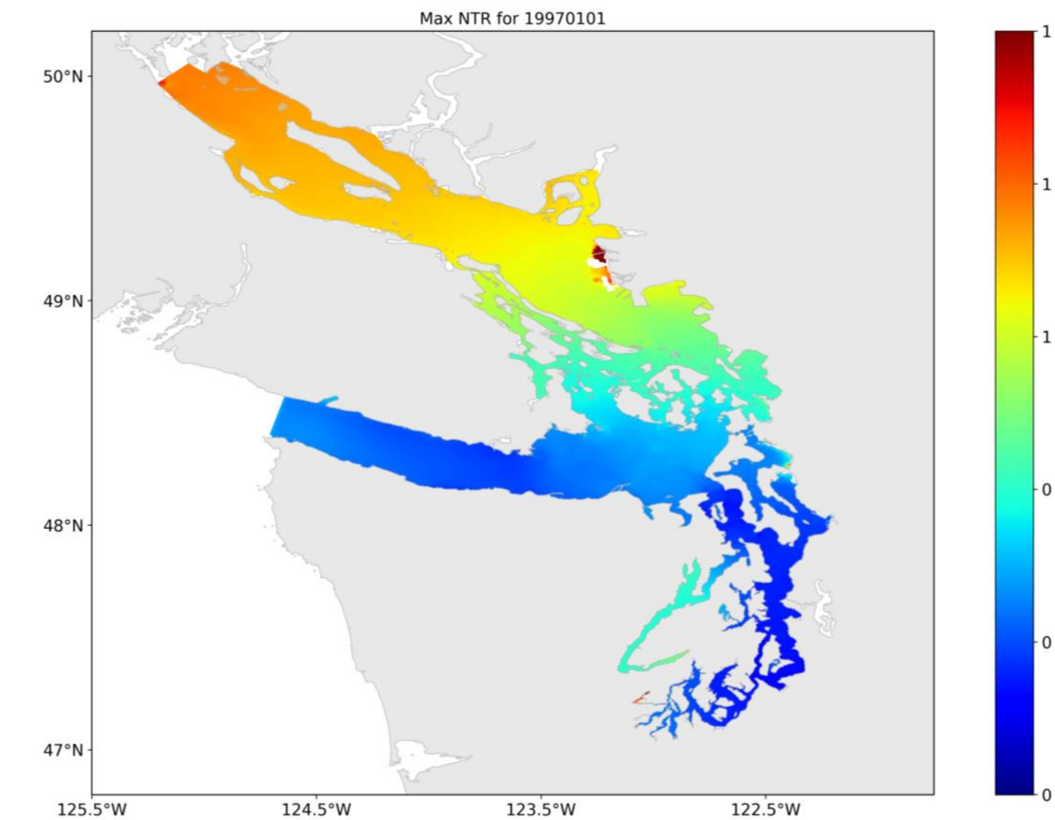

Figure 3.8. Maximum NTR distributions in the Salish Sea for storm event 1997-1-1.

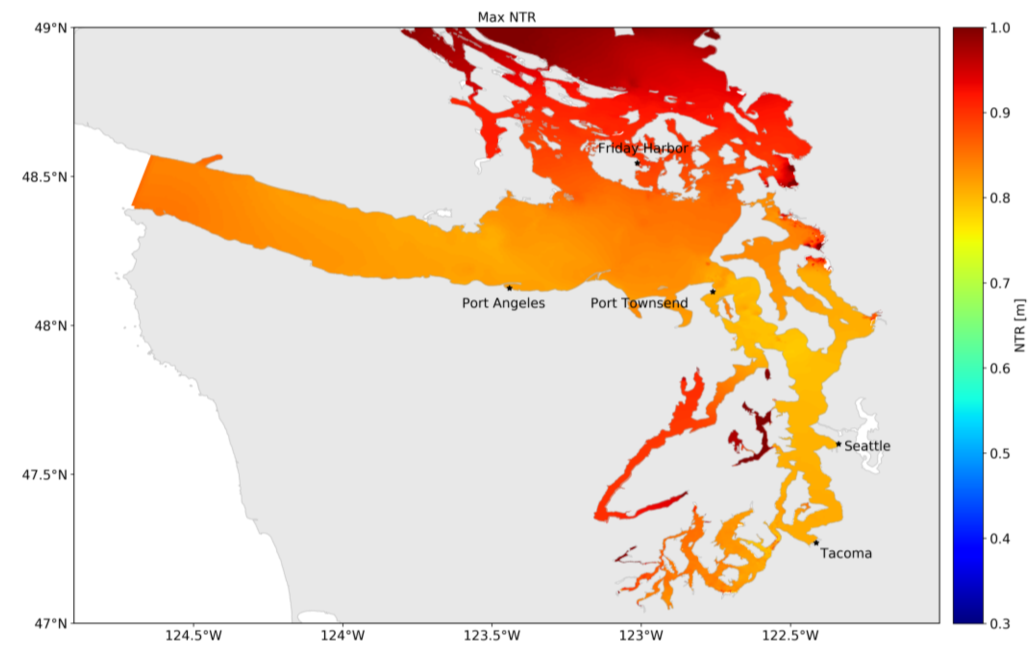

Figure 3.9. Maximum NTR distributions in Puget Sound based on the model output for all 34 storm events.

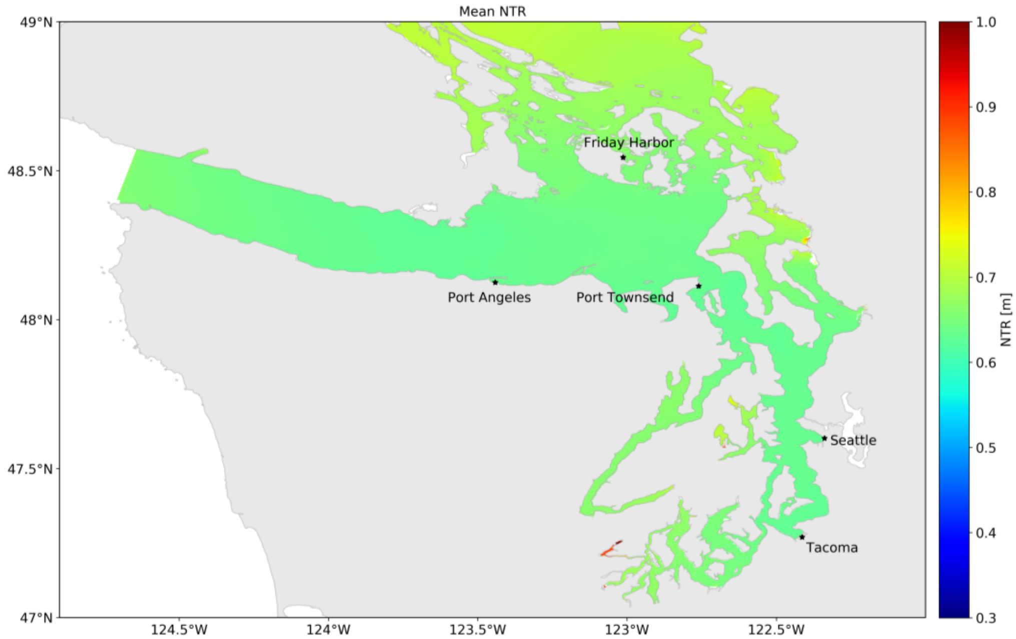

Figure 3.10. Mean NTR distribution in Puget Sound based on the model outputs from all 34 storm events.

4.0 References

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Appendix A – Times Series Plots

The appendix contains the times series plots that compare model-predicted total water level and NTR with field observations for all 34 storm events.

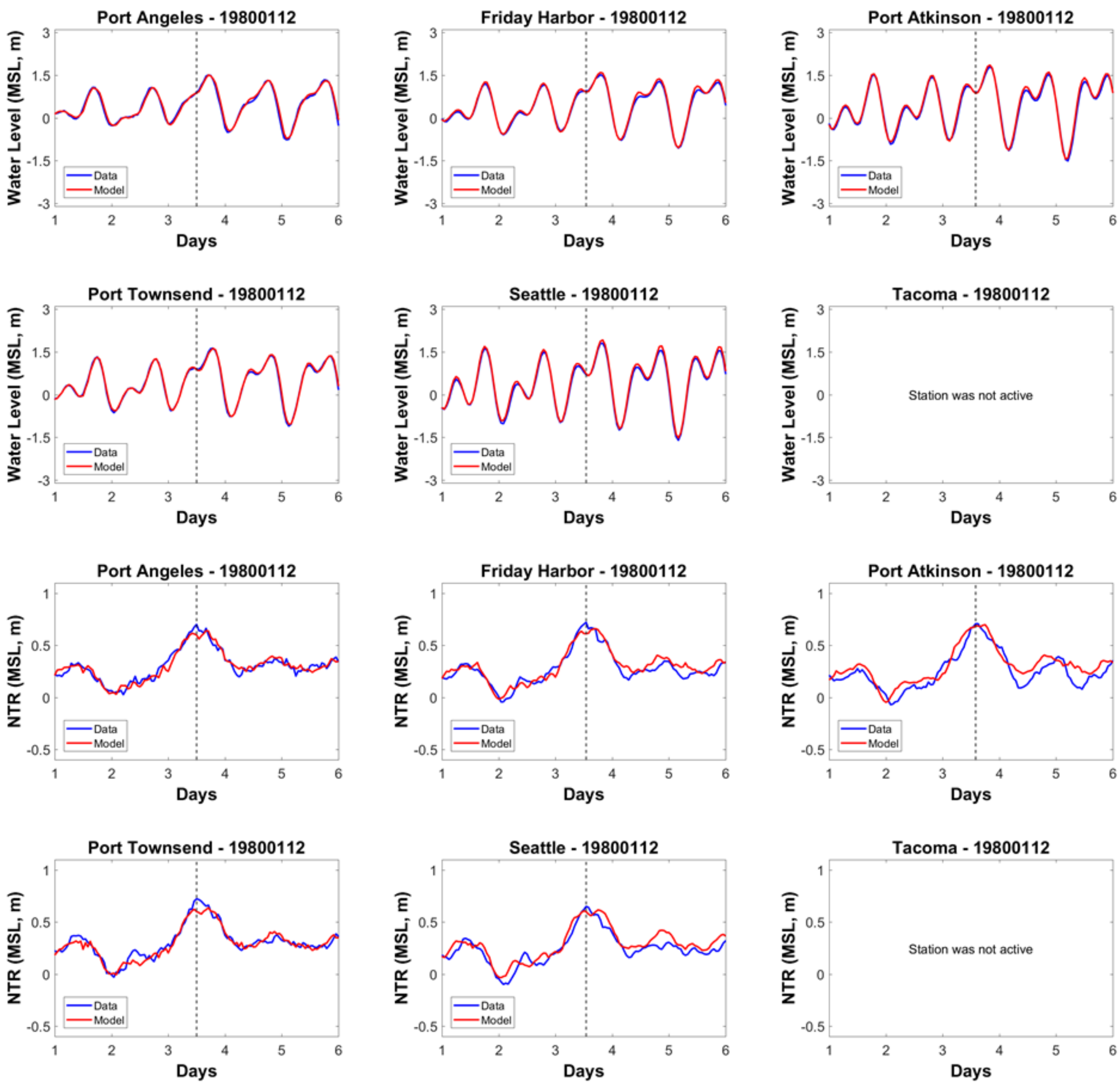

Figure A.1. Time series comparisons of total water level and NTR for storm event 19800112 at six tidal stations inside the model domain.

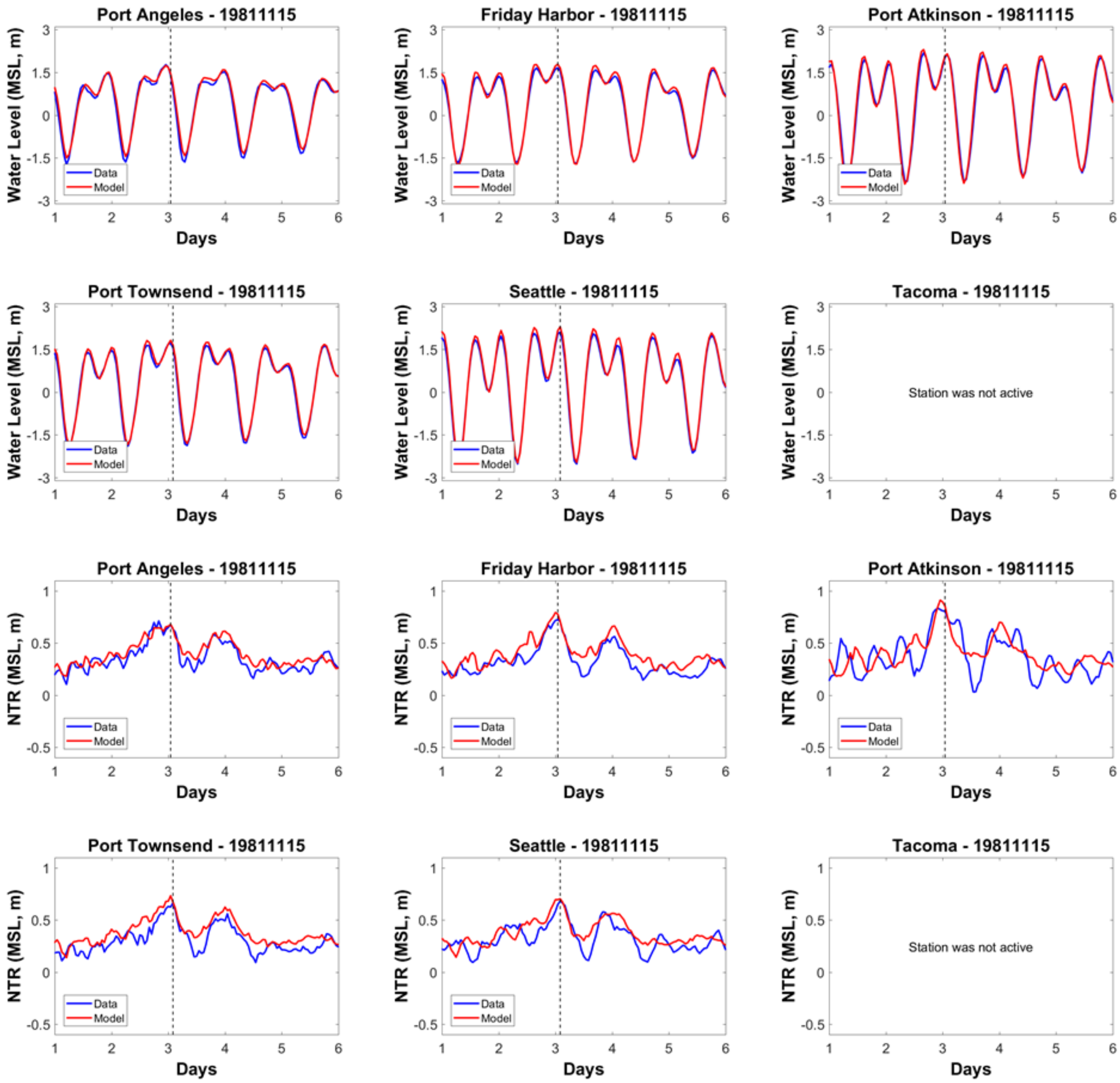

Figure A.2. Time series comparisons of total water level and NTR for storm event 19811115 at six tidal stations inside the model domain.

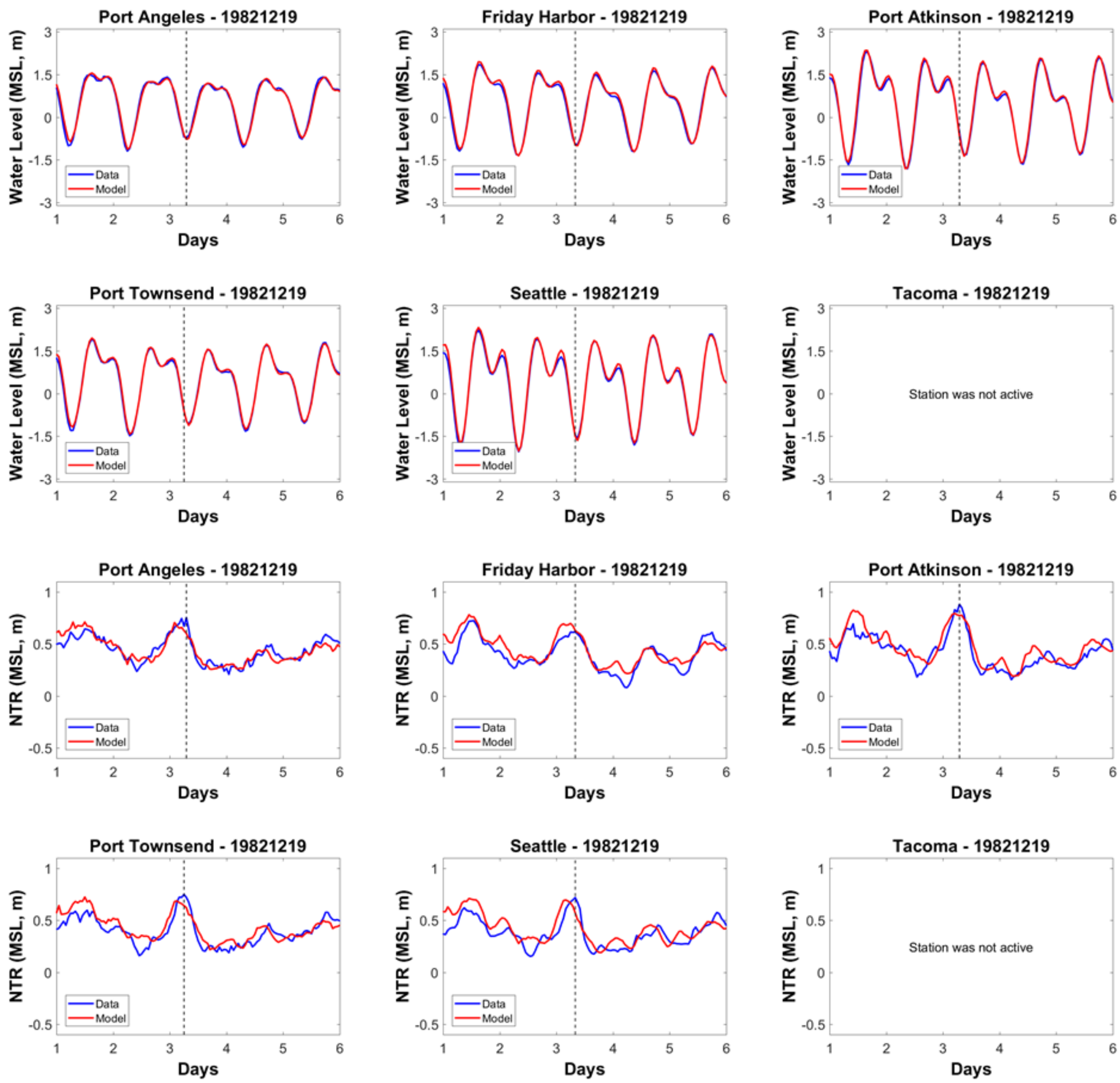

Figure A.3. Time series comparisons of total water level and NTR for storm event 19821219 at six tidal stations inside the model domain.

