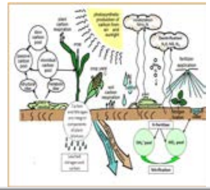
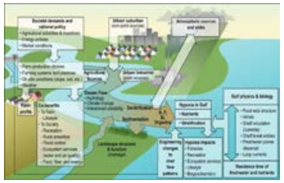
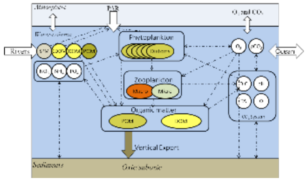
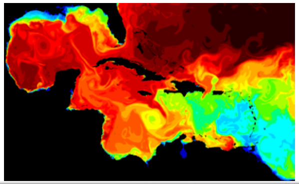





Modeling Coastal Acidification (and Hypoxia) Linkages with Land-based Nutrient Loads

John Lehrter
U.S. EPA Gulf Ecology Division

December 8, 2015

Collaboration

EPA Office of Research and Development
  Gulf Ecology Division, Gulf Breeze, FL
  Mid-Continent Ecology Division, Grosse Ile, MI
  Atmospheric Modeling and Analysis Division, RTP, NC

EPA Office of Environmental Information
  Environmental Modeling and Visualization Lab, RTP, NC

Naval Research Lab, Stennis, MS

Dalhousie University, Halifax, Nova Scotia
Louisiana State University, Baton Rouge, LA
Texas A&M University, College Station, TX

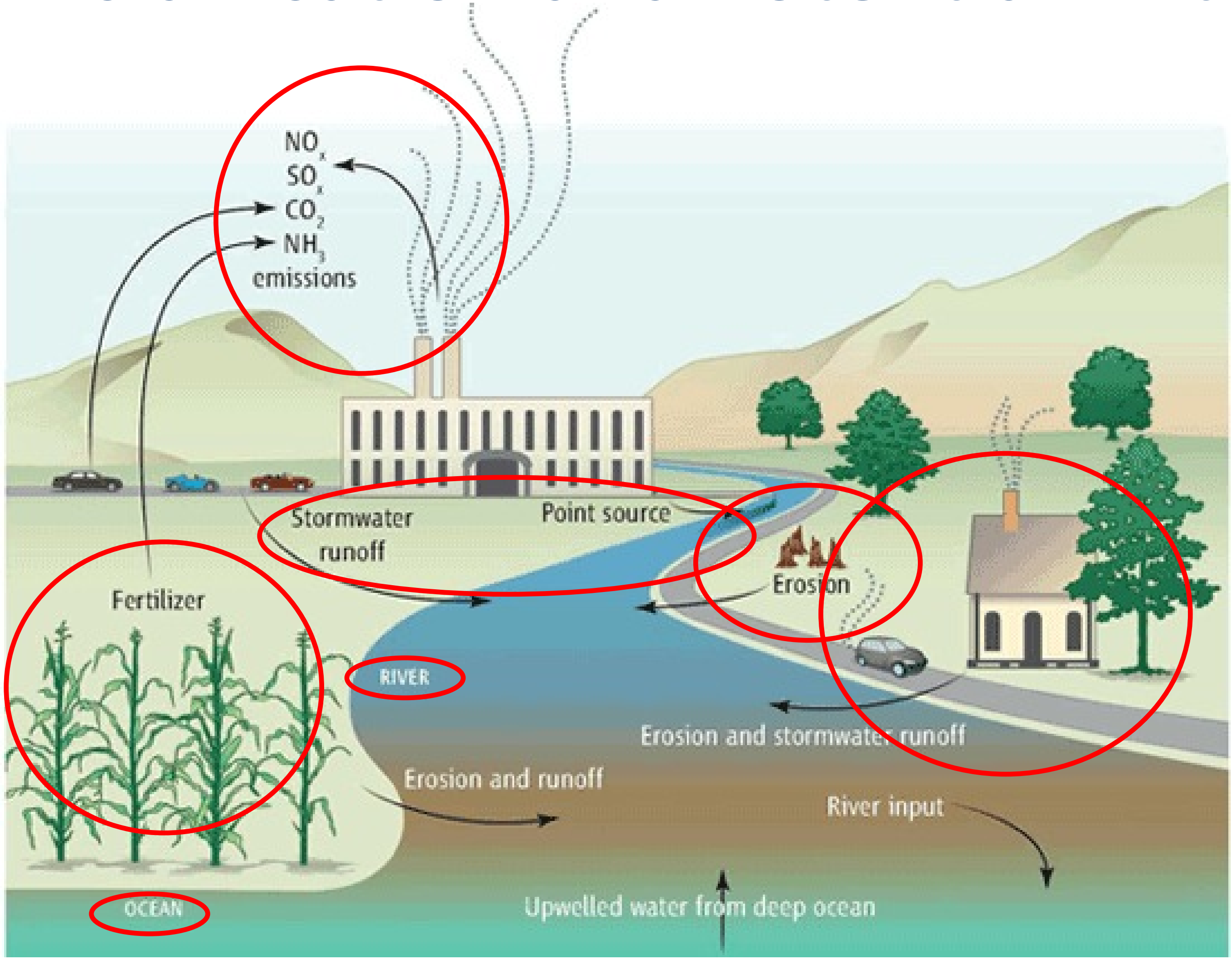
Outline

1. The coastal acidification and hypoxia problem and linkage to land-based nutrients
2. Model development
3. Case study application to northern Gulf of Mexico
4. Simple model scenarios for nutrient load reductions and climate change

Low pH and O_2 Aquatic Life Impacts

- Lower pH threatens shellfish, coral reefs and other flora/fauna
- Little is known about synergistic effects of multiple stressors (e.g., hypoxia, increase in sea temperature) or adaptation of marine populations.
  - Combinations of low pH and low O2 have greater impact than either stressor alone, e.g. Gobler et al. (2014)
  - Majority of research is lab-based. More field studies needed.

Land-Based Contributors to Coastal Acidification and Potential Mitigation

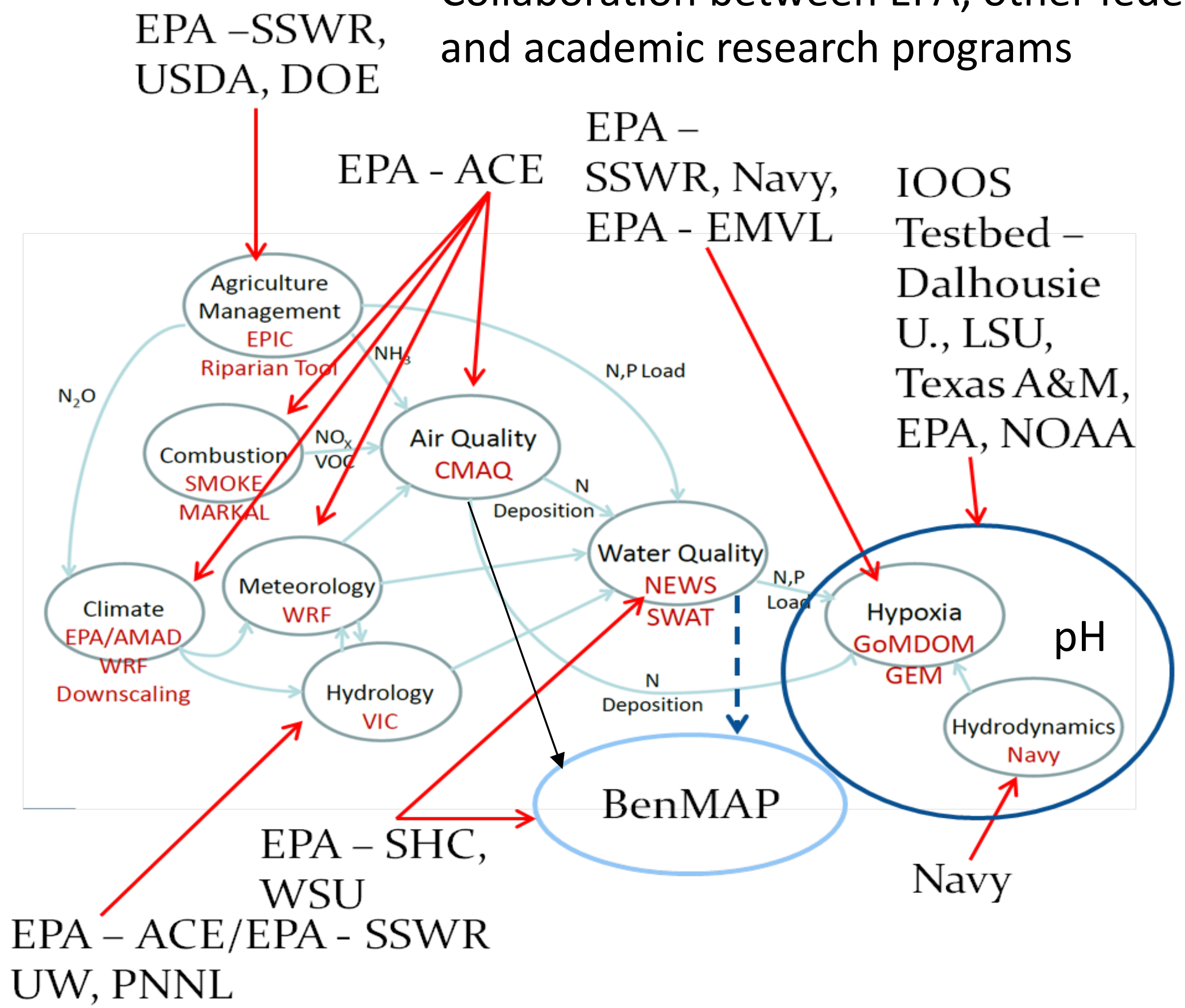


- **Clean Water Act**
- **Clean Air Act**
- **Coastal Zone Management Act**
- **State and Local**

Kelly et al. (2011)

