Probabilistic Modeling to Assess Temporal Change in Complex Aquatic Systems

Chesapeake Bay Program

Scientific and Technical Advisory Committee (STAC) Workshop

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Daniel R. Obenour, Ph.D., obenour@umich.edu

University of Michigan Water Center

Outline

1. Developing robust metrics for tracking environmental change
   (geostatistical modeling of Gulf hypoxia)
2. Identifying a system in transition
   (empirical modeling of Lake Erie HABs)
3. Exploring controlling processes
   (mechanistic modeling of Gulf hypoxia)
4. Applications to Chesapeake Bay…

1. Developing robust metrics for tracking environmental change

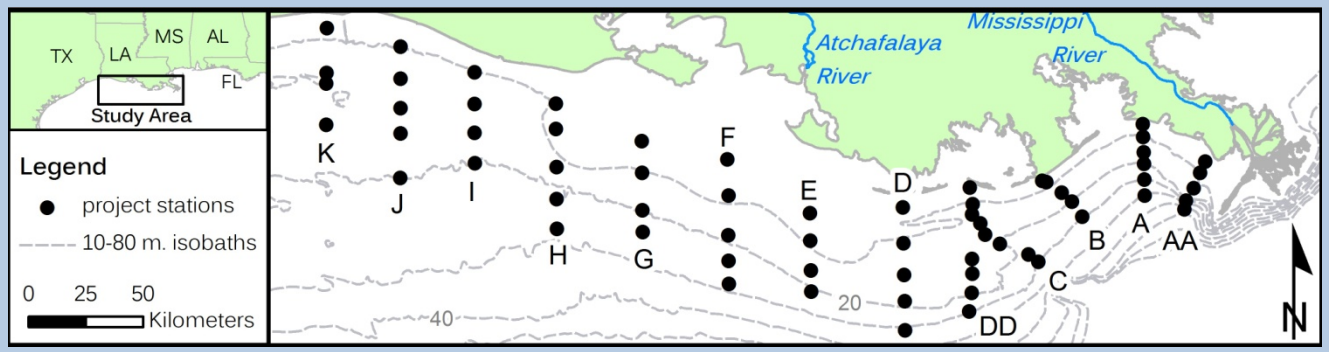
- Reconstruct 27-year history of mid-summer Gulf hypoxia using geostatistics
- Quantify uncertainty
- Account for different instrumentation
- Include spatial and bathymetric trends
- Estimate volume (in addition to area)

Obenour, D.R., D. Scavia, N.N. Rabalais, R.E. Turner, & A.M. Michalak (**2013**). Retrospective analysis of mid-summer hypoxic area and volume in the northern Gulf of Mexico, 1985-2011. *Environmental Science and Technology*, 47(17), 9808–9815.

Background: Gulf hypoxia monitoring


R/V Pelican, source: LUMCON

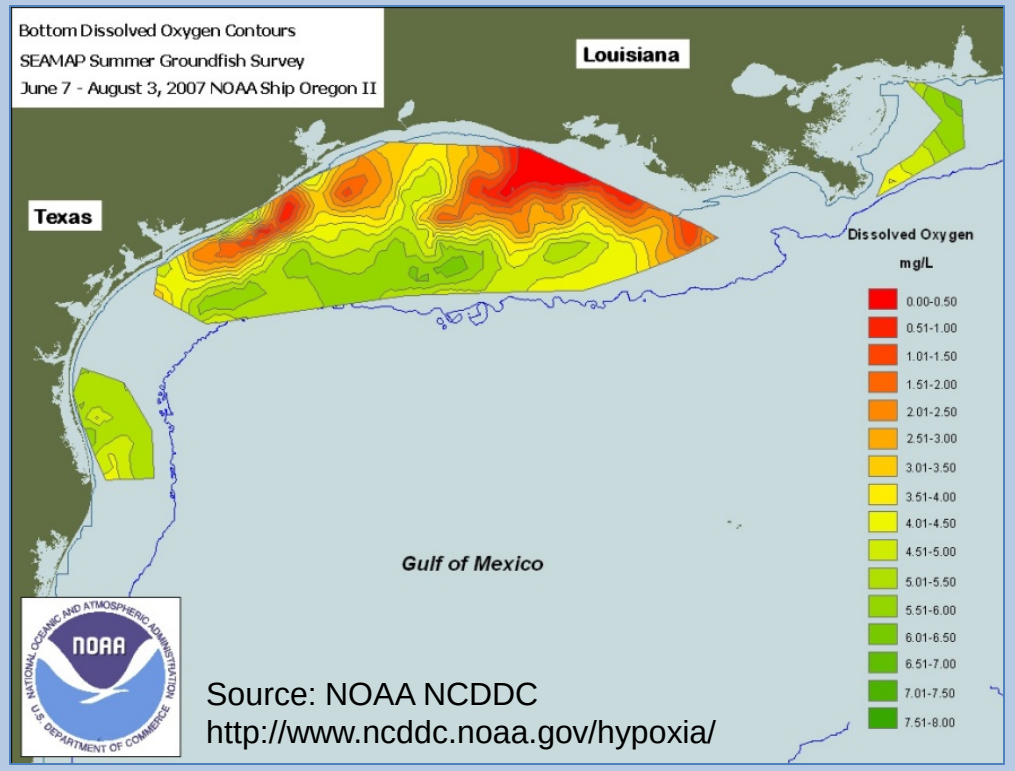
LUMCON annual shelf-wide cruises (since 1985)



Sites regularly sampled during LUMCON shelf-wide cruises

Challenges for traditional approaches

- Estimating outside of cruise extent
- Quantifying uncertainty



Geostatistical Model Formulation

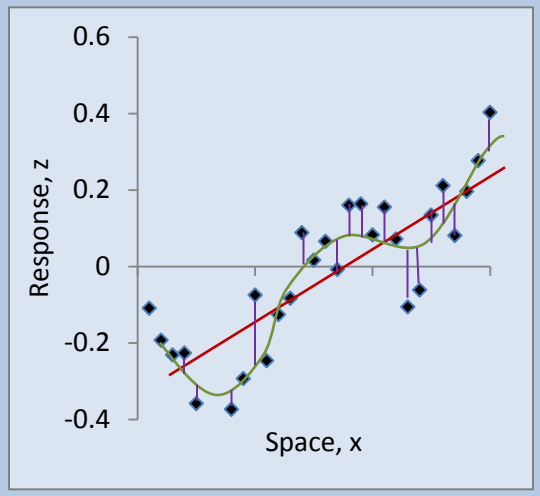
$$z = X\beta + \eta + \epsilon$$

Response Variable

Deterministic Component (trends with space and other covariates)

Spatially Correlated Stochasticity

Uncorrelated Stochasticity



Application of Model to Shelfwide Cruises: **deterministic component**

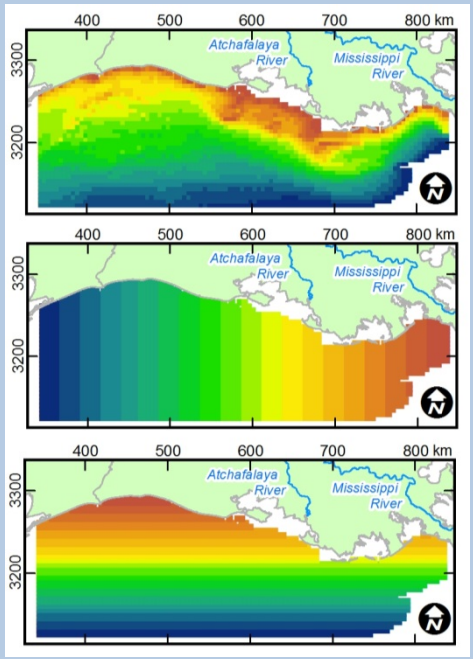
$$z = X\beta + \eta + \epsilon$$

- Candidate Variables (**X**)

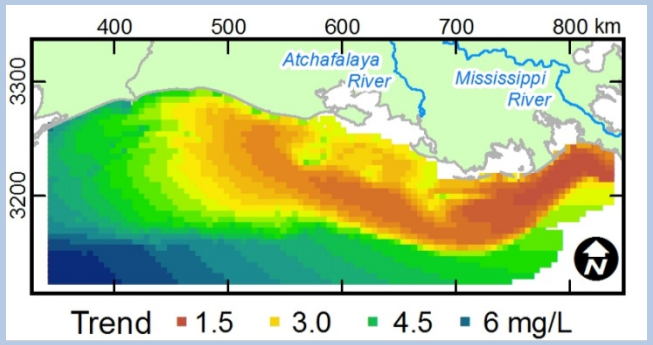
Depth

Easting

Northing



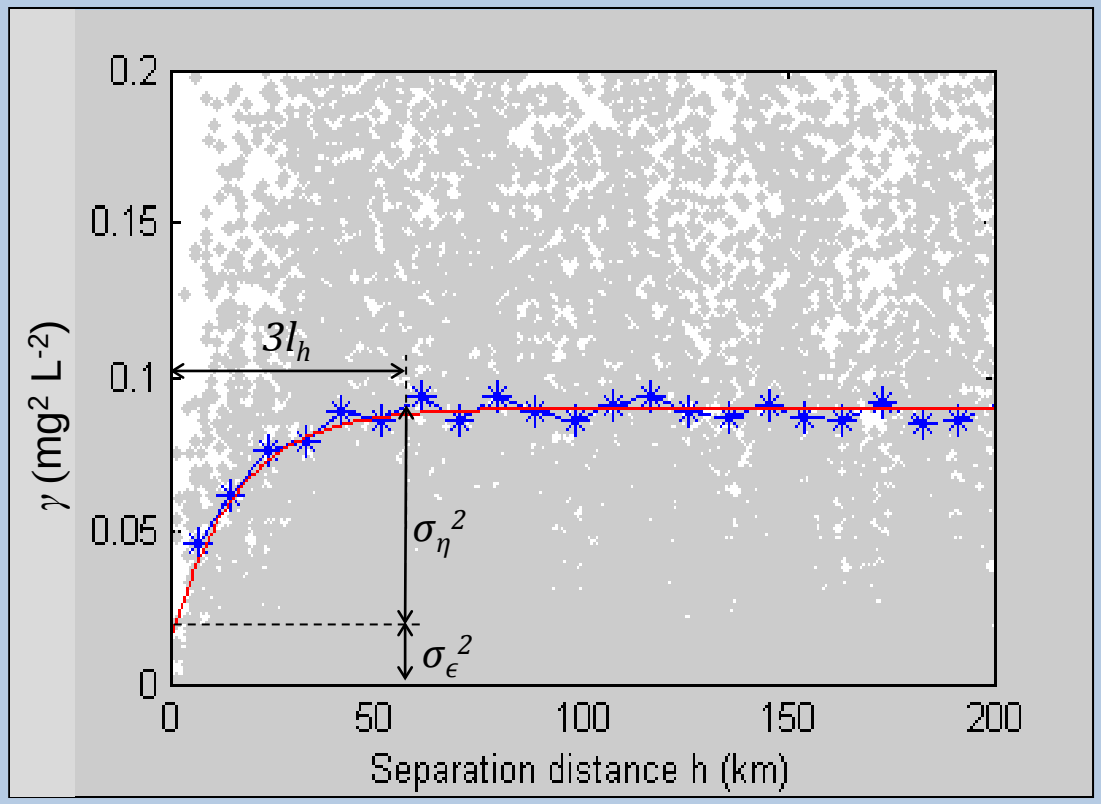
Overall BWDO trend



- Variable Selection: BIC
- Parameterization: GLS

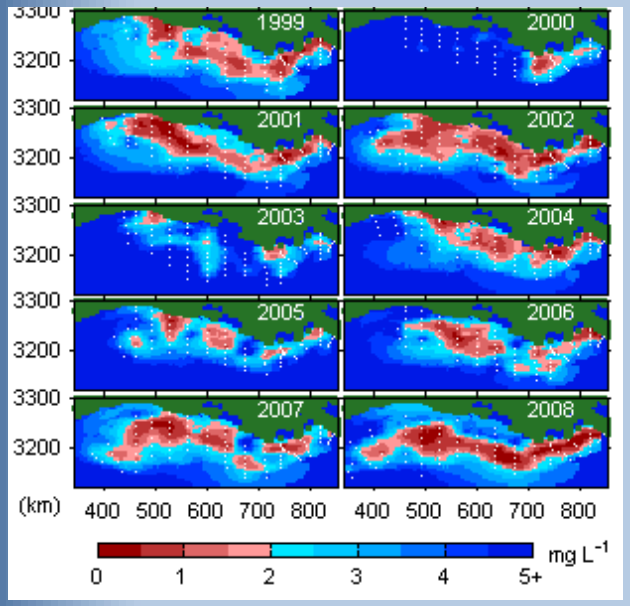
Application of Model to Shelfwide Cruises: **stochastic components**