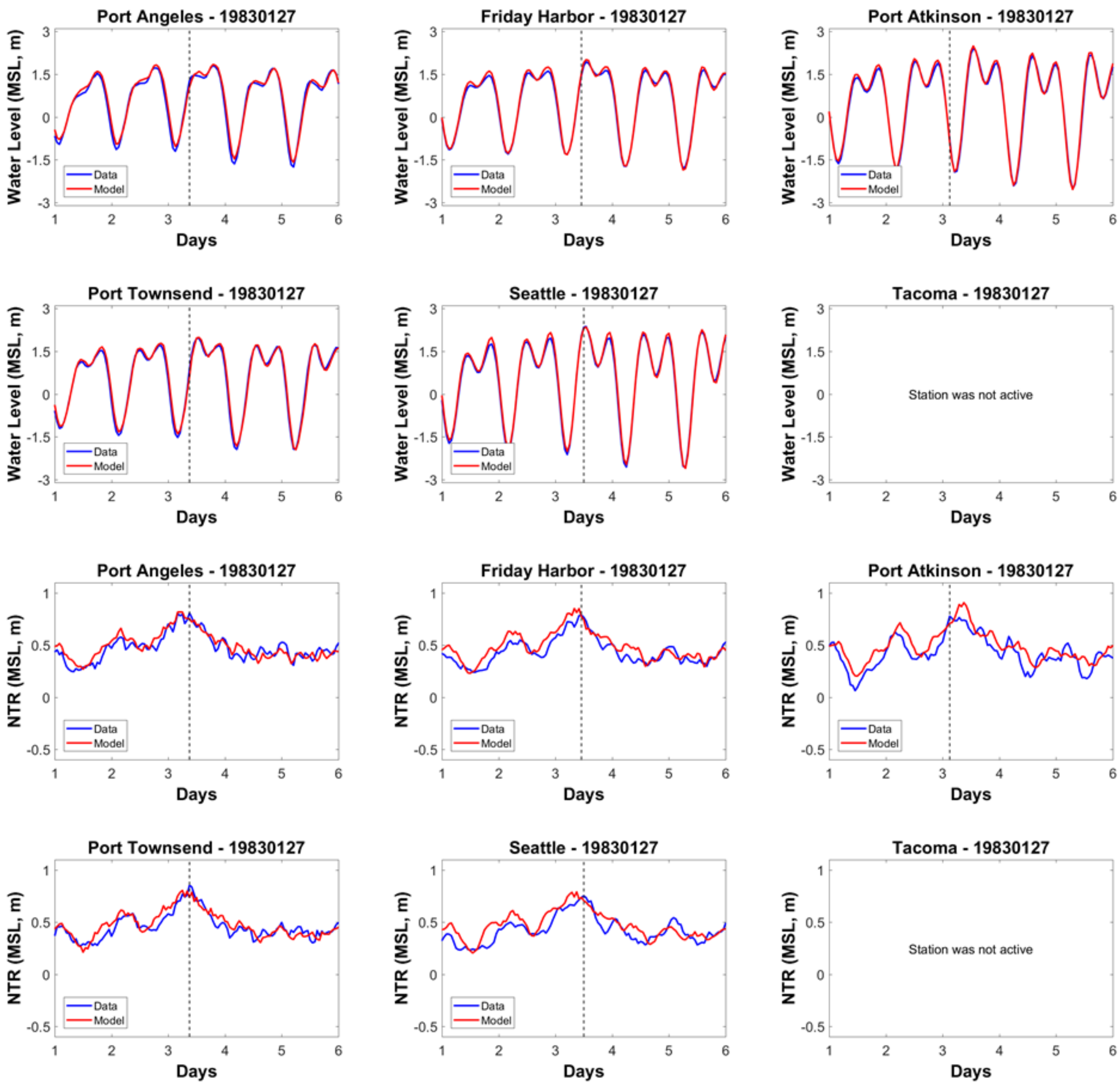

Figure A.4. Time series comparisons of total water level and NTR for storm event 19830127 at six tidal stations inside the model domain.

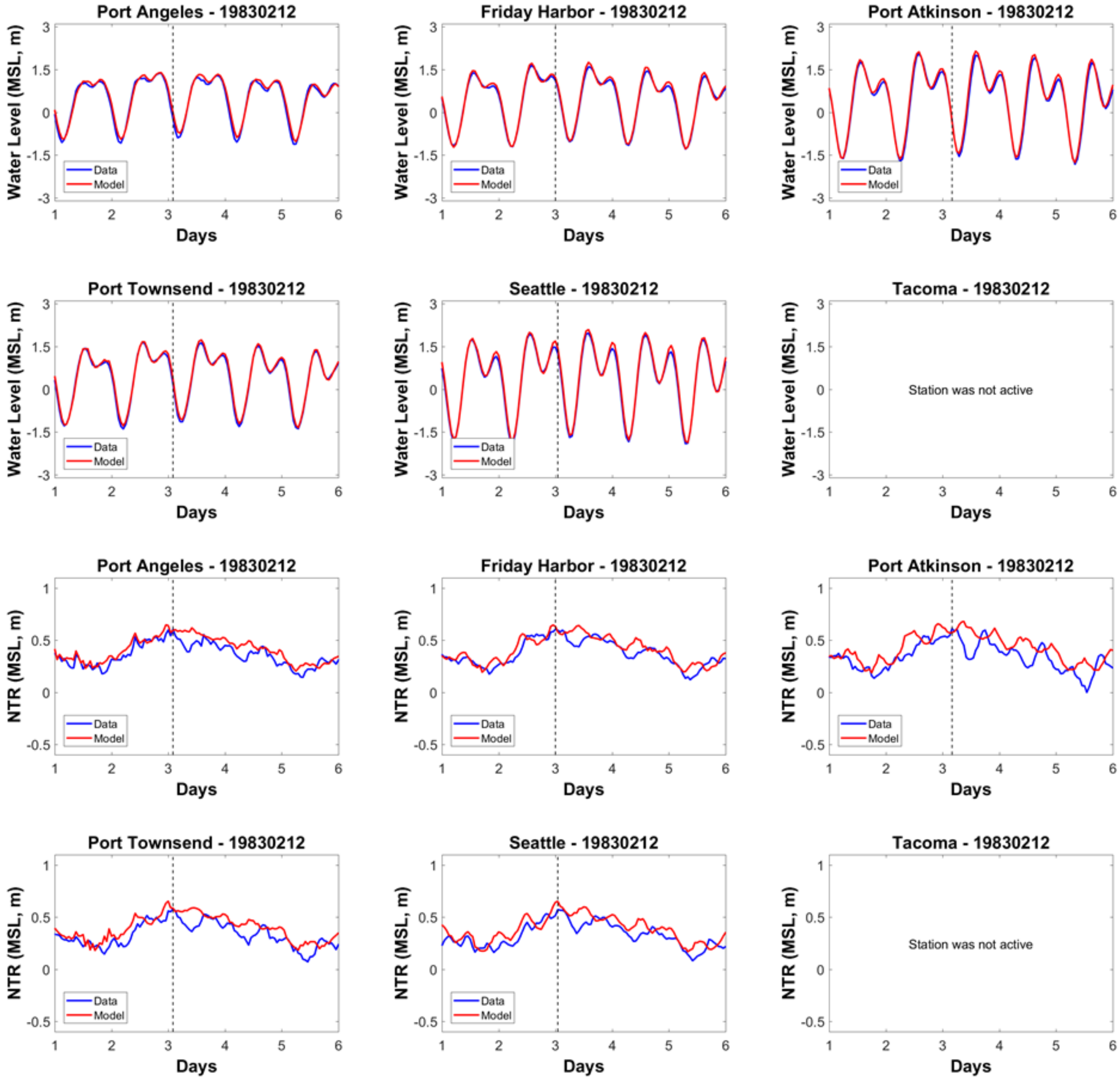

Figure A.5. Time series comparisons of total water level and NTR for storm event 19830212 at six tidal stations inside the model domain.

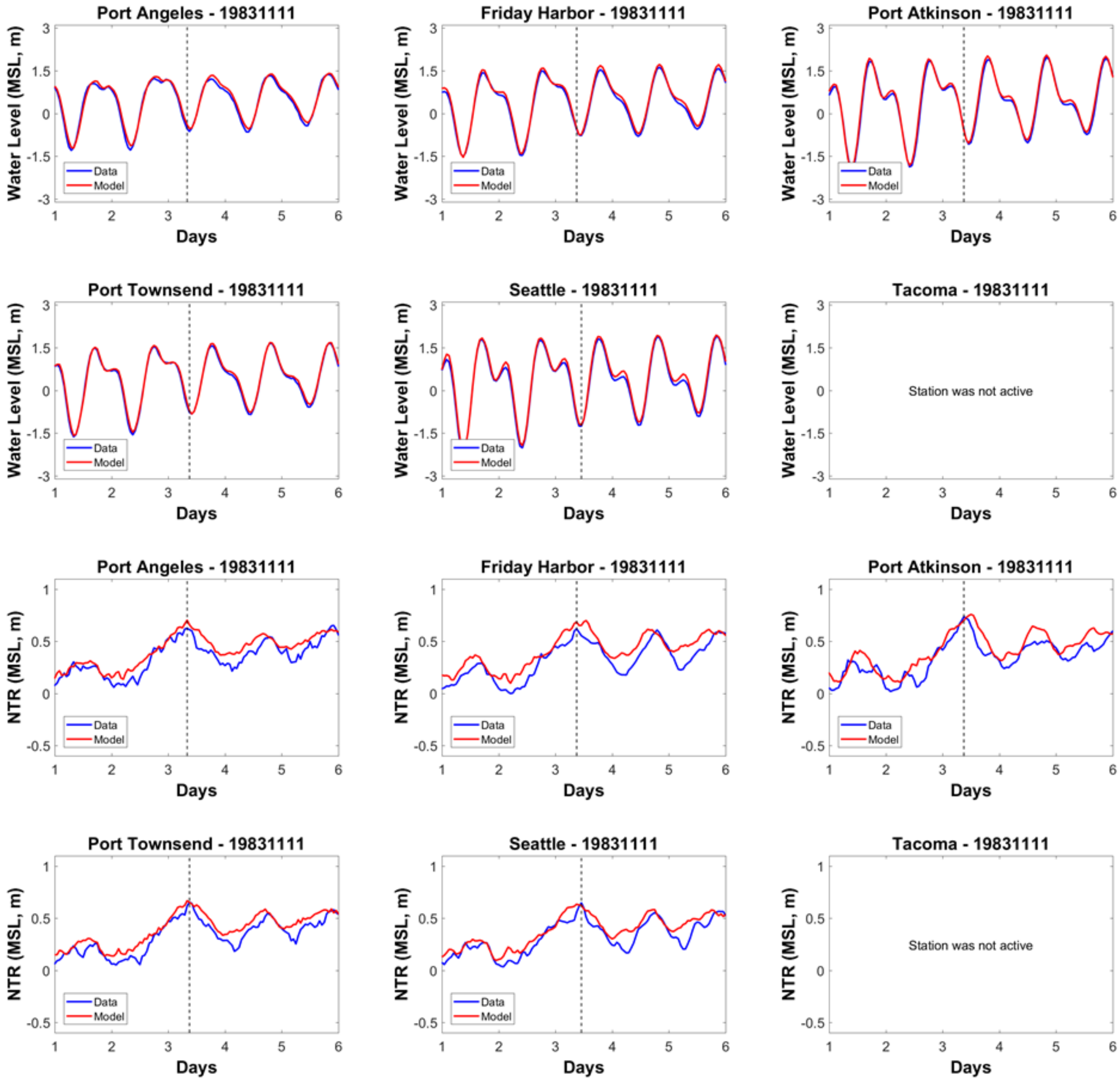

Figure A.6. Time series comparisons of total water level and NTR for storm event 19831111 at six tidal stations inside the model domain.

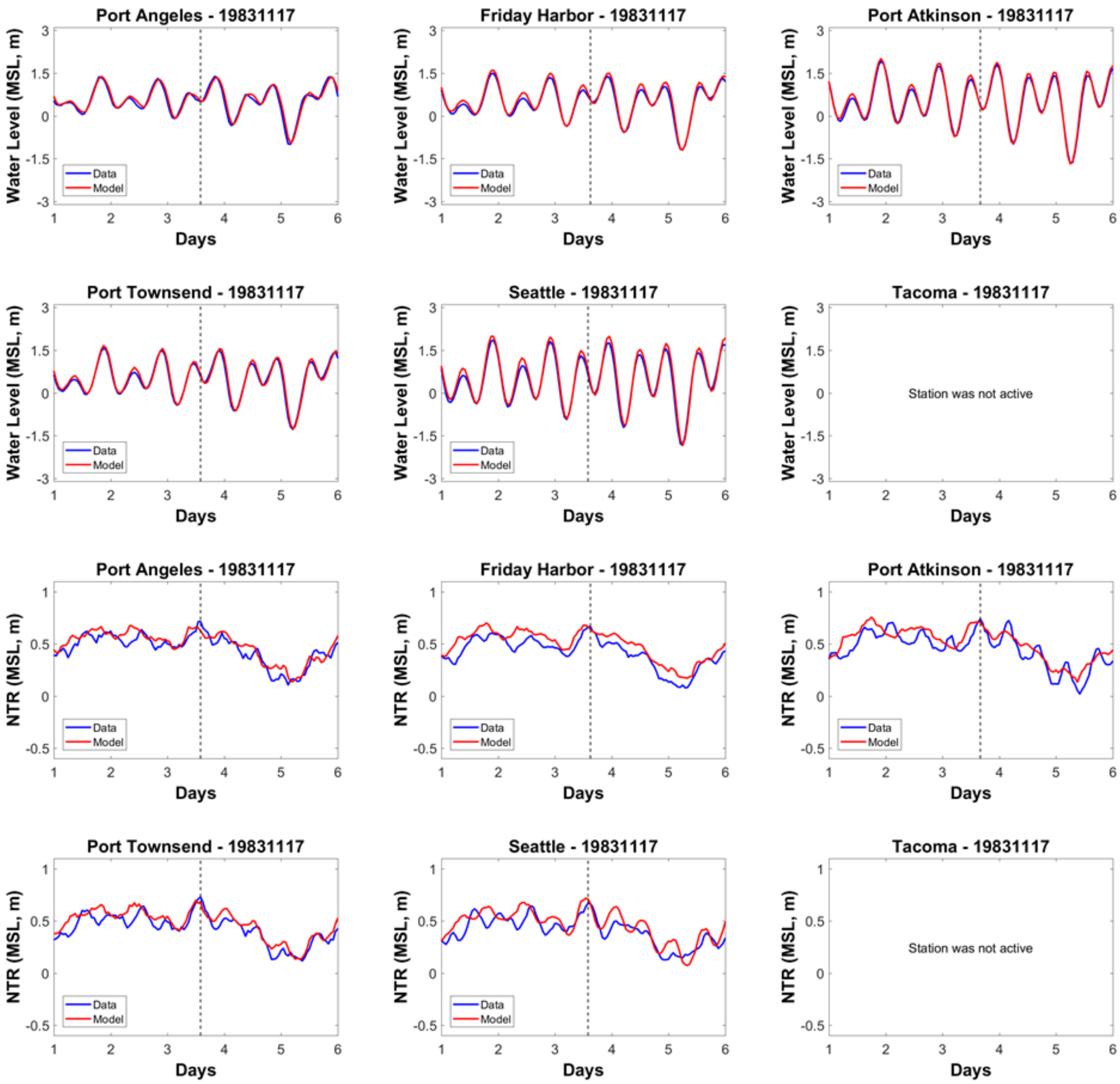

Figure A.7. Time series comparisons of total water level and NTR for storm event 19831117 at six tidal stations inside the model domain.

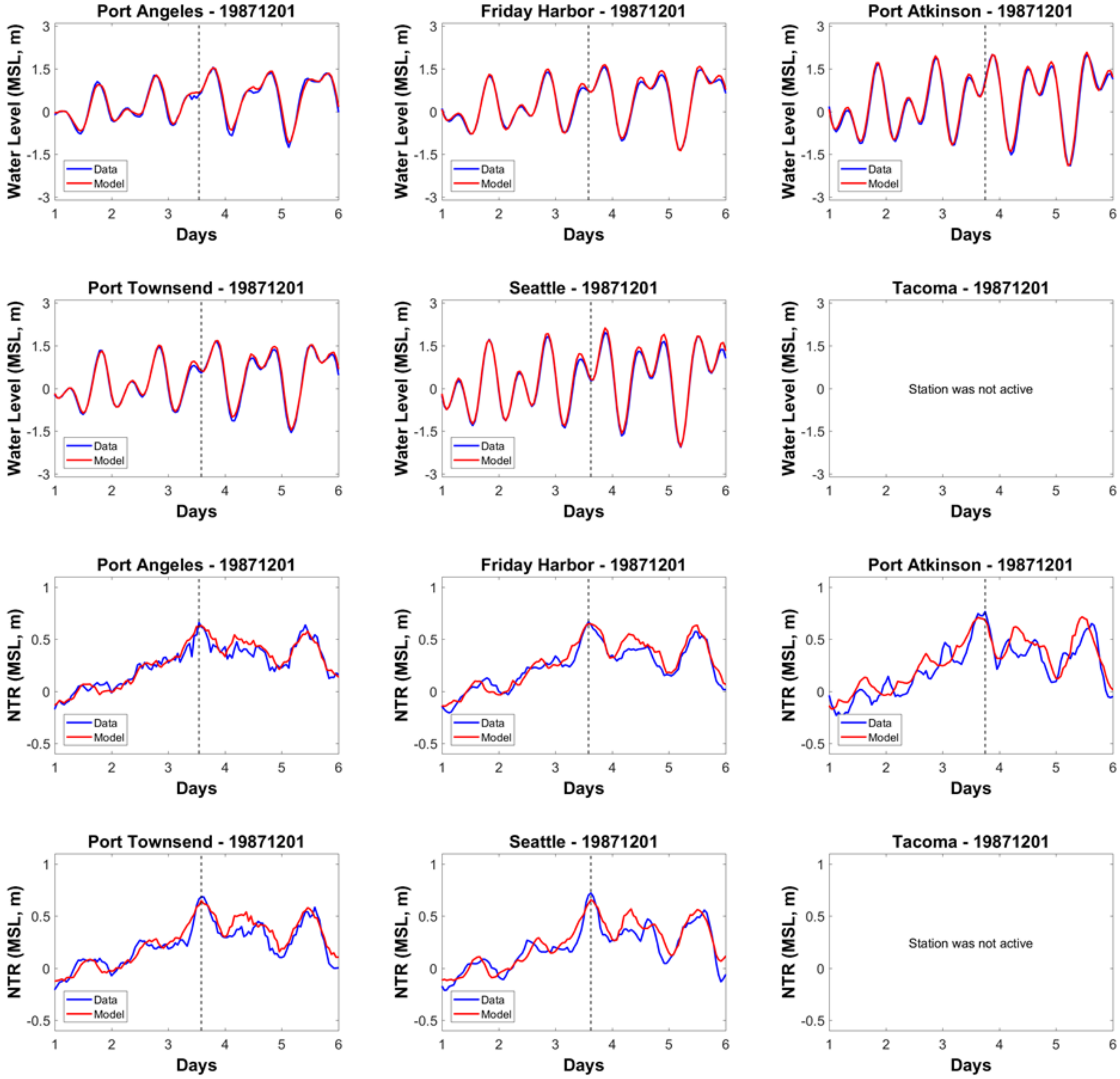

Figure A.8. Time series comparisons of total water level and NTR for storm event 19871201 at six tidal stations inside the model domain.

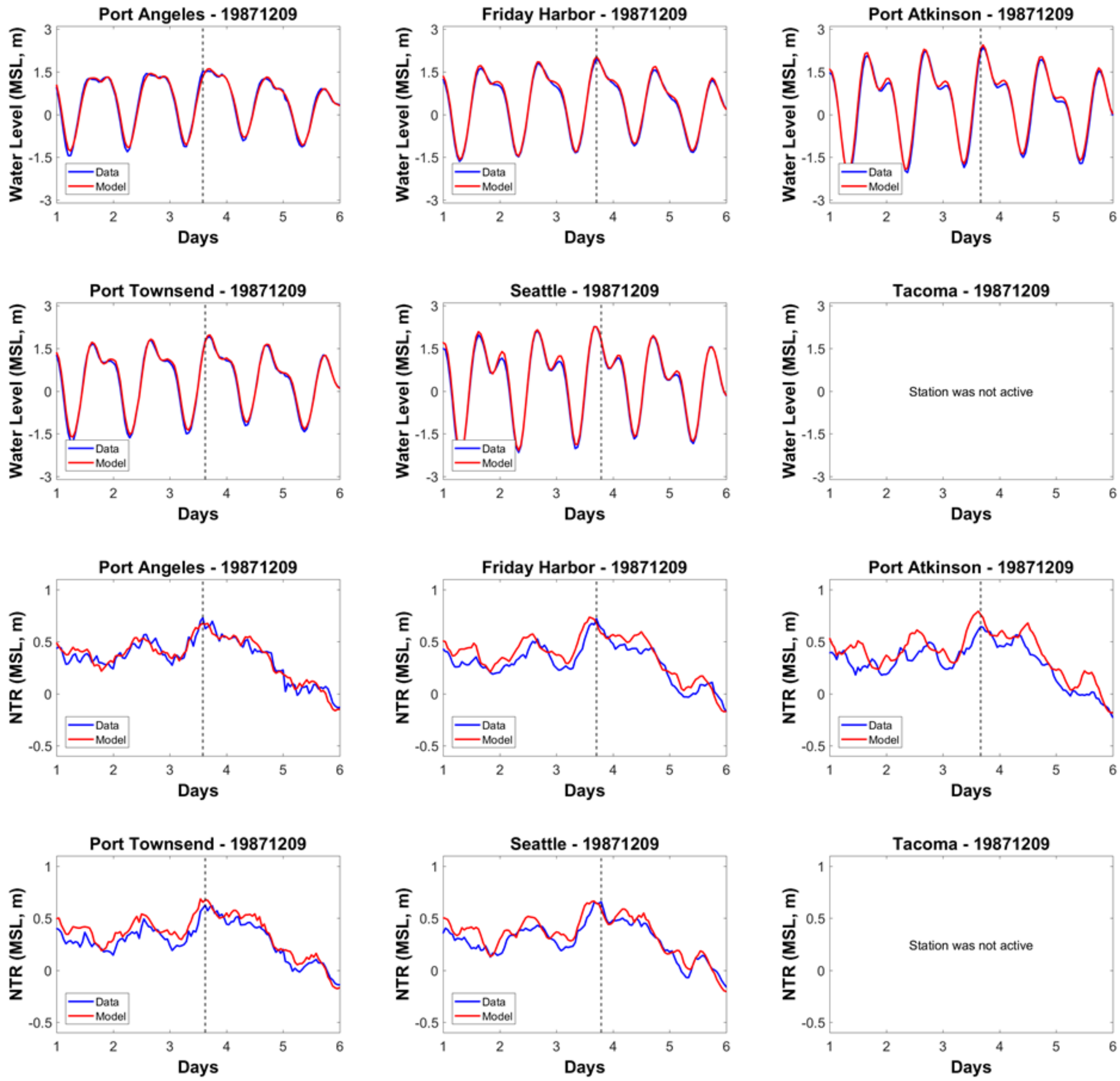

Figure A.9. Time series comparisons of total water level and NTR for storm event 19871209 at six tidal stations inside the model domain.

