Quantifying the drivers of hypoxia onset variability in the Chesapeake Bay

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Integrated Trends Analysis Team (ITAT) Meeting
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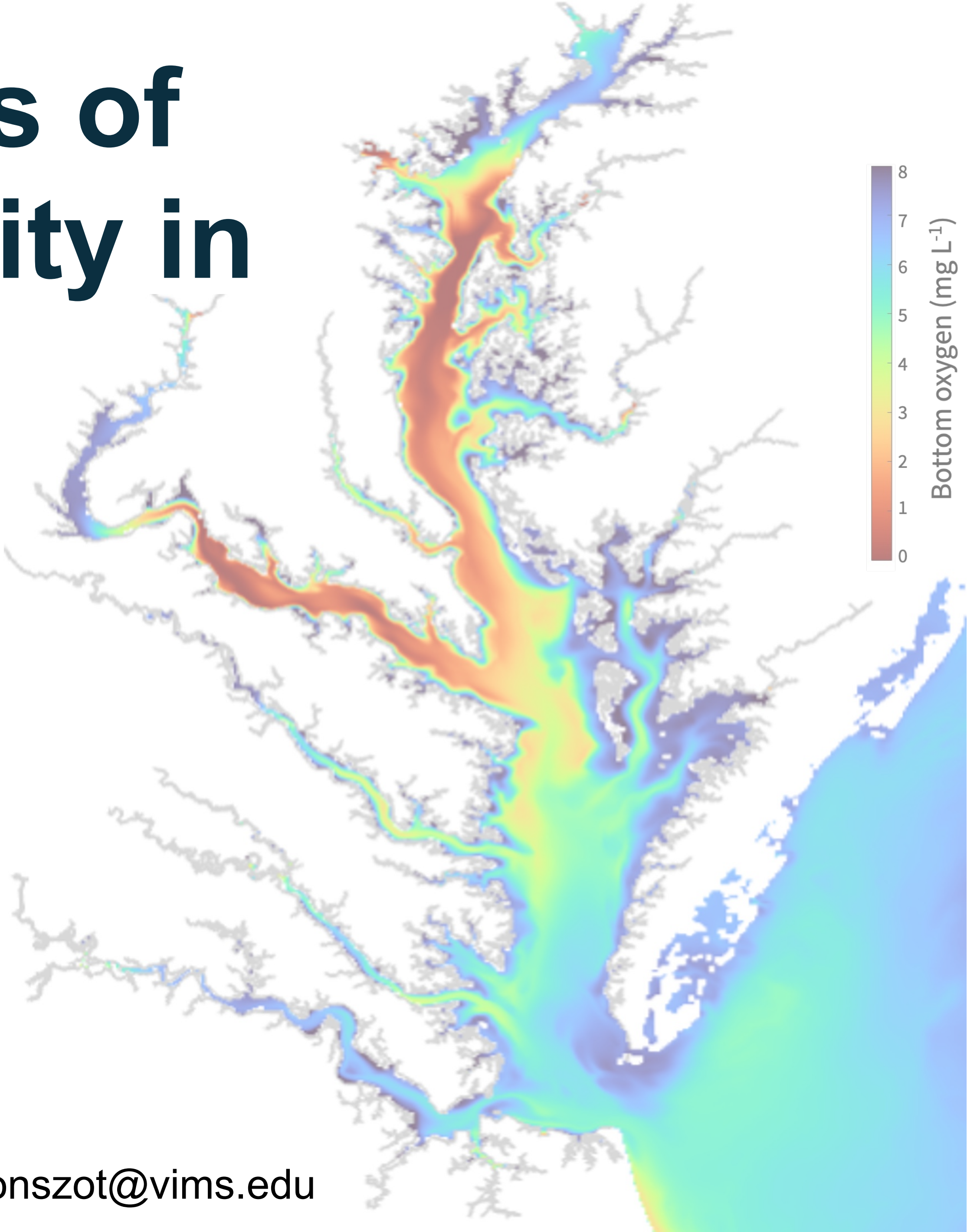

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Previous studies show high year-to-year variability of hypoxia onset timing

Hypoxia in Chesapeake Bay, 1950–2001: Long-term Change in Relation to Nutrient Loading and River Flow

JAMES D. HAGY*, WALTER R. BOYNTON, CAROLYN W. KEEFE, and KATHRYN V. WOOD

TABLE 5. Estimated rate of DO decline in bottom waters at station CB4.3C (Fig. 1) during the spring period of linear DO decline and the estimated date on which bottom waters reached anoxia. Bottom waters at CB4.3C became anoxic every summer and remained anoxic until early fall.

Year	Rate of DO Decline (mg l^{-1} d^{-1})	Onset of Anoxia (Date)
1985	0.103	June 20
1986	0.096	June 22
1987	0.146	May 28
1988	0.182	May 26
1989	0.093	July 5
1990	0.119	May 20
1991	0.089	June 6
1992	0.095	July 3
1993	0.184	May 21
1994	0.100	June 3
1995	0.075	July 3
1996	0.107	June 10
1997	0.085	June 28
1998	0.196	May 2
1999	0.114	June 14
2000	0.141	May 15
2001	0.121	June 2

Latest onset date

Earliest onset date

Edited from Hagy et al. 2004

Spatial and Temporal Patterns of Winter–Spring Oxygen Depletion in Chesapeake Bay Bottom Water

Jeremy M. Testa · W. Michael Kemp

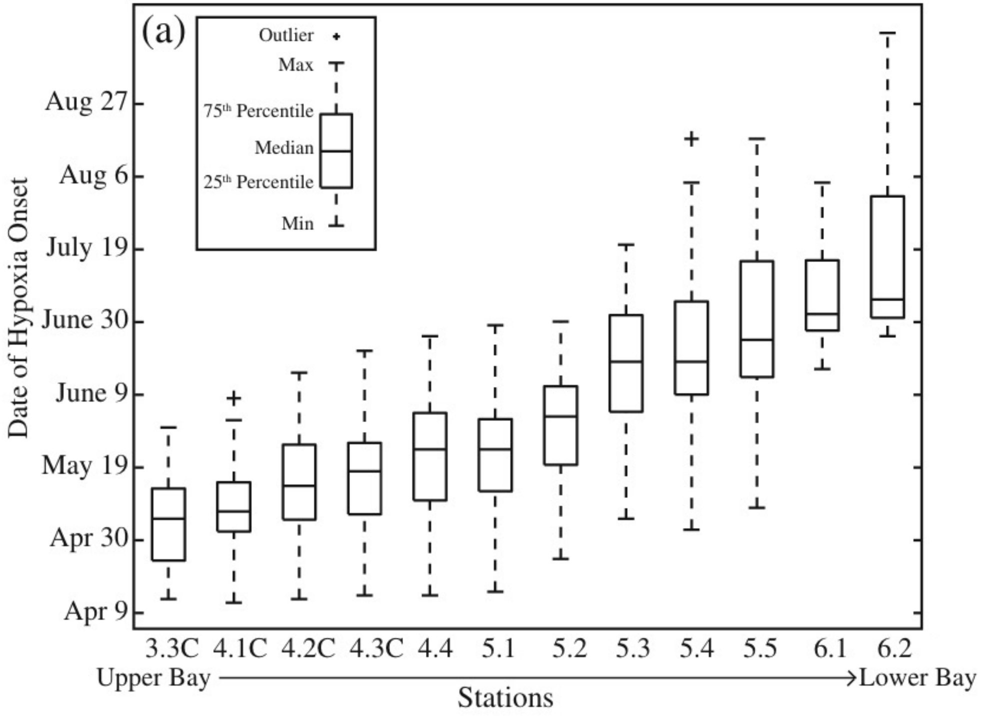
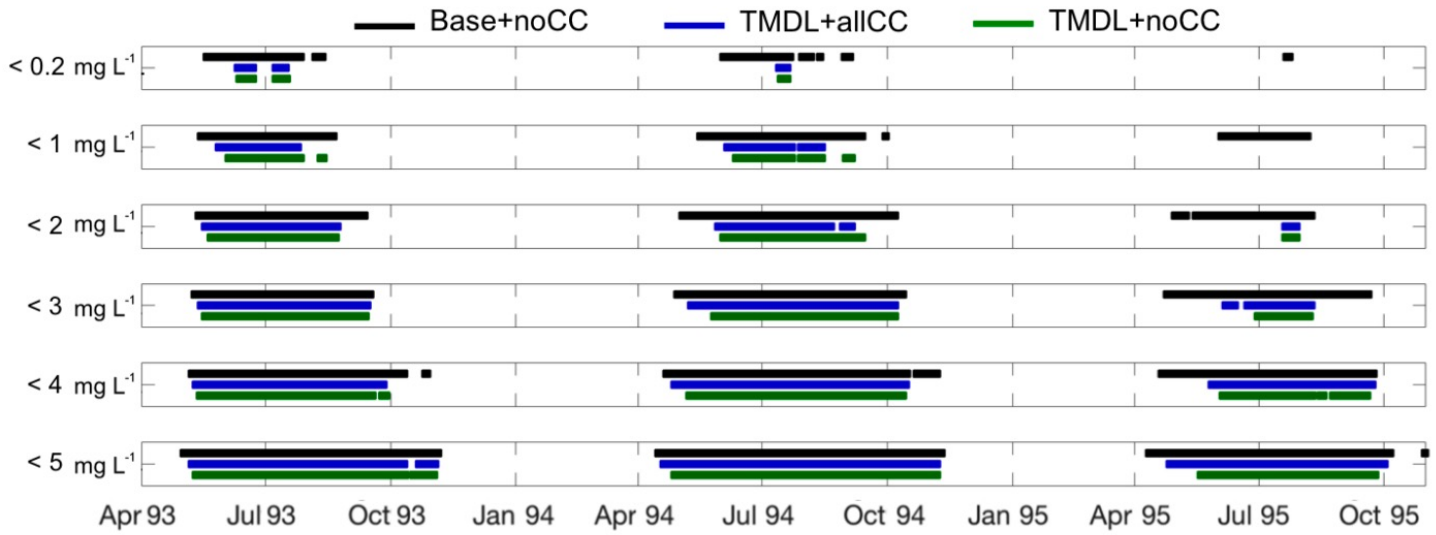


