Salish Sea Model:

Puget Sound Nutrient Source Reduction Project

September 20, 2018

Puget Sound Nutrient Forum

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Environmental Assessment Program

Near the mouth of the Elwha
Photo Courtesy: CMAP, SEA Program, Department of Ecology

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Contributors – thank you!

Data, Monitoring Tools, and Observations

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http://www.ecy.wa.gov/programs/eap/mar_wat/index.html

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http://www.ecy.wa.gov/programs/eap/fw_riv/index.html

Fisheries and Oceans Canada http://www.dfo-mpo.gc.ca/index-eng.htm

Padilla Bay National Estuarine Research Reserve System – data downloaded online, with assistance from Nicole Burnett and Jude Apple http://cdmo.baruch.sc.edu/

King County – data from Stephanie Jaeger and Kim Stark
http://green2.kingcounty.gov/marine/Monitoring/Offshore

University of Washington – UW PRISM cruise data in collaboration with NOAA, data from Simone Alin (NOAA) and Jan Newton (UW), Parker MacCready provided Matlab scripts
http://www.prism.washington.edu/home

Puget Sound Ecosystem Monitoring Program
http://www.ecy.wa.gov/PROGRAMS/WQ/psmonitoring/index.html

Many staff members of the wastewater treatment plants (WWTPs), particular in South and Central Puget Sound – provided data and assistance in collecting samples as part of the South Puget Sound Dissolved Oxygen Study for their facilities, which are the basis of some of the nutrient load estimates used in the model.

Ecology staff collected information under the separate South Puget Sound Dissolved Oxygen Study that was used as a basis for load analyses in the Salish Sea Model:

- Karen Burgess and Greg Zentner managed communications with the WWTPs through the permit writers (Mahbub Alam, Mike Dawda, Dave Dougherty, Alison Evans, Mark Henley, Tonya Lane), and Marc Heffner provided input regarding the Simpson industrial discharge.
- Chuck Hoffman analyzed and performed WWTP regressions.
- Ryan McEliece, Chris Moore, and Brandon Slone conducted all freshwater monitoring, including coordinating with WWTP staff for composite sample collection, in South and Central Puget Sound.
- Steve Golding helped develop the South and Central Puget Sound WWTP monitoring program.
- Dave Hallock and Bill Ward coordinated supplemental freshwater monitoring in South and Central Puget Sound.

Peer Reviewers

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Individual Project Applications

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NW Straits Commission

Skagit River System Cooperative

Skagit Watershed Council

Tulalip Tribe

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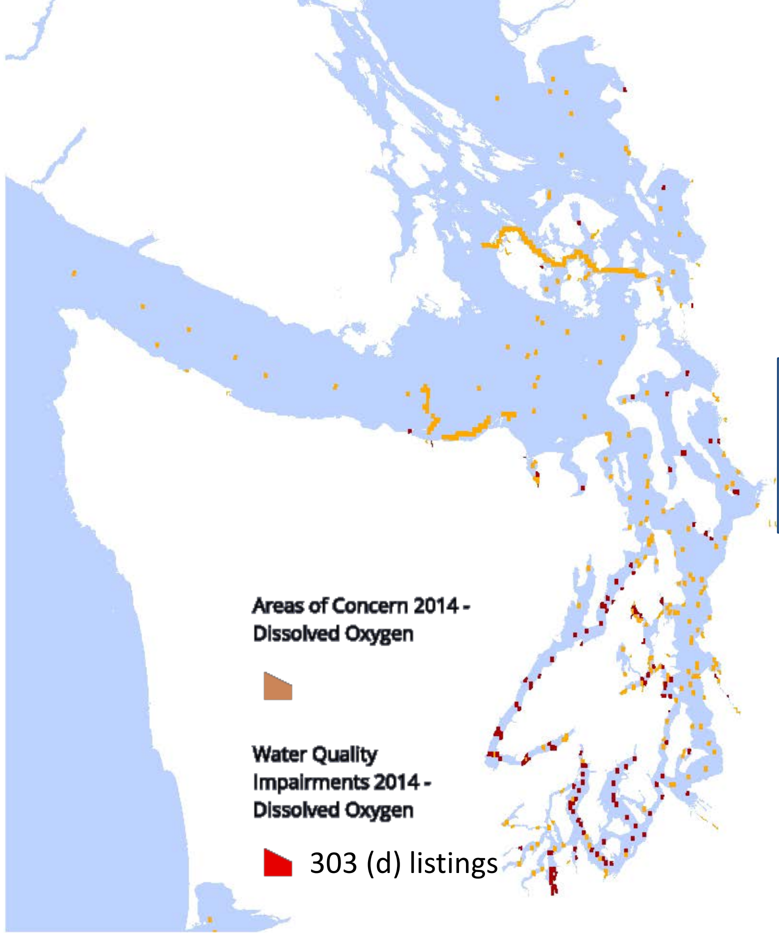
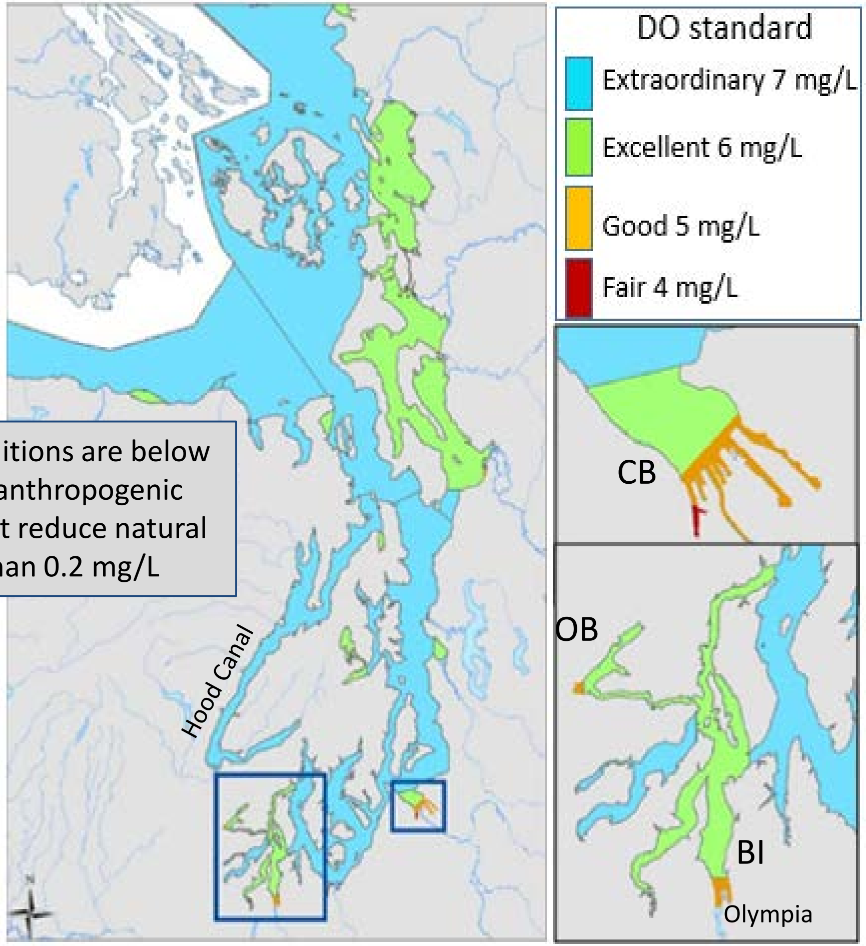
NW Regional Modeling Consortium http://www.atmos.washington.edu/cliff/consortium.html

Oxygen levels are low



If natural conditions are below the standard, anthropogenic sources cannot reduce natural DO by more than 0.2 mg/L

Numeric Criteria for DO: WAC 173-201A

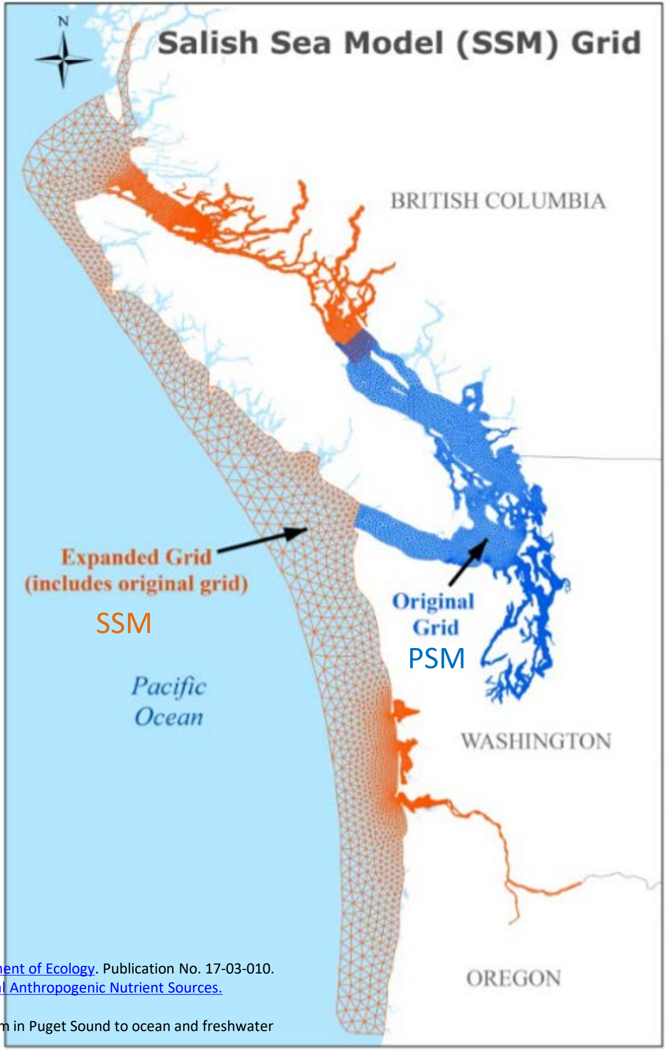


Major processes involving DO dynamics :

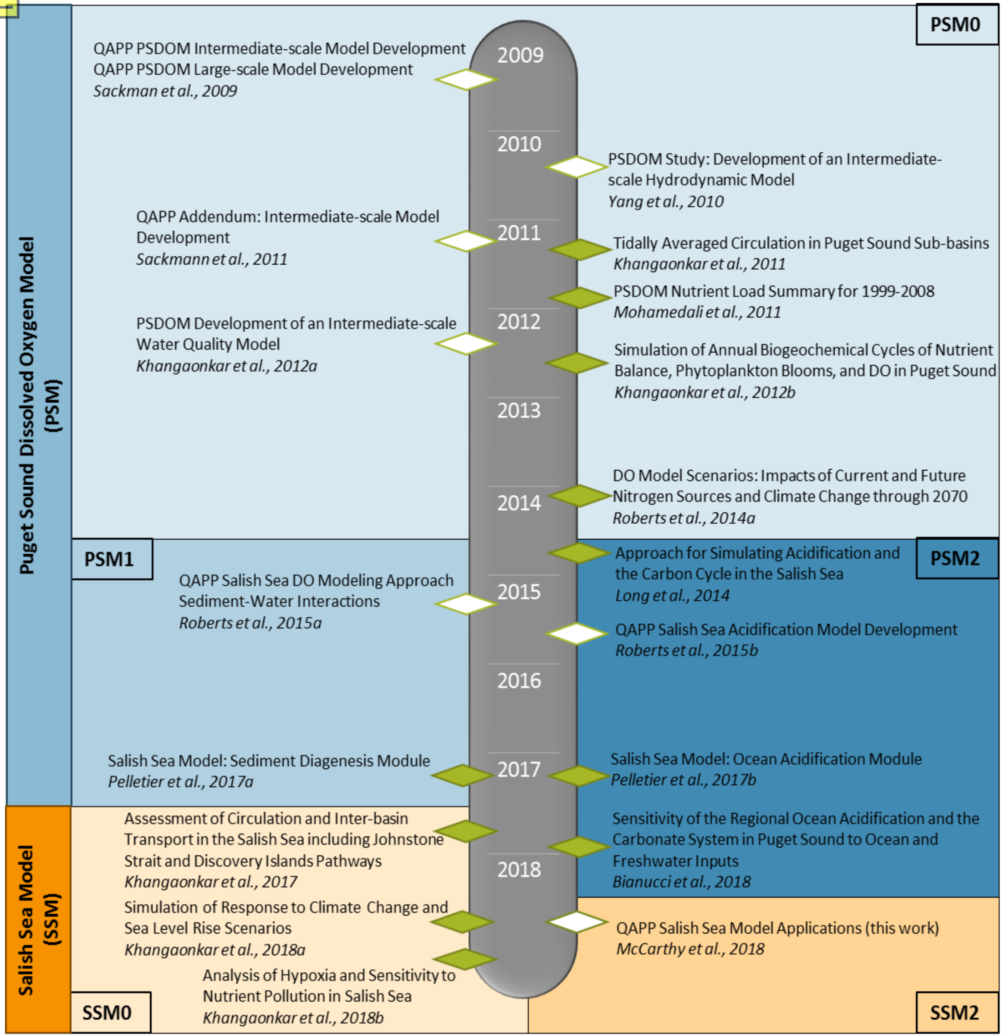
- Reaeration (wind and concentration induced)
- Photosynthesis (sunlight, CO2, nutrients, algal growth)
- Nitrification - Denitrification
- Respiration and die-off
- Organic matter decomposition (decay rates, BOD)
- Sediment oxygen demand (sediment diagenesis)
- Estuarine circulation, stratification, residence times
- Freshwater (watershed and WWTP) and oceanic inputs

What is the Salish Sea Model?

- Unstructured grid – smaller grid cells in the inlets
- 3D model (both horizontal and vertical grids)
- Hydrodynamics – FVCOM (Uni. Of Massachusetts)
- Water quality – CE-QUAL-ICM (US Army Corps)
- Sediment diagenesis module (Pelletier et al. 2017a)
- Acidification module (Pelletier et al. 2017b, Bianucci et al. 2018)
- Ocean boundary tidal forcing based on tidal components
- Meteorology (UW/WRF model)
- Ocean boundary WQ (DFO observations)
- Rivers and Marine Point Sources



- Pelletier, G., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky. 2017a. Salish Sea Model Sediment Diagenesis Module. Washington State Department of Ecology. Publication No. 17-03-010.
- Pelletier, G., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky. 2017b. Salish Sea Model Ocean Acidification Module and the Response to Regional Anthropogenic Nutrient Sources. Washington State Department of Ecology. Publication No. 17-03-009.
- Bianucci L, W Long, T Khangaonkar, G Pelletier, A. Ahmed, T. Mohamedali, M Roberts, C. Figueroa-Kaminsky. (2018). Sensitivity of the regional ocean acidification and the carbonate system in Puget Sound to ocean and freshwater inputs. *Elementa Science of the Anthropocene*, 6(1): 22



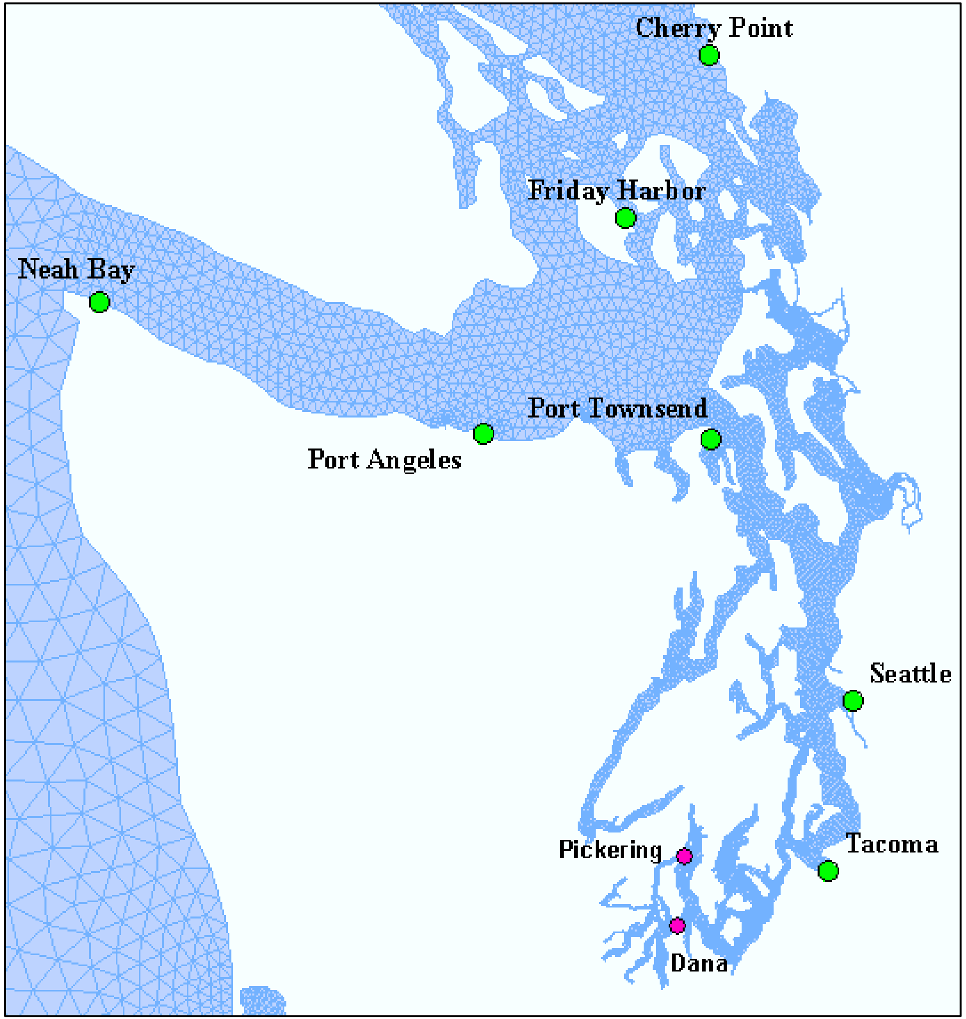
24 peer-reviewed papers and technical reports

