Chesapeake Hypoxia Analysis & Modeling Program (CHAMP):

Predicting impacts of climate change on the success of management actions in reducing Chesapeake Bay hypoxia

Marjorie Friedrichs[1] and Kyle Hinson[1,2]

[1]*Virginia Institute of Marine Science*

[2]*now at Pacific Northwest National Laboratory*

May 7, 2024

Chesapeake Hypoxia Analysis & Modeling Program (CHAMP):

Predicting impacts of climate change on the success of management actions in reducing Chesapeake Bay hypoxia:

CHAMP PIs:

Marjorie Friedrichs (VIMS)
Pierre St-Laurent (VIMS)
Ray Najjar (PSU)
Lewis Linker (CBP/EPA)
Gary Shenk (CBP/USGS)
Hanqin Tian (Auburn/Boston Coll.)
Eileen Hofmann (ODU)

CHAMP MTAG:

Don Boesch
Bruce Michael
James Davis-Martin
Beth McGee
Mark Bennett
Dinorah Dalmasy

NOAA
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF COMMERCE

Spring 2016 – Spring 2023

Chesapeake Bay Program
Science. Restoration. Partnership.

CHAMP Goal

Develop a Chesapeake Bay scenario-forecast modeling system to:

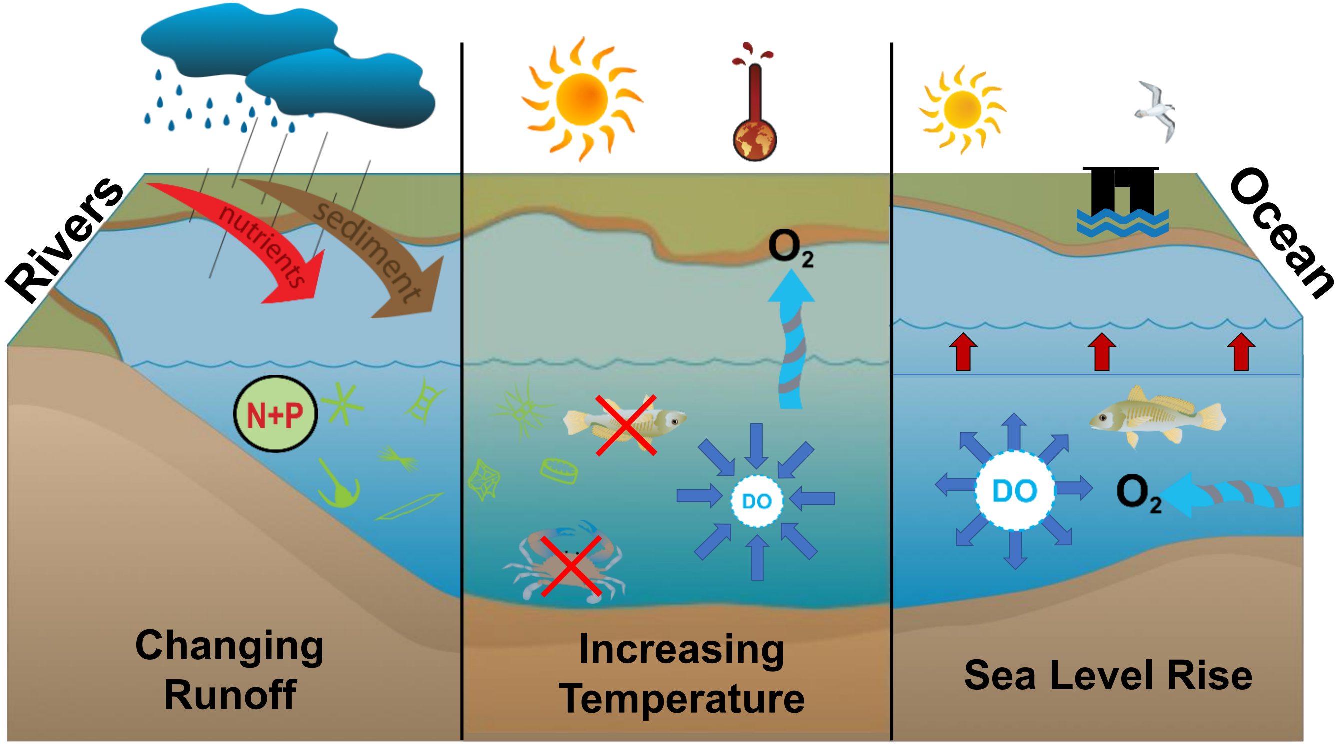
- Provide a best estimate (with uncertainty) of how climate change will impact hypoxia by the mid-21st century, and the mechanisms responsible for these impacts

- Isolate future impacts on Chesapeake hypoxia of *climate change* from those due to *anthropogenic nutrient inputs*

→ Via a multi-model comparison

Estuarine model: ROMS-ECB, WQSTM
Watershed model: DLEM, Phase 6

Climate change affects Chesapeake Bay O_2 in multiple ways



- Plus, changes in winds, solar radiation, ocean conditions??

Multiple sources of uncertainty in future O_2

- **Future atmospheric conditions**
  which Earth System Model (ESM) will we use?
- **Future ocean conditions**
  which ESM will we use, if any?
- **Downscaling technique**
  which downscaling technique will we use?
- **Future emissions scenario**
  which emissions scenario will we use? Does it matter by 2050? (No?)

Outline: CHAMP results

Marjy:

Ike Irby et al., 2018
Pierre St-Laurent et al., 2019
Kyle Hinson et al., 2022
Luke Frankel et al., 2022
Colin Hawes et al., in prep
Olivia Szot et al., in prep

Kyle:

Kyle Hinson et al., 2023
Kyle Hinson et al., submitted

ROMS-ECB: coupled hydrodynamic-WQ model

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

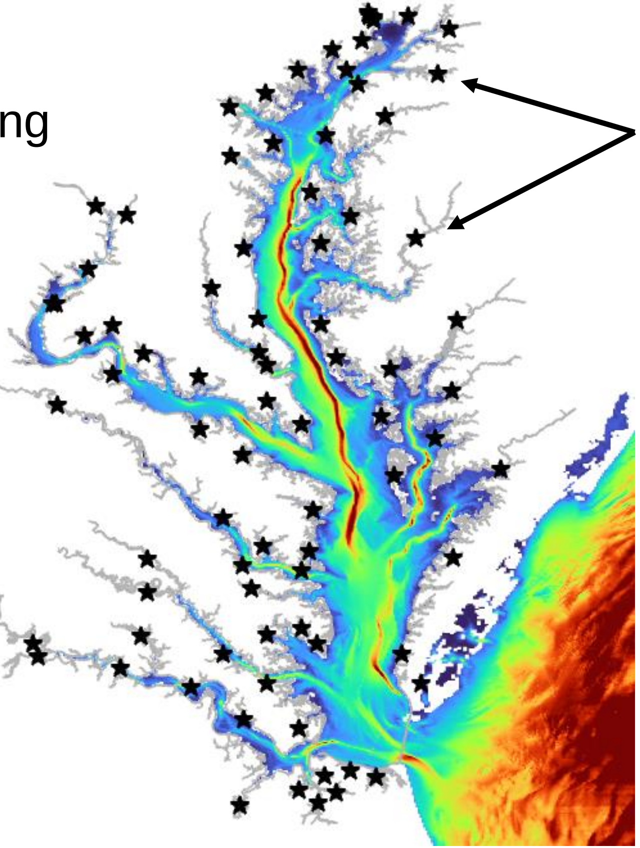
Modeling System:

Regional Ocean Modeling System (ROMS)

600m x 600m grid resolution
20 vertical levels

Estuarine Carbon and Biogeochemistry (ECB)

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



Forcing:

Terrestrial ★

CBP’s Phase 6 watershed model & USGS data

Atmospheric

ERA5 Atmospheric Reanalysis & NAM Forecast System

Oceanic

In situ data

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

Szot, 2024

Projecting 2050s hypoxia (Irby et al.)

Biogeosciences, 15, 2649–2668, 2018
https://doi.org/10.5194/bg-15-2649-2018

Biogeosciences Open Access EGU

The competing impacts of climate change and nutrient reductions on dissolved oxygen in Chesapeake Bay

Isaac D. Irby, Marjorie A. M. Friedrichs, Fei Da, and Kyle E. Hinson

Virginia Institute of Marine Science, College of William & Mary, Gloucester Point, VA 23062, USA

Correspondence: Isaac D. Irby (isaacirby@gmail.com) and Marjorie A. M. Friedrichs (marjy@vims.edu)

Received: 9 October 2017 – Discussion started: 17 October 2017
Revised: 25 February 2018 – Accepted: 4 April 2018 – Published: 4 May 2018

Projecting 2050s hypoxia (Irby et al.)

In 2050s, relative to 1990s, we assume:

Water Temperature

1.75°C

Sea Level Rise (SLR)

0.5m

Watershed/rivers

0-15% flow

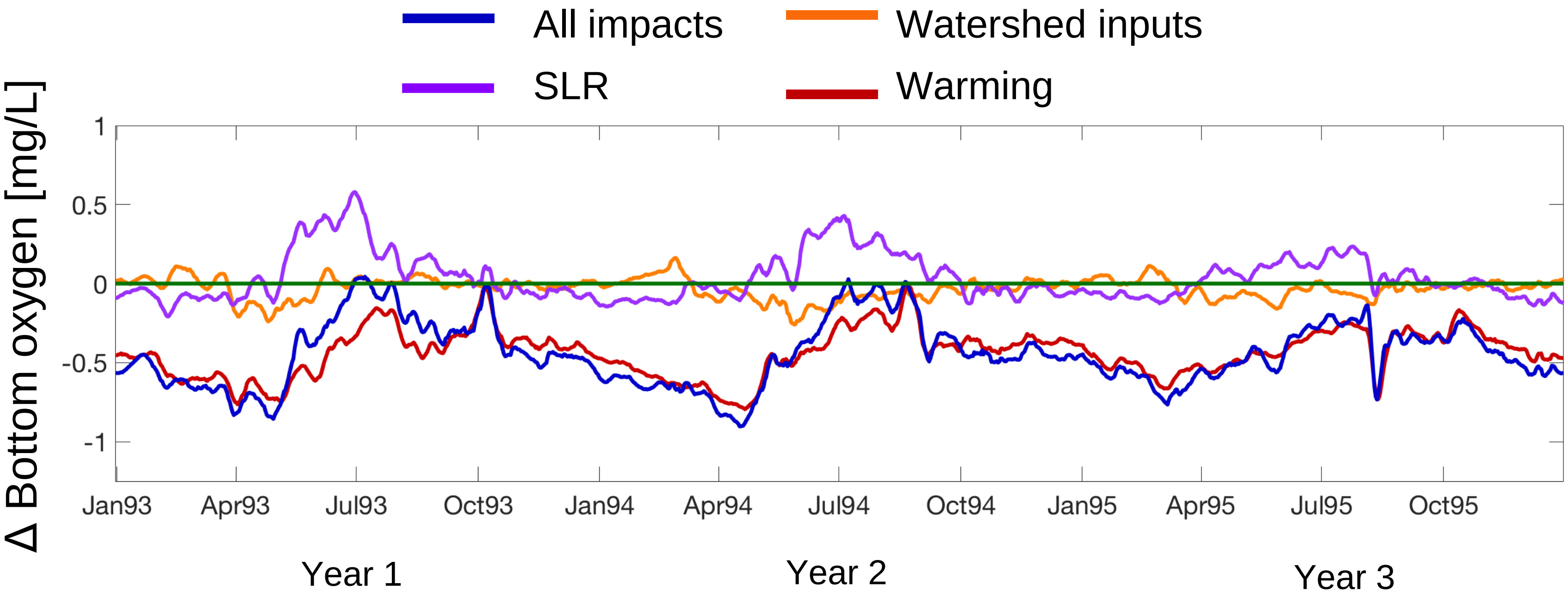
(From Hinson, Bhatt & Shenk)

Examined scenarios:

With and without climate change (T, SLR, watershed)

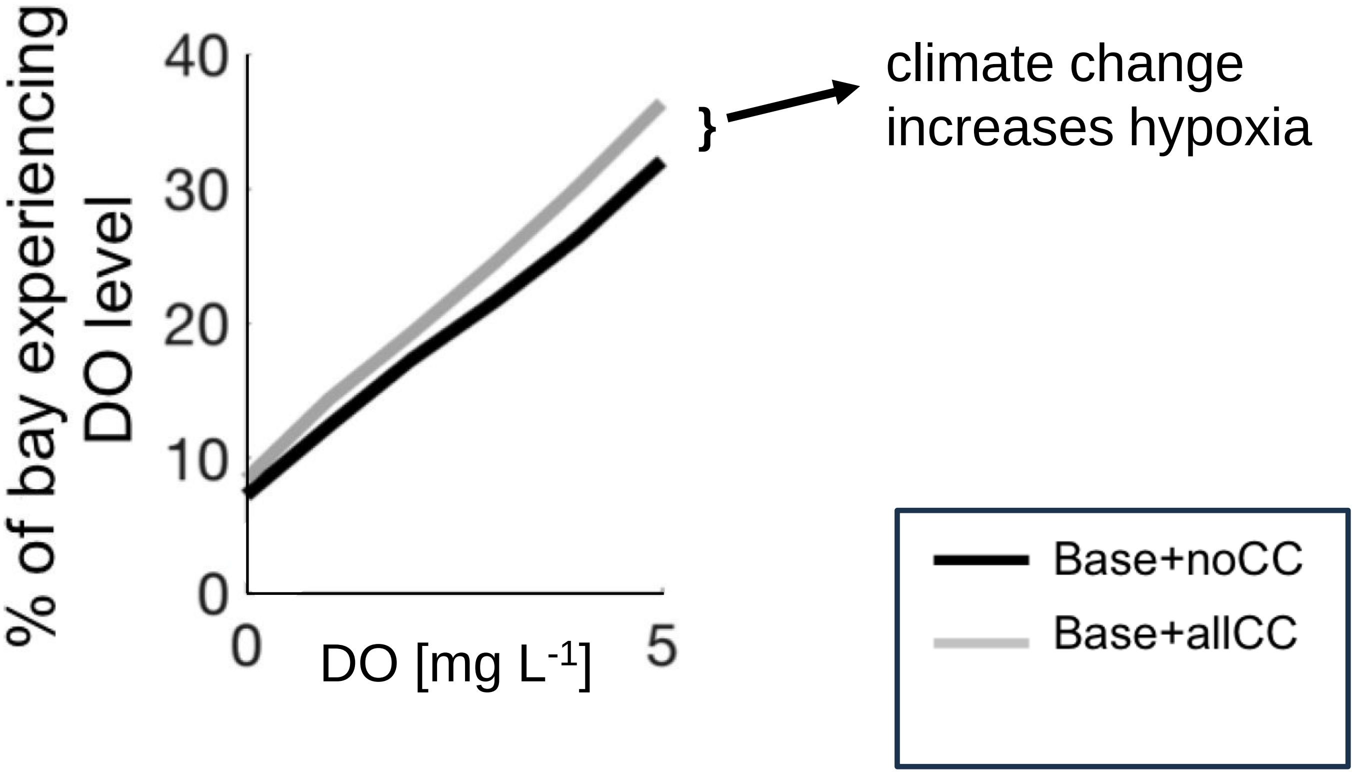
With and without TMDLs

Warming explains most of decrease in bottom O_2



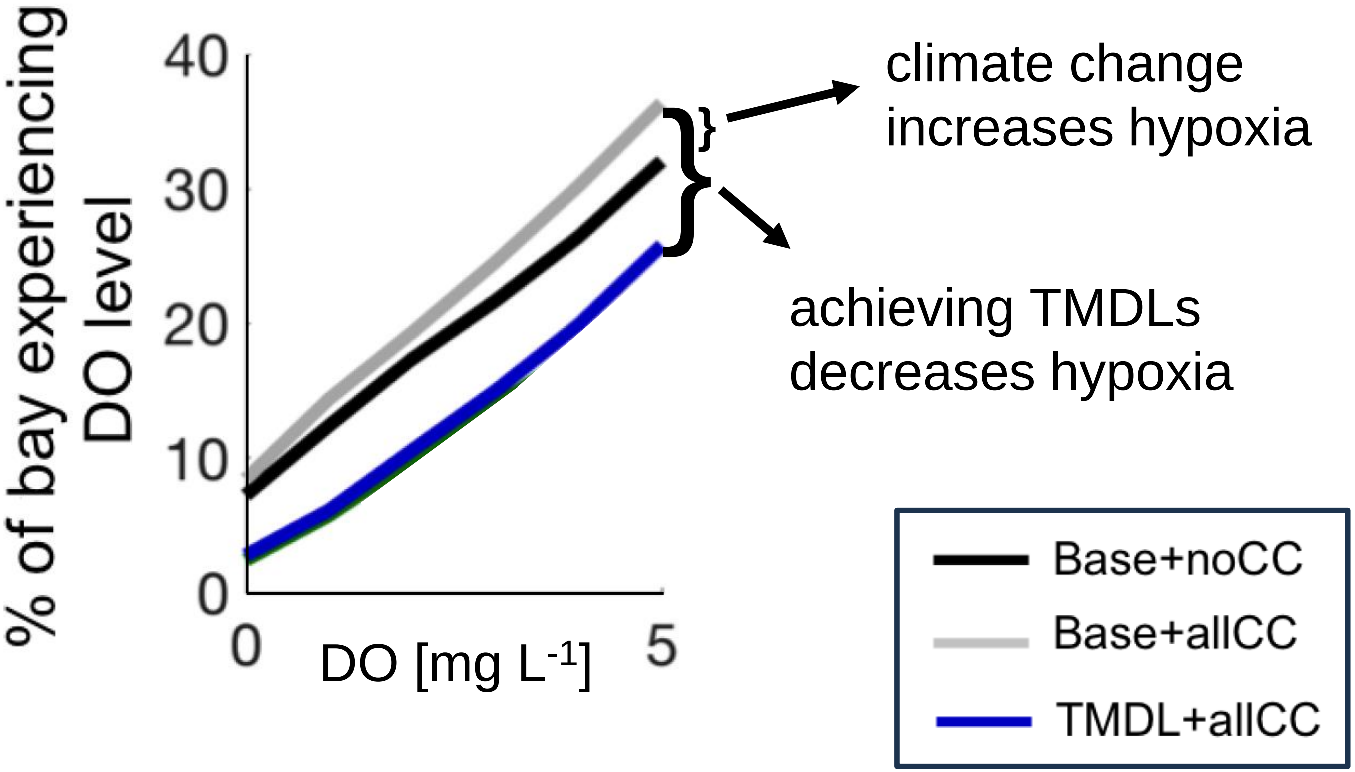
- **SLR** slightly ***increases*** summer bottom O_2
- **Watershed** slightly ***decreases*** bottom O_2
- **Warming** causes ***large decrease*** in bottom O_2

Impact of TMDLs on O_2 >> climate change



climate change increases hypoxia

Impact of TMDLs on O_2 >> climate change



Impacts of sea level rise on hypoxia in the Chesapeake Bay: A model intercomparison

Chesapeake Bay Program Report
October 2019

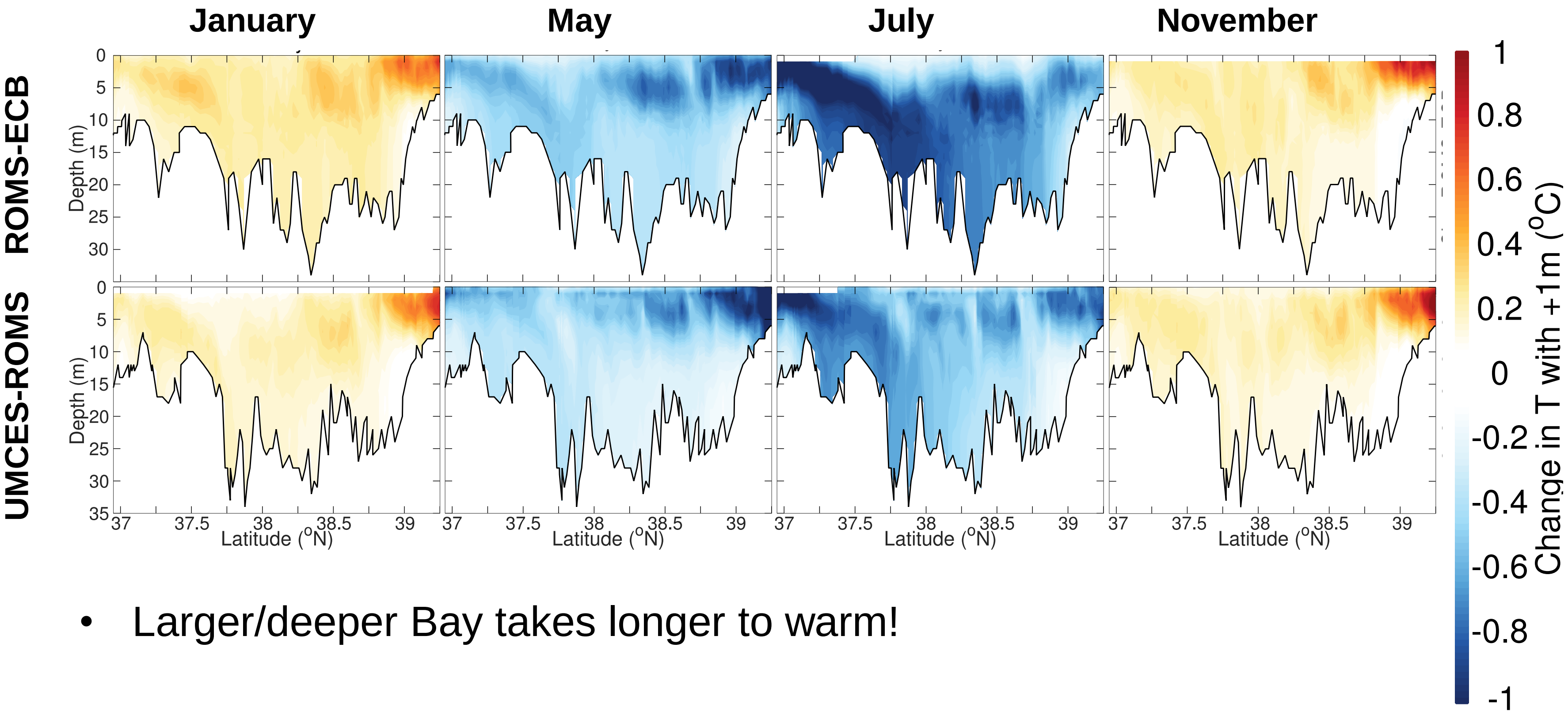
CBPO Publication Number: CBP/TRS-329-19

Pierre St-Laurent, Marjorie Friedrichs, Ming Li, Wenfei Ni

Comparison of four models:

- ROMS-ECB (CHAMP)
- UMCES-ROMS
- WQSTM (CBP Phase 6)
- SCHISM (CBP Phase 7)

SLR causes higher T in fall/winter, and lower T in spring/summer



- Larger/deeper Bay takes longer to warm!

