

4-Dimensional (4-D) Water Quality Interpolator 101

Clean Water Goal Team

October 26, 2026

Peter Tango (USGS@CBPO)

Co-chair of Bay Oxygen Research Group Action Team (BORG)

CBP team and developers:

Rebecca Murphy (UMCES), Elgin Perry (statistics consultant), Jon
Harcum (Tetra Tech), Breck Sullivan (USGS), Kaylyn Gootman (EPA),
Allison Welch (CRC), Peter Tango (USGS)

Historical interest in 4-dimensional (4D) water quality interpolation: 2008 STAC Expert Panel

Assessing the feasibility of developing a four-dimensional (4-D) interpolator for use in impaired waters listing assessment December 2008 STAC Publication 08-008

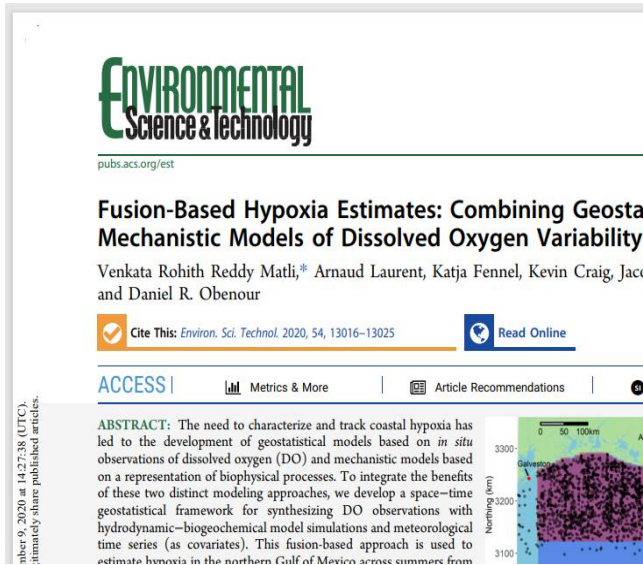
Recommendations from the STAC Expert Panel

- Frank Curriero (Johns Hopkins University)
- Eileen Hofmann (Old Dominion University)
- Ragu Murtugudde (University of Maryland)
- Jian Shen (Virginia Institute of Marine Science)
- J. Andrew Royle (U.S. Geological Survey)

2008 Findings

- Insufficient information to evaluate the feasibility of a 4-D interpolator
- The panel recommended a study to evaluate the different approaches available for developing a 4-D interpolator
- Data analysis studies should be initiated to develop the statistical basis for a 4-D interpolator.

Since 2008 – new research is making 4D reality



Gulf Coast example

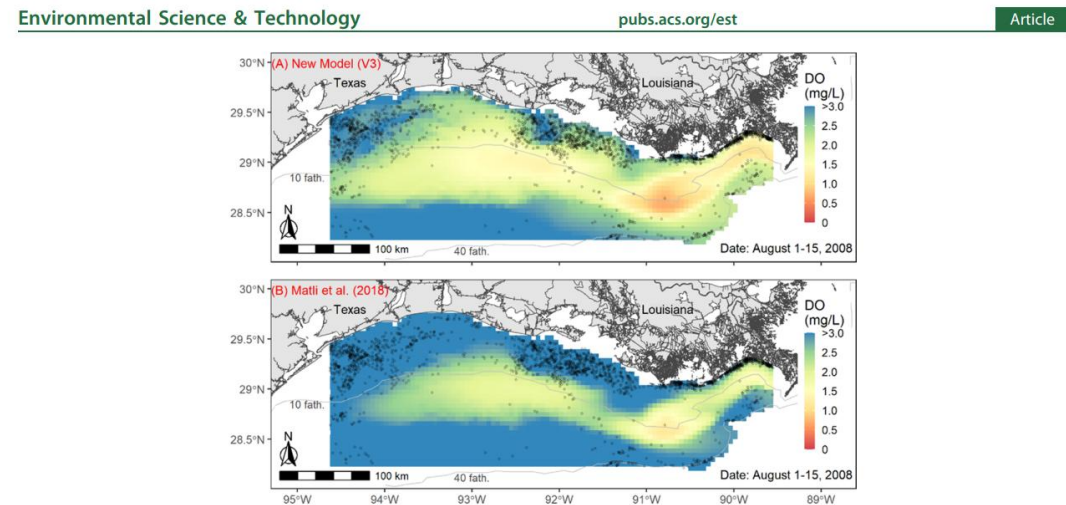


Figure 3. Two week average (August 1–15, 2008) bottom DO estimates from (A) the new model (V3) and (B) Matli et al. (2018) relative to the location of individual shrimp tows during the same period (black circles).^{16,39} Note that this period was selected to illustrate a time when there is substantial variation between the two approaches.

Bay Oxygen Research Group:

Interpolation methods considered

Machine Learning - may be conceptually feasible but is not presently considered a suitable, efficient option

Bayesian approach (e.g., D. Obenour, NC State) is a viable framework, used for 4-D assessment of hypoxia in our southern Gulf.

Starting from scratch in Chesapeake Bay represented a feasible but cost/time intensive option to involve experts in the technique at this time.

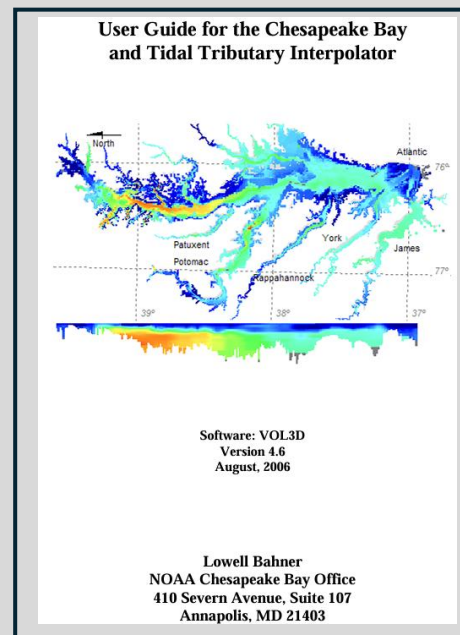


Generalized Additive Models (non-Bayesian) – exploratory work using GAMs for 4D water quality estimation (e.g., Perry, Murphy) demonstrated the feasibility of applying this approach to the problem.



Current 3D interpolation:

Inverse distance weighting approach



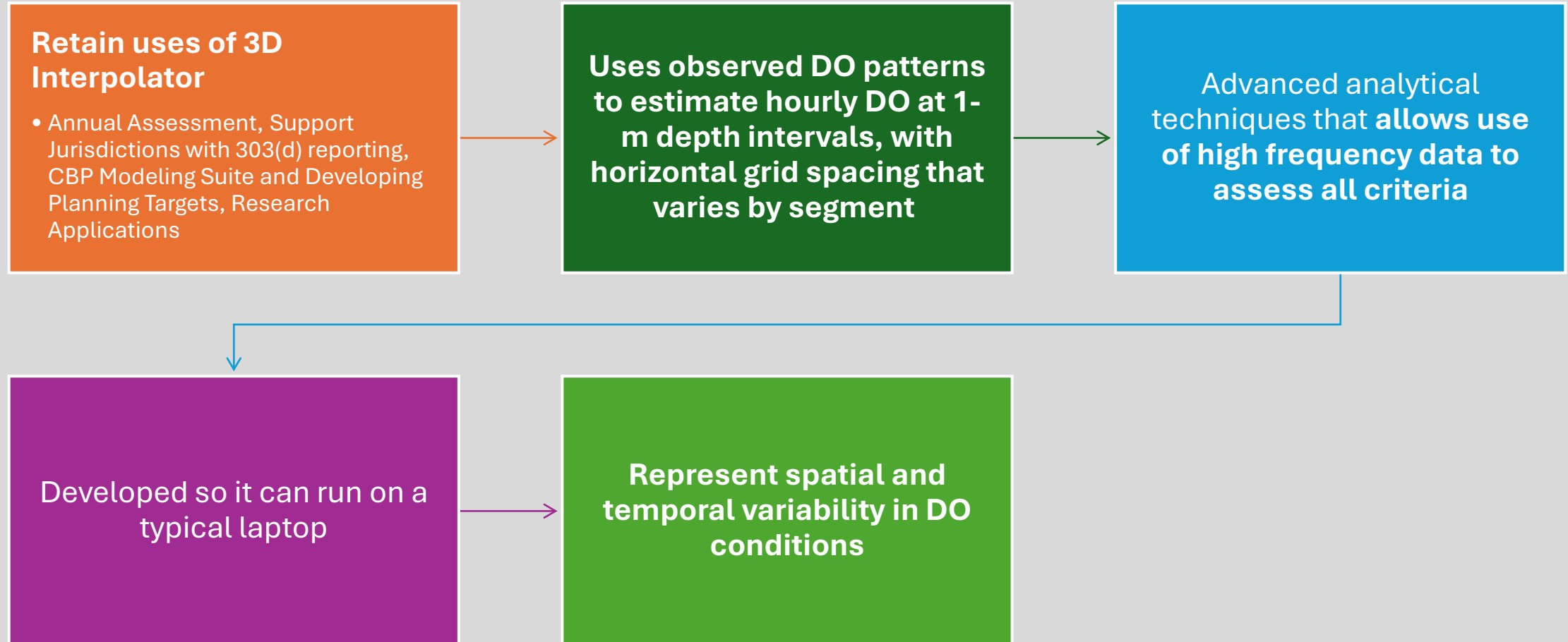
Problems with current interpolation

- 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:

