Intercomparison of Hypoxia Models for the Northern Gulf of Mexico and Nutrient Load Scenarios

PIs

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Partners

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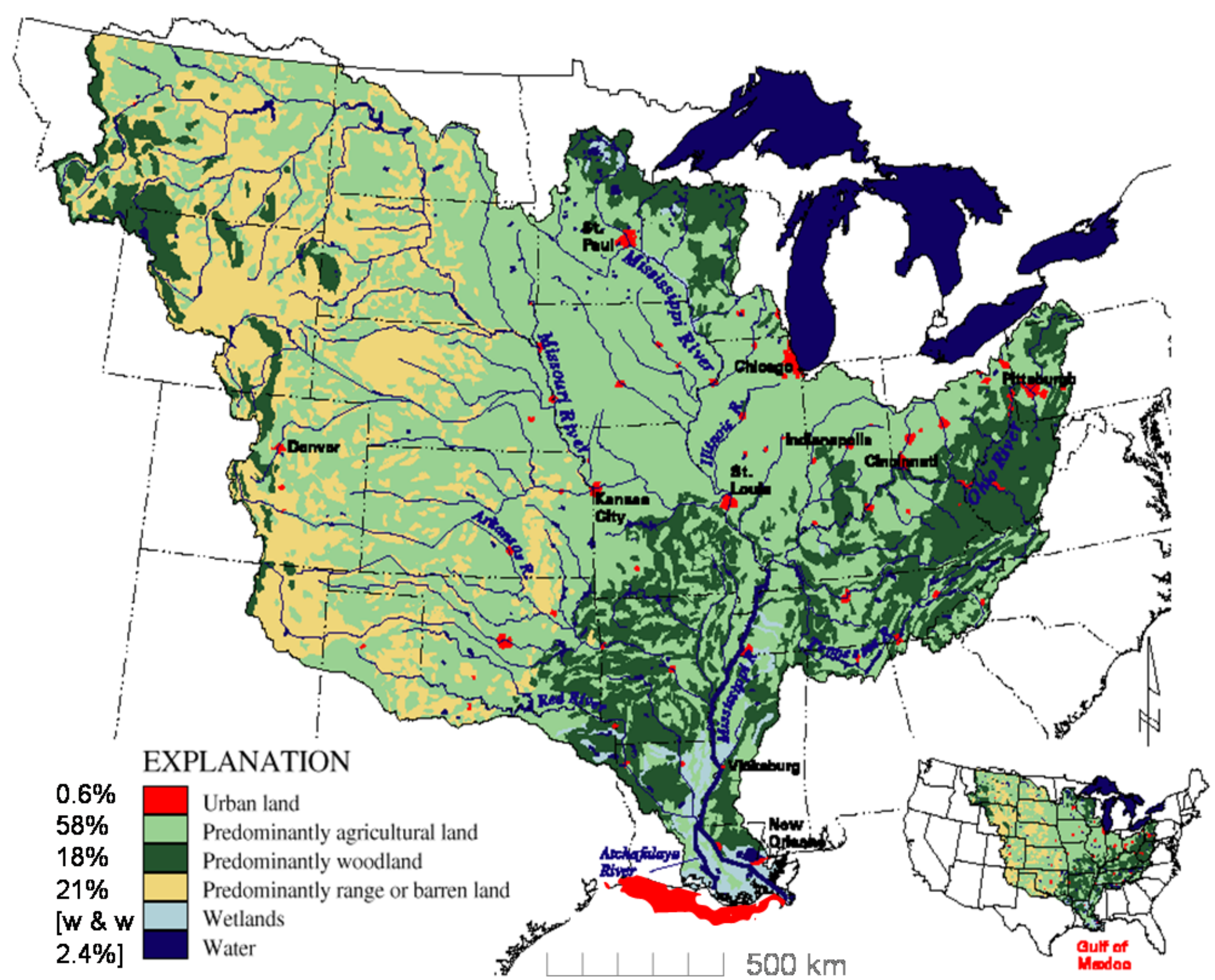
John Lehrter (EPA)

Mike Murrell (EPA)



Applications

Federal Entities/Partners

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- NOAA - Ecological Roadmap

- Hypoxia Task Force (states, federal agencies incl. NOAA, EPA, and tribes) - Action Plan

- EPA - Clean Water Act

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- short-term hypoxia forecasts
- seasonal hypoxia forecasts
- scenarios (nutrient load, climate change)
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Skillful application need good process understanding. Black box is likely not providing useful predictive capabilities with known error statistics.
Practical considerations for operational use (computational cost, robustness, data needs). Different models will be appropriate for the different uses.

COMT SH models

- ROMS small domain
  - simple hypoxia model
  - full bgc model
- ROMS large domain
  - simple hypoxia model
  - full bgc model
  - quasi-operational physical model
- FVCOM
  - simple hypoxia model
  - WASP model
- NCOM
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COMT SH models

research mode,
hindcasts only,
run at Dal

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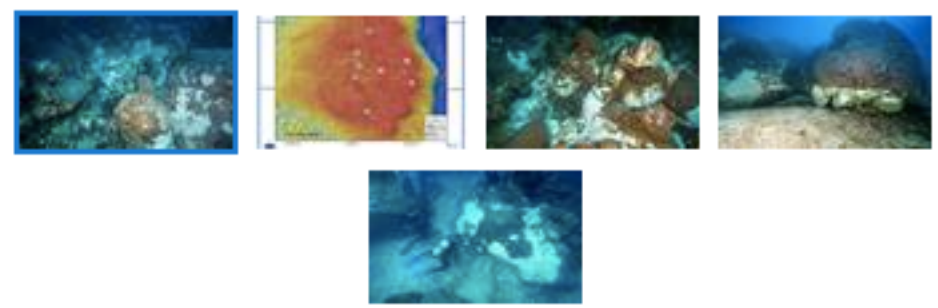
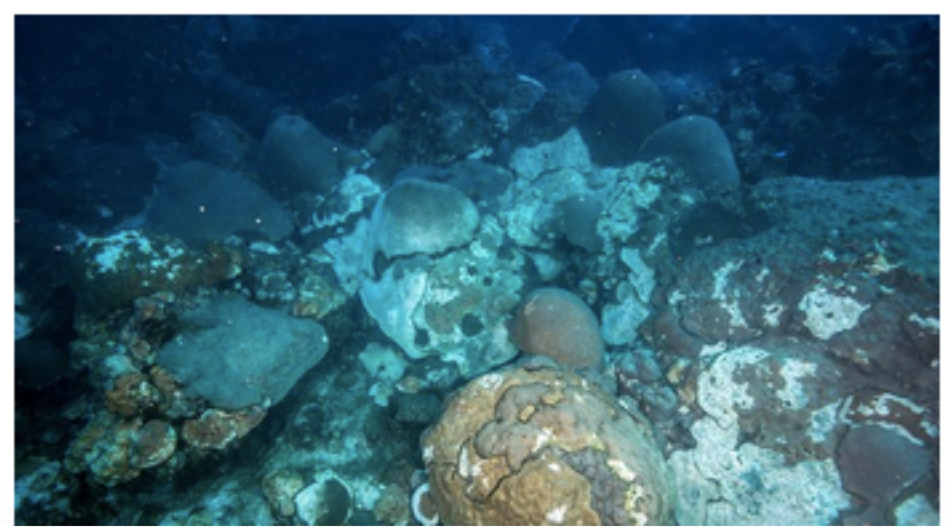
Posted by Eric Haun | August 12, 2016

Why is Coral Dying at East Flower Garden Bank?



Normally the reefs of Flower Garden Banks National Marine Sanctuary (FGBNMS) are considered to be the healthiest in the region, but now scientists from around the world are trying to figure out what's behind a mysterious event in the area that's killed thousands of coral colonies and associated reef invertebrates.



On July 25, sport divers on the M/V Fling reported green, hazy water, huge patches of ugly white mats on corals and sponges, and dead animals littering the bottom at East Flower Garden Bank, buoy #4. The charter captain notified FGBNMS and the U.S. Bureau of Ocean Energy Management (BOEM) researchers,

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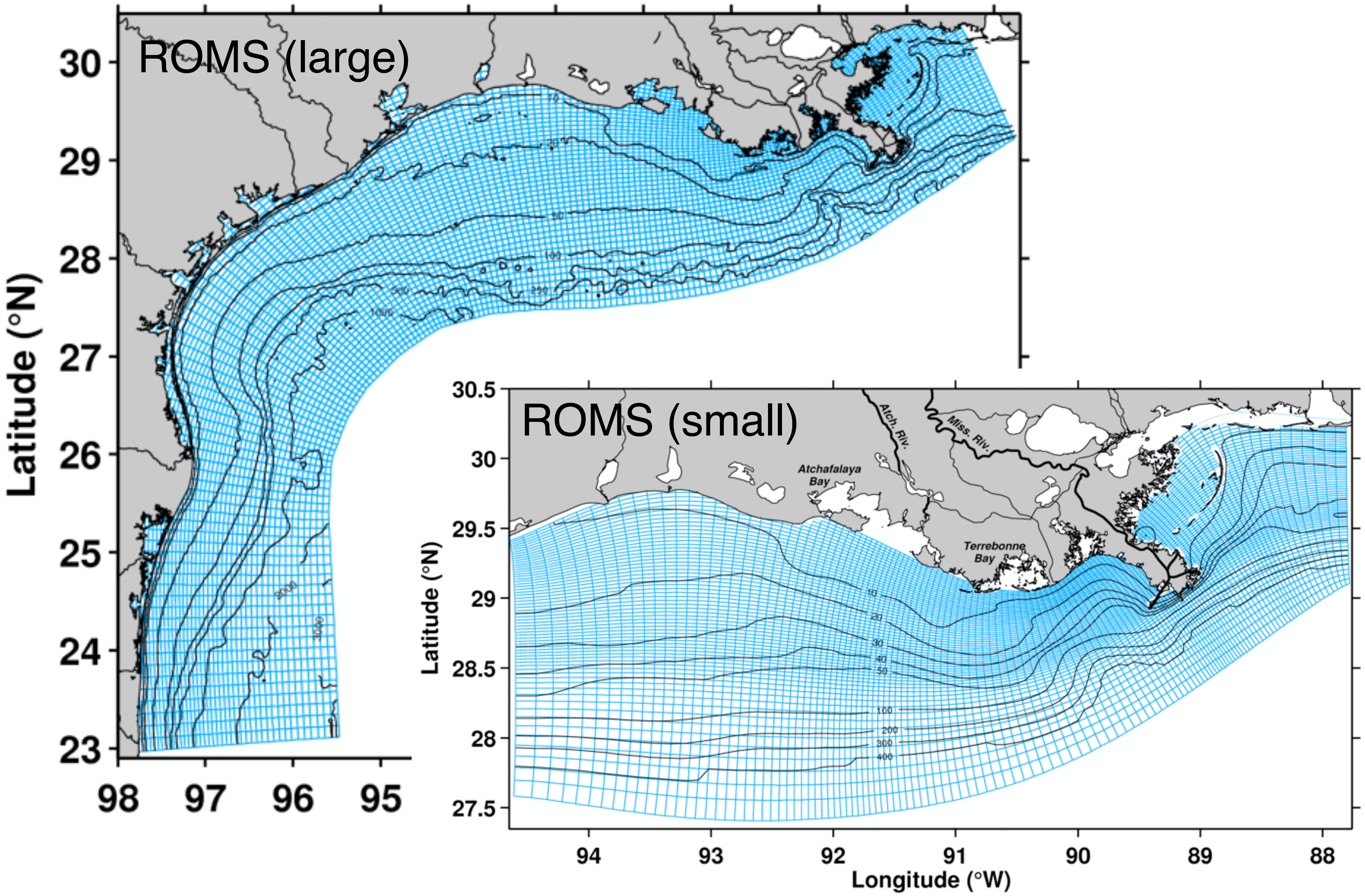
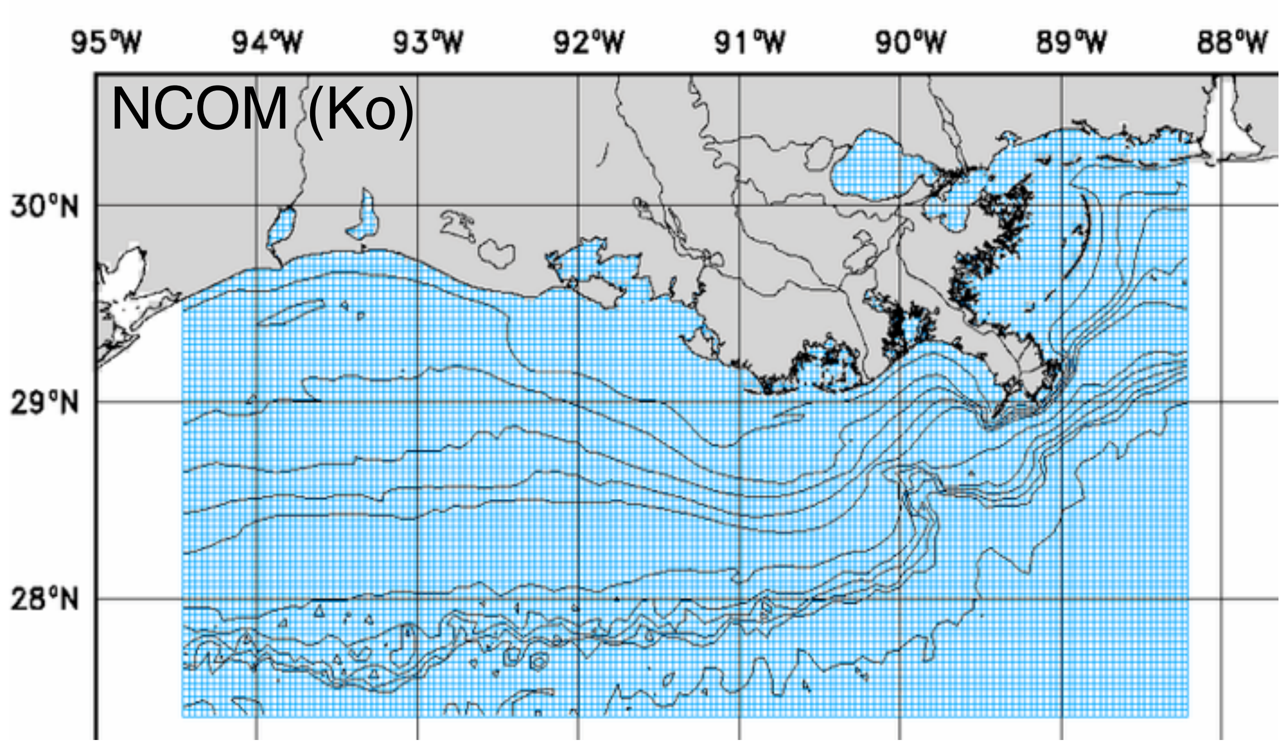
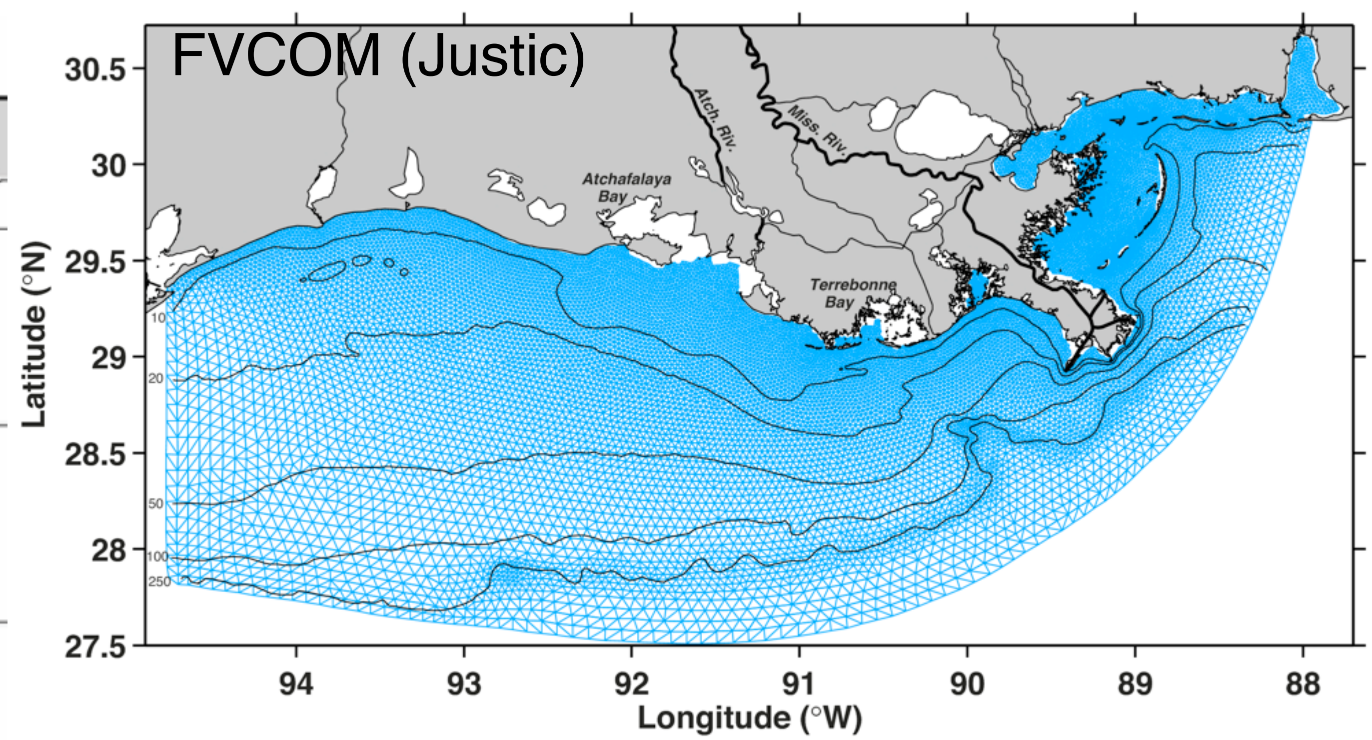
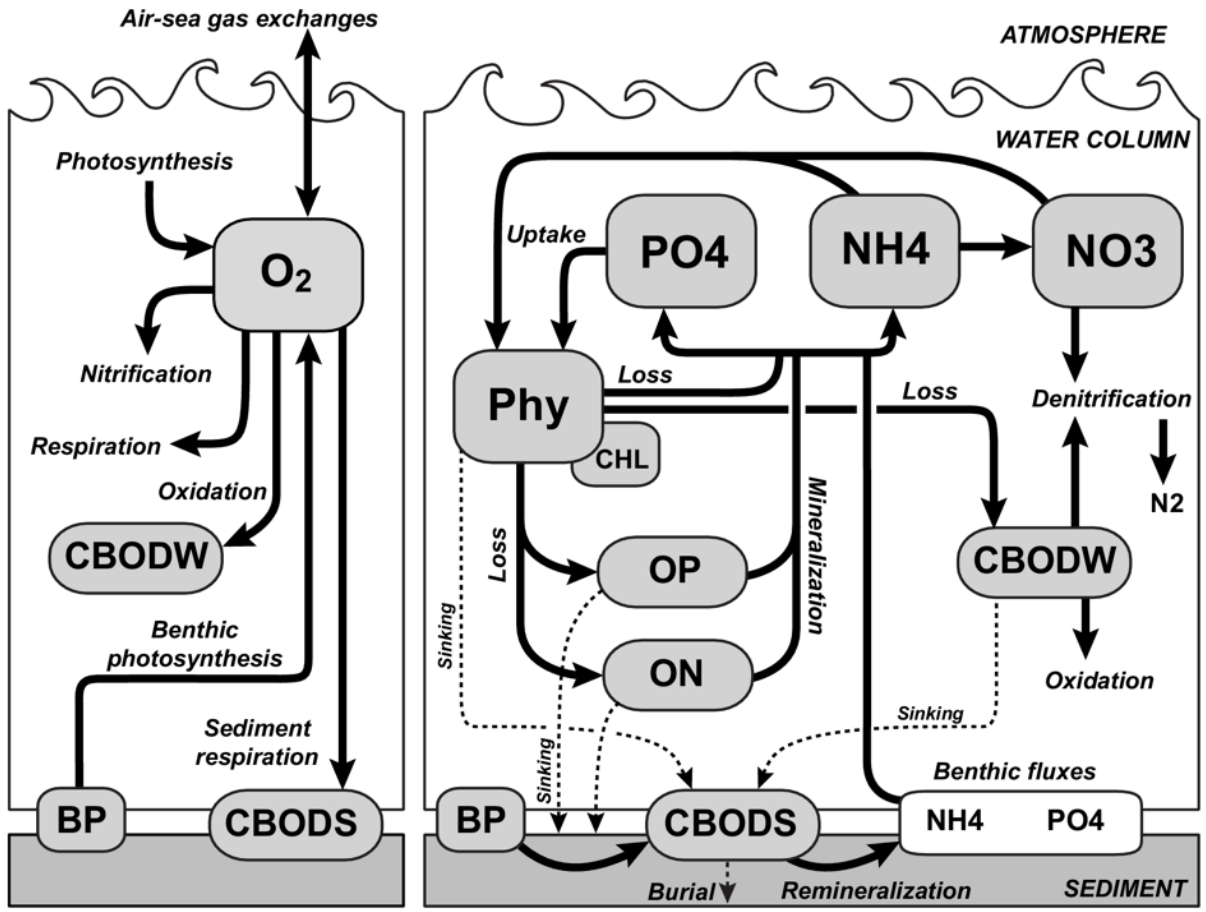
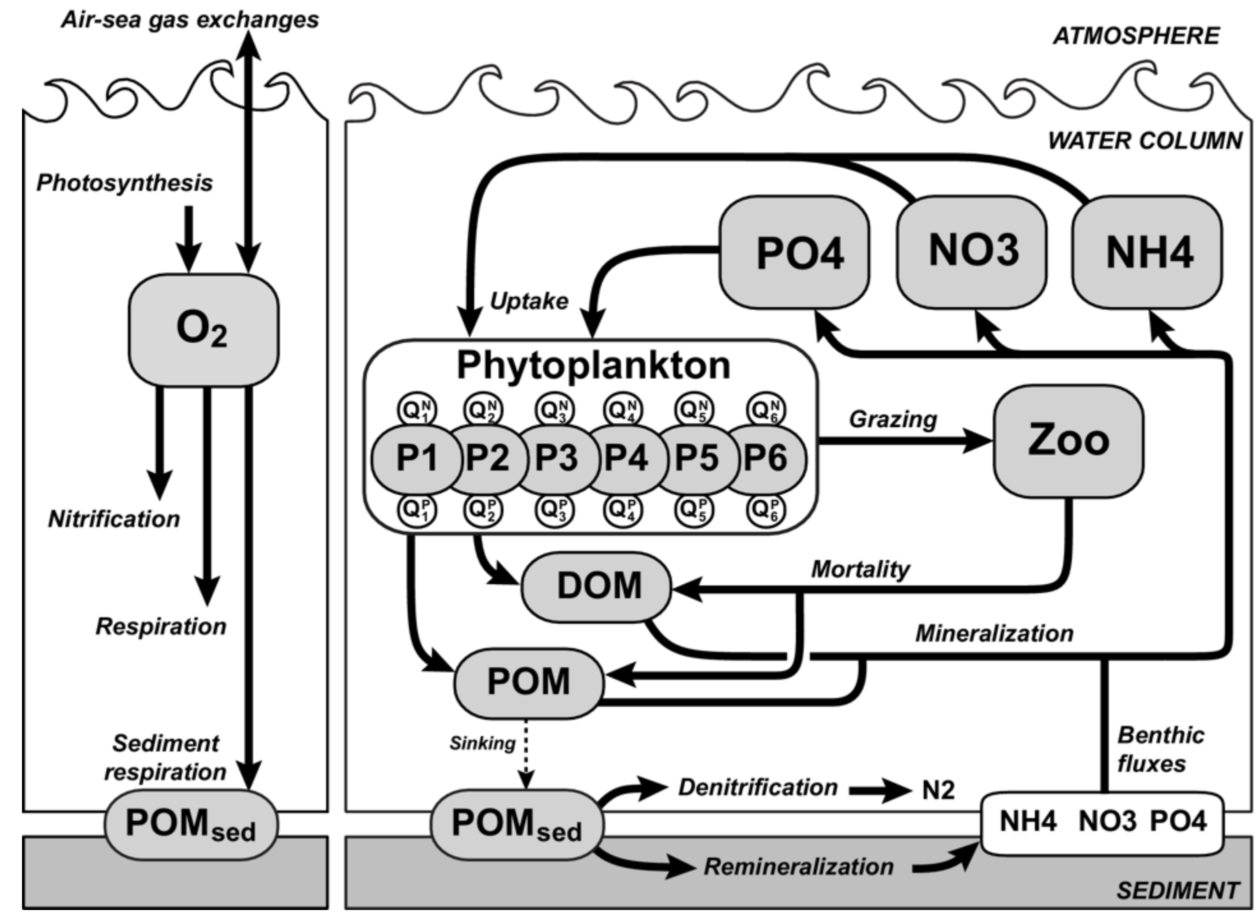


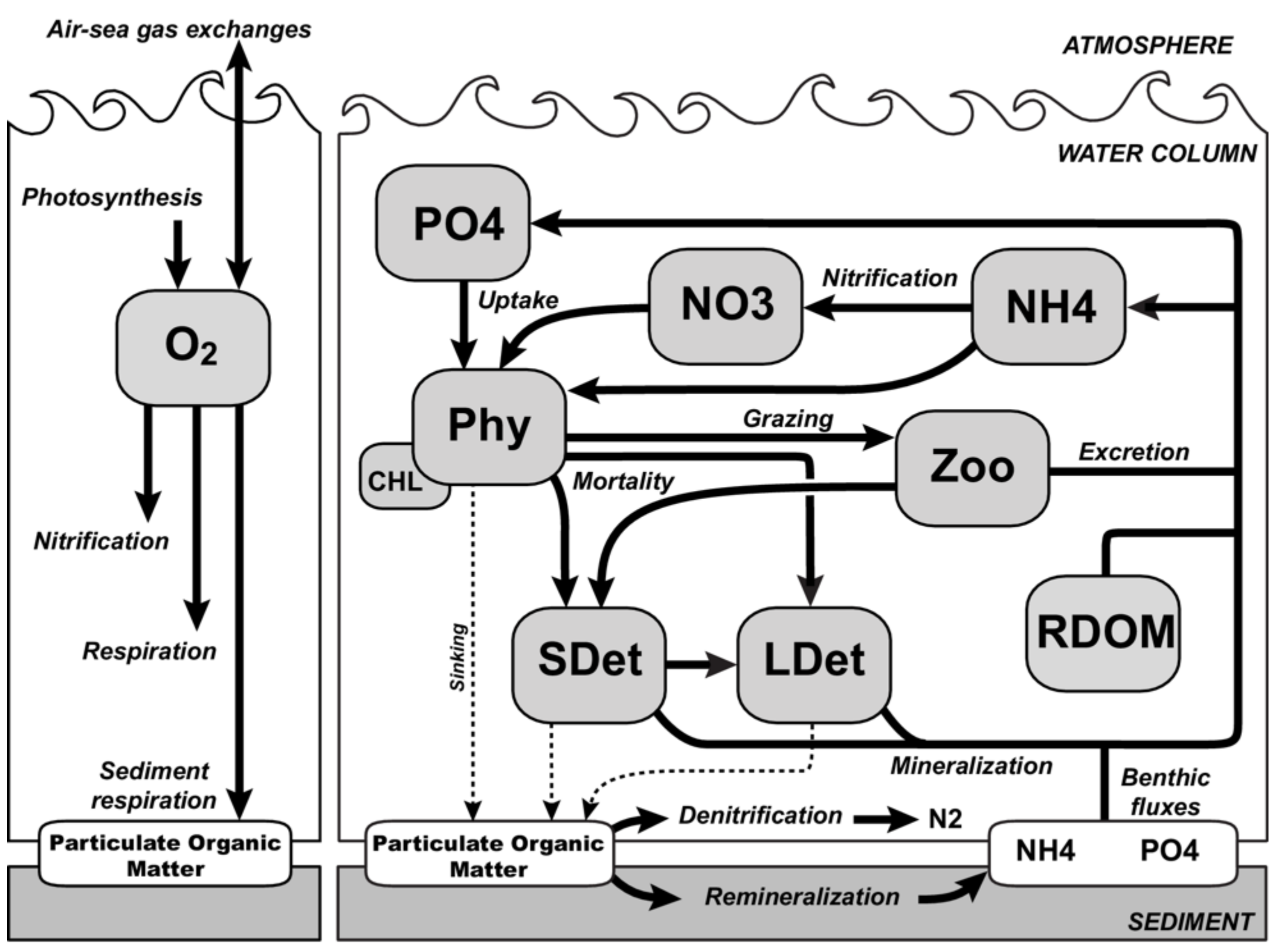
- **ROMS (large and small domain)**
- **FVCOM**
- **NCOM**





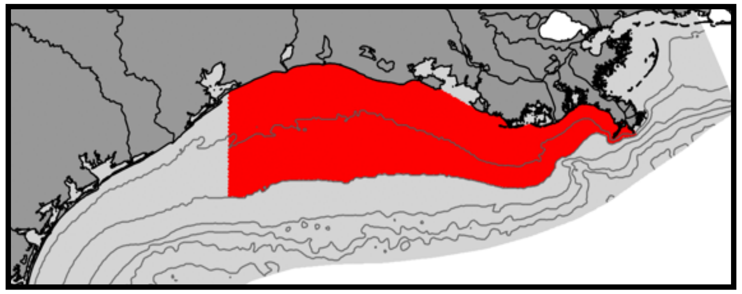


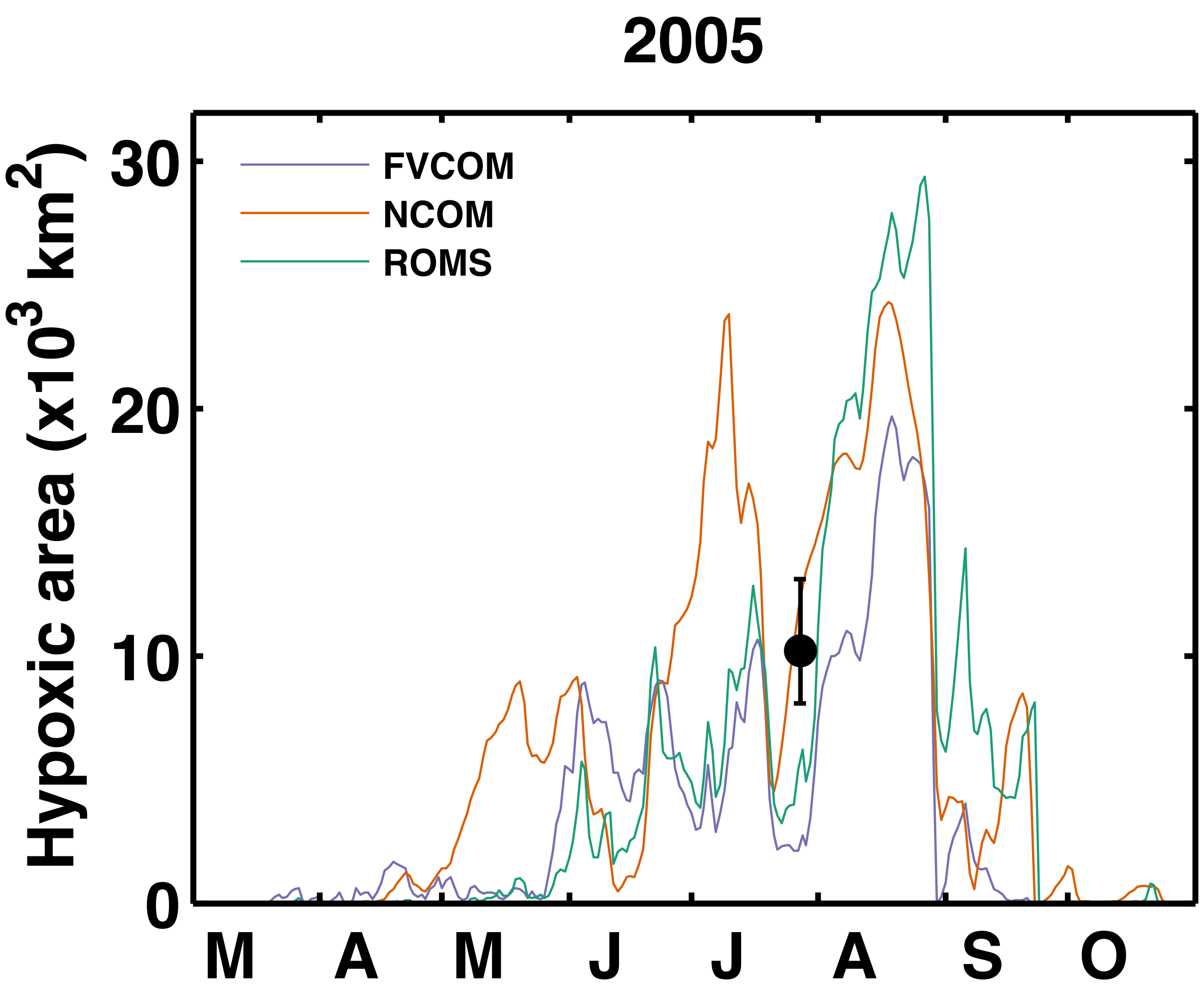


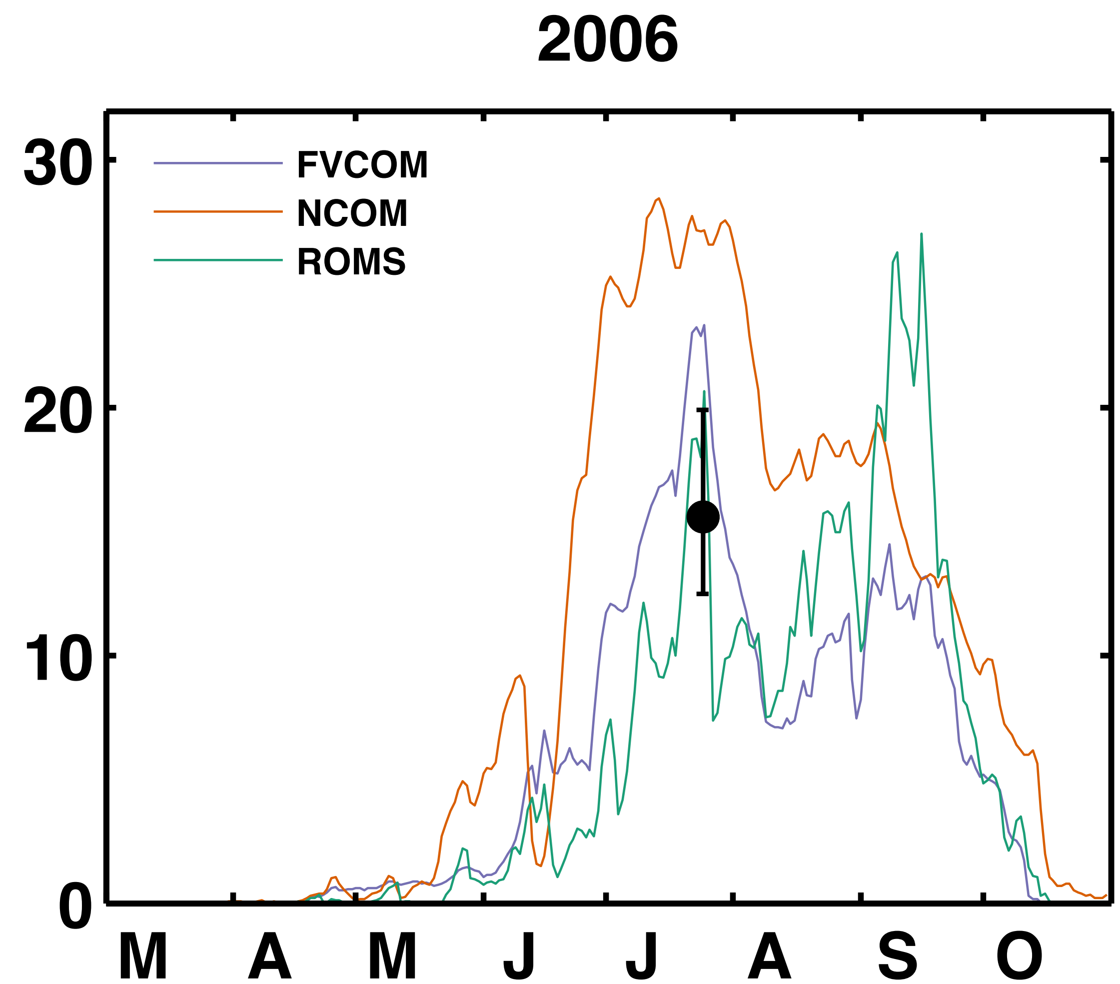


- **FVCOM (WASP)**
- **NCOM (GEM)**
- **ROMS**

Hypoxic area: full biogeochemical models







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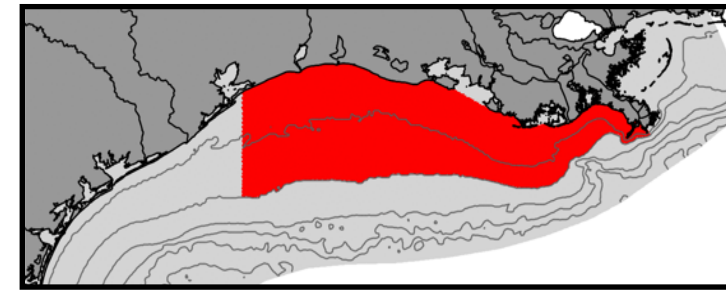
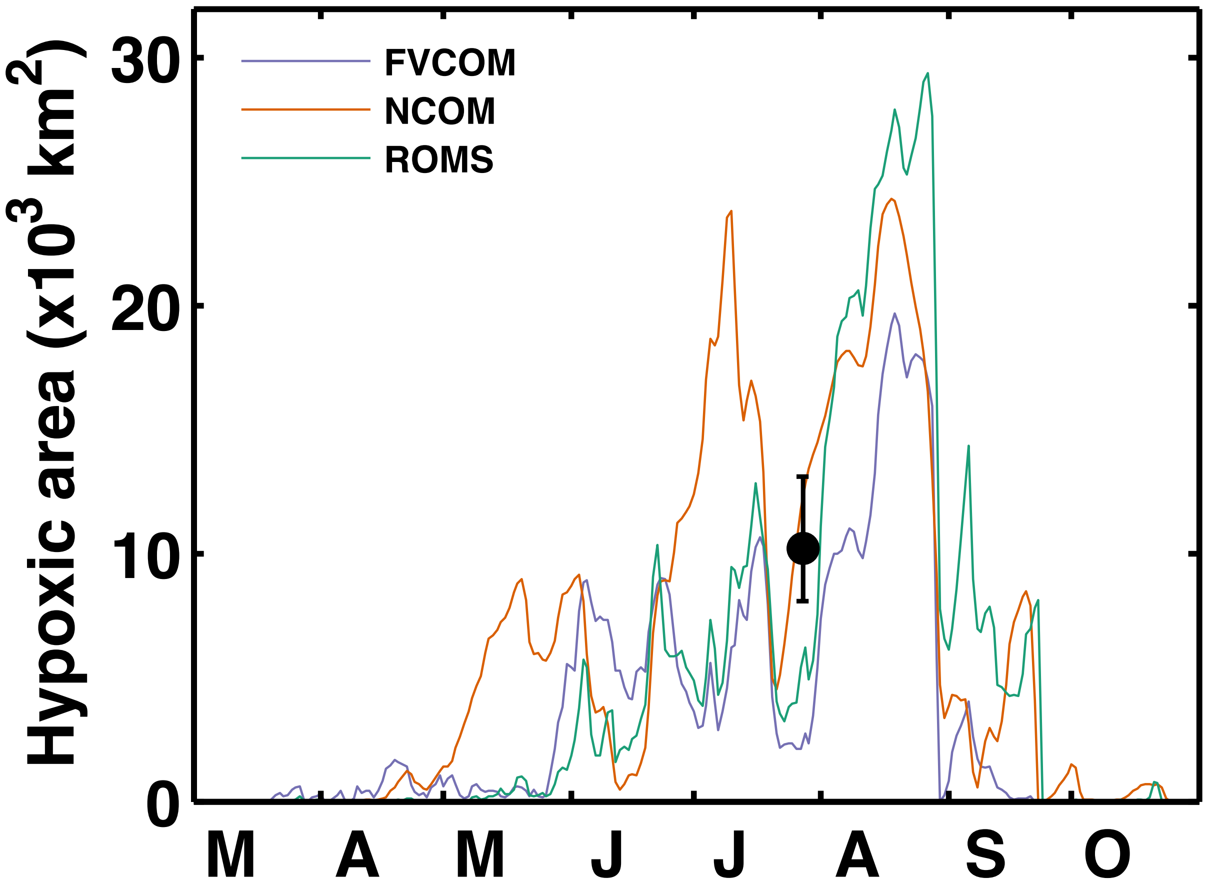
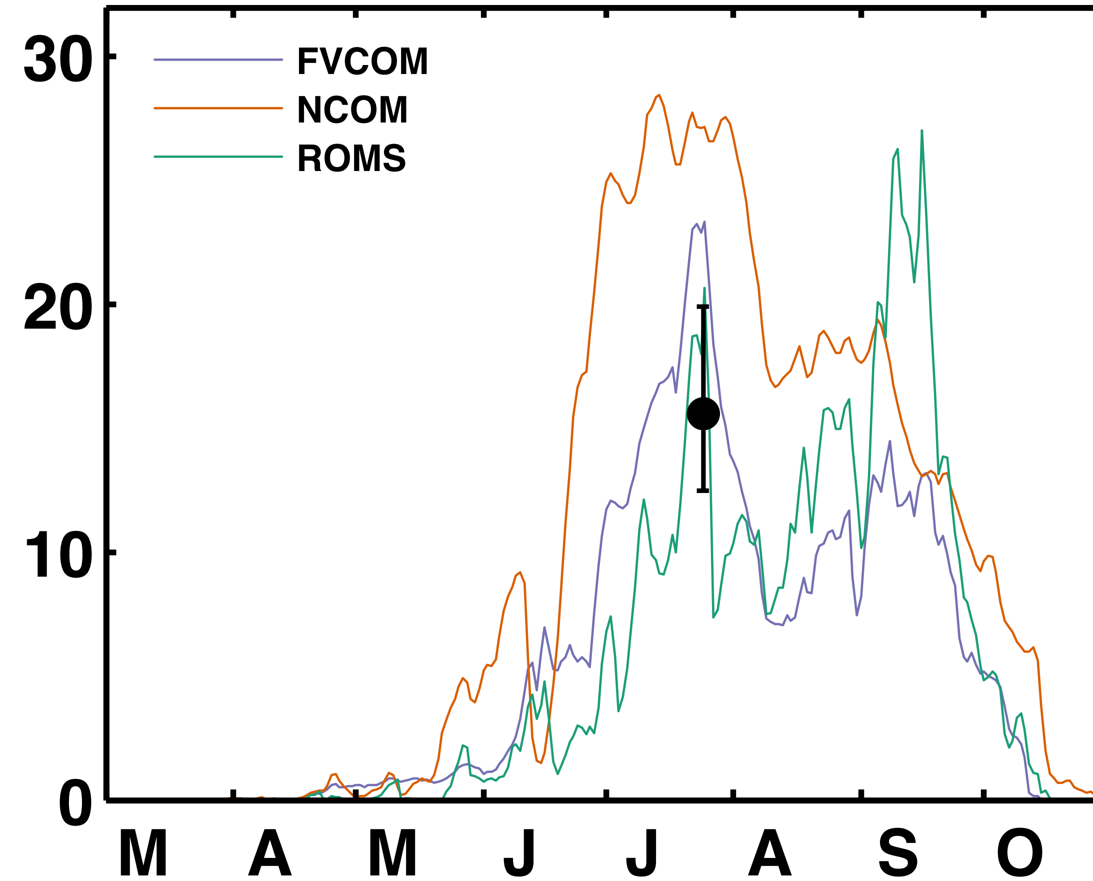


2005



2006



Differences in hypoxia predictions could be due to differences in model physics and/or biology.

Need to disentangle both effects.

Using simple oxygen parameterization by Yu et al. (JGR 2015) (same in all models) includes air-sea gas exchange, water column respiration (WR) and sediment oxygen consumption (SOC)

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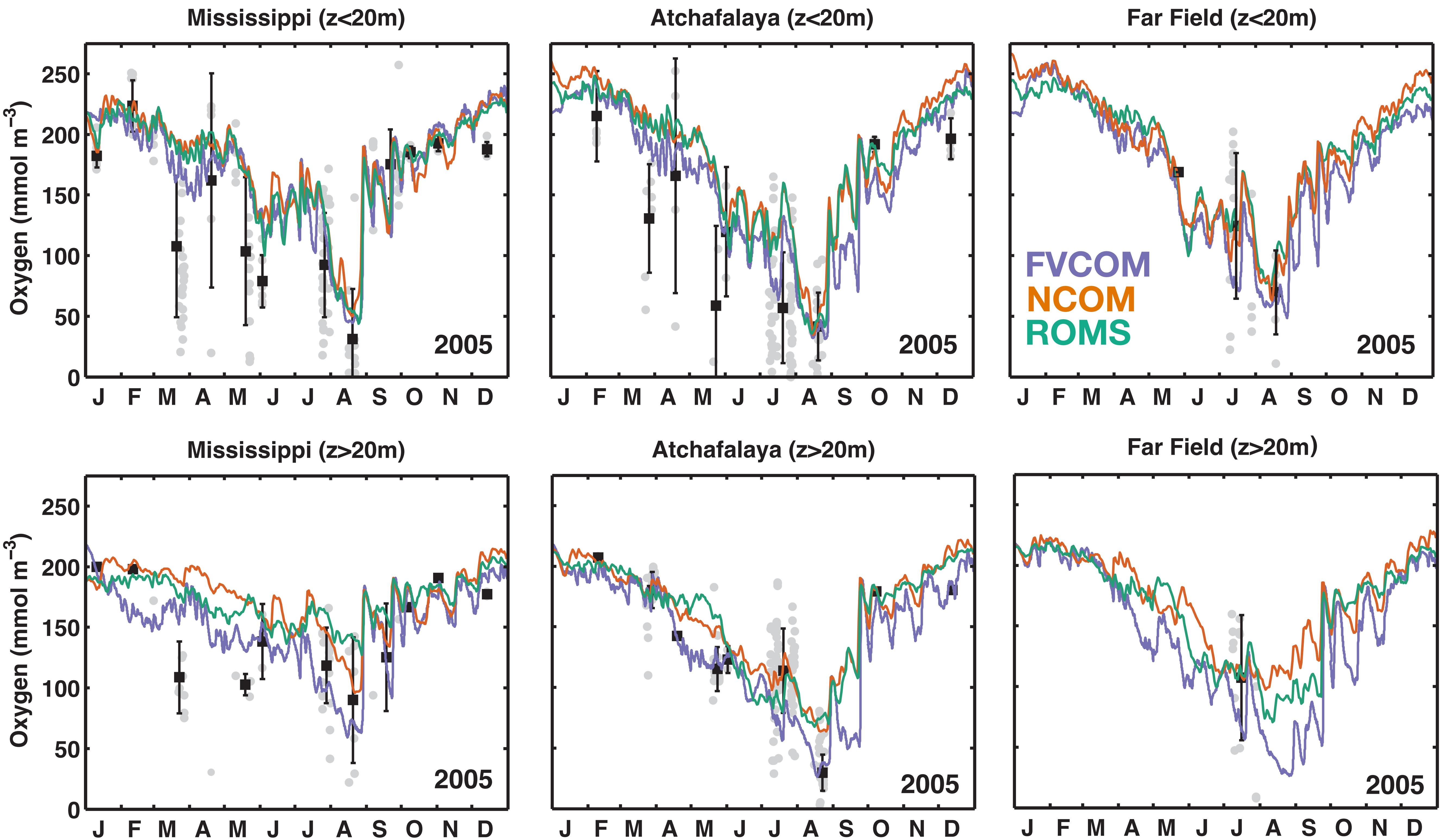
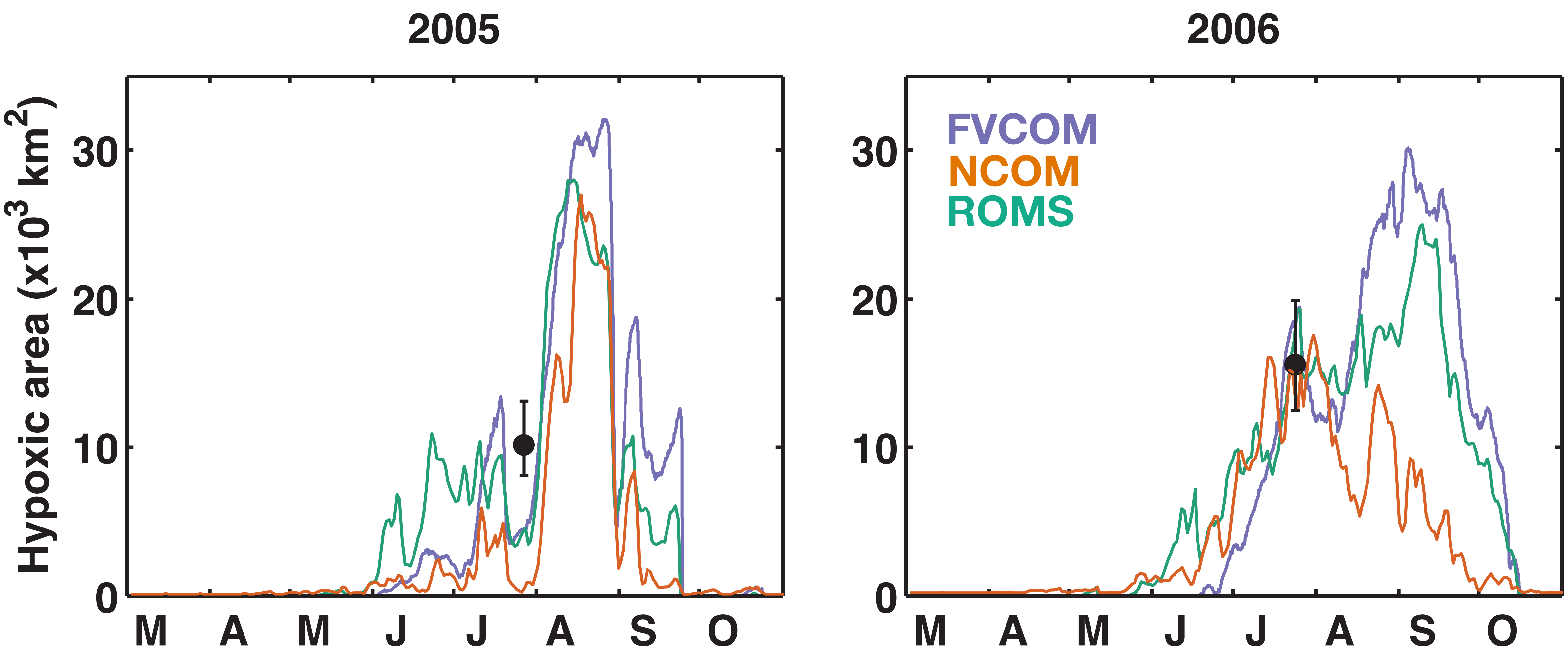
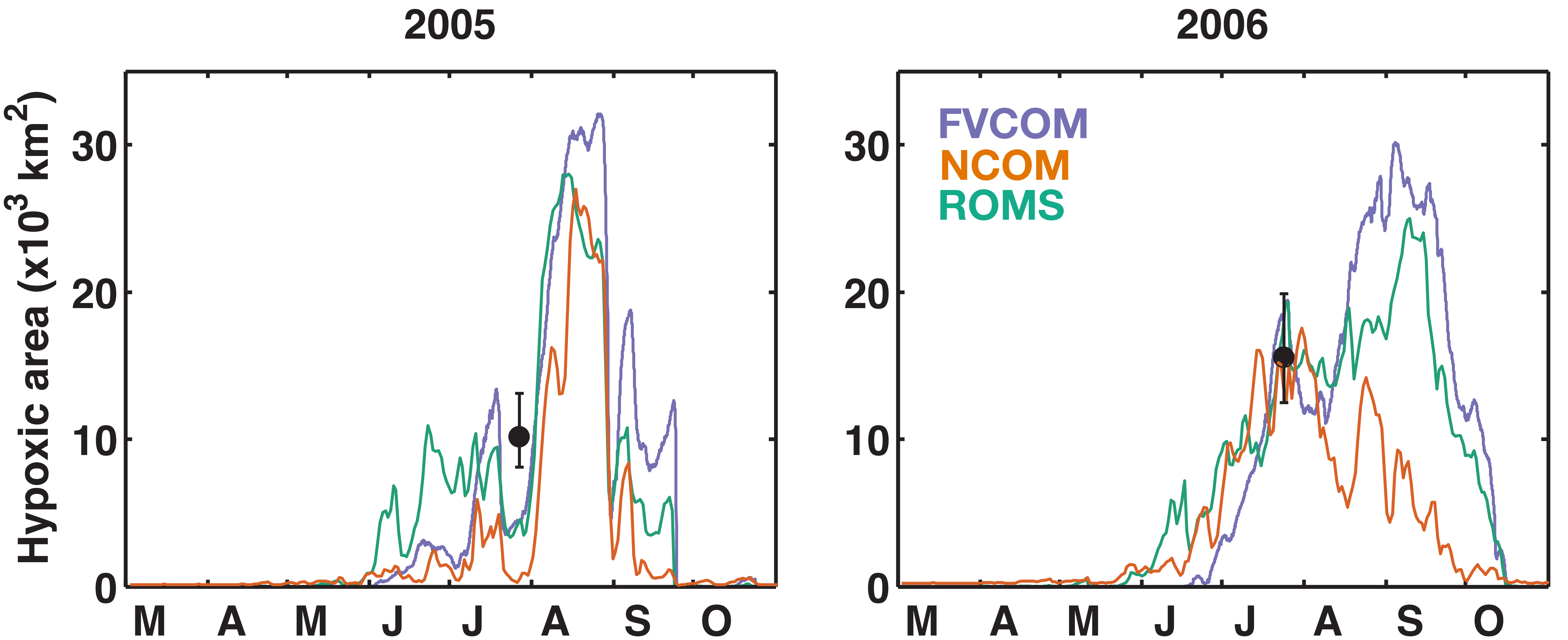


Find the odd one out!

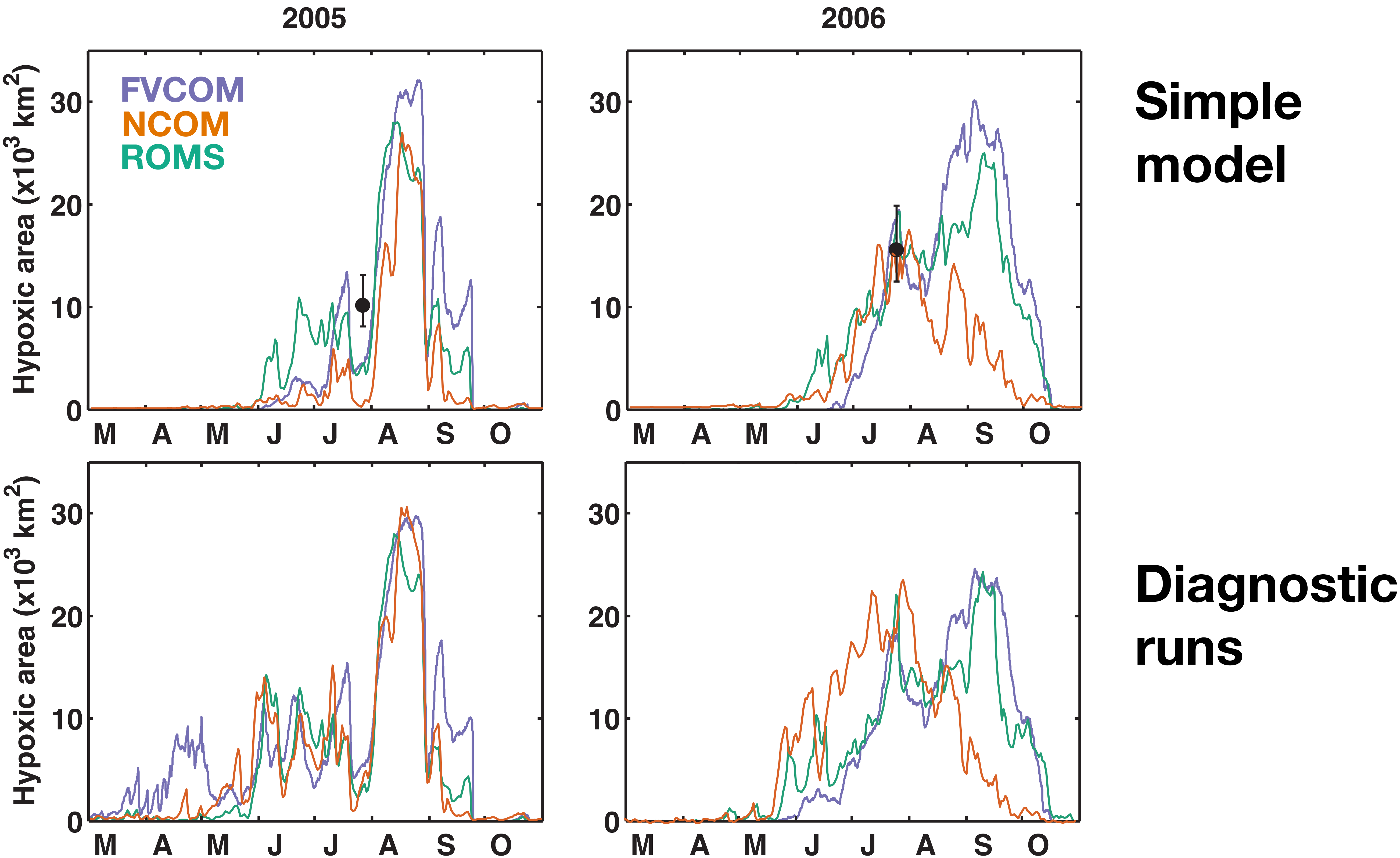
oxygen consumption in the water column	vertical stratification	oxygen consumption by the sediment	bottom drag parameter	vertical attenuation of shortwave radiation

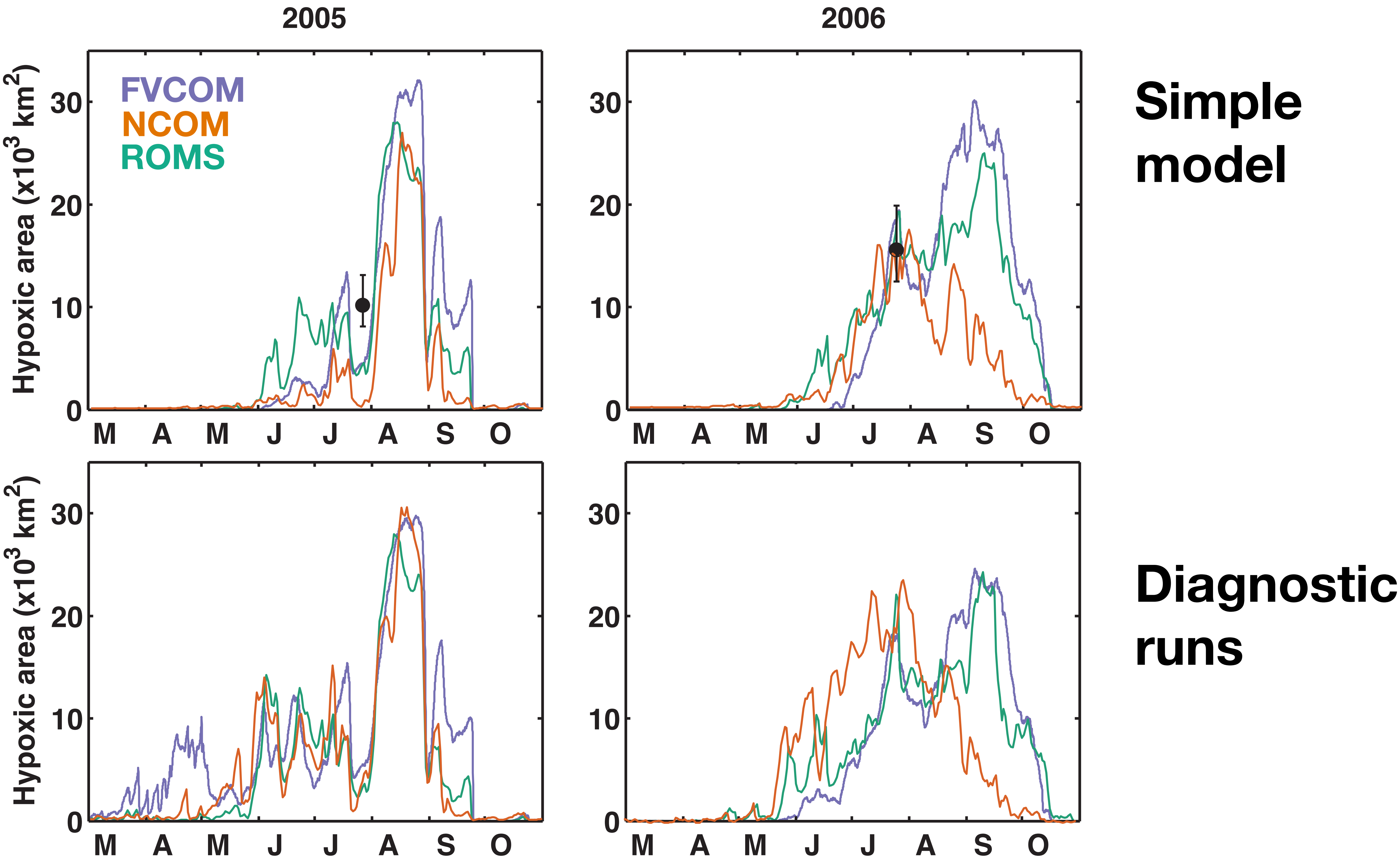

2005
2006
Hypoxic area (x10^3 km^2)
0
10
20
30
M
A
M
J
J
A
S
O
FVCOM
NCOM
ROMS



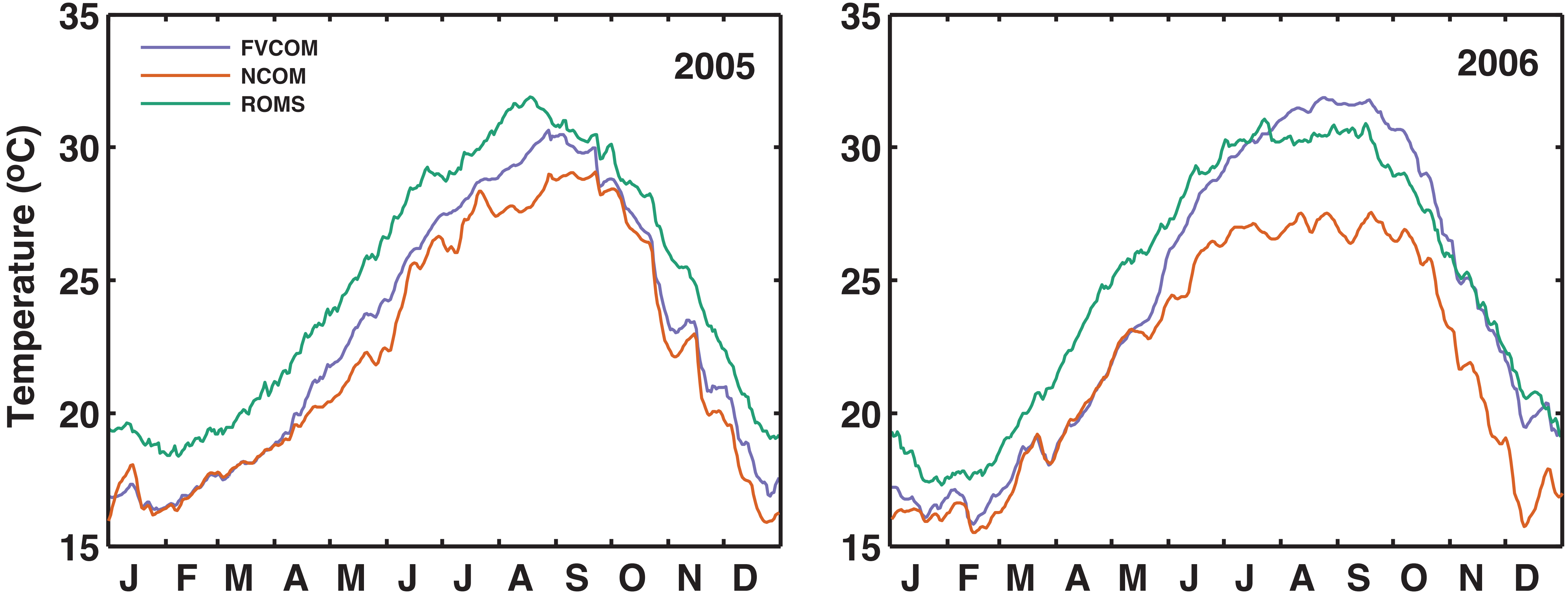
Oxygen concentration is controlled by the balance of oxygen supply and oxygen consumption.

In these simple hypoxia models water column respiration is equal among all models, but sediment oxygen consumption depends on bottom water temperature.

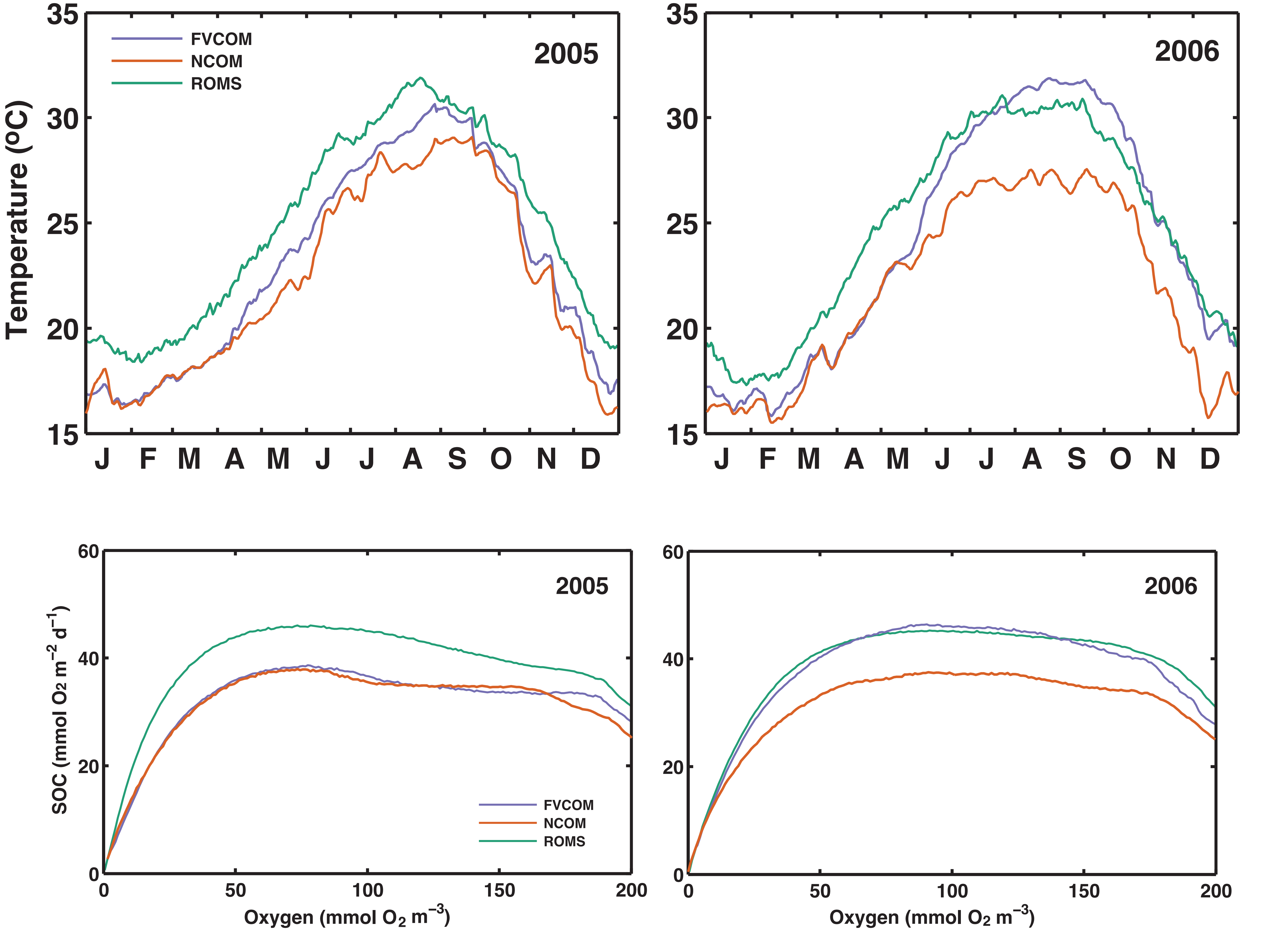

2005
2006
FVCOM
NCOM
ROMS
Simple model
Diagnostic runs
Hypoxic area (x10^3 km^2)
Hypoxic area (x10^3 km^2)
0
10
20
30
M A M J J A S O



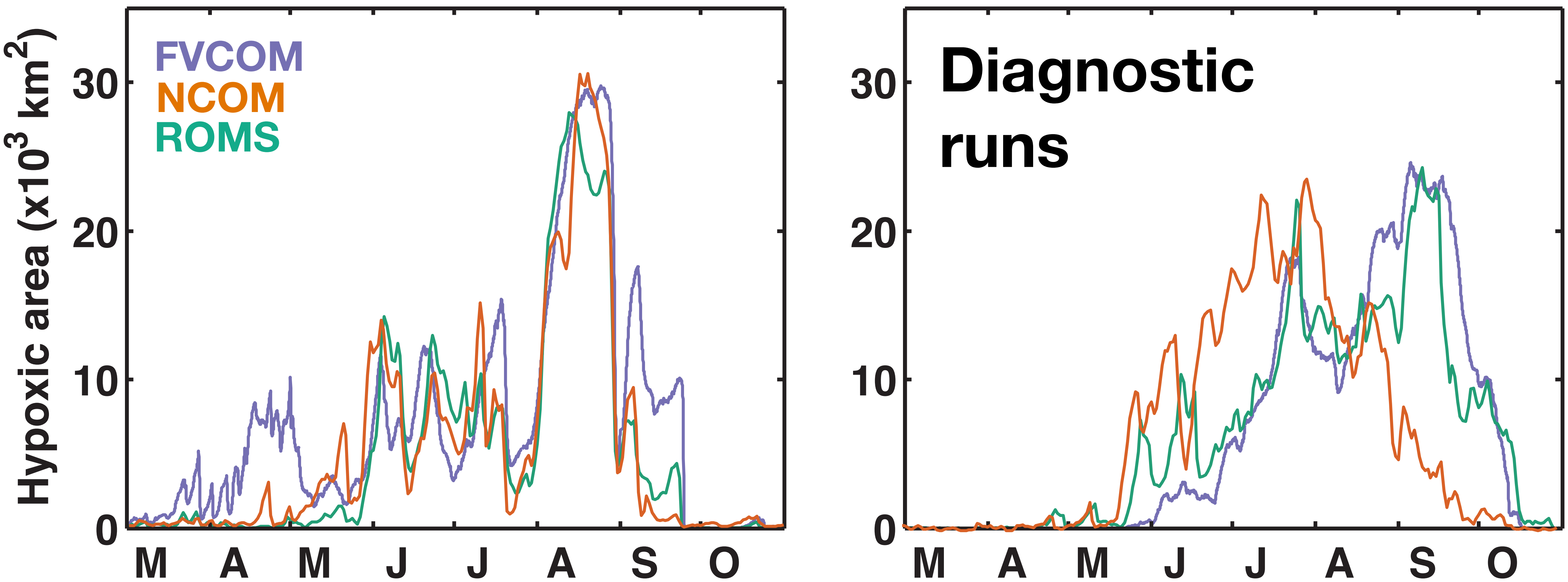
1. Effects of bottom water temperature



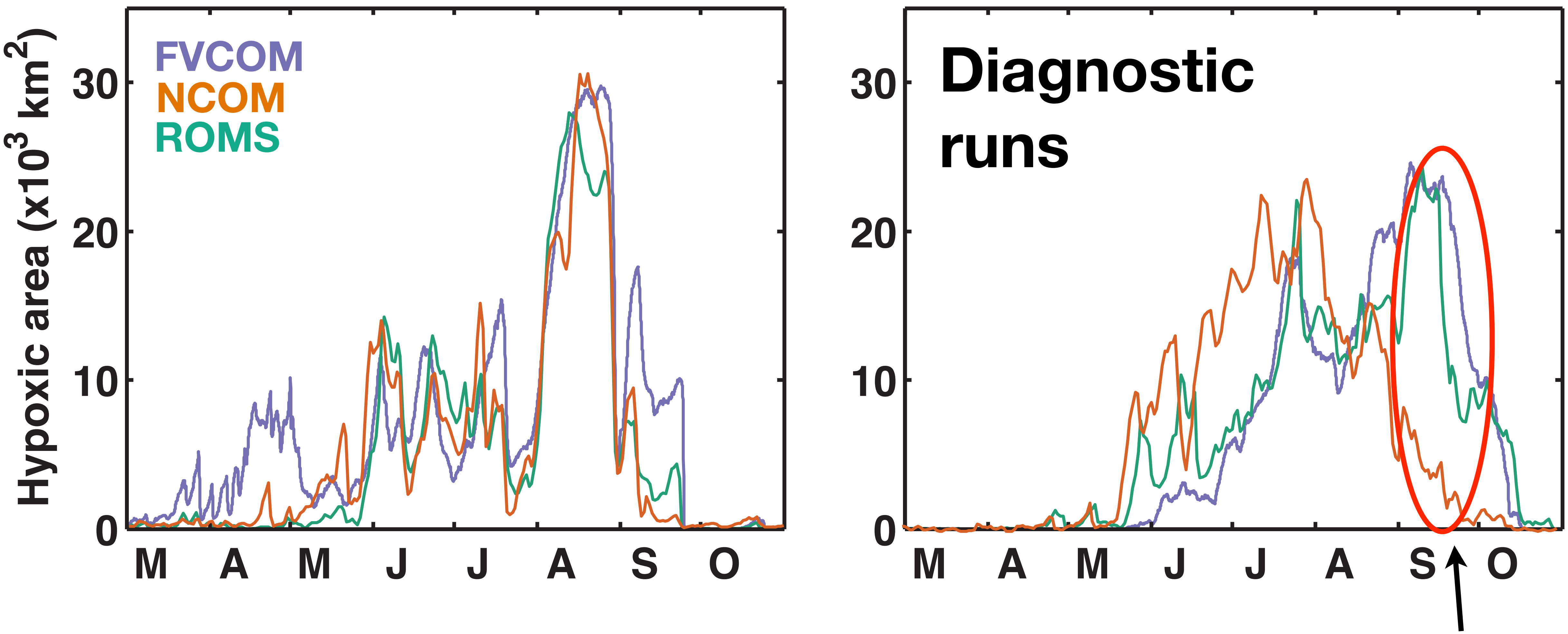
Temperature (oC)
35
30
25
20
15
FVCOM
NCOM
ROMS
2005
2006
J F M A M J J A S O N D



2005
2006
Temperature (oC)
FVCOM
NCOM
ROMS
J F M A M J J A S O N D
SOC (mmol O2 m-2 d-1)
Oxygen (mmol O2 m-3)

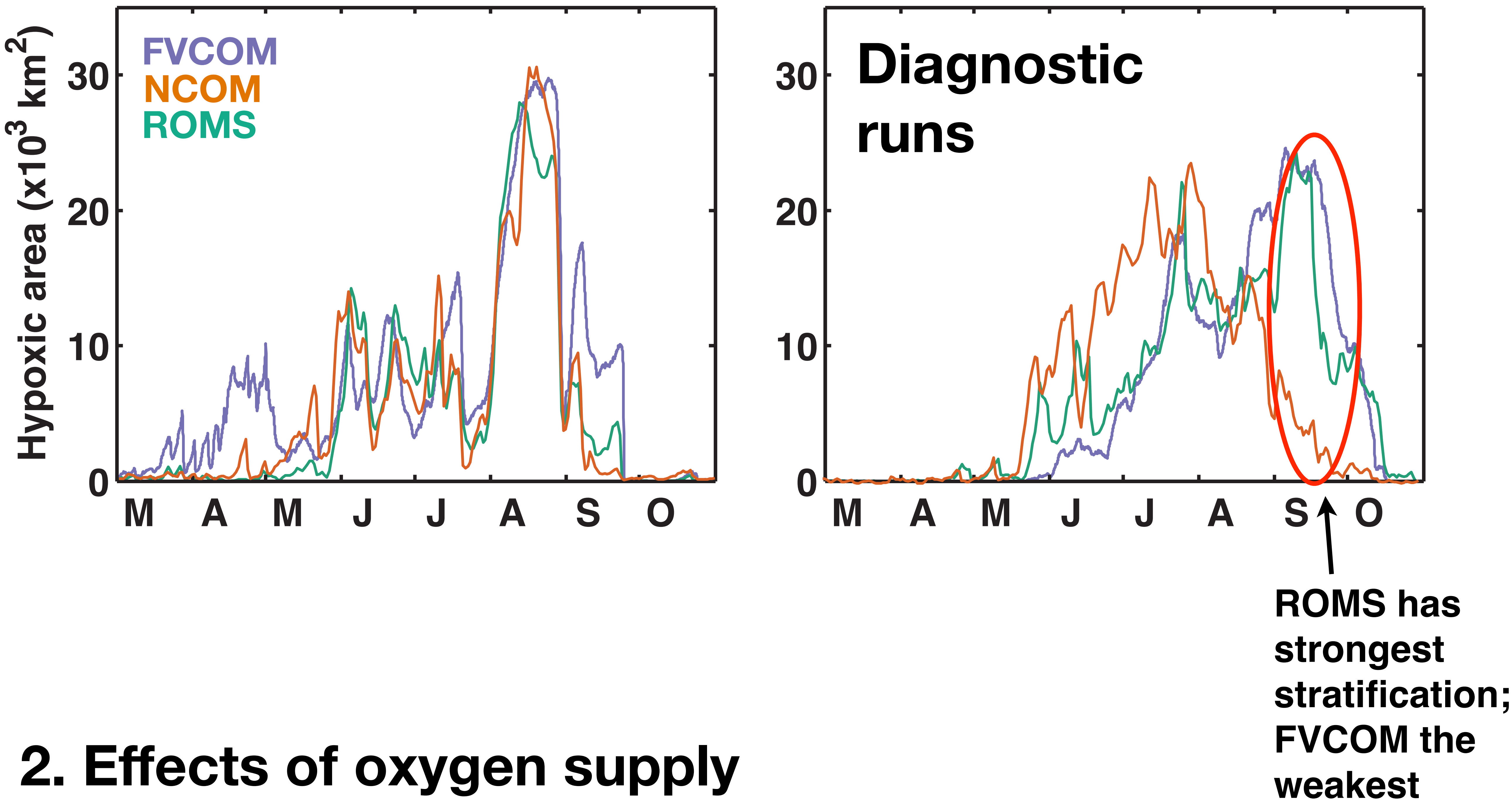


2. Effects of oxygen supply



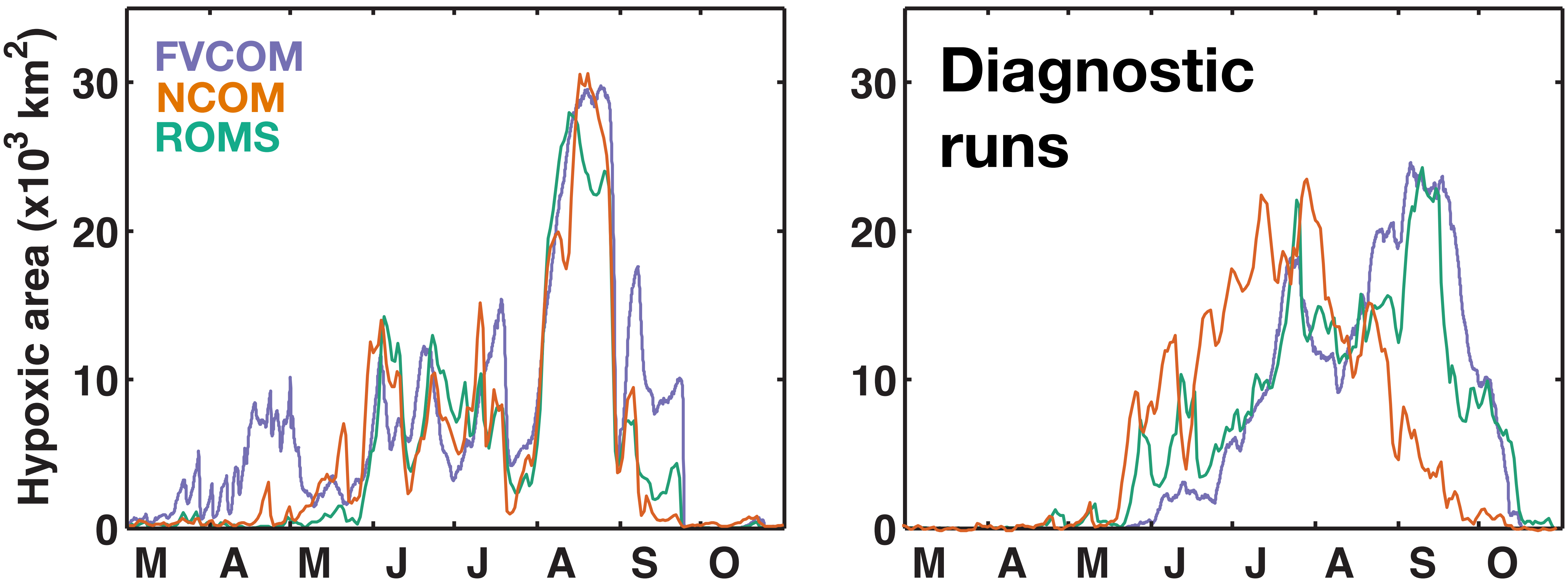
ROMS has strongest stratification; FVCOM the weakest

2. Effects of oxygen supply



2. Effects of oxygen supply

It's not overall stratification strength.



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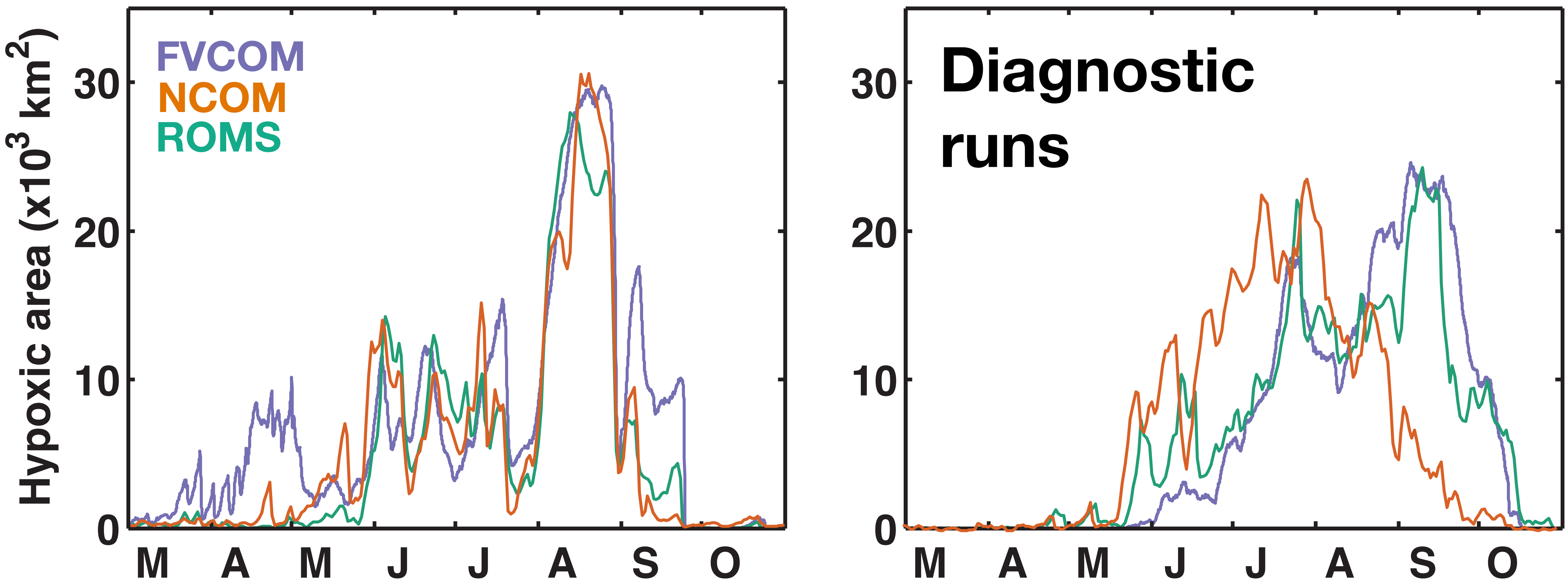

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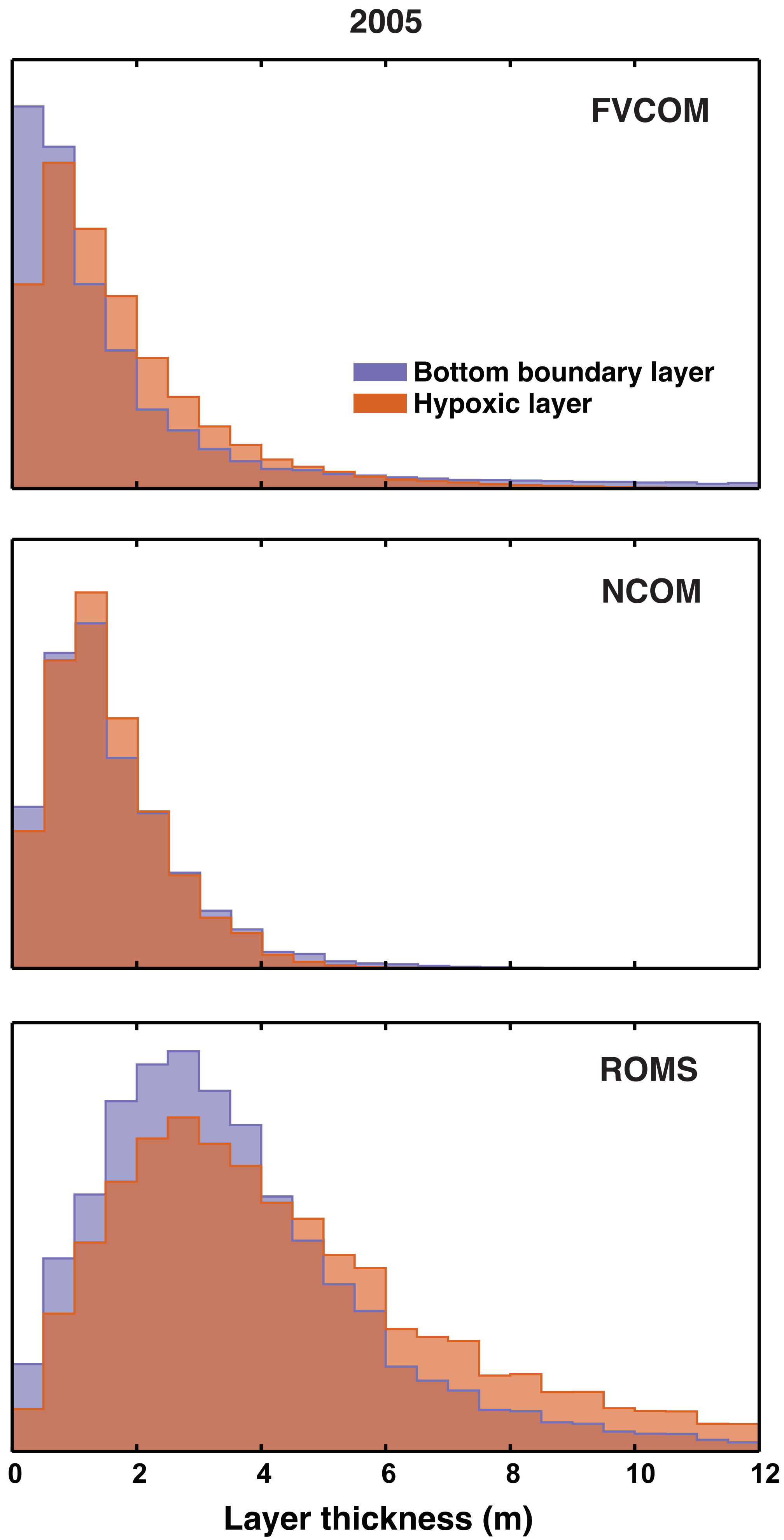
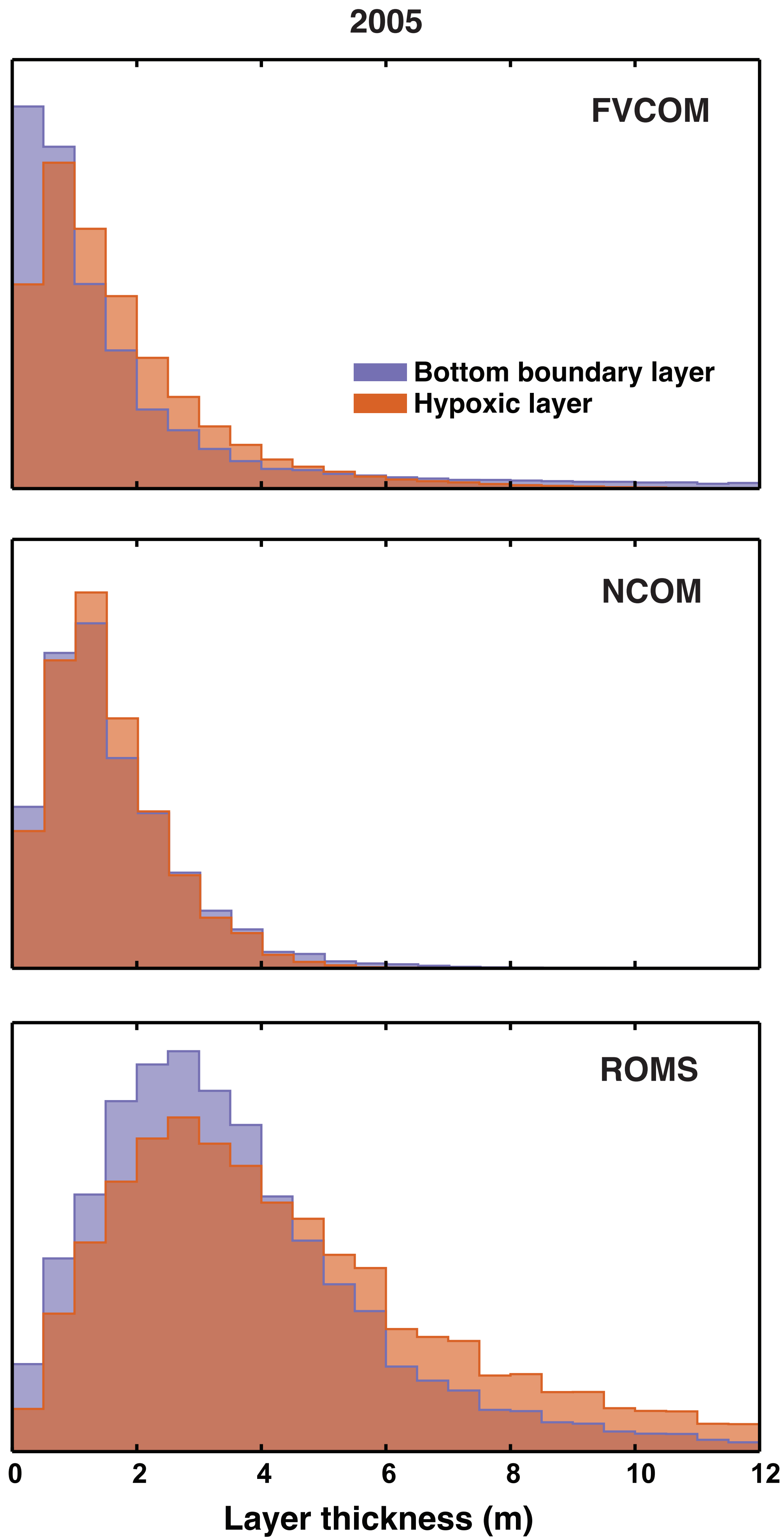
Differences in BBL (hypoxic layer = BBL).



Hypoxic layer and BBL coincide in all models.

BBL in ROMS is thicker than in the other two models.

Driving a thick BBL to hypoxia requires more oxygen consumption than a thin BBL.



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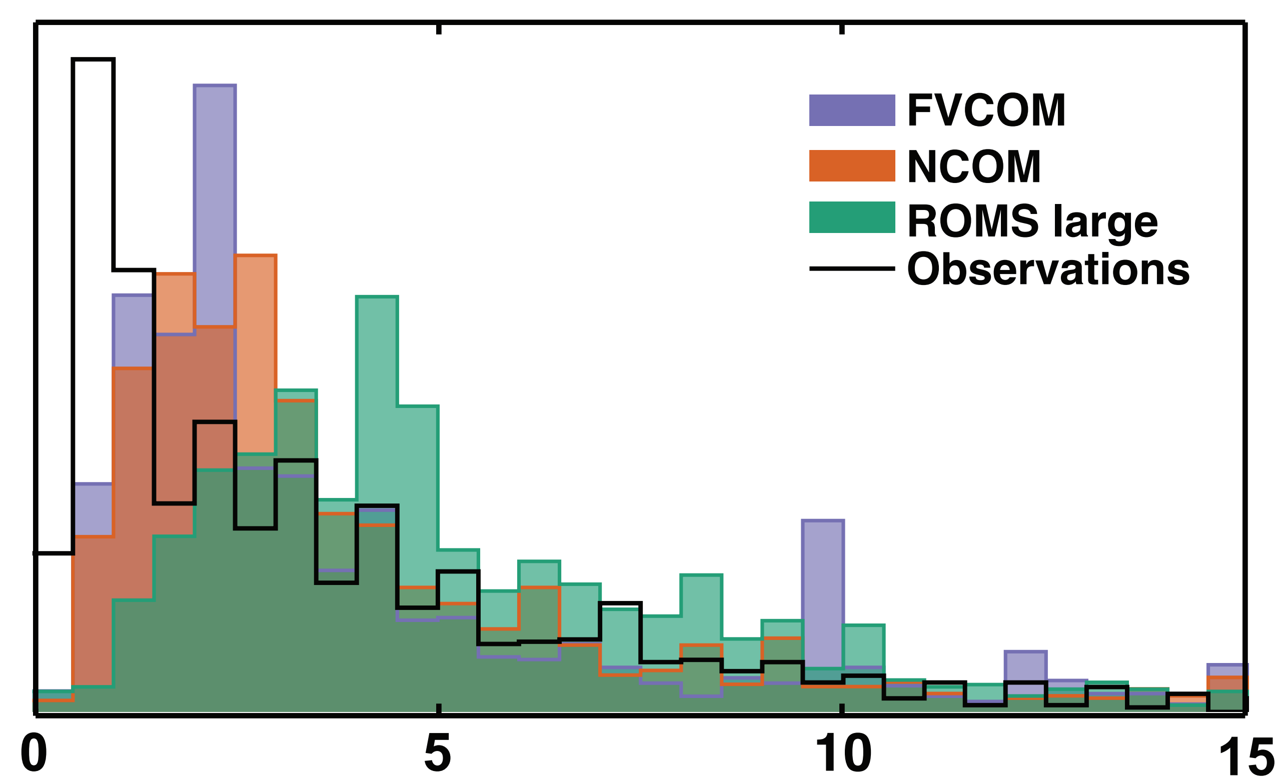

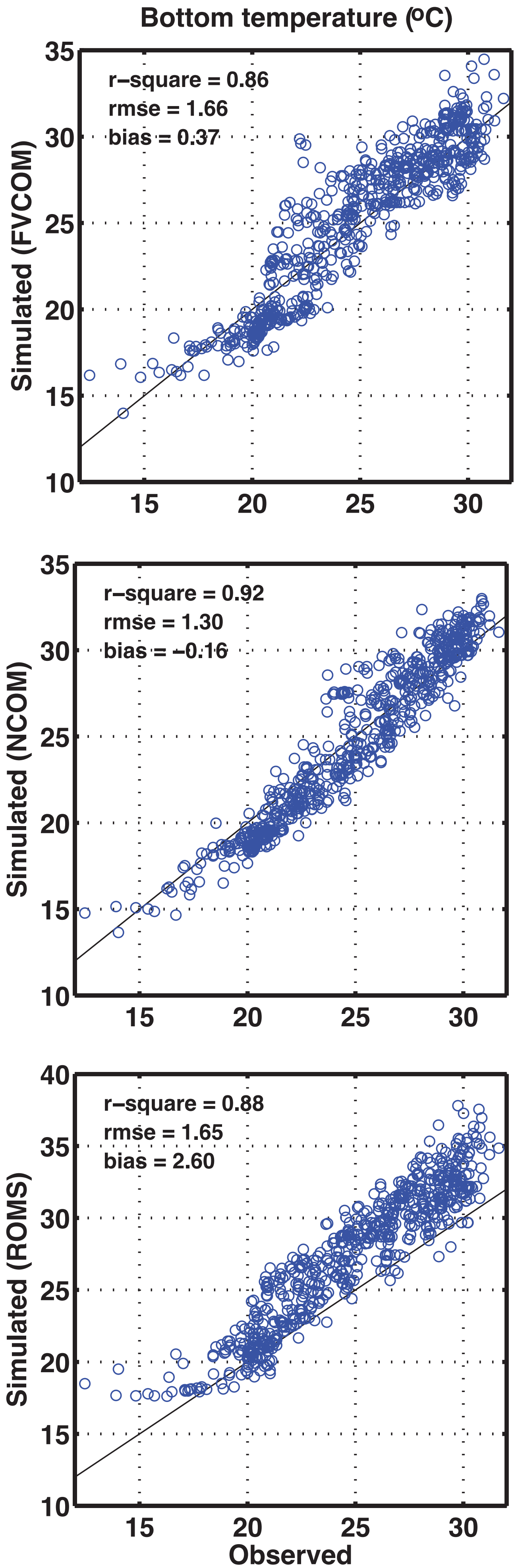
Bottom temperature (ºC)
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rmse = 1.66
bias = 0.37
Simulated (FVCOM)
r–square = 0.92
rmse = 1.30
bias = –0.16
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r–square = 0.88
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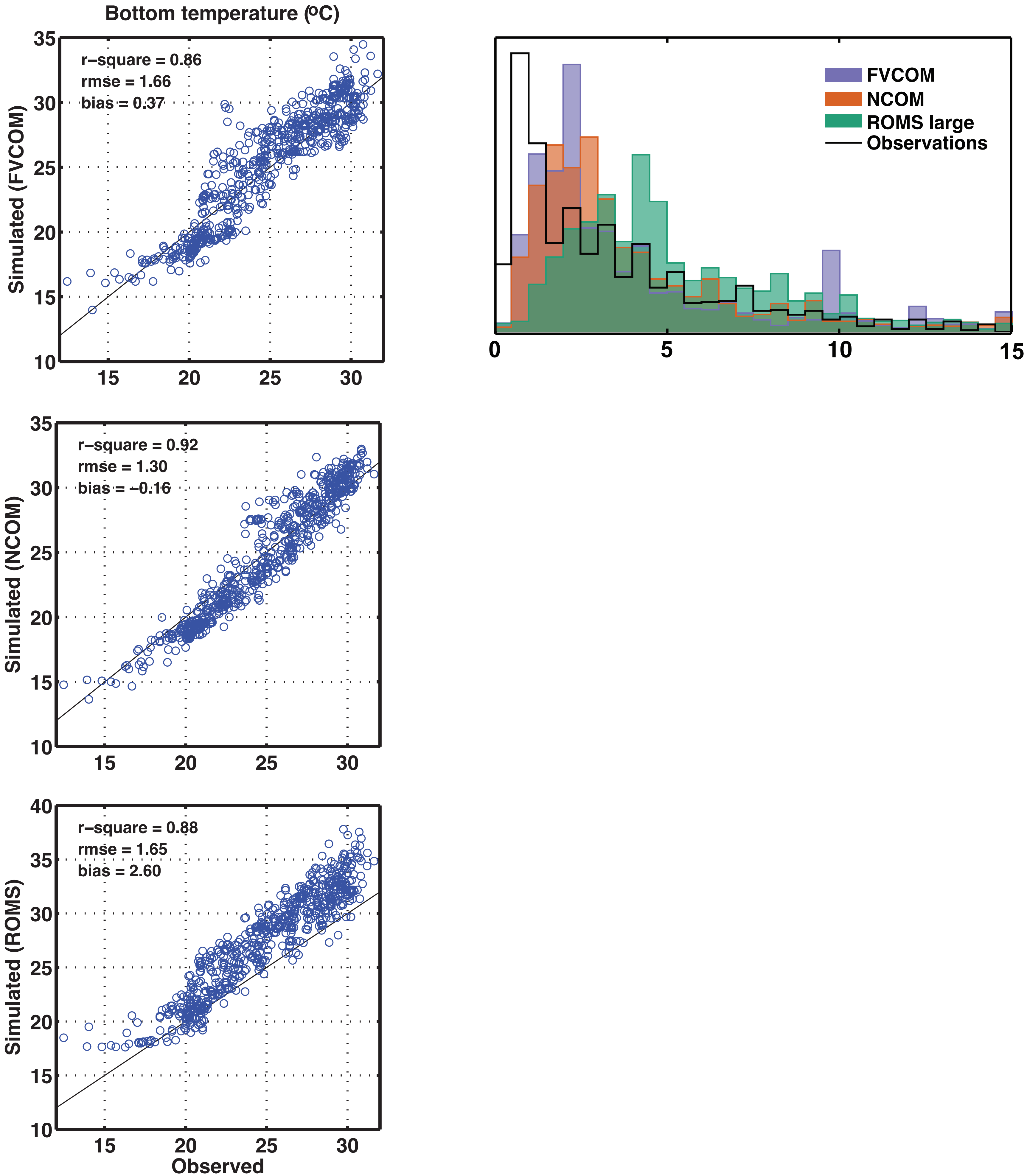
bias = 2.60
Simulated (ROMS)
Observed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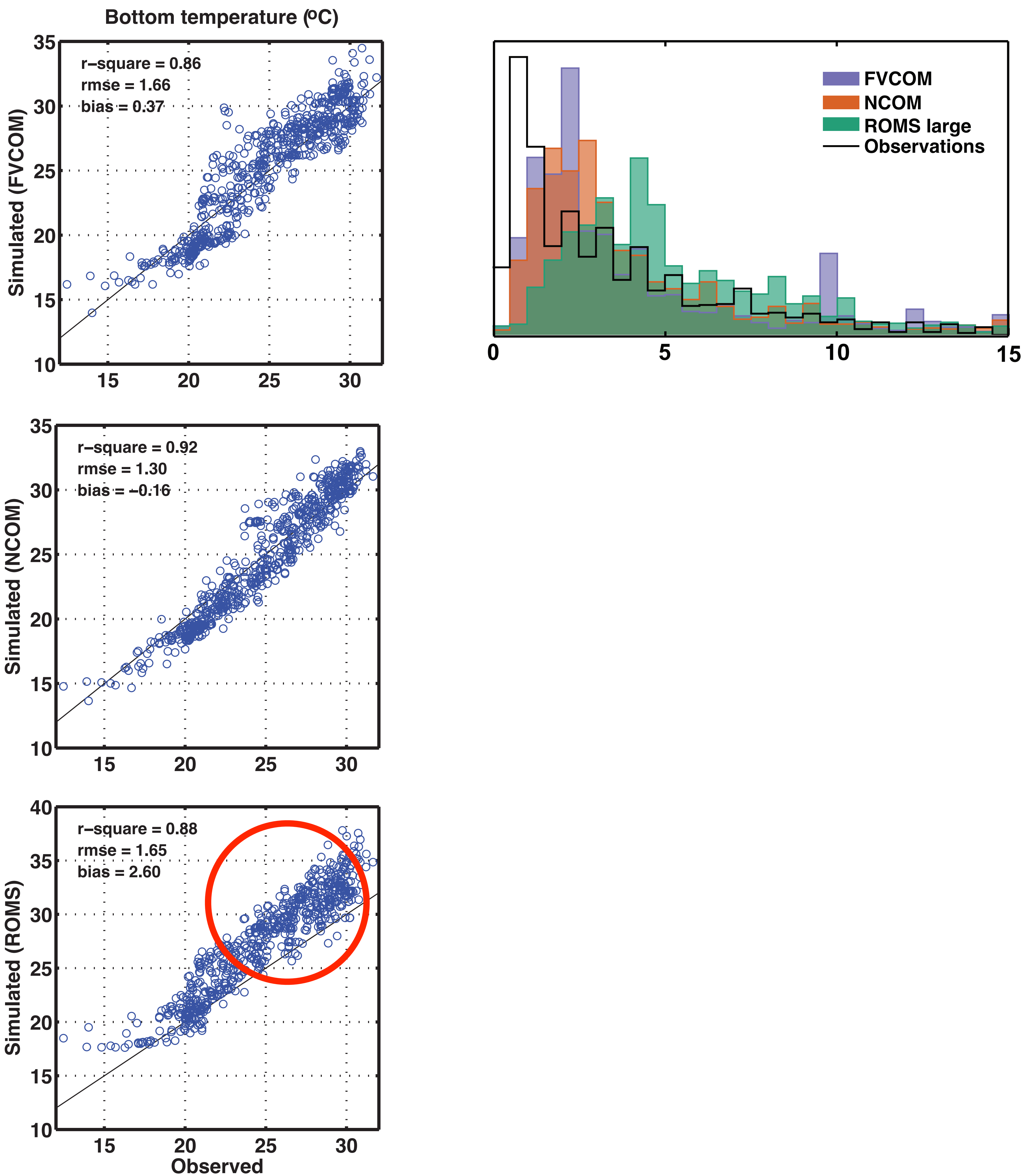
Observed
FVCOM
NCOM
ROMS large
Observations



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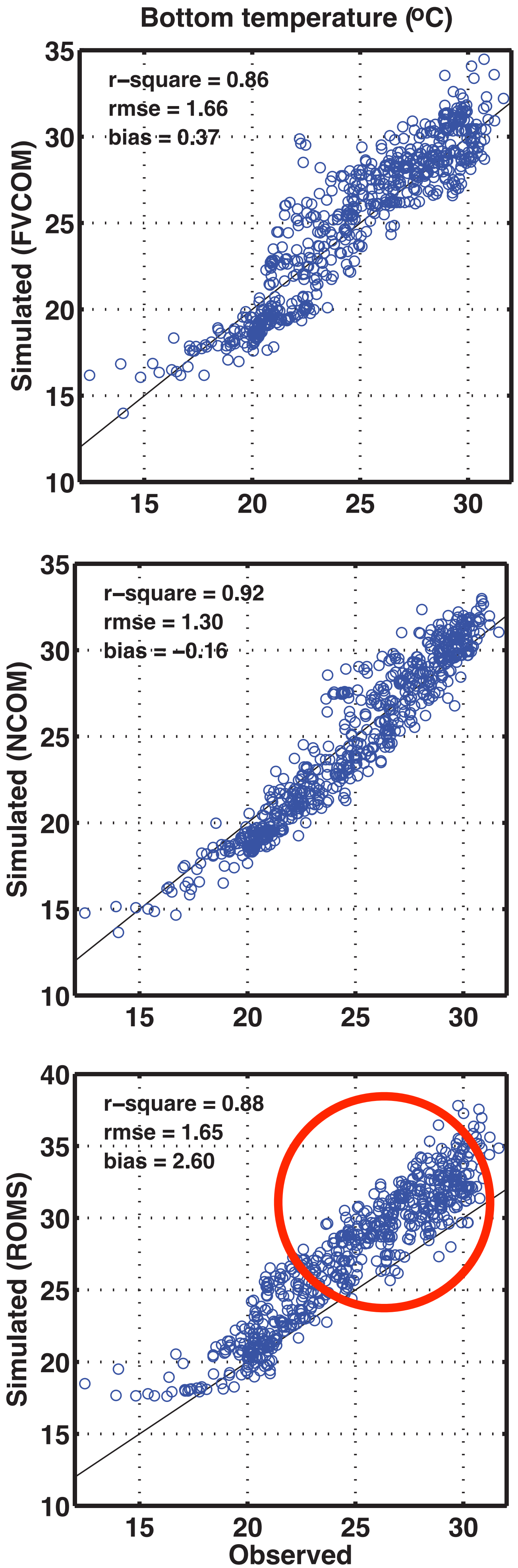

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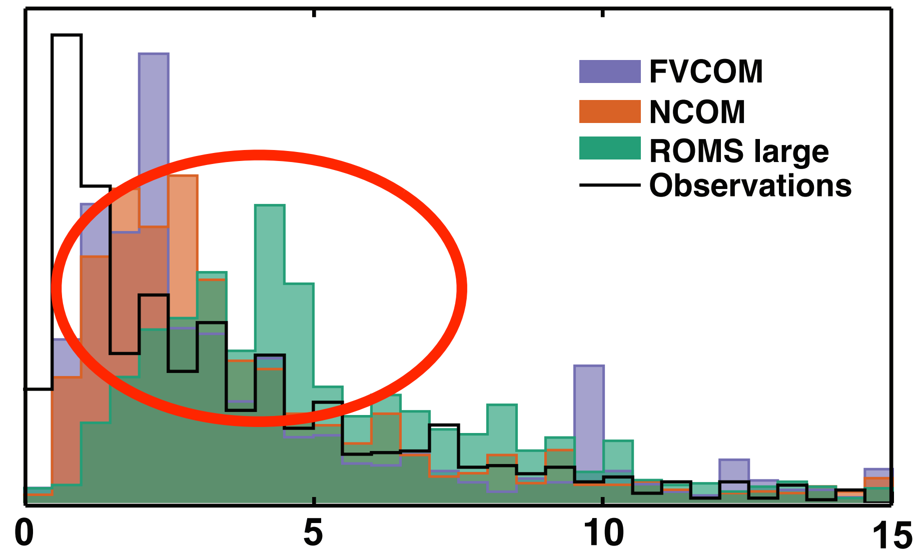
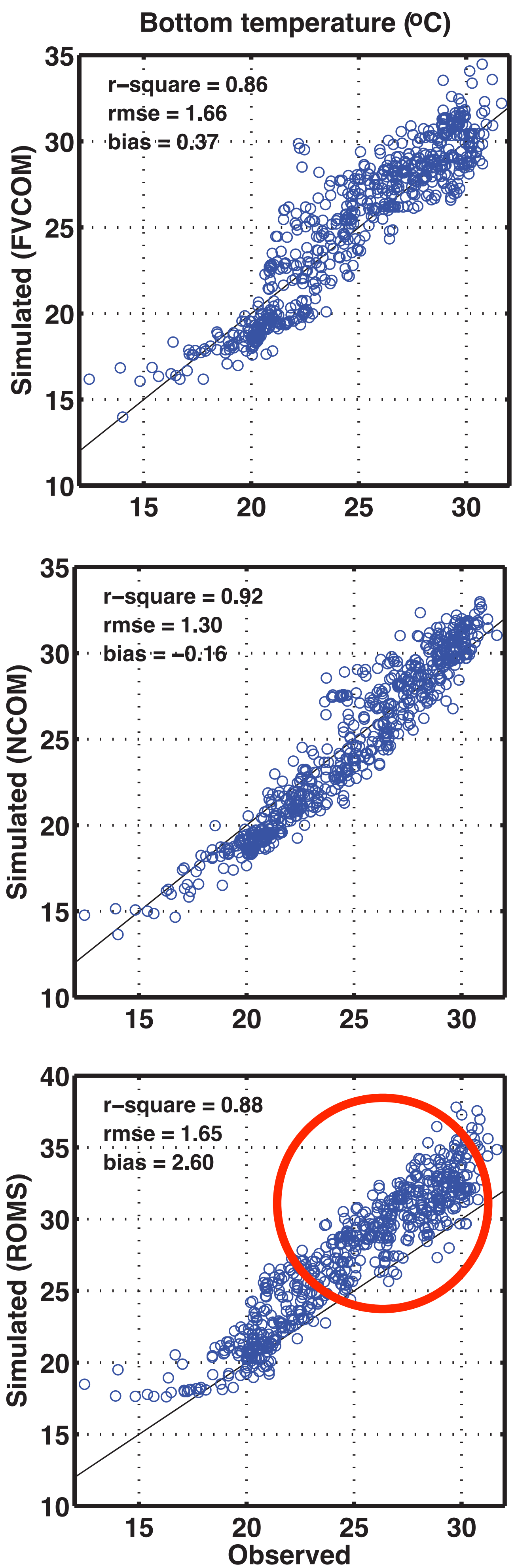
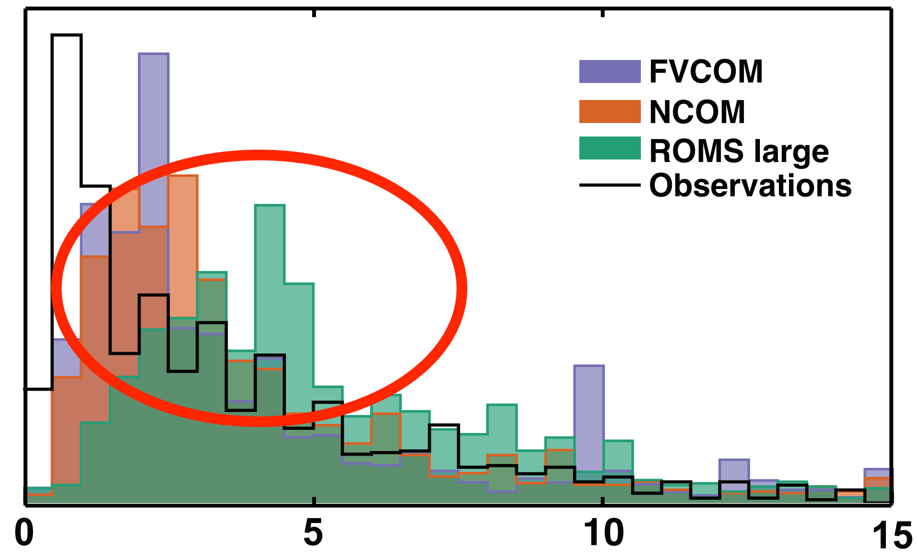


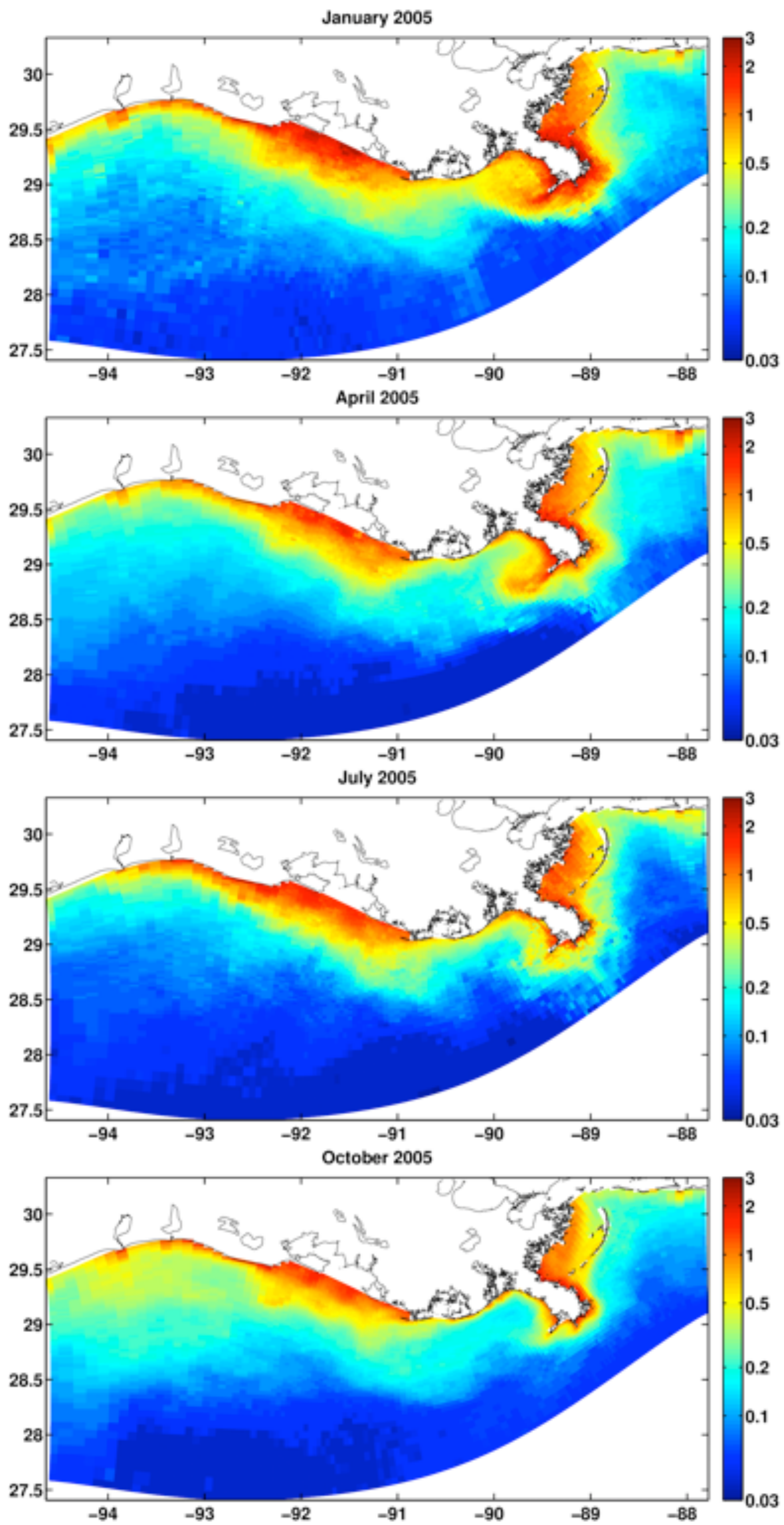
FVCOM
NCOM
ROMS large
Observations



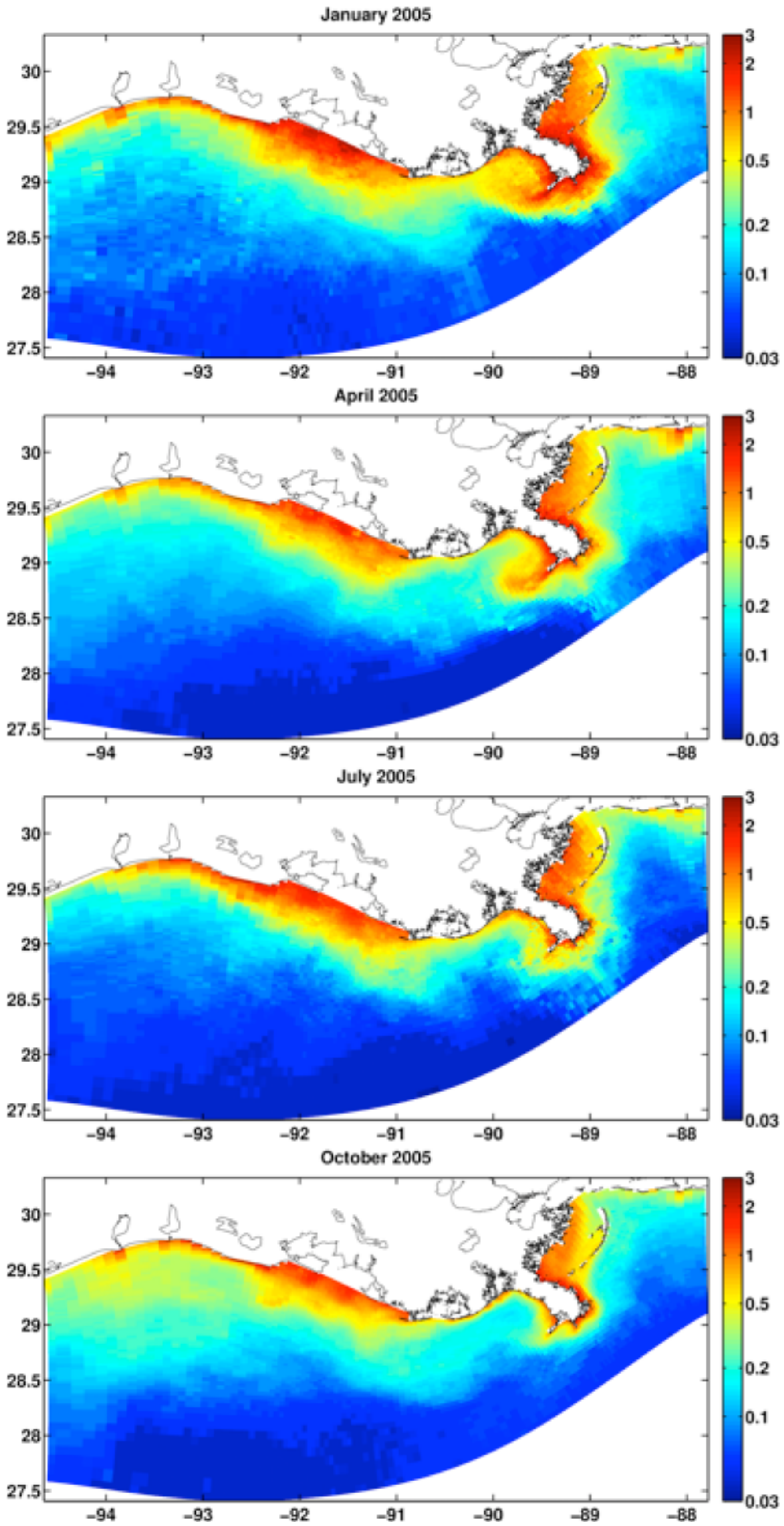


- BBL and hypoxia sensitive to bottom drag

- vertical attenuation of shortwave radiation k_D



MODIS-derived values of k_D (Schaeffer et al. 2011)



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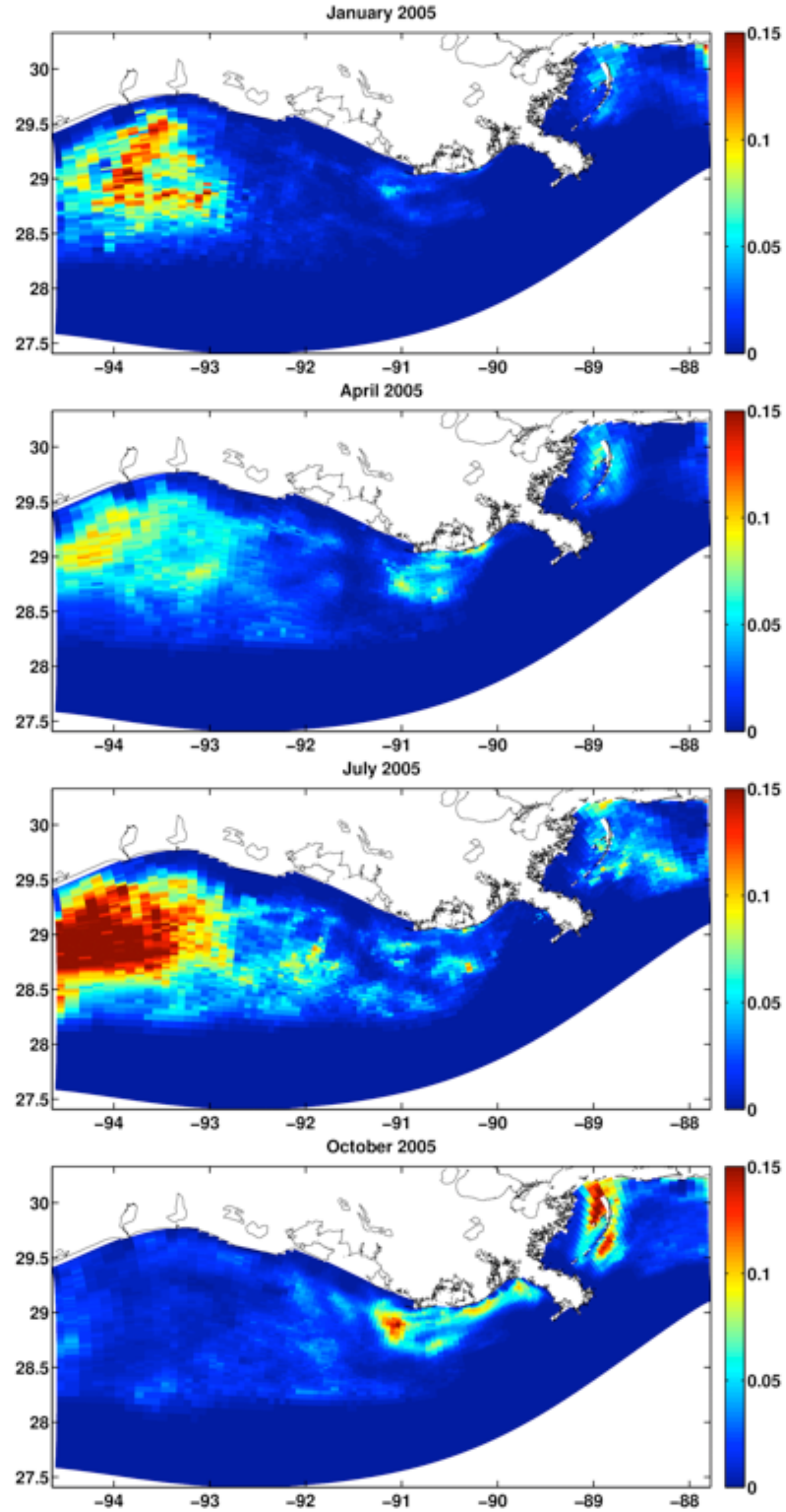
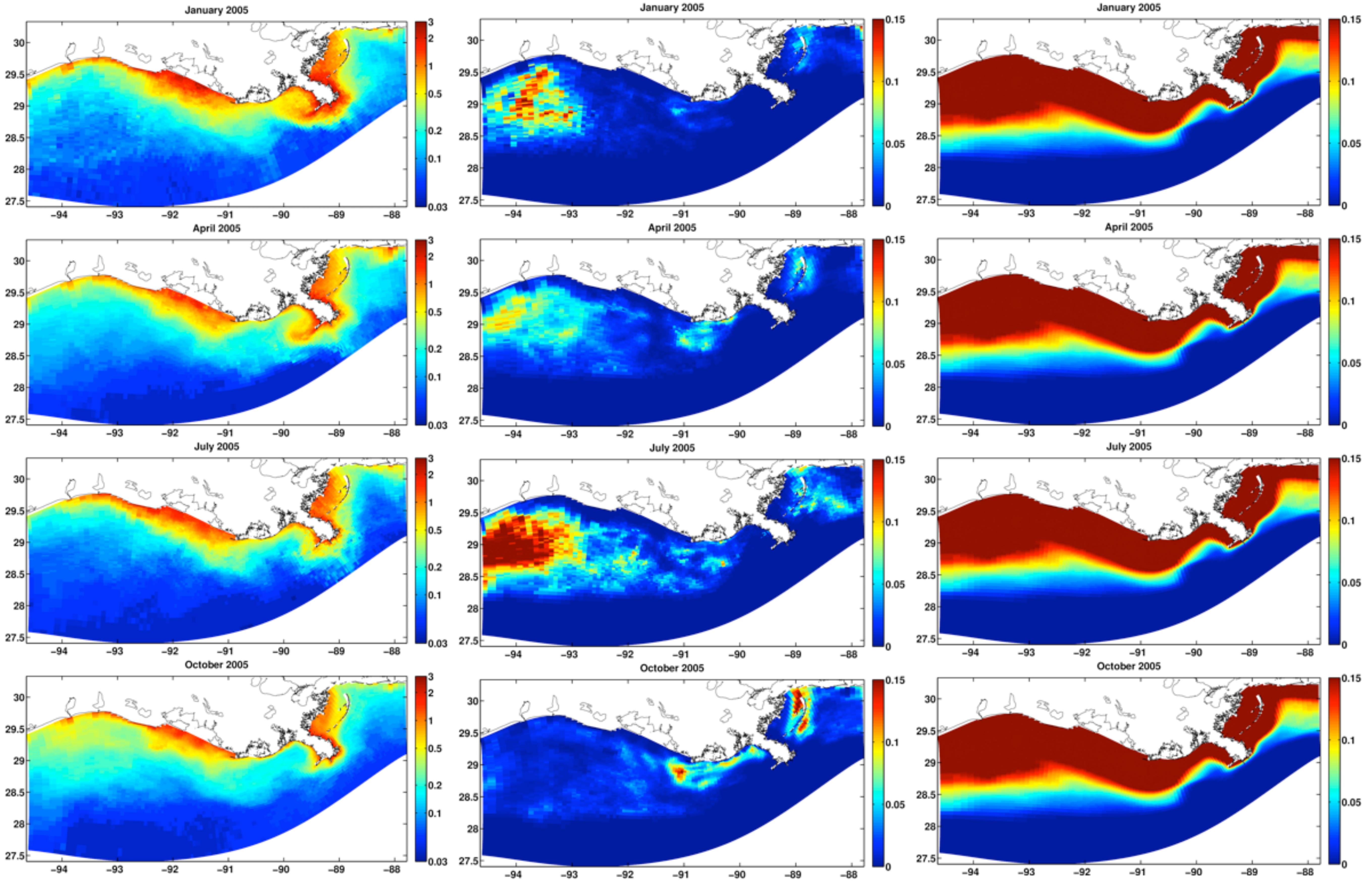


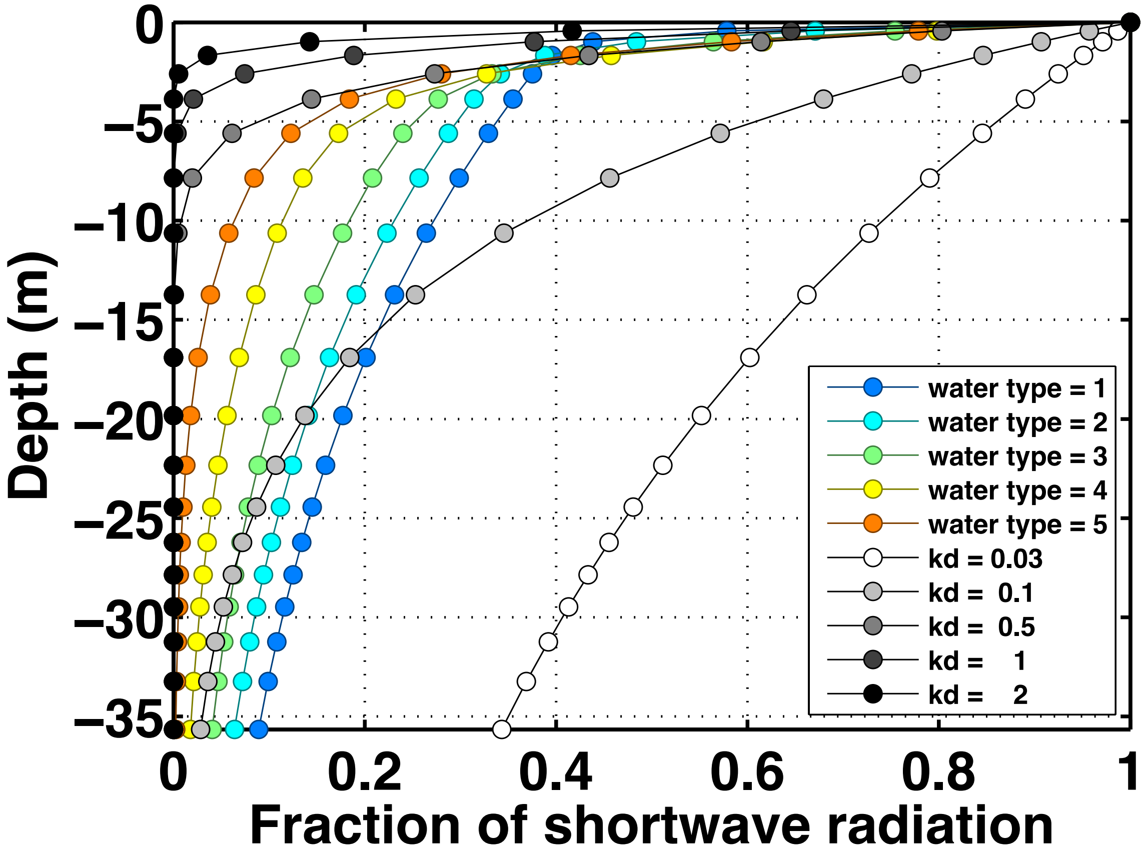
% of SW radiation reaching bottom w/ MODIS k_D



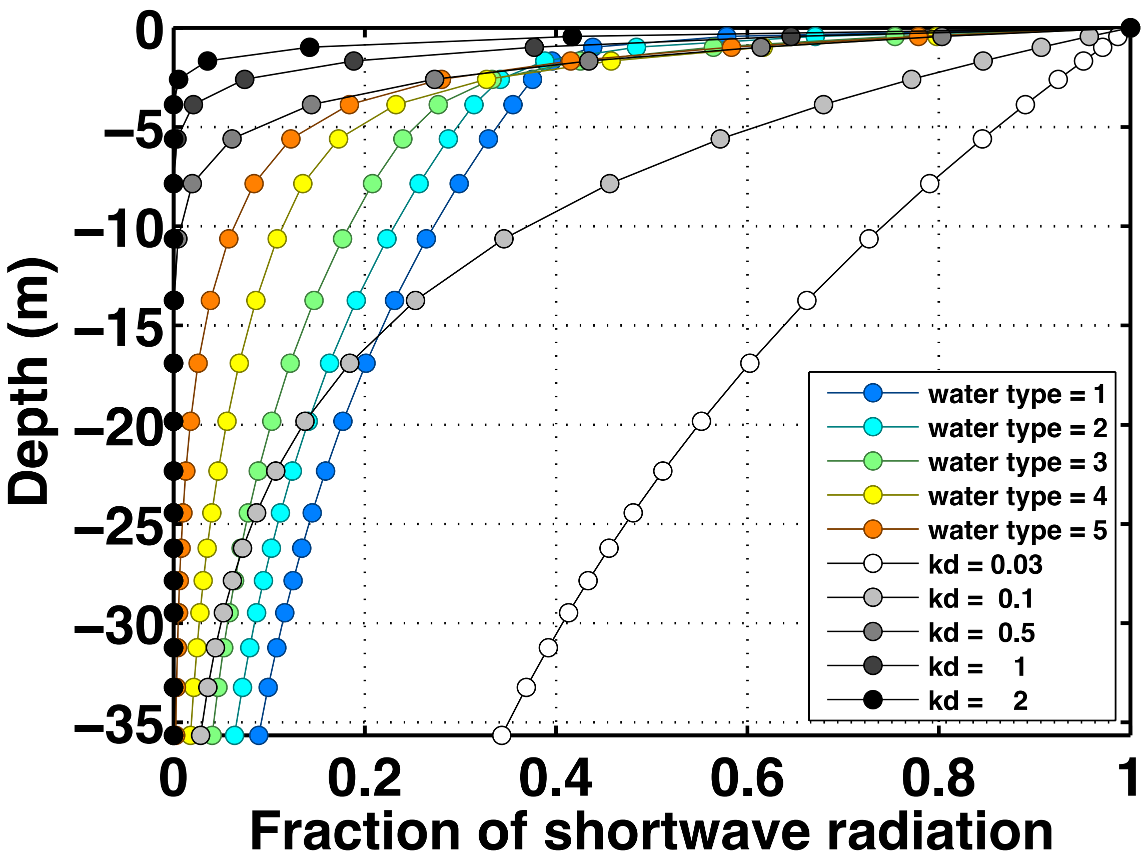
MODIS-derived values of k_D (Schaeffer et al. 2011)

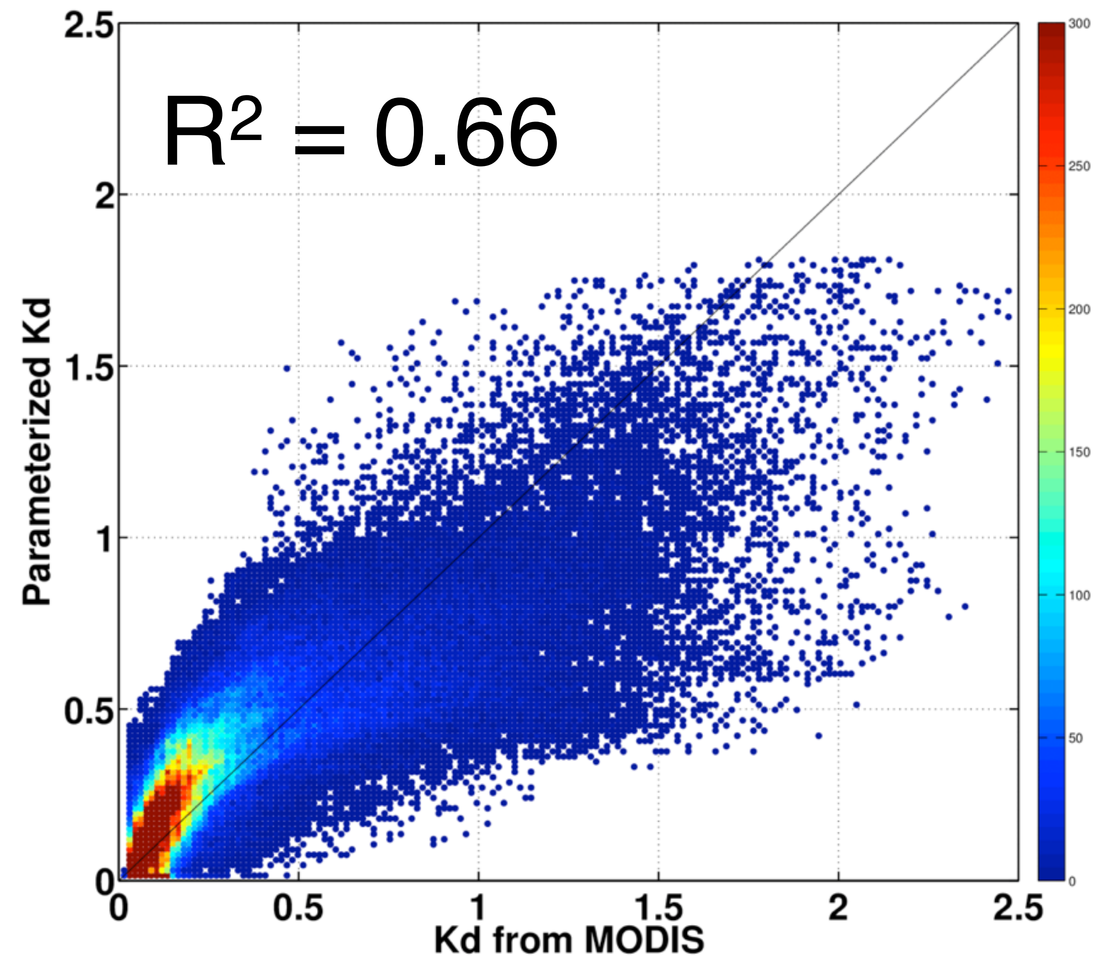
% of SW radiation reaching bottom w/ MODIS k_D

% of SW radiation reaching bottom w/ wtype 1 in ROMS



Depth (m)
0
−5
−10
−15
−20
−25
−30
−35
0
0.2
0.4
0.6
0.8
1
Fraction of shortwave radiation
water type = 1
water type = 2
water type = 3
water type = 4
water type = 5
kd = 0.03
kd = 0.1
kd = 0.5
kd = 1
kd = 2

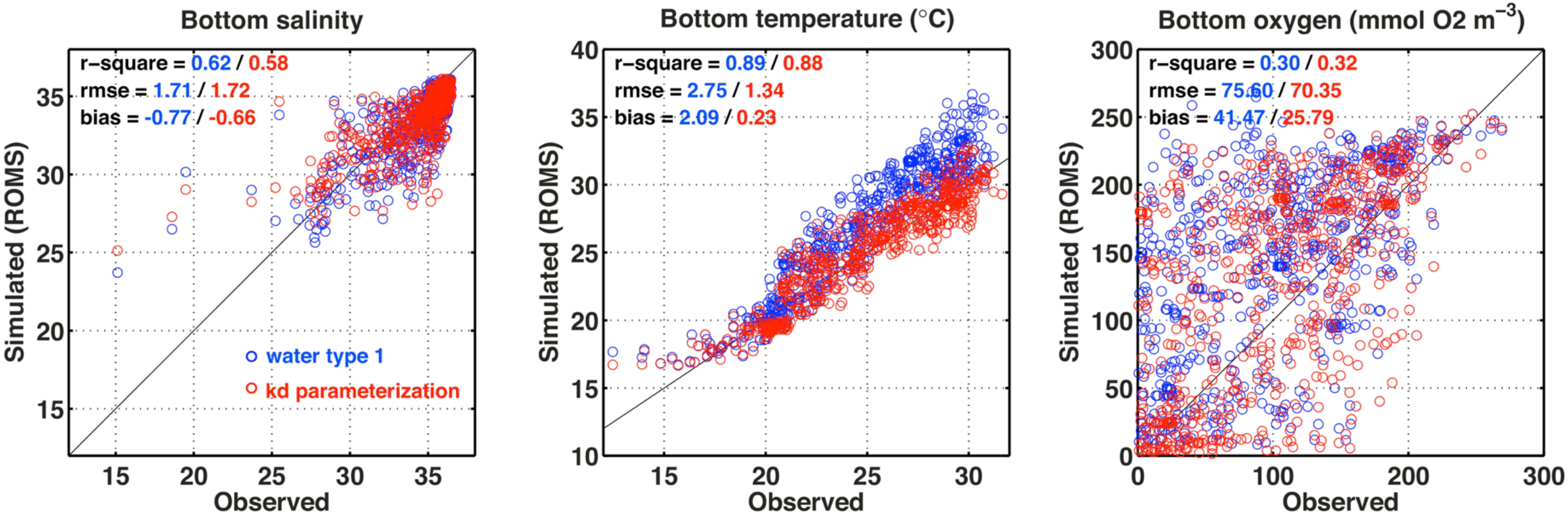


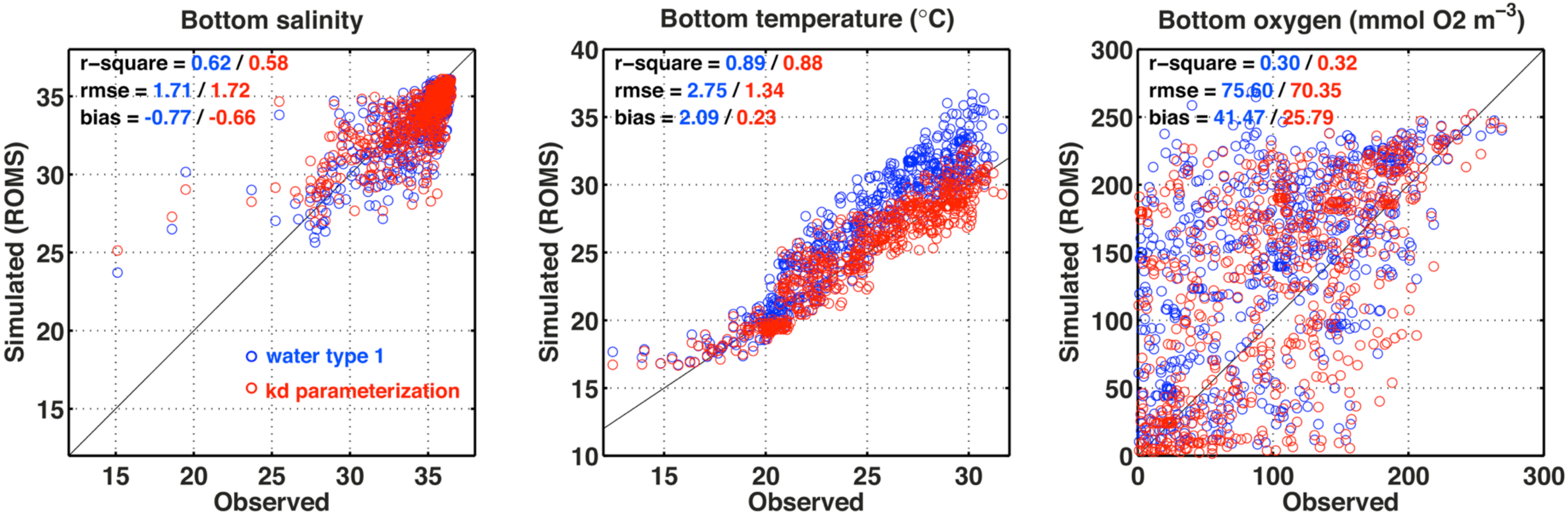


kd = a1 + a2*H + a3*S + a4*T + a5*LON + a6*LAT

a1 = -0.421962219 (m^{-1})
a2 = -0.0000338347 (m)
a3 = -0.0478813776
a4 = -0.0145770602 (°C)
a5 = 0.005204748 (°W, negative)
a6 = 0.1058210282 (°N)

A minimum Kd is set to 0.027 m^{-1} as determined by Smith and Baker (1978) for clear ocean waters.


Bottom salinity
r−square = 0.62 / 0.58
rmse = 1.71 / 1.72
bias = -0.77 / -0.66
water type 1
kd parameterization
Simulated (ROMS)
Observed
Bottom temperature (°C)
r−square = 0.89 / 0.88
rmse = 2.75 / 1.34
bias = 2.09 / 0.23
Bottom oxygen (mmol O2 m−3)
r−square = 0.30 / 0.32
rmse = 75.60 / 70.35
bias = 41.47 / 25.79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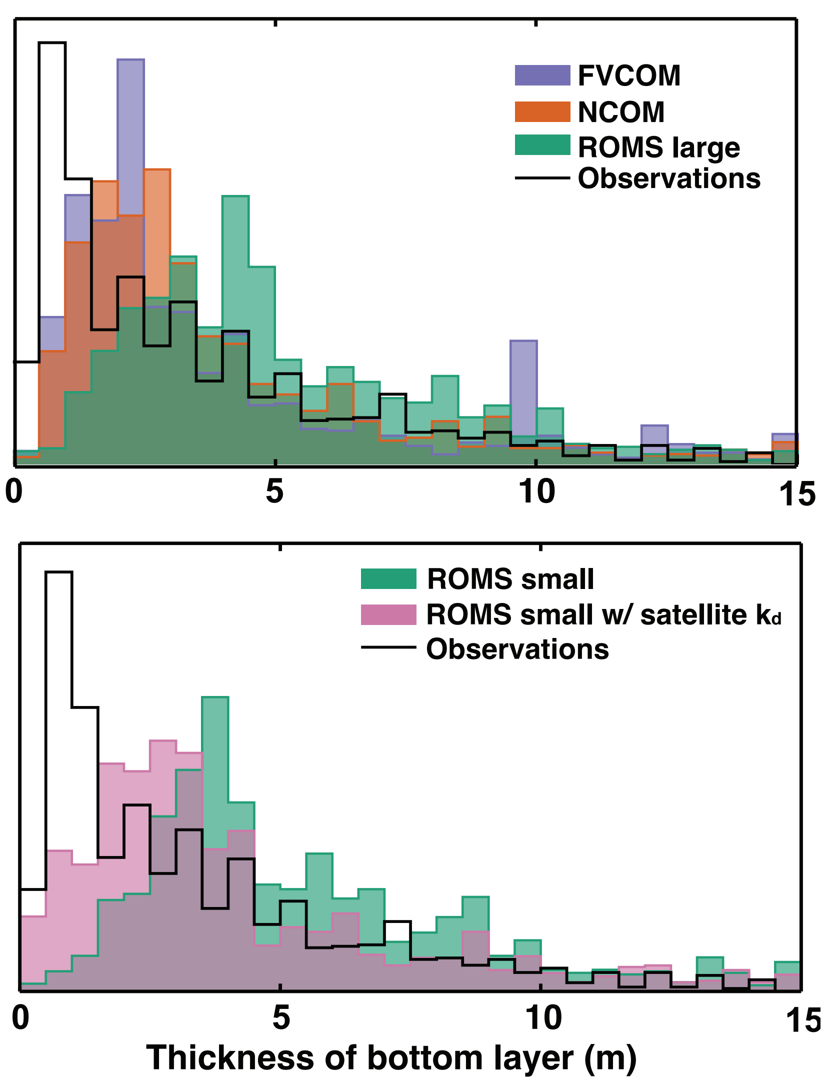
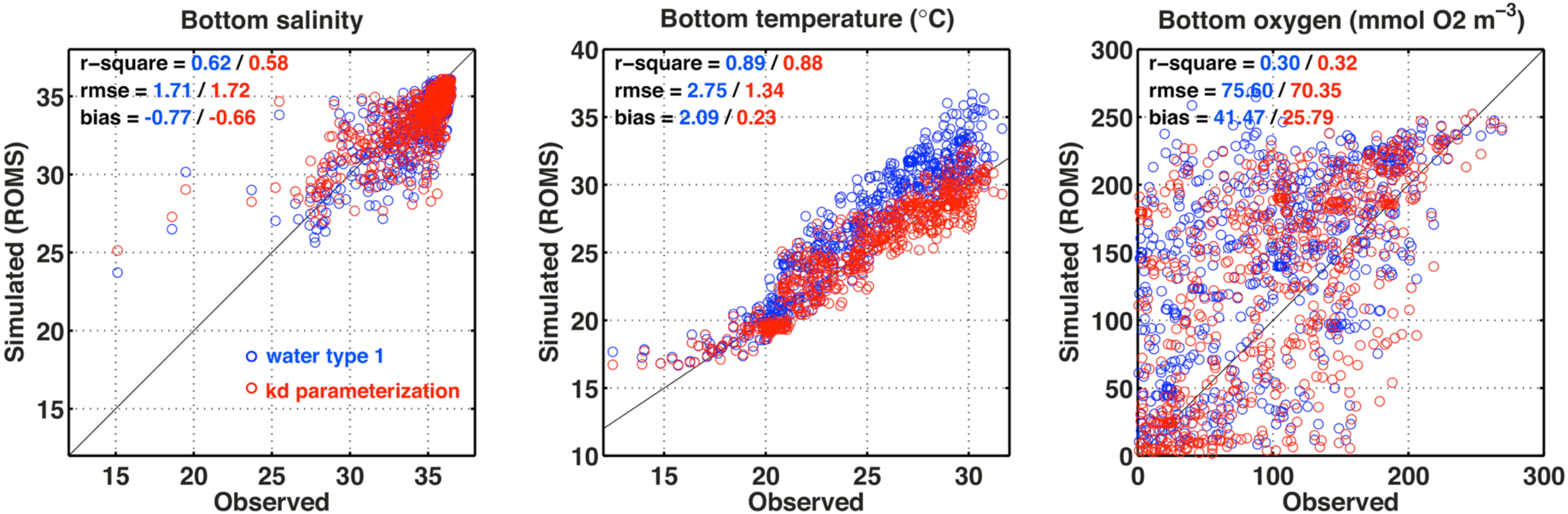
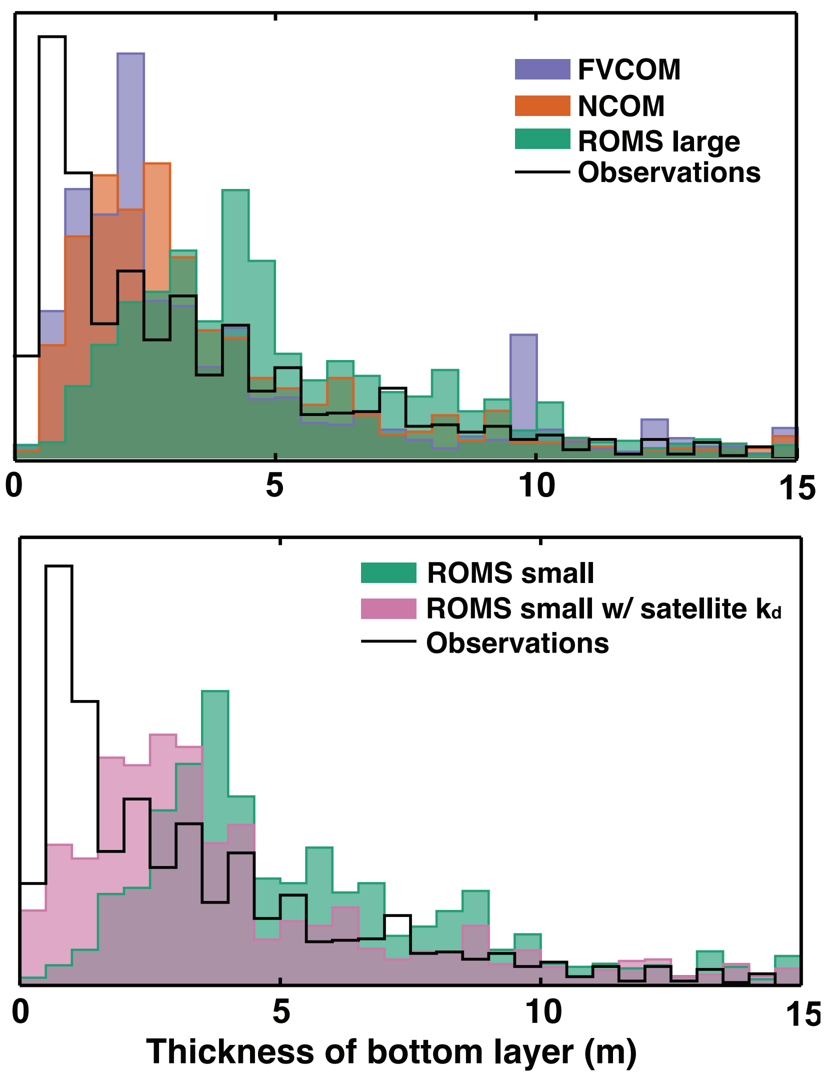
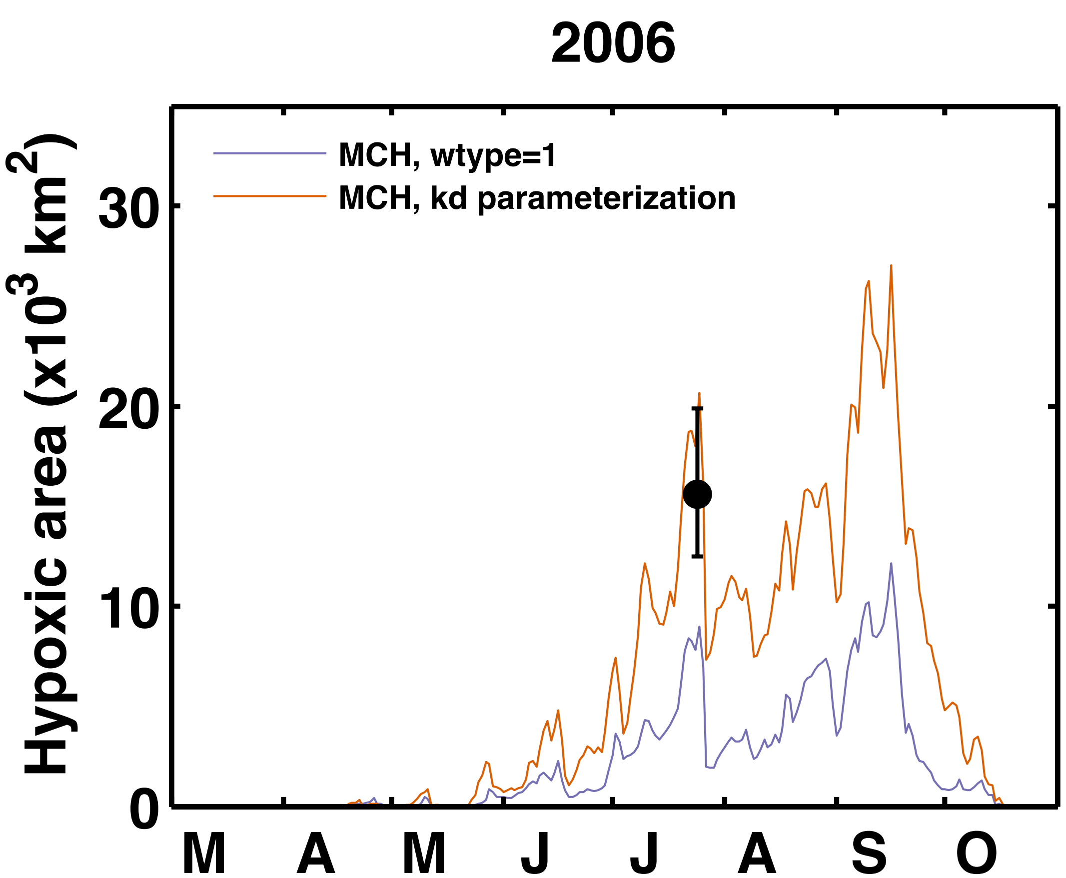
Bottom oxygen (mmol O2 m−3)
r−square = 0.30 / 0.32
rmse = 75.60 / 70.35
bias = 41.47 / 25.79
Simulated (ROMS)
Observed


FVCOM
NCOM
ROMS large
Observations
ROMS small
ROMS small w/ satellite kd
Observations
Thickness of bottom layer (m)







ROMS w/ full bgc

Find the odd one out!

oxygen consumption in the water column	vertical stratification	oxygen consumption by the sediment	bottom drag parameter	vertical attenuation of shortwave radiation

Find the odd one out!

~~oxygen consumption in the water column~~	vertical stratification	oxygen consumption by the sediment	bottom drag parameter	vertical attenuation of shortwave radiation

AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Oceans

RESEARCH ARTICLE

10.1002/2015JC011577

Key Points:

- Model intercomparison of three hypoxia models of the northern Gulf of Mexico is presented
- Bottom water temperature and bottom boundary layer thickness are important for hypoxia simulation
- Overall stratification strength does not explain model-to-model differences in hypoxic conditions

Supporting Information:

- Supporting Information S1

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K. Fennel,
Katja.Fennel@dal.ca

Citation:
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Effects of model physics on hypoxia simulations for the northern Gulf of Mexico: A model intercomparison

Katja Fennel[1], Arnaud Laurent[1], Robert Hetland[2], Dubravko Justić[3], Dong S. Ko[4], John Lehrter[5], Michael Murrell[5], Lixia Wang[3], Liuqian Yu[1], and Wenxia Zhang[1,2]

[1]Department of Oceanography, Dalhousie University, Halifax, Nova Scotia, Canada, [2]Department of Oceanography, Texas A&M University, College Station, Texas, USA, [3]Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, Louisiana, USA, [4]Oceanography Division, Naval Research Laboratory, Stennis Space Centre, Hancock County, Mississippi, USA, [5]Gulf Ecology Division, U.S. Environmental Protection Agency, Gulf Breeze, Florida, USA

Abstract A large hypoxic zone forms every summer on the Texas-Louisiana Shelf in the northern Gulf of Mexico due to nutrient and freshwater inputs from the Mississippi/Atchafalaya River System. Efforts are underway to reduce the extent of hypoxic conditions through reductions in river nutrient inputs, but the response of hypoxia to such nutrient load reductions is difficult to predict because biological responses are confounded by variability in physical processes. The objective of this study is to identify the major physical model aspects that matter for hypoxia simulation and prediction. In order to do so, we compare three different circulation models (ROMS, FVCOM, and NCOM) implemented for the northern Gulf of Mexico, all coupled to the same simple oxygen model, with observations and against each other. By using a highly simplified oxygen model, we eliminate the potentially confounding effects of a full biogeochemical model and can isolate the effects of physical features. In a systematic assessment, we found that (1) model-to-model differences in bottom water temperatures result in differences in simulated hypoxia because temperature influences the uptake rate of oxygen by the sediments (an important oxygen sink in this system), (2) vertical stratification does not explain model-to-model differences in hypoxic conditions in a straightforward way, and (3) the thickness of the bottom boundary layer, which sets the thickness of the hypoxic layer in all three models, is key to determining the likelihood of a model to generate hypoxic conditions. These results imply that hypoxic area, the commonly used metric in the northern Gulf which ignores hypoxic layer thickness, is insufficient for assessing a model's ability to accurately simulate hypoxia, and that hypoxic volume needs to be considered as well.

Recommendation: For short-term hypoxia forecasts, a well-calibrated simple oxygen model coupled to excellent physical model is the strategy.

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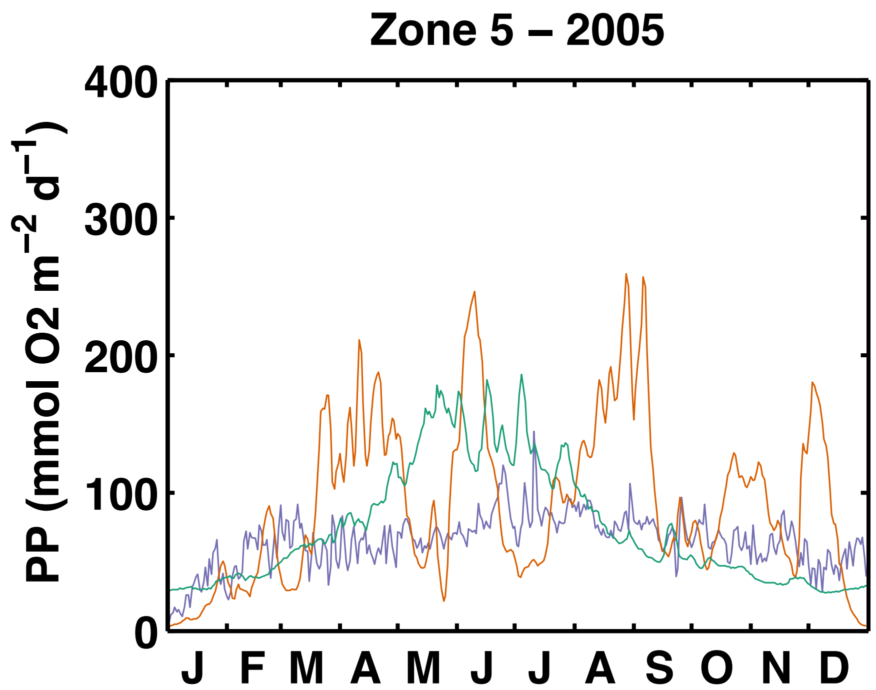
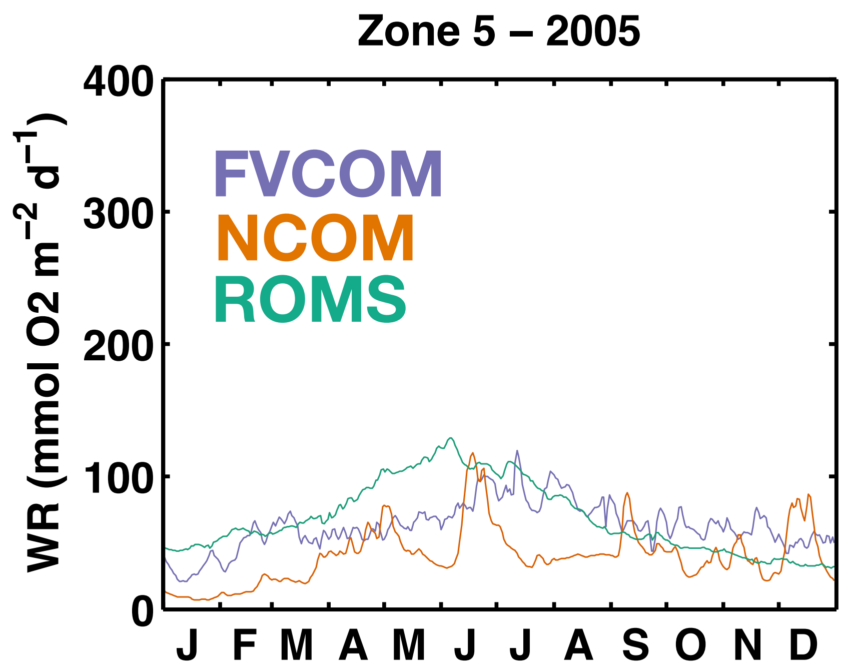
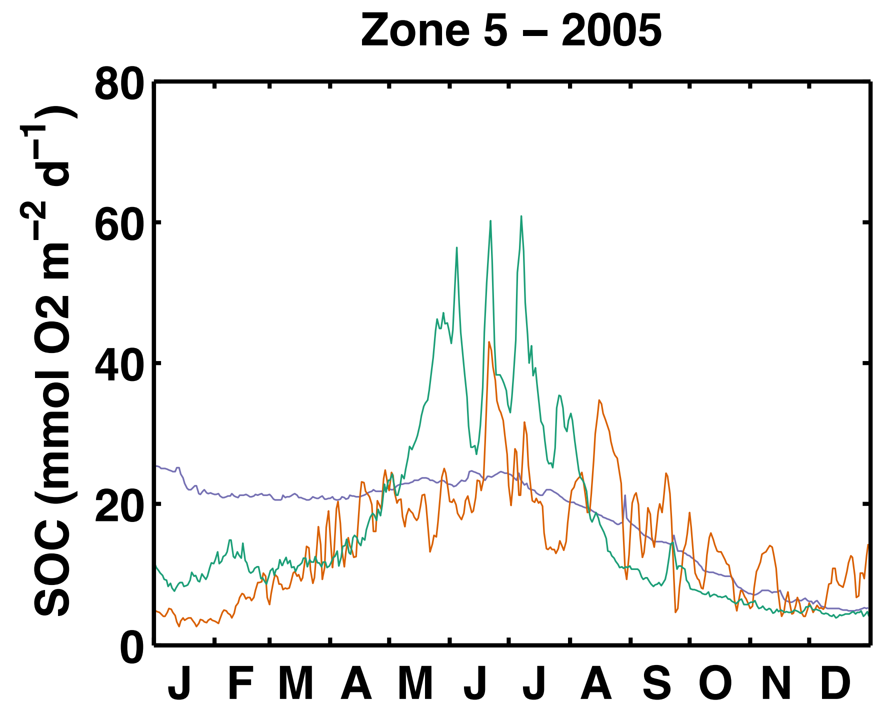
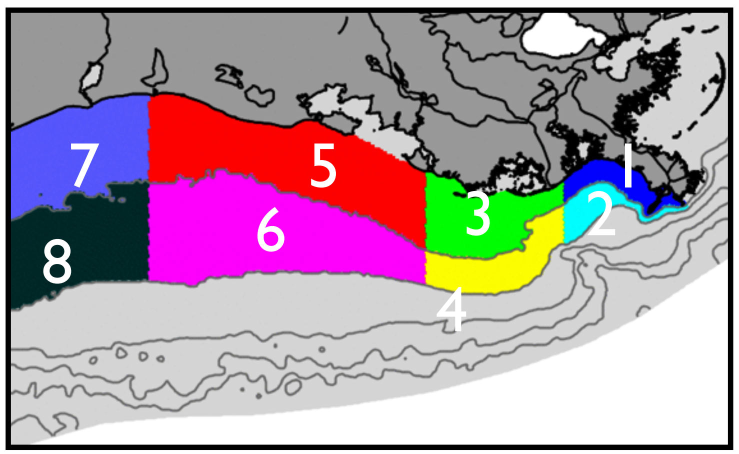
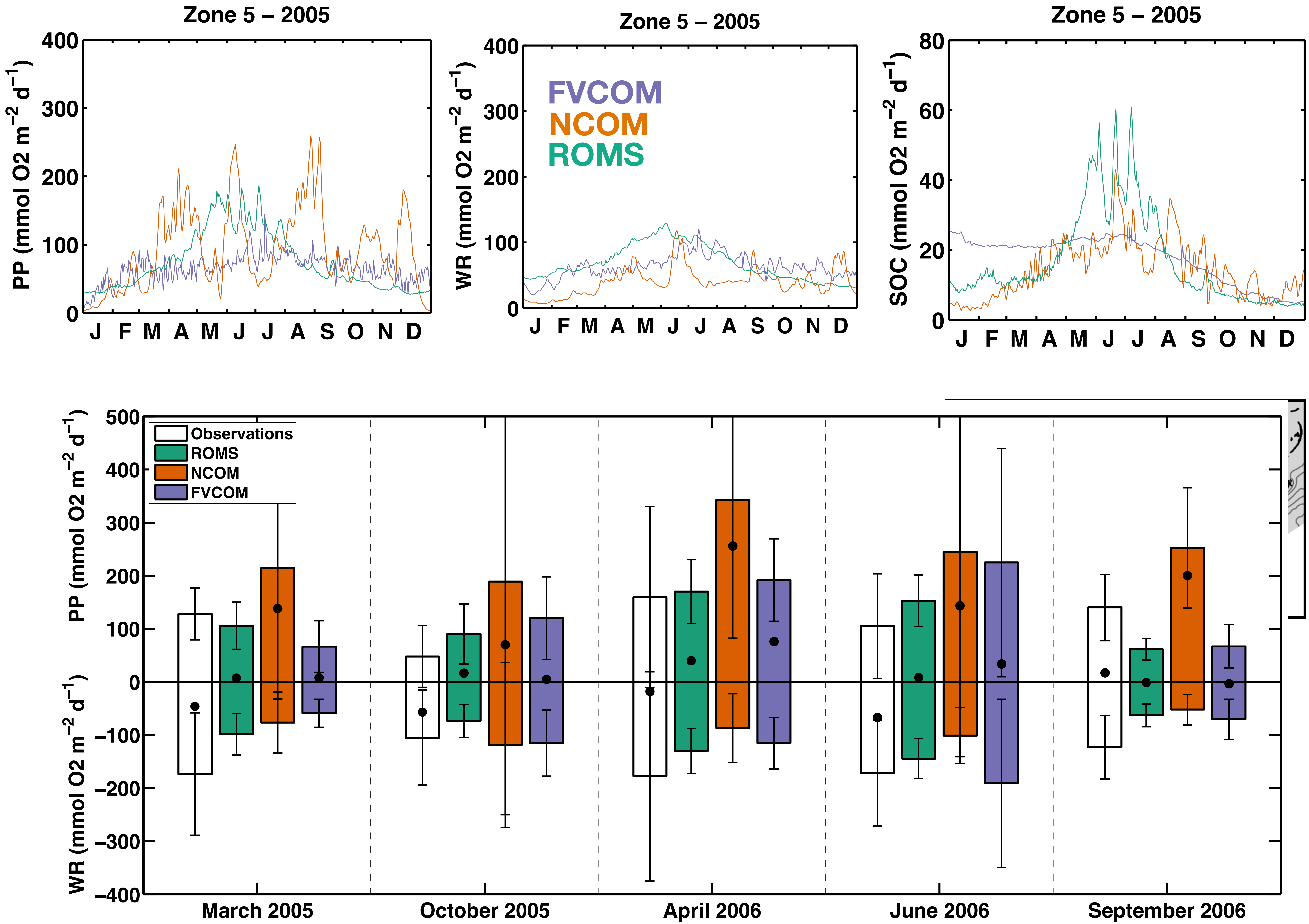
But for nutrient load reduction scenarios a full biogeochemical model is needed.


Zone 5 – 2005
PP (mmol O2 m−2 d−1)
400
300
200
100
0
J F M A M J J A S O N D


Zone 5 – 2005
WR (mmol O2 m−2 d−1)
400
300
200
100
0
FVCOM
NCOM
ROMS
J F M A M J J A S O N D


Zone 5 – 2005
SOC (mmol O2 m−2 d−1)
80
60
40
20
0
J F M A M J J A S O N D


7
5
1
3
2
8
6
4



Zone 5 – 2005
PP (mmol O2 m^{-2} d^{-1})
400
300
200
100
0
J F M A M J J A S O N D
Zone 5 – 2005
WR (mmol O2 m^{-2} d^{-1})
FVCOM
NCOM
ROMS
400
300
200
100
0
J F M A M J J A S O N D
Zone 5 – 2005
SOC (mmol O2 m^{-2} d^{-1})
80
60
40
20
0
J F M A M J J A S O N D
PP (mmol O2 m^{-2} d^{-1})
WR (mmol O2 m^{-2} d^{-1})
Observations
ROMS
NCOM
FVCOM
500
400
300
200
100
0
−100
−200
−300
−400
March 2005
October 2005
April 2006
June 2006
September 2006

Goal: Multi-model estimates of necessary nutrient load reductions

How far do N and/or P loads have to be reduced in order to affect desired reductions in hypoxia?

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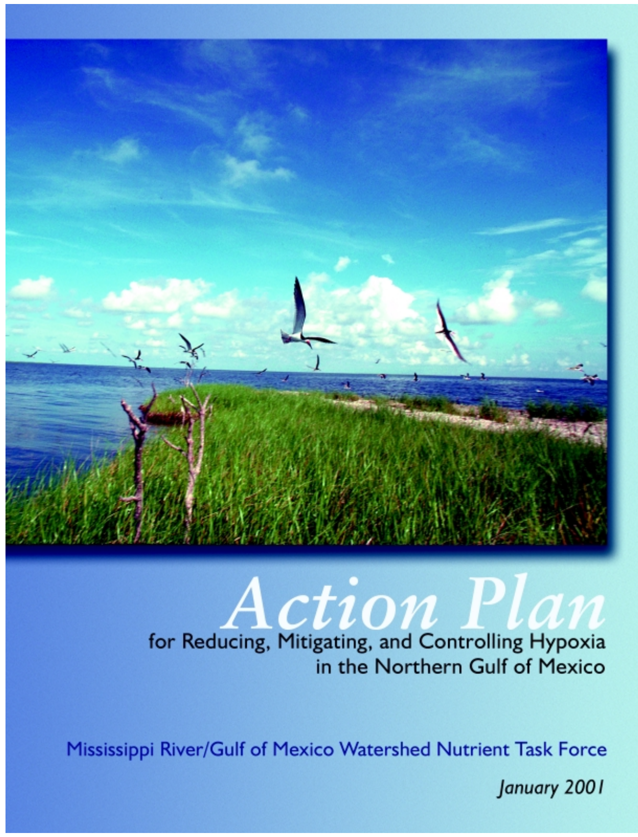

"By the year 2015 .. reduce the five-year running average areal extent of the Gulf of Mexico hypoxic zone to less than 5,000 square km" (p.9)

"The best current science indicates .. a 30% reduction .. in nitrogen discharges .. is consistent with the goal.." (p.21)

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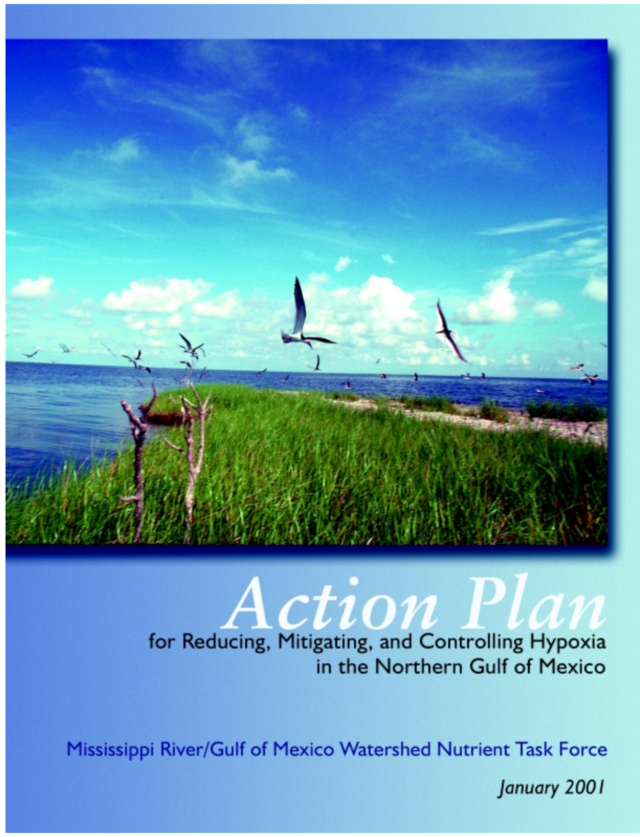

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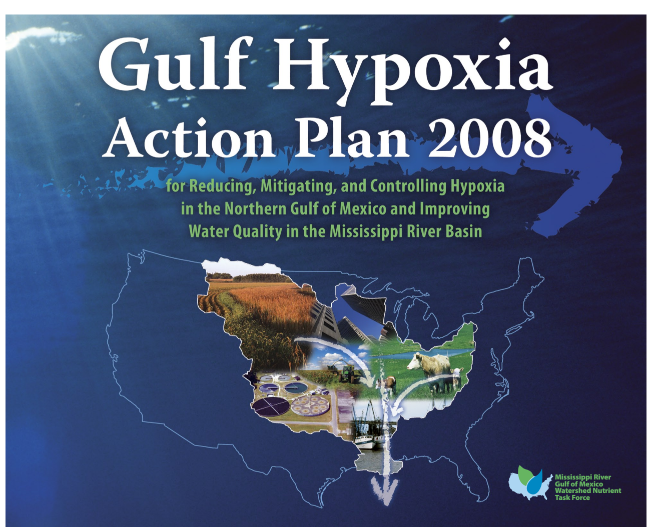

".. must reduce nitrogen and phosphorus in .. the River Basin." (p.29)

How far do N and/or P loads have to be reduced in order to affect desired reductions in hypoxia?

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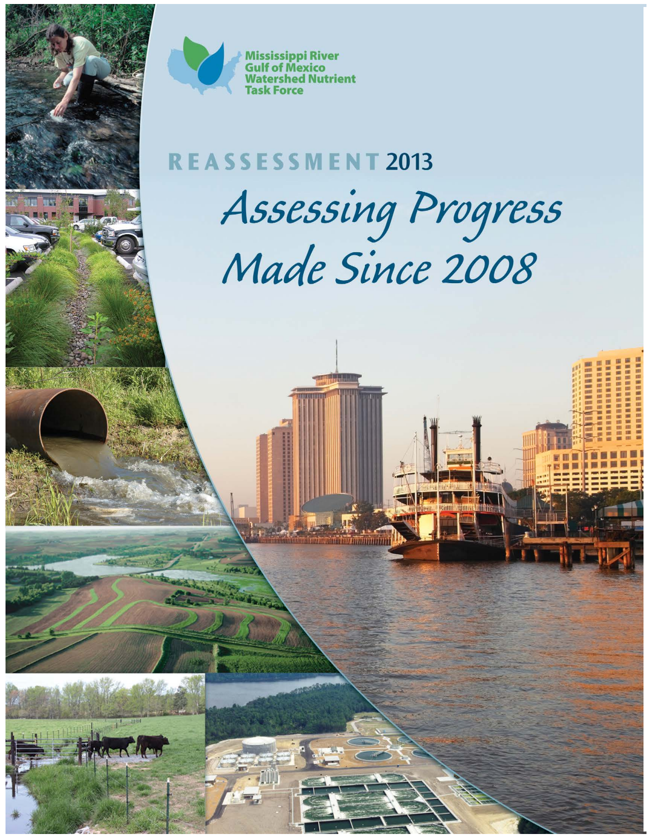
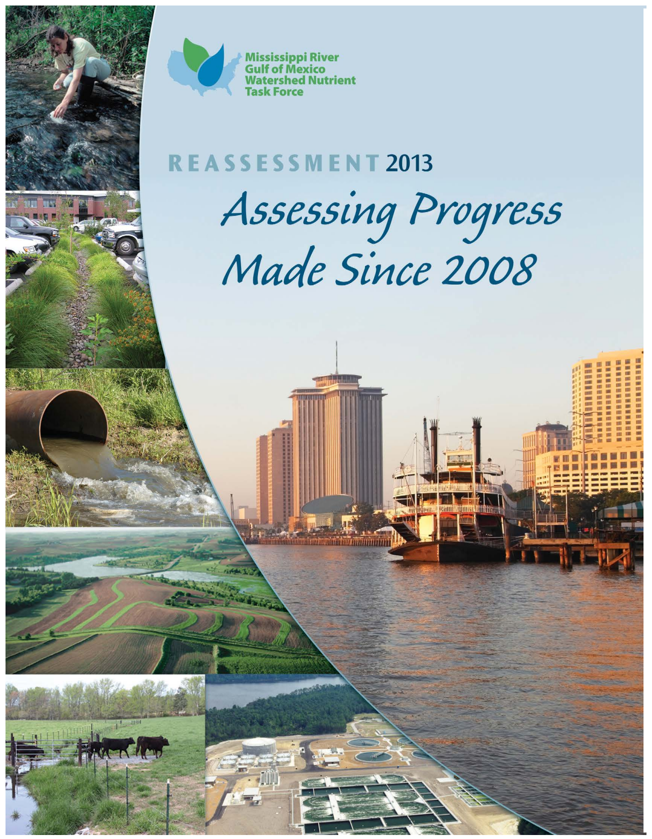


"Decrease scientific uncertainty of nitrogen and phosphorus effects on hypoxia" (p.48)

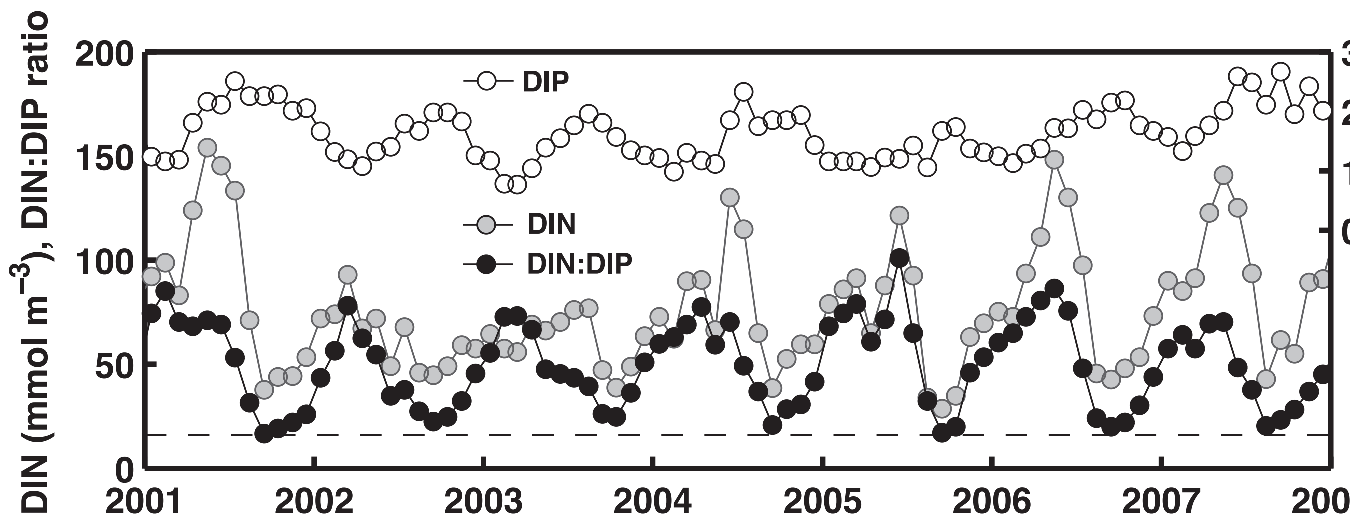
How far do N and/or P loads have to be reduced in order to affect desired reductions in hypoxia?



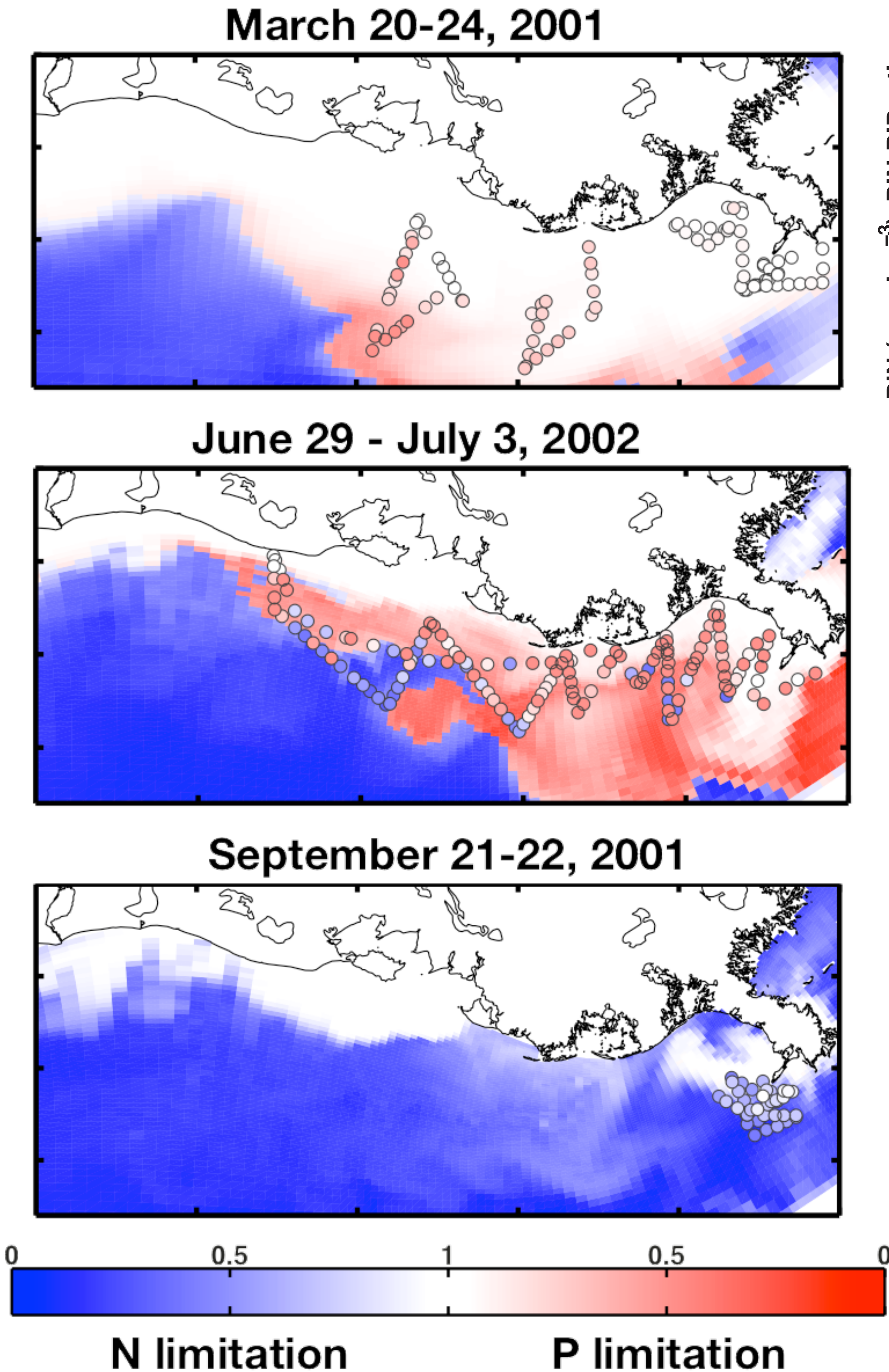
"Decrease scientific uncertainty of nitrogen and phosphorus effects on hypoxia" (p.48)

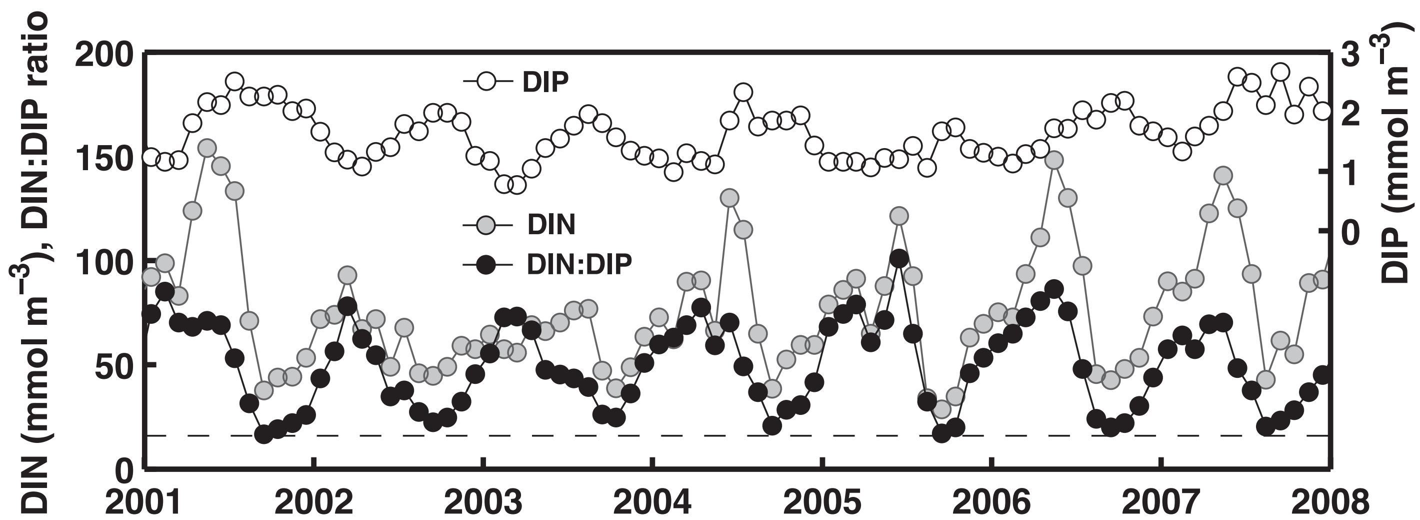
"Retain 2008 Action plan goal of 5,000 km^2 by year 2035." (p.1)

"Interim target of 20% nutrient load reduction by year 2025." (p.1)



DIP
DIN
DIN:DIP
DIN (mmol m^{-3}), DIN:DIP ratio
DIP (mmol m^{-3})
200
150
100
50
0
3
2
1
0
2001
2002
2003
2004
2005
2006
2007
2008





Laurent et al. *Biogeosciences* (2012) using observations from Sylvan et al. *EST* (2006)

Nutrient reduction strategies in the Mississippi Basin have long focused on N assuming it is the *ultimate* limiting nutrient while P is only limiting in a *proximate* sense.

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prox•i•mate | ˈpräksəmit | **immediate**

ul•ti•mate | ˈəltəmit | **final**

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In Ecology (after Tyrrell 1999):

The *proximate limiting nutrient* is the one that is locally (or temporarily) limiting Primary Production (PP). Its addition will immediately enhance PP.

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In Ecology (after Tyrrell 1999):

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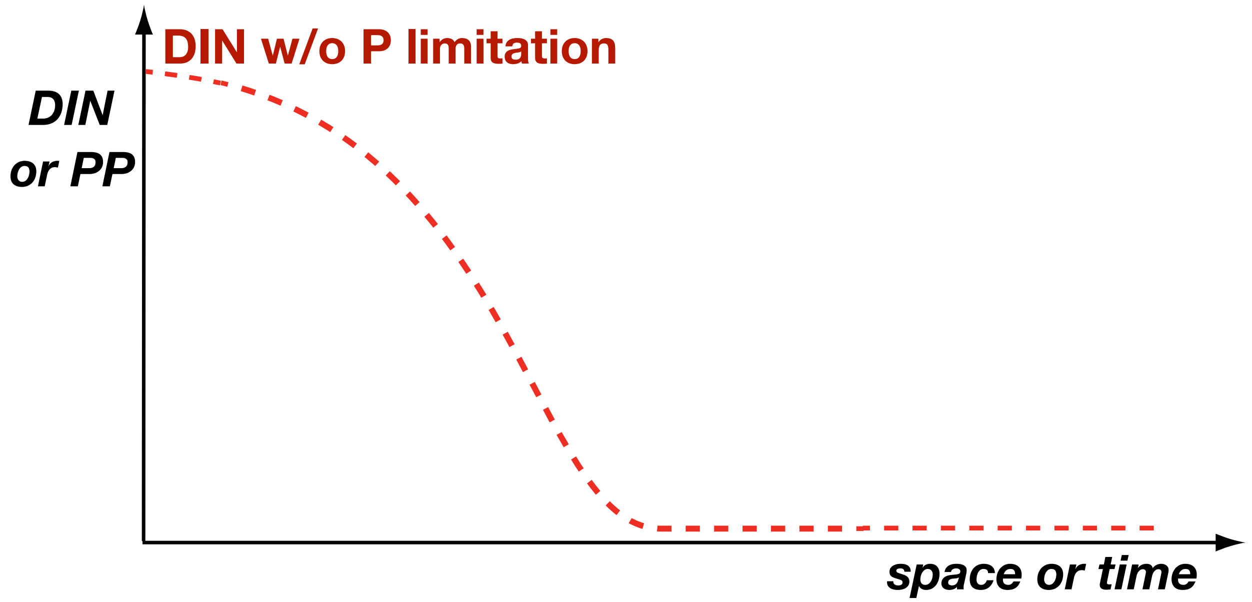
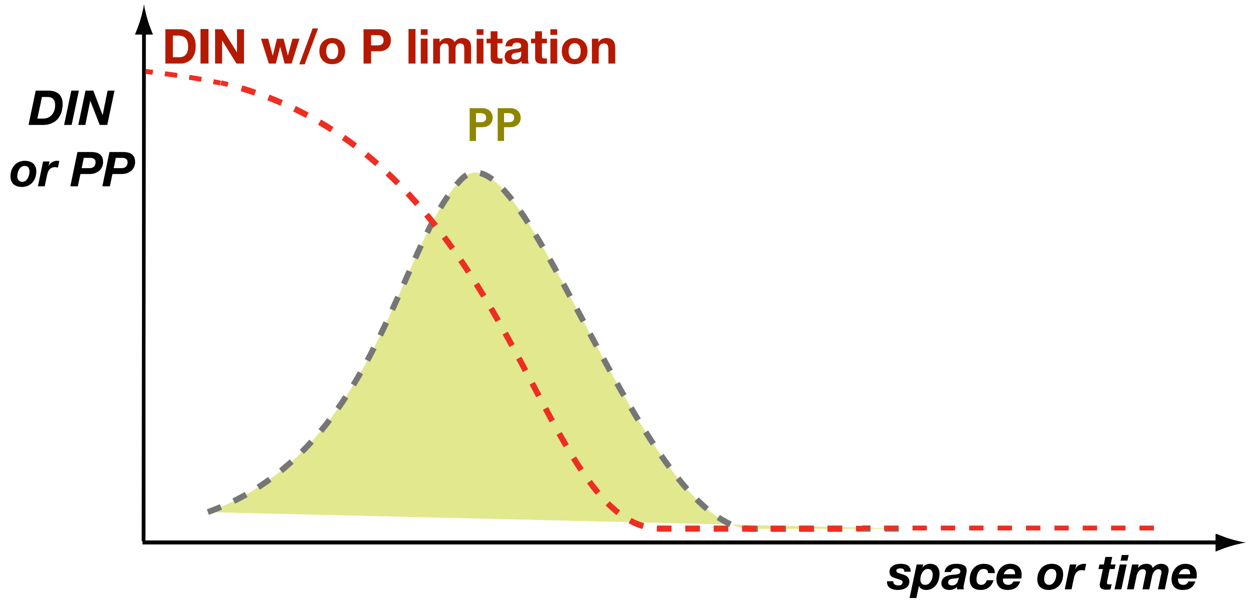
The supply of the *ultimate limiting nutrient* determines system productivity over long time scales.



Implications of P limitation



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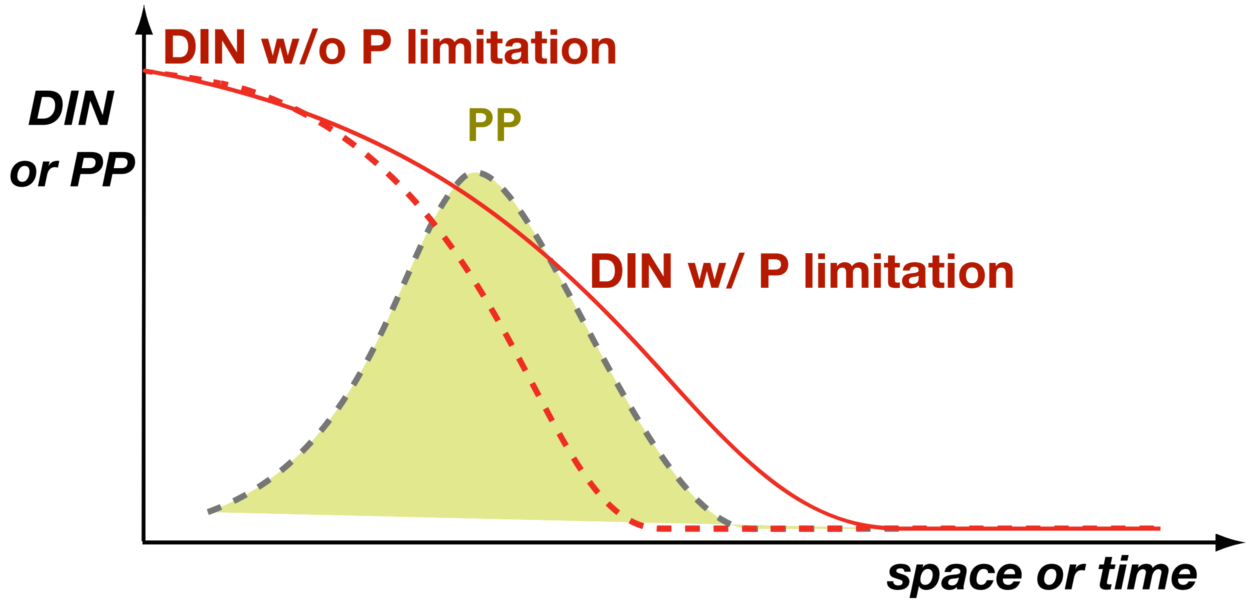

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