Cooler T → less respiration → higher bottom O_2

Additional analysis with both ROMS models indicated that SLR leads to:

→ cooler early summer temperatures
→ decreases in bottom oxygen utilization
→ higher bottom O_2

Increases in hypoxia due to warming may (at certain times and certain locations) be partially mitigated by SLR, but the effect is relatively small and complex!

Chesapeake Bay Has Been Warming!

By How Much? Where? When? Why? (Hinson et al., 2022)

Kyle Hinson

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

AMERICAN WATER RESOURCES ASSOCIATION

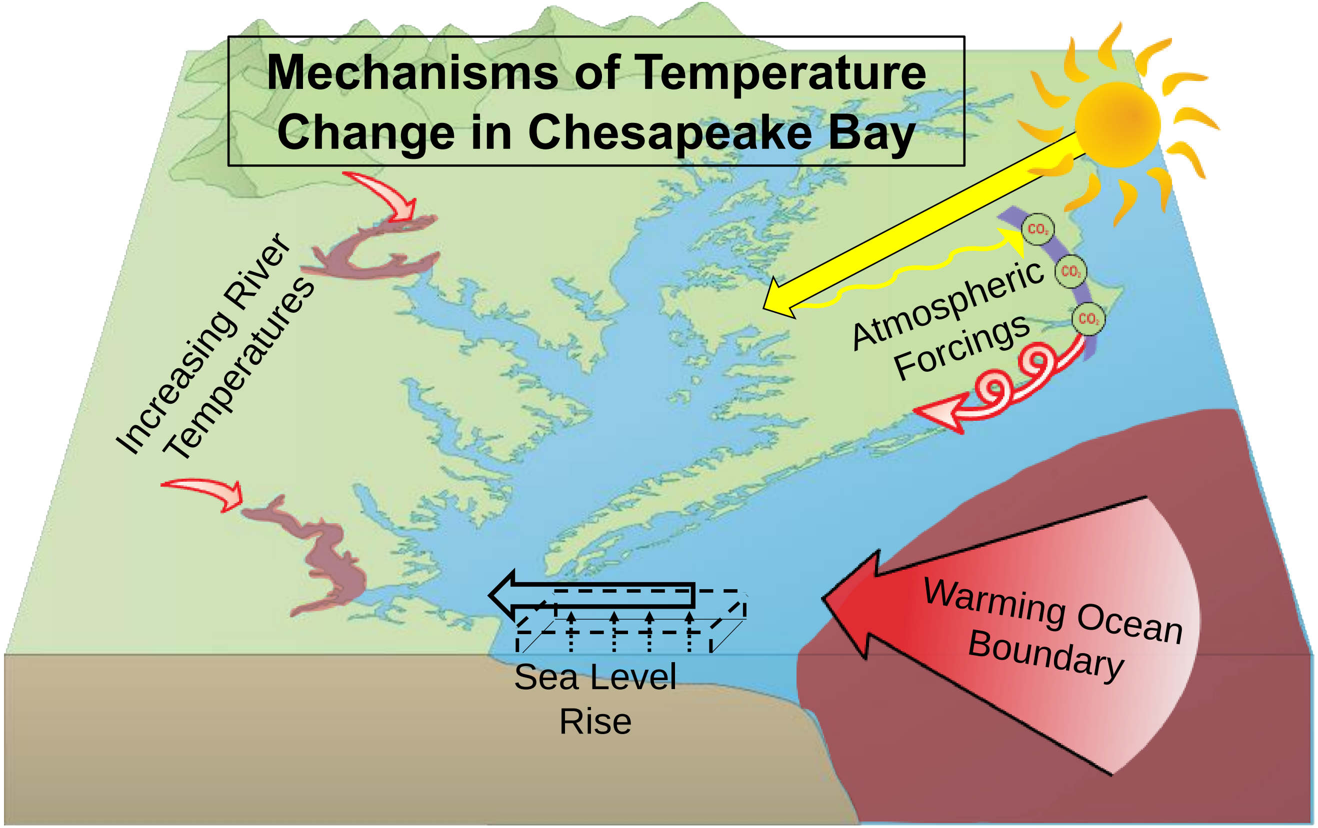
Extent and Causes of Chesapeake Bay Warming

Kyle E. Hinson, Marjorie A.M. Friedrichs, Pierre St-Laurent, Fei Da, and Raymond G. Najjar

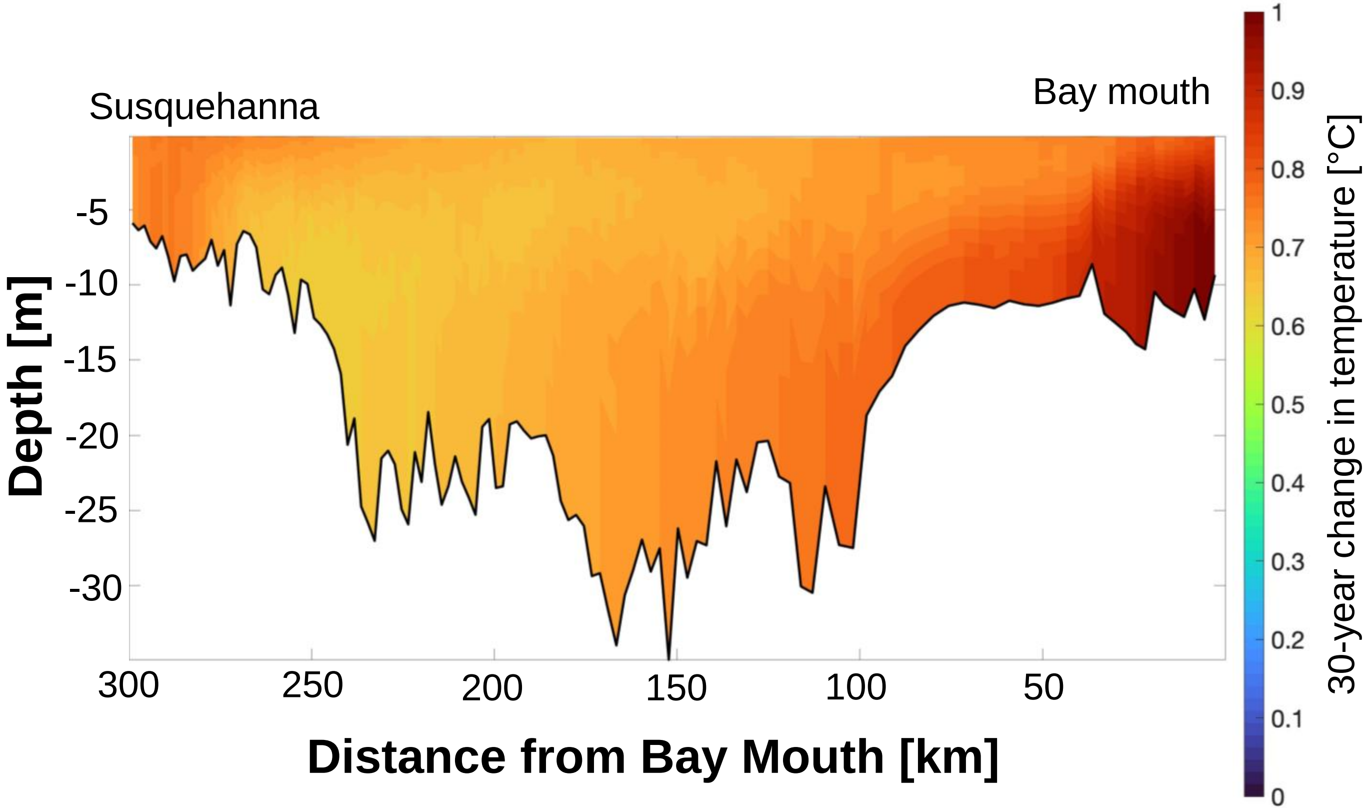
Research Impact Statement: Since 1985, the Chesapeake Bay has warmed three to four times faster in warmer than cooler months; this has been driven primarily by atmospheric changes and by ocean warming in the lower Bay.

ABSTRACT: Coastal environments such as the Chesapeake Bay have long been impacted by eutrophication stressors resulting from human activities, and these impacts are now being compounded by global warming trends. However, there are few studies documenting long-term estuarine temperature change and the relative contributions of rivers, the atmosphere, and the ocean. In this study, Chesapeake Bay warming, since 1985, is quantified using a combination of cruise observations and model outputs, and the relative contributions to that warming are estimated via numerical sensitivity experiments with a watershed–estuarine modeling system. Throughout the Bay's main stem, similar warming rates are found at the surface and bottom between the late 1980s and late 2010s (0.02 ± 0.02°C/year, mean ± 1 standard error), with elevated summer rates (0.04 ± 0.01°C/year) and lower rates of winter warming (0.01 ± 0.01°C/year). Most (~85%) of this estuarine warming is driven by atmospheric effects. The secondary influence of ocean warming increases with proximity to the Bay mouth, where it accounts for more than half of summer warming in bottom waters. Sea level rise has slightly reduced summer warming, and the influence of riverine warming has been limited to the heads of tidal tributaries. Future rates of warming in Chesapeake Bay will depend not only on global atmospheric trends, but also on regional circulation patterns in mid-Atlantic waters, which are currently warming faster than the atmosphere.

How is Chesapeake Bay temperature changing?



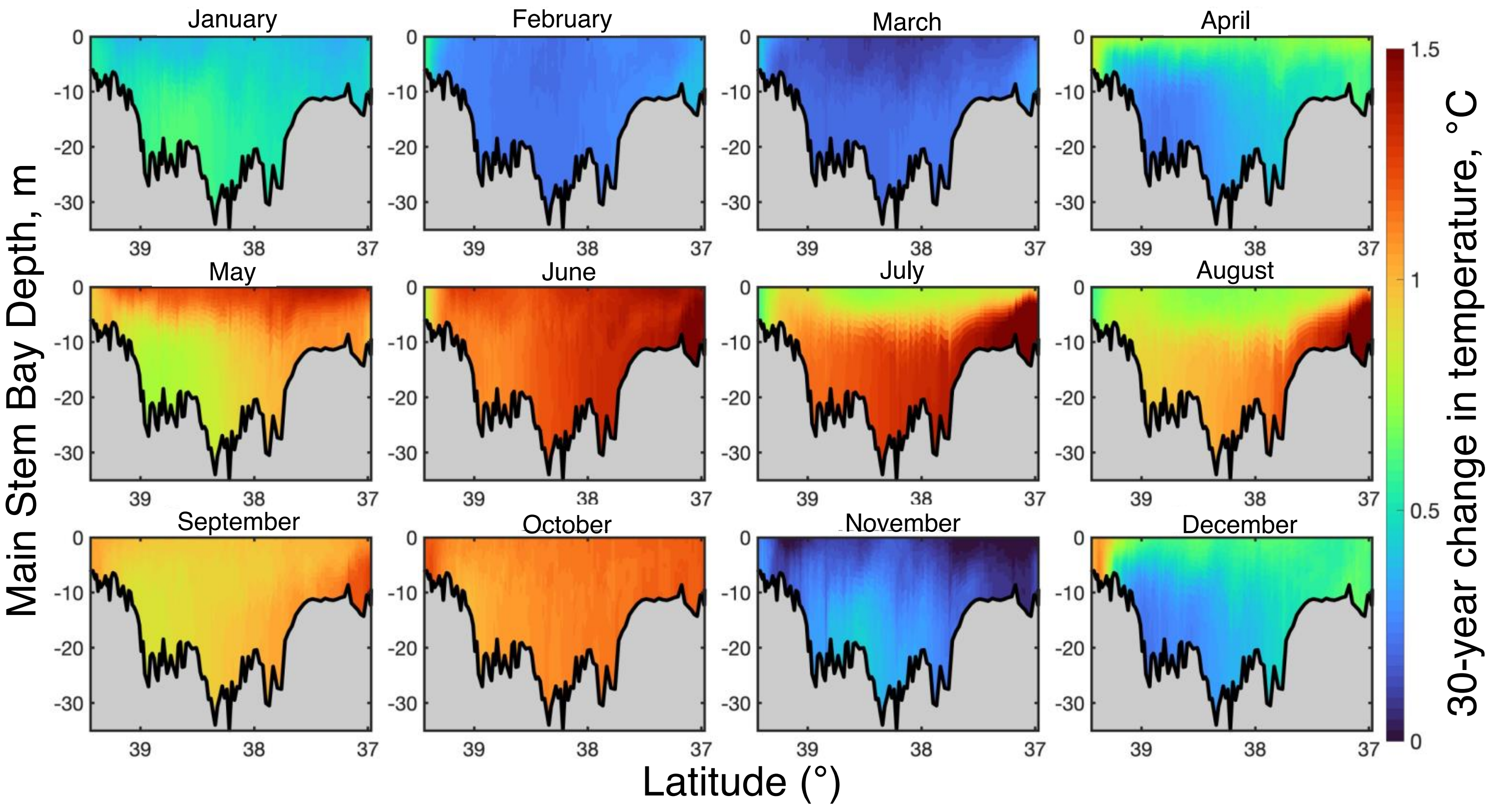
Bay has warmed ~0.7ºC over past 30 years



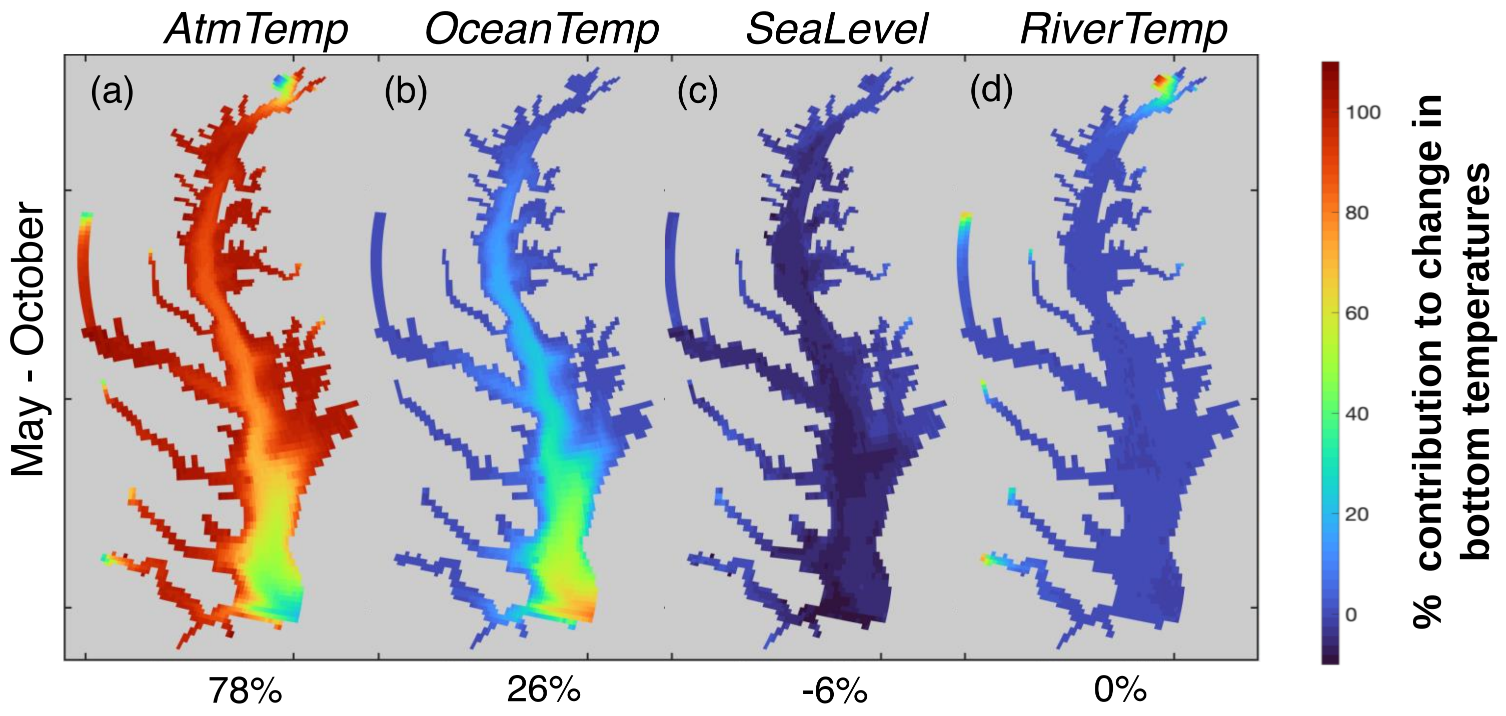
Where?

- Similar warming at bottom and surface
- More warming near Bay mouth

Bay has warmed 3 times more in summer months



Bay is warming due to atmospheric and oceanic warming



- Atmospheric warming dominates
- Ocean warming is important in VA waters
- Sea level rise cools Bay everywhere
- Rivers only important at heads of tributaries

Have nutrient management efforts been working? (Frankel et al., 2022)

Or…. How bad would Chesapeake Bay hypoxia be if nutrient reductions had *not* taken place over the past 35 years?

