Chesapeake Bay Hypoxia Coastal Ocean Modeling Testbed

Marjorie Friedrichs[1], Carl Friedrichs[1], Isaac Irby[1], Aaron Bever[2], Raleigh Hood[3], Hao Wang[3] & Malcolm Scully[4]

[1]VIMS [2]Anchor QEA [3]UMCES [4]WHOI

Federal Partners: Aijun Zhang (CO-OPS/NOS/NOAA)
Lewis Linker (CBP/EPA)
Gary Shenk (CBP/USGS)

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

IOOS | EYES ON THE OCEAN™

Motivation – Why Chesapeake Bay?

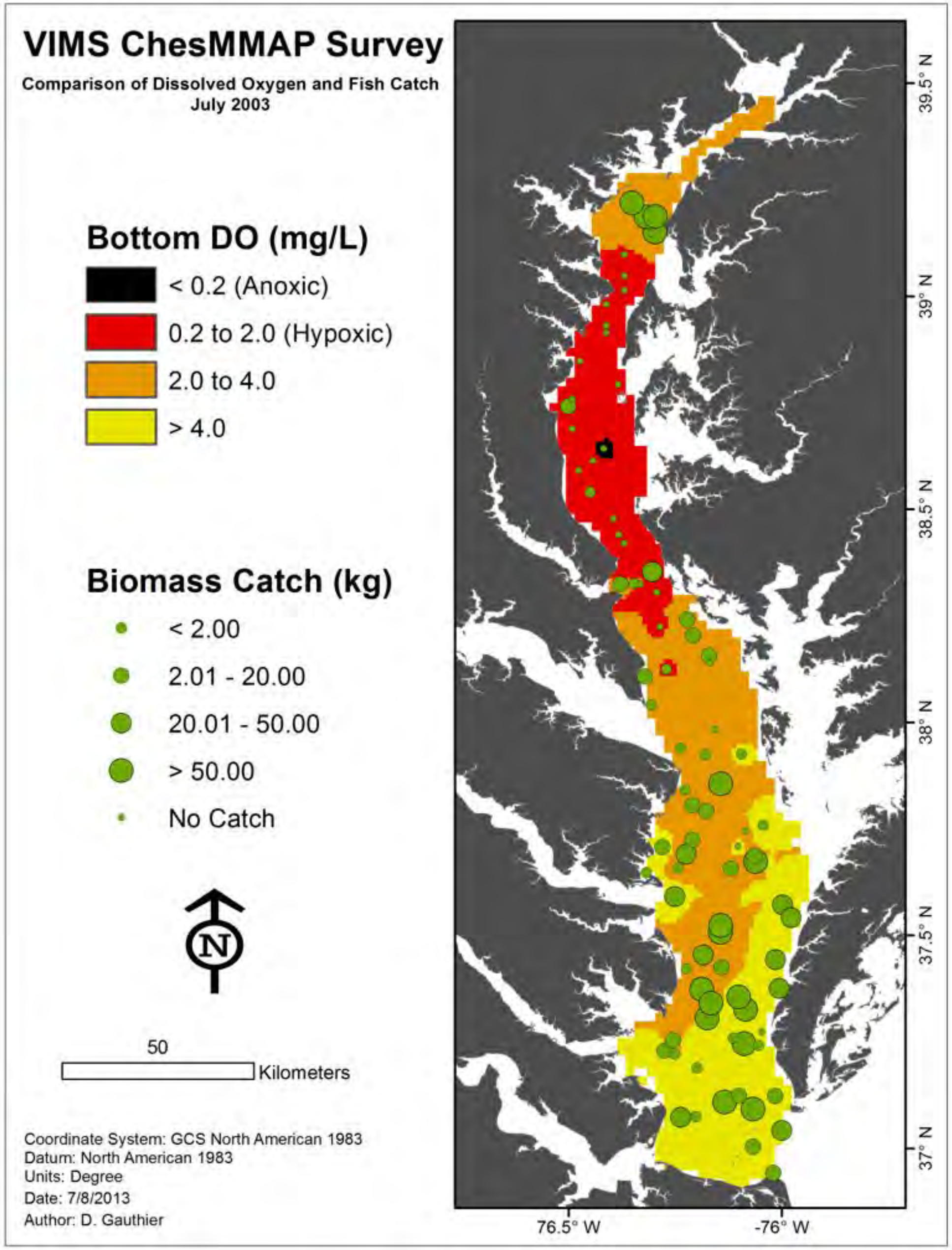
The Chesapeake Bay:

- Largest estuary in U.S.
- Benefits derived from Bay > $100 Billion annually
- Major anthropogenic impacts threatens Chesapeake's economic/social services
- Additional impacts of climate change are not yet known
- One of longest & most comprehensive data sets (1985-present)

Motivation – Why focus on hypoxia?

Hypoxic (low oxygen) waters:

- Impact ecological resources in Bay, particularly demersal fish (low catches where DO < 3 mg/L)



COMT **Chespeake Hypoxia** Objectives:

- Evaluate short-term forecast skill of hypoxia events
- Transition hypoxia forecasts to operations
- Work with stakeholders to better understand how they prefer to receive this forecast information
- Evaluate scenario-based forecasts
    - How will decreased nutrient inputs impact hypoxia?
    - How will climate change impact hypoxia?

Outline

- **Short-term operational forecasts (M. Friedrichs/A. Bever)**
  - Review of Year 3 accomplishments
  - Quasi-operational forecasts (VIMS website)
  - Operational forecasts (dev) (CBOFS website)
  - Additional skill assessment of forecasts
- **Improvements to Hypoxia-SRM (M. Scully/C. Friedrichs)**
- **Seasonal patterns in P biomass & PP variability (R. Hood/H. Wang)**
- **Scenario-based operational forecasts (I. Irby/M. Friedrichs)**
  - Evaluating uncertainty in forecasts of nutrient reduction impacts
  - Assessing impacts of climate change on nutrient reduction impacts
- **Year 5 plans (M. Friedrichs)**

Chesapeake Hypoxia – previous work

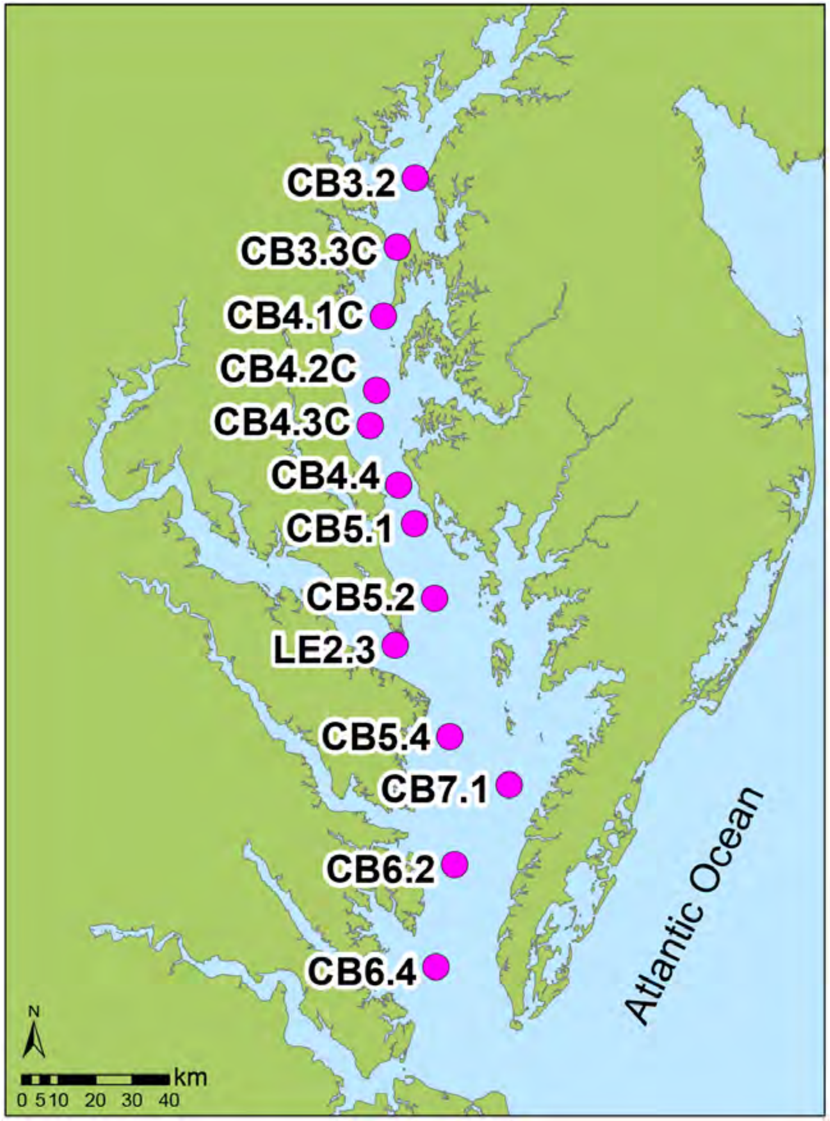
Previous COMT work identified and compared skill of multiple Chesapeake Bay oxygen models

Models:

- Eight models were compared, including multiple physical and biogeochemical variants

Available data:

- Models were assessed by monthly data (semi-monthly in summer) at multiple locations throughout Bay from 1985-present
- Data includes S, T, DO and multiple other ecological parameters



IOOS | EYES ON THE OCEAN

Chesapeake Hypoxia – previous work

Results:

Year 2-3: Multiple model comparison (Irby et al. 2016):

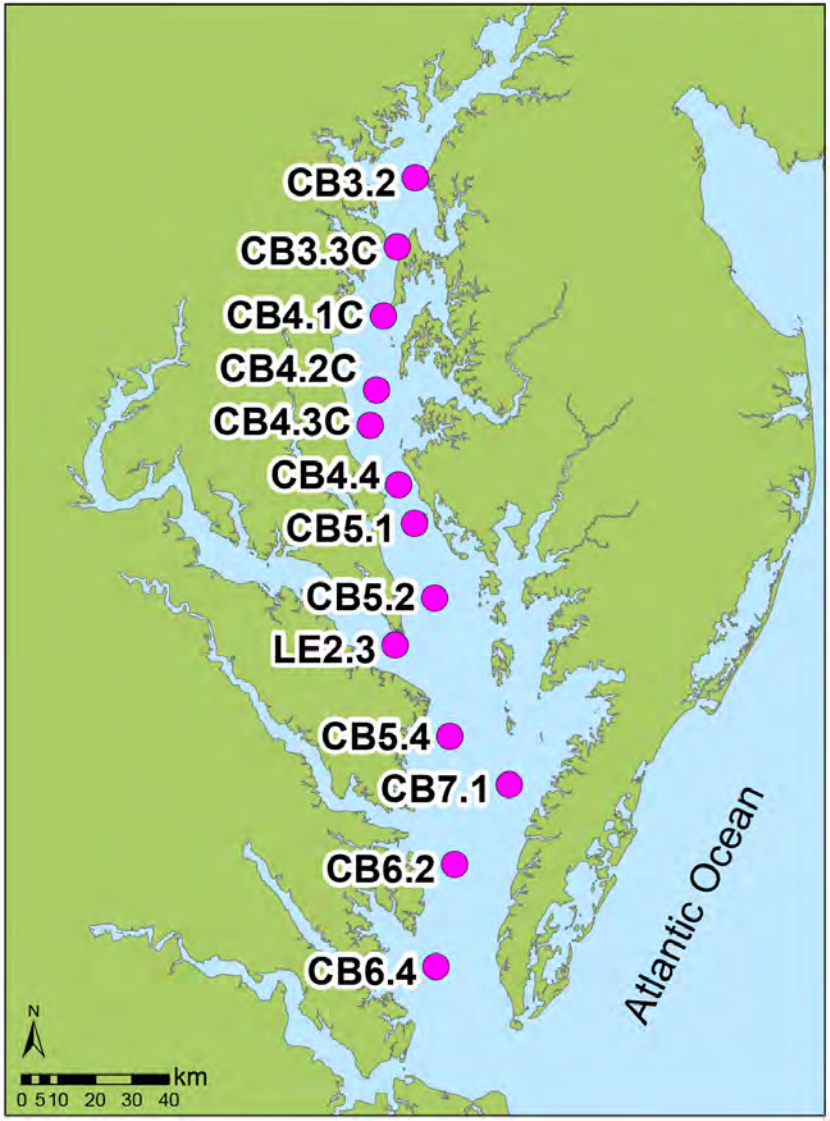
- Simple models performed as well as more complex models
- Mean of multiple models performed best

Year 3: Examined nowcast vs. hindcast skill of CBOFS bottom DO:

- Nowcast bottom DO skill > hindcast bottom DO skill!

Year 3: Quasi-operational forecasts came online on VIMS website:

- Focus Groups & Stakeholder Workshops



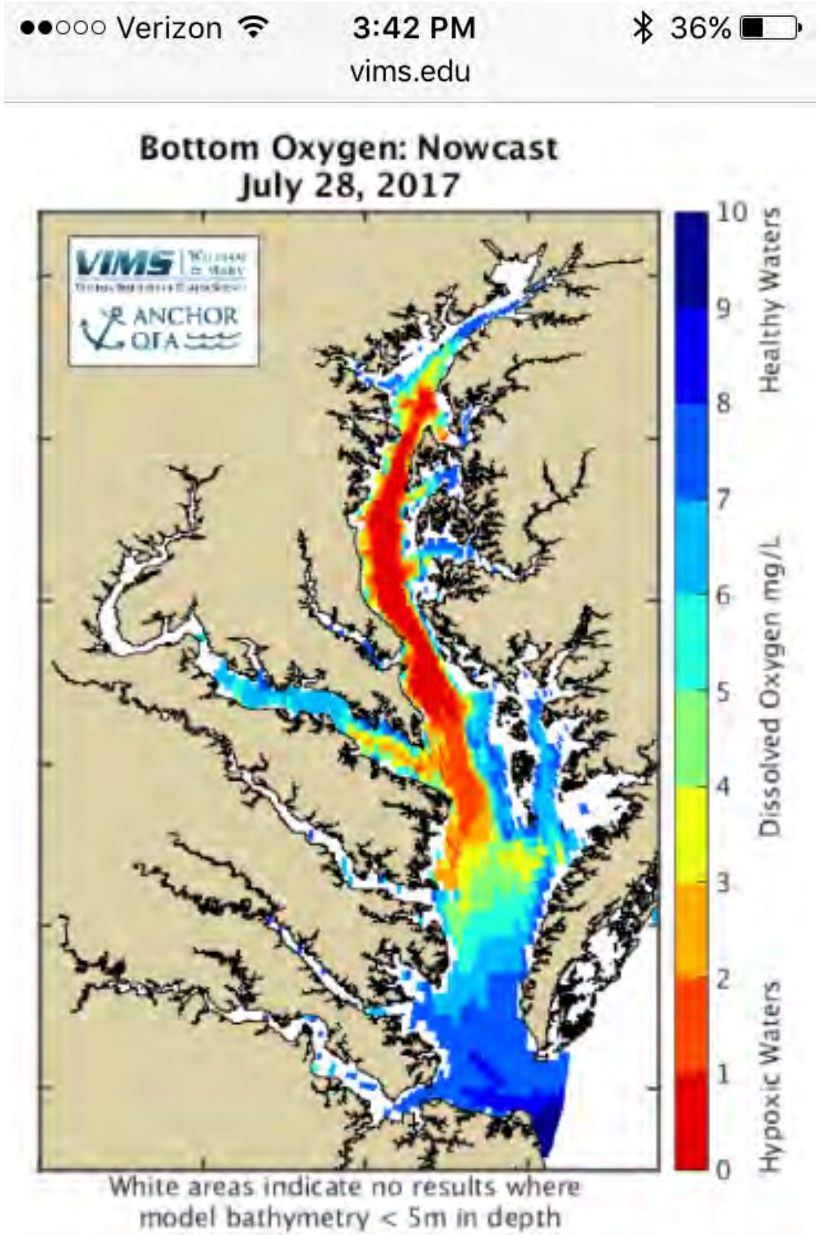
Stakeholder Workshop summary:

- Strong enthusiasm for hypoxia forecasts as complementary tool with other information sources
- Several captains already use real-time observations for planning (e.g., water clarity, temperature, wave heights) and/or short-term model forecasts (e.g., currents from CBOFS)
- Little interest in hypoxia forecasts beyond 2-3 days because of limited trust in detailed weather/wind forecasts beyond 2-3 days
- Provided specific feedback on website presentation

Year 4 Forecast improvements:

- Forecast now uses CBOFS operational forcing
- Forecast now shows mean of two models
  - SRM = Simple Respiration Model
  - ECB = Estuarine Carbon Biogeochemistry model
- SRM has been improved with seasonally variable respiration rate
- New (more detailed) color scale
- Improved appearance on mobile devices

