Sediment Exchange Workshop Summary

Last Updated: December 23, 2022

Overview

We enjoyed a smaller and focused technical discussion on nutrient-related sediment exchange fluxes with the water column on October 17, 2022. Around 30 experts who model, monitor, or research sediment exchange reflected on the driving scientific question:

> When and where does sediment have an important impact on nitrogen cycling and low dissolved oxygen impacts?

Dr. David Shull, with Western Washington University, shared insights from both historical and recent monitoring. Some key themes include:

- Sediments contribute nearly 20% of oxygen demand in some basins of Puget Sound
- Sediments have an oxygen demand "memory" that decouples dissolved oxygen consumption from organic matter mineralization
- Sulfate reduction and sulfide oxidation play important roles
- Denitrification and burial remove a significant fraction of nitrogen, particularly in Hood Canal due its long residence time. Denitrification also important in shallow bays such as Bellingham Bay
- Seasonal data are needed to better quantify the role of sediment-water exchange on nitrogen and dissolved oxygen
- Burial rates of nitrogen may be significant; the few existing estimates suggest it is on par with the rates of denitrification. Therefore, it would be beneficial to study burial rates of nitrogen in more detail

The discussion then turned to how sediment exchange is represented in models, specifically LiveOcean and the Salish Sea Model, with experts presenting such as Dr. Parker MacCready. There was excitement to potentially use measured sediment oxygen demand data like David is collecting as inputs to improve the accuracy and robustness of all of the various models and reduce uncertainty. Attendees also reflected on some proposed modeling analyses and preliminary results to refine our understanding of when and where sediment has an important impact on nitrogen cycling and low dissolved oxygen impacts.

Materials

Links to the materials for the *Sediment Exchange* workshop:

- Slides
- Full video
- Highlight video
- Chat

A recap for each workshop in The Science of Puget Sound Water Quality workshop series is available on our website. The recaps include a summary, highlight video, full recording, chat, and slides. The videos from the workshop series are also available directly via this YouTube playlist.

Highlights

Note: for the full presentation slides and resulting discussion please see the links above. Below are some highlights from the presentations, followed by questions and key discussion points.

Monitoring

Dr. David Shull, Western Washington University

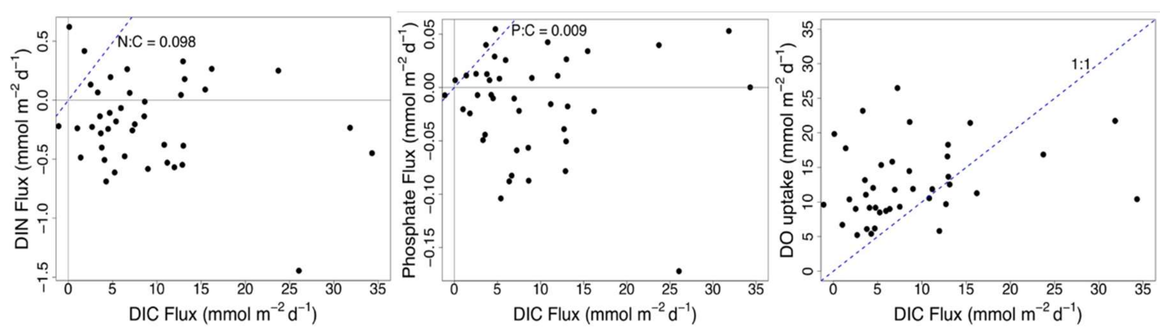
- Mario Pamatmat measured oxygen consumption near the seabed over 50 years ago. Since then, there has been relatively little work on benthic fluxes. Sheibley and Paulson (2014) reviewed some of the research on sediment-water exchange, most of which has been in shallow inlets
    - However, David reflected that this was certainly not enough information to be able to even estimate the average effect of sediment-water exchange on nutrient cycling and dissolved oxygen consumption
- Measuring some parameters allows us to take a mass balance approach to estimate other parameters we have not or cannot measure directly, thereby further constraining unknowns
- David has monitored and continues to monitor benthic solute fluxes in Puget Sound
    - In coordination with the Department of Ecology, he measured sediment-water fluxes of oxygen, DIC, nutrients, and alkalinity at 40 stations throughout Puget Sound to (1) quantify these fluxes and estimate the significance of benthic processes in oxygen consumption and nutrient cycling, and (2) determine how and why these rates vary from place to place
    - He has also measured fluxes of O2, DIC, and nutrients in Bellingham Bay for about 15 years
- Sediments contribute nearly 20% of oxygen demand in some basins of Puget Sound