Science of the Total Environment 814 (2022) 152722

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

ELSEVIER

Nitrogen reductions have decreased hypoxia in the Chesapeake Bay: Evidence from empirical and numerical modeling

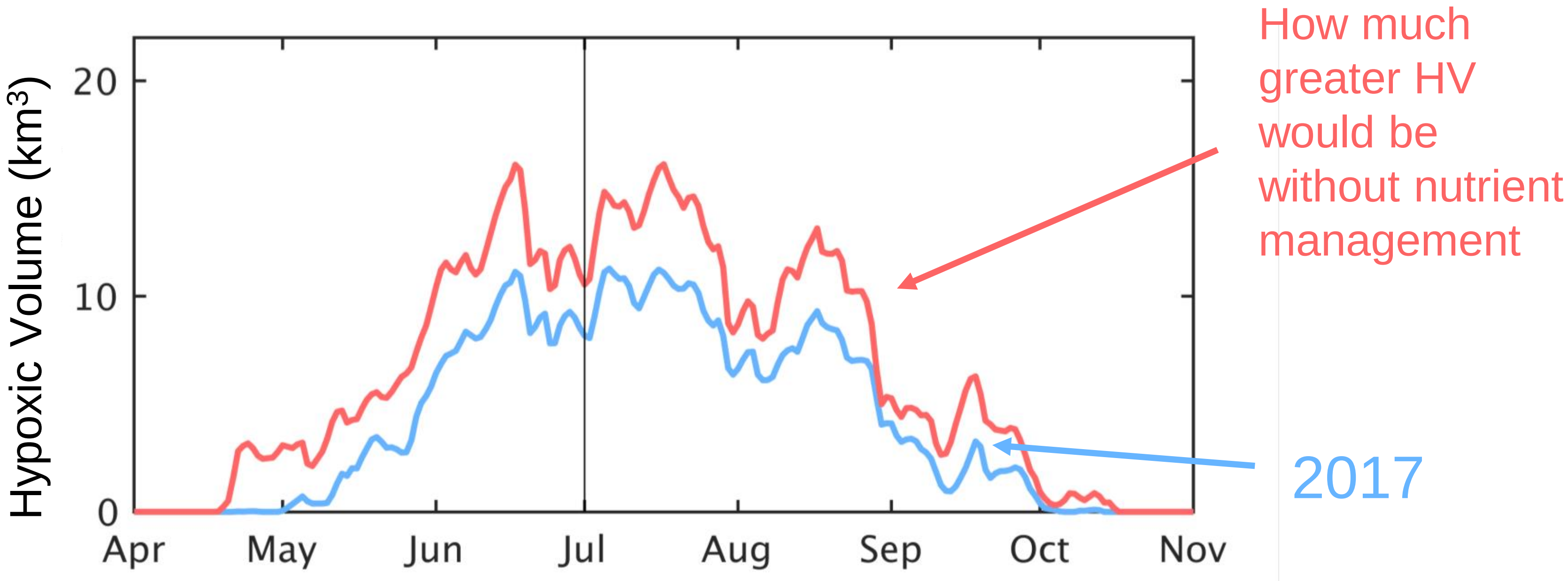
Check for updates

Luke T. Frankel[a,*], Marjorie A.M. Friedrichs[a], Pierre St-Laurent[a], Aaron J. Bever[b], Romuald N. Lipcius[a], Gopal Bhatt[c,d], Gary W. Shenk[c,e]

[a] Virginia Institute of Marine Science, William & Mary, 1370 Greate Road, Gloucester Point, VA, USA
[b] Anchor QEA LLC, 1201 3rd Avenue, Suite 2600, Seattle, WA, USA
[c] Chesapeake Bay Program Office, 1750 Forest Drive, Suite 130, Annapolis, MD, USA
[d] Department of Civil & Environmental Engineering, The Pennsylvania State University, 212 Sackett Building, University Park, PA, USA
[e] U.S. Geological Survey, Virginia and West Virginia Water Science Center, 1730 East Parham Road, Richmond, VA, USA

Without nutrient reductions, hypoxic volume would be 20-120% greater

(depending on year, and watershed model used)



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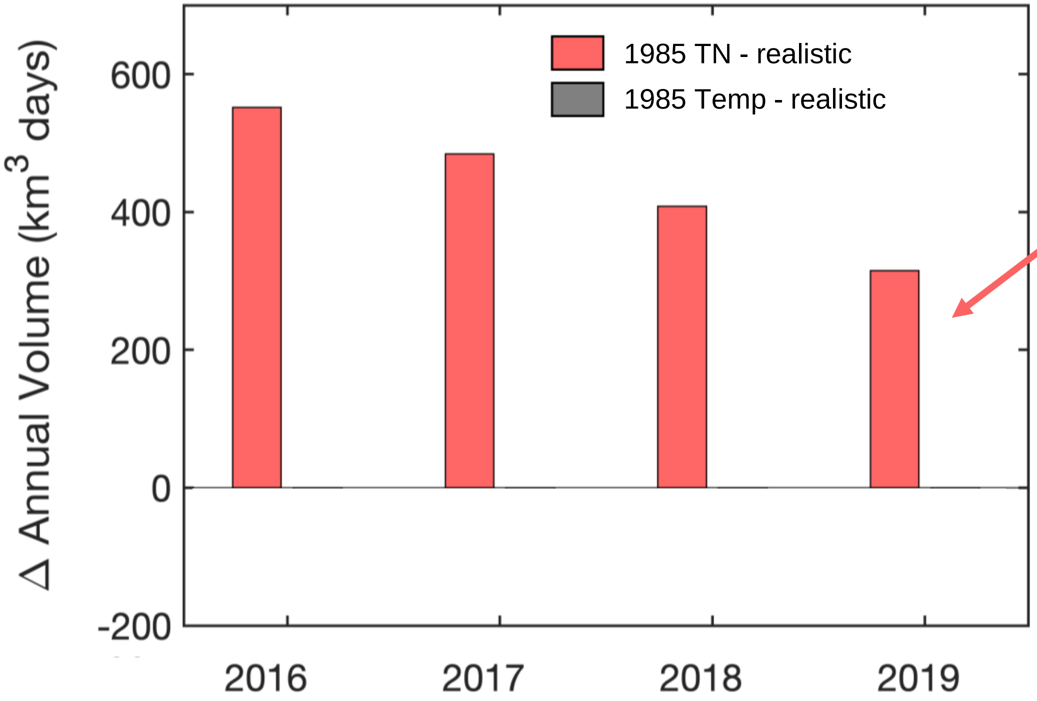
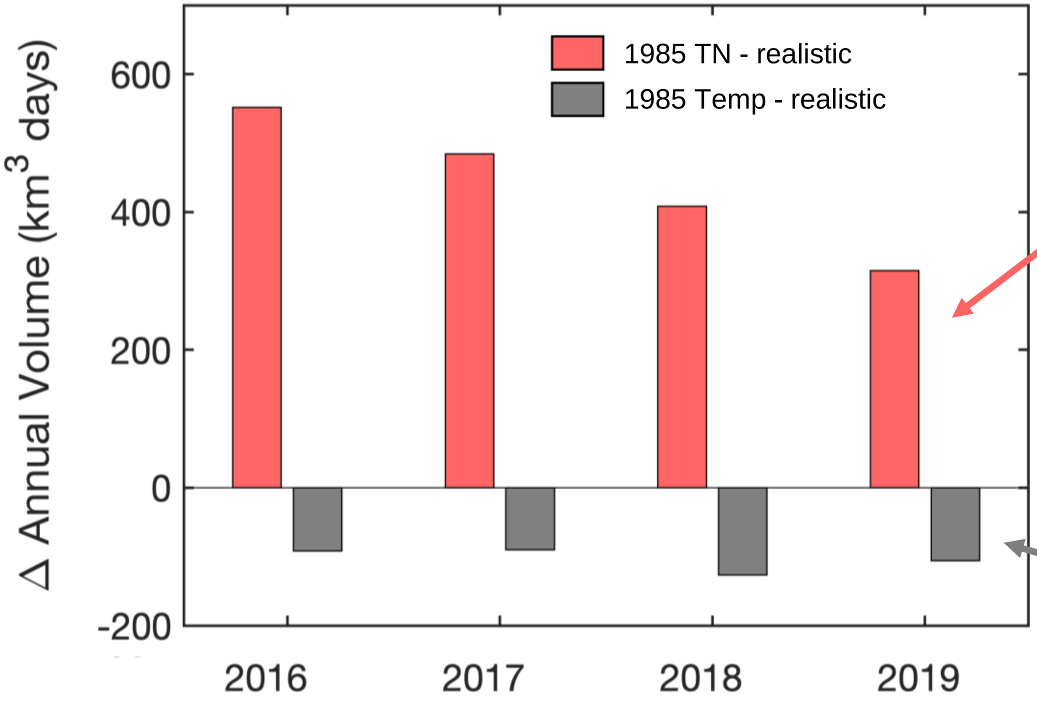


How much greater HV would be without nutrient management

Bay warming has offset 10-30% of improvements due nutrient reductions

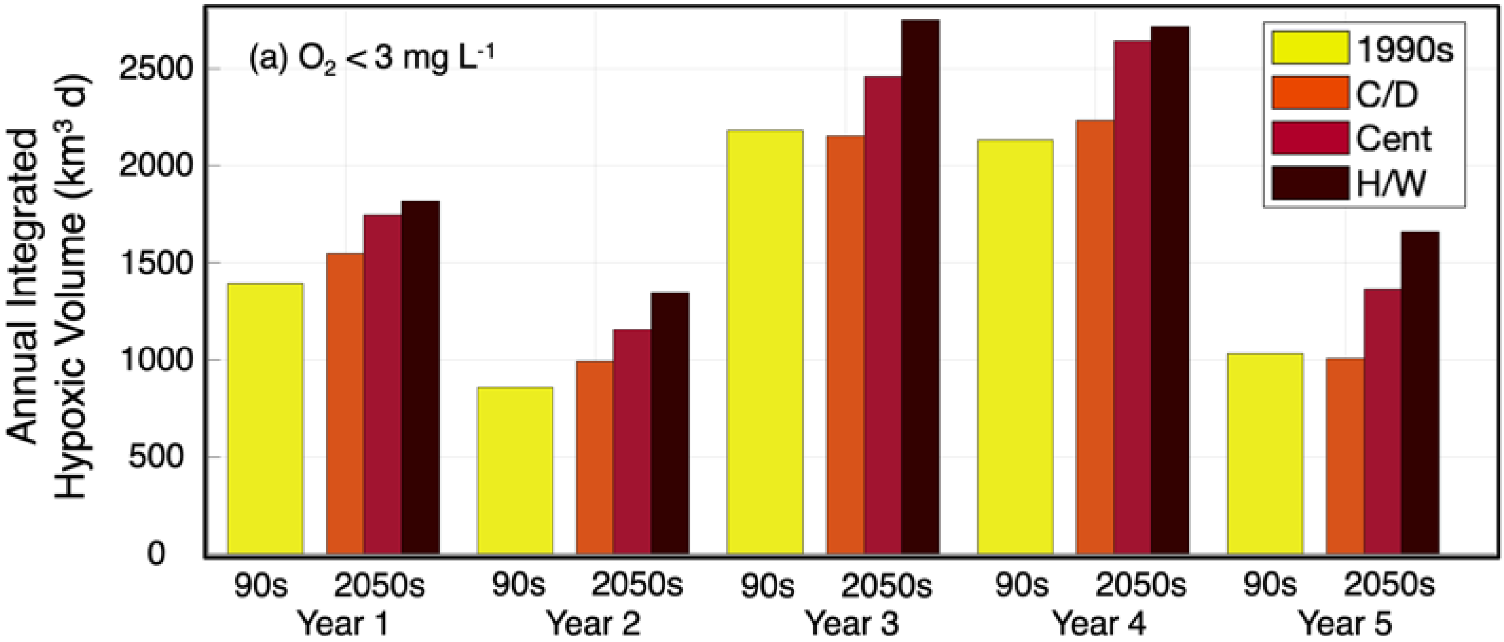


How much greater HV would be without nutrient management

How much better HV would be without climate change

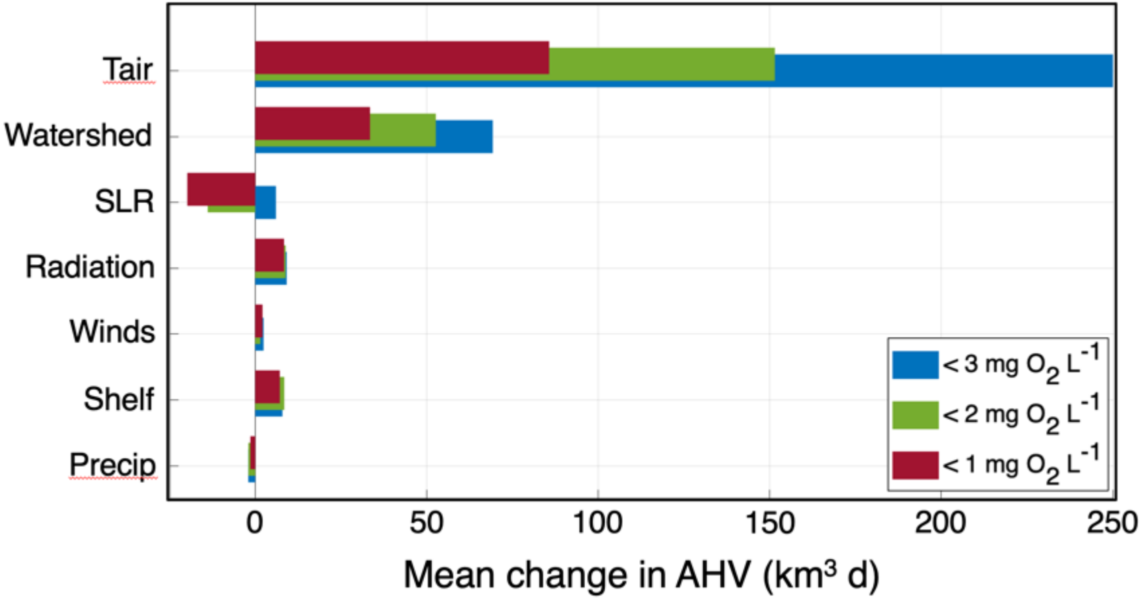
How much does future hypoxia depend on choice of ESM?

Magnitude of HV increase depends strongly on ESM used



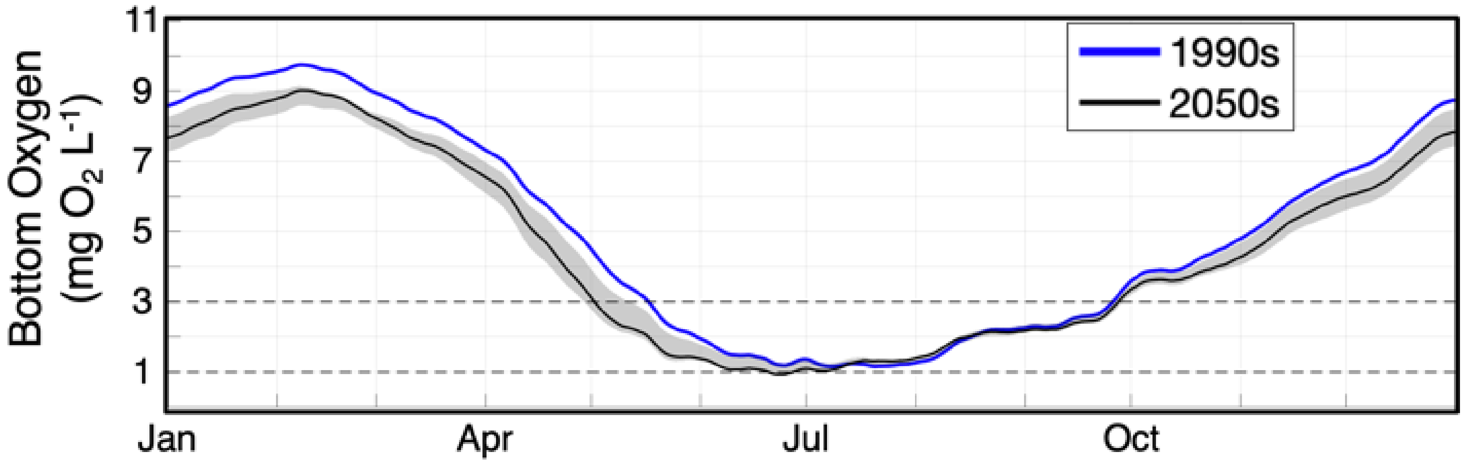
- All ESMs show increase in future hypoxia
- Magnitude of future change depends greatly on ESM
- Difference between wet and dry year > difference between 1990s and 2050s
- Similar magnitude of future change in all years (greater % increase in dry years)

Air temperature is responsible for most of increased hypoxic volume



Between 1990s and 2050s

Bottom O_2 is reduced all year
(except when O_2 is already near zero)



- Earlier start of hypoxia
- Similar date of termination

What will 2024 bring?

CHESAPEAKE BAY ENVIRONMENTAL FORECAST SYSTEM

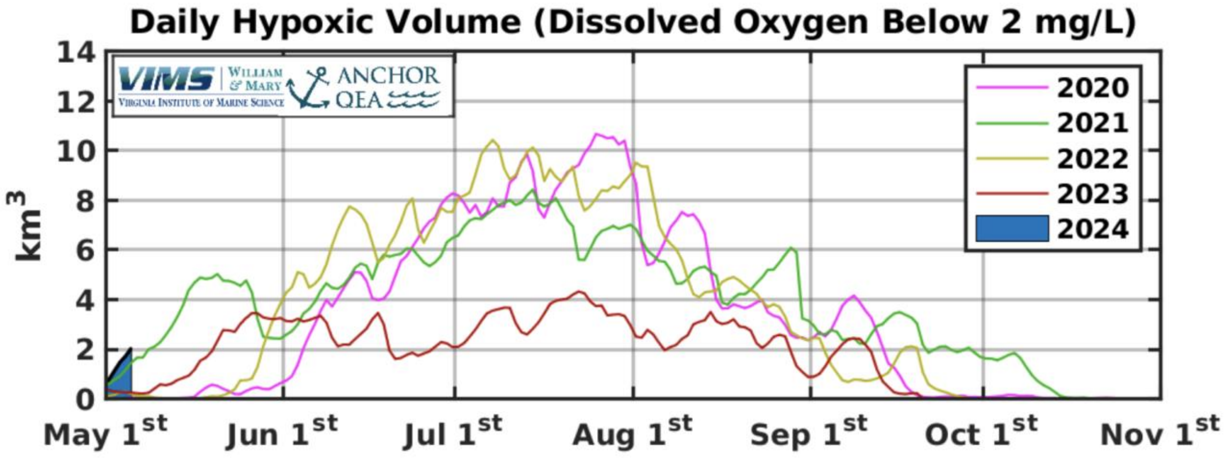
Background

Hypoxia (Oxygen)

Home / ... / CBEFS / Dead Zone Size

Real-time Estimates of Hypoxic Water Volume

Chesapeake Bay



Olivia Szot, in prep.