Updated Salish Sea Model (SSM) Performance

- How does model perform in predicting observed <u>water surface elevations, currents, temperature and salinity</u>
- How does model perform in predicting observed <u>water quality</u>
- Model uncertainty in predicting exceedances of DO standard
- Years simulated:
  - SSM updates: 2006, 2008, 2014
- Model uncertainty compared with:
  - PSM 2008: (Bianucci et. al 2018) and
  - SSM 2014: (Khangaonkar et al. 2018)

Bianucci L, W Long, T Khangaonkar, G Pelletier, A. Ahmed, T. Mohamedali, M Roberts, C. Figueroa-Kaminsky. (2018). Sensitivity of the regional ocean acidification and the carbonate system in Puget Sound to ocean and freshwater inputs. *Elementa Science of the Anthropocene*, 6(1): 22. doi: 10.1525/elementa.151

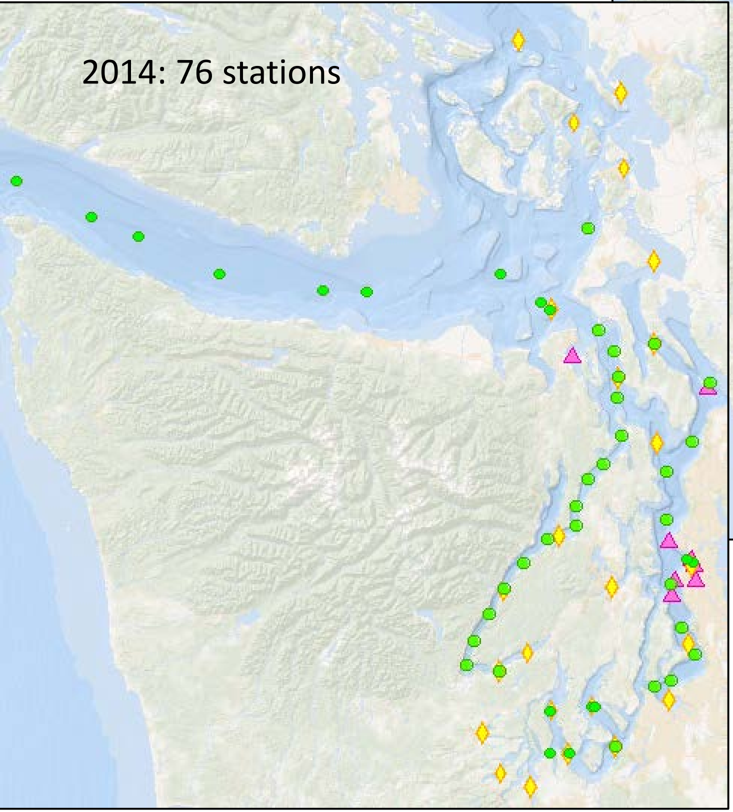
Khangaonkar T, A Nugraha, W Xu, W Long, L Bianucci, A Ahmed, T Mohamedali, and G Pelletier. 2018. Analysis of Hypoxia and Sensitivity to Nutrient Pollution in Salish Sea. *Journal of Geophysical Research: Oceans*, 123,4735–4761. https://doi.org/10.1029/2017JC013650

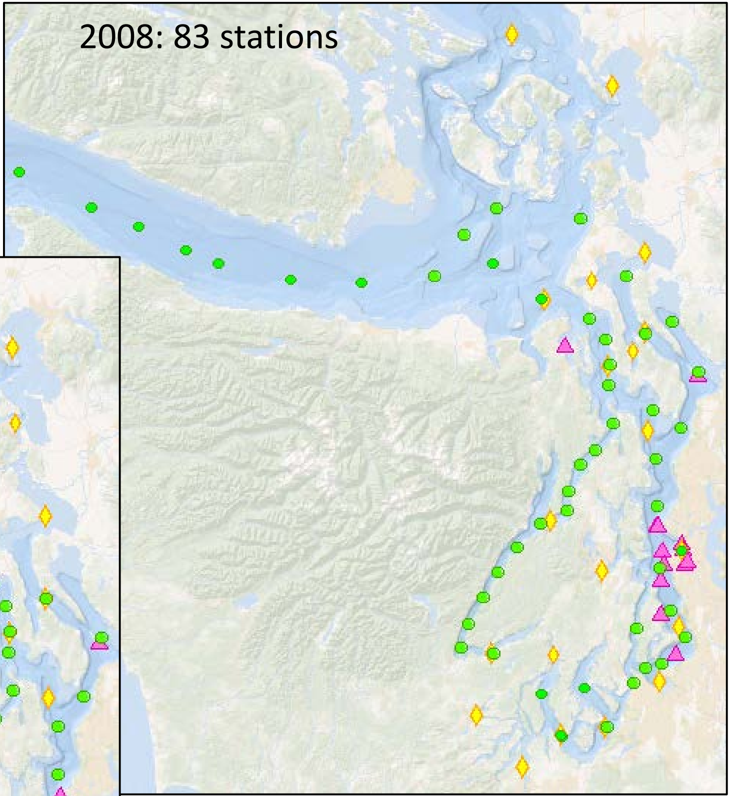


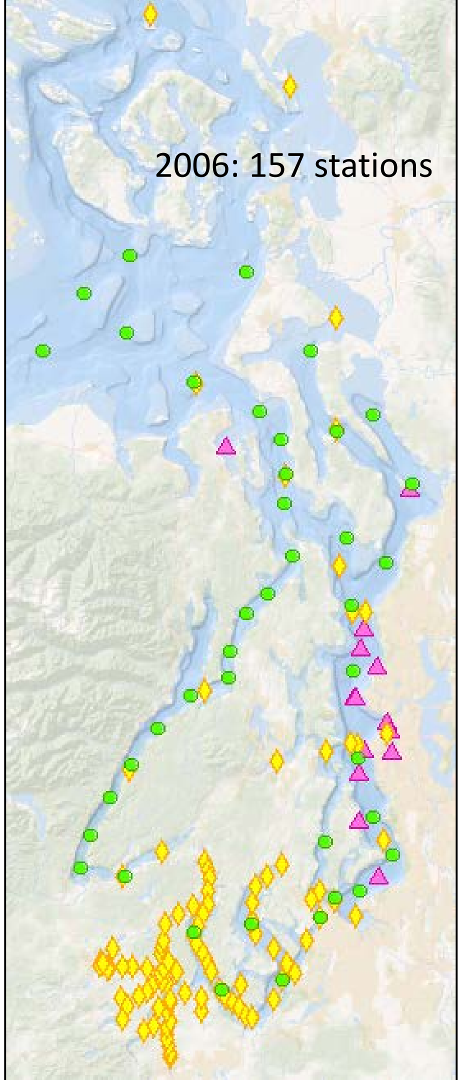
Stations for assessing model performance for water surface elevations and currents

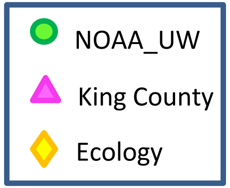
- Water surface elevation stations
- Water current stations

Stations where model performance was evaluated for water quality

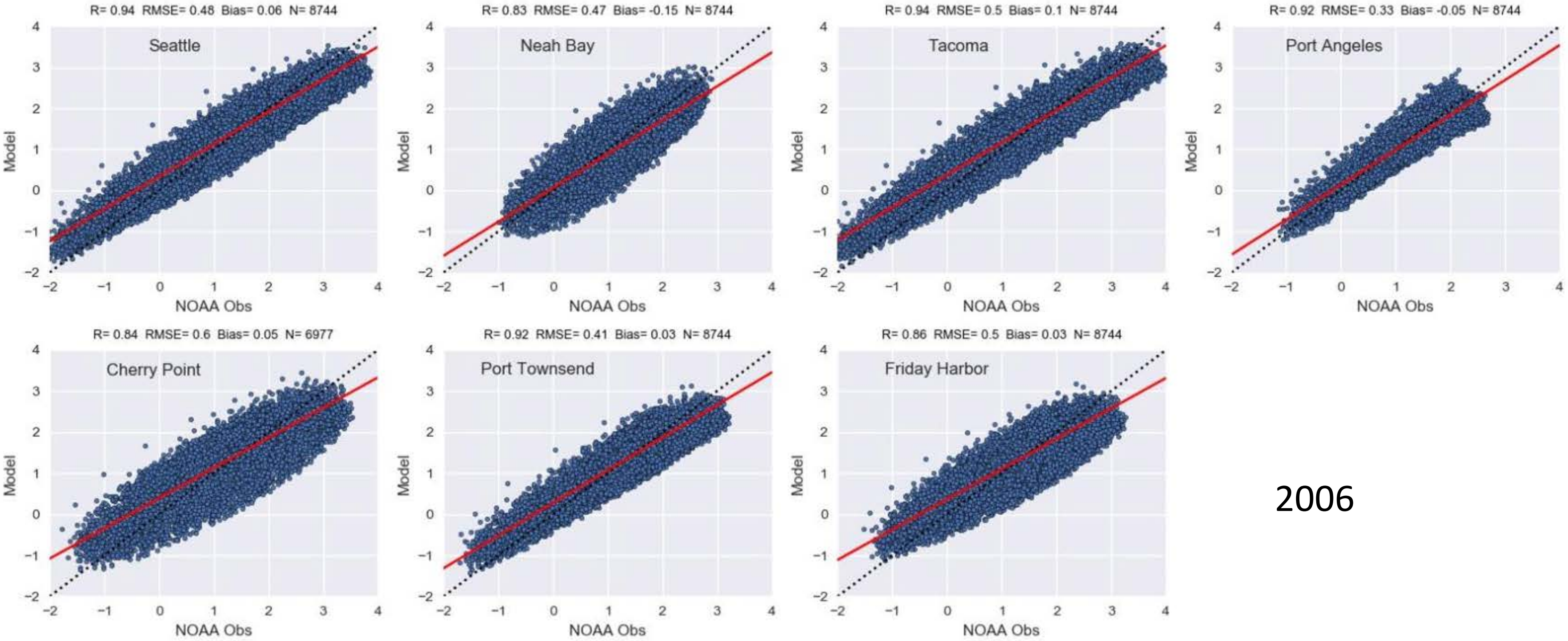






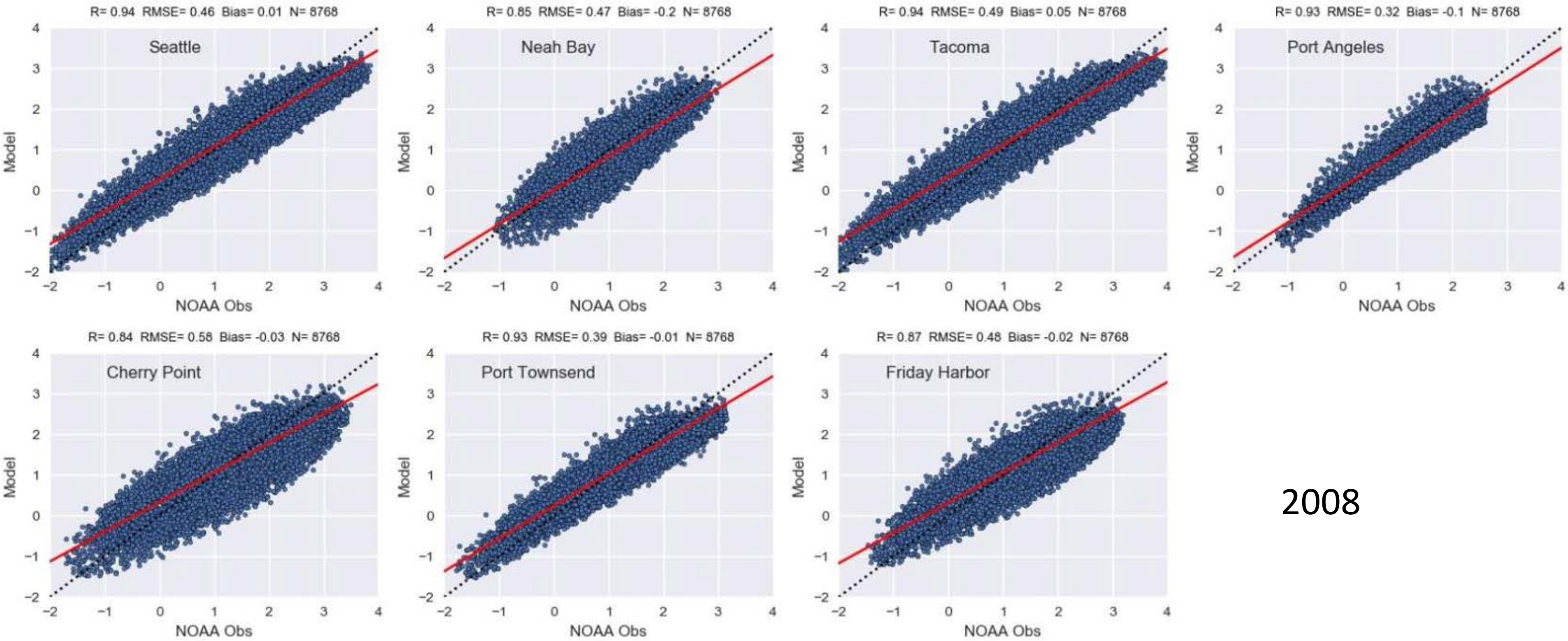


Water Surface Elevations: model versus observed data, (NAVD88, m)



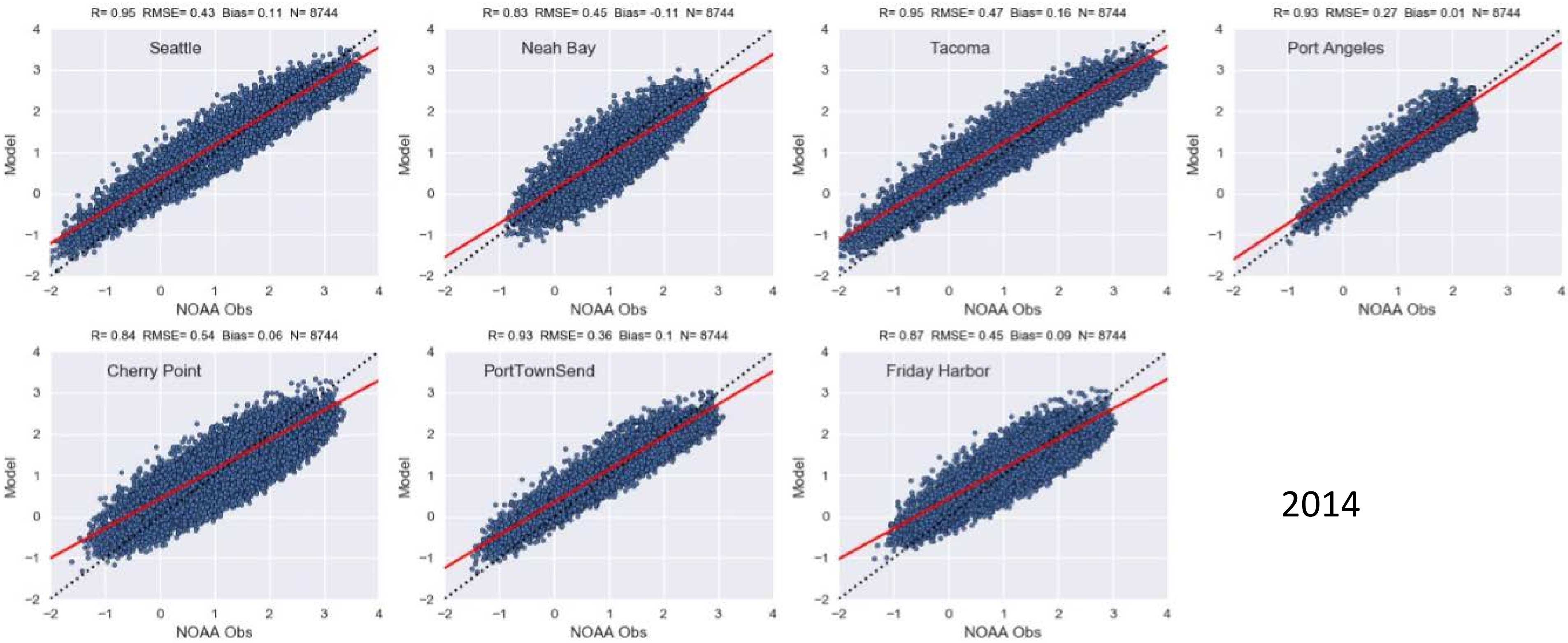
2006

Water Surface Elevations: model versus observed data (NAVD88, m)