Chesapeake Hypoxia Forecast: www.vims.edu/hypoxia



iPhone Screenshot from Friday

Blues → High bottom oxygen
= Good bottom water
= Bottom fish and crabs

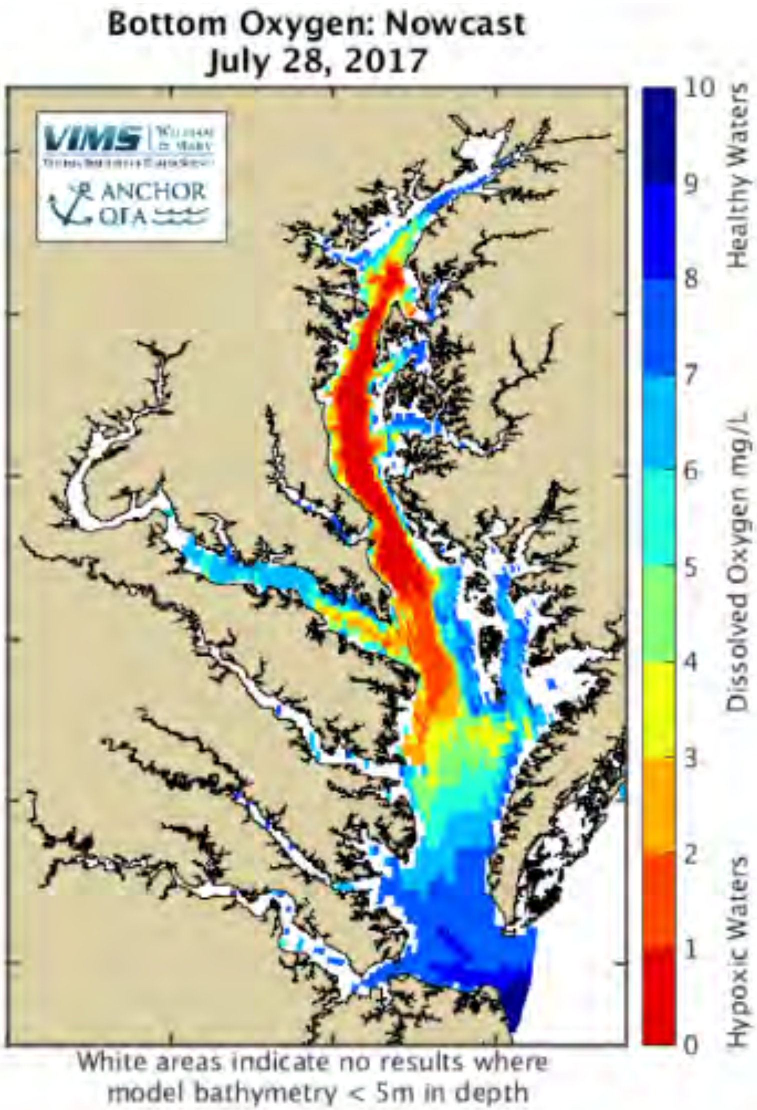
yellow/green → Moderate to low oxygen
= Poor bottom water
= Fewer bottom fish and crabs

red/orange → Very low bottom oxygen
= Bad bottom water
= No bottom fish or crabs

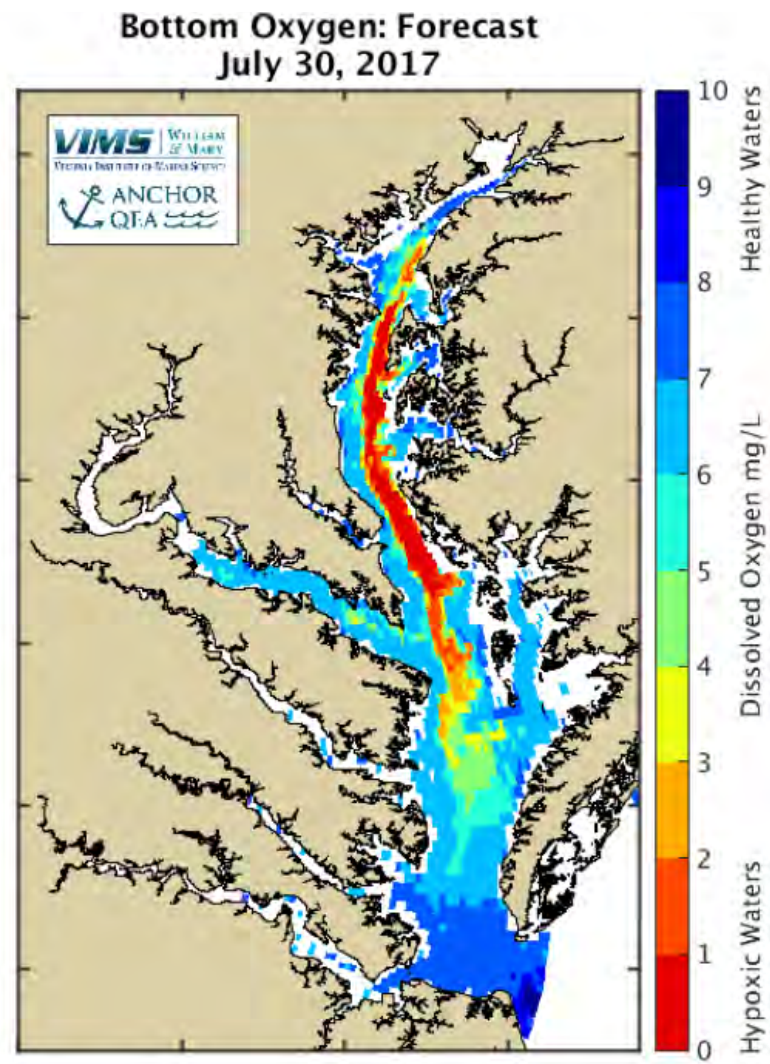
IOOS | EYES ON THE OCEAN

Chesapeake Hypoxia Forecast: www.vims.edu/hypoxia

Friday's Nowcast



Friday's Forecast

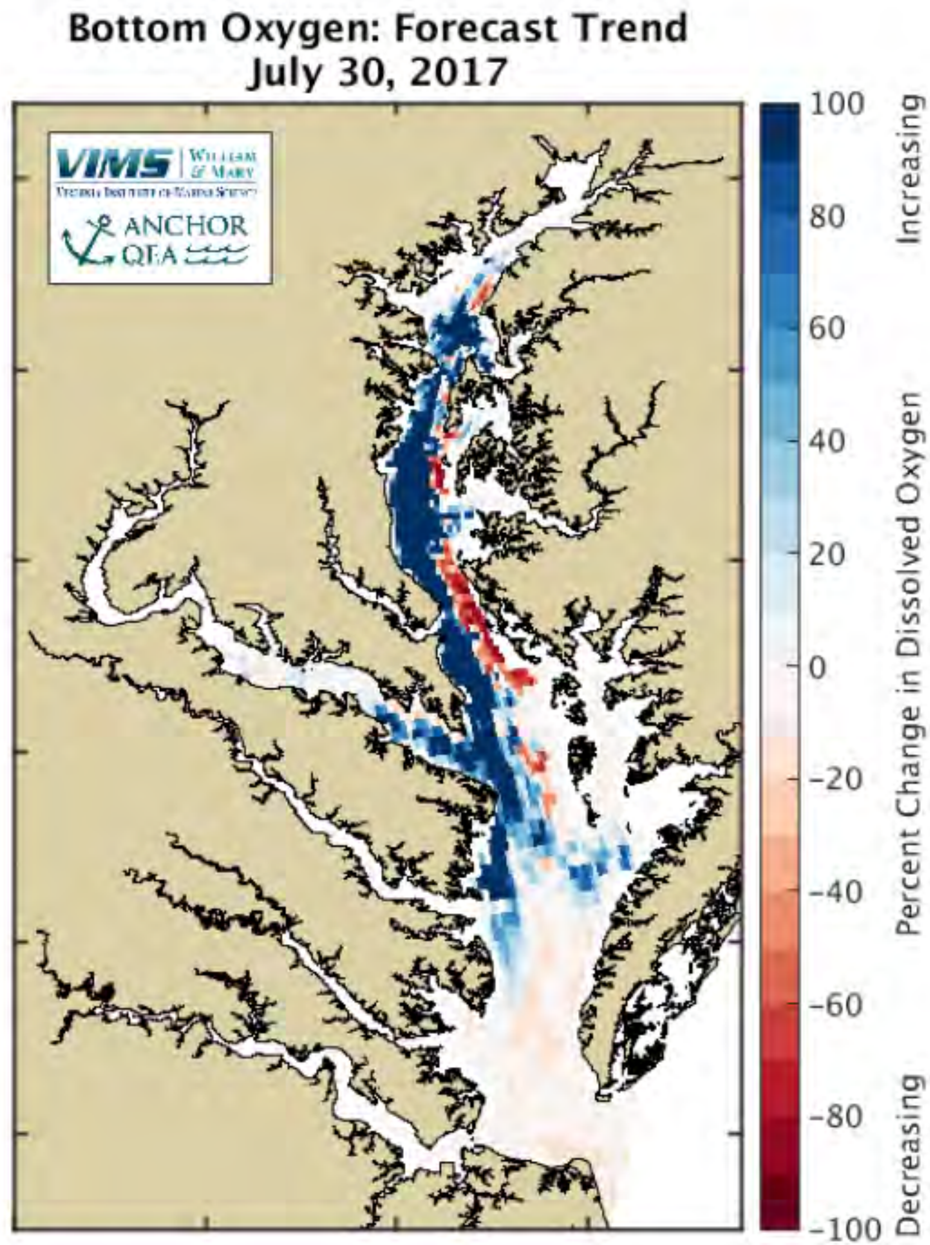


Chesapeake Hypoxia Forecast: www.vims.edu/hypoxia

Blue → Increasing oxygen
(Improving bottom water in western Bay)

Red → Decreasing oxygen
(Degrading bottom water in eastern Bay)

Due to forecast of strong NNW winds over the weekend



Chesapeake Hypoxia Forecast: www.vims.edu/hypoxia

U.S.News & WORLD REPORT

VIMS' New Forecast Tool Can Help Anglers Find Good Fishing

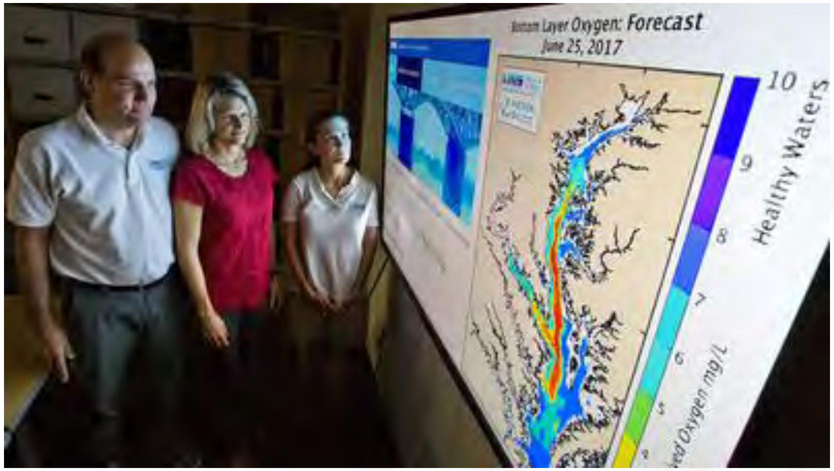
VIMS' new dead zone forecast tool can help anglers find good fishing.

Daily Press

VIMS' new dead zone forecast tool can help anglers find good fishing

The Washington Post

VIMS' new forecast tool can help anglers find good fishing



From July 2017

Chesapeake Hypoxia Forecast Transition

"Quasi-operational" forecasts

on VIMS website:

http://www.vims.edu/hypoxia

↓

Transition

(Hypoxia_SRM now in ROMS trunk!!!)

↓

"Truly operational" forecasts

on NOAA CBOFS (dev) site:

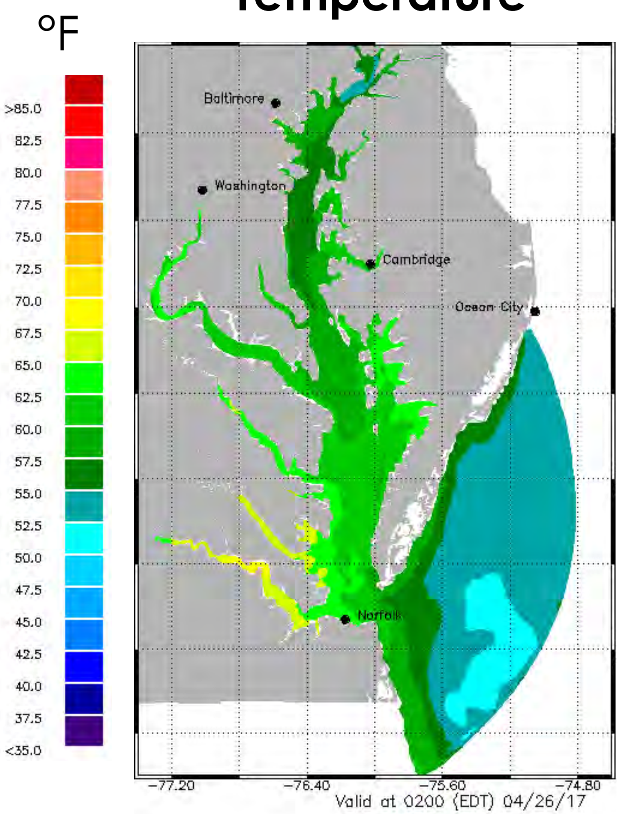
https://tidesandcurrents.noaa.gov/ofs/dev/cbofs/cbofs.html

Chesapeake Hypoxia Forecast Transition

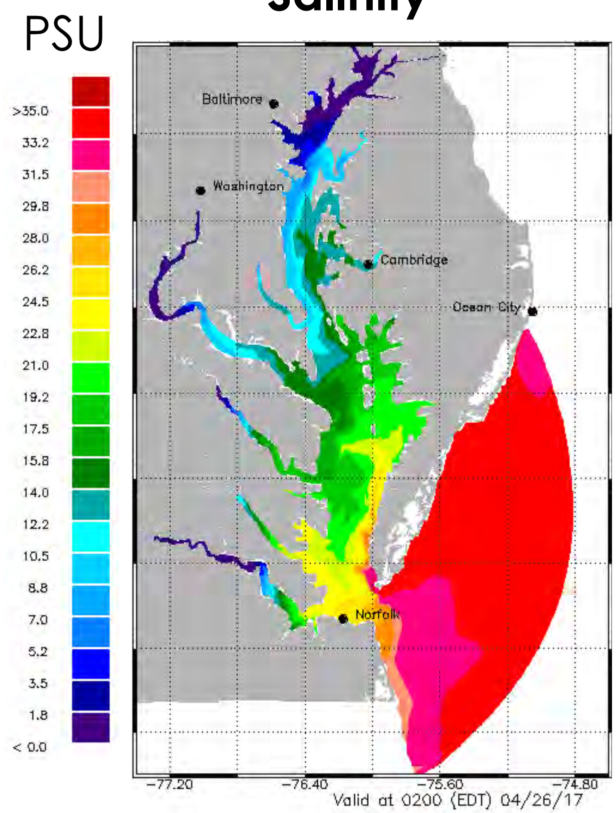
Operational Forecast Site

Developmental Site

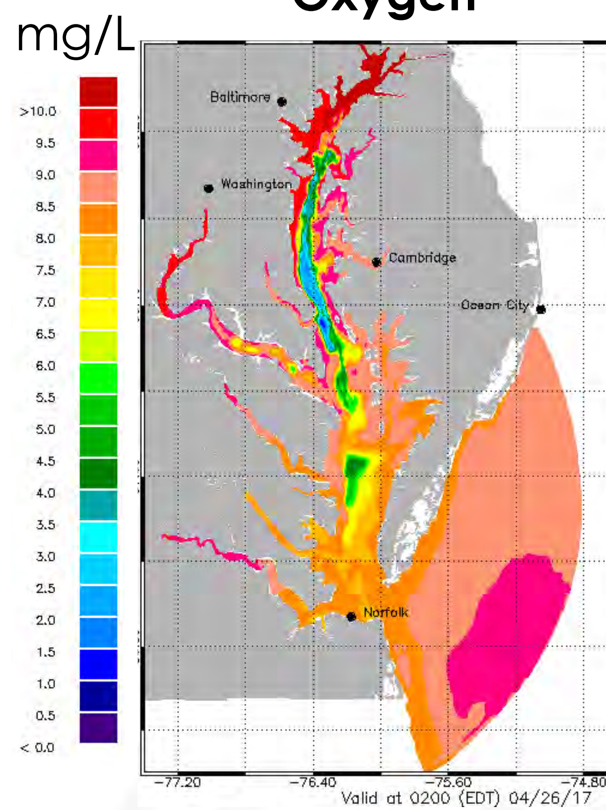
Surface Temperature



Surface Salinity



Bottom Oxygen



Outline

- **Short-term operational forecasts (M. Friedrichs/A. Bever)**
  - Review of Year 3 accomplishments
  - Quasi-operational forecasts (VIMS website)
  - Operational forecasts (dev) (CBOFS website)
  - **Additional skill assessment of forecasts (A. Bever)**
- **Improvements to Hypoxia-SRM (M. Scully/C. Friedrichs)**
- **Seasonal patterns in P biomass & PP variability (R. Hood/H. Wang)**
- **Scenario-based operational forecasts (I. Irby/M. Friedrichs)**
  - Evaluating uncertainty in forecasts of nutrient reduction impacts
  - Assessing impacts of climate change on nutrient reduction impacts
- **Year 5 plans (M. Friedrichs)**

Chesapeake Hypoxia Forecast - Testing

Additional Year 4 objectives:

- How does the nowcast skill of SRM vs. ECB compare?
- How does the forecast skill of both models degrade over 6 - 48 hours?

