Impacts and uncertainties of climate-induced changes in watershed inputs on estuarine hypoxia

Kyle Hinson, Marjy Friedrichs, Ray Najjar, Maria Herrmann, Zihao Bian, Gopal Bhatt, Pierre St-Laurent, Hanqin Tian, Gary Shenk

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VIMS BioCOM Lab

Marjy Friedrichs

Pierre St-Laurent

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- VIMS Academic Studies Office

Coauthors and Collaborators

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- Auburn University: Hanqin Tian, Yuanzhi Yao, & Zihao Bian
- USEPA Chesapeake Bay Program: Gary Shenk, Gopal Bhatt, & Lewis Linker

Motivation and Overview

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EGU

Research article

Impacts and uncertainties of climate-induced changes in watershed inputs on estuarine hypoxia

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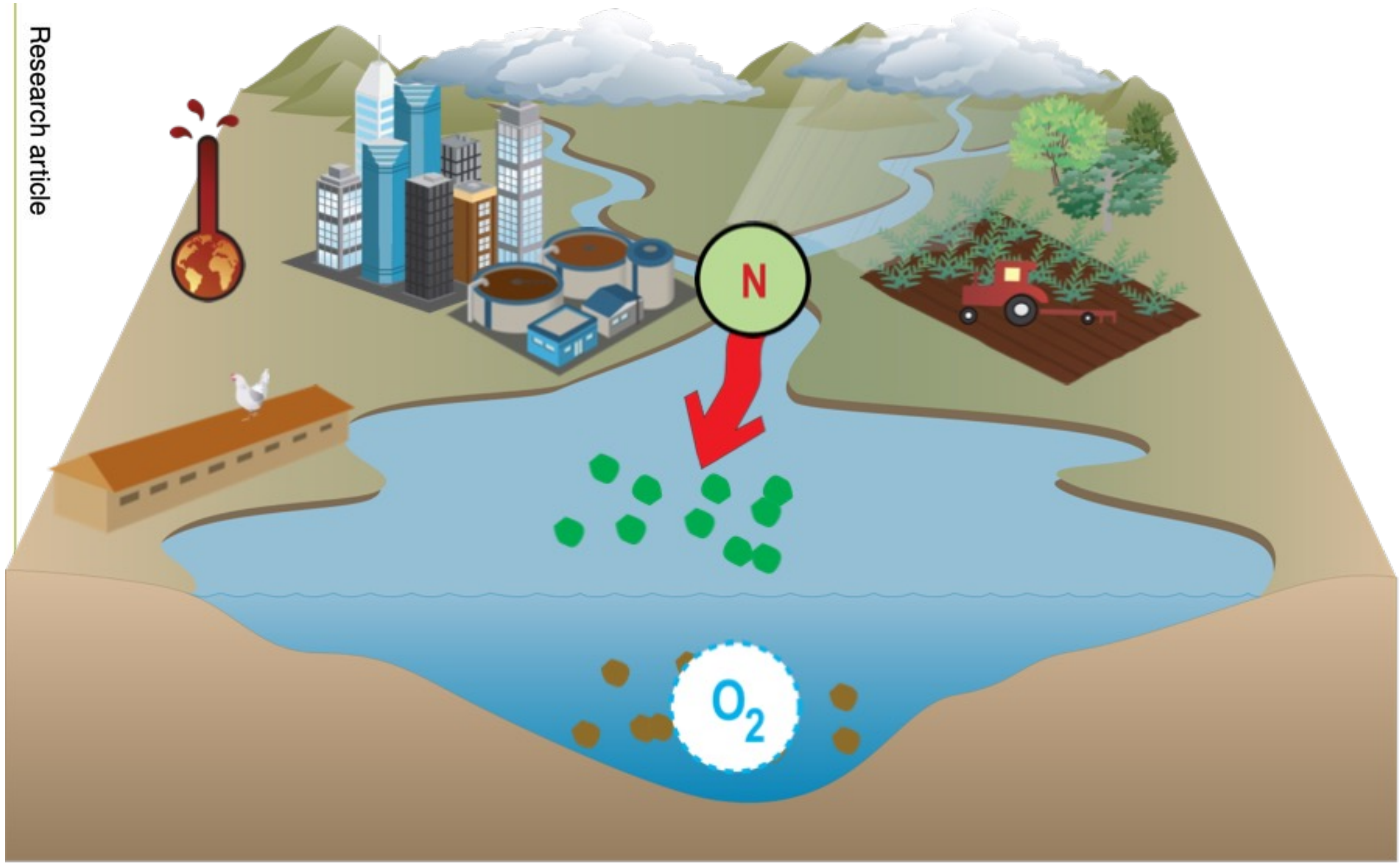
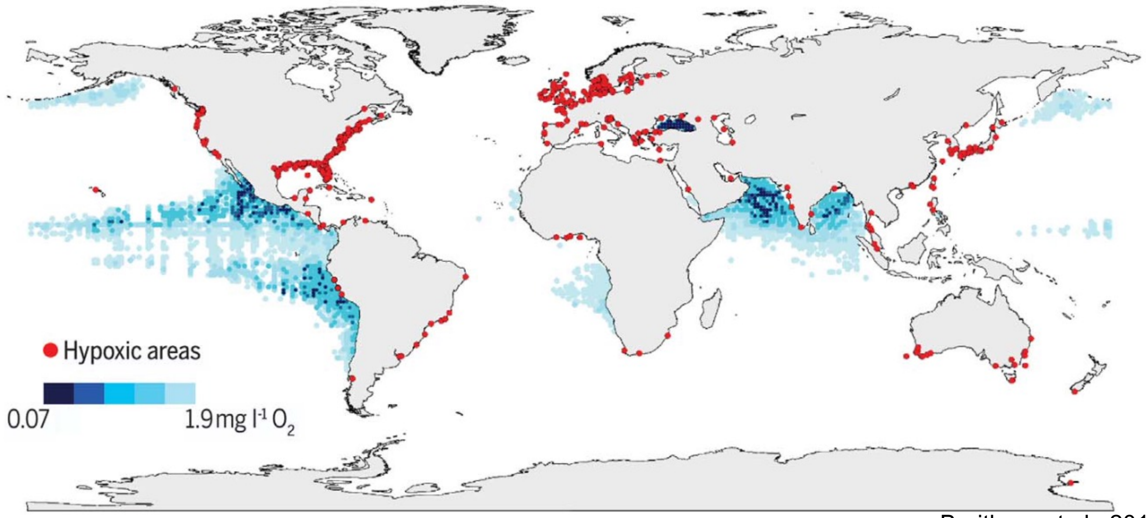
[Article Link]



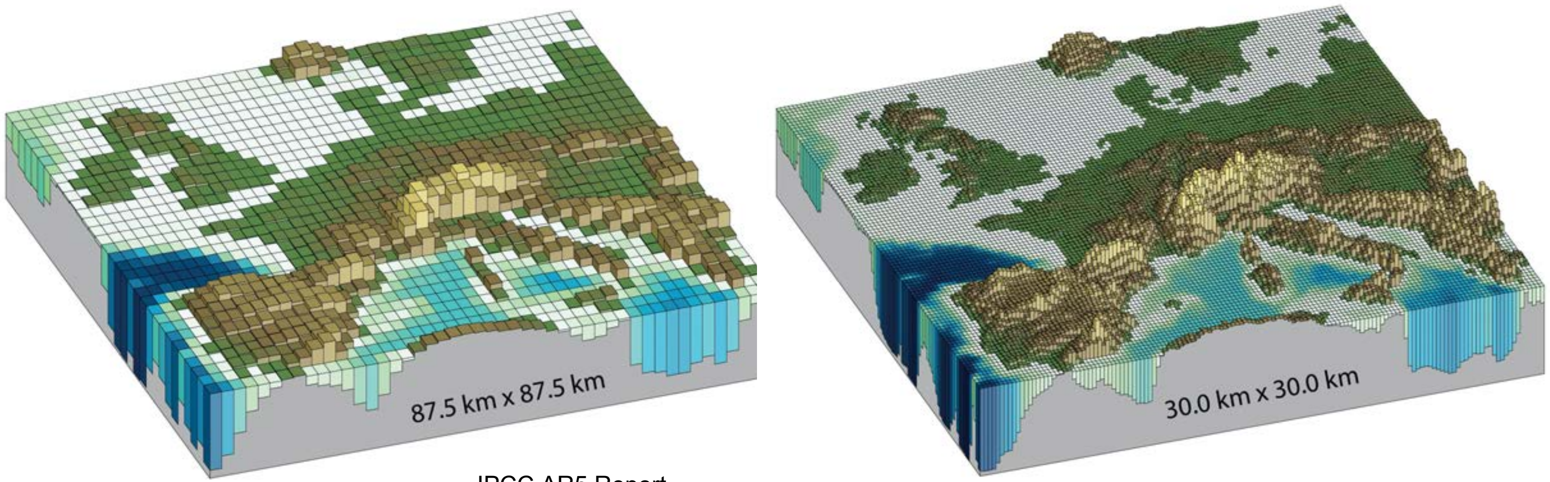
How confident are we in future projections of hypoxia based on watershed changes?

Coastal Ecosystems, Climate, and Hypoxia

- Documented impacts of climate on hypoxia are global and expanding
- Projecting future climate impacts in coastal regions is infeasible with Earth System Models (ESMs)



Breitburg et al., 2018



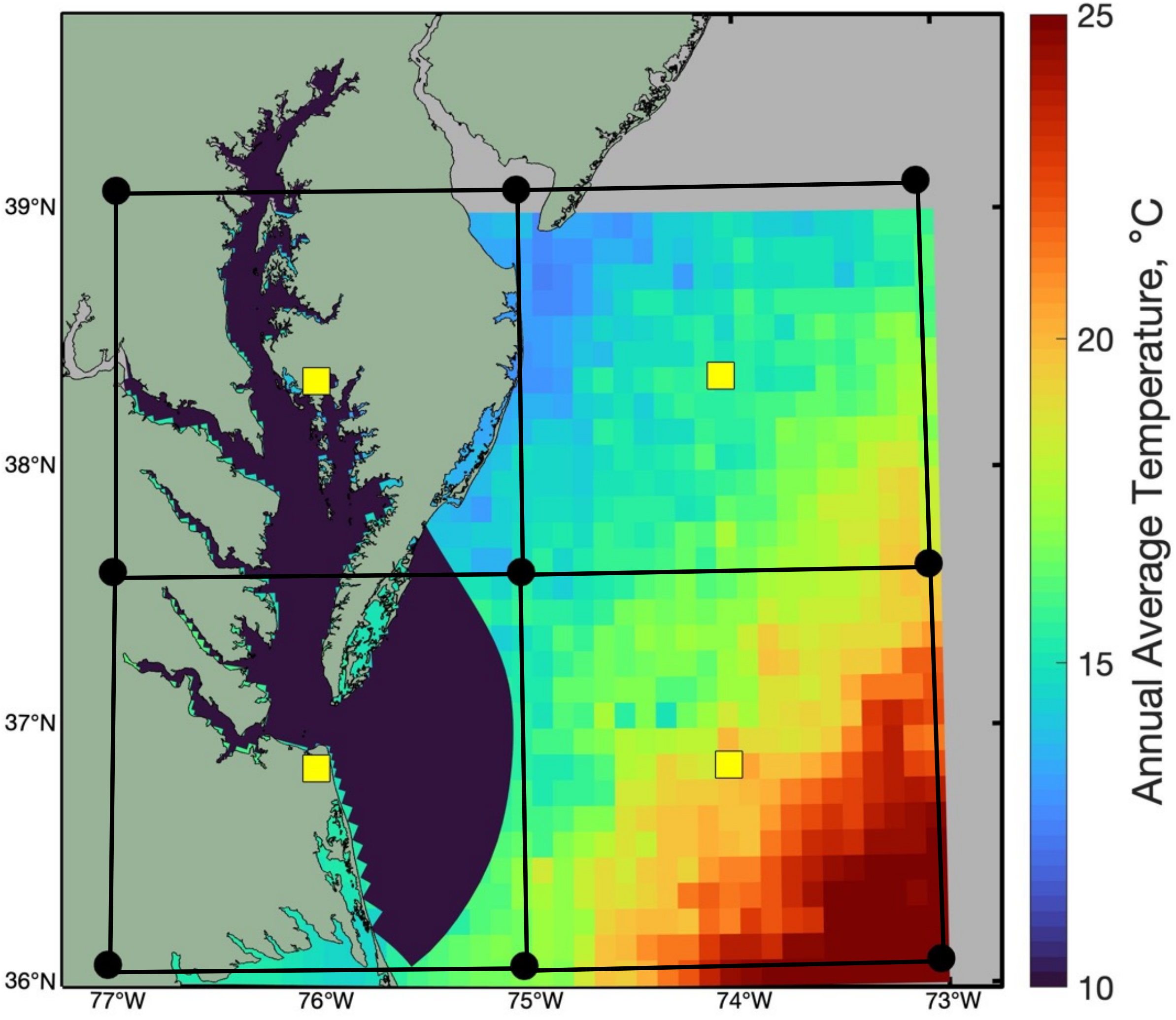
IPCC AR5 Report

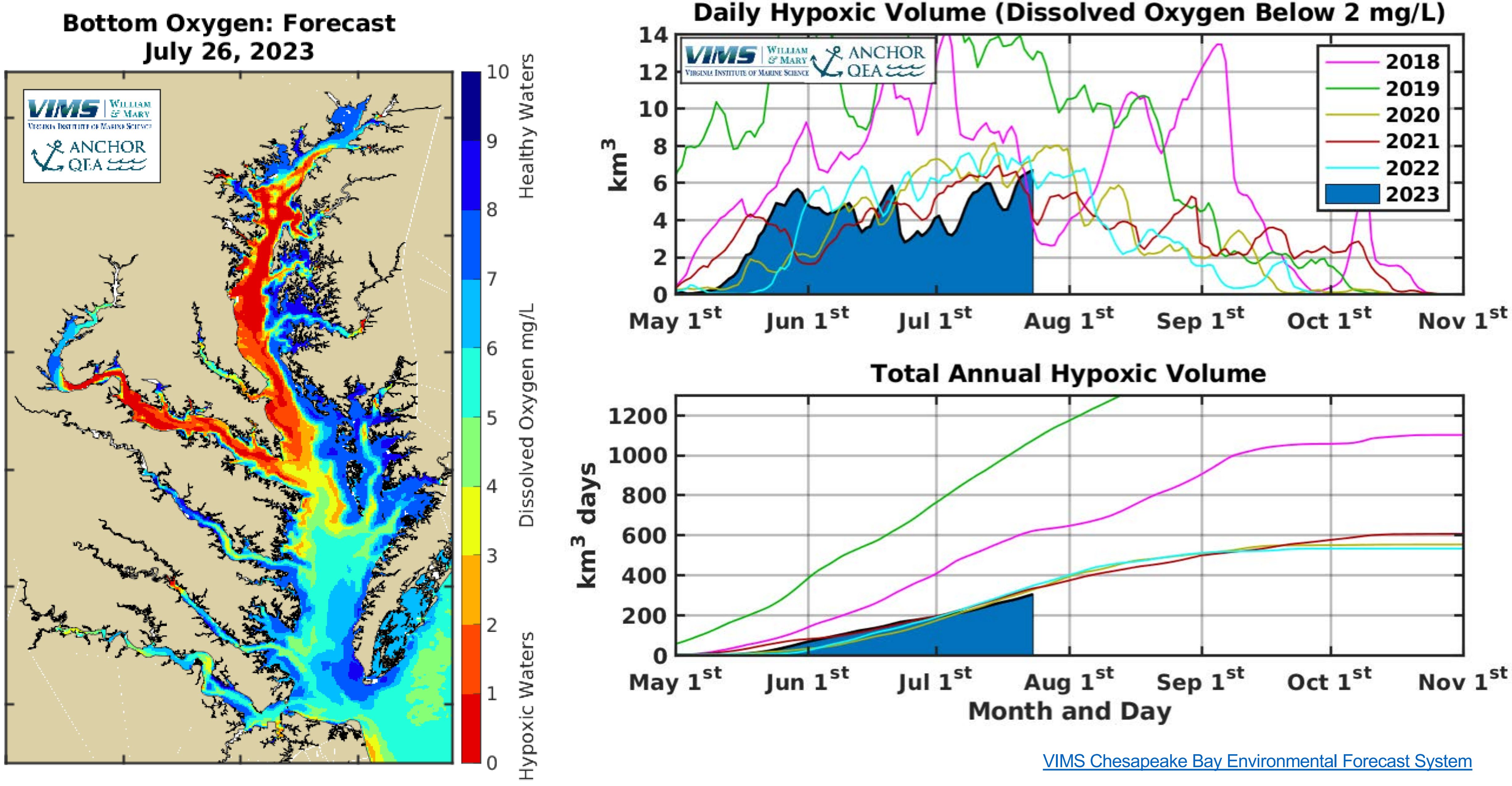
Coastal Ecosystems, Climate, and Hypoxia

- Documented impacts of climate on hypoxia are global and expanding

- Projecting future climate impacts in coastal regions is infeasible with Earth System Models (ESMs)

- *Bay-wide analyses require finer spatial resolutions*





[VIMS Chesapeake Bay Environmental Forecast System]

