Salish Sea Model Refresher

Puget Sound Nutrient Source Reduction Project

March 9, 2021

Puget Sound Nutrient Forum

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

DEPARTMENT OF ECOLOGY
State of Washington

Contributors – thank you!

Data, Monitoring Tools, and Observations

Ecology's Marine Monitoring Unit – data received from Mya Keyzers, Julia Bos, Skip Albertson, Carol Maloy, Christopher Krembs
http://www.ecy.wa.gov/programs/eap/mar_wat/index.html

Ecology's Freshwater Monitoring Unit – Marcus Von Prause, Dave Hallock, Bill Ward
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 (affiliation at time of peer review)

Bob Ambrose, Ben Cope - U.S. Environmental Protection Agency

Stephanie Jaeger, Randy Shuman - King County

Tarang Khangaonkar, PNNL & SSMC

Christopher Krembs, Tom Gries, Will Hobbs, Dustin Bilhimer, Nuri Mathieu, Skip Albertson, Sandy Weakland - Washington Department of Ecology

Parker MacCready - University of Washington

Brian Rappoli - Ocean and Coastal Acidification and Coral Reef Protection Program, U.S. Environmental

Samantha Siedlecki - Joint Institute for the Study of the Atmosphere and Ocean, University of Washington

Funding & In-kind Contributions

Framework Development

Pacific Northwest National Laboratory /SSMC

Washington State Department of Ecology

United States Environmental Protection Agency

Individual Project Applications

National Estuarine Program

Nature Conservancy

National Oceanic and Atmospheric Administration

NW Straits Commission

Skagit River System Cooperative

Skagit Watershed Council

Tulalip Tribe

U.S. Army Corps of Engineers

Additional Support

Pacific Northwest National Laboratory (PIC) program: http://pic.pnnl.gov/

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

Salish Sea Model Publications

29 peer-reviewed papers and technical reports

Puget Sound Dissolved Oxygen Model (PSM) Versions:
PSM0 PSM1 PSM2

Salish Sea Model (SSM) Versions:
SSM0 SSM2

QAPP PSDOM Intermediate-scale Model Development
QAPP PSDOM Large-scale Model Development
(Sackman et al, 2009)

2010

PSDOM Study: Development of an Intermediate-scale Hydrodynamic Model
(Yang et al, 2010)

QAPP Addendum: Intermediate-scale Model Development
(Sackman et al, 2011)

Tidally Averaged Circulation in Puget Sound Subbasins
(Khangaonkar et al, 2011)

PSDOM Nutrient Load Summary for 1999-2008
(Mohamedali et al, 2011)

2012

PSDOM Development of an Intermediate-scale Water Quality Model
(Khangaonkar et al, 2012)

Simulation of Annual Biogeochemical Cyclces of Nutrient Balance, Phytoplankton Blooms, and DO in Puget Sound
(Khangaonkar et al, 2012)

DO Model Scnarios: Impacts of Current and Future Nitrogen Sources and Climate Change through 2070
(Roberts et al, 2014)

2014

Approach for Simulating Acidification and the Carbon Cycle in the Salish Sea
(Long et al, 2014)

QAPP Salish Sea DO Modeling Approach: Sediment-Water Interactions
(Roberts et al, 2015)

QAPP Salish Sea Acidification Model Development
(Roberts et al, 2015)

2016

Salish Sea Model: Sediment Diagenesis Module
(Pelletier et al, 2017)

Salish Sea Model: Ocean Acidification Module
(Pelletier et al, 2017)

Assessment of Circulation and Inter-basin Transport in the Salish Sea including Johnstone Strait and Discovery Island Pathways
(Khangaonkar et al, 2017)

2018

QAPP Salish Sea Model Applications
(McCarthy et al, 2018)

Sensitivity of the Regional Ocean Acidification and the Carbonate System in Puget Sound to Ocean and Freshwater Inputs
(Bianucci et al, 2018)

Analysis of Hypoxia and Sensitivity to Nutrient Pollution in Salish Sea
(Khangaonkar et al, 2018)

Puget Sound Nutrient Source Reduction Project Volume 1: Model Updates & Bounding Scenarios
(Ahmed et al, 2019)

Salish Sea Response to Global Climate Change, Sea Level Rise, and Future Nutrient Loads
(Khangaonkar et al, 2019)

Modeling QAPP for Salish Sea Model - Continuing Development of New Capabilities and Applications: Development of a Toxics Module Using PCBs
(Khangaonkar and Premathilake, 2019)

2020

Suspect and Nontarget Screening for Contaminants of Emerging Concern in an Urban Estuary
(Tian et al, 2020)

Puget Sound Nutrient Source Reduction Project Technical Memorandum: Optimization Scenarios
(Ahmed et al, 2021)

Evaluating Exposures of Bay Mussels to Contaminants of Emerging Concern through Environmental Sampling and Hydrodynamic Modeling
(James et al, 2020)

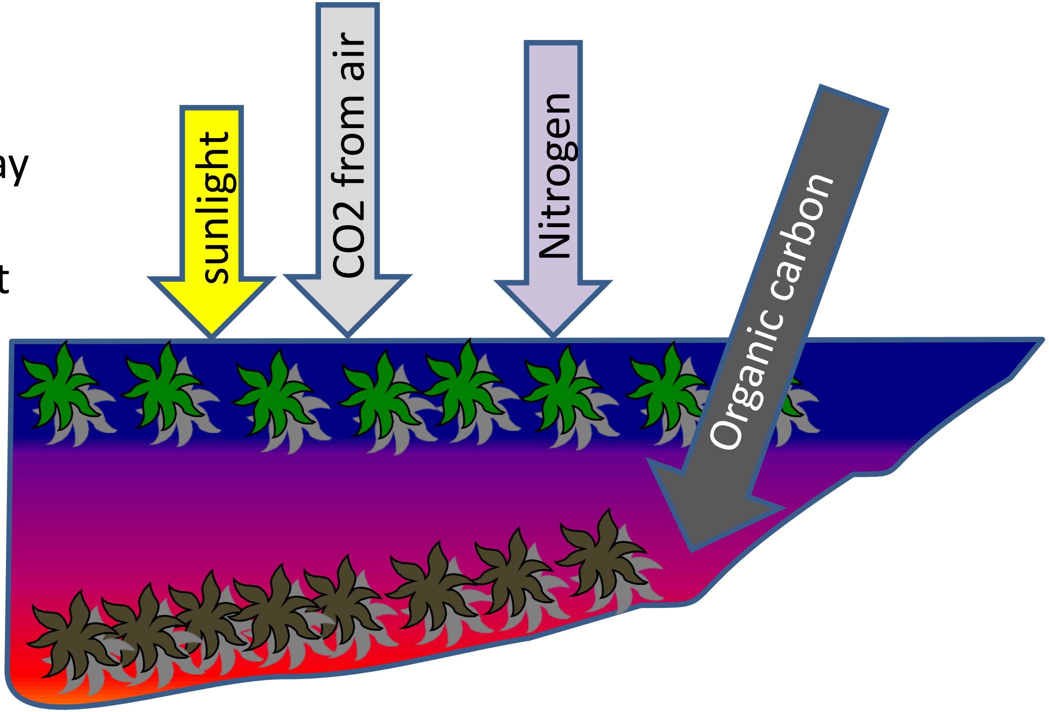
Salish Sea Model

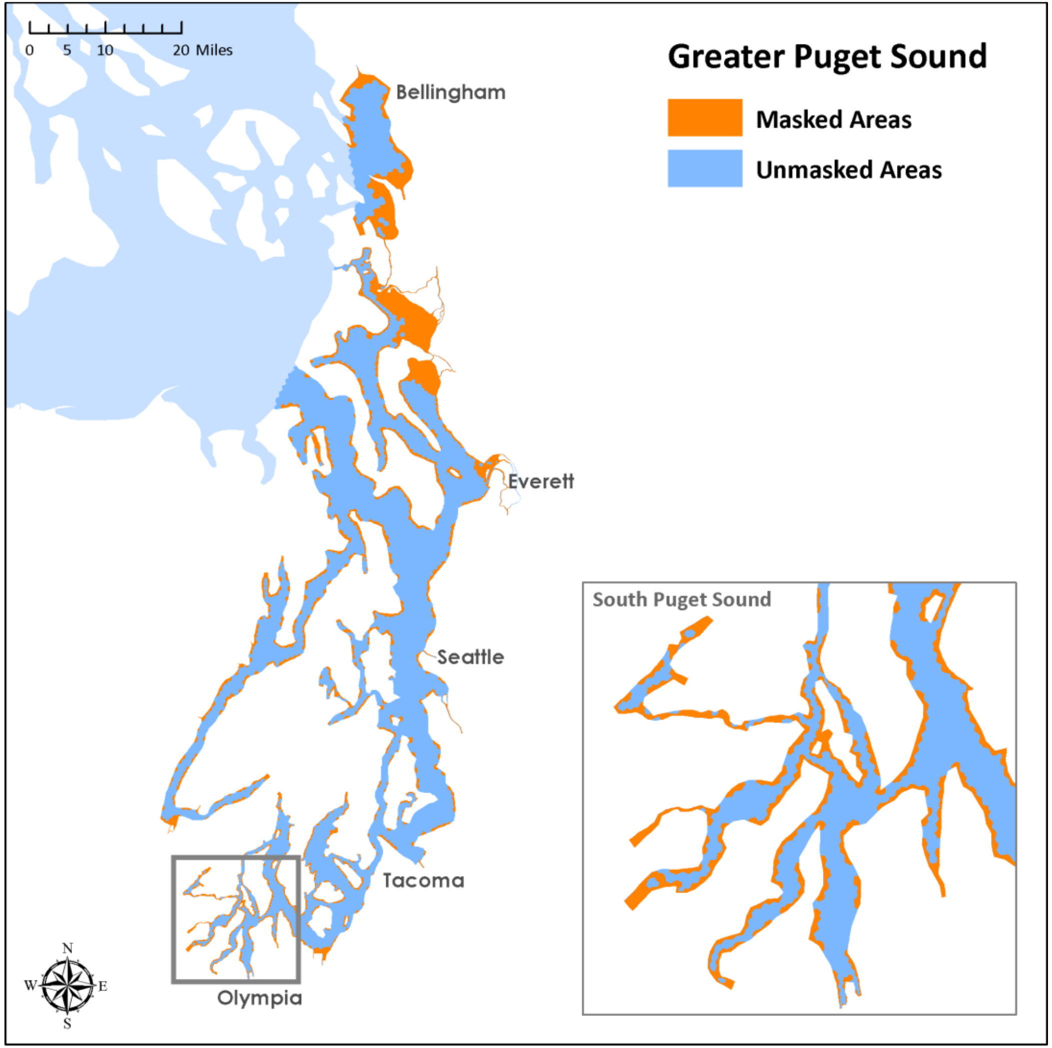
(Khangaonkar et al. 2018)