- Timing of onset is determined by May winds and temperatures
- Magnitude of hypoxic volume is determined by nutrient inputs

www.vims.edu/cbefs

Outline: CHAMP results

Marjy:

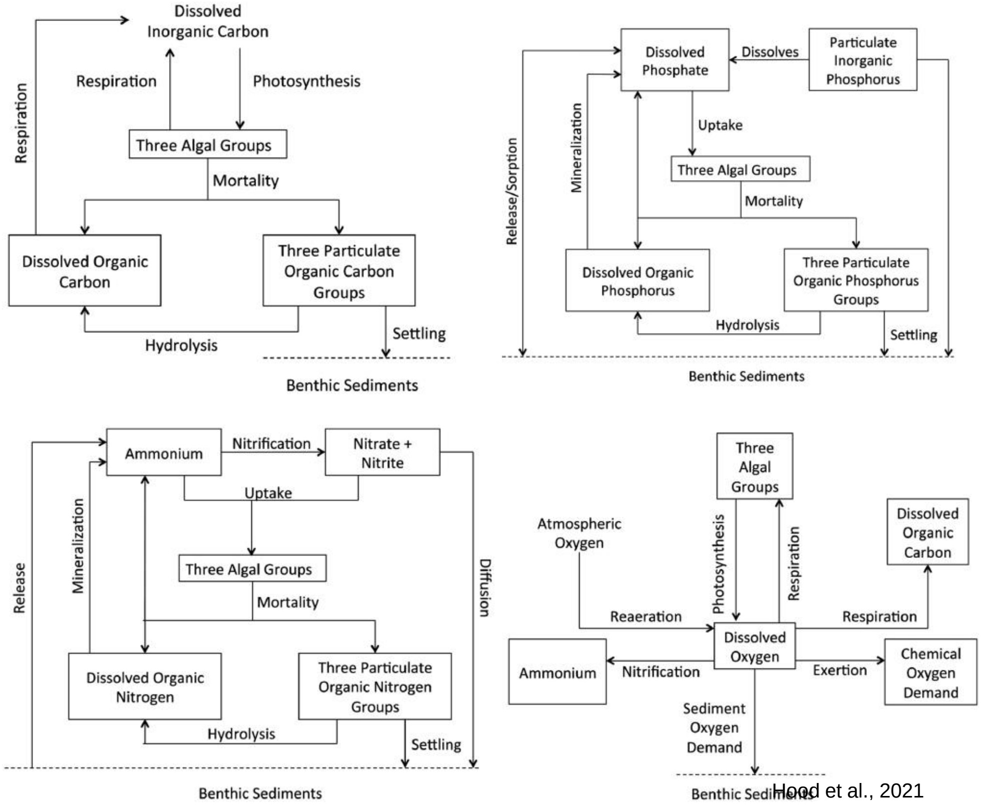
Ike Irby et al., 2018
Pierre St-Laurent et al., 2019
Kyle Hinson et al., 2021
Luke Frankel et al., 2022
Colin Hawes et al., in prep
Olivia Szot et al., in prep

Kyle:

Kyle Hinson et al., 2023
Kyle Hinson et al., submitted

Uncertainties in Climate Projections

- Our confidence in future hypoxia projections is dependent on:
  - Internal model dynamics



Hood et al., 2021

Uncertainties in Climate Projections

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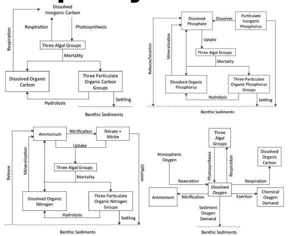
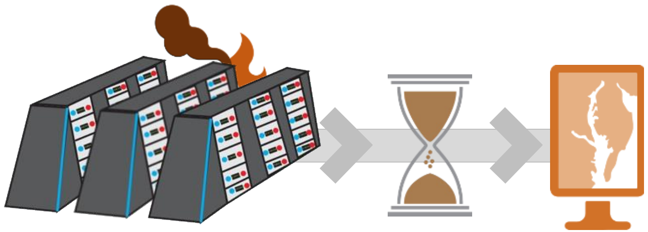
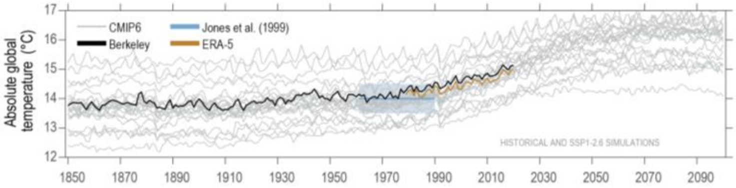


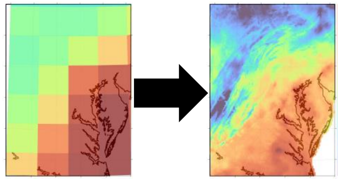
  - How many climate scenarios we simulate



  - How we select future climate scenarios

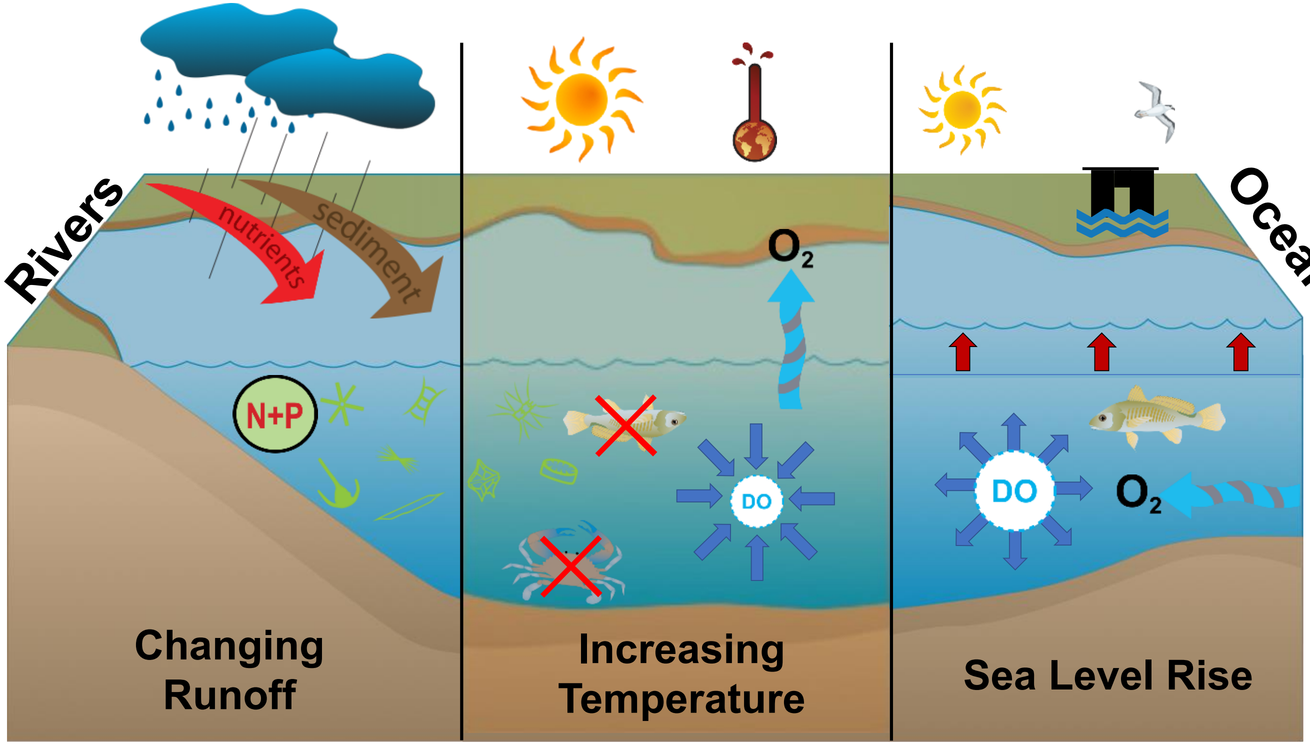


  - Applied methods to convert global to regional forcings



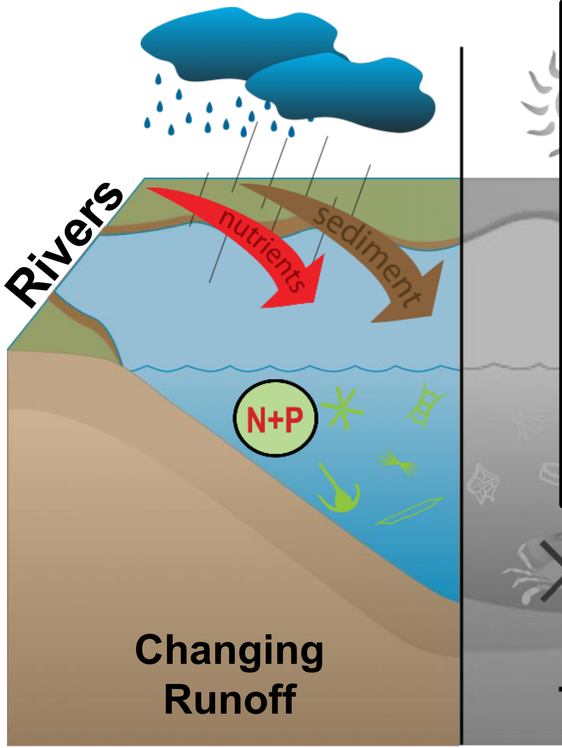
External Climate Inputs

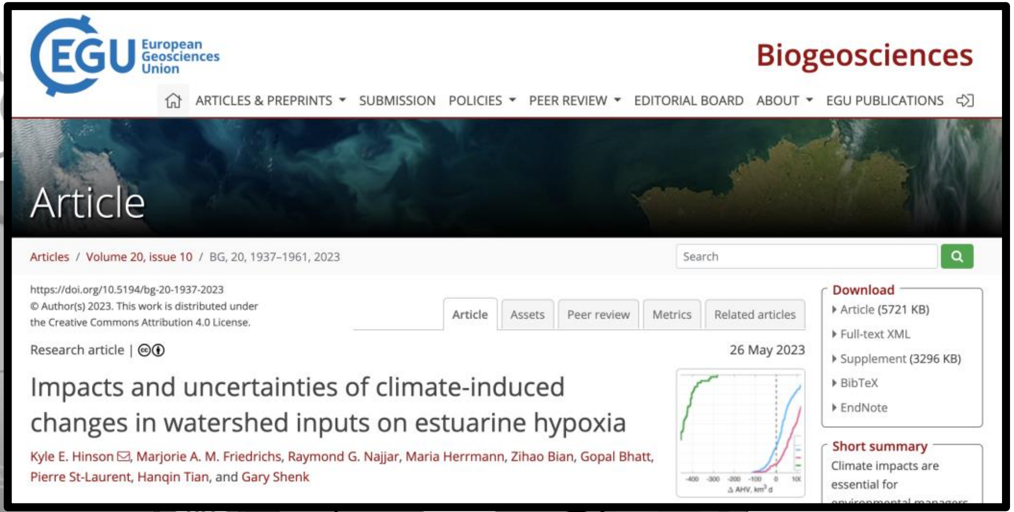
Climate Change and Watershed Impacts



- Climate change affects Chesapeake Bay oxygen levels in multiple ways

Climate Change and Watershed Impacts





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Research article | 26 May 2023

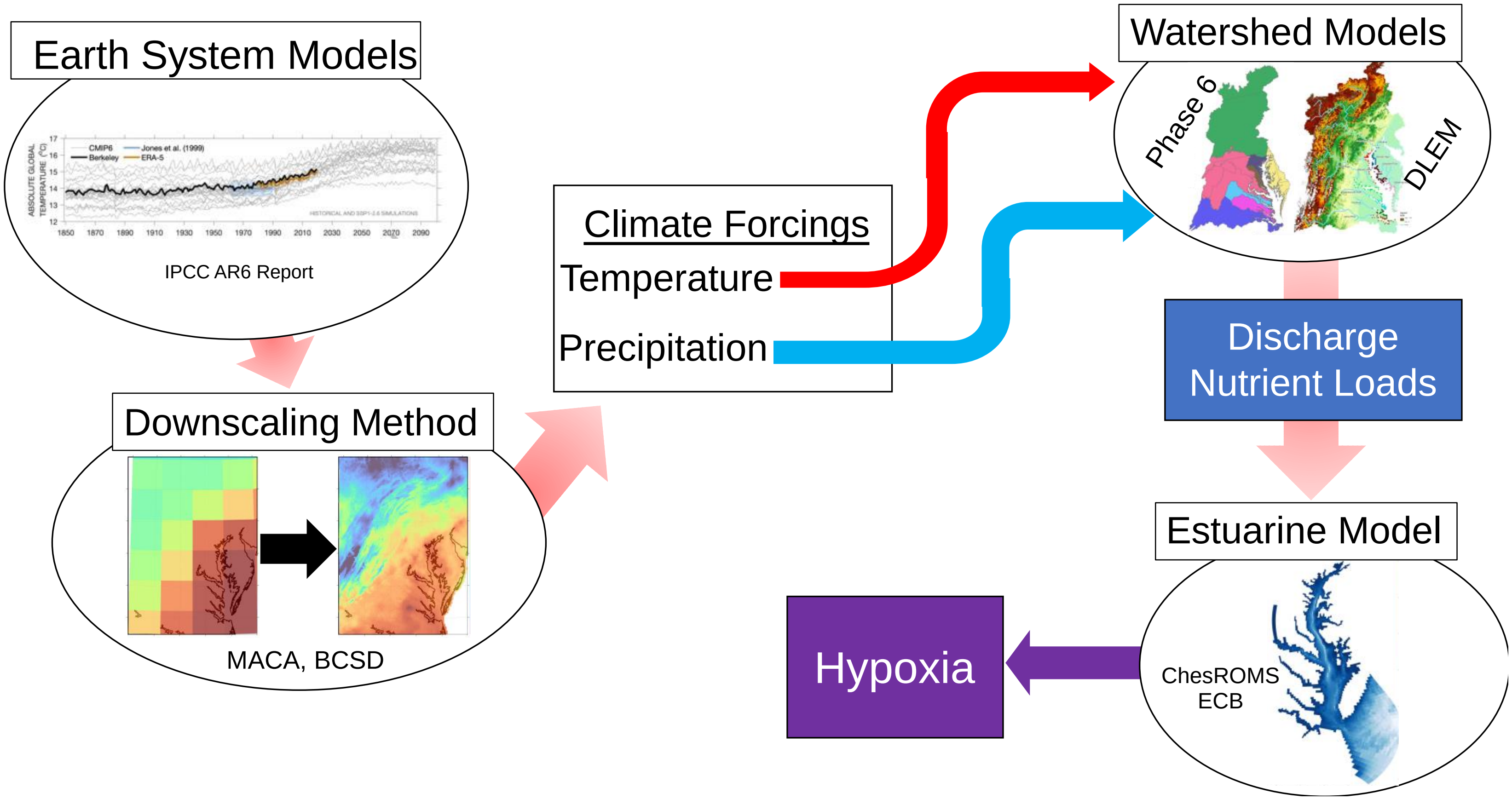
Impacts and uncertainties of climate-induced changes in watershed inputs on estuarine hypoxia

Kyle E. Hinson, Marjorie A. M. Friedrichs, Raymond G. Najjar, Maria Herrmann, Zihao Bian, Gopal Bhatt, Pierre St-Laurent, Hanqin Tian, and Gary Shenk

Download
- Article (5721 KB)
- Full-text XML
- Supplement (3296 KB)
- BibTeX
- EndNote

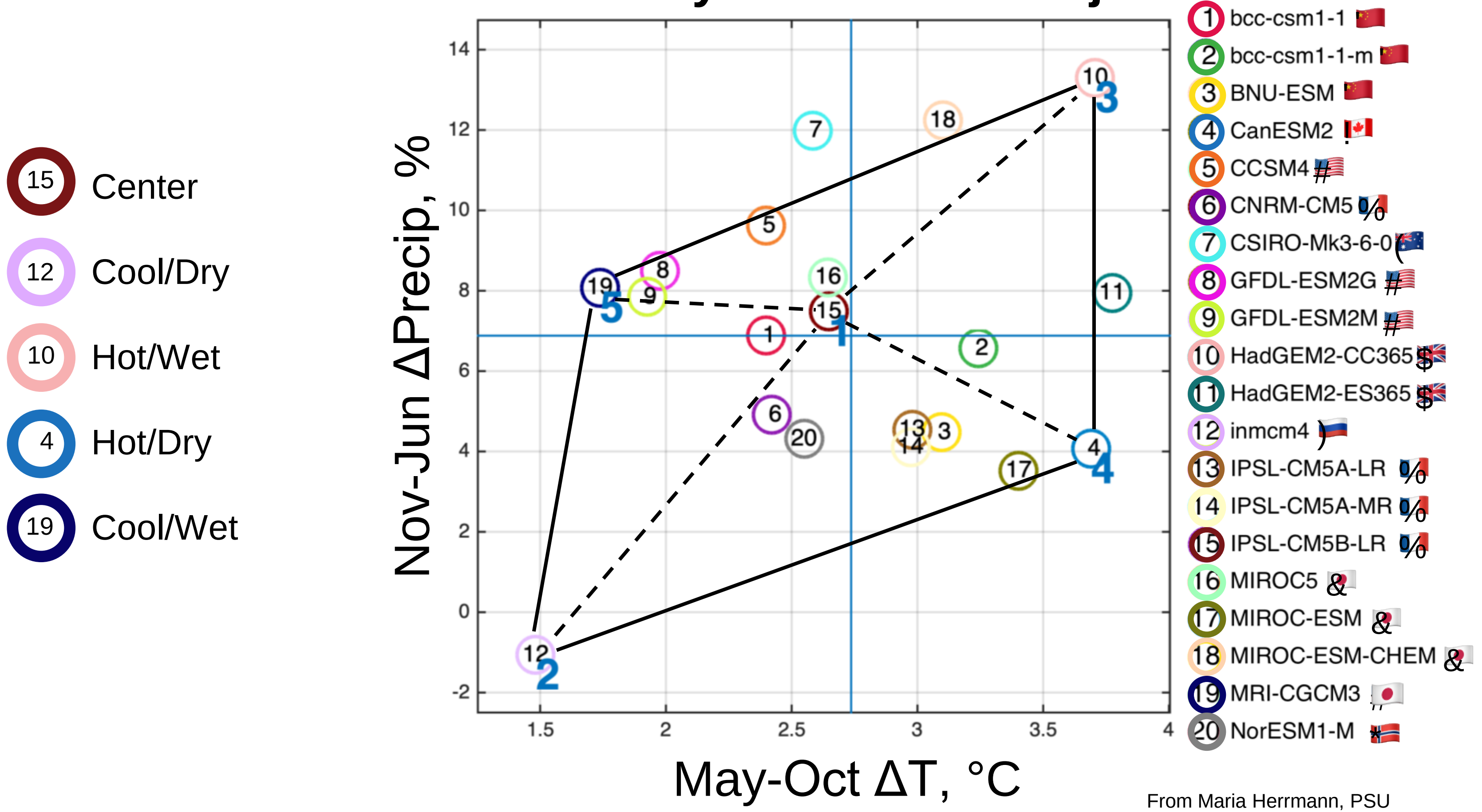
Short summary
Climate impacts are essential for environmental managers

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

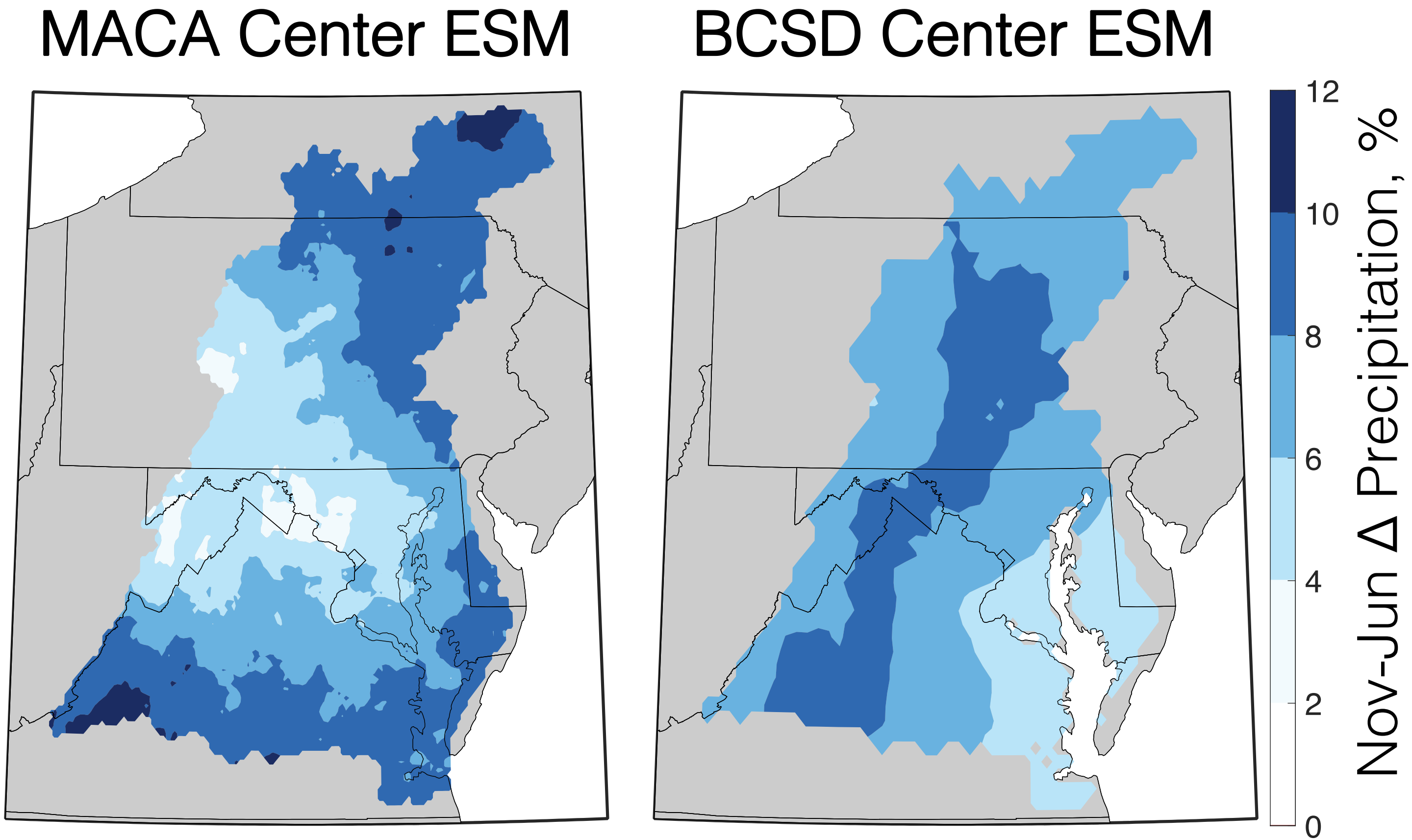


Numerous sources of uncertainty are implicitly built into climate projections.