Fig. 6 Box plots of hypoxia onset day (**a**) and water column O_2 depletion rate (**b**) at 12 stations along the Chesapeake Bay axis for the years 1985 to 2009 (see Fig. 1) Edited from Testa et al. 2014

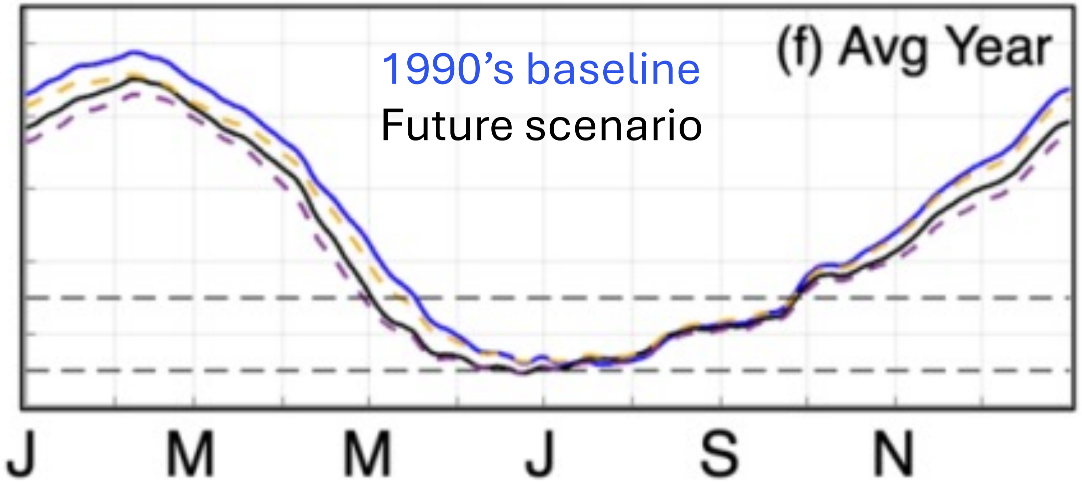
Climate scenario experiments indicate future changes in onset timing

"This study also demonstrates that compared to conditions in the early 1990s, hypoxia may start two weeks earlier on average by the mid-21st century...."

Hawes 2024



Edited from Hawes 2024



Edited from Irby et al. 2018

"The most consistent impact across all levels of low-DO waters due to climate change is an earlier onset of hypoxic and low-DO conditions by an average of ~ 7 days."

Irby et al 2018

Why do we care about when hypoxia starts …

1. Ecological impact
Earlier onset can extend the time that environment is under stress

2. Water quality management
Understanding the drivers of onset timing can improve forecasts and allow for more targeted management approaches

3. Climate change indicator
Changes in onset timing can serve as an indicator of environmental changes

What causes this year-to-year variability in hypoxia onset timing?

Known drivers of hypoxia:

Wind patterns

- (De)stratification
- Mixing
- Surface air interaction

Temperature

- Gas solubility
- Biological rates
- Stratification

Terrestrial input

- Nutrient availability
- Stratification
- Estuarine circulation

Objective

Quantify the relative influence wind patterns (speed, direction, waves), air temperature, and terrestrial inputs on hypoxia onset

ROMS-ECB

Feng et al, 2015; St-Laurent and Friedrichs, 2024

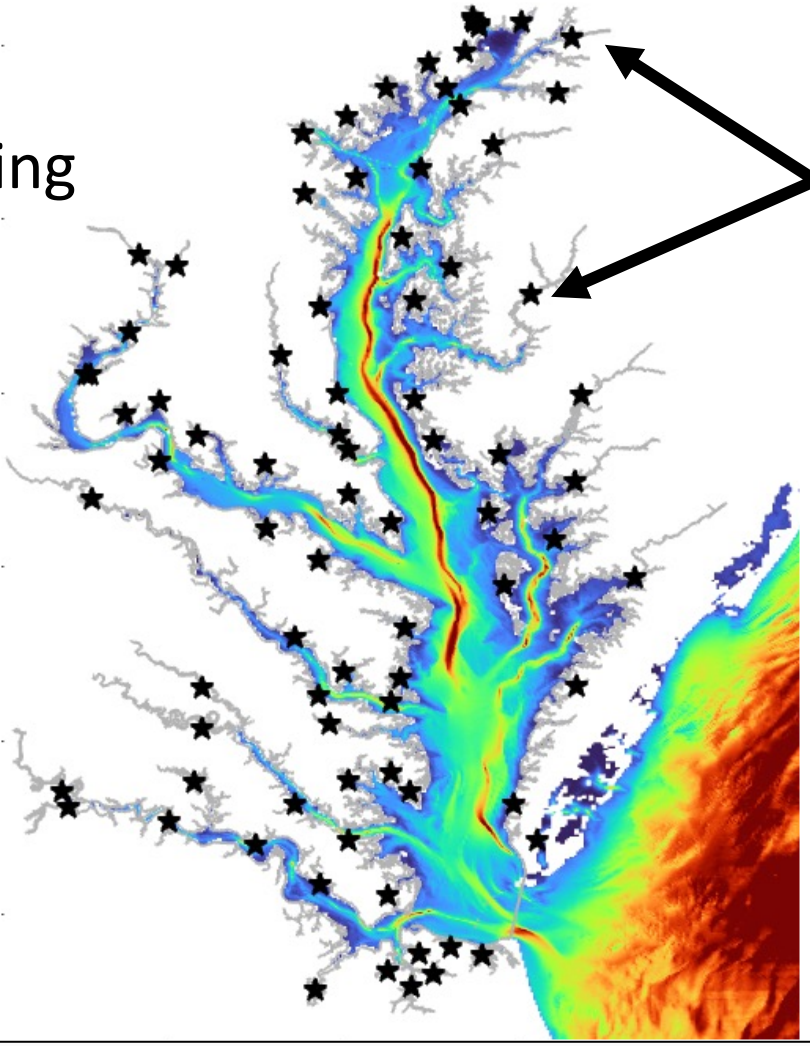
Modeling System:

Regional Ocean Modeling System (ROMS)

600m x 600m grid resolution
20 terrain-following levels

Estuarine Carbon and Biogeochemistry (ECB)

Full carbon and nitrogen cycles
Sinks and sources of O_2
Air/sea exchanges
Biogeochemical fluxes at bed
Sediment transport module



Forcing:

Terrestrial ★

CBP's Phase 6 watershed model and USGS data

Atmospheric

ERA5 Atmospheric Reanalysis and NAM Forecast System

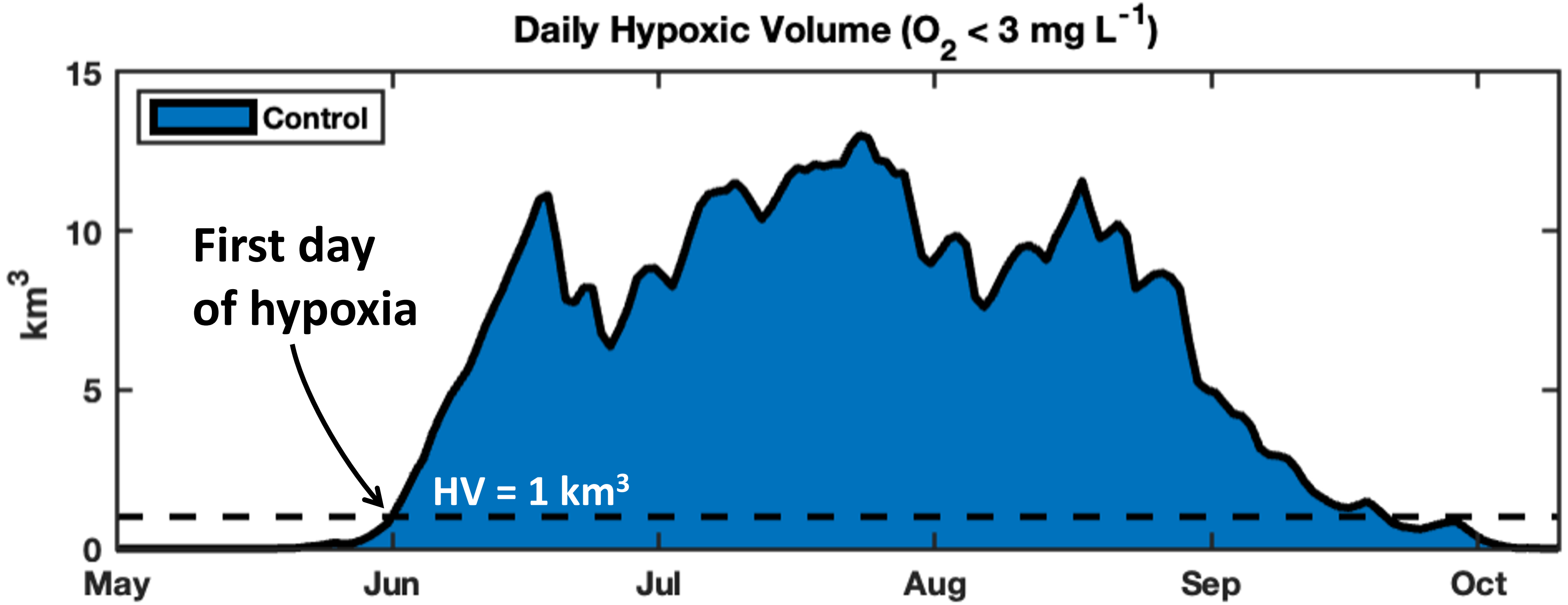
Waves

SWAN model

Data collected from stations throughout the Bay from 1985 to present were used to develop and evaluate the model

Methods: Control Run

Control: 1 year simulation 2017 with climatological air temperature and terrestrial inputs



Hypoxia onset date is defined as first day hypoxic volume reaches 1 km^3

Methods: Experimental Simulations

Control: 1 year simulation 2017 with climatological air temperature and terrestrial inputs

Forcing Modified	Months Modified	Experiment 1	Experiment 2
Wind speed (*Wspd)*	March, April, May	+1 SD	–1 SD
Wind direction (*Wdir)*	March, April, May	+1 SD	–1 SD
Wind waves (*Wwave)*	March, April, May	+1 SD	–1 SD
Air Temperature (*Tair)*	March, April, May	+1 SD	–1 SD
Terrestrial Inputs (*Terr)*	January, February, March, April, May	+1 SD	–1 SD
Freshwater Discharge (*FW)*	January, February, March, April, May	+1 SD	–1 SD

- All terrestrial inputs including freshwater, nutrients, organic matter, and sediment were modified.
- Only freshwater discharge was modified.
- SD = standard deviation calculated from 25 years (1996-2020) of historical data