- Unstructured grid – smaller grid cells in the inlets
- 3D model (both horizontal and vertical grids)
- Hydrodynamics – FVCOM (Uni. Of Massachusetts) UMass | Dartmouth
- 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 (ENPAC model)
- Meteorology (UW/WRF model) The Northwest Regional Modeling Consortium
- Ocean boundary WQ:
  - DFO observations Fisheries and Oceans Canada
  - HYCOM
- Rivers and Marine Point Sources

Major processes involving DO dynamics :

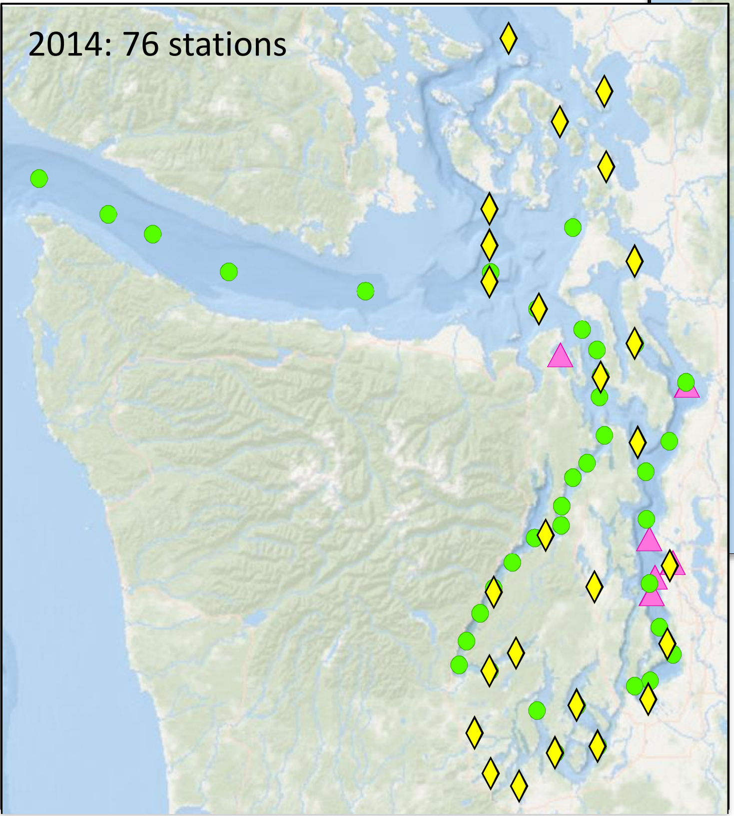
- **Reaeration** (wind and concentration induced)
- **Photosynthesis** (sunlight, CO2, nutrients, algal growth)
- **Nitrification - Denitrification**
- **Respiration and die-off**
- **Organic matter decomposition** (decay rates, BOD)
- **Sediment oxygen demand** (sediment diagenesis)
- **Estuarine circulation,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

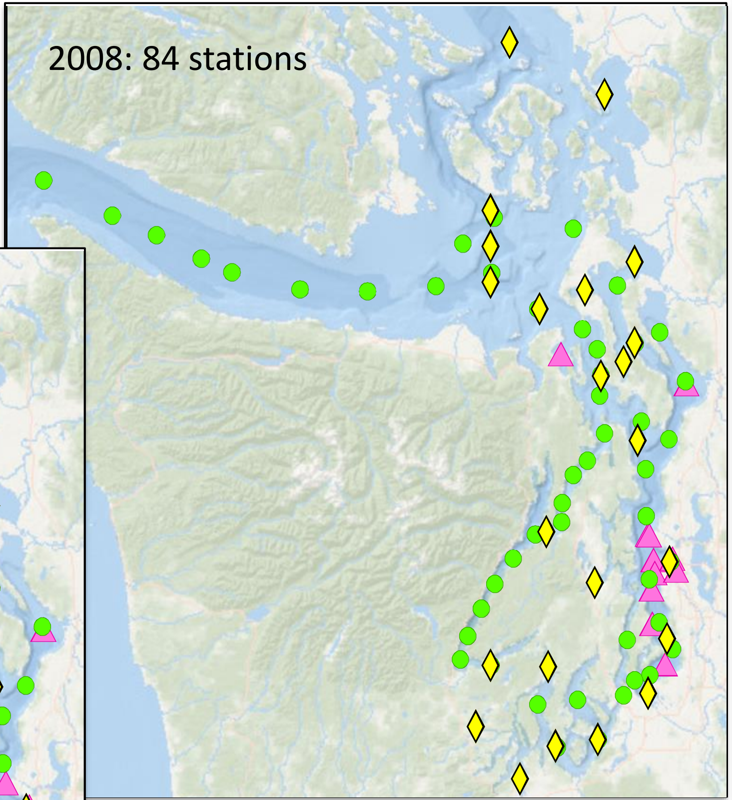


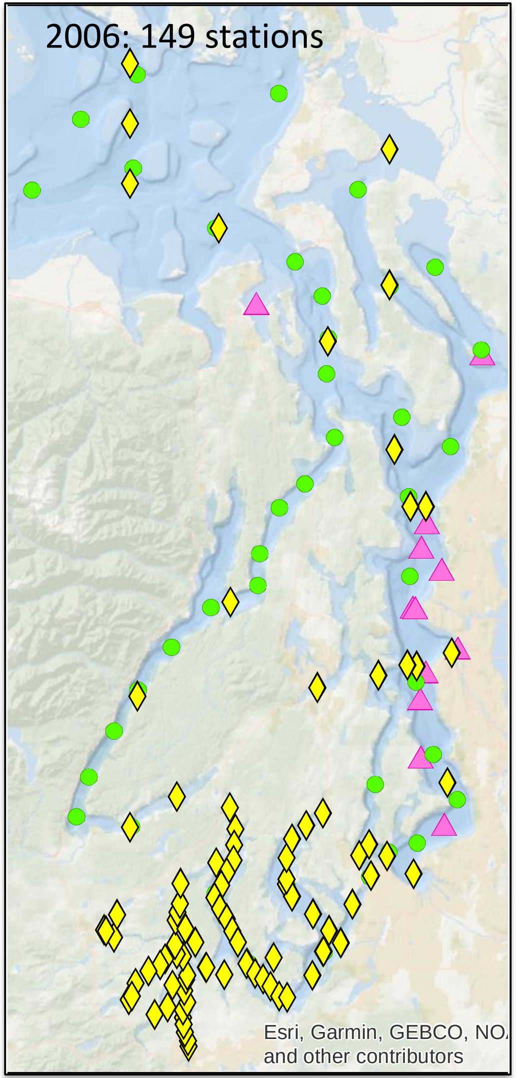


Masked areas are not currently assessed for regulatory purposes

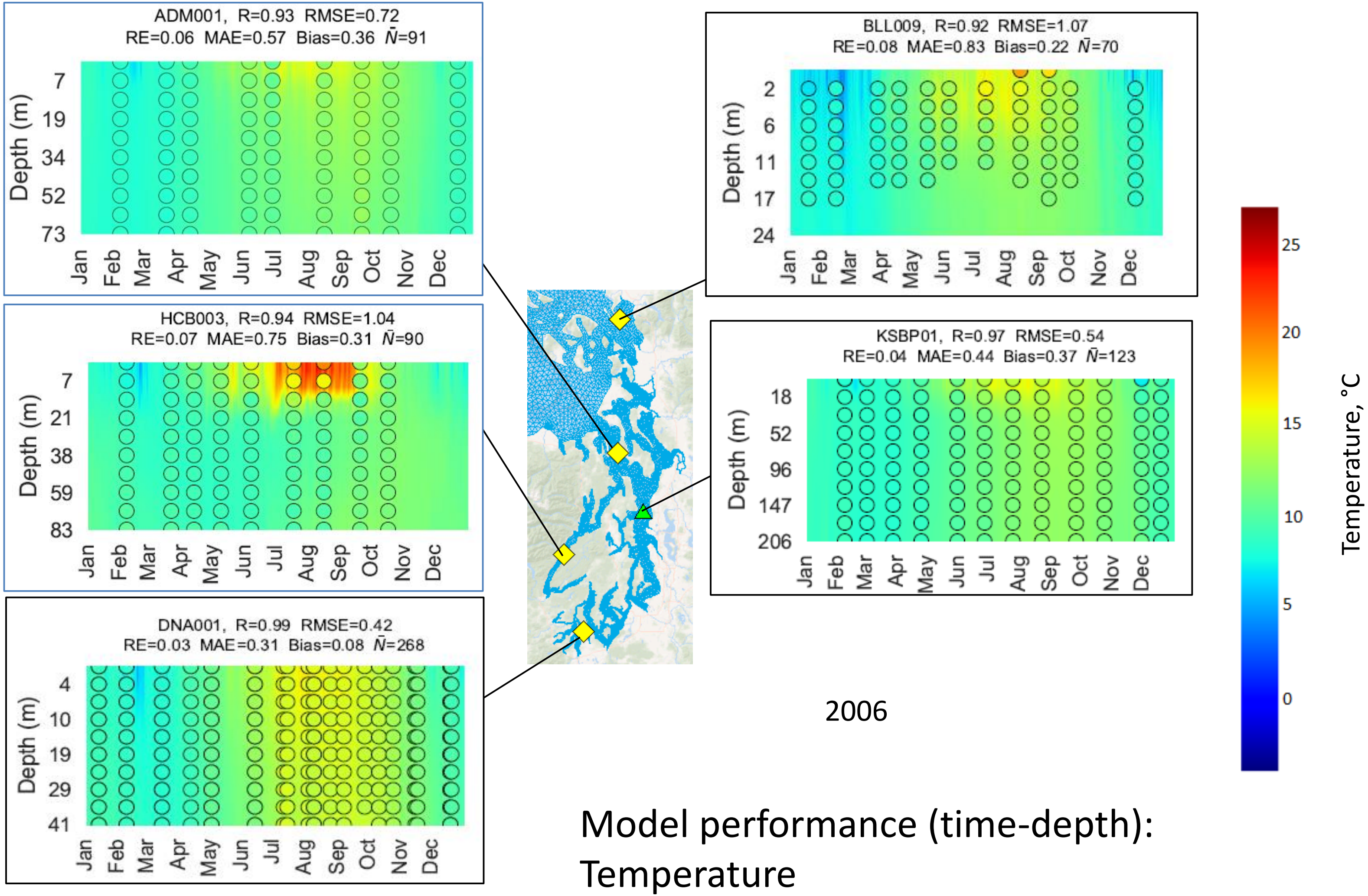
Stations where model performance was evaluated for water quality