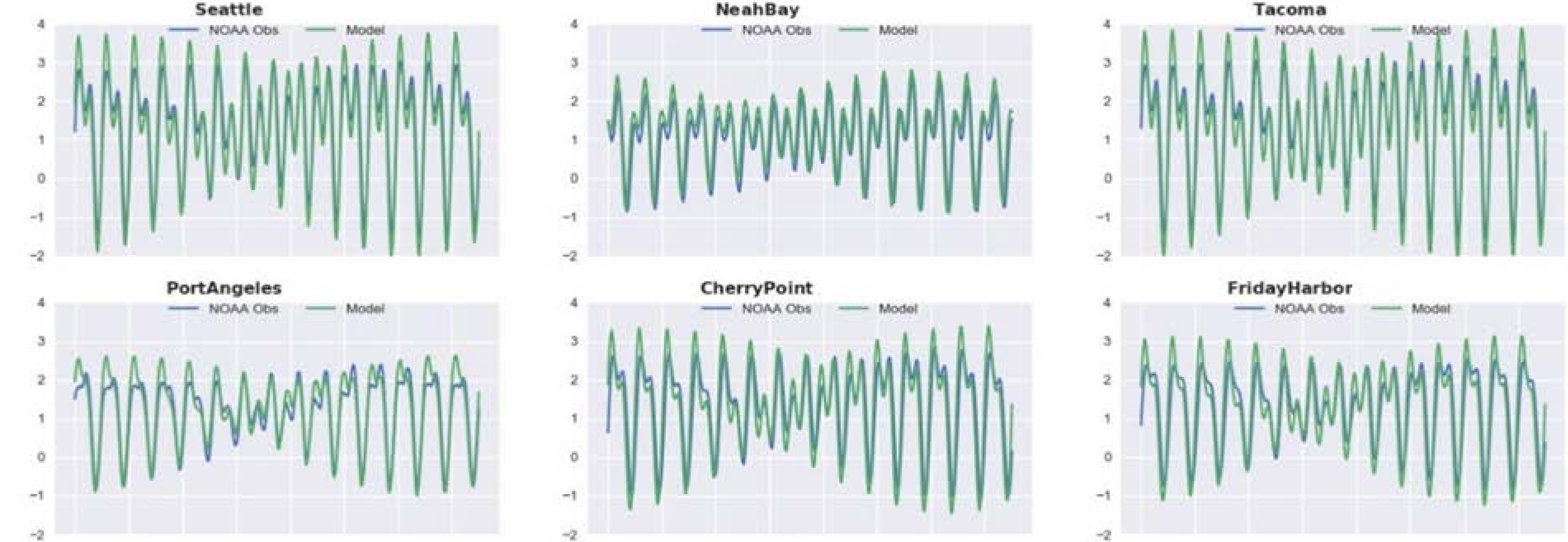


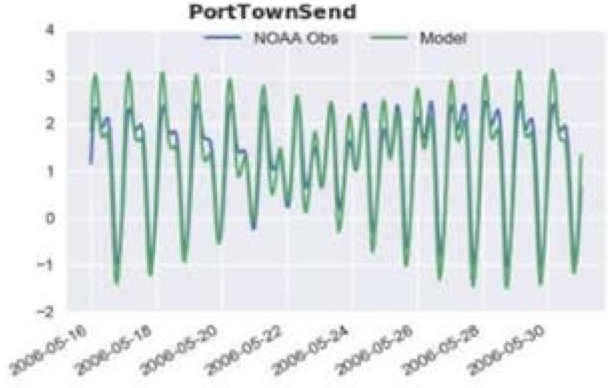
2008

Water Surface Elevations: model versus observed data: (NAVD88, m)

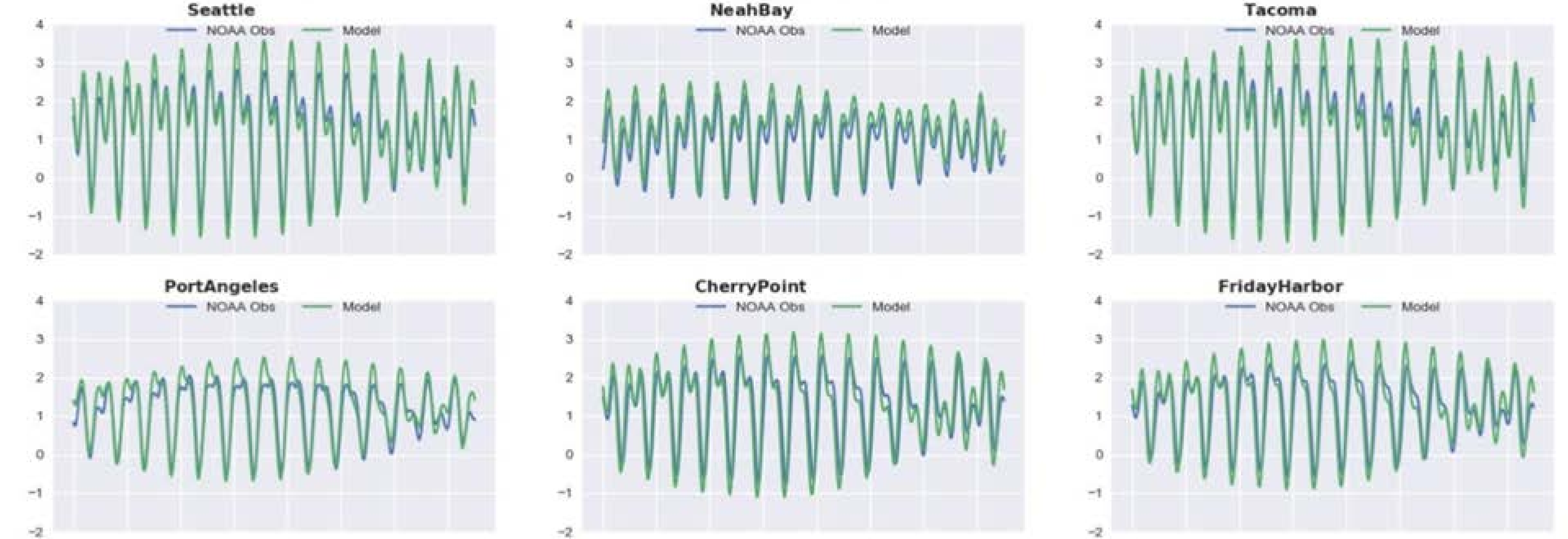


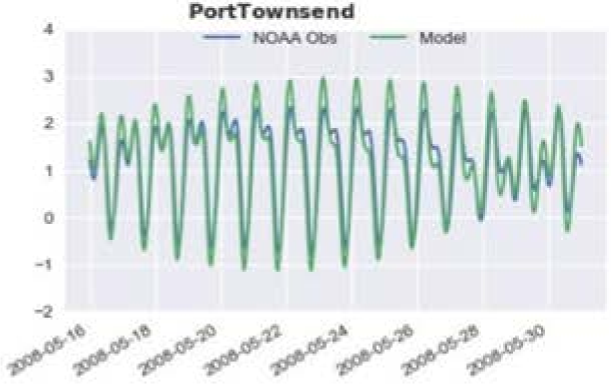
2014





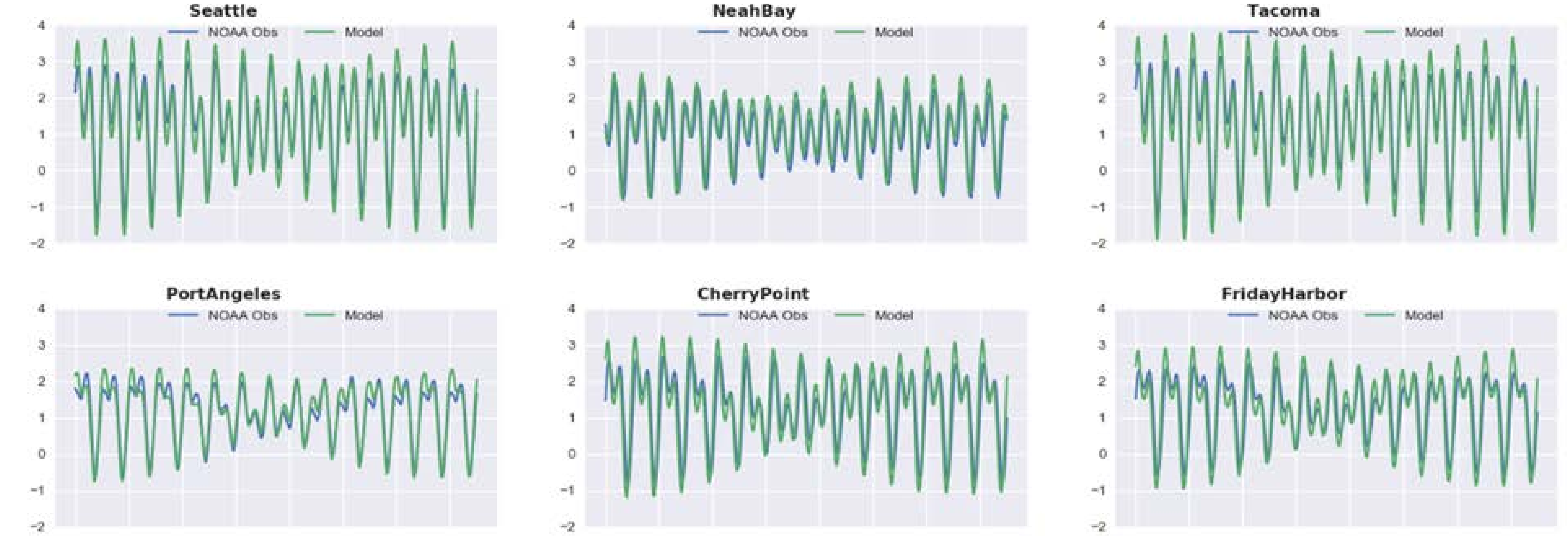
<u>Water Surface Elevations (NAVD88, m)</u>
model versus observed data: May 16-30, 2006

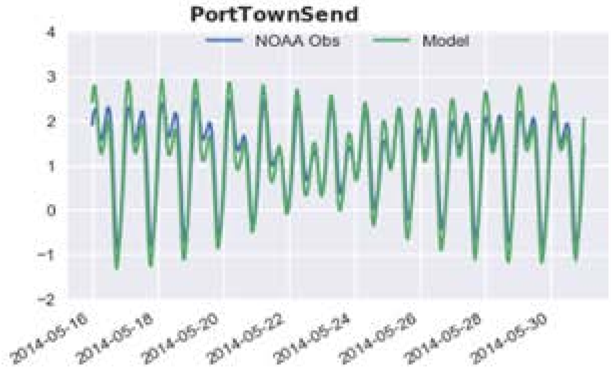




<u>Water Surface Elevations (NAVD88, m)</u>

model versus observed data: May 16-30, 2008



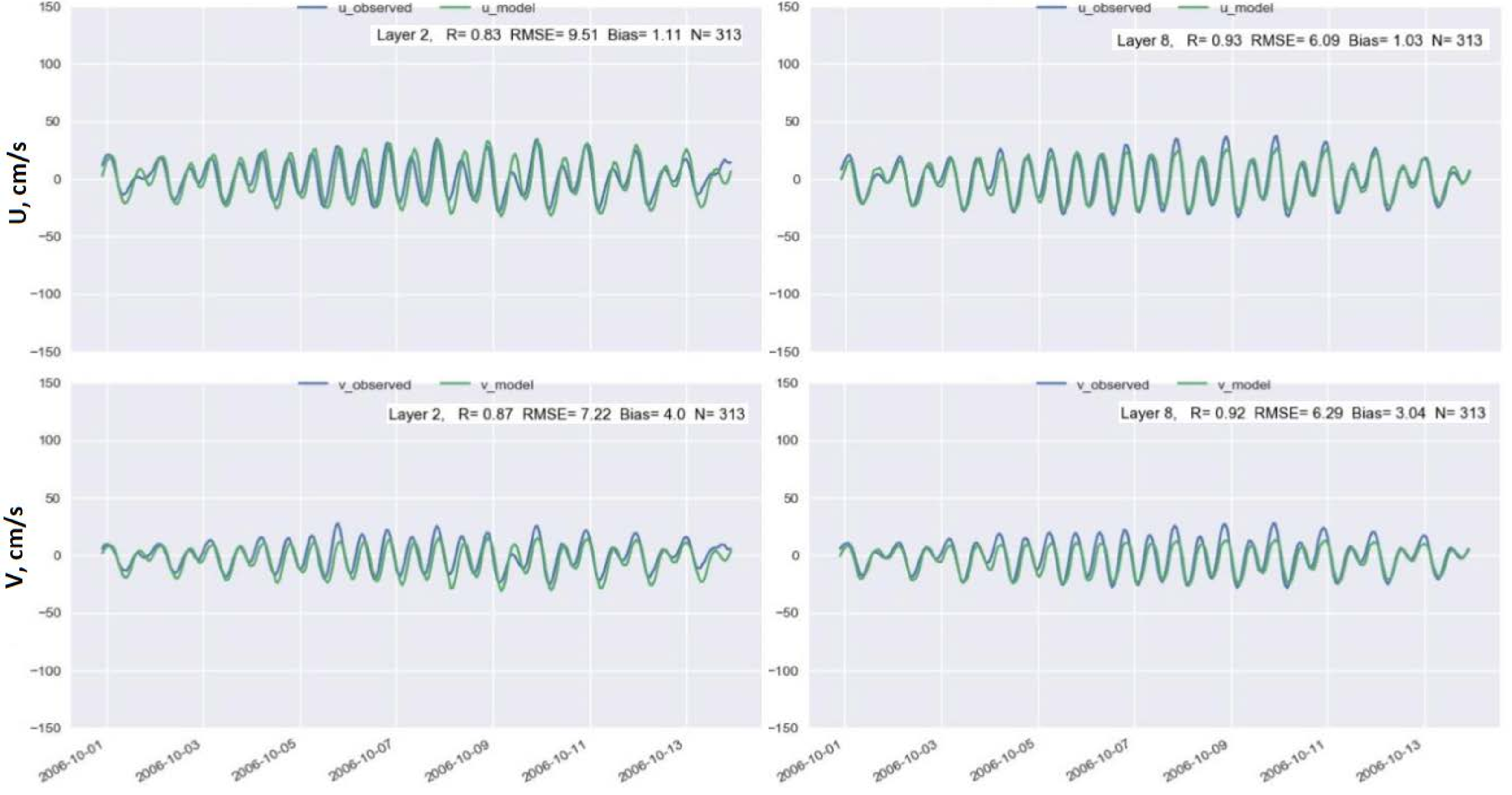


<u>Water Surface Elevations (NAVD88, m)</u>

model versus observed data: May 16-30, 2014

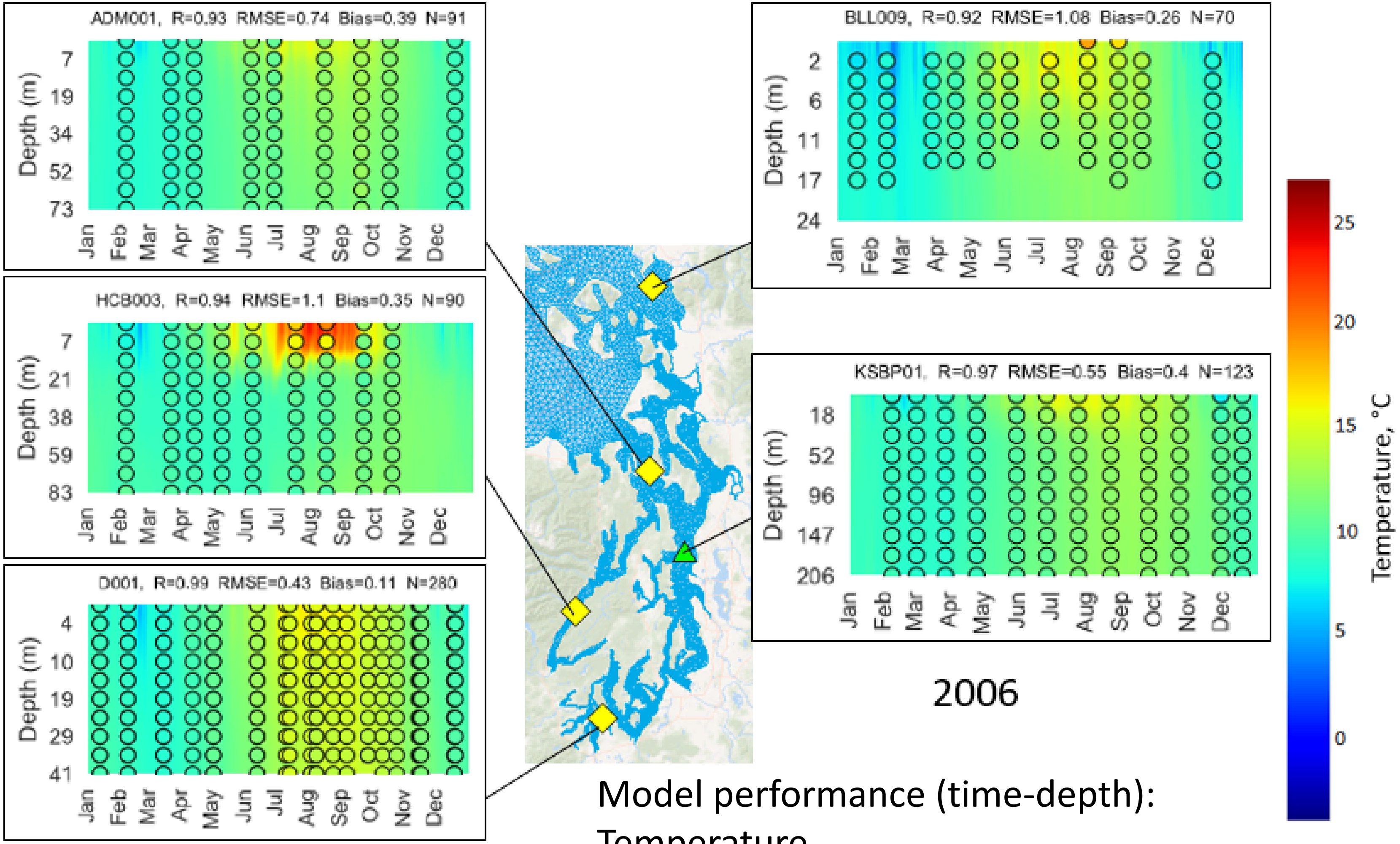
currents 2006 (Oct 1-14)