$$z = X\beta + \eta + \epsilon$$

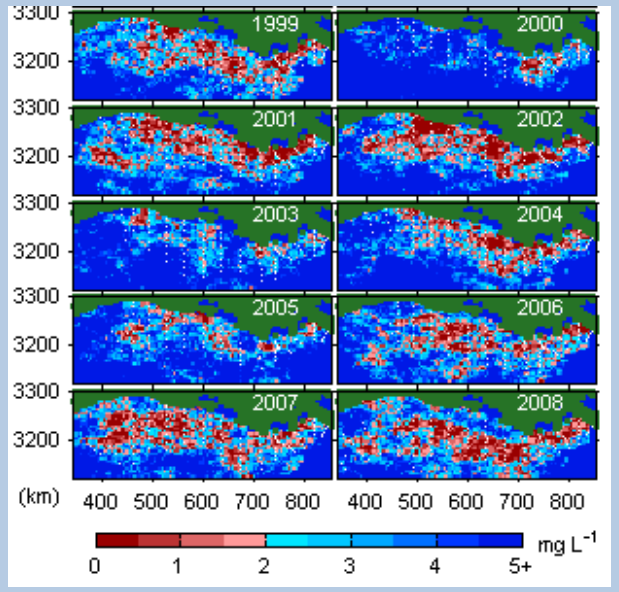


Example Results for BWDO/hypoxic area

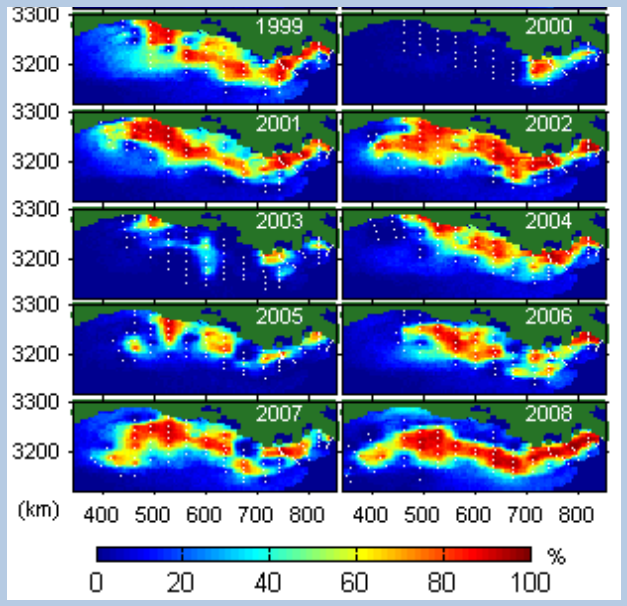
Kriged BWDO



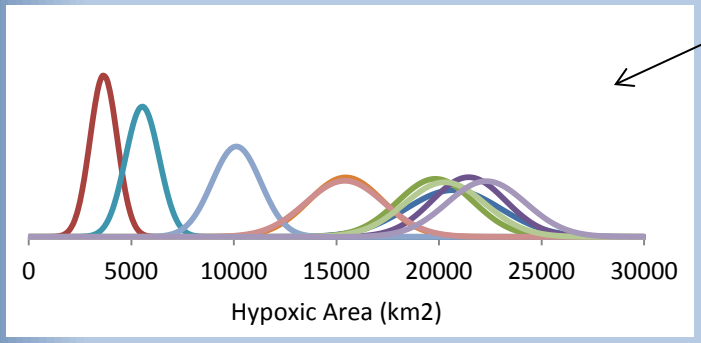
Conditional realizations of BWDO, "*spatially consistent* Monte Carlo simulations" – Chiles & Delfiner



Probability of hypoxia



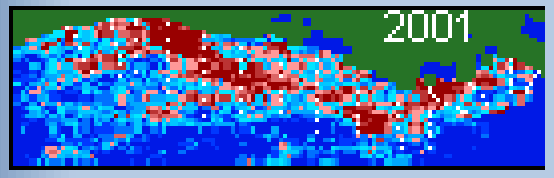
x 1000



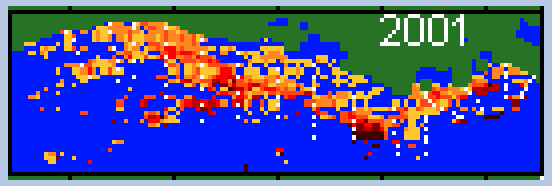
Hypoxic Volume

- Simulation in two steps…

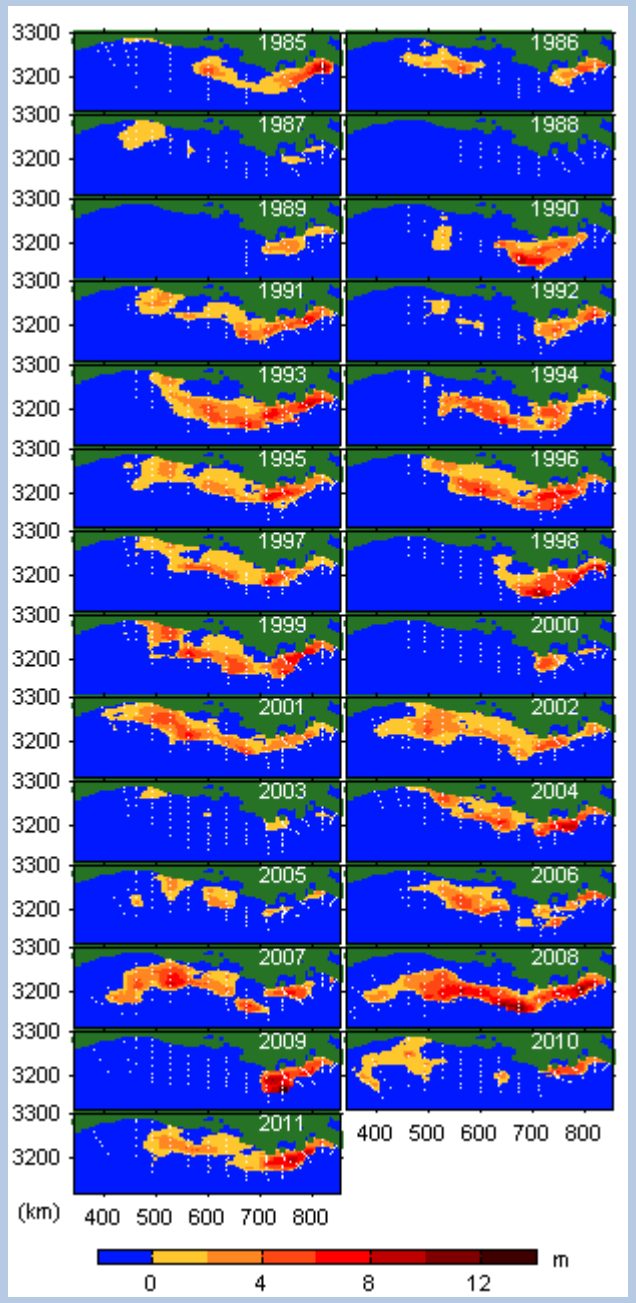
1. Simulate BWDO



2. Simulate Hypoxic Frac/Thickness



Median thickness from conditional realizations

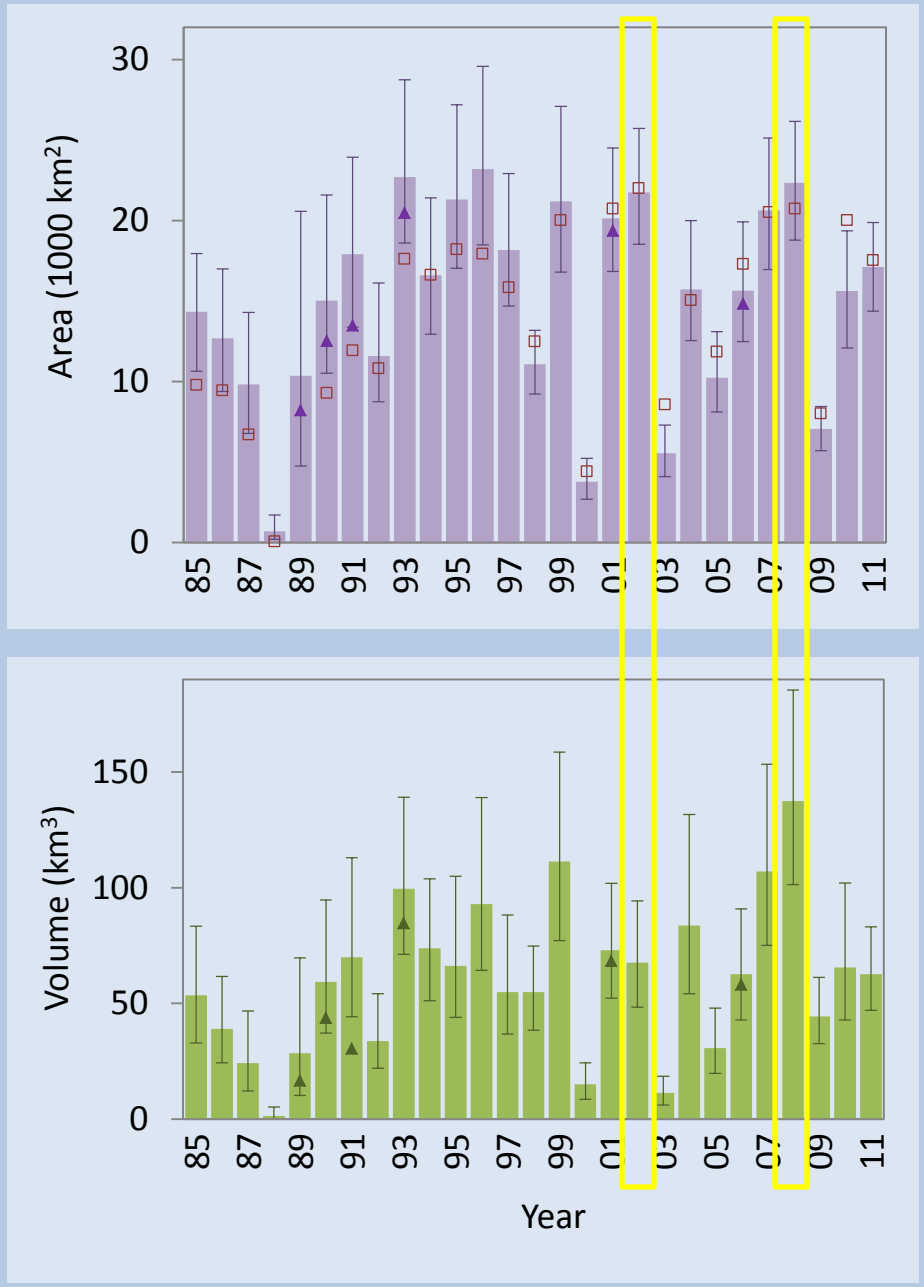


Hypoxic Extents 1985-2011

New estimates (with 95% CI)

Without instrument bias adjustment

Original LUMCON estimates



Obenour et al., (2013, ES&T)

2. Identifying a system in transition

- Empirical model relating late-summer Lake Erie cyanobacteria bloom to TP loading.
- Identify any underlying temporal trends or change points.
- Calibrate model to multiple sets of bloom observations using a Bayesian hierarchical approach.
- Develop forecasts.