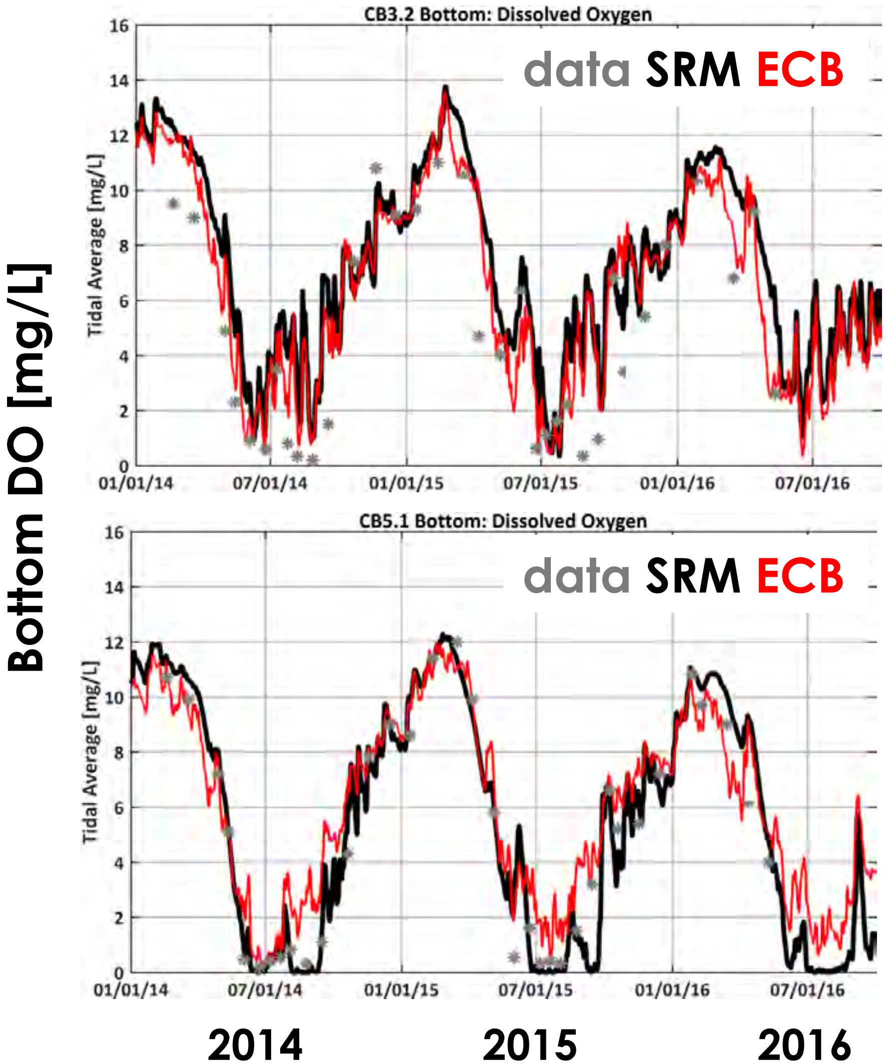
Methods:

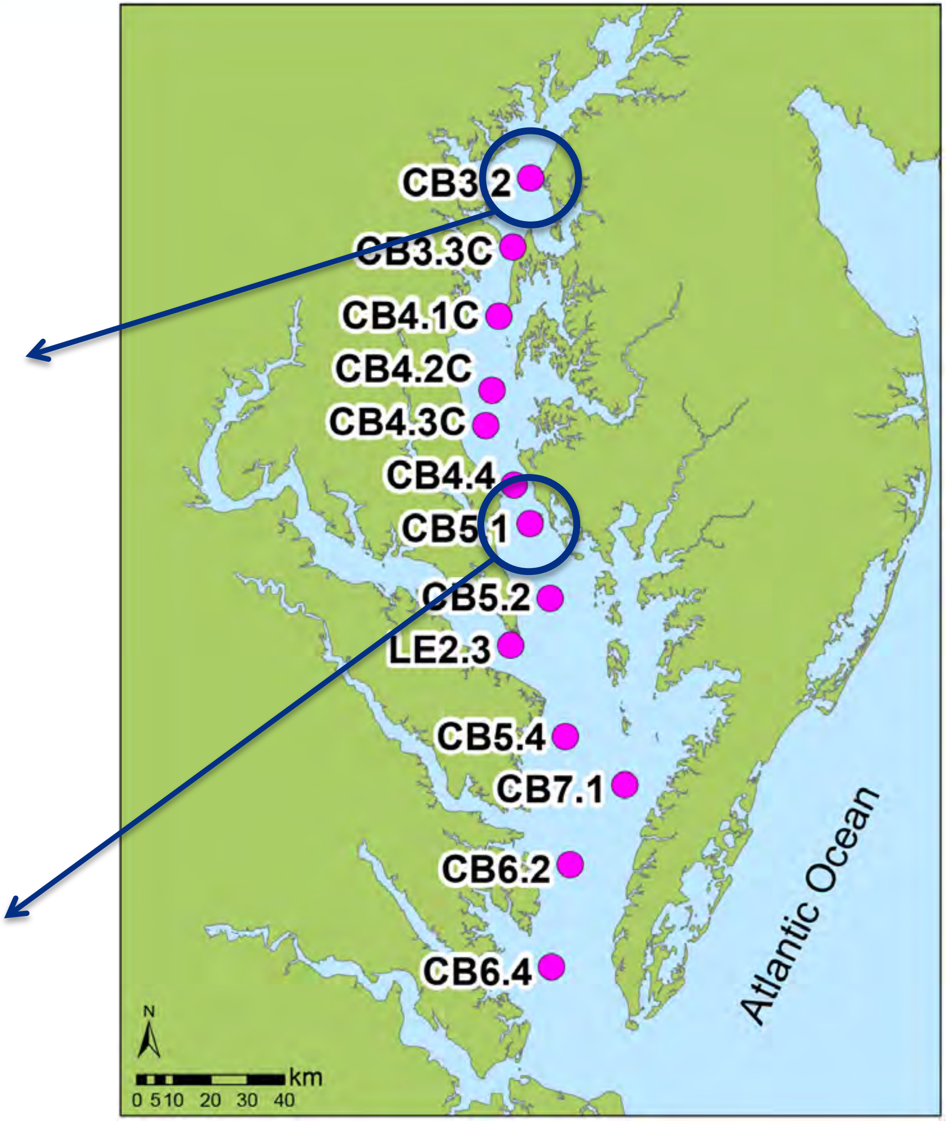
- Improve SRM by imposing seasonally varying respiration rate
- Use 2.75 years of CBOFS operational forcing:

  Jan. 2014 – Sept. 2016
- Apply identical forcing to both models
- Run 2.25 day simulation every six hours for the full 2.75 years, generating continually overlapping nowcasts and forecasts (6h, 12h, 18h, 24h, 30h, 36h, 42h, 48h)

Chesapeake Hypoxia Forecast - Testing

Compare nowcast skill of ECB vs. SRM





IOOS | EYES ON THE OCEAN

Chesapeake Hypoxia Forecast - Testing

→ ChesROMS-ECB and ChesROMS-SRM produce nowcasts with similar skill (and that are equally skillful as hindcasts)

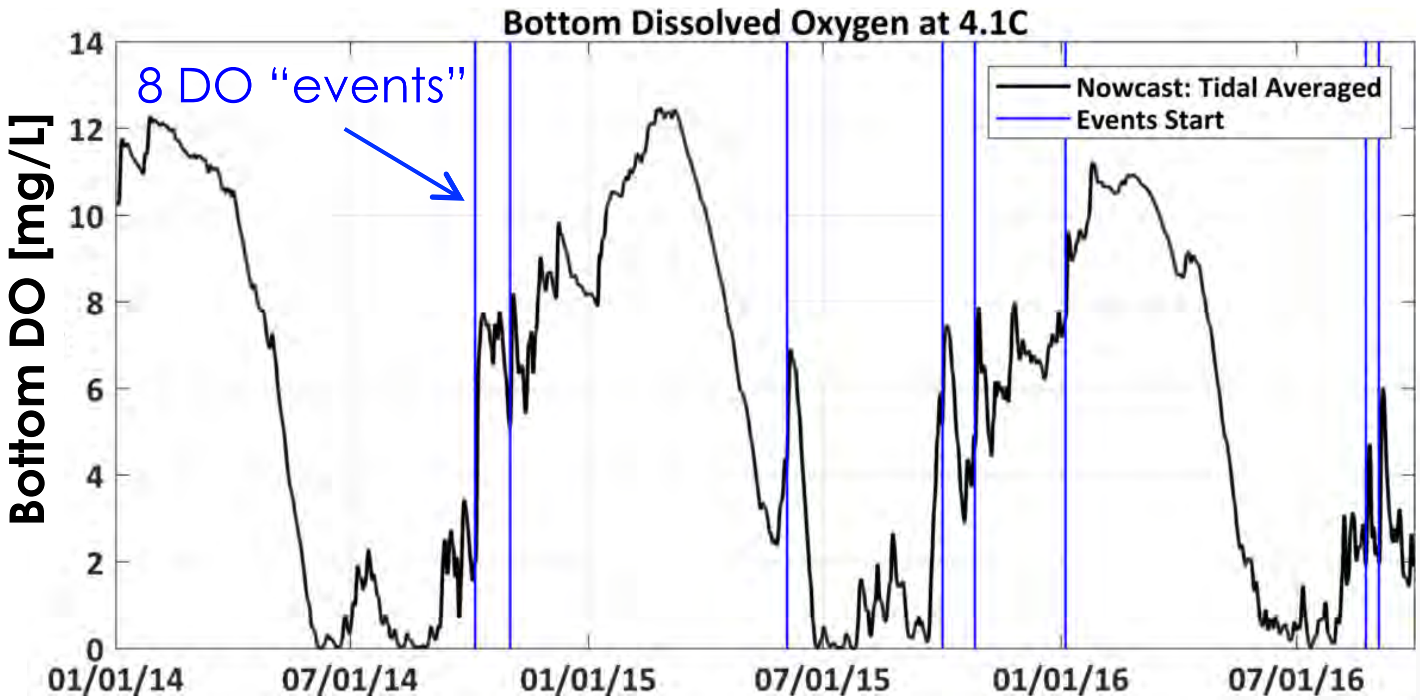
WHAT ABOUT FORECAST SKILL?

- Do forecasts predict same timing of DO events as nowcasts?
- Are forecasts skillful enough at predicting relatively large changes in DO, such that stakeholders can use the forecasts to plan their daily activities?

Chesapeake Hypoxia Forecast - Testing

Methods:

- Significant "events" were defined as daily averaged bottom DO changing by ≥ 2mg/L over ≤ 2 days

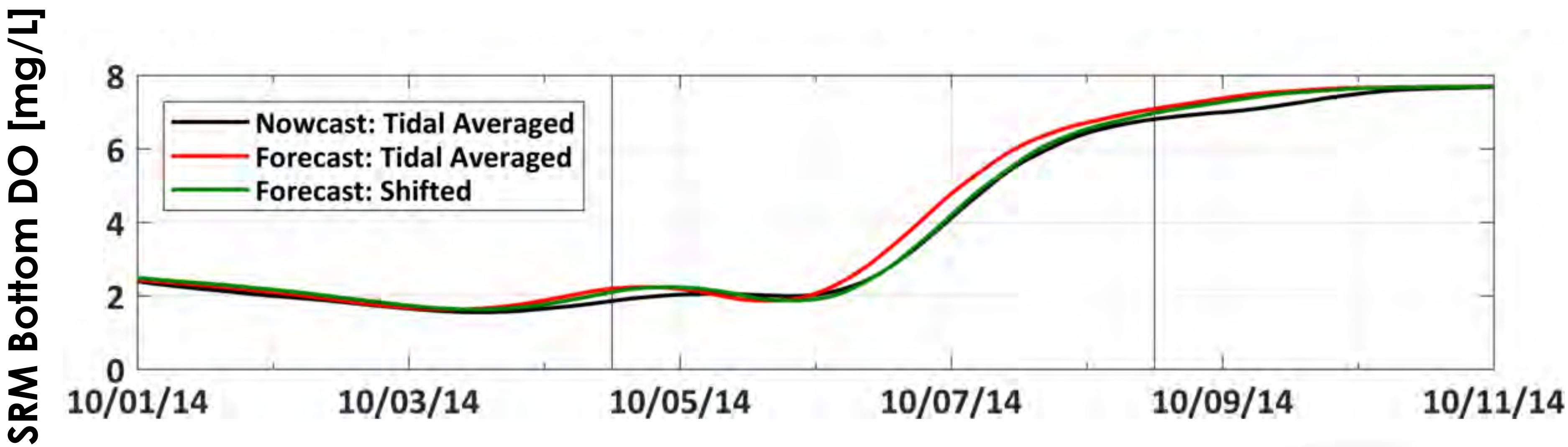


Chesapeake Hypoxia Forecast - Testing

Methods:

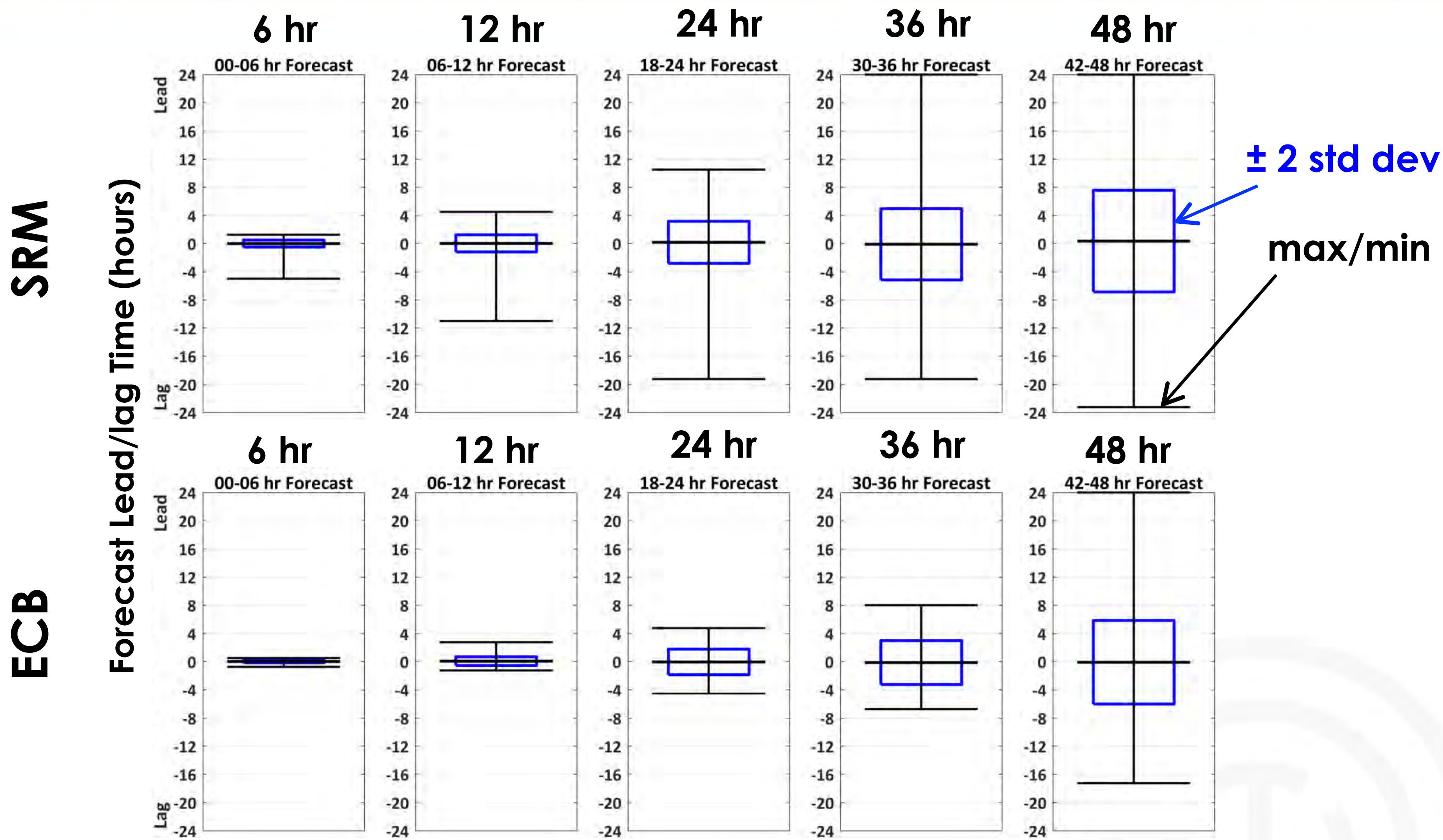
- Significant “events” were defined as daily averaged bottom DO changing by ≥ 2mg/L over ≤ 2 days
- Error (lag/lead time) of forecast is determined by time-shifting the forecast output and determining the time shift with the highest r^2 value between the nowcasted and forecasted DO
- Examined results at 11 stations for both models

Chesapeake Hypoxia Forecast - Testing



Forecast leads nowcast by 4.3h, for SRM at CB4.1C

Chesapeake Hypoxia Forecast - Testing



Error in 48 hour forecast is ~6h (ECB) to 7.5h (SRM)

Chesapeake Hypoxia Forecast – Year 5 plans

Next year's work (Year 5):

- Complete transition of hypoxia forecasts to **operational** CBOFS site (*AJ Zhang*)
- Provide forecast information for posting on **MARACOOS** Ocean Obs site (*K. Knee*)
- Examine feasibility of improving hypoxia forecasts by incorporating bottom **oxygen data** (*A. Bever*)
- Examine feasibility of including habitat suitability information for **HABs & pathogens** (*R. Hood*)
- Improve presentation of information provided on VIMS site through **outreach with end-users** (*S. Musick*)
    - Add salinity, temperature (HABs, vibrio?)
    - Add time series
    - Add climatological information

Outline

- Short-term operational forecasts (M. Friedrichs/A. Bever)
    - Review of Year 3 accomplishments
    - Quasi-operational forecasts (VIMS website)
    - Operational forecasts (dev) (CBOFS website)
    - Skill assessment of forecasts
- **Improvements to Hypoxia-SRM (M. Scully/C. Friedrichs)**
- Seasonal patterns in P biomass & PP variability (R. Hood/H. Wang)
- Scenario-based operational forecasts (I. Irby/M. Friedrichs)
    - Evaluating uncertainty in forecasts of nutrient reduction impacts
    - Assessing impacts of climate change on nutrient reduction impacts
- Year 5 plans (M. Friedrichs)

Simple Approaches to Modeling Dissolved Oxygen

By Malcolm Scully (presented by Carl Friedrichs)

Goals and Motivation:

- Develop a method for estimating Primary Production (PP) from time-series measurements of dissolved oxygen (O_2) that can provide estimates of fundamental rates to rigorously test biogeochemical models.
- Incorporate a light-dependent formulation for PP into a simple model for O_2 that is suitable for operational forecast modeling.