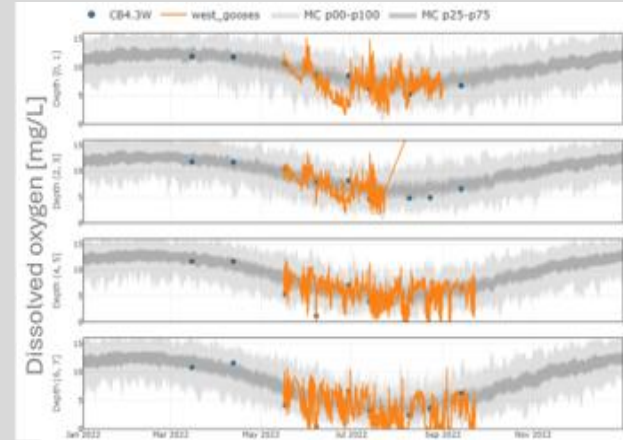
- Use high frequency data
- Interpolate all data together, not in layers.
- Interpolate in time, so that we do not have to artificially split time periods.
- Statistical – allowing for multiple realizations of interpolation results.

Key Features for the new 4D WQ Interpolator



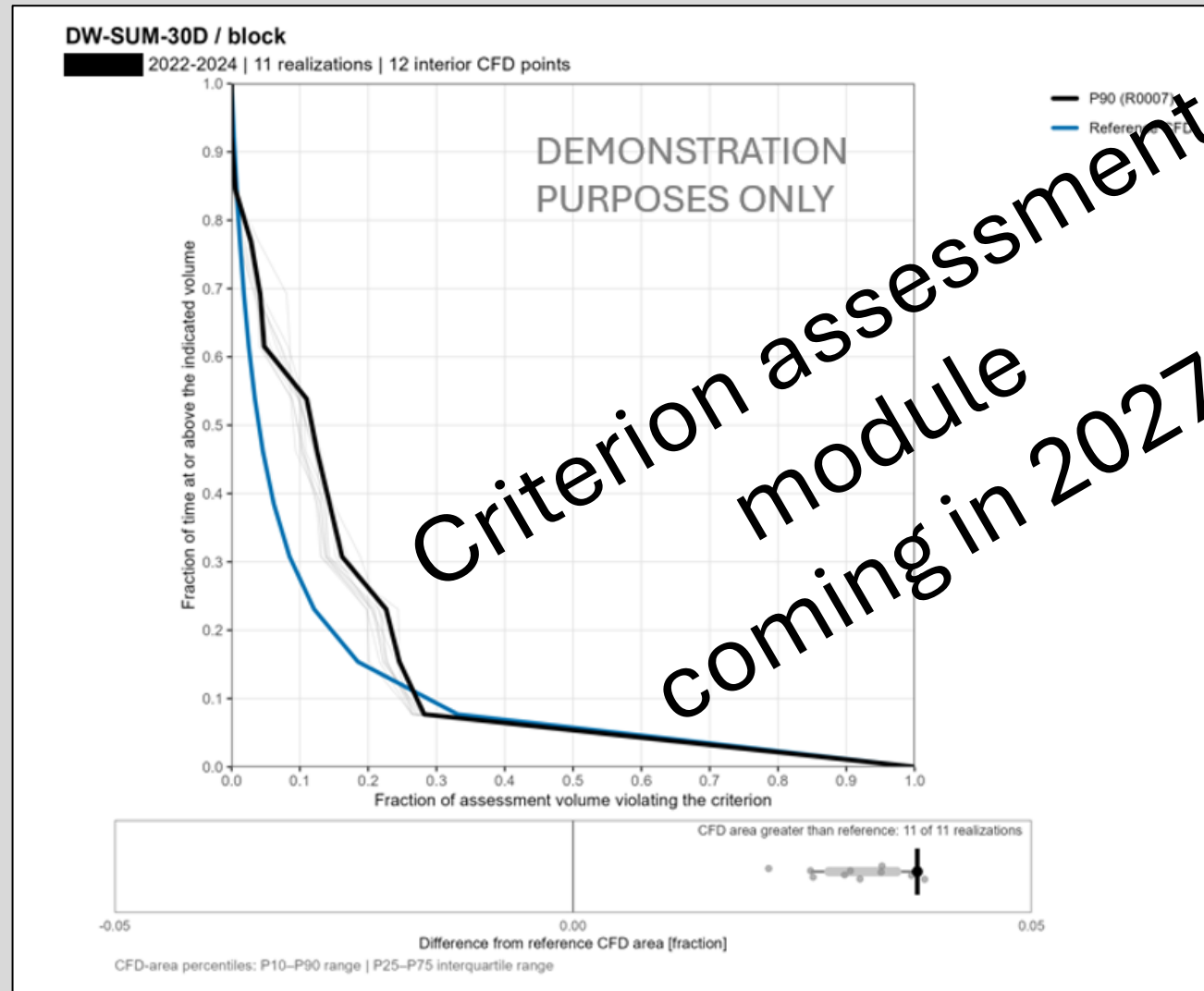
The new 4D water quality interpolator

Does produce hourly realizations of dissolved oxygen patterns in space and time for the Bay



Does not, on its own, create water quality criterion tests or produce stoplight plots on criterion attainment





Criterion assessment is separate module under development



New tool fundamentals



4-D Interpolator: Mapping dissolved oxygen in space and through time in Chesapeake Bay

Data
Gathering

†
“Data Lake”

Mean Mid-Day Interpolation: *Run 1 year at a time, by region*

Interpolation

Diagnostics

Parameterization:

