A space-time interpolation tool for Chesapeake Bay dissolved oxygen (4D Tool): Development and method summary

Breck Sullivan[4] Rebecca Murphy[1], Jon Harcum[2],
Elgin Perry[3], and Peter Tango[4],

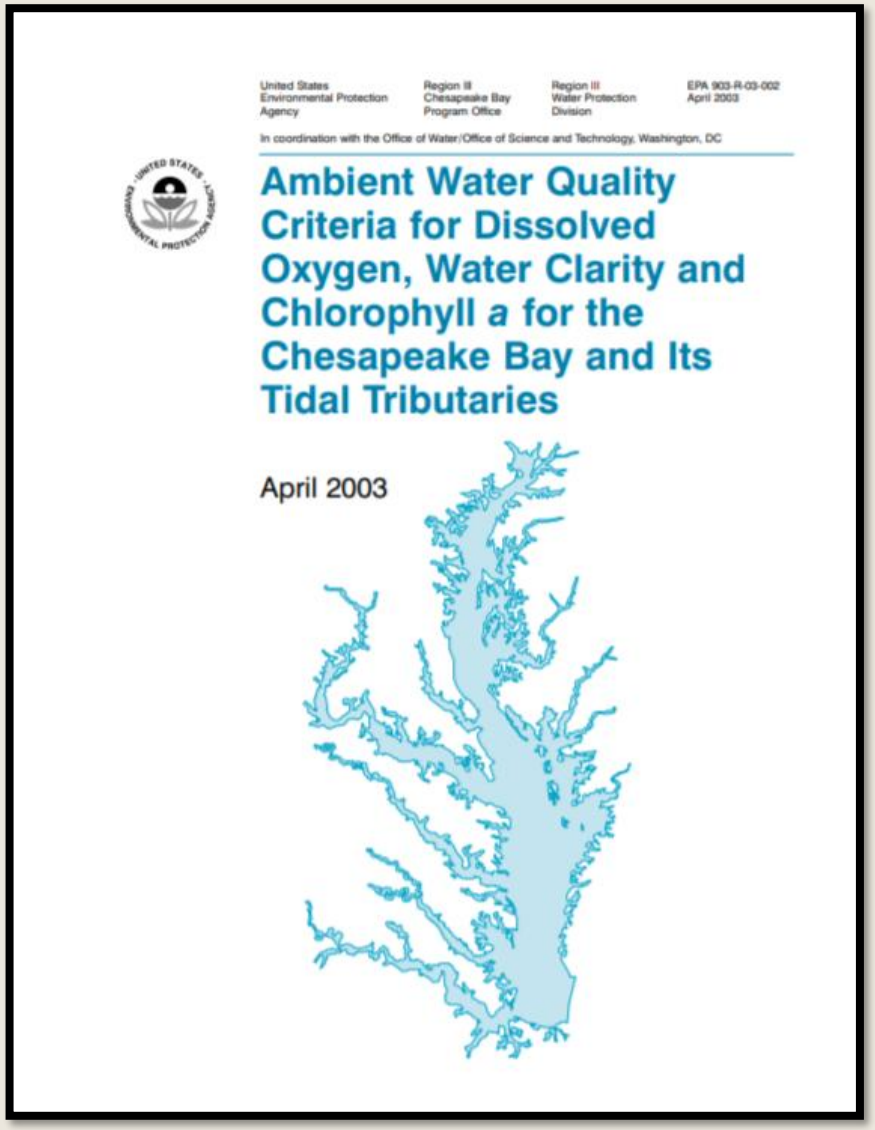
[1]University of Maryland Center for Environmental Science at the Chesapeake Bay Program (CBP),
[2]Tetra Tech,[3]Statistics Consultant, [4]USGS at the CBP,

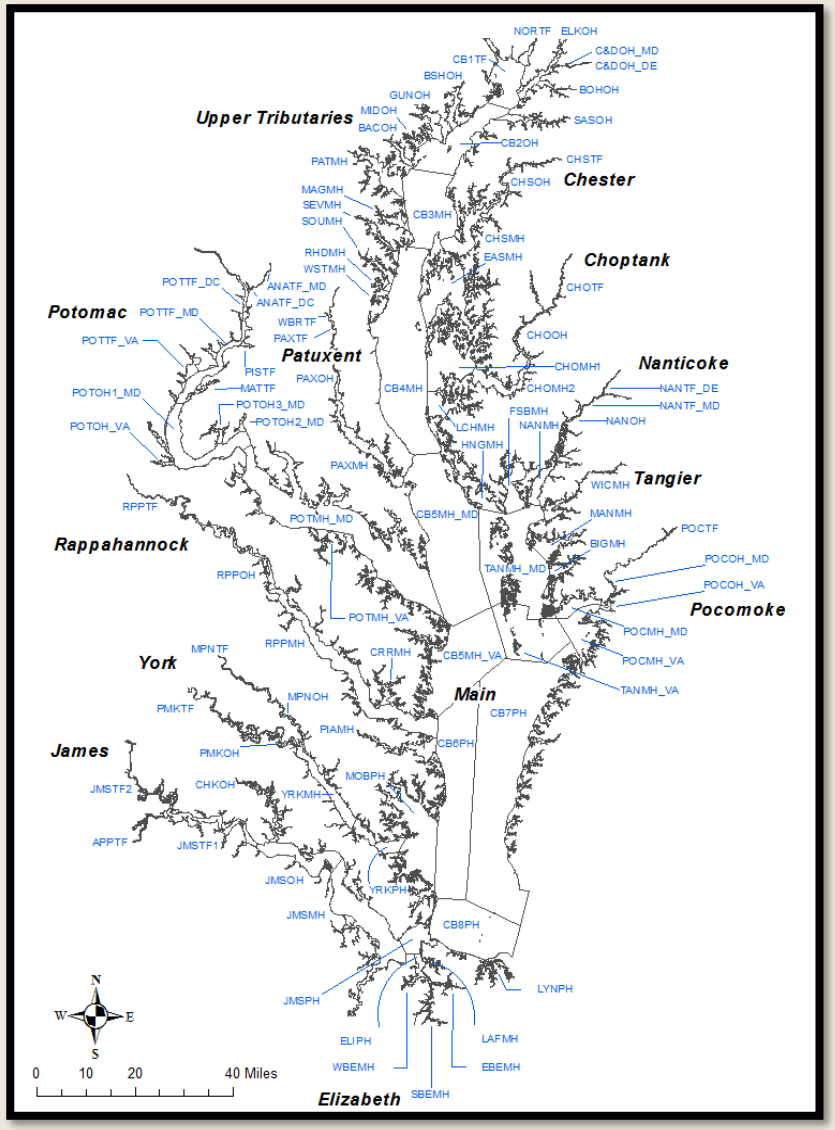
Chesapeake Bay Program
Science. Restoration. Partnership.

University of Maryland
CENTER FOR ENVIRONMENTAL SCIENCE

CBP Modeling Quarterly
April 7, 2026

Purpose: Build a tool for more complete criteria assessment





U.S. Environmental Protection Agency 2003 EPA 903-R-03-002

Purpose: Build a tool for more complete criteria assessment

Table 1. Chesapeake Bay dissolved oxygen criteria.

Designated Use	Criteria Concentration/Duration	Protection Provided	Temporal Application
Migratory fish spawning and nursery use	7-day mean $\geq$ 6 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species.	February 1 - May 31
	Instantaneous minimum $\geq$ 5 mg liter^{-1}	Survival and growth of larval/juvenile migratory fish; protective of threatened/endangered species.	
	Open-water fish and shellfish designated use criteria apply		June 1 - January 31
Shallow-water bay grass use	Open-water fish and shellfish designated use criteria apply		Year-round
Open-water fish and shellfish use	30-day mean $\geq$ 5.5 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species.	Year-round
	30-day mean $\geq$ 5 mg liter^{-1} (tidal habitats with >0.5 ppt salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species.	
	7-day mean $\geq$ 4 mg liter^{-1}	Survival of open-water fish larvae.	
	Instantaneous minimum $\geq$ 3.2 mg liter^{-1}	Survival of threatened/endangered sturgeon species.[1]	
Deep-water seasonal fish and shellfish use	30-day mean $\geq$ 3 mg liter^{-1}	Survival and recruitment of bay anchovy eggs and larvae.	June 1 - September 30
	1-day mean $\geq$ 2.3 mg liter^{-1}	Survival of open-water juvenile and adult fish.	
	Instantaneous minimum $\geq$ 1.7 mg liter^{-1}	Survival of bay anchovy eggs and larvae.	
	Open-water fish and shellfish designated-use criteria apply		October 1 - May 31
Deep-channel seasonal refuge use	Instantaneous minimum $\geq$ 1 mg liter^{-1}	Survival of bottom-dwelling worms and clams.	June 1 - September 30
	Open-water fish and shellfish designated use criteria apply		October 1 - May 31

[1] At temperatures considered stressful to shortnose sturgeon (>29°C), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg liter^{-1} will protect survival of this listed sturgeon species.

From EPA 2003 Ambient Water Quality Criteria

Purpose: Build a tool for more complete criteria assessment

DO criteria that currently can be evaluated with existing approaches and data

Table 1. Chesapeake Bay dissolved oxygen criteria.

Designated Use	Criteria Concentration/Duration	Protection Provided	Temporal Application
Migratory fish spawning and nursery use *	7-day mean ≥ 6 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Survival/growth of larval/juvenile tidal-fresh resident fish; protective of threatened/endangered species.	February 1 - May 31
	Instantaneous minimum ≥ 5 mg liter^{-1}	Survival and growth of larval/juvenile migratory fish; protective of threatened/endangered species.	
	Open-water fish and shellfish designated use criteria apply		June 1 - January 31
Shallow-water bay grass use	Open-water fish and shellfish designated use criteria apply		Year-round
Open-water fish and shellfish use	30-day mean ≥ 5.5 mg liter^{-1} (tidal habitats with 0-0.5 ppt salinity)	Growth of tidal-fresh juvenile and adult fish; protective of threatened/endangered species.	Year-round
	30-day mean ≥ 5 mg liter^{-1} (tidal habitats with >0.5 ppt salinity)	Growth of larval, juvenile and adult fish and shellfish; protective of threatened/endangered species.	
	7-day mean ≥ 4 mg liter^{-1}	Survival of open-water fish larvae.	
	Instantaneous minimum ≥ 3.2 mg liter^{-1}	Survival of threatened/endangered sturgeon species.[1]	
Deep-water seasonal fish and shellfish use	30-day mean ≥ 3 mg liter^{-1}	Survival and recruitment of bay anchovy eggs and larvae.	June 1 - September 30
	1-day mean ≥ 2.3 mg liter^{-1}	Survival of open-water juvenile and adult fish.	
	Instantaneous minimum ≥ 1.7 mg liter^{-1}	Survival of bay anchovy eggs and larvae.	
	Open-water fish and shellfish designated-use criteria apply		October 1 - May 31
Deep-channel seasonal refuge use	Instantaneous minimum ≥ 1 mg liter^{-1}	Survival of bottom-dwelling worms and clams.	June 1 - September 30
	Open-water fish and shellfish designated use criteria apply		October 1 - May 31

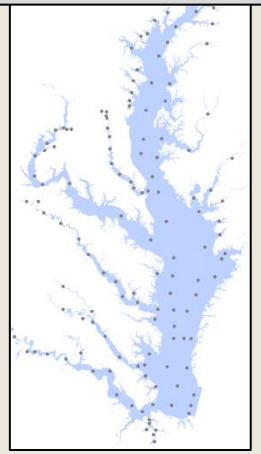
[1] At temperatures considered stressful to shortnose sturgeon (>29°C), dissolved oxygen concentrations above an instantaneous minimum of 4.3 mg liter^{-1} will protect survival of this listed sturgeon species.