Outline:

- Method for estimating PP and fundamental rates from observed O_2.
- Validation of the method with output from biogeochemical model (ECB).
- Modeling results from simple 1-term model with improved representation of biological processes (oxygen production).

IOOS | EYES ON THE OCEAN

Method for Estimating PP from O_2 Time-Series

α = init. slope of P-I curve
P_m = Max. growth rate
I = Irradiance (Light)

(Jassby & Platt 1976)

$$\frac{dO_2}{dt} = \underbrace{P_m \tanh\left(\frac{\alpha I}{P_m}\right)}_{\text{Primary Production (PP)}} + C$$

Hourly change in O_2

Primary Production (PP)
changes hourly with light

Constant

Data Needs:

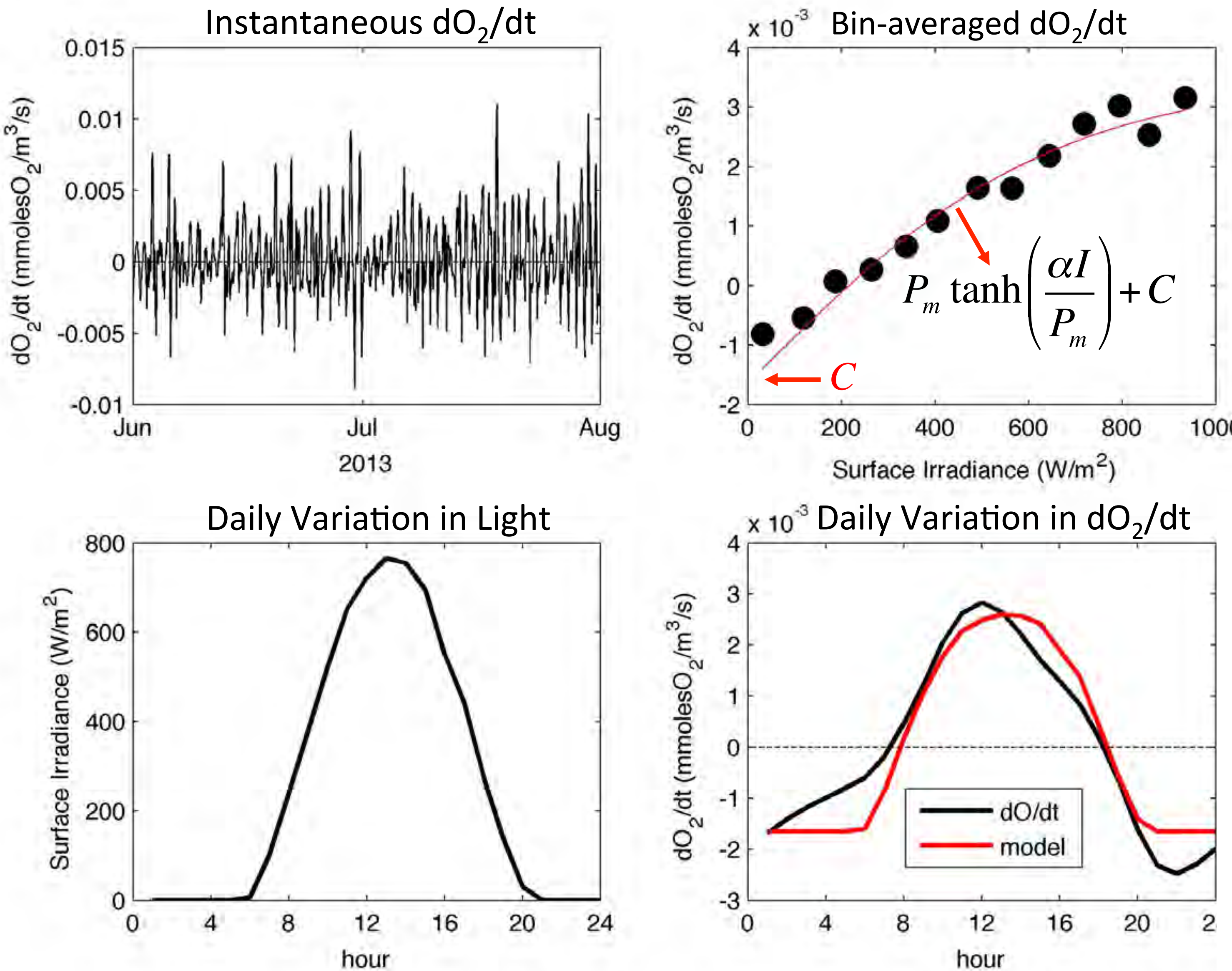
- Continuous (hourly) measurements of near surface O_2 (CBIBS buoys)
- Continuous estimates of incoming solar radiation (NARR model)

Procedure:

- Calculate time-rate of change of oxygen (dO_2/dt) from buoy data.
- Estimate coefficient (C) by taking the average value of dO_2/dt at night (this represents both biological drawdown and physical processes).
- Perform least-squares fit to $P_m \tanh(\alpha I/P_m)$ to obtain estimates of P_m (maximum phytoplankton growth rate) and α (initial slope of P-I curve) over a 20-day moving window.