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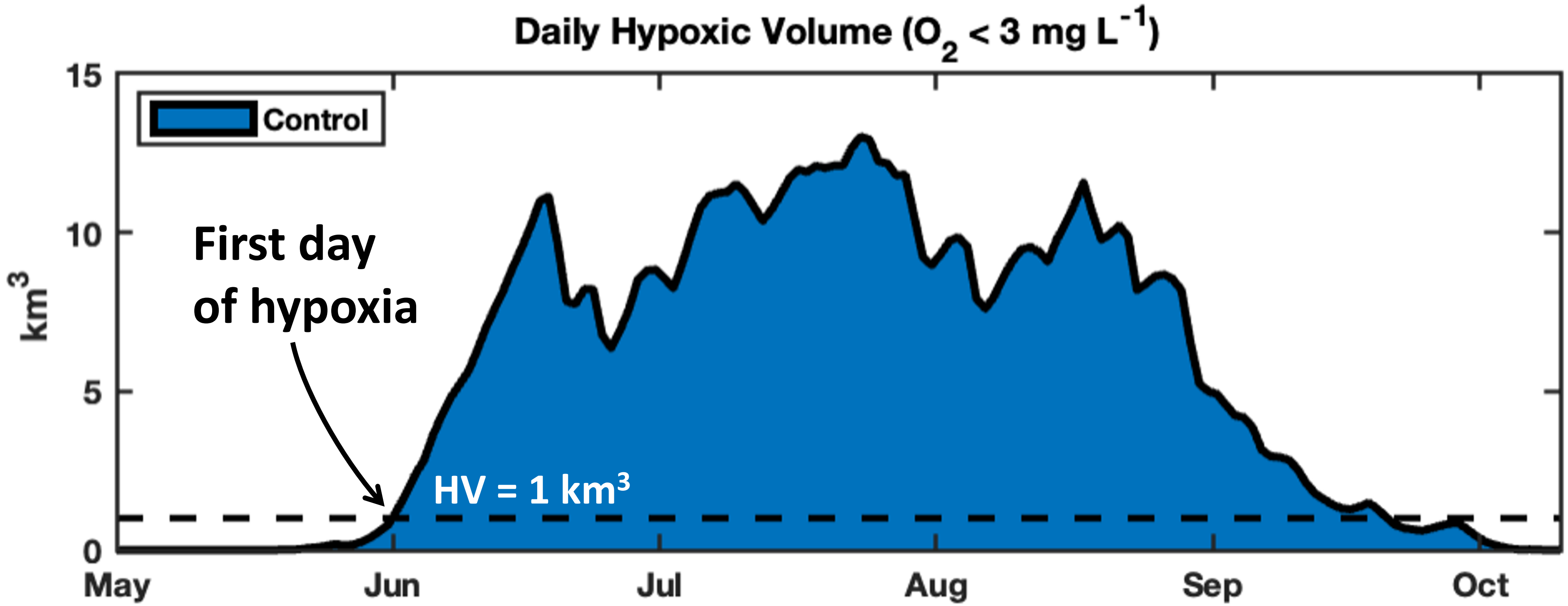
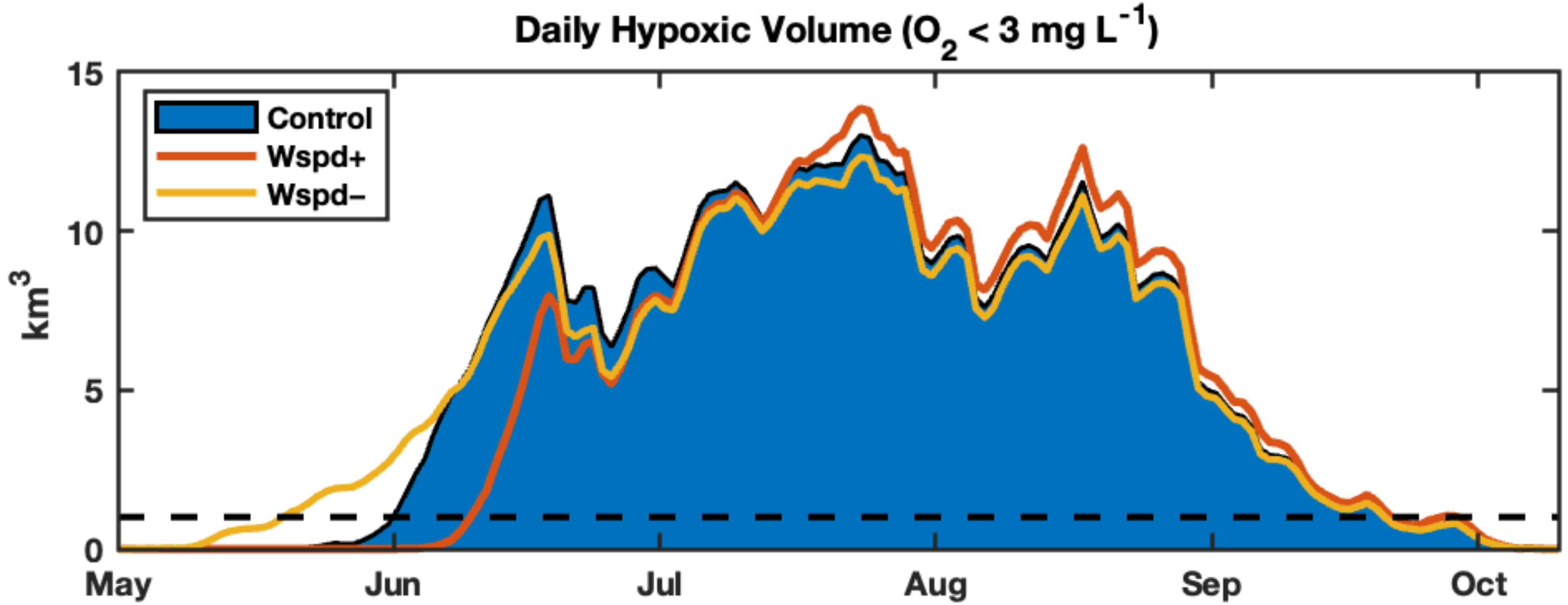
Control: Baseline for experiments



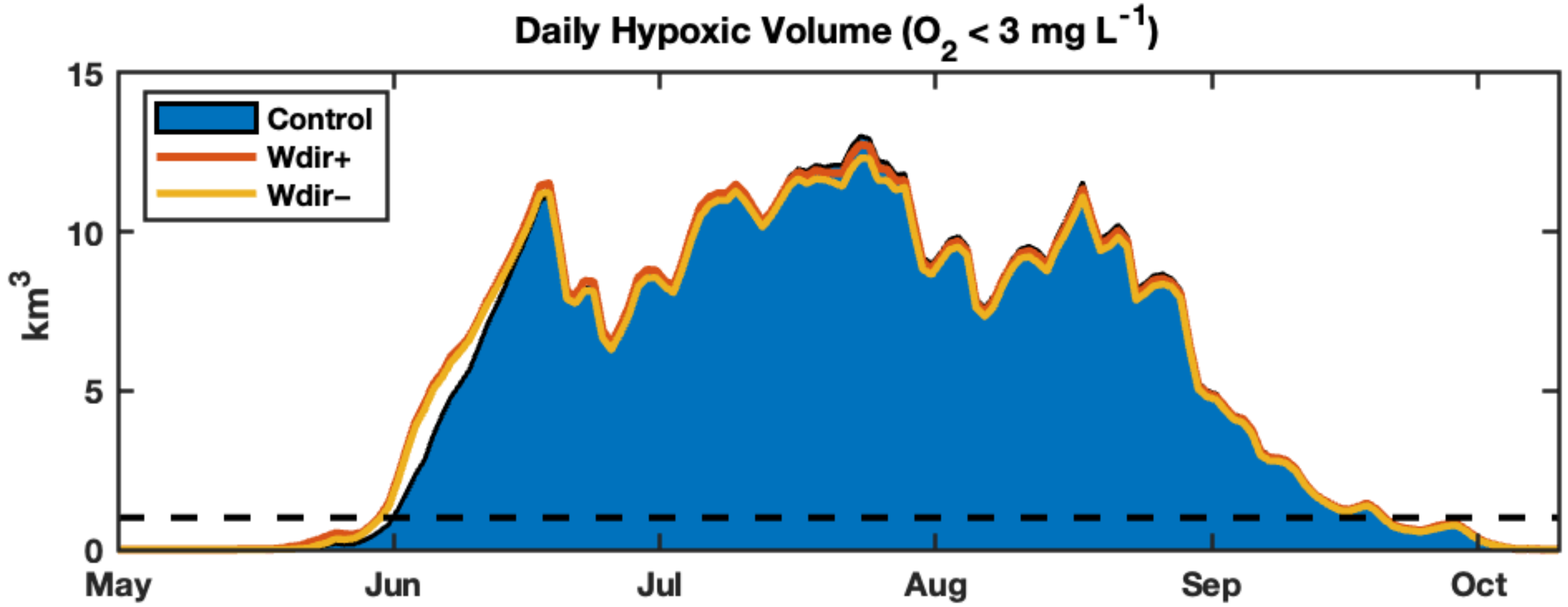
Wind speed led to onset range of ~ 3 weeks