Obenour, D.R., A.D. Gronewold, C.A. Stow, & D. Scavia. (***In Review***). Using a Bayesian hierarchical model with a gamma error distribution to improve Lake Erie cyanobacteria bloom forecasts.

Background: Lake Erie cyanobacteria blooms

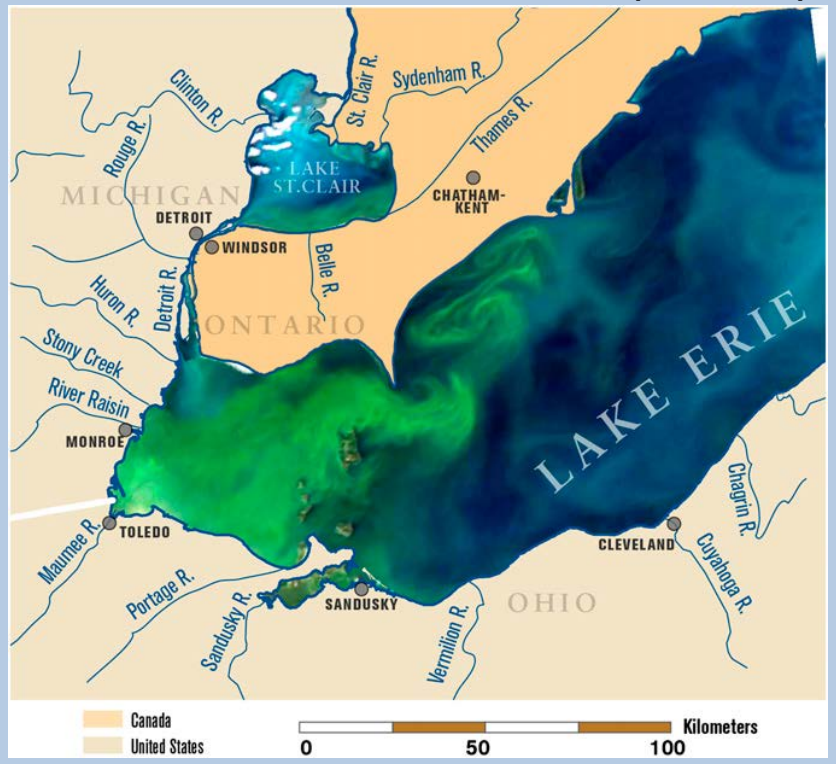
Exceptional Blooms

- 2011 was most severe lake-wide bloom on record
- 2013 was most severe bloom in Maumee Bay on record

Possible causes

- Increased nutrient loads
- Climatic conditions
- Invasive species
- Increasing seed pool
- …?

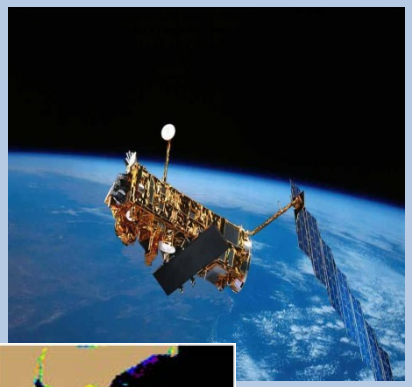
Michalak et al., (2013, PNAS)

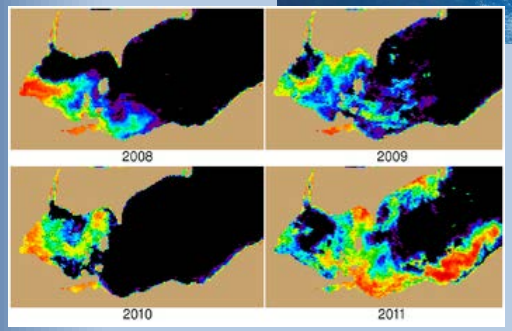


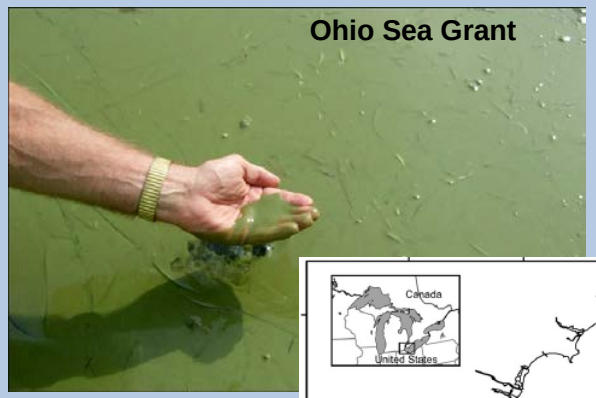
Cyanobacteria bloom measurements

Observation set 1:
2002-2012 via MERIS
Stumpf et al., 2012, PLoS ONE

Observation set 2:
2002-2013 via Plankton Tows
Bridgeman et al., 2011, JGLR







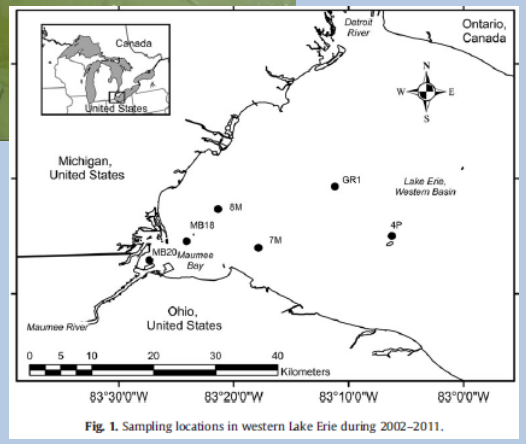
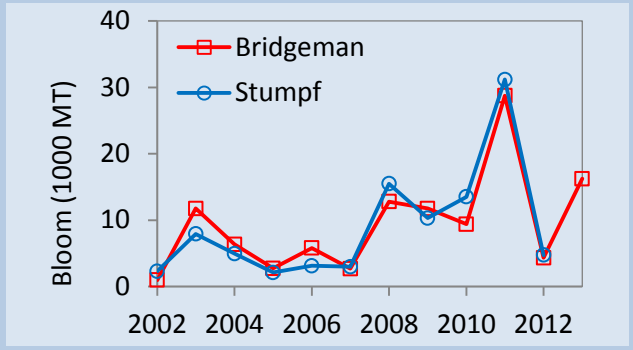


Fig. 1. Sampling locations in western Lake Erie during 2002–2011.



Hierarchical model formulation

$$z = X\beta + \gamma + \epsilon$$

where…

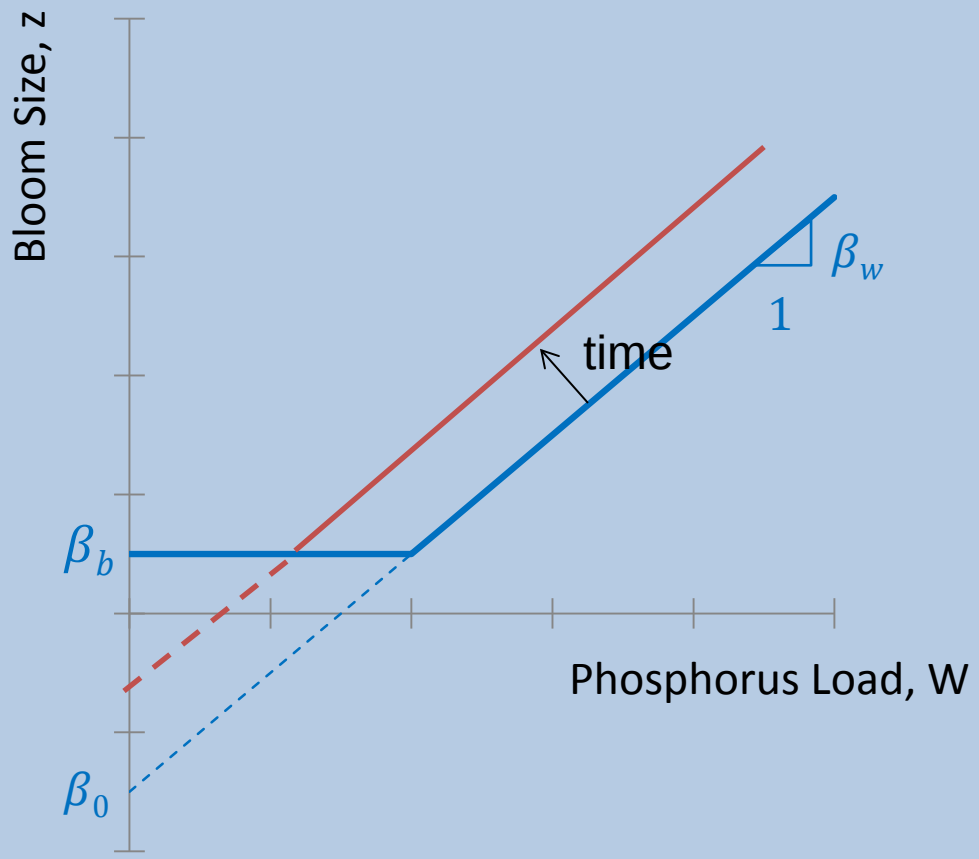
z is the "observed" bloom measurement

$X\beta$ is the deterministic prediction
(from a regression-type P loading model)

γ is deterministic model error
(a yearly "random effect")