ChesROMS-ECB Overview

Atmospheric Inputs

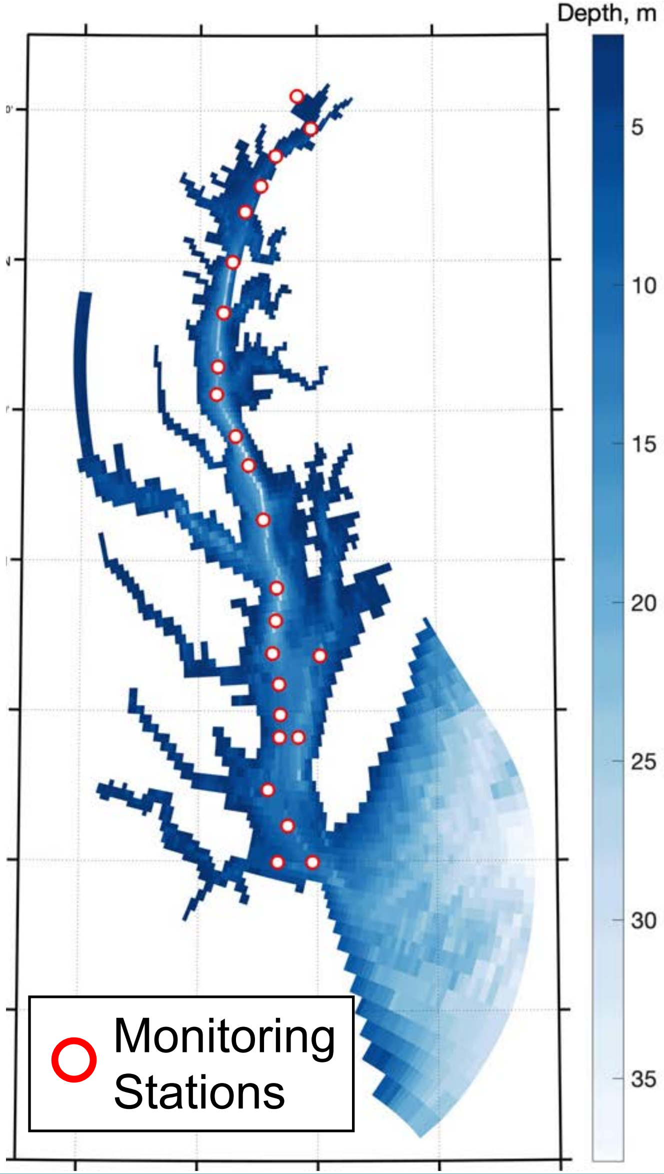
→ Hindcast weather data

Coastal Fluxes

→ Climatological data

Riverine Inputs

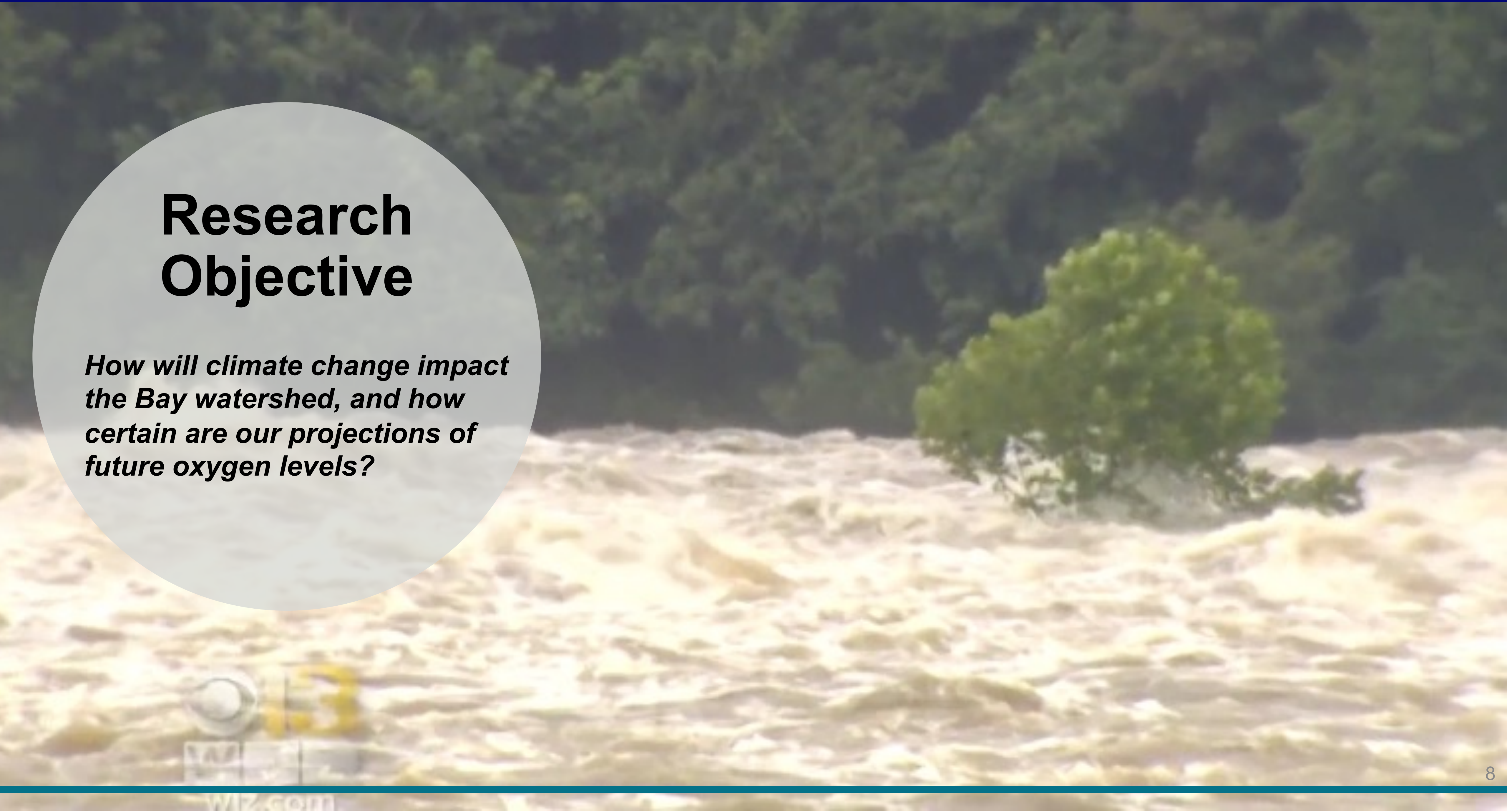
→ Watershed Model



Model Information
3-D model, 20 depth levels Daily outputs

Model Outputs

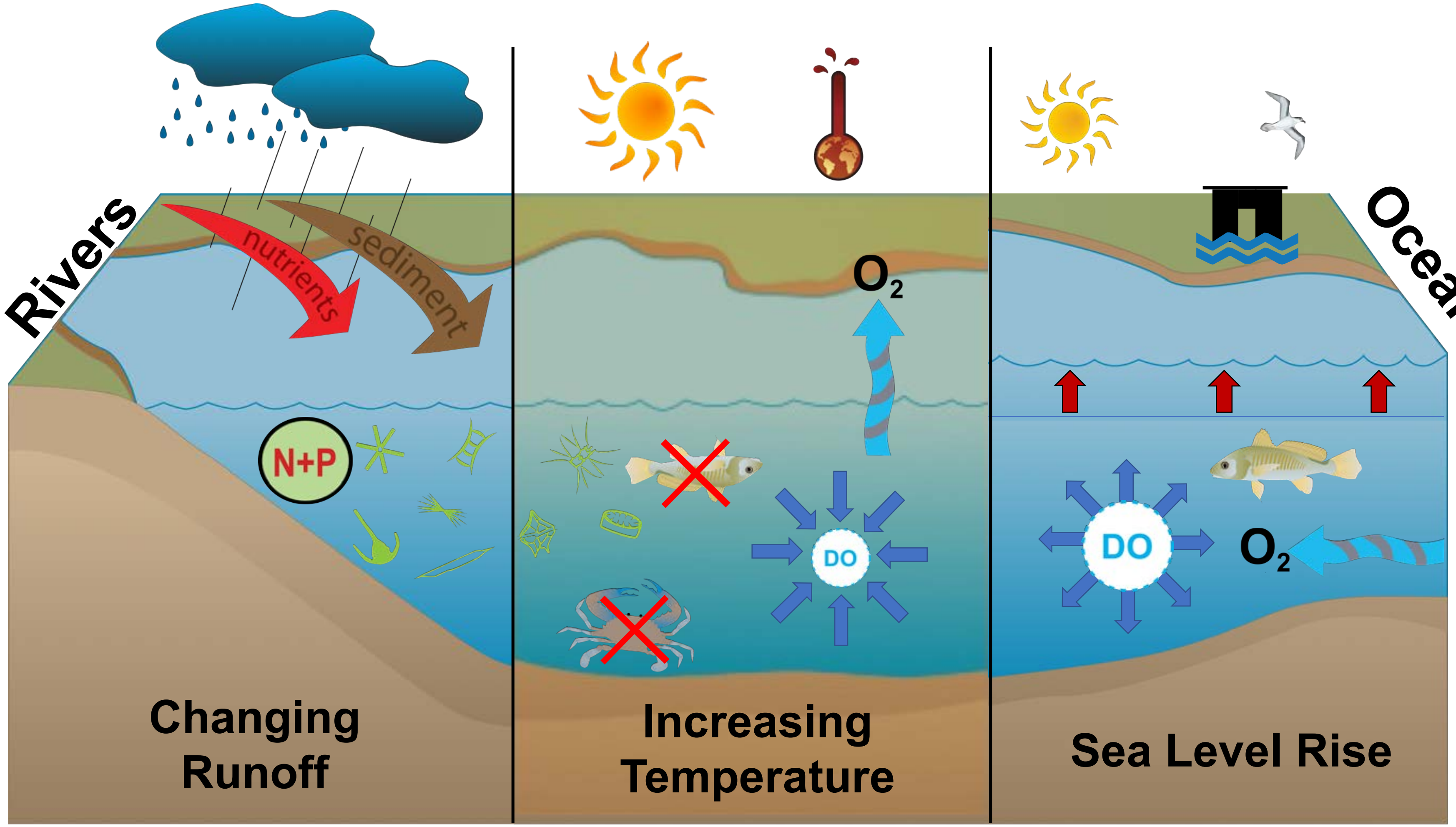
Hydrodynamics and Biogeochemistry



Research Objective

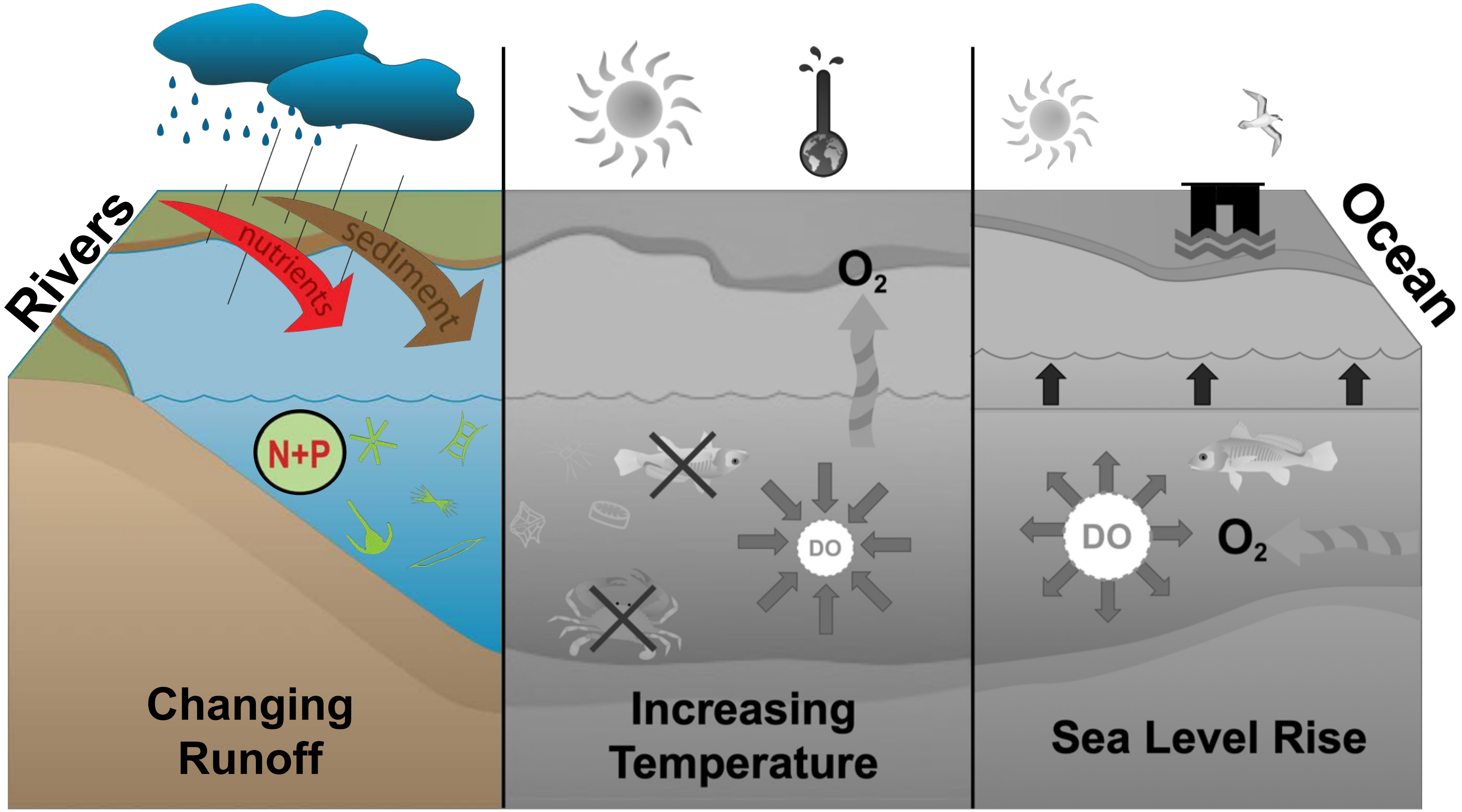
How will climate change impact the Bay watershed, and how certain are our projections of future oxygen levels?

Climate Change and Chesapeake Bay



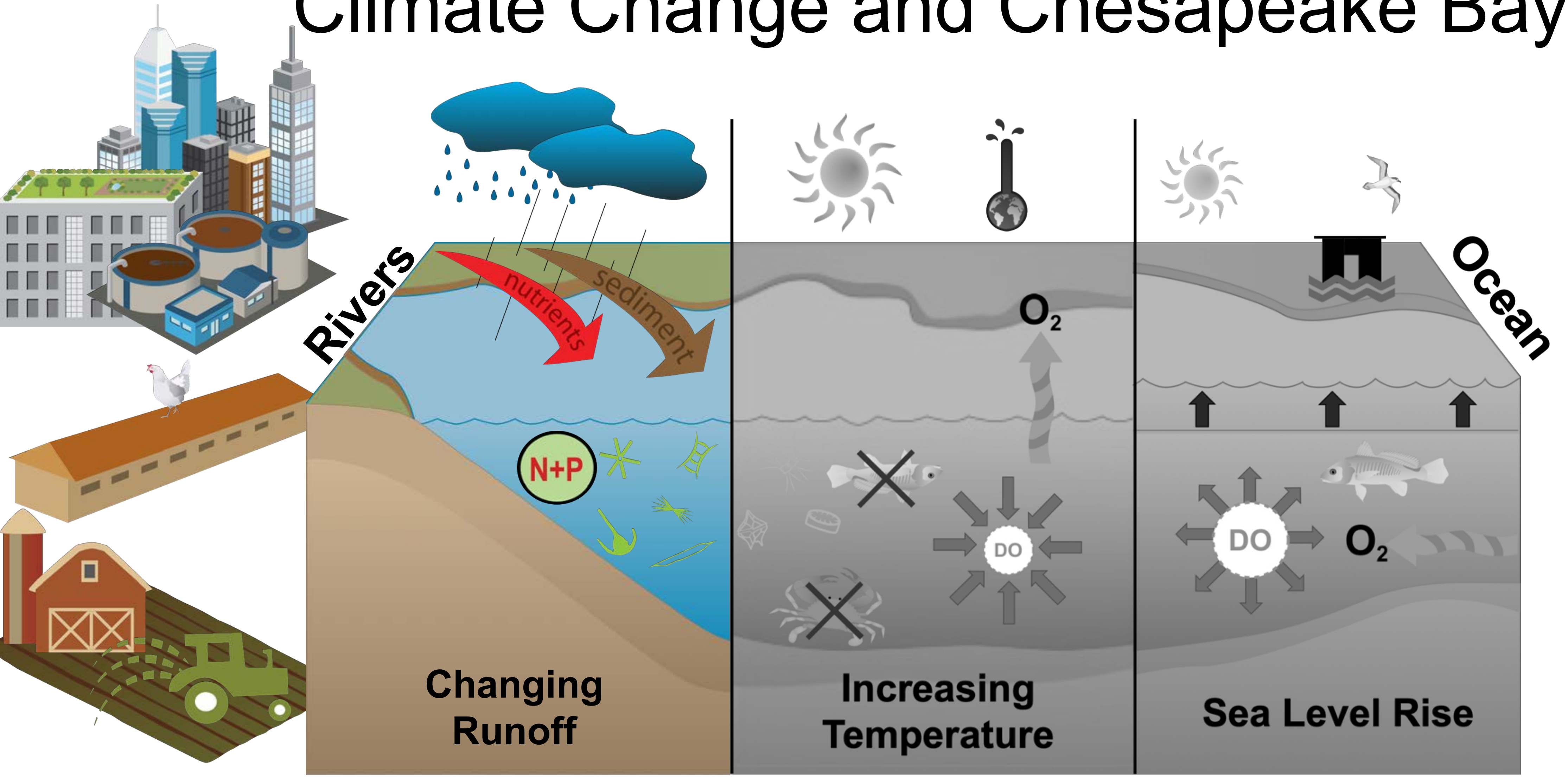
- Climate change affects Chesapeake Bay oxygen levels in multiple ways

Climate Change and Chesapeake Bay

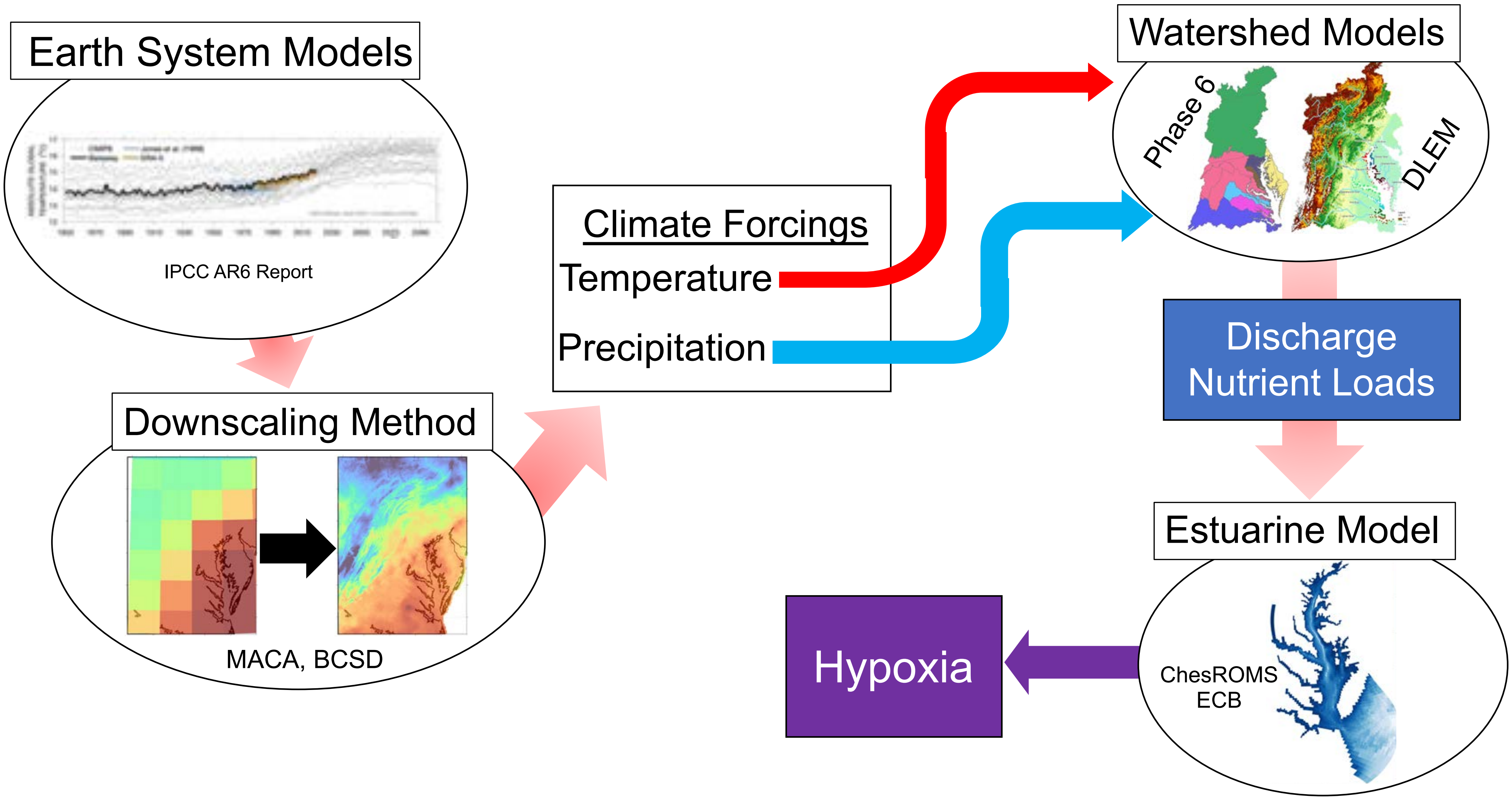


- Climate change impacts on terrestrial runoff are focus of this presentation

Climate Change and Chesapeake Bay

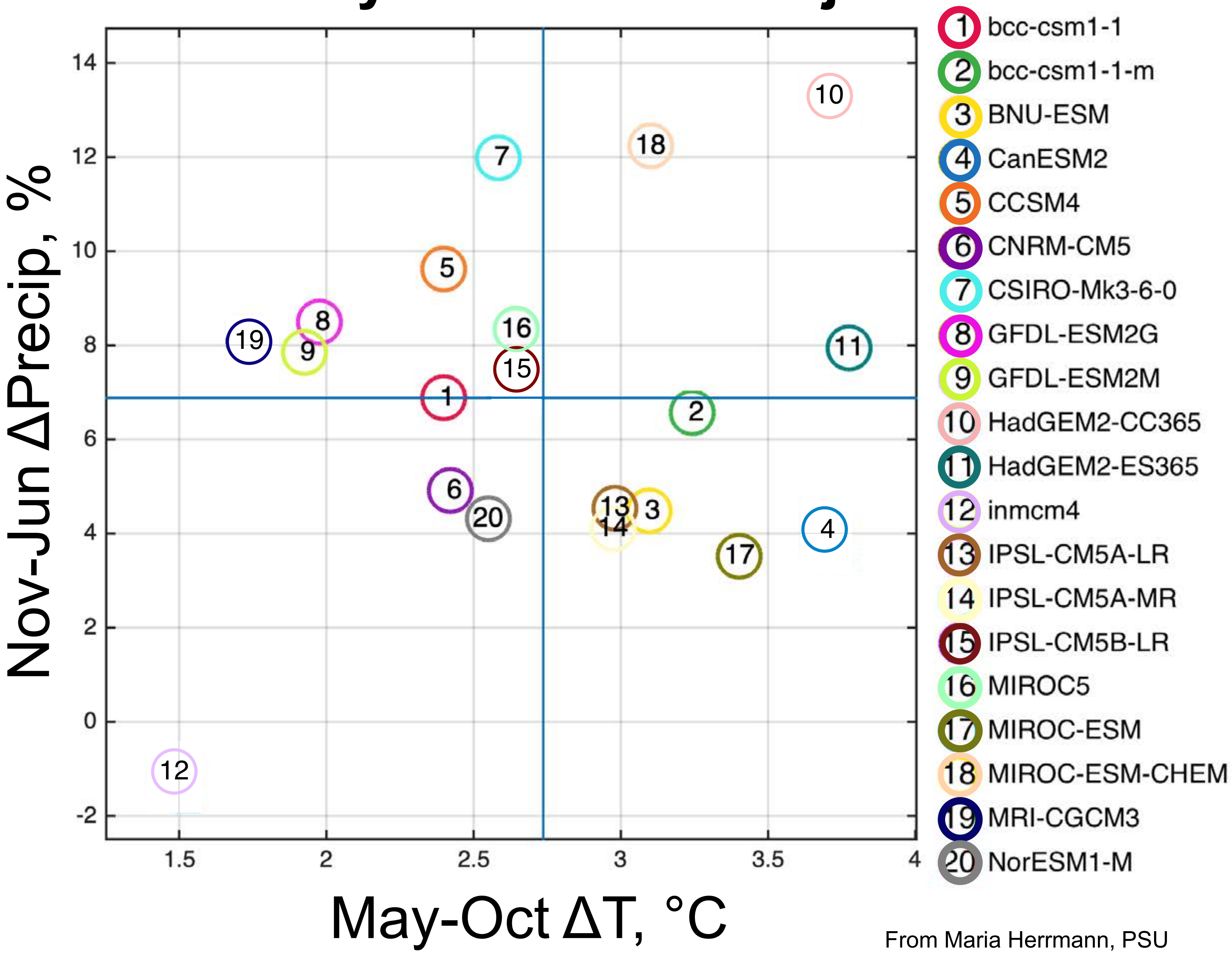


- Environmental managers can have greatest impacts on watershed actions



Numerous sources of uncertainty are implicitly built into climate projections.