↑ wind speed led to <u>later onset by 9 days</u>

↓ wind speed led to <u>earlier onset by 12 day</u>

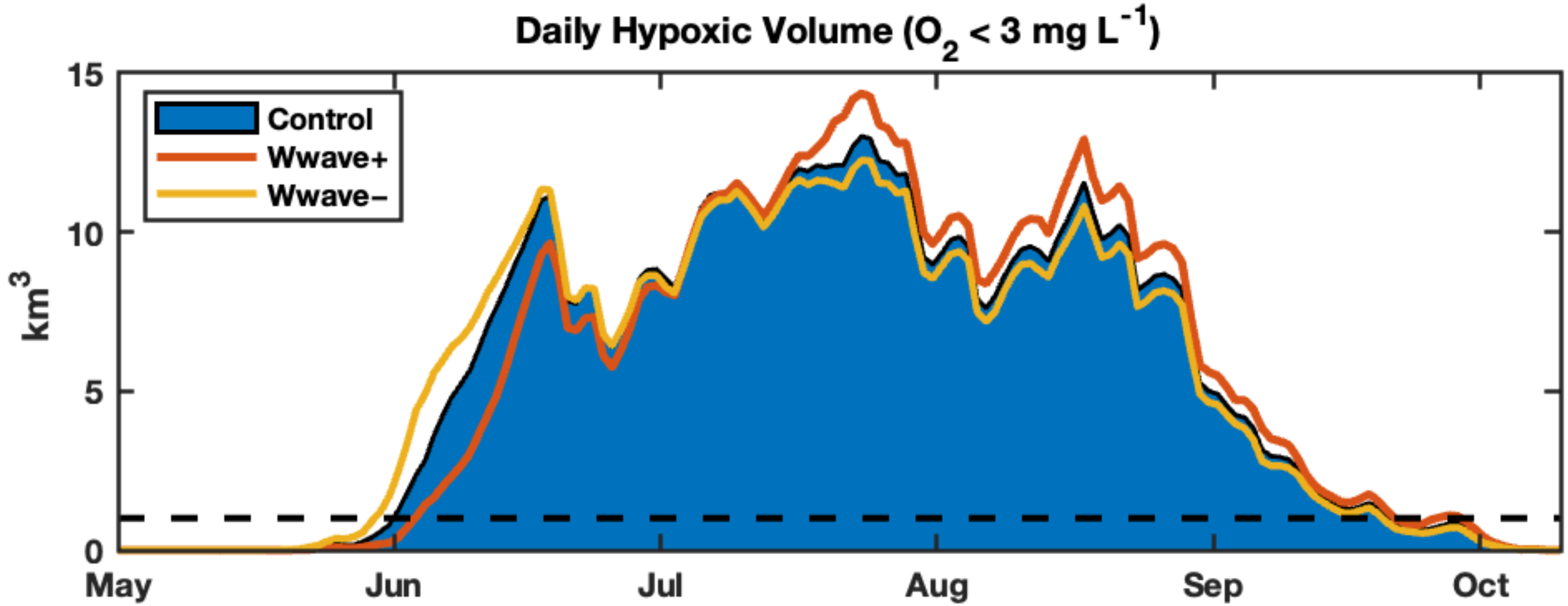
Wind direction has minor influence on hypoxia onset timing



↻ wind direction led to earlier onset by ≤ 2 days

↺ wind direction led to earlier onset by ≤ 2 days

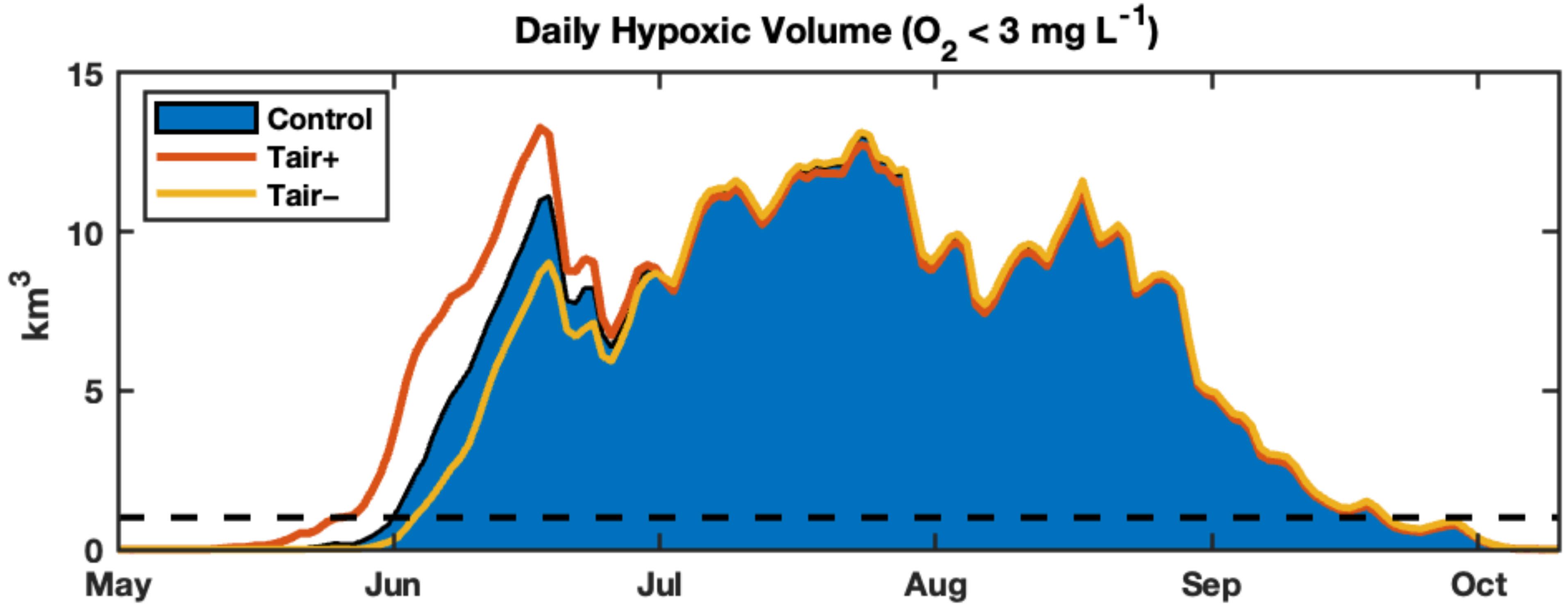
Wind waves have minor influence on hypoxia onset timing



↑ waves led to <u>later onset by ≤ 2 days</u>

↓ waves led to <u>earlier onset by ≤ 2 days</u>

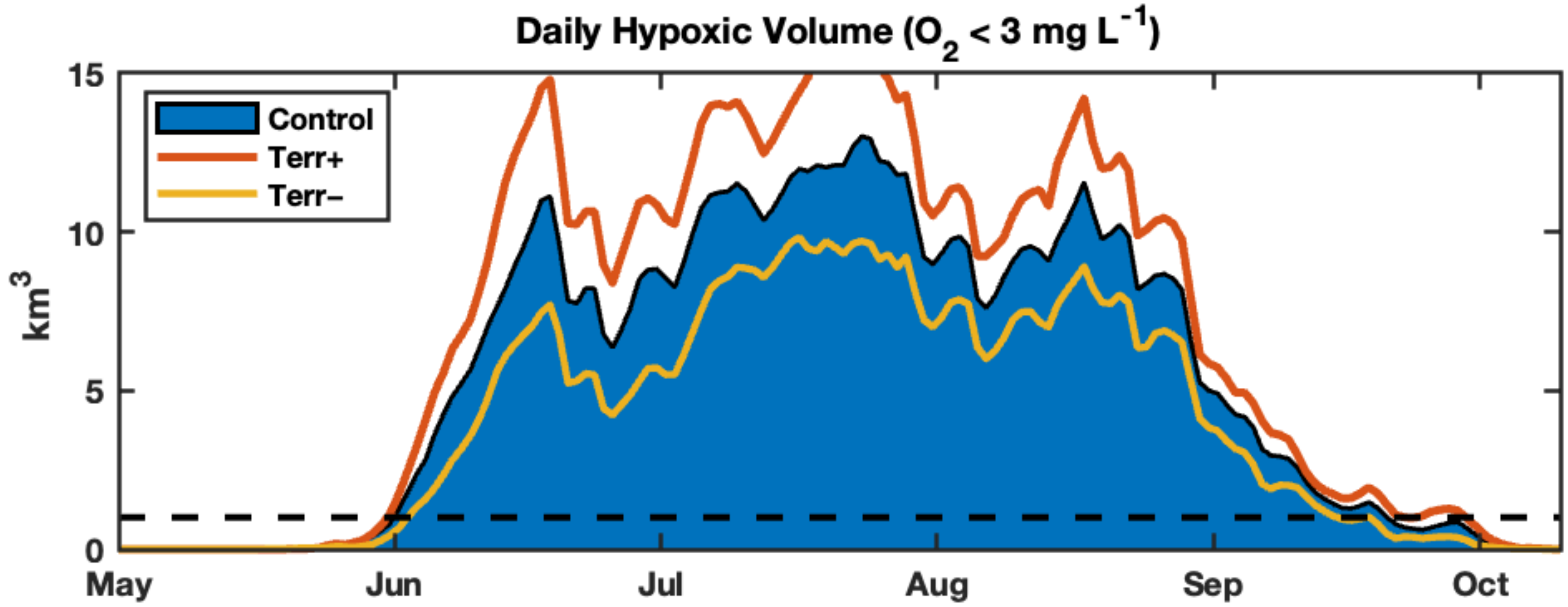
Onset date varies by ~1 week due to air temperature