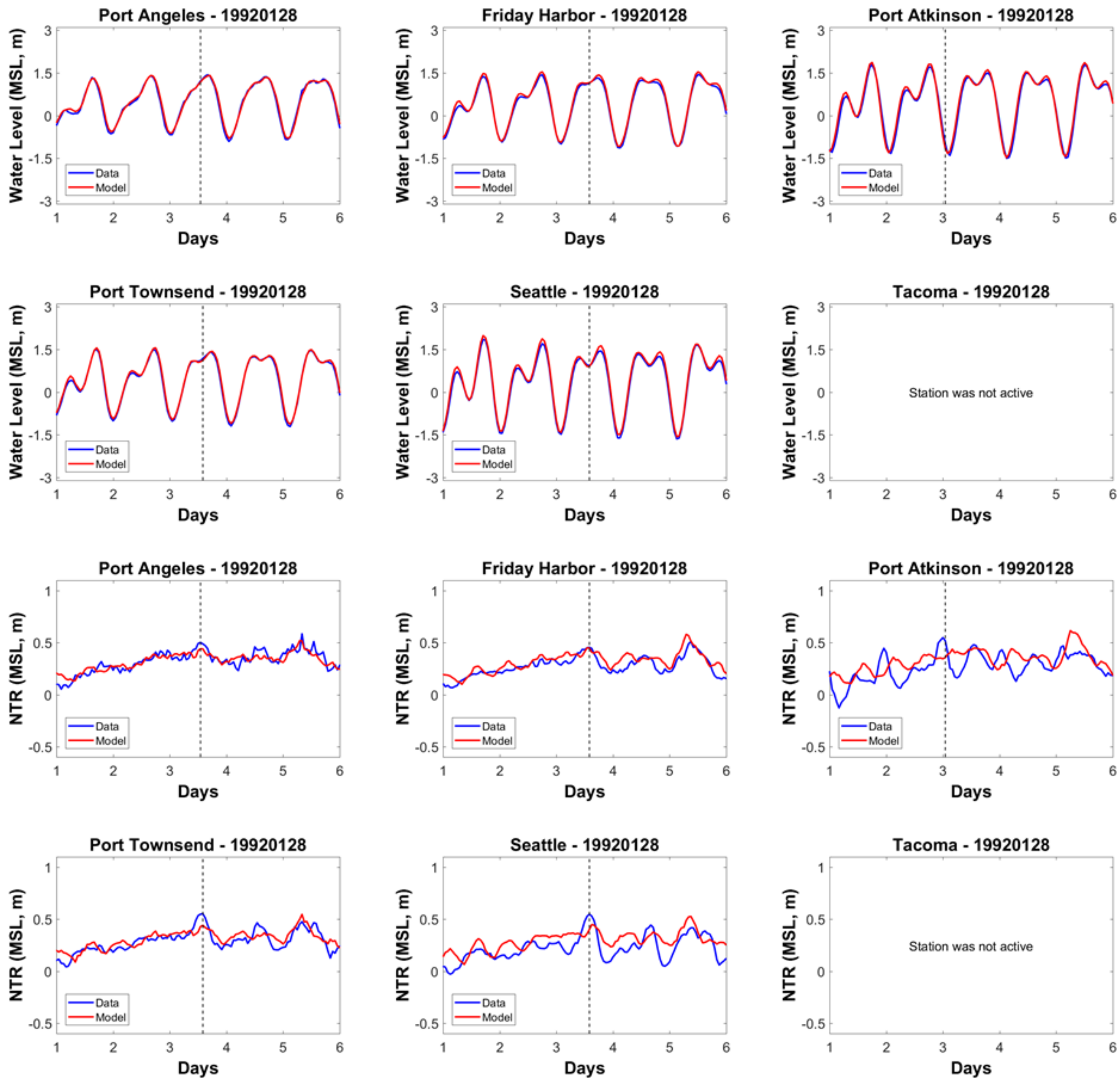

Figure A.10. Time series comparisons of total water level and NTR for storm event 19920128 at six tidal stations inside the model domain.

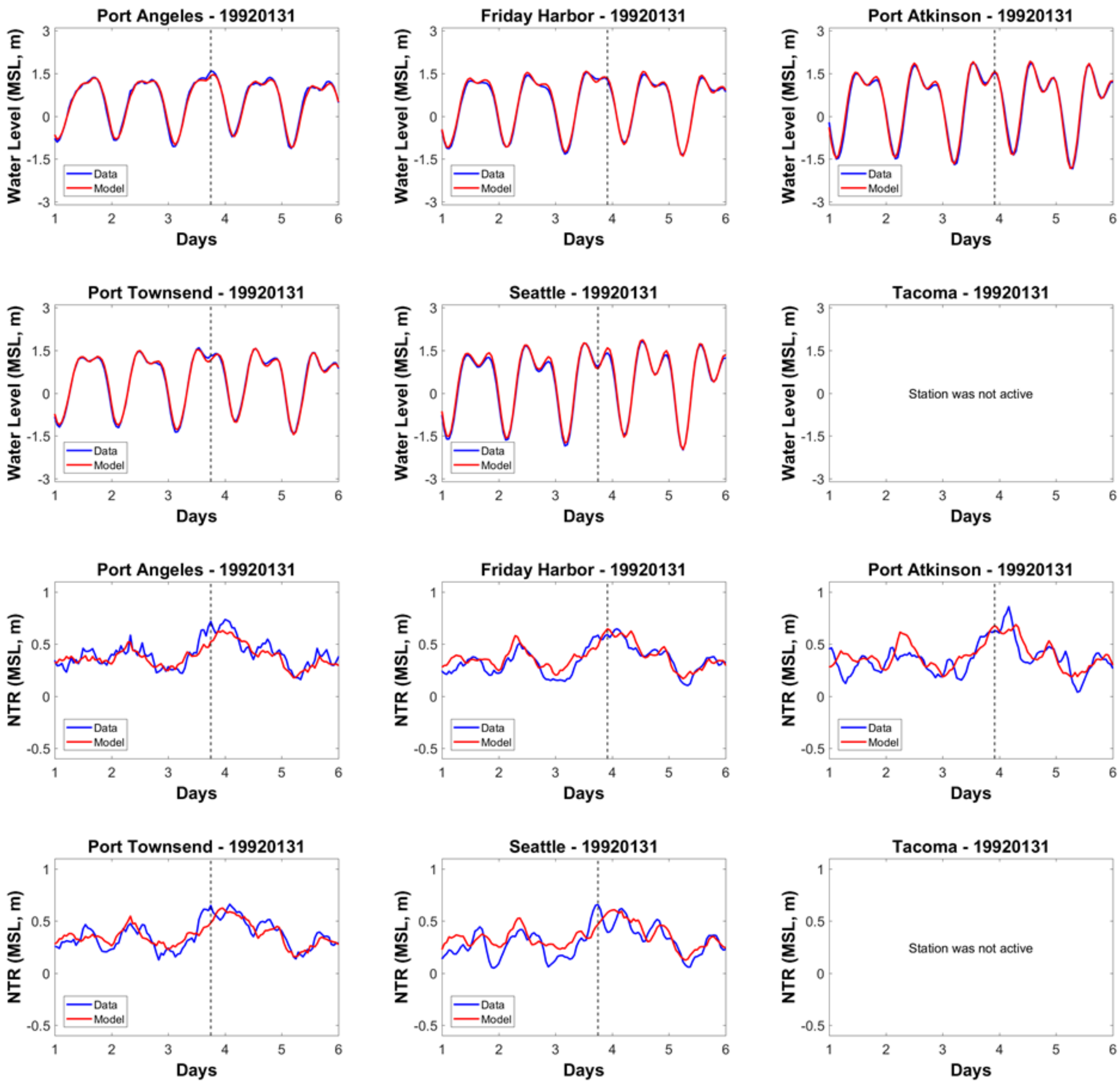

Figure A.11. Time series comparisons of total water level and NTR for storm event 19920131 at six tidal stations inside the model domain.

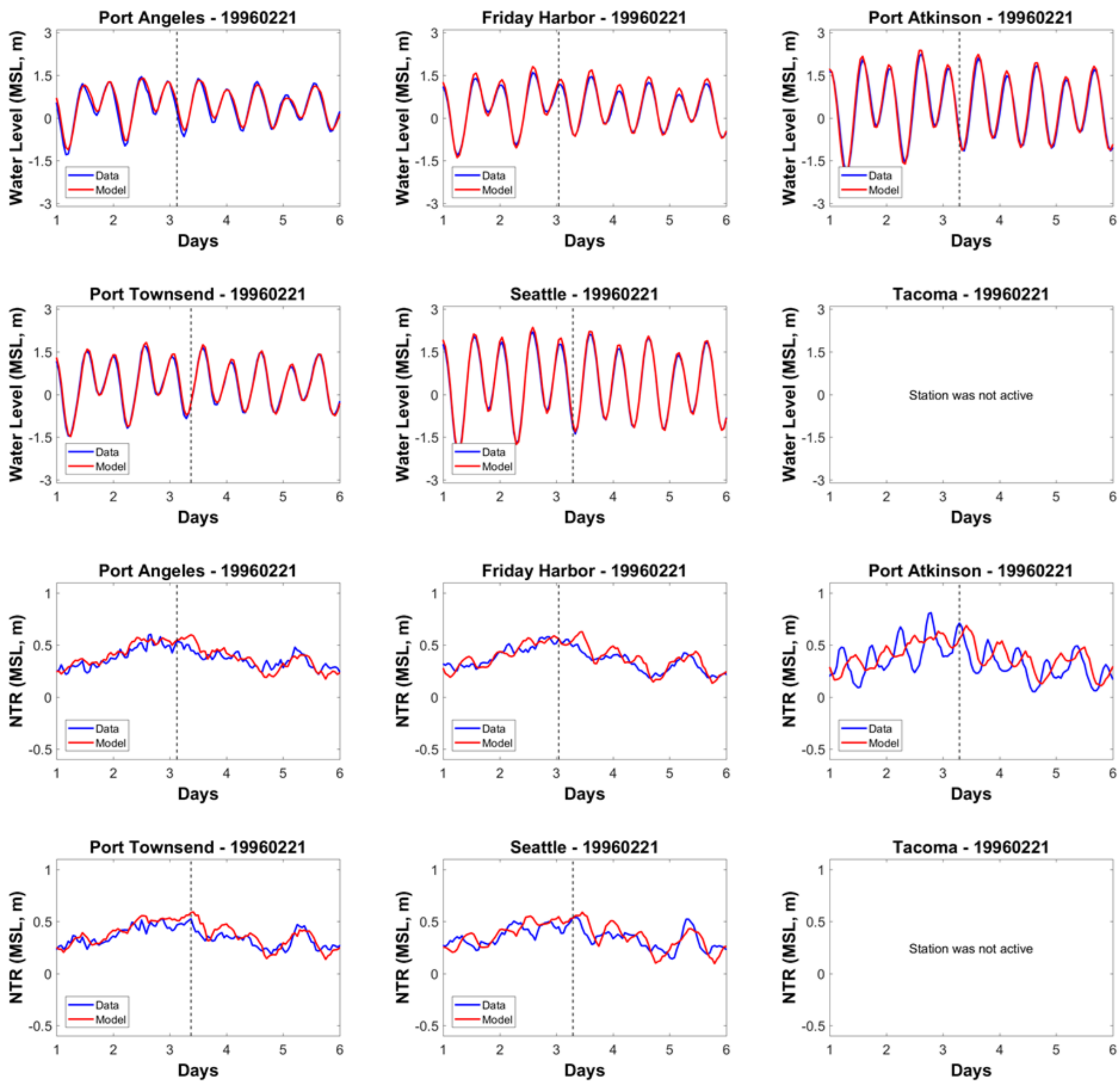

Figure A.12. Time series comparisons of total water level and NTR for storm event 19960221 at six tidal stations inside the model domain.

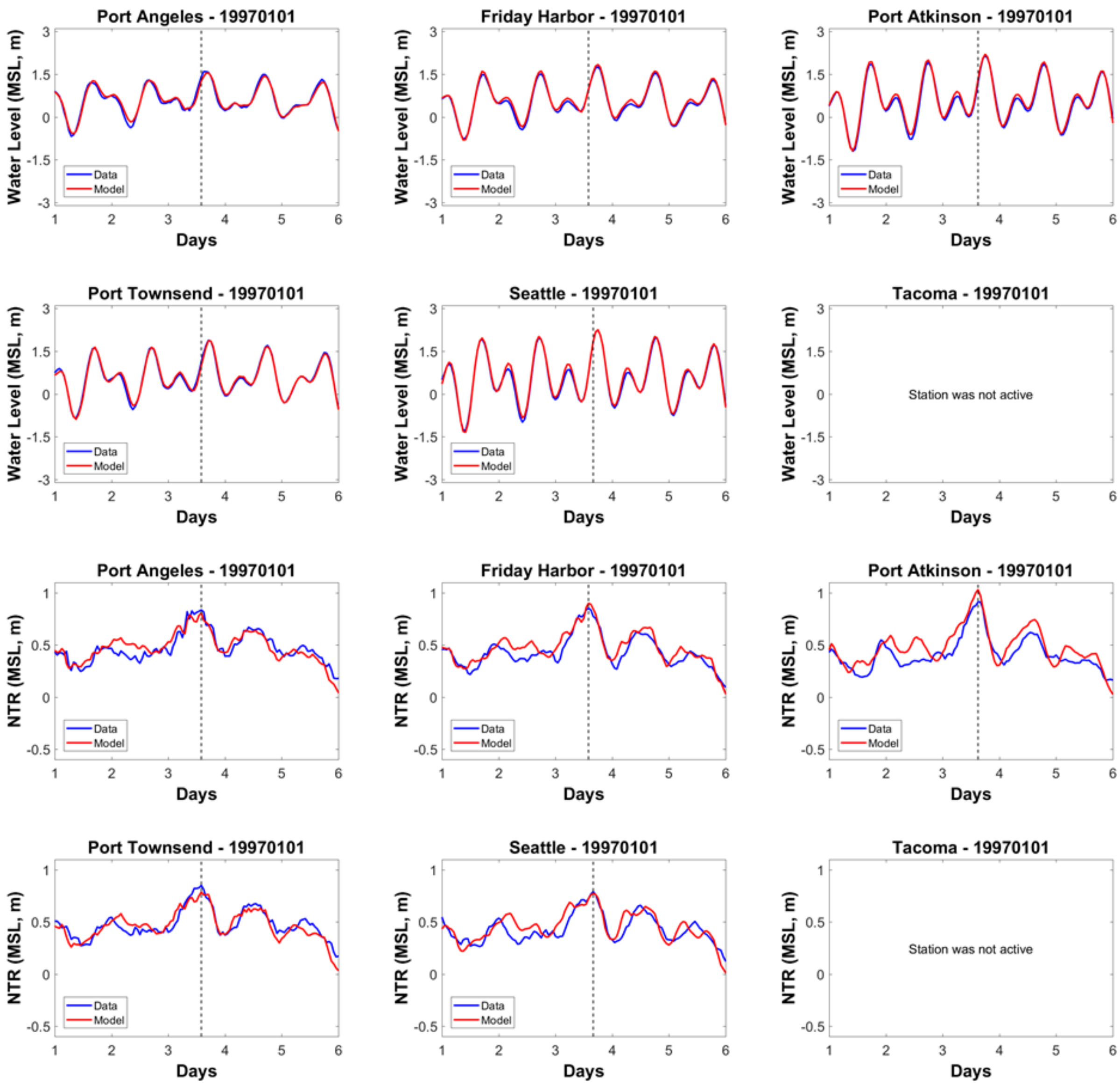

Figure A.13. Time series comparisons of total water level and NTR for storm event 19970101 at six tidal stations inside the model domain.

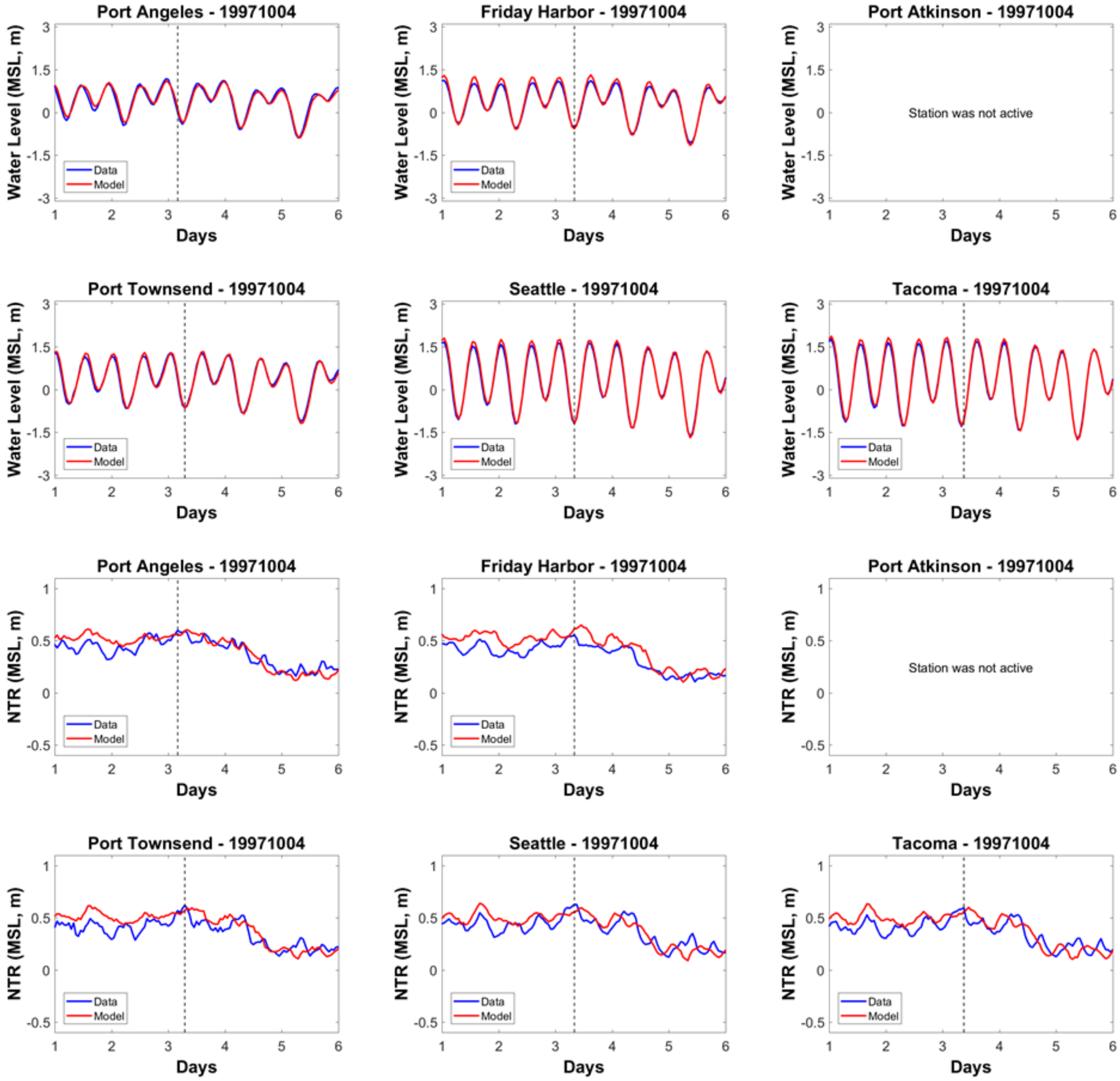

Figure A.14. Time series comparisons of total water level and NTR for storm event 19971014 at six tidal stations inside the model domain.