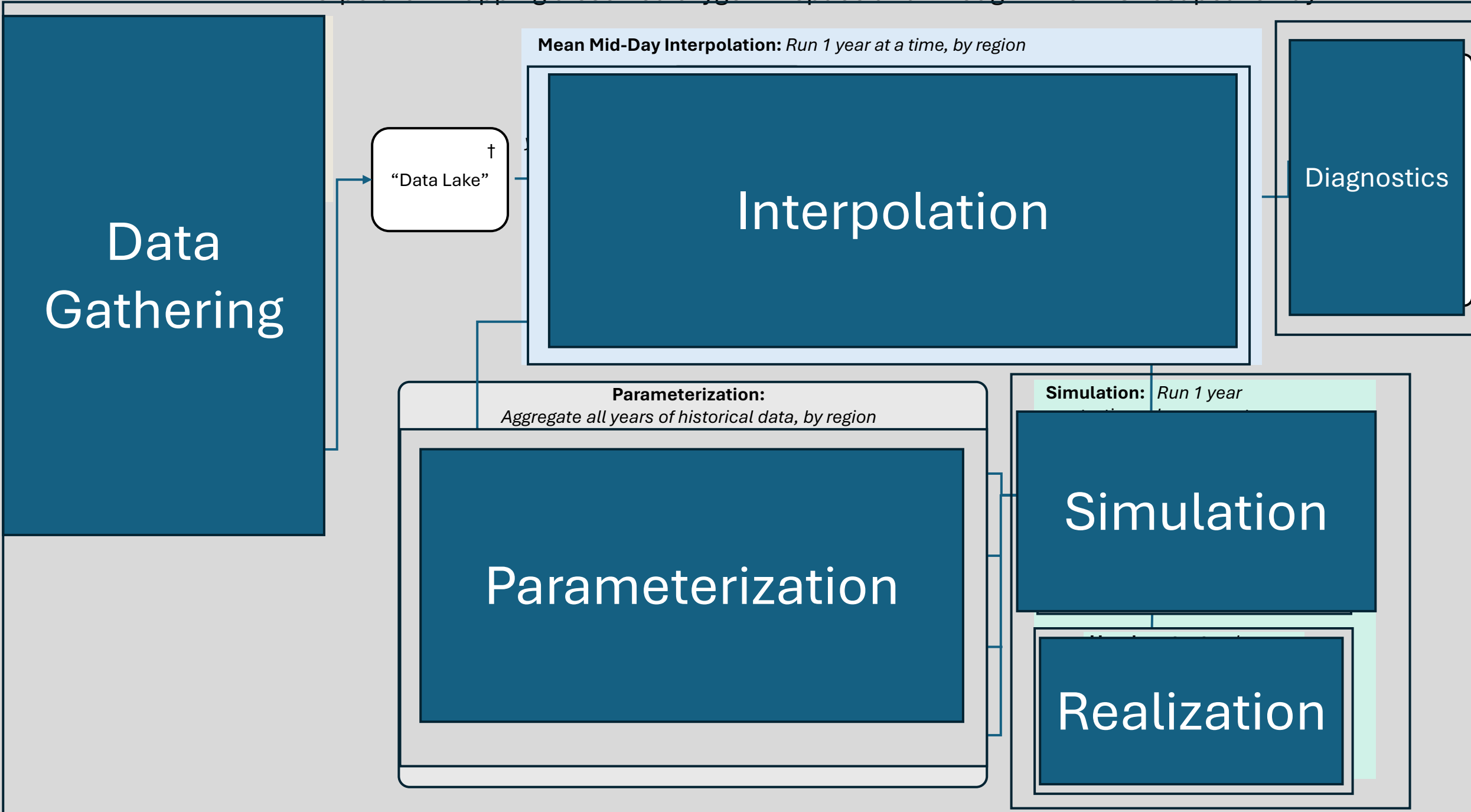
Aggregate all years of historical data, by region

Parameterization

Simulation: *Run 1 year*

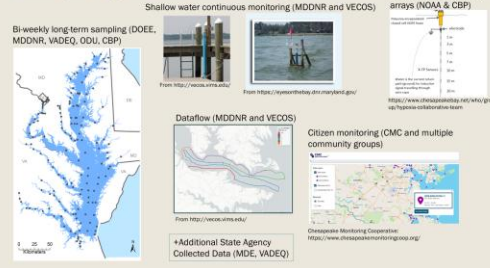
Simulation

Realization



4-D Interpolator: Mapping dissolved oxygen in space and through time in Chesapeake Bay

Multiple Types of Data Being Used



Organize Data:

All years and tidal waters

Depth (m)	DO (mg/l)	Temp (°C)
0	7.87	15
0.5	7.88	15
1	7.88	15
1.5	7.86	15
2	7.86	15
2.5	7.84	15

†
“Data Lake”

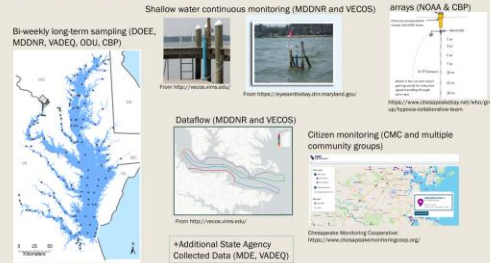
We start with the data

Multiple types of data are used :

- Long-term monitoring
- Dataflow
- ConMon
- Vertical Arrays
- Community Science

4-D Interpolator: Mapping dissolved oxygen in space and through time in Chesapeake Bay

Multiple Types of Data Being Used



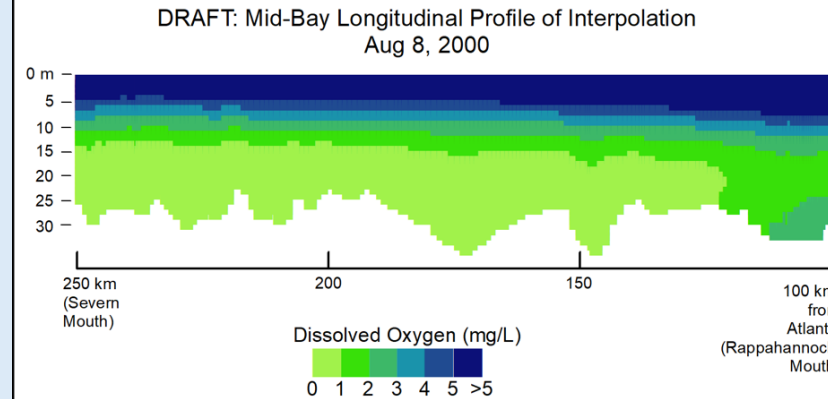
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Mean Mid-Day Interpolation: Run 1 year at a time, by region

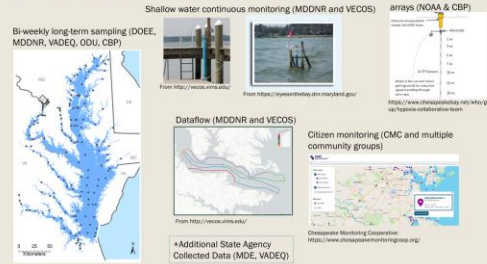


Generalized Additive Models (GAMs)

Generalized Additive Models
are then used to create the mean
mid-day dissolved oxygen pattern
interpolating data each day.

4-D Interpolator: Mapping dissolved oxygen in space and through time in Chesapeake Bay

Multiple Types of Data Being Used



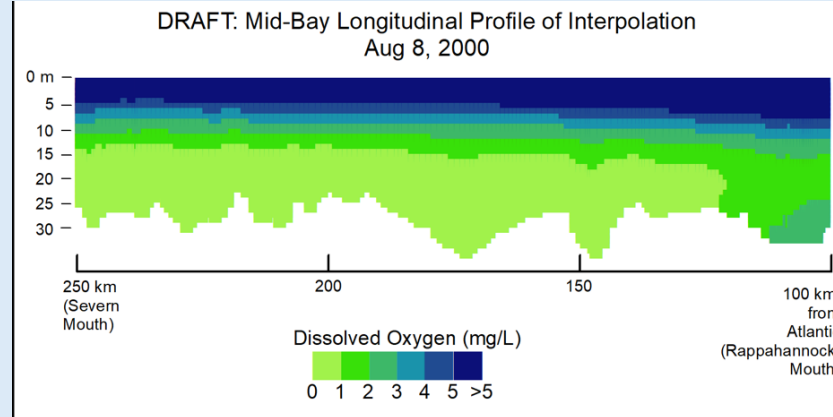
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“Data Lake”

Mean Mid-Day Interpolation: Run 1 year at a time, by region



Parameterization:

Aggregate all years of historical data, by region

Example: Fourier analysis with just daily cycle to fit hourly DO (DO_h)

$$DO_h = lc * h + sc * \sin\left(\frac{2\pi * h}{24}\right) + cc * \cos\left(\frac{2\pi * h}{24}\right) + \tau$$

coefficients $h = \text{hour } 1:24$

Large-scale correlation of DO GAM residuals

Day to day

Day 1 Day 2

1 day apart

Depth

1 m apart

Horizontal

Site A Site B

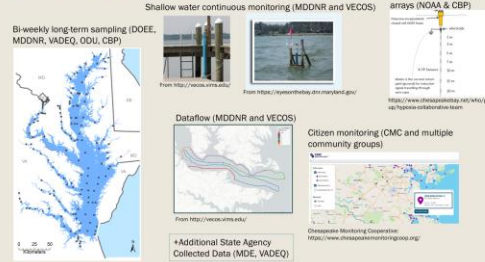
1 km apart

Regional models supply correlations for one residual field.