Basin	Average rates of dissolved oxygen consumption among basins mmol O2 m-3 d-1			Percent DIN supply removed by denitrification*	Percent phosphorous stored in sediments**	Denitrification mmol/m2/d	Nitrogen burial mmol/m2/d***
	Water Column	Benthos	% Removed by Sediment				
Main	?	0.13	7.5%?	1.20%	94 ± 37%	0.76	3
Whidbey	1.7 (a)	0.19	10%	2.80%	136 ± 46%	?	?

South Sound	2.2 (a)	0.5	18.40%	2.70%	146 ± 37%	?	?
Hood Canal	0.92 (s)	0.22	19.40%	10.90%	111 ± 43%	1.3	1.15

a) From Apple (2019) report, April and May averages. (s) From Shull et al., July average
* DIN supply = Avg deep-water DIN/Avg basin residence time (from Babson et al. 2006)
** Comparison of DIC to P flux, assuming Redfield proportions of C and P
***Data from Brandenberger et al. (2008), (mass accumulation rate) (N/mass sediment). Two locations in the Main Basin and Hood Canal

- Sediment cores show high variability among replicates
- The reason for spatial variation in denitrification is not understood. They are not correlated with organic matter remineralization rate
    - There is strong spatial variability in oxygen consumption rates, dissolved inorganic carbon fluxes, and denitrification fluxes, respectively
        - For example, oxygen consumption rates tend to be higher in certain hotspots which are often in shallow embayments, but not all shallow embayments have high rates
    - It is unclear what is controlling the variation observed from site to site, but some of the sources of variation in solute fluxes include:
        - Depth is the best correlate with dissolved oxygen
        - Bottom water dissolved oxygen concentration is positively correlated with dissolved oxygen flux. If you have a lot of bottom water oxygen, you create a strong diffusive flux into the sediment, which generally happens in shallow water
        - Interestingly, dissolved oxygen flux has a strong correlation with H+ flux, which is consistent with the idea that much of the oxygen consumption in the sediment is reoxidizing stored reduced compounds
        - DIC correlates with Si flux
- Looking at DO vs. DIC plot suggests sediments have an oxygen demand “memory” that decouples DO consumption from organic matter mineralization

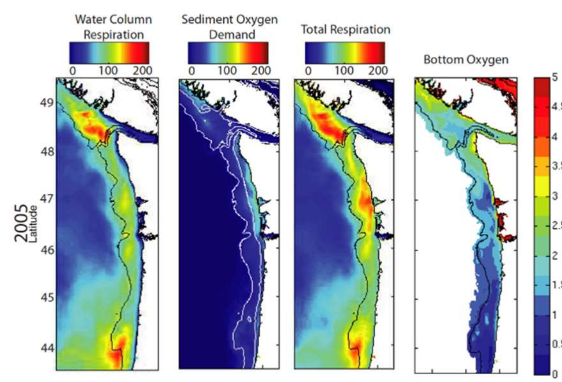


- Sulfate reduction and sulfide oxidation play important roles
  - Saw a unique pattern in Bellingham Bay after the spring bloom, where the dissolved oxygen and carbon flux are actually greater than the oxygen flux. Expect this pattern is the result of seasonal storage and the reoxidation of reduced compounds, particularly sulfides
- Denitrification and burial remove a significant fraction of N, particularly in Hood Canal due to its long residence time. Denitrification also important in shallow bays such as Bellingham Bay
  - Nearly all of the sites had lower dissolved oxygen and nitrogen fluxes than expected, which indicates that the removal process in the sediment are inhibiting the release of nitrogen in the water column
  - In Bellingham Bay, more DIN is released nearshore and denitrification rates are more spatially uniform.
  - 2022 nutrient budget for Bellingham Bay estimates 95% of nitrogen is from deep water, about 4% from the Nooksack River, and less than 2% from the wastewater treatment plant. Of the nitrogen supplied to Bellingham Bay about 11% is lost due to denitrification
- Seasonal data are needed to better quantify the role of sediment-water exchange on nitrogen and dissolved oxygen
  - David measured dissolved inorganic carbon flux and the dissolved oxygen flux at one station over the course of the year. The seasonal variation reinforces that there is a "memory" that the oxygen consumption is spread out throughout the year as the reduced compounds are broken down
- Burial rates of N may be significant; the few existing estimates suggest it is on par with the rates of denitrification. Therefore, it would be beneficial to study burial rates of N in more detail