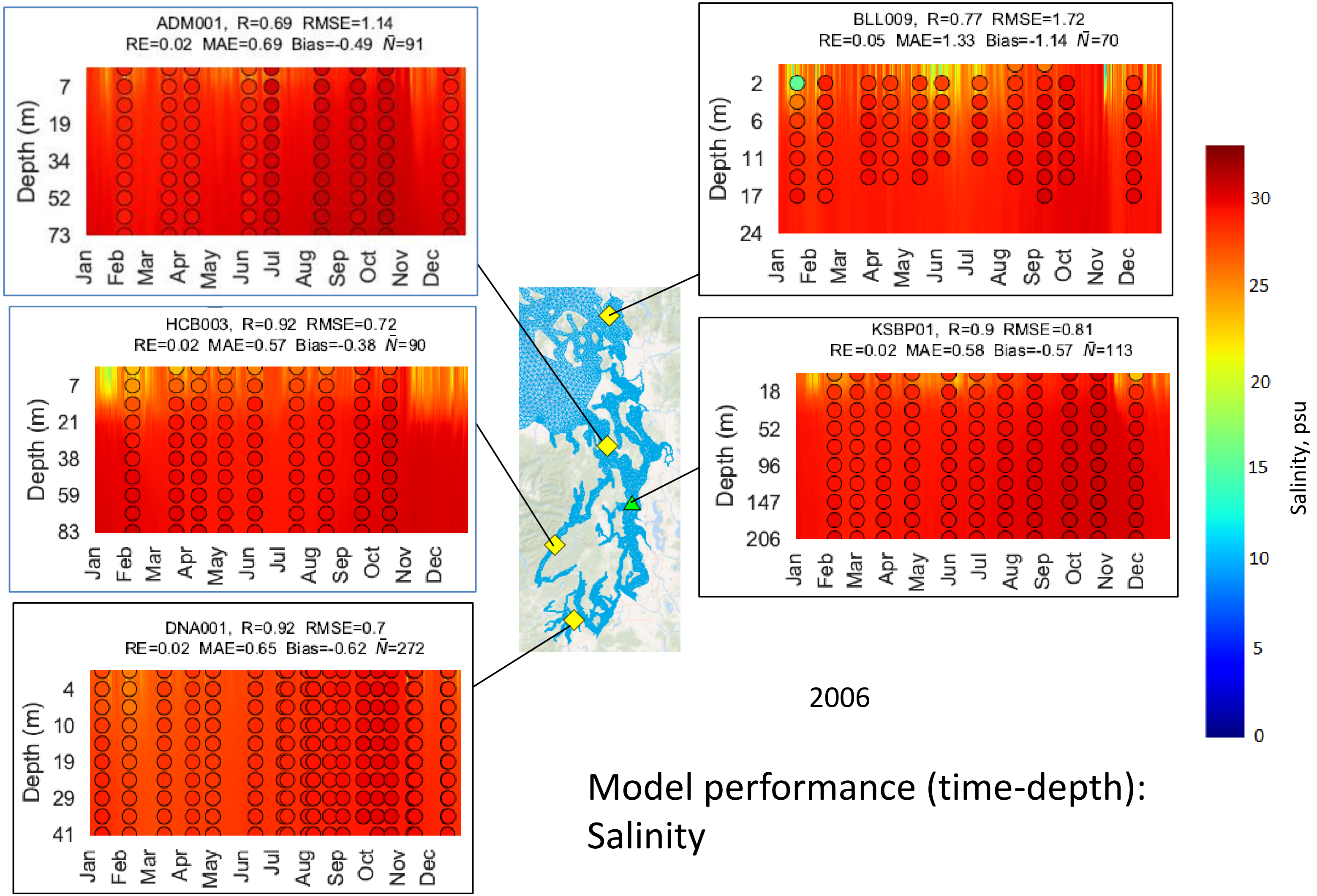
NOAA_UW
King County
Ecology



Model performance (time-depth): Temperature

Model Performance for Temperature:

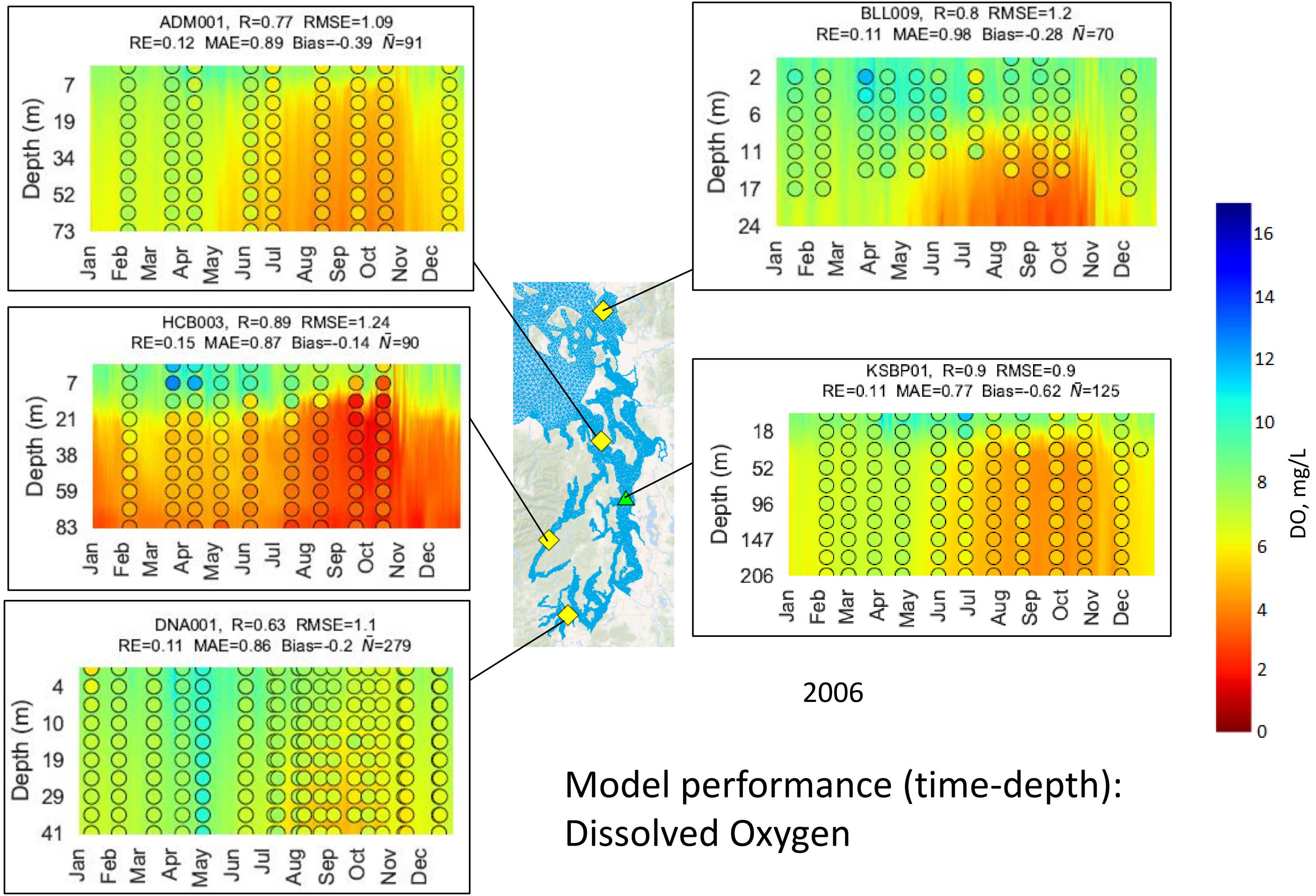
Model Run	R	RMSE, (°C)	$RMSE_c$ (°C)	Bias (°C)	n	WSS	RE	MAE
	correlation coefficient	square root of the variance of the residuals		mean of the residuals	no. of observations	Wilmott Skill Score	relative error	mean absolute error
2008 PSM (Bianucci et. al 2018)	0.90	1.48		1.28	67858			
2014 SSM (Khangaonkar et al. 2018)	0.93	0.76		-0.28	38218	0.96		
2006 SSM_(Ahmed et al. 2021 draft)	0.95	0.69	0.58	0.38	145919	0.96	0.05	0.53
2008 SSM_(Ahmed et al. 2019)	0.95	0.56	0.56	-0.05	67857	0.97	0.04	0.35
2014 SSM_(Ahmed et al. 2021 draft)	0.95	0.78	0.74	-0.23	97687	0.94	0.06	0.62