Parameters for simulations are estimated using Bay data pooled across all available years

4-D Interpolator: Mapping dissolved oxygen in space and through time in Chesapeake Bay

Multiple Types of Data Being Used



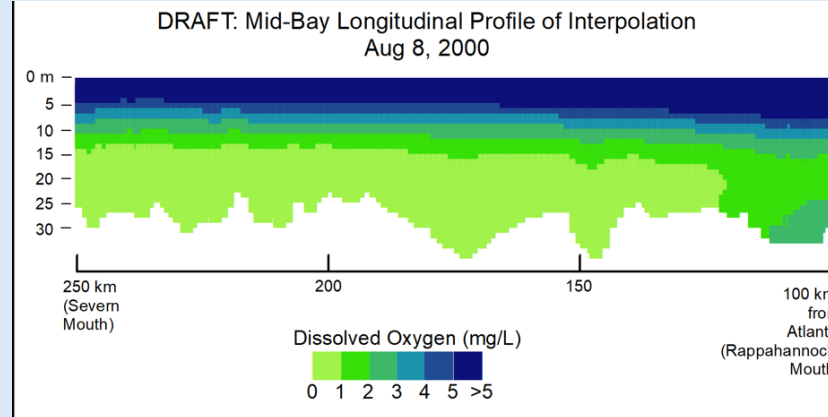
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“Data Lake”

Mean Mid-Day Interpolation: Run 1 year at a time, by region



Diagnostics, reports, and data files for:

- Pycnocline,
- Daily DO,
- Hourly DO Results.

Simulations
create hourly DO
outputs;
Diagnostics are
available

Parameterization:

Aggregate all years of historical data, by region

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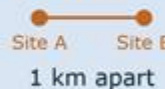
Day to day



Depth

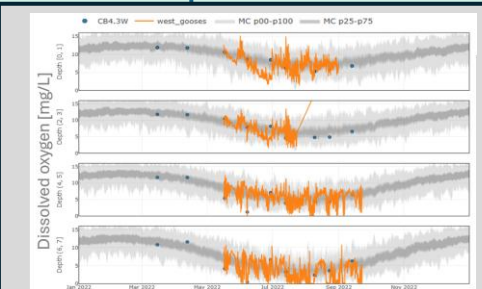


Horizontal

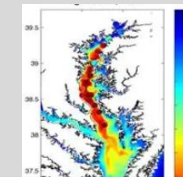


Regional models supply correlations for one residual field.

Simulation: Run 1 year at a time, by segment



Hourly outputs, by segment



4-D Interpolator: Mapping dissolved oxygen in space and through time in Chesapeake Bay

Data
Gathering

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“Data Lake”

Mean Mid-Day Interpolation: *Run 1 year at a time, by region*

Interpolation

Diagnostics

Parameterization:

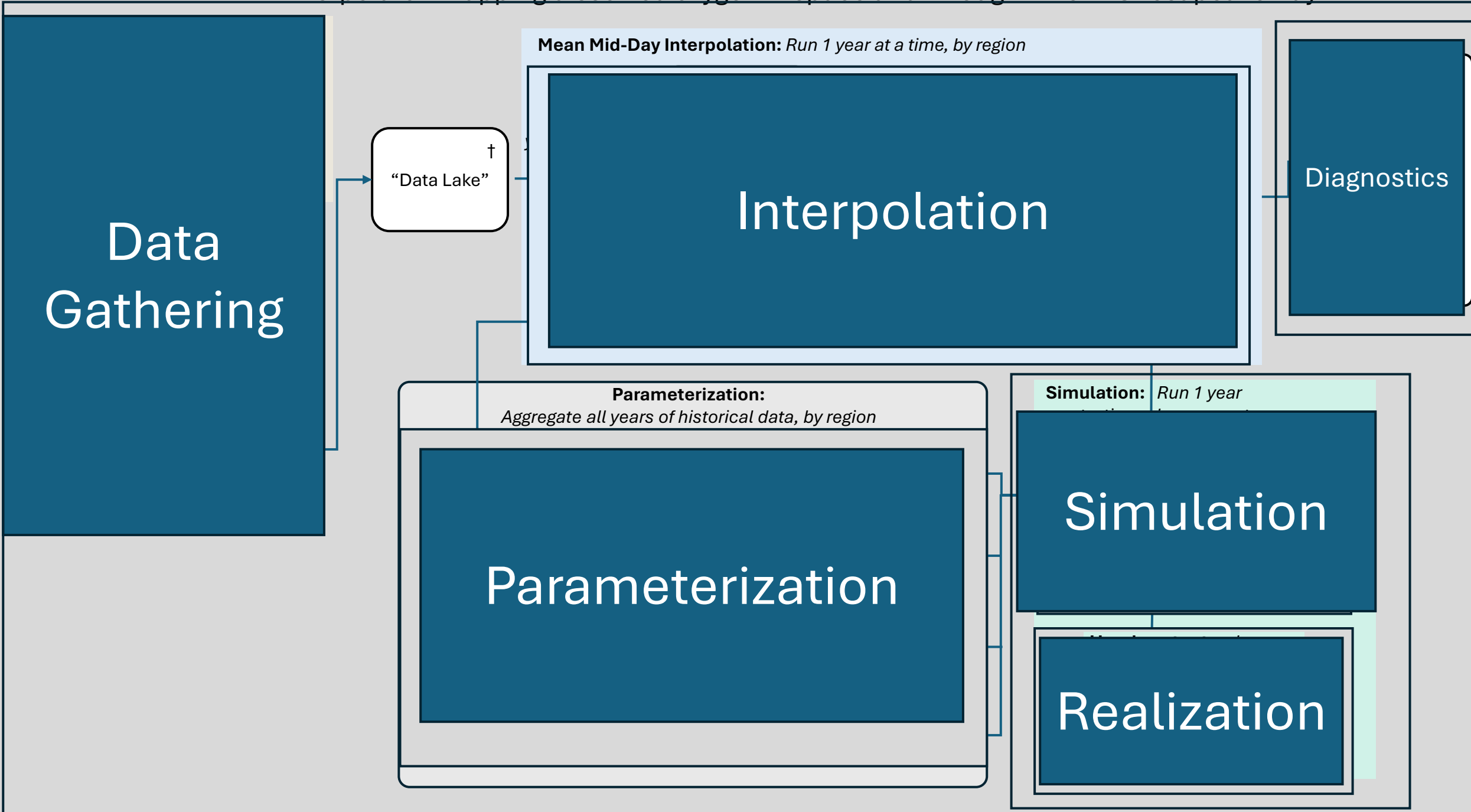
Aggregate all years of historical data, by region