↑ **air temperature** **led to** **<u>earlier onset by 6 days</u>**

↓ **air temperature** **led to** **<u>later onset by 2 days</u>**

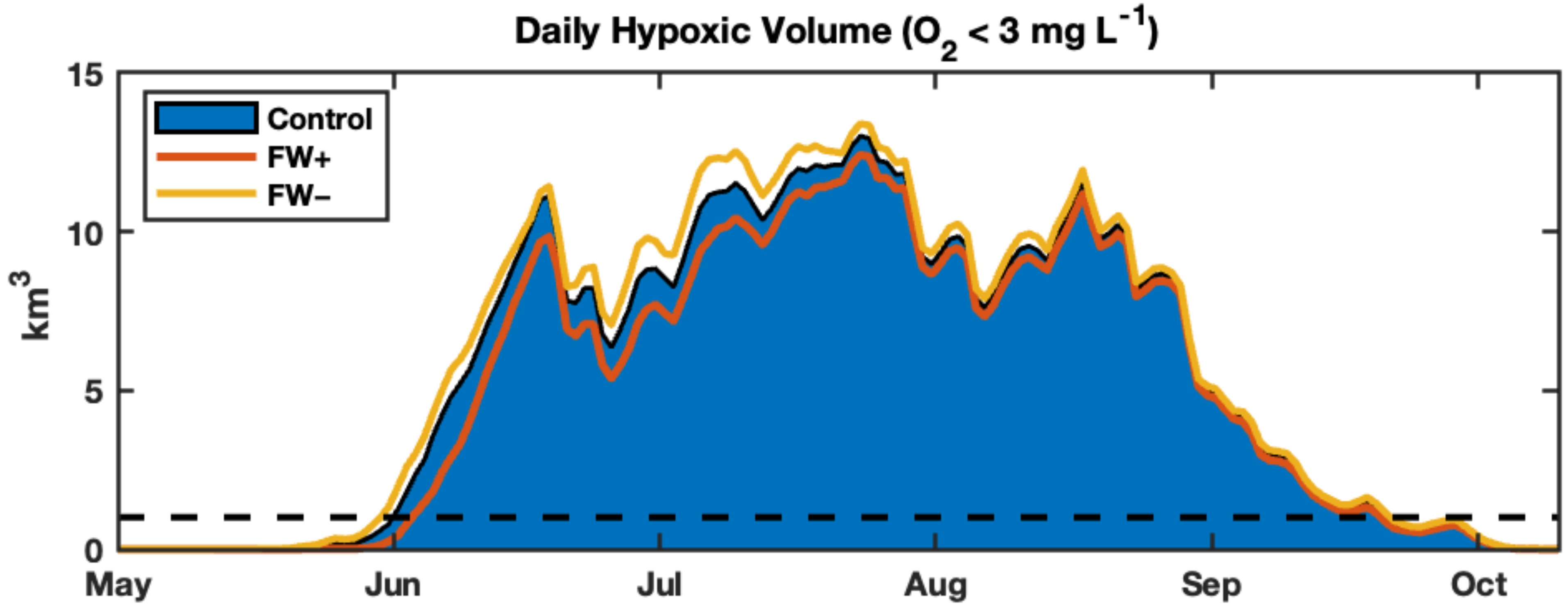
Terrestrial input has little influence on timing; large influence on magnitude of hypoxia



↑ terrestrial inputs led to <u>earlier onset by ≤ 2 day</u> & increase in hypoxia by ~<u>25%</u>

↓ terrestrial inputs led to <u>later onset by ≤ 2 day</u> & decrease in hypoxia by ~<u>25%</u>

Freshwater discharge has little influence on hypoxia onset



↑ freshwater discharge led to <u>later onset by ≤ 2 days</u> & decrease in hypoxia by 9%

↓ freshwater discharge led to <u>earlier onset by ≤ 2 day</u> & increase in hypoxia by 6%

Takeaways

- **Wind speed → <u>~3 weeks onset range</u>**
- **Air temperature → ~<u>1 week onset range</u>**
- **Wind direction and waves have small impact → <u>≤ 2 days onset difference</u>**
- **Terrestrial inputs had little influence on hypoxia onset but had the most impact on total annual hypoxic volume → ~<u>25% difference</u>**

Implications

- **Wind speed → ~3 weeks onset range**

  High uncertainty in future hypoxia onset time with uncertain future changes to wind patterns

- **Air temperature → ~1 week onset range**

  Anticipate earlier hypoxia onset in the future

- **Wind direction and waves have small impact → ≤ 2 days onset difference**
- **Terrestrial inputs had little influence on hypoxia onset but had the most impact on total annual hypoxic volume → ~25% difference**