*Note a 30-day mean 6 mg/L MSN value is evaluated for purpose of the WQ indicator.

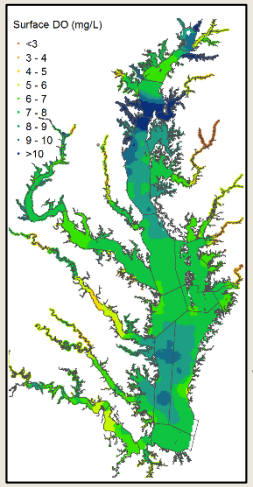
From EPA 2003 Ambient Water Quality Criteria

Criteria Assessment Method

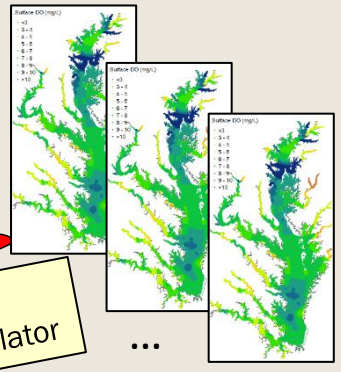
1. Collect bi-weekly to monthly data at each monitoring station



2. Interpolate bay-wide for a single cruise

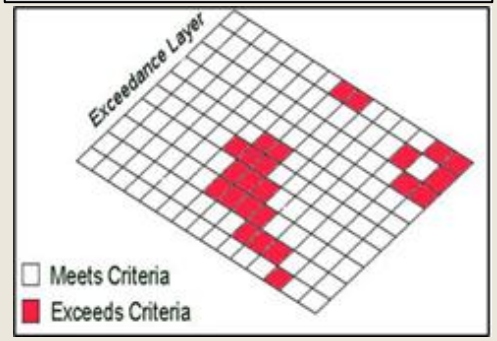


3. Conduct interpolations for a season over the 3-year period



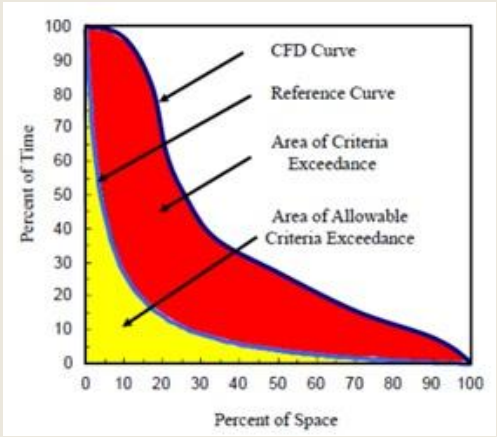
3D Interpolator

4. Average monthly if 30-day criterion in segment, and compare the interpolated values with appropriate criterion values

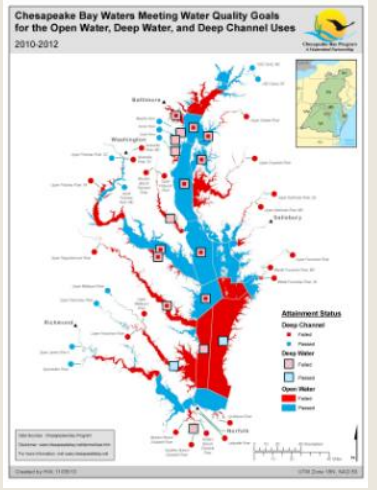


5. Repeat Step 4 throughout the 3-year period

6. Calculate the cumulative frequency distribution (CFD) for extent of exceedance in space and time



7. Quantify attainment status (attaining or not) for the 3-year period



Monitoring data inform annual assessments AND this process is used in the Phase 6 suite of models

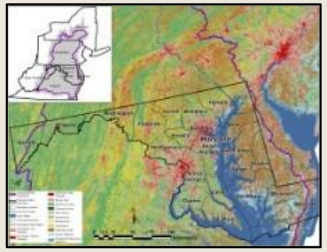
From Peter Tango

Process source USEPA 2003

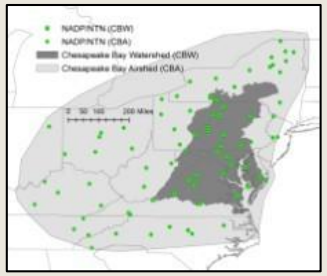
CBP Suite of Models

Data and Model Inputs

BMP Data
Land Use Data
Point Sources Data
Septic Data
U.S. Census Data
Agricultural Data



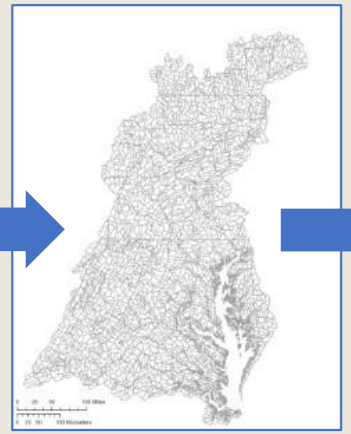
Land Use Change Model



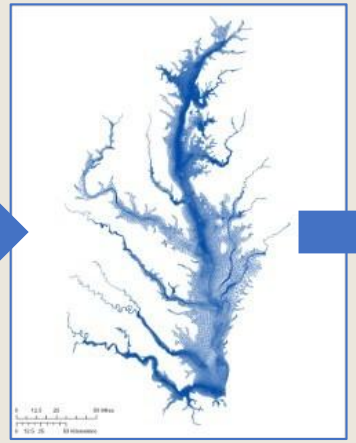
Airshed Model

Precipitation Data
Meteorological Data
Elevation Data
Soil Data

Phase 7 Watershed Model/CAST



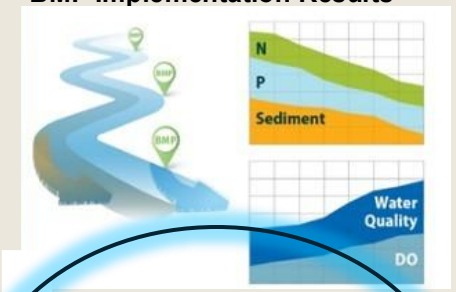
Main Bay Model Multiple Tributary Models



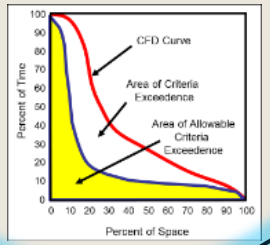
Model Outputs

Prediction of Impacts

BMP Implementation Results



Criteria Assessment Procedures



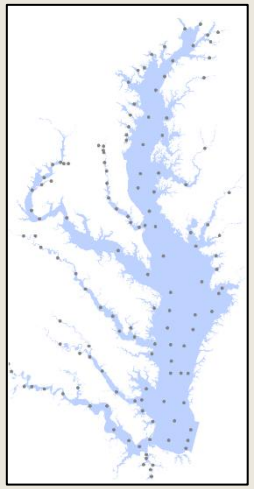
Nutrient and sediment targets for CBP state and Federal partnership

Effects

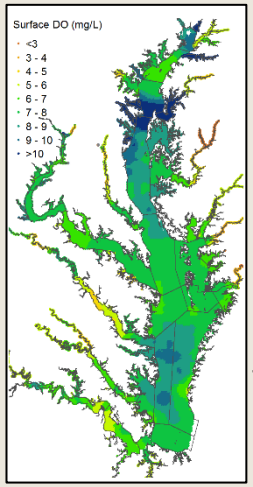
Targets

Criteria Assessment Method

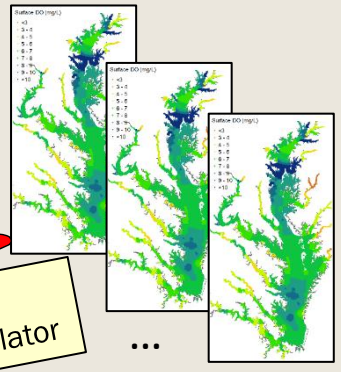
1. Using the Phase 6, use model output here via scenarioing



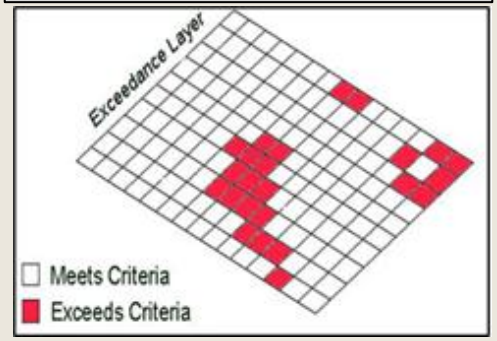
2. Interpolate bay-wide for a single cruise



