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

Salish Sea Model

Modeling Team Members

Pacific Northwest National Laboratory

Tarang Khangaonkar, Ph.D, P.E.
Wen Long, Ph.D.
Laura Bianucci, Ph.D.

Washington State Department of Ecology

Anise Ahmed, Ph.D, P.E.
Teizeen Mohamedali, P.E.
Greg Pelletier, P.E.
Cristiana Figueroa-Kaminsky, P.E.

With support from:

U.S. Environmental Protection Agency
Ben Cope

With past contributions from:

Taeyun Kim, Ph.D.
Rochelle Labiosa, Ph.D.
Mindy Roberts, Ph.D, P.E.
Brandon Sackmann, Ph.D.
Taiping Wang, Ph.D.
Zhaoqing Yang, Ph.D.

DEPARTMENT OF ECOLOGY
State of Washington

Salish Sea Model:

Significant Support from the Regional Scientific Community

Photo Courtesy: CMAP, SEA Program, Department of Ecology

- Observational records
- Shared insights
- Input data from other models
- Peer Review
- Opportunities for applications
- Numerous contributors

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

Simone Alin - Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration

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

Stephanie Jaeger - Department of Natural Resources and Parks, Water and Land Resources Division, King County

Christopher Krembs, Tom Gries, Will Hobbs, Dustin Bilhimer - Washington Department of Ecology

Parker MacCready - University of Washington

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

Randy Shuman - King County

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

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

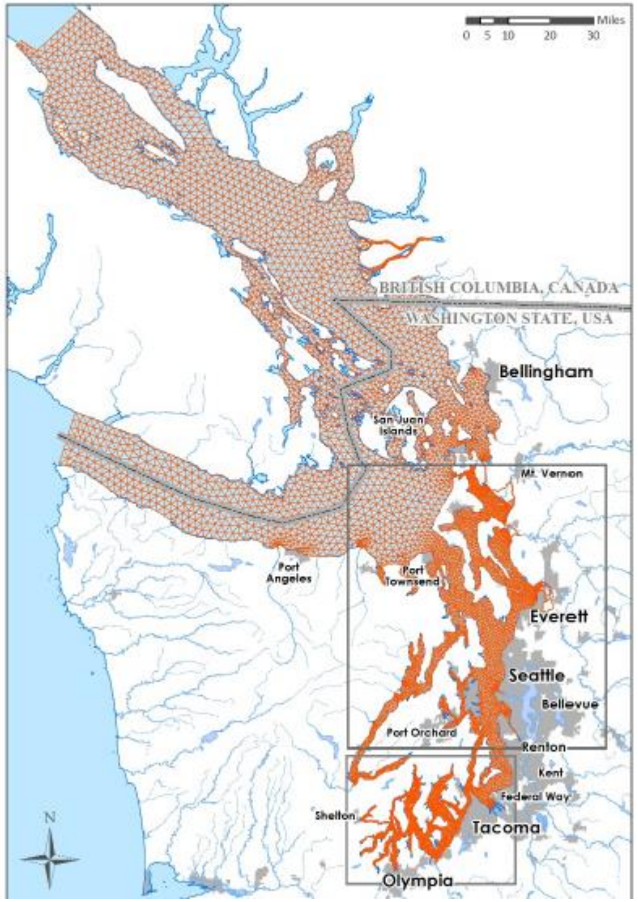
Salish Sea Model: What is it? Why is it needed?

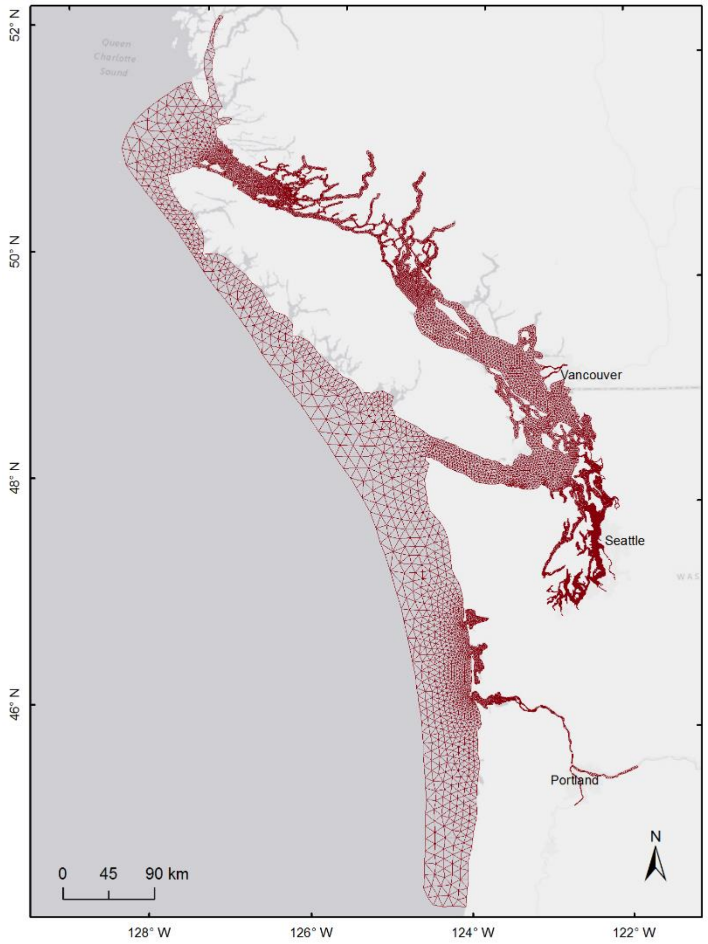
- SSM is a 3-D biogeochemical diagnostic tool for predicting responses to key ecosystem parameters due to discrete changes.

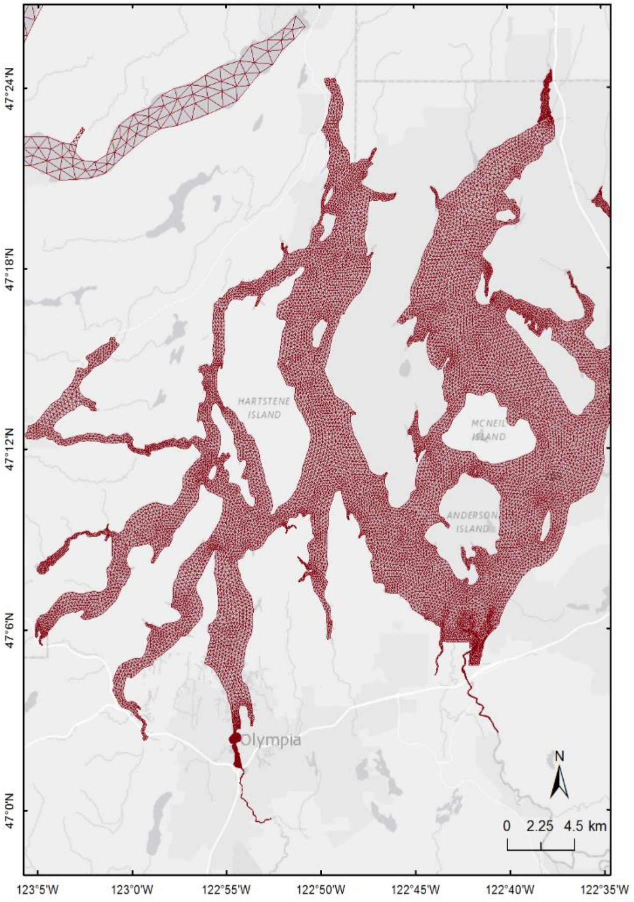
- It is needed to support in the assessment of impacts to our estuarine system. It is the backbone tool that will be used in the Puget Sound Nutrient Reduction Strategy.

24 Peer reviewed papers and technical reports

Spatial Scale: Model has evolved--larger domain with finer horizontal grids focusing on Puget Sound. Ten vertical layers.



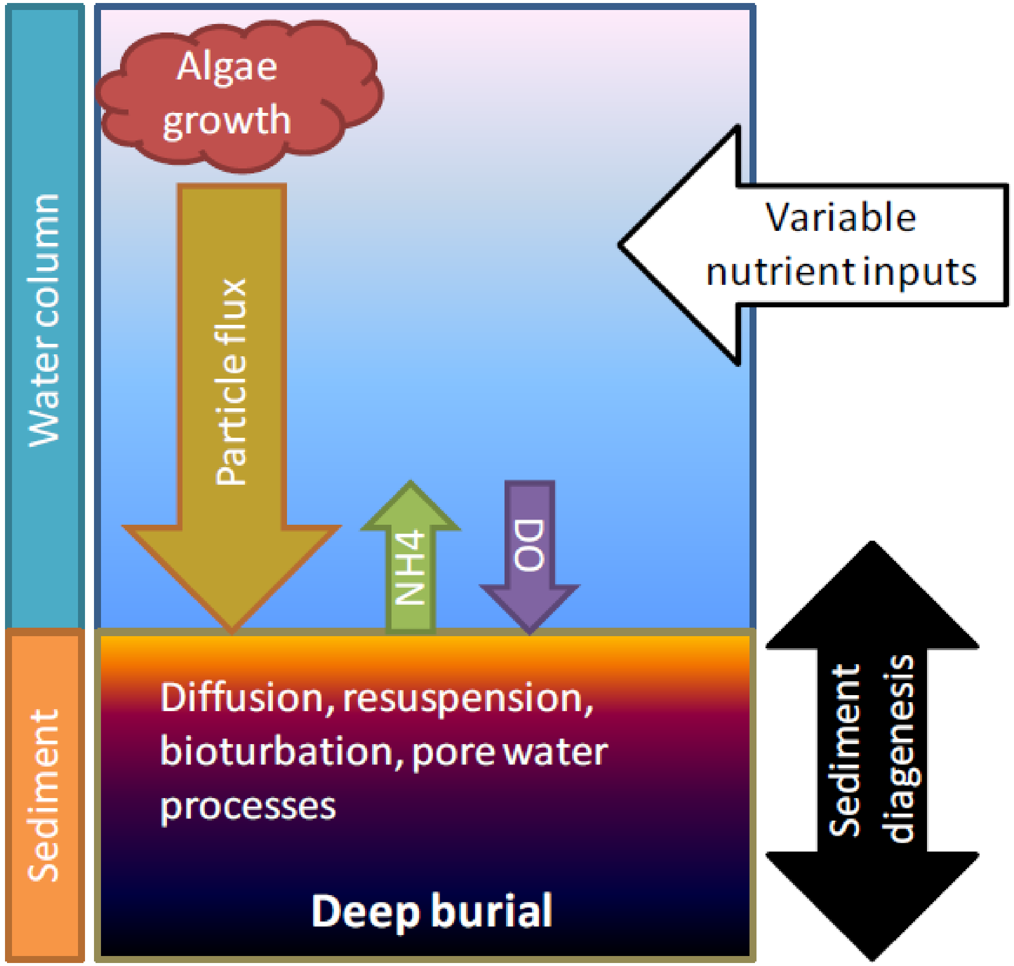


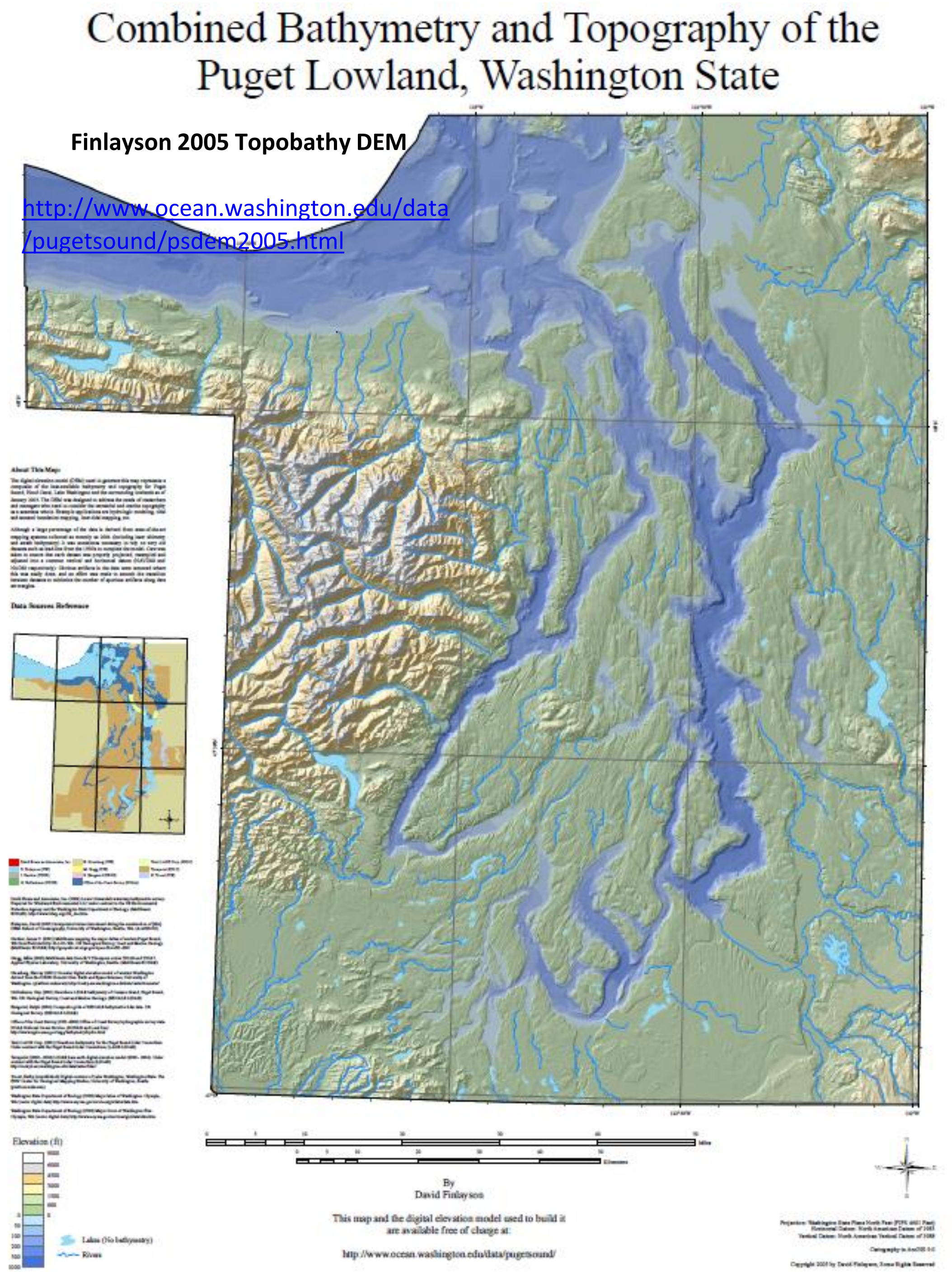


Intermediate scale model has a resolution varying from 250 meters in the inlets and bays to 800 meters in main basin, and up to 3000 meters in the strait of Juan de Fuca.

Finer scale grid has inlets and bays going down to approximately 40-50 m in South and Central Sound.

SSM: Approximating the biology, chemistry and physics of the Salish Sea

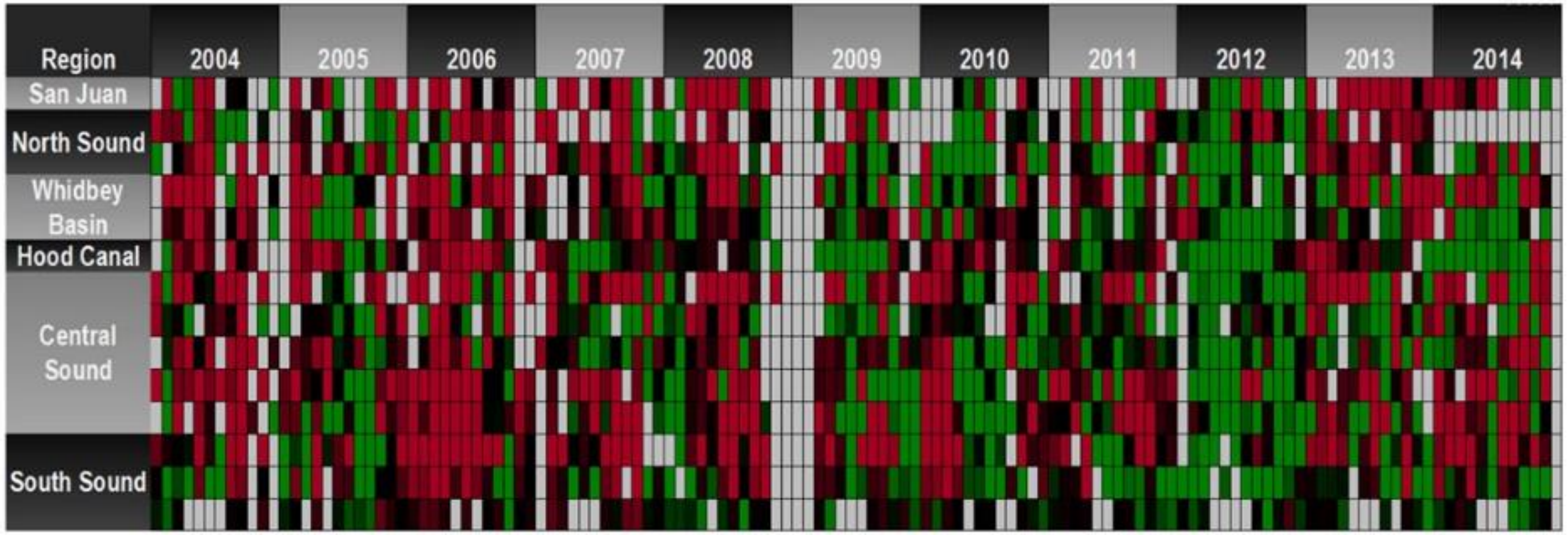




Temporal Scale: Annual Simulations, Hourly output

SSM simulations presented today will reference three separate years

Dissolved Oxygen



Source: MWCI, Department of Ecology, Christopher Krembs, Julia Bos, Skip Albertson, Mya Keyzers, Laura Hermanson and Carol Maloy

2014

- Relative to previous years, Hood Canal DO conditions improved.
- Historic mean river flows exceeded in Spring.
- In September and October, the "Blob" moved in.

PSEMP 2014 Report

2006

"In September 2006, thousands of dead fish washed up on shore in Hood Canal."

http://www.seattletimes.com/seattle-news/fish-kill-risk-in-hood-canal/

2008

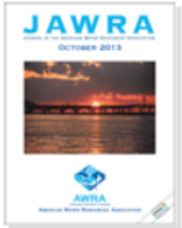
High rates of shellfish larvae die-offs reported by Hood Canal commercial shellfish growers

Personal communication, Bill Dewey

Comparable approach used to study Chesapeake Bay

JAWRA Journal of the American Water Resources Association

Explore this journal >



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

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

First published: 4 September 2013 Full publication history

Comparable model performance

Mean Difference Between Model and Observations		
Range of annual statistics	DO (mg/L)	Chlorophyll (µg/L)
Salish Sea	-1.56 to 0.35	-0.31 to 0.82
Chesapeake Bay	-0.522 to 0.775	0.32 to 1.55

An Overview of the *Salish Sea Model*:

(A tool for Water Quality and Ecosystem Management)

Hydrodynamics, Biogeochemistry, & Sediments …

Model Framework and Skill

Tarang Khangaonkar, Wen Long, Laura Bianucci, Wenwei Xu, Adi Nugraha
Pacific Northwest National Laboratory (PNNL)

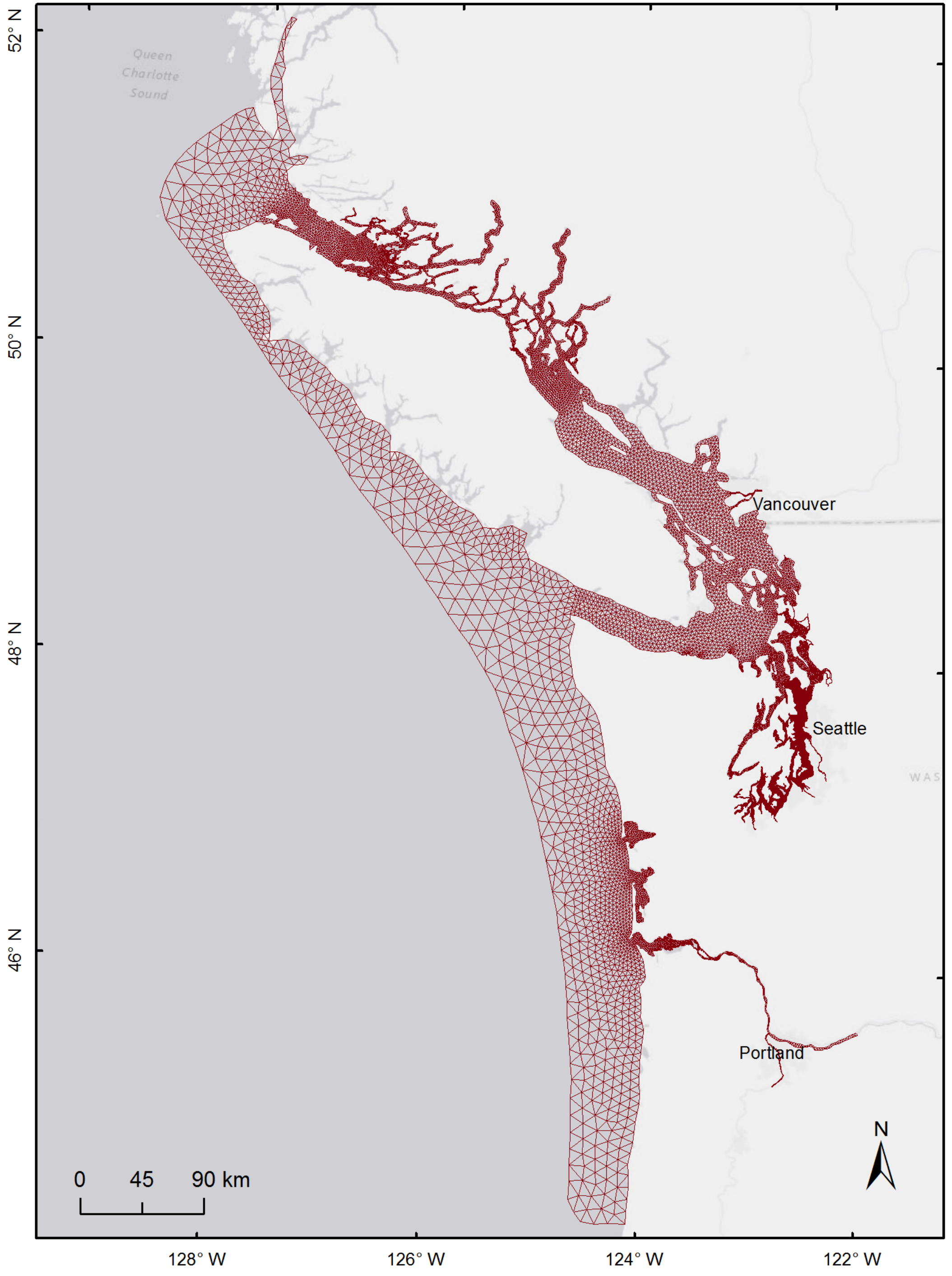
EPA United States Environmental Protection Agency

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle *Since 1965*

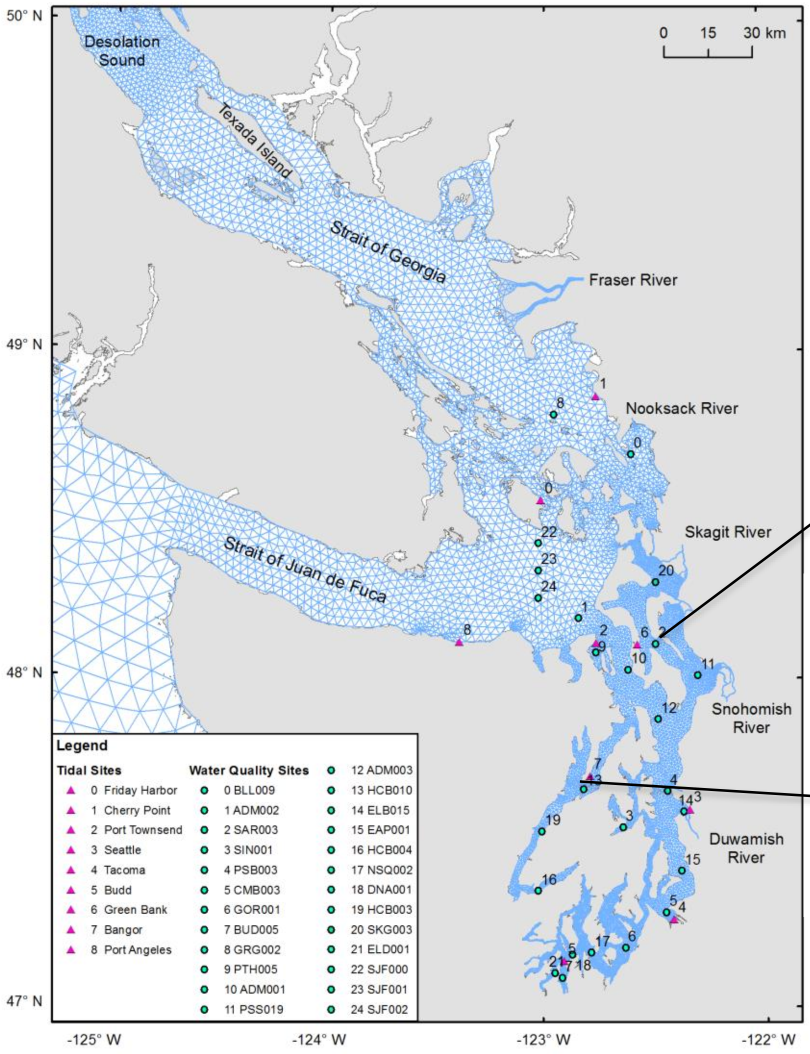
Salish Sea Model (2017)
Hydrodynamic Component