ϵ is observation "measurement" error

Deterministic model form, Xβ

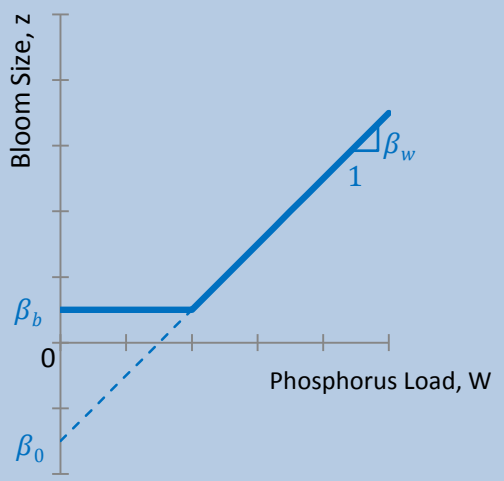


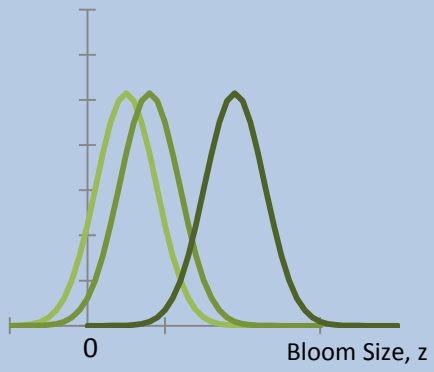
Candidate model forms

Deterministic Form

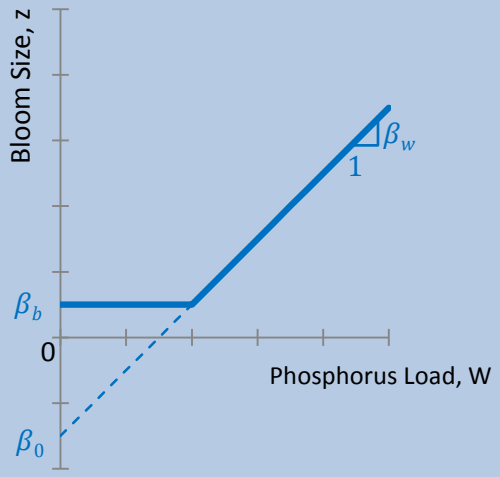
Error Distribution

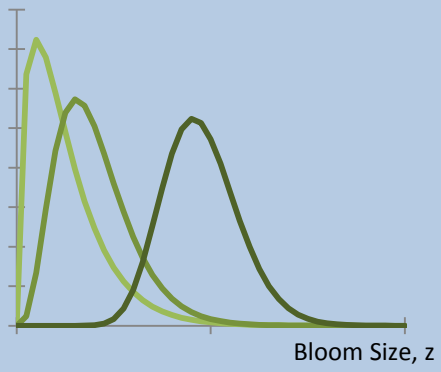
Normal Model



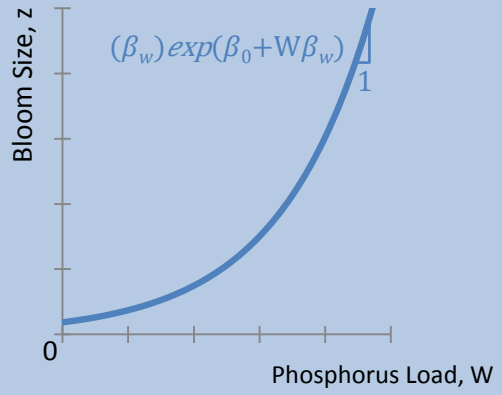


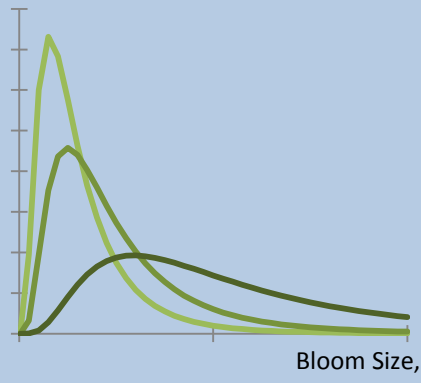
Gamma Model





Log-Normal Model





Model Cross Validation Results

Normal Model | Gamma Model | Log-Normal Model

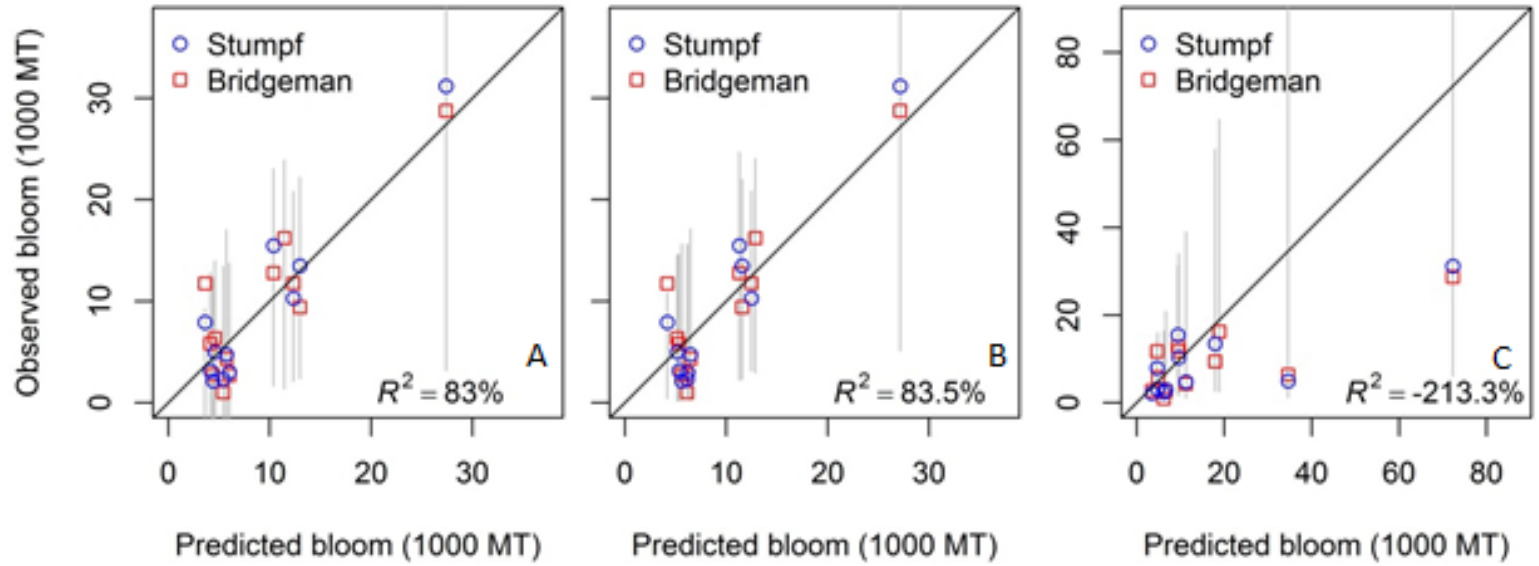
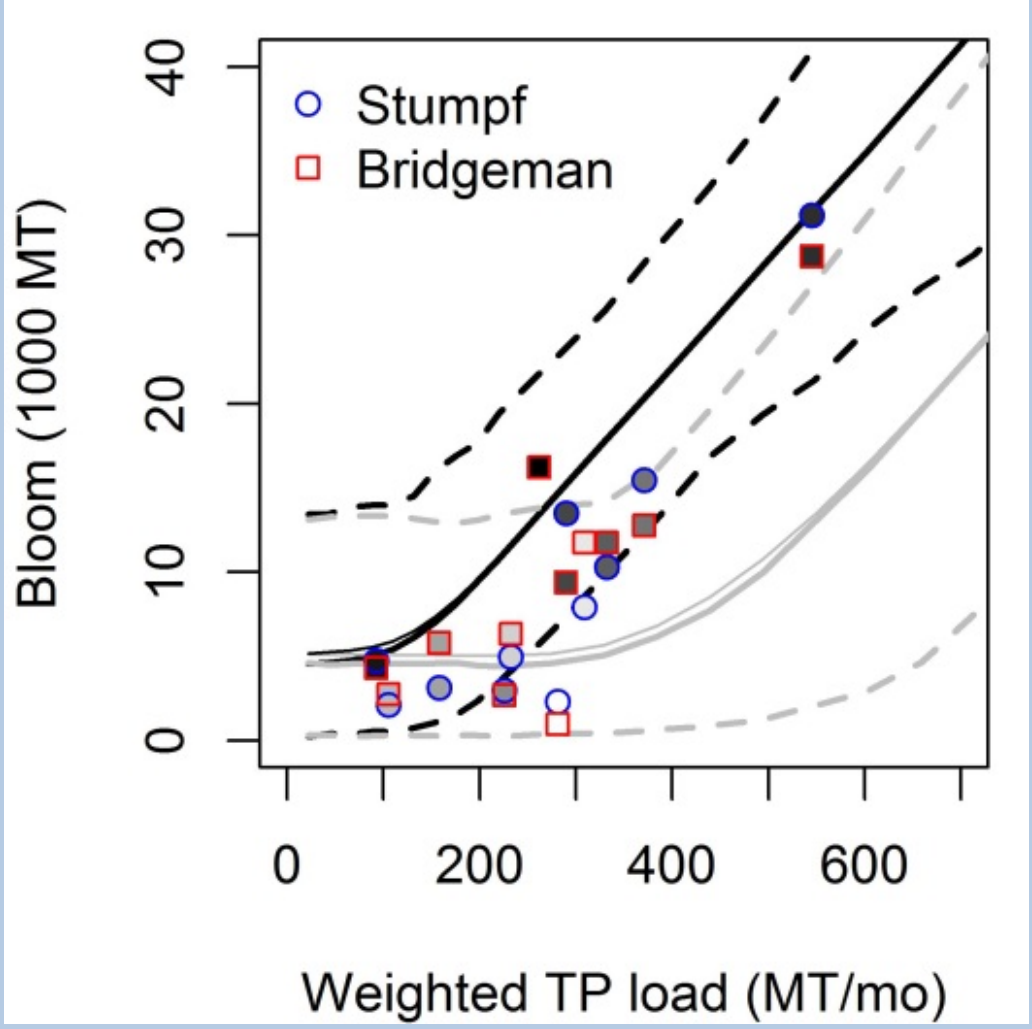
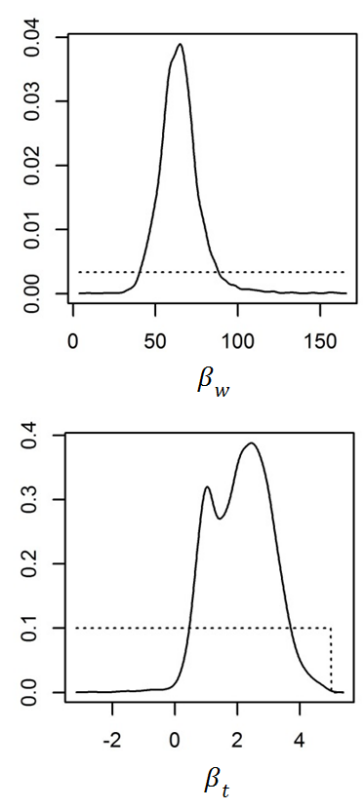


Figure 6: Observed versus CV predicted bloom for the normal model (A), gamma model (B), and log-normal model (C) with 95% predictive intervals.