3. Conduct interpolations for a season over the 3-year period

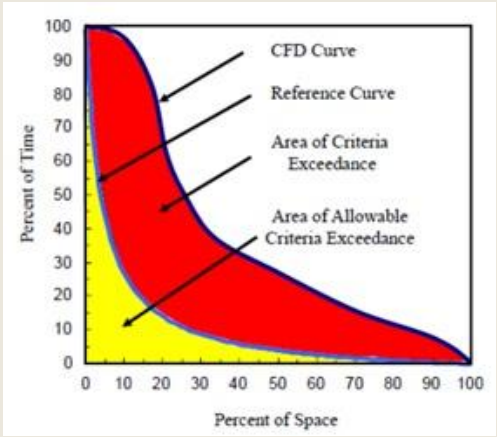


4. Average monthly if 30-day criterion in segment, and compare the interpolated values with appropriate criterion values

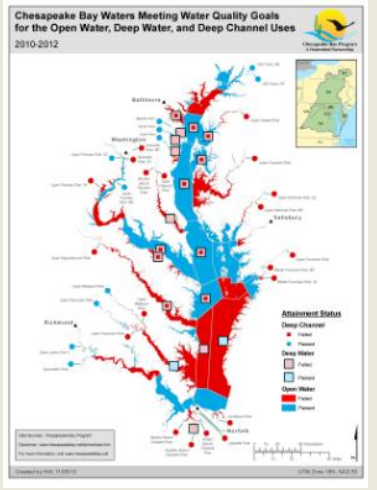


5. Repeat Step 4 throughout the 3-year period

6. Calculate the cumulative frequency distribution (CFD) for extent of exceedance in space and time



7. Quantify attainment status (attaining or not) for the 3-year period

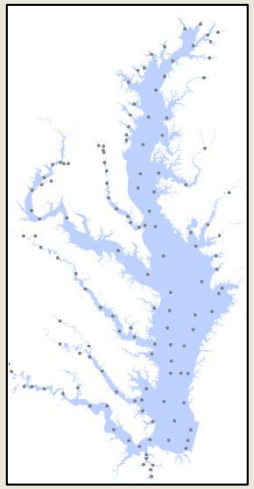


From Peter Tango

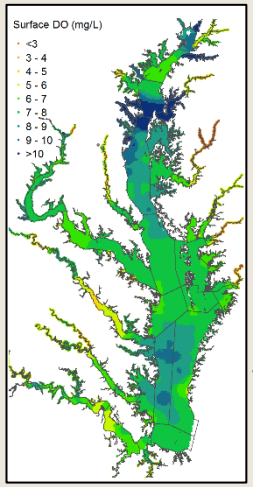
Process source USEPA 2003

Criteria Assessment Method

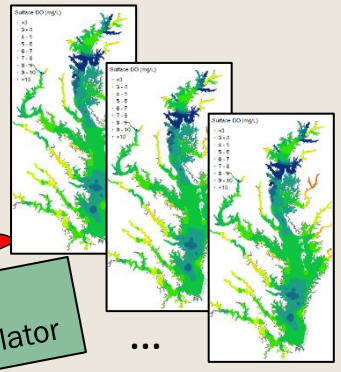
1. Using the **Phase 7**, use model output here via scenarioing



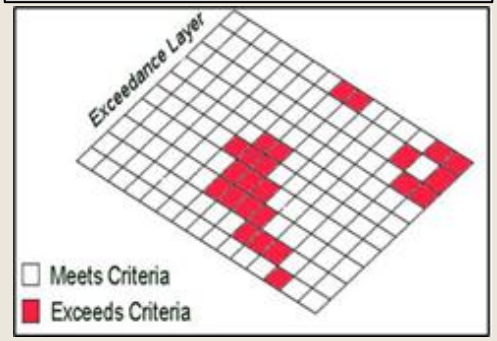
2. Interpolate bay-wide for a single cruise



3. Conduct interpolations for a season over the 3-year period

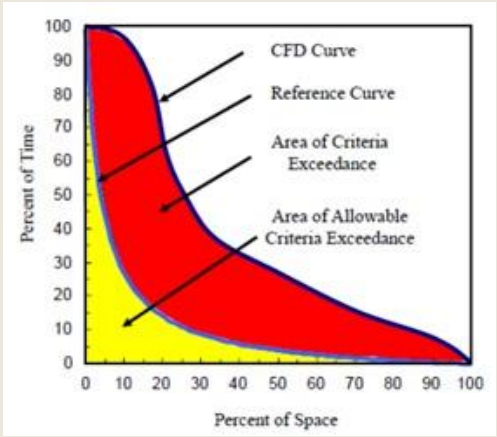


4. Average monthly if 30-day criterion in segment, and compare the interpolated values with appropriate criterion values

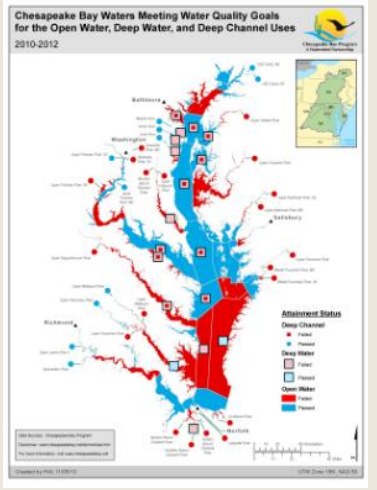


5. Repeat Step 4 throughout the 3-year period

6. Calculate the cumulative frequency distribution (CFD) for extent of exceedance in space and time



7. Quantify attainment status (attaining or not) for the 3-year period



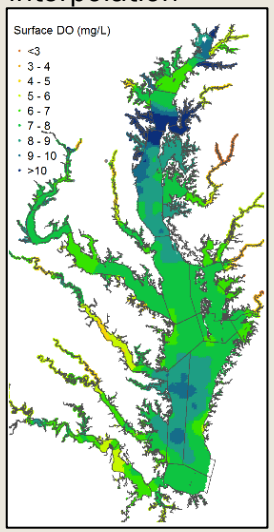
From Peter Tango

Process source USEPA 2003

Current interpolation:

Inverse distance weighting

Example spatial interpolation



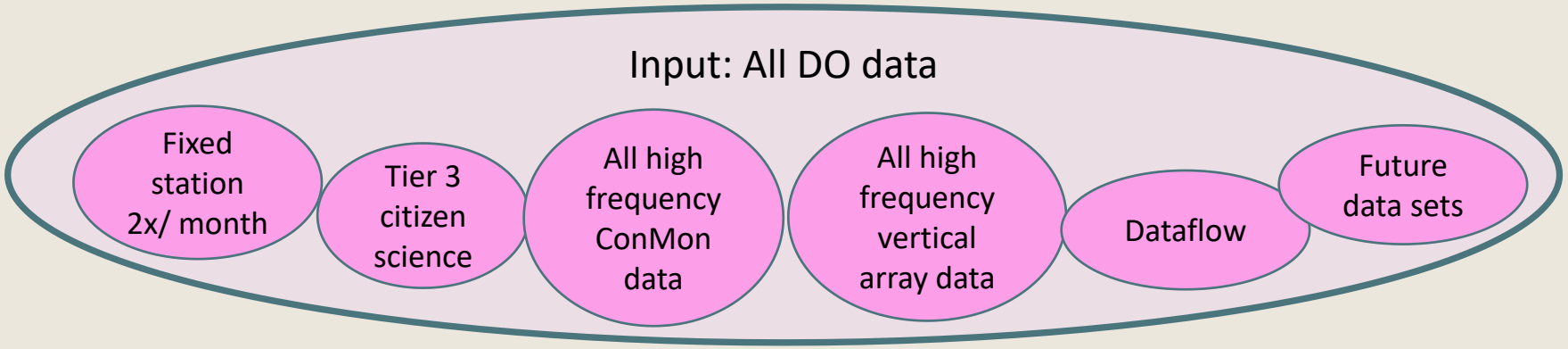
Problems with current interpolation

- Does not use the high frequency data
- Vertical layers interpolated horizontally and stacked;
- One cruise at a time, meaning a 2-week period assumed static; and
- Not statistical.

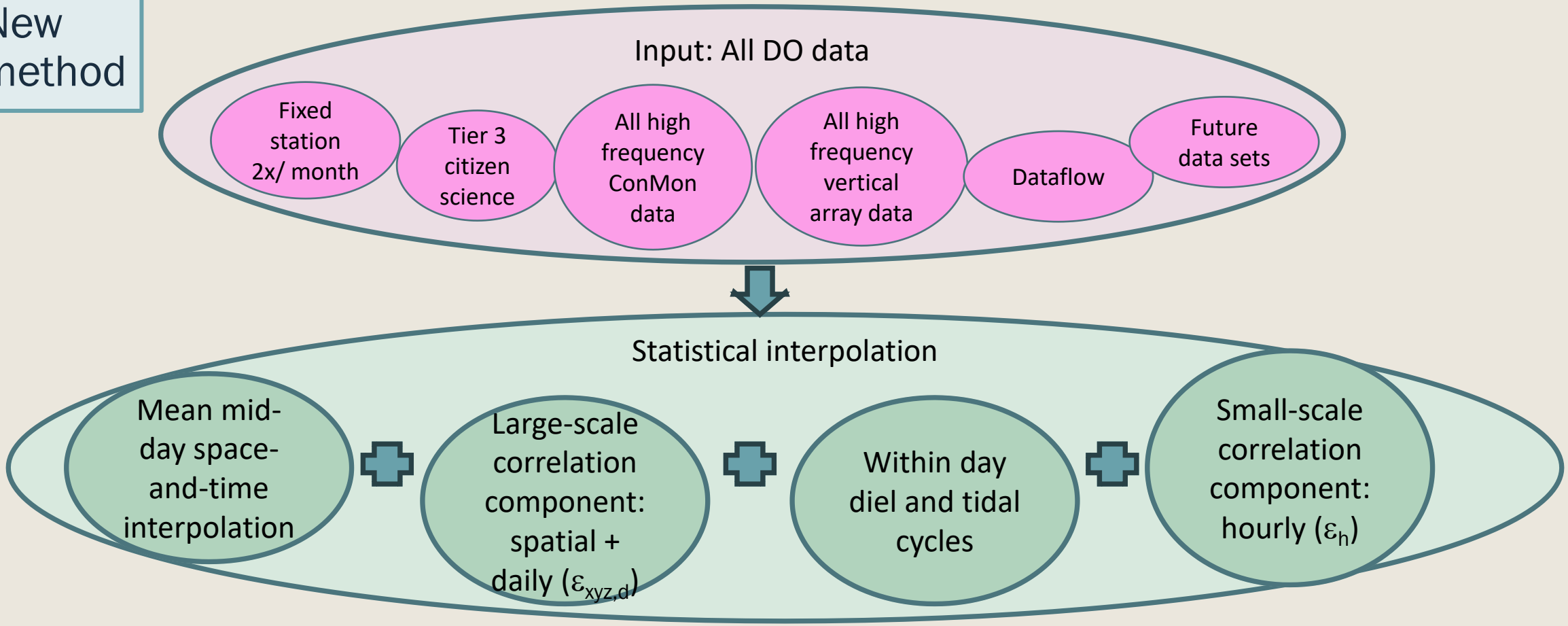
This NEW "4-D" interpolation will:

- Use all high frequency data
- Interpolate all data together, not in layers.
- Interpolate in time, so that we do not have to artificially split time periods.
- Statistical – allowing for multiple realizations of interpolation results.