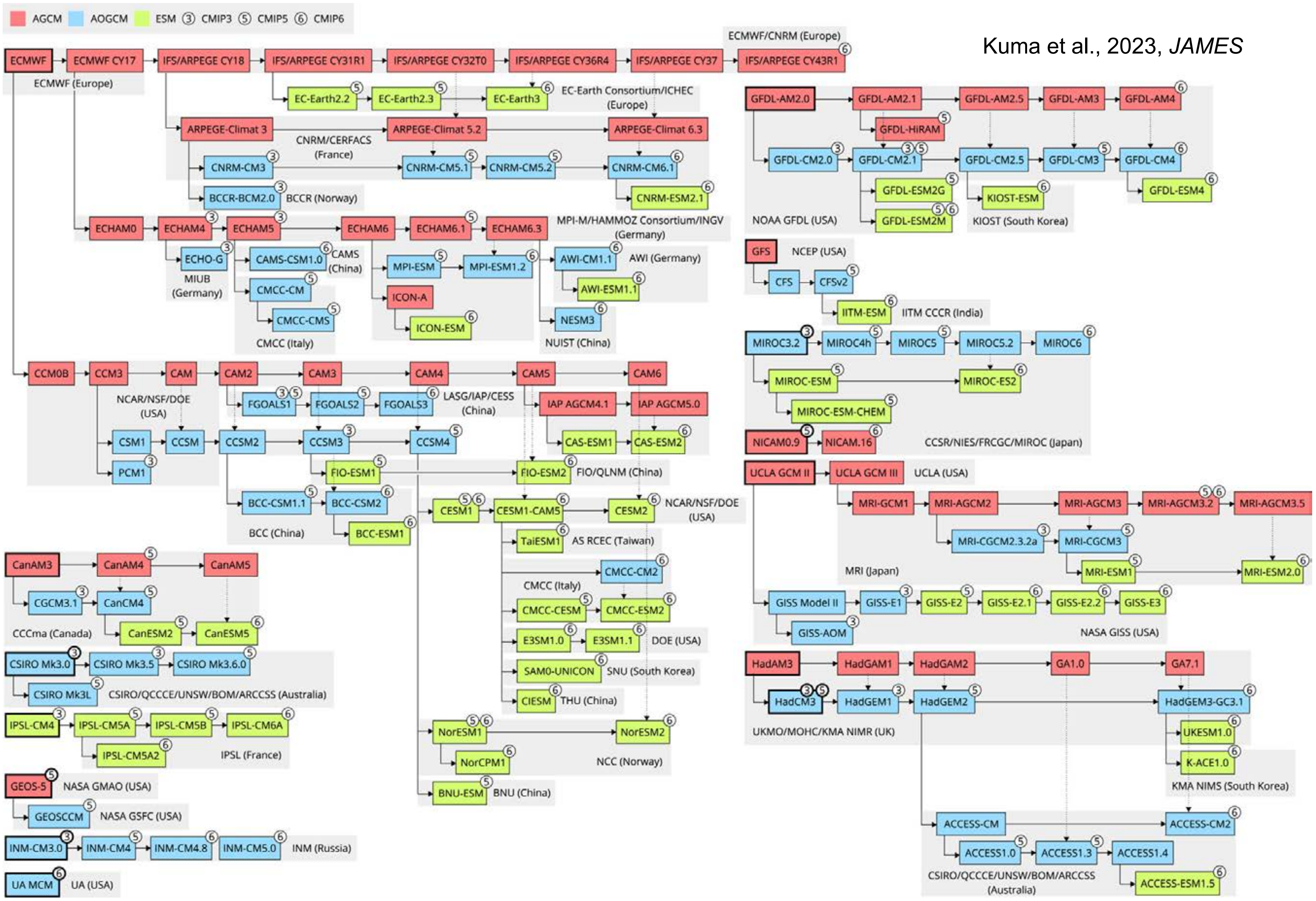
2050 Earth System Model Projections



From Maria Herrmann, PSU

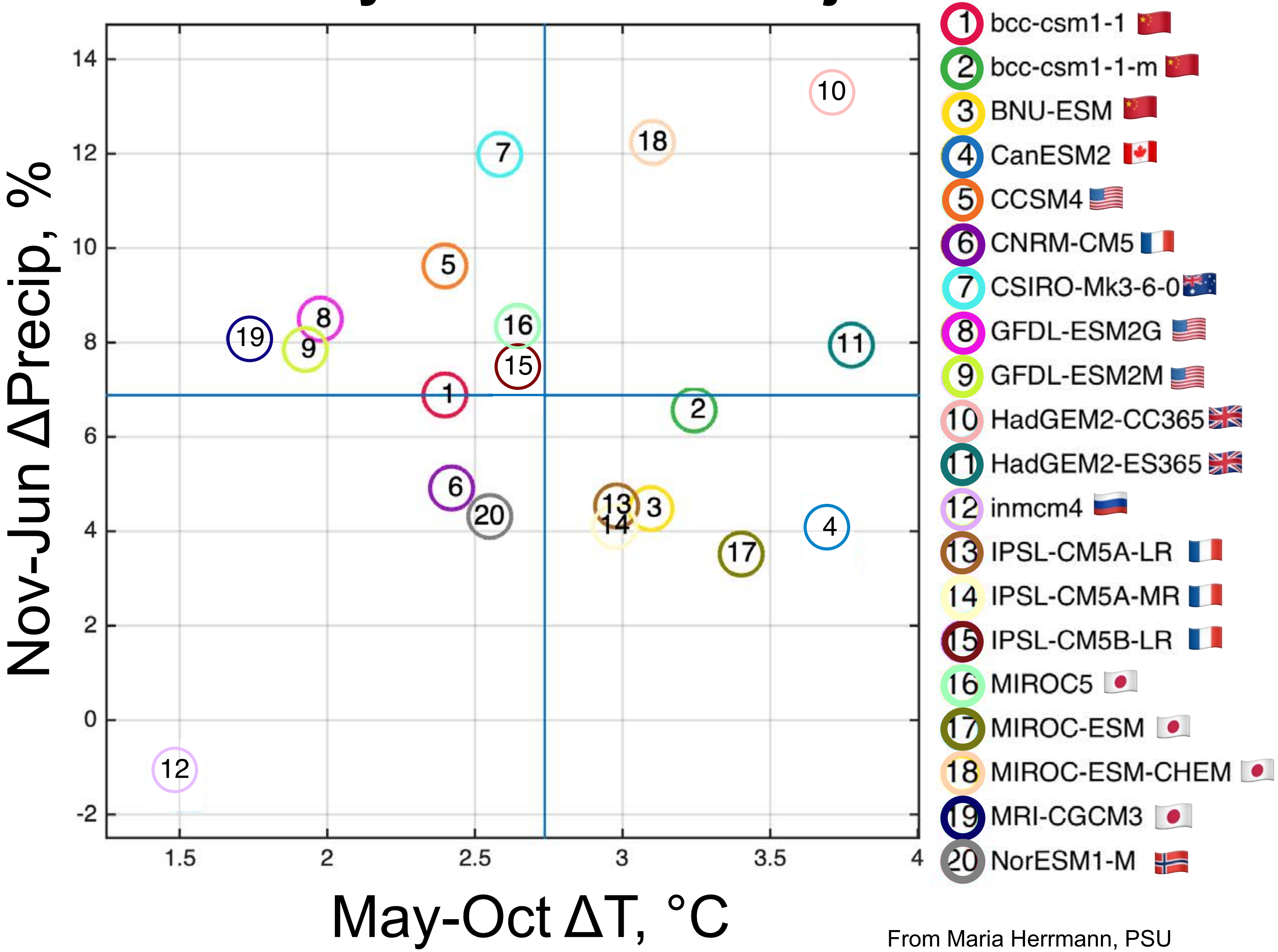
Selecting ESMs

- Development of ESMs has been a long, overlapping, and convoluted process
- Overlapping climate model code genealogies means that samples may be less than independent



Kuma et al., 2023, *JAMES*

2050 Earth System Model Projections



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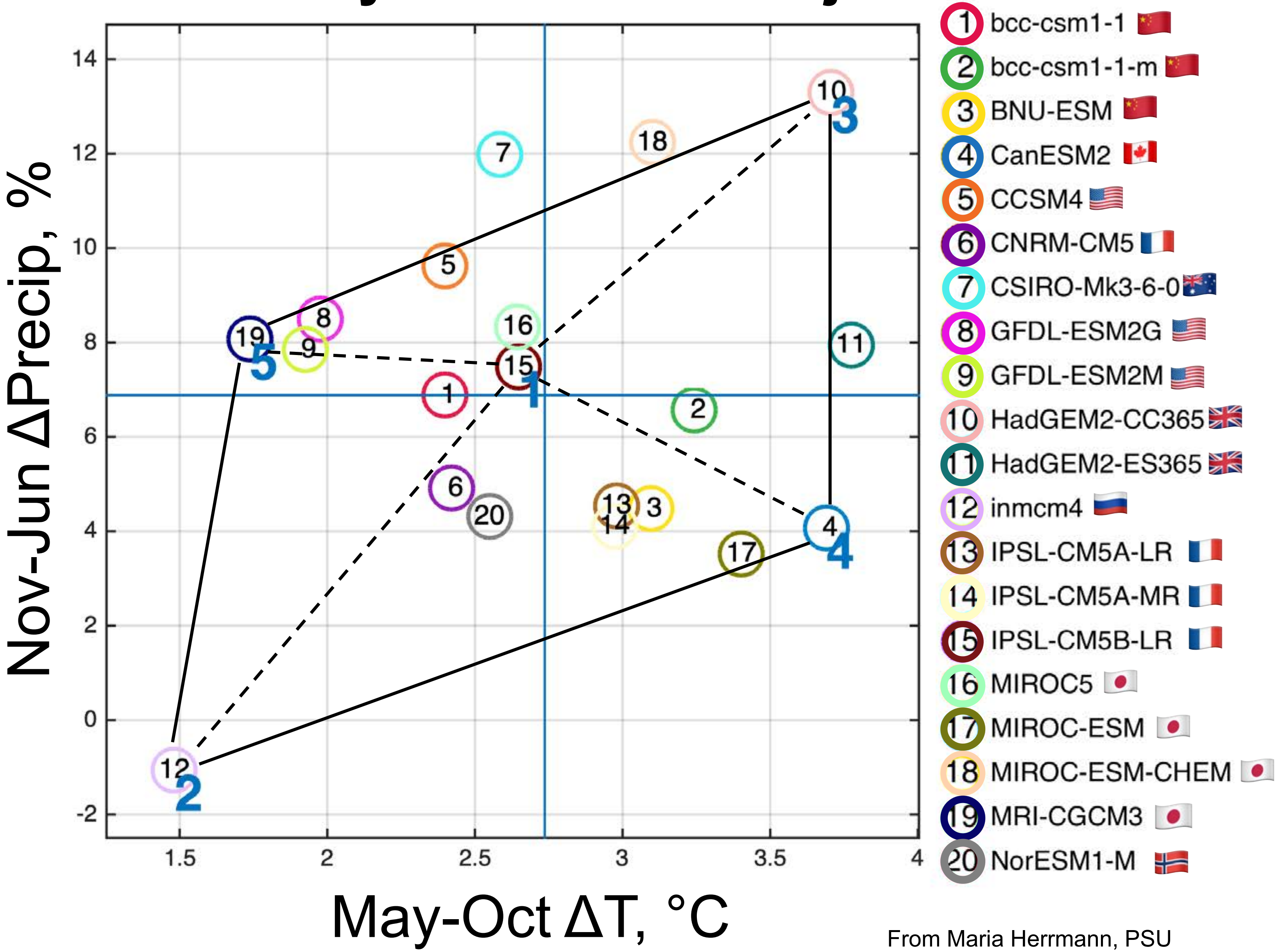

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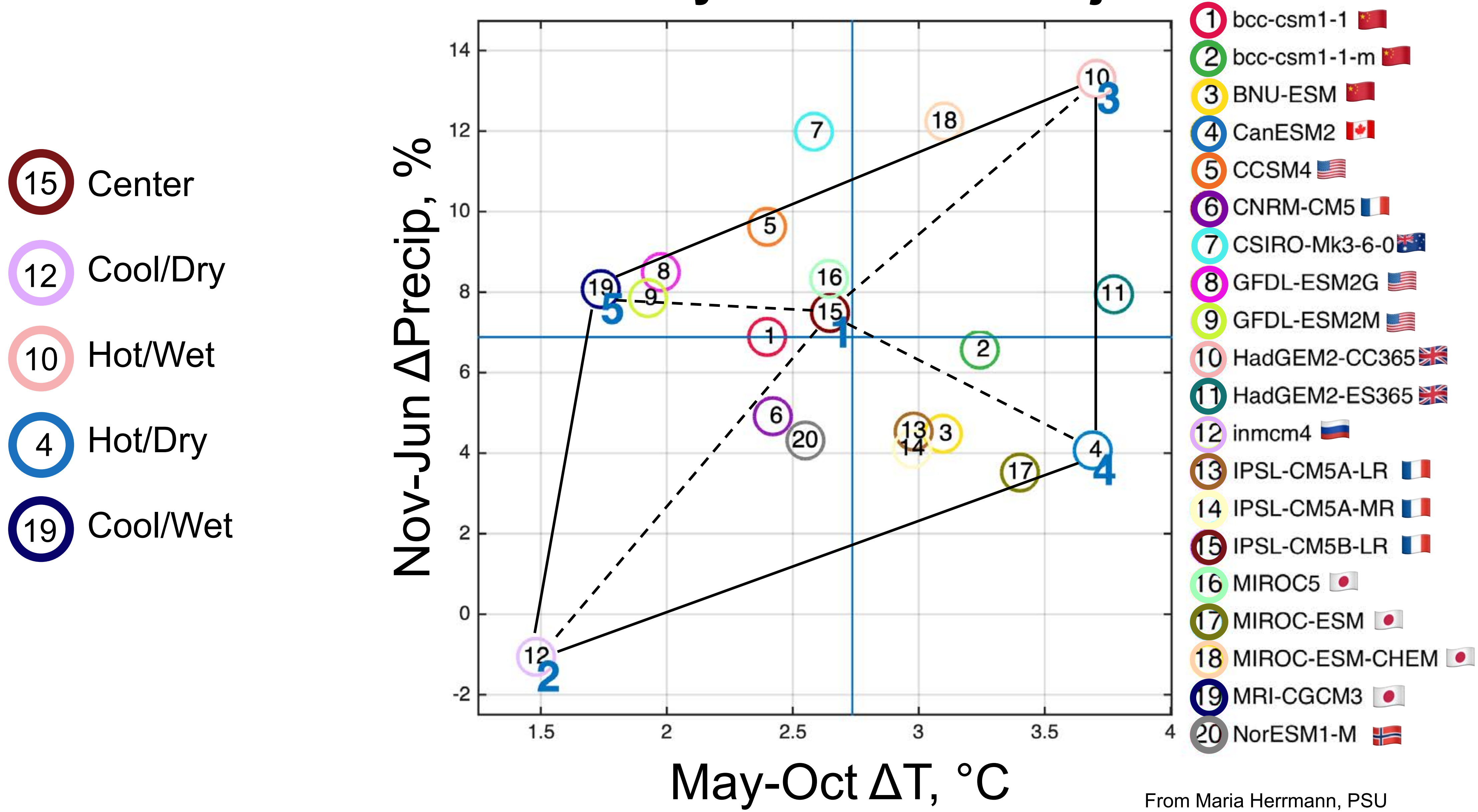