Multi-Media Nutrient Modeling

Collaboration between EPA, other federal, and academic research programs

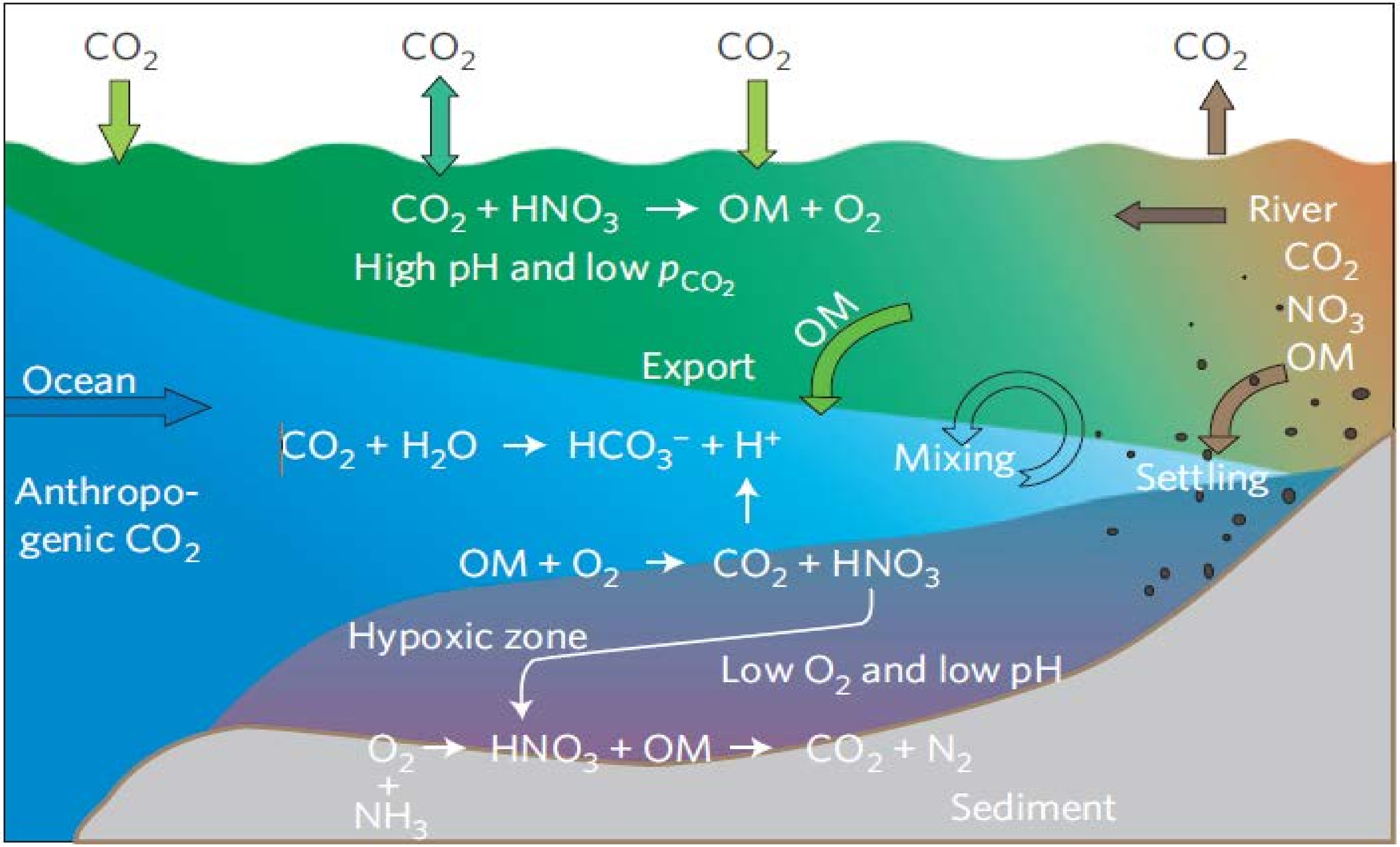


U.S. EPA (2015), Nitrogen & Co-pollutants Cross-cutting Research Roadmap. http://www2.epa.gov/research/research-roadmaps

Coastal Acidification

Key Points

- Nutrients stimulate phytoplankton production of organic matter
- Organic matter sinks and is respired creating CO_2 and consuming O_2
- Coastal waters mix with open ocean water with declining pH

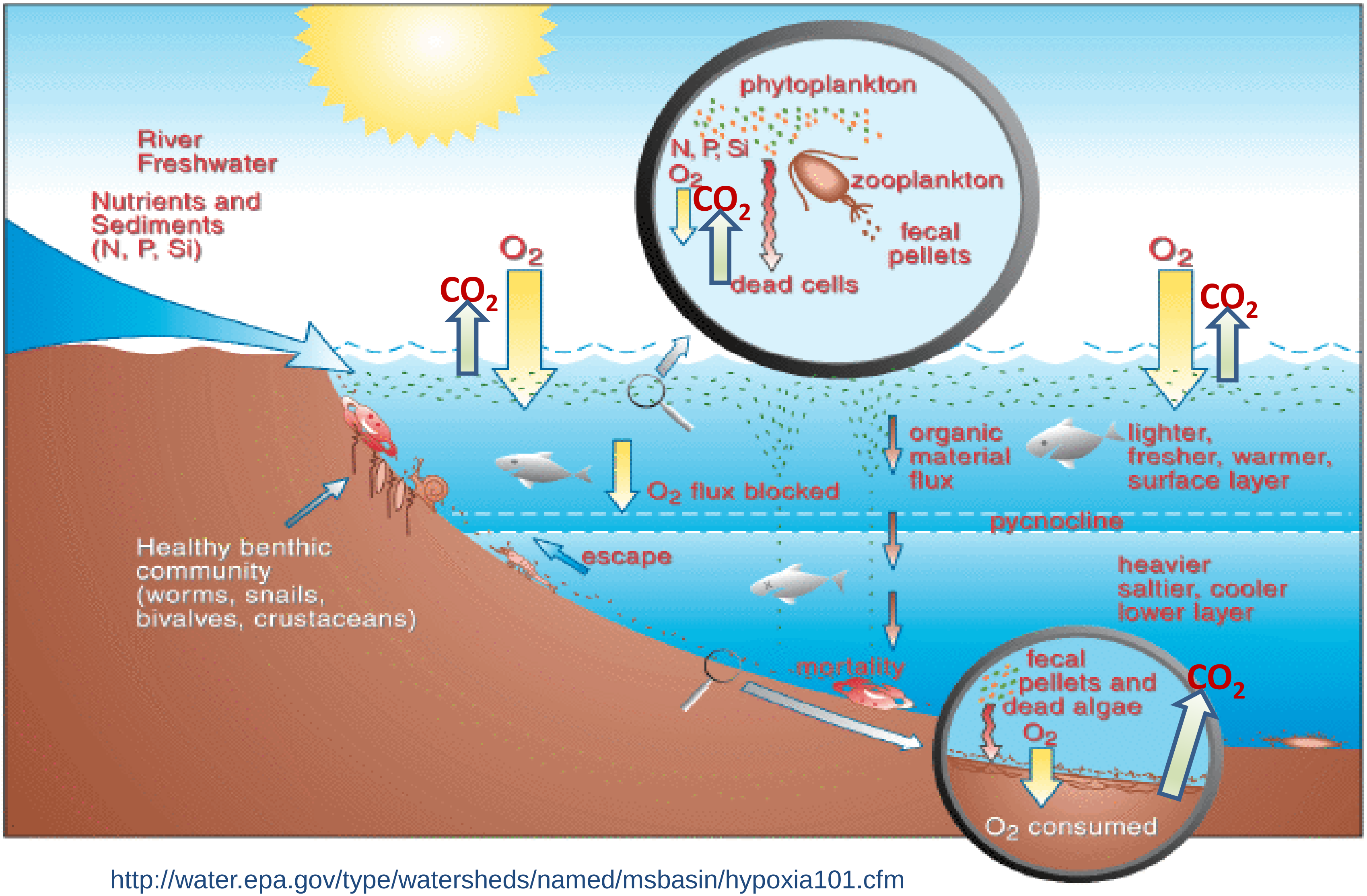


Cai et al. (2011)

Outline

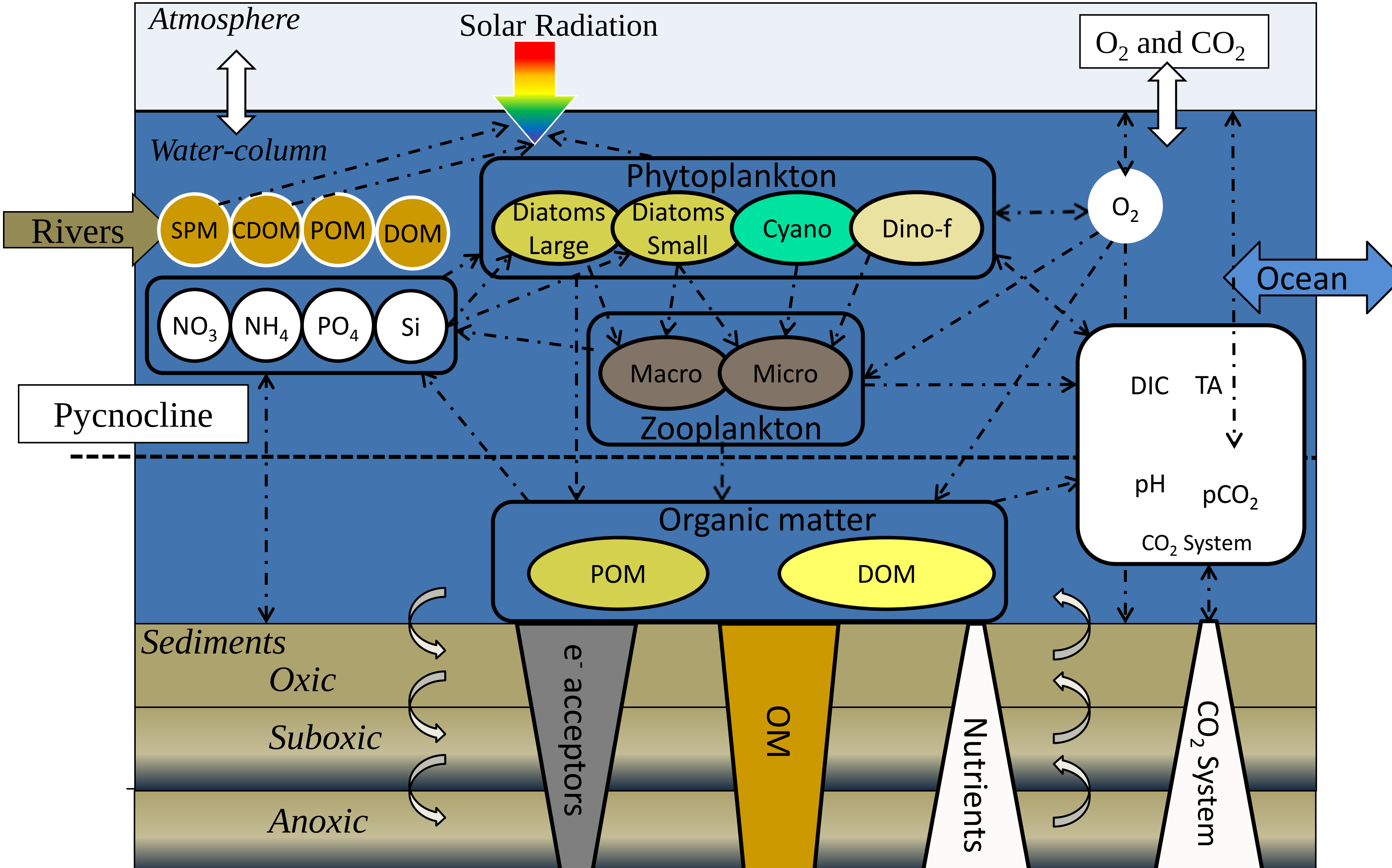
1. The coastal acidification and hypoxia problem and linkage to land-based nutrients
2. **Model development**
3. Case study application to northern Gulf of Mexico
4. Model scenarios for nutrient load reductions and climate change

Hypoxia Conceptual Model



http://water.epa.gov/type/watersheds/named/msbasin/hypoxia101.cfm

Coastal General Ecosystem Model (CGEM)