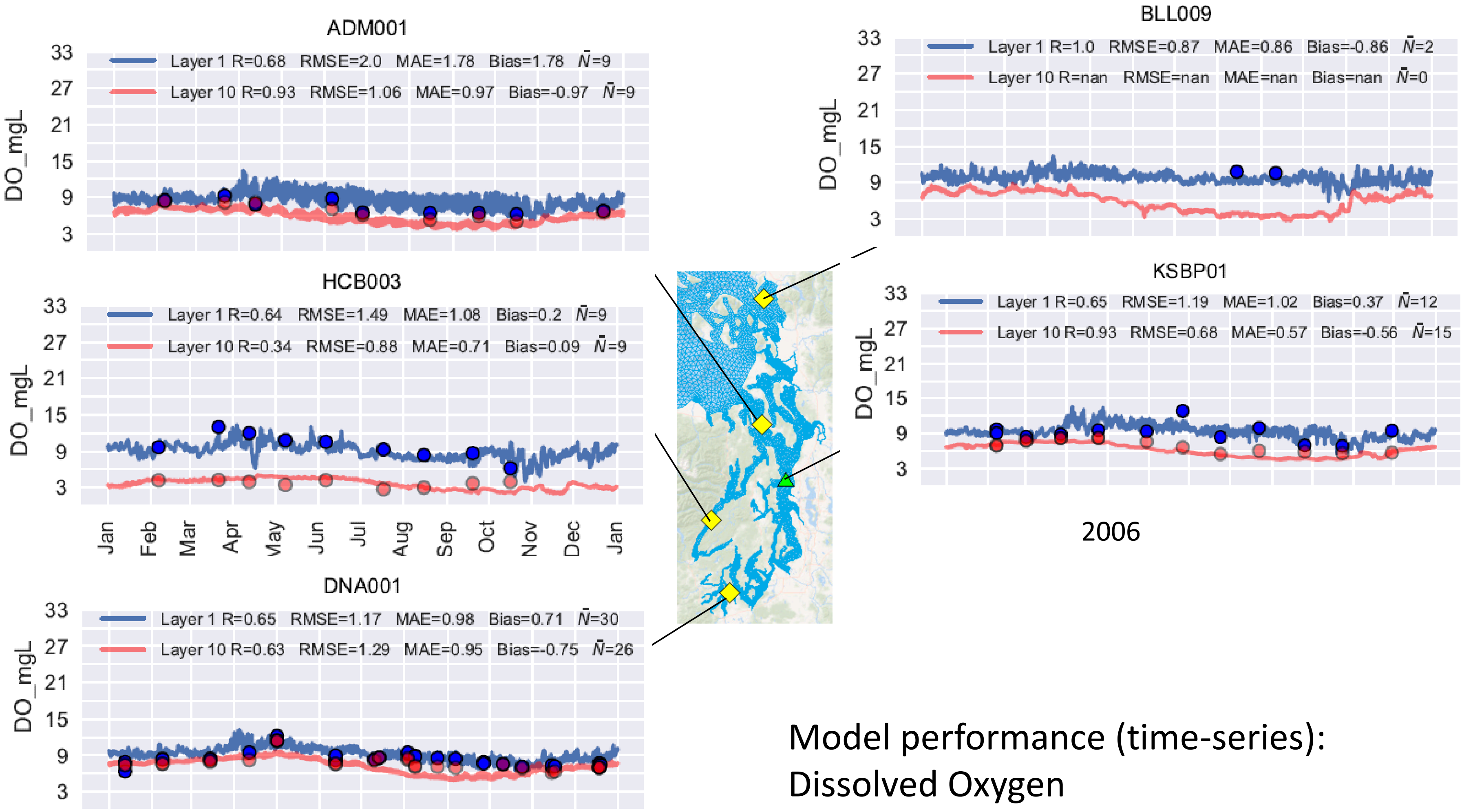
Model performance (time-depth): Salinity

Model Performance for Salinity:

Model Run	R	RMSE (psu)	$RMSE_c$ (psu)	Bias (psu)	n	WSS	RE	MAE
	correlation coefficient	square root of the variance of the residuals		mean of the residuals	no. of observations	Wilmott Skill Score	relative error	mean absolute error
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_(Ahmed et al. 2021 draft)	0.86	0.74	0.57	-0.47	144850	0.88	0.02	0.53
2008 SSM_(Ahmed et al. 2019)	0.76	0.81	0.81	0.03	66958	0.86	0.01	0.36
2014 SSM_(Ahmed et al. 2021 draft)	0.82	0.84	0.71	-0.44	97487	0.87	0.02	0.51

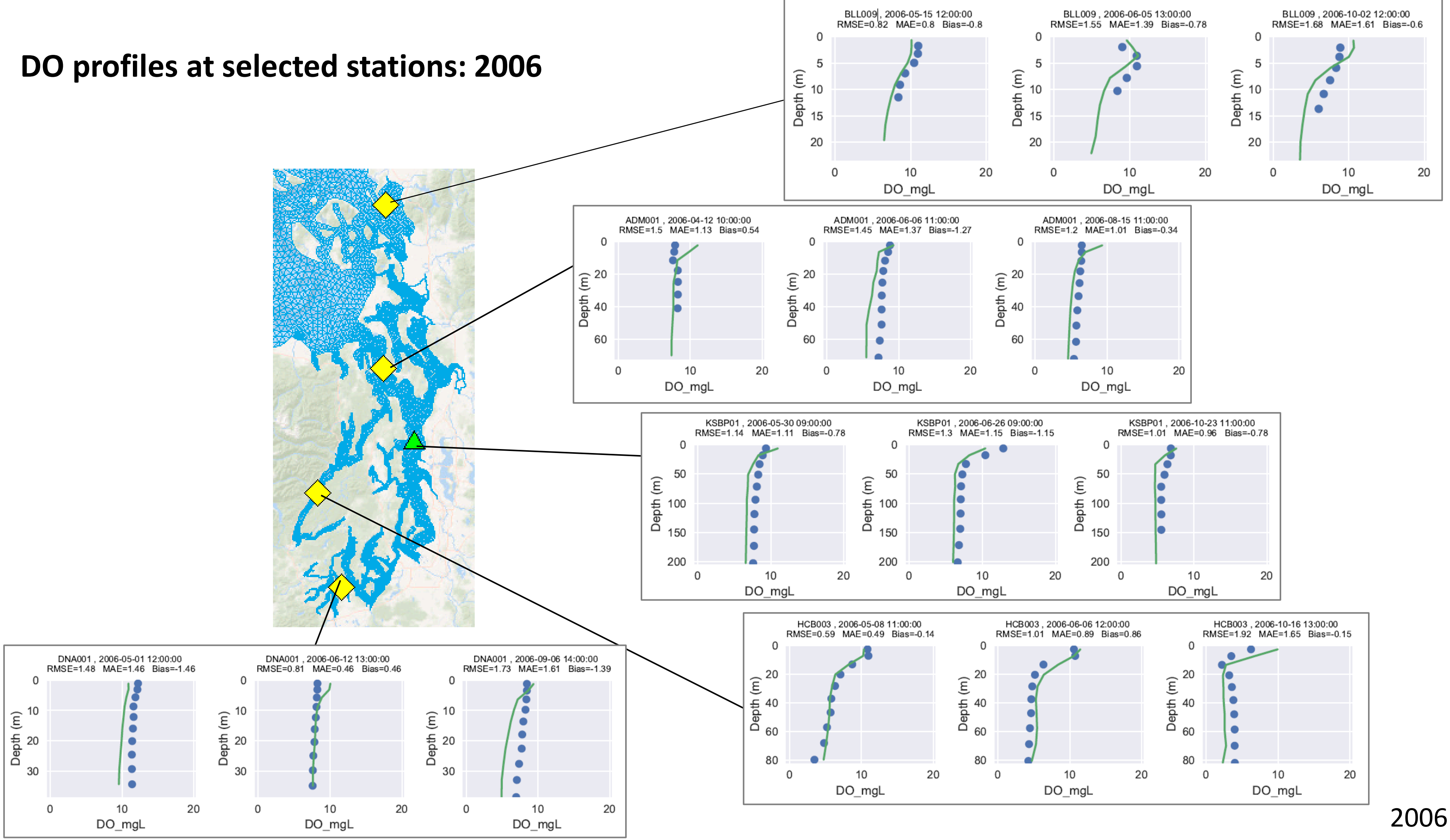


Model performance (time-depth): Dissolved Oxygen

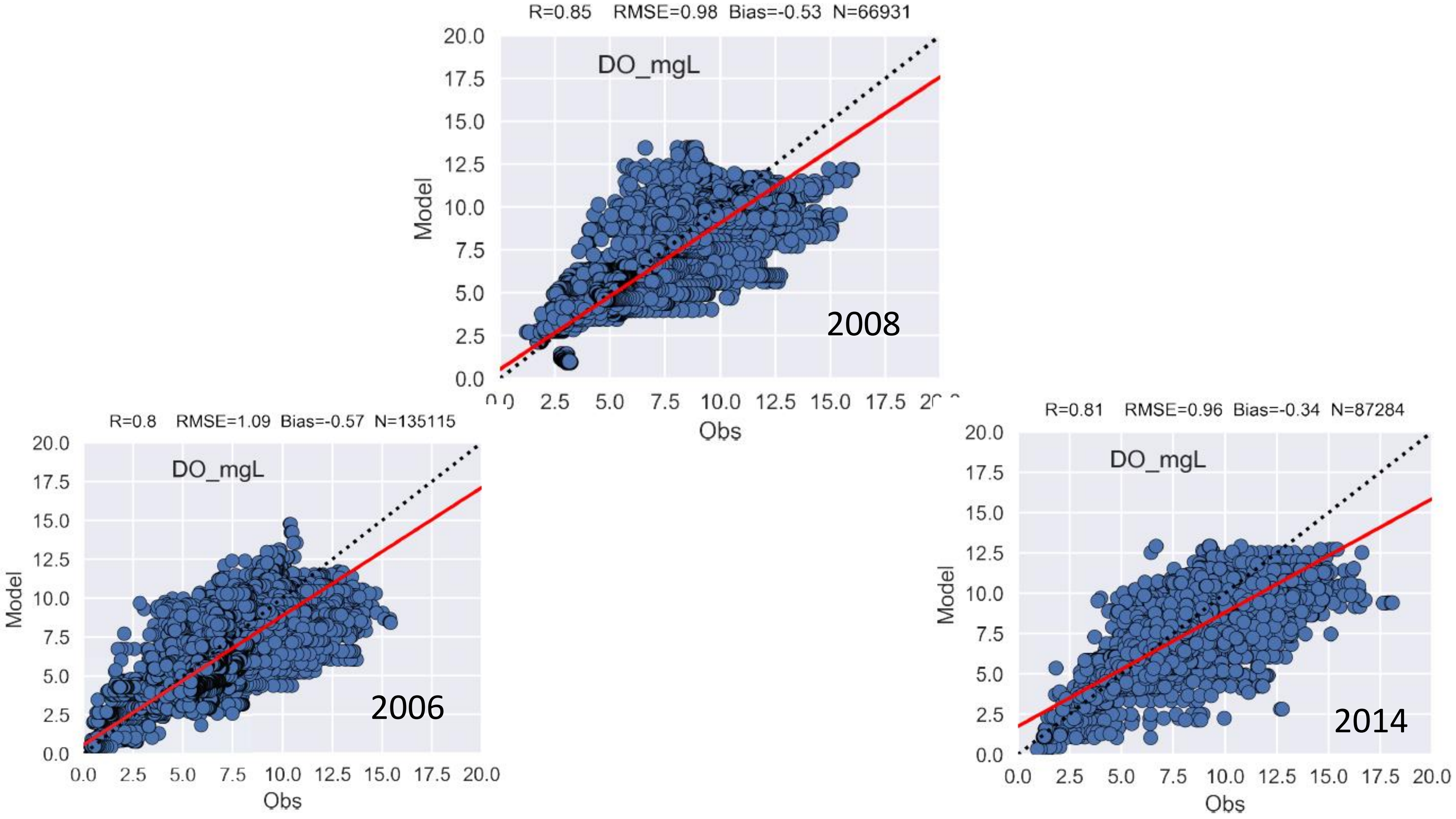


Model performance (time-series): Dissolved Oxygen

DO profiles at selected stations: 2006



2006


R=0.85 RMSE=0.98 Bias=-0.53 N=66931
DO_mgL
Model
Obs
2008
R=0.8 RMSE=1.09 Bias=-0.57 N=135115
DO_mgL
Model
Obs
2006
R=0.81 RMSE=0.96 Bias=-0.34 N=87284
DO_mgL
Model
Obs
2014