Obenour, Gronewold, Stow, and Scavia (in review)

Forecasting curves (gamma model)





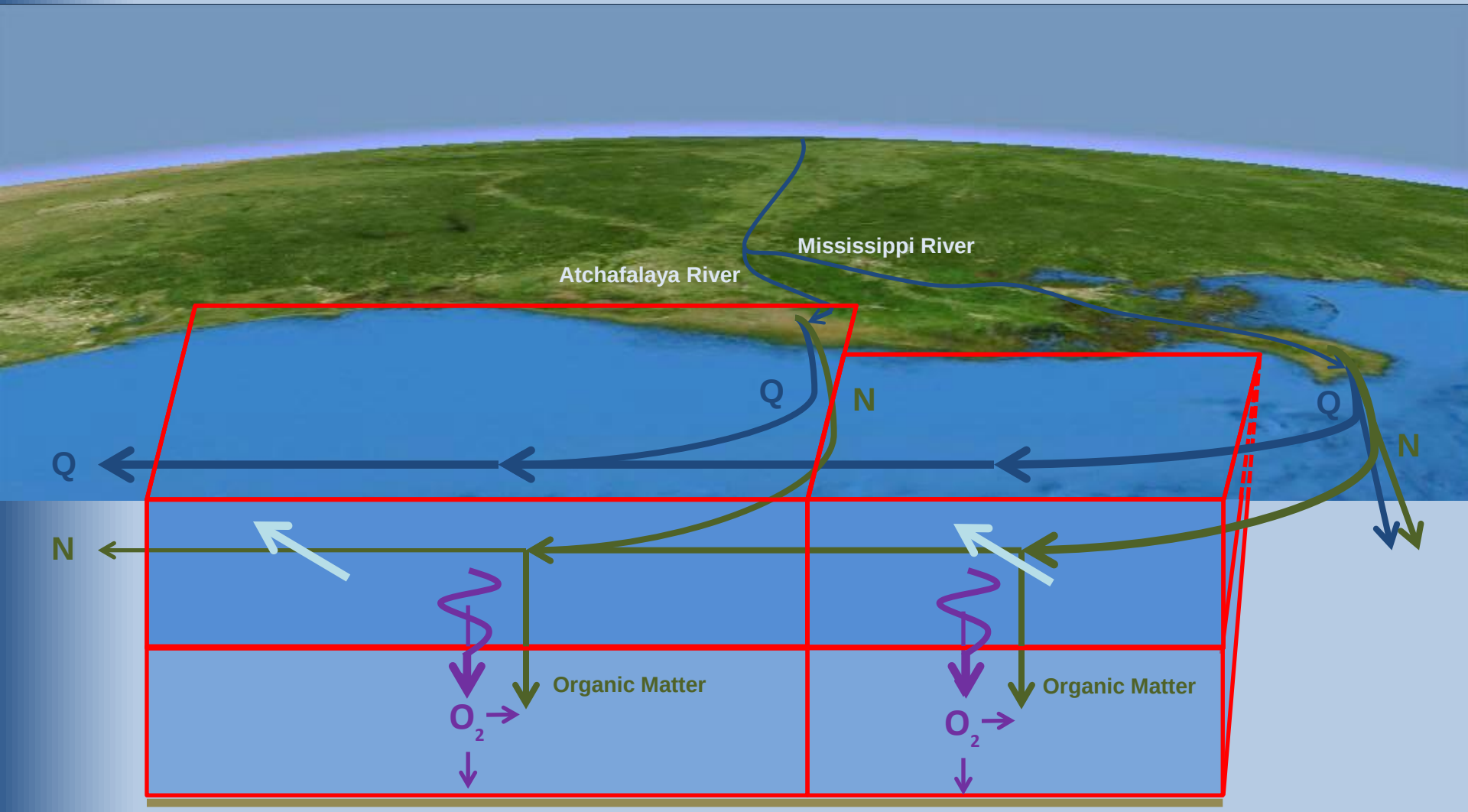
Obenour, Gronewold, Stow, and Scavia (in review)

3. Exploring controlling processes

- Develop **parsimonious** mechanistic model for mid-summer Gulf hypoxia
- Use Bayesian framework to develop probabilistic calibration/results.
- Inputs: wind, flow, and nutrient load data
- Explore possible temporal trends

Obenour, D.R., A.M. Michalak, & D. Scavia. (***In Review***). Assessing biophysical controls on Gulf of Mexico hypoxia through probabilistic modeling.

Model Setup


Mississippi River
Atchafalaya River
Q
N
Q
N
Q
N
Organic Matter
O_2
Organic Matter
O_2

Model formulation

$$DO = \frac{1}{(K_a + B/C_{O,B})}\left(K_a C_{O,S} - \frac{\omega R_{O:N} L_N}{([Q_r + Q_c]/v_s + A)}\right)$$

Calibration Parameters
- v_s ~ effective settling rate (m/d)
- ω ~ oxygen demand adjustment (-)
- B ~ benthic oxygen demand (g/m^2/d)
- Q_c ~ spring coastal flow, (Gm^3/d)

"Known" Parameters
- $C_{O,B}$ ~ reference DO concentration for B (g/m^3)
- $C_{O,S}$ ~ saturation DO concentration (g/m^3)
- $R_{O:N}$ ~ ratio of net oxygen demand:nitrogen
- A ~ area (Gm^2)

Sub-model
- K_a ~ reaeration rate (m/d)

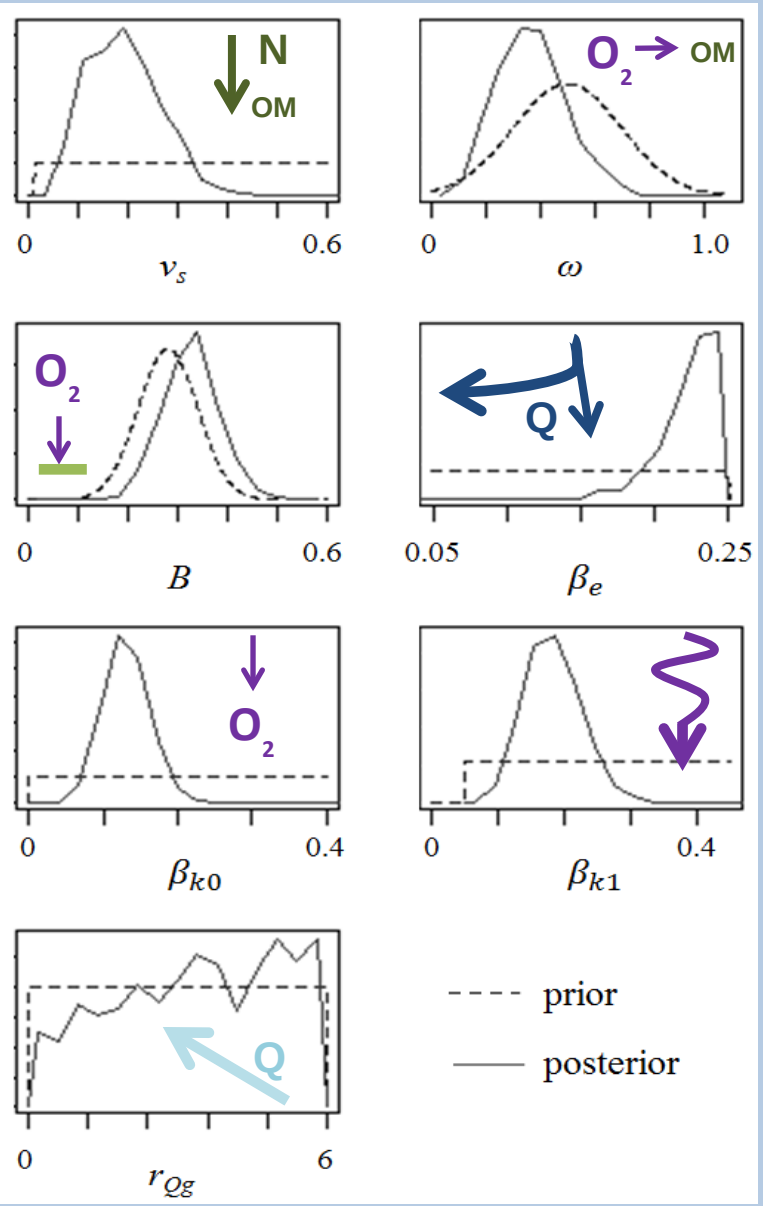
Input data
- L_N ~ spring nitrate loading, (Gg/d)
- Q_r ~ spring river discharge,(Gm^3/d)

Flow partitioning equation, **f(*w*)**

Model Calibration

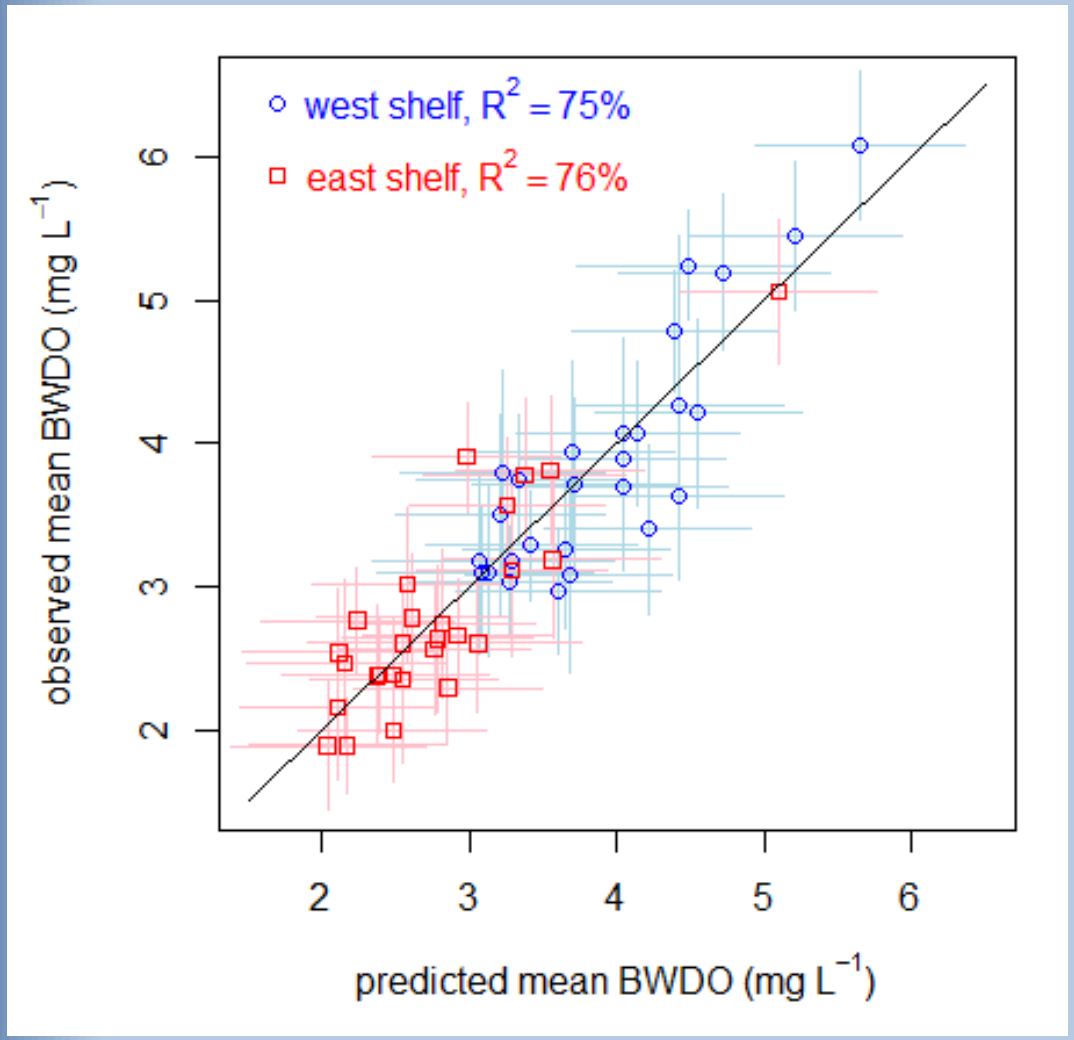
Bayesian Inference:

- Non-linear model formulations
- Incorporates prior information
- Rigorous accounting of uncertainty



Skill Assessment

Obenour, Michalak, and Scavia (in review)