Parameterization

Simulation: *Run 1 year*

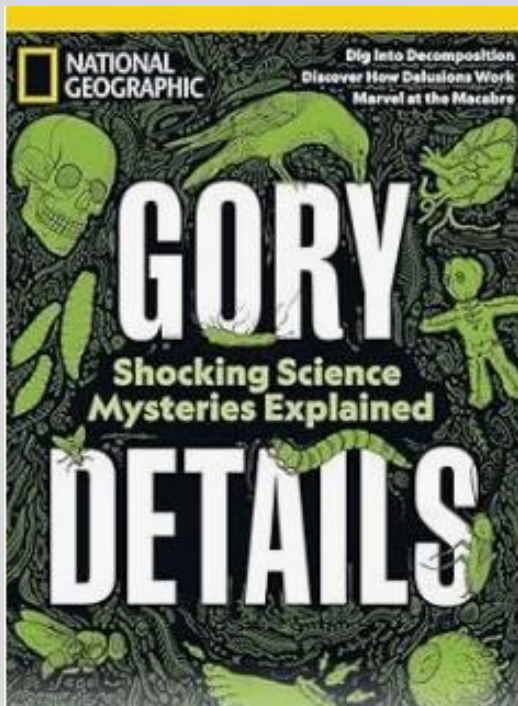
Simulation

Realization

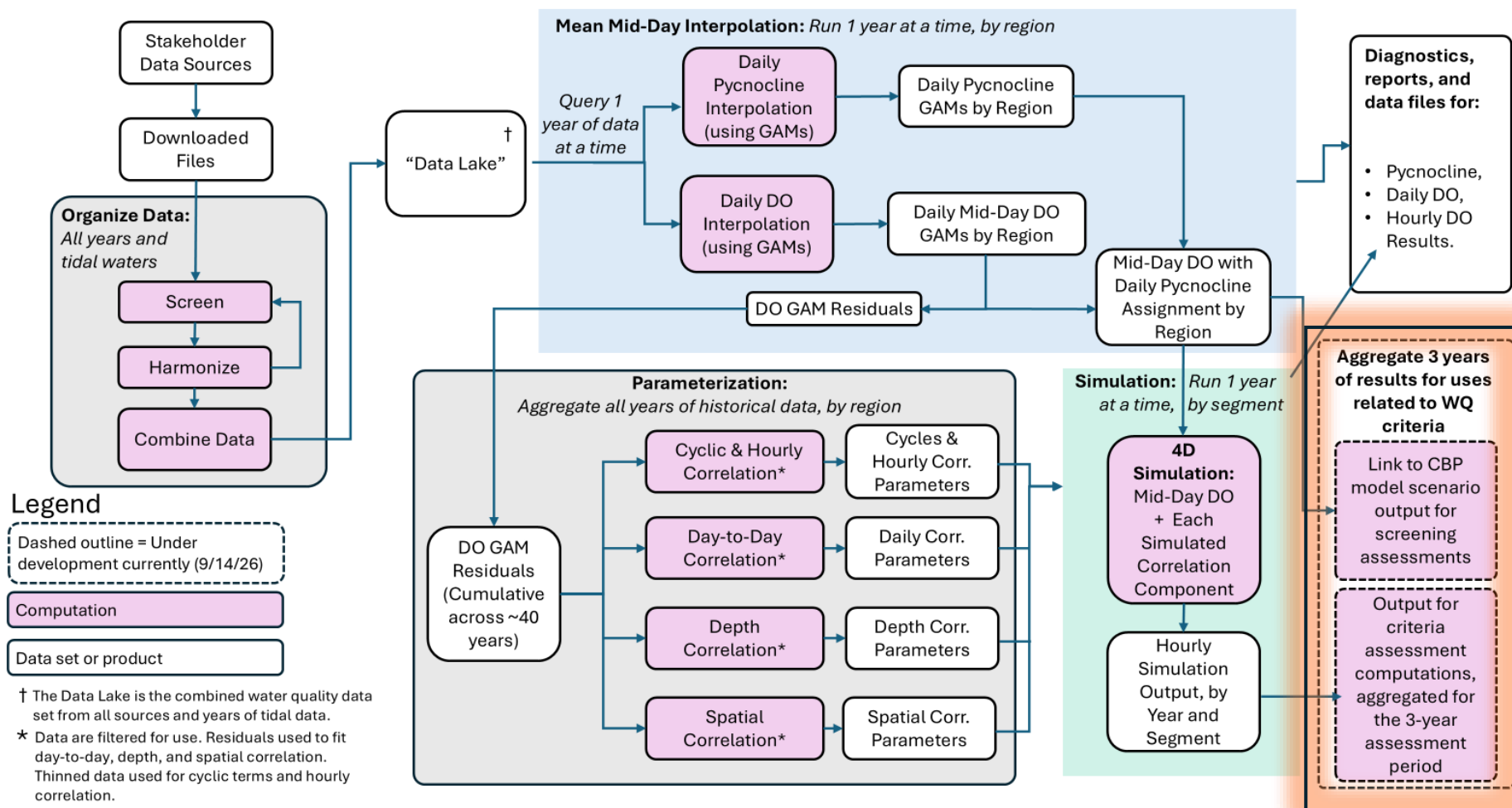


And, what
about water
quality
criterion
assessment?





4-D Interpolator Workflow (v9-14-26)



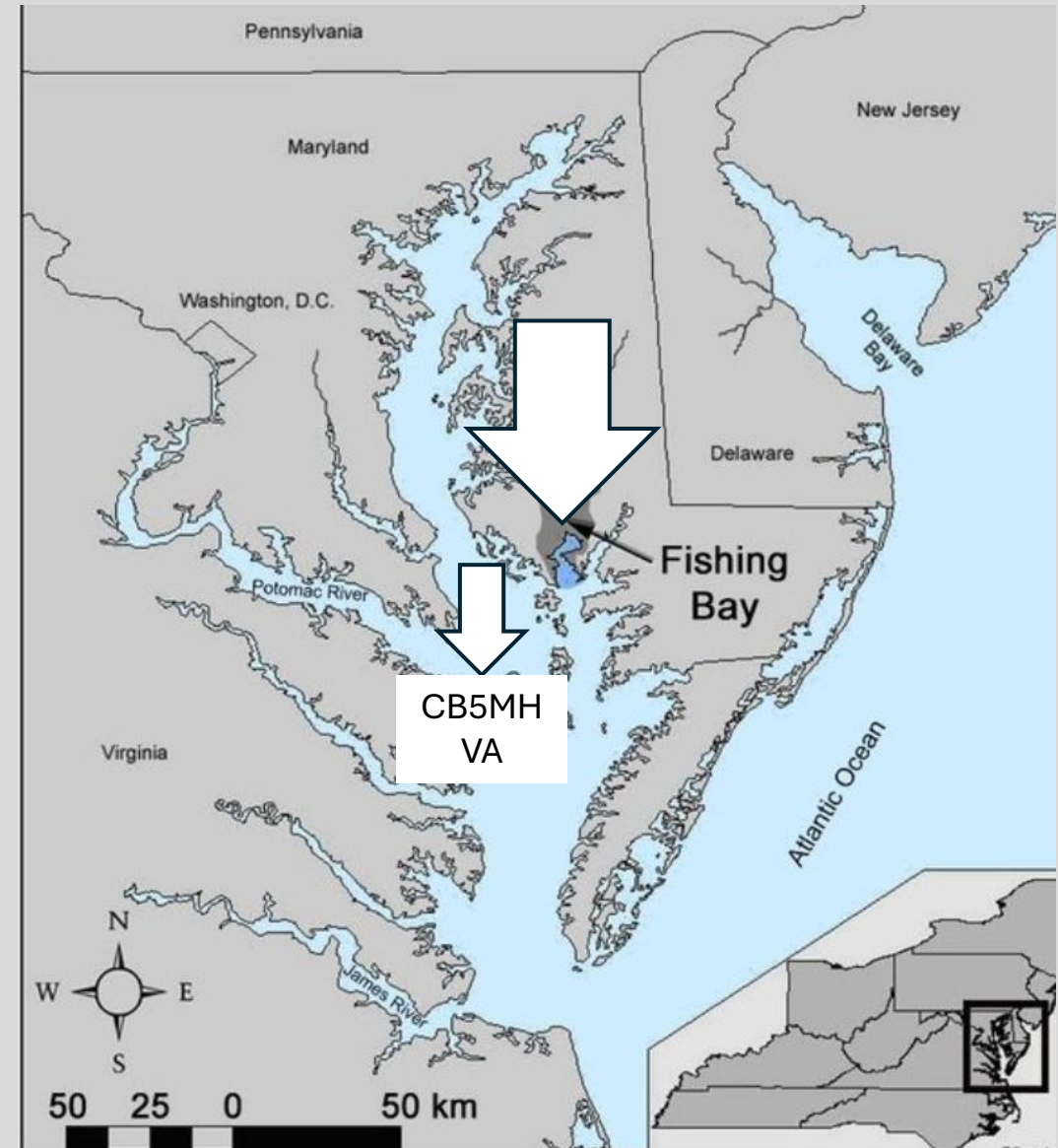
Criterion Assessment
and other assessments are add-ons here

The Big Question: Performance of the 4D versus 3D?