- Expanded Salish Sea Model
  - The NW Straits
  - Vancouver Island
  - Continental shelf
- 18 Major Rivers and 145 fresh water & WWTP point sources
- Additional Rivers (Pacific Ocean)
  - Columbia / Willamette Rivers
  - Chehalis River
  - Willapa River
- Tidal forcing
- Meteorology
  - UW / WRF Model
- Ocean boundary conditions
  - Monitoring data or WOA

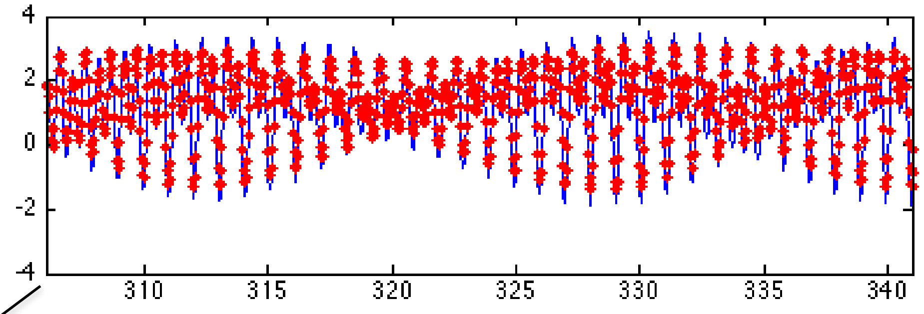


Model Calibration – Tides, S, & T

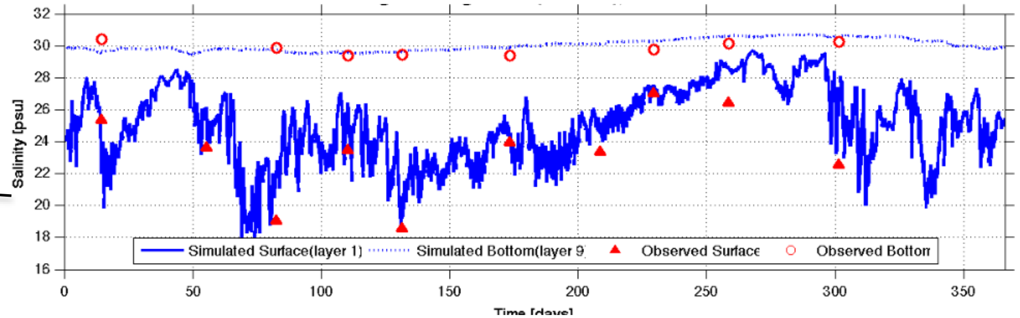
Year 2014

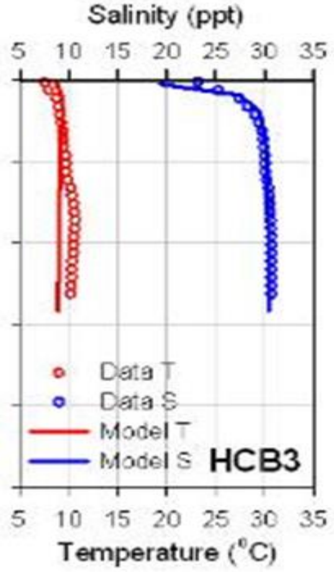


Tides – Greenbank, Whidbey Basin

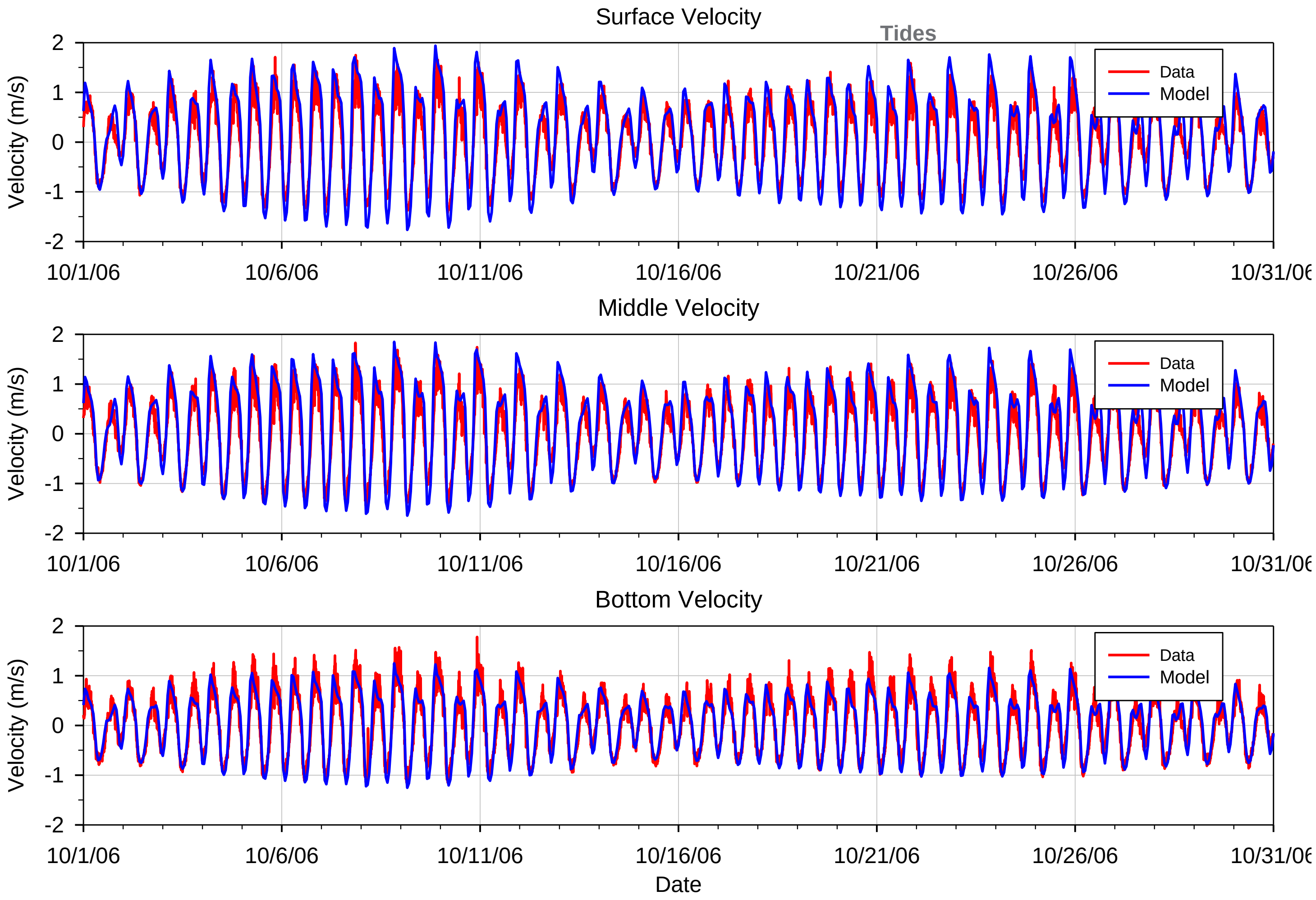


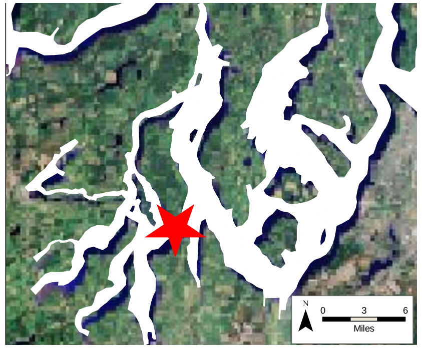
Salinity – Bangor, Hood Canal



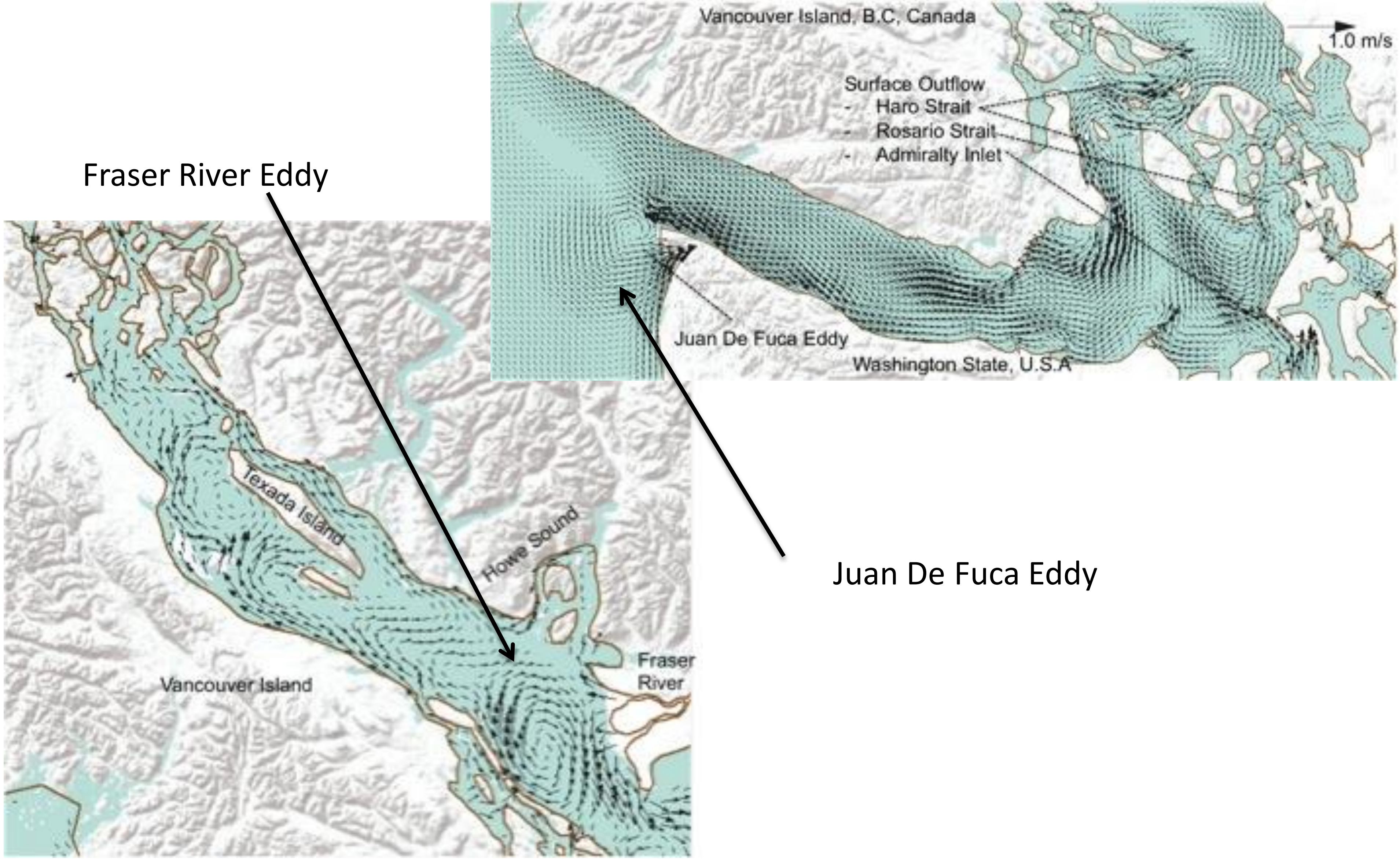


Calibration: Velocity
Dana Passage (example)



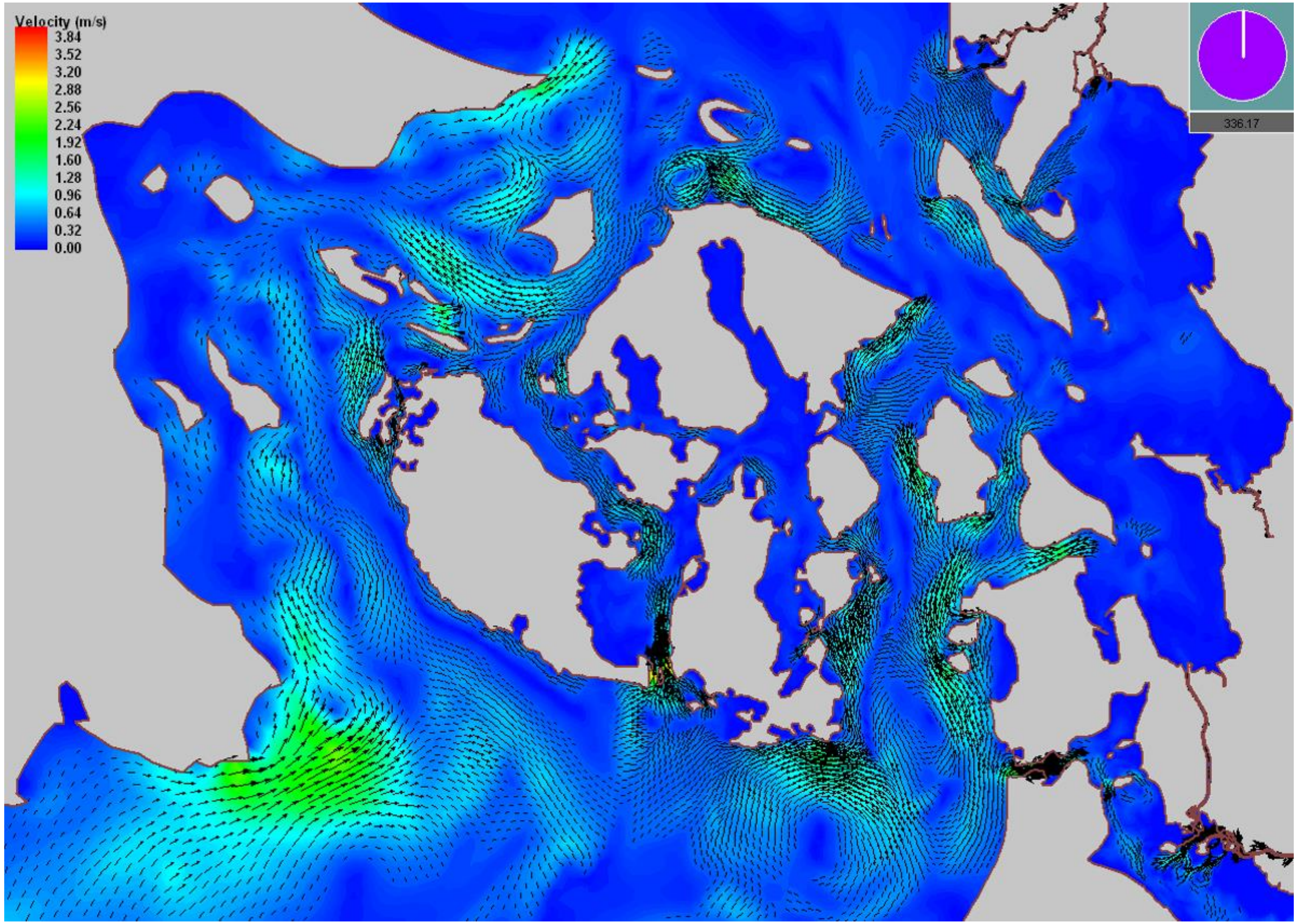


Surface Currents



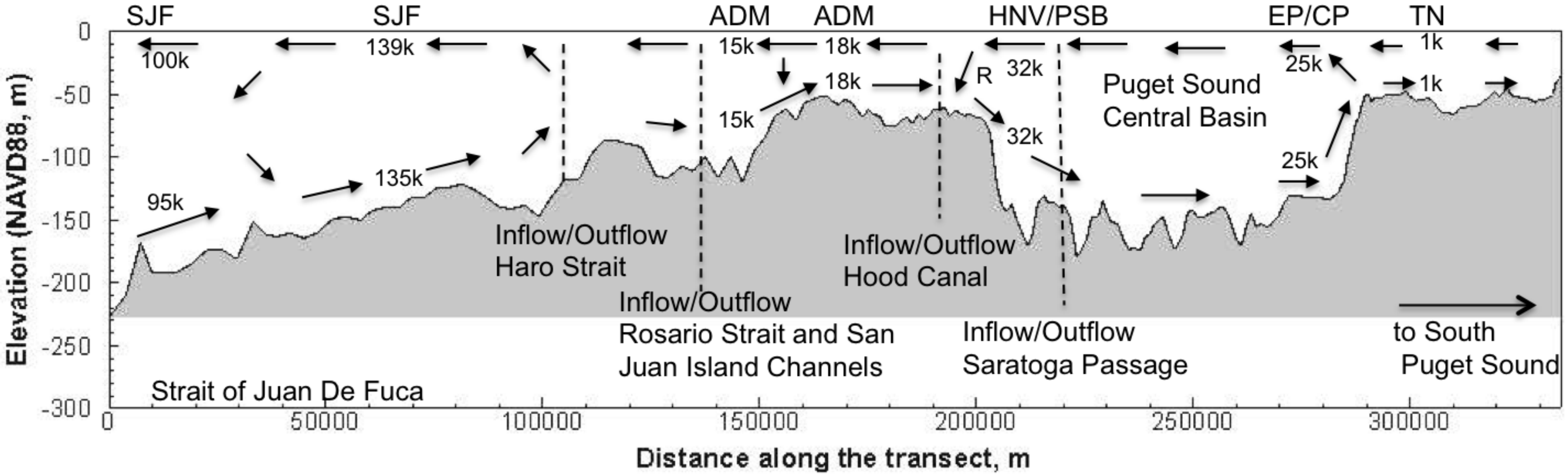
Tidal Currents – San Juan Islands

High Resolution - Subdomain



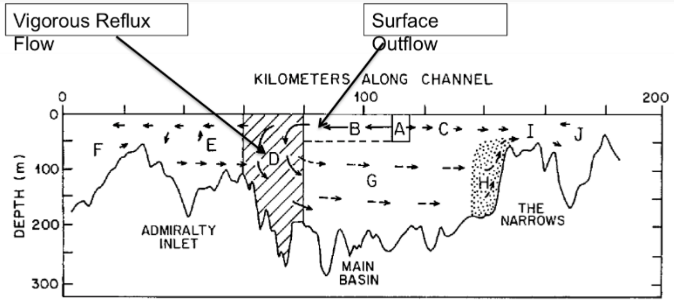
Circulation in the Salish Sea

Puget Sound – Reflux flows



SJF = Strait of Juan De Fuca
ADM = Admiralty Inlet
HARO = Haro Strait
R = Reflux Flow at Admiralty Sill (estimated at 19 k, ≈ 60% of surface outflow)

HNV/PSB = Hansville, Puget Sound
EP/CP = East Passage / Colvos Passage
TN = Tacoma Narrows



Reflux Flow ≈ 2/3rd Surface Outflow

“Circulation in Embracing Sills”
- Ebbesmeyer et al. 1984

Simulated Surface Constituents (2006)