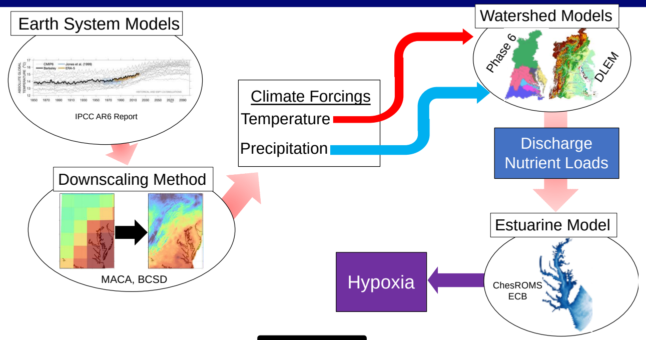
2050 Earth System Model Projections



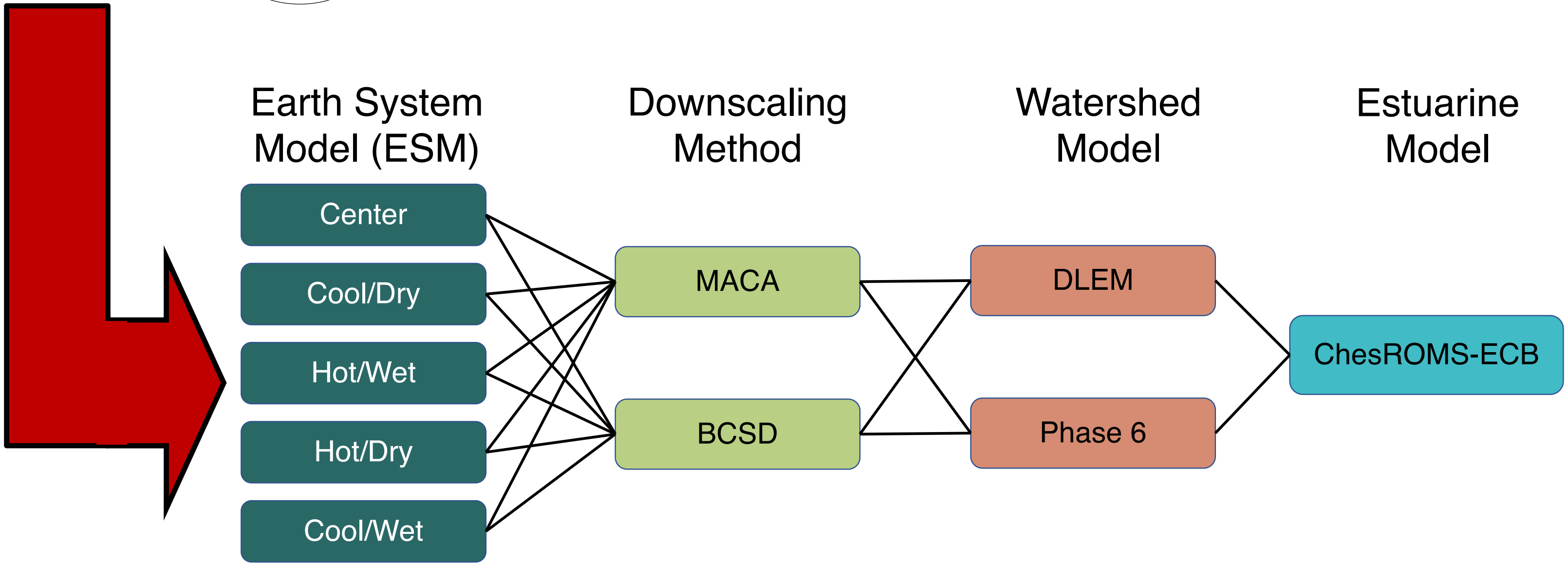
From Maria Herrmann, PSU



- Downscaling methodology affects spatial distribution of future climate inputs



Multiple uncertainties addressed using 20+ 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

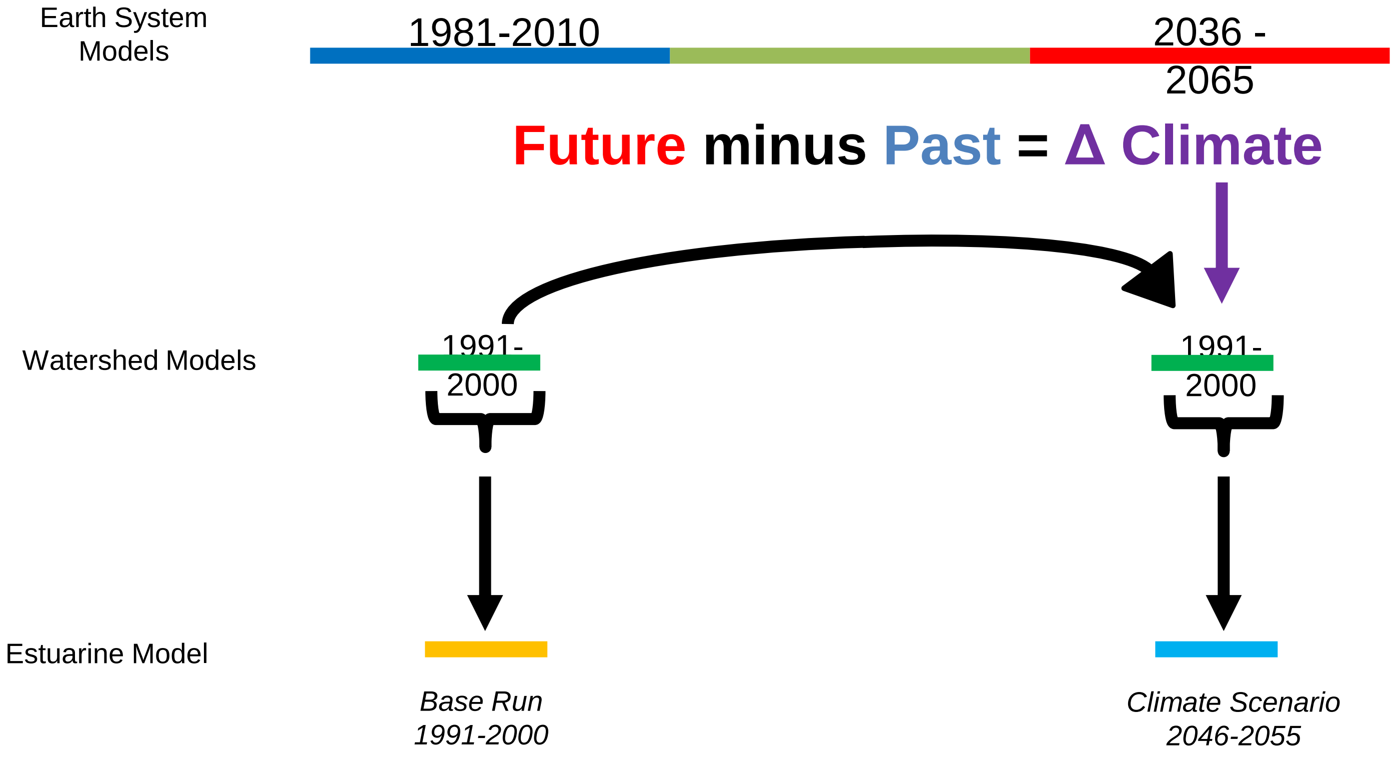
Watershed Models

1991-2000

Estuarine Model

Base Run 1991-2000

Climate Forcing – Delta Method



ChesROMS-ECB Overview

Atmospheric Inputs

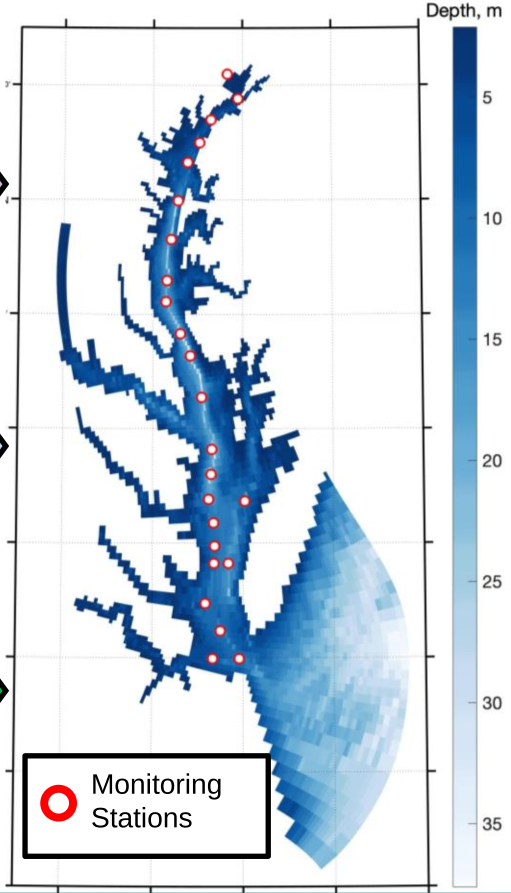
→ Hindcast weather data

Coastal Fluxes

→ Climatological data

Riverine Inputs

→ Phase 6 Watershed Model
→ DLEM Watershed Model



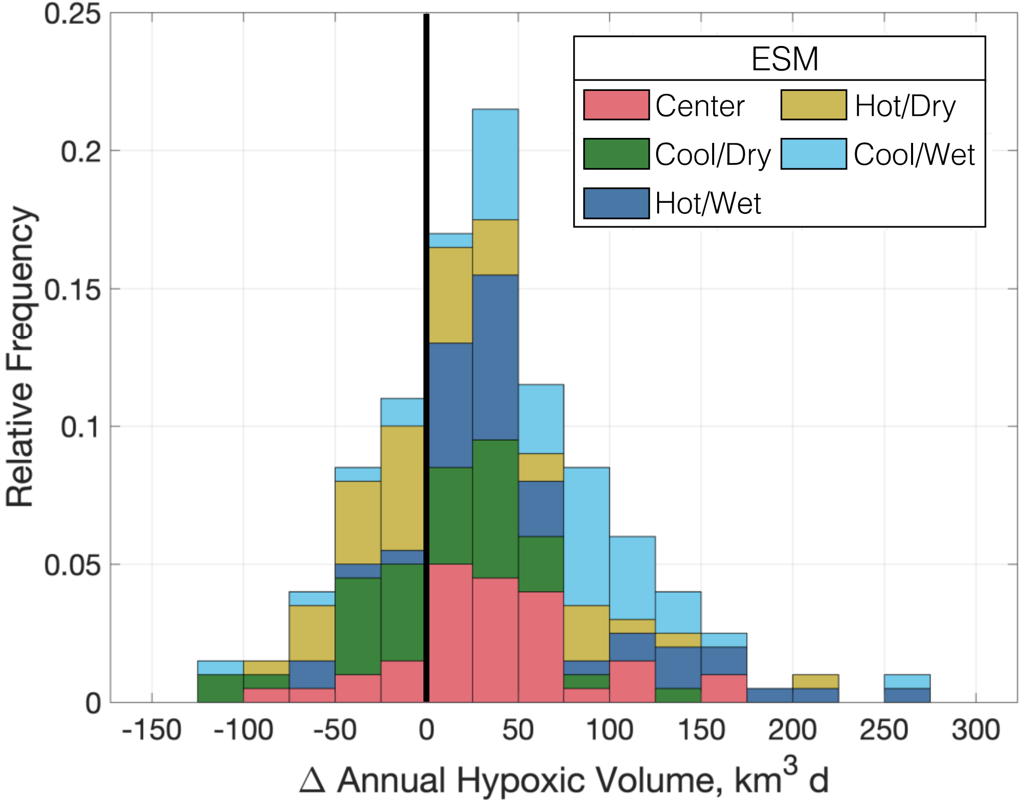
Model Information

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

Model Outputs

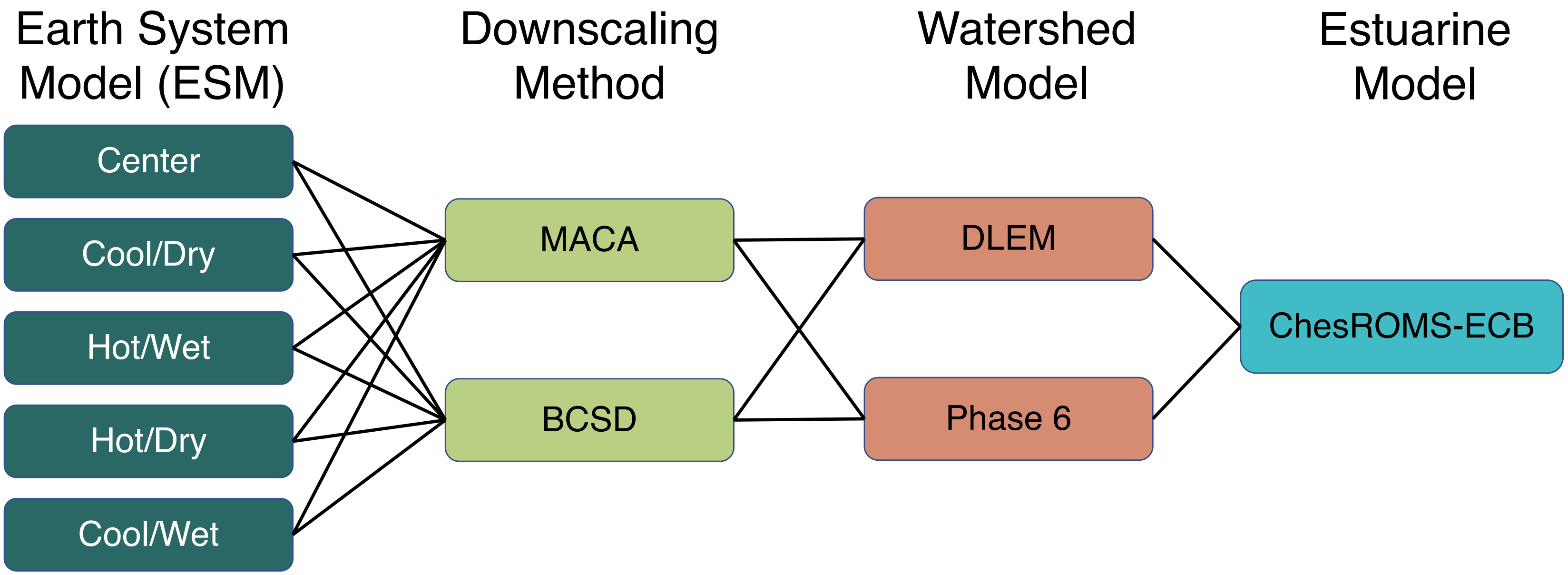
Hydrodynamics and Biogeochemistry

Quantifying Scenario Uncertainty



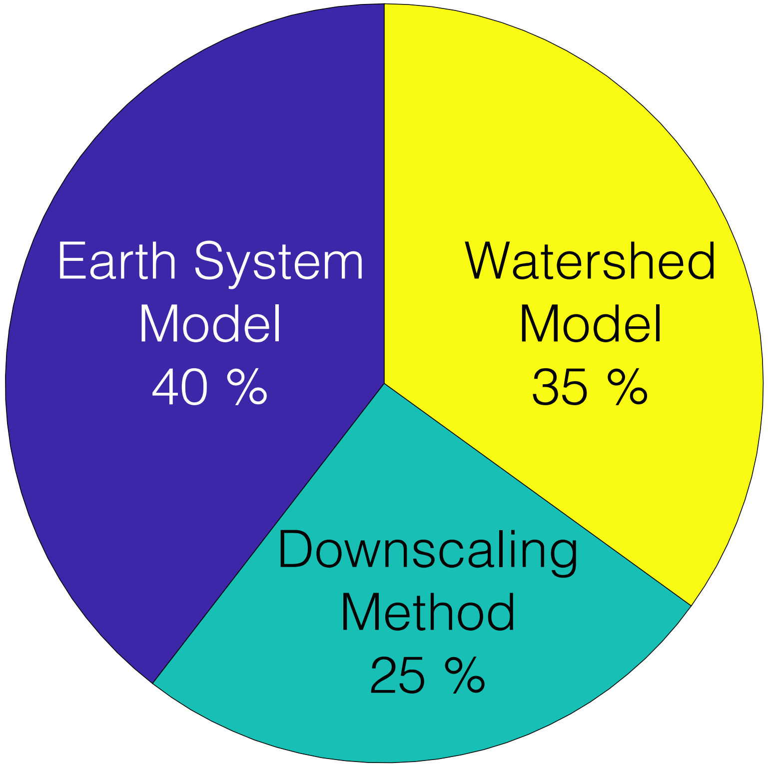
- Average increase in Bay hypoxia of 4±7%, ~3/4 of scenarios decrease O_2

Quantifying Scenario Uncertainty

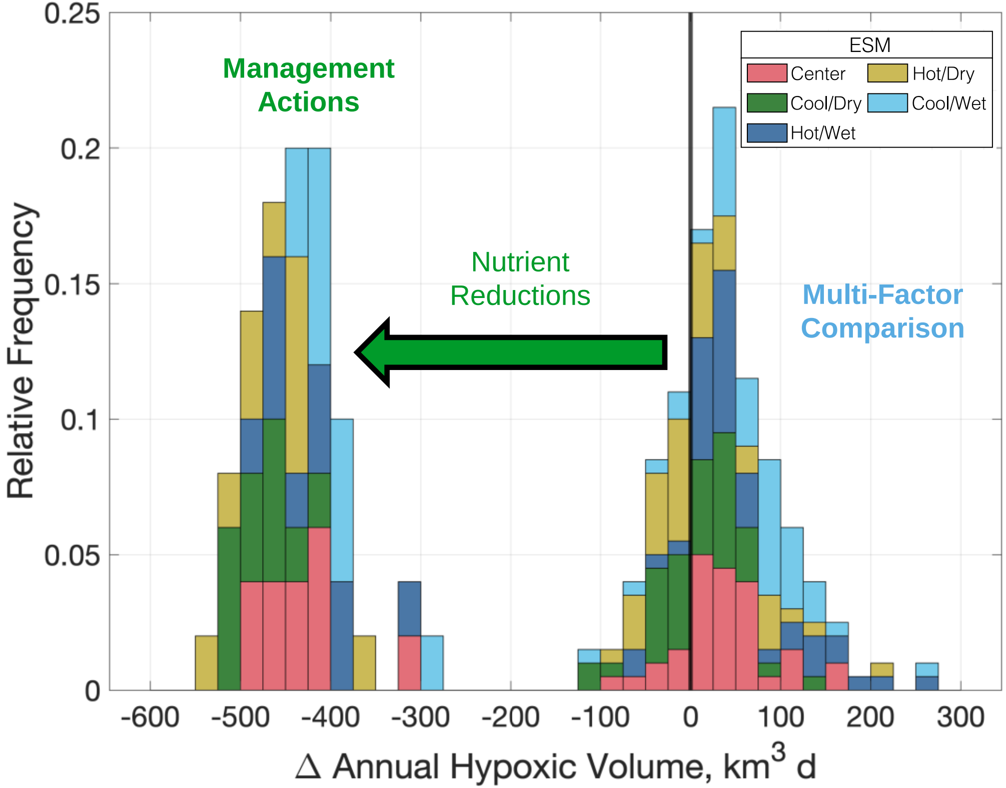


Hypoxia Cumulative Uncertainty

- 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.
- *How do these results compare to uncertainties in management actions?*