Just a first taste here

Fishing Bay, Maryland

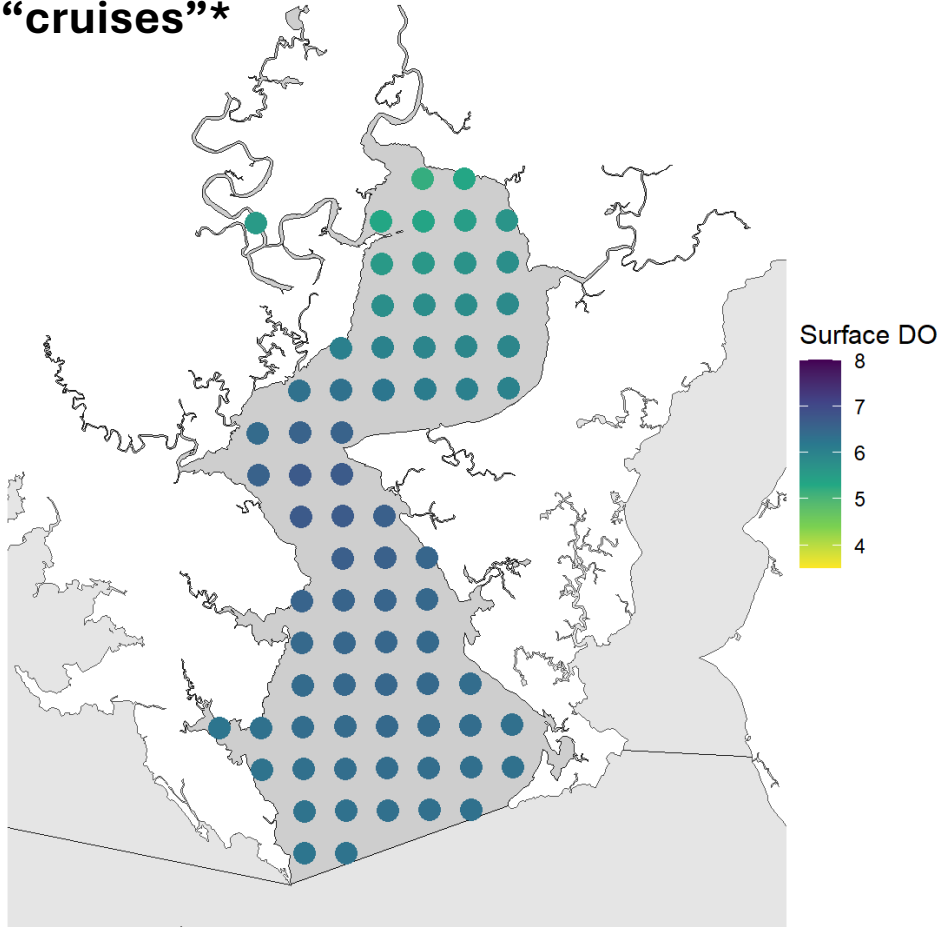
CB5MH_VA



Compare spatial pattern: July 2022

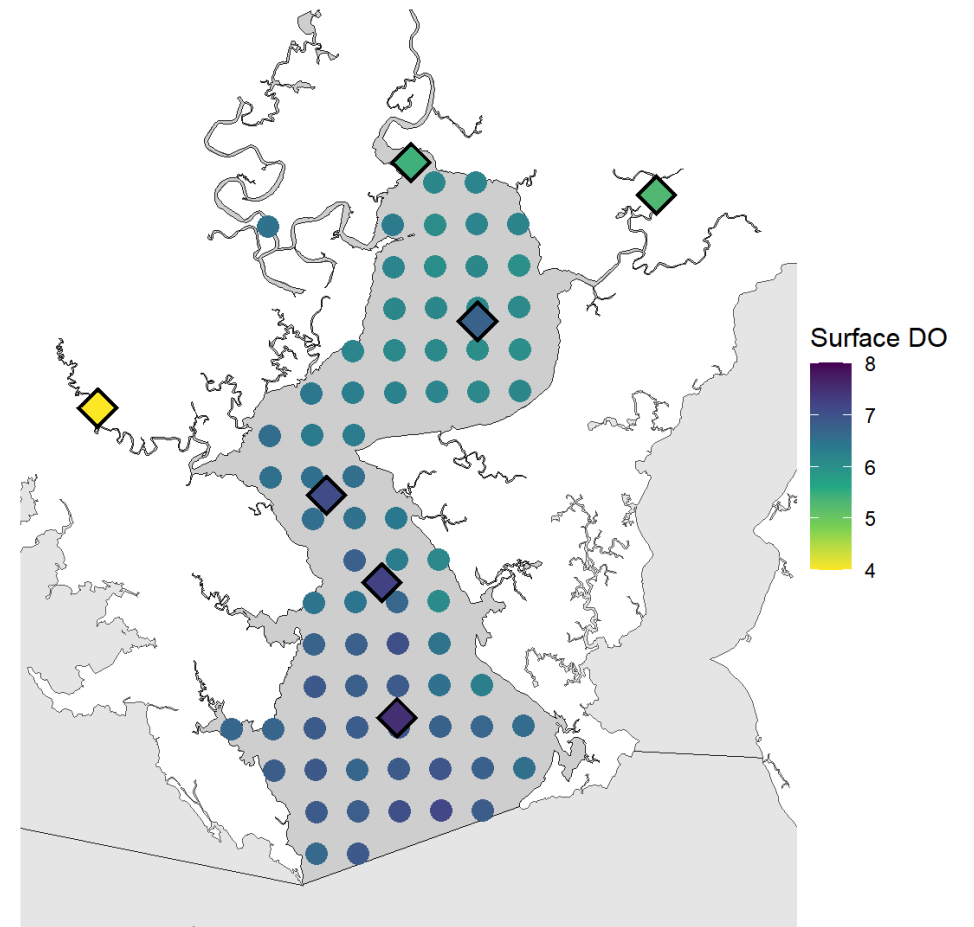
When DO data is evenly distributed in the month = Spatial pattern fairly similar between 3D and 4D.

**3D: July average of two
“cruises”***



Interpolation: 3D IDW with grab sample data only

4D: 30 day rolling average on July 15



Interpolation: 4D, data are monthly avg of all surface obs

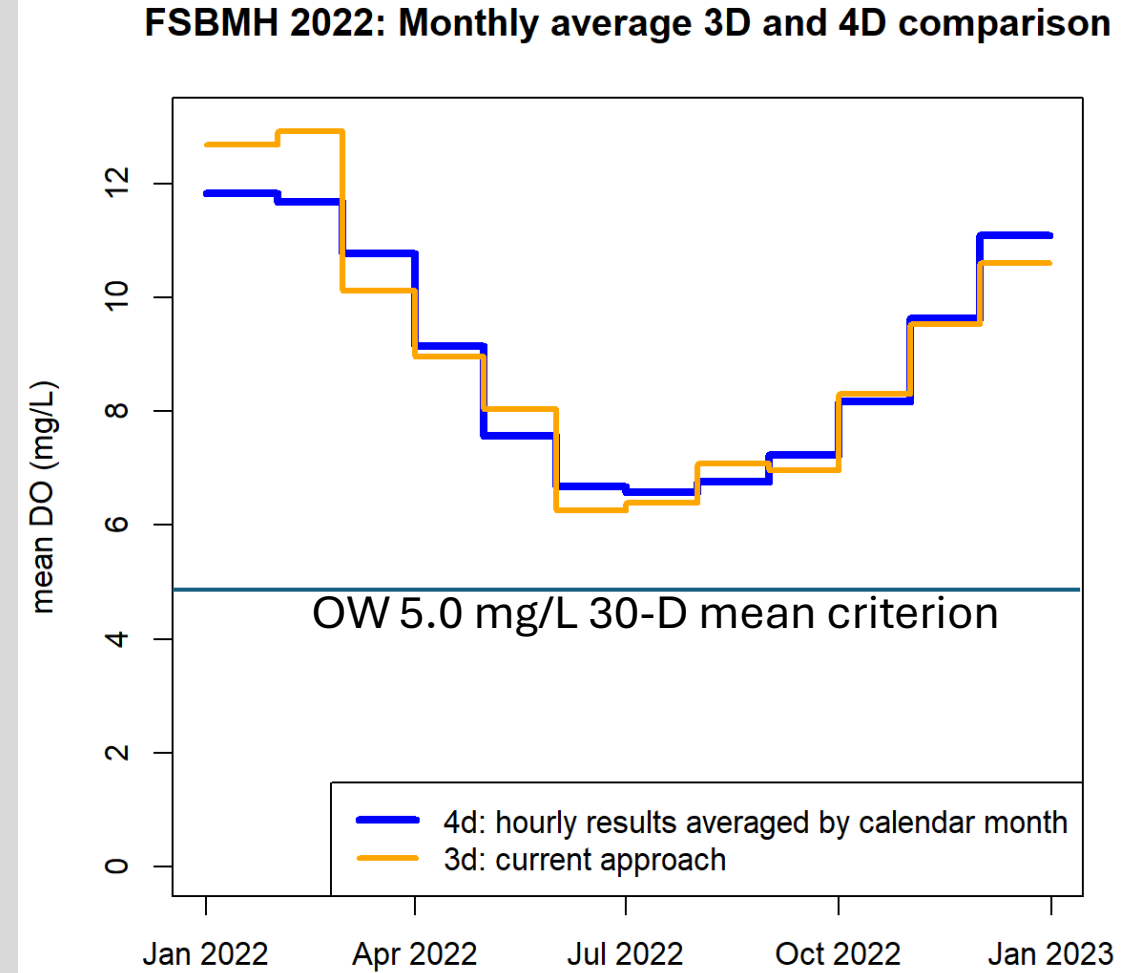
*For 3D: Data was split into “early” and “late” and is not shown here. But July had more equal station distribution than June.