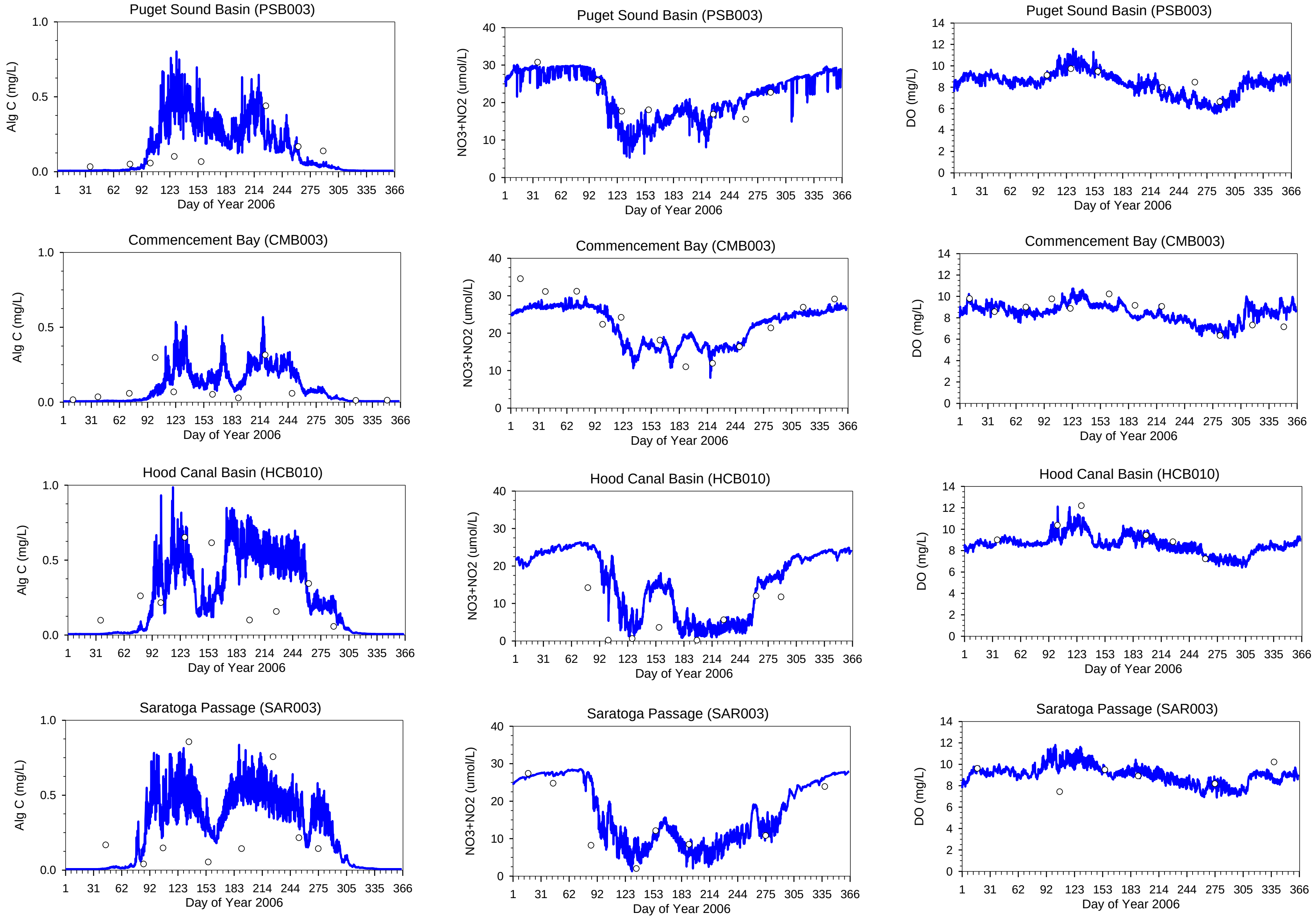
Pacific Northwest NATIONAL LABORATORY

Proudly Operated by **Battelle** *Since 1965*

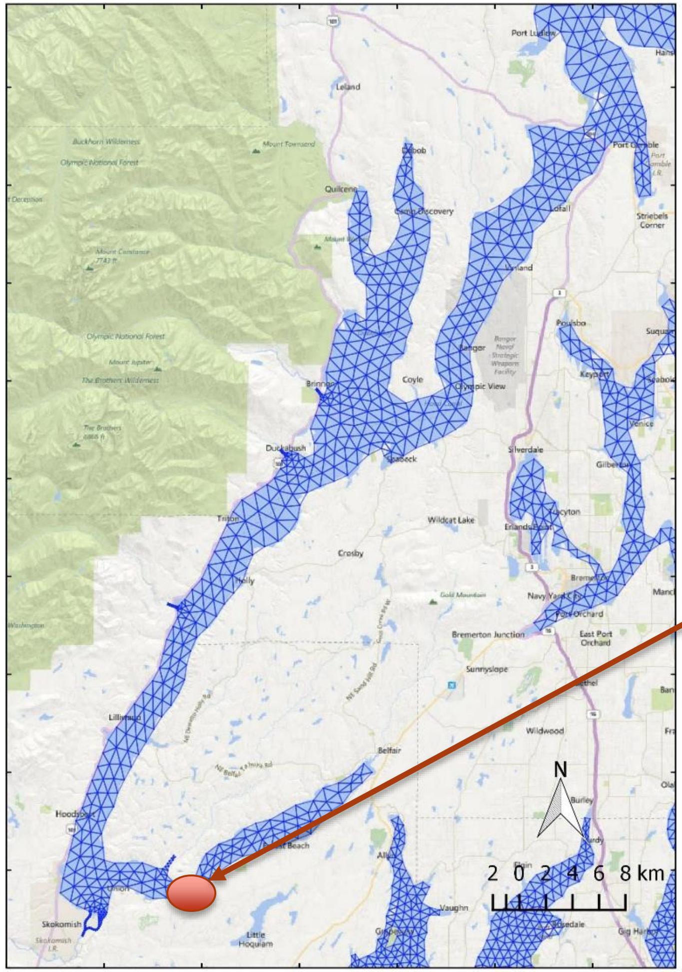
Algae

NO3+NO2

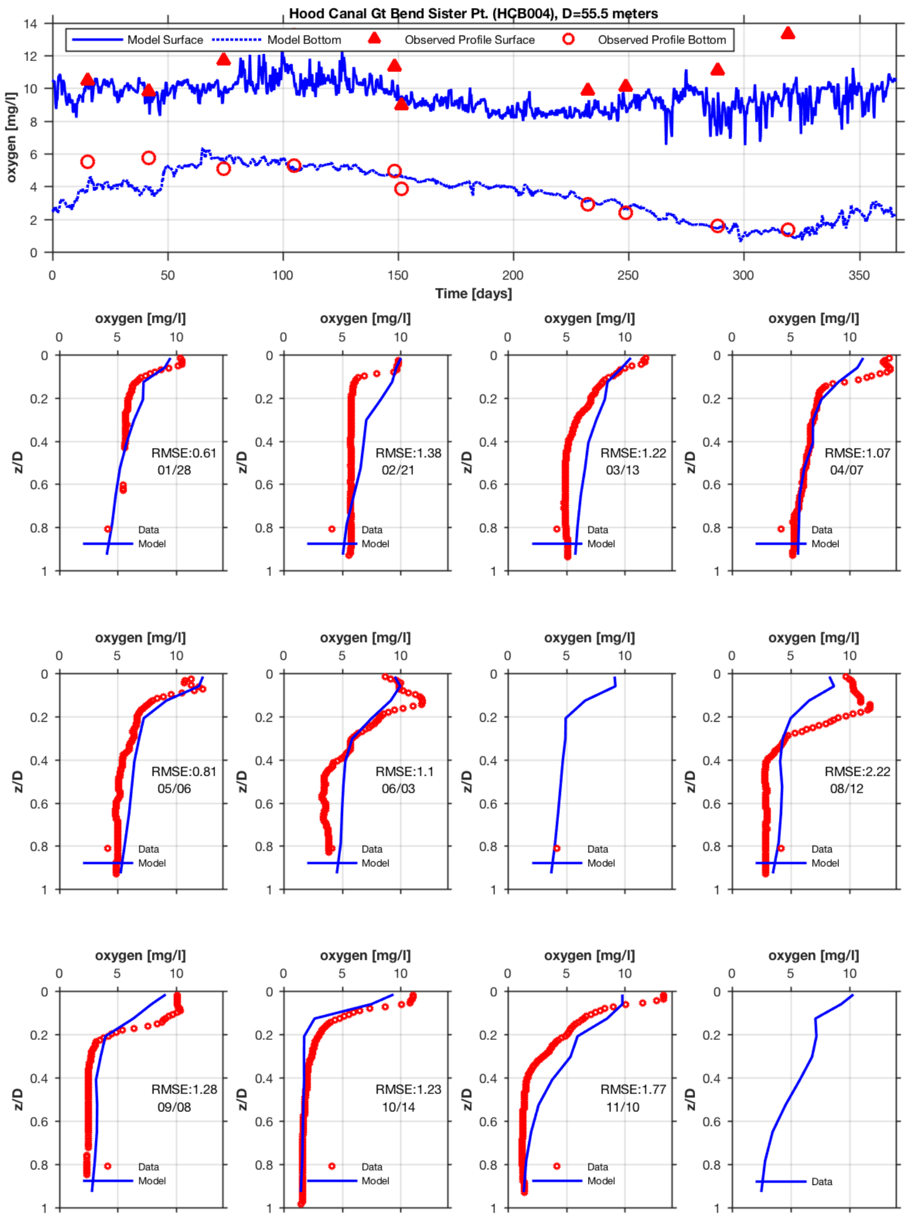
DO



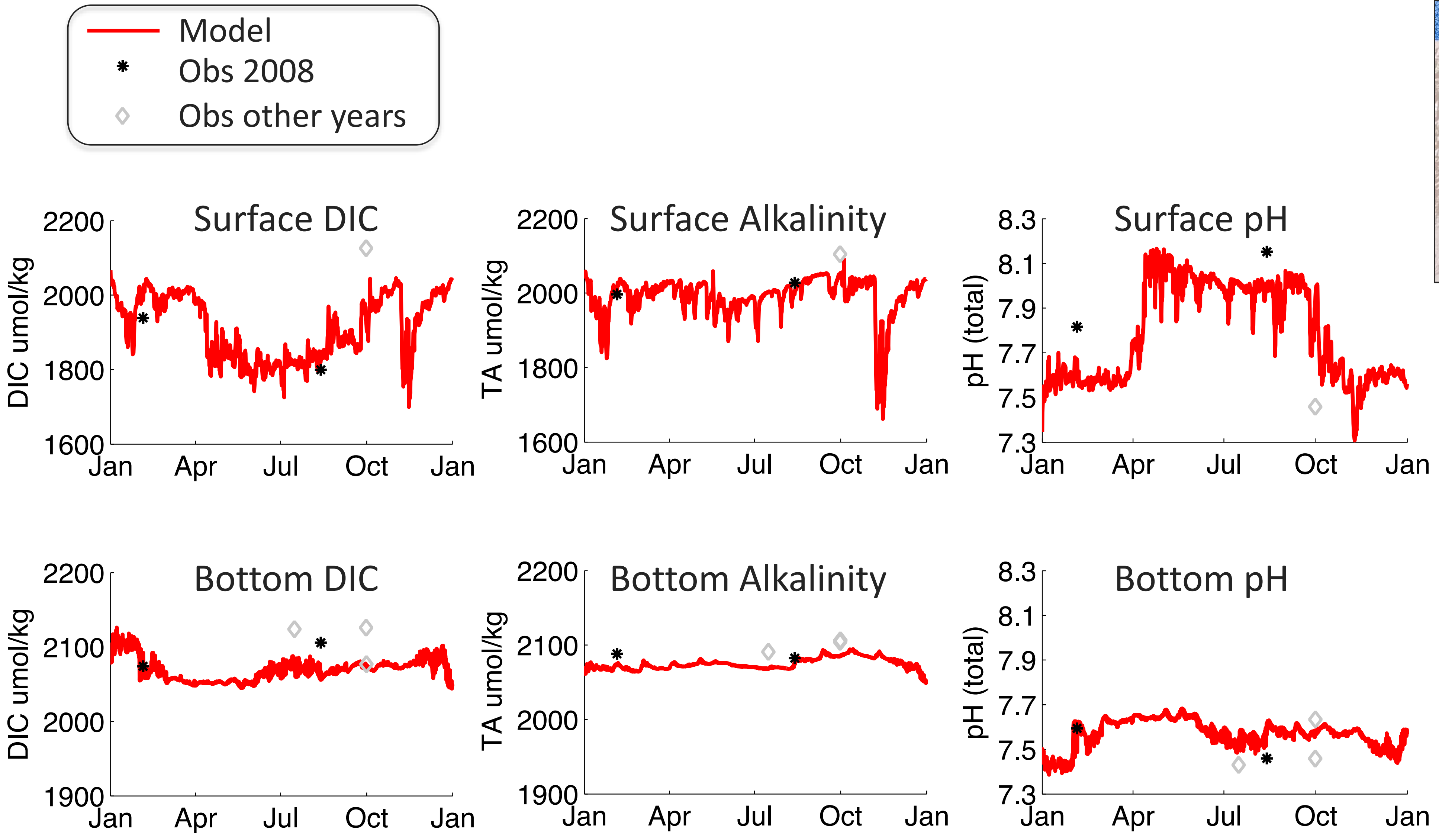
Simulation of Hypoxia - Hood Canal

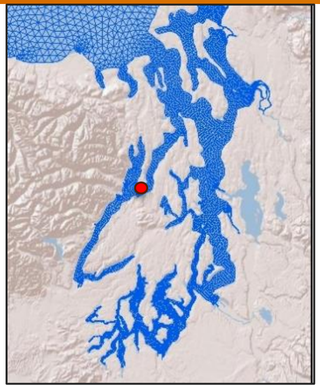


Lynch Cove, Hood Canal –
Ecology Station HCB004



The model can predict ocean acidification





Representative Model Error Statistics

Hydrodynamics

Tides

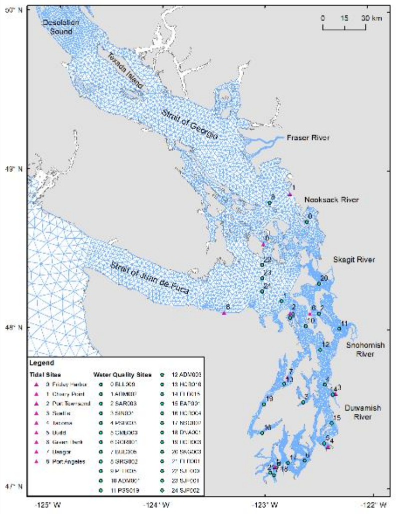
ME (m)	MAE (m)	RMSE (m)	RME (%)
-0.03	0.29	0.35	**7.8%**

Salinity

ME (ppt)	RMSE (ppt)
0.35	**1.2**

Temperature

ME (°C)	RMSE (°C)
0.32	**0.83**



Water Quality

DO

ME (mg/L)	RMSE (mg/L)
0.35	**0.99**

Nitrate

ME (ug/L)	RMSE (uM/L)
0.99	**6.53**

Algae (Chl – *a*)

ME (ug/L)	RMSE (ug/L)
0.82	**4.37**

Phosphate

ME (mg/L)	RMSE (mg/L)
-0.69	**0.94**

pH

ME	RMSE
0.12	**0.21**

Salish Sea Model summary

- Hydrodynamic Model of Salish Sea
  - http://salish-sea.pnnl.gov/
- Expanded Domain Improvement
  - Validation of the Circulation in Embracing Sills concepts proposed by Ebbesmeyer and Barnes (1980)
    - Nearly 2/3rd of surface outflow is refluxed back to Puget Sound near the Admiralty Inlet sill
- Biogeochemical Model of Salish Sea
  - Nutrients, phytoplankton (two algae groups) and carbon
  - Sediment diagenesis
  - Carbonate chemistry – alkalinity and pH

[Khangaonkar & Wang (2013) – *Appl. Ocean Research*]
[Khangaonkar et al. (2011) – *Estuary Coast and Shelf Science*]
[Yang and Khangaonkar. (2010) – *Ocean Dynamics*]

[Khangaonkar et al. (2017) – *Ocean Modelling*]

[Khangaonkar et al. (2016) - *Northwest Science*]
[Kim and Khangaonkar. (2011) – *Environmental Modelling Software*]

[Khangaonkar et al. (2012) – *Ocean Dynamics*]

[Bianucci et al. (2017 *submitted*)]

`

EPA United States Environmental Protection Agency

Fisheries and Oceans Canada

US Army Corps of Engineers

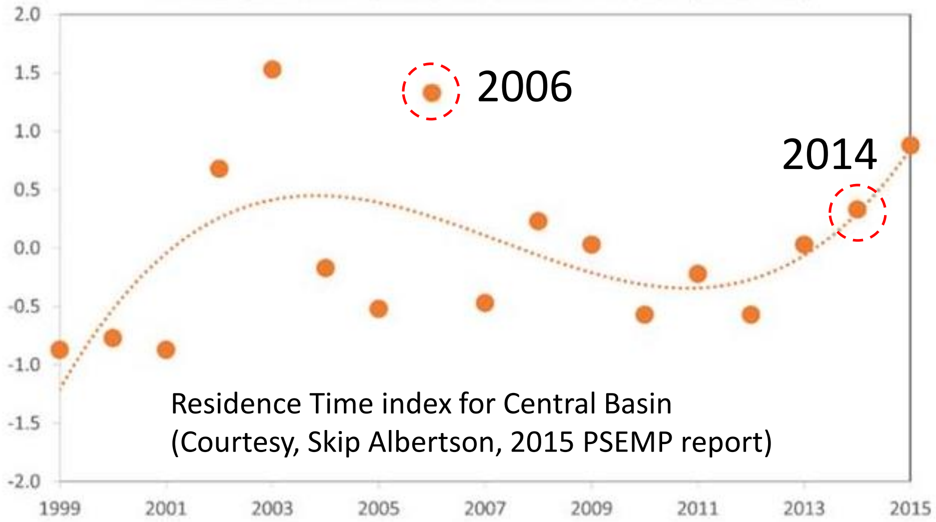
USGS science for a changing world

Residence Times in Salish Sea

How long a mass of water stays at a certain location?

Longer residence times promotes :

a. Buildup of pollutant concentrations
b. Increased productivity and depletion of nutrients
c. Oxidation of ammonia to nitrate which depletes oxygen
d. Decomposition of organic carbon (dead algae) by heterotrophic bacteria which deplete oxygen
e. hot spots for biogeochemical stressors



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

Anise Ahmed

Pacific Northwest NATIONAL LABORATORY

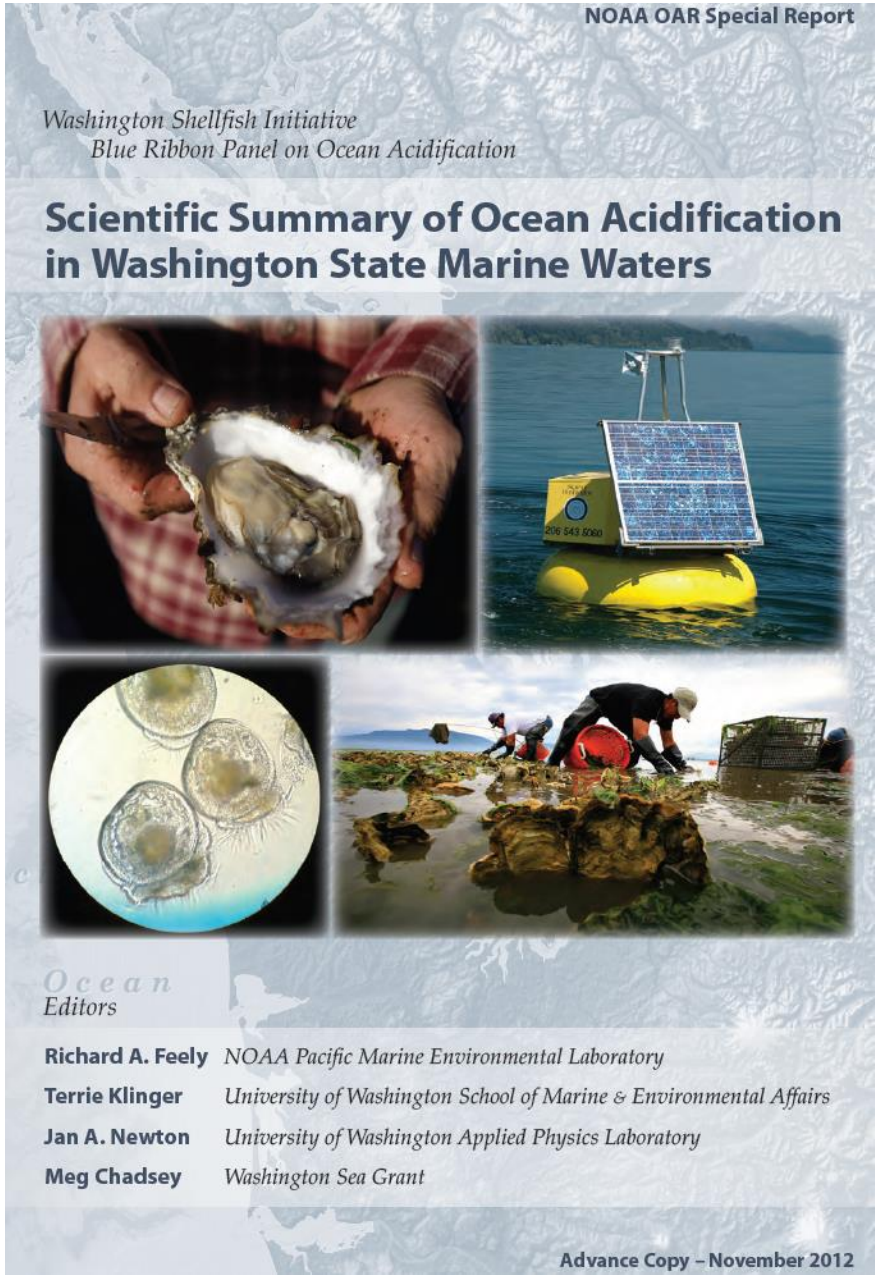
DEPARTMENT OF ECOLOGY State of Washington

Washington Shellfish Institute:
Blue Ribbon Panel on Ocean Acidification, 2012

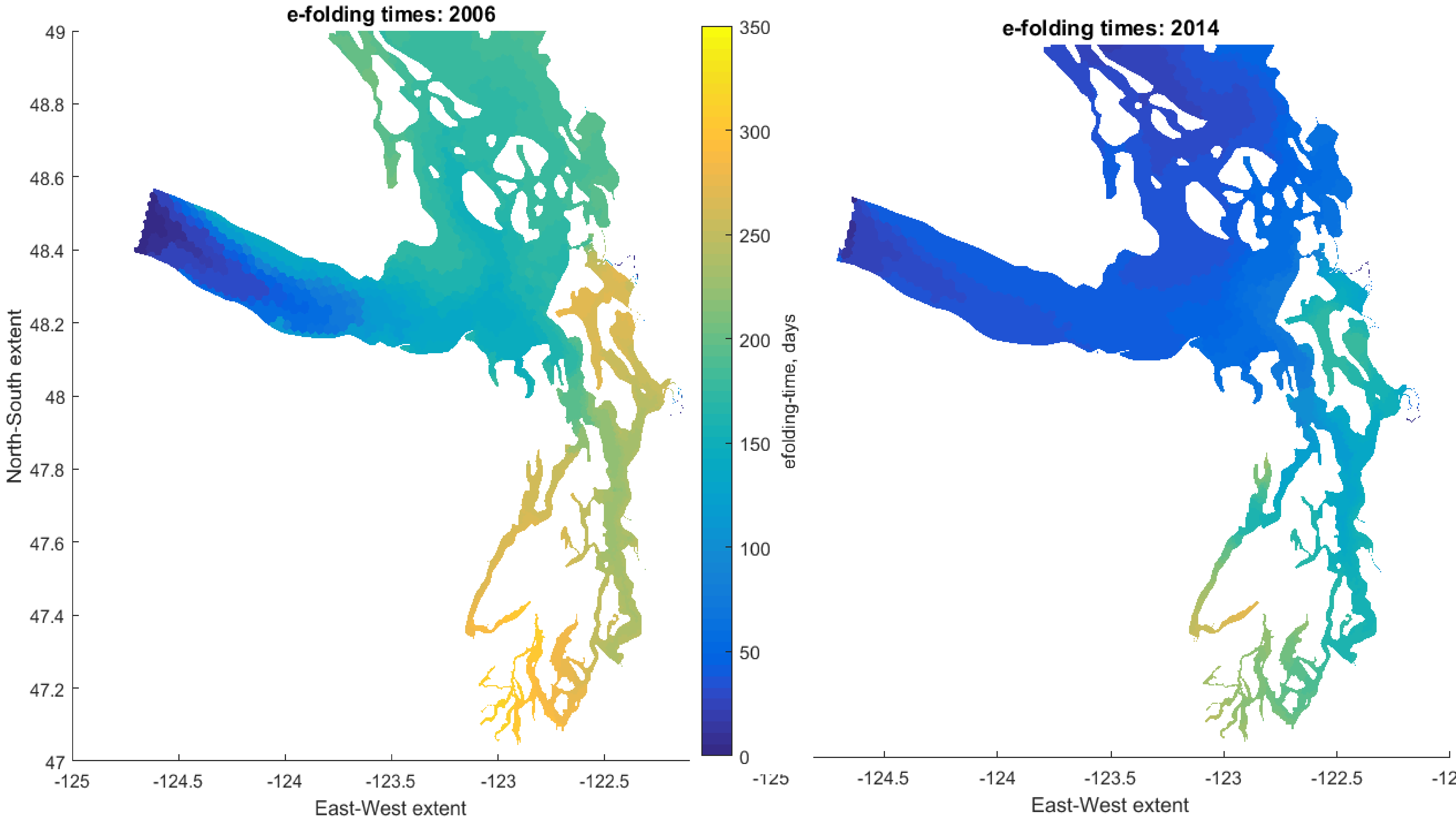
“ **What is *not* known** is the magnitude of the effect that the anthropogenic nitrogen inputs have on pH or aragonite saturation levels.

Resolving this issue is not trivial; **it will require new knowledge of residence times**, export production (the amount of particulate organic carbon that sinks out of the euphotic zone and is remineralized at depth), and oceanic boundary conditions (baseline pH and carbon species signals from the coast).”

“Basins with strong stratification and **long residence times** should be the most susceptible to land-based and human sourced inputs of nitrogen”.

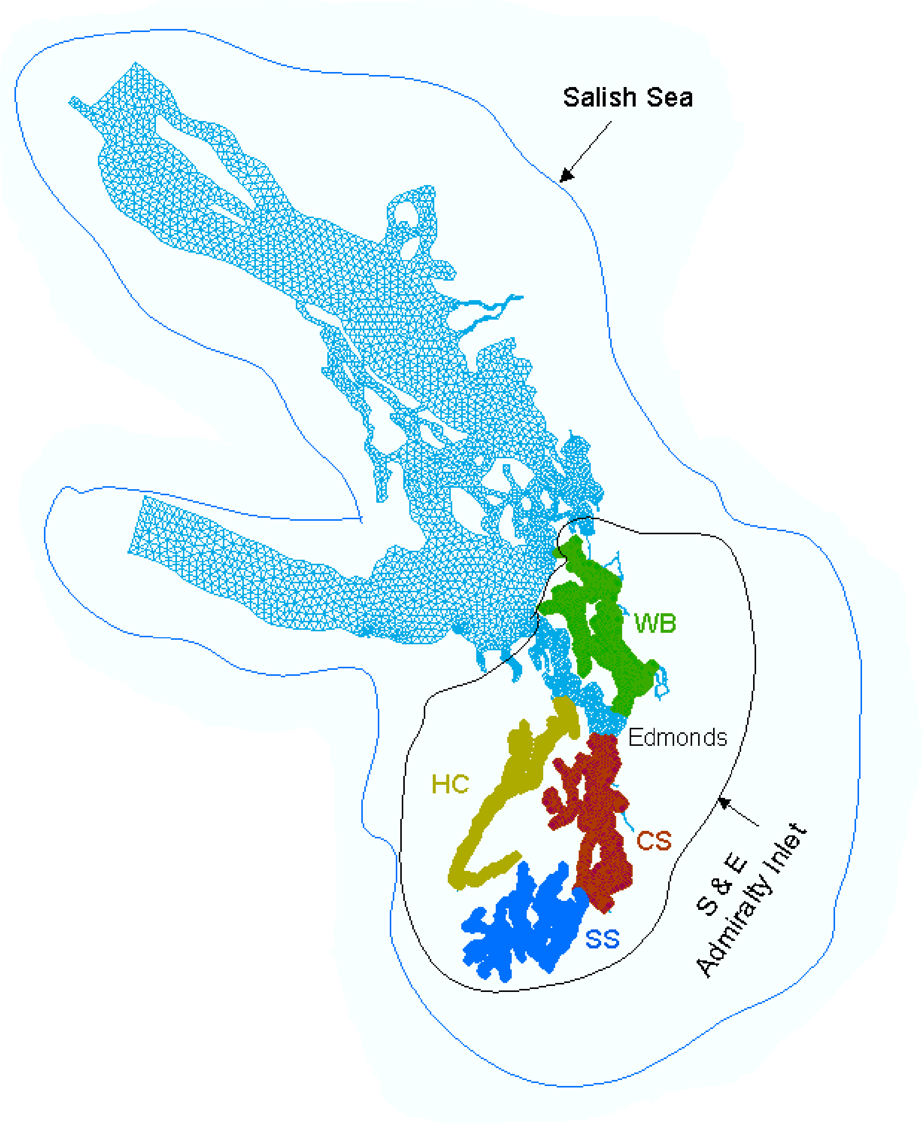


https://pmel.noaa.gov/co2/files/wa_shellfish_initiative_blue_ribbon_panel_oa_11-27-2012.pdf



e-folding times: 2006
e-folding times: 2014
North-South extent
East-West extent
East-West extent
efolding-time, days
49
48.8
48.6
48.4
48.2
48
47.8
47.6
47.4
47.2
47
-125
-124.5
-124
-123.5
-123
-122.5
0
50
100
150
200
250
300
350

Residence times in different basins, days



Annual average flows, cms		
Fraser	2179	2940
Skagit	470	574
Stillaguamish	274	320