  Reinforces the need for nutrient reductions

Acknowledgements

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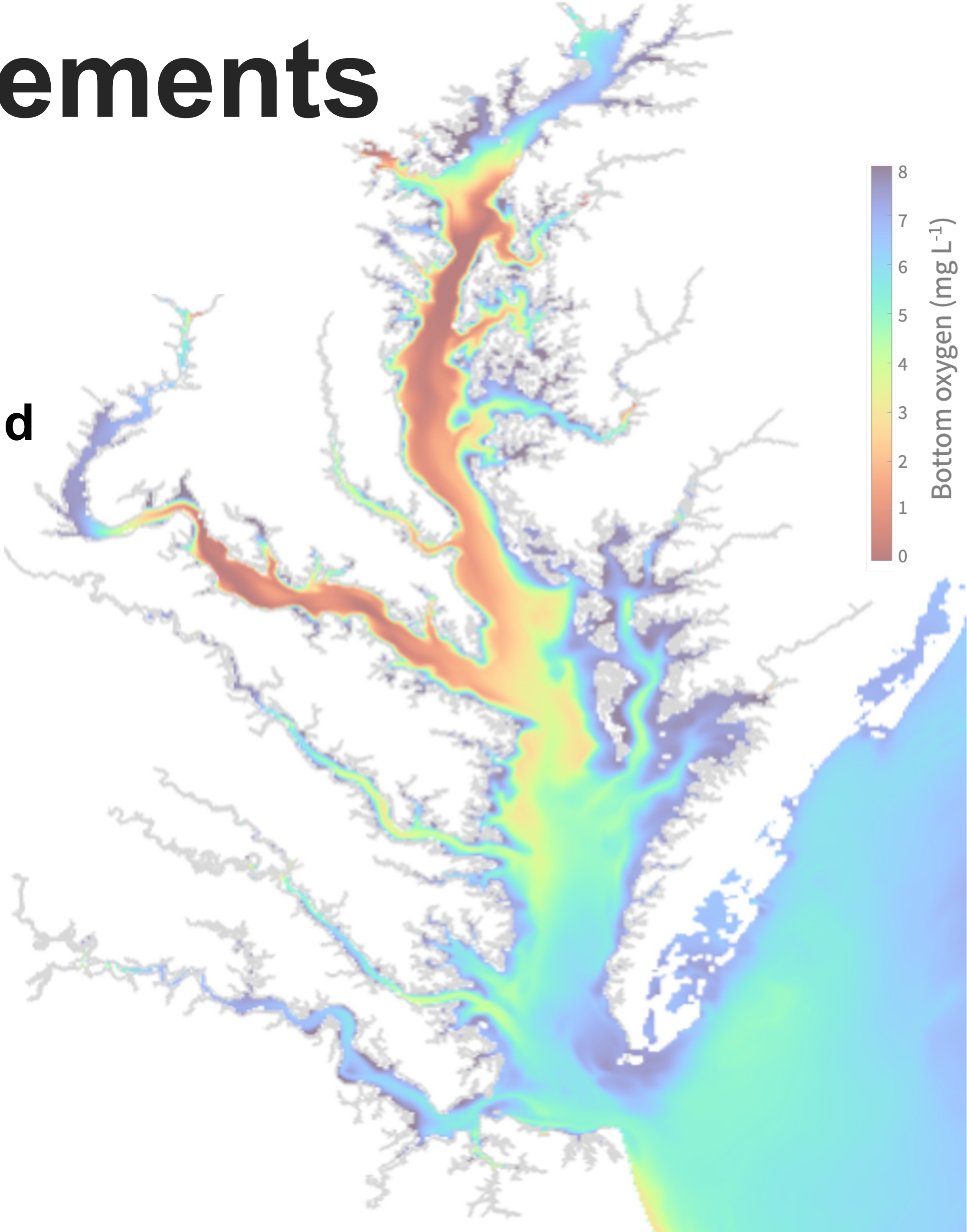
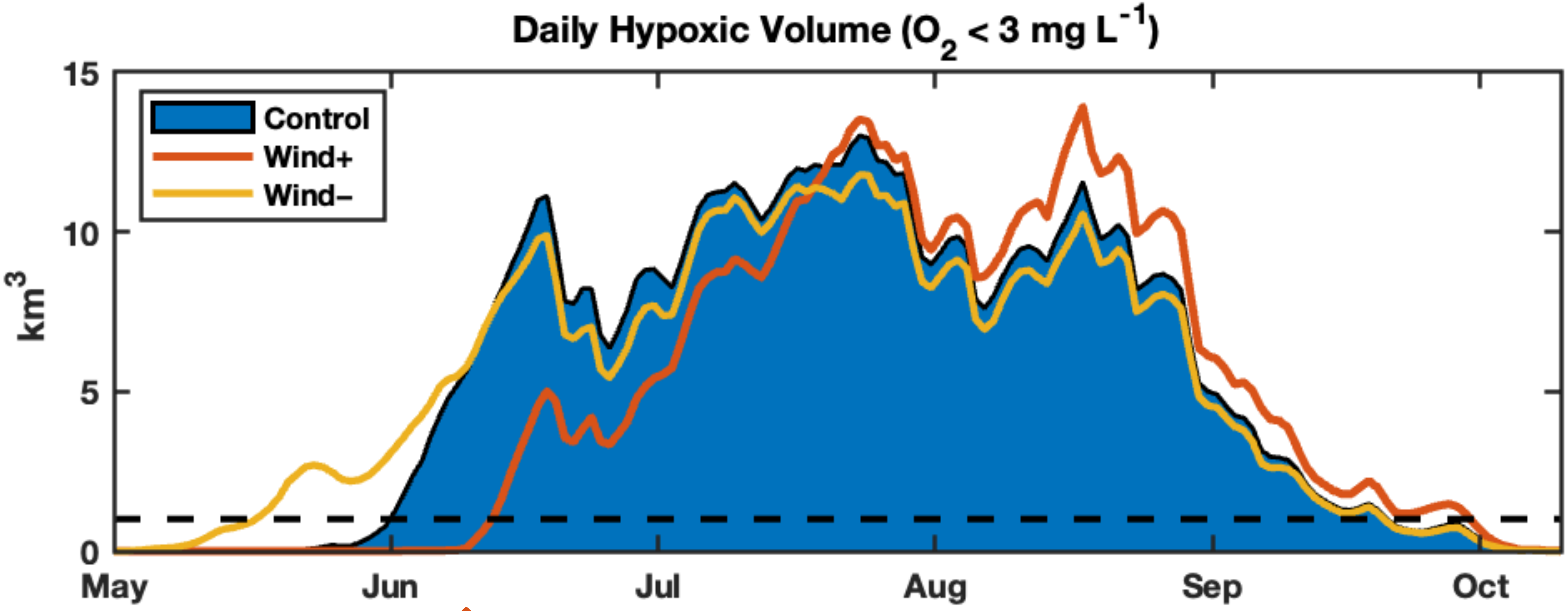
Ocean Information for a Changing World



Additional Slides

Wind pattern combination led to onset range of ~ 4 weeks



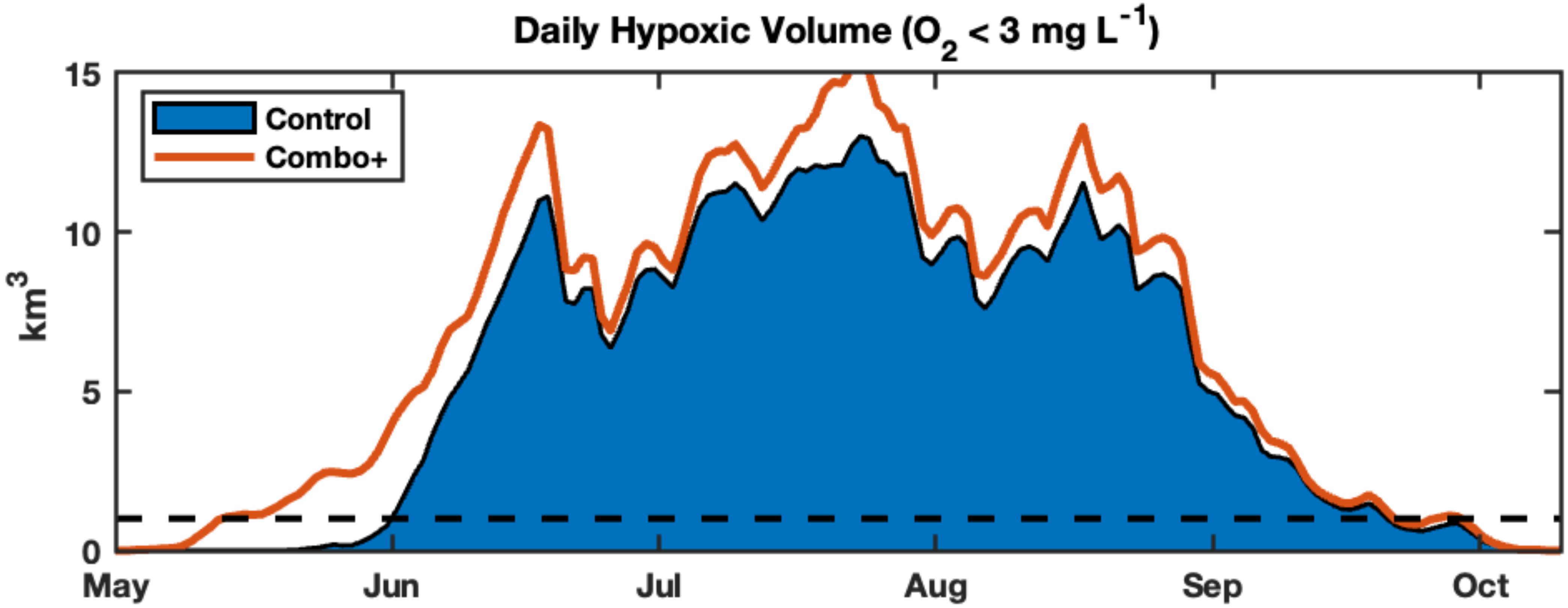
↑ Wind led to <u>later onset by 11 days</u>

↓ Wind led to <u>earlier onset by 15 days</u>

Wind+ : Increase wind speed, increase waves, rotate wind directions clockwise

Wind– : Decrease wind speed, decrease waves, rotate wind directions counterclockwise