Model Performance for DO:

Model Run	R	RMSE (mg/L)	$RMSE_c$ (mg/L)	Bias (mg/L)	n	WSS	RE	MAE
	correlation coefficient	square root of the variance of the residuals		mean of the residuals	no. of observations	Wilmott Skill Score	relative error	mean absolute error
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_(Ahmed et al. 2021 draft)	0.80	1.13	0.94	-0.62	134591	0.85	0.14	0.92
2008 SSM_(Ahmed et al. 2019)	0.85	0.98	0.82	-0.53	66931	0.89	0.11	0.77
2014 SSM_(Ahmed et al. 2021 draft)	0.83	0.98	0.89	-0.43	96152	0.89	0.11	0.74

JAWRA Journal of the American Water Resources Association
Explore this journal >

Featured Collection: Chesapeake Bay Total Maximum Daily Load Development and Application

Twenty-One-Year Simulation of Chesapeake Bay Water Quality Using the CE-QUAL-ICM Eutrophication Model†

Carl F. Cerco, Mark R. Noel

View issue TOC
Volume 49, Issue 5
October 2013
Pages 1119–1133

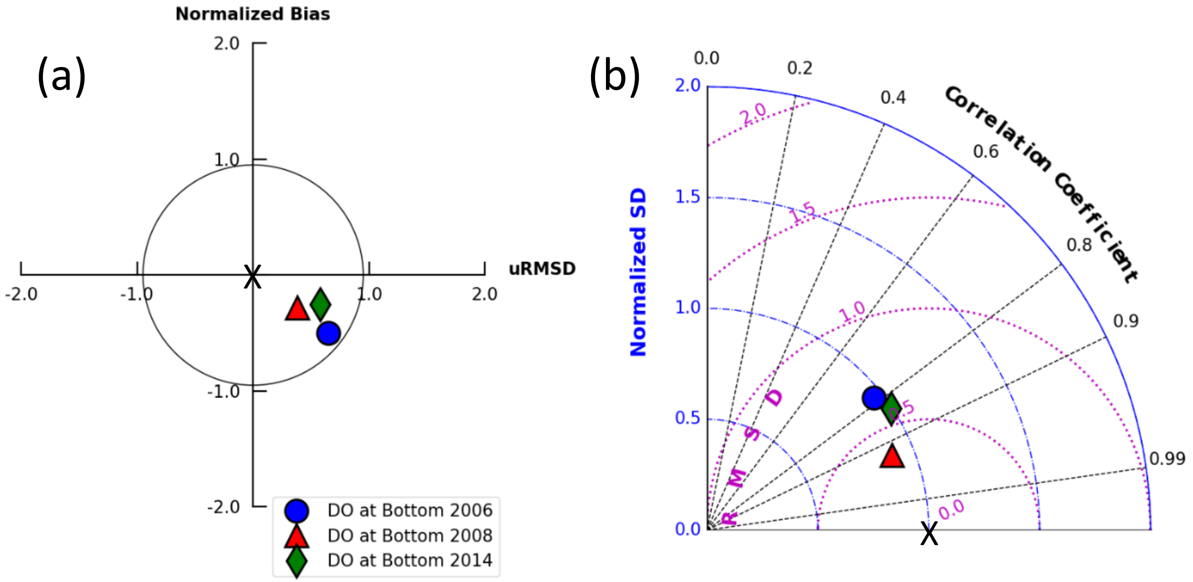
First published: 4 September 2013 Full publication history

SSM model performance is comparable to Chesapeake Bay model

Model Skill Statistics for Dissolved Oxygen, mg/L			
SSM statistics computed to match the same CB published range of statistics for bottom layer, summer (June-August) period within a year.	Bias or Mean Difference	Relative Difference/ Relative Error (percent)	Absolute Mean Difference
Salish Sea (PSNSRP)	-0.77 to -0.51	10 to 18	0.61-1.06
Chesapeake Bay TMDL model	-0.522 to 0.775	27.7 to 44.9	1.24-1.94

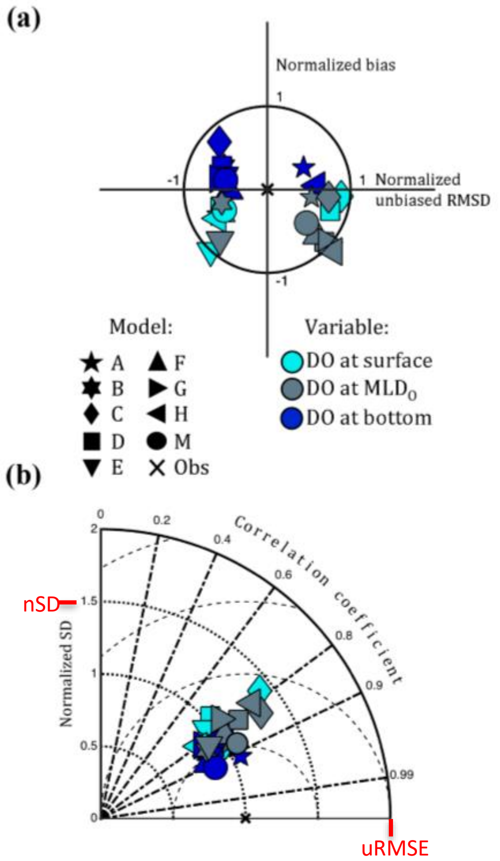
Chesapeake Bay statistics published in Table 3 (Cerco and Noel, 2013) and refer to four different phases of model improvements.

Uncertainty of predicted DO is well within acceptable range



Salish Sea Model

Ahmed et al. 2019
Ahmed et al. 2021 (in preparation)

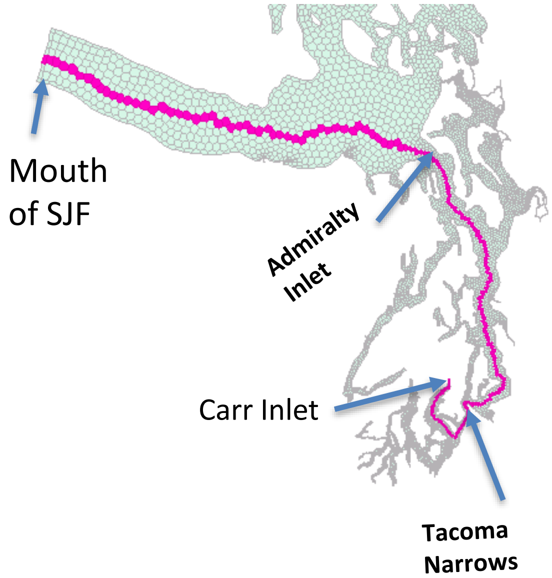


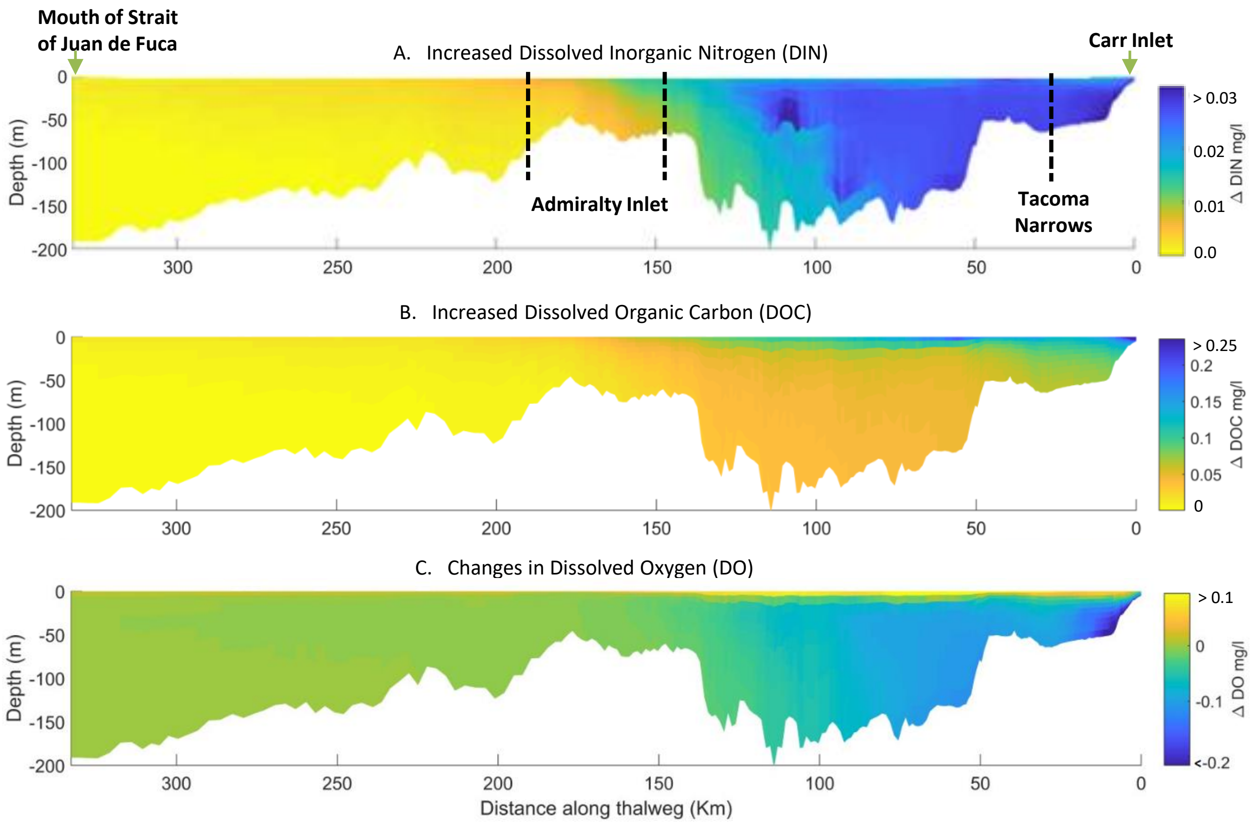
Chesapeake Bay Models

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

Chla					
Model Run	**R**	**RMSE (ug/L)**	**Bias (ug/L)**	**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	0.51	4.48	0.20	110580	0.64
2008 SSM_(Ahmed et al. 2019)	0.49	3.1	0.33	66941	0.66
2014 SSM_updates	0.52	3.42	-0.11	87671	0.67