* Not for use in publication at this time

2022: 1 year of monthly-average DO for the Fishing Bay segment

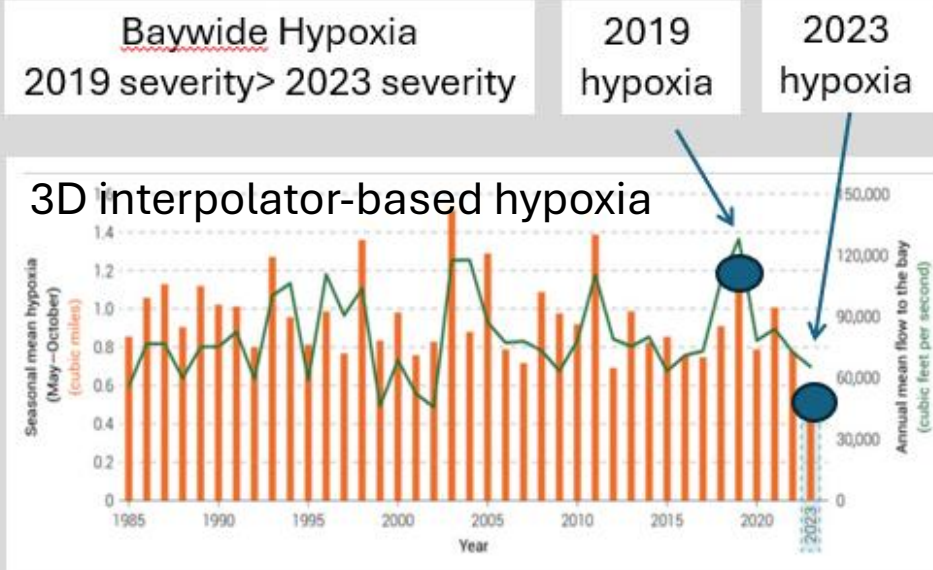
Compare 3D to similarly-aggregated 4D DO results

- 3D is predominantly used to generate monthly average results by cell. This graphic is designed to compare a similar 4D output aggregation. ➡
- Differences in input data:
 - 4D is interpolating all the high frequency data across hours,
 - 3D interpolates grab samples manually split into bi-weekly periods.
- Difference in results:
 - 4D: Hourly interpolation results are averaged to the month.
 - 3D: Two bi-weekly estimates are averaged to the month.



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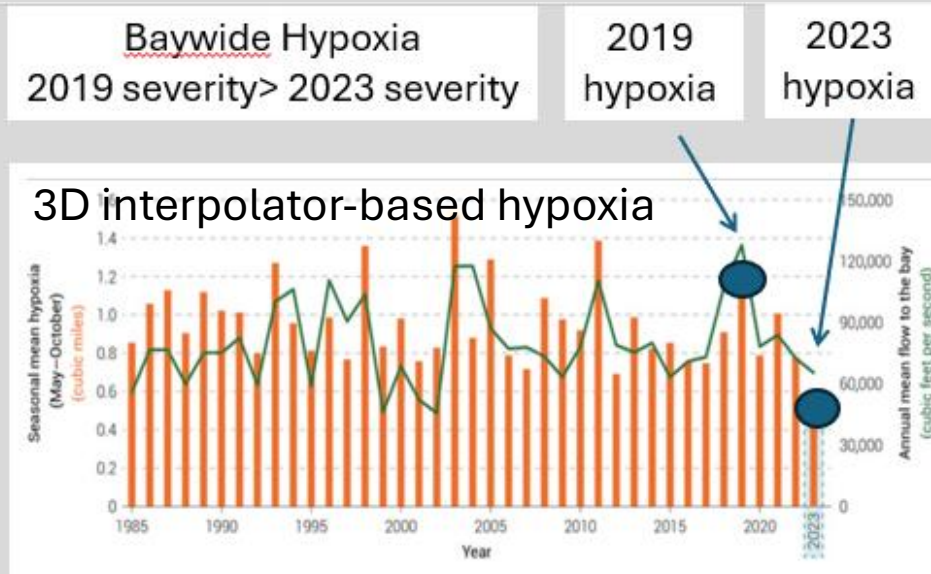
Approximate Hypoxia Comparison 2019 and 2023 highlighted



2019 Seasonal Mean Hypoxia > 2023 by over 2x
(Tango et al. 2025)

3D interpolator assessments
2019 and 2023 severity highlighted

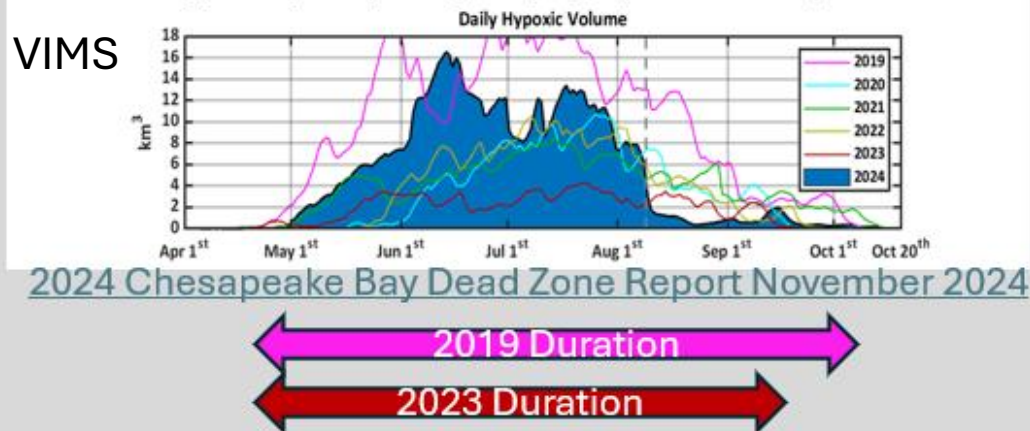
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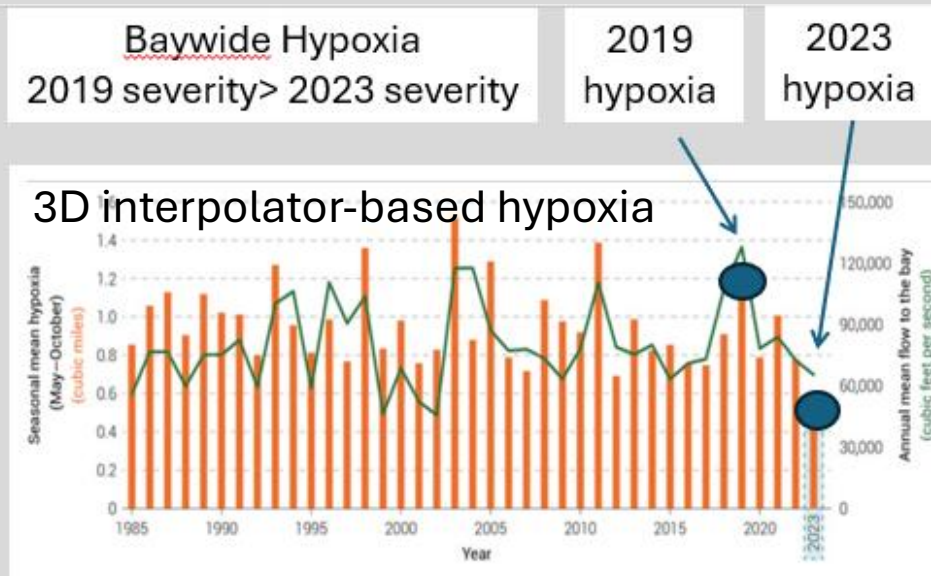
3D interpolator assessments
2019 and 2023 severity highlighted

Figure 1. Hypoxic volumes for 2019 to 2024 and wind speed over Chesapeake Bay for 2024. The remnants of Hurricane Debby passed by Chesapeake Bay in early August (vertical dashed line).