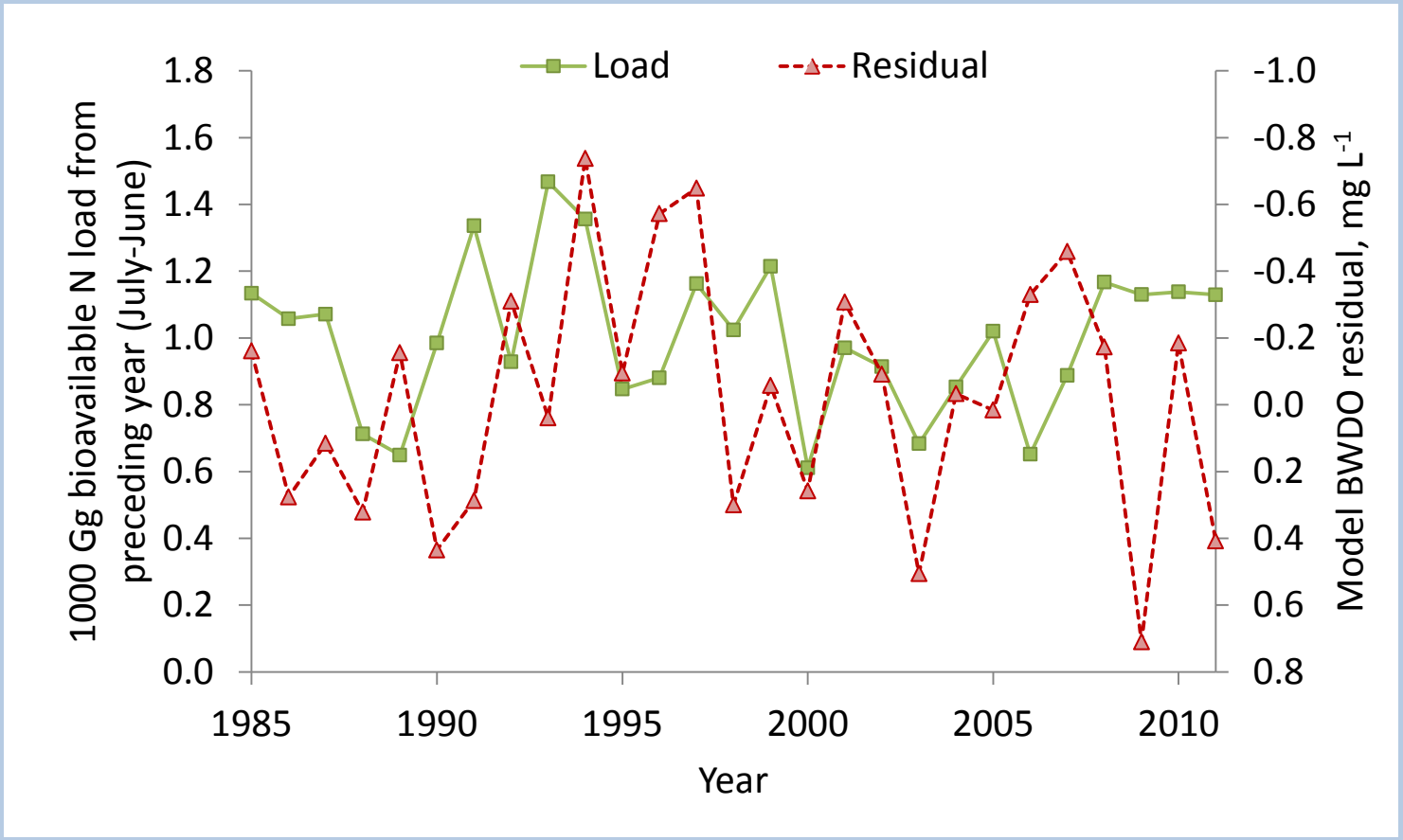
← (no "outlier" years)

In cross validation mode:

West shelf R^2 = 72%

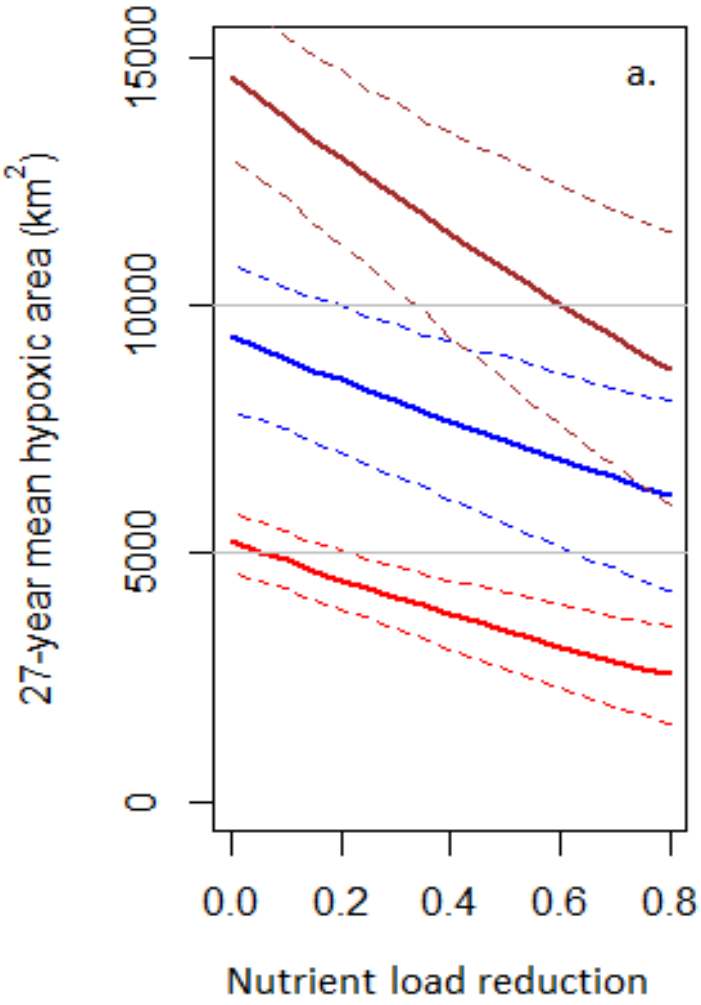
East shelf R^2 = 72%

Model Residuals over Time



Obenour, Michalak, and Scavia (in review)

Management Applications



Legend
Total shelf –
West shelf –
East shelf –

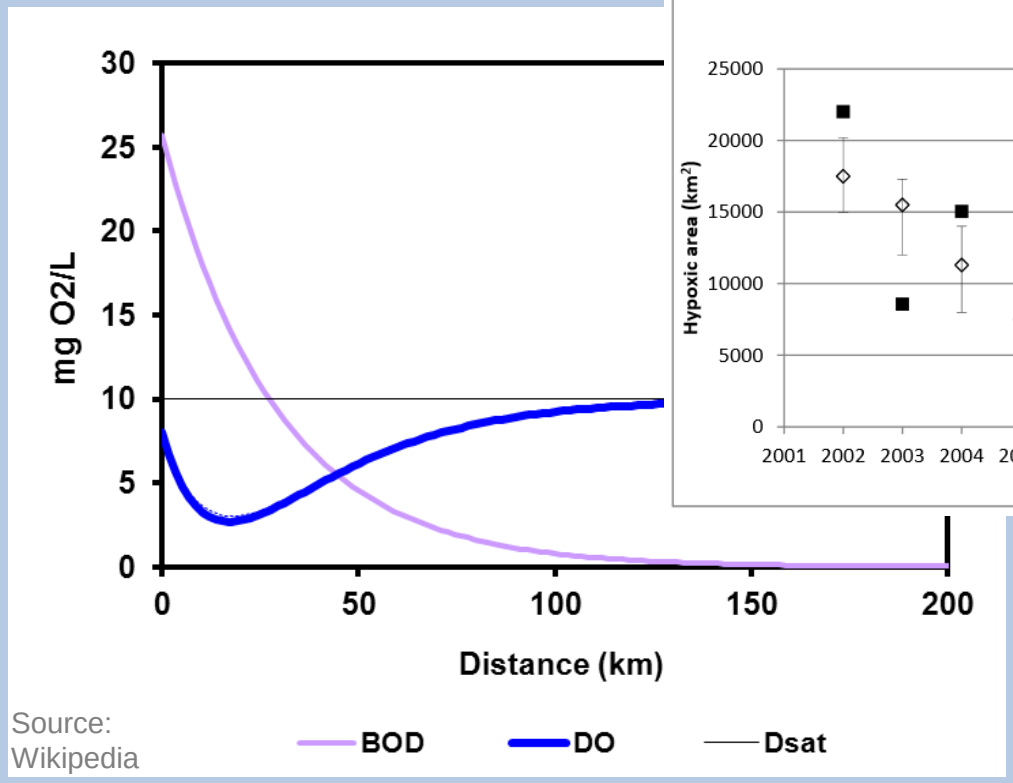
Obenour, Michalak, and Scavia (in review)

Forecasting GOM hypoxia

Classical Engineering River Model

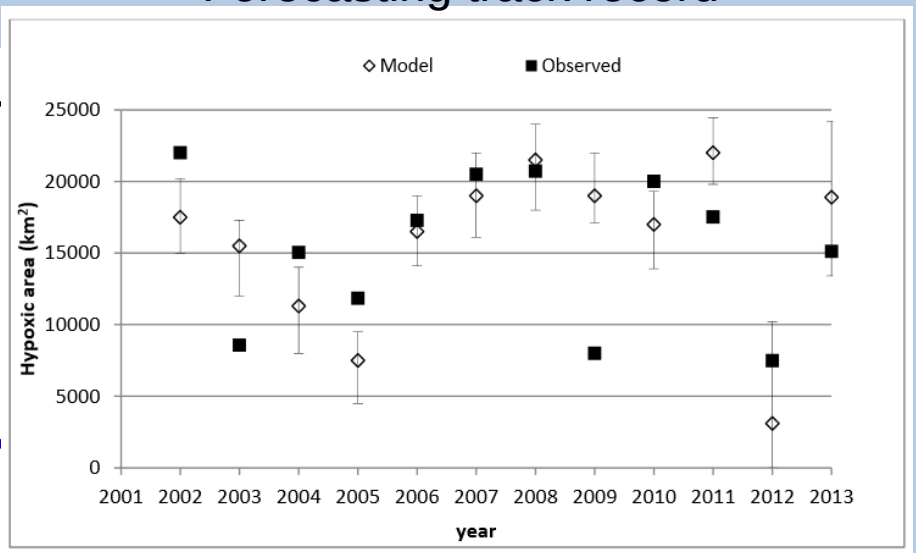
Streeter-Phelps DO Sag Curve

Don Scavia et al., (2002-present)