Method for Estimating PP from O_2 Time-Series

Example from CBIBS Goose's Reef Buoy for July-August 2013



Application of Method to ECB Output

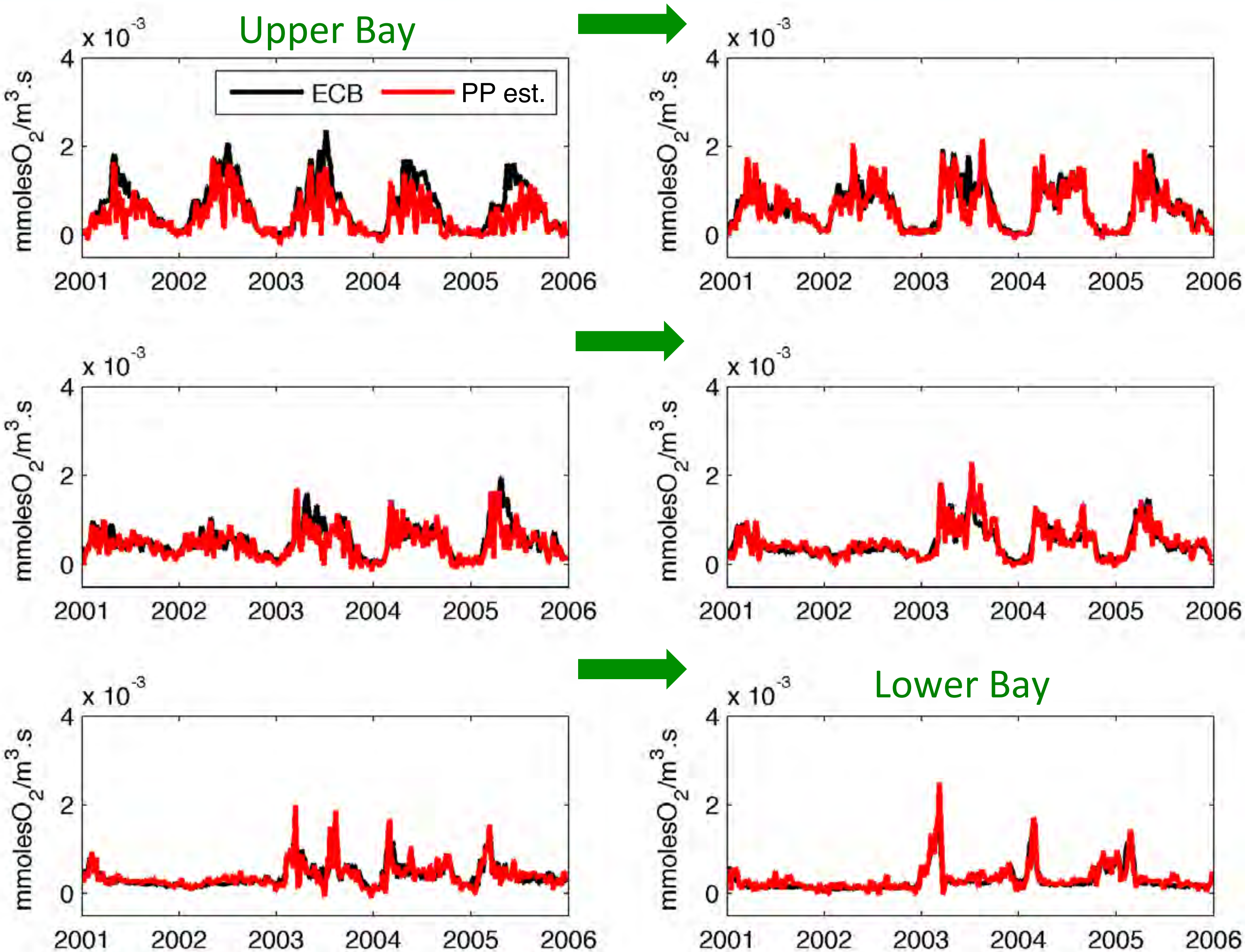
y-axes are PP in units of O_2/vol/time

ECB = direct PP output

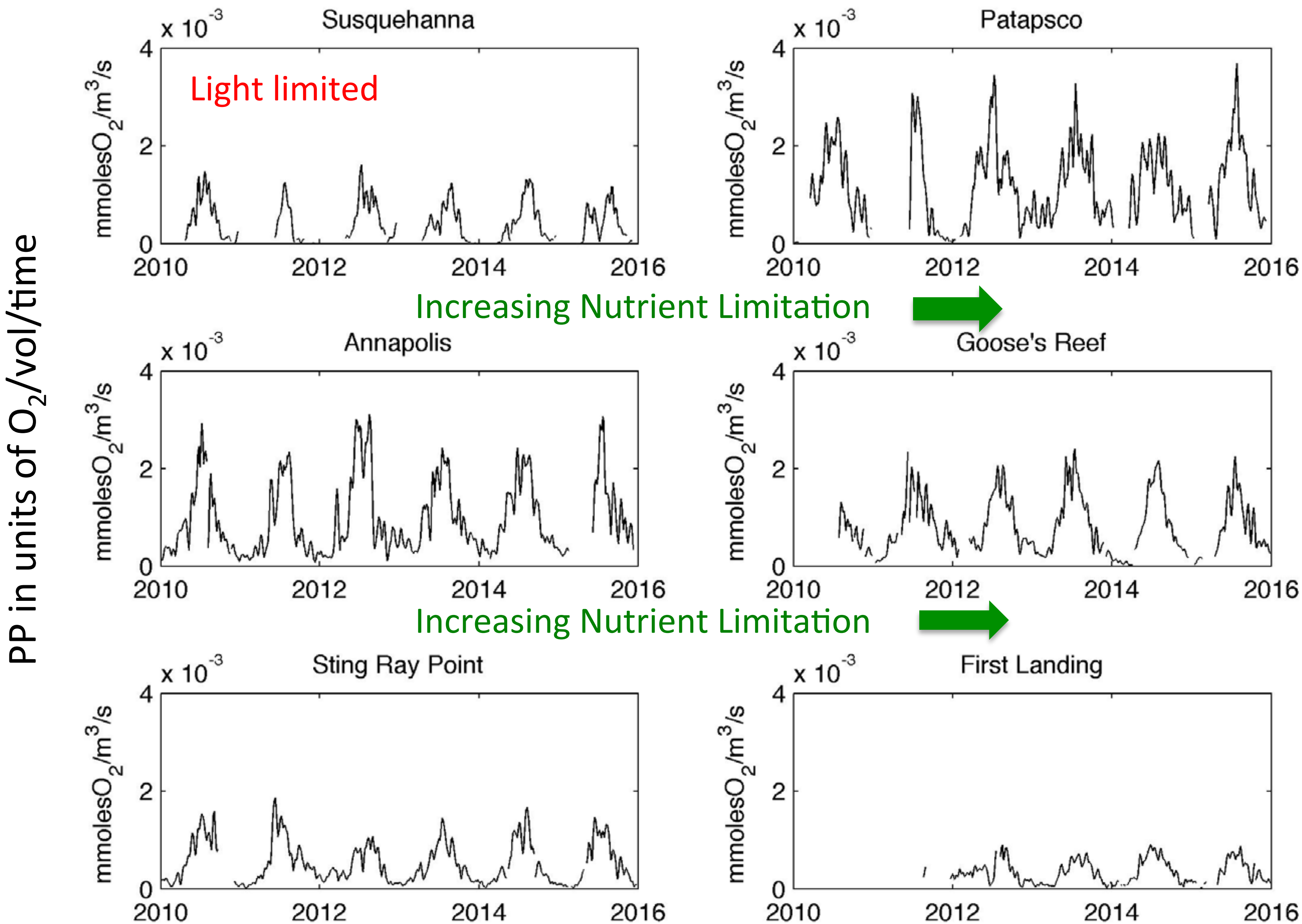
PP est. =

$$P_m \tanh\left(\frac{\alpha I}{P_m}\right)$$

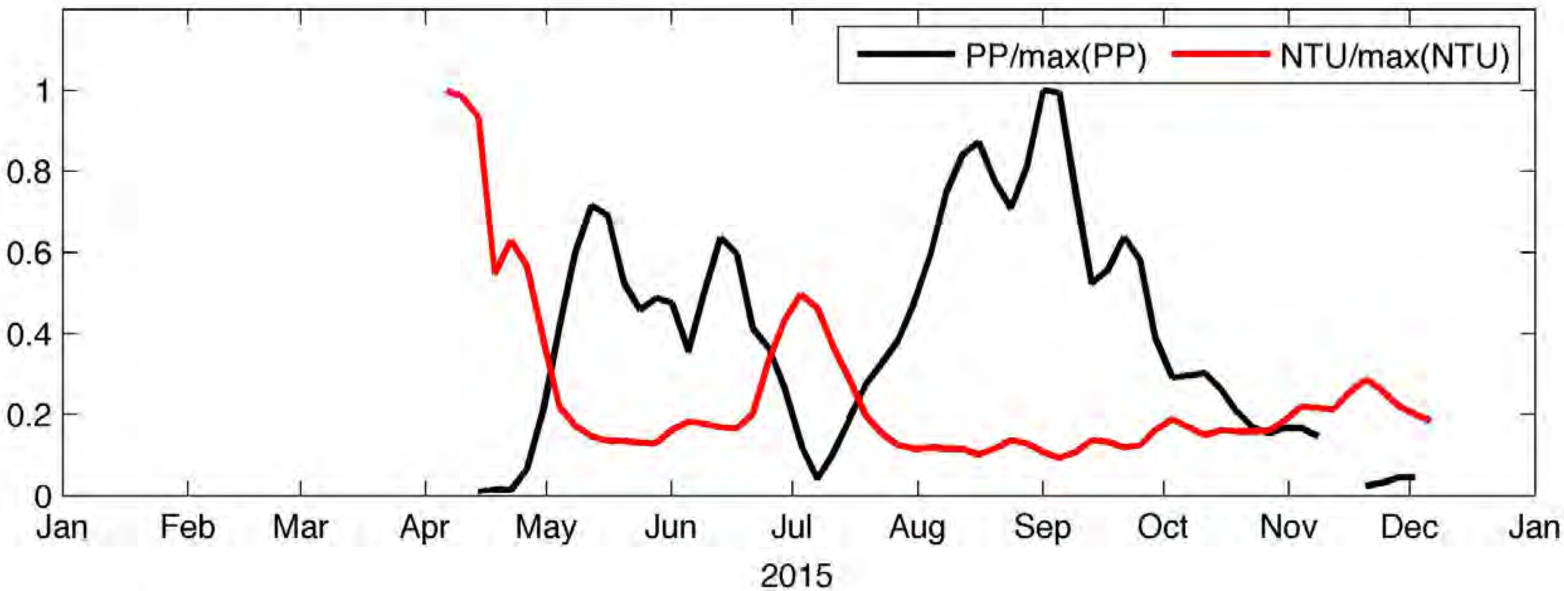
inferred from near-surface ECB O_2

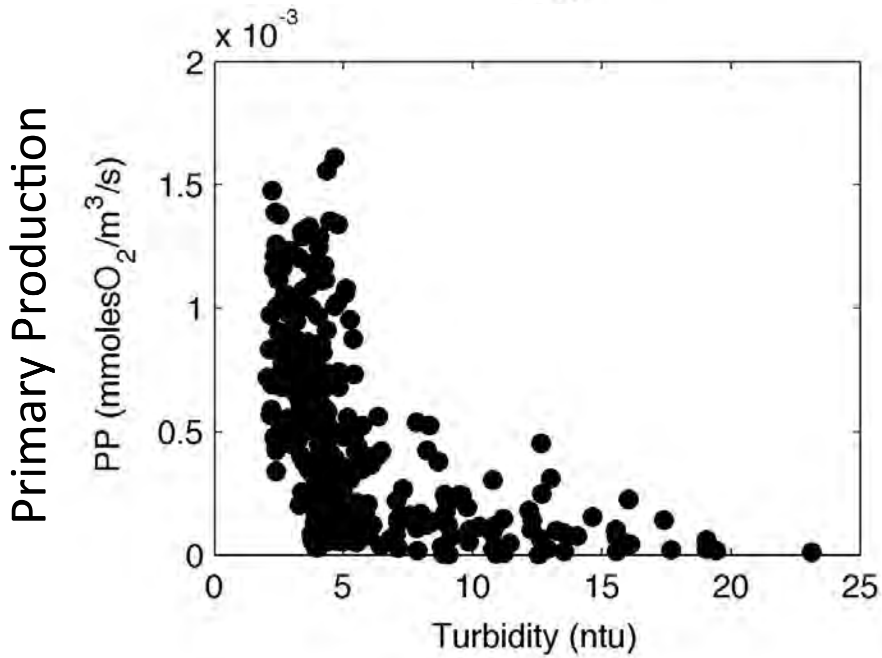


Estimates of Primary Production from CBIBS Buoys



Evidence for Light Limitation at Susquehanna Buoy





IOOS | EYES ON THE OCEAN™

Simple O_2 Model including Primary Production

$$\frac{\partial O_2}{\partial t} = PP + CR + u\nabla O_2 + \frac{\partial}{\partial z}\left\langle O_2' w' \right\rangle$$

Temperature dependent slope of P-I curve

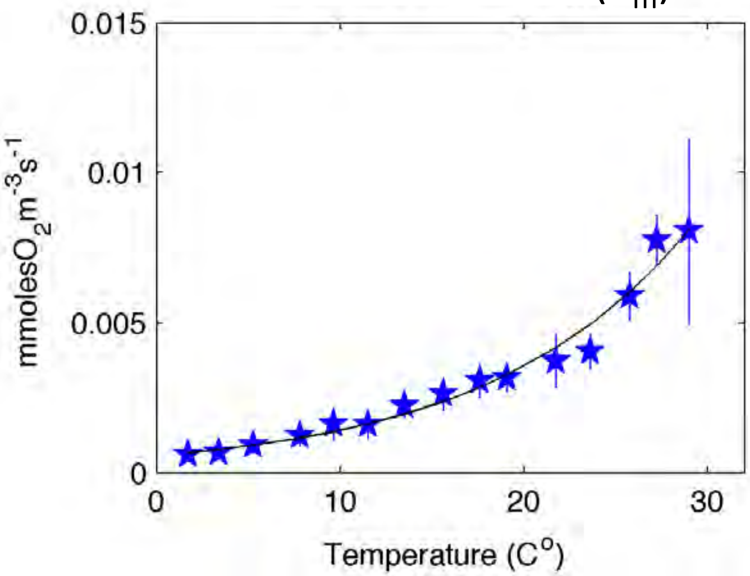
$$PP = P_m \tanh\left(\frac{\alpha I}{P_m}\right)$$

Temperature dependent maximum growth rate

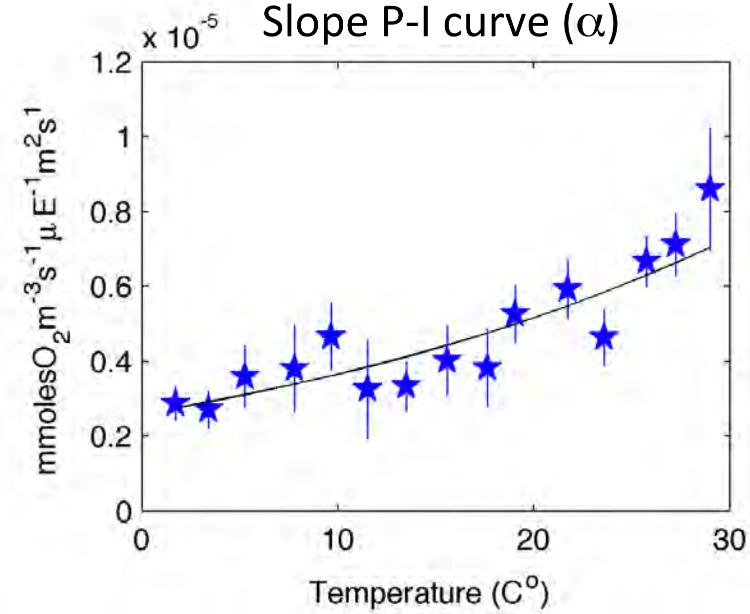
Depth-invariant seasonally-varying oxygen consumption. Modeled as simple Gaussian function with max at end of July

Relationships derived from CBIBS Buoys

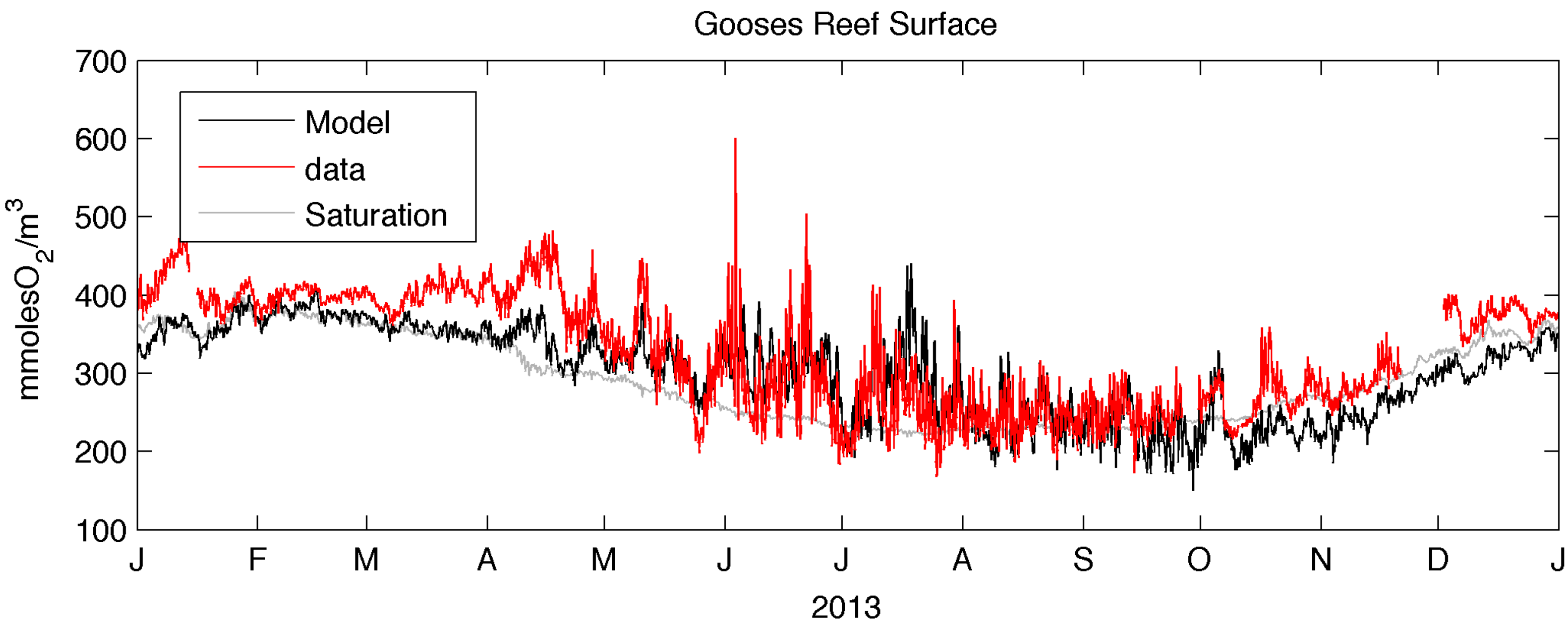
Max Growth Rate (P_m)



Slope P-I curve (α)

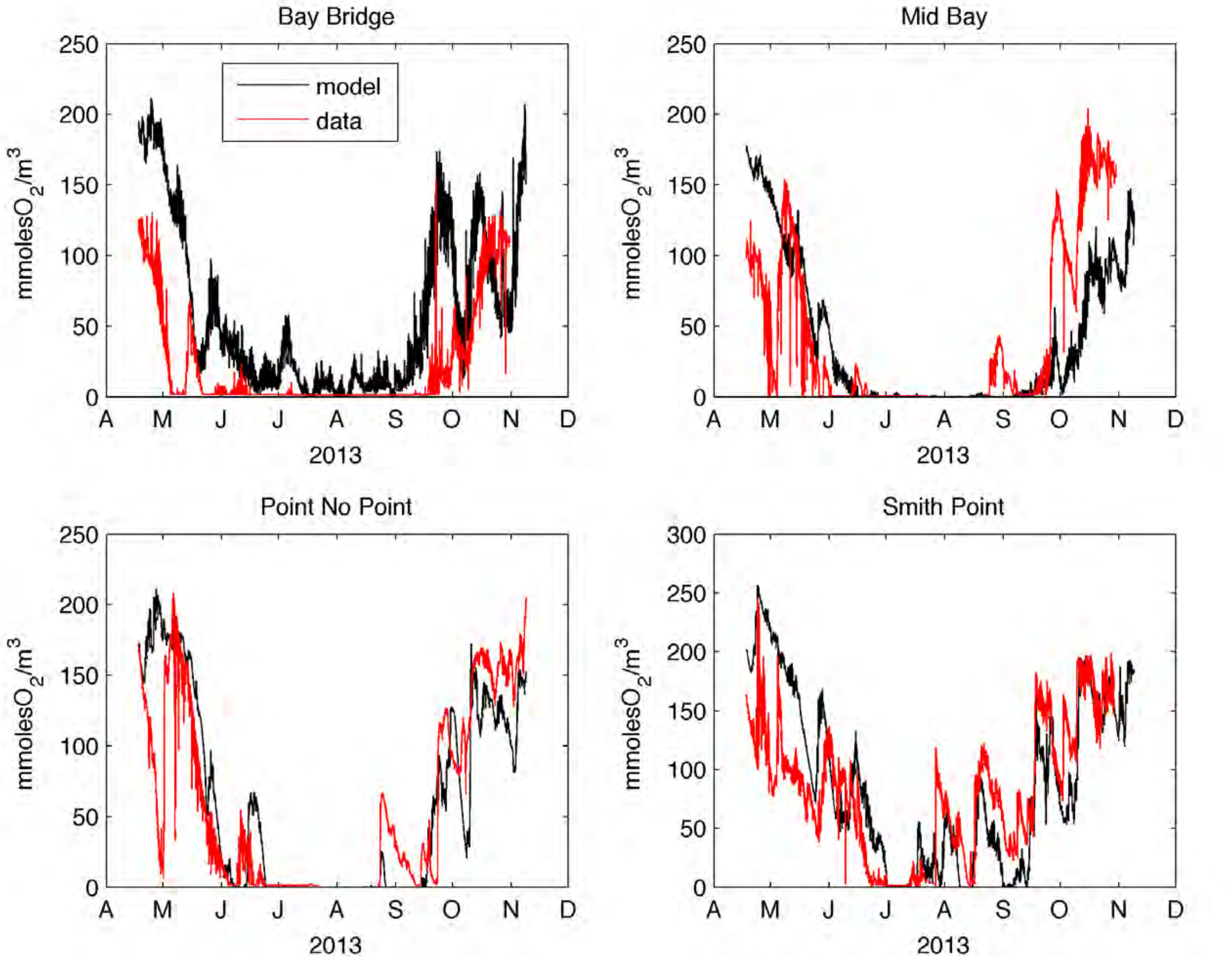


Model Comparison of Surface O_2 at Goose's Reef



- Previously, the Simple Respiration Model assumed that surface oxygen concentration was maintained at saturation value.
- New formulation captures time variations (including super-saturation) in a much more realistic way.

Model Comparison of Bottom O_2 (Scully 2013 data)



Outline

- **Short-term operational forecasts (M. Friedrichs/A. Bever)**
  - Review of Year 3 accomplishments
  - Quasi-operational forecasts (VIMS website)
  - Operational forecasts (dev) (CBOFS website)
  - Skill assessment of forecasts
- **Improvements to Hypoxia-SRM (M. Scully/C. Friedrichs)**
- **Seasonal patterns in P biomass & PP variability (R. Hood/H. Wang)**
- **Scenario-based operational forecasts (I. Irby/M. Friedrichs)**
  - Evaluating uncertainty in forecasts of nutrient reduction impacts
  - Assessing impacts of climate change on nutrient reduction impacts
- **Year 5 plans (M. Friedrichs)**

UMCES: Raleigh Hood and Hao Wang

Overarching Questions:

- Do current generation biogeochemical models capture observed seasonal patterns in phytoplankton biomass and primary production variability in Chesapeake Bay?
- What is the role of lateral transport in supplying organic matter to the deep channel of the mainstem Chesapeake Bay?
- Can we use our BGC model as a dynamic interpolator to provide insight into the temporal and spatial variability in denitrification in Chesapeake Bay?

UMCES: Raleigh Hood and Hao Wang

Overarching Questions:

- Do current generation biogeochemical models capture observed seasonal patterns in phytoplankton biomass and primary production variability in Chesapeake Bay?
- What is the role of lateral transport in supplying organic matter to the deep channel of the mainstem Chesapeake Bay?
- Can we use our BGC model as a dynamic interpolator to provide insight into the temporal and spatial variability in denitrification in Chesapeake Bay?