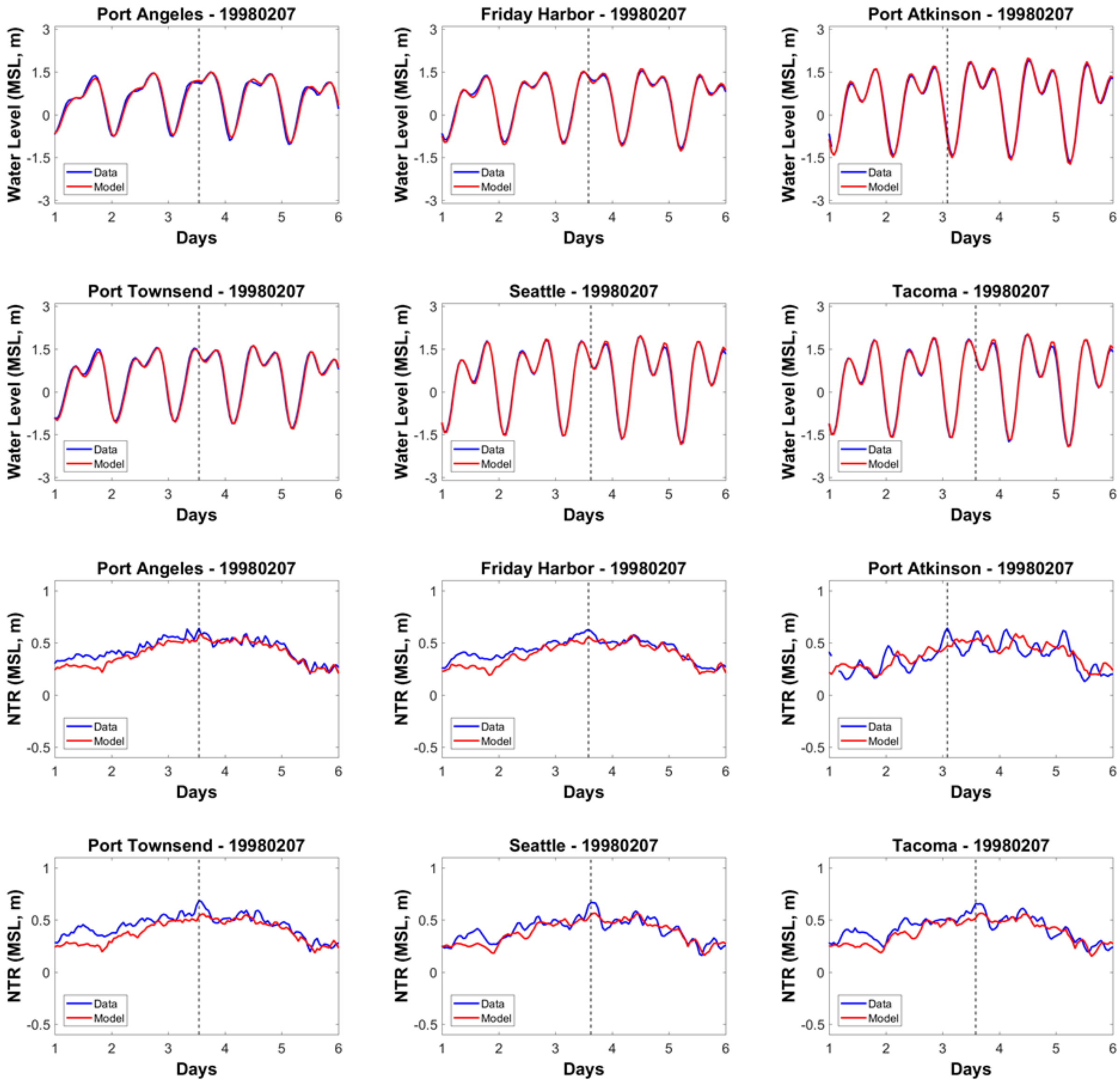

Figure A.15. Time series comparisons of total water level and NTR for storm event 19980207 at six tidal stations inside the model domain.

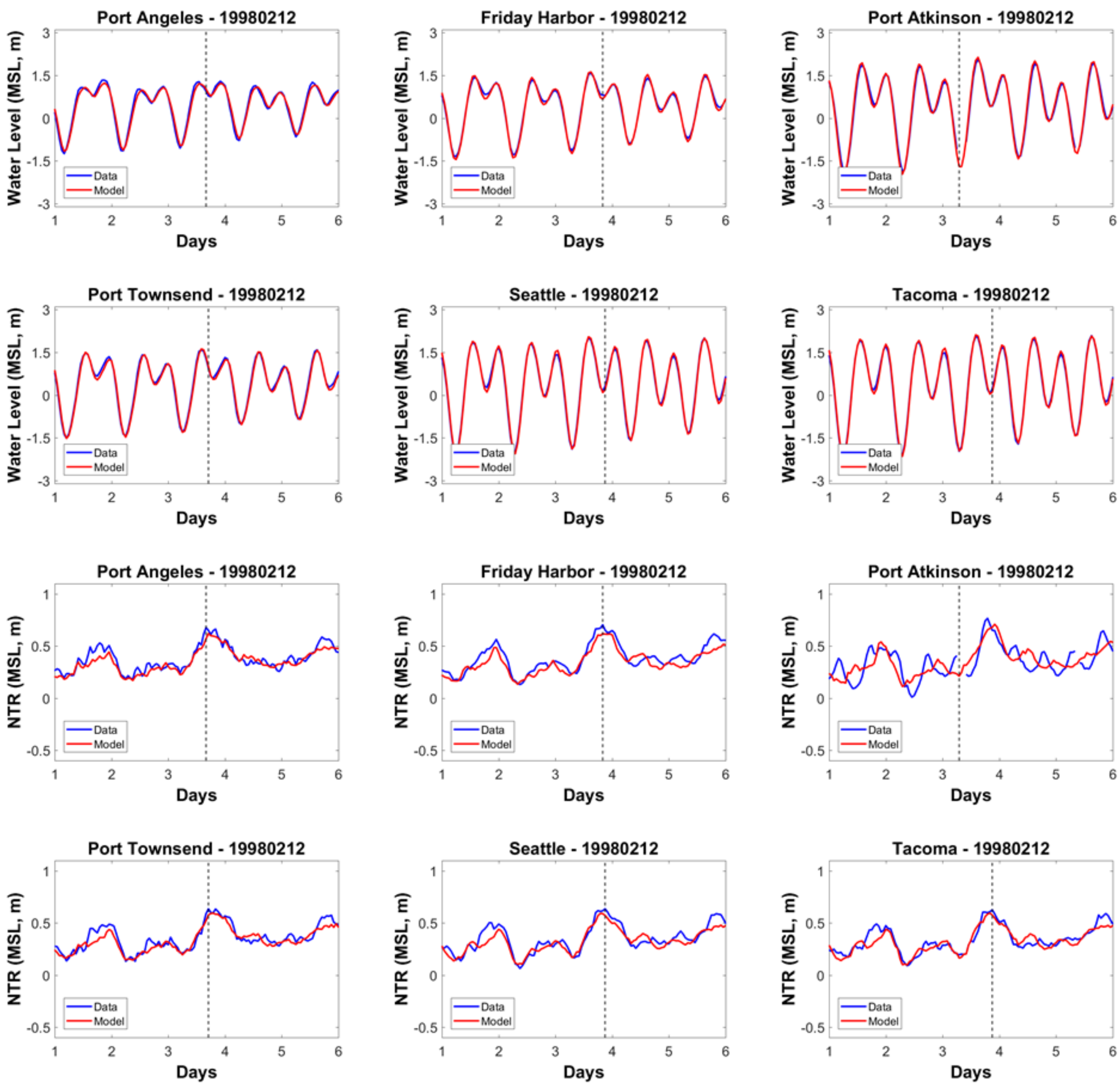

Figure A.16. Time series comparisons of total water level and NTR for storm event 19980212 at six tidal stations inside the model domain.

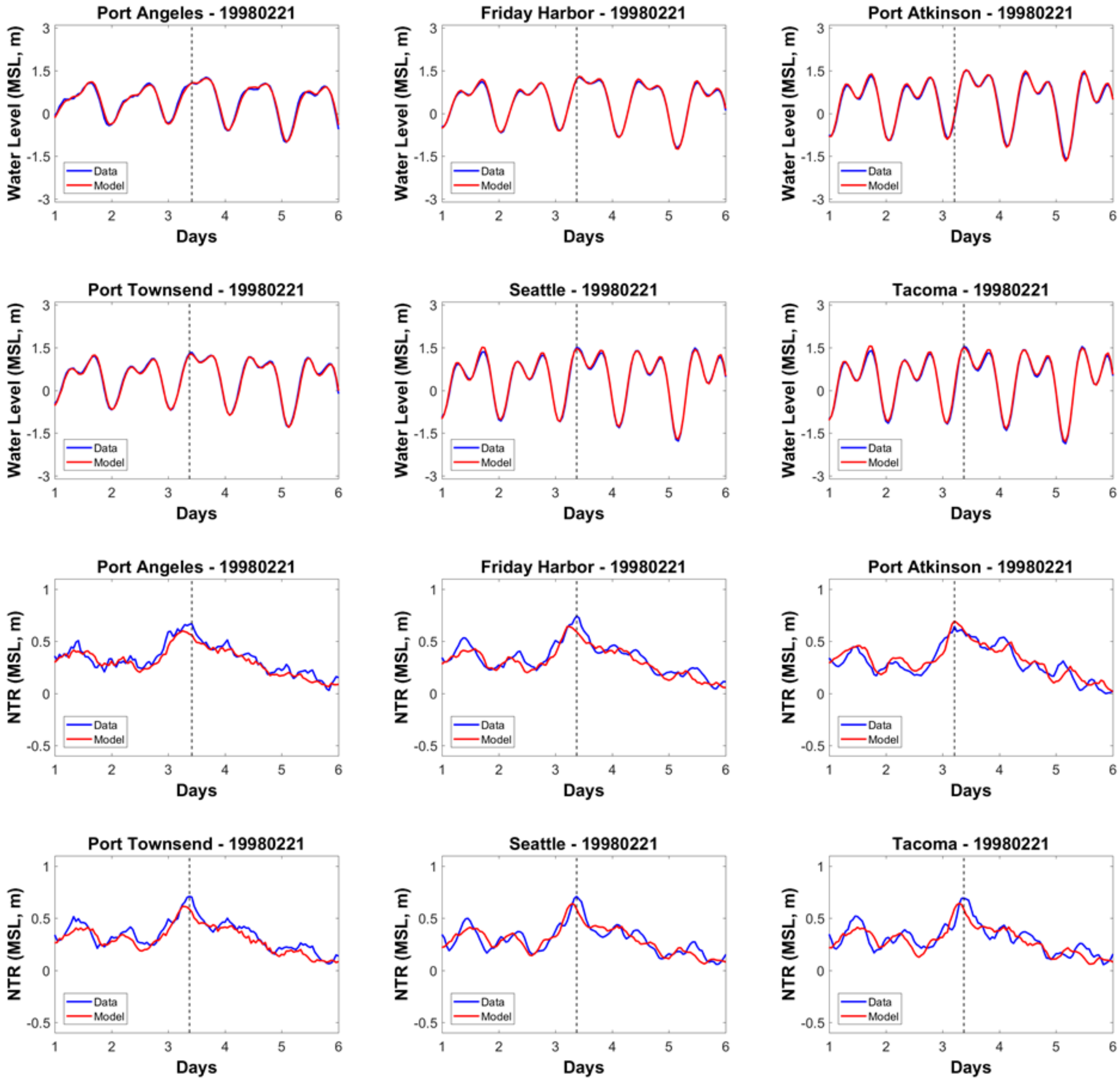

Figure A.17. Time series comparisons of total water level and NTR for storm event 19980221 at six tidal stations inside the model domain.

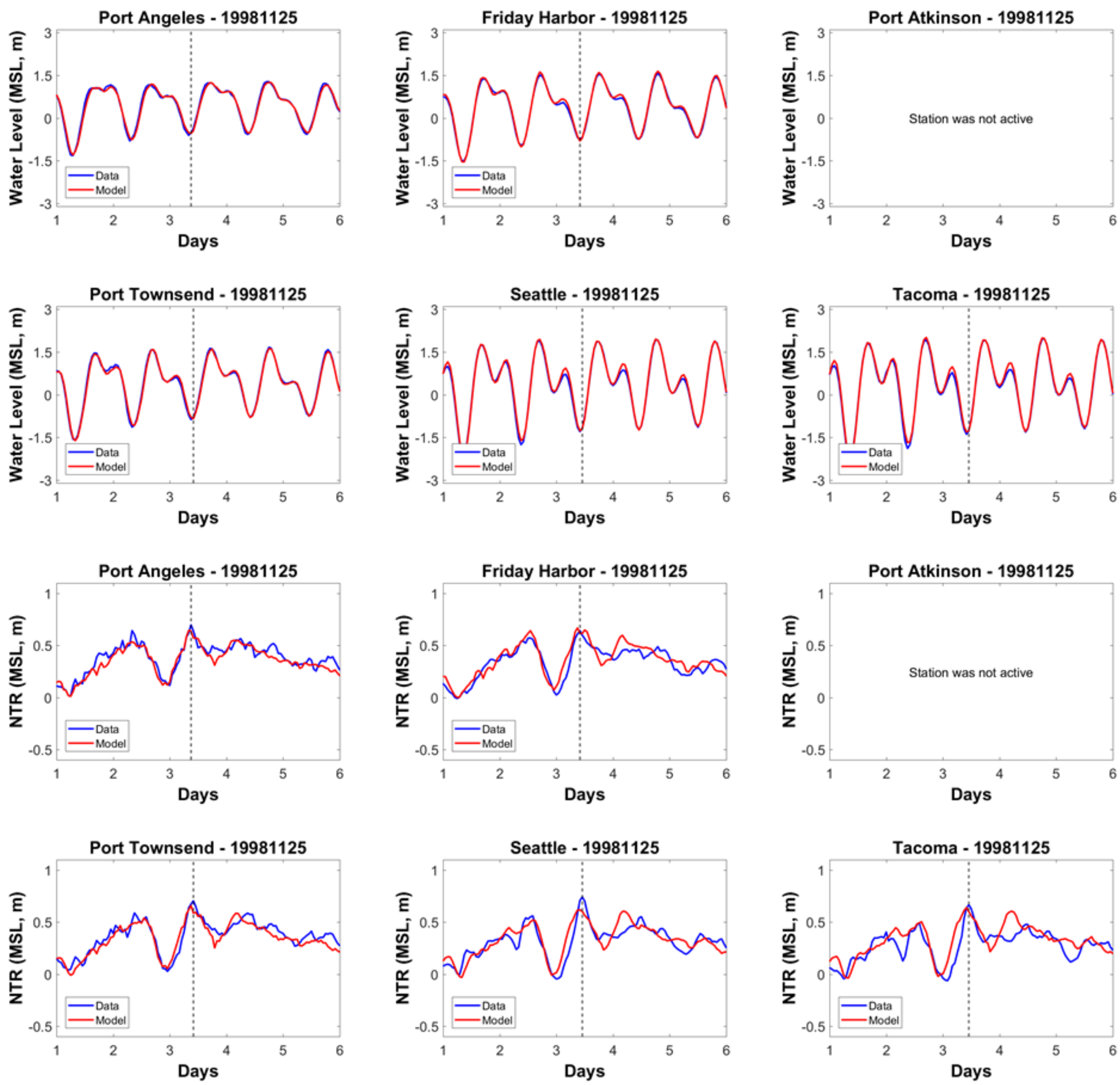

Figure A.18. Time series comparisons of total water level and NTR for storm event 19981125 at six tidal stations inside the model domain.

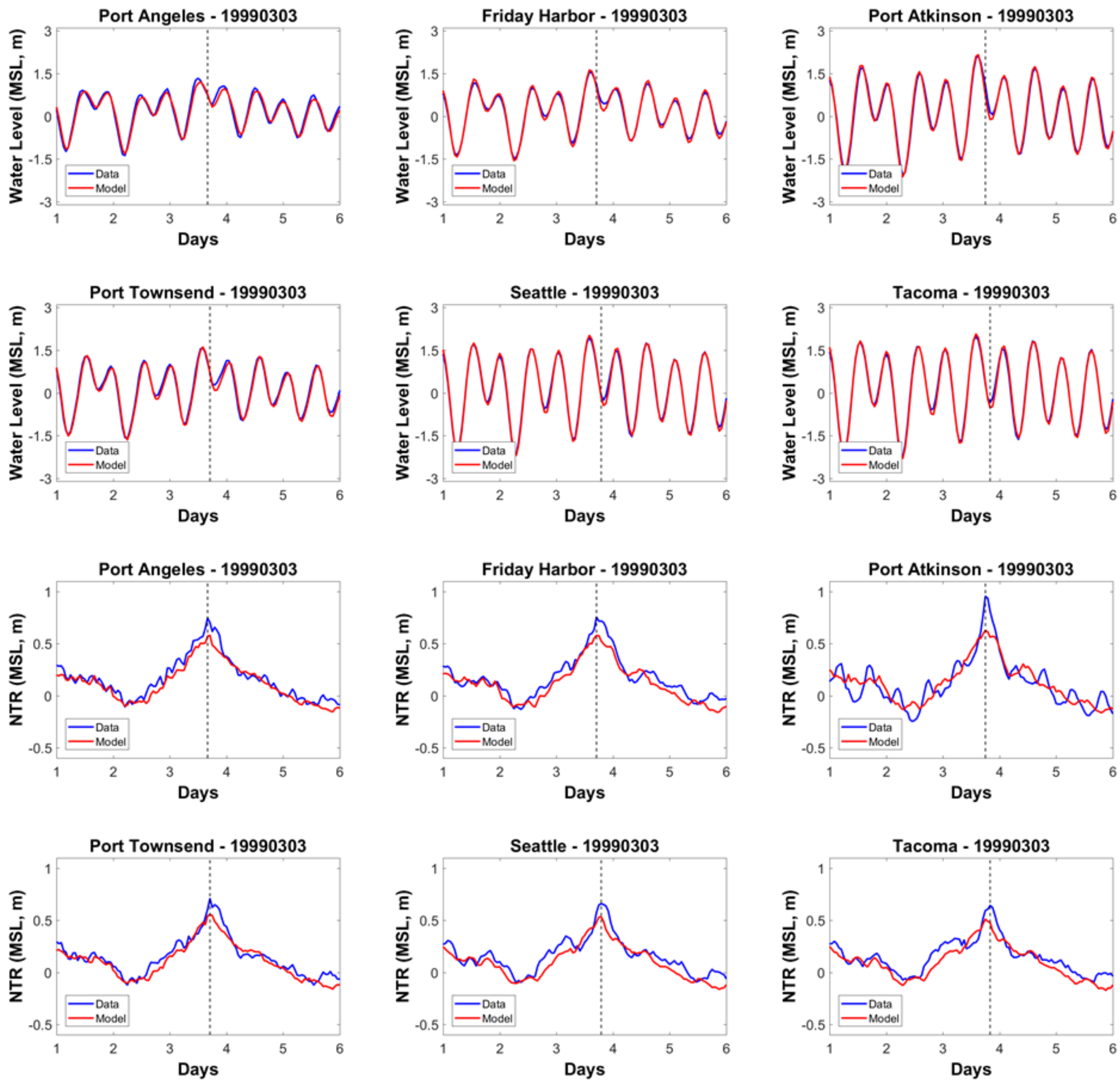

Figure A.19. Time series comparisons of total water level and NTR for storm event 19990303 at six tidal stations inside the model domain.