Lehrter et al. in prep. CGEM Model Description

O_2, DIC, and Alkalinity

Change in concentration | Microbial Respiration | Phytoplankton Production | Phytoplankton Respiration | Zooplankton Respiration

$$\frac{d}{dt}O2 = RO2 + PrimProd - ArespC - ZrespC \pm Air\text{-}Sea\ Exchange$$

$$\frac{d}{dt}DIC = RDIC - PrimProd + ArespC + ZrespC \pm Air\text{-}Sea\ Exchange$$

$$[DIC] = [CO_2^*] + [HCO_3^-] + 2[CO_3^{2-}]$$

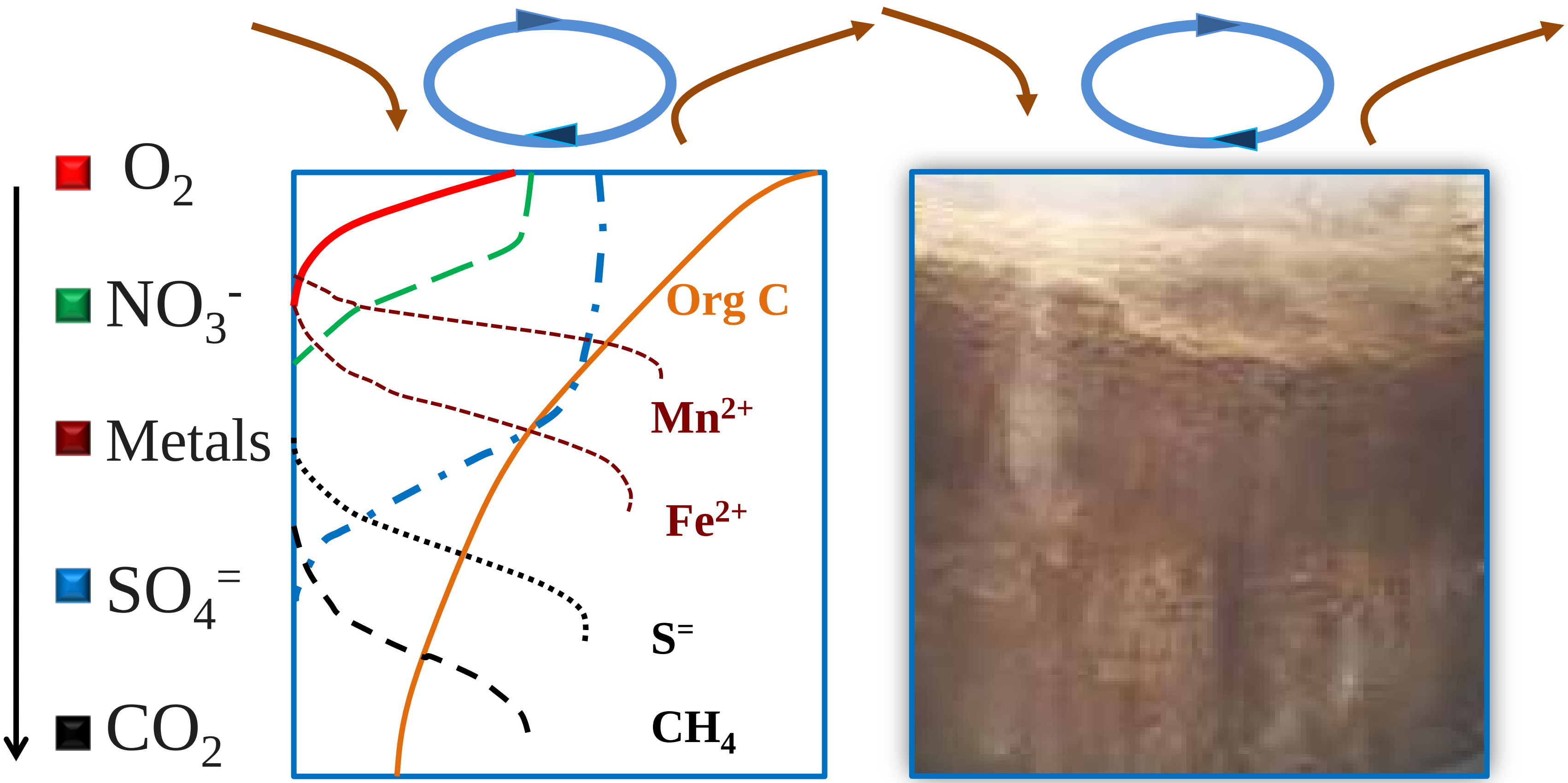
Phytoplankton uptake of NO_3^- | Phytoplankton uptake of NH_4^+ | Phytoplankton uptake of SO_4^{2-}

$$\frac{d}{dt}ALK = RALK + AupN \cdot \frac{NO3}{NO3 + NH4} - AupN \cdot \frac{NH4}{NO3 + NH4} + AupP + 4.8 \cdot AupP$$

$$Alk = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] + [HPO_4^{2-}] + 2[PO_4^{3-}] + [SiO(OH)_3^-] + [NH_3] + [HS^-] - [H^+] - [HF] - [H_3PO_4] + [organic\ alkalinity]$$

Dickson (1981); Wolf-Gladrow et al. (2007)

Sediment Diagenesis



Eldridge and Morse (2008);
Lehrter et al. (2012);
Devereux et al. (2015)

Organic Matter Oxidation Reactions

e$^-$ acceptor

O_2

$$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + (x+2y)O_2 + (y+2z)HCO_3^- \xrightarrow{R_1/x} (x+y+2z)CO_2 + yNO_3^- + zHPO_4^{2-} + (x+2y+2z)H_2O$$

NO_3^-

$$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + \left(\frac{4x+3y}{5}\right)NO_3^- \xrightarrow{R_2/x} \left(\frac{2x+4y}{5}\right)N_2 + \left(\frac{x-3y+10x}{5}\right)CO_2 + \left(\frac{4x+3y-10z}{5}\right)HCO_3^- + zHPO_4^{2-} + \left(\frac{3x+6y+10z}{5}\right)H_2O$$

Mn

$$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + 2xMnO_2 + (3x+y-2z)CO_2 + (x+y-2z)H_2O \xrightarrow{R_3/x} 2xMn^{2+} + (4x+y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-}$$

Fe

$$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + 4xFe(OH)_3 + (7x+y-2z)CO_2 \xrightarrow{R_4/x} 4xFe^{2+} + (8x+y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-} + (3x-y+2z)H_2O$$

SO_4^{3-}

$$(CH_2O)_x(NH_3)_y(H_3PO_4)_z + \frac{x}{2}SO_4^{2-} + (y-2z)CO_2 + (y-2z)H_2O \xrightarrow{R_5/x} \frac{x}{2}H_2S + (x+y-2z)HCO_3^- + yNH_4^+ + zHPO_4^{2-}$$

Van Cappellen and Wang (1996)

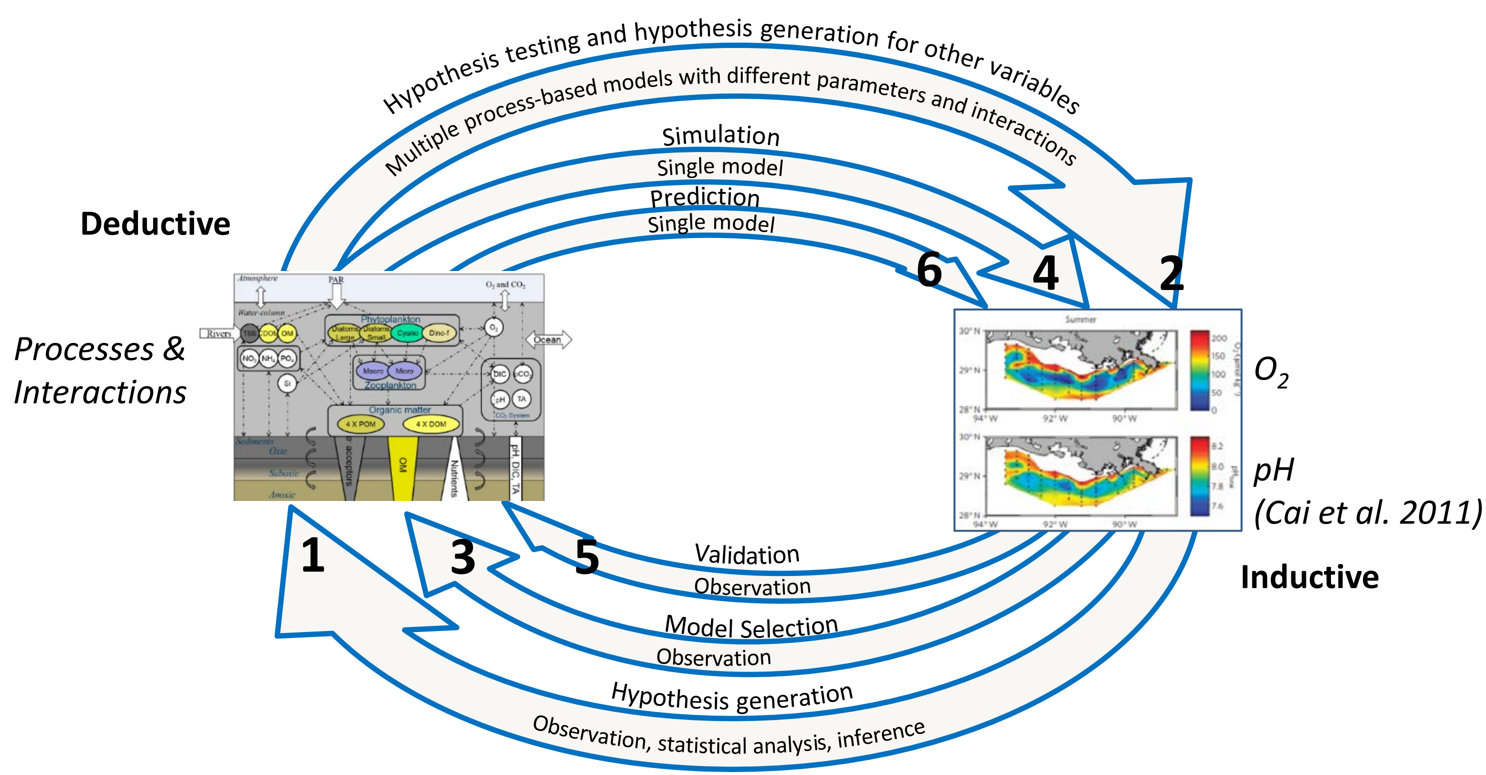
CO2 System Calculations with *mocsy 2.0*

Orr and Epitalon (2015)
(http://ocmip5.ipsl.jussieu.fr/mocsy/index.html)

- Interoperable Fortran code
- Computes the carbon dioxide system variables with inputs of atmospheric pressure, depth, latitude, *T*, *S*, *ALK*, *DIC*, *Si*, and *PO4*.
- Computes air-sea gas exchange