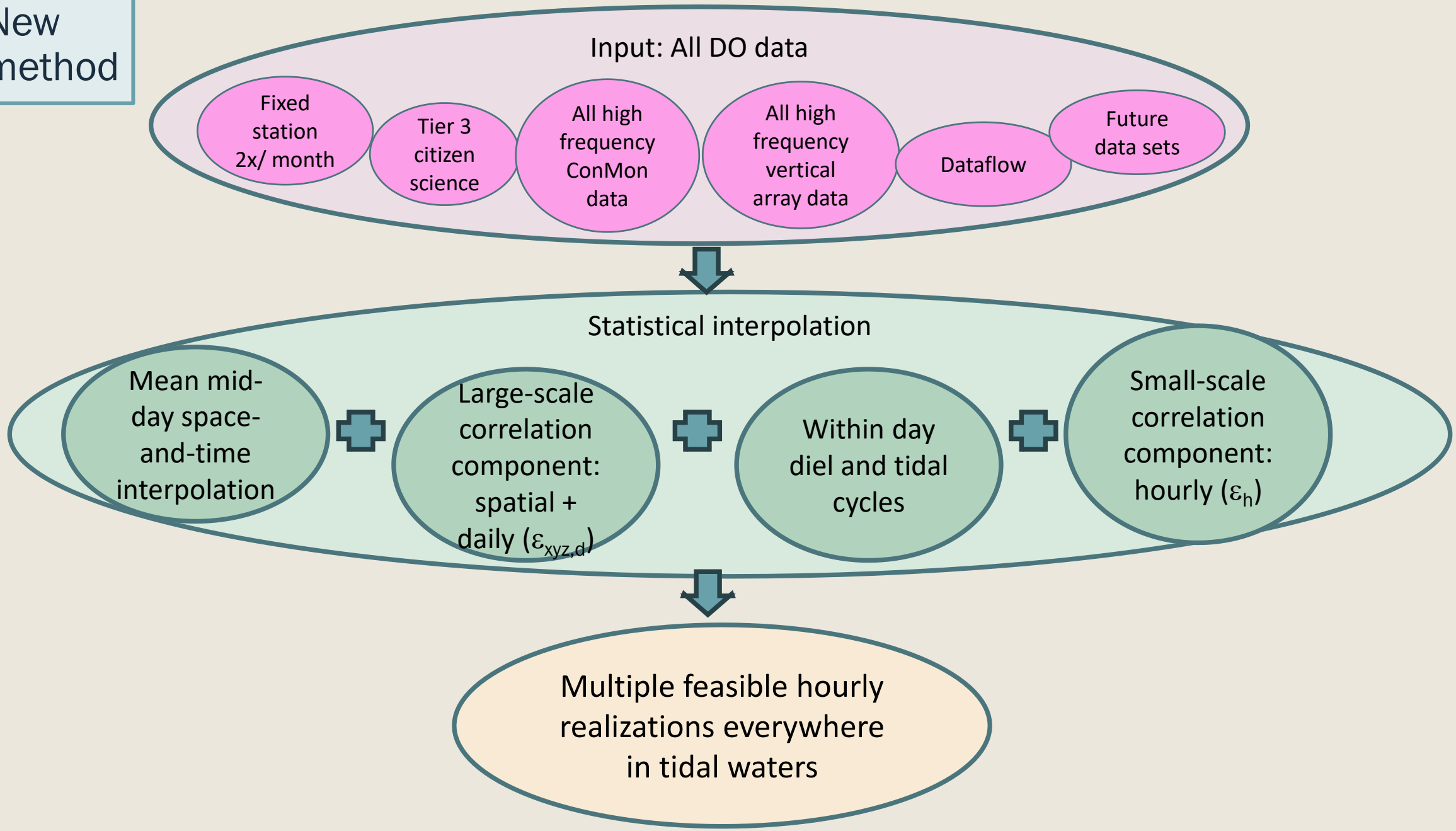
New method

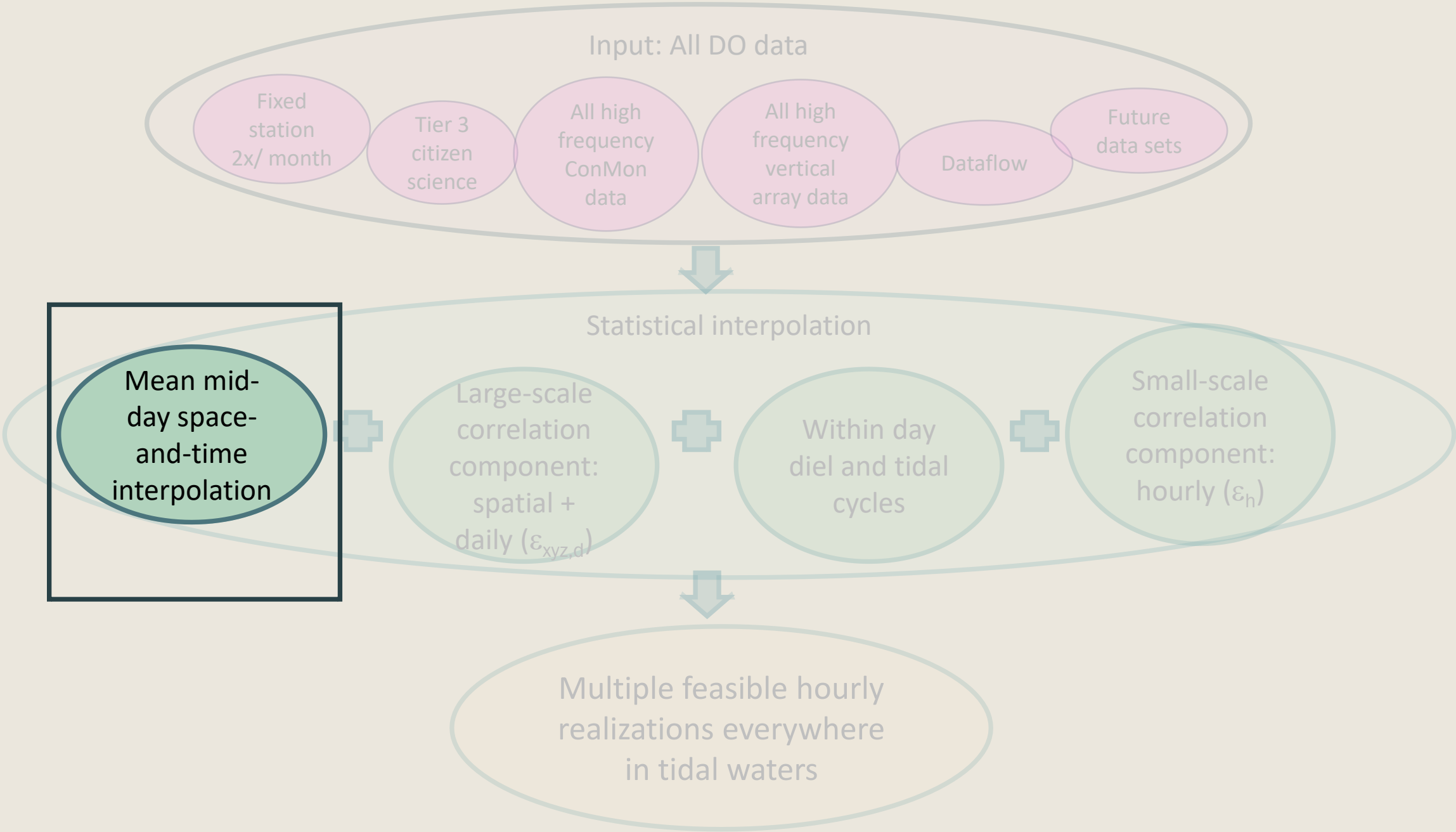

Input: All DO data
Fixed station 2x/ month
Tier 3 citizen science
All high frequency ConMon data
All high frequency vertical array data
Dataflow
Future data sets

New method


Input: All DO data
Fixed station 2x/ month
Tier 3 citizen science
All high frequency ConMon data
All high frequency vertical array data
Dataflow
Future data sets
Statistical interpolation
Mean mid-day space-and-time interpolation
Large-scale correlation component: spatial + daily ($\varepsilon_{xyz,d}$)
Within day diel and tidal cycles
Small-scale correlation component: hourly (ε_h)

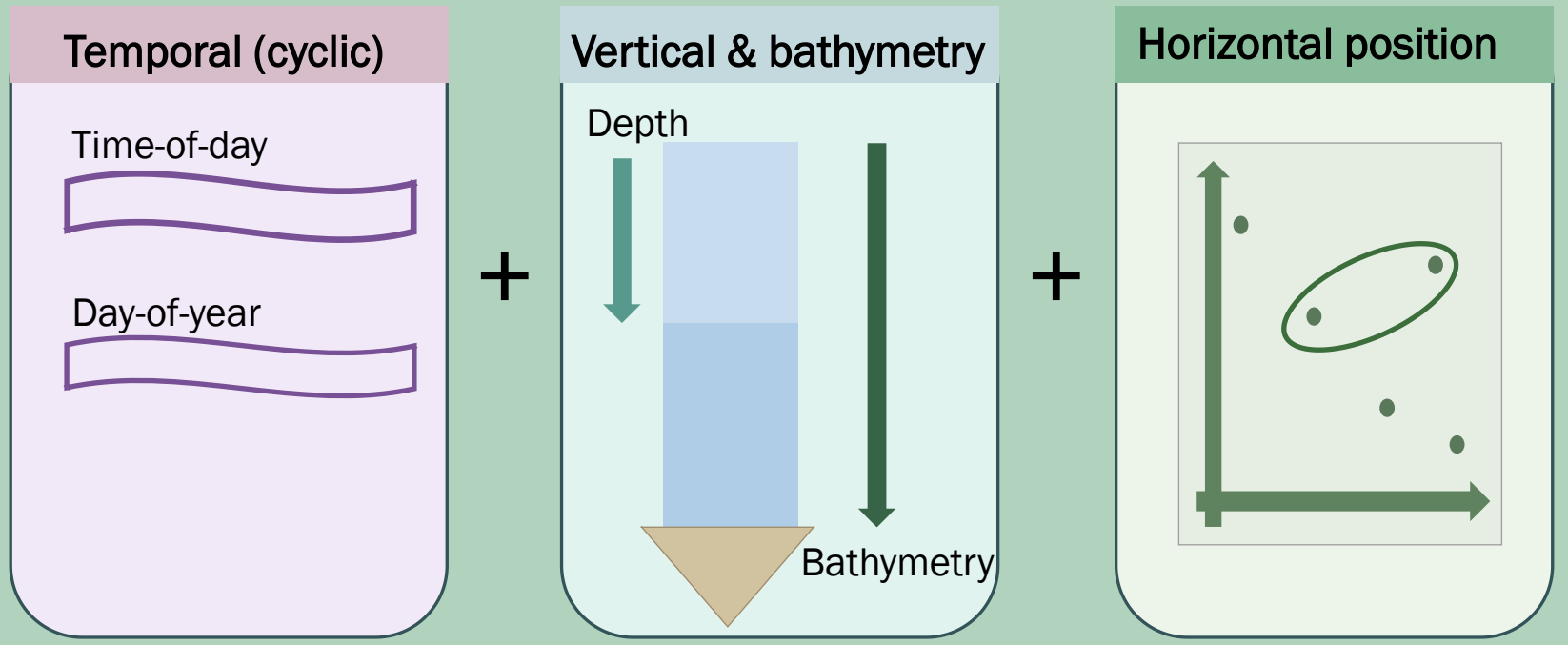
New method


Input: All DO data
Fixed station 2x/ month
Tier 3 citizen science
All high frequency ConMon data
All high frequency vertical array data
Dataflow
Future data sets
Statistical interpolation
Mean mid-day space-and-time interpolation
Large-scale correlation component: spatial + daily ($\varepsilon_{xyz,d}$)
Within day diel and tidal cycles
Small-scale correlation component: hourly (ε_h)
Multiple feasible hourly realizations everywhere in tidal waters