Source: Wikipedia

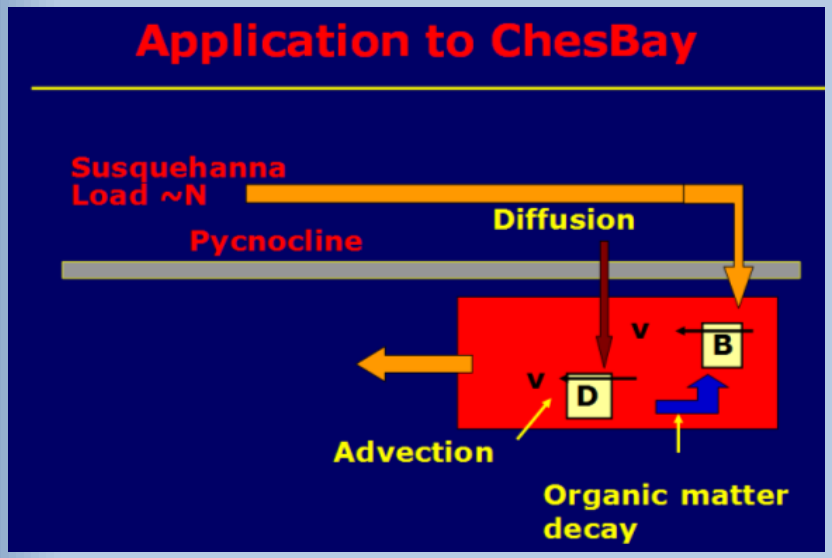
Forecasting track record

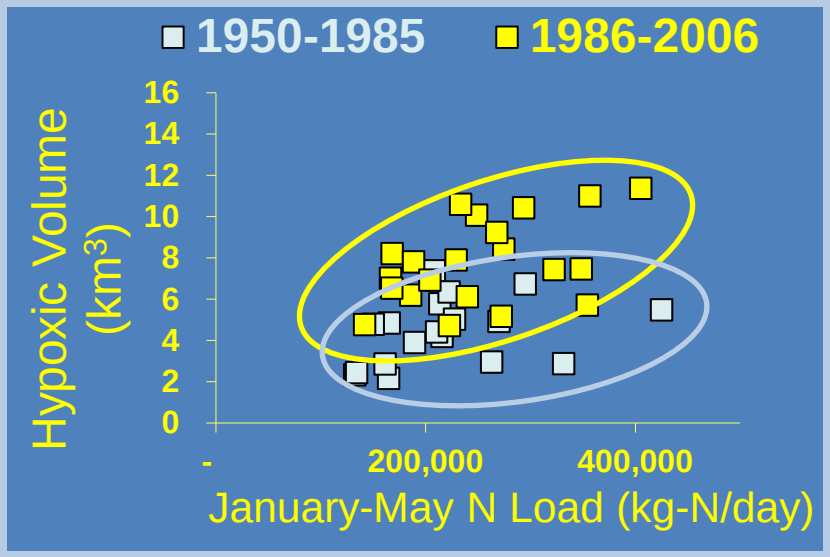


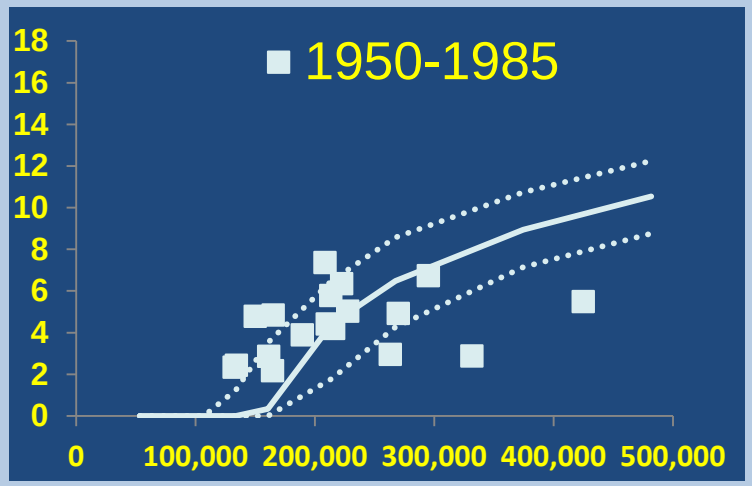
4. Applications to Chesapeake Bay

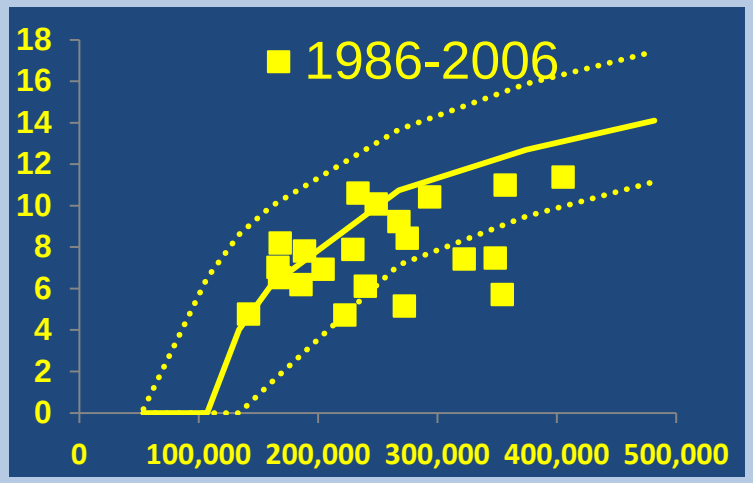
Chesapeake Hypoxia Forecasting

Scavia et al., (2006 – present)



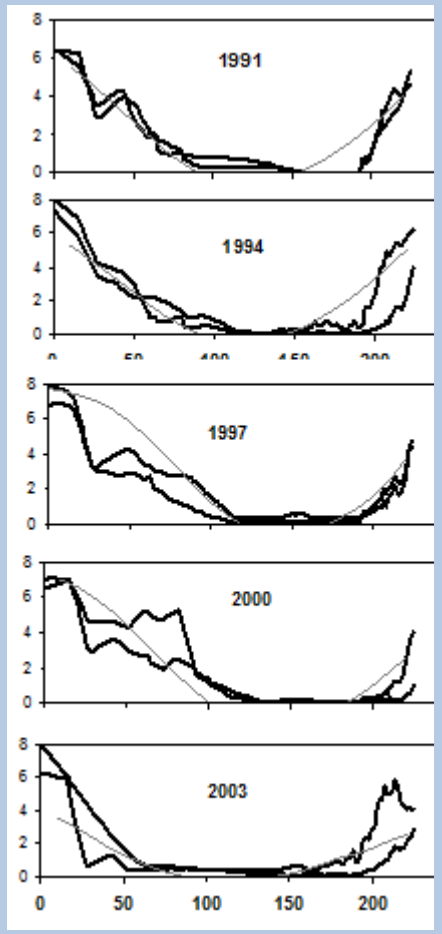




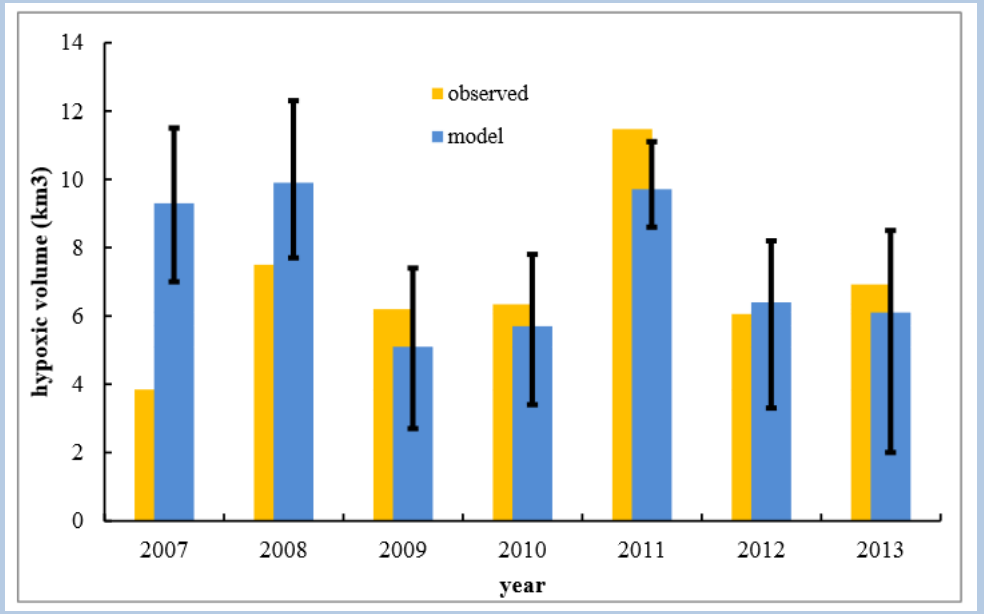


Chesapeake Hypoxia Forecasting (continued)