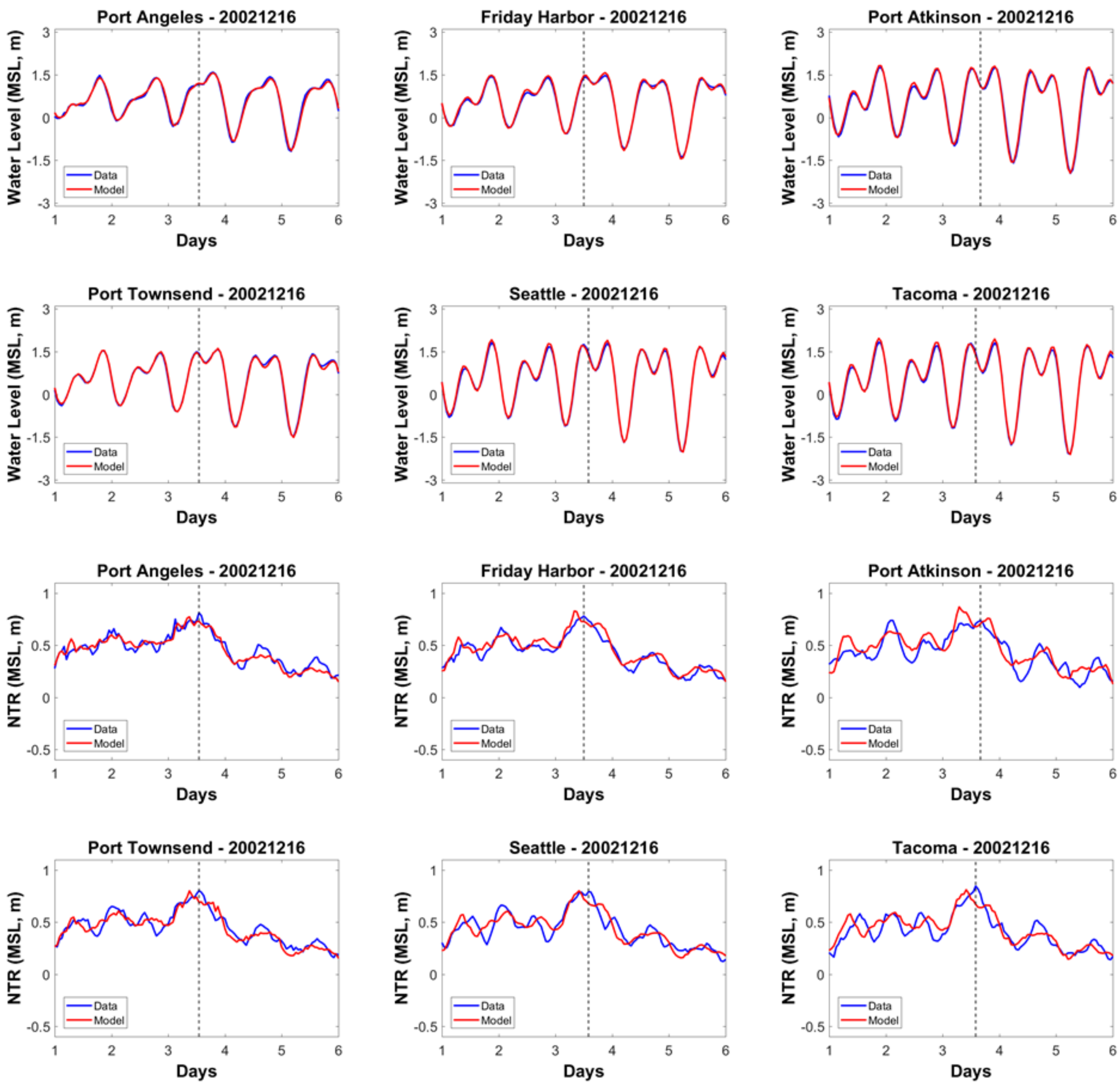

Figure A.20. Time series comparisons of total water level and NTR for storm event 20021216 at six tidal stations inside the model domain.

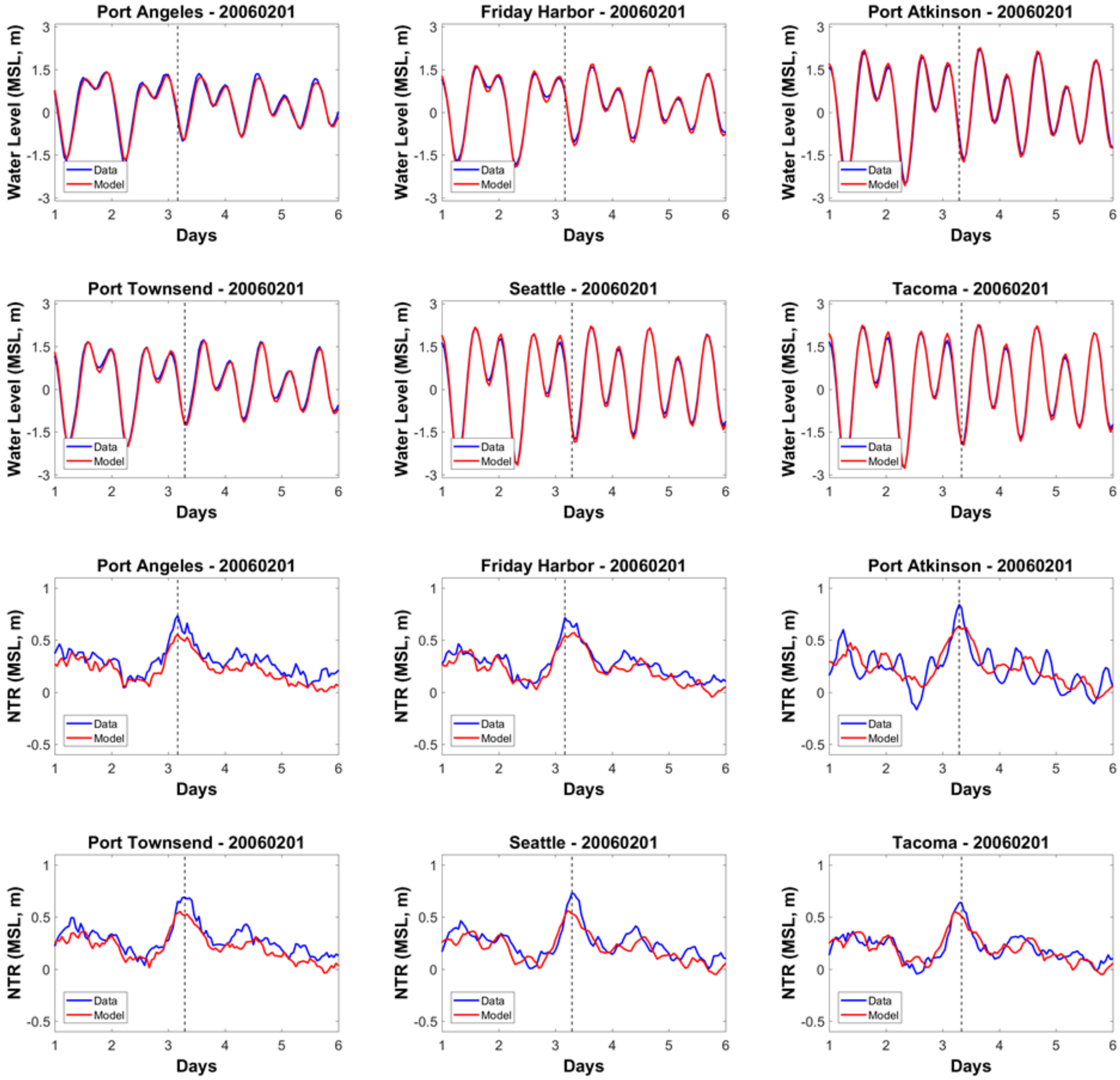

Figure A.21. Time series comparisons of total water level and NTR for storm event 20060201 at six tidal stations inside the model domain.

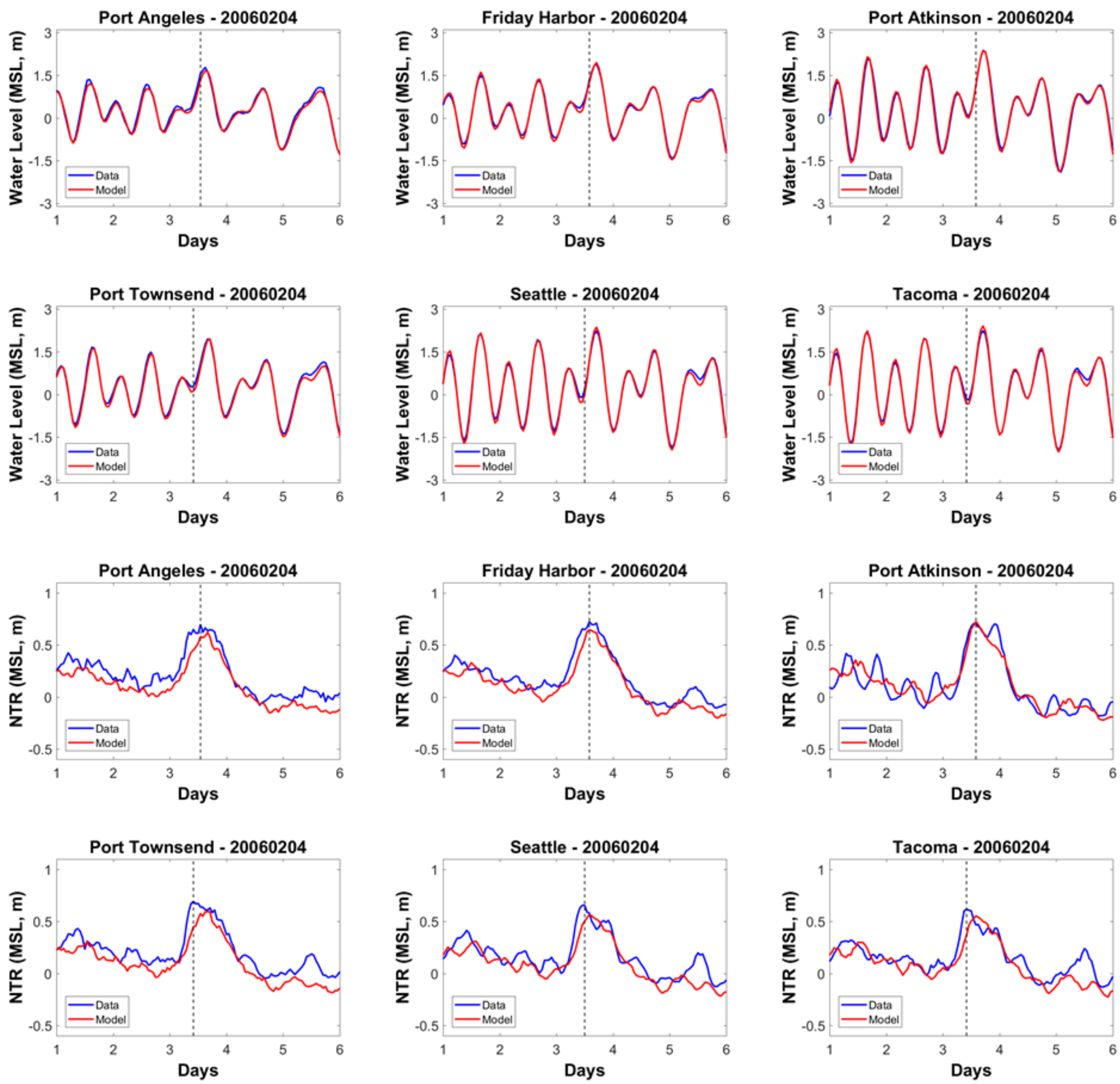

Figure A.22. Time series comparisons of total water level and NTR for storm event 20060204 at six tidal stations inside the model domain.

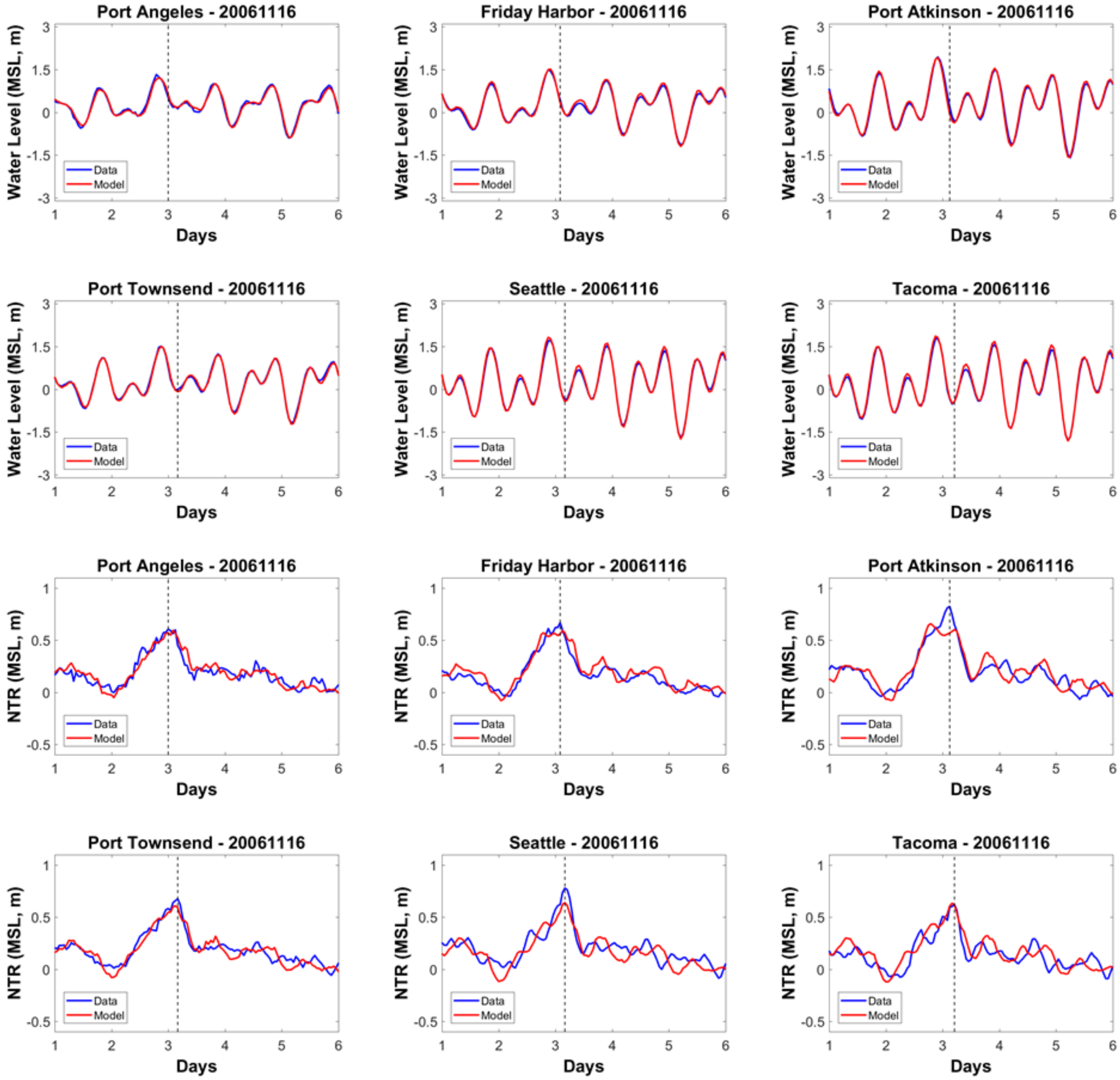

Figure A.23. Time series comparisons of total water level and NTR for storm event 20061116 at six tidal stations inside the model domain.

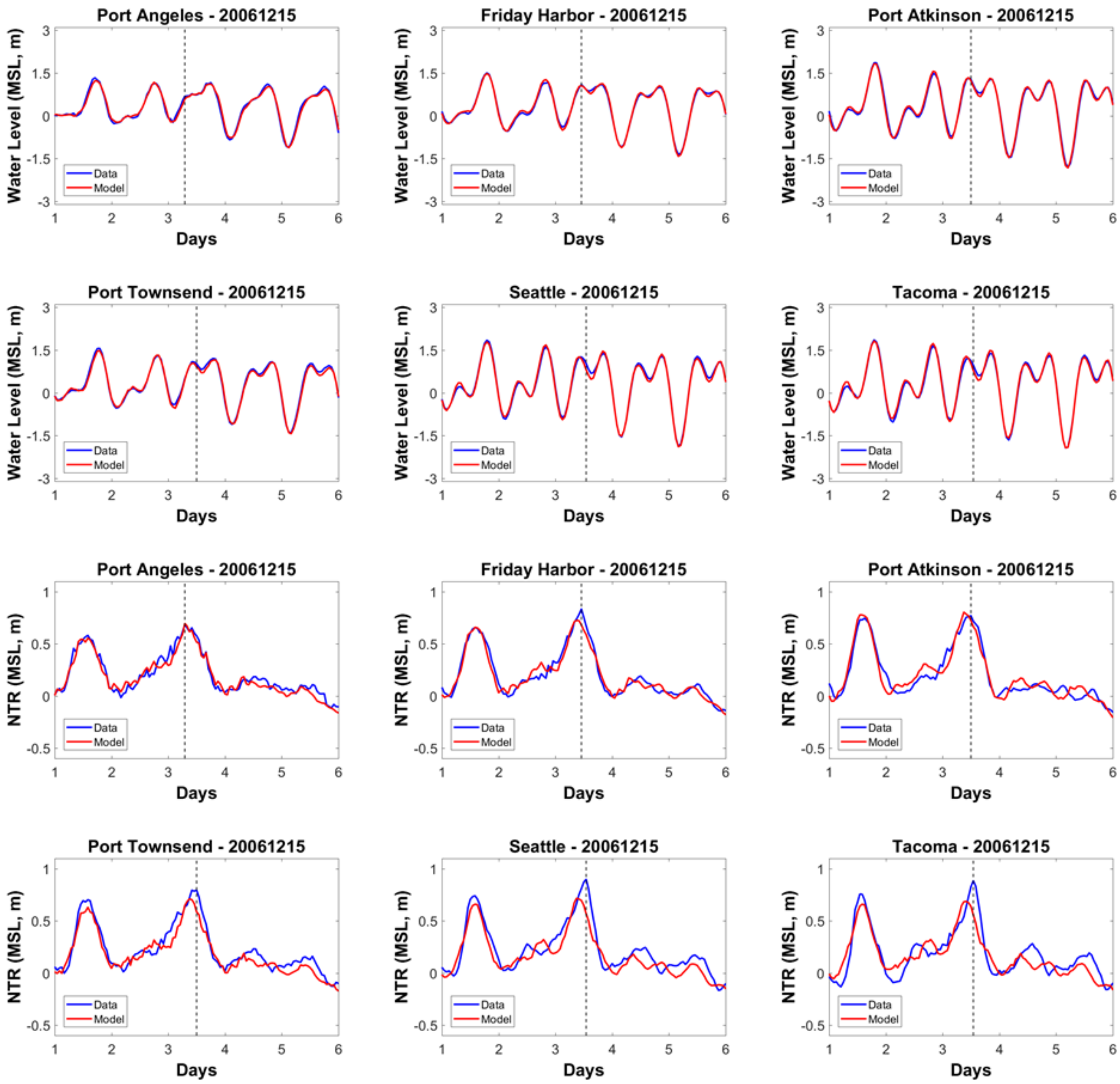

Figure A.24. Time series comparisons of total water level and NTR for storm event 20061215 at six tidal stations inside the model domain.

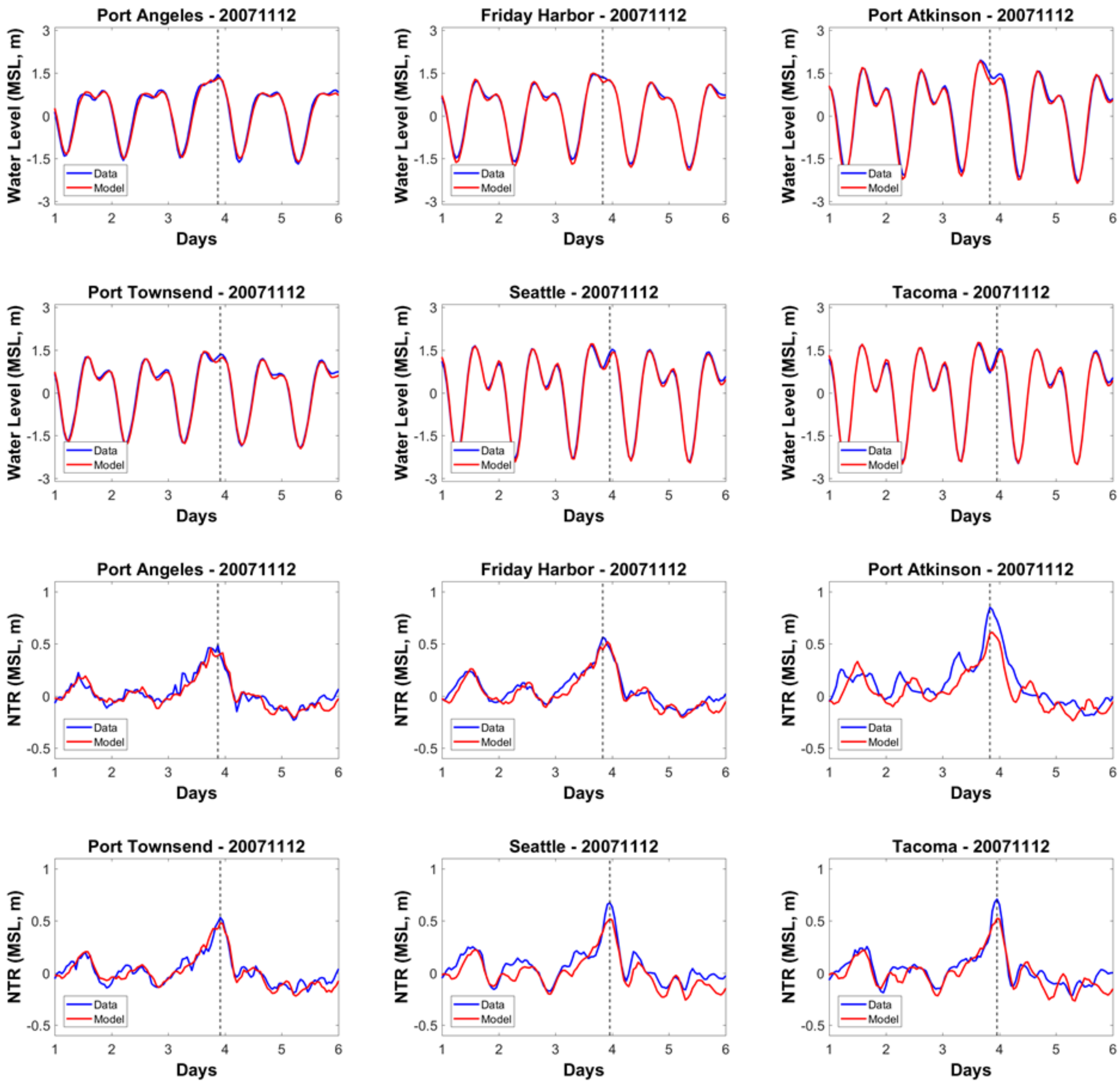

Figure A.25. Time series comparisons of total water level and NTR for storm event 20071112 at six tidal stations inside the model domain.