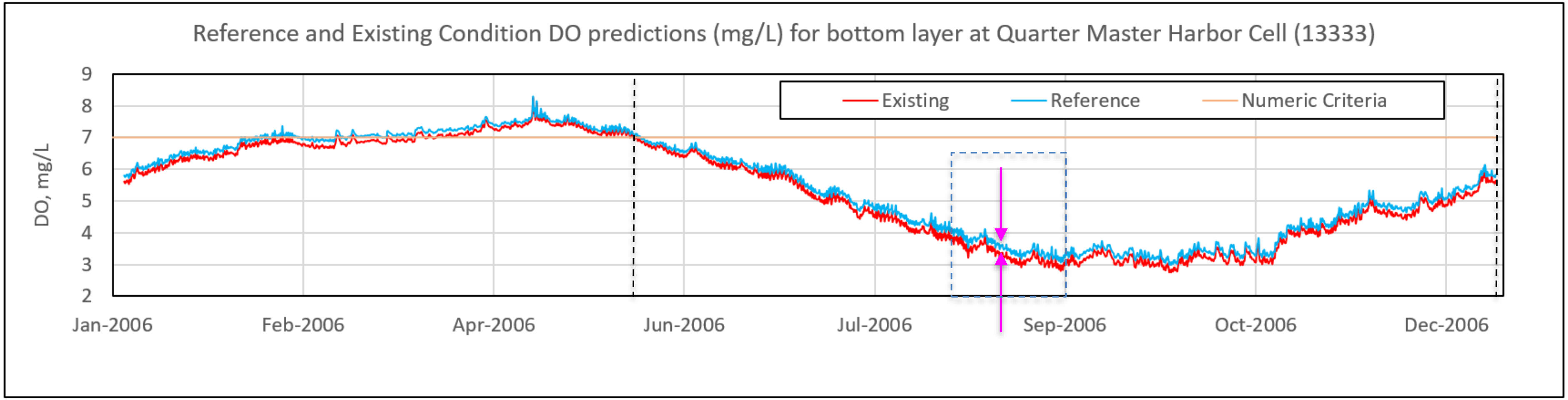
NO3					
Model Run	**R**	**RMSE(mg/L)**	**Bias (mg/L)**	**n**	**WSS**
2008 PSM (Bianucci et. al 2018)	0.80	0.08	-0.001	1902	
2014 SSM (Khangaonkar et al. 2018)	0.82	0.09	0.013	1187	0.9
2006 SSM_updates	0.82	0.08	0	2356	0.9
2008 SSM_(Ahmed et al. 2019)	0.80	0.09	-0.04	1381	0.85
2014 SSM_updates	0.84	0.07	0	1934	0.9

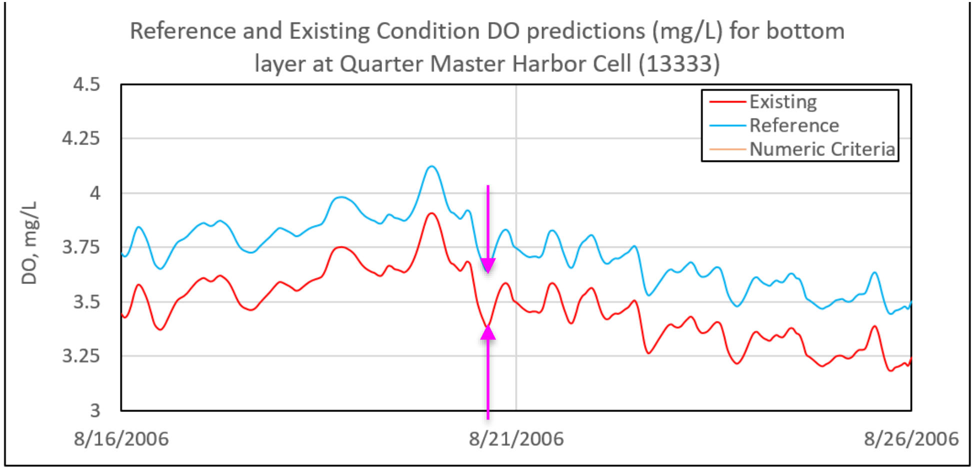




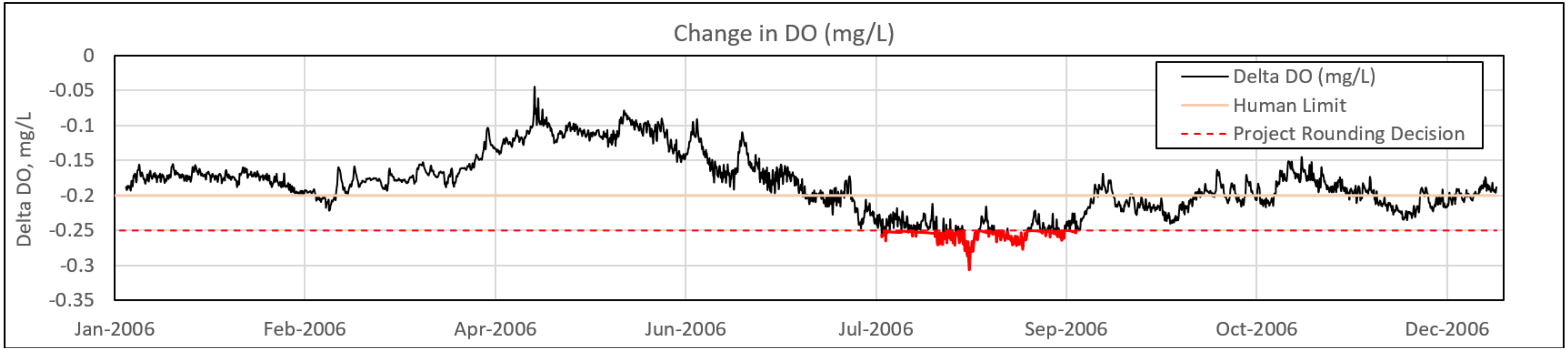
Annual Average Transect plots: 2006 Bounding Scenario Report (Ahmed et al. 2019)