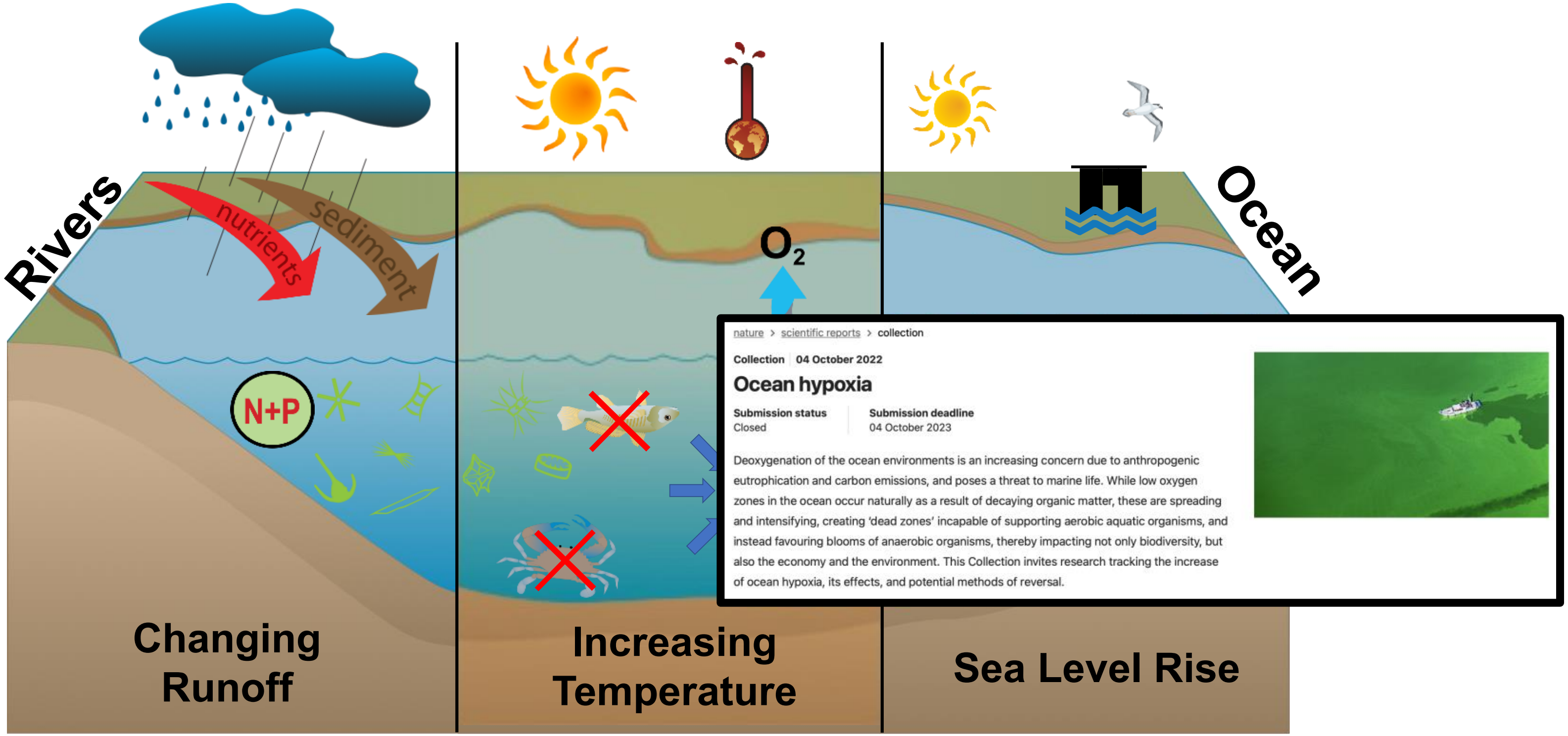


Management Context



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

Climate Scenario Method Comparison



nature > scientific reports > collection

Collection | 04 October 2022

Ocean hypoxia

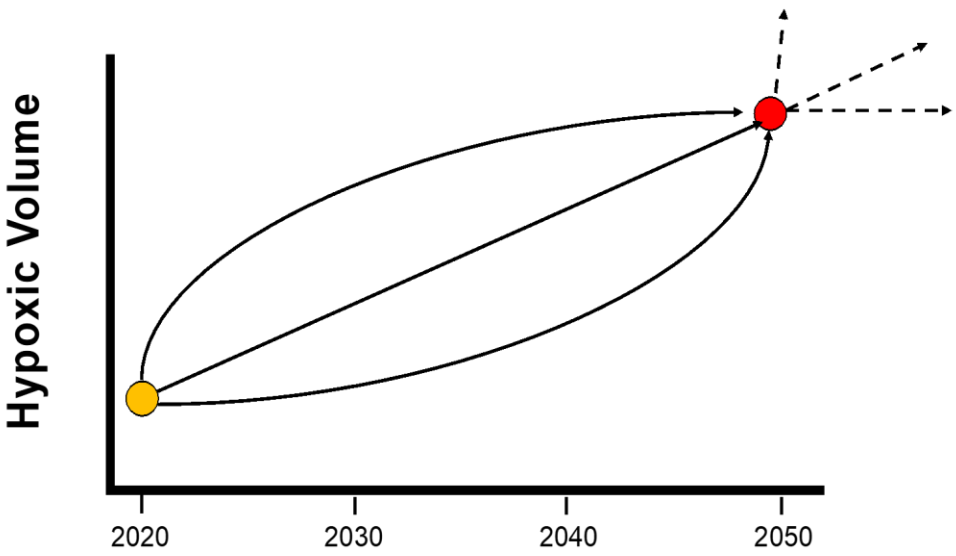
Submission status
Closed

Submission deadline
04 October 2023

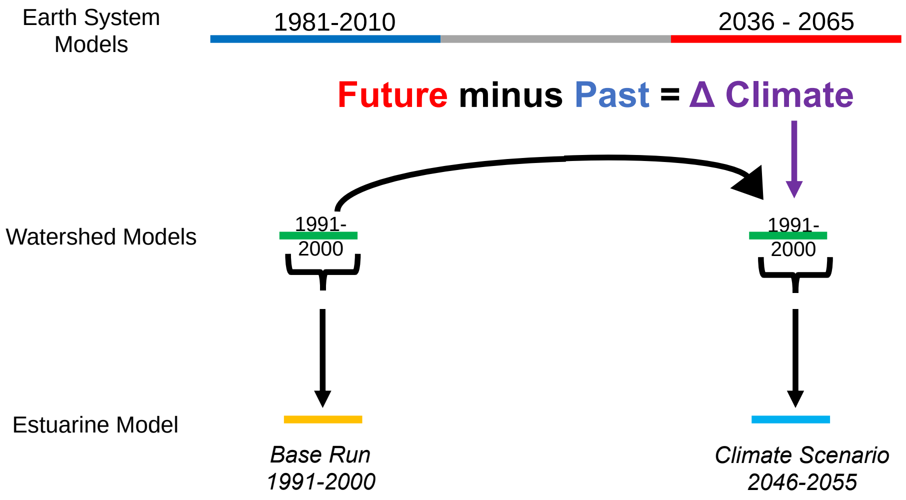
Deoxygenation of the ocean environments is an increasing concern due to anthropogenic eutrophication and carbon emissions, and poses a threat to marine life. While low oxygen zones in the ocean occur naturally as a result of decaying organic matter, these are spreading and intensifying, creating 'dead zones' incapable of supporting aerobic aquatic organisms, and instead favouring blooms of anaerobic organisms, thereby impacting not only biodiversity, but also the economy and the environment. This Collection invites research tracking the increase of ocean hypoxia, its effects, and potential methods of reversal.

- All climate change impacts applied to future Chesapeake Bay scenarios

Climate Scenario Method Comparison



Continuous Simulation

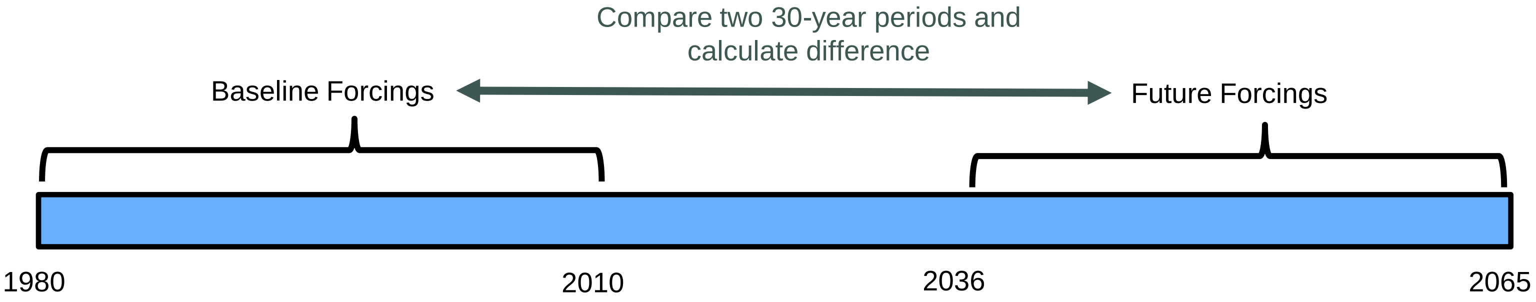


Delta Simulation

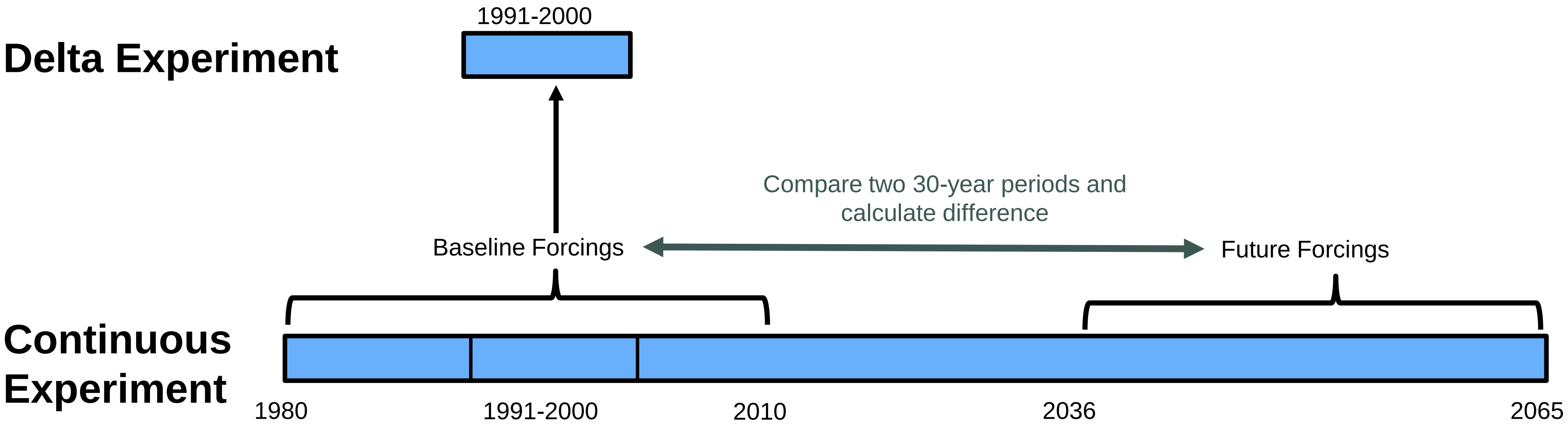
- Does the method used have a substantial impact on hypoxia projections?

Experimental Design

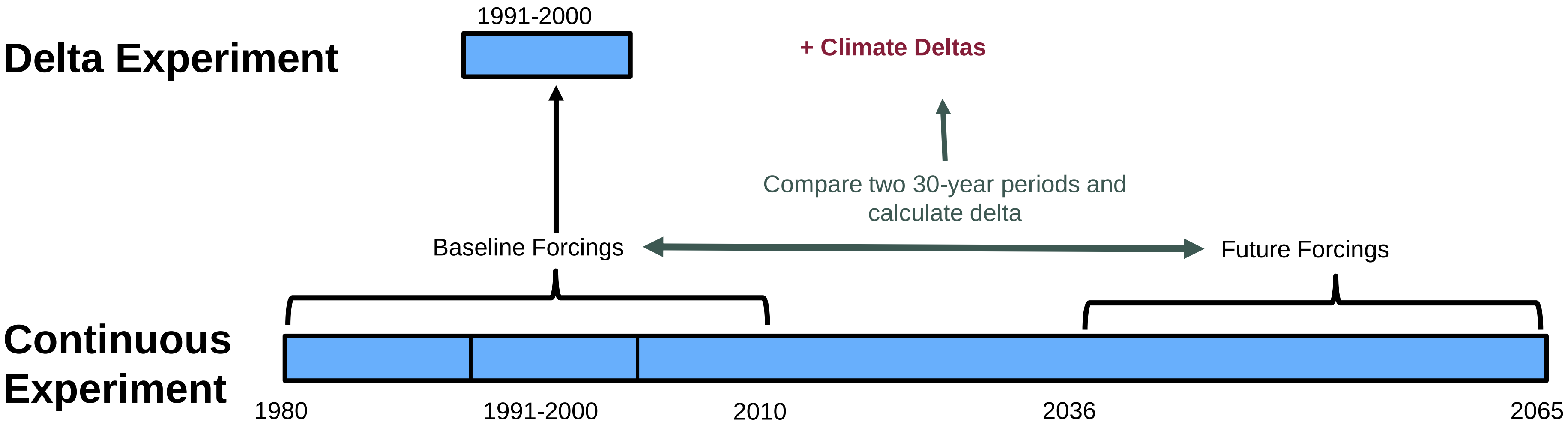
Continuous Experiment



Experimental Design



Experimental Design



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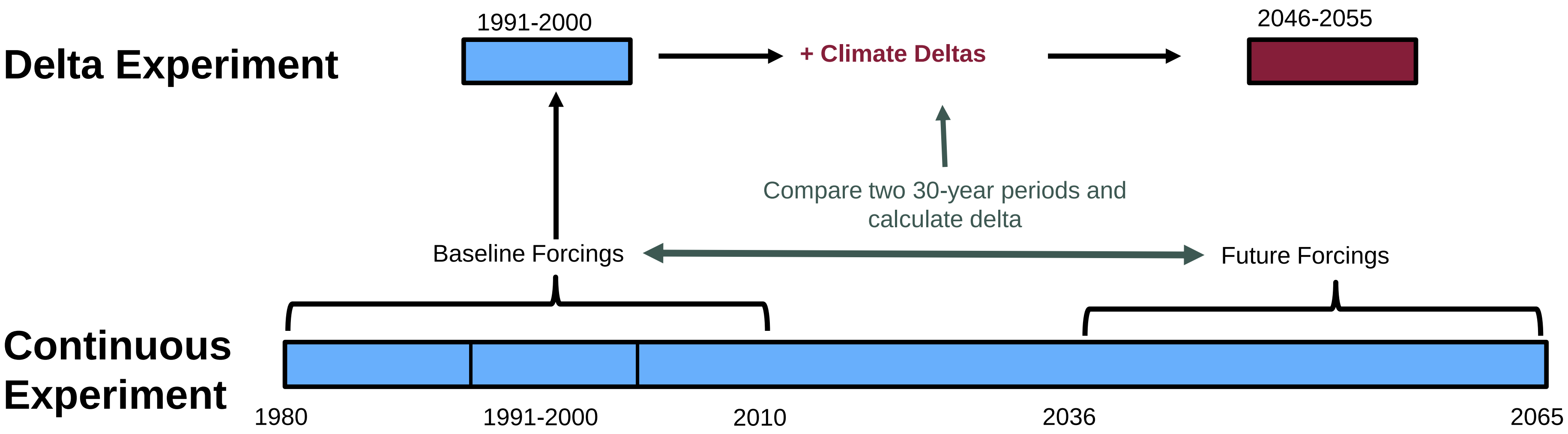

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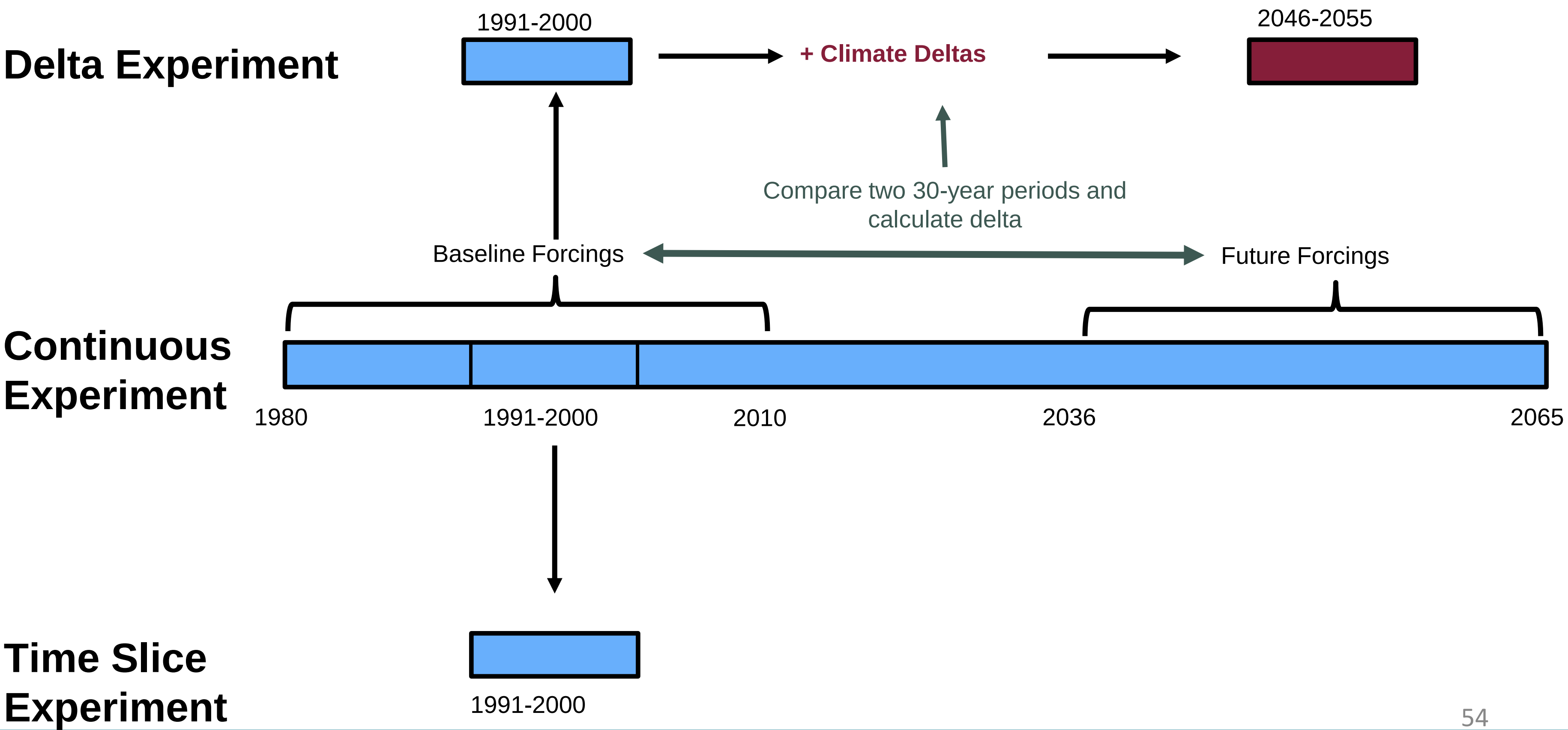

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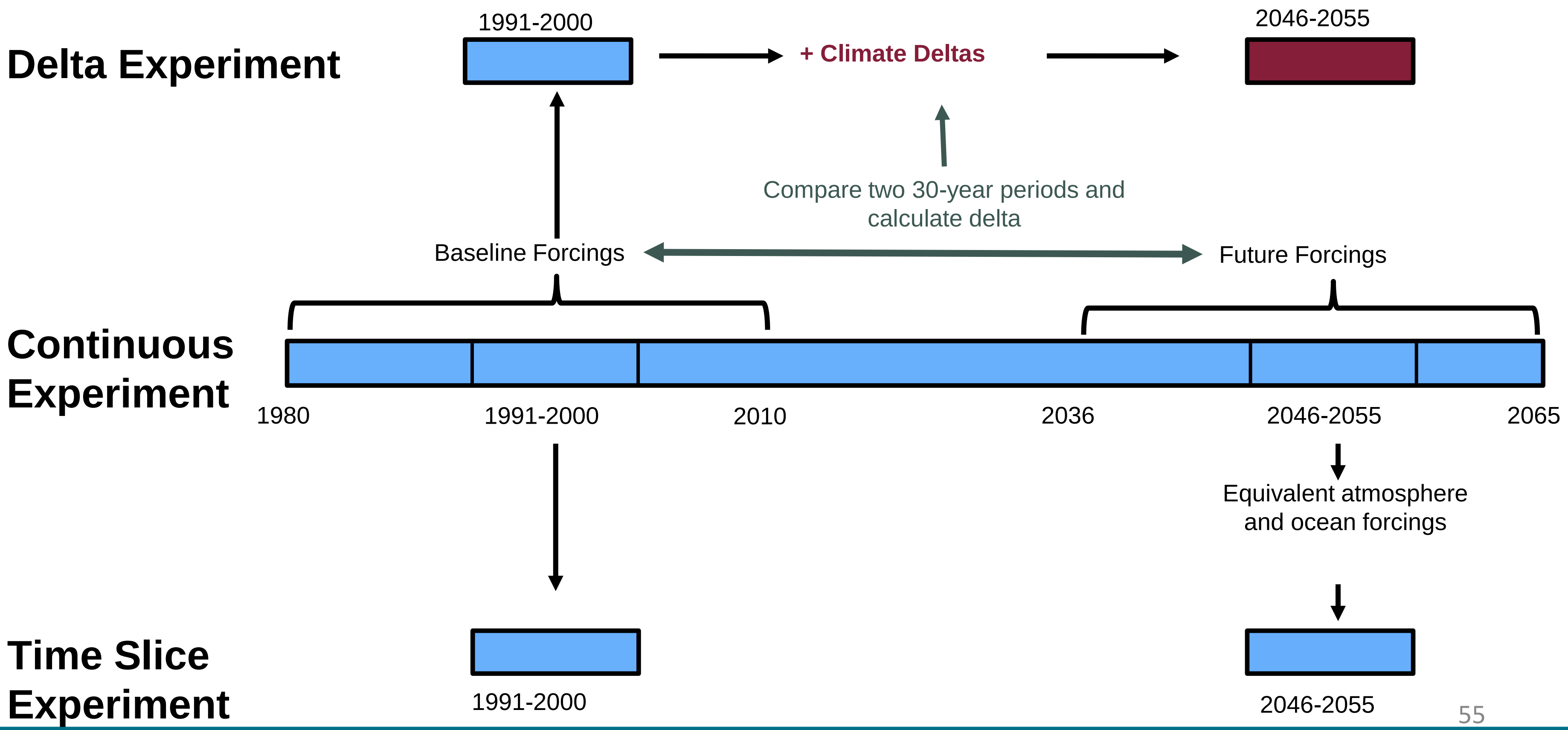