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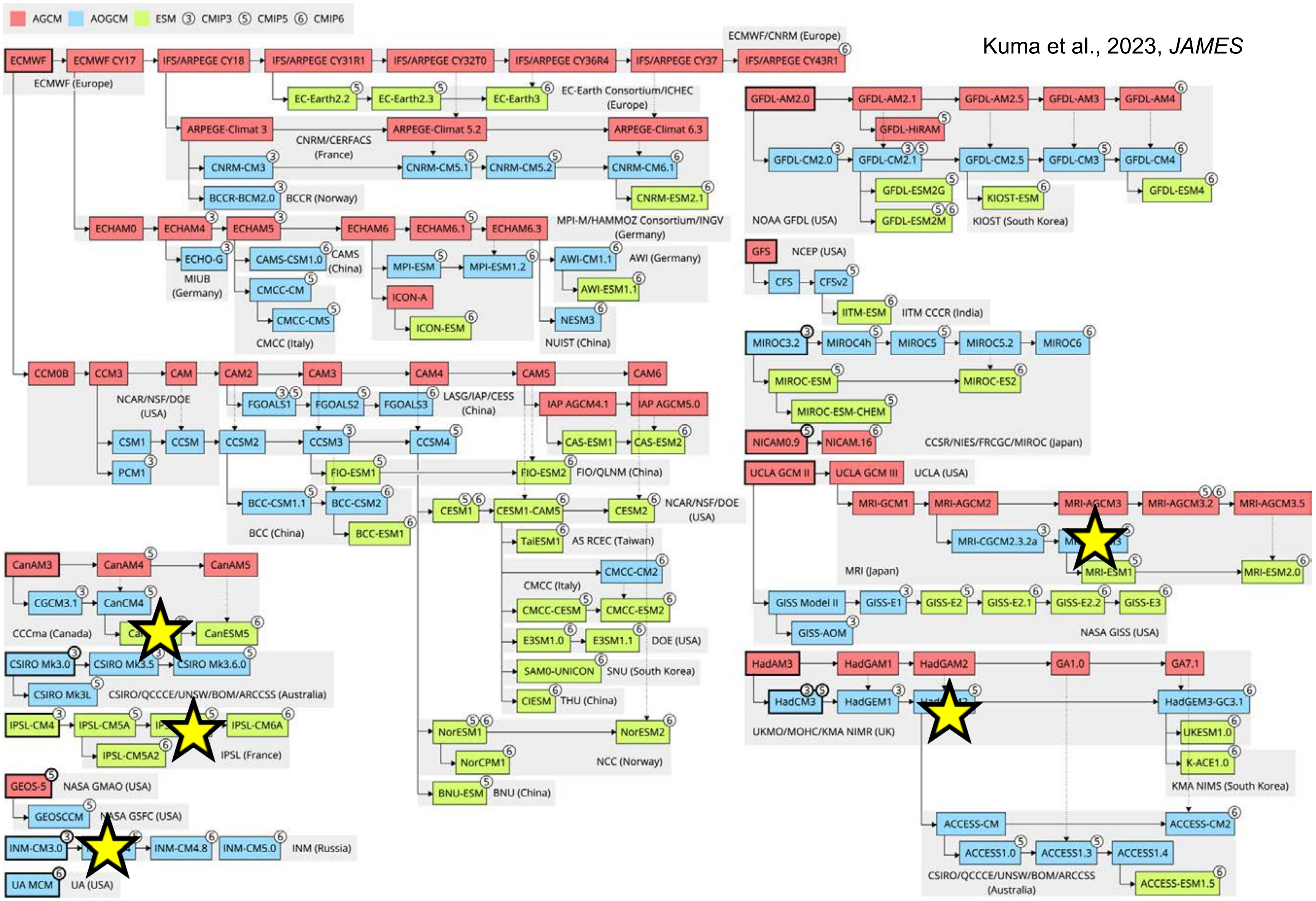
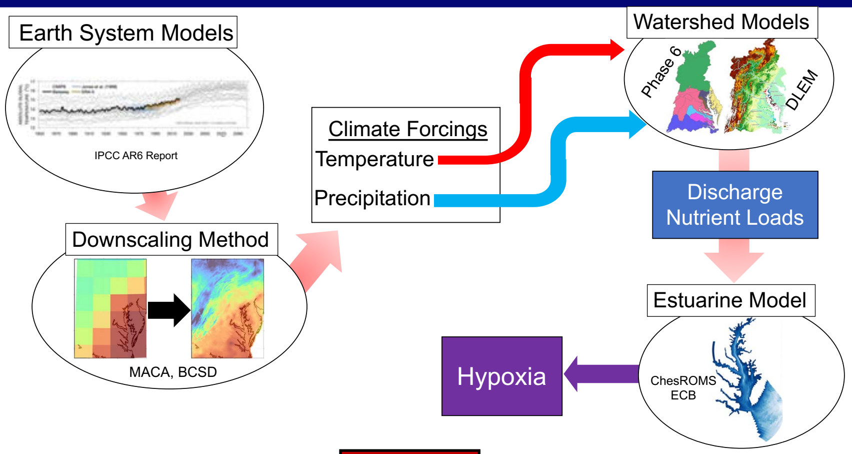
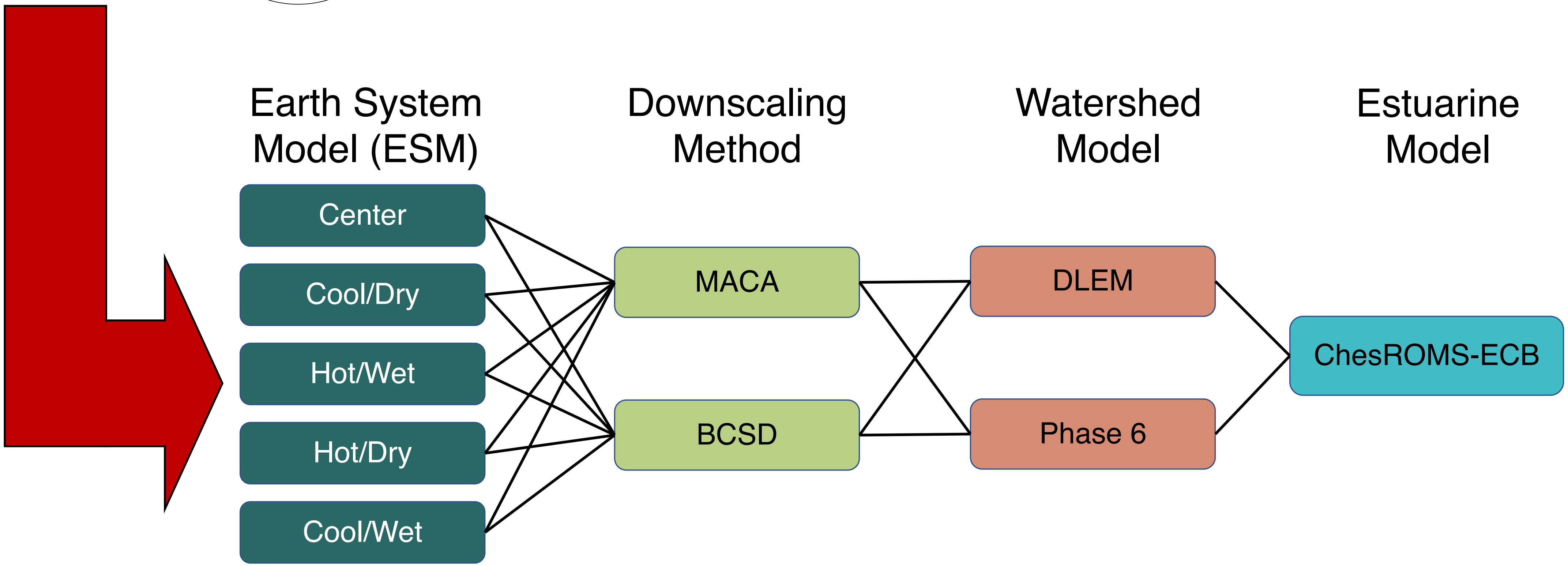


Kuma et al., 2023, *JAMES*



Multiple uncertainties can be addressed using a factorial design for model experiments



Climate Forcing – Delta Method

Earth System Models

1981-2010

2036 - 2065

Climate Forcing – Delta Method

Earth System Models

1981-2010

2036 - 2065

Watershed Models

1991-2000

Estuarine Model

Base Run
1991-2000

Climate Forcing – Delta Method

Earth System Models

1981-2010

2036 - 2065

Future minus Past = Δ Climate

Watershed Models

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Estuarine Model

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1991-2000

Climate Forcing – Delta Method

Earth System Models

1981-2010 | 2036 - 2065

Future minus **Past** = **Δ Climate**

Watershed Models

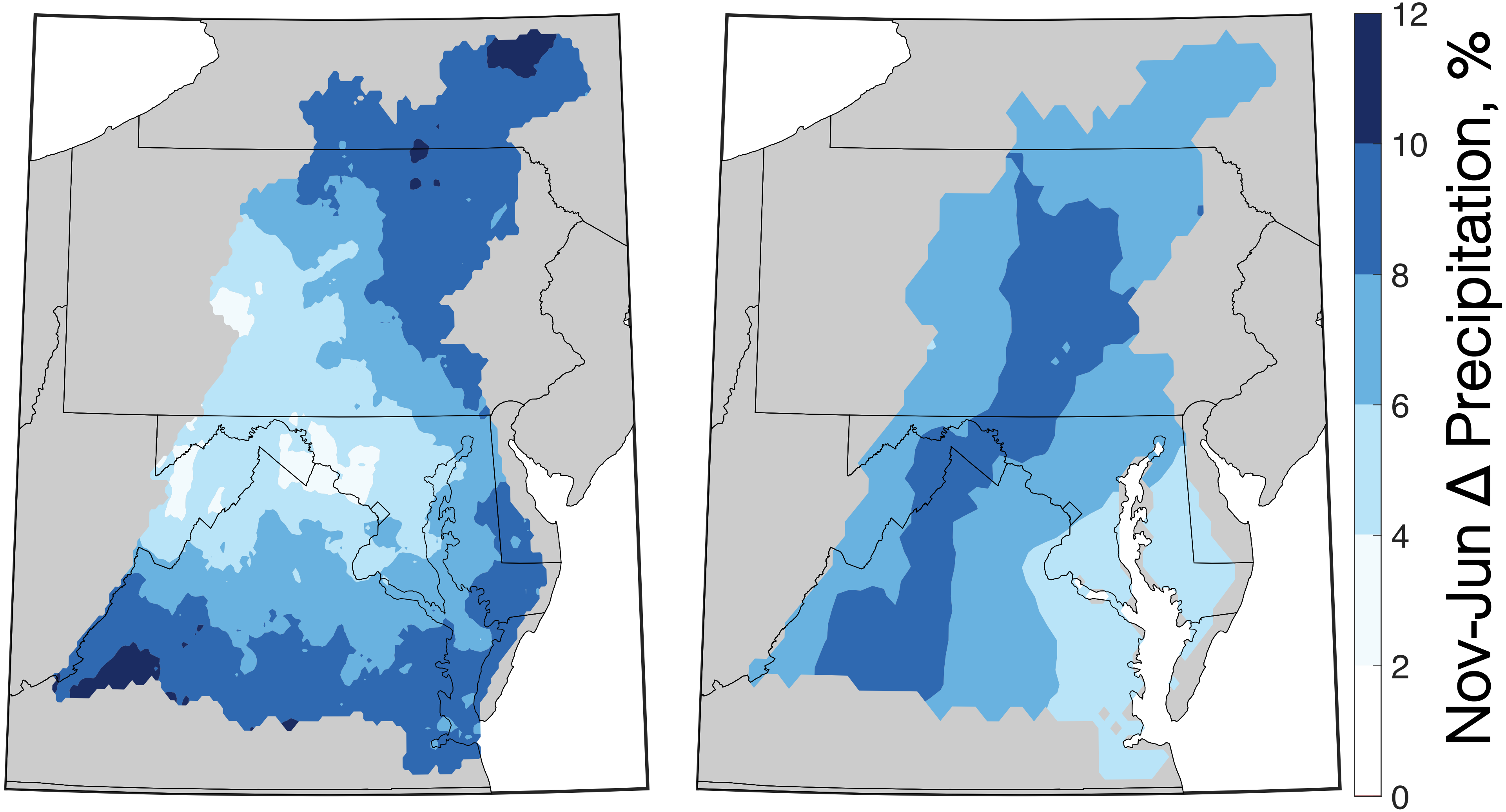
1991-2000 | 1991-2000

Estuarine Model

Base Run
1991-2000

Climate Scenario
2046-2055

MACA Center ESM — BCSD Center ESM



- High spatial heterogeneity in downscaled estimates of watershed precipitation change
- Both increase precip. by ~7-8%, but spatial differences can affect discharge/loadings

ChesROMS-ECB Overview

Atmospheric Inputs

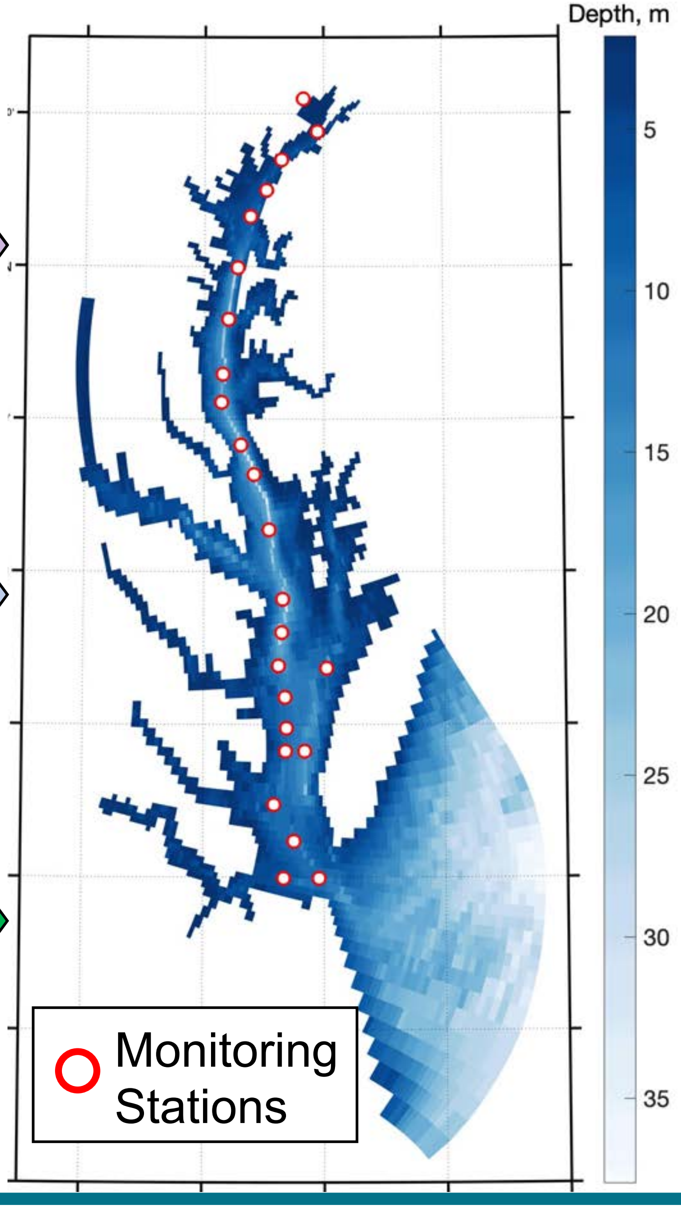
→ Hindcast weather data

Coastal Fluxes

→ Climatological data

Riverine Inputs

→ Phase 6 Watershed Model
→ DLEM Watershed Model



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3-D model, 20 depth levels
Daily outputs
Past and Future Scenarios

Model Outputs

Hydrodynamics and Biogeochemistry

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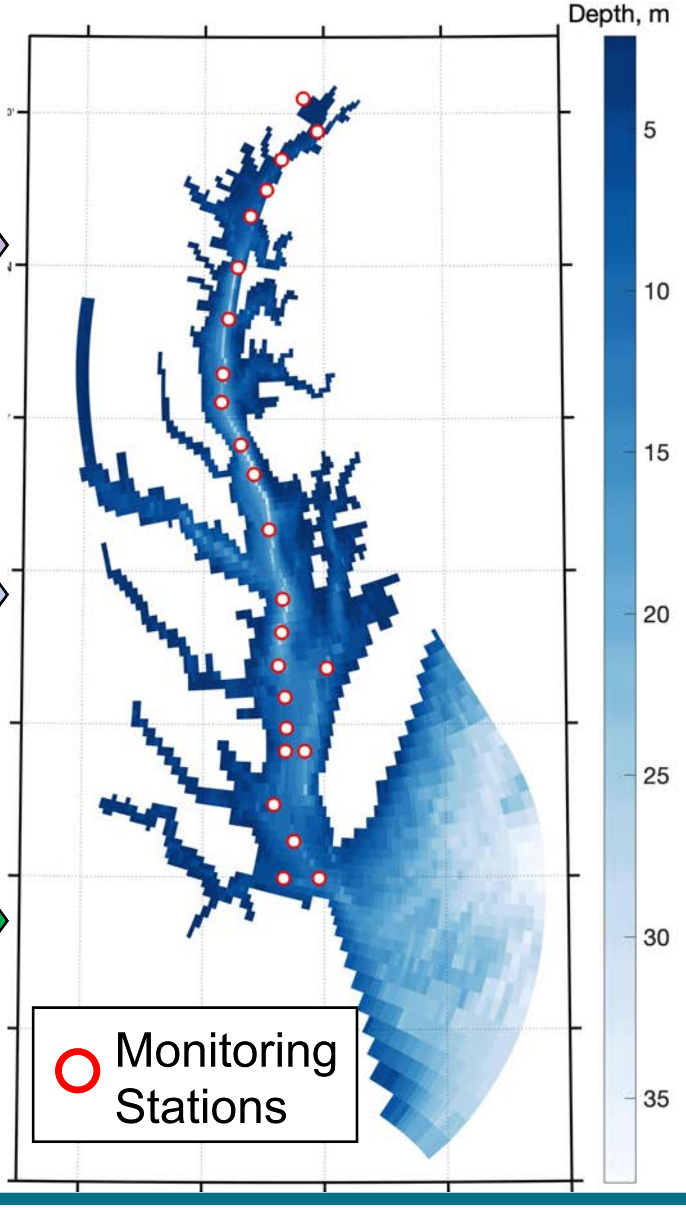