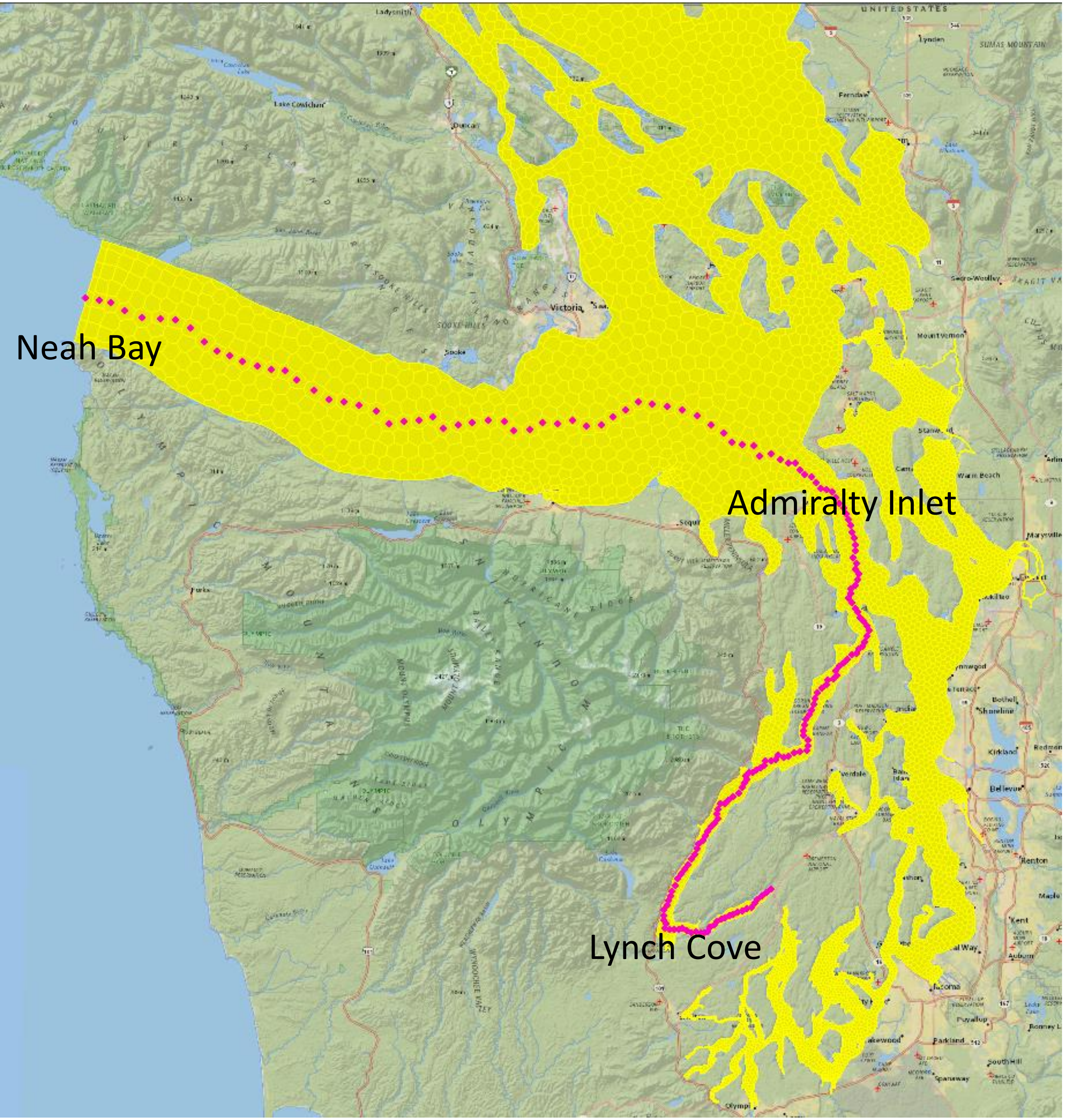
Basin	2006	2014
Salish Sea	160	54
South Sound	289	208
South & Central *	249	165
Whidbey Basin	258	154
Hood Canal	261	181
South & East Admiralty	249	158

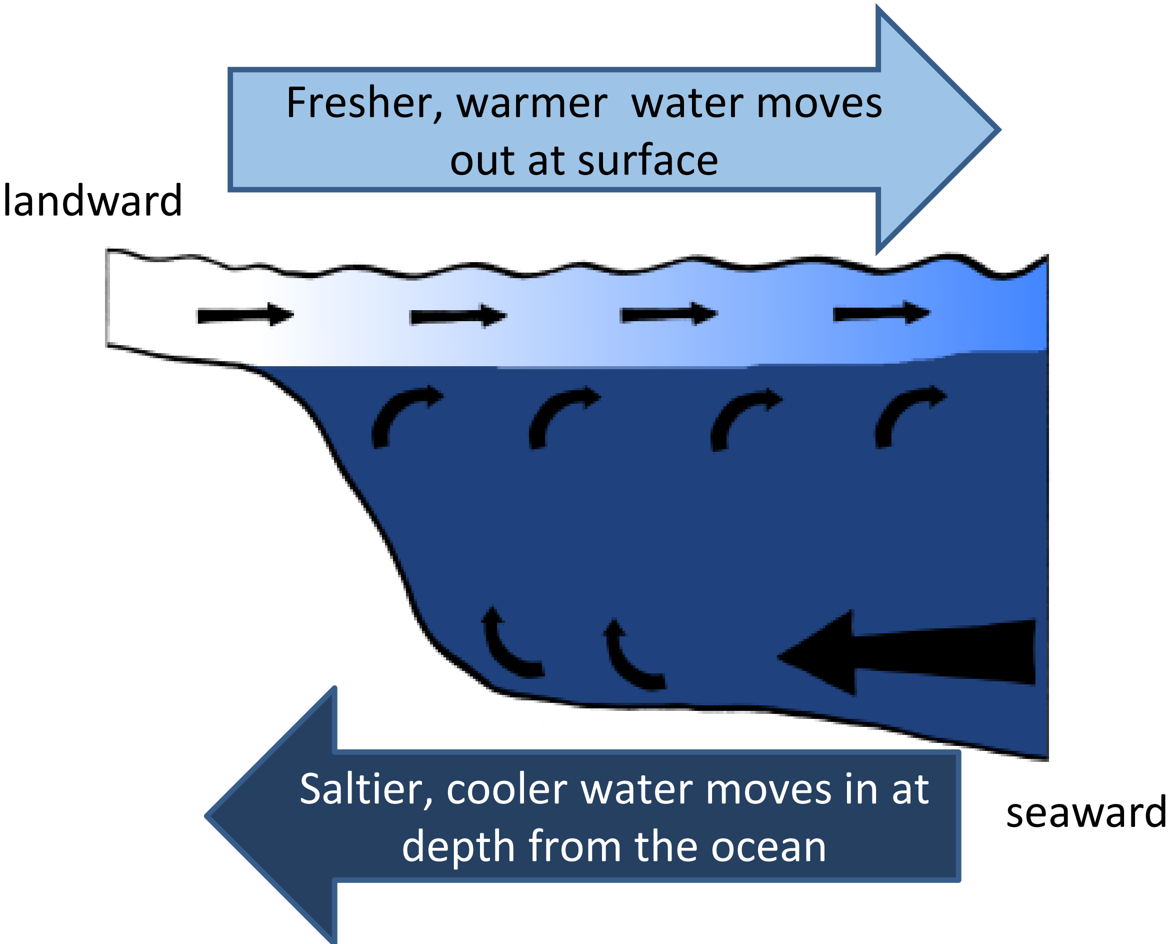
* South of Edmonds

Thalweg animation:

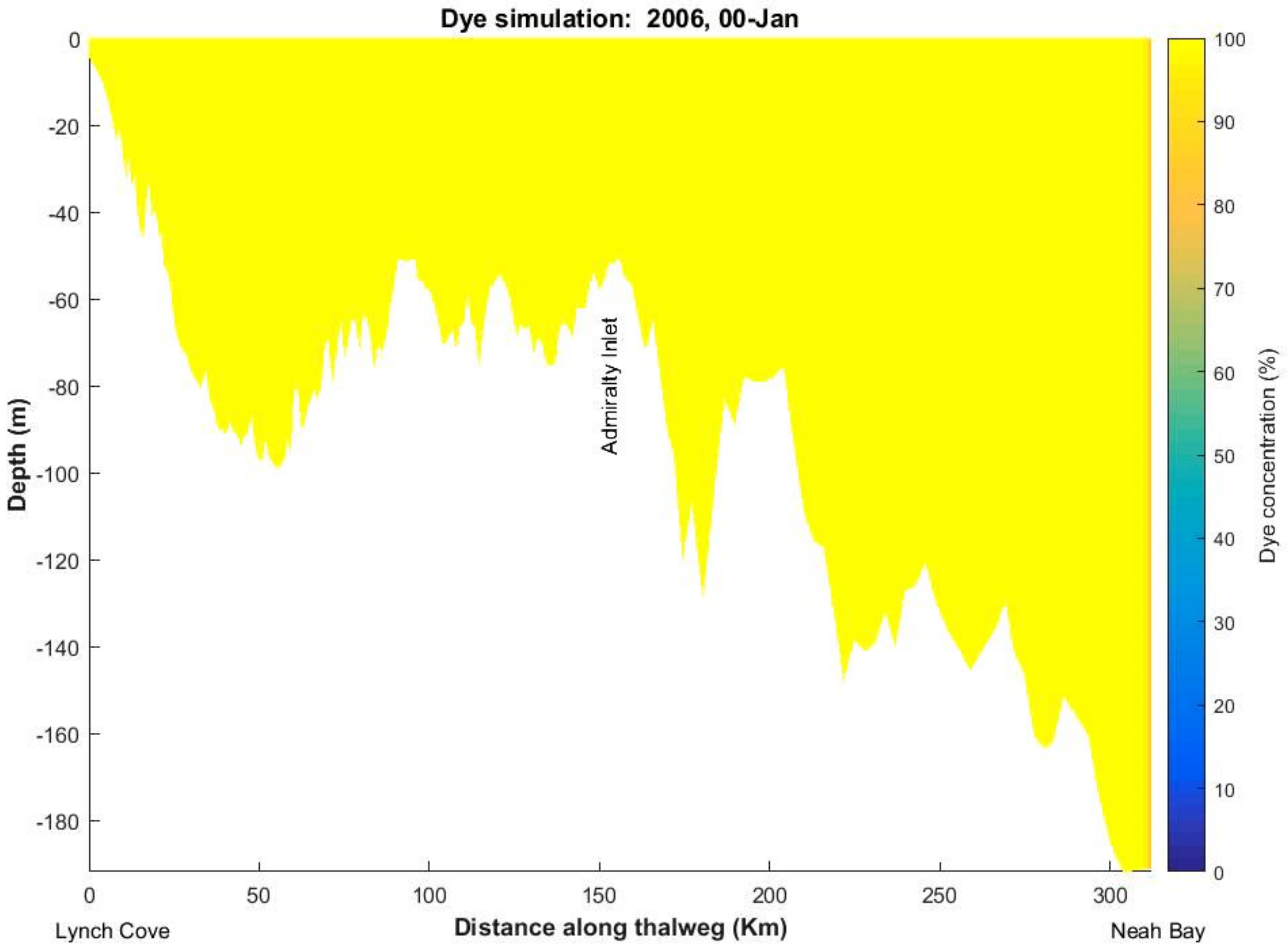
Lynch Cove to Neah Bay

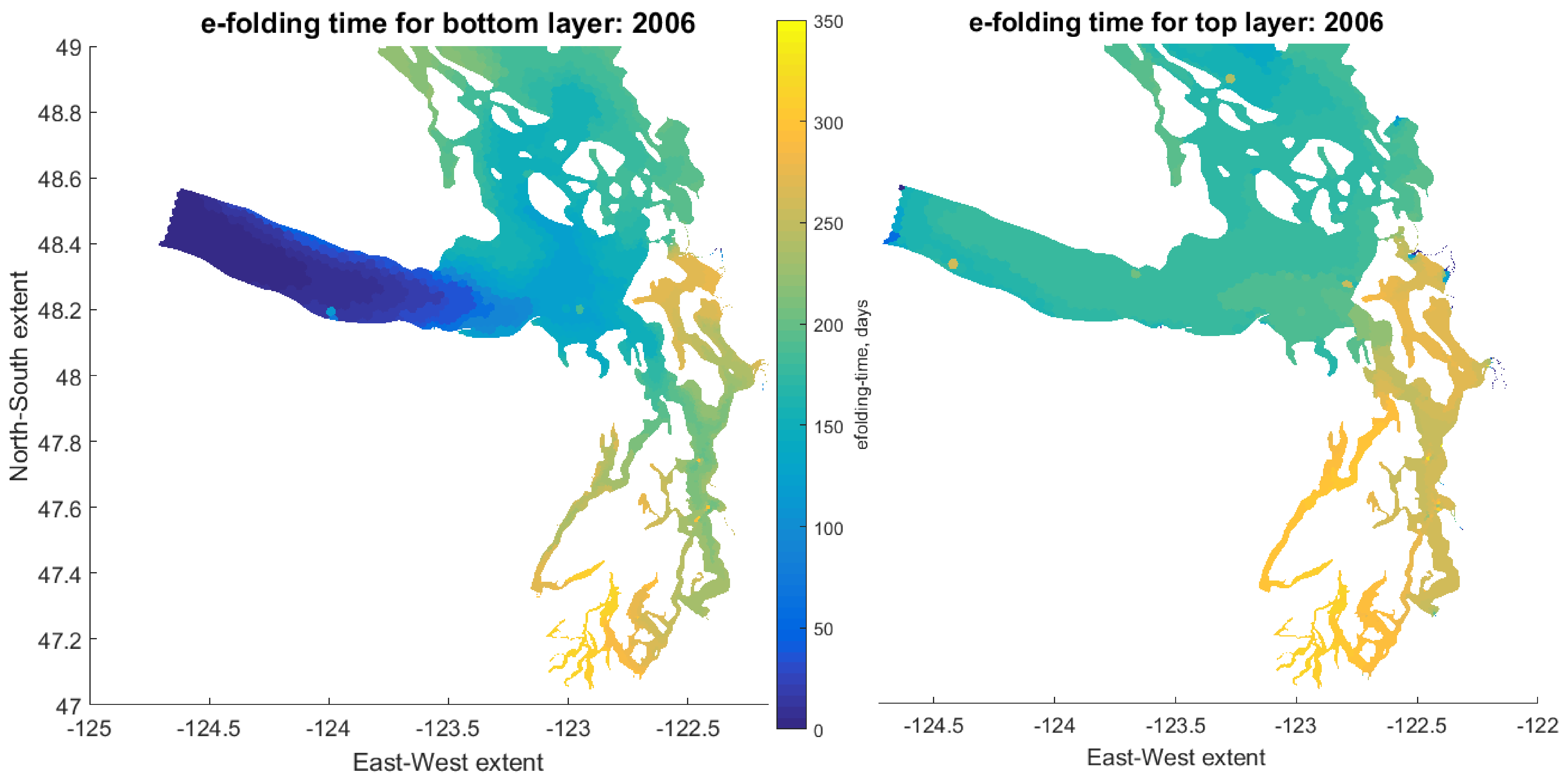
(residence times in bottom and surface layers)





Lynch Cove – Neah Bay Thalweg dye animation




e-folding time for bottom layer: 2006
e-folding time for top layer: 2006
North-South extent
East-West extent
East-West extent
efolding-time, days
49
48.8
48.6
48.4
48.2
48
47.8
47.6
47.4
47.2
47
-125
-124.5
-124
-123.5
-123
-122.5
-122
350
300
250
200
150
100
50
0

Conclusions

1. Longer residence times occur in remote inlets and “trapped” basins
2. In general, longer residence times occur for surface waters compared to bottom waters
3. Longer residence times occur with poor estuarine circulation from low freshwater flows
4. We can now use the Salish Sea model as tool to quantify residence times for any portion of the model domain or year.
5. Residence time maps show us areas that are susceptible to biogeochemical stressors, and can be made available to the scientific community

Puget Sound Nutrient Loading

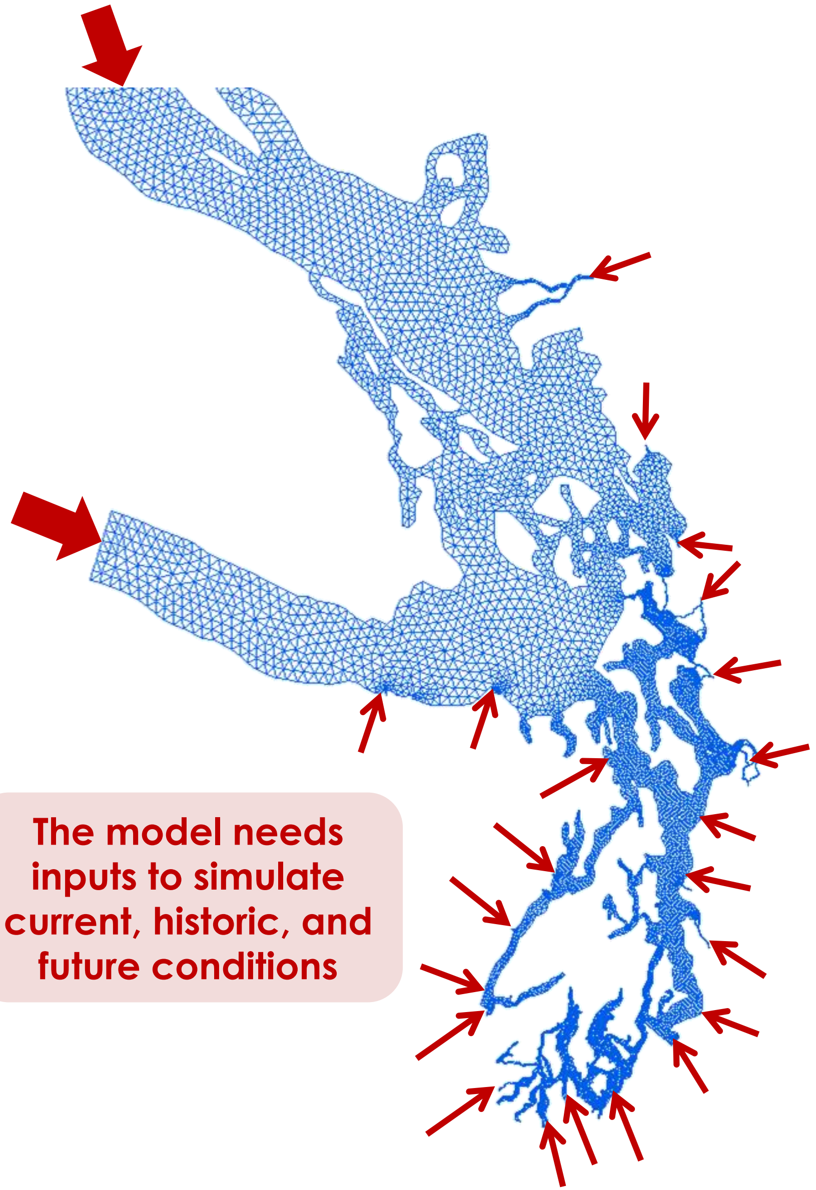
SOURCES AND MAGNITUDES


PHOTO COURTESY:
Marine Monitoring Unit, WA State Dept. of Ecology

Teizeen Mohamedali, P.E.

Puget Sound Nutrient Dialogue
July 19, 2017

Nutrients entering the Salish Sea Model



The model needs inputs to simulate current, historic, and future conditions

Sources of Loading?

+

Magnitude of loading?

+

Timing of loading?

What happens when these loads enter Puget Sound?

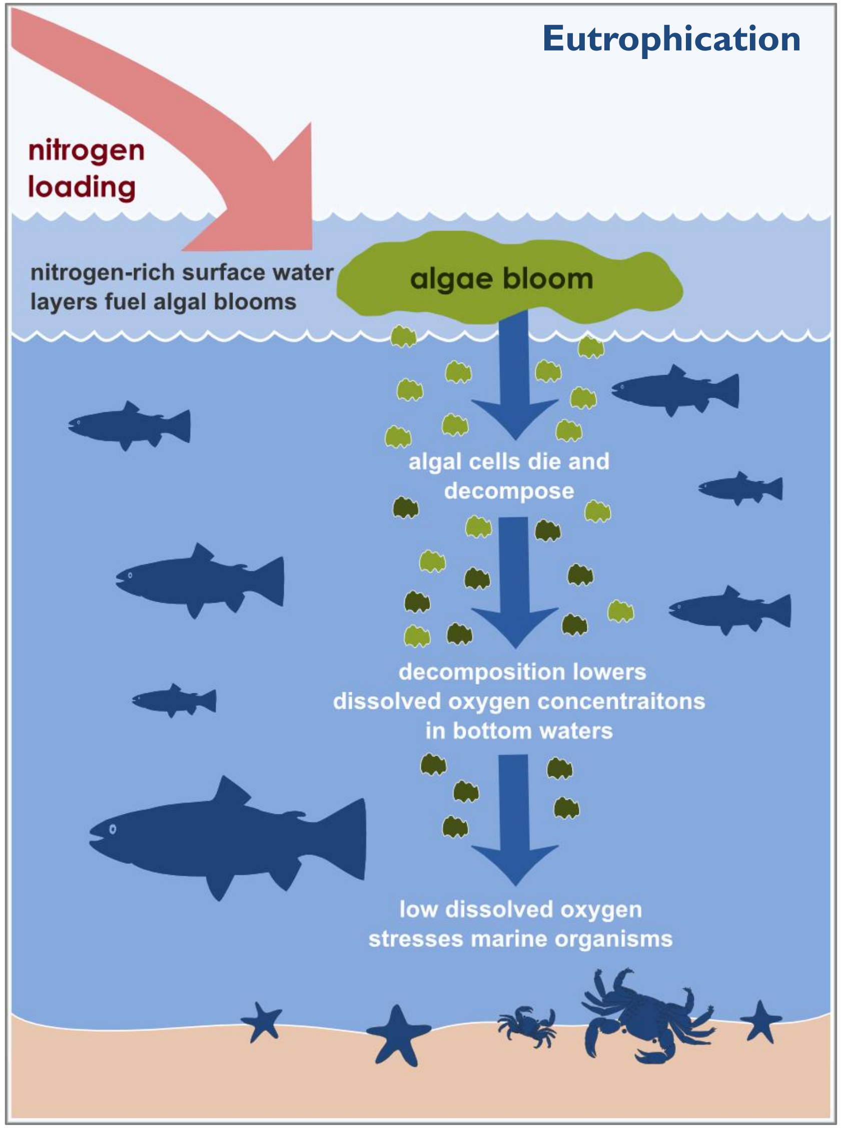
What proportion of modeled effects are caused by human activities?