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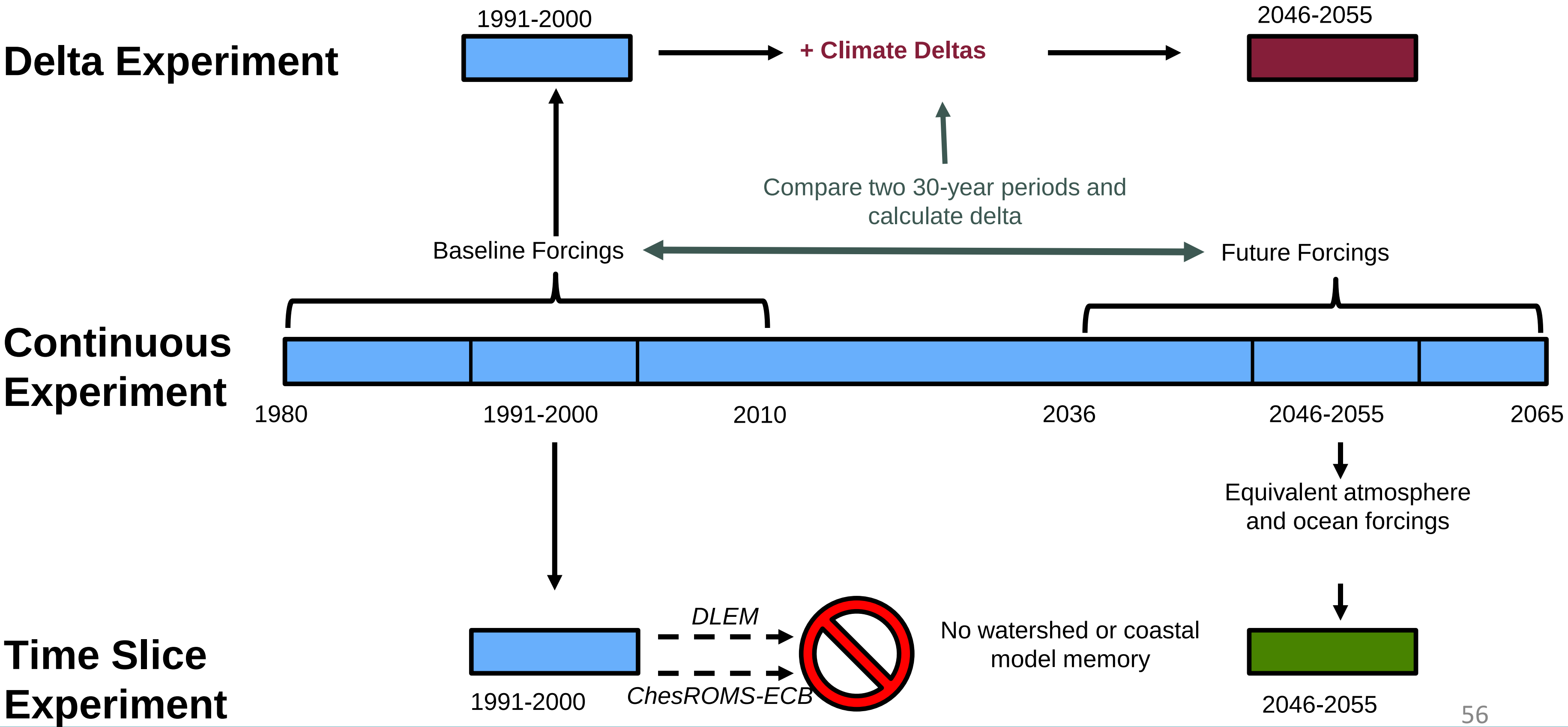
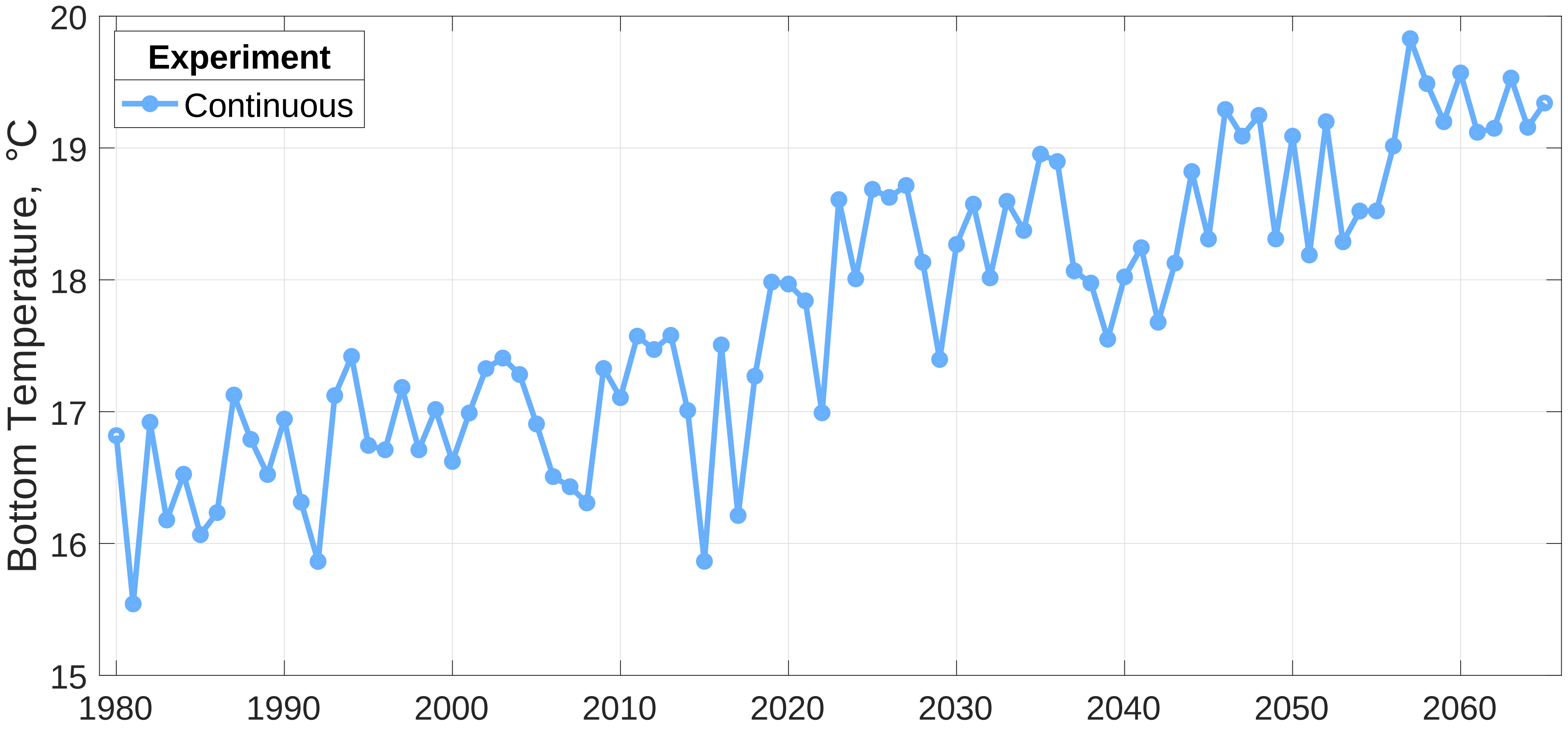
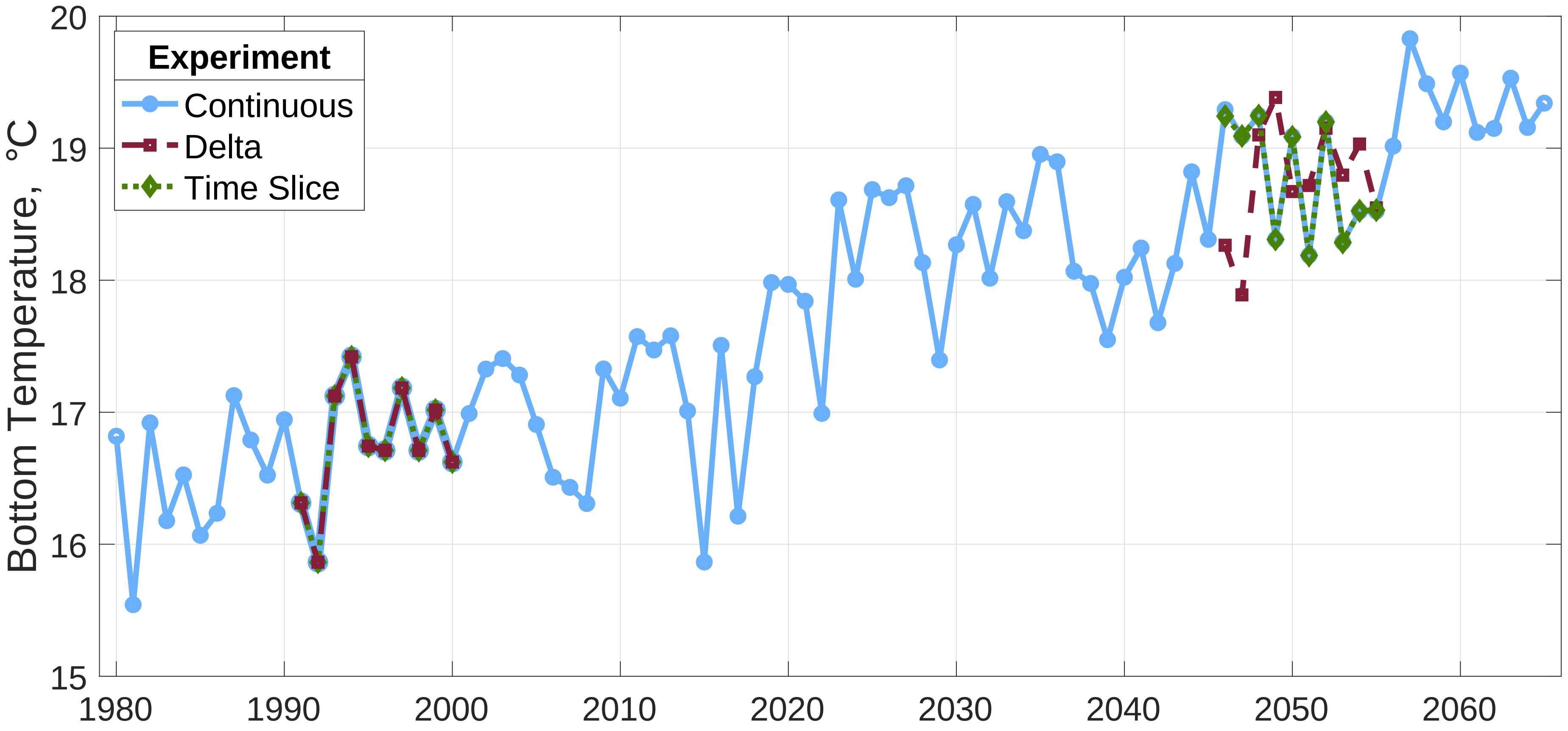
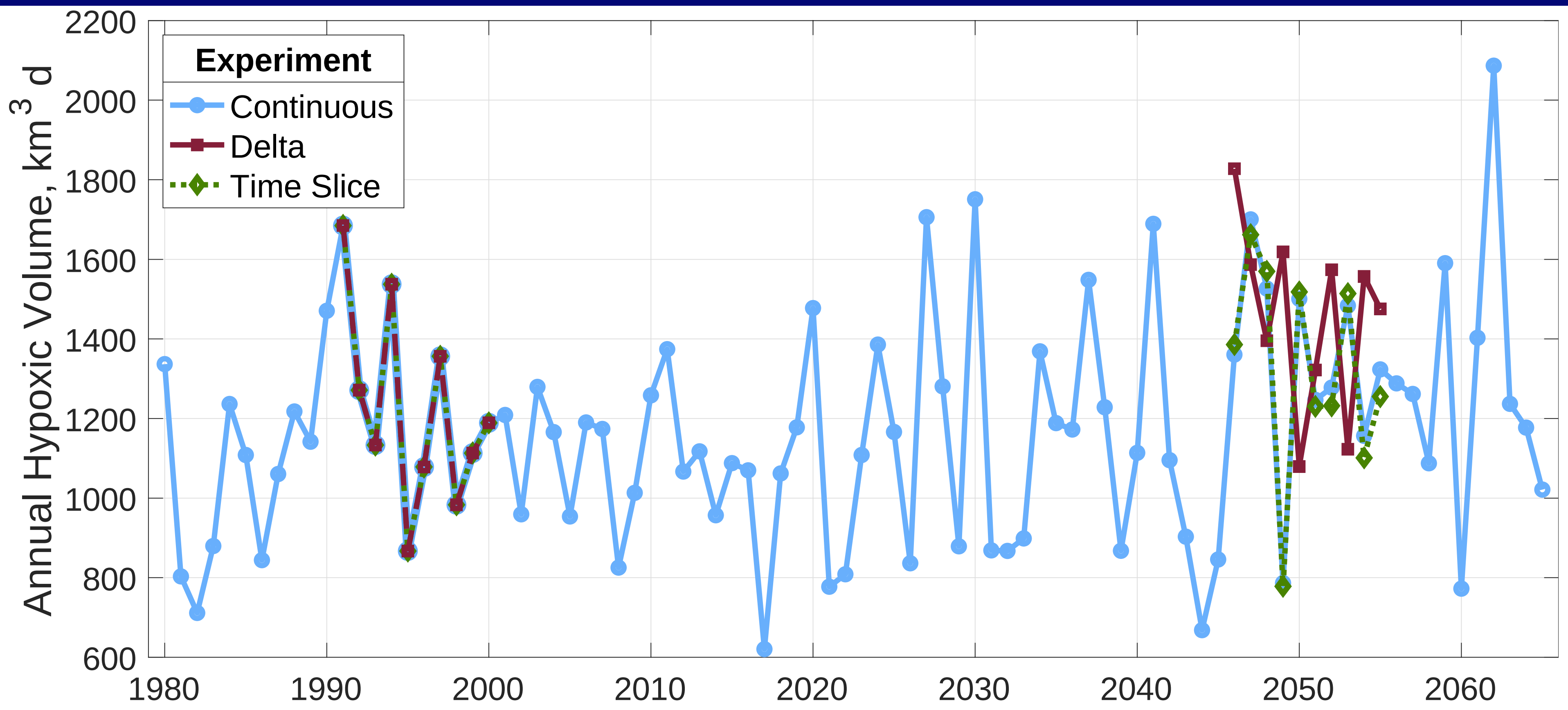




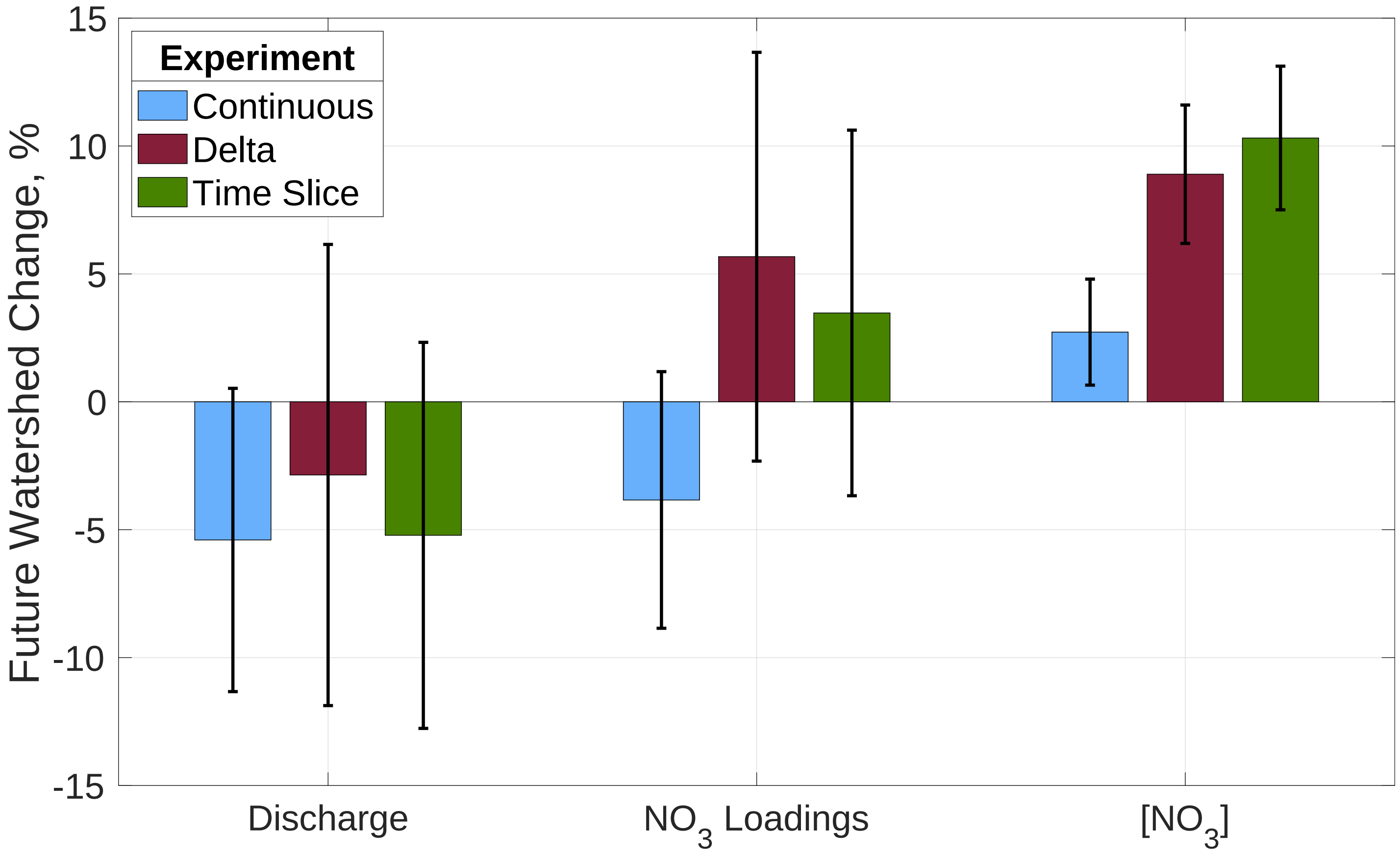
- Rapidly increasing bottom temperatures → ≈ 2 °C from baseline to future



- Equivalent increase in average temperatures for Delta and Time Slice experiments