Modeling: LiveOcean

Dr. Parker MacCready, University of Washington LiveOcean

- Prioritized alignment with the dynamics on the shelf. There are likely differences in the Salish Sea, for example there is less wave resuspension of bottom sediment
- NPZD-O Model is described in Siedlecki at al. (2015) and based on observations on the WA shelf in Fuchsman et al. (2015)
  - Organic particles (N units) sink at 8 and 80 m/day
  - For flux of organic particles that get to the sea floor:
    - Generally, the model uses "instantaneous remineralization" of F back to NH_4 and DO is lost at a rate of (108/16) F
    - There is also a steady drawdown of bottom NO_3 of 1.2 mmol N m-2 day-2 (if F can support it)



        - If instead bottom water has very low DO, the model assumes denitrification, and bottom NO_3 is lost at a rate F
- In general water column remineralization is greater than benthic

Modeling: Salish Sea Model

Dr. Stefano Mazzilli, University of Washington Puget Sound Institute

Salish Sea Model:

- Based on Di Toro et al. (2001), which has been used in the Chesapeake, and applied in WASP (Martin and Wool, 2013)
- 2-layer aerobic and anerobic processes that incorporate the deposition of particulate organic matter, diageneses/decomposition, solute forum reactions and exchange with the water column, and release of methane and Nitrogen gas as well as burial
- The module uses uniform parameterization throughout the domain that is similar to that used by Testa et. al., 2013 for the Chesapeake Bay, as well as uniform layer depths for the two layers (0.1 cm and 10 cm). It does not explicitly incorporate resuspension
- The Salish Sea Modeling Center website provides a synthesis of the module. To learn more about how the sediment diagenesis module for the Salish Sea Model was implemented, as well as what steps have been taken to validate and undertake sensitivity analysis, see the following key reports and publications, and those referenced within: Ahmed et al. (2019) + appendices, Pelletier et al. (2017a), Bianucci et al. (2018), and Khangaonkar (2018)
- Clarification: The Salish Sea Model includes the sulfate reduction module as part of the default parameters

Modeling: Proposed Modeling Analysis & Preliminary Results

Dr. Stefano Mazzilli, University of Washington Puget Sound Institute

Proposed Modeling Analysis that would further improve confidence in the sediment oxygen demand module application in the Salish Sea Model

1. Further validation of the sediment module using measured data
    - Expand the data set for model development and validation across models to include USGS (2014), Pelletier et al. (2017), and Merritt (2017) data
    - Analyze seasonal variations in Nitrogen fluxes by comparing monthly averages at Dabob, Budd and Bellingham in 2014 to USGS (2014) and Merritt (2017) data
    - Compare springtime predictions for dissolved oxygen, nitrogen, carbon, phosphorous, and silicate to observations at 40 sites including shallow embayments in April and May, 2018 to Rigby (2019) data
2. Examination of modeled sediment flux responses to changing nutrient loading. This might consider:
    - Does the model behave as expected with varying loadings across different seasons and depths?

- Calculate existing and reference scenarios, and the difference between the two runs for the year 2014 to compare nitrate, ammonium, and sediment oxygen demand fluxes. Where possible consider in the context of bottom water nitrate, net primary production, temperature, and salinity.

3. Analysis of Salish Sea Model sediment exchange model spin up and stability

Discussion

Monitoring

In response to questions, David shared that:

- Observed water column respiration rates would be helpful, particularly in the Main Basin
- The transport of particulate organic carbon from the water column to the sediment is a much trickier measurement to make. You can either use sediment traps, tracers like thorium, or some sediment trap data that gives you the carbon to thorium ratio. It was agreed those numbers would be great to have, but would require a significantly higher effort
- There is high variability on all spatial scales to take into consideration, from replicate samples taken within seven meters of each other, to variability among basins
- He looked at the correlation between benthic biomass and oxygen consumption rates and could not find a correlation. However, he noted there are examples where the respiration rate of large benthic macrofauna can play a huge role in oxygen consumption. This is particularly the case in high latitude environments where perhaps the microbial consumption rate is damped a bit because of temperature, but you can get a big calm or brittle star that can consume most of the oxygen
- Mark Lever asked if there is any evidence that in places where the disconnect between oxygen demand and mineralization rates is the greatest that there is more reworking?
  - David measured rates of bioturbation extensively at just one station in Bellingham Bay since it is a significant amount of work to measure. About 25% of the organic matter was remineralized by sulfate reduction at that location. At that same location, David also saw low rates of iron reduction and fairly low rates of sulfate reduction
- Marked Lever added could micro-sensors or relative abundance studies of micro bacteria potentially be useful to look at oxygen and hydrogen sulfide concentration gradients to see if they actually meet, and whether there could be a movement of hydrogen sulfide into the very top layer of sediment where oxygen is present or into the overlying water?
  - David reflected that hydrogen sulfide concentrations likely do not ramp up until pretty deep in the sediment because there is a lot of iron, so perhaps micro-sensor studies would be useful. There is a lot of sulfate reduction happening even without high concentrations of sulfide. Ultimately, the rate of sulfate reduction is probably the key to understanding the role of sulfate reduction in the system

> **Discussion Questions**
>
> 1. Are we satisfied with our state of knowledge on sediment exchange in terminal embayments? If not, what additional modeling and monitoring would you propose to improve our understanding?
> 2. In addition to Ahmed et al. (2019) and prior papers what further validation and sensitivity analysis would you like to see?
> 3. How would you further improve confidence in the application of the models in terms of sediment exchange?

    - Relative abundance studies of micro bacterial would also likely tell us more about these processes and their importance

- *Monitoring Methods*
    - Studies have shown that benthic flux chambers *in situ* and core incubations generally compare well if you can do the incubation in a quiet place, control the temperature, and minimize core disturbance
    - Incubation *ex-situ* allows you to cover a lot of ground, but you never know for sure if the rates you are measuring in an incubator are exactly what is happening on the bottom
    - Bioturbation, particularly bio-irrigation, can have a significant impact on oxygen consumption for whole core incubation. For example, the fluxes are generally small when the boat is running and takeoff once in the incubator, which suggests the animals are frightened by the noise. So, when sampling, David commented that they try to take sediment cores that are deep enough to collect all the organisms and try to keep the animals as happy as possible

Modeling

- Tarang Khangaonkar reflect that if water column respiration is 80-90% of the total respiration and the rest is benthic it seems like the amount of organic matter that gets to the benthos is critically important for modeling the benthic respiration
- Amber Holdsworth asked that since sulfate reduction sulfide oxidation may play a strong role, how can we potentially parameterize this process in our models without including the full cycle, and what time frames are important? David shared:
    - The process of sulfate reduction in sulfate reduction sulfide oxidation is that oxygen consumption is spread out over a longer time period, rather than everything happening instantaneously once the organic matter hits. Furthermore, they require bioturbation to get activated. So, if oxygen demand is spread out over a longer time period, the models might overestimate the oxygen consumption during those critical time periods of hypoxia in the summer if they do not account for the "memory" in the system
    - It may be difficult to accurately model these processes without considering sulfate reduction on longer time scales
    - The annual timescale is important when considering seasonal variations, particularly to modeling. This is because it appears that there is this sort of seasonal cycle of production and oxidation of other oxygen-utilizing compounds as well. Furthermore, there is a longer time scale to consider that are ultimately the difference between the dissolved inorganic flux and the oxygen flux. These would be a function of how much these reduced compounds are ultimately buried and preserved over the longer time period. So, the relevant timescale depends on your question and focus within sediment/water column fluxes, however the annual time frame is the most important to start
    - Laura responded that there is not as much data available in the Strait of Georgia, however perhaps with the rich dataset for Puget Sound discussed, it would be possible to do sensitivity analysis to see which remineralization time frame matches observed data and improve modeling
- Tarang commented that the modeled benthic fluxes responded as observed in David's studies: shallow embayments have a larger flux than deeper waters which were less significant. Settling rates were set during the calibration process to ensure the model has higher sediment oxygen demand in shallow embayments (i.e., 0 – 1 g/m2) and lower flux in the deeper basins (2 – 10 g/m2)