VIMS hypoxia tracking: 2024 Dead Zone Report
2019 and 2023 duration highlighted

4D spot check of main bay hypoxia consistent story with other assessments 2019 vs 2023: Segment CB5MH-VA

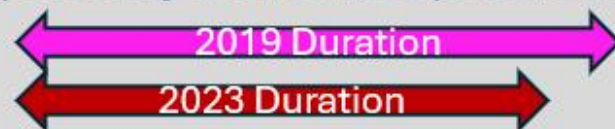


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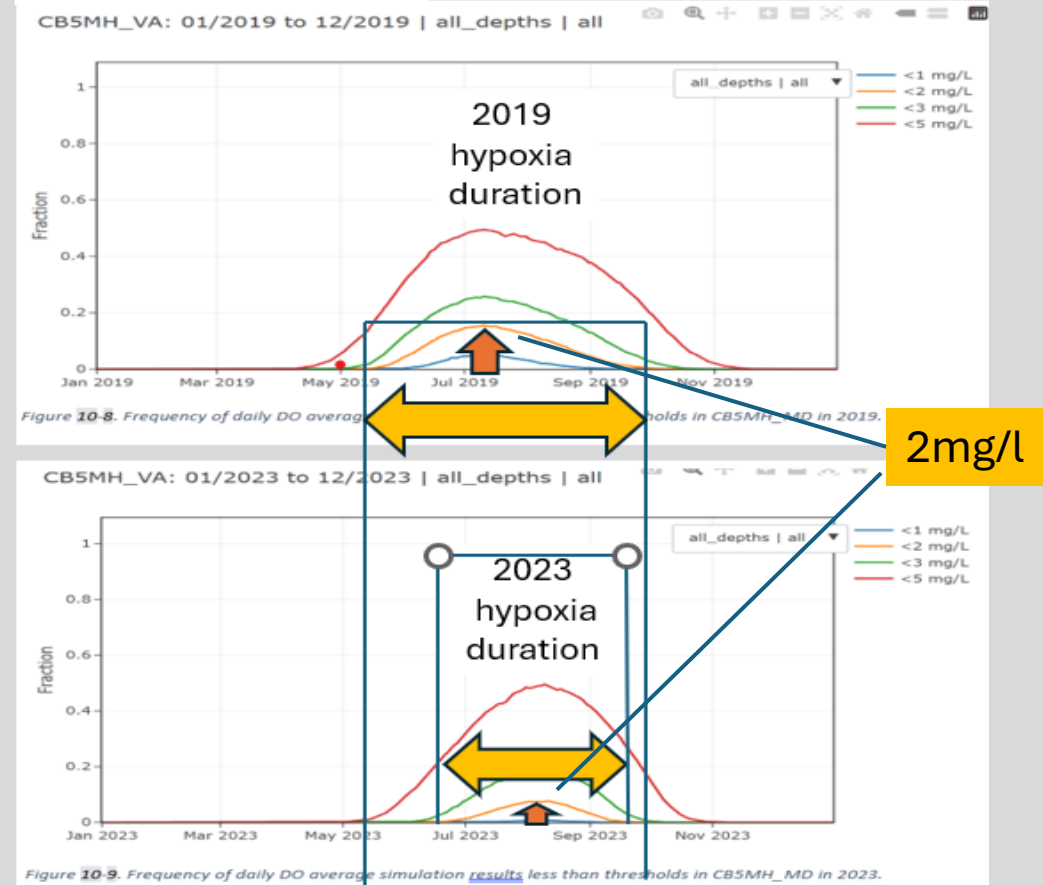
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2024 Chesapeake Bay Dead Zone Report November 2024



4D Interpolator Hypoxia



4D evaluation of CB5MH 2019 vs 2023 bay data

- 2019 peak hypoxia about 2x of 2023
- 2019 hypoxia duration is longer



* Not for use in publication at this time

Summary, Next steps

Our CBP community has collectively created a new tidal bay monitoring and assessment ecosystem

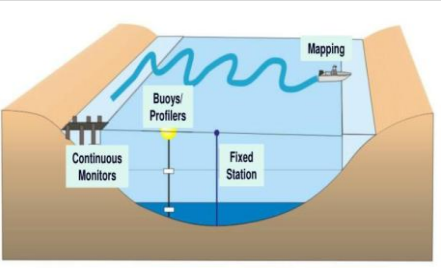
Adaptive Monitoring
New, robust, con-mon
monitoring tech development
and investments

Robust Mapping
New statistical tool mapping
hourly dissolved oxygen patterns

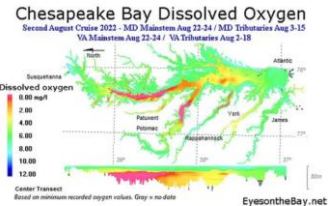
Expanded Assessment
New, complete DO criteria
Assessment Protocol
rule set proposed

'Adequate' Level of Monitoring
USEPA 2003

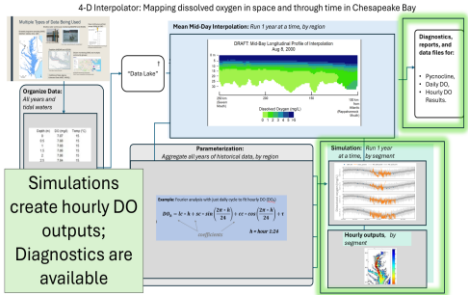
Assuming that funding will not be available for the 'recommended' monitoring approach, an alternative would be to place a limited number of continuous monitors at representative locations in the Chesapeake Bay and tidal tributaries. The number of continuous monitors would be relatively small, but the number would be established to characterize different types of settings in the Chesapeake Bay. Those representative temporal records would then be combined with fixed-station data in



Low and Hi-frequency Space-Time Monitoring (w/ arrays)
Hyp Collab 2020+

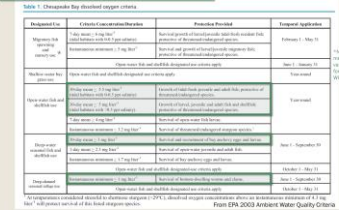
**Chesapeake Bay Dissolved Oxygen**
Second August Cruise 2022 - MD Mainstem Aug 22-24 / MD Tributaries Aug 3-15
VA Mainstem Aug 22-24 / VA Tributaries Aug 3-15
EyesontheBay.net

**3D snapshots
Nonstatistical mapping
1980s-2025**

**4-D Interpolator: Mapping dissolved oxygen in space and through time in Chesapeake Bay**
Simulations create hourly DO outputs; Diagnostics are available

4D space-time Interpolation
BORG Team
2026+

Purpose: Build a tool for more complete criteria assessment
DO criteria that can be used for evaluation with existing operations and data



2003-2025 Incomplete DO assessment Indicator rules estimator

Table 2: Dissolved oxygen assessment combinations identified for

Row	Assessment ID	Designated use / season	Period definition	Criterion
1	MFEN-DPS-7D	MFEN—spring	Feb 1–May 31	7-day mean
2	MFEN-SFB-IM	MFEN—spring	Feb 1–May 31	Instantaneous minimum
3	OW-SUM-30D	OW—summer	Jun 1–Sep 30	30-day mean
4	OW-SUM-7D	OW—summer	Jun 1–Sep 30	7-day mean
5	OW-SUM-IM	OW—summer	Jun 1–Sep 30	Instantaneous minimum
6	OW-NSB-30D	OW—non-summer	Oct 1–May 31	30-day mean
7	OW-NSB-7D	OW—non-summer	Oct 1–May 31	7-day mean
8	OW-NSB-IM	OW—non-summer	Oct 1–May 31	Instantaneous minimum
9	DW-SUM-30D	DW—summer	Jun 1–Sep 30	30-day mean
10	DW-SUM-7D	DW—summer	Jun 1–Sep 30	7-day mean
11	DW-SUM-IM	DW—summer	Jun 1–Sep 30	Instantaneous minimum
12	DC-SUM-IM	DC—summer	Jun 1–Sep 30	Instantaneous minimum

Full DO protocol proposal for Assessment module

2026 CAP AT w/ BORG AT

Next Steps

STAC review of the new
tool
(November 2026-March
2027)

Work with the Criteria
Assessment Protocol AT
on correctly coding the
DO criterion assessment
module

Work with our partners
on User-interface
development into
summer 2027

Coordinating with
Modeling WG in
preparation for scenario
output evaluations in
2027 and beyond.

4-D Interpolator Workflow (v9-14-26)