Input: All DO data
Fixed station 2x/ month
Tier 3 citizen science
All high frequency ConMon data
All high frequency vertical array data
Dataflow
Future data sets
Statistical interpolation
Mean mid-day space-and-time interpolation
Large-scale correlation component: spatial + daily ($\varepsilon_{xyz,d}$)
Within day diel and tidal cycles
Small-scale correlation component: hourly (ε_h)
Multiple feasible hourly realizations everywhere in tidal waters

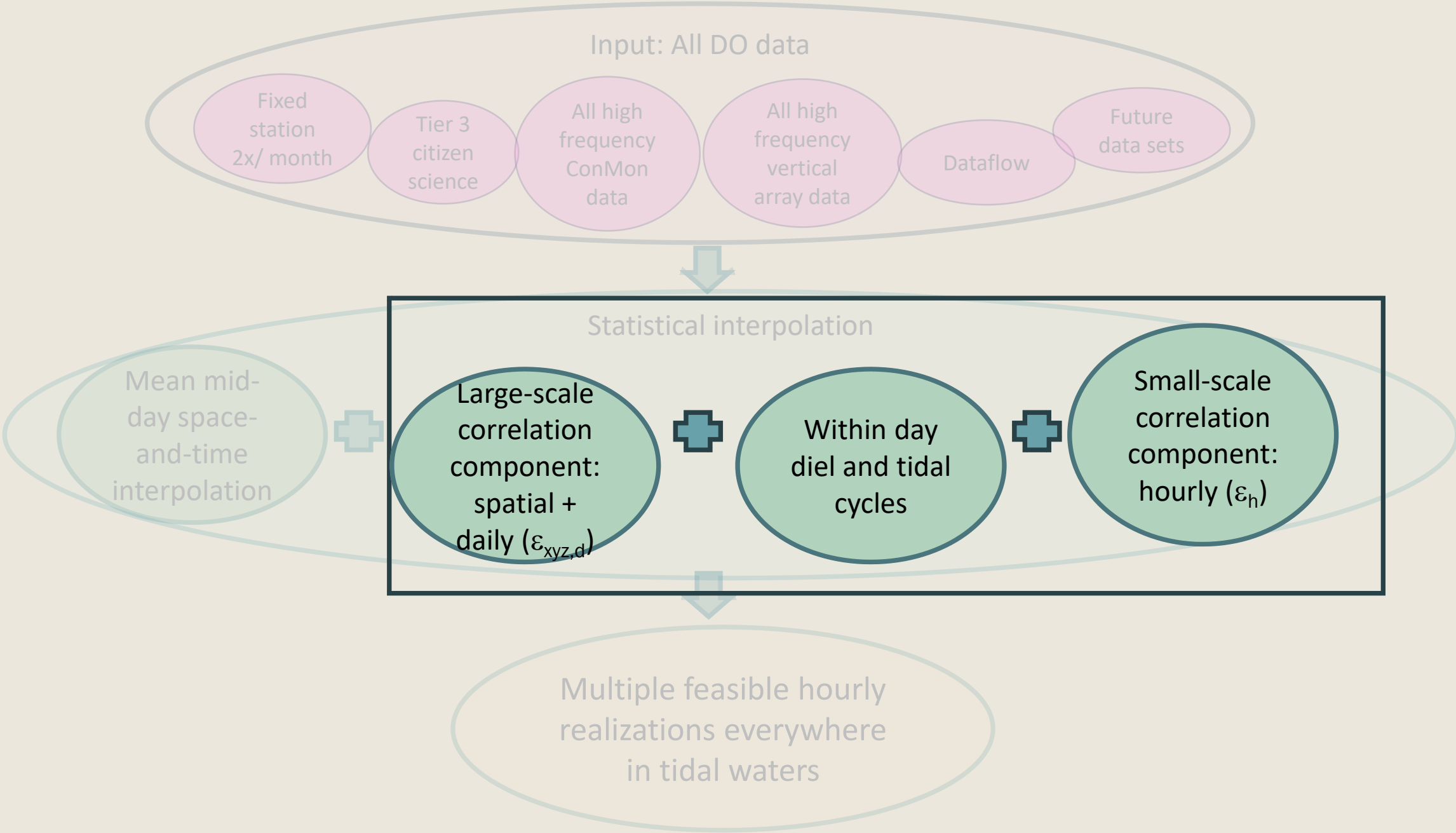
Mean mid-day space-and-time interpolation

- **Goal:** Capture broad spatial pattern from day to day. Output an estimate every day and everywhere.



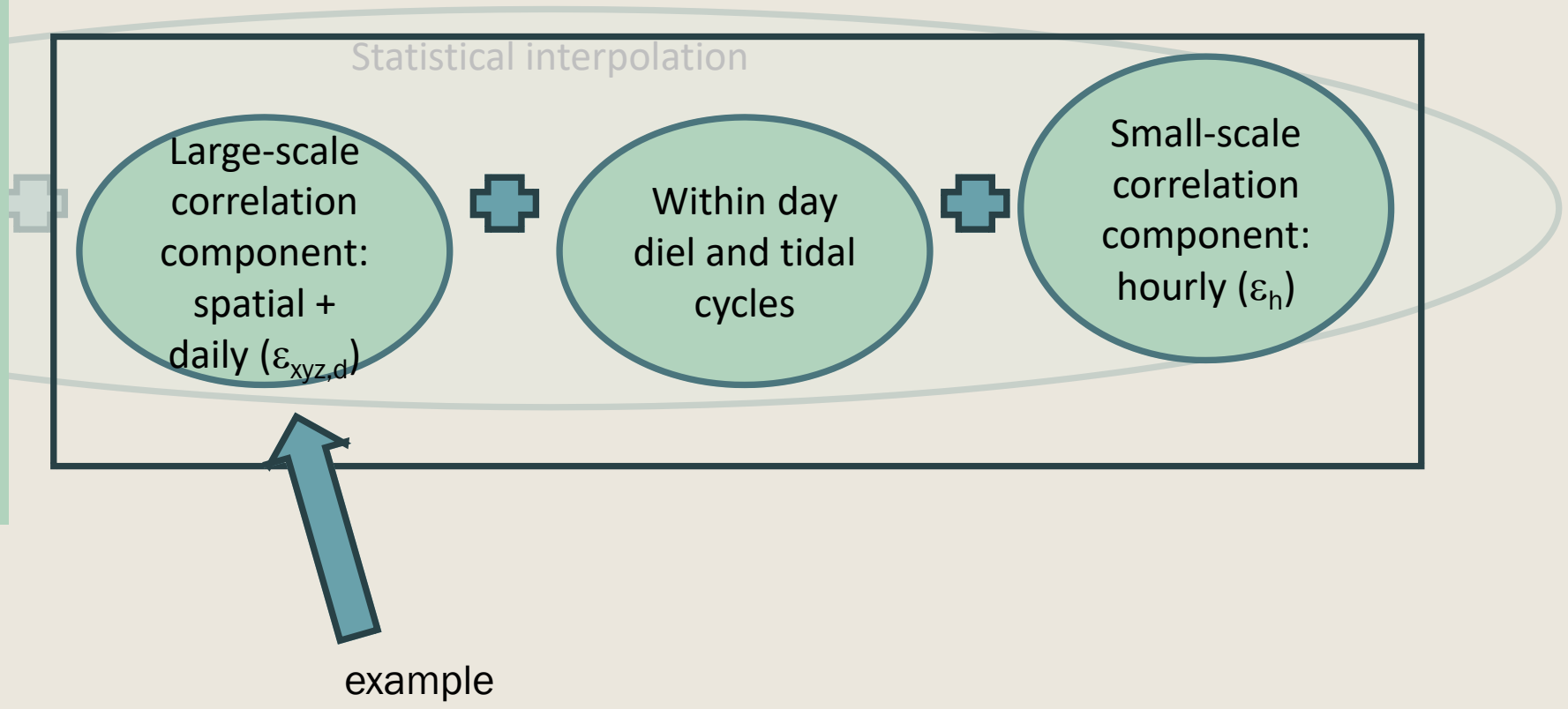
Uses Generalized Additive Models (GAMs) with:

- **Cyclic smooths (cc)** for time-of-day and day-of-year.
- **Tensor-product smooths (ti)** to model interactions among depth, bathymetry, and horizontal position.


Input: All DO data
Fixed station 2x/ month
Tier 3 citizen science
All high frequency ConMon data
All high frequency vertical array data
Dataflow
Future data sets
Statistical interpolation
Mean mid-day space-and-time interpolation
Large-scale correlation component: spatial + daily ($\varepsilon_{xyz,d}$)
Within day diel and tidal cycles
Small-scale correlation component: hourly (ε_h)
Multiple feasible hourly realizations everywhere in tidal waters

Evaluate high-frequency data for between-day, within-day, and location variability.

Apply those patterns to generate hourly simulation results.