Using best estimate of anthropogenic DO signal

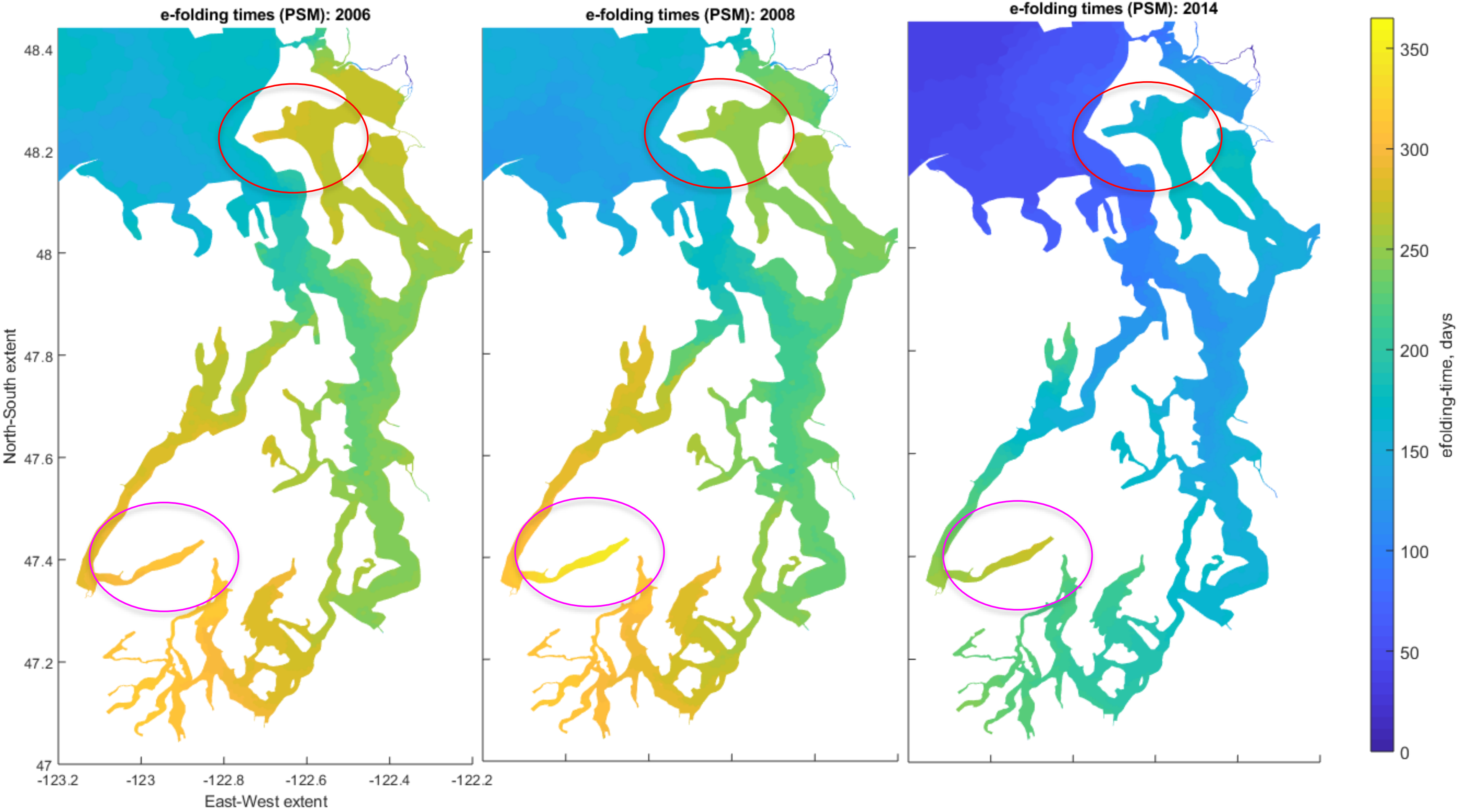


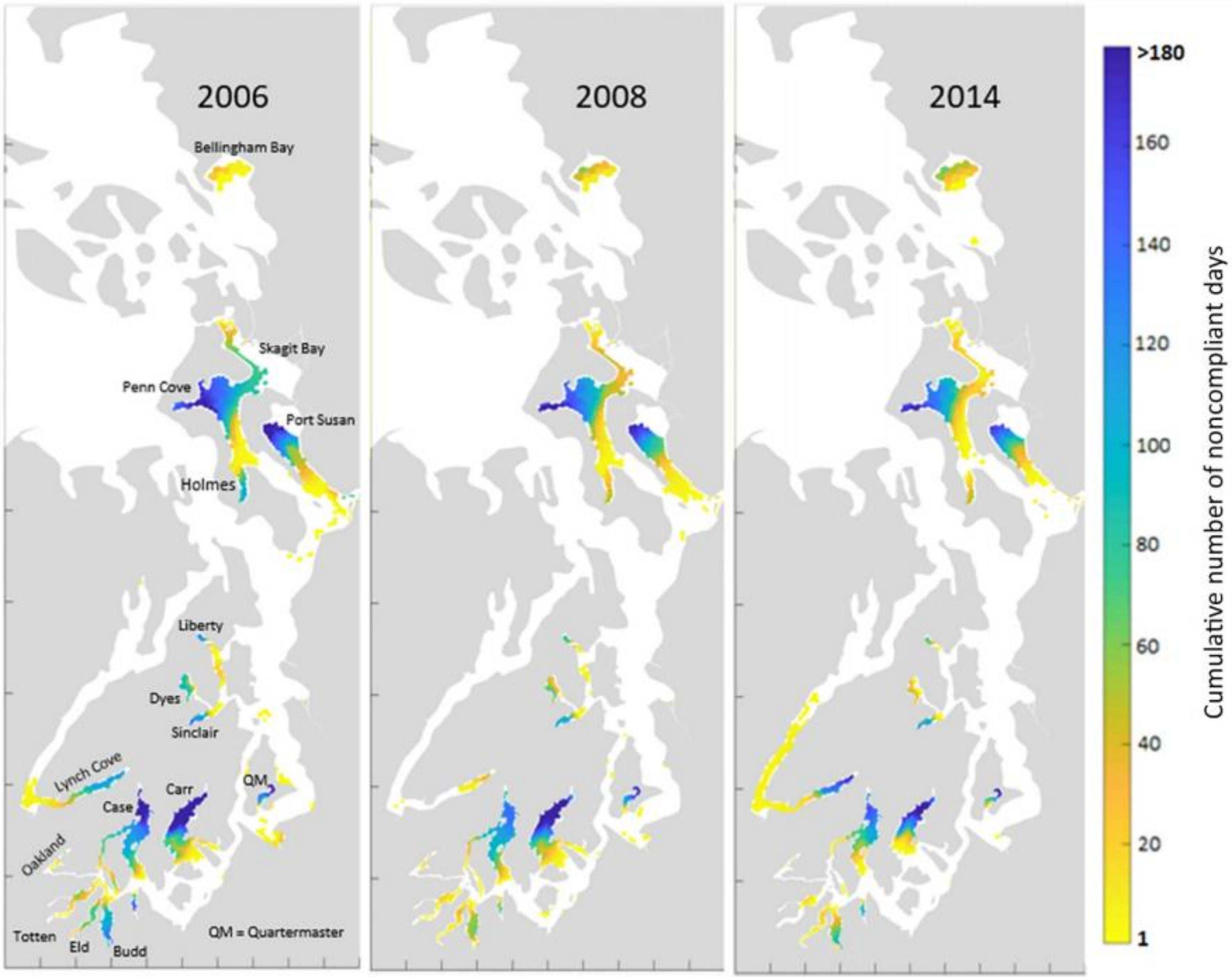


Using best estimate of anthropogenic DO signal



PSM: residence times




2006
2008
2014
Bellingham Bay
Skagit Bay
Penn Cove
Port Susan
Holmes
Liberty
Dyes
Sinclair
Lynch Cove
Case
Carr
QM
Oakland
Totten
Eld
Budd
QM = Quartermaster
>180
160
140
120
100
80
60
40
20
1
Cumulative number of noncompliant days

Next Steps:

Informing the **Puget Sound Nutrient Reduction Project (PSNRP)**

1. Optimization Year 1 Scenarios (upcoming Technical memo Ecology 2021):
    - impact of regional nutrient reductions from WWTPs and watersheds
    - Impact of projected population growth
    - Annual and Seasonal BNR
    - Comprehensive WWTP and watershed reductions

2. Optimization Year 2 Scenarios: Optimize nutrient reductions from WWTPs and watersheds.

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/

Salish Sea Modeling Center: https://www.pugetsoundinstitute.org/salish-sea-modeling-center/

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

Salish Sea Model Downloadable files for Bounding Scenarios:
https://fortress.wa.gov/ecy/ezshare/EAP/SalishSea/SalishSeaModelBoundingScenarios.html

Salish Sea Model Web Map for Bounding Scenario Report:
Salish Sea Model web map

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State of Washington

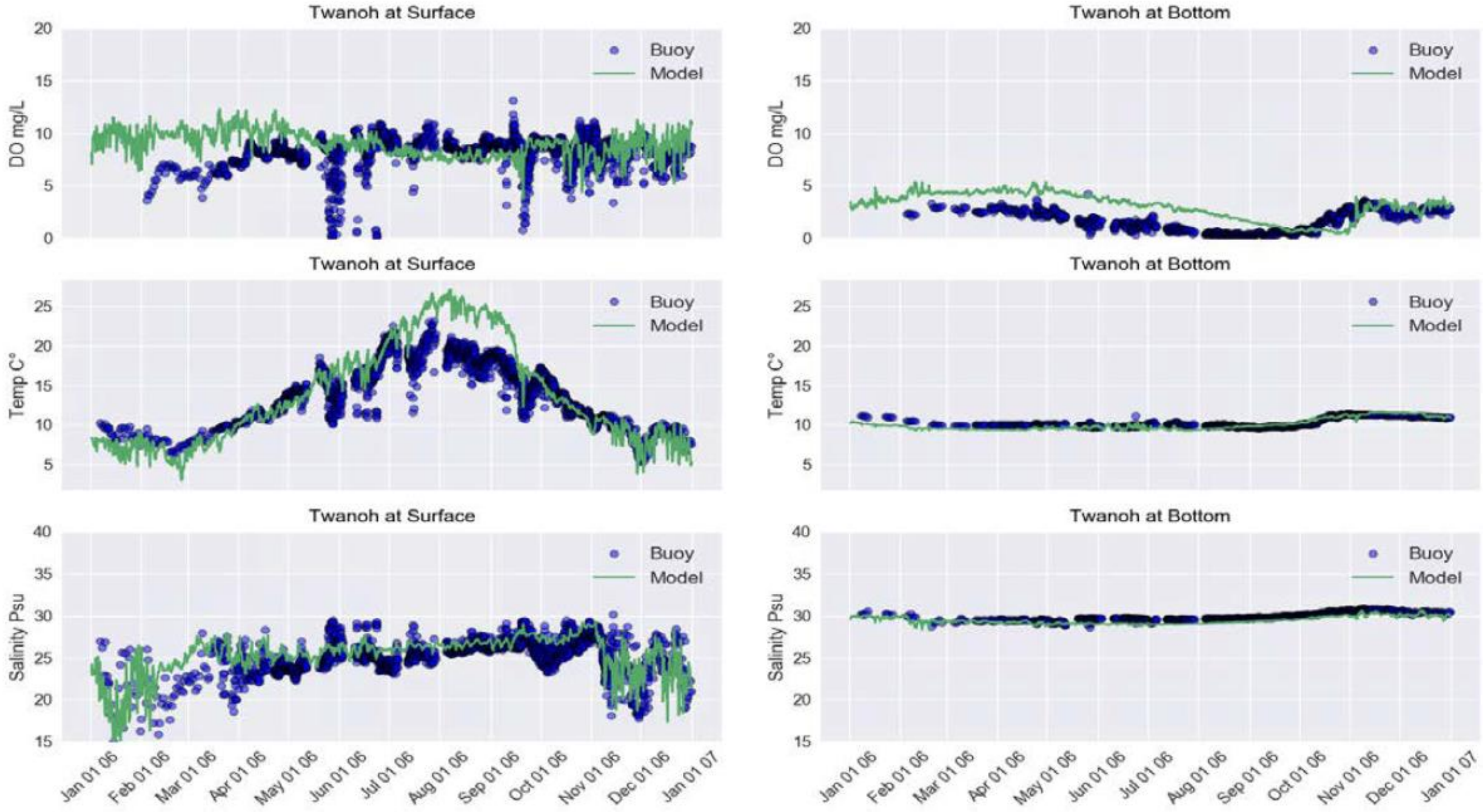

Figure J2: 2006 SSM vs. Twanoh buoy data for DO, temperature, and salinity at surface and bottom layers. Model results are captured at a 1 hour frequency while ORCA data collection frequency largely varies.