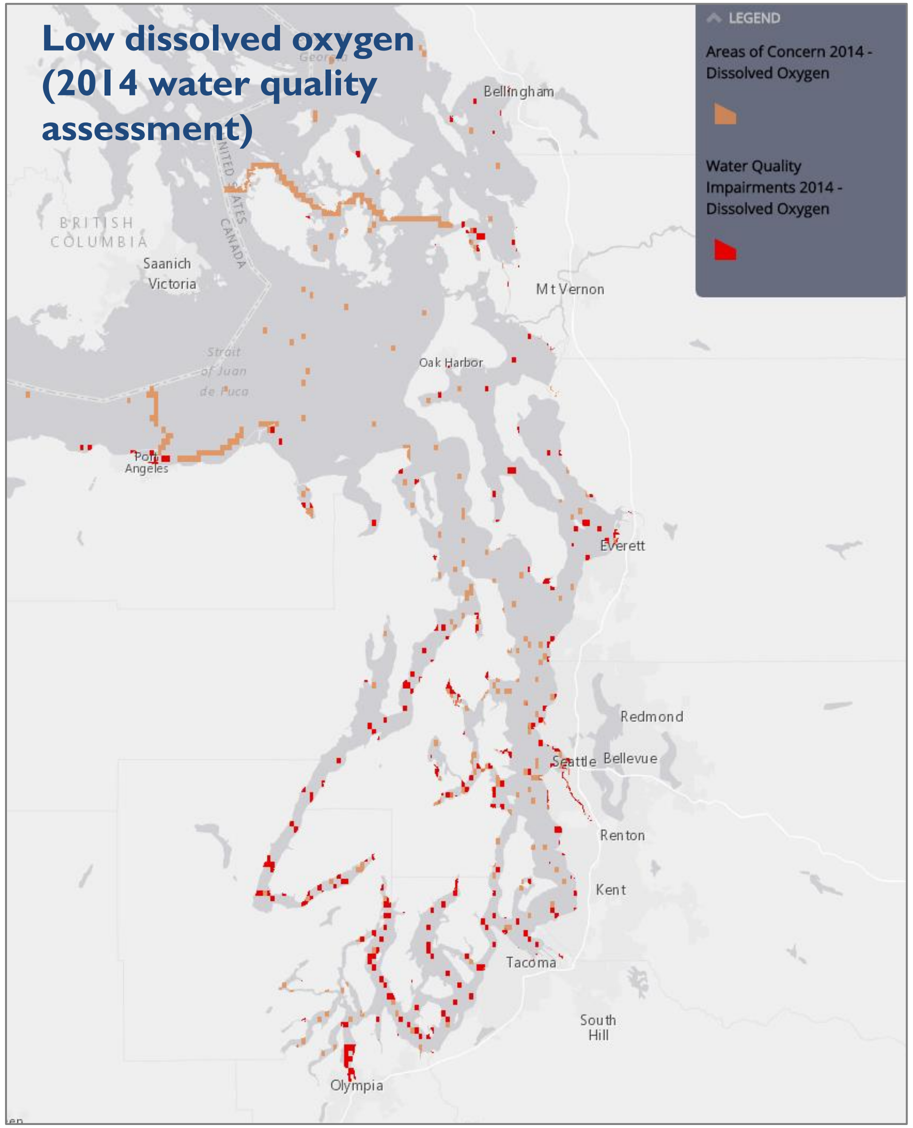
Nutrient parameters

- Model includes a full suite of water quality parameters, including:
  - nitrogen
  - phosphorus
  - carbon
- Both nitrogen and carbon parameters affect oxygen levels and acidification parameters and were both modified in the estimate of reference conditions
- Focus on this presentation is on inorganic nitrogen – limiting nutrient in growing season
- But, model results also show that organic carbon from human sources also plays a role

Parameter Name	Parameter Abbreviation
Measured Parameters	
Nitrate + Nitrite	NO23N
Ammonium	NH4N
Total Persulfate Nitrogen	TPN
Dissolved Total Persulfate Nitrogen	DTPN
Ortho-Phosphate	OP
Total Phosphorus	TP
Dissolved Total Phosphorus	DTP
Total Organic Carbon	TOC[1]
Dissolved Organic Carbon	DOC[1]
Calculated Parameters	
Dissolved Inorganic Nitrogen	DIN
Particulate Organic Nitrogen	PON
Dissolved Organic Nitrogen	DON
Particulate Organic Phosphorus	POP
Dissolved Organic Phosphorus	DOP
Particulate Organic Carbon	POC

Excess nutrients are a problem



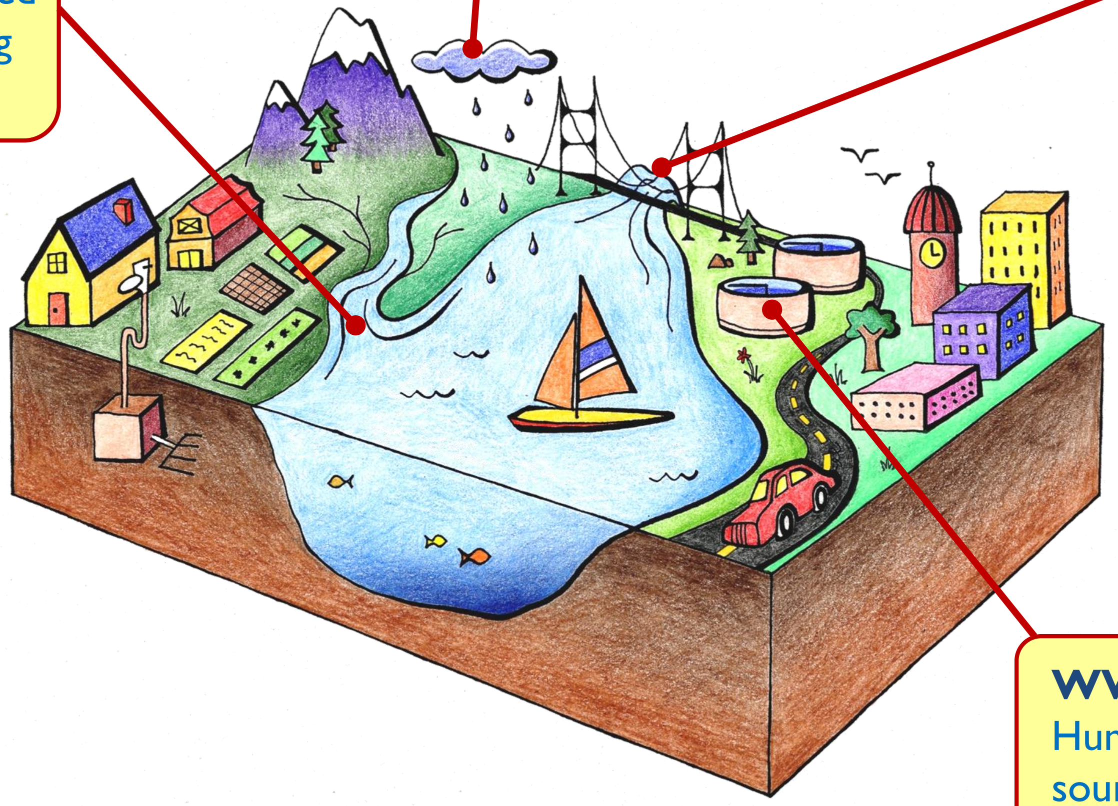


Sources of nutrients

Atmospheric Deposition
Deposition of atmospheric nutrients (from natural sources plus emissions) onto watersheds and directly onto marine waters

Rivers
Includes all upstream sources that drain into rivers, and are transformed by stream dynamics, before entering Puget Sound at their mouths

Net Ocean Exchange
Nutrients from the Pacific Ocean and Puget Sound get exchanged at the Strait of Juan de Fuca and Admiralty Inlet



Sources included implicitly:

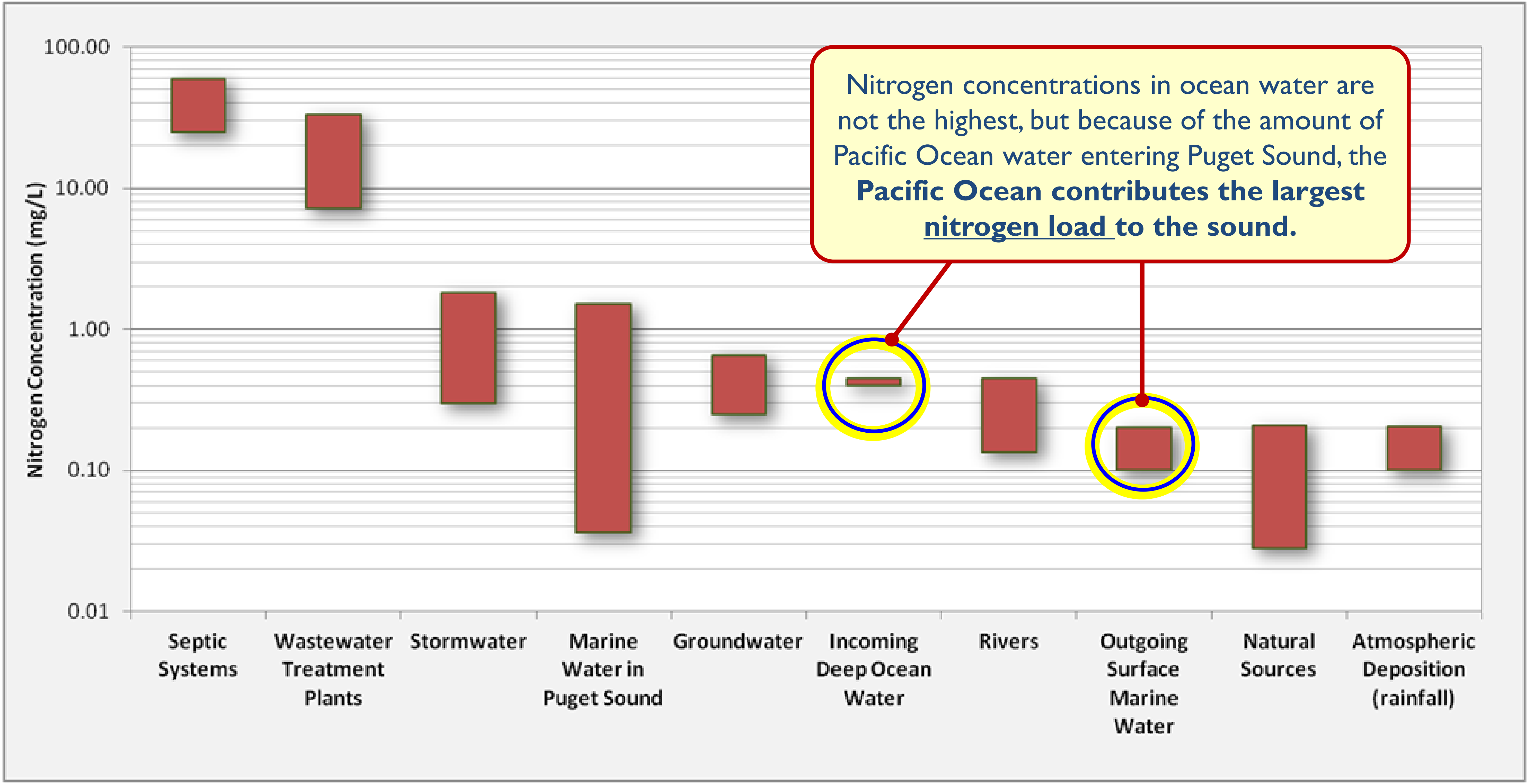
- near-shore septic systems
- direct marine discharge of groundwater

Sources not included:

- net pens
- vessel discharges
- Combined sewer outflows

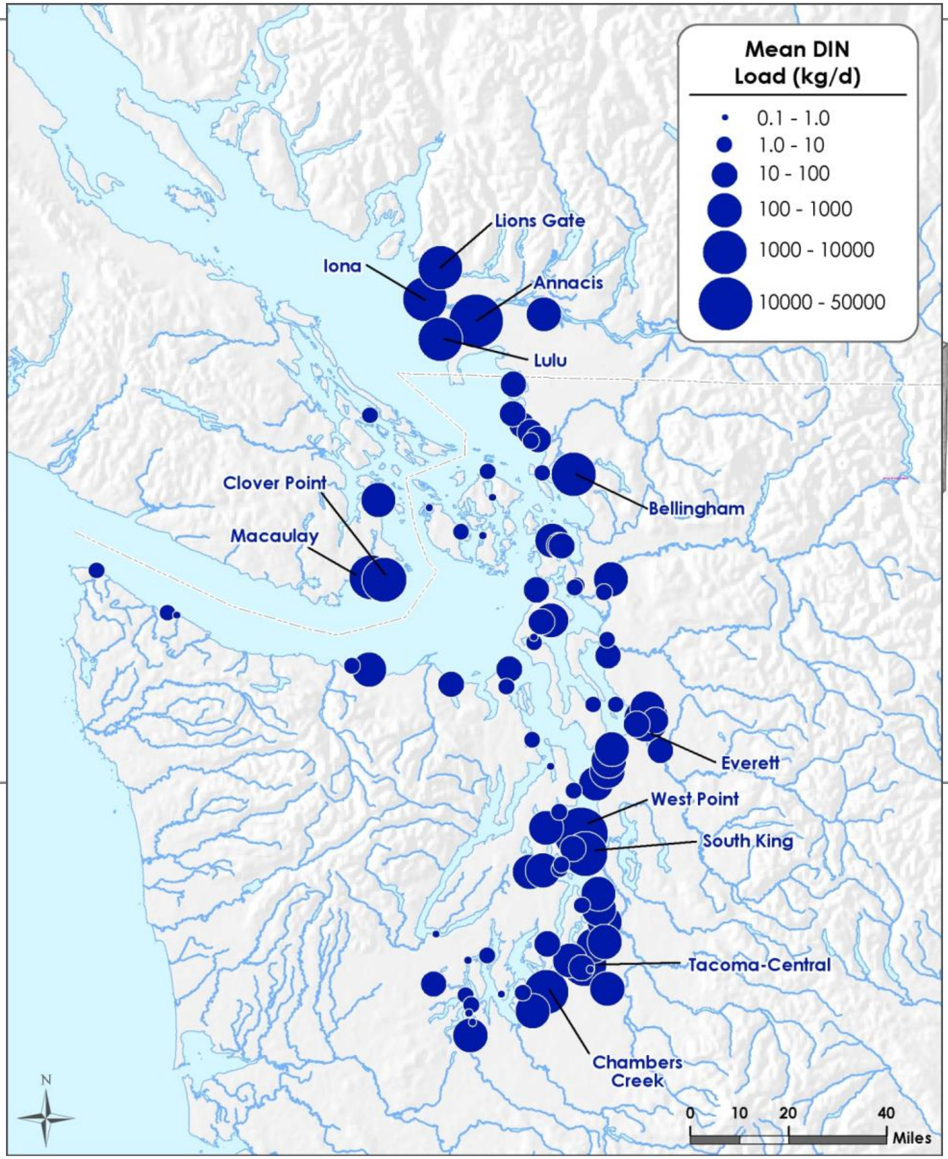
WWTPs + other point sources
Human wastewater and industrial point sources with outfalls in marine waters

Nitrogen concentrations



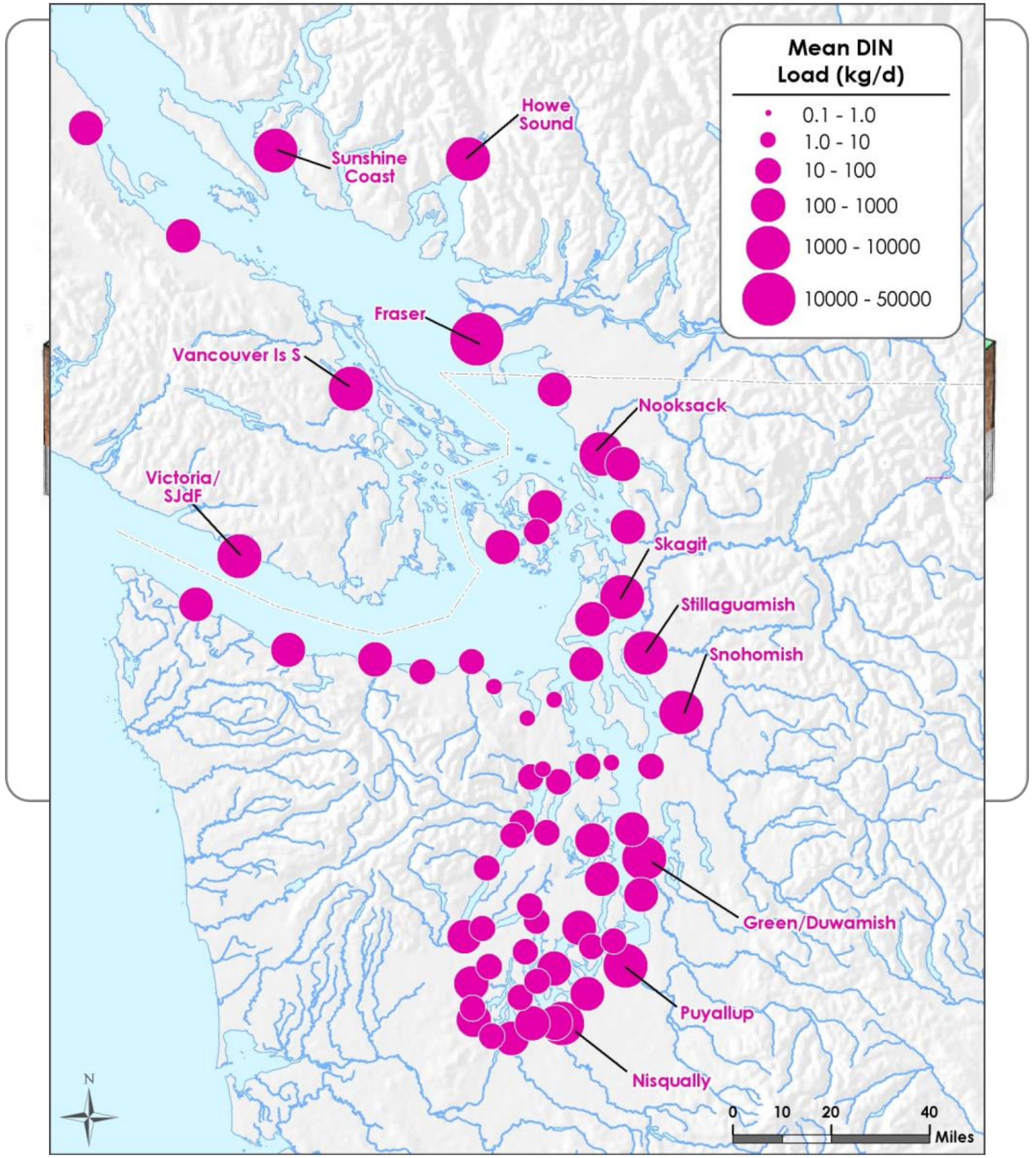
Nitrogen from point sources

- All facilities that have outfalls in marine waters
- Model includes discharges from:
    - 78 US wastewater facilities
    - 10 US industrial facilities
    - 9 Canadian wastewater facilities
- Largest DIN loads coincide with the largest population centers



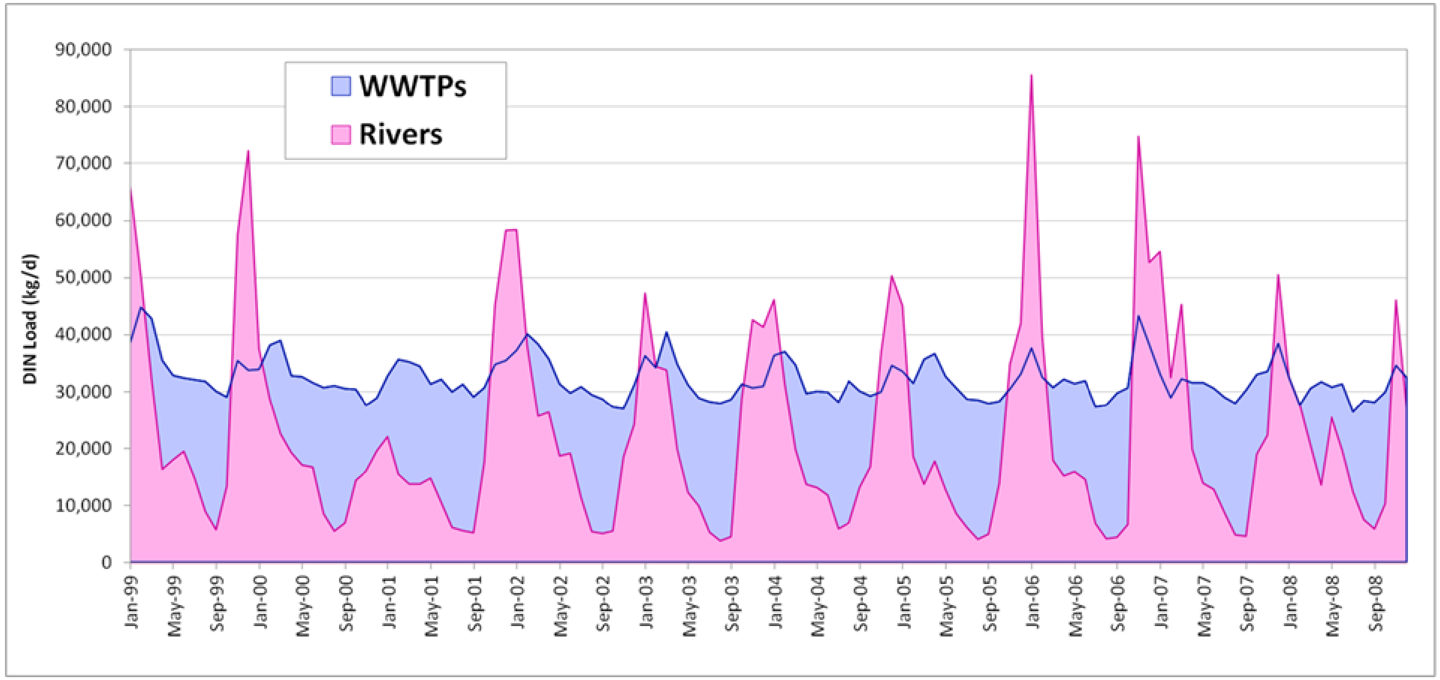
Nitrogen from nonpoint sources

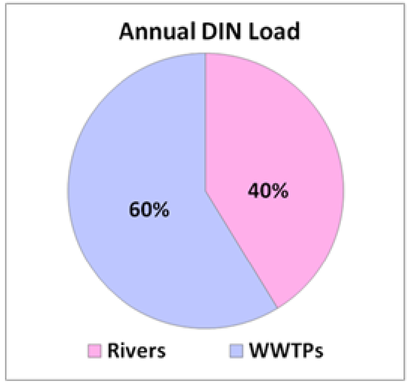
- Model needs nutrients entering the model domain from all watersheds/river/nonpoint sources
- **Estimates shown are at the mouth of each river and stream and include all upstream sources:**
  - Stormwater runoff
  - Livestock manure
  - Agricultural and urban fertilizer application
  - Natural sources
  - Watershed septic systems
  - Point sources with outfalls in rivers/streams
  - Groundwater baseflow in streams
- Further source tracking studies may be necessary to identify upstream nutrient reduction strategies

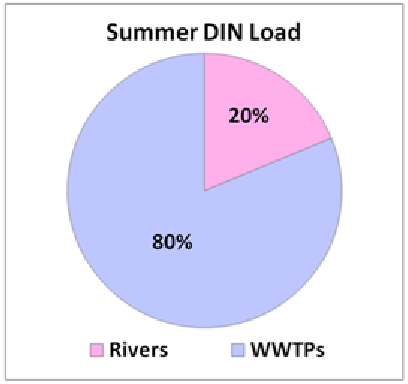


Seasonality of river and WWTP nitrogen loading

Monthly DIN loads entering Puget Sound south of Admiralty Inlet

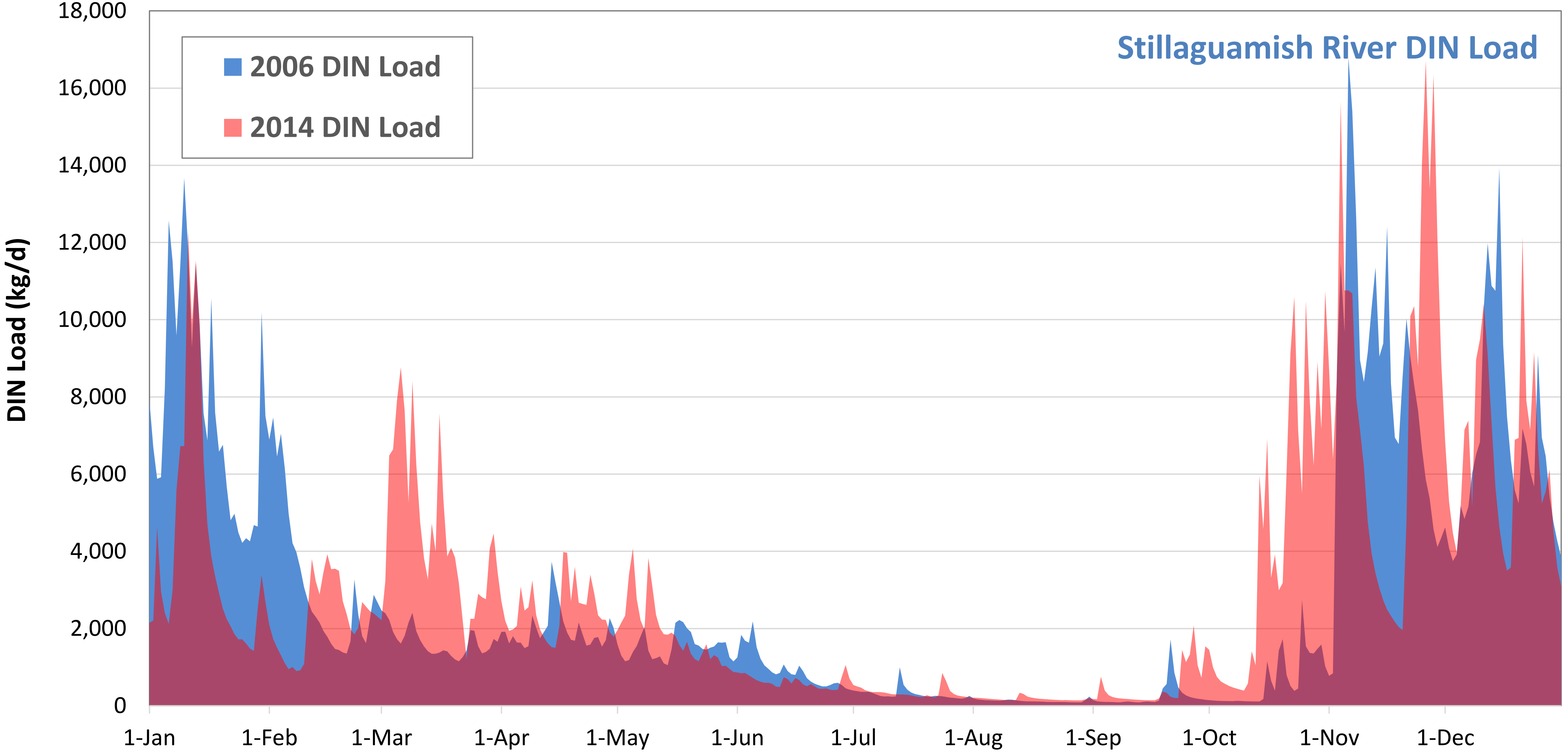




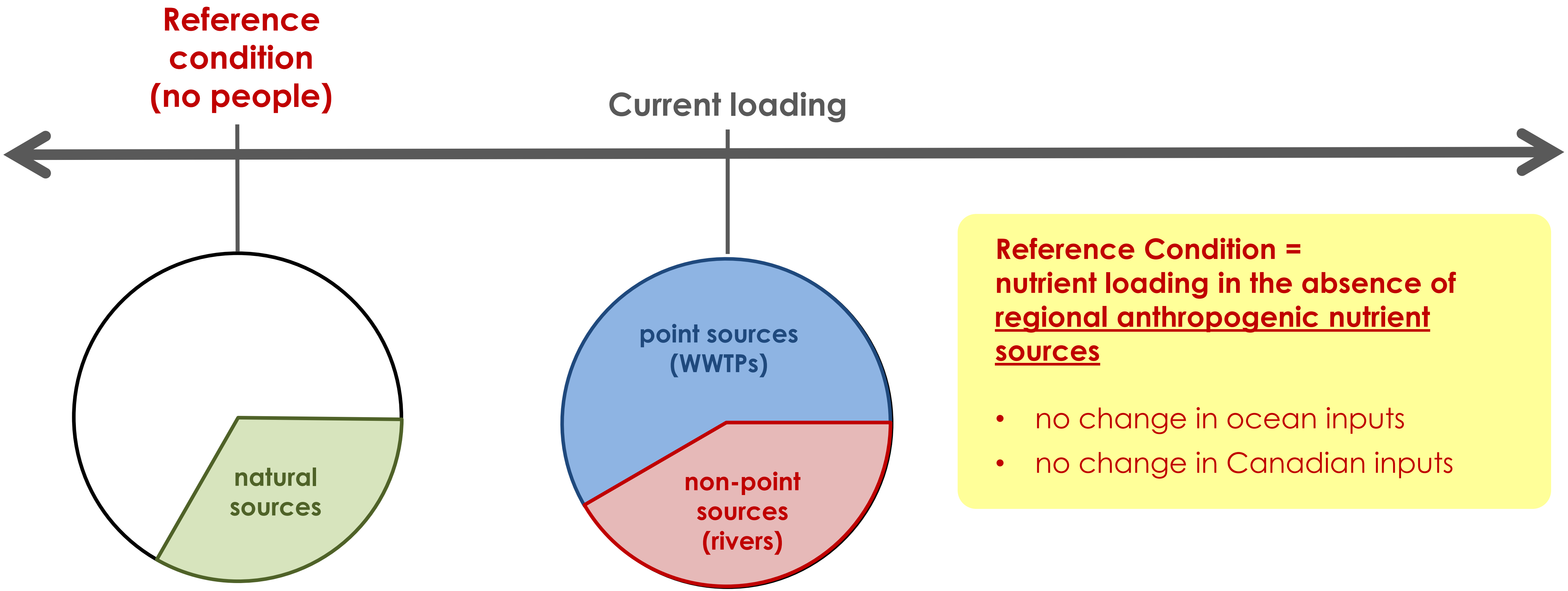


	Annual DIN Load	SUMMER DIN Load
Rivers	22,630 kg/d	6,760 kg/d
WWTPs	32,210 kg/d	29,320 kg/d