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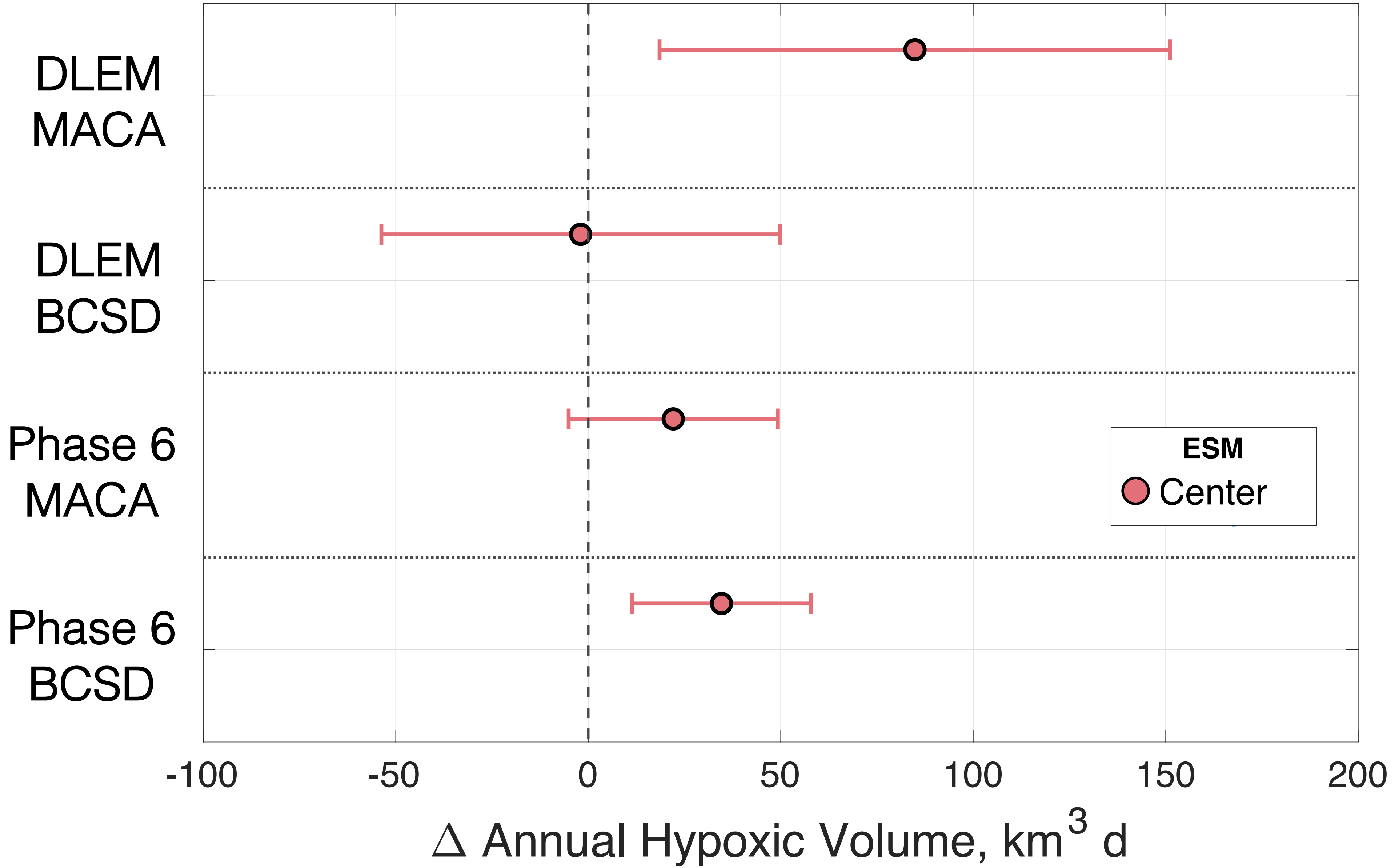
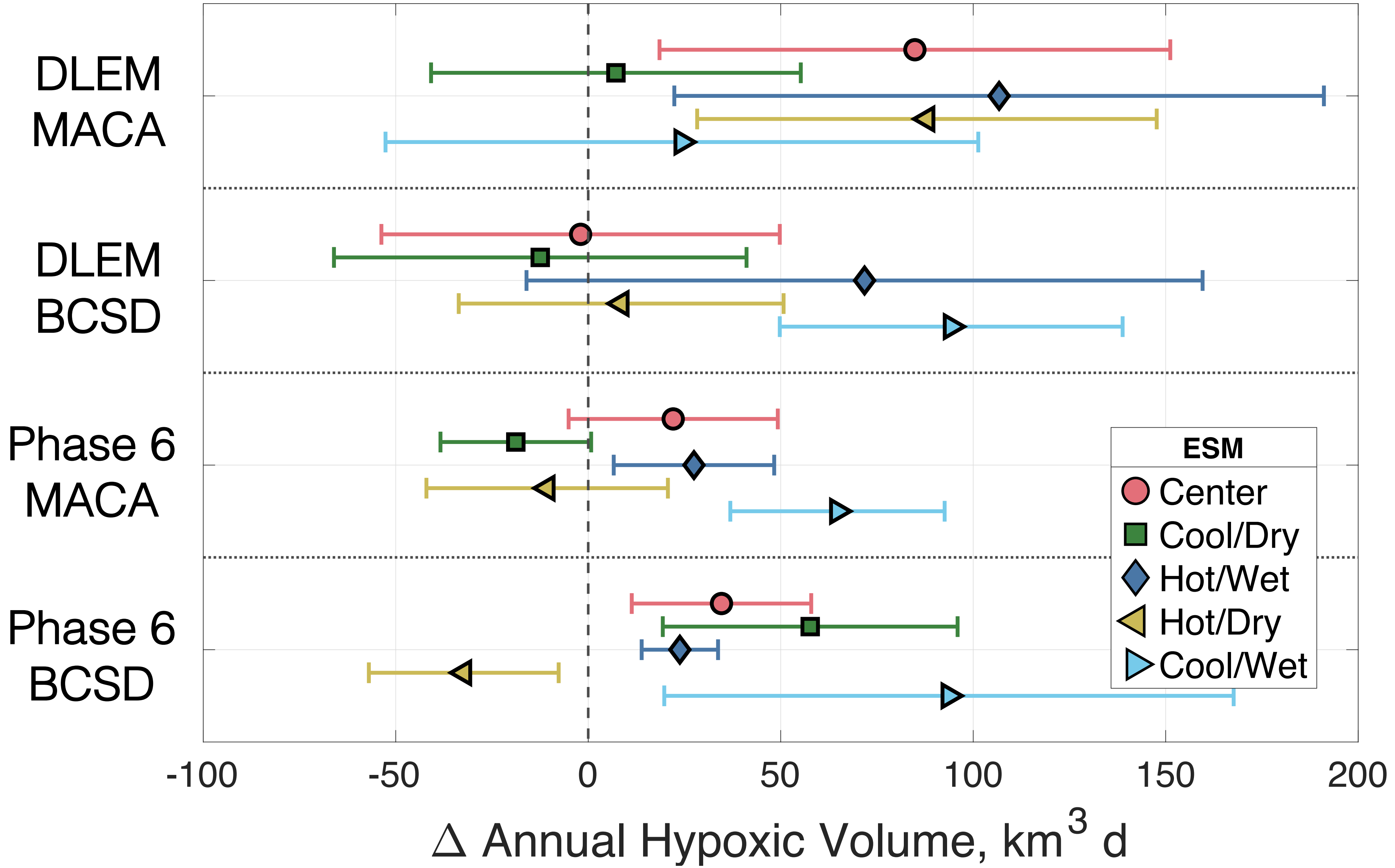
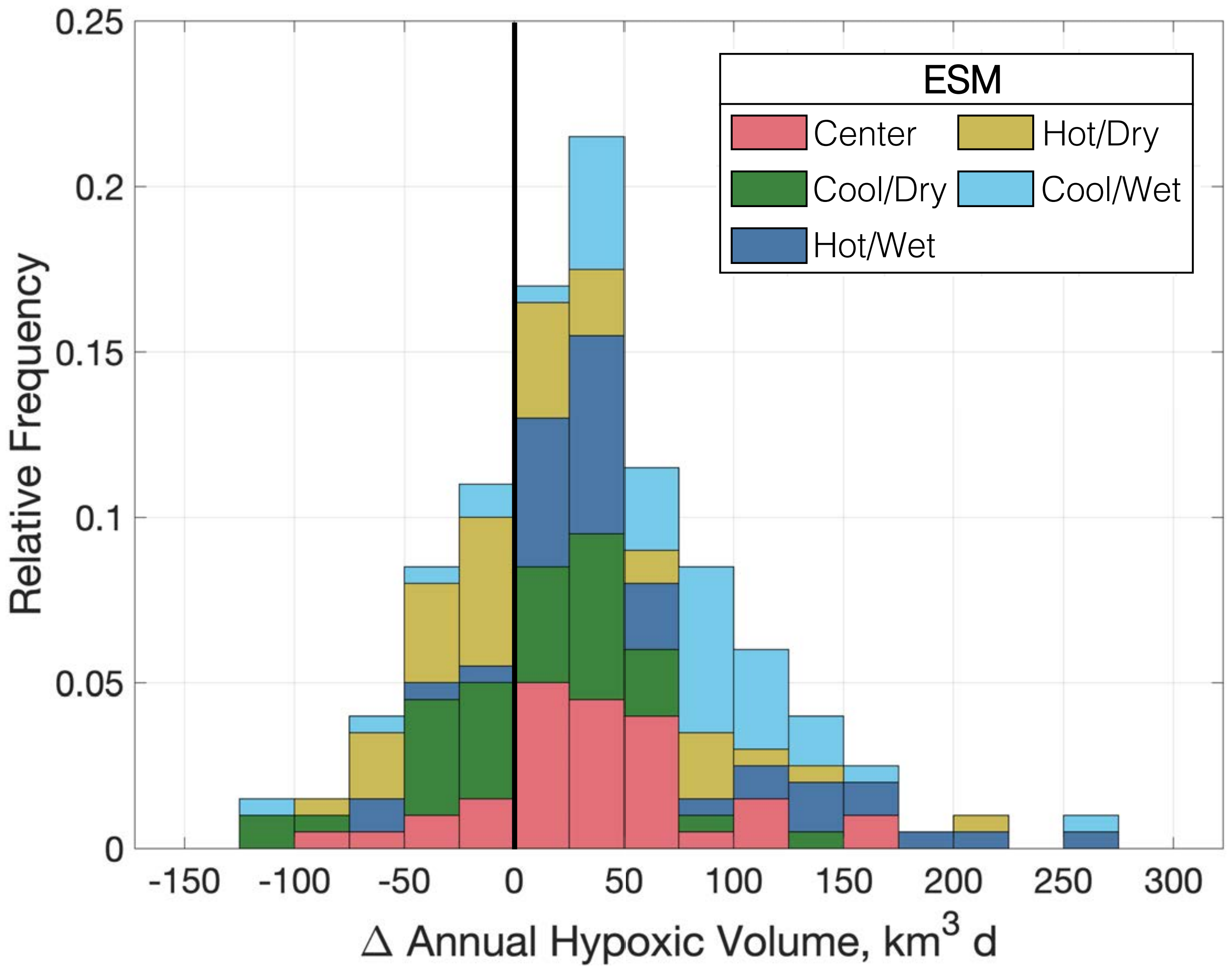


- Moderate interannual variability, DLEM slightly more than Phase 6

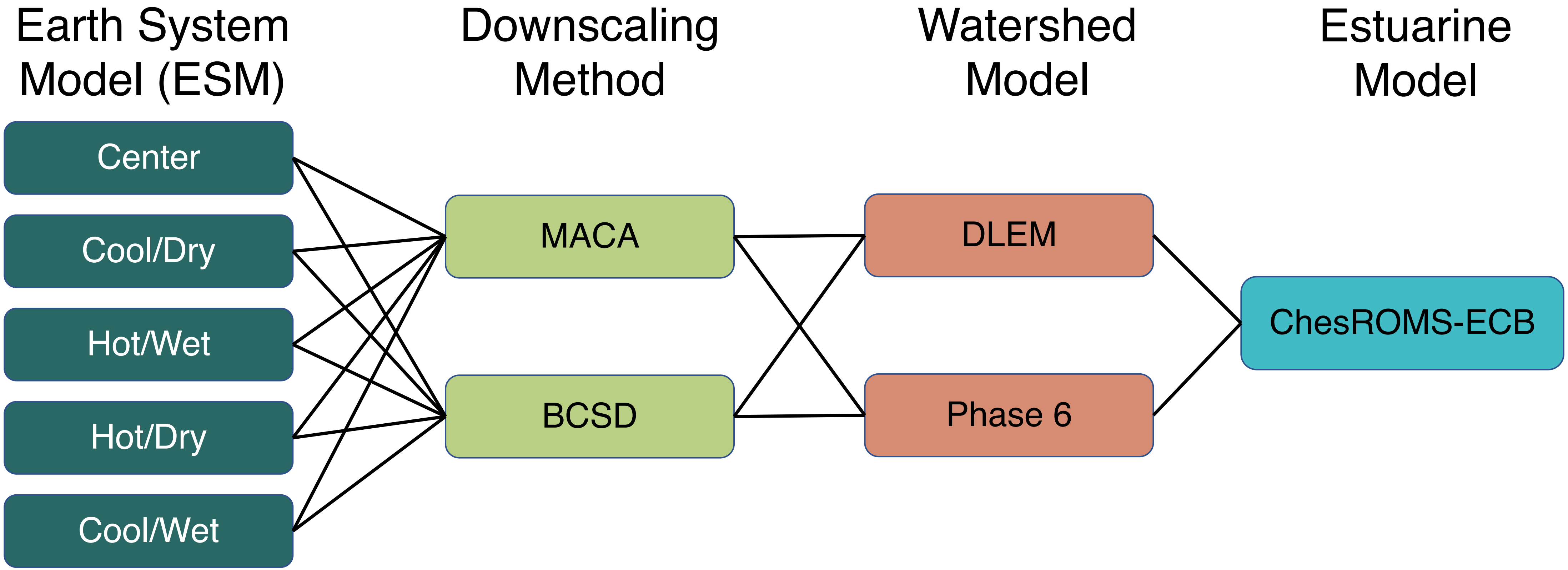


- Moderate interannual variability, DLEM produces more hypoxia than Phase 6



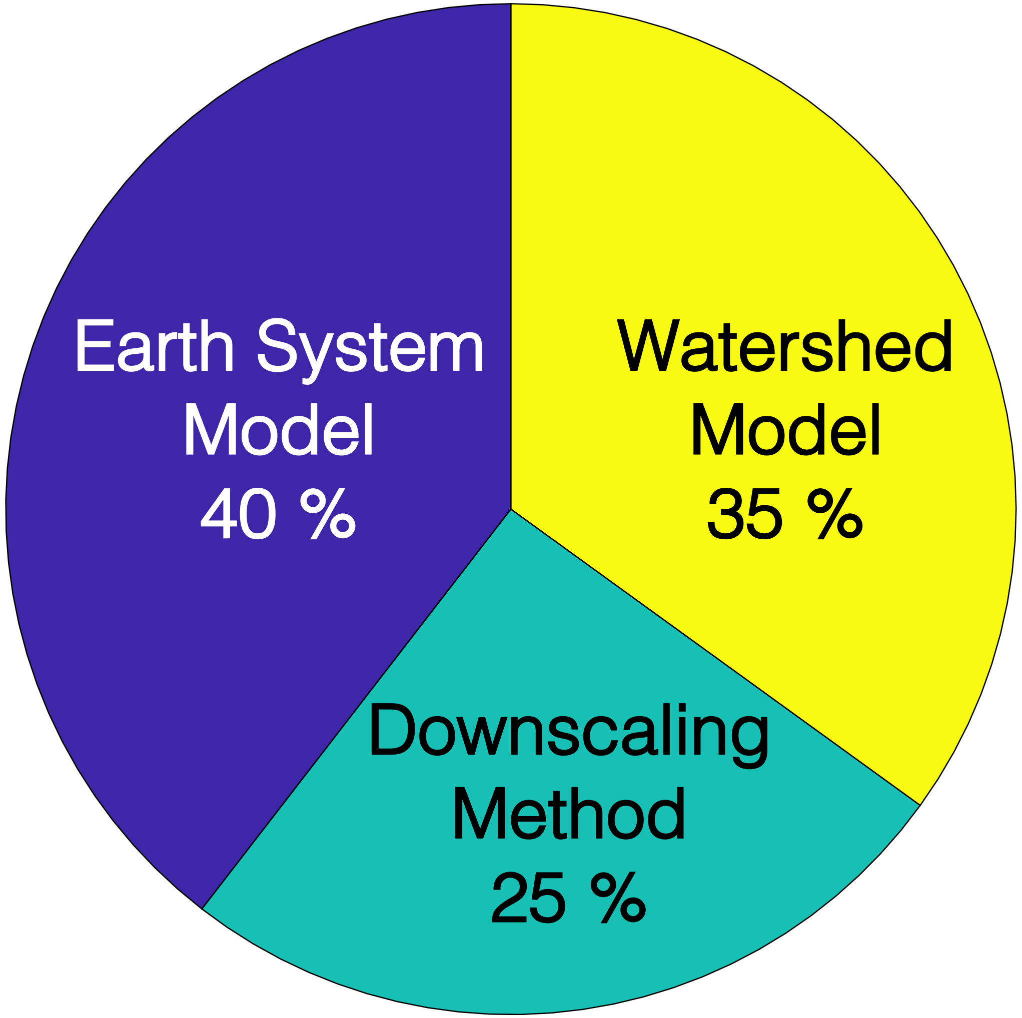
- Climate scenarios estimate an average Bay hypoxic volume increase of 4±7%
- 72% of outcomes project that watershed changes will worsen dissolved oxygen

Quantifying Scenario Uncertainty



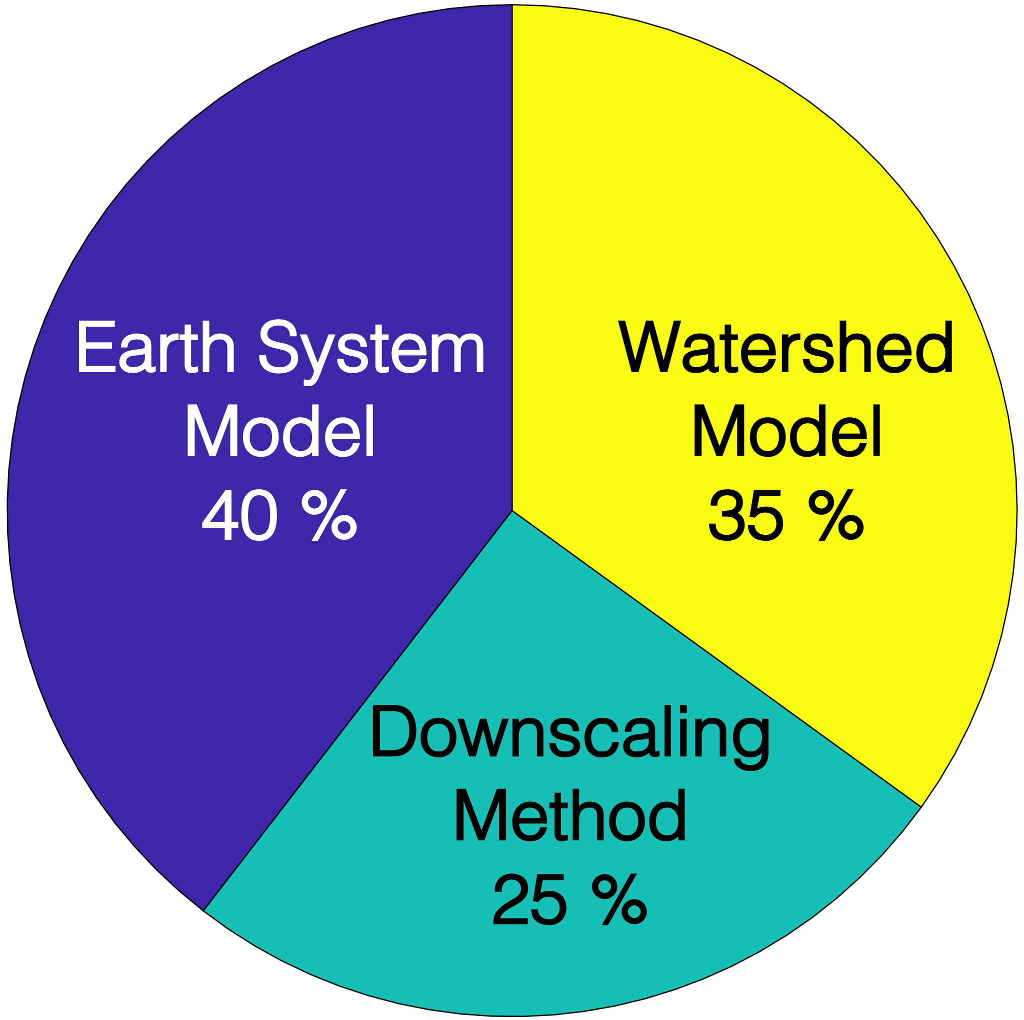
Hypoxia Cumulative Uncertainty

- All factors in the setup of a climate scenario are important for projecting future hypoxia
- Selecting a single ESM, downscaling method, or WSM may substantially limit range of outcomes.

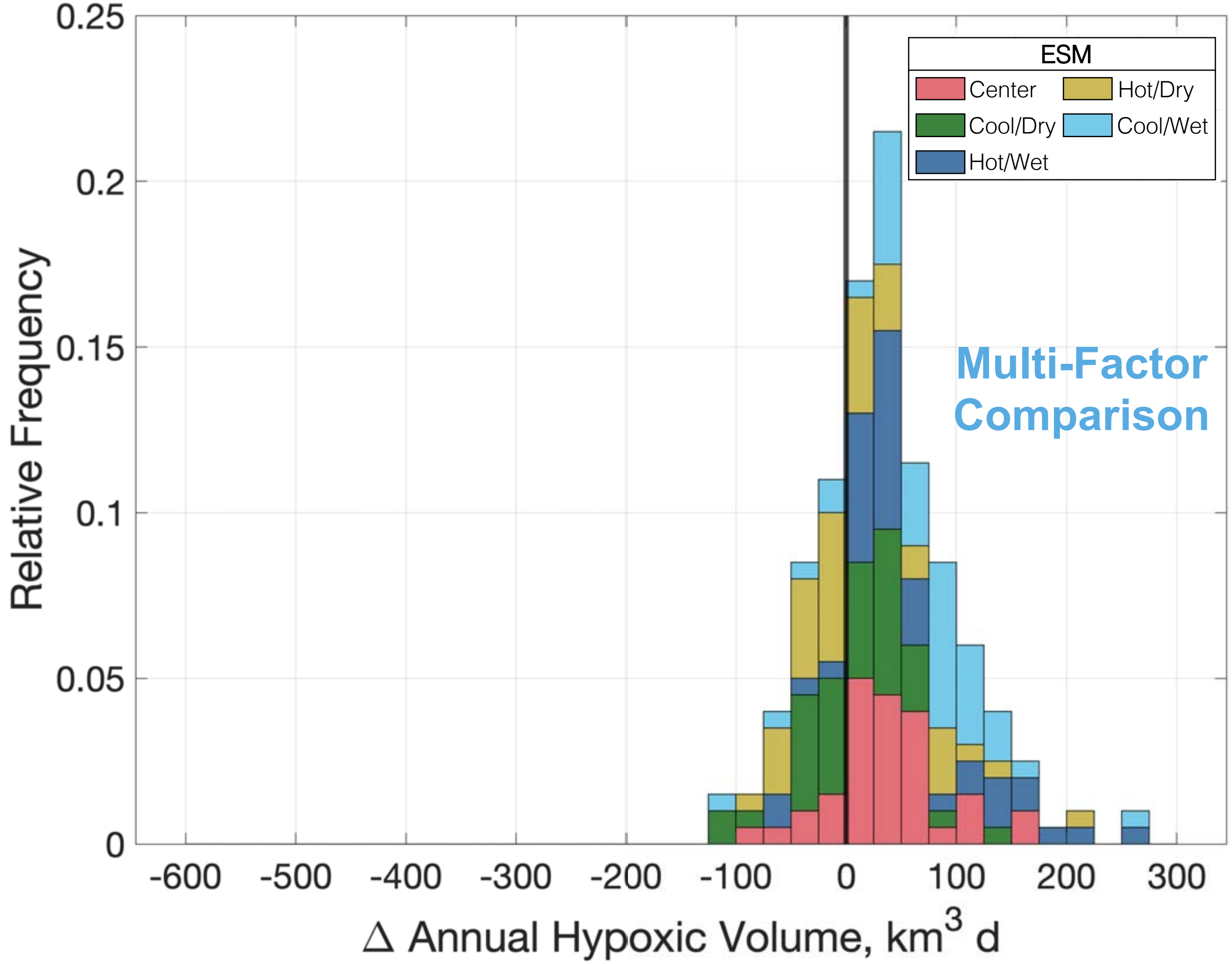


Hypoxia Cumulative Uncertainty

- All factors in the setup of a climate scenario are important for projecting future hypoxia
- Selecting a single ESM, downscaling method, or WSM may substantially limit range of outcomes.
- *How do these results compare to uncertainties in management actions?*