Variability of biomass and productivity

Classic Conceptual Model of Biomass and Production Variability:

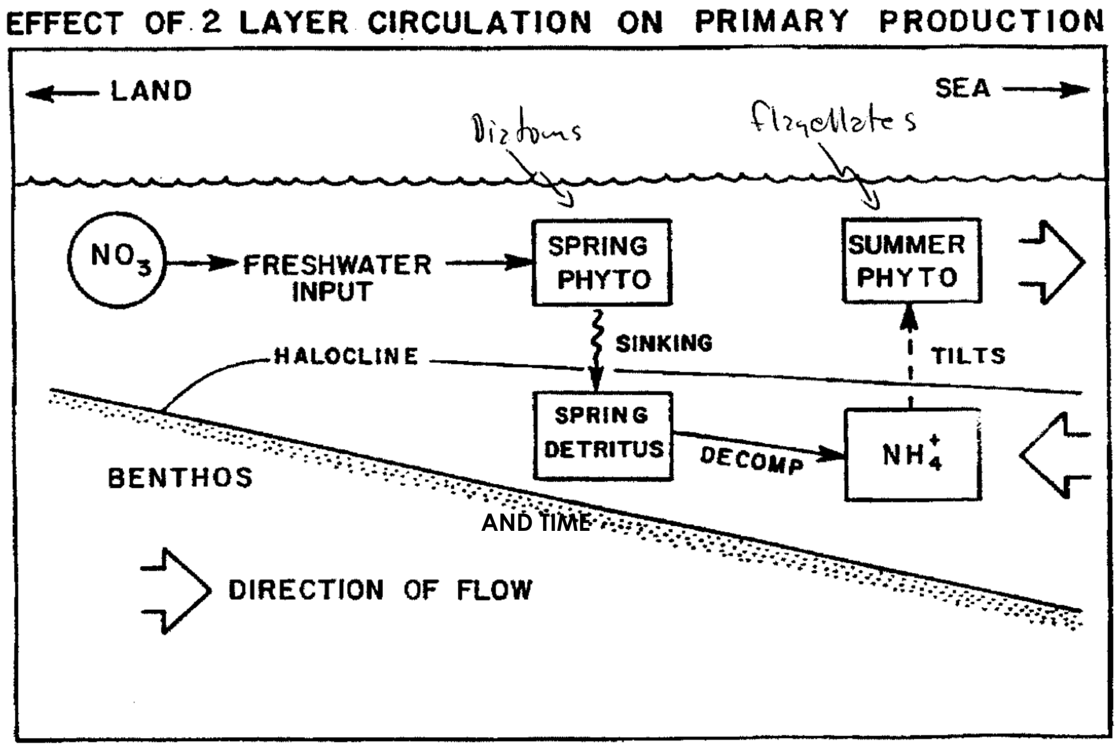
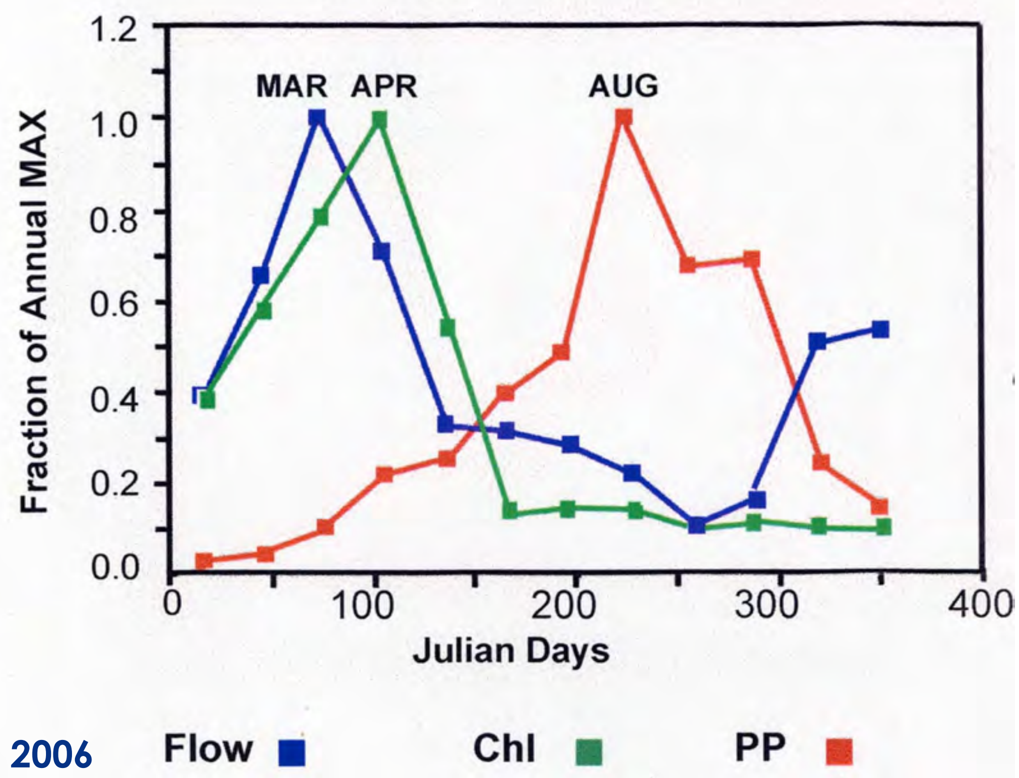


Figure courtesy of M. Kemp

- Freshet drives the spring diatom bloom and leads to export to the bottom.
- Increasing summer temperatures lead to remineralization of organic matter on the bottom.
- Upward diffusive mixing and transport of nutrients to the surface during summer leads to high summer production.

Variability of biomass and productivity

Classic Conceptual Model of Biomass and Production Variability:

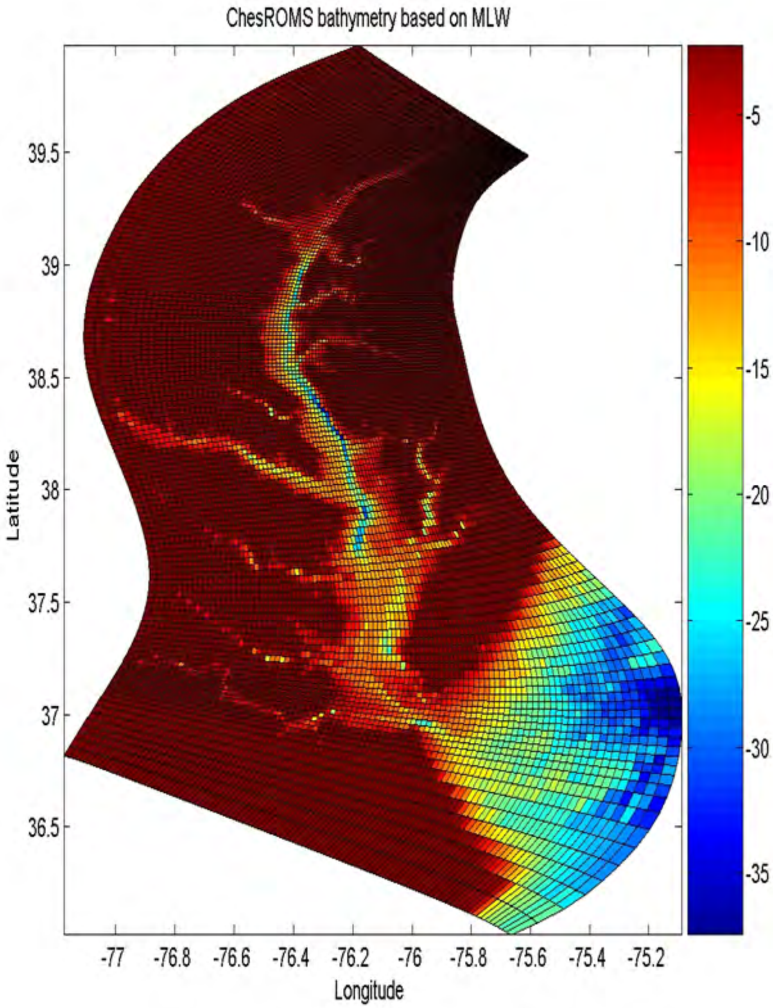


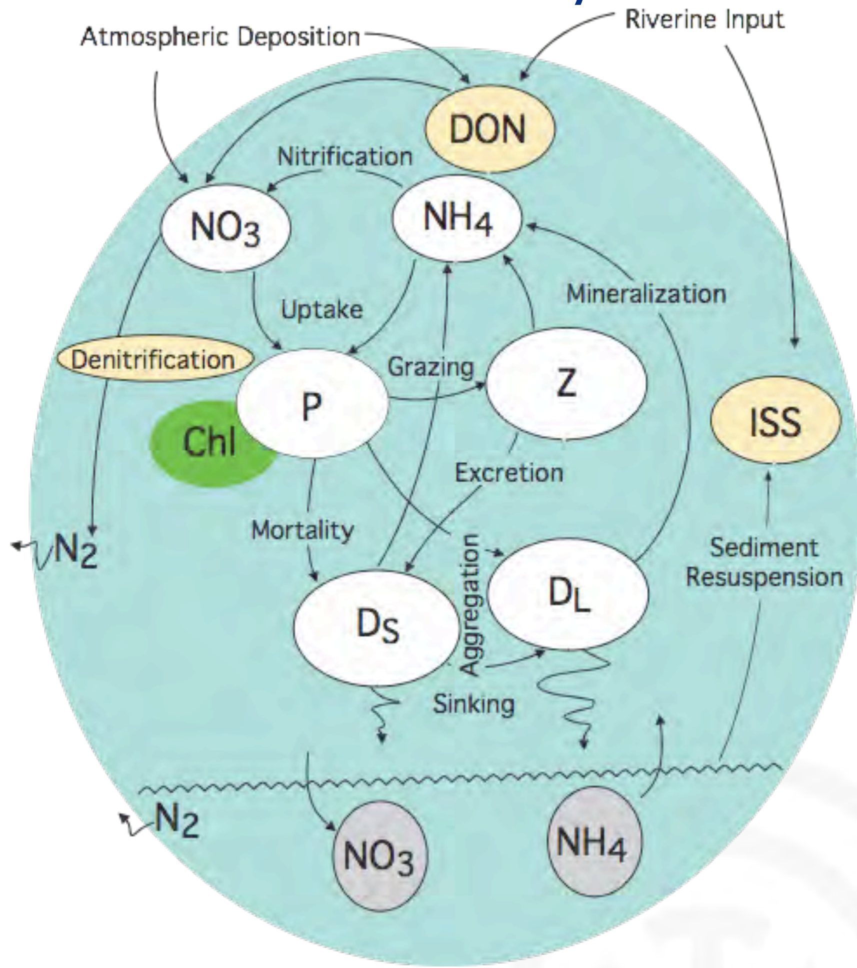
From Malone, 1991
See also Adolf et al. 2006

- The spring diatom bloom is associated with freshet, but its not a productivity maximum.
- During summer have maximum productivity. This summer production is fueled largely by recycling of organic matter from the bottom that was put there during spring.
- Also see a shift in size: large diatoms in spring - > smaller flagellates and dinoflagellates in summer.

Variability of biomass and productivity

Model Configuration (ChesROMS BGC):





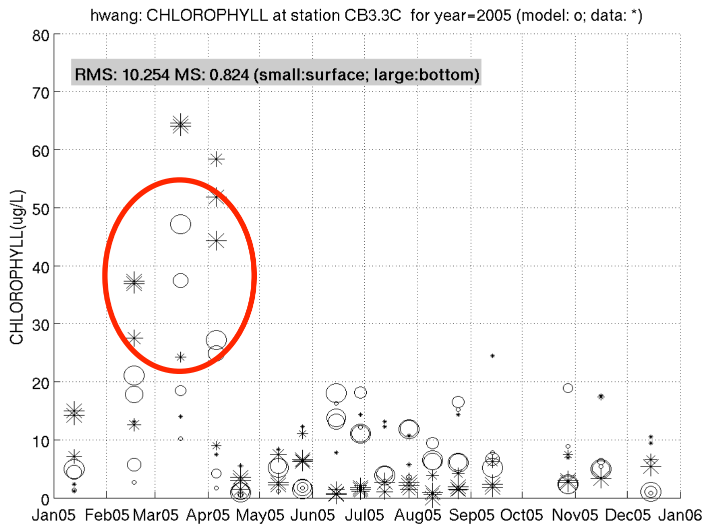
- Xu et al. (2012)
- Grid: 100x150x20

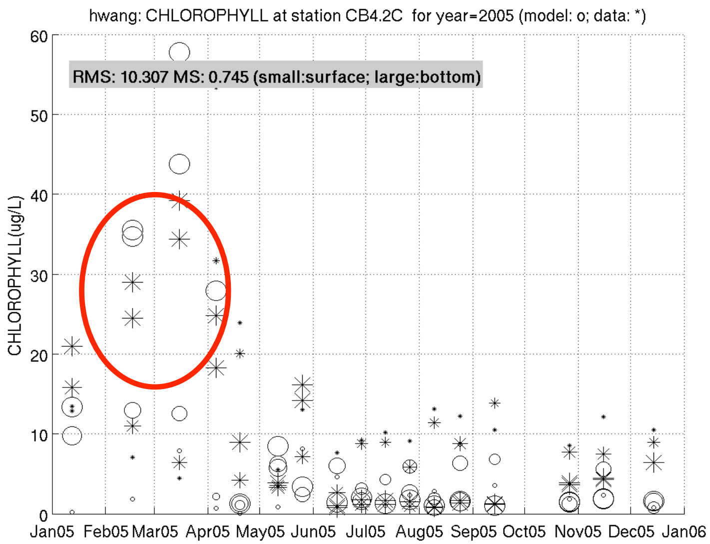
- Brown et al. (2013), Wiggert et al. (2017)
- Fennel et al. (2006) with water column and benthic denitrification.

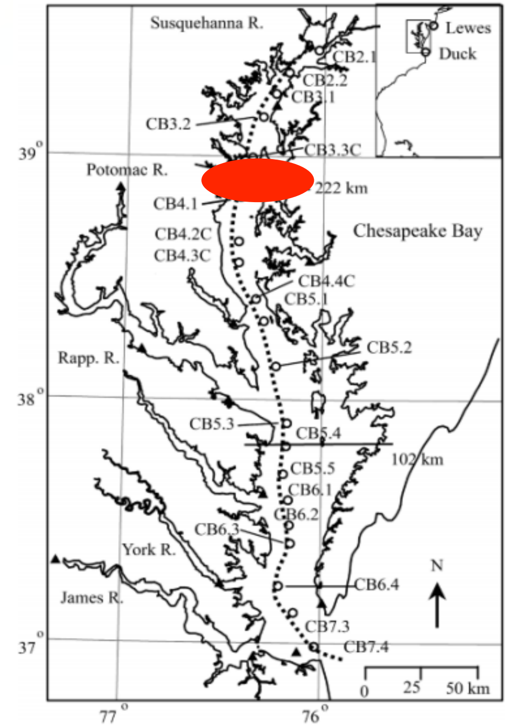
IOOS | EYES ON THE OCEAN™

Variability of biomass and productivity

Modeled Phytoplankton Biomass:





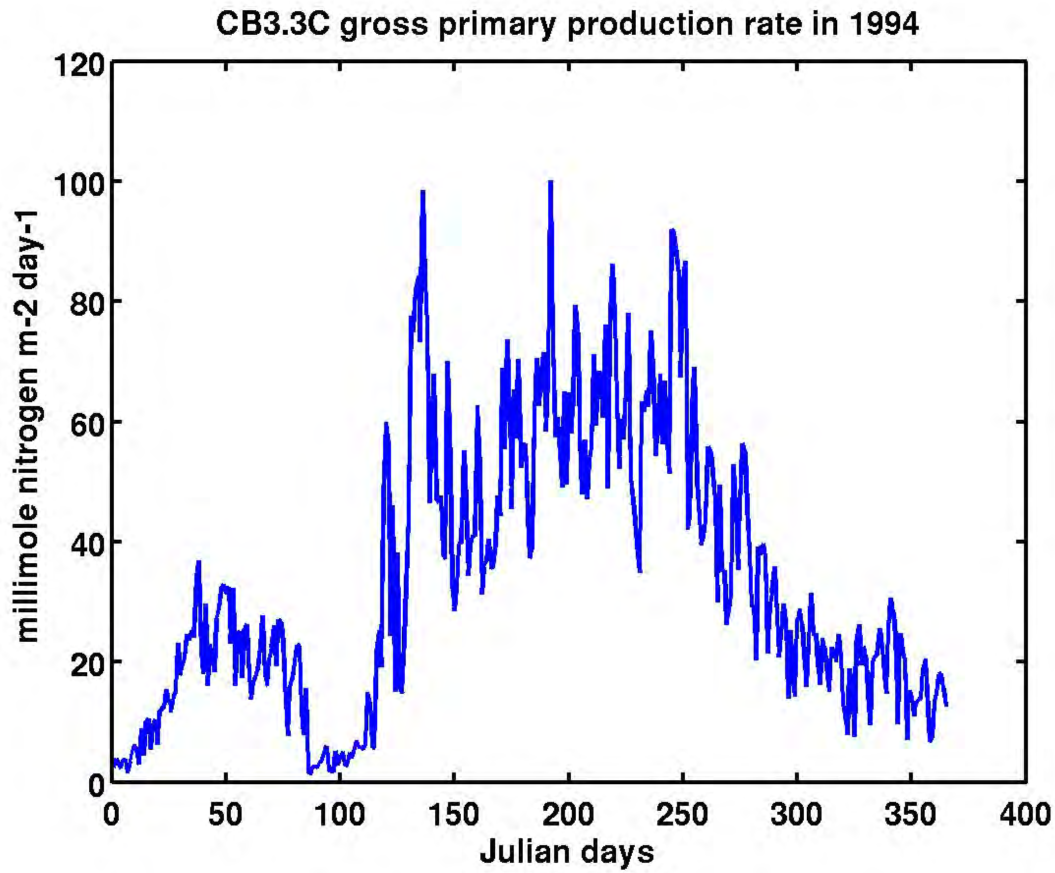


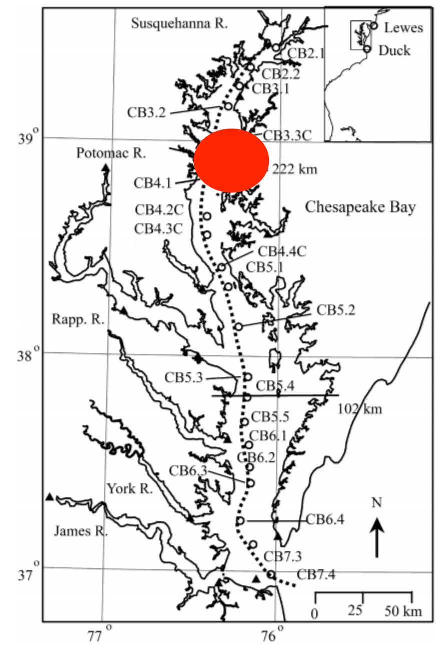
Models Capture:

- Spring bloom
- Deep chlorophyll accumulation in Spring
- Low biomass during summer

IOOS EYES ON THE OCEAN

Modeling Primary Production Rate:

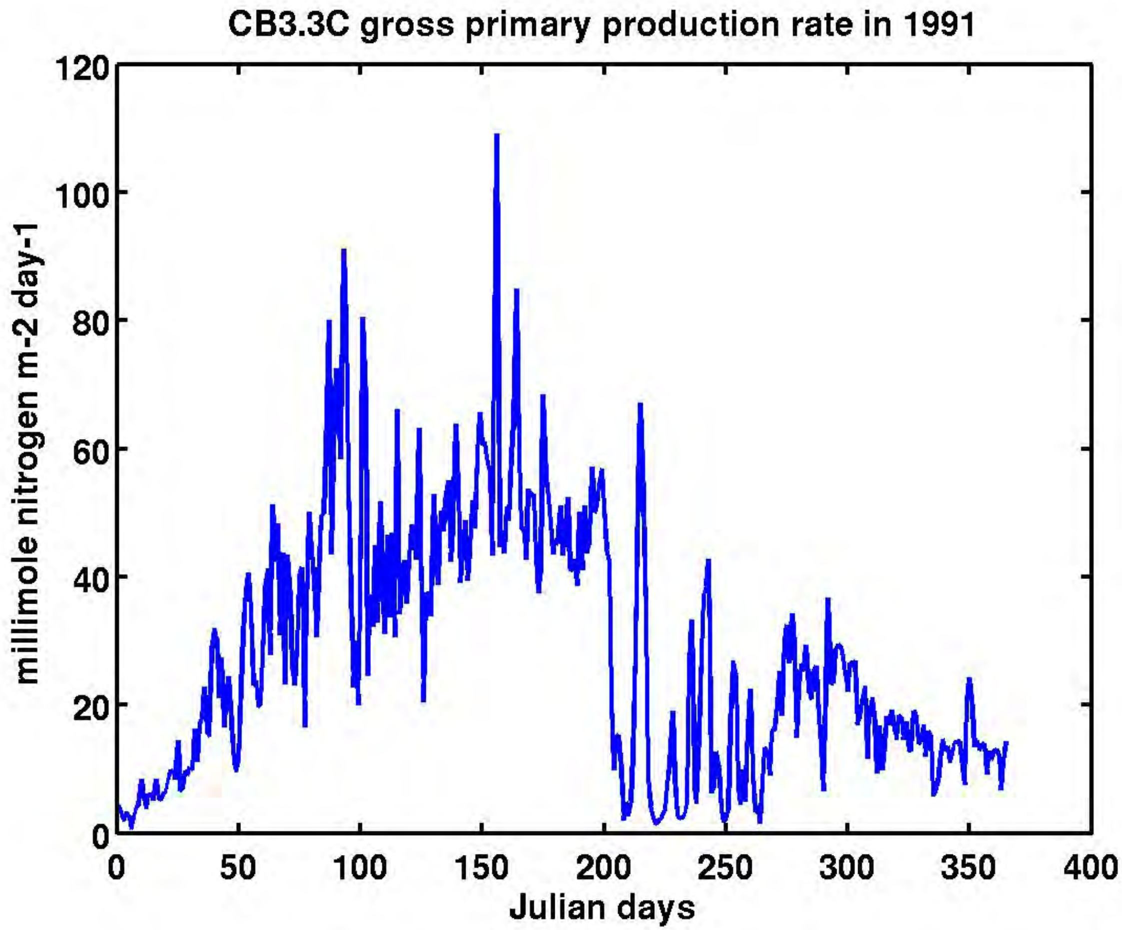


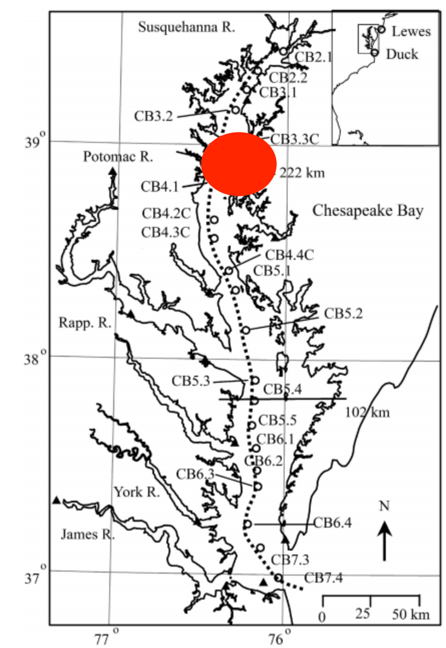


- Model captures the seasonal variability of the primary production in some years: e.g., 1994 highest production during summer as observed.

Variability of biomass and productivity

Modeling Primary Production Rate:



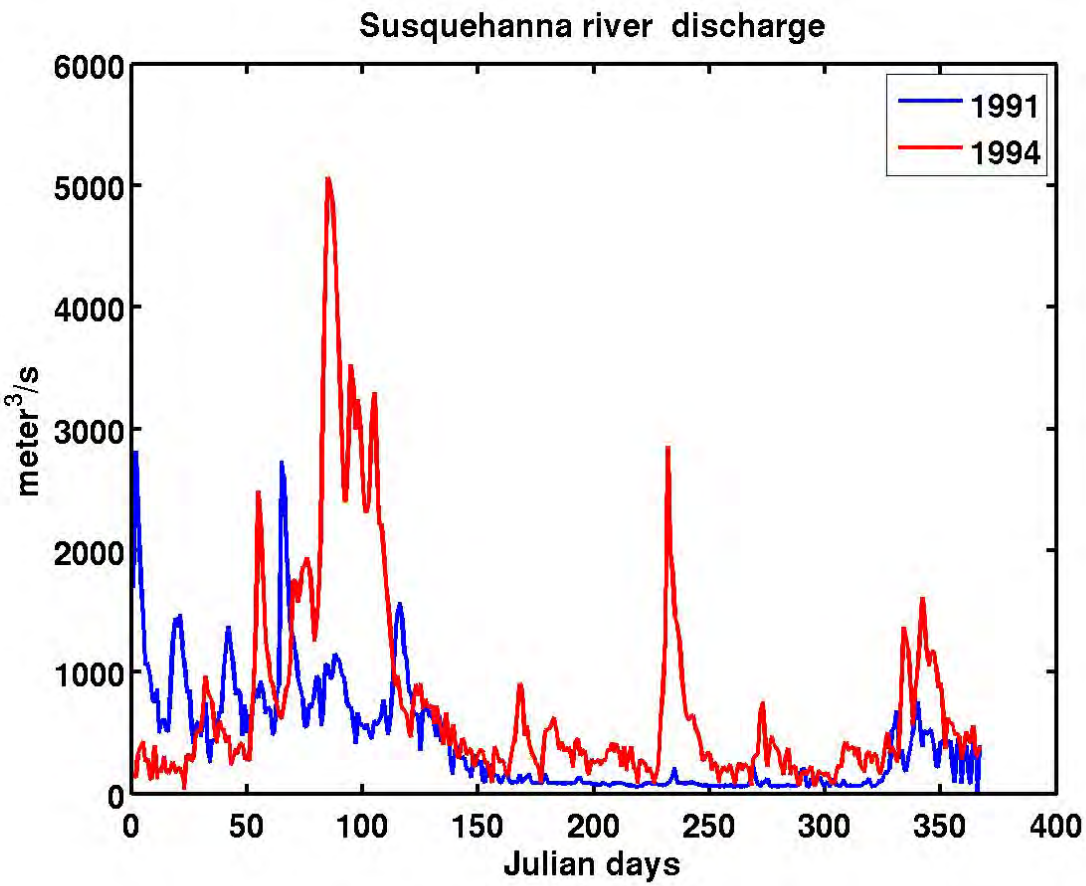


- But not in others: e.g., in 1991 see a dramatic drop in the summer which is not consistent with observations.

IOOS | EYES ON THE OCEAN™

Variability of biomass and productivity

Role of River Forcing:



- River discharge plays a role in this interannual variability.
- Years with high river nutrient loading during summer tend to capture observed high summertime primary production (e.g., 1994).

- Years with low nutrient loading during summer tend to have primary production rates that are too low during summer (e.g., 1991).

Variability of biomass and productivity

Classic Conceptual Model of Biomass and Production Variability:

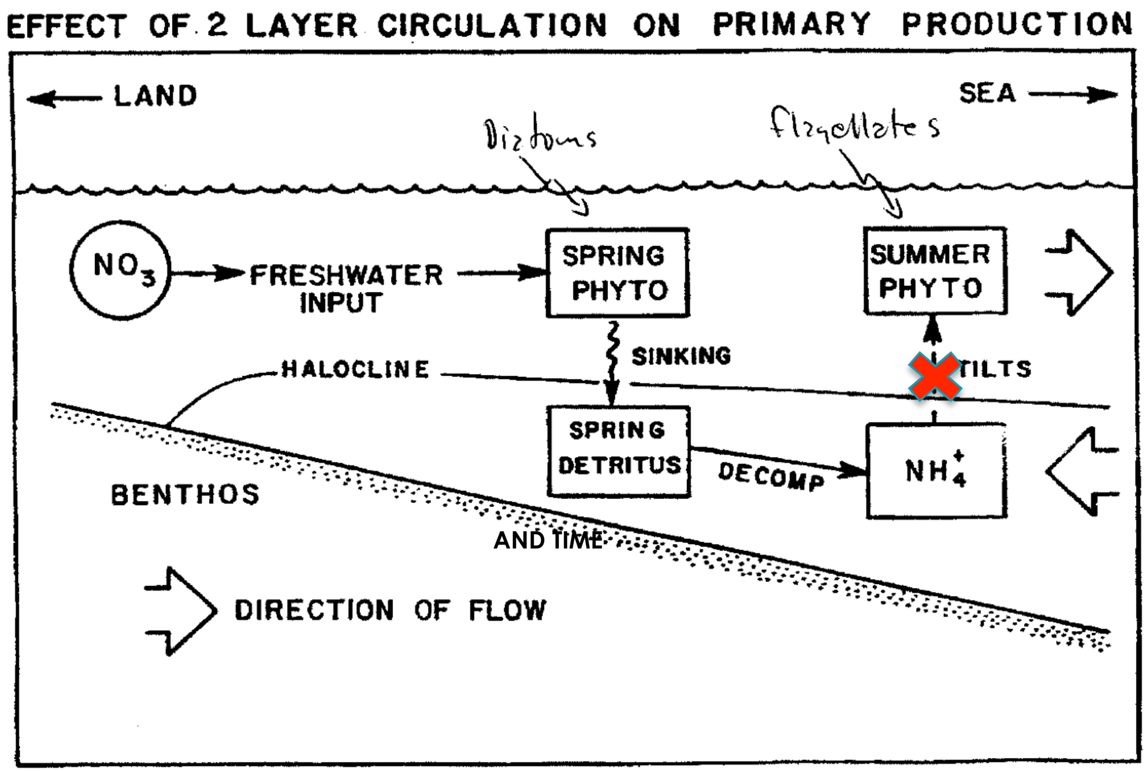


Figure courtesy of M. Kemp

- We hypothesize that there is insufficient upward diffusion and mixing of nutrients to support high summertime production in our models when river nutrient inputs during summer are low.

Variability of biomass and productivity

Conclusions:

- Models can capture observed seasonal and vertical variability in phytoplankton biomass but they do not consistently capture seasonal primary production variability.
- Models require lateral nutrient inputs from rivers to maintain high production during summer.
- Low lateral supply during summer results in nutrient limitation and unrealistically low summertime production.
- We hypothesize that there is insufficient upward diffusion and mixing of nutrients to support high summertime production in these models when summertime river nutrient inputs are low.

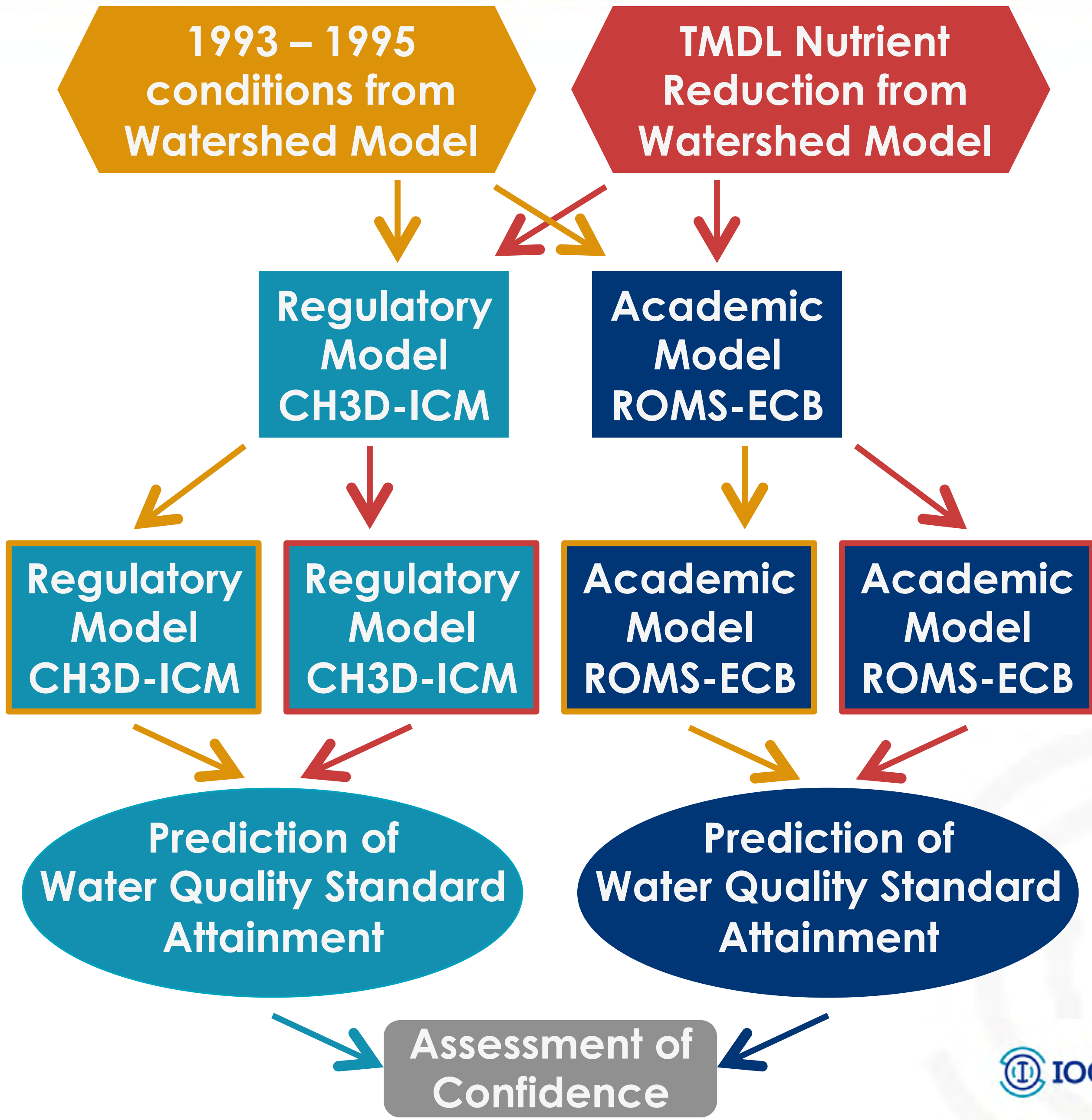
Outline

- Short-term operational forecasts (M. Friedrichs/A. Bever)
  - Review of Year 3 accomplishments
  - Quasi-operational forecasts (VIMS website)
  - Operational forecasts (dev) (CBOFS website)
  - Skill assessment of forecasts
- Improvements to Hypoxia-SRM (M. Scully/C. Friedrichs)
- Seasonal patterns in P biomass & PP variability (R. Hood/H. Wang)
- **Scenario-based operational forecasts (I. Irby/M. Friedrichs)**
  - Evaluating uncertainty in forecasts of nutrient reduction impacts
  - Assessing impacts of climate change on nutrient reduction impacts
- Year 5 plans (M. Friedrichs)

Impact of Nutrient Reduction

Evaluating confidence in the impact of regulatory (TMDL) nutrient reduction on Chesapeake Bay water quality

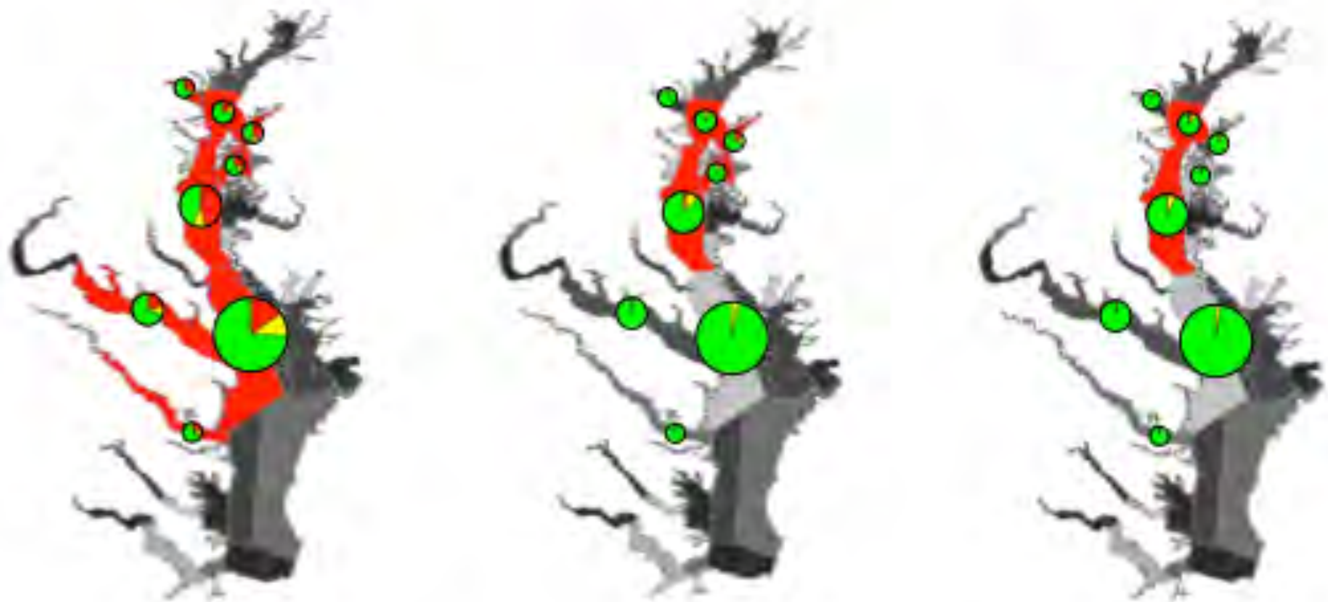
Impact of Nutrient Reduction



Impact of Nutrient Reduction

Are dissolved oxygen standards attained with nutrient reduction?