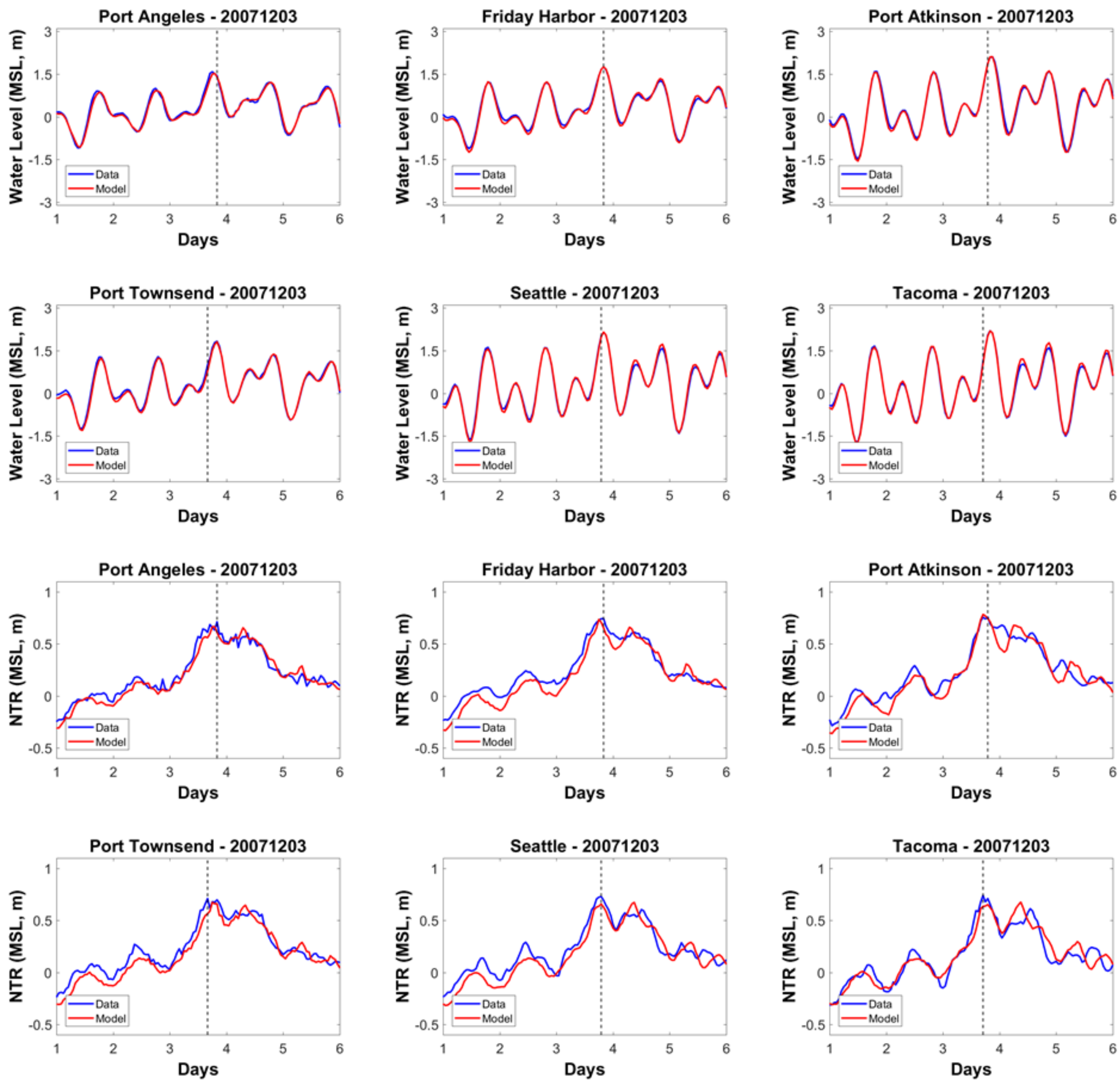

Figure A.26. Time series comparisons of total water level and NTR for storm event 20071203 at six tidal stations inside the model domain.

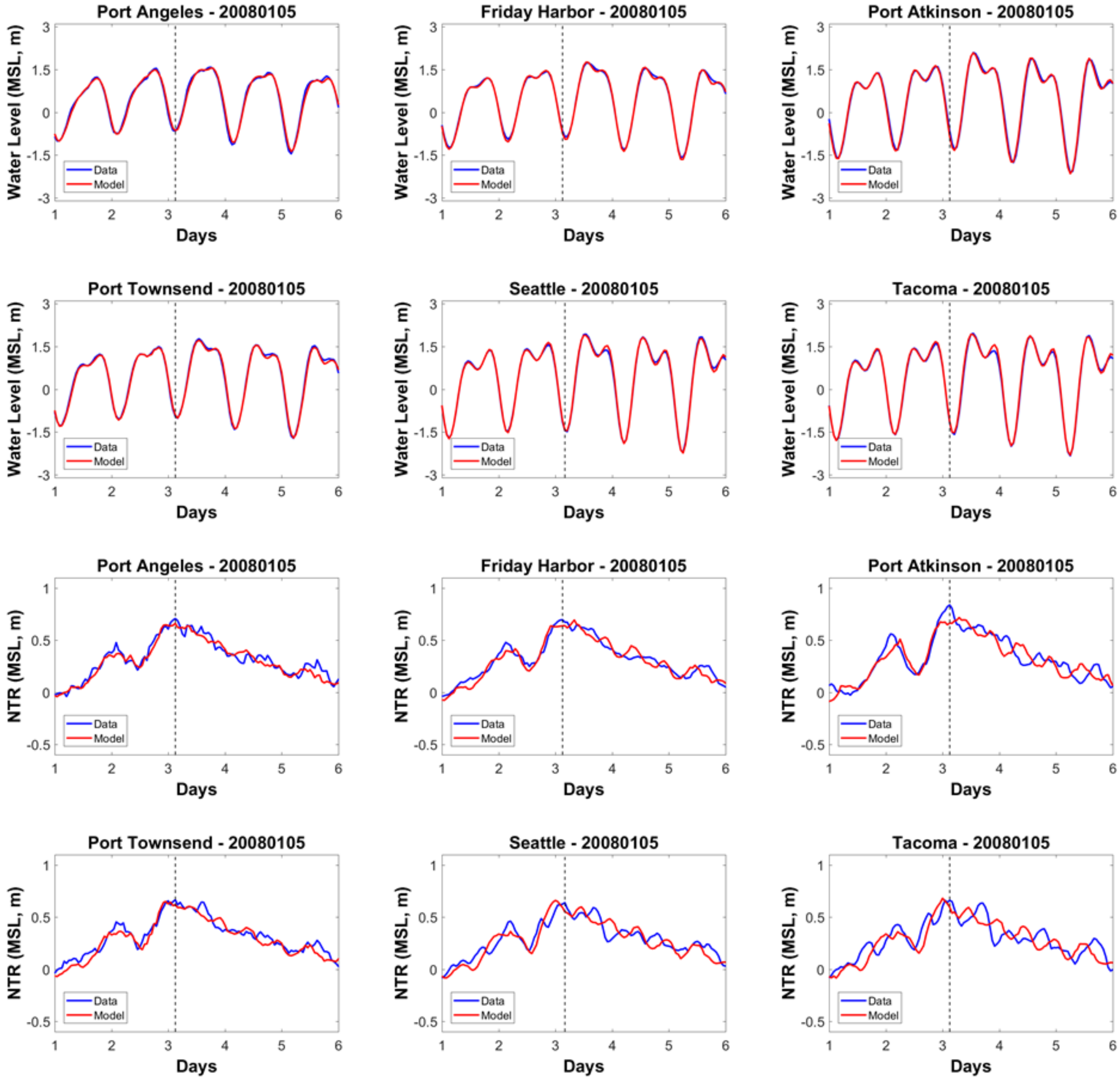

Figure A.27. Time series comparisons of total water level and NTR for storm event 20080105 at six tidal stations inside the model domain.

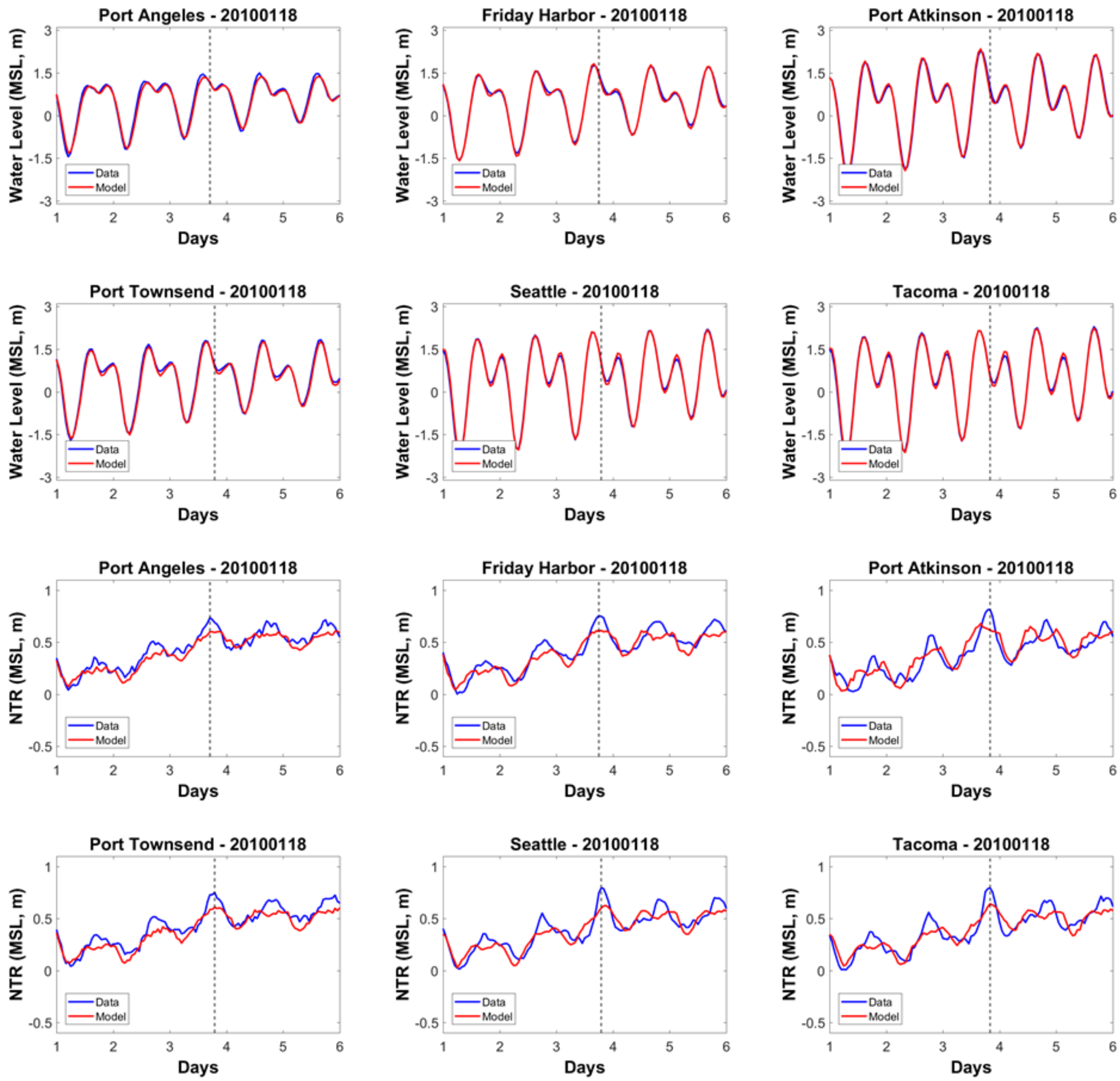

Figure A.28. Time series comparisons of total water level and NTR for storm event 20100118 at six tidal stations inside the model domain.

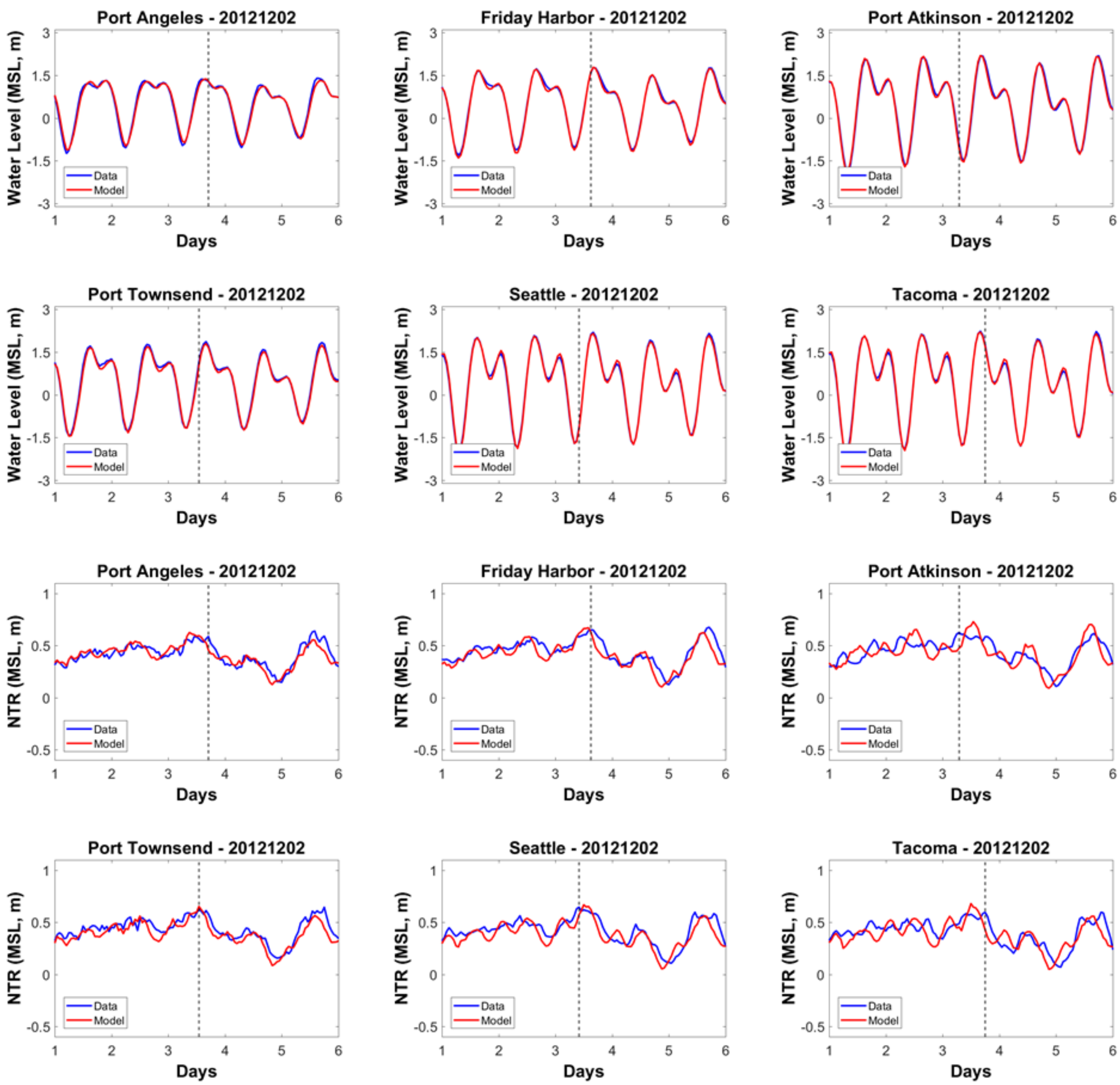

Figure A.29. Time series comparisons of total water level and NTR for storm event 20121202 at six tidal stations inside the model domain.

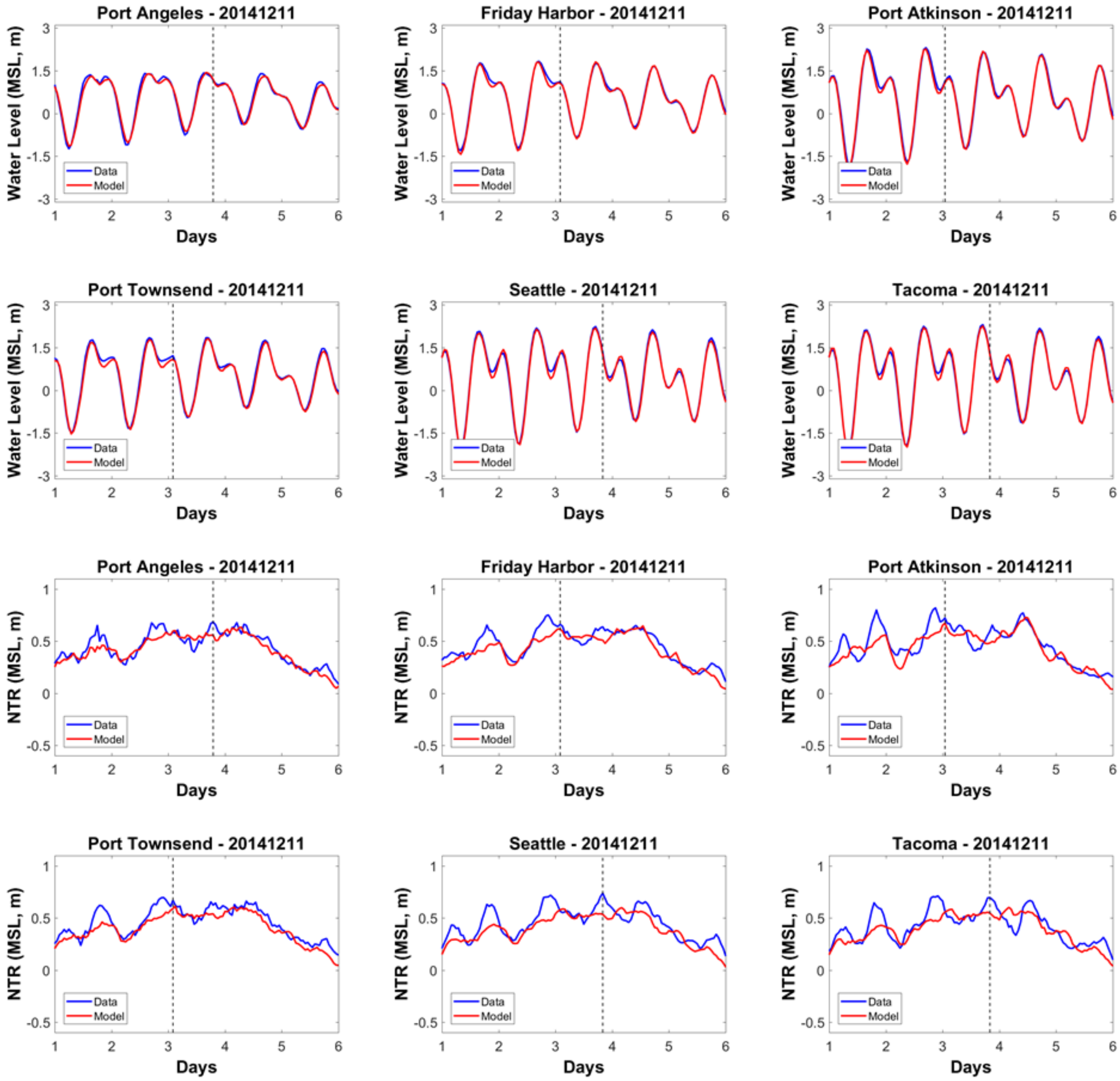

Figure A.30. Time series comparisons of total water level and NTR for storm event 20141211 at six tidal stations inside the model domain.