    - He added that being able to use measured sediment oxygen demand data like David is collecting as inputs to the model will improve the accuracy and robustness of all of the various models, and reduce uncertainty
- It appears that there is one modeled location in the Salish Sea Model preliminary results slides Stefano Mazzilli presented that appears to behave very differently, with low O2 fluxes in the late summer while other sites exhibit very high fluxes. It was suggested by Mark Lever that it would be interesting to look at these or other locations that might be anoxic or hypoxic for part of the year for comparison in measured and modeled data in the future
- Jeremy reflected on similar challenges faced in the Chesapeake and monitoring and modeling activities they have done that might be relevant to answer the questions and challenges raised in this discussion
    - Running a simplified version of the model as a stand-alone is possible; this was done in the Chesapeake. It allows you to get at the net deposition of sulfate to the sediments and calculate what the pool and fluxes are if sediments turn anoxic
    - However, this might not be worthwhile since most of the water is deep. After thirty to forty meters the contributions of sediment oxygen demand becomes pretty small, so there are diminishing returns to refining this aspect of the model in deeper basins. Therefore, Jeremy reflected it is reasonable to address this in the model the way it is, at least for the deeper basins

Resources

Additionally shared

- Deng, L., Meile, C., Fiskal, A., Bölsterli, D., Han, X., Gajendra, N., Dubois, N., Bernasconi, S. M., & Lever, M. A. (2022). Deposit-feeding worms control subsurface ecosystem functioning in intertidal sediment with strong physical forcing. *PNAS Nexus*, *1*(4), pgac146. Available at: https://doi.org/10.1093/pnasnexus/pgac146
- Van Grinsven, S., Meier, D. V., Michel, A., Han, X., Schubert, C. J., & Lever, M. A. (2022). Redox Zone and Trophic State as Drivers of Methane-Oxidizing Bacterial Abundance and Community Structure in Lake Sediments. *Frontiers in Environmental Science*, *10*, 857358. Available at: https://doi.org/10.3389/fenvs.2022.857358
- Han, X., Schubert, C. J., Fiskal, A., Dubois, N., & Lever, M. A. (2020). Eutrophication as a driver of microbial community structure in lake sediments. *Environmental Microbiology*, *22*(8), 3446–3462. Available at: https://doi.org/10.1111/1462-2920.15115
- Fiskal, A., Deng, L., Michel, A., Eickenbusch, P., Han, X., Lagostina, L., Zhu, R., Sander, M., Schroth, M. H., Bernasconi, S. M., Dubois, N., & Lever, M. A. (2019). Effects of eutrophication on sedimentary organic carbon cycling in five temperate lakes. *Biogeosciences*, *16*(19), 3725–3746. Available at: https://doi.org/10.5194/bg-16-3725-2019
- Han, X., Tolu, J., Deng, L., Fiskal, A., Schubert, C. J., Winkel, L. H. E., & Lever, M. A. (2022). Long-term preservation of biomolecules in lake sediments: Potential importance of physical shielding by recalcitrant cell walls. *PNAS Nexus*, *1*(3), pgac076. Available at: https://doi.org/10.1093/pnasnexus/pgac076

Referenced in the presentations

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- Apple, J., & Bjornson, S. (2019). Spatial and seasonal variability in Salish Sea bottom-water microbial respiration (p. 16). Available upon request
- Rigby, E. I. (2019). *Springtime benthic fluxes in the Salish Sea: Environmental parameters driving spatial variation in the exchange of dissolved oxygen, inorganic carbon, nutrients, and alkalinity between the sediments and overlying water. WWU Graduate School Collection*. 903. Available at: https://cedar.wwu.edu/wwuet/903
- Belley, R., Snelgrove, P. V., Archambault, P., & Juniper, S. K. (2016). Environmental Drivers of Benthic Flux Variation and Ecosystem Functioning in Salish Sea and Northeast Pacific Sediments. *PloS one, 11*(3), e0151110. Available at: http://doi.org/10.1371/journal.pone.0151110
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- Fuchsman, C. A., Devol, A. H., Chase, Z., Reimers, C. E., & Hales, B. (2015). Benthic fluxes on the Oregon shelf. *Estuarine, Coastal and Shelf* Science*, 163*, 156-166. Available at: http://doi.org/10.1016/j.ecss.2015.06.001
- Sheibley, R., & Paulson, A. J. (2014). Quantifying Benthic Nitrogen Fluxes in Puget Sound, Washington—A Review of Available Data. *Scientific Investigations Report*, *2014–5033*. Available at: http://dx.doi.org/10.3133/sir20145033
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- Mackas, D. L., & Harrison, P. J. (1997). Nitrogenous Nutrient Sources and Sinks in the Juan de Fuca Strait/Strait of Georgia/Puget Sound Estuarine System: Assessing the Potential for Eutrophication. *Estuarine, Coastal and Shelf Science, 44*, 1-21. Available at: http://doi.org/10.1006/ecss.1996.0110
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Modeling