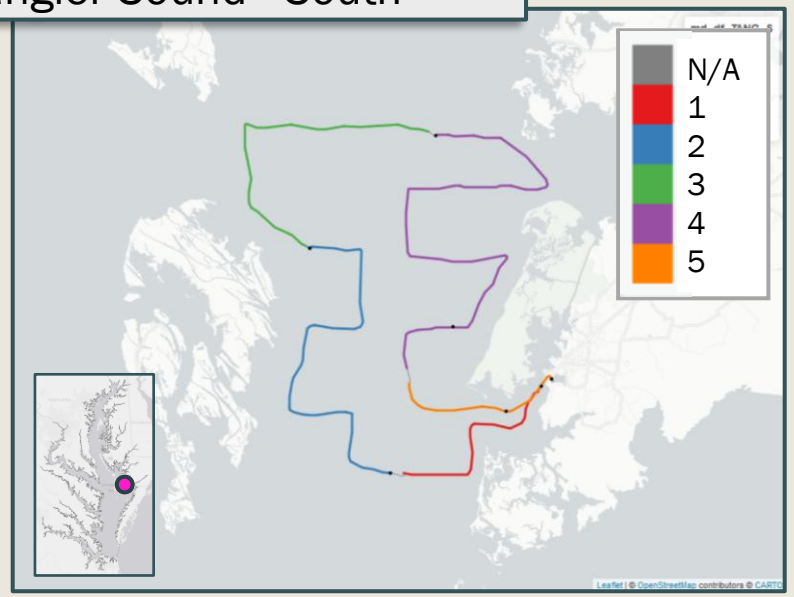
Example High freq data use

Correlation: Horizontal (along- and cross-bay)

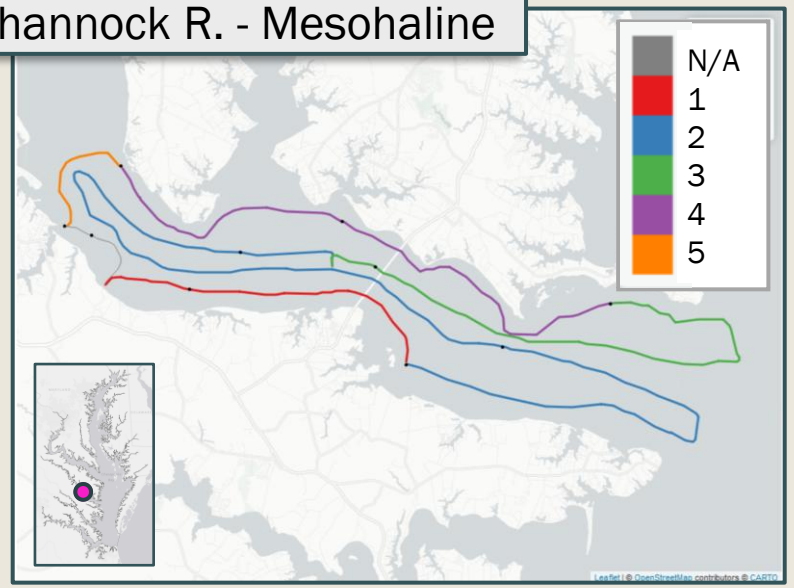
- DataFlow—high frequency underway surveys (~0.5 m intake)
  - **MD DNR Eyes on the Bay (EOTB)**: ~63 “cruise locations”, 2001-2023
  - **Virginia Estuarine and Coastal Observing System (VECOS)**: ~36 “cruise locations” 2003-2024
- Map lines show survey legs (1–5)

Source: https://eyesonthebay.dnr.maryland.gov/

Tangier Sound - South



Rappahannock R. - Mesohaline

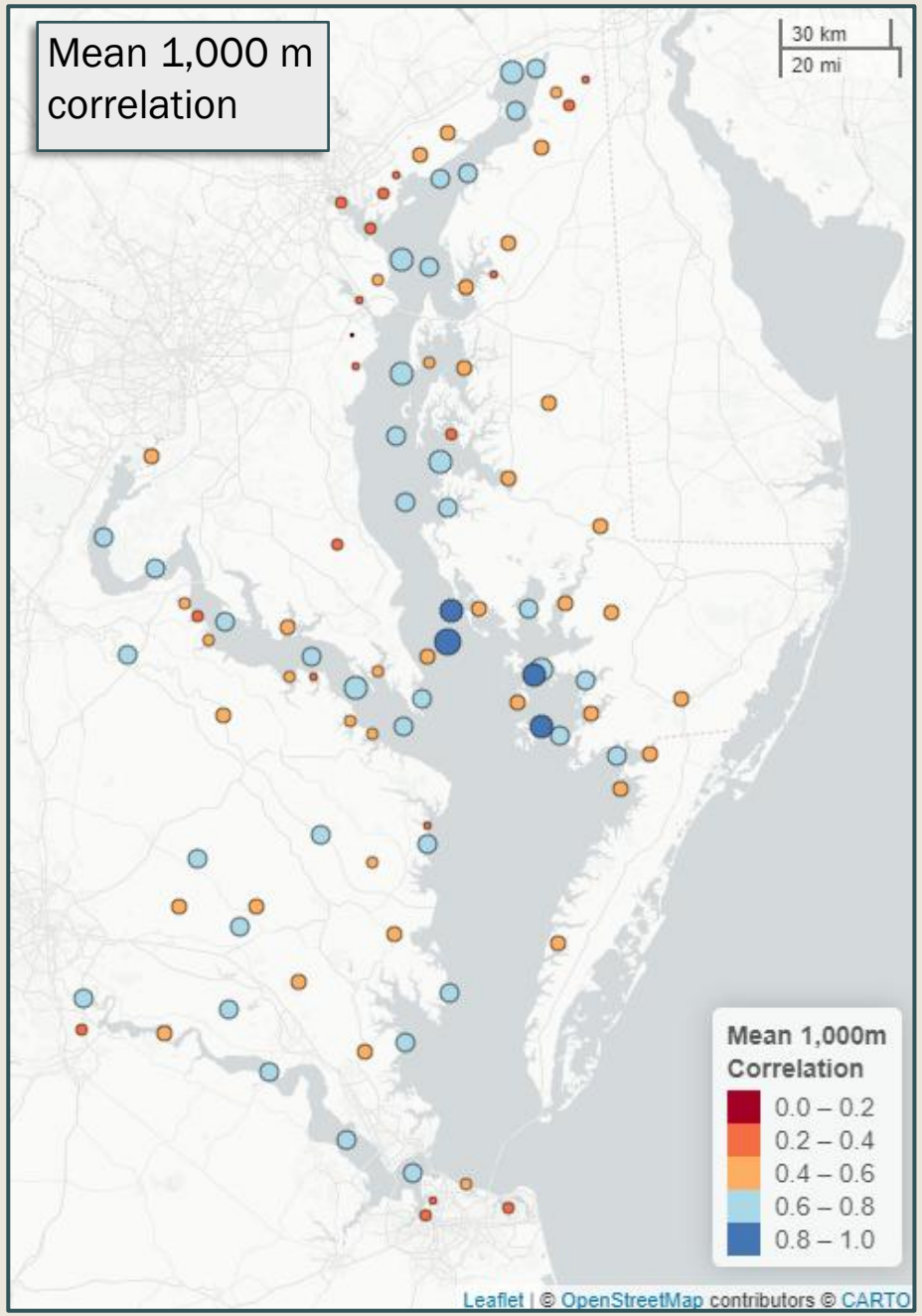


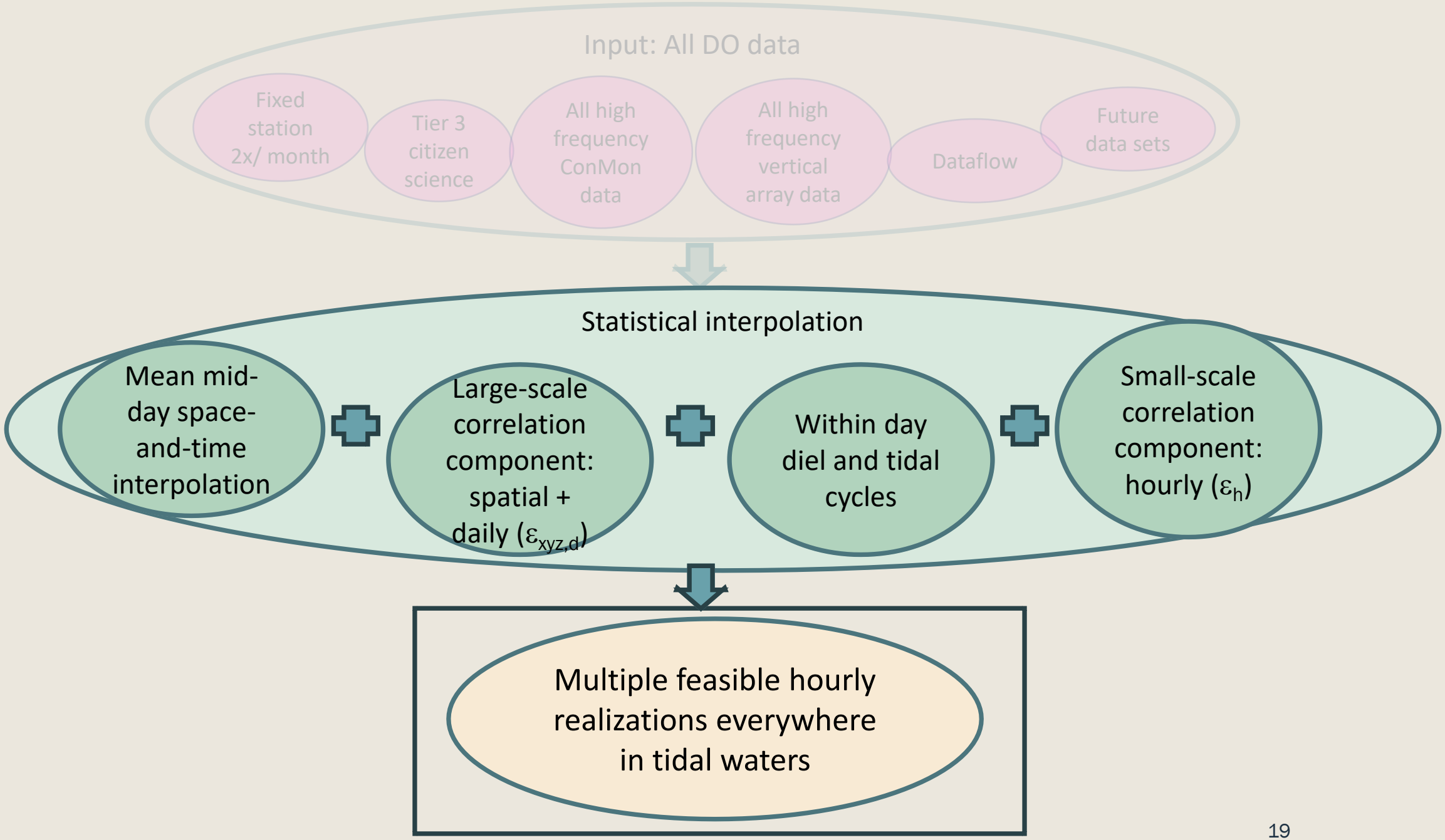
Example High freq data use

Correlation: Horizontal (along- and cross-bay)

How is this processed data used in the tool?