Observation and Modeling to Extract Causality from Complexity

Larsen et al. (2014), *Eos* 95:285-286

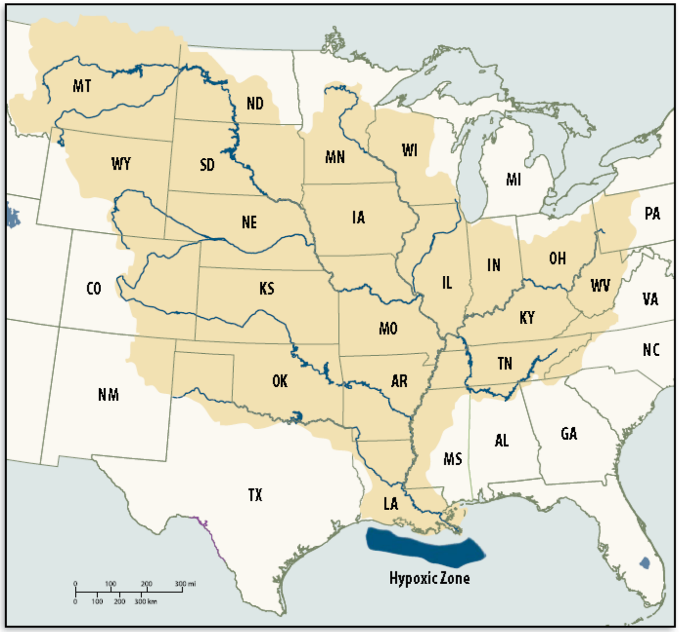


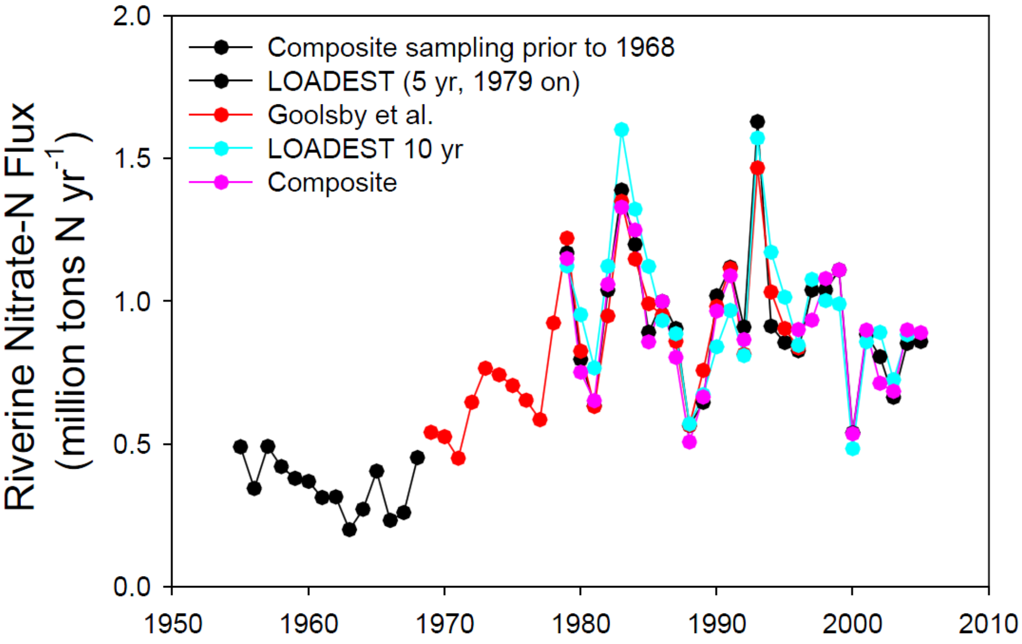
Modified from Larsen et al. (2014)

Outline

1. The coastal acidification and hypoxia problem and linkage to land-based nutrients
2. Model development
3. **Case study application to northern Gulf of Mexico**
4. Model scenarios for nutrient load reductions and climate change

Case Study Area: Mississippi River Basin

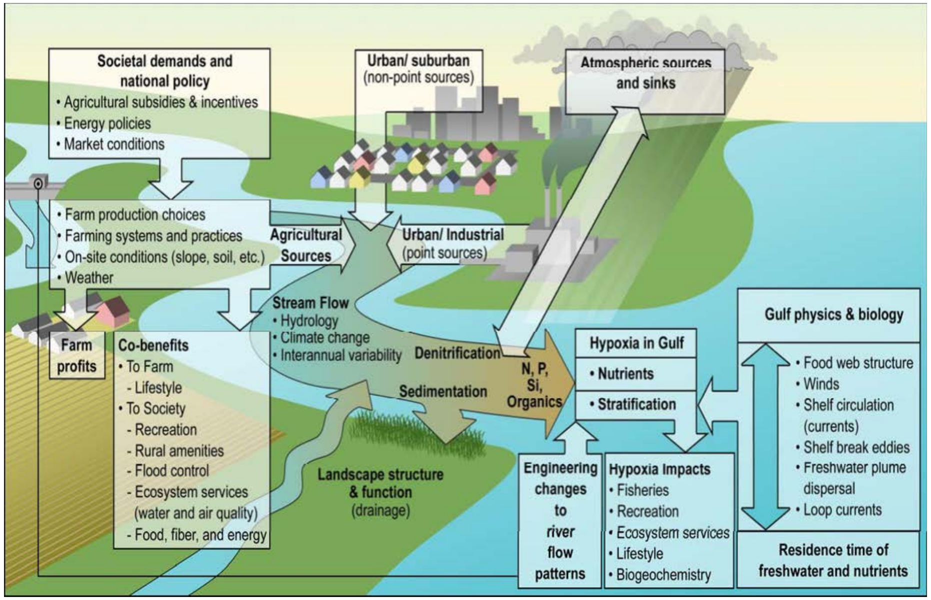




http://water.epa.gov/type/watersheds/named/msbasin/upload/hypoxia_reassessment_508.pdf

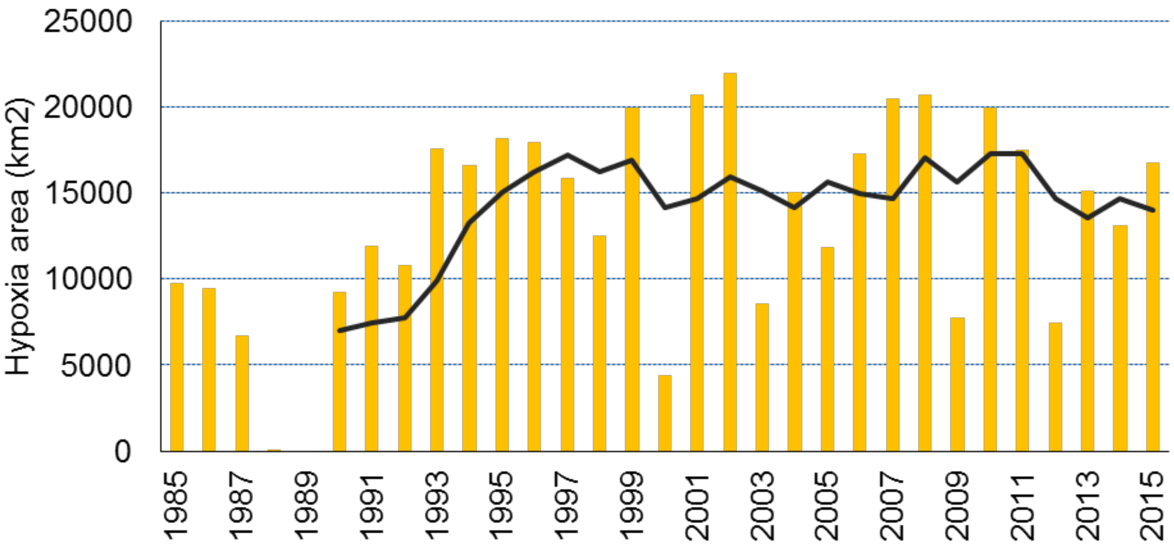
EPA SAB (2008)
http://water.epa.gov/type/watersheds/named/msbasin/upload/2008_1_31_msbasin_sab_report_2007.pdf

Modeling Objectives

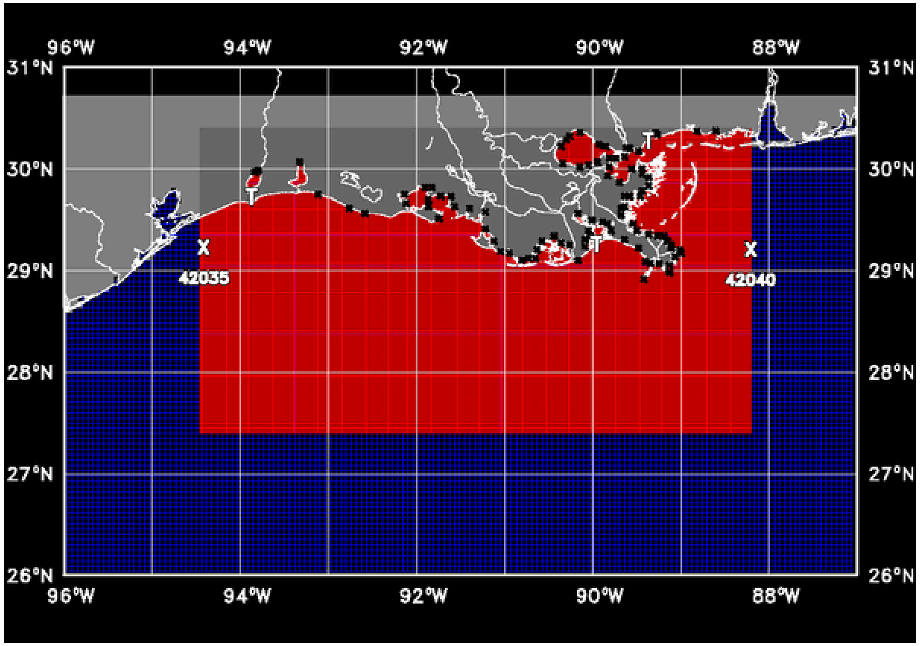


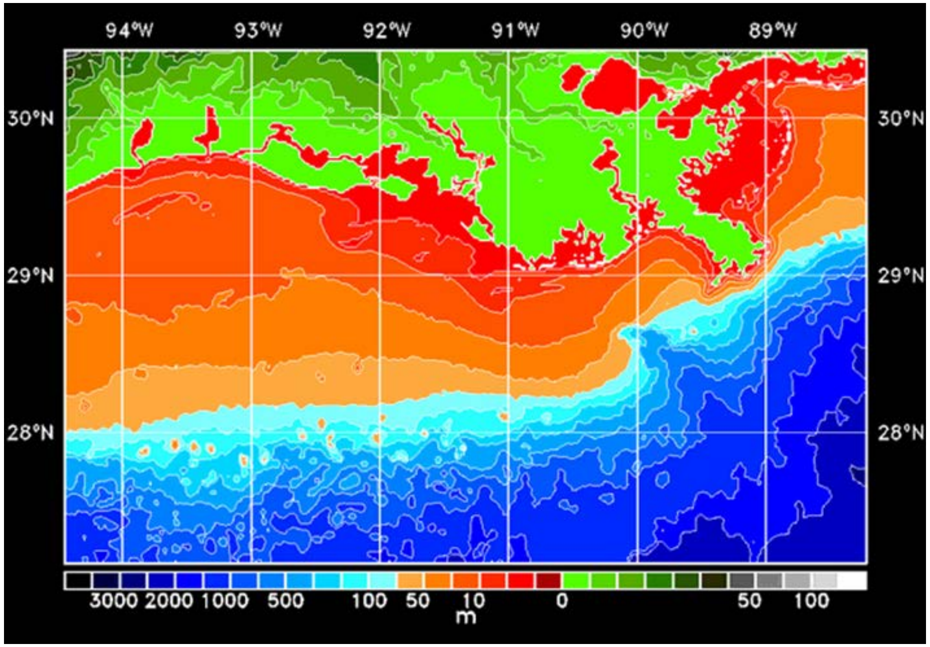
http://water.epa.gov/type/watersheds/named/msbasin/upload/2008_1_31_msbasin_sab_report_2007.pdf

- Quantify nutrient sources, transport, fate, and effects
- Examine effects of policy
- Predict the load reductions required to achieve management goals



NCOM Hydrodynamic Model

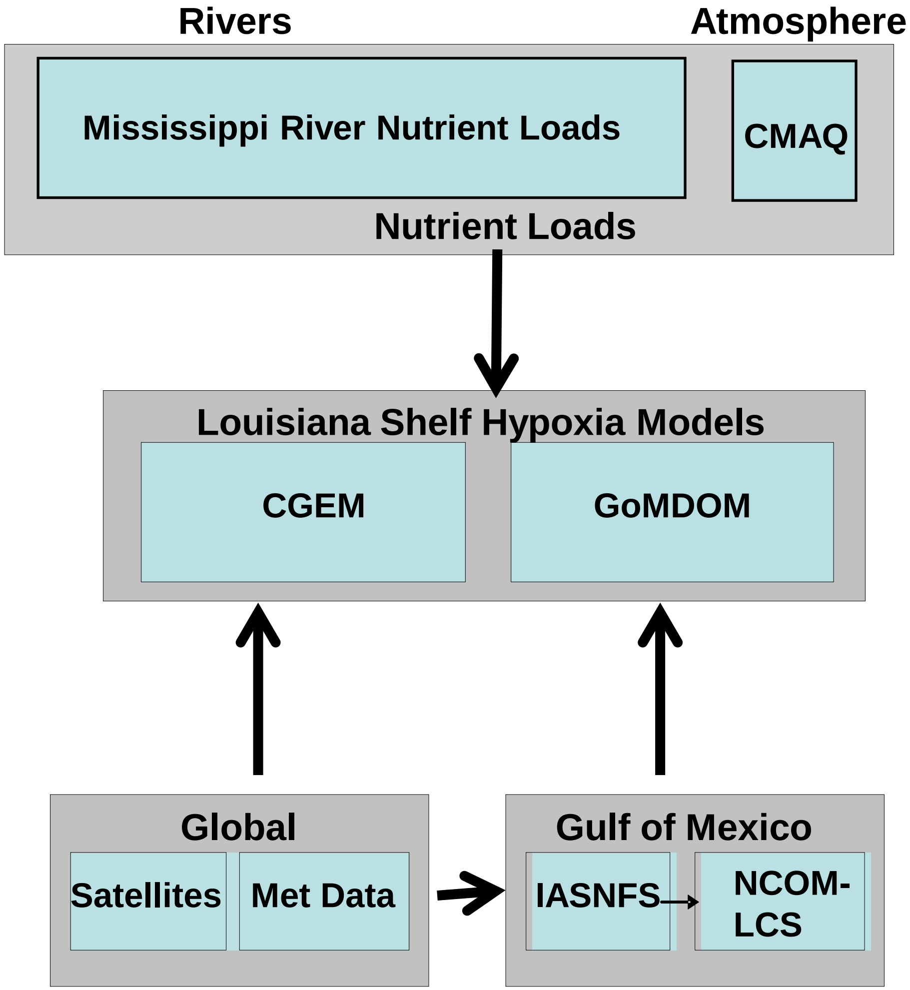




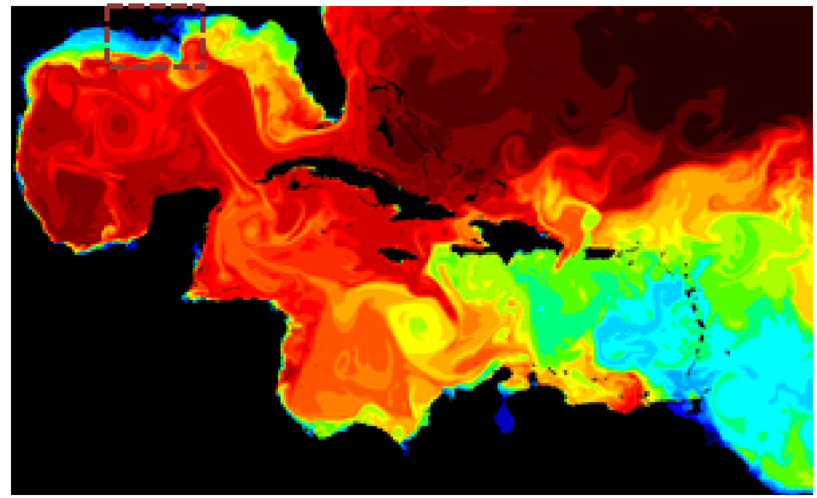
- Domain : Louisiana Continental Shelf (LCS) (27.4° - 30.4°N 88.2° - 94.5°W)
- Resolution : Horizontal ~1.9 km (320x176); Vertical 35 layers (20 layers on shelf)
- Realistic topography from NRL DBDB2 and NGDC/NGA bathymetry data
- 95 Rivers with freshwater discharge rates from USACE/USGS
- Data assimilation of satellite SSH and SST, radiative
- Parent model is NCOM - Intra-Americas Sea Nowcast/Forecast System (IASNFS)

Ko (2008); Lehrter et al. (2013)

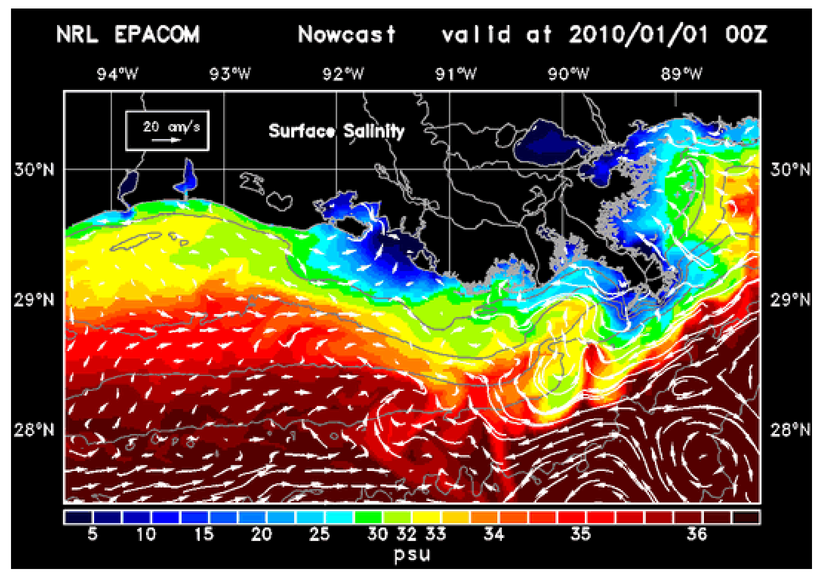
Model Forcing



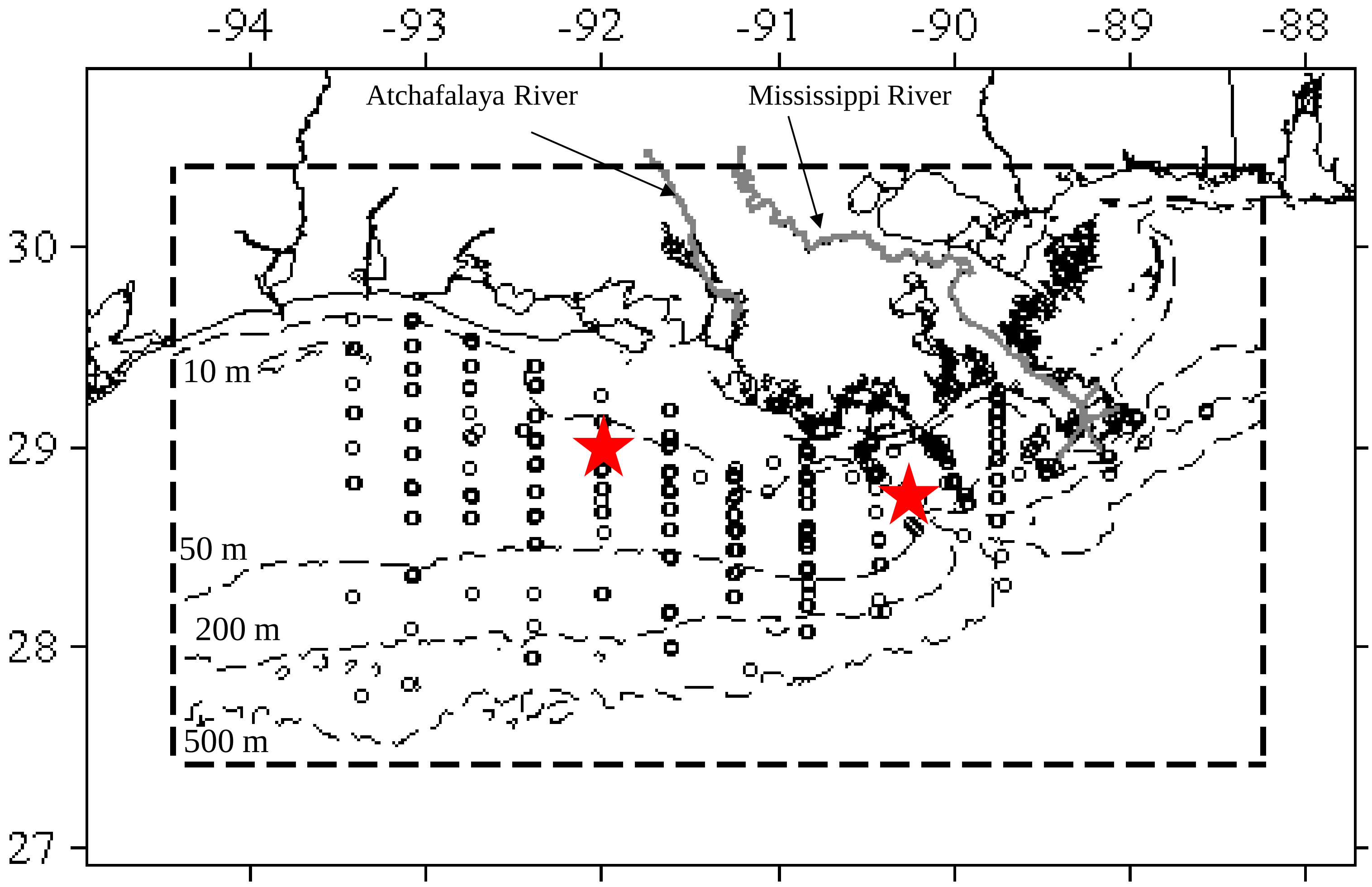
NCOM-IASNFS



NCOM-LCS



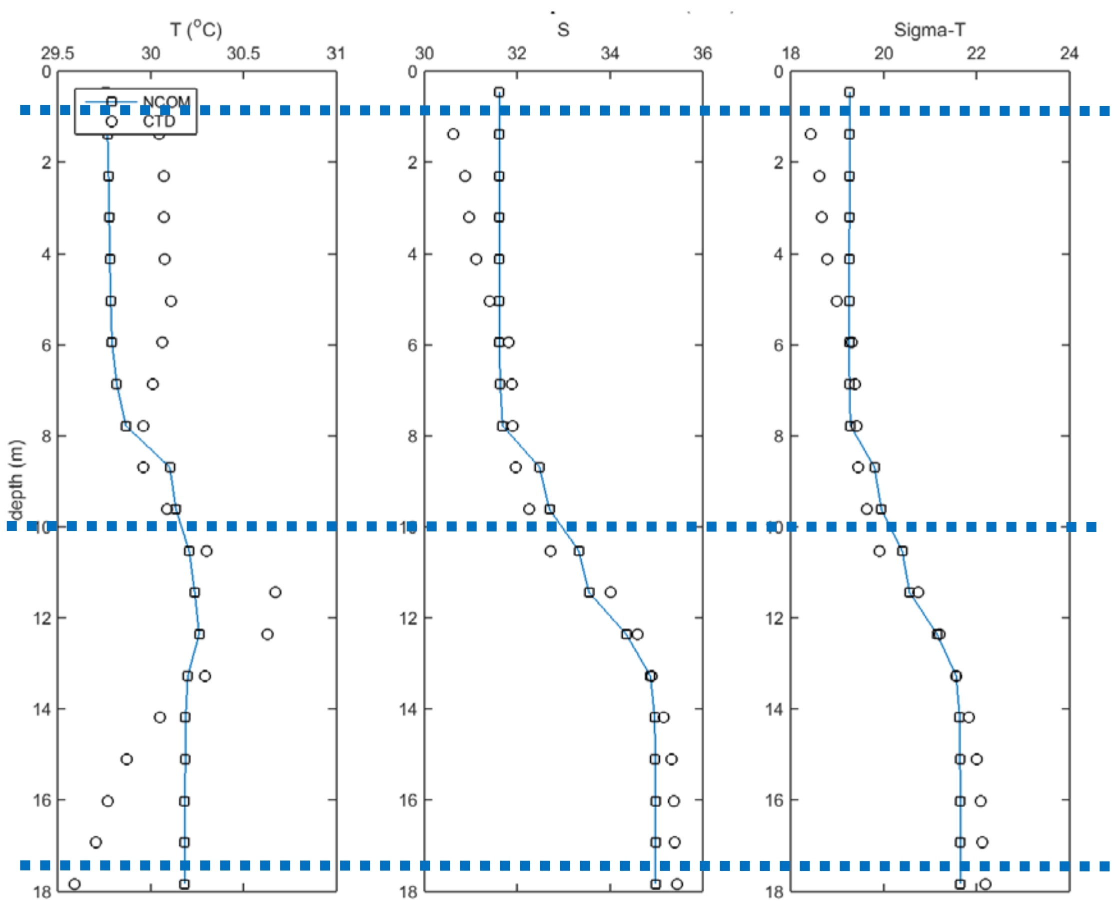
Model Error and Skill



Observations summarized in Murrell et al. (2014)

Model Hydrography

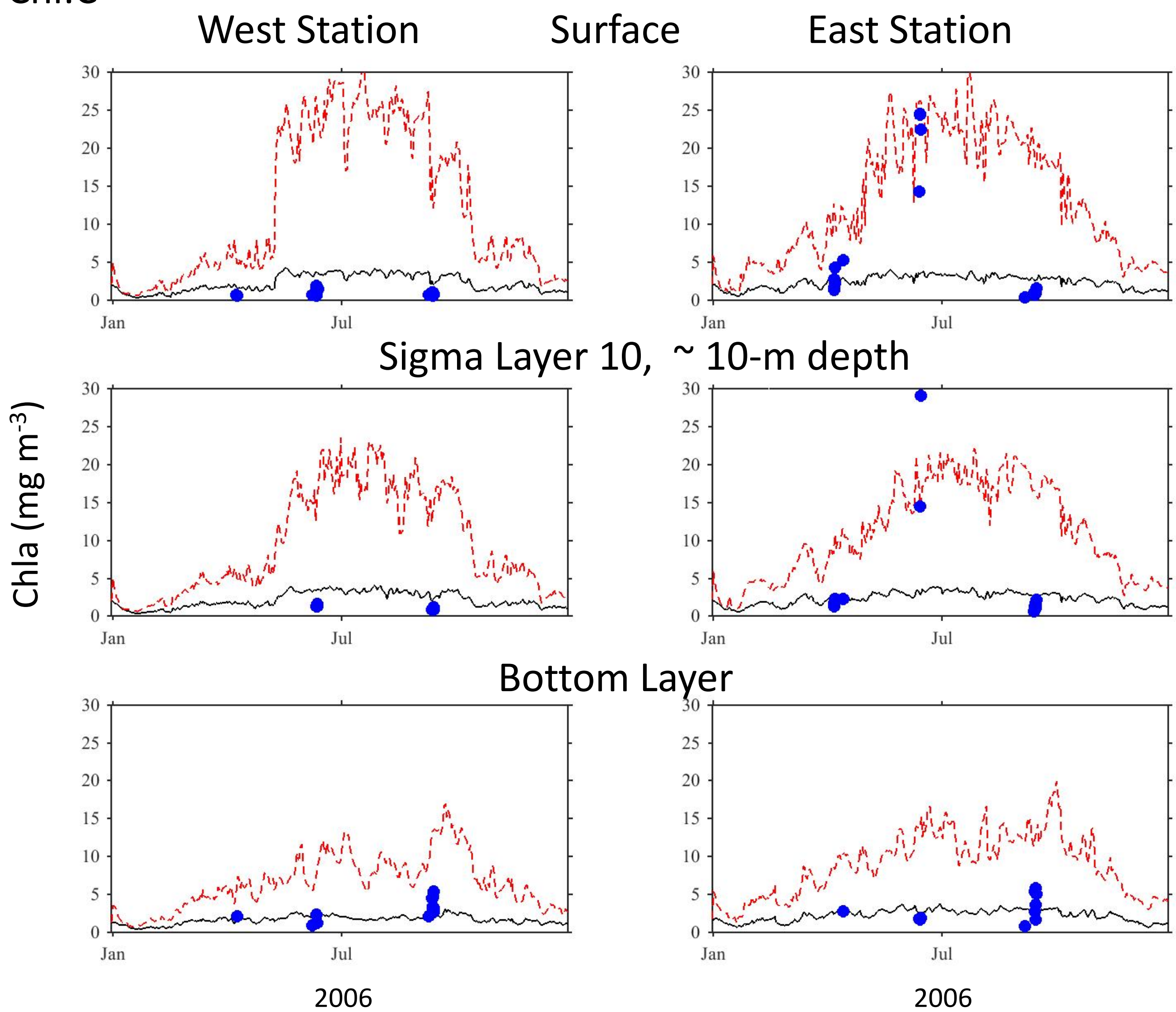
	Bias (M-O)	RMSE	Model Skill
T	0.02	0.97	0.94
S	-0.39	1.75	0.67
Sigma-T	-0.31	1.39	0.76



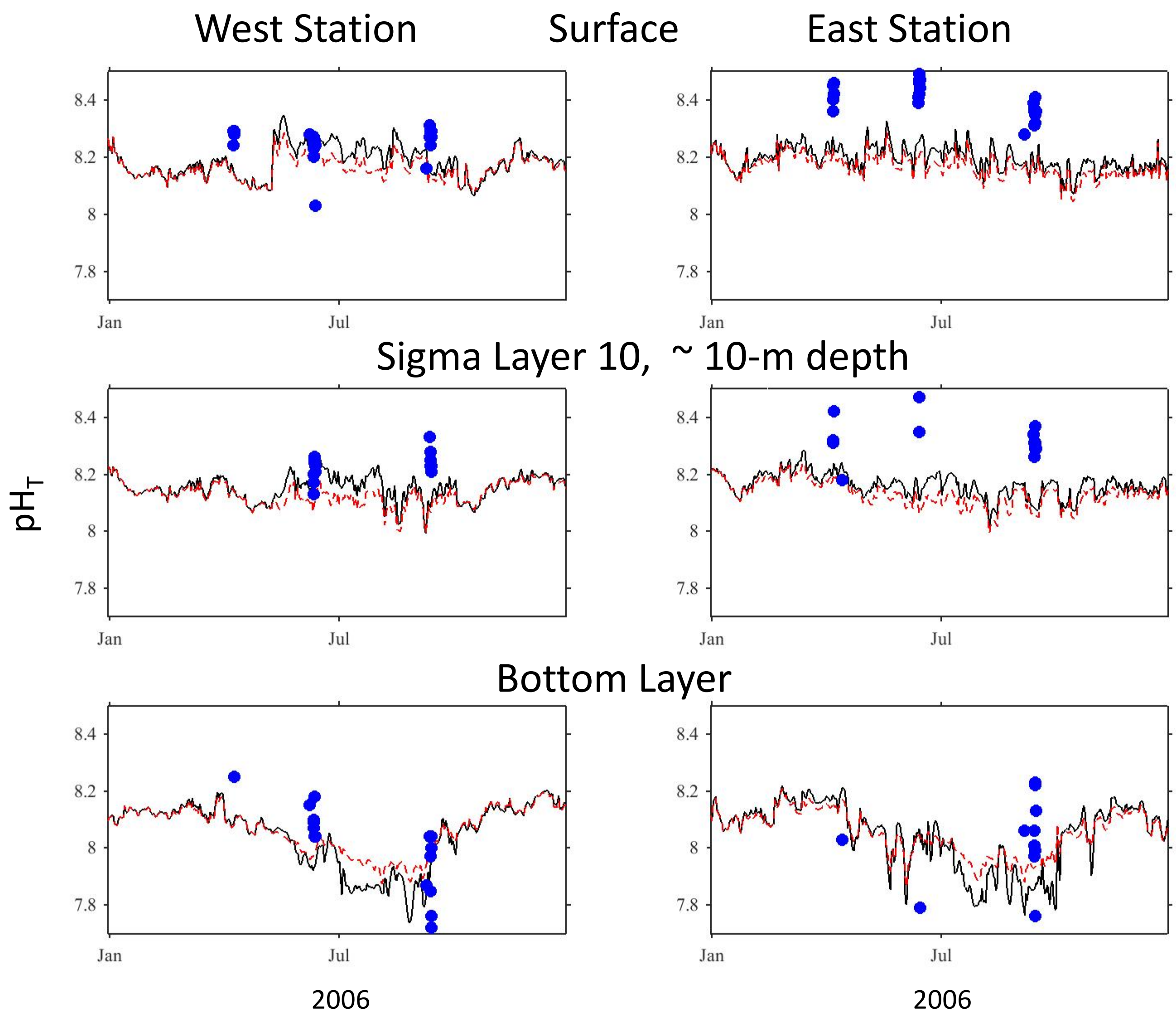
Modeled Chl

Red: dynamic Chl:C (Cloern 1995)

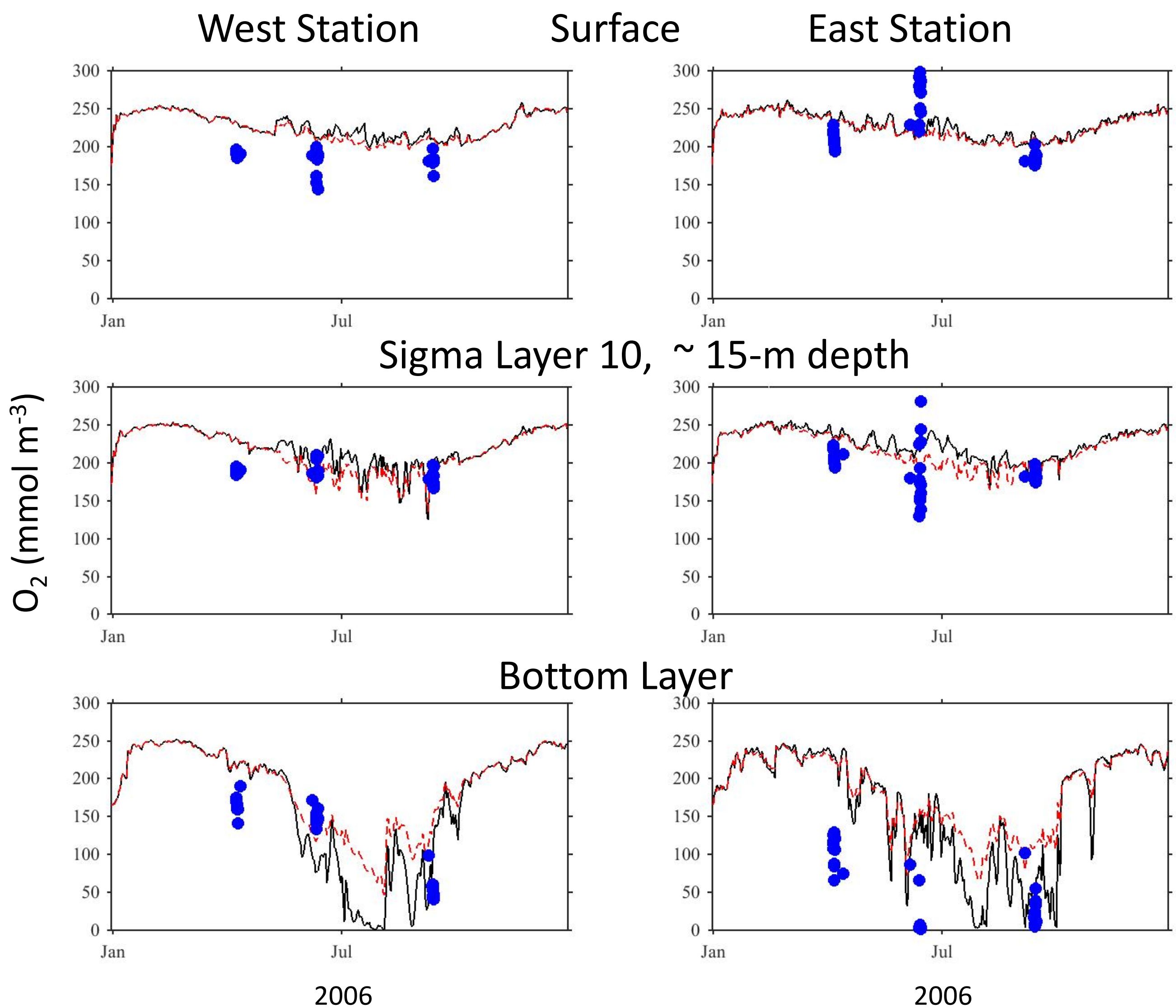
Black: fixed Chl:C



Modeled pH


West Station
Surface
East Station
8.4
8.2
8
7.8
Jan
Jul
Sigma Layer 10, ~ 10-m depth
pH$_T$
Bottom Layer
2006
2006

Modeled O2



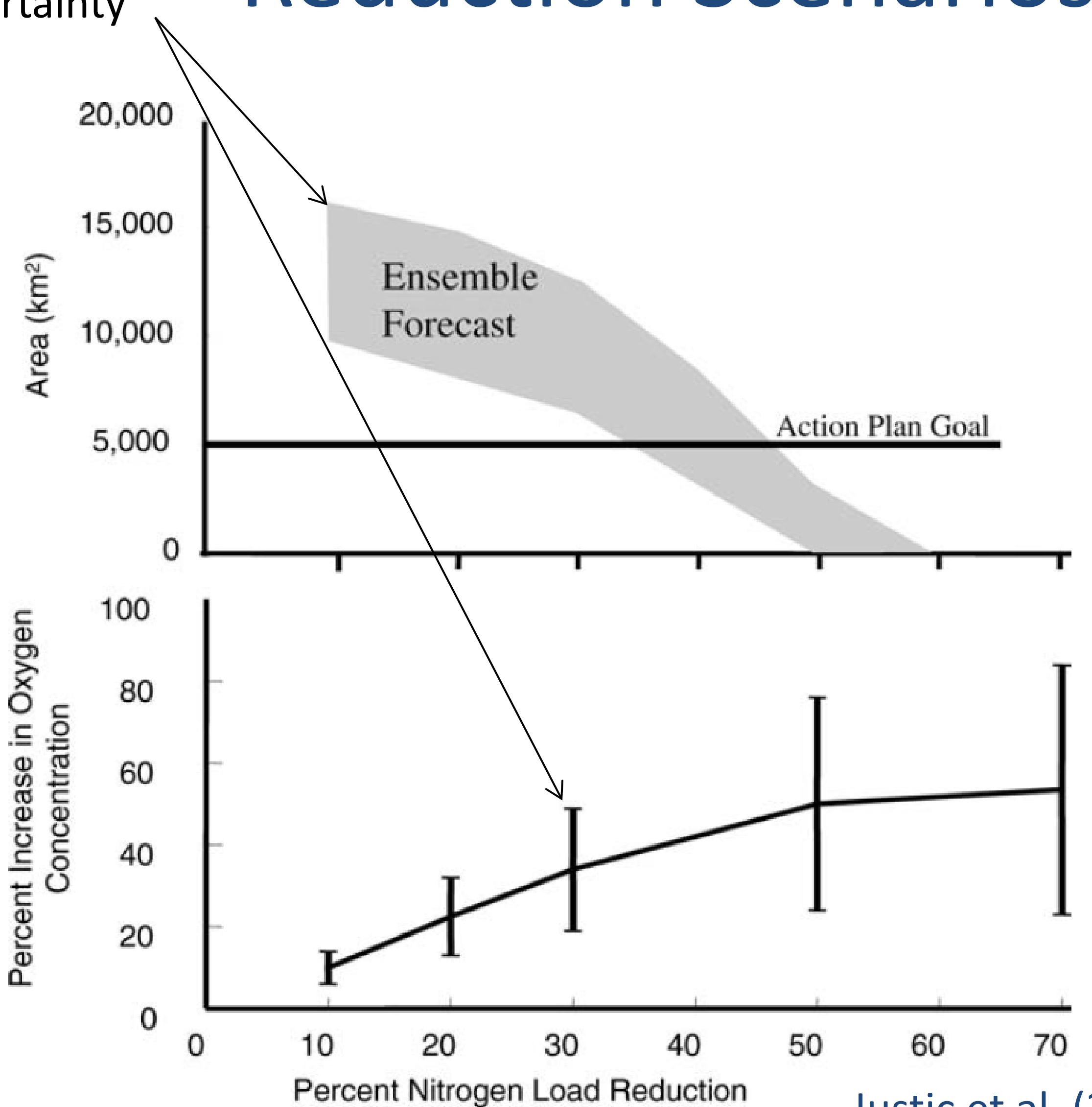
West Station
Surface
East Station
Sigma Layer 10, ~ 15-m depth
Bottom Layer
O_2 (mmol m^{-3})
300
250
200
150
100
50
0
Jan
Jul
2006
2006

Outline

1. The coastal acidification and hypoxia problem and linkage to land-based nutrients
2. Model development
3. Case study application to northern Gulf of Mexico
4. **Model scenarios for nutrient load reductions and climate change**

Example Nutrient Reduction Scenarios

model uncertainty



Justic et al. (2007)

Expected Climate Impacts

- + 2-4 ºC by late 21st century (IPCC 2014)
- River Discharge (Sperna Weiland et al. 2012)
  - Global river discharge increases by 11%
  - Miss R: -5%, but large uncertainty
- Hypoxia (Justic et al. 1996; 2003a; 2003b; Donner and Scavia 2007; Rabalais et al. 2009; Altieri and Gedan 2015)
  - ↑T, ↓ S, ↑Stratification
  - ↑ Primary Production and Respiration
  - ↑ Increased Hypoxia

Future Climate Scenario

Base Year = 2006

+3^{o}C Air Temp

+10% River Discharge

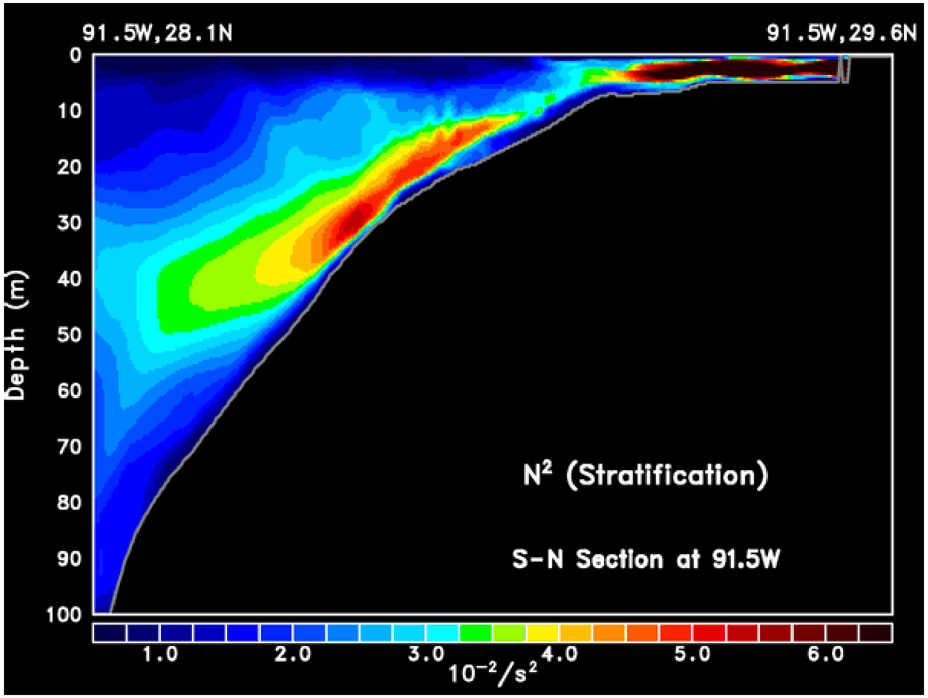
Similar to scenarios used in the Baltic (Meier et al. 2011)

+ 2.7-3.8ºC

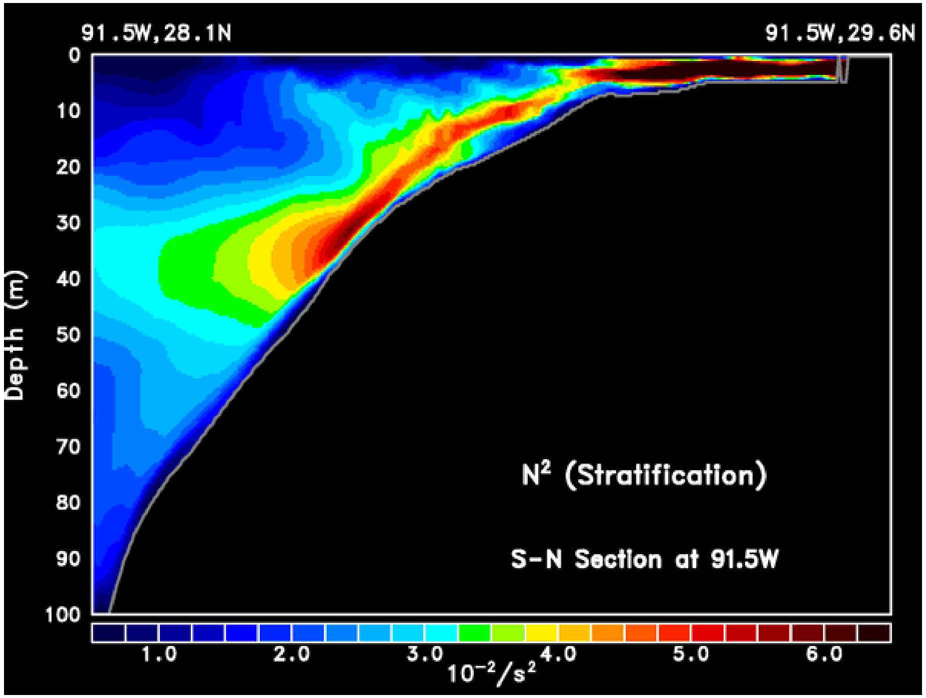
+15-22% Discharge

Future T, S, and Stratification

	LA Shelf <20 m	LA Shelf 20-50 m	Baltic (Meier et al. 2011)
T	+1.3	+1.1	+2.5
S	-0.43	-0.19	-1.7



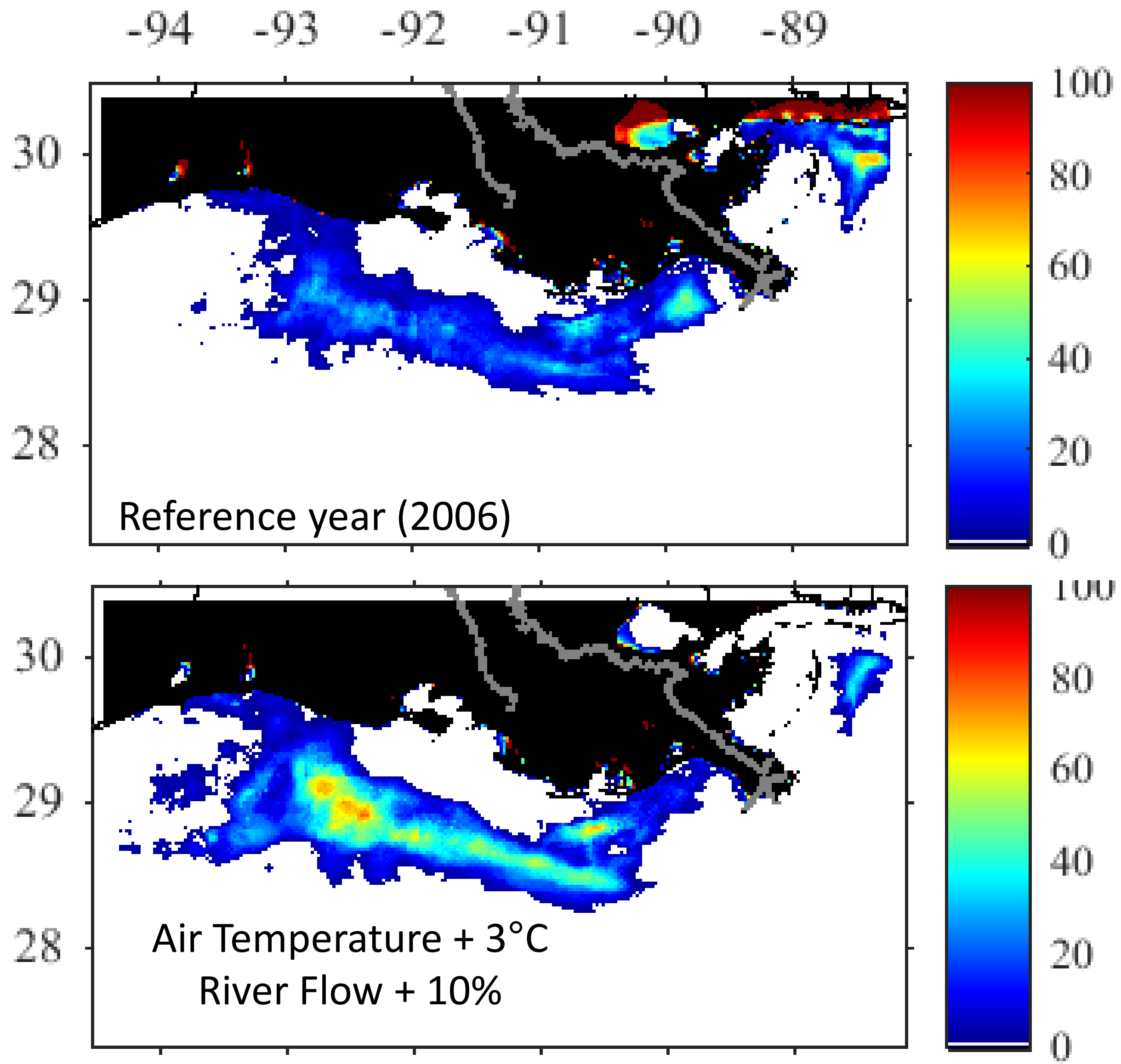
Reference year (2006)



Air Temperature + 3°C
River Flow + 10%

Lehrter et al. in prep. CGEM with climate change scenarios

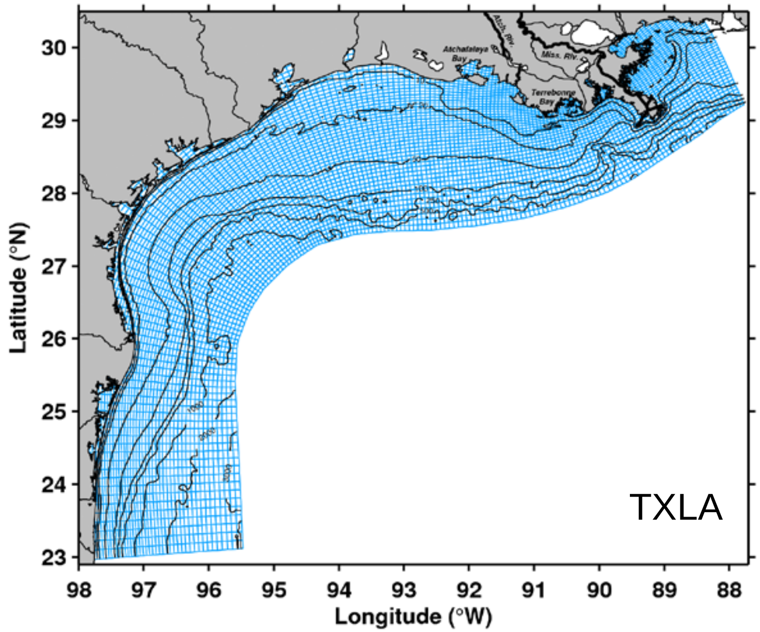
Annual Number of Days with Hypoxia

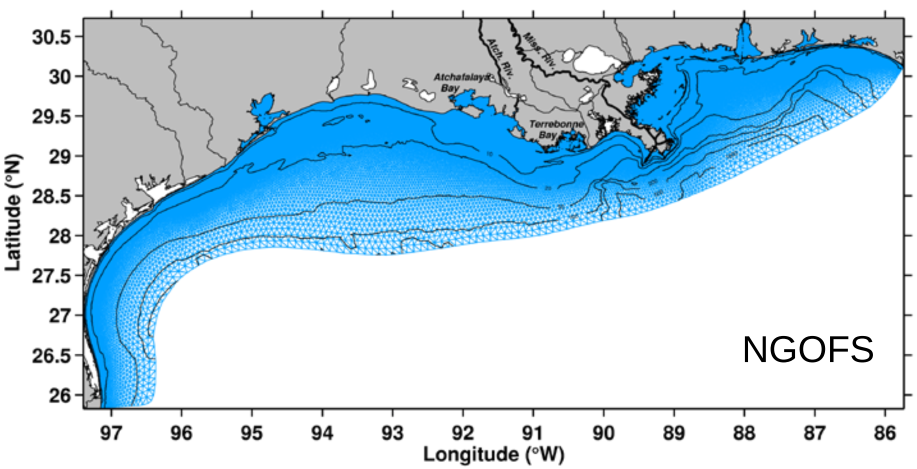


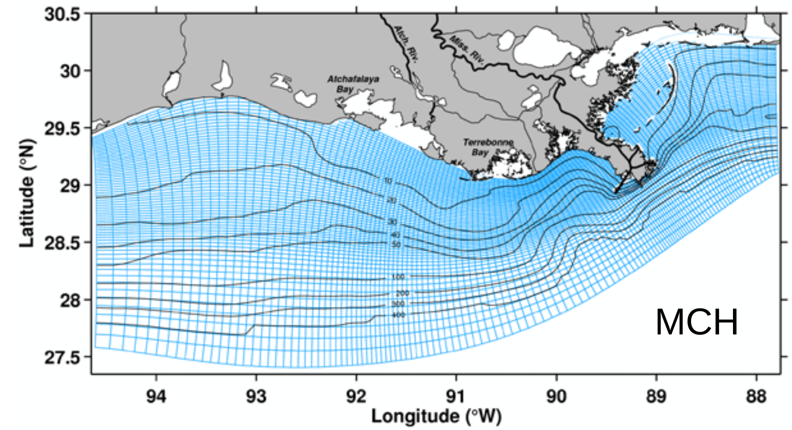
Current and Future Work

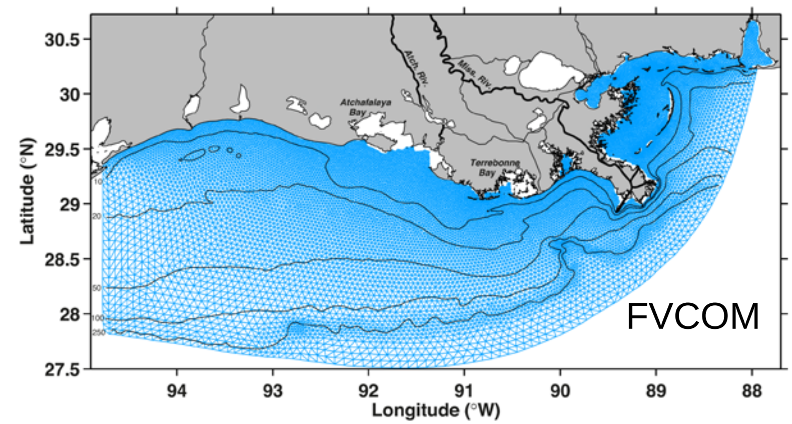
- Model experiments and uncertainties
  - Sediment representation: internal versus external DIC, Alk, and pH sources
  - Parameter sets
  - Model inter-comparison (COMT)
- Scenarios with multi-media modeling framework
  - Land, air, and water loading
  - Down-scaled GCMs: RCP 4.5, 6.0, 8.5
- Field and lab studies in northern Gulf, New England, and Pacific Northwest

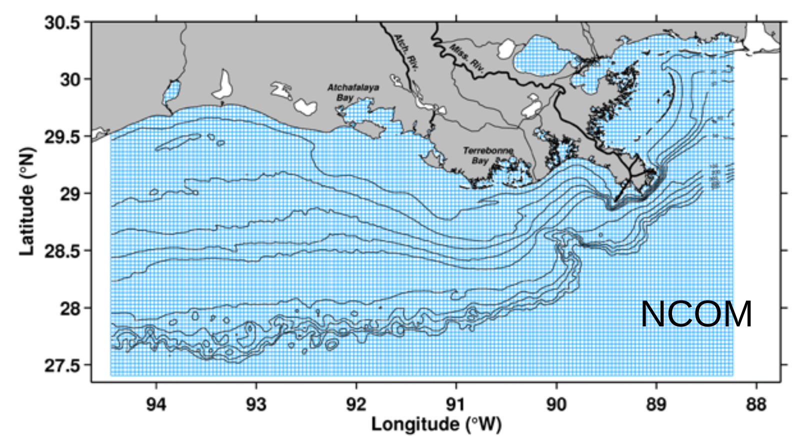
Coastal and Ocean Modeling Testbed: Shelf Hypoxia











http://www.ioos.noaa.gov/modeling/testbed.html

FishTank GEM

- **Now available by request; soon to website**
- **Contains the minimal set of inputs to run the code**
- **Can be run as a single cell, or with any user defined grid**


Contact: lehrter.john@epa.gov
UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
EPA Gulf Ecology Division