LiveOcean

- Siedlecki, S. A., Banas, N. S., Davis, K. A., Giddings, S. N., Hickey, B. M., MacCready, P., Connolly, T. P., & Geier, S. (2015). Seasonal and interannual oxygen variability on the Washington and Oregon continental shelves. *Journal of Geophysical Research: Oceans, 120*(2), 608-633. Available at: https://doi.org/10.1002/2014JC010254
- Babson, A. L., Kawase, M., & MacCready, P. (2006). Seasonal and interannual variability in the circulation of Puget Sound, Washington: A box model study. *Atmosphere-Ocean*, *44*(1), 29–45. Available at: https://doi.org/10.3137/ao.440103

Salish Sea Model

To learn more about how the sediment diagenesis module is designed, validated, and analyzed for sensitivity, you can reference the workshop slides as well as the following papers:

- Ahmed, A., Figueroa-Kaminsky, C., Gala, J., Mohamedali, T., Pelletier, G., & Sheelagh, M. (2019). *Puget Sound Nutrient Source Reduction Project. Volume 1: Model Updates and Bounding Scenarios* (No. 19-03–001; p. 102). Department of Ecology. https://apps.ecology.wa.gov/publications/SummaryPages/1903001.html
    - **Note:** There is helpful detail in Appendix E1, Appendix I, and Appendix C
- Bianucci, L., Long, W., Khangaonkar, T., Pelletier, G., Ahmed, A., Mohamedali, T., Roberts, M., & Figueroa-Kaminsky, C. (2018). Sensitivity of the regional ocean acidification and carbonate system in Puget Sound to ocean and freshwater inputs. *Elementa: Science of the Anthropocene*, *6*, 22. Available at: https://doi.org/10.1525/elementa.151
- Khangaonkar, T., Nugraha, A., Xu, W., Long, W., Bianucci, L., Ahmed, A., Mohamedali, T., & Pelletier, G. (2018). Analysis of Hypoxia and Sensitivity to Nutrient Pollution in Salish Sea. *Journal of Geophysical Research: Oceans*, *123*(7), 4735–4761. Available at: https://doi.org/10.1029/2017JC013650
- Pelletier, G., Bianucci, L., Long, W., Khangaonkar, T., Mohamedali, T., Ahmed, A., & Figeuroa-Kaminsky, Cristiana. (2017). *Salish Sea Model: Sediment Diagenesis Module* (No. 17-03–010; p. 113). Department of Ecology. Available at: https://apps.ecology.wa.gov/publications/documents/1703010.pdf

Engaging in the workshop series

Our region is navigating complex and challenging decisions on how best to manage nitrogen, dissolved oxygen, and the potential impacts on the key habitats and species of the Salish Sea. The University of Washington Puget Sound Institute is supporting a series of scientific workshops to help address technical uncertainties, advance modeling, and refine monitoring to improve our understanding of nutrients and broader water quality in the Salish Sea. Learn more about upcoming workshops or review the recordings and presentation materials from previous workshops.

Continue the discussion

- If you have not already, please join the listserv to receive periodic updates about Puget Sound Institute's program to foster regional water quality science, including information about upcoming workshops
- Join us for the follow up workshops to dig into these technical uncertainties
- Reach out to Stefano Mazzilli (mazzilli@uw.edu) and Marielle Larson (marlars@uw.edu) if you:
    - Are interested in contributing or helping with one of the upcoming workshops or modeling and monitoring analyses
    - Want to recommend another expert, program, or study for us to connect with to help advance the research
    - Have additional ideas or questions