Pickering Passage

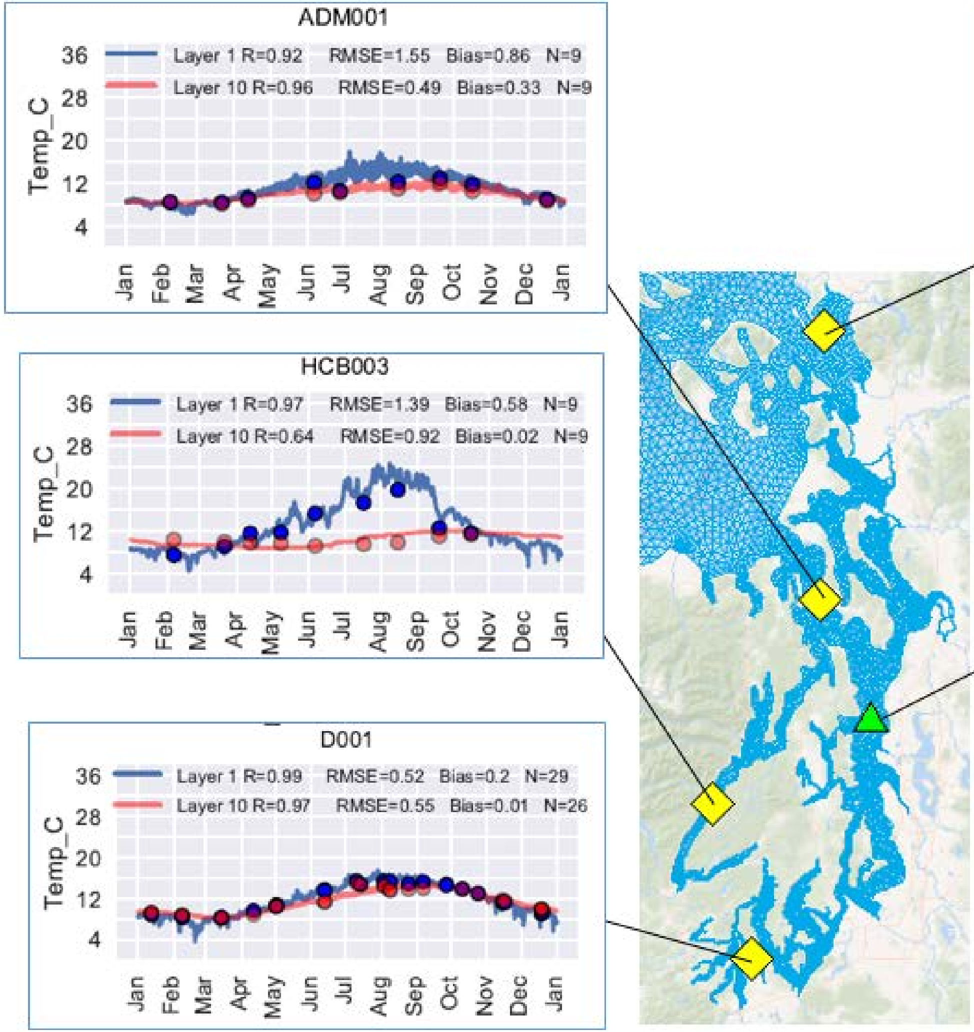


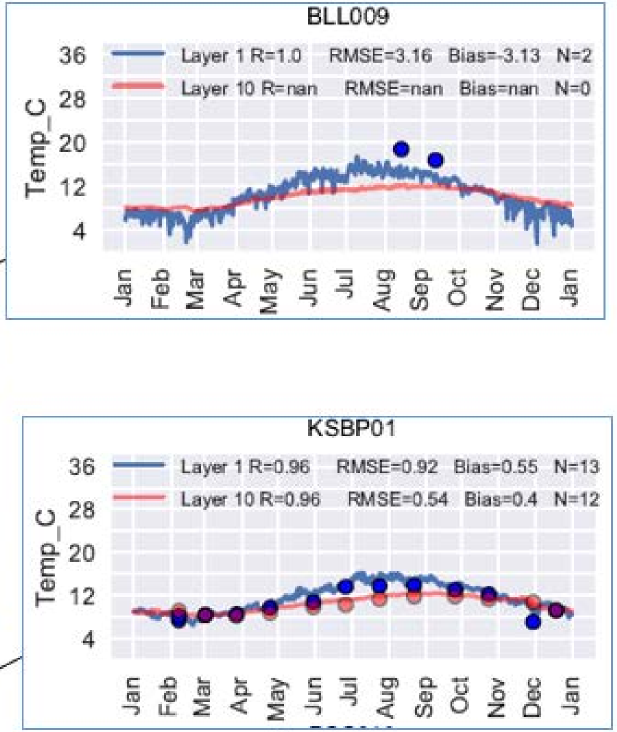
Model Performance for water surface elevations (RMSE as % tidal range):

Station	SSM-updated			SSM
	2014	2008	2006	2014, Khangaonkar et al. (2018)
Cherry Point	11.6	12.4	12.0	≤ 10
Friday Harbor	10.9	11.4	11.4	≤ 10
Port Angeles	6.8	7.5	7.3	≤ 10
Port Townsend	8.2	8.7	8.6	≤ 10
Seattle	8.0	8.5	8.5	≤ 10
Tacoma	8.6	8.8	8.9	≤ 10
Neah Bay	10.6	10.7	10.7	



Model performance (time-depth): Temperature

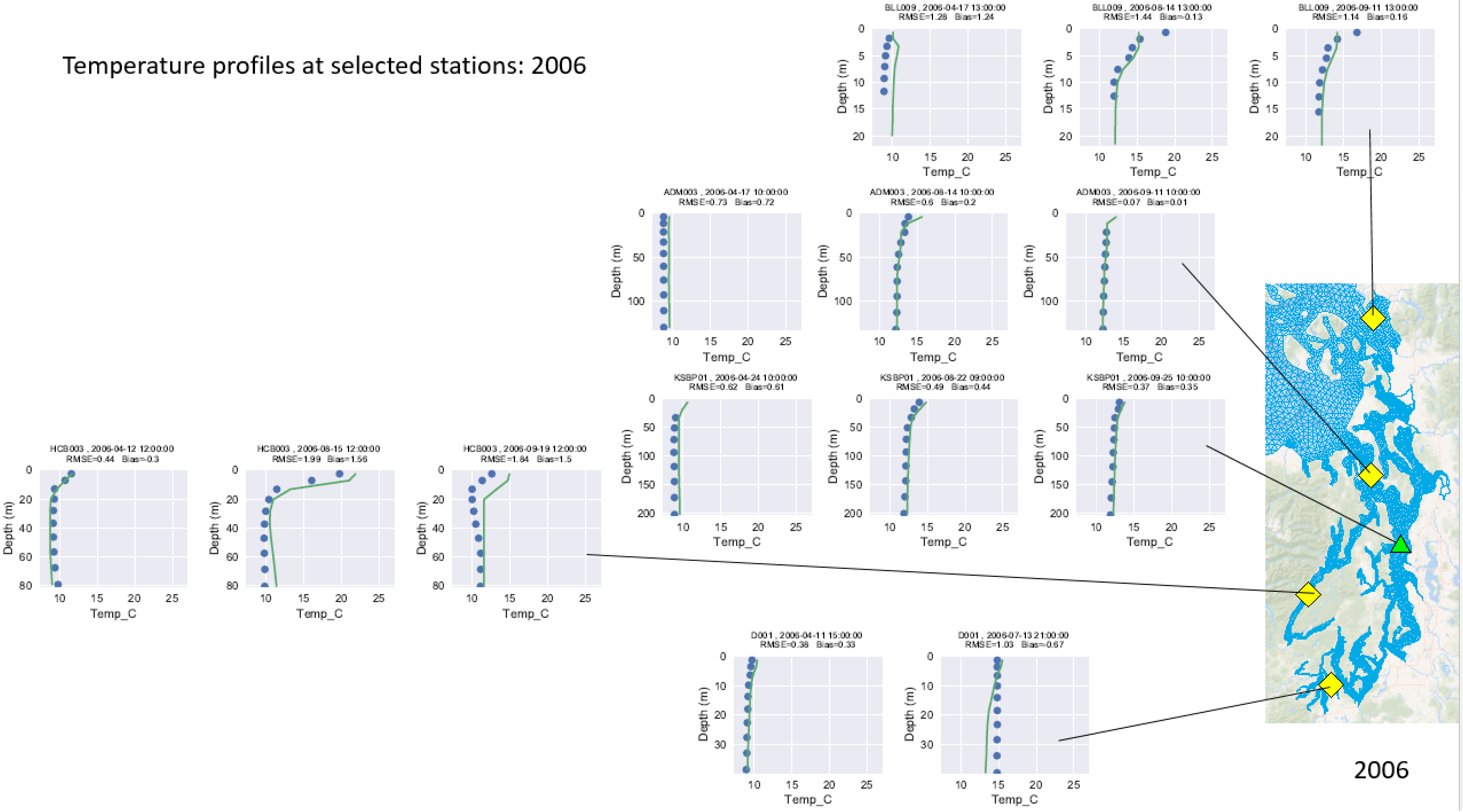


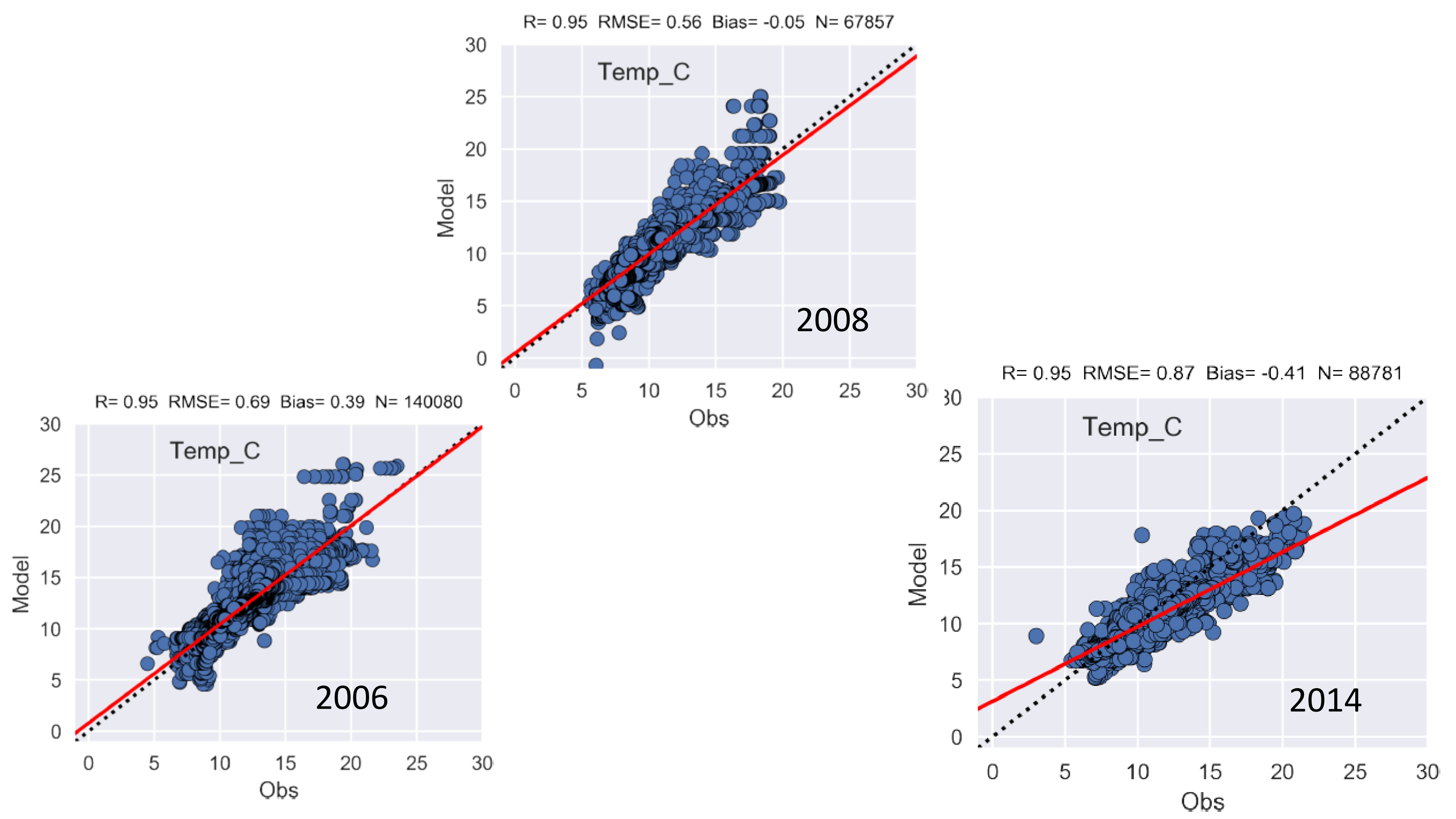


2006

Model performance (time-series): Temperature

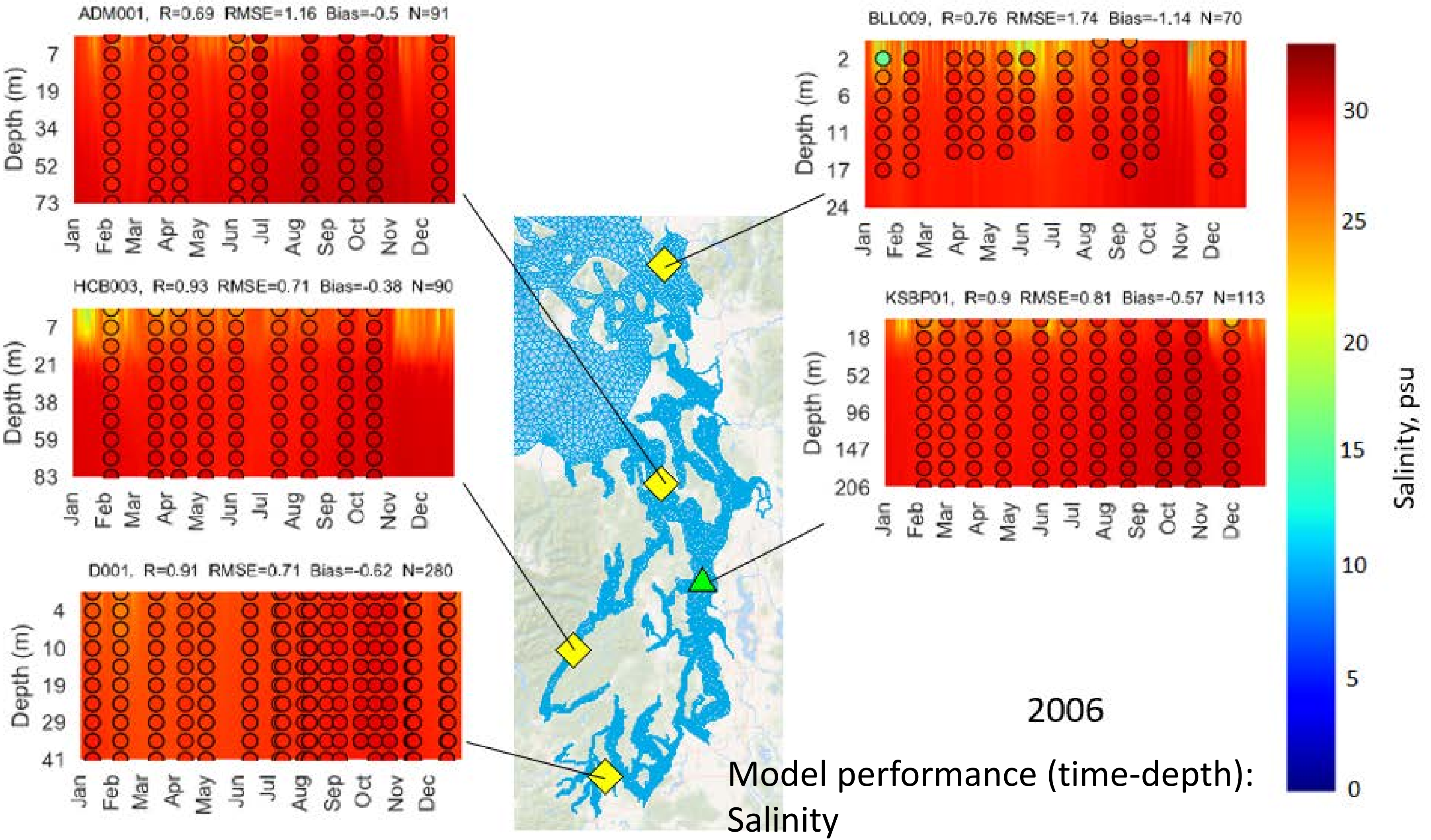
Temperature profiles at selected stations: 2006