Inter-annual variability of river loading



Nutrient loading scenarios



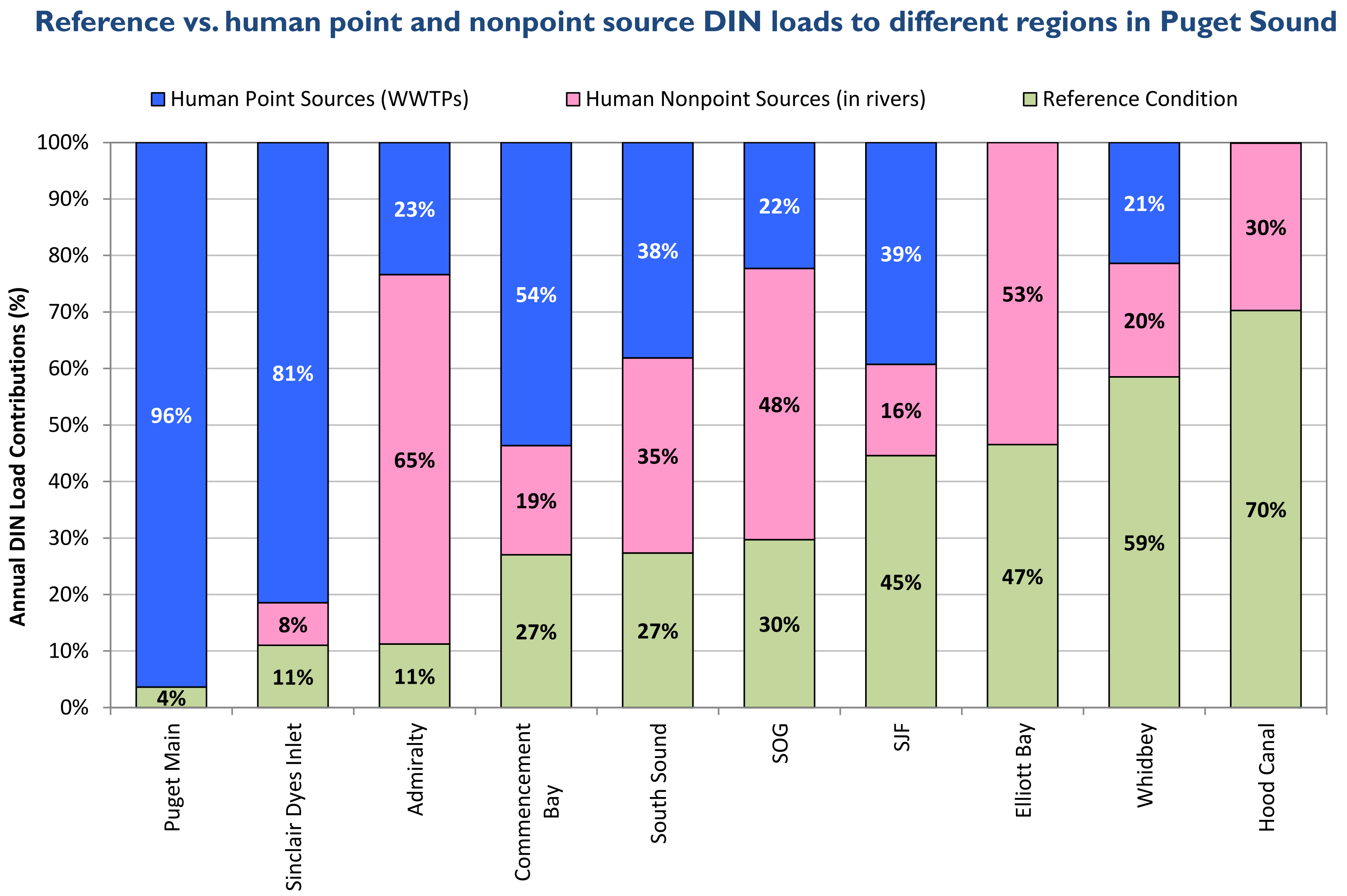
Published in Mohamedali et. al. (2011), updated in Pelletier et. al. (2017, Appendix B), estimates may be refined further in 2017-2018

Published in Mohamedali et. al. (2011)

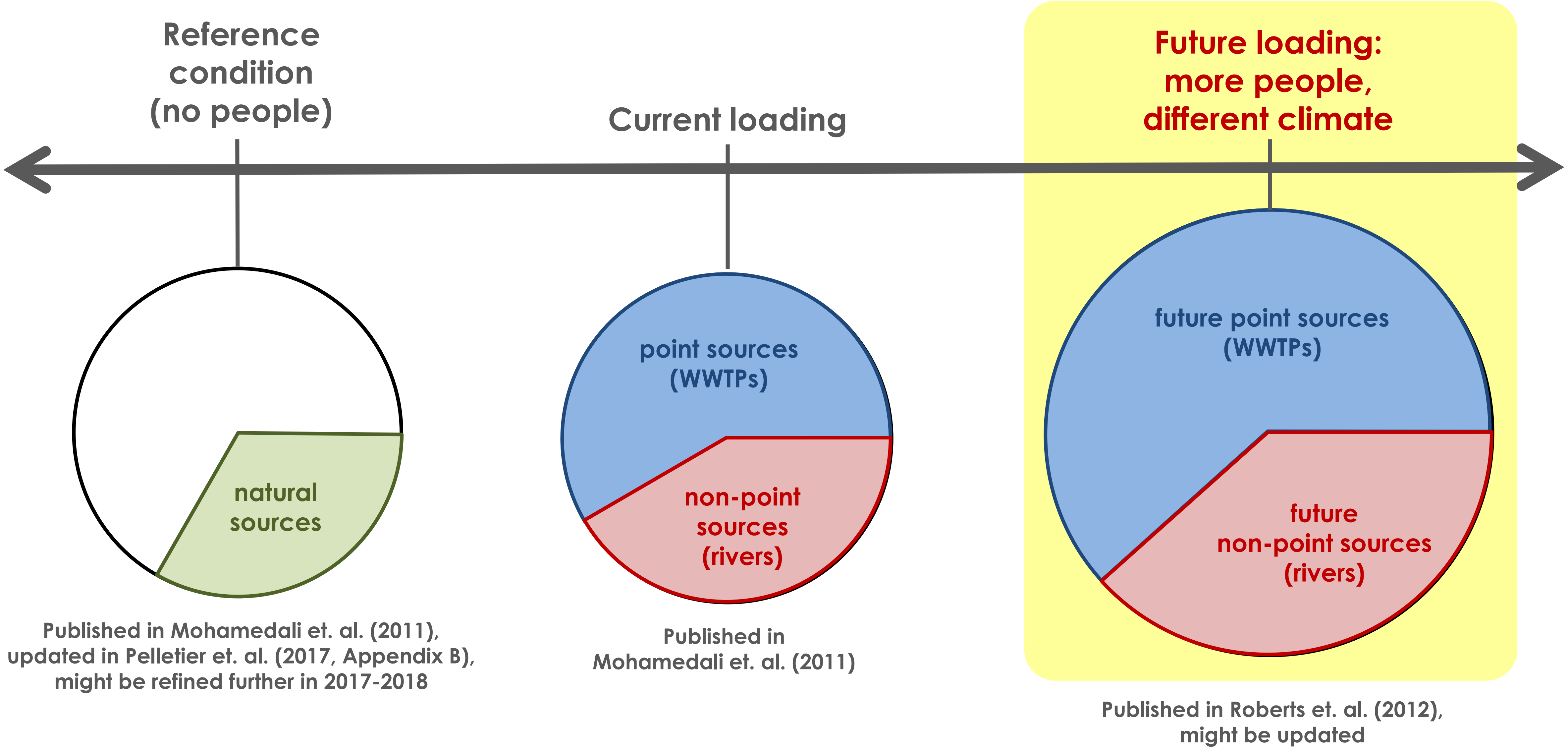
Reference Condition = nutrient loading in the absence of <u>regional anthropogenic nutrient sources</u>

- no change in ocean inputs
- no change in Canadian inputs

Reference condition point and nonpoint source loading



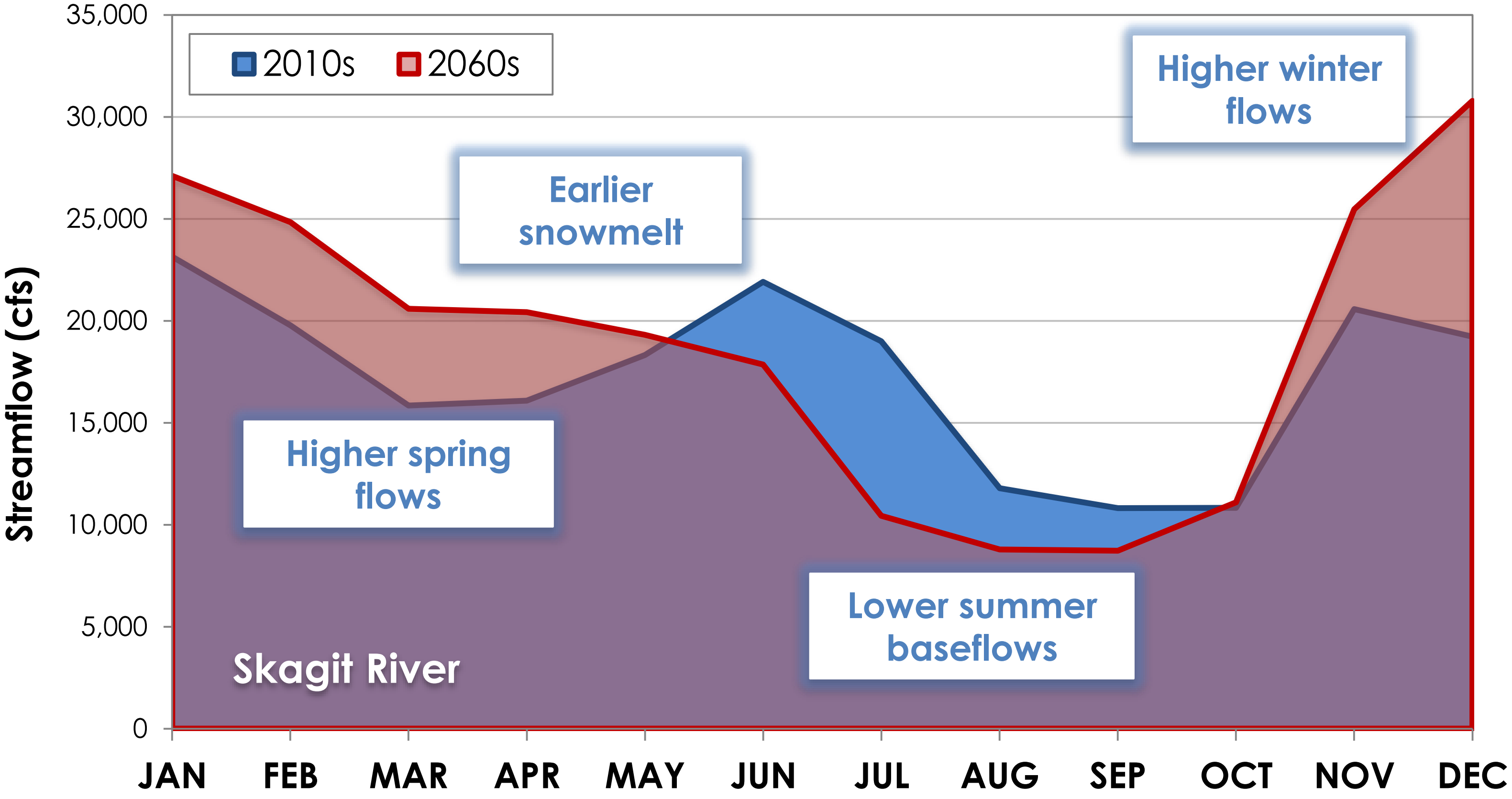
Nutrient loading scenarios



Future nutrient loading

1. **Climate Change**
   - Changes in precipitation
   - Changes to river hydrology
   - Change in timing of freshwater flows and nitrogen loads to Puget Sound

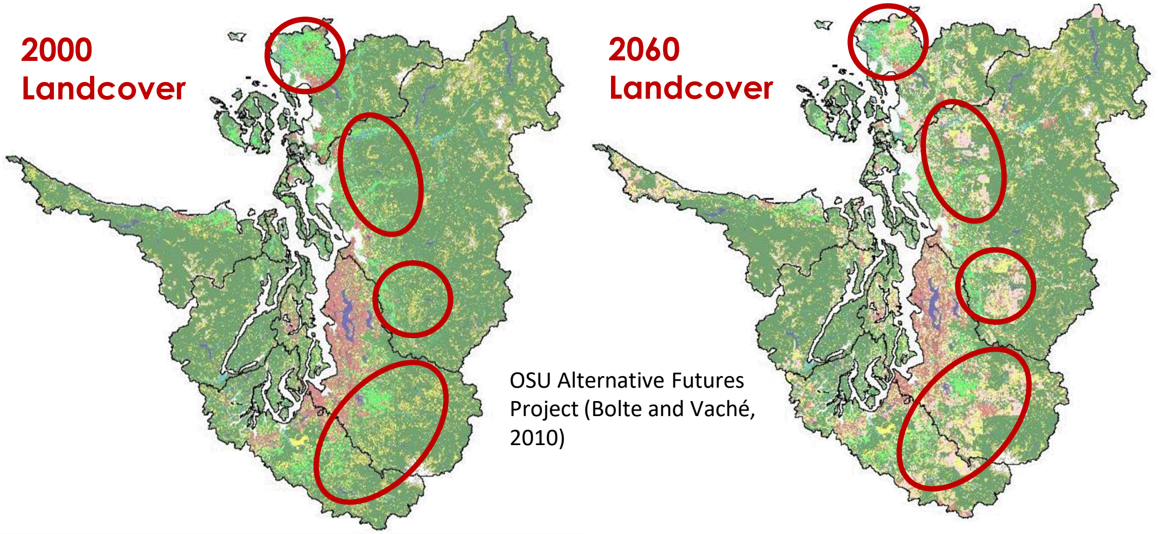
2. **Population Growth**



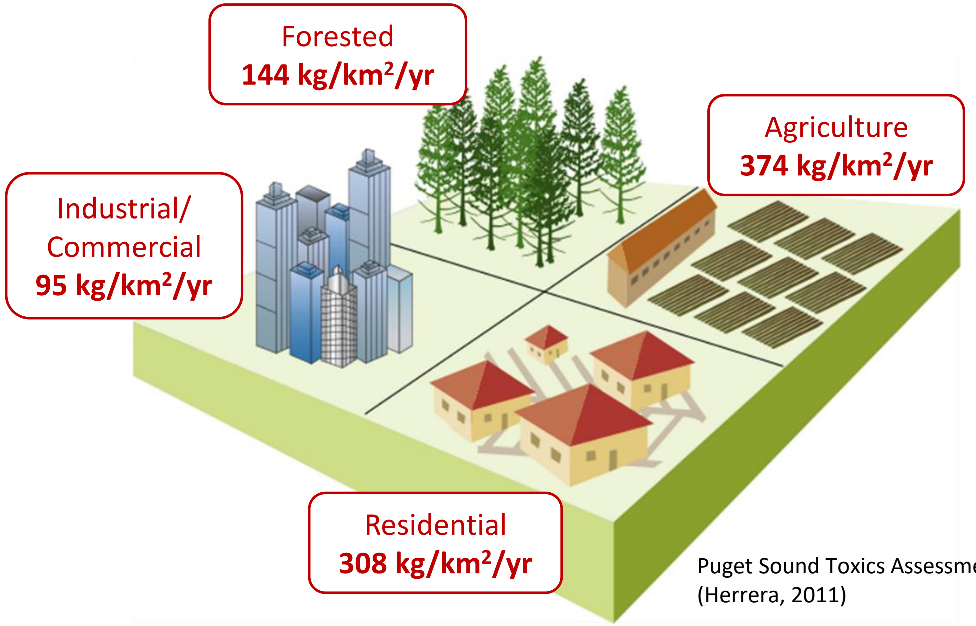
Future nutrient loading

1. Climate Change
   - Changes in precipitation
   - Changes to river hydrology
   - Change in timing of freshwater flows and nitrogen loads to Puget Sound

2. **Population Growth**
   - Urbanization & development
   - Less forested/natural lands
   - Agriculture may or may not increase
   - More people = more wastewater
   - Possible technology changes to wastewater treatment



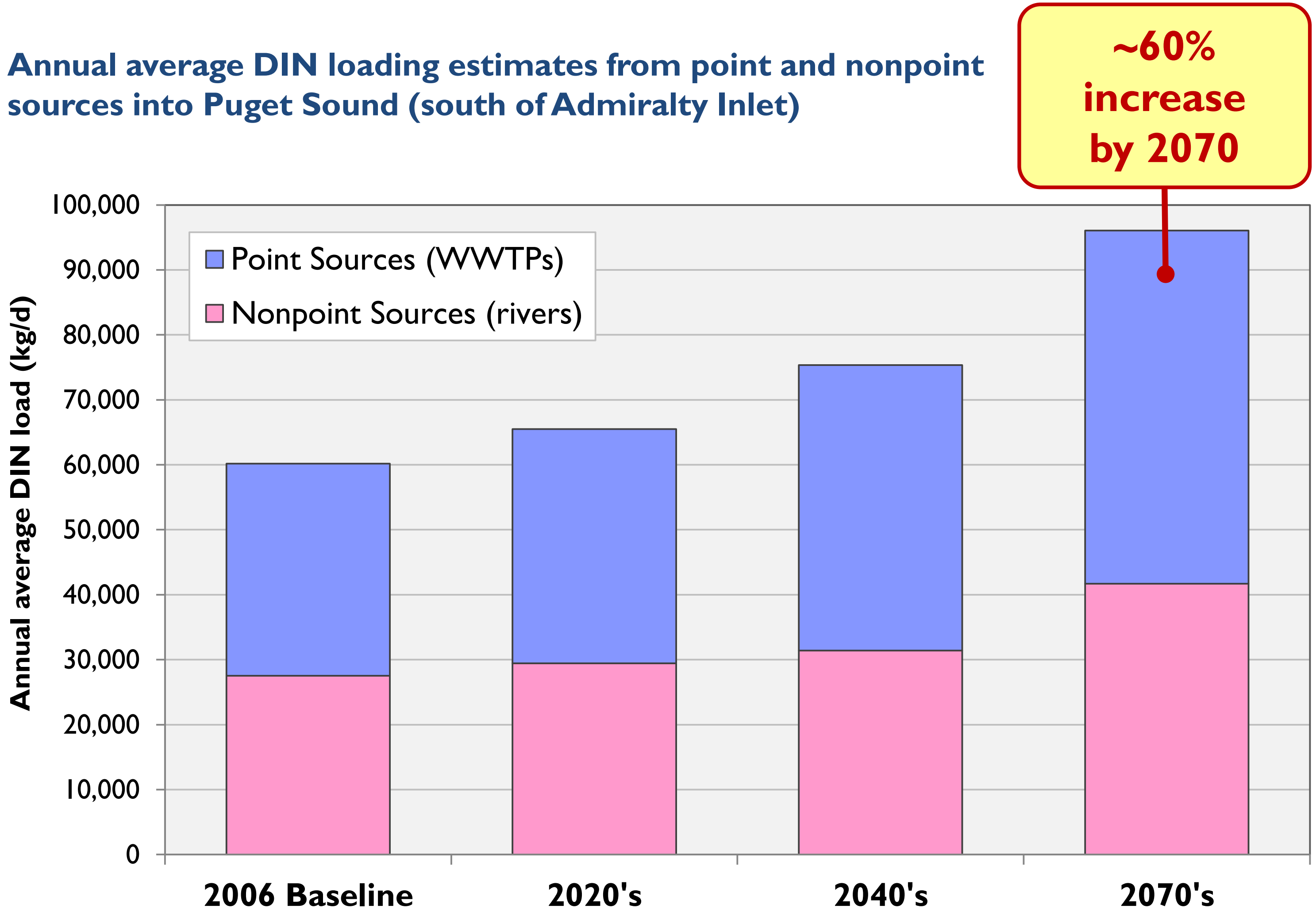
OSU Alternative Futures Project (Bolte and Vaché, 2010)



Puget Sound Toxics Assessment (Herrera, 2011)

Future point and nonpoint source loading

Annual average DIN loading estimates from point and nonpoint sources into Puget Sound (south of Admiralty Inlet)

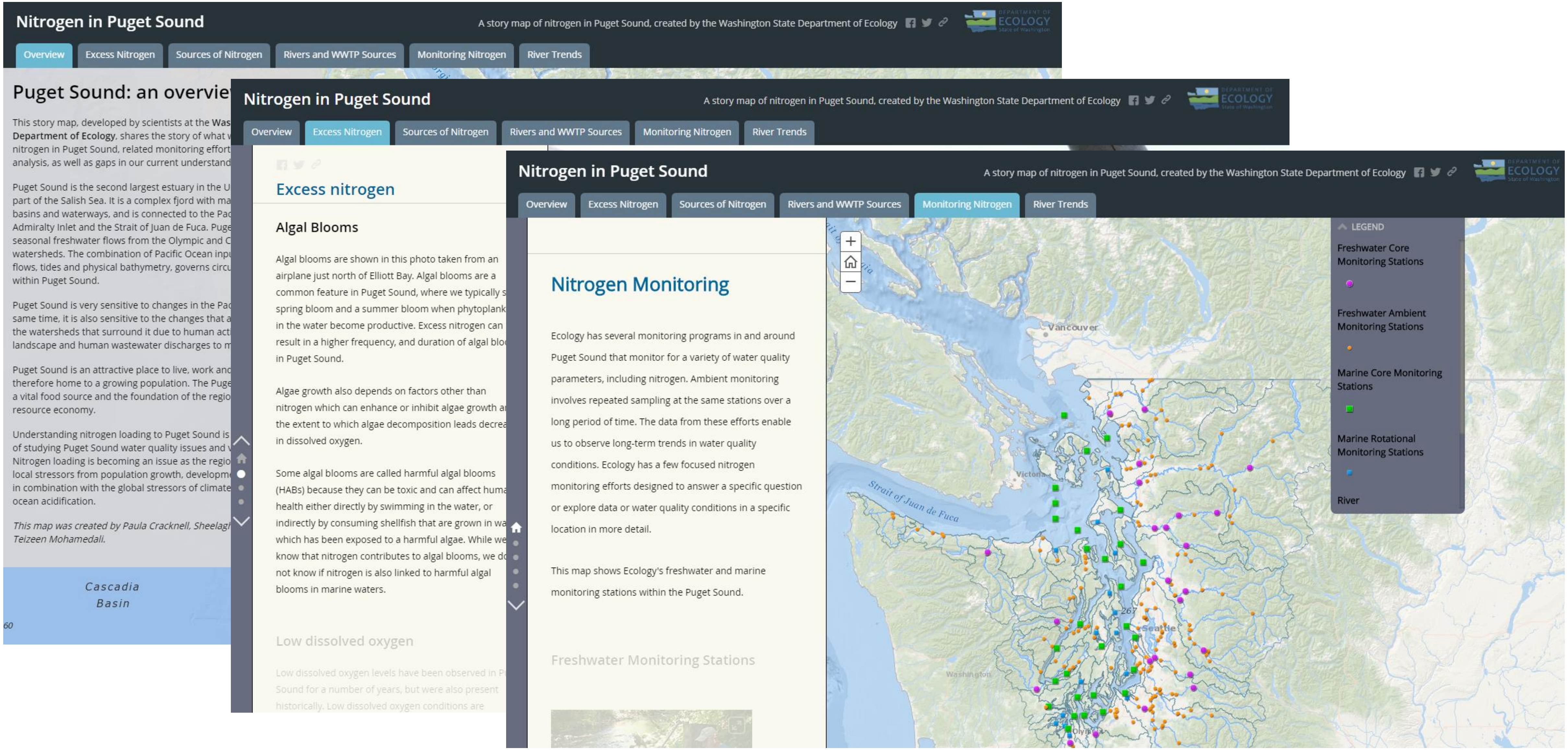


Key assumptions:

- OFM 2012 'medium' population projections
- No change in WWTP treatment processes/technologies or per capita wastewater flow, no new facilities
- Future hydrology from UW Climate Impacts Group VIC model based on downscaled A/B emissions scenarios
- Future nitrogen nonpoint source concentrations are only a function of empirical relationships to land use
- Future land use based on a 'status quo' of current land use trends in the region

Published in Roberts et. al. (2012), might be updated

‘Nitrogen in Puget Sound’ Story Map: (coming soon!)