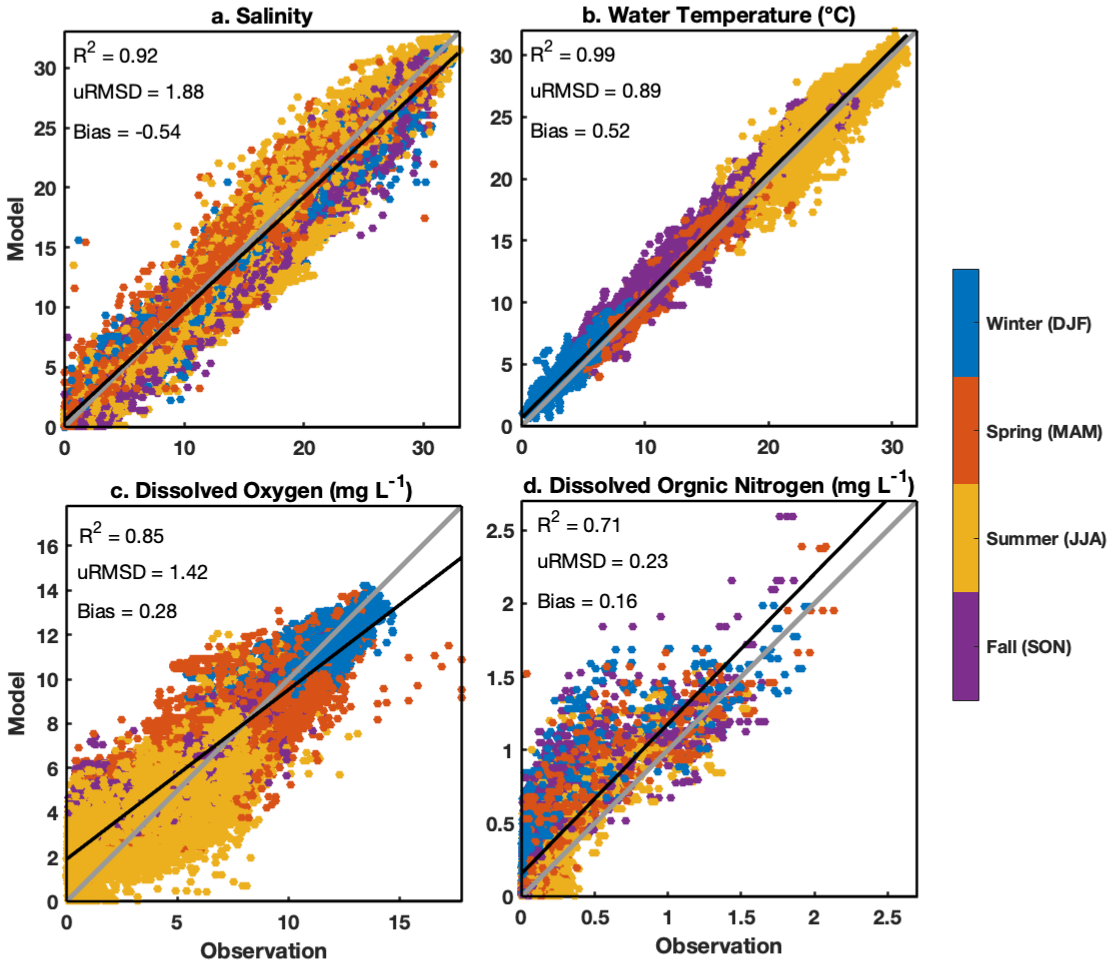
Combination run



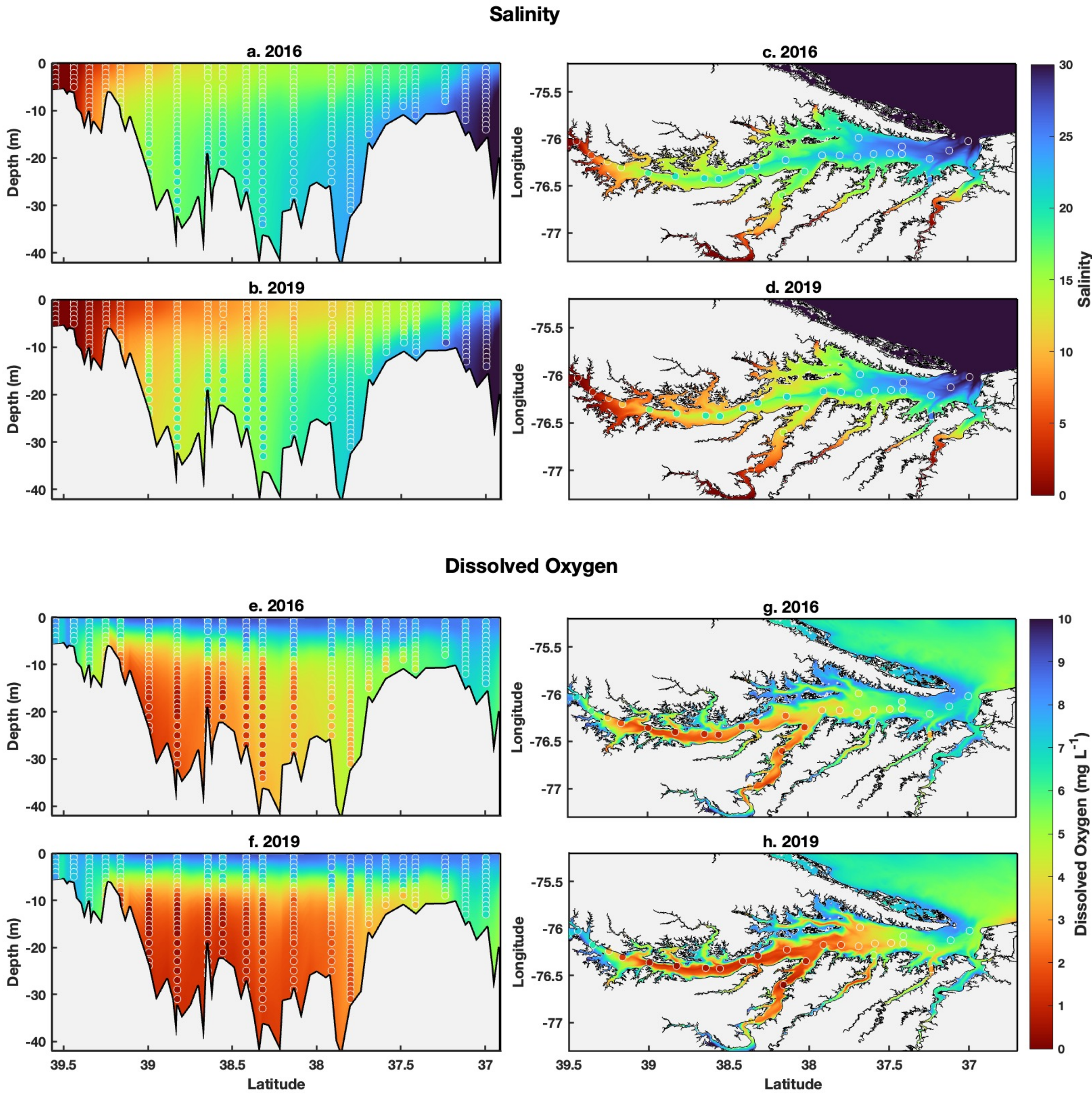
Combo led to earlier onset by 19 days

Combo : Decrease wind speed, increase terrestrial inputs, increase air temperature during May

Model-data comparison



Modeled vs. observed (a) dissolved oxygen (mg L^{-1}), (b) salinity, (c) water temperature (°C), and (d) dissolved inorganic nitrogen (mg L^{-1}) throughout the water column from 2016-2022, as a function of season (color bar). Simple linear regression line is black; 1-1 line is grey.



Modeled salinity (a-d) and dissolved oxygen (e-h) averaged over May 1 – October 1 during an average discharge year (2016; a, c, e, g), and an above average discharge year (2019; b, d, f, h) with observational data overlayed (circles outlined in white). Panels on left (a-b, e-f) show the water column along a mainstem transect (see Figure 1 for station locations). Panels on the right (c-d, g-h) show near bottom values.