Deep Channel	Observed 1993 – 1995	TMDL CH3D-ICM	TMDL ROMS-ECB



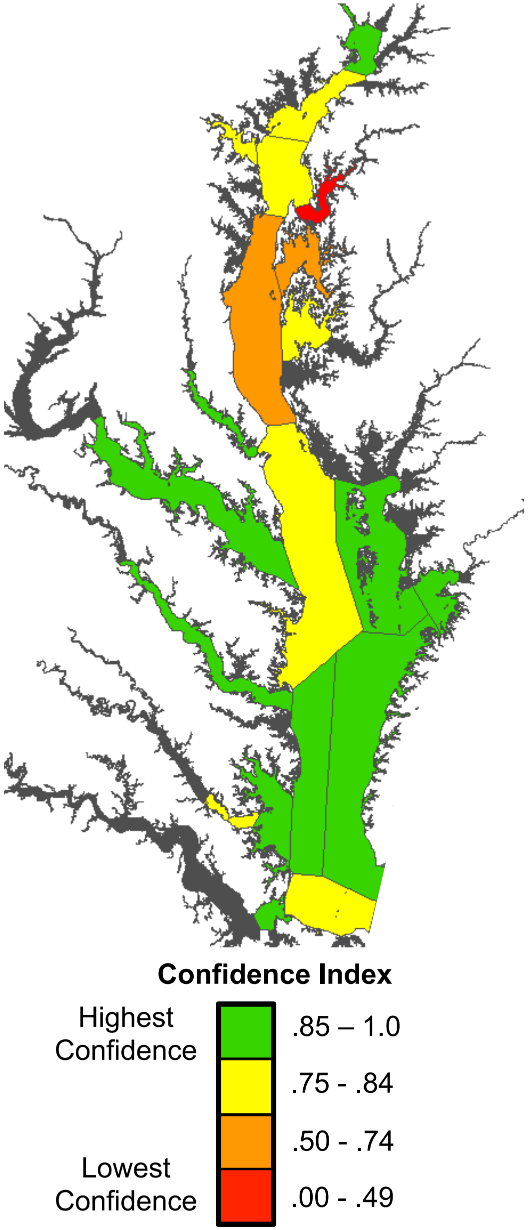
- Pass
- "Pass"
- Fail

IOOS | EYES ON THE OCEAN

Impact of Nutrient Reduction

Confidence Index

- Across habitats
- Across years
- Across methodology



Issues Identified

- Chester River: Regulatory (EPA) Model
- Eastern River: Academic Model
- TMDL regression methodology

Impact of Nutrient Reduction

Results:

- High similarity/confidence in terms of prediction of attainment of water quality standards resulting from planned nutrient reductions

- Large difference in the intermediate steps to get to water quality standard attainment

- Comparing models can elucidate issues in models and methodology

Climate Change & Nutrient Reduction

The competing impacts of climate change and nutrient reduction on dissolved oxygen

Climate Change & Nutrient Reduction

2050 Relative to 1993-1995

Temperature	Sea Level Rise	River Flow
↑ 1.75°C	↑ 0.5m	↑ ~15% winter
↓ Oxygen Solubility	↑ Seawater intrusion	↑ Fresh water
↑ Biologic Rates	↑ Bay volume	↑ Nutrient load

Climate Change & Nutrient Reduction

Climate Change Scenarios

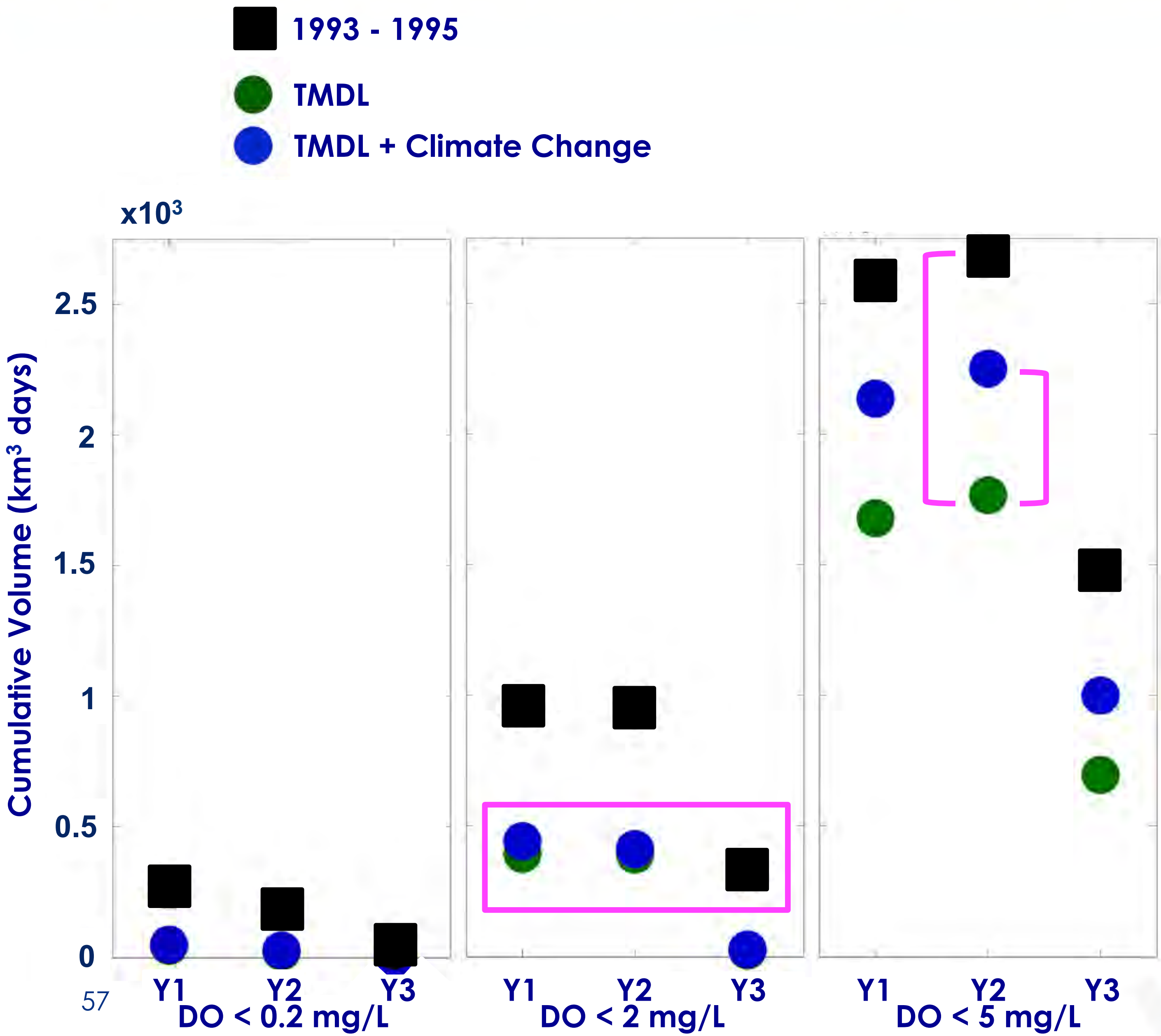
Current

TMDL

TMDL + Climate Change

- TMDL + Temperature
- TMDL + River Flow
- TMDL + Sea Level Rise

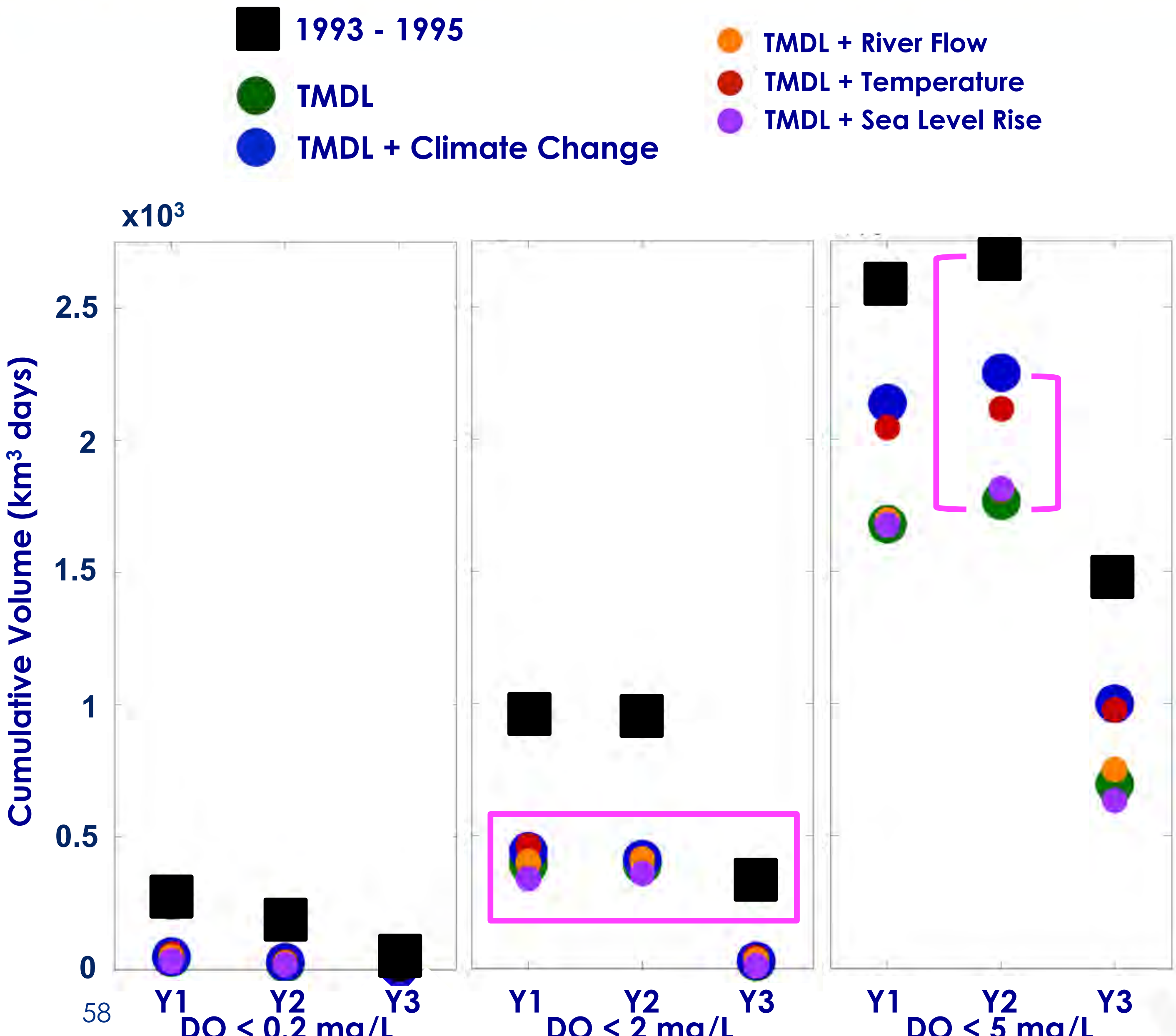
Climate Change & Nutrient Reduction



Impact of TMDL is greater than impact of climate change

A TMDL wet year looks like a current dry year

Climate Change & Nutrient Reduction



Impact of TMDL is greater than impact of climate change

A TMDL wet year looks like a current dry year

Temperature is the biggest driver of climate change impact

IOOS | EYES ON THE OCEAN™

Climate Change & Nutrient Reduction

Results:

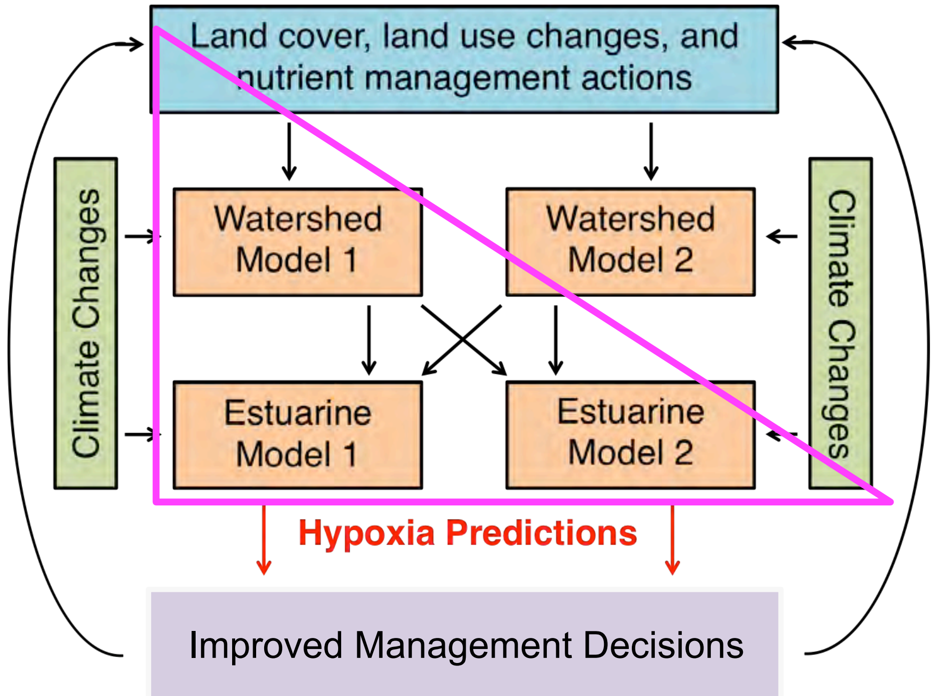
- TMDL > Climate Change
- Higher Temperature > Sea Level Rise & Increased River Flow
- Hypoxia starts ~7 days earlier with climate change

Climate Change & Nutrient Reduction

FUTURE RESEARCH DIRECTIONS

CHAMP: Chesapeake Hypoxia Analysis and Modeling Program

- Predict the impacts of future climate change and pollution on hypoxia
- Predict the future effectiveness of various pollution reduction scenarios on reducing hypoxia



Funded by NOAA CSCOR – Coastal Ocean Program, 2016-2021

Outline

- **Short-term operational forecasts (M. Friedrichs/A. Bever)**
    - Review of Year 3 accomplishments
    - Quasi-operational forecasts (VIMS website)
    - Operational forecasts (dev) (CBOFS website)
    - Skill assessment of forecasts
- **Improvements to Hypoxia-SRM (M. Scully/C. Friedrichs)**
- **Seasonal patterns in P biomass & PP variability (R. Hood/H. Wang)**
- **Scenario-based operational forecasts (I. Irby/M. Friedrichs)**
    - Evaluating uncertainty in forecasts of nutrient reduction impacts
    - Assessing impacts of climate change on nutrient reduction impacts
- **Year 5 plans (M. Friedrichs)**

Year 5 plans

- **Scenario-based operational forecasts: CHAMP (NOAA-CSCOR)**
- **Improvement of Hypoxia-SRM (inclusion of simple PP model)**
- **Evaluating skill of habitat suitability models for nowcasting/ forecasting HAB species and bacterial pathogens**
- **Expanding hypoxia forecasts**
    - Available on MARACOOS site
    - Available on CBOFS site
    - Improved forecasts using available data (CBIBS)
    - Continued work with stakeholder focus groups