Summary

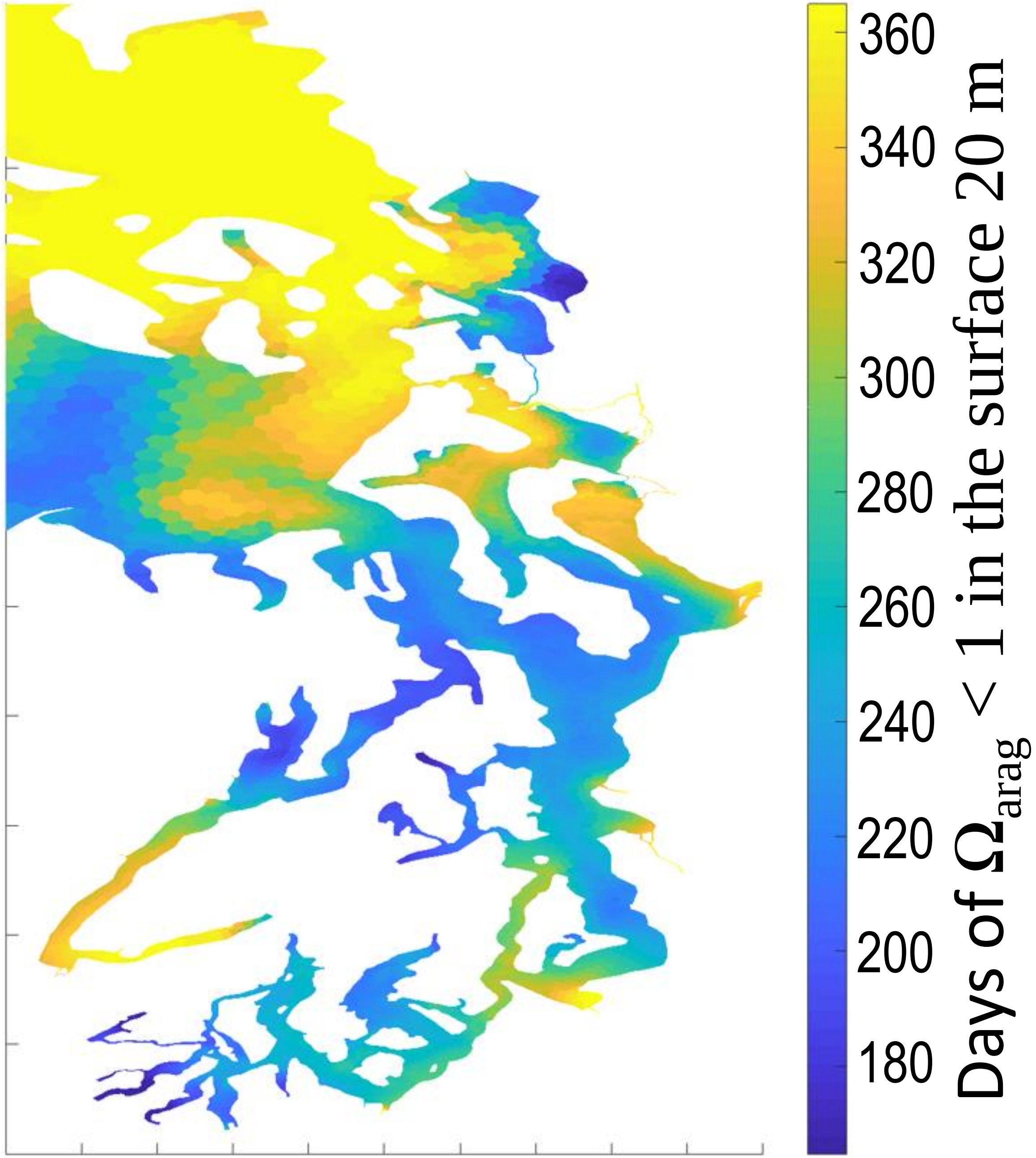
- **Dynamic variation in time and space is important**
  - Inter-annual variability
  - Residence time matters: higher flows = higher loads ≠ higher impact
  - Location matters: largest loads do not necessarily coincide with largest impact
  - Need to consider interaction between processes at different temporal and spatial scales
- **Pacific Ocean:**
  - Future conditions are highly uncertain and may change: incoming temperature, oxygen and nutrient levels, timing and duration of upwelling events
  - While highly influential, we are limited in our ability to manage these changes
- **Extent of human influence:**
  - Future nutrient loading will likely exacerbate local human impacts
  - Existing and reference condition model inputs can be used to run model scenarios in order to estimate the impact of human nutrients on Puget Sound, something we have not been able to do before – Greg's presentation (next)

Salish Sea Model

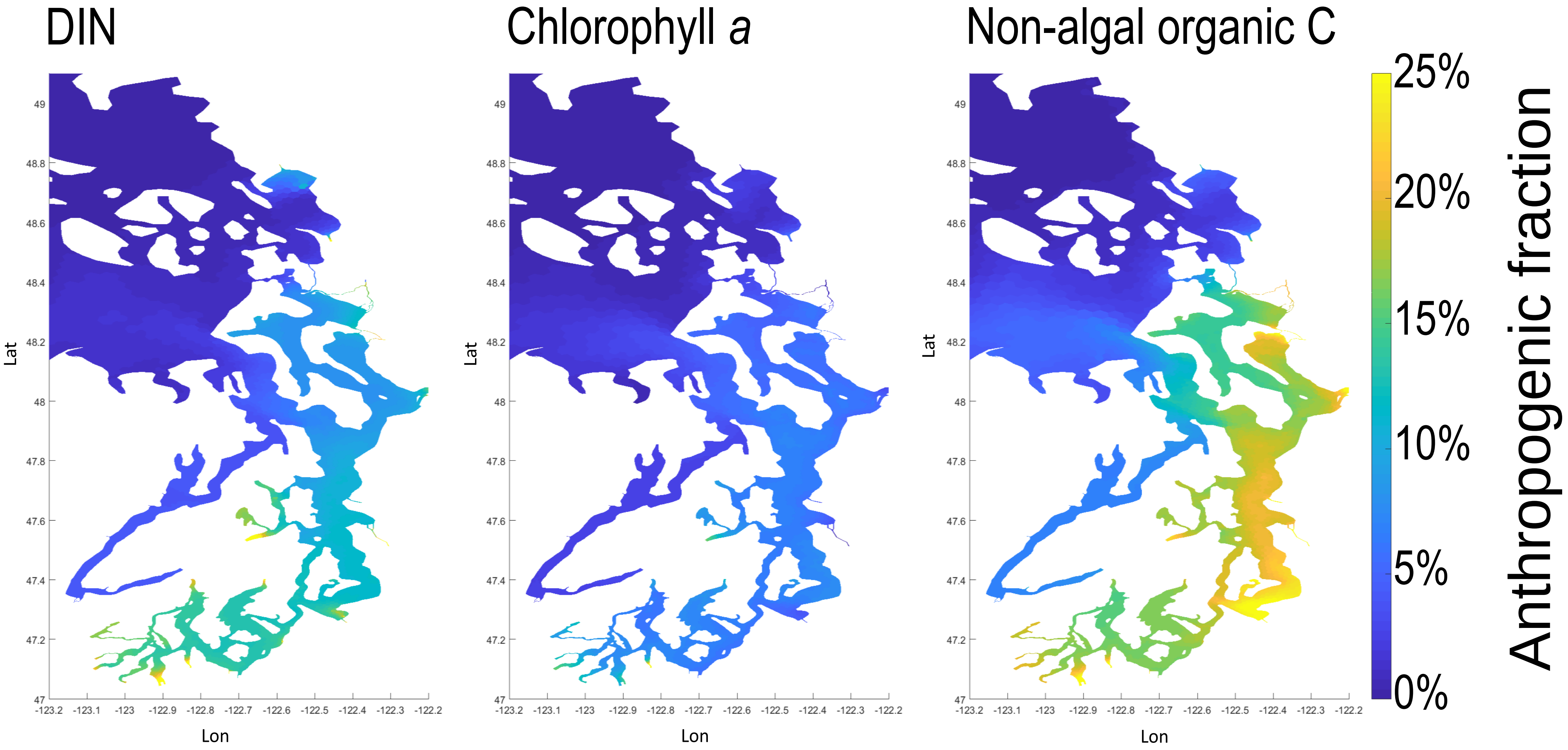
Current model results and the response to regional anthropogenic nutrient sources

Greg Pelletier
Department of Ecology

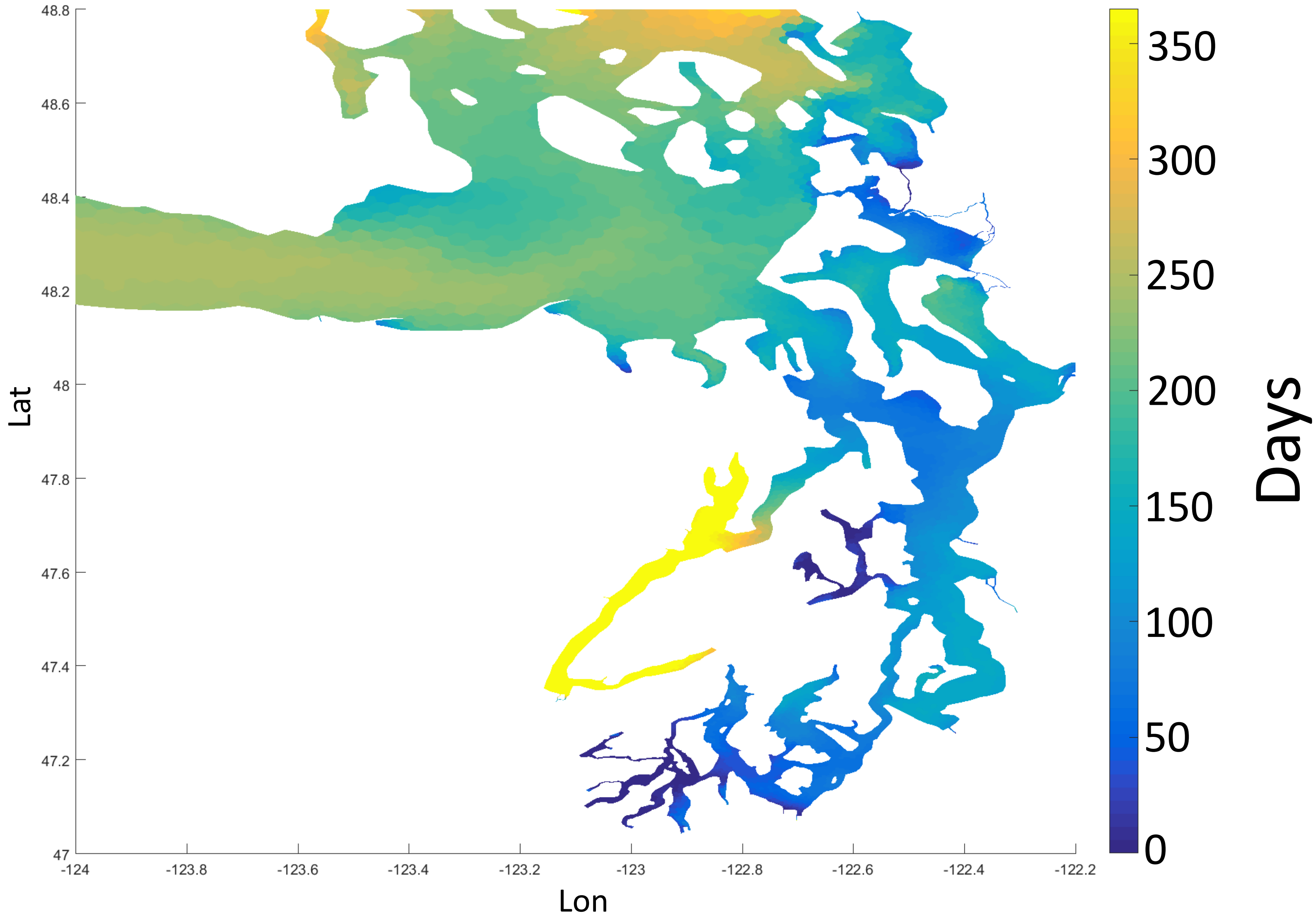
Puget Sound Nutrient Dialogue, 19 Jul 2017



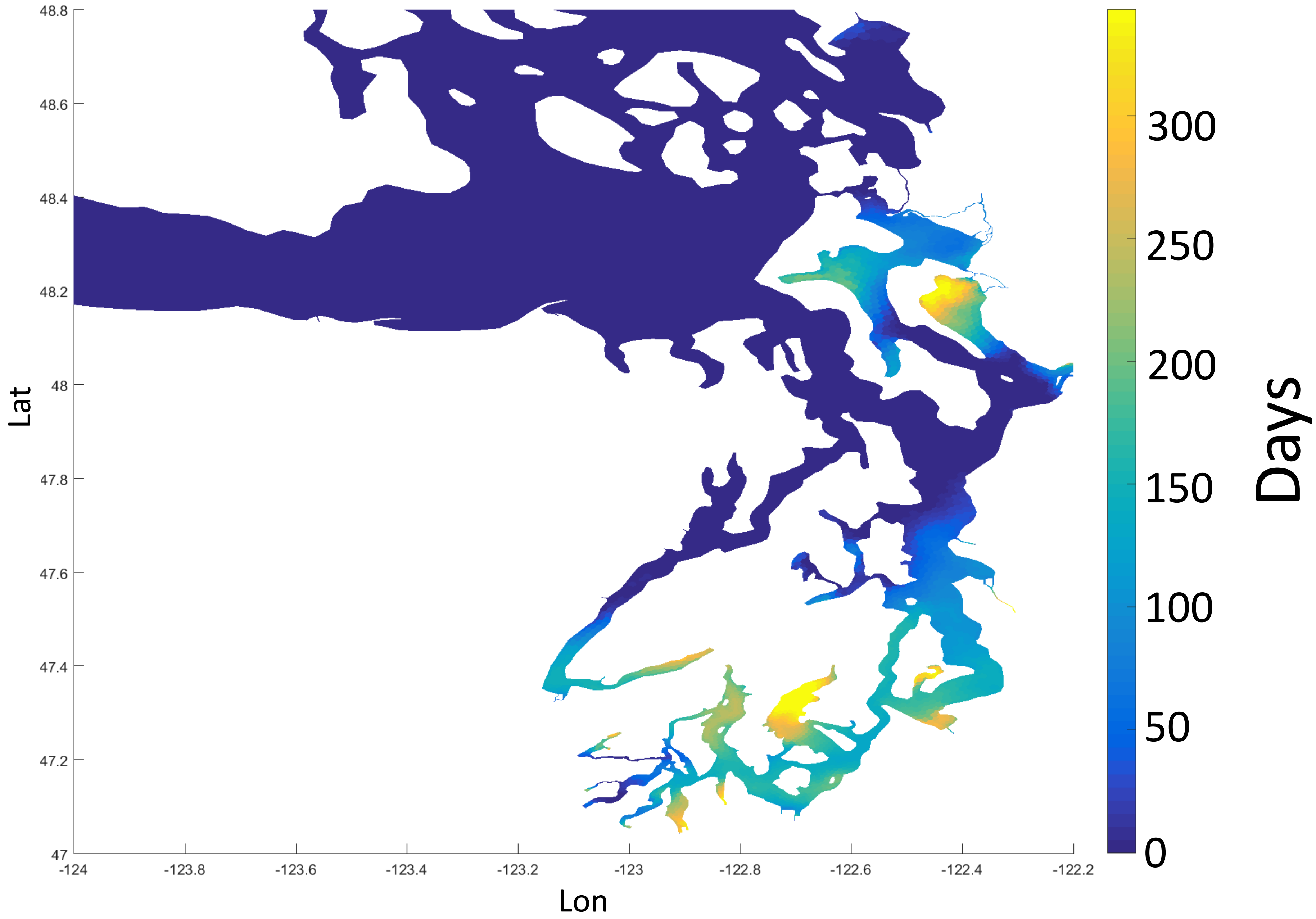
Fraction of May-Sep DIN, chlorophyll *a*, and non-algal organic C due to anthropogenic nutrient loads, surface 20 m

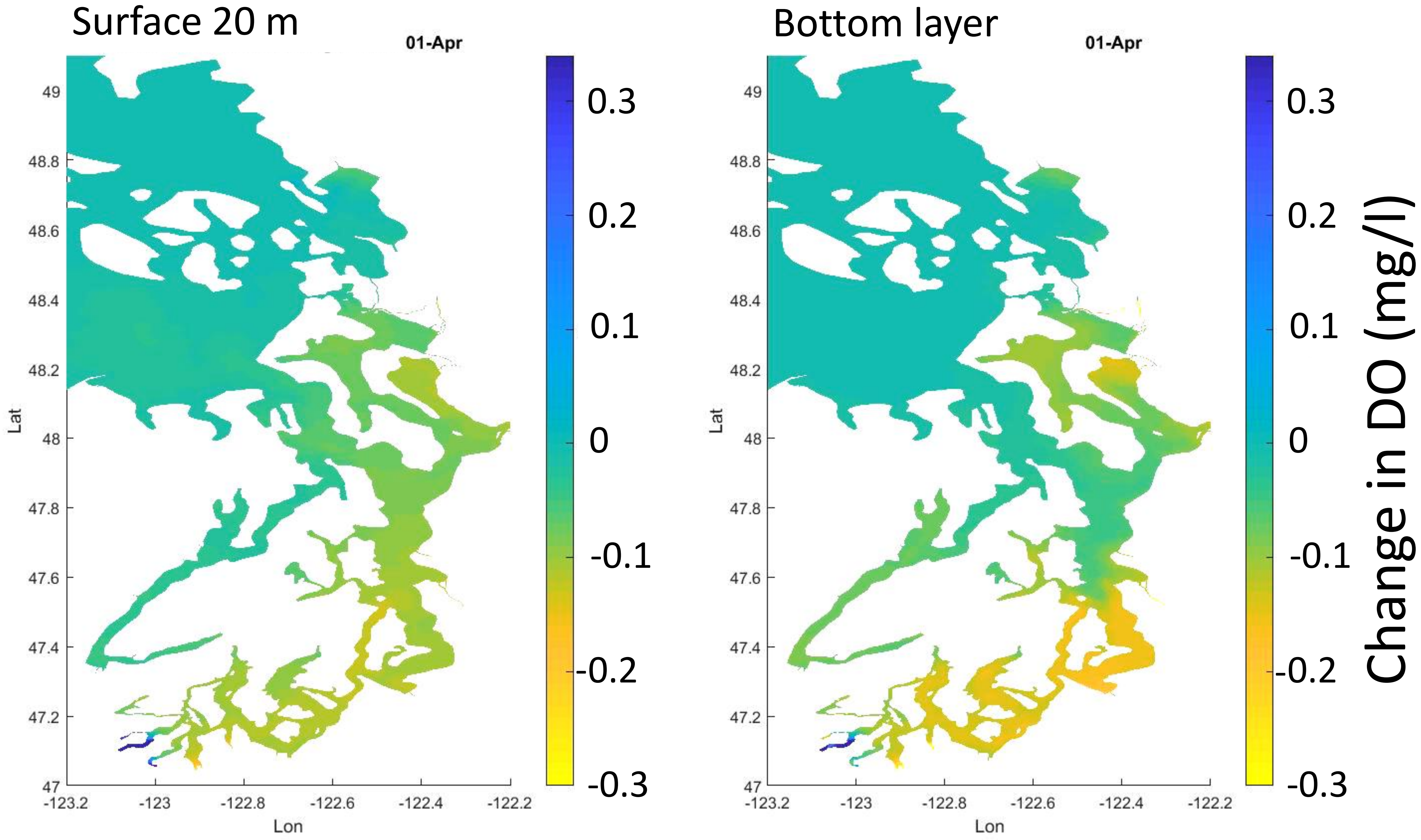


Cumulative days with DO less than 5 mg/l during 2006



Cumulative days with DO depletion > 0.2 mg/l during 2006

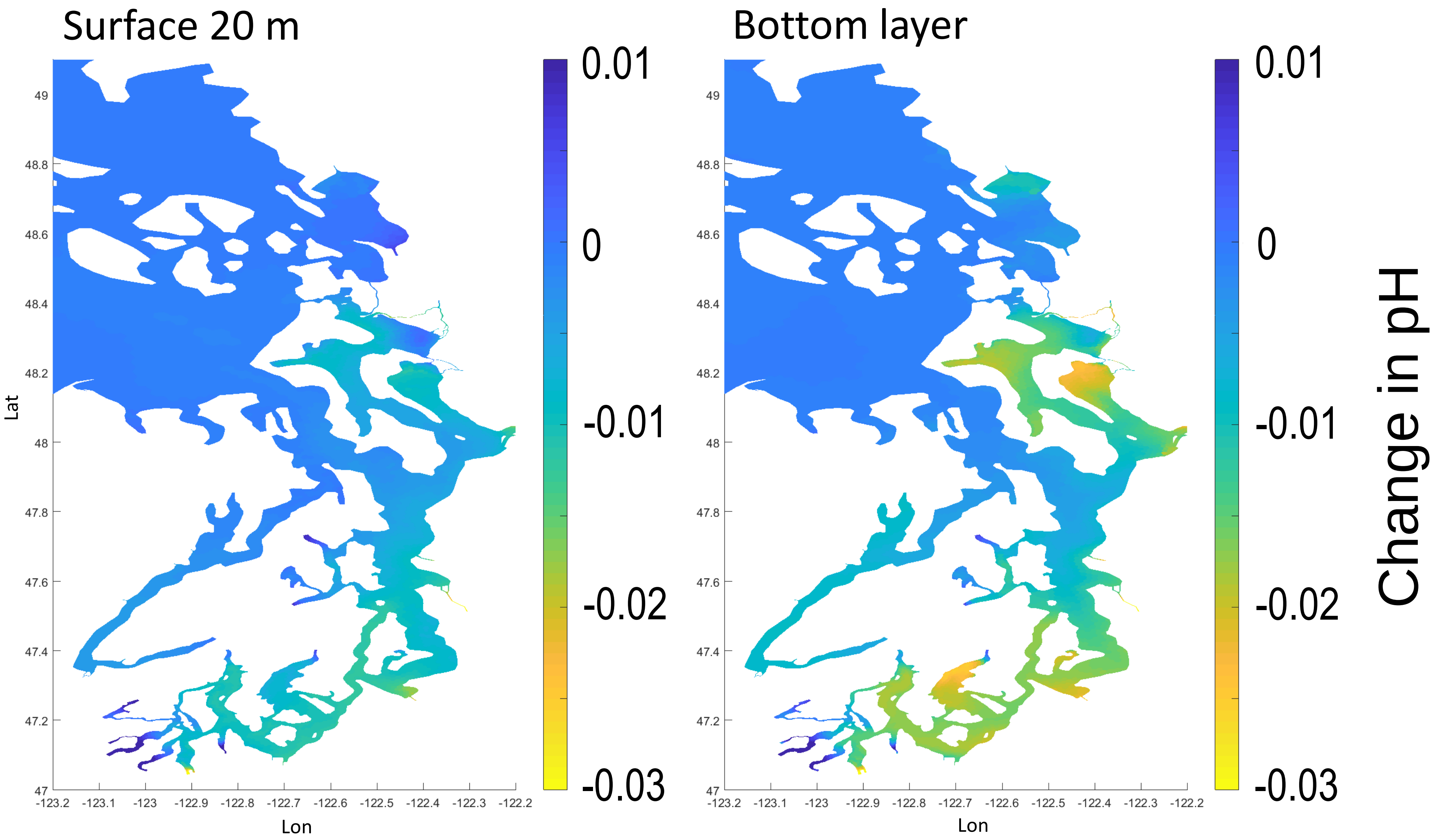



Surface 20 m
01-Apr
Bottom layer
01-Apr
Lat
Lon
49
48.8
48.6
48.4
48.2
48
47.8
47.6
47.4
47.2
47
-123.2
-123
-122.8
-122.6
-122.4
-122.2
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
Change in DO (mg/l)