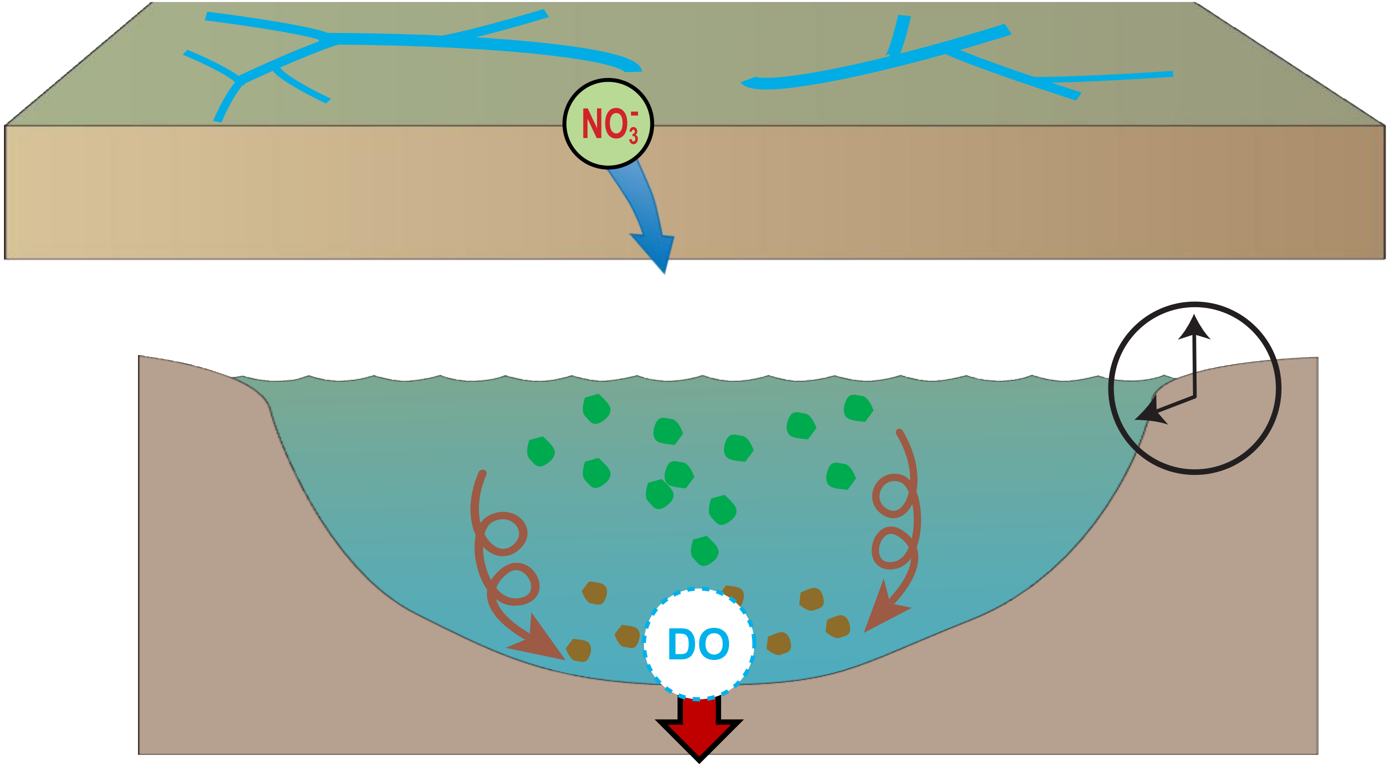


- Nearly equivalent results for Continuous and Time Slice experiments
- Increase in future Delta experiment hypoxia is ~2x greater

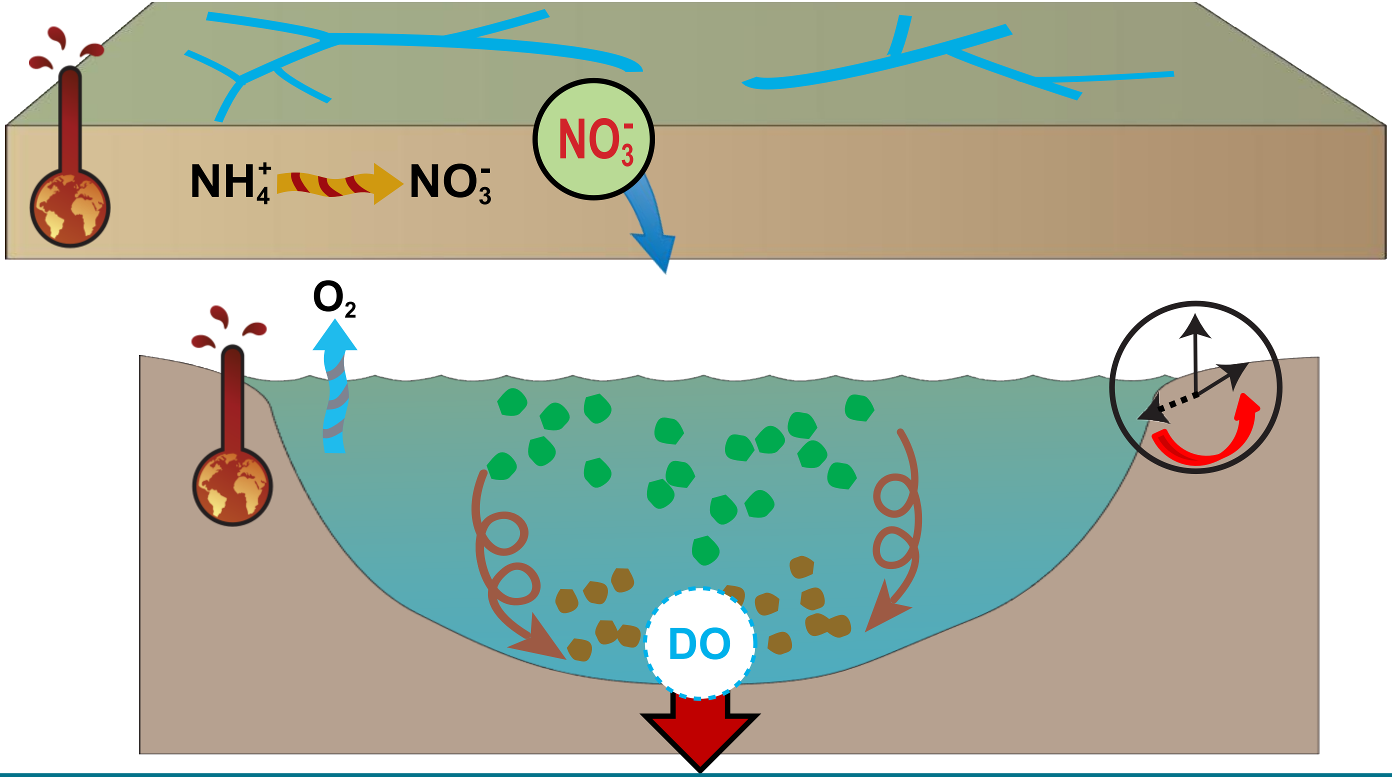


- NO_3 loadings *increase* in Delta and Time Slice, but *decrease* in Continuous
- Difference due to changing discharge and nitrate concentrations

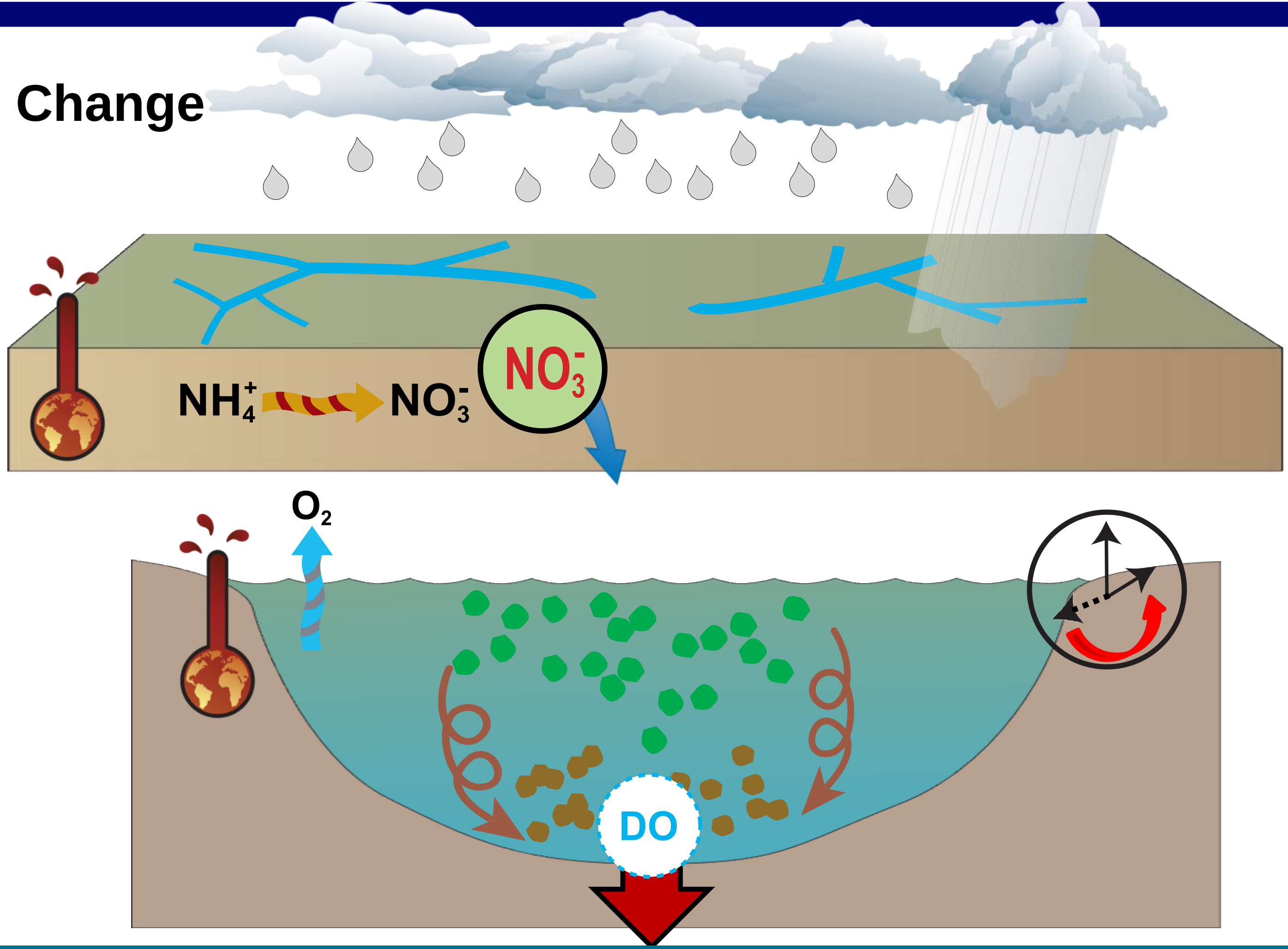
Normal Conditions



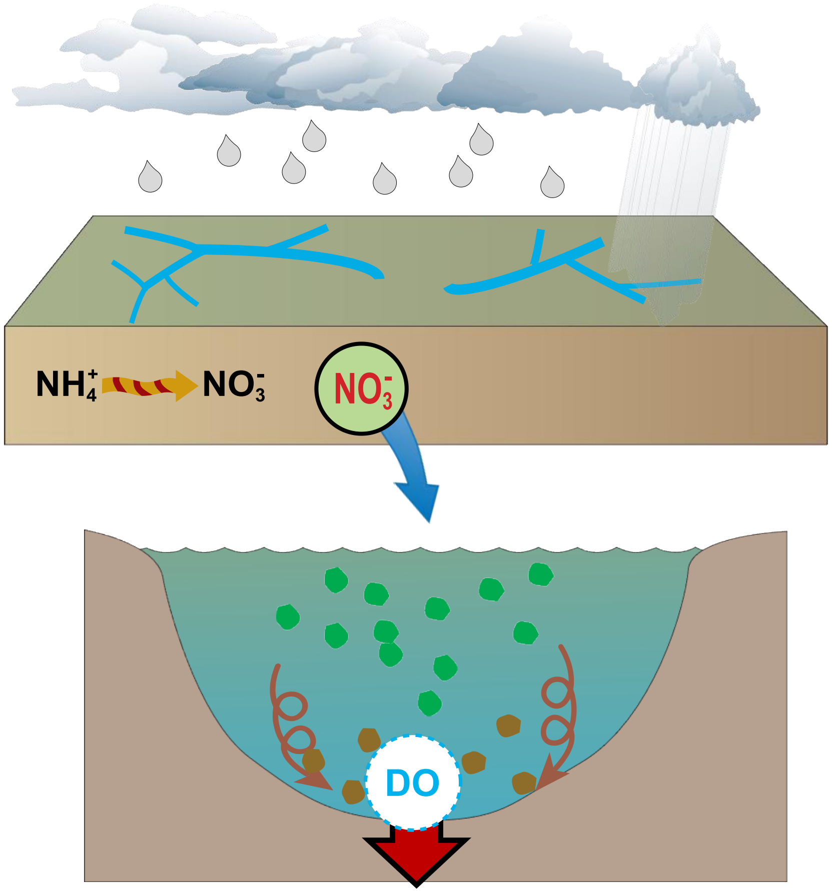
Climate Change



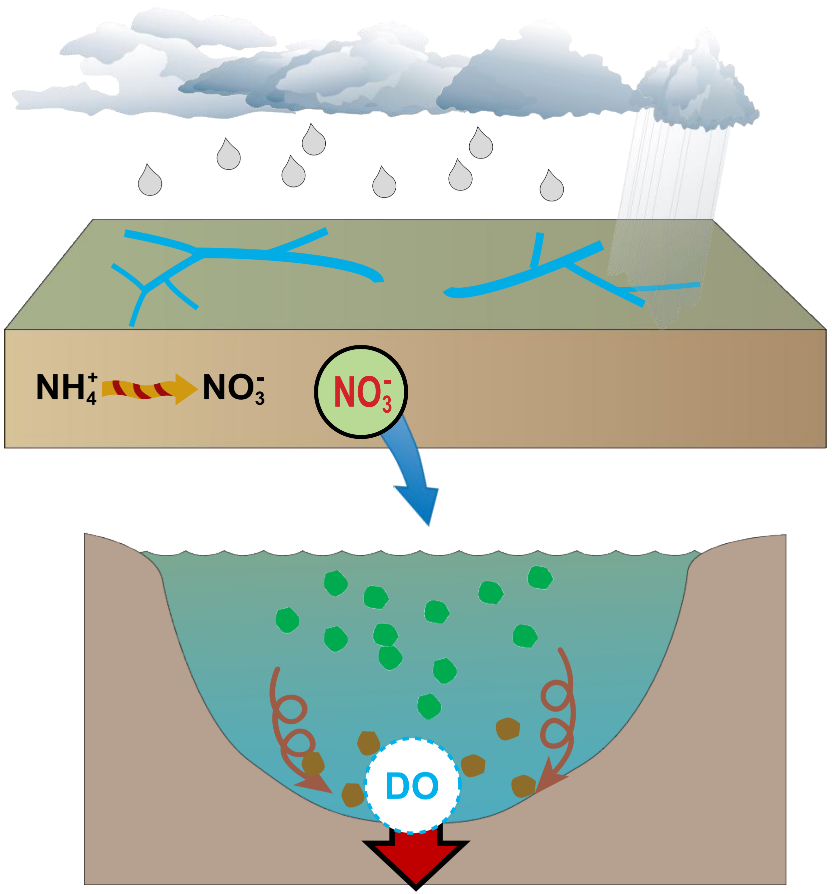
Climate Change



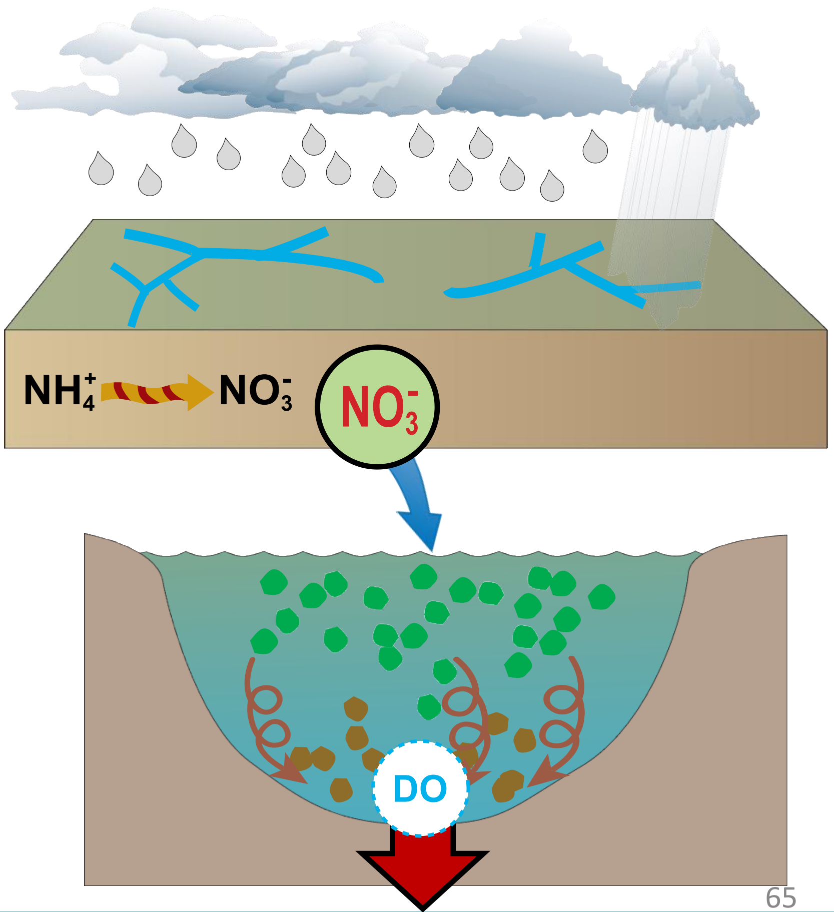
Continuous Experiment	Delta Experiment



Continuous Experiment

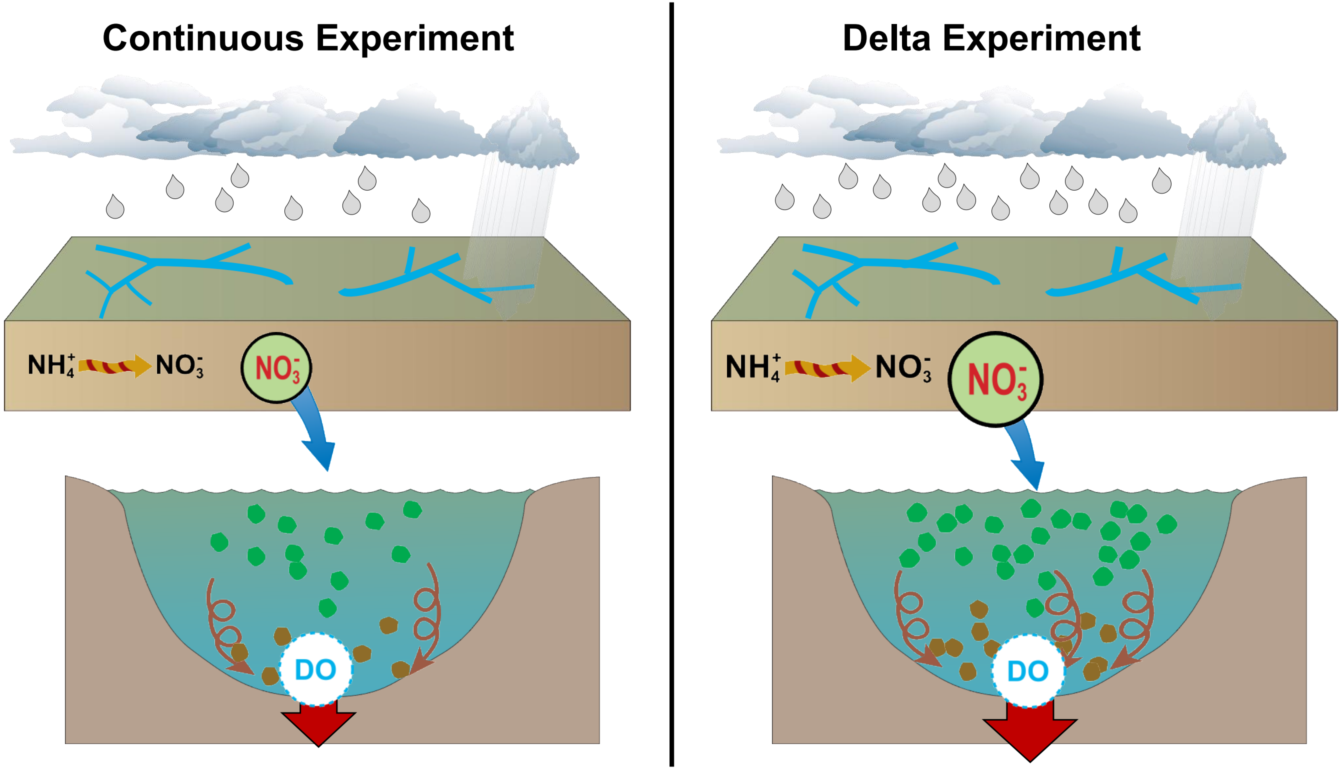


Delta Experiment



Takeaways

- Future hypoxia affected by biogeochemical changes in Chesapeake Bay *and* its watershed
- Choice of method strongly affects O_2 projections
- Role of ecosystem memory should also be explored further



Future Directions

- Consideration of possible feedbacks with larger-scale climate modeling
- Multi-institution effort to simulate future scenarios (previously done in Baltic Sea)
- Preparation for marine CO_2 removal modeling & field trials