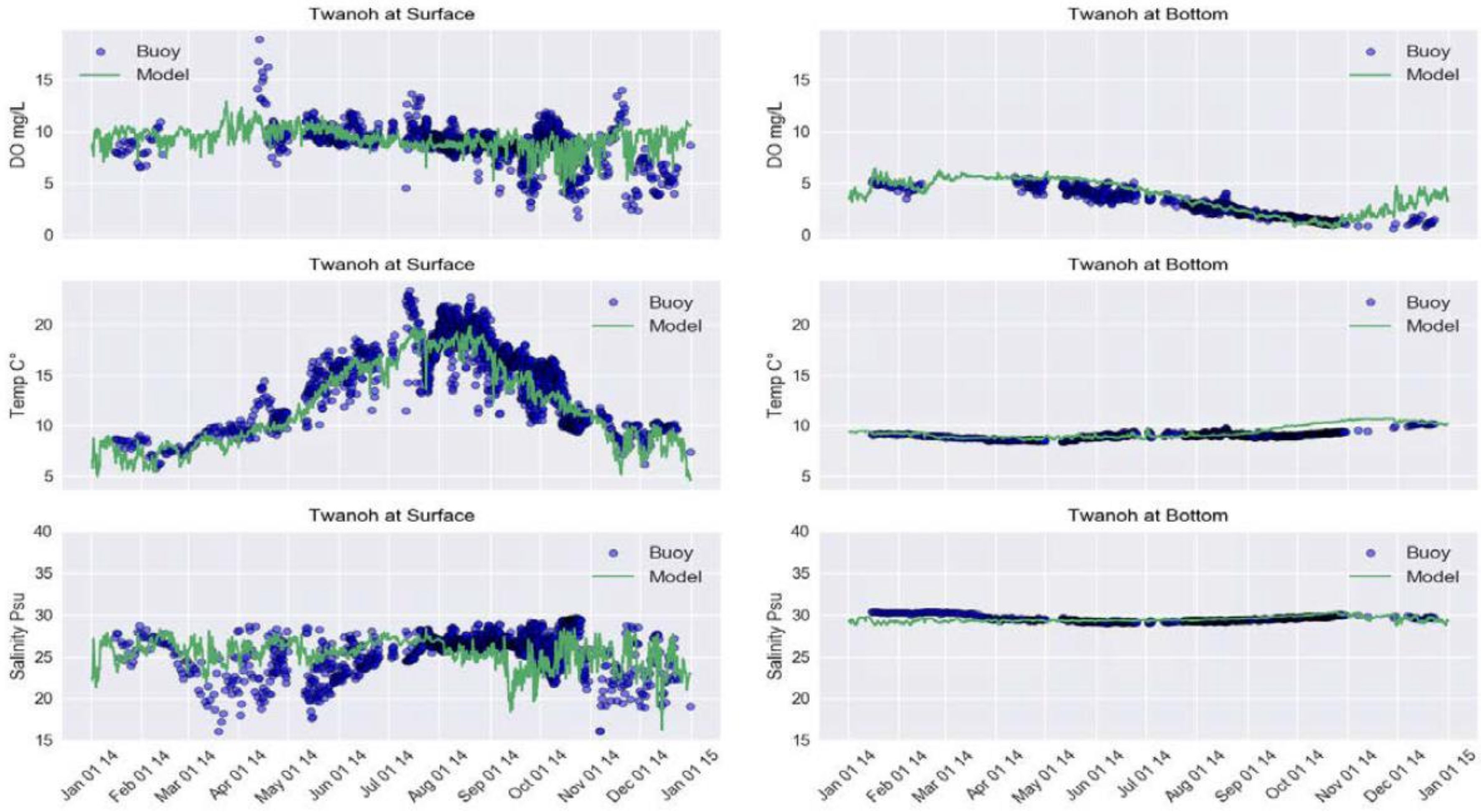

Figure J9: 2014 Model vs. Twanoh buoy data for DO, temperature, and salinity at surface and bottom layers. Model results are captured at a 1 hour frequency while ORCA data collection frequency largely varies.

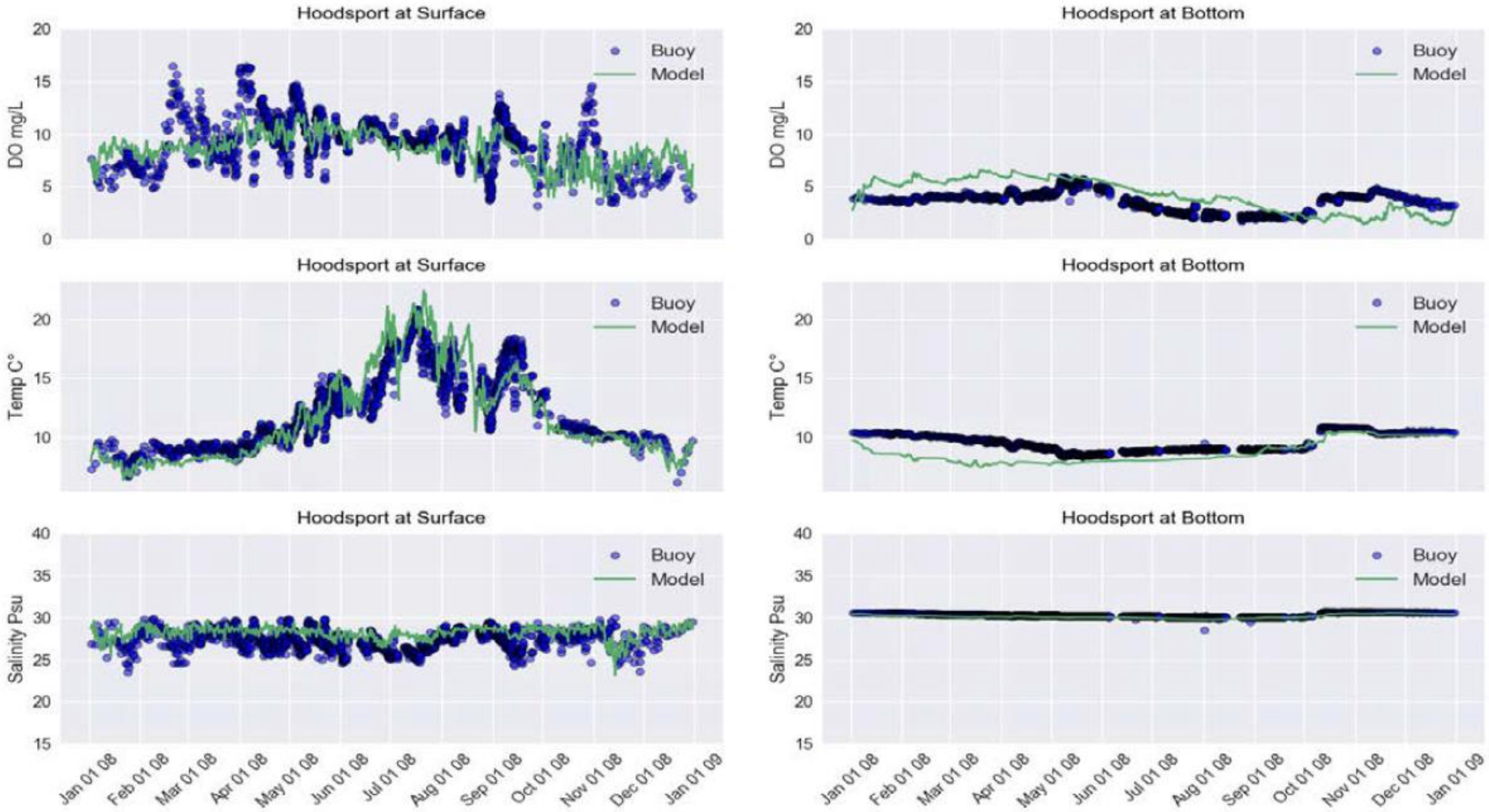

Figure J4: 2008 SSM vs. Twanoh buoy data for DO, temperature, and salinity at surface and bottom layers. Model results are captured at a 1 hour frequency while ORCA data collection frequency largely varies.

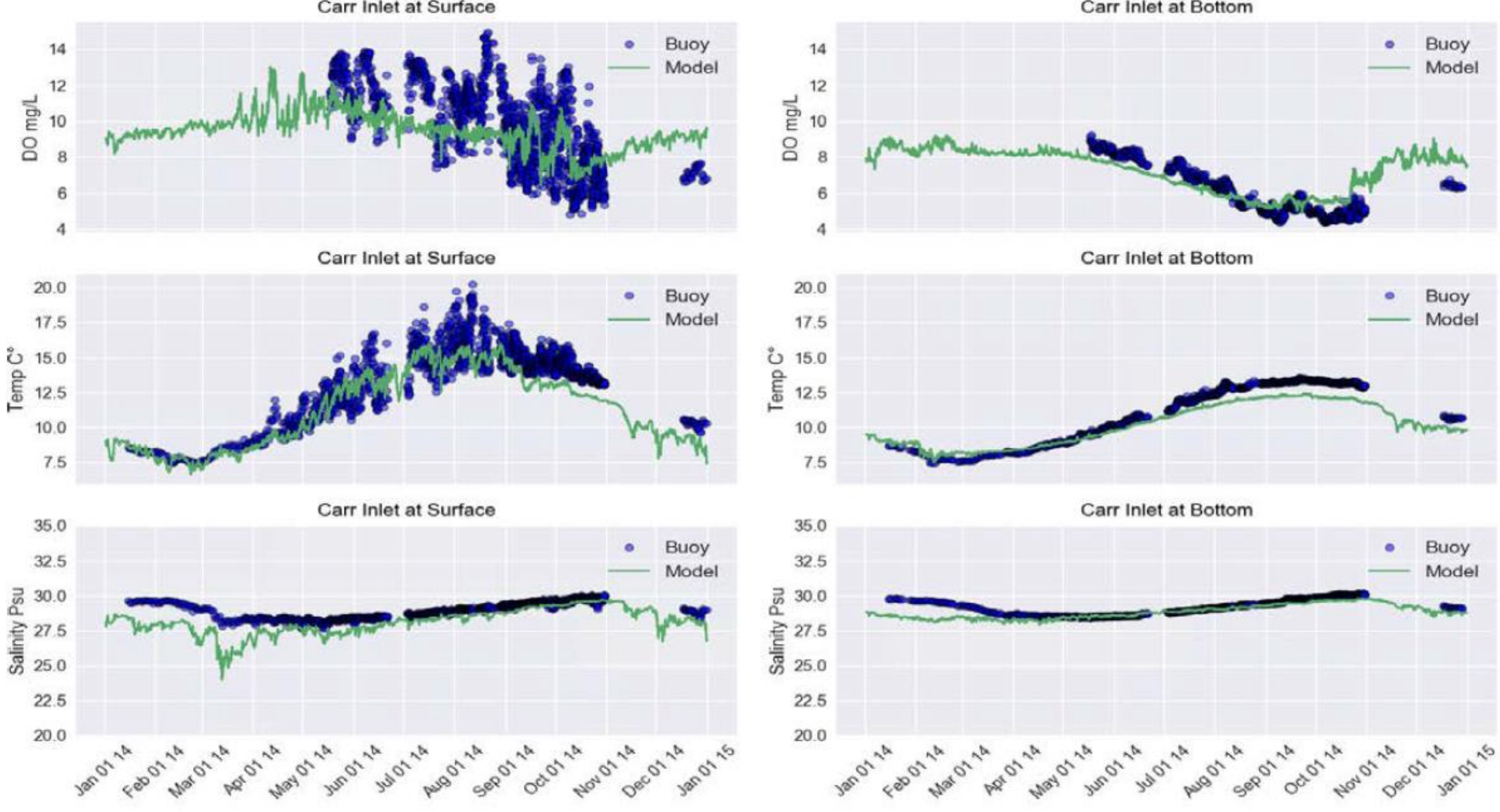

Figure J6: 2014 SSM vs. Carr Inlet buoy data for DO, temperature, and salinity at surface and bottom layers. Model results are captured at a 1 hour frequency while ORCA data collection frequency largely varies.