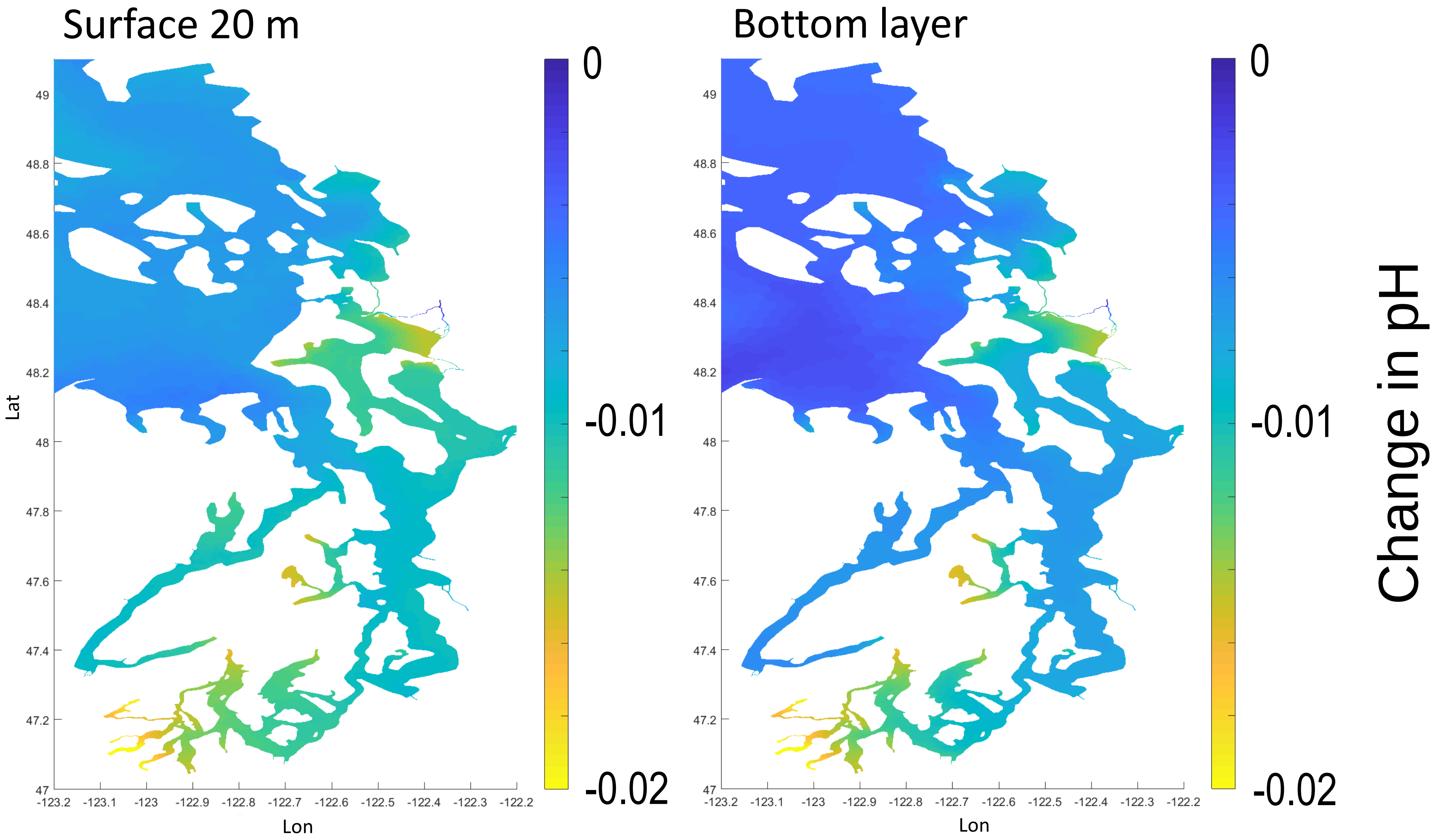
Changes in pH and Ω_{arag} due to anthropogenic sources

	Regional anthropogenic nutrient sources (this study) Range of monthly average differences between historical (2008) and estimated pre-industrial	**Global anthropogenic sources (Feely et al. 2010)** Difference between cruise observations (February and August, 2008) and estimated pre-industrial
pH (surface 20 m)	-0.07 to 0.06	-0.11 to 0.03
pH (bottom)	-0.10 to 0.05	-0.06 to 0.00
Ω_{arag} (surface 20 m)	-0.06 to 0.19	-0.33 to -0.09
Ω_{arag} (bottom)	-0.12 to 0.17	-0.16 to -0.02

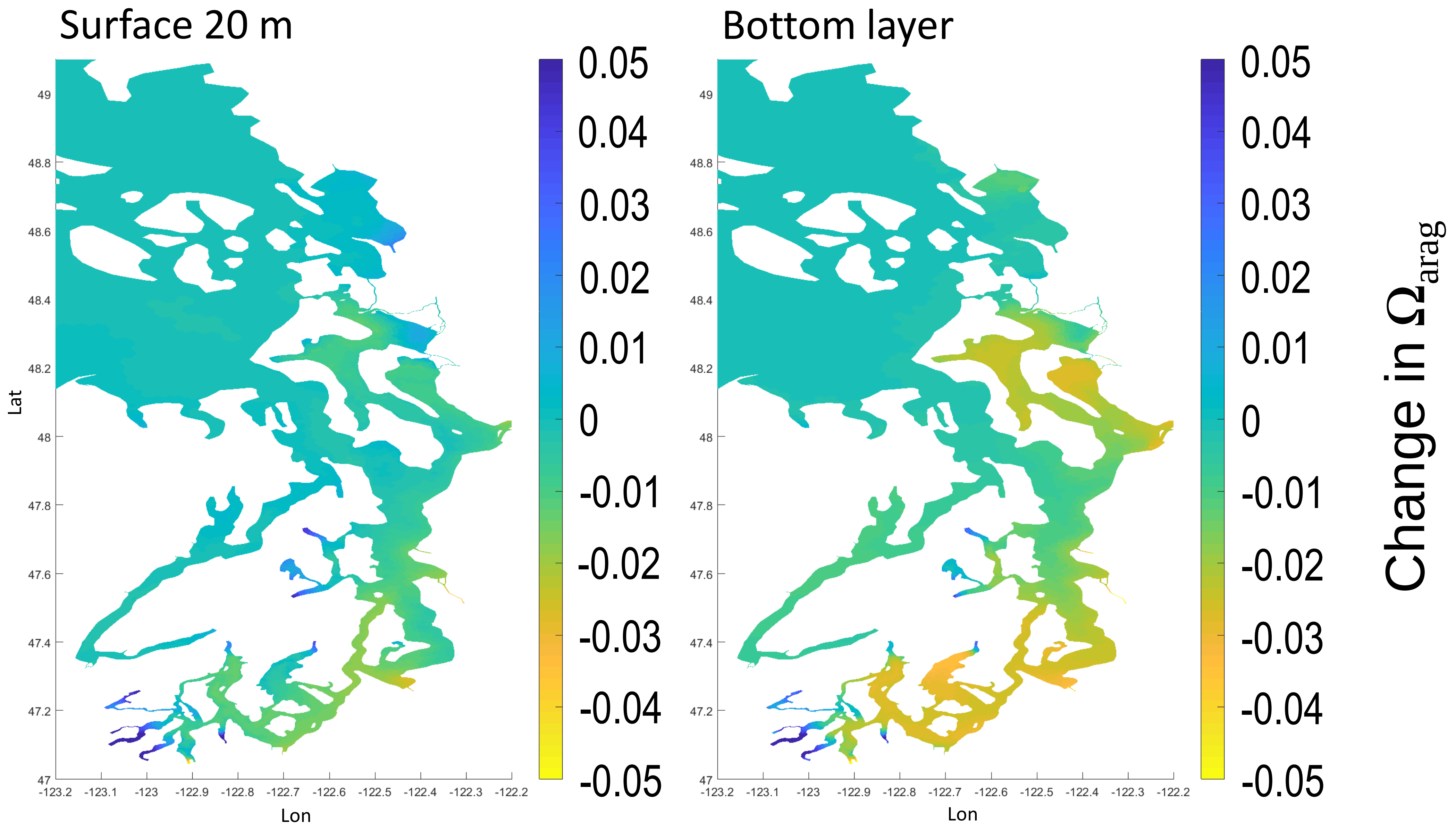
Annual average change in pH due to regional anthropogenic nutrient sources



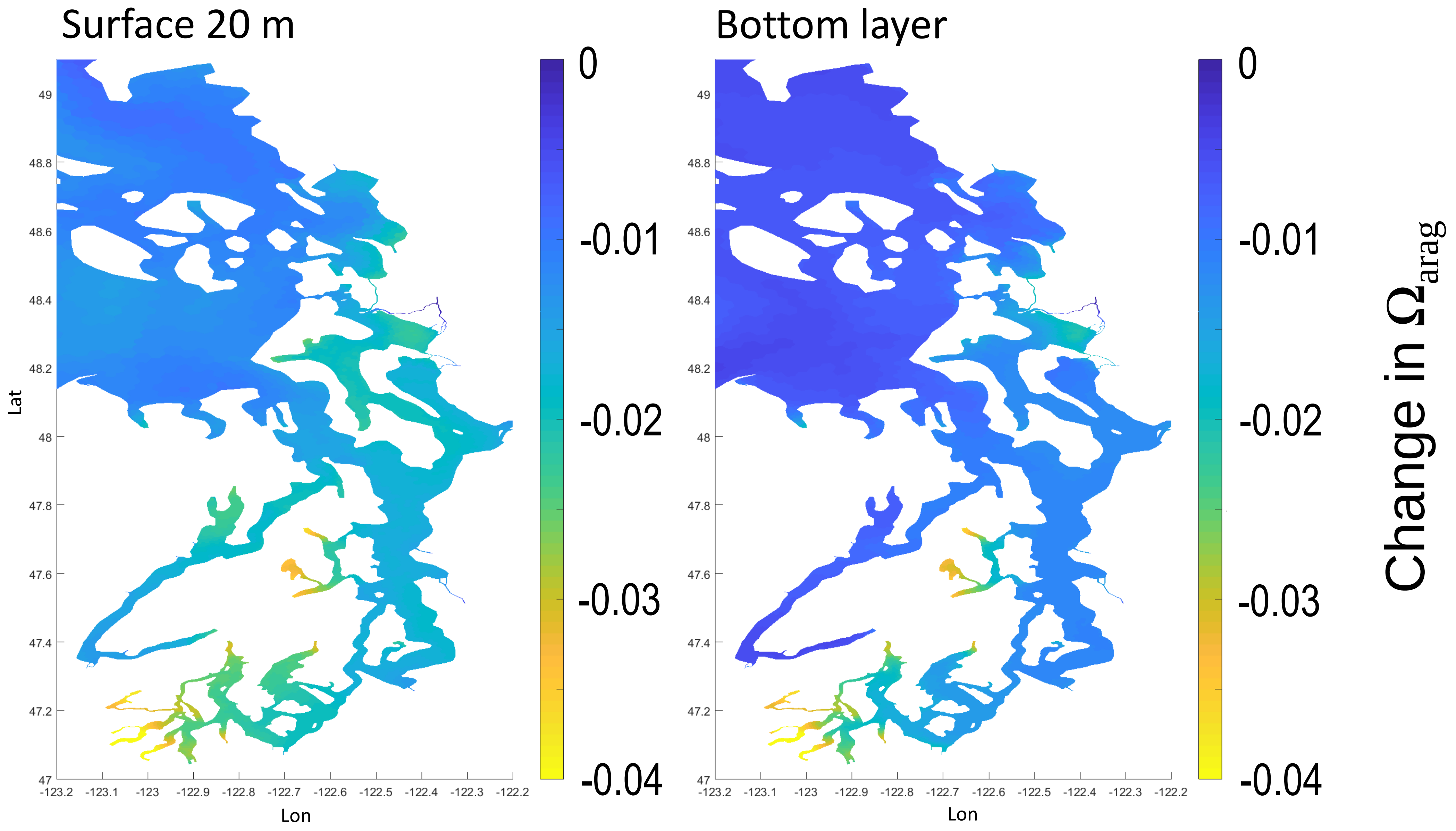
Change in pH due to regional atmospheric CO_2 increase from 400 to 450 ppm

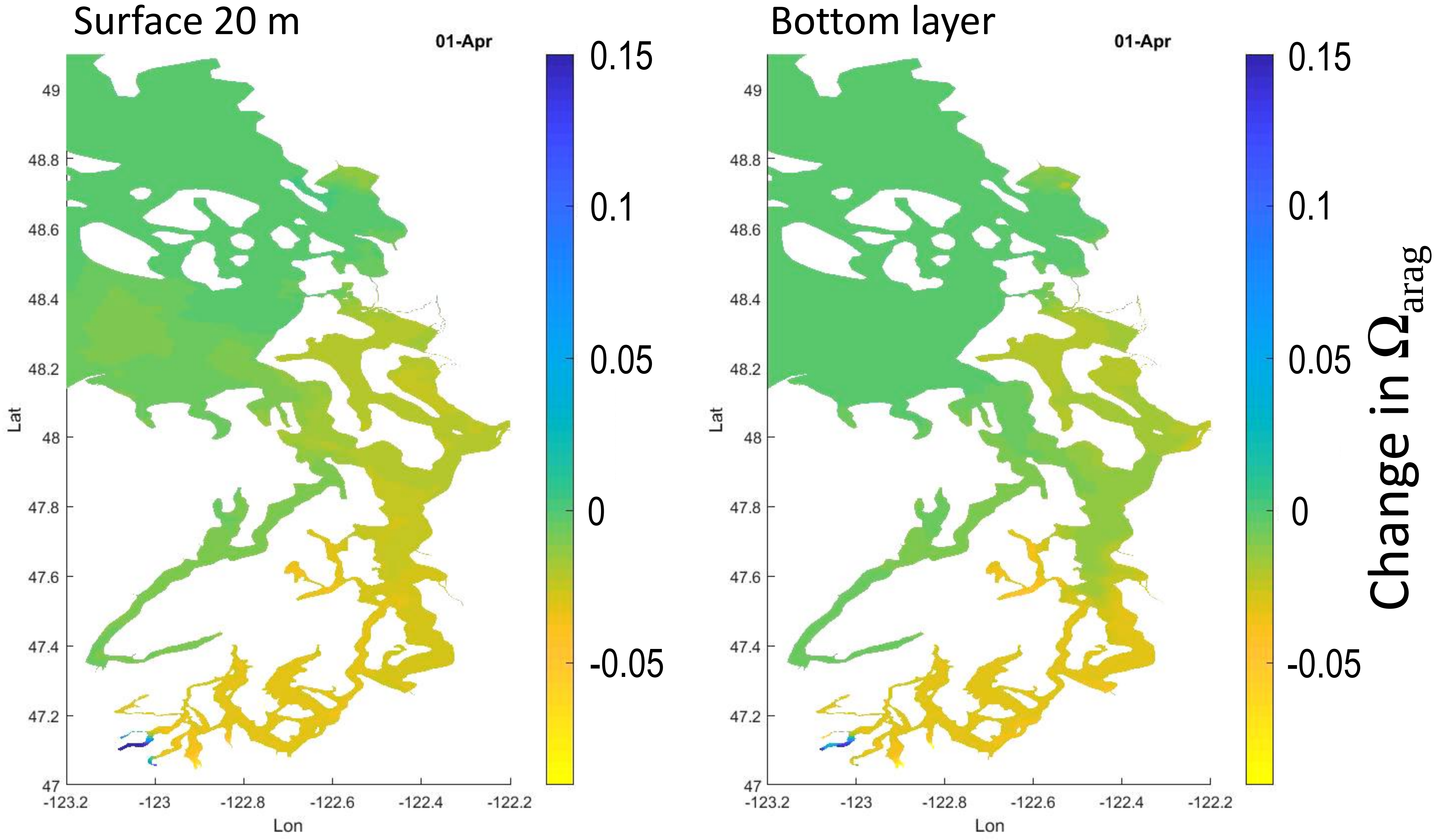


Annual average change in Ω_{arag} due to regional anthropogenic nutrient sources



Change in Ω_{arag} due to regional atmospheric CO_2 increase from 400 to 450 ppm





Surface 20 m
01-Apr
Bottom layer
01-Apr
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
0.15
0.1
0.05
0
-0.05
Change in Ω_{arag}

Conclusions

- Regional anthropogenic nutrient sources significantly deplete DO
- Regional anthropogenic nutrient sources significantly decrease pH and Ω_{arag}, especially in the deep layer
- pH and Ω_{arag} are sensitive to expected increases in local atmospheric CO_2, especially in the surface 20 m


A view of Mt Rainier from Tolmie State Park, Photo Courtesy: Andrew Diaz

Salish Sea Model Next Steps:

Updated reference conditions

Organic N, carbon (before it was only DIN) . May update again after further review/analysis

Refining nutrient loading inputs for refined model grid – finer delineations

Scenario Runs

Reference condition & future scenarios to be run on expanded, refined grid

Model Improvements

Salish Sea Model Journal Publications & Technical Reports

Bianucci, L., W. Long, T. Khangaonkar, G. Pelletier, A. Ahmed, T. Mohamedali, M. Roberts, and C. Figueroa-Kaminsky. 2017. Sensitivity of the regional ocean acidification and the carbonate system in Puget Sound to ocean and freshwater inputs. (submitted to Elementa for the special feature on ocean acidification)

Long W, T Khangaonkar, M Roberts, and G Pelletier. 2014. *Approach for Simulating Acidification and the Carbon Cycle in the Salish Sea to Distinguish Regional Source Impacts.* Publication No. 14-03-002. Washington State Department of Ecology, Olympia.

Khangaonkar T and T Kim. 2009. *Model Selection Recommendations for DO Model of Puget Sound.* Technical Memorandum prepared for the Washington State Department of Ecology, PNNL, Seattle, WA.

Khangaonkar, T, W Long, B Sackmann, T Mohamedali, and A Hamlet. 2016. Sensitivity of Circulation in the Skagit River Estuary to Sea Level Rise and Future Flows, *Northwest Science*, 90(1):94-118.doi: 10.3955/046.090.0108

Khangaonkar T, W Long, B Sackmann, T Mohamedali, and M Roberts. 2012. *Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate Scale Water Quality Model.* PNNL-20384 Rev 1, prepared for the Washington State Department of Ecology (Publication No. 12-03-049), by Pacific Northwest National Laboratory, Richland, Washington.

Khangaonkar, T, W Long, and W Xu. 2017. Assessment of circulation and inter-basin transport in the Salish Sea including Johnstone Strait and Discovery Islands pathways, *Ocean Modelling*, 109:11-32.doi: 10.1016/j.ocemod.2016.11.004

Khangaonkar, T, B Sackmann, W Long, T Mohamedali, and M Roberts. 2012. Simulation of annual biogeochemical cycles of nutrient balance, phytoplankton bloom(s), and DO in Puget Sound using an unstructured grid model. *Ocean Dynamics*, 62(9):1353-1379.doi: 10.1007/s10236-012-0562-4

Khangaonkar, T and T Wang. 2013. Potential alteration of fjordal circulation due to a large floating structure—Numerical investigation with application to Hood Canal basin in Puget Sound, *Applied Ocean Research*, 39:146-157.doi: 10.1016/j.apor.2012.11.003

Khangaonkar, T, Z Yang, T Kim, and M Roberts. 2011. Tidally Averaged Circulation in Puget Sound Sub-basins: Comparison of Historical Data, Analytical Model, and Numerical Model. *Journal of Estuarine Coastal and Shelf Science*, 93(4):305-319. doi: 10.1016/j.ecss.2011.04.016

Khangaonkar, T and Z Yang, 2011. A High Resolution Hydrodynamic Model of Puget Sound to Support Nearshore Restoration Feasibility Analysis and Design. Ecological Restoration. *Ecological Restoration*, 29(1-2):173-184. doi: 10.3368/er.29.1-2.173

Kim, T and T Khangaonkar. 2012. An Offline Unstructured Biogeochemical Model (UBM) for Complex Estuarine and Coastal Environments. *Environmental Modelling & Software*, 31:47-63. doi: 10.1016/j.envsoft.2011.11.010

Mohamedali T, M Roberts, B Sackmann, and A Kolosseus. 2011. *Puget Sound Dissolved Oxygen Model Nutrient Load Summary for 1999?2008.* Publication No. 11-03-057, Washington State Department of Ecology, Olympia, Washington.

New: Pelletier, G.J., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky. 2017. *Salish Sea Model, Ocean Acidification Module and the Response to Regional Anthropogenic Nutrient Sources*. Washington State Department of Ecology, Olympia, WA. Publication No. 17-03-009.

New: Pelletier, G.J., L. Bianucci, W. Long, T. Khangaonkar, T. Mohamedali, A. Ahmed, and C. Figueroa-Kaminsky. 2017. *Salish Sea Model, Sediment Diagenesis Module*. Washington State Department of Ecology, Olympia, WA. Publication No. 17-03-010.

Pelletier, G., M. Roberts, M. Keyzers, and S.A. Alin. 2017. Seasonal variation in aragonite saturation in surface waters of Puget Sound – a pilot study. (submitted to Elementa for the special feature on ocean acidification)

Roberts M, J Bos, and S Albertson. 2008. *South Puget Sound Dissolved Oxygen Study.* Interim Data Report, Publication No. 08-03-037, Washington State Department of Ecology, Olympia, Washington.

Roberts M, T Mohamedali, B Sackmann, T Khangaonkar, and W Long. 2014. *Dissolved Oxygen Model Scenarios for Puget Sound and the Straits: Impacts of Current and Future Nitrogen Sources and Climate Change through 2070.* Publication No. 14-03-007, Washington State Department of Ecology, Olympia.

Roberts, M., G. Pelletier, T. Khangaonkar, and W. Long. 2015a. *Quality Assurance Project Plan: Salish Sea Dissolved Oxygen Modeling Approach: Sediment-Water Interactions*. Washington State Department of Ecology Publication No. 15-03-103.

Roberts, M., G. Pelletier, T. Khangaonkar, W. Long, and L. Bianucci. 2015b. *Quality Assurance Project Plan: Salish Sea Acidification Model Development*. Washington State Department of Ecology Publication No. 15-03-109.

Sackmann, B. 2009. *Quality Assurance Project Plan: Puget Sound Dissolved Oxygen Modeling Study: Intermediate-scale Model Development*. Washington State Department of Ecology Publication No. 09-03-110.

Wang, T, T Wang, W Long, and G Gill. 2014. Development of a Kelp-Type Structure Module in a Coastal Ocean Model to Assess the Hydrodynamic Impact of Seawater Uranium Extraction Technology, *Journal of Marine Science and Engineering*, 2(1):81-92.doi: 10.3390/jmse2010081

Yang, Z and T Khangaonkar, 2010. Multi-scale Modeling of Puget Sound Using an Unstructured-grid Coastal Ocean Model: from Tide flats to Estuaries and Coastal Waters. *Ocean Dynamics*, 60(6):1621-1637. doi: 10.1007/s10236-010-0348-5

Yang Z, T Khangaonkar, RG Labiosa, and T Kim. 2010. *Puget Sound Dissolved Oxygen Modeling Study: Development of an Intermediate-Scale Hydrodynamic Model.* PNNL-18484, Pacific Northwest National Laboratory, Richland, Washington.