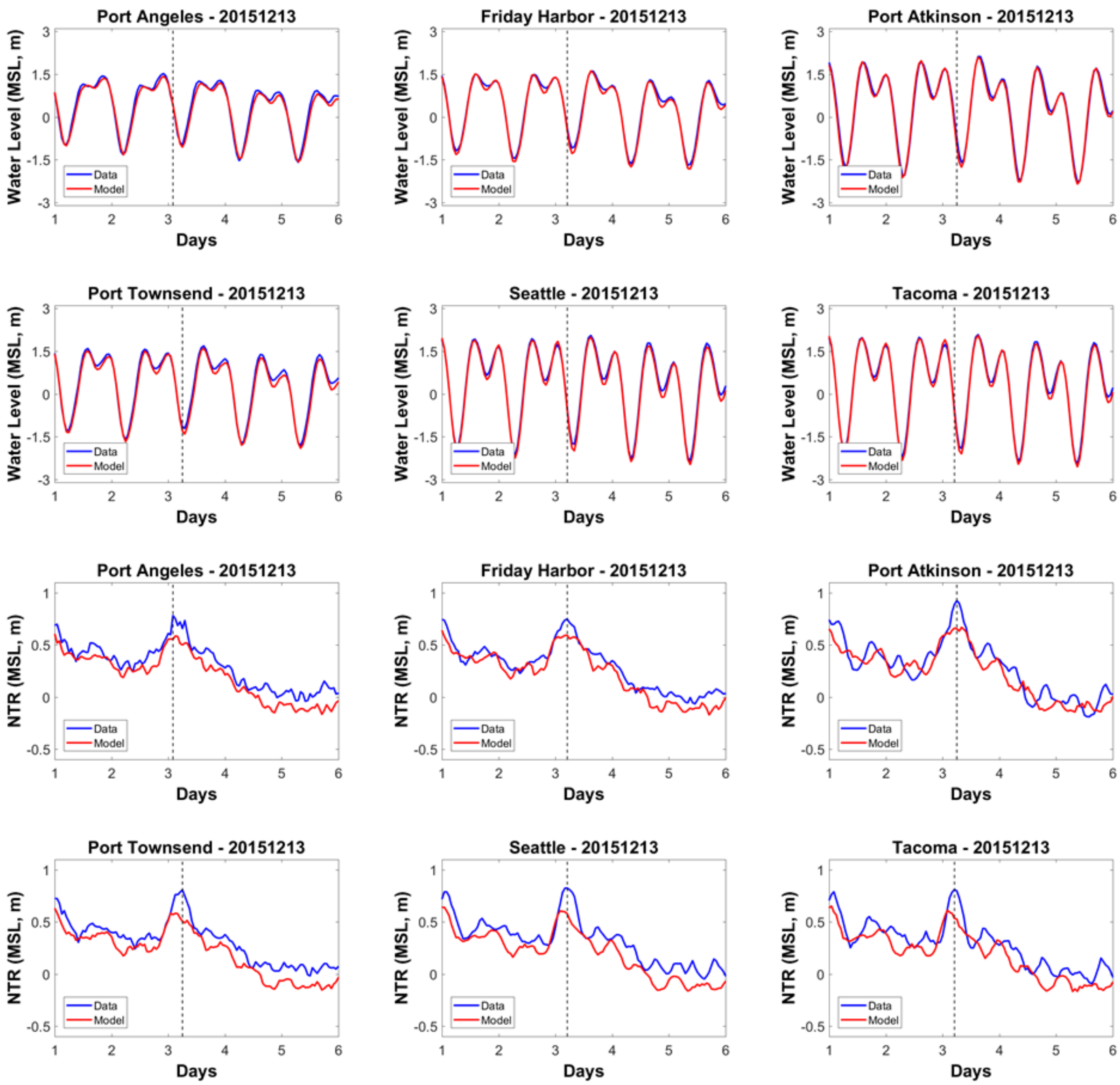

Figure A.31. Time series comparisons of total water level and NTR for storm event 20151213 at six tidal stations inside the model domain.

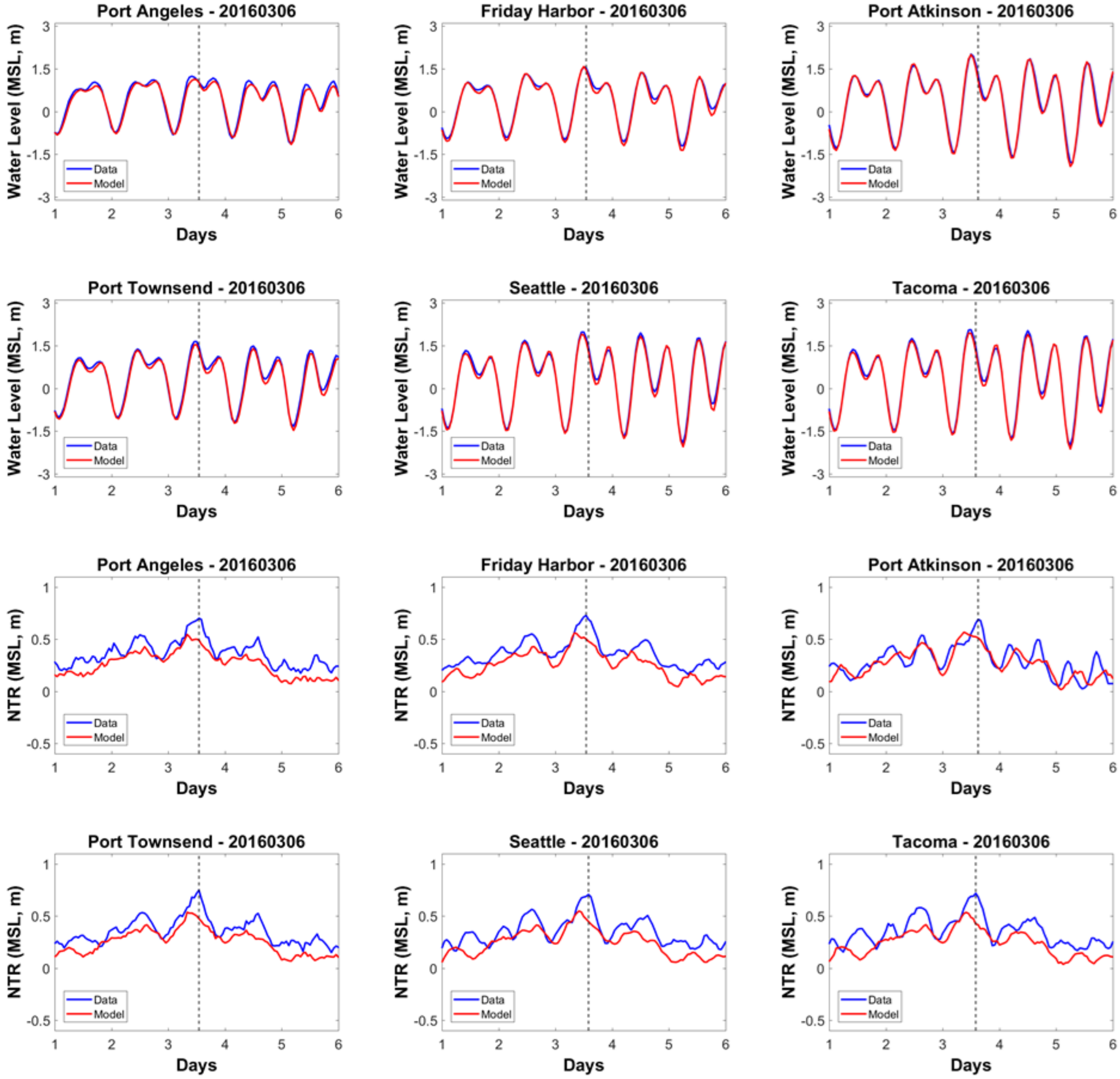

Figure A.32. Time series comparisons of total water level and NTR for storm event 20160306 at six tidal stations inside the model domain.

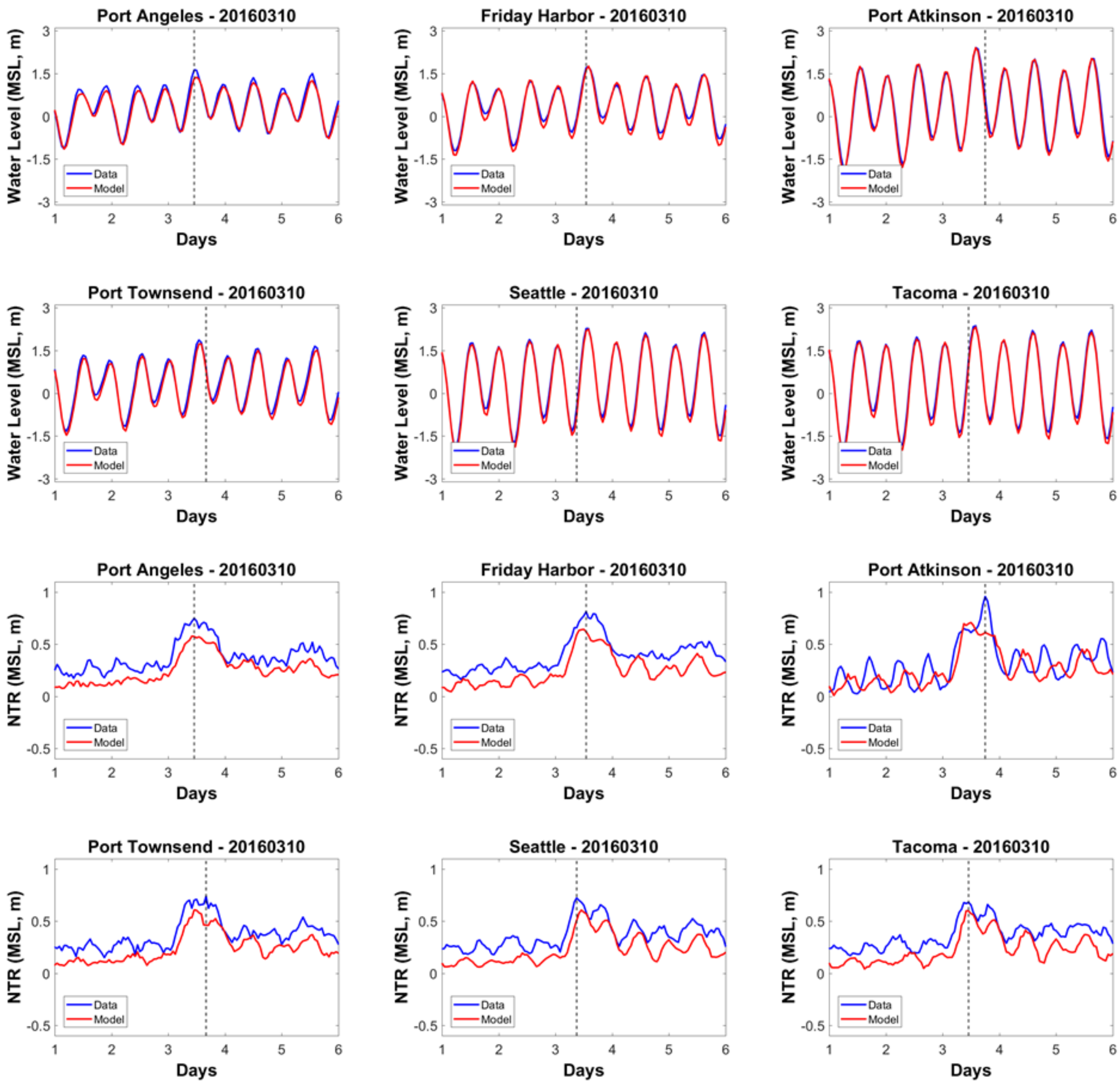

Figure A.33. Time series comparisons of total water level and NTR for storm event 20160310 at six tidal stations inside the model domain.

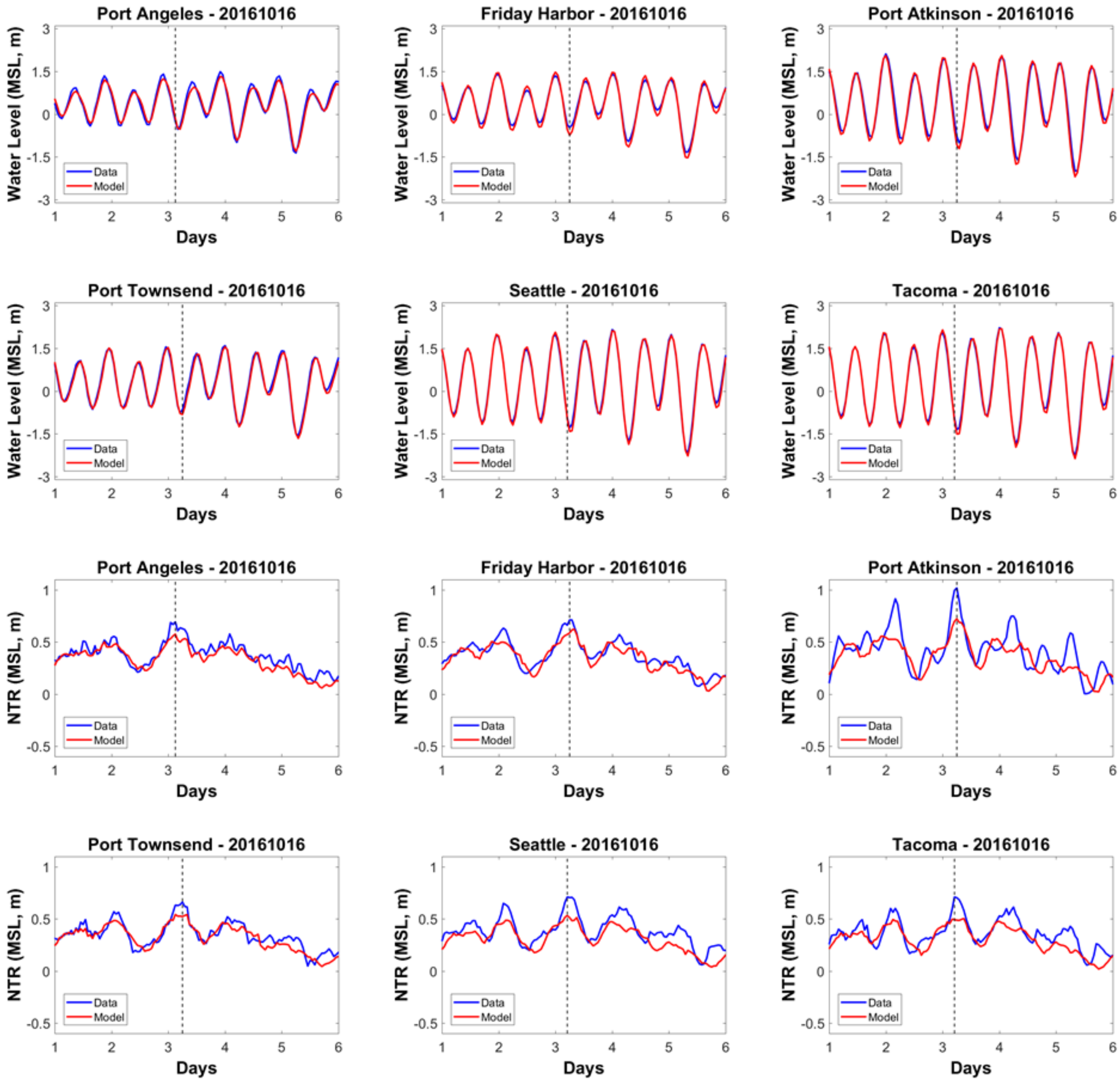

Figure A.34. Time series comparisons of total water level and NTR for storm event 20161016 at six tidal stations inside the model domain.

Appendix B – Error Statistics Parameters for All 34 Storm Events

This appendix summarizes the error statistics parameters for all 34 storm events

Table B.1. Summary of RMSE for all 34 storm events.

Event	RMSE											
	NTR						Water Level					
	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson
19800112	0.04	0.06	0.05	0.07		0.06	0.08	0.06	0.05	0.08		0.09
19811115	0.07	0.10	0.10	0.11		0.08	0.15	0.11	0.13	0.14		0.16
19821219	0.06	0.08	0.08	0.09		0.07	0.09	0.10	0.07	0.11		0.09
19830127	0.06	0.08	0.06	0.09		0.08	0.14	0.09	0.12	0.11		0.10
19830212	0.07	0.07	0.09	0.09		0.07	0.11	0.08	0.09	0.11		0.13
19831111	0.09	0.11	0.09	0.09		0.08	0.11	0.10	0.08	0.12		0.10
19831117	0.07	0.09	0.08	0.10		0.07	0.11	0.11	0.10	0.15		0.09
19871201	0.06	0.07	0.08	0.09		0.08	0.11	0.08	0.09	0.11		0.12
19871209	0.05	0.10	0.09	0.09		0.10	0.10	0.08	0.10	0.11		0.13
19920128	0.05	0.07	0.07	0.12		0.09	0.08	0.09	0.07	0.12		0.14
19920131	0.07	0.07	0.07	0.11		0.09	0.08	0.07	0.07	0.10		0.11
19960221	0.06	0.07	0.06	0.09		0.10	0.13	0.11	0.10	0.10		0.17
19970101	0.07	0.07	0.07	0.09		0.08	0.09	0.08	0.07	0.09		0.11
19971004	0.07	0.10	0.09	0.08	0.10		0.10	0.09	0.08	0.09	0.10	
19980207	0.06	0.06	0.08	0.06	0.07	0.09	0.10	0.06	0.08	0.06	0.06	0.09
19980212	0.05	0.06	0.05	0.06	0.06	0.09	0.11	0.07	0.09	0.08	0.08	0.11
19980221	0.05	0.06	0.06	0.07	0.08	0.08	0.07	0.04	0.05	0.06	0.07	0.07
19981125	0.06	0.07	0.06	0.09	0.11		0.09	0.06	0.07	0.08	0.10	
19990303	0.07	0.08	0.06	0.09	0.08	0.10	0.12	0.08	0.11	0.09	0.10	0.11
20021216	0.05	0.05	0.06	0.07	0.08	0.07	0.07	0.06	0.05	0.06	0.08	0.09
20060201	0.10	0.08	0.10	0.09	0.08	0.09	0.12	0.08	0.11	0.10	0.10	0.14
20060204	0.12	0.09	0.13	0.11	0.12	0.12	0.10	0.07	0.10	0.08	0.08	0.11
20061116	0.05	0.07	0.06	0.10	0.10	0.12	0.07	0.06	0.05	0.07	0.08	0.09
20061215	0.06	0.05	0.08	0.10	0.11	0.10	0.07	0.05	0.07	0.07	0.08	0.07
20071112	0.05	0.05	0.06	0.09	0.08	0.10	0.11	0.08	0.09	0.08	0.07	0.13
20071203	0.06	0.08	0.08	0.09	0.08	0.14	0.08	0.07	0.07	0.07	0.07	0.09
20080105	0.05	0.05	0.06	0.08	0.11	0.08	0.08	0.05	0.06	0.06	0.07	0.09
20100118	0.06	0.07	0.08	0.08	0.09	0.07	0.11	0.06	0.10	0.07	0.07	0.10
20121202	0.06	0.07	0.07	0.08	0.09	0.08	0.10	0.06	0.09	0.07	0.06	0.10
20141211	0.07	0.08	0.08	0.10	0.10	0.11	0.11	0.08	0.11	0.09	0.09	0.10
20151213	0.12	0.09	0.13	0.15	0.14	0.10	0.13	0.10	0.14	0.12	0.10	0.13
20160306	0.11	0.12	0.12	0.13	0.14	0.12	0.11	0.08	0.12	0.10	0.10	0.09
20160310	0.14	0.16	0.14	0.16	0.16	0.15	0.15	0.12	0.15	0.13	0.13	0.15
20161016	0.07	0.07	0.06	0.10	0.10	0.09	0.13	0.10	0.11	0.09	0.09	0.15

Table B.2. Summary of MAE for all storm events.