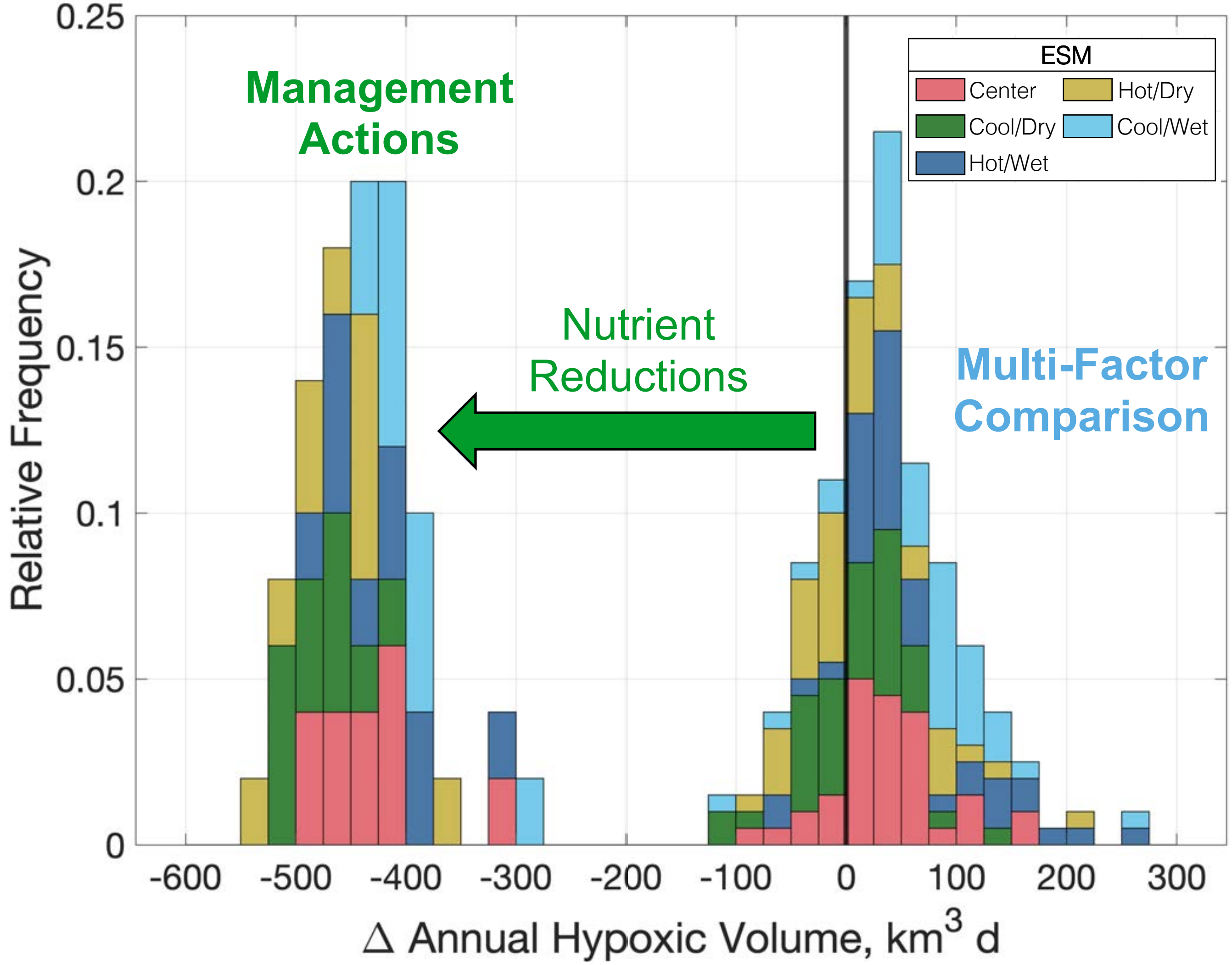


Management Context



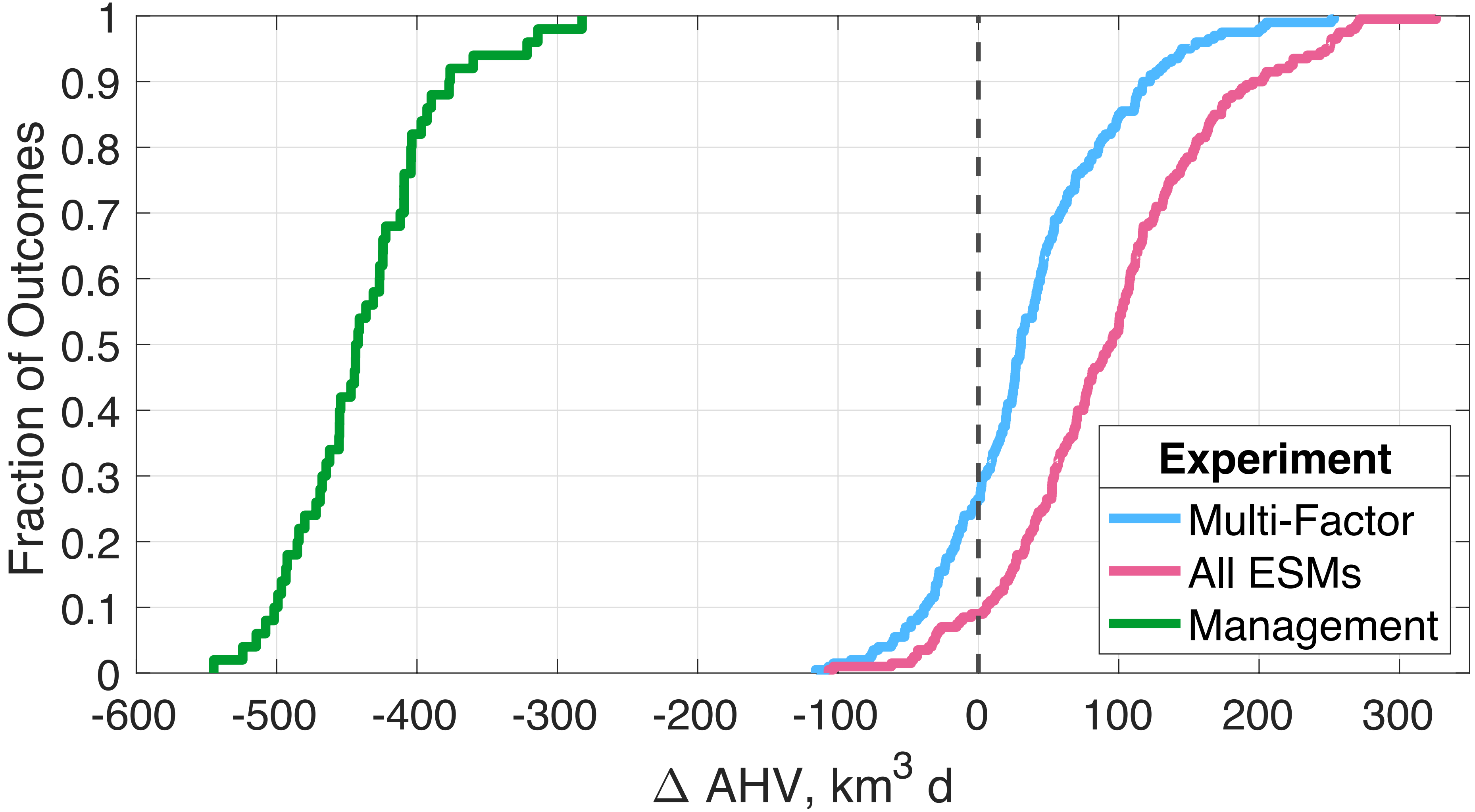
- How does climate scenario uncertainty compare to management actions?

Management Context



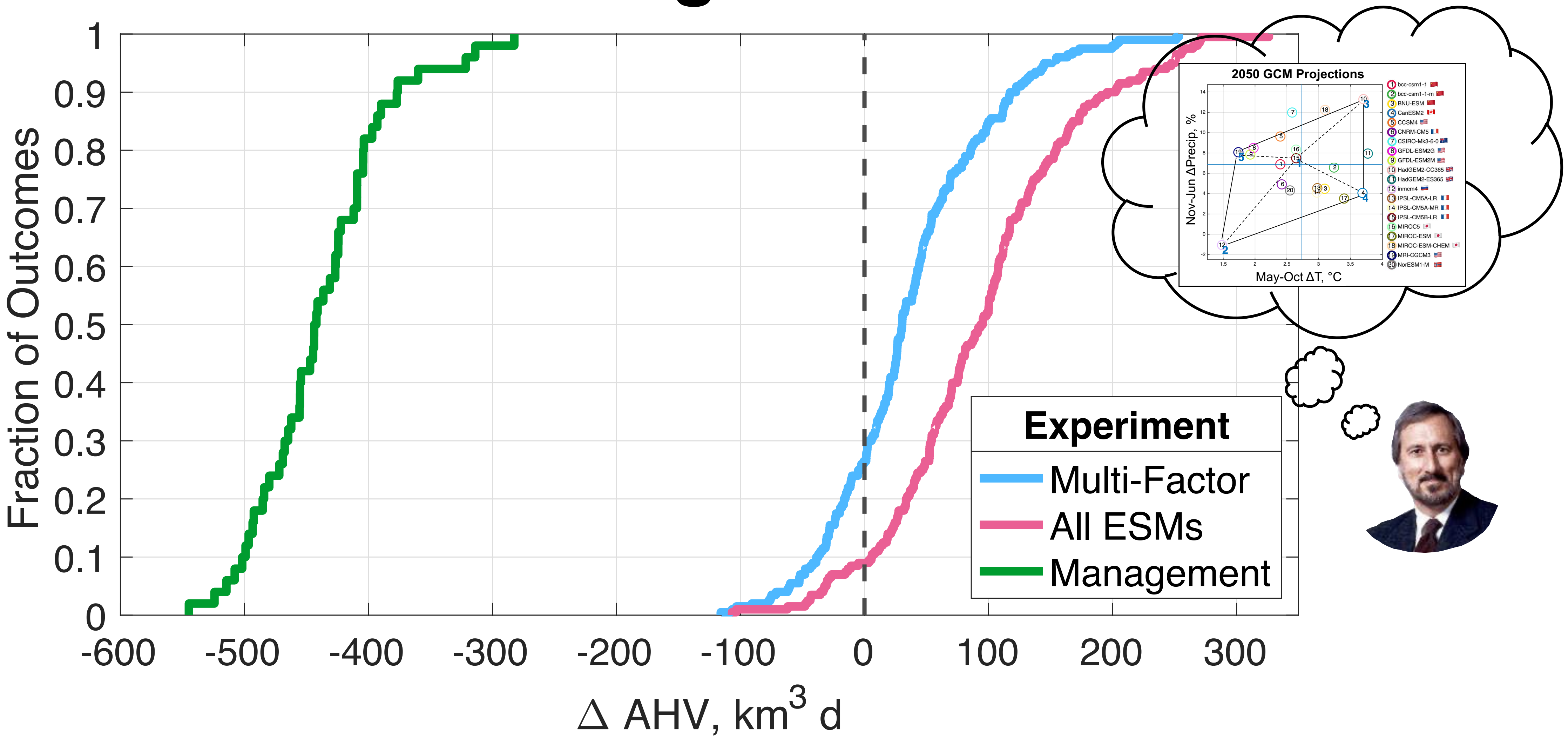
- Reducing nutrient inputs projected to decrease average hypoxia levels by 50 ± 7%

Effects of Management Caveats



- Mgmt. scenarios assume complete implementation, may be biased by use of 1 watershed model
- Whether BMPs maintain their efficacy in the future is an open question

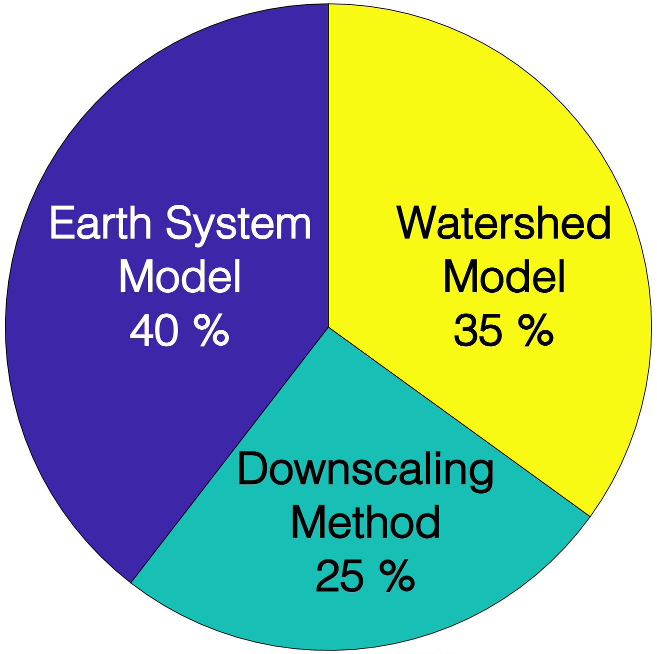
Effects of Management Caveats

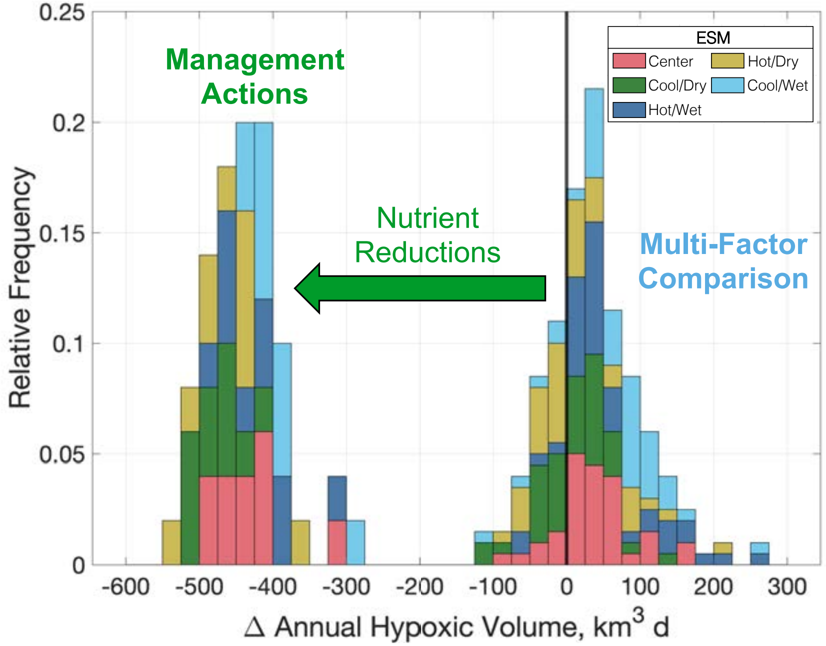


- Mgmt. scenarios assume complete implementation, may be biased by use of 1 watershed model
- Whether BMPs maintain their efficacy in the future is an open question

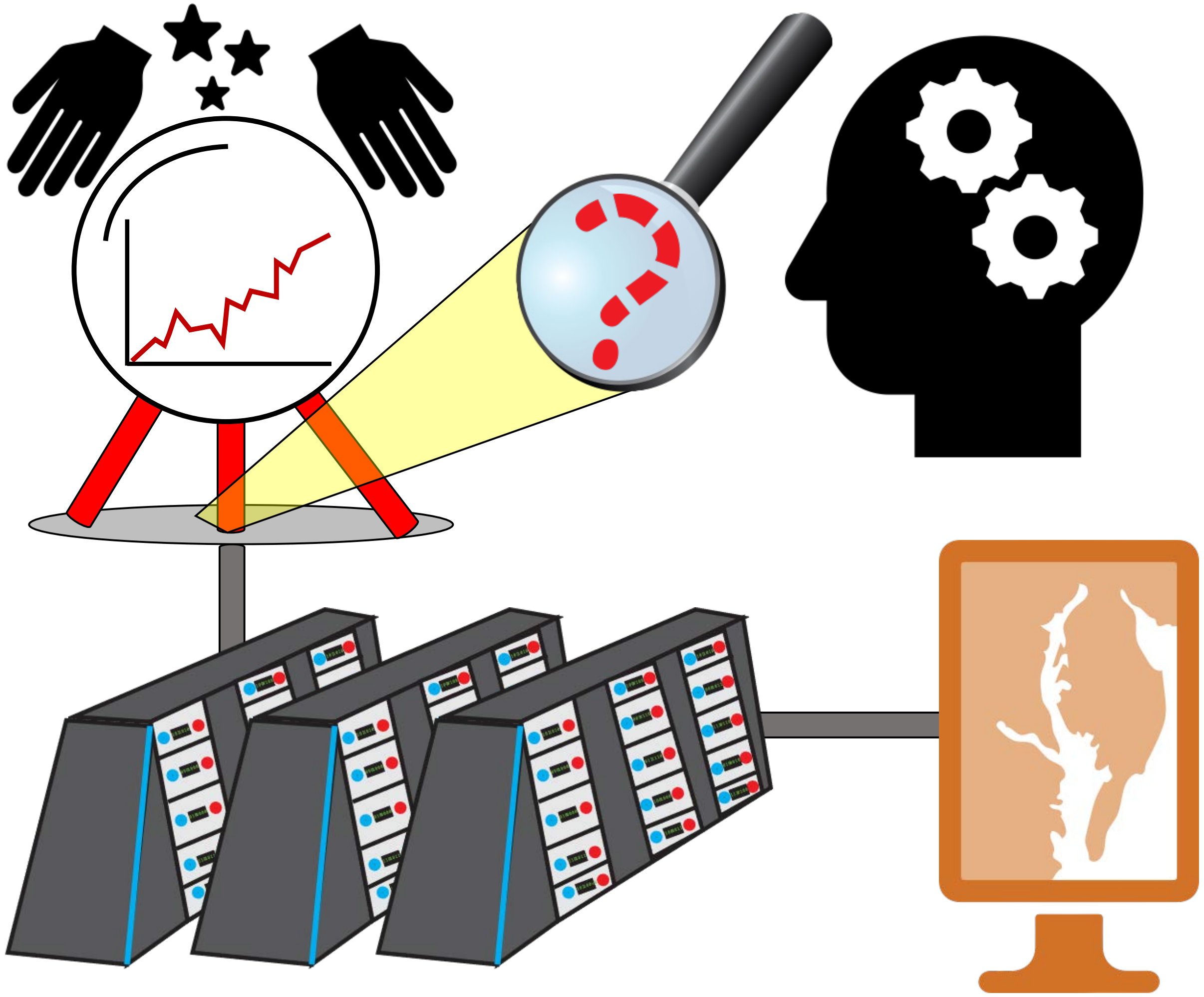
Conclusions

- Uncertainties in climate scenario and watershed inputs produce highly variable hypoxia responses
- All future simulation factors (ESM, downscaling, watershed model) contribute to scenario uncertainty
- Full implementation of management actions to reduce nutrients is greatest source of uncertainty