- We process the data for each cruise to get the spatial correlation in our model over 1 km spacing.
  - We will fit a smooth spatial function (GAM) to these correlation values so that we can represent how they vary by location (e.g., correlation is higher in deeper waters, lower in shallower).
  - For any spot we are interpolating DO, we will pull out the appropriate correlation parameter for that location to use.
- Spatial differences dominate variability more than temporal effects.

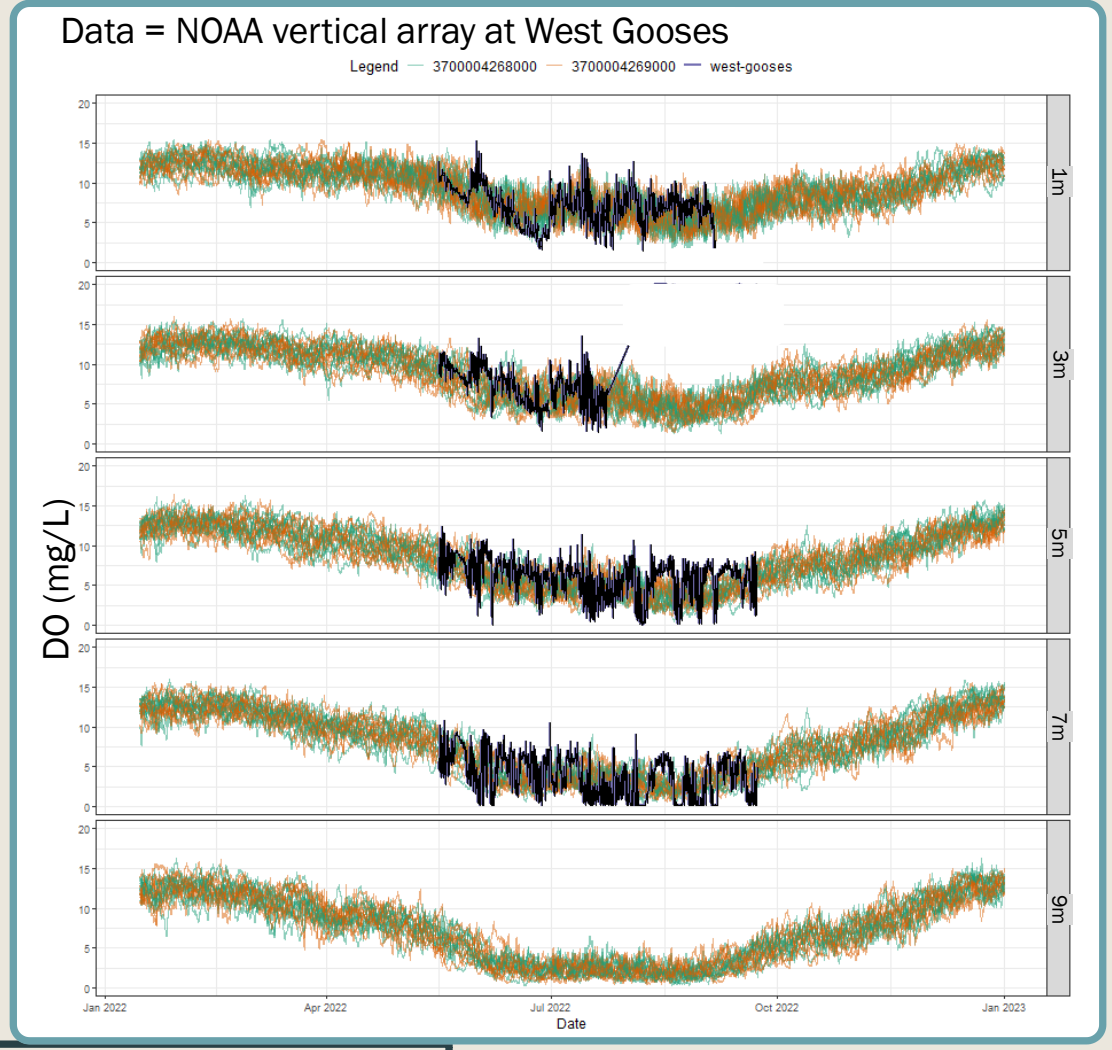



Input: All DO data
Fixed station 2x/ month
Tier 3 citizen science
All high frequency ConMon data
All high frequency vertical array data
Dataflow
Future data sets
Statistical interpolation
Mean mid-day space-and-time interpolation
Large-scale correlation component: spatial + daily ($\varepsilon_{xyz,d}$)
Within day diel and tidal cycles
Small-scale correlation component: hourly (ε_h)
Multiple feasible hourly realizations everywhere in tidal waters

100 realizations of hourly estimates everywhere for a year.

This example was an early test at one location, compared to observed high frequency data (black lines).

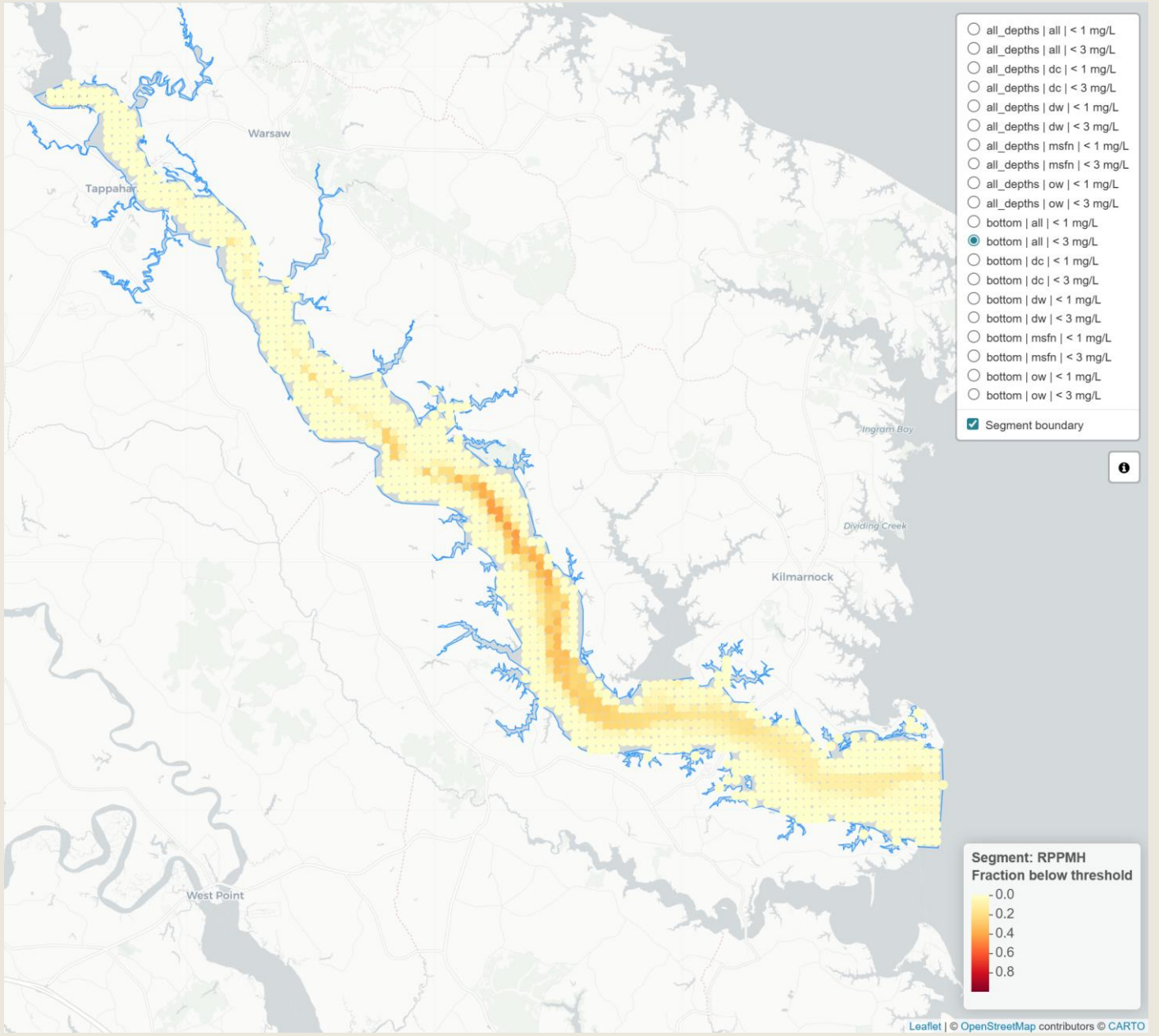
Evaluation with recent 4-D updates is being done now with data like this currently.