Comparison to historical data



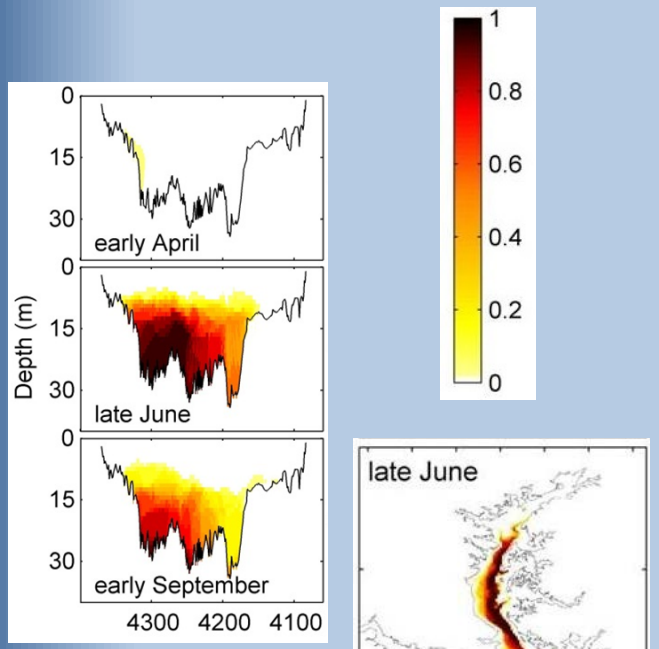
Forecasting track record

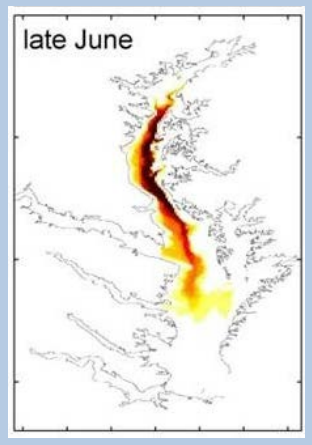


Chesapeake Geostatistical Analysis

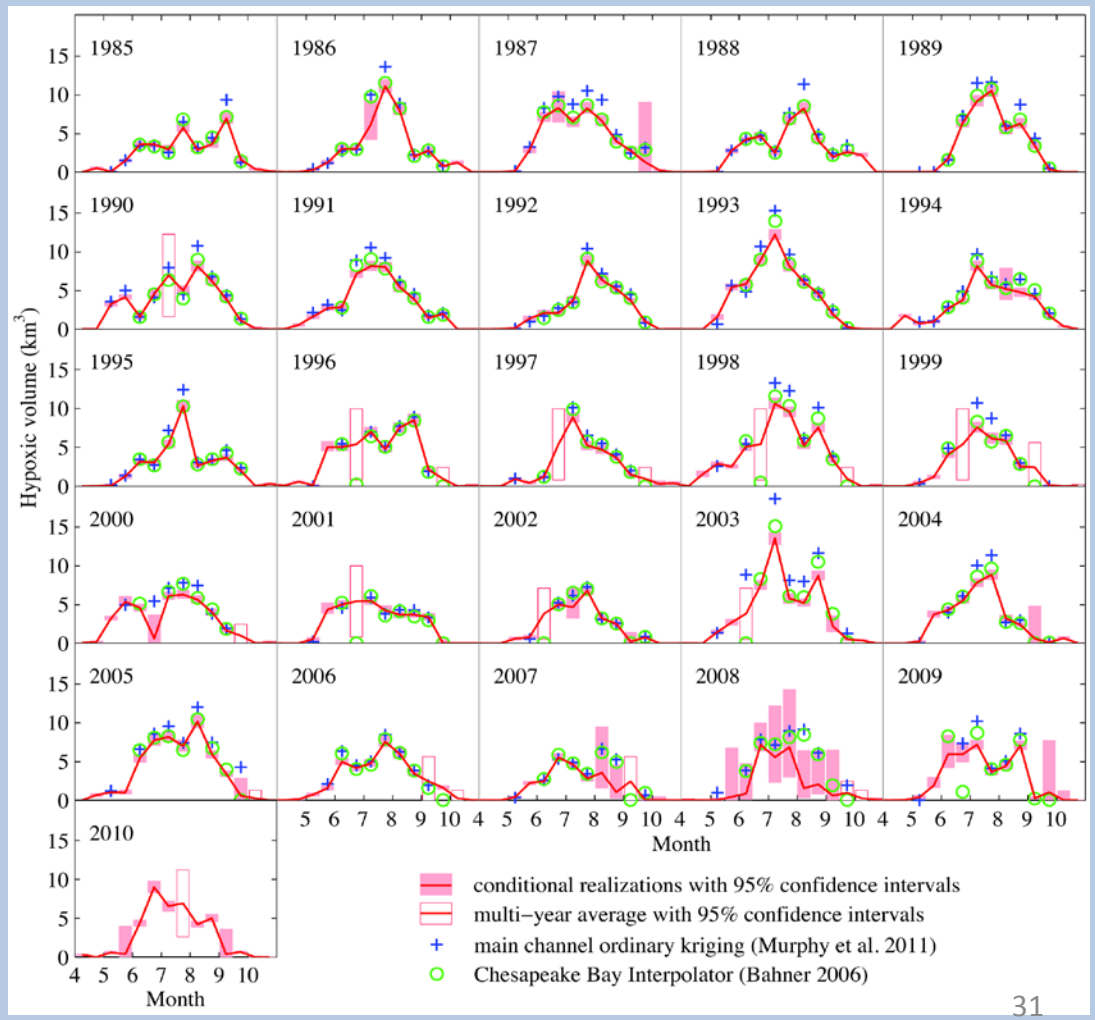
Zhou, Scavia and Michalak, 2014, L&O

Hypoxic frequency

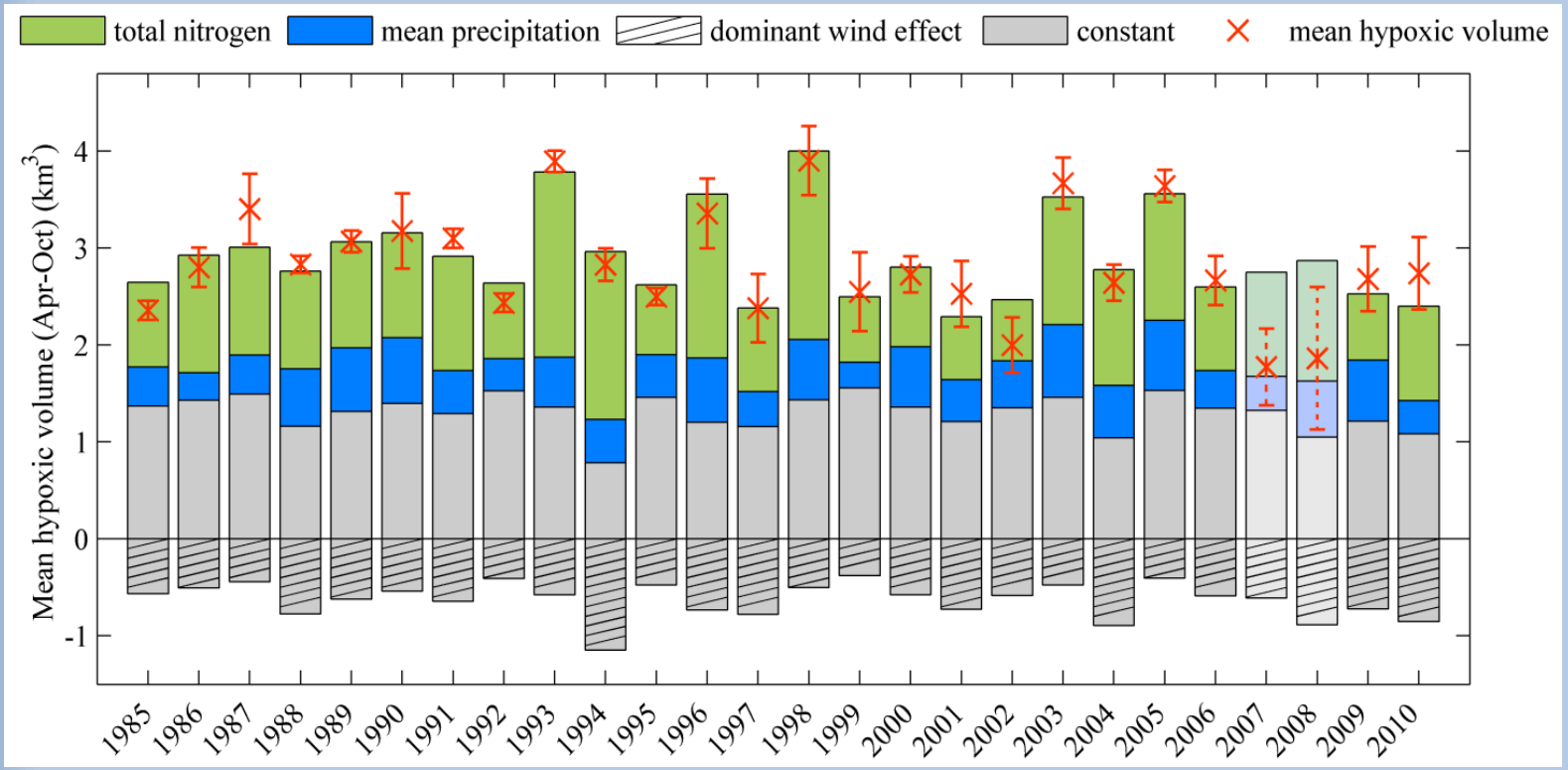




Time history of hypoxia



Chesapeake Geostatistical Analysis (continued)



Zhou, Scavia and Michalak, 2014, L&O

- TN: more loads, more hypoxia.
- Precipitation: more precipitation, more hypoxia.
- Dominant wind effect (i.e.,[SW duration] / [NE duration]): more wind effect, less hypoxia.

Summary

- Parametric models ("empirical" and "mechanistic") can be developed within advanced statistical frameworks to yield probabilistic results.
- Probabilistic models can be used to rigorously test for controlling factors, temporal change points, and long-term trends.
- The efficacy of these models for forecasting and management is still heavily reliant on a process-based understanding of the system, as reflected in the model formulation.

Primary Research Collaborators

- Donald Scavia (University of Michigan)
- Anna Michalak and Yuntao Zhou (Michigan/Stanford)
- Nancy Rabalais and Gene Turner (LUMCON and LSU)
- Drew Gronewold (NOAA GLERL)

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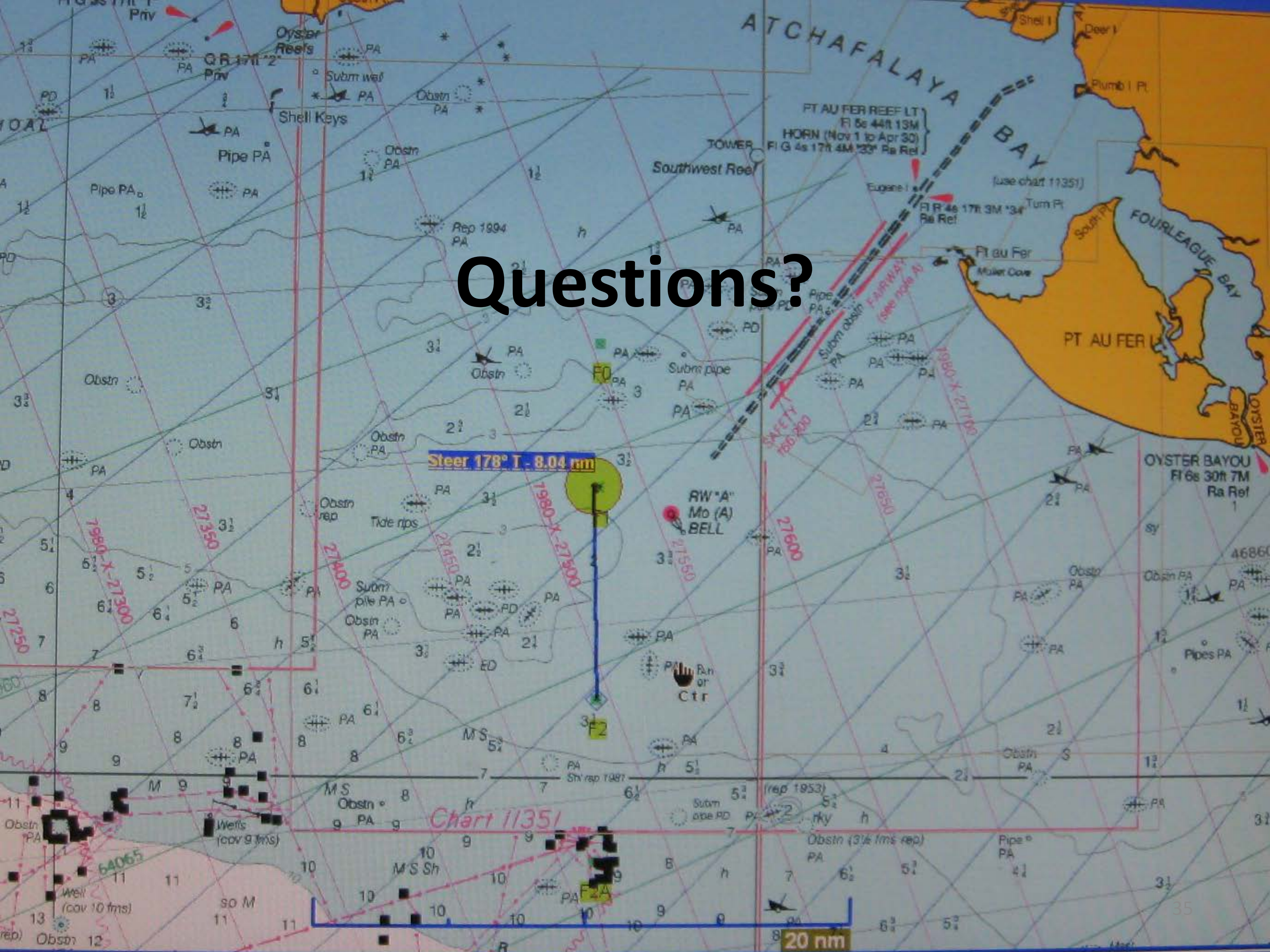
Questions?



ATCHAFALAYA BAY
PT AU FER REEF LT
Fl 6s 44ft 13M
HORN (Nov 1 to Apr 30)
Fl G 4s 17ft 4M "33" Ra Ref
TOWER
Southwest Reef
Shell Keys
Oyster Reefs
Subm well
Pipe PA
(use chart 11351)
FOURLEAGUE BAY
Pt au Fer
PT AU FER I
OYSTER BAYOU
Fl 6s 30ft 7M
Ra Ref
Steer 178° T - 8.04 nm
RW "A"
Mo (A)
BELL
Tide rips
Subm pipe PA
Chart 11351
Wells (cov 9 fms)
Well (cov 10 fms)
Obstn (3½ fms rep)
(rep 1953)
F0
F2
F2A
20 nm