MAE												
Event	**NTR**						**Water Level**					
	Port Angeles	**Friday Harbor**	**Port Townsend**	**Seattle**	**Tacoma**	**Port Atkinson**	**Port Angeles**	**Friday Harbor**	**Port Townsend**	**Seattle**	**Tacoma**	**Port Atkinson**
19800112	0.03	0.05	0.04	0.06		0.05	0.06	0.06	0.04	0.07	0.08	0.07
19811115	0.06	0.08	0.08	0.09		0.06	0.12	0.09	0.10	0.12	0.15	0.13
19821219	0.05	0.07	0.07	0.08		0.05	0.07	0.08	0.06	0.08	0.09	0.08
19830127	0.05	0.07	0.05	0.07		0.07	0.11	0.08	0.09	0.09	0.11	0.09
19830212	0.06	0.06	0.08	0.07		0.06	0.09	0.07	0.07	0.09	0.11	0.10
19831111	0.07	0.10	0.07	0.07		0.07	0.09	0.09	0.06	0.11	0.11	0.09
19831117	0.06	0.08	0.06	0.08		0.05	0.09	0.09	0.09	0.13	0.15	0.08
19871201	0.05	0.06	0.06	0.07		0.06	0.08	0.07	0.07	0.09	0.10	0.11
19871209	0.04	0.08	0.07	0.07		0.08	0.08	0.07	0.08	0.09	0.10	0.11
19920128	0.04	0.05	0.06	0.10		0.08	0.06	0.08	0.06	0.10	0.10	0.11
19920131	0.05	0.06	0.06	0.09		0.07	0.06	0.06	0.05	0.08	0.09	0.09
19960221	0.04	0.05	0.05	0.08		0.08	0.11	0.09	0.08	0.08	0.12	0.14
19970101	0.06	0.06	0.06	0.07		0.06	0.07	0.07	0.05	0.07	0.08	0.09
19971004	0.05	0.09	0.08	0.07	0.08		0.08	0.08	0.07	0.08	0.08	
19980207	0.05	0.05	0.07	0.05	0.06	0.07	0.08	0.05	0.07	0.05	0.05	0.08
19980212	0.04	0.05	0.04	0.05	0.04	0.08	0.10	0.06	0.08	0.07	0.07	0.09
19980221	0.04	0.05	0.05	0.06	0.07	0.07	0.06	0.03	0.04	0.05	0.05	0.06
19981125	0.05	0.06	0.05	0.06	0.09		0.07	0.05	0.06	0.06	0.07	
19990303	0.05	0.06	0.05	0.07	0.07	0.08	0.11	0.07	0.09	0.07	0.07	0.09
20021216	0.04	0.04	0.05	0.06	0.07	0.06	0.06	0.05	0.04	0.05	0.06	0.08
20060201	0.09	0.07	0.08	0.08	0.06	0.07	0.10	0.07	0.09	0.08	0.07	0.12
20060204	0.10	0.08	0.11	0.09	0.09	0.10	0.08	0.05	0.08	0.07	0.06	0.09
20061116	0.04	0.05	0.05	0.09	0.08	0.10	0.06	0.05	0.04	0.05	0.06	0.07
20061215	0.04	0.04	0.07	0.08	0.09	0.09	0.06	0.04	0.06	0.06	0.07	0.06
20071112	0.04	0.04	0.05	0.07	0.06	0.08	0.10	0.06	0.08	0.07	0.06	0.10
20071203	0.05	0.07	0.06	0.08	0.06	0.11	0.07	0.06	0.06	0.05	0.05	0.07
20080105	0.04	0.04	0.05	0.07	0.09	0.07	0.07	0.04	0.05	0.05	0.05	0.07
20100118	0.05	0.06	0.06	0.07	0.07	0.06	0.08	0.05	0.09	0.05	0.06	0.09
20121202	0.04	0.05	0.05	0.06	0.08	0.06	0.08	0.05	0.08	0.05	0.05	0.08
20141211	0.05	0.06	0.06	0.08	0.08	0.09	0.09	0.06	0.09	0.08	0.08	0.08
20151213	0.10	0.08	0.12	0.13	0.11	0.08	0.11	0.07	0.12	0.10	0.09	0.10
20160306	0.10	0.10	0.10	0.11	0.12	0.11	0.09	0.07	0.10	0.08	0.09	0.08
20160310	0.12	0.14	0.13	0.14	0.14	0.13	0.12	0.10	0.13	0.10	0.11	0.12
20161016	0.06	0.06	0.05	0.09	0.08	0.07	0.12	0.09	0.09	0.07	0.07	0.12

Table B.3. Summary of SI for all storm events.

Event	SI											
	NTR						Water Level					
	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson
19800112	0.13	0.19	0.16	0.24		0.18	0.14	0.10	0.08	0.10		0.11
19811115	0.18	0.25	0.26	0.29		0.20	0.16	0.10	0.12	0.11		0.12
19821219	0.13	0.19	0.19	0.22		0.14	0.11	0.10	0.07	0.10		0.08
19830127	0.12	0.15	0.13	0.19		0.17	0.13	0.08	0.11	0.08		0.07
19830212	0.18	0.18	0.24	0.24		0.17	0.14	0.09	0.10	0.10		0.12
19831111	0.21	0.27	0.22	0.23		0.20	0.14	0.12	0.09	0.12		0.11
19831117	0.14	0.18	0.16	0.22		0.14	0.17	0.15	0.15	0.18		0.11
19871201	0.23	0.25	0.30	0.38		0.26	0.18	0.11	0.13	0.12		0.13
19871209	0.15	0.26	0.25	0.26		0.26	0.12	0.08	0.10	0.10		0.12
19920128	0.15	0.22	0.21	0.40		0.29	0.11	0.11	0.09	0.12		0.14
19920131	0.18	0.20	0.20	0.31		0.22	0.09	0.08	0.07	0.09		0.10
19960221	0.15	0.17	0.17	0.25		0.24	0.21	0.15	0.13	0.09		0.16
19970101	0.15	0.15	0.15	0.19		0.17	0.13	0.12	0.10	0.11		0.14
19971004	0.17	0.23	0.22	0.21	0.24		0.17	0.14	0.12	0.11	0.11	
19980207	0.14	0.17	0.21	0.16	0.19	0.22	0.13	0.07	0.09	0.05	0.06	0.09
19980212	0.15	0.18	0.16	0.19	0.17	0.26	0.16	0.08	0.11	0.08	0.08	0.11
19980221	0.17	0.21	0.21	0.23	0.26	0.26	0.12	0.06	0.07	0.07	0.08	0.08
19981125	0.18	0.20	0.18	0.26	0.35		0.13	0.08	0.09	0.09	0.10	
19990303	0.57	0.66	0.60	0.85	0.86	0.58	0.24	0.12	0.16	0.10	0.10	0.12
20021216	0.11	0.12	0.14	0.17	0.20	0.15	0.10	0.07	0.06	0.06	0.07	0.09
20060201	0.49	0.37	0.47	0.46	0.38	0.36	0.17	0.10	0.12	0.09	0.08	0.13
20060204	1.13	0.87	1.27	1.22	1.34	0.61	0.17	0.10	0.15	0.10	0.09	0.13
20061116	0.26	0.34	0.35	0.59	0.58	0.55	0.16	0.13	0.10	0.10	0.11	0.14
20061215	0.30	0.29	0.47	0.59	0.69	0.44	0.14	0.08	0.12	0.10	0.11	0.10
20071112	0.53	0.44	0.53	0.71	0.67	0.67	0.14	0.09	0.10	0.08	0.06	0.12
20071203	0.31	0.44	0.44	0.54	0.51	0.52	0.16	0.13	0.13	0.09	0.09	0.13
20080105	0.16	0.18	0.21	0.29	0.39	0.26	0.10	0.05	0.06	0.05	0.06	0.08
20100118	0.16	0.19	0.20	0.22	0.23	0.19	0.14	0.07	0.12	0.07	0.07	0.10
20121202	0.14	0.17	0.17	0.20	0.25	0.18	0.13	0.07	0.10	0.06	0.06	0.09
20141211	0.16	0.19	0.20	0.25	0.25	0.25	0.14	0.09	0.13	0.09	0.09	0.10
20151213	0.57	0.43	0.66	0.75	0.71	0.35	0.17	0.10	0.15	0.10	0.09	0.11
20160306	0.43	0.46	0.46	0.54	0.58	0.44	0.18	0.11	0.15	0.10	0.10	0.10
20160310	0.54	0.63	0.60	0.72	0.74	0.58	0.26	0.18	0.22	0.12	0.12	0.15
20161016	0.20	0.21	0.20	0.34	0.34	0.25	0.23	0.15	0.16	0.09	0.08	0.16

Table B.4. Summary of bias for all storm events.

Bias												
Event	NTR						Water Level					
	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson
19800112	0.00	0.02	-0.01	0.04		-0.02	0.02	0.05	0.01	0.07		0.05
19811115	0.04	0.08	0.08	0.06		0.02	0.07	0.08	0.08	0.11		0.04
19821219	0.00	0.05	0.03	0.05		0.00	0.01	0.05	0.03	0.07		0.05
19830127	0.01	0.05	0.02	0.05		-0.01	0.07	0.06	0.04	0.08		0.06
19830212	0.05	0.04	0.06	0.06		0.01	0.06	0.06	0.06	0.09		0.08
19831111	0.07	0.09	0.07	0.06		0.05	0.07	0.09	0.06	0.11		0.07
19831117	0.04	0.07	0.05	0.05		0.03	0.04	0.08	0.05	0.11		0.05
19871201	0.02	0.03	0.04	0.04		0.01	0.05	0.05	0.06	0.09		0.05
19871209	0.02	0.07	0.07	0.05		0.07	0.02	0.07	0.06	0.09		0.10
19920128	0.00	0.04	0.02	0.07		-0.03	0.03	0.08	0.05	0.10		0.06
19920131	-0.03	0.03	0.00	0.05		-0.04	-0.01	0.05	0.01	0.07		0.03
19960221	0.02	0.02	0.02	0.02		-0.04	0.06	0.07	0.03	0.06		0.05
19970101	0.01	0.04	-0.01	0.02		0.00	0.02	0.06	0.00	0.05		0.06
19971004	0.03	0.08	0.05	0.03	0.04		0.00	0.06	0.01	0.05	0.06	
19980207	-0.04	-0.05	-0.06	-0.03	-0.04	-0.07	0.00	-0.01	-0.03	0.01	0.02	0.01
19980212	-0.03	-0.04	-0.02	-0.02	-0.02	-0.08	-0.01	-0.01	-0.03	0.01	0.02	0.00
19980221	-0.03	-0.03	-0.04	-0.01	-0.02	-0.07	0.00	0.01	-0.02	0.03	0.04	0.02
19981125	-0.03	0.02	-0.02	0.01	0.05		-0.01	0.03	-0.01	0.05	0.06	
19990303	-0.04	-0.05	-0.03	-0.05	-0.05	-0.08	-0.03	-0.01	-0.04	-0.01	-0.01	0.00
20021216	-0.01	0.02	-0.01	0.00	0.01	-0.01	-0.01	0.03	0.00	0.03	0.05	0.03
20060201	-0.09	-0.05	-0.07	-0.05	0.00	-0.05	-0.04	-0.02	-0.05	-0.01	0.01	0.01
20060204	-0.10	-0.07	-0.11	-0.07	-0.06	-0.10	-0.05	-0.02	-0.07	-0.04	-0.02	0.00
20061116	0.00	0.03	-0.01	-0.03	0.02	-0.01	-0.01	0.03	-0.01	0.02	0.04	0.01
20061215	-0.02	-0.01	-0.05	-0.05	-0.02	-0.04	-0.01	0.01	-0.03	-0.01	0.02	0.00
20071112	-0.02	-0.03	-0.01	-0.06	-0.04	-0.08	-0.02	-0.04	-0.03	-0.02	0.01	-0.07
20071203	-0.02	-0.05	-0.05	-0.05	0.01	-0.08	-0.01	-0.03	-0.03	-0.01	0.02	-0.04
20080105	-0.01	-0.01	-0.02	-0.01	-0.01	-0.07	0.00	-0.01	-0.02	0.00	0.03	-0.01
20100118	-0.04	-0.03	-0.05	-0.02	-0.01	-0.05	-0.03	-0.01	-0.06	0.00	0.00	0.01
20121202	0.00	-0.03	-0.04	-0.04	-0.02	-0.03	0.00	-0.03	-0.05	0.00	0.00	-0.01
20141211	-0.03	-0.05	-0.05	-0.06	-0.04	-0.07	-0.03	-0.04	-0.06	-0.03	-0.02	-0.04
20151213	-0.10	-0.07	-0.12	-0.12	-0.10	-0.08	-0.08	-0.07	-0.11	-0.09	-0.07	-0.06
20160306	-0.10	-0.10	-0.10	-0.10	-0.11	-0.11	-0.07	-0.06	-0.09	-0.07	-0.07	-0.03
20160310	-0.12	-0.14	-0.13	-0.14	-0.14	-0.13	-0.08	-0.09	-0.12	-0.10	-0.10	-0.05
20161016	-0.05	-0.03	-0.03	-0.08	-0.06	-0.04	-0.03	-0.04	-0.05	-0.04	-0.04	-0.06

Table B.5. Summary of bias (%) for all storm events.

Event	Bias (%)											
	NTR						Water Level					
	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson
19800112	1.00	7.37	-4.06	16.80		-4.86	3.48	7.51	2.18	9.24		6.49
19811115	11.01	23.80	25.48	17.72		5.20	7.69	7.18	7.31	8.82		2.99
19821219	1.11	12.12	8.70	12.15		0.57	0.88	5.62	2.86	6.33		4.15
19830127	2.81	10.59	3.59	11.39		-1.93	6.51	5.59	3.57	5.69		4.92
19830212	14.53	9.39	18.68	18.27		2.97	7.32	6.55	6.46	8.11		7.99
19831111	20.45	28.57	20.97	19.61		14.03	9.12	11.12	6.72	11.30		8.04
19831117	8.91	17.52	11.86	13.43		7.24	5.74	12.23	6.85	13.47		6.81
19871201	8.82	12.56	15.12	15.94		2.90	8.18	7.09	8.14	9.58		5.83
19871209	4.32	22.68	22.26	17.71		21.59	2.18	7.15	5.92	7.72		8.67
19920128	-0.84	15.99	7.07	33.55		-7.87	4.34	9.68	6.28	10.84		6.34
19920131	-6.44	9.25	0.78	15.28		-8.36	-0.83	5.07	1.24	6.51		2.96
19960221	4.13	4.82	6.92	4.83		-9.41	9.05	9.67	4.62	5.50		4.73
19970101	2.33	8.86	-2.51	4.88		0.55	3.14	9.85	0.64	5.70		8.71
19971004	6.58	22.03	14.32	7.05	10.29		0.58	9.88	1.10	6.54	6.96	
19980207	-9.46	-11.11	-13.54	-6.31	-9.80	-14.54	-0.10	-1.67	-3.47	0.57	1.43	-1.80
19980212	-6.83	-9.74	-6.25	-6.71	-4.50	-13.89	-1.74	-1.08	-3.38	0.67	1.46	-6.43
19980221	-8.54	-9.15	-11.15	-2.26	-6.08	-18.12	-0.34	2.05	-2.13	3.44	4.88	1.89
19981125	-7.45	6.78	-5.58	4.00	16.73		-1.31	4.55	-1.16	5.40	6.79	
19990303	-23.81	-24.98	-19.61	-30.30	-30.51	-35.99	-4.90	-0.81	-6.34	-1.36	-1.51	0.22
20021216	-2.47	5.25	-1.75	-0.04	2.87	-1.79	-0.97	3.42	-0.34	3.36	4.95	3.21
20060201	-28.71	-19.64	-25.64	-18.63	-2.25	-17.85	-5.53	-2.27	-5.95	-0.99	1.16	0.89
20060204	-47.21	-33.89	-49.28	-36.19	-35.28	-42.67	-9.08	-3.34	-10.54	-4.52	-2.03	-0.56
20061116	2.36	15.15	-4.20	-15.23	12.49	-6.37	-1.38	6.98	-2.13	3.71	6.61	1.56
20061215	-7.29	-4.53	-19.16	-21.54	-7.73	-15.88	-2.13	0.93	-5.15	-2.02	2.06	0.66
20071112	-15.18	-23.76	-7.55	-47.04	-32.40	-45.47	-2.51	-4.55	-3.29	-1.75	0.77	-6.47
20071203	-9.35	-19.54	-19.60	-20.61	2.90	-26.26	-2.74	-5.93	-6.11	-0.82	3.17	-5.13
20080105	-3.19	-4.28	-7.25	-4.37	-4.38	-16.77	0.55	-1.49	-1.58	0.35	2.78	-1.08
20100118	-8.09	-7.22	-12.14	-4.84	-2.93	-10.64	-3.88	-0.96	-6.10	0.11	-0.42	1.02
20121202	-0.57	-7.28	-9.66	-8.57	-4.93	-6.62	-0.26	-3.28	-5.48	-0.07	-0.30	-0.93
20141211	-6.06	-10.00	-11.59	-13.66	-8.70	-14.70	-3.17	-4.65	-6.95	-2.88	-2.08	-3.81
20151213	-32.29	-24.86	-36.55	-37.69	-32.05	-25.65	-8.83	-7.50	-11.47	-7.81	-6.22	-4.78
20160306	-27.67	-28.19	-28.51	-29.90	-31.77	-28.49	-9.70	-7.44	-11.24	-6.82	-7.34	-3.14
20160310	-33.18	-36.14	-34.95	-38.35	-39.37	-33.08	-12.30	-13.70	-17.33	-9.62	-9.60	-5.59
20161016	-12.20	-8.20	-8.50	-19.76	-16.44	-10.04	-4.39	-6.58	-6.73	-3.59	-3.44	-6.03

Table B.6. Summary of R for all storm events.

	R											
Event	NTR						Water Level					
	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson	Port Angeles	Friday Harbor	Port Townsend	Seattle	Tacoma	Port Atkinson
19800112	0.962	0.944	0.957	0.935		0.943	0.991	0.998	0.997	0.999		0.996
19811115	0.903	0.882	0.873	0.740		0.878	0.992	0.998	0.996	0.998		0.994
19821219	0.896	0.883	0.856	0.810		0.915	0.993	0.996	0.998	0.997		0.997
19830127	0.907	0.896	0.895	0.845		0.840	0.993	0.998	0.995	0.998		0.998
19830212	0.904	0.867	0.826	0.839		0.861	0.992	0.998	0.998	0.998		0.996
19831111	0.942	0.929	0.946	0.923		0.934	0.994	0.998	0.998	0.998		0.998
19831117	0.914	0.937	0.914	0.826		0.918	0.977	0.993	0.989	0.993		0.996
19871201	0.961	0.965	0.946	0.928		0.947	0.990	0.997	0.996	0.998		0.994
19871209	0.969	0.948	0.961	0.941		0.936	0.994	0.999	0.997	0.999		0.997
19920128	0.879	0.844	0.792	0.670		0.673	0.995	0.998	0.998	0.998		0.992
19920131	0.874	0.873	0.847	0.749		0.821	0.995	0.998	0.998	0.998		0.995
19960221	0.869	0.857	0.868	0.691		0.790	0.982	0.997	0.993	0.998		0.990
19970101	0.883	0.925	0.884	0.834		0.911	0.988	0.997	0.994	0.995		0.994
19971004	0.913	0.916	0.867	0.847	0.813		0.981	0.997	0.992	0.997	0.997	
19980207	0.936	0.923	0.873	0.875	0.866	0.916	0.990	0.998	0.996	0.999	0.999	0.961
19980212	0.916	0.930	0.922	0.906	0.908	0.915	0.988	0.997	0.995	0.997	0.998	0.929
19980221	0.949	0.926	0.939	0.875	0.848	0.963	0.992	0.999	0.997	0.998	0.998	0.997
19981125	0.926	0.907	0.929	0.855	0.783		0.992	0.998	0.996	0.998	0.997	
19990303	0.969	0.952	0.952	0.922	0.917	0.956	0.982	0.996	0.992	0.997	0.997	0.995
20021216	0.952	0.953	0.928	0.895	0.868	0.912	0.994	0.998	0.998	0.998	0.998	0.996
20060201	0.900	0.913	0.880	0.830	0.837	0.916	0.990	0.997	0.995	0.998	0.998	0.994
20060204	0.950	0.956	0.922	0.885	0.849	0.957	0.993	0.997	0.997	0.998	0.998	0.994
20061116	0.942	0.934	0.919	0.831	0.820	0.818	0.990	0.996	0.997	0.997	0.997	0.992
20061215	0.964	0.974	0.952	0.930	0.881	0.930	0.993	0.997	0.995	0.996	0.996	0.996
20071112	0.938	0.960	0.922	0.927	0.907	0.971	0.992	0.998	0.997	0.998	0.999	0.996
20071203	0.978	0.973	0.972	0.959	0.946	0.917	0.990	0.996	0.995	0.997	0.997	0.995
20080105	0.970	0.964	0.958	0.910	0.839	0.970	0.995	0.999	0.998	0.999	0.999	0.997
20100118	0.955	0.937	0.945	0.893	0.889	0.945	0.991	0.998	0.996	0.998	0.998	0.996
20121202	0.854	0.868	0.886	0.843	0.717	0.858	0.992	0.998	0.997	0.998	0.999	0.996
20141211	0.918	0.906	0.917	0.864	0.820	0.894	0.991	0.997	0.995	0.997	0.997	0.996
20151213	0.963	0.970	0.959	0.927	0.904	0.977	0.992	0.998	0.996	0.998	0.999	0.996
20160306	0.904	0.879	0.886	0.805	0.795	0.933	0.991	0.997	0.996	0.998	0.998	0.996
20160310	0.928	0.892	0.899	0.824	0.821	0.886	0.982	0.997	0.993	0.998	0.998	0.992
20161016	0.924	0.893	0.899	0.852	0.803	0.865	0.981	0.997	0.992	0.997	0.998	0.992

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