Multiple feasible hourly realizations everywhere in tidal waters

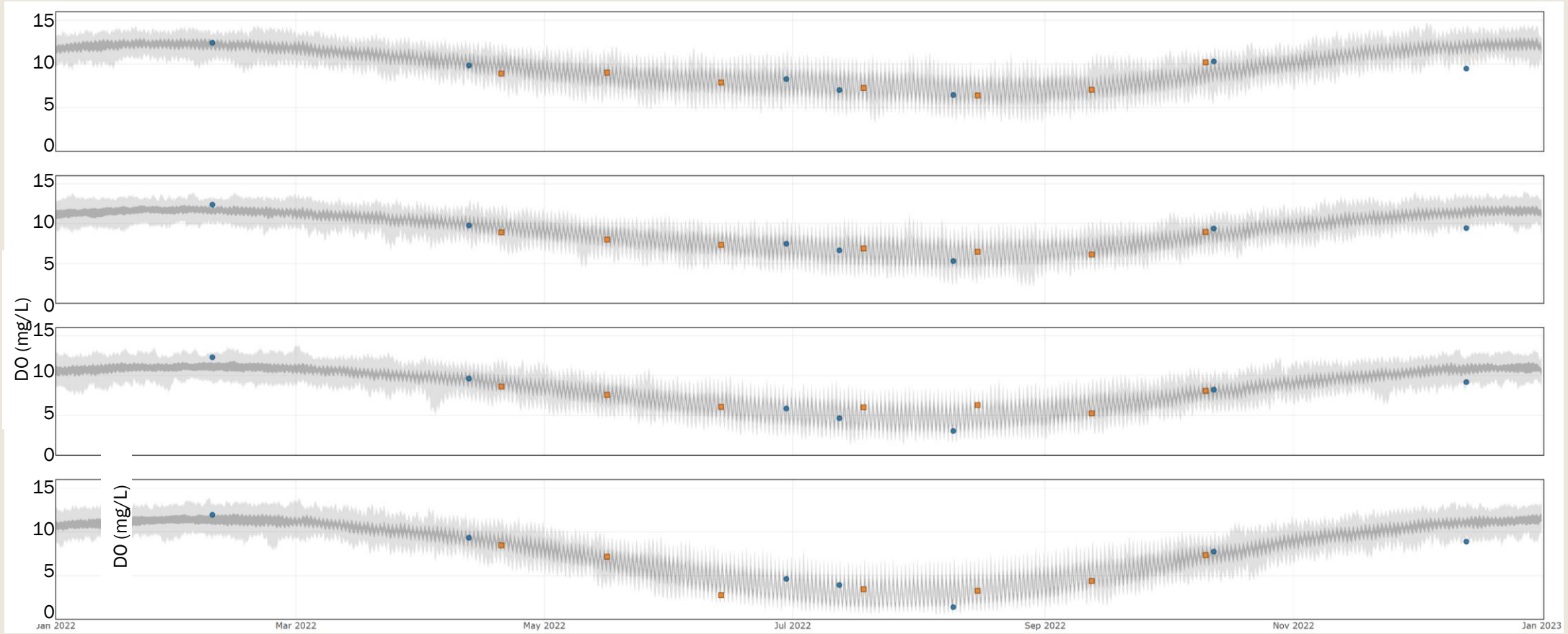
Potential Visuals– can summarize by segment all gridded interpolation results:

For example: Fraction of time bottom is <3 mg/L

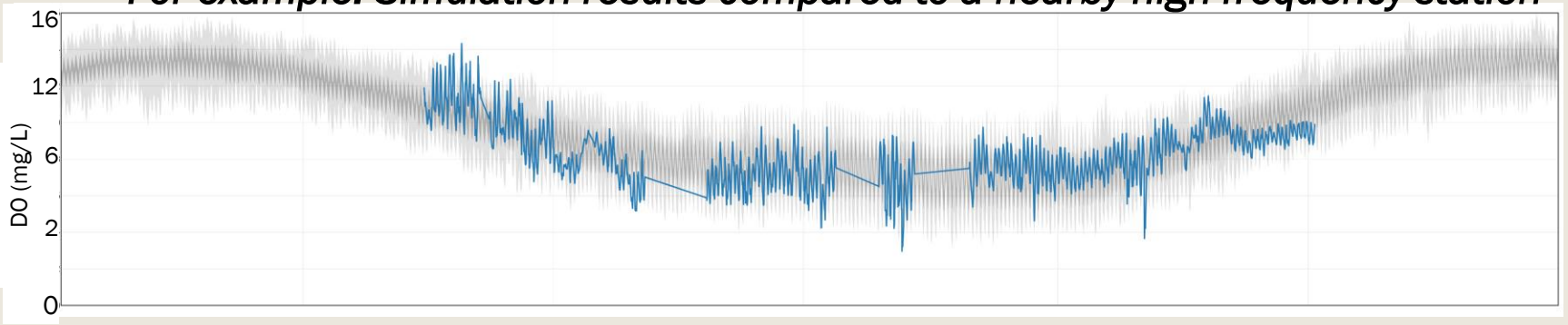


Potential Visuals – can compare at places and times with data:

For example: 100 Simulation results compared to two nearby fixed stations, multiple depths

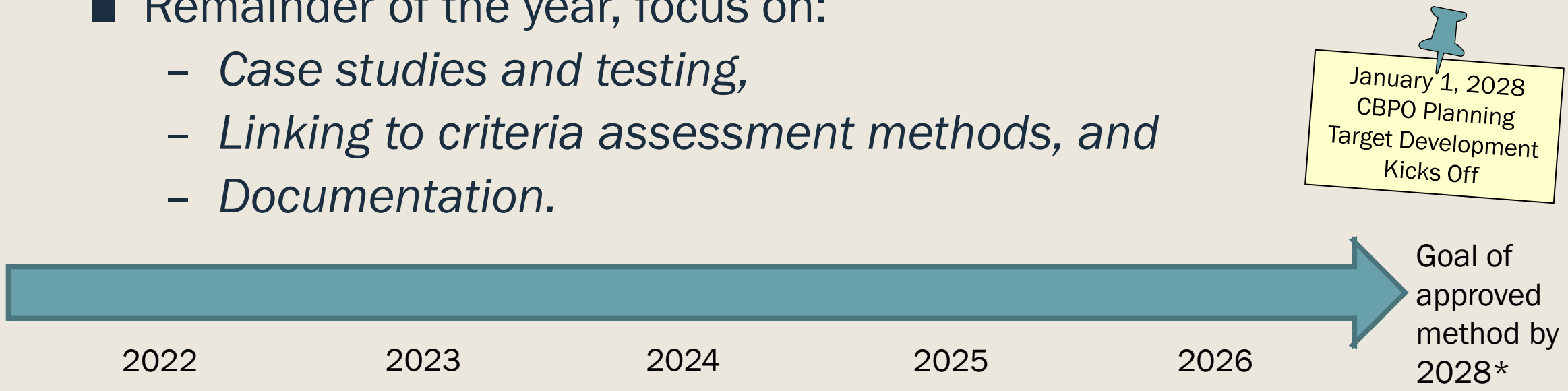


For example: Simulation results compared to a nearby high frequency station



Summary

- Work continues in next few months finishing development tasks.
- Remainder of the year, focus on:
  - *Case studies and testing,*
  - *Linking to criteria assessment methods, and*
  - *Documentation.*



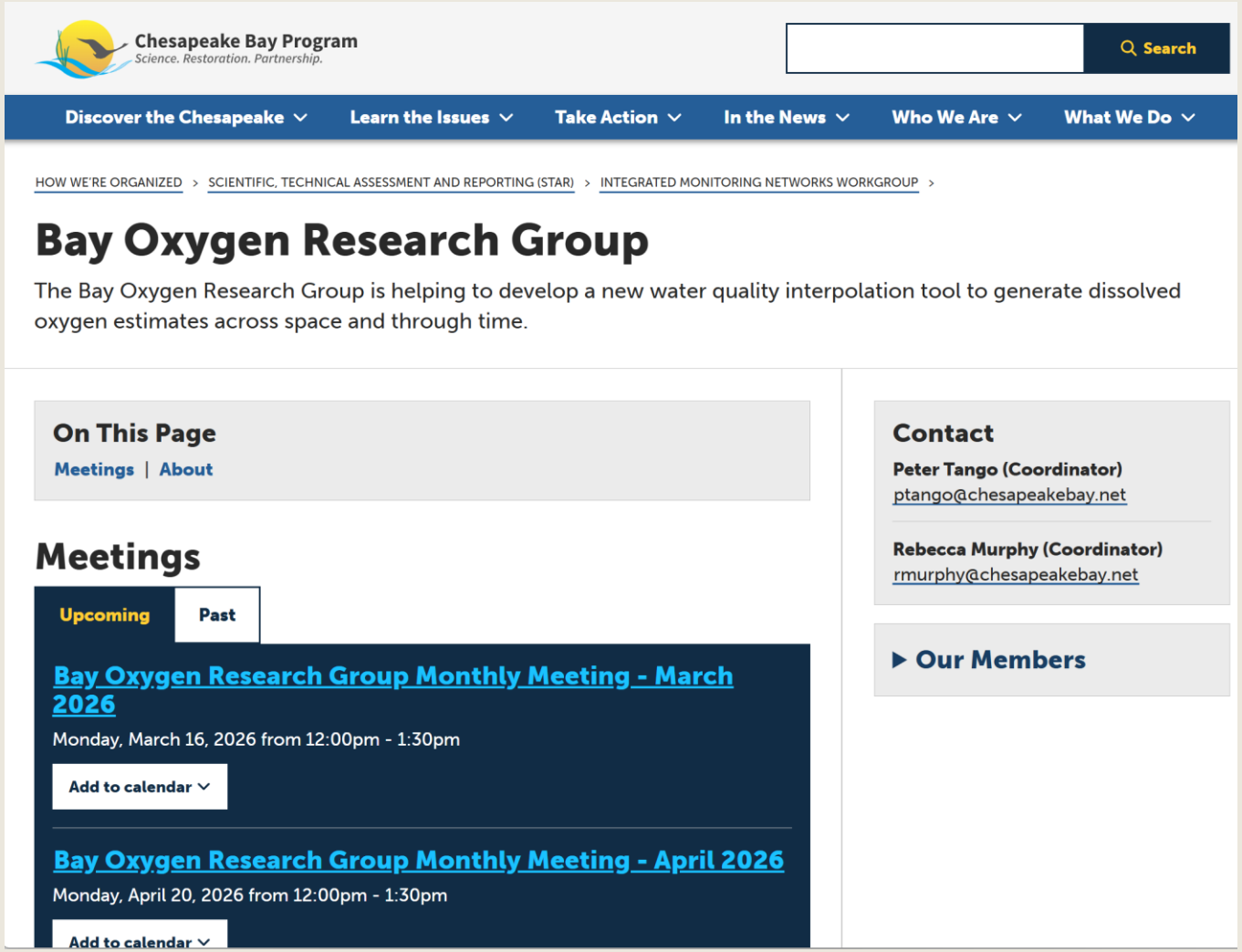
*with 2030 goal of reporting on all criteria

Next steps relevant to modeling team

- Remaining development:
  - *Finish 4-D simulation approach and initial parameterization (next few months).*
  - *Evaluate and compare to data and 3-D interpolator via case study (2026)*
  - *Implement/test methods for using interpolation results to evaluate high frequency criteria based on CAP's direction (2026-2027).*

- Integration of 4-D interpolation into the Phase 7 suite of models:
  - *Join our BORG meetings! Providing updates at BORG and Modeling WG Quarterly meetings.*
  - *We should be able to input "model-as-data" estuarine model results into 4-D interpolation, just like 3-D is done (2026-2027).*
  - *We will be informing the high frequency variability with data collected after the 1990s.*

Chesapeake Bay Program (CBP) Bay Oxygen Research Group



- Group of CBP partners providing guidance, ideas, and review.
- Meets monthly during this development phase.
- Attendees include future users; state teams involved in criteria assessment; EPA, NOAA and USGS federal partners; and academic collaborators.
- Feel free to join if you're interested.

https://www.chesapeakebay.net/who/group/bay-oxygen-research-group