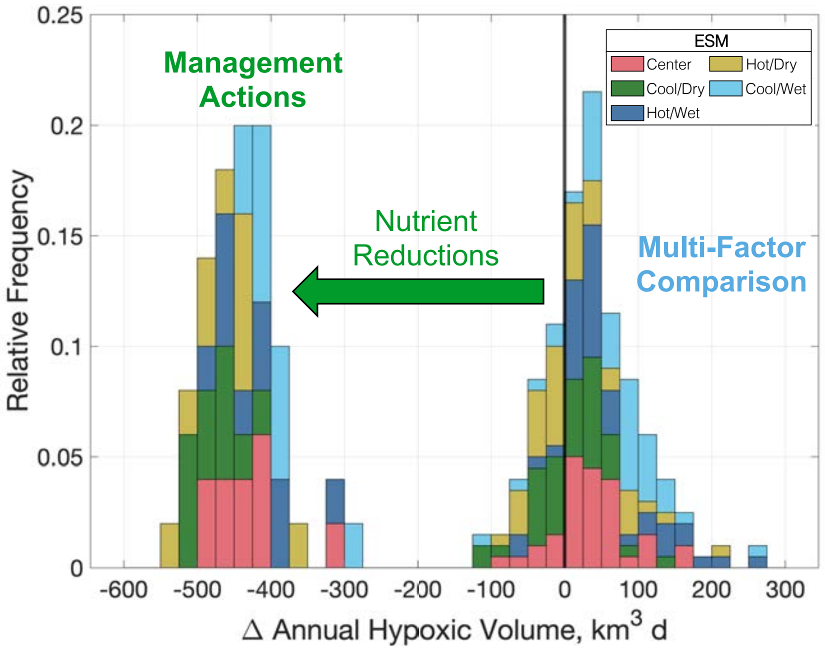


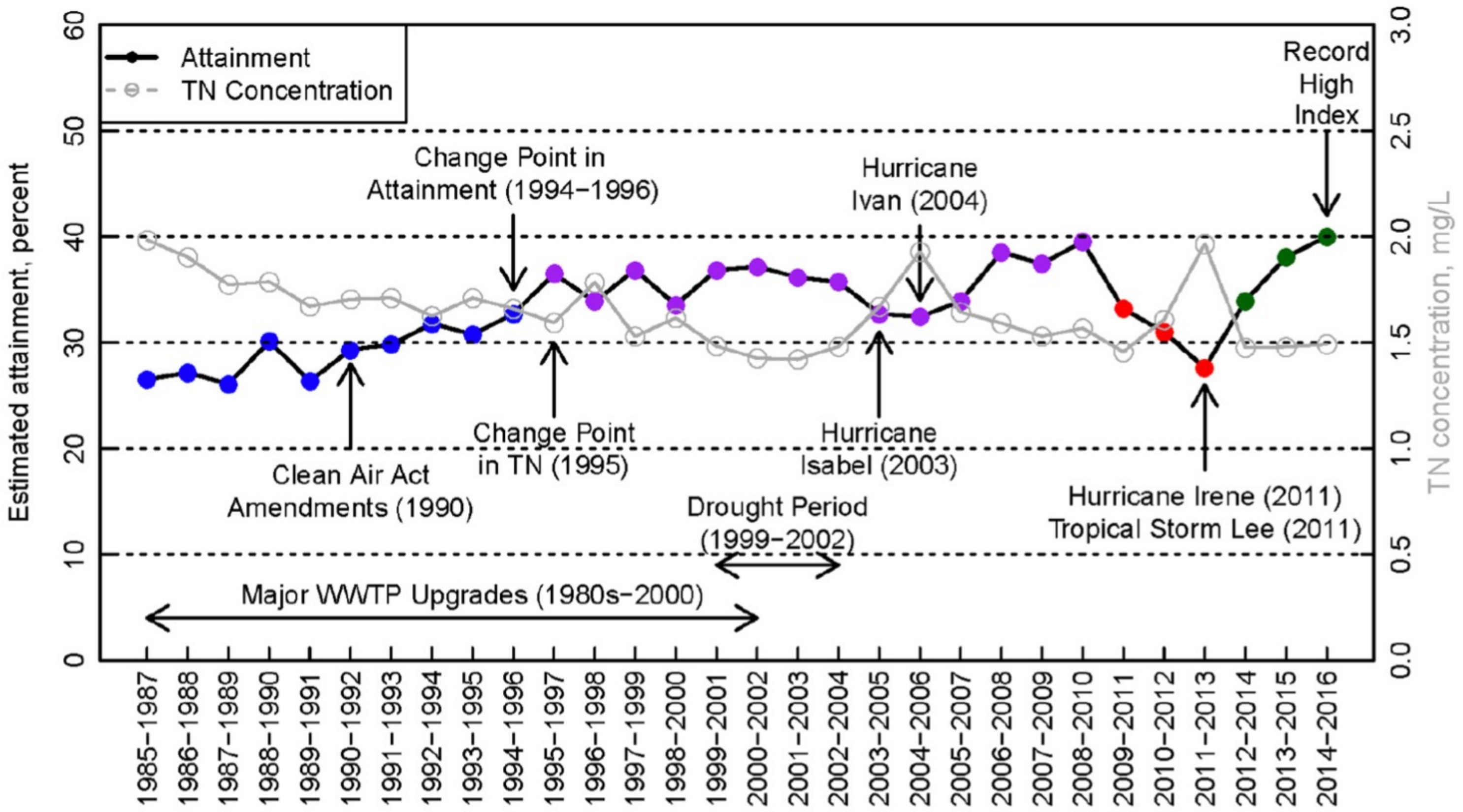
Implications and Future Work



Implications and Future Work

Importance of Nutrient Reductions





Zhang et al., 2018, Sci. Tot. Env.

Implications and Future Work

Need for Collaborative Modeling Efforts

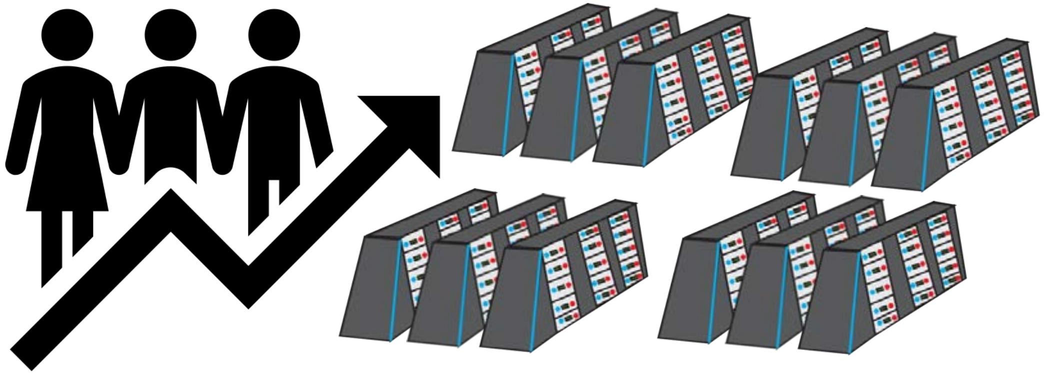


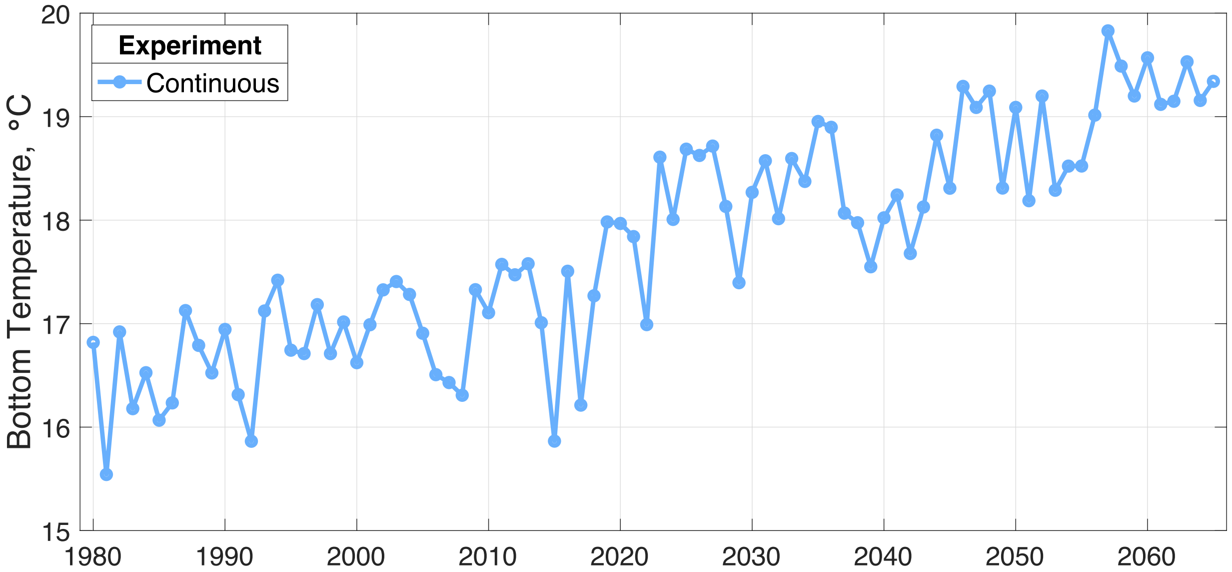
Table 6. A summary comparison of simulated mid-21st century climate change impacts on Chesapeake Bay hypoxia relative to observed conditions.

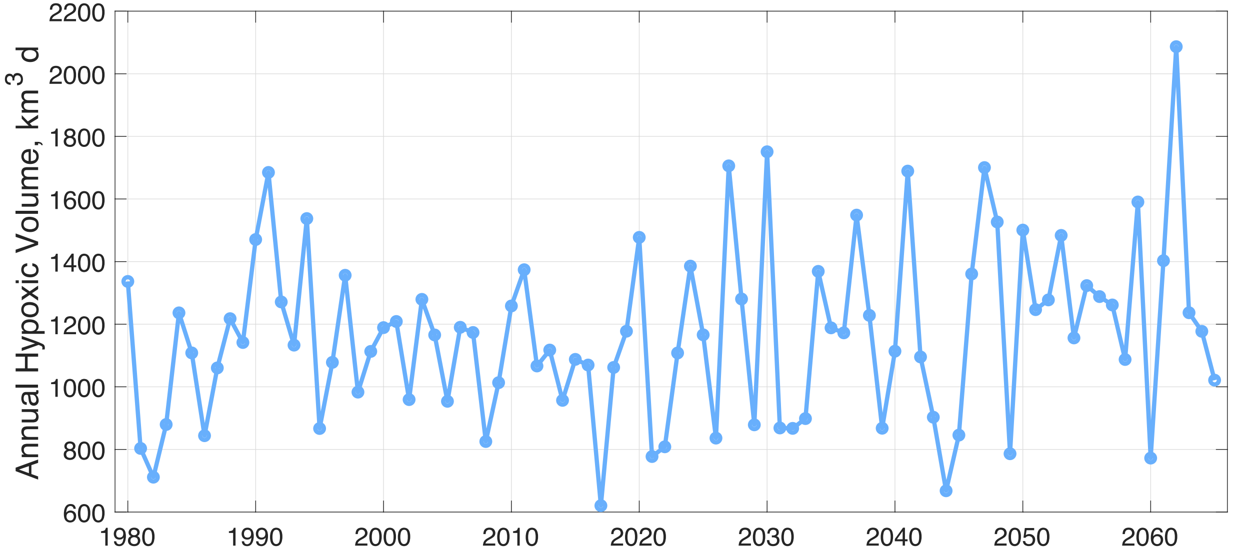
Published research	Climate change factors	Future oxygen change
Watershed changes		
Wang et al. (2017)	Increased watershed nitrogen loadings by +5 % to +10 %	No AHV estimate provided Increase in AAV[a]: +9.7 % to +18.7 %
Irby et al. (2018)	Changed watershed streamflow by −2 % to +17 % (varying by month); assumed nutrient reductions	Increase in AHV: +5 %
Hinson et al. (2023)[b] (this paper)	Changed watershed streamflow and loadings according to two watershed models, two downscaling techniques, and five ESMs	Increase in AHV: +4.4 ± 7.4 % Increase in AAV: +10.0 ± 16.5 %
Temperature changes		
Irby et al. (2018)	Increased estuarine temperatures by 1.75 °C; assumed nutrient reductions	Increase in AHV: +13 %
Tian et al. (2021)	Increased atmosphere and ocean temperature by ∼ 1 °C	[c]Increase in AHV: +9 %
Sea Level Rise		
Irby et al. (2018)	Increased sea level by 0.5 m; assumed nutrient reductions	Decrease in AHV: −13 %
St-Laurent et al. (2019)	Increased sea level by 0.5 m for four different models	Increase in summertime bottom O_2 in all four models
Cai et al. (2021)	Increased sea level by 0.5 m	Increase in AHV by +8 %
Cerco and Tian (2022)	Increased sea level by 0.22 to 1 m and simulated wetland losses	Increase in DO criteria exceedances
Multiple environmental changes		
Irby et al. (2018)	Combined atmosphere, watershed, and sea level change, assuming nutrient reductions	Increase in AHV: +9 %
Ni et al. (2019)[b]	Combined atmosphere, watershed, and ocean change – multiple downscaled scenarios that increased air temperatures, monthly streamflow, ocean temperatures, and sea surface height	Increase in AHV: +9 % to 31 % Increase in AAV: +2 % to 29 %
Basenback et al. (2022)	Modified timing of nutrient delivery and warming within the estuary	Change in AHV: −10 % to +18 %

AAV – annual anoxic volume; AHV – annual hypoxic volume. [a] AAV defined as $O_2 < 1\ mg\ L^{-1}$ in Wang et al. (2017) and $O_2 < 0.2\ mg\ L^{-1}$ for all others. [b] Applied downscaled ESMs in projecting changes to Chesapeake Bay hypoxia. [c] No 2050 estimate provided; results based on 2025 projected changes.

Implications and Future Work

Simulating Long-Term Evolution of Climate Impacts





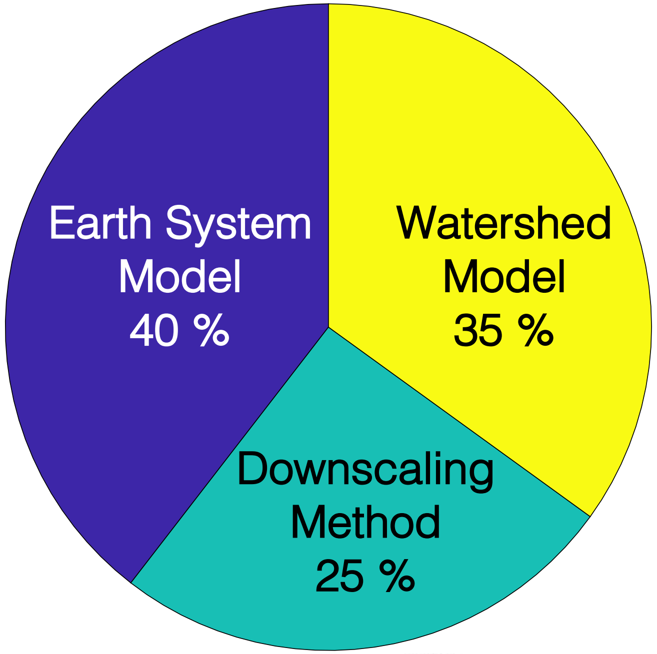
- Projected rapid increase in average bottom temperatures → ≈ +2 °C
- Increase in average hypoxic volume levels by approximately 10%

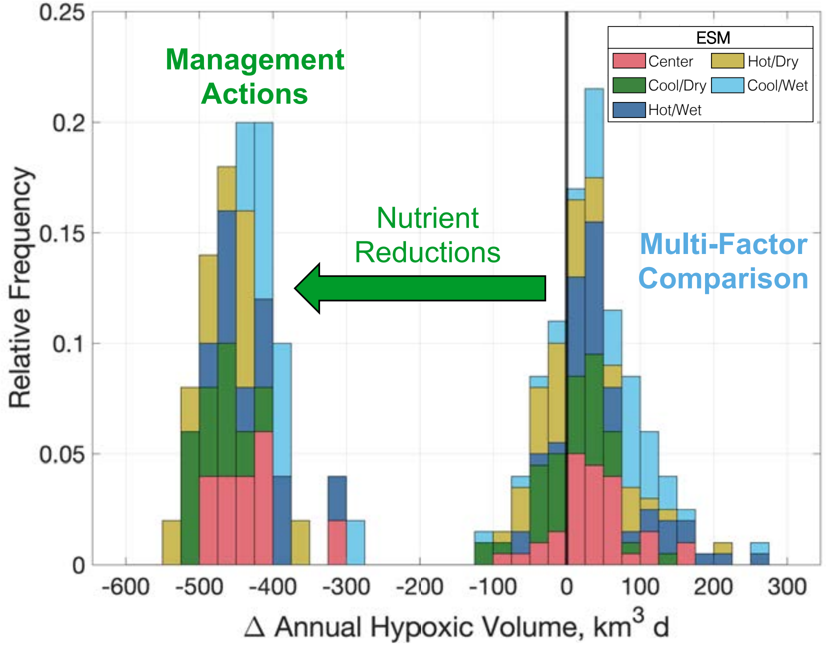
Conclusions

- Uncertainties in climate scenario and watershed inputs produce highly variable marine hypoxia responses

- All future simulation factors (ESM, downscaling, watershed model) contribute to scenario uncertainty

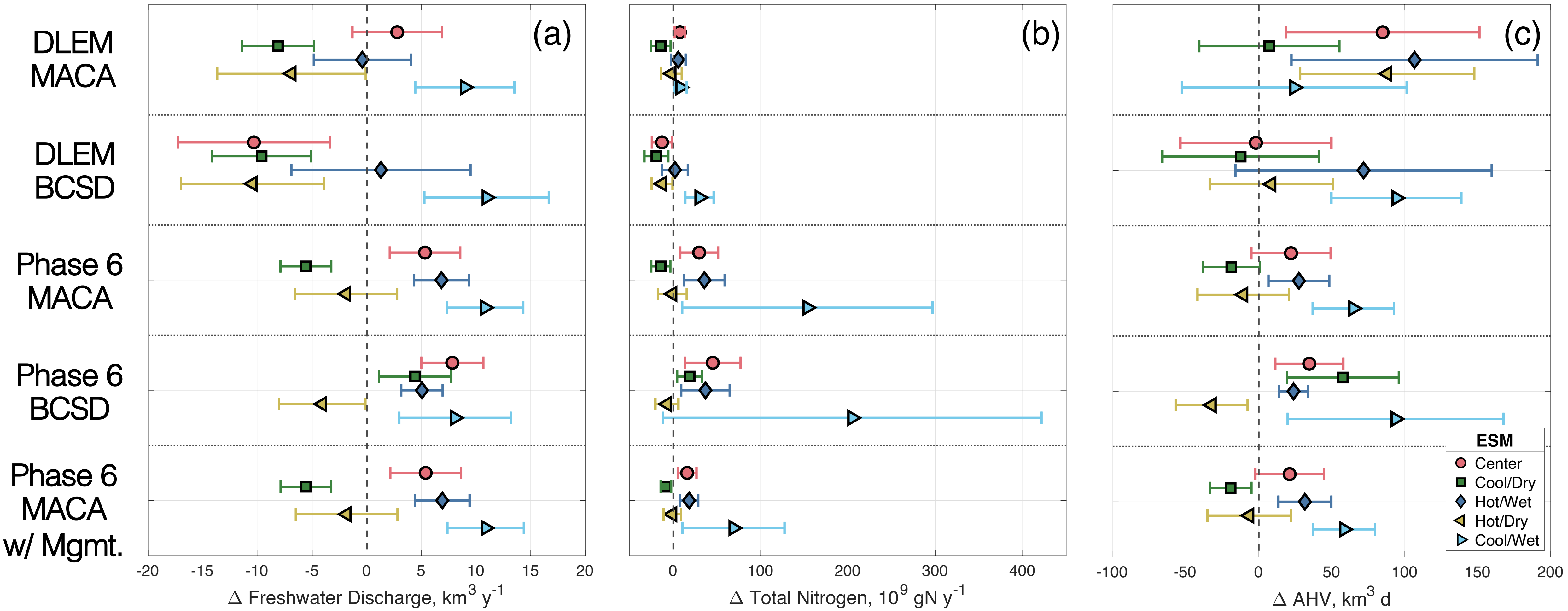
- Full implementation of management actions to reduce nutrients is greatest source of uncertainty