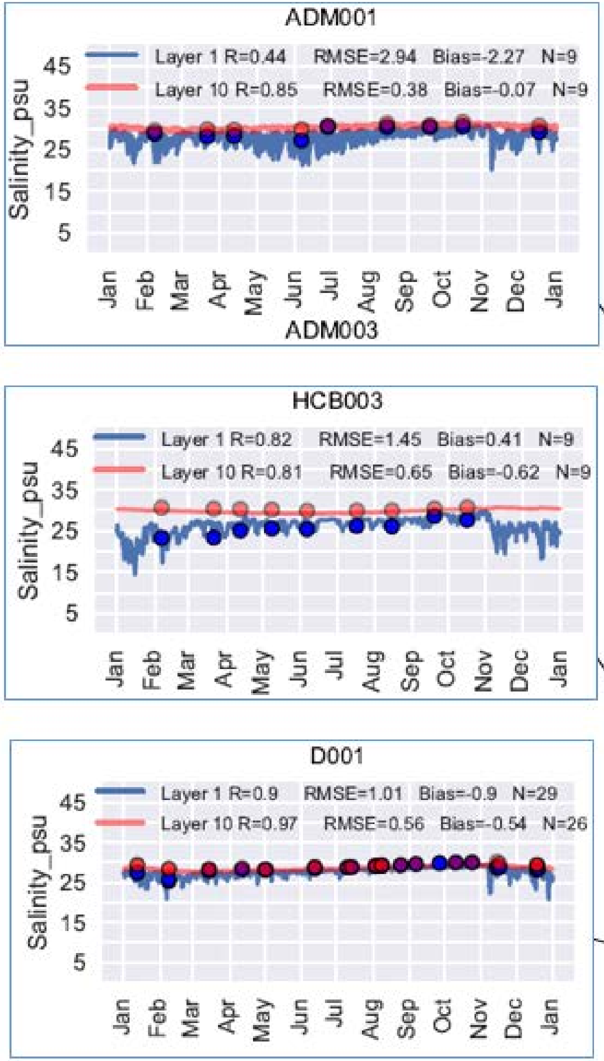

R= 0.95 RMSE= 0.56 Bias= -0.05 N= 67857
Temp_C
Model
Obs
2008
R= 0.95 RMSE= 0.69 Bias= 0.39 N= 140080
Temp_C
Model
Obs
2006
R= 0.95 RMSE= 0.87 Bias= -0.41 N= 88781
Temp_C
Model
Obs
2014

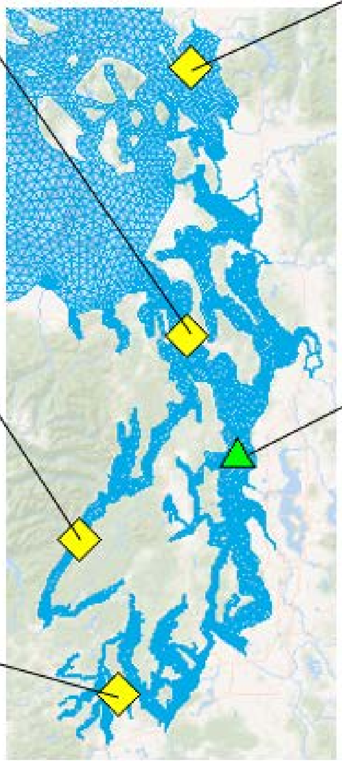
Model Performance for Temperature:

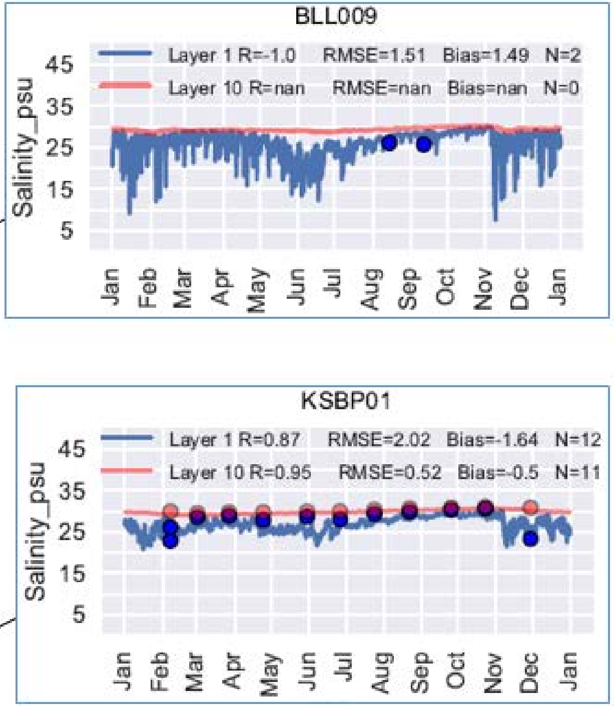
Temp (°C)					
Model Run	**R**	**RMSE**	**Bias**	**n**	**WSS**
2008 PSM (Bianucci et. al 2018)	0.90	1.48	1.28	67858	
2014 SSM (Khangaonkar et al. 2018)	0.93	0.76	-0.28	38218	0.96
2006 SSM_updates	0.95	0.69	0.39	140080	0.95
2008 SSM_updates	0.95	0.56	-0.05	67857	0.97
2014 SSM_updates	0.95	0.87	-0.41	89222	0.93



Model performance (time-depth): Salinity



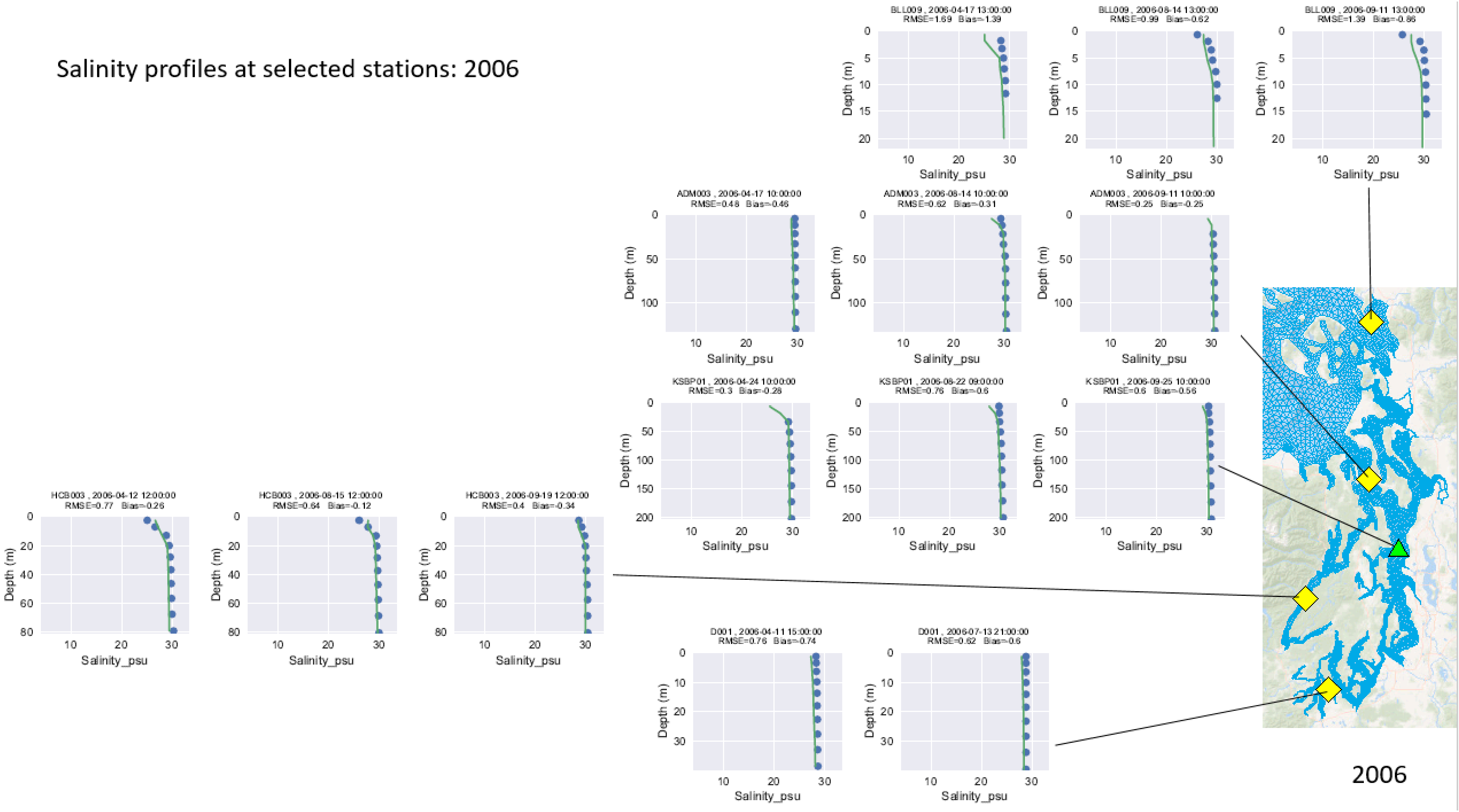


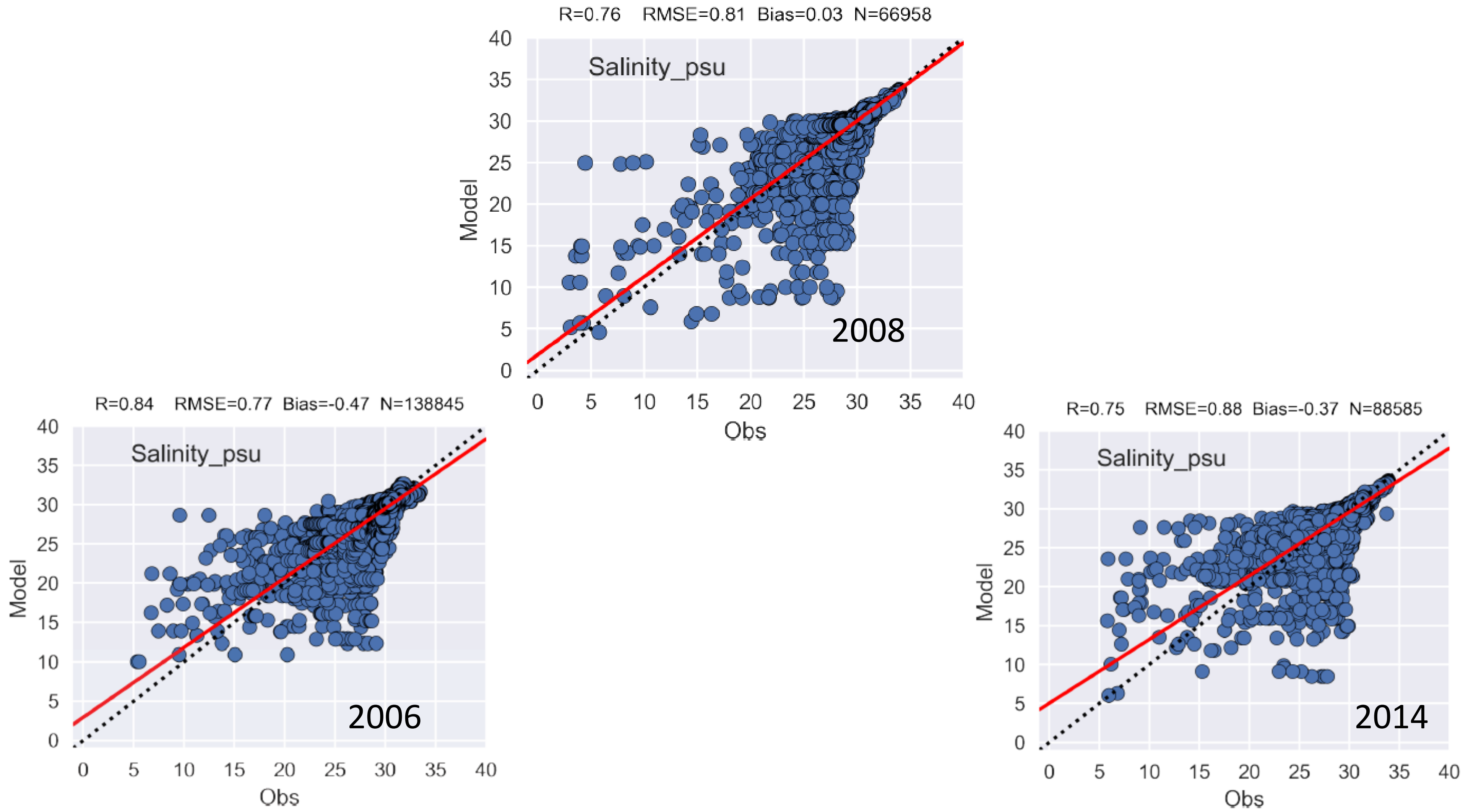


2006

Model performance (time-series): Salinity

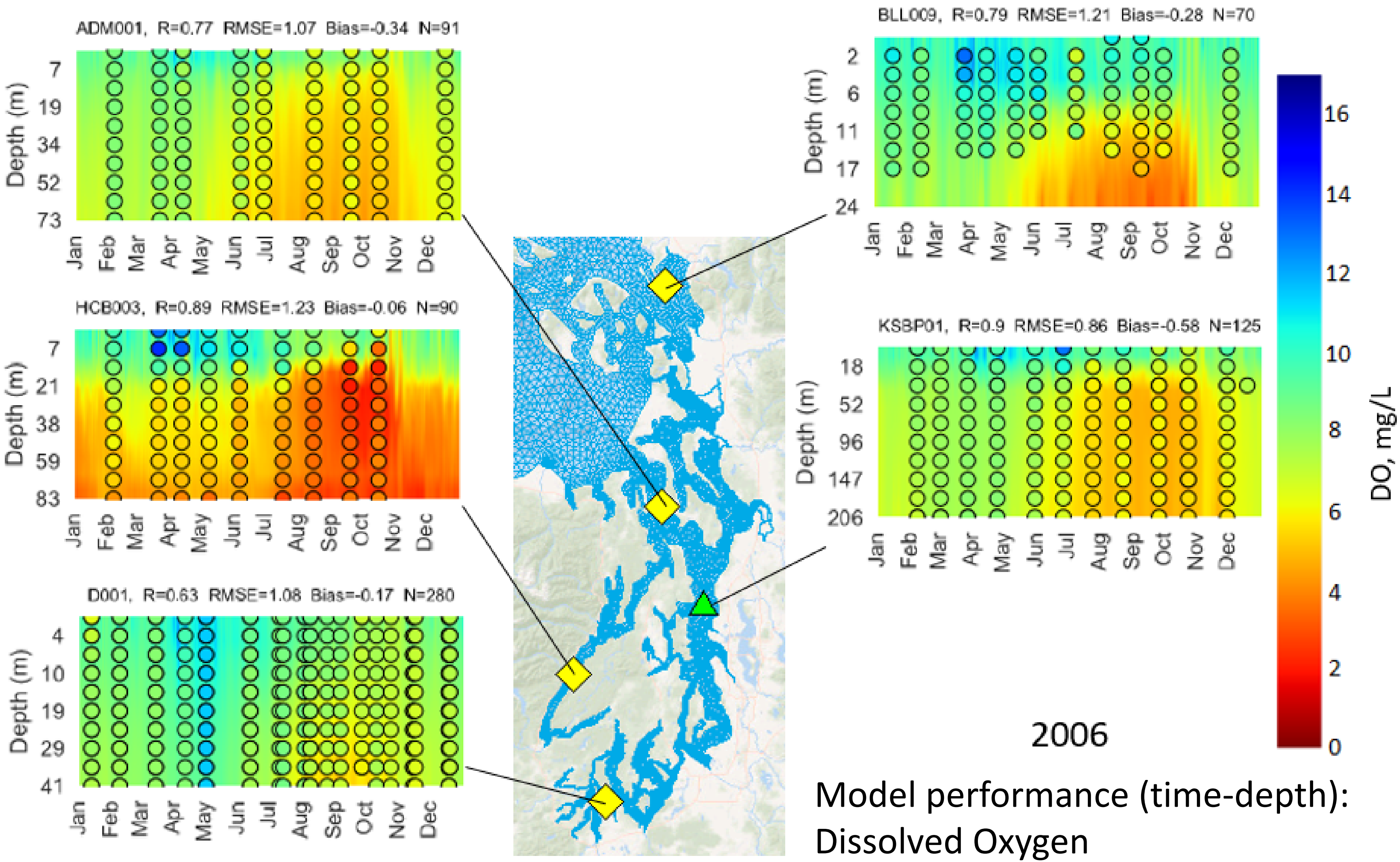
Salinity profiles at selected stations: 2006



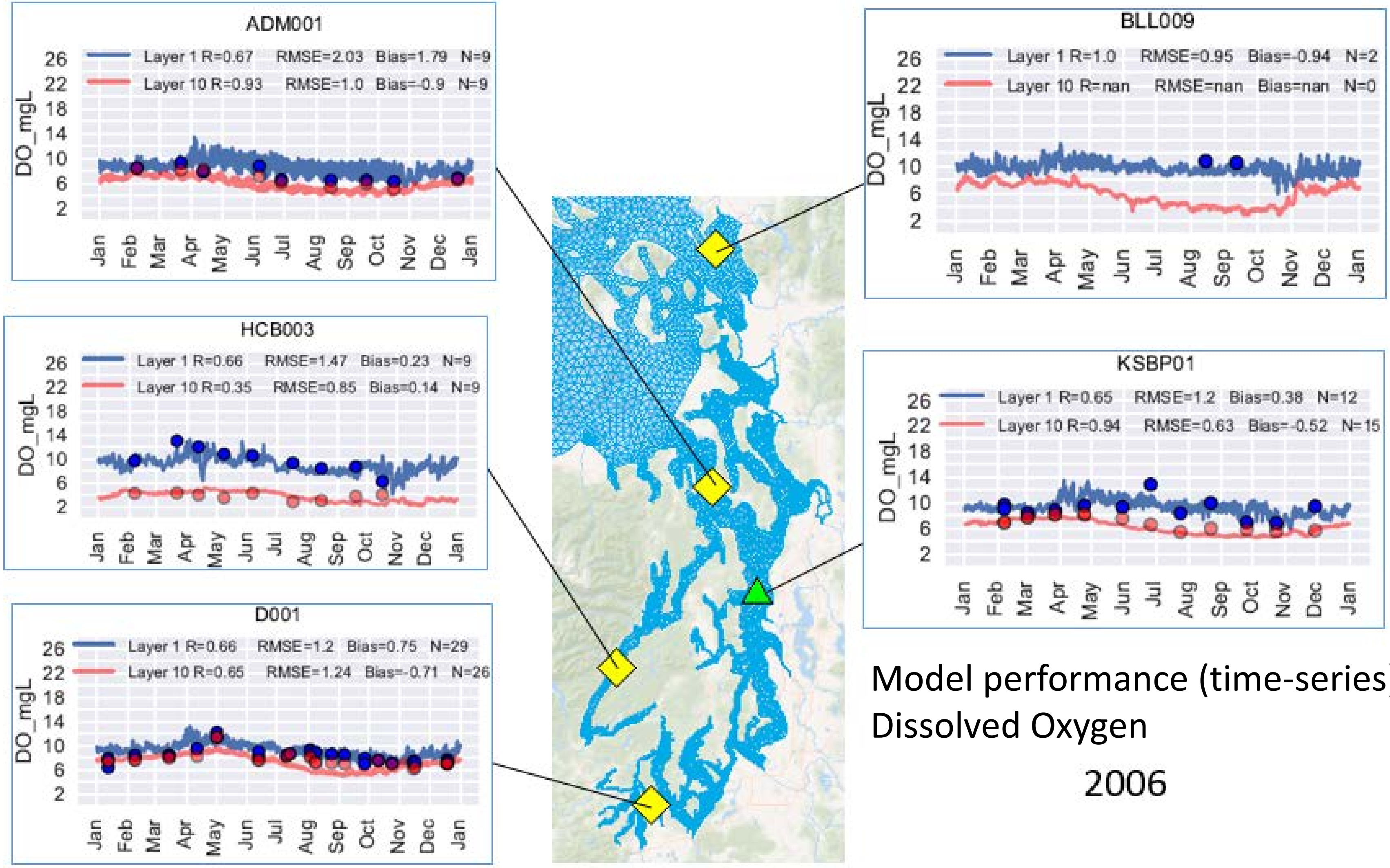

R=0.76 RMSE=0.81 Bias=0.03 N=66958
Salinity_psu
Model
Obs
2008
R=0.84 RMSE=0.77 Bias=-0.47 N=138845
Salinity_psu
Model
Obs
2006
R=0.75 RMSE=0.88 Bias=-0.37 N=88585
Salinity_psu
Model
Obs
2014

Model Performance for Salinity:

Salinity, psu					
Model Run	**R**	**RMSE**	**Bias**	**n**	**WSS**
2008 PSM (Bianucci et. al 2018)	0.61	1.33	-0.68	66934	
2014 SSM (Khangaonkar et al. 2018)	0.75	0.97	-0.12	38043	0.84
2006 SSM_updates	0.84	0.77	-0.47	138845	0.87
2008 SSM_updates	0.76	0.81	0.03	66958	0.86
2014 SSM_updates	0.75	0.88	-0.37	89025	0.83



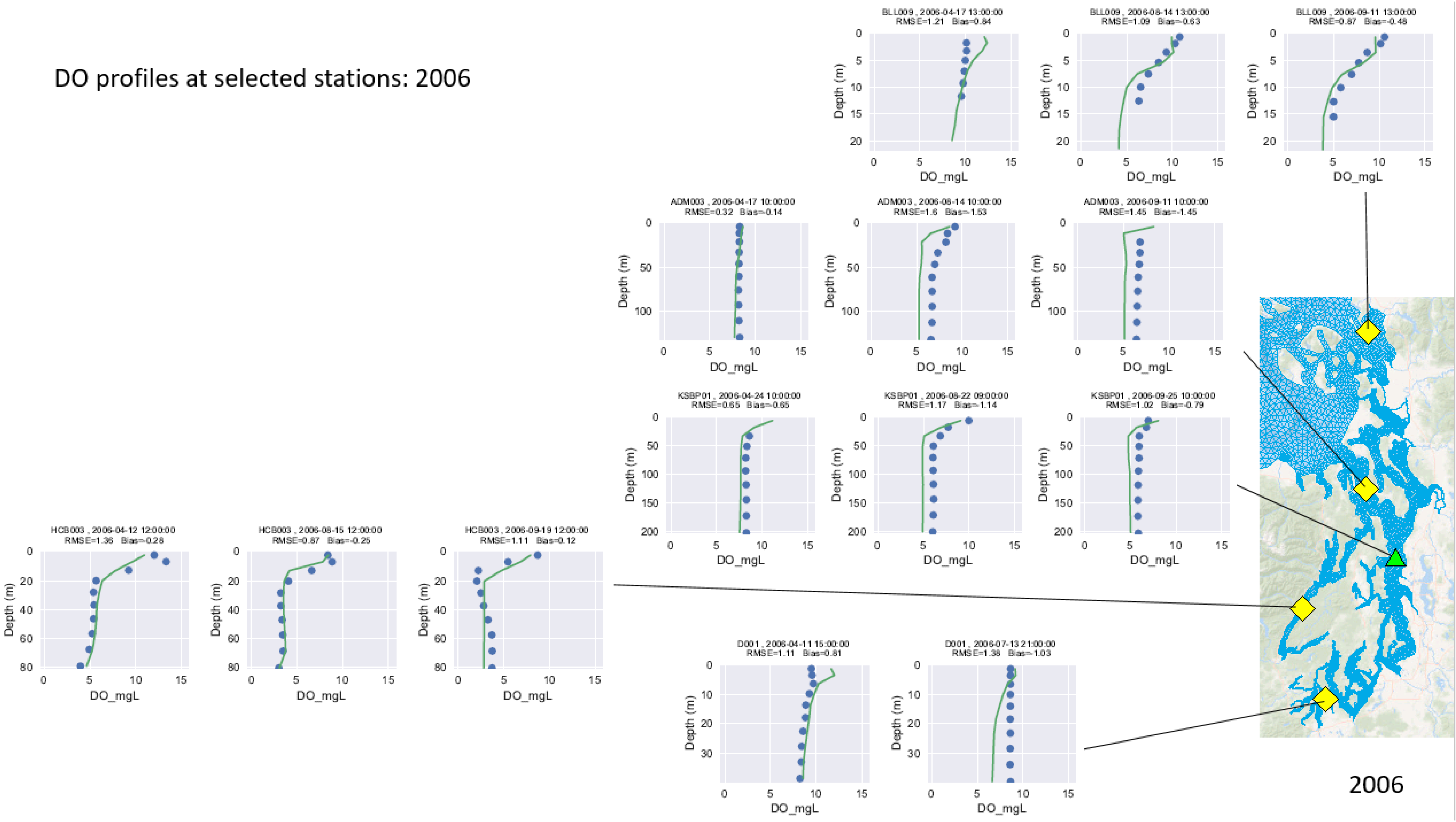
Model performance (time-depth): Dissolved Oxygen

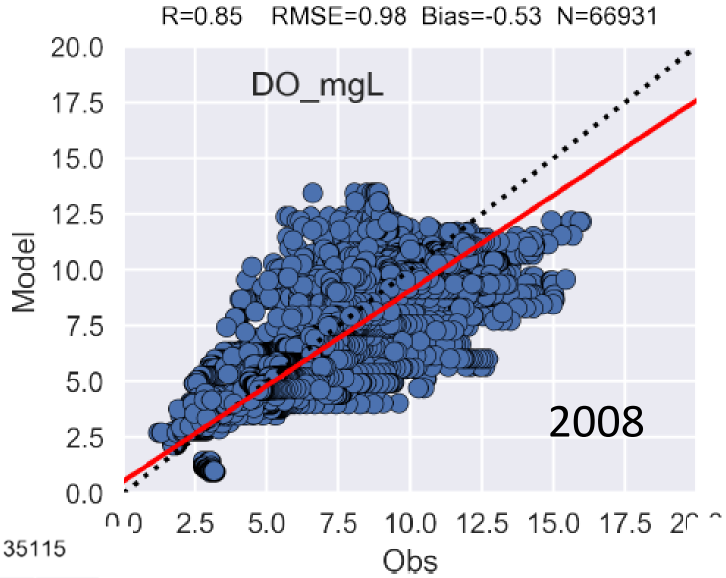


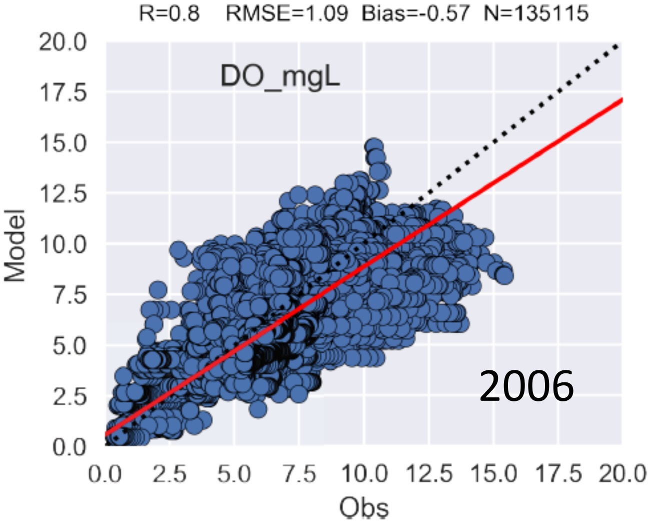
Model performance (time-series): Dissolved Oxygen

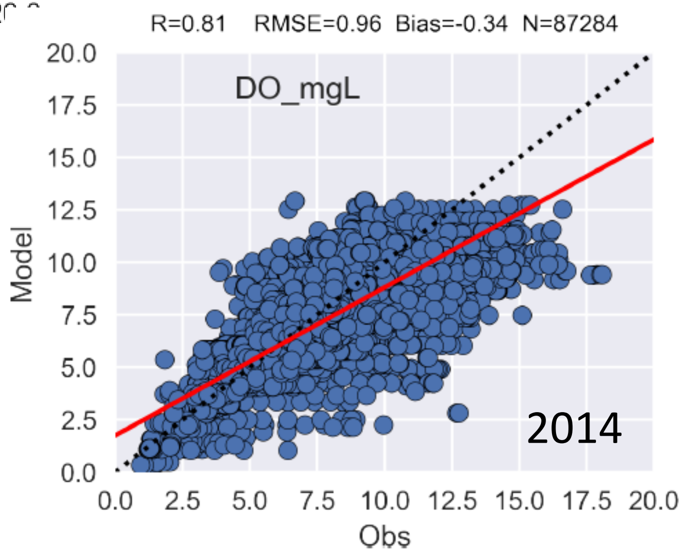
2006

DO profiles at selected stations: 2006




R=0.85 RMSE=0.98 Bias=-0.53 N=66931
DO_mgL
2008
Model
Obs


R=0.8 RMSE=1.09 Bias=-0.57 N=135115
DO_mgL
2006
Model
Obs


R=0.81 RMSE=0.96 Bias=-0.34 N=87284
DO_mgL
2014
Model
Obs

Model Performance for DO:

DO (mg/L)					
Model Run	**R**	**RMSE**	**Bias**	**n**	**WSS**
2008 PSM (Bianucci et. al 2018)	0.80	1.8	-1.56	66538	
2014 SSM (Khangaonkar et al. 2018)	0.83	0.99	-0.24	26082	0.90
2006 SSM_updates	0.80	1.09	-0.57	135115	0.89
2008 SSM_updates	0.85	0.98	-0.53	66931	0.89
2014 SSM_updates	0.81	0.96	-0.34	87725	0.88

Uncertainty of predicted DO is well within acceptable range

Updated SSM and Chesapeake Bay Model		
	Mean bias, mg/L	Correlation Coefficient
Salish Sea	-0.57 to -0.34	0.8 – 0.85
Chesapeake Bay	-0.52 to 0.775 *	See plot on right**

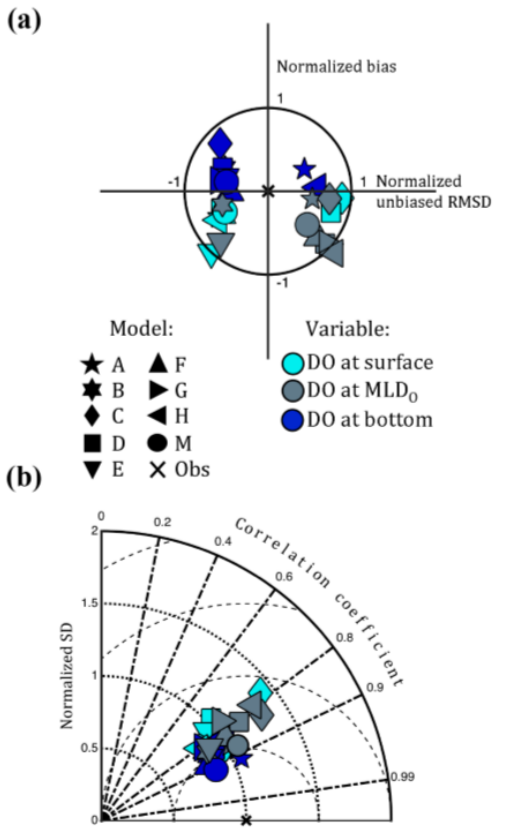


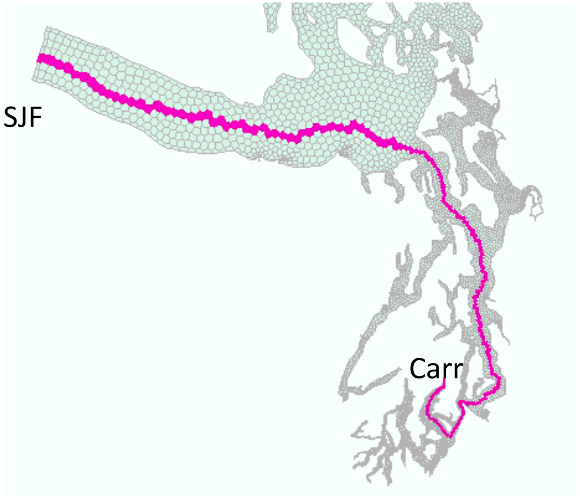
Figure 4. Normalized summary **(a)** target and **(b)** Taylor diagrams illustrating model skill of dissolved oxygen at the surface, MLD$_O$, and bottom for 13 Chesapeake Bay stations in 2004–2005. The "**x**" represents the skill of a model that perfectly reproduces the observations. The dotted, dashed-dot, and dashed lines on the Taylor diagram represent lines of constant standard deviation, correlation coefficient, and unbiased RMSD, respectively.

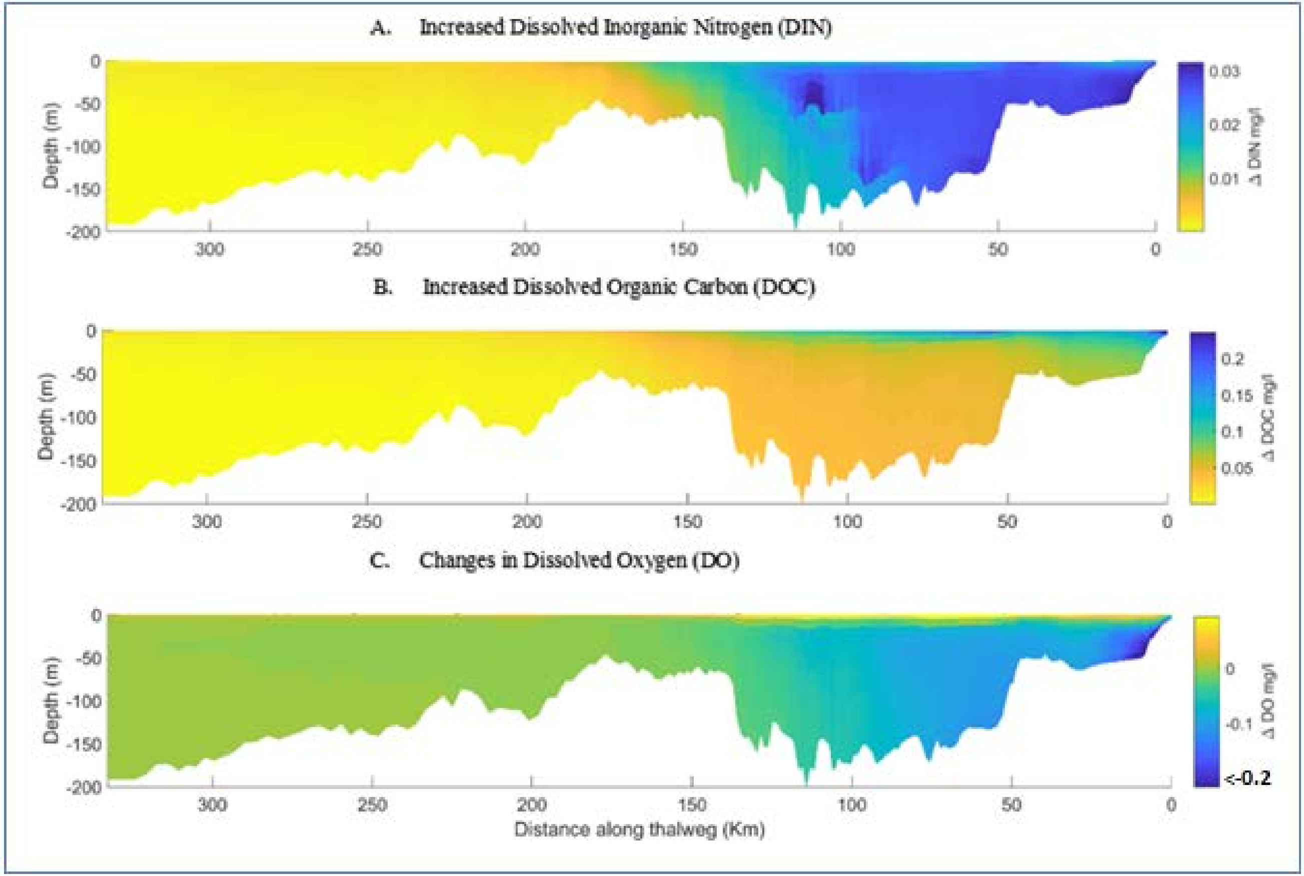
* Cerco and Noel. 2013. Twenty-one-year simulation of Chesapeake Bay Water Quality Using the CE-QUAL-ICM Eutrophication Model. JAWRA. Vol 40. Issue 5. pp:1119-1133

** Irby et al. 2016. Challenges associated with modeling low-oxygen waters in Chesapeake Bay: a multiple model comparison. Biogeosciences. 13, 2011–2028.

Chla (ug/L)					
Model Run	**R**	**RMSE**	**Bias**	**n**	**WSS**
2008 PSM (Bianucci et. al 2018)	0.50	2.8	-0.3	66041	
2014 SSM (Khangaonkar et al. 2018)	0.54	4.4	0.83	26940	0.69
2006 SSM_updates	0.45	4.5	0.23	64442	0.59
2008 SSM_updates	0.49	3.1	0.33	66941	0.66
2014 SSM_updates	0.52	3.5	-0.125	89338	0.67

NO3 (mg/L)					
Model Run	**R**	**RMSE**	**Bias**	**n**	**WSS**
2008 PSM (Bianucci et. al 2018)	0.80	0.08	-0.001	1902	
2014 SSM (Khangaonkar et al. 2018)	0.82	0.09	0.013	1187	0.9
2006 SSM_updates	0.81	0.07	-0.01	678	0.84
2008 SSM_updates	0.80	0.09	-0.04	1381	0.85
2014 SSM_updates	0.84	0.07	-0.003	1489	0.91





Annual Average Transect plots: 2006

How DO standard exceedances are evaluated with the model

Tier 1

Reference condition = 8 mg/L

DO std (7 mg/L)

DO exceedance = depletion below std. = 1 mg/L

Existing = 6 mg/L

Tier 2

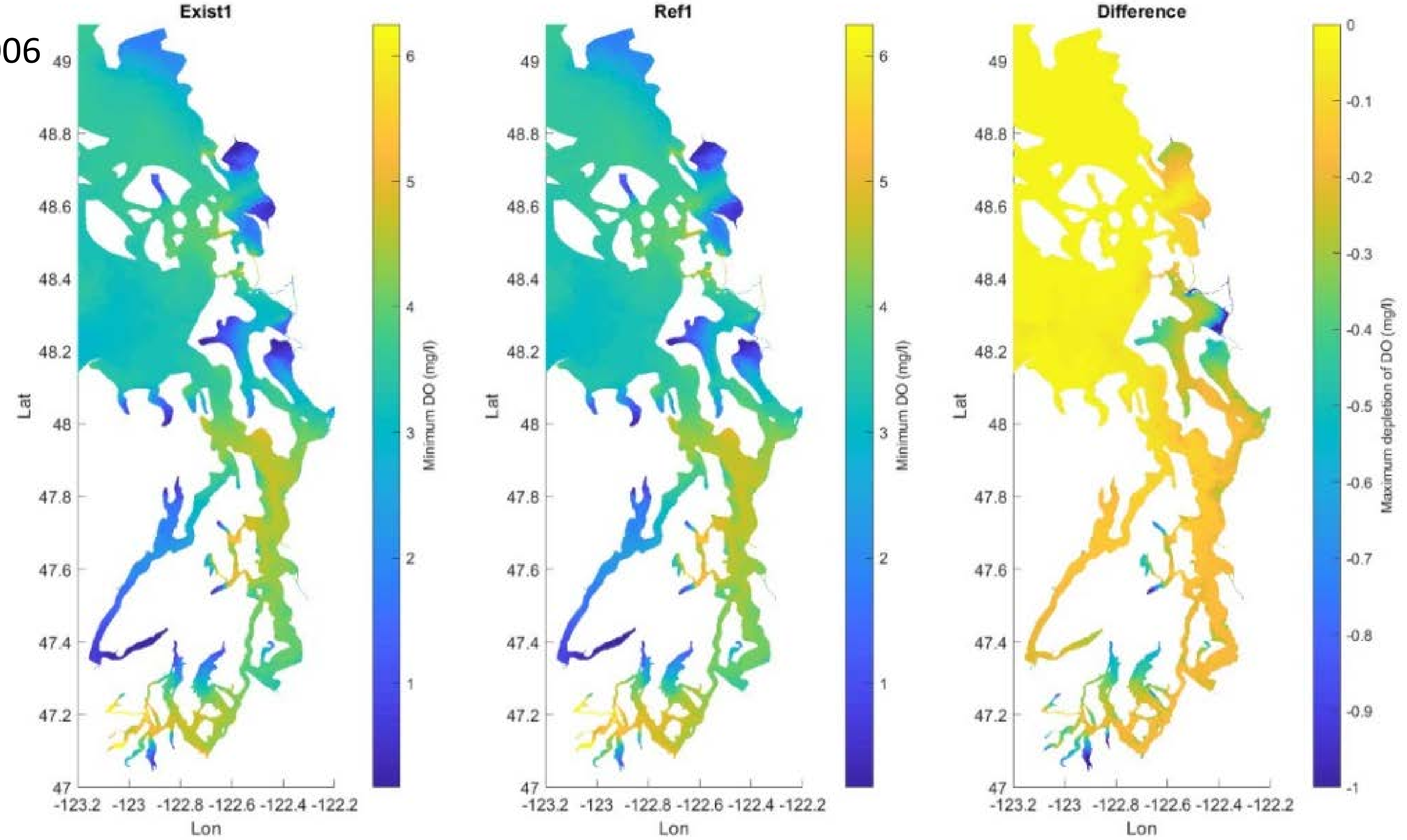
DO std(7 mg/L)

Reference condition = 6 mg/L

DO exceedance = depletion below reference of > 0.2 = 0

Existing = 5.8 mg/L

2006



Exist1
Ref1
Difference
Minimum DO (mg/l)
Maximum depletion of DO (mg/l)
Lat
Lon
49
48.8
48.6
48.4
48.2
48
47.8
47.6
47.4
47.2
47
-123.2 -123 -122.8 -122.6 -122.4 -122.2
6
5
4
3
2
1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
-0.8
-0.9
-1

Uncertainty in DO difference (i.e. delta DO) estimates

[a] $RMSE_{diff} = \sqrt{RMSE^2_{exist} + RMSE^2_{ref} - 2 * R * RMSE_{exist} + RMSE_{ref}}$

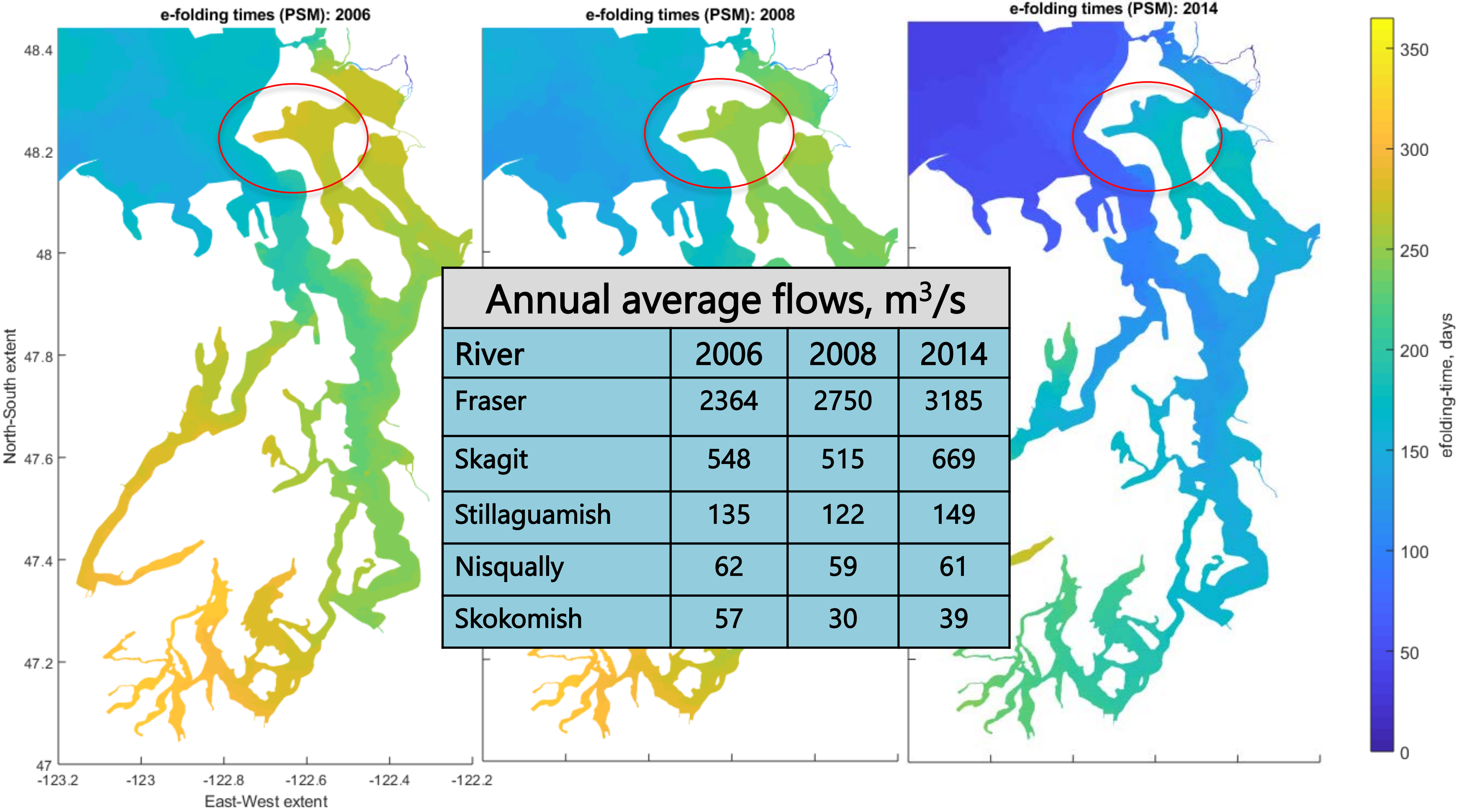
Assumption: $RMSE_{exist} = RMSE_{ref}$

R = Pearson's correlation coefficient between existing and reference conditions

	RMSE of existing and reference	RMSE of difference
2008	0.98	0.03
2006	1.09	0.05
2014	0.96	0.04

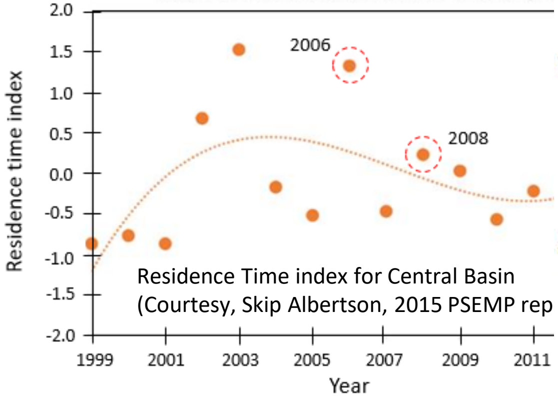
[a] Snedecor, G. and Cochran, W. (1989) Statistical Methods. Eighth Edition Iowa State University Press

PSM: residence times

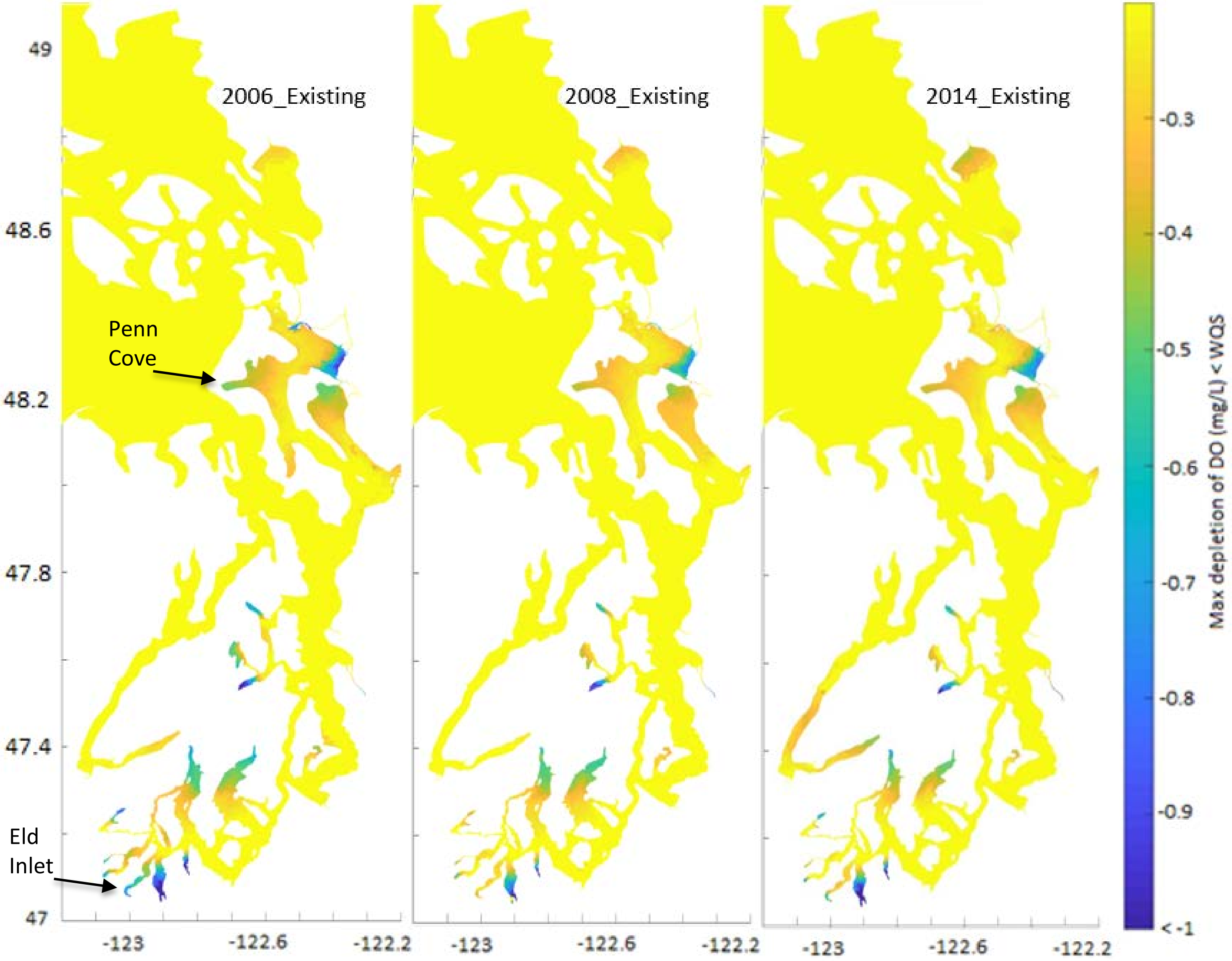


Annual average flows, m^3/s			
River	2006	2008	2014
Fraser	2364	2750	3185
Skagit	548	515	669
Stillaguamish	135	122	149
Nisqually	62	59	61
Skokomish	57	30	39

Inter annual variability

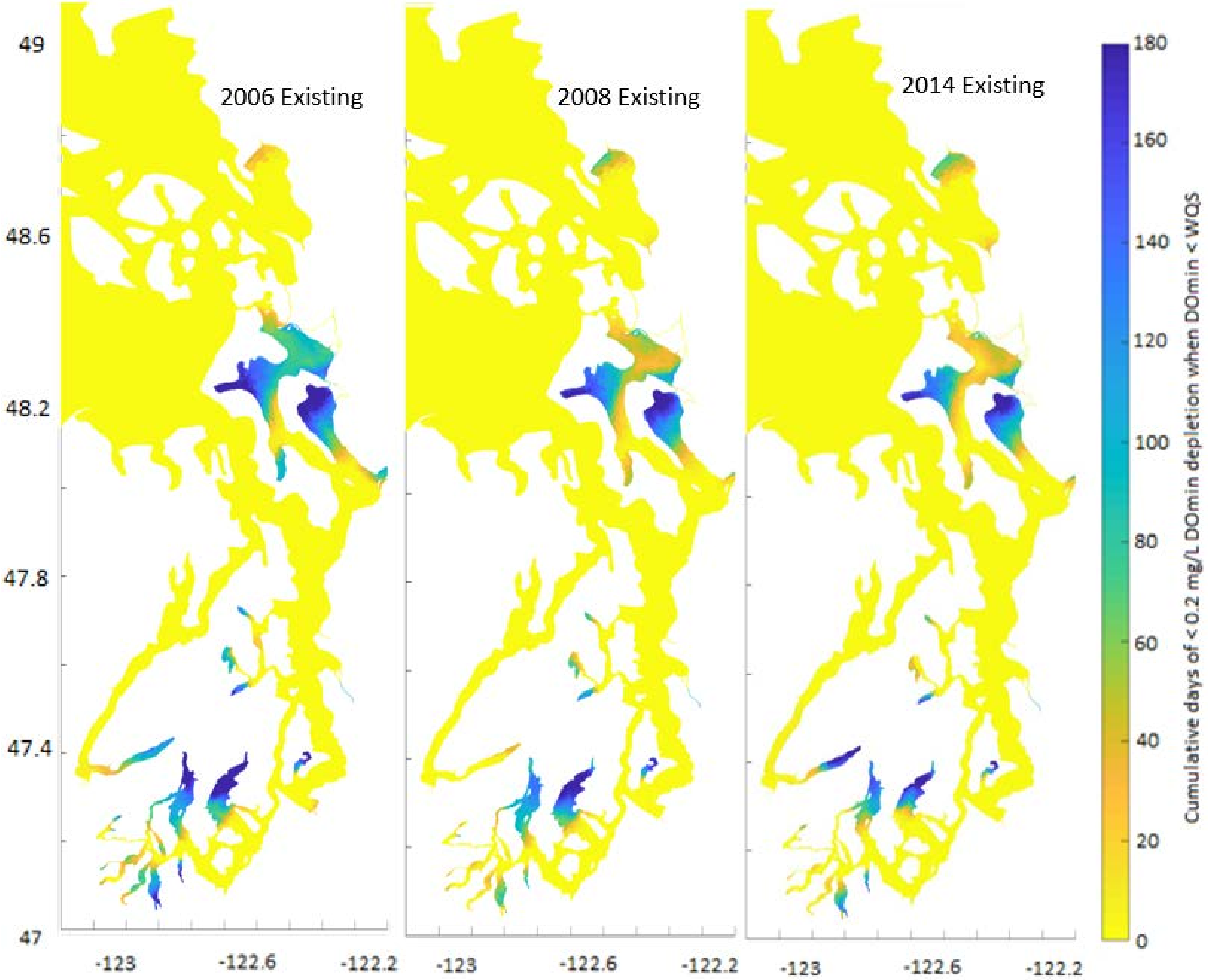


Residence Time index for Central Basin (Courtesy, Skip Albertson, 2015 PSEMP rep



Inter-annual variability

Cumulative Duration of Exceedances



Application of Salish Sea Model:

Inform **the** Puget Sound Nutrient Reduction Project (PSNRP), led by Dustin Bilhimer (WQP)

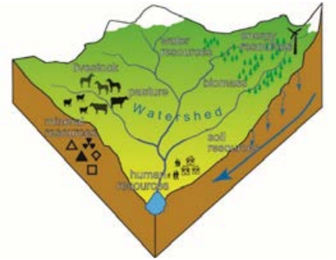
DO improvement through Anthropogenic Nutrient Reduction Strategies

Bounding Scenarios

- What is the maximum improvement in DO with BNR at WWTPs?
- What is the maximum improvement in DO from nutrient reductions in watersheds?

Strategic Scenarios through collaborative process

- Impact of BNR at selected WWTPs?
- Impact of different nutrient reduction levels in watersheds?
- Combination of BNR and watershed reductions?



Application of Salish Sea Model

Bounding scenario: What if WWTP had BNR?

BNR levels for ammonia and nitrate set by Puget Sound WWTP report (2011)*

- Use only dry weather treatment (April – Oct)
- DIN (ammonia + nitrate) = 8 mg/L (NH_3 = 0.25 mg/L, NO_3 = 7.75 mg/L)
- $CBOD_5$ = 8 mg/L

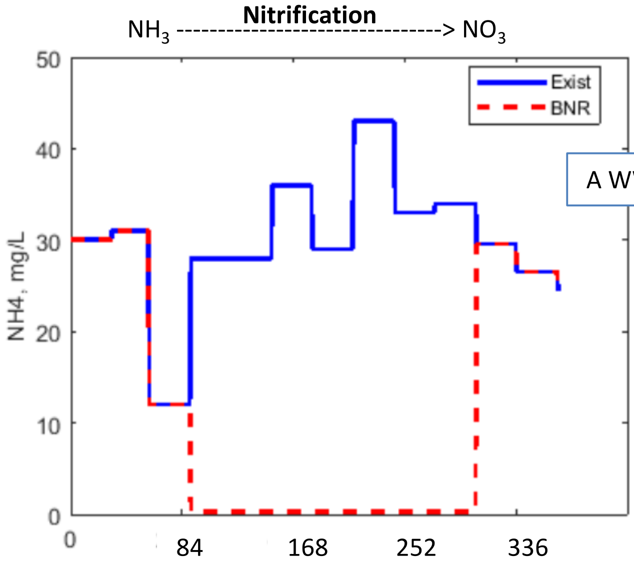
LOTT has already achieved levels of DIN = 3 mg/L BOD_5 = 8 mg/L during this period

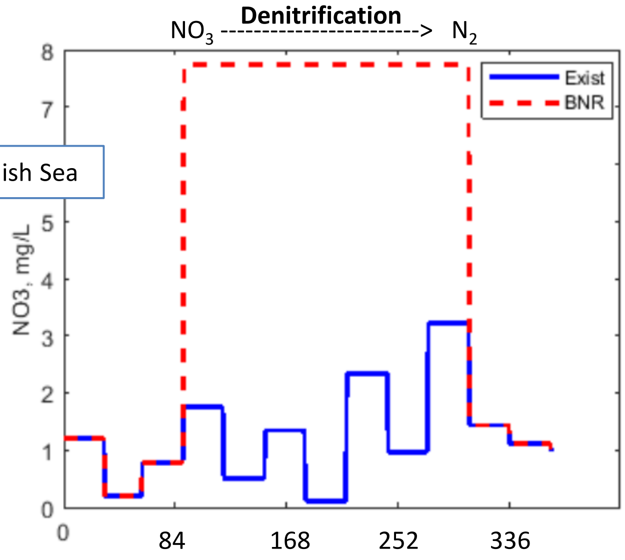
* TetraTech 2011. Technical and Economic Evaluation of Nitrogen and Phosphorus Removal at Municipal Wastewater Treatment Facilities in Washington State. Ecology Publication Number 11-10-060

Application of Salish Sea Model

A WWTP in Salish Sea

Bounding scenario: WWTP at BNR?



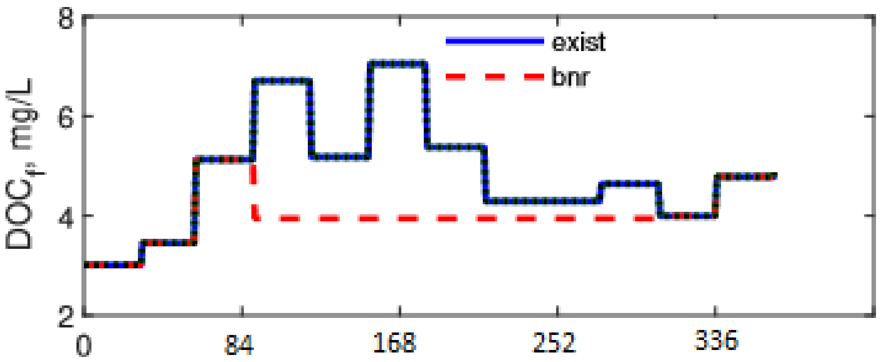


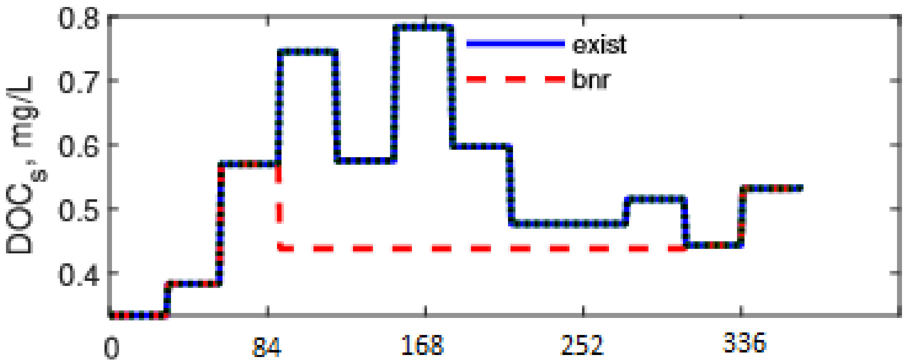
Application of Salish Sea Model

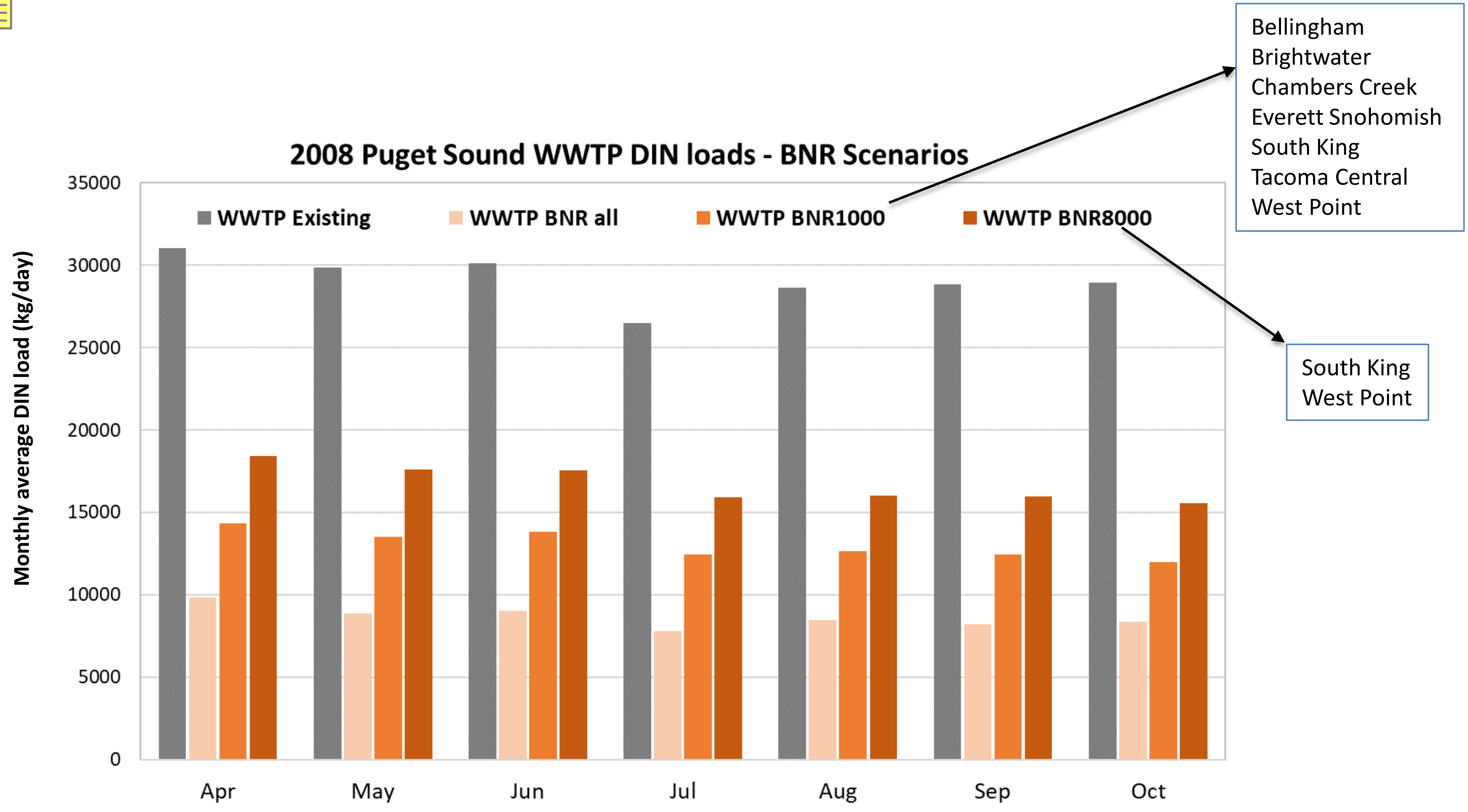
BOD5 target under advanced treatment scenario of 8 mg/L

Convert BOD5 to DOC:

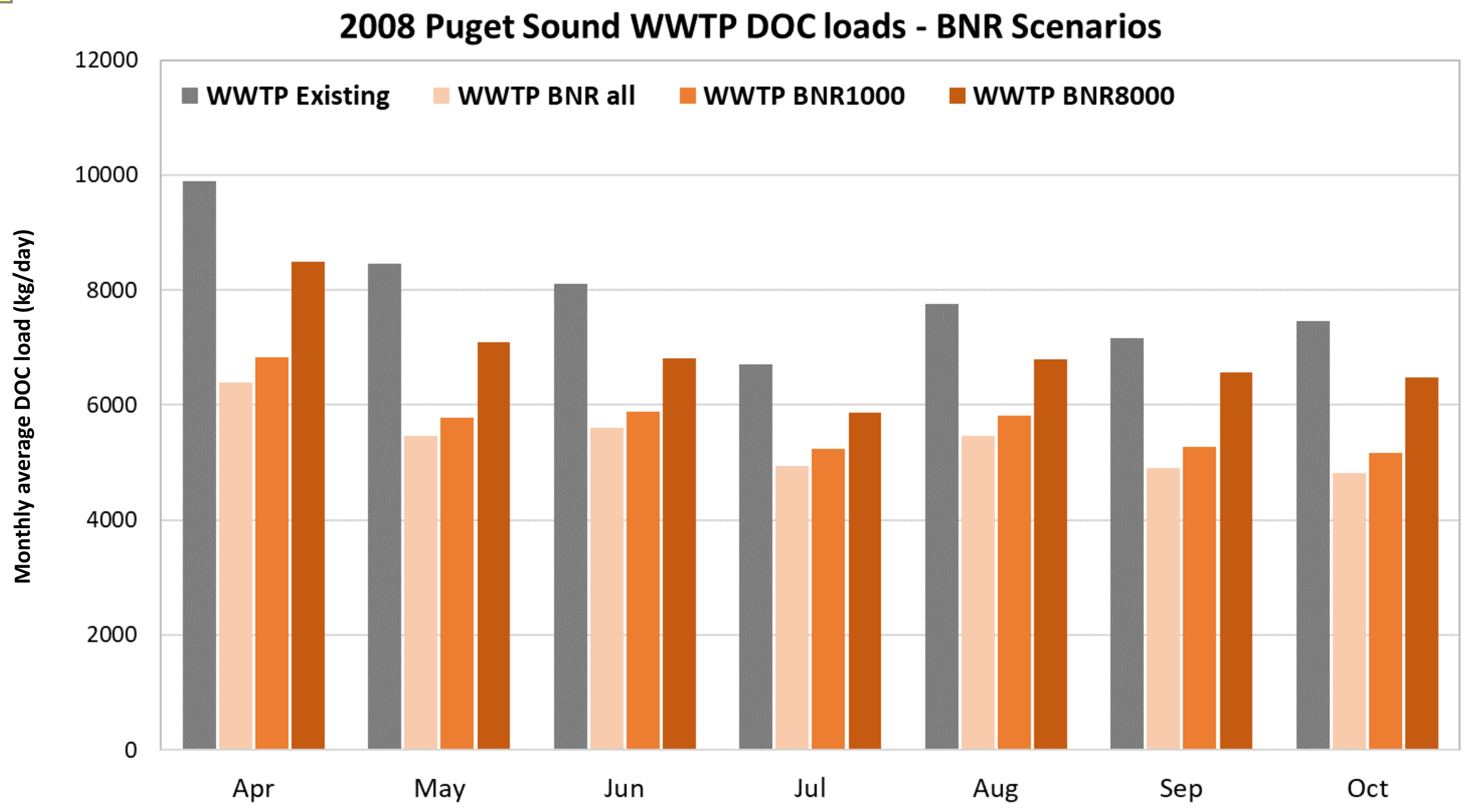
1. Convert BOD5 to ultimate BOD: BOD5= BODu $(1\text{-}e^{kt})$
2. Convert BODu to carbon = BODu/2.67







2008 Puget Sound WWTP DIN loads - BNR Scenarios
WWTP Existing
WWTP BNR all
WWTP BNR1000
WWTP BNR8000
Monthly average DIN load (kg/day)
35000
30000
25000
20000
15000
10000
5000
0
Apr
May
Jun
Jul
Aug
Sep
Oct
Bellingham
Brightwater
Chambers Creek
Everett Snohomish
South King
Tacoma Central
West Point
South King
West Point


2008 Puget Sound WWTP DOC loads - BNR Scenarios
WWTP Existing
WWTP BNR all
WWTP BNR1000
WWTP BNR8000
Monthly average DOC load (kg/day)
12000
10000
8000
6000
4000
2000
0
Apr
May
Jun
Jul
Aug
Sep
Oct

Next Steps

- **2018 report: Bounding Scenarios…** potential improvement in DO from global anthropogenic nutrient reductions
- **Optimization model runs for PSNRP – Spring 2019 – Spring 2021**
- **Additional monitoring – some funding dependent**
    - Freshwater monitoring - continuous monitoring of nitrate/nitrite at a few major Puget Sound rivers and monitoring for organic N and organic C during specific rain events
    - Marine monitoring – particulate and total organic carbon, alkalinity and DIC, respiration rates
    - Sediment monitoring – measurement of biogeochemical fluxes, already begun as a pilot
- **Future Scenarios (also funding dependent) –** updating future nutrient loading estimates under climate change and population growth

Questions?

For more information:

Ecology webpage for the Salish Sea Model: https://ecology.wa.gov/Research-Data/Data-resources/Models-spreadsheets/Modeling-the-environment/Salish-Sea-modeling (includes links to all model related publications)

Pacific Northwest National Laboratory webpage for the Salish Sea Model: https://salish-sea.pnnl.gov/

Reducing nutrients in Puget Sound: https://ecology.wa.gov/Water-Shorelines/Puget-Sound/Helping-Puget-Sound/Reducing-Puget-Sound-nutrients

Nitrogen in Puget Sound - A Story Map:
https://waecy.maps.arcgis.com/apps/MapSeries/index.html?appid=907dd54271f44aa0b1f08efd7efc4e30

DEPARTMENT OF ECOLOGY
State of Washington