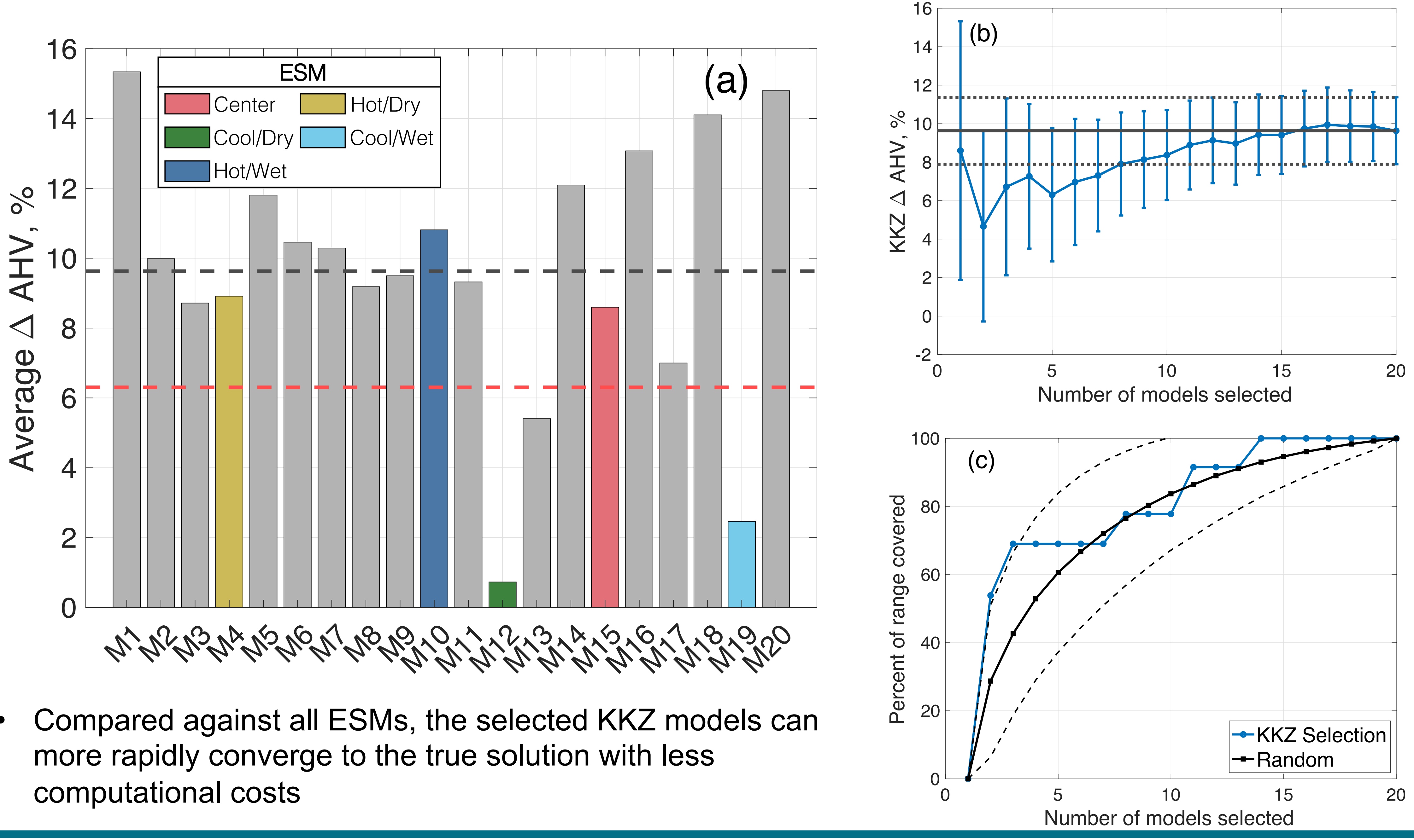




Questions?

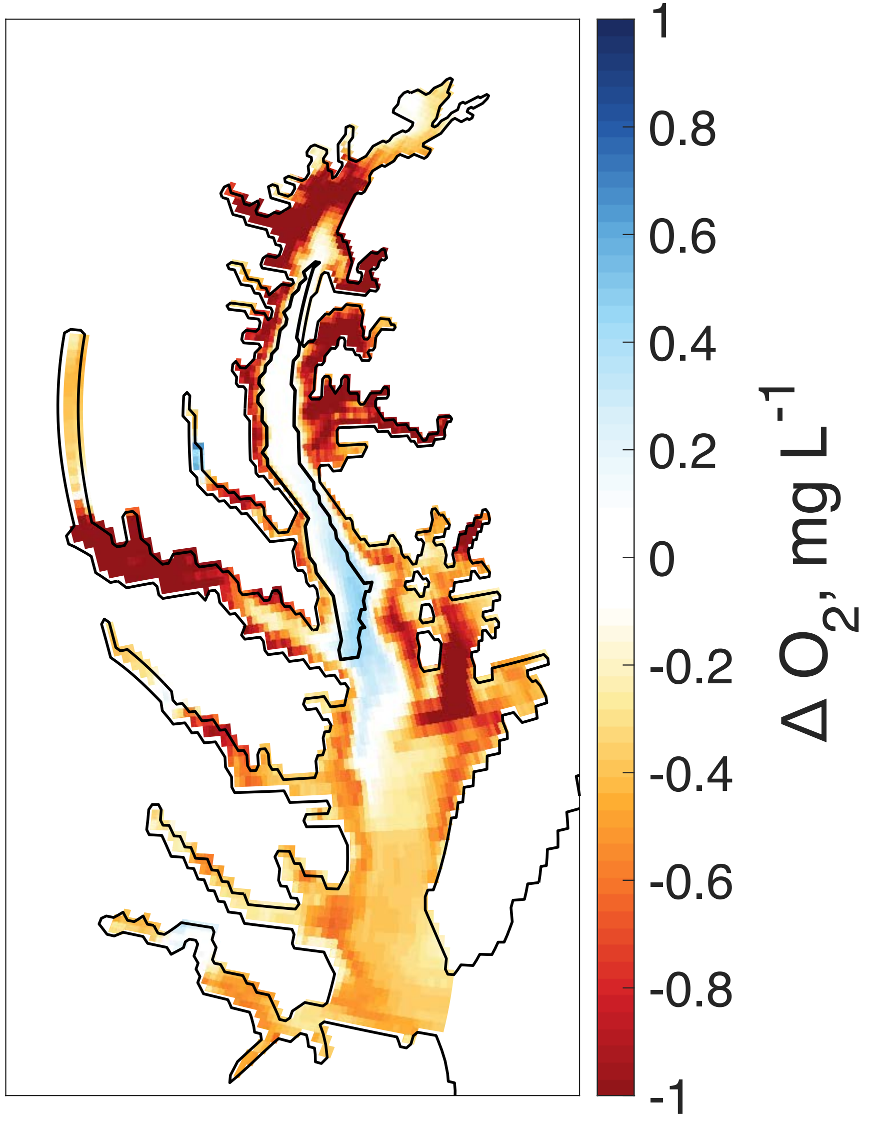
Appendix

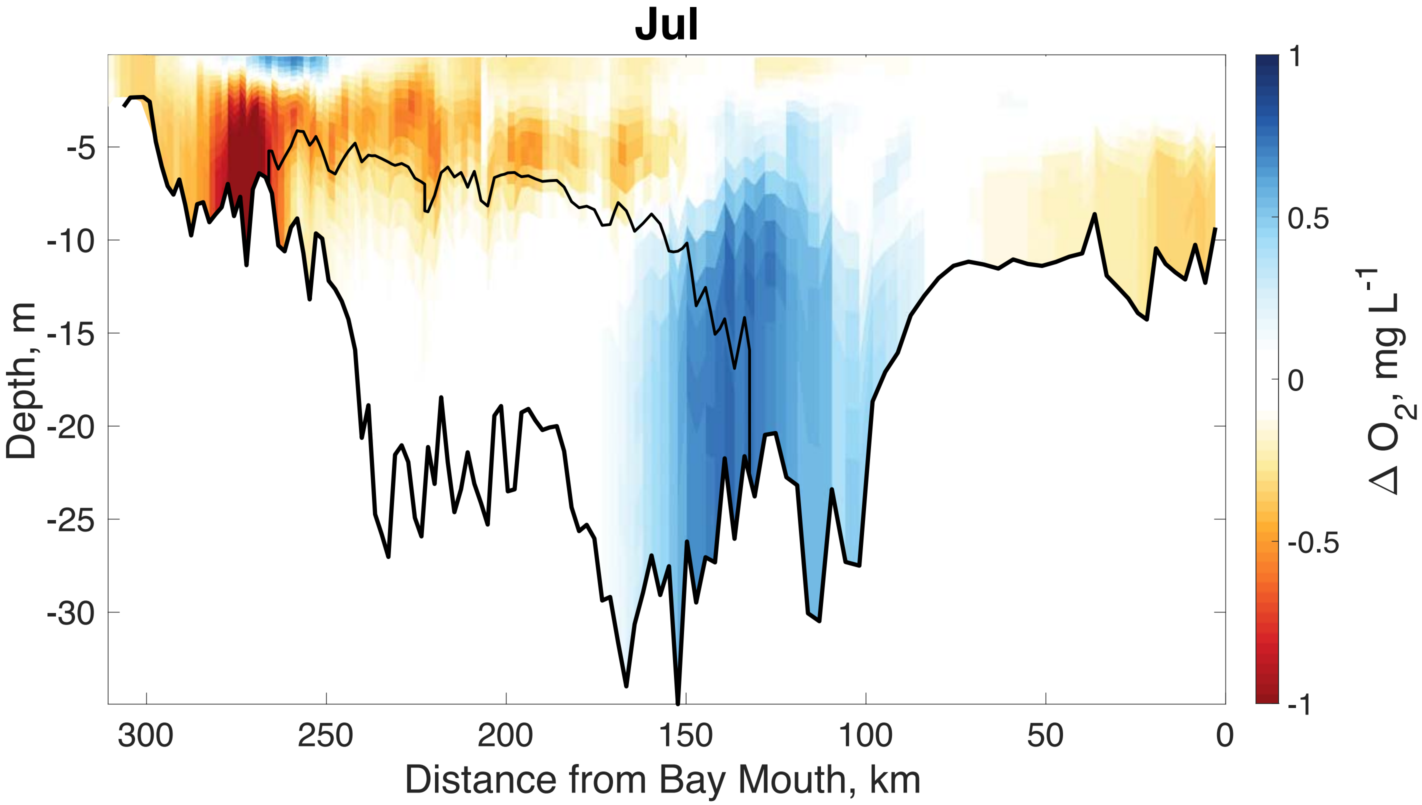

DLEM MACA
DLEM BCSD
Phase 6 MACA
Phase 6 BCSD
Phase 6 MACA w/ Mgmt.
(a)
(b)
(c)
-20 -15 -10 -5 0 5 10 15 20
Δ Freshwater Discharge, km3 y-1
0 100 200 300 400
Δ Total Nitrogen, 109 gN y-1
-100 -50 0 50 100 150 200
Δ AHV, km3 d
ESM
Center
Cool/Dry
Hot/Wet
Hot/Dry
Cool/Wet



- Compared against all ESMs, the selected KKZ models can more rapidly converge to the true solution with less computational costs

Continuous Future Simulation (1980-2065)

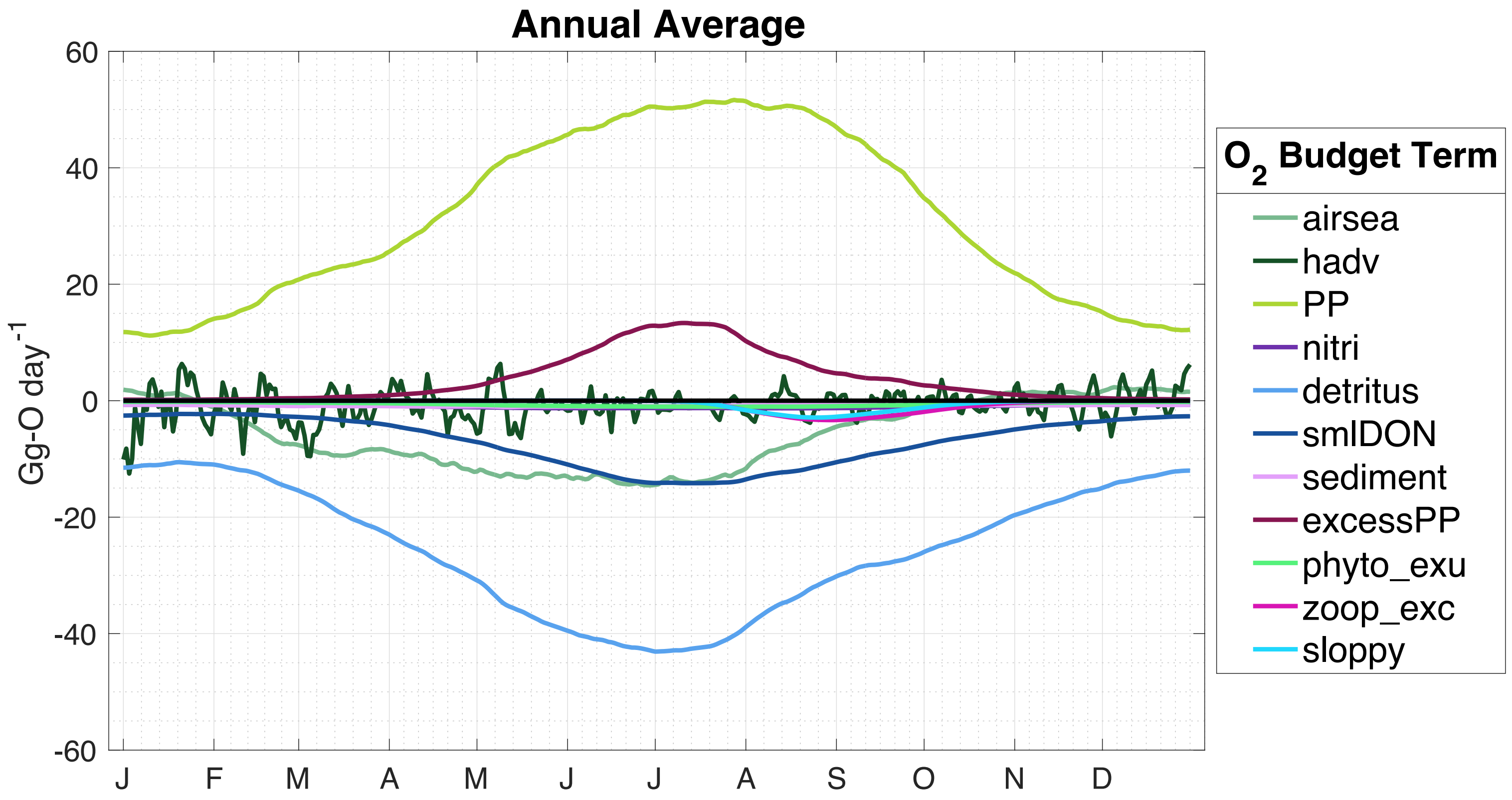




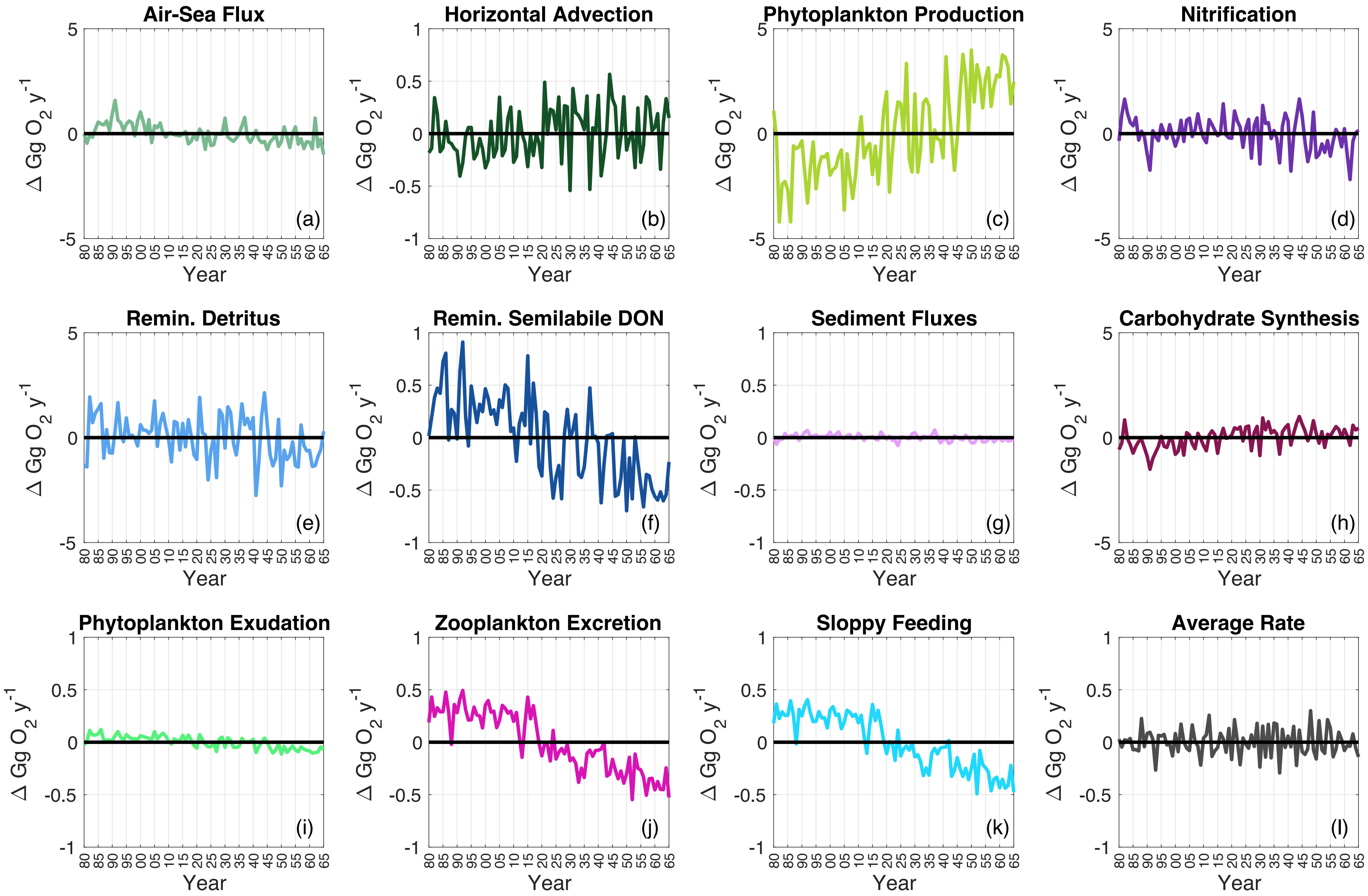
- Increase in summer bottom O_2 driven by sped-up remineralization rates

Oxygen $(O2)$	Rate of change =	$\partial O2/\partial t =$
	+ Production	$+\mu\, L_I\, (\eta_{O2:NO3}\, L_{NO3} + \eta_{O2:NH4}\, L_{NH4})\, P$
	− Exudation	$-\omega\, f_{NTR}\, \eta_{O2:NH4}\, \mu\, L_I\, (L_{NO3} + L_{NH4})\, P$
	+ Synthesis of carbohydrates	$+\gamma_P^C\, \eta_{C:N}^P\, \mu\, L_I\, (1 - L_{NO3} - L_{NH4})\, P$
	− Nitrification	$-2\, n\, f_{NTR}\, NH4$
	− Sloppy feeding	$-\eta_{O2:NH4}\, (1-\beta)\, \lambda\, (1-\delta_N)\, g\, Z$
	− Basal metabolism	$-\eta_{O2:NH4}\, l_{BM}\, Z$
	− Excretion	$-\eta_{O2:NH4}\, l_E\, \beta\, P^2\, (K + P^2)^{-1}\, Z$
	− Remineralization	$-\eta_{O2:NH4}\, f_{NTR}\, \exp(\psi_{resp} T)$
		$\times [r_{DON}\, DON_{SL} + (1-\delta_N)\, (r_{SD}\, SD + r_{LD}\, LD)]$

St-Laurent et al. 2020



- Bay dissolved oxygen likely not decreasing solely due to physical climate impacts
- Budget analysis can better quantify effects of changing internal model biogeochemical processes on O_2


Air-Sea Flux
Horizontal Advection
Phytoplankton Production
Nitrification
Remin. Detritus
Remin. Semilabile DON
Sediment Fluxes
Carbohydrate Synthesis
Phytoplankton Exudation
Zooplankton Excretion
Sloppy Feeding
Average Rate
Δ Gg O2 y-1
Year
80 85 90 95 00 05 10 15 20 25 30 35 40 45 50 55 60 65
(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
(i)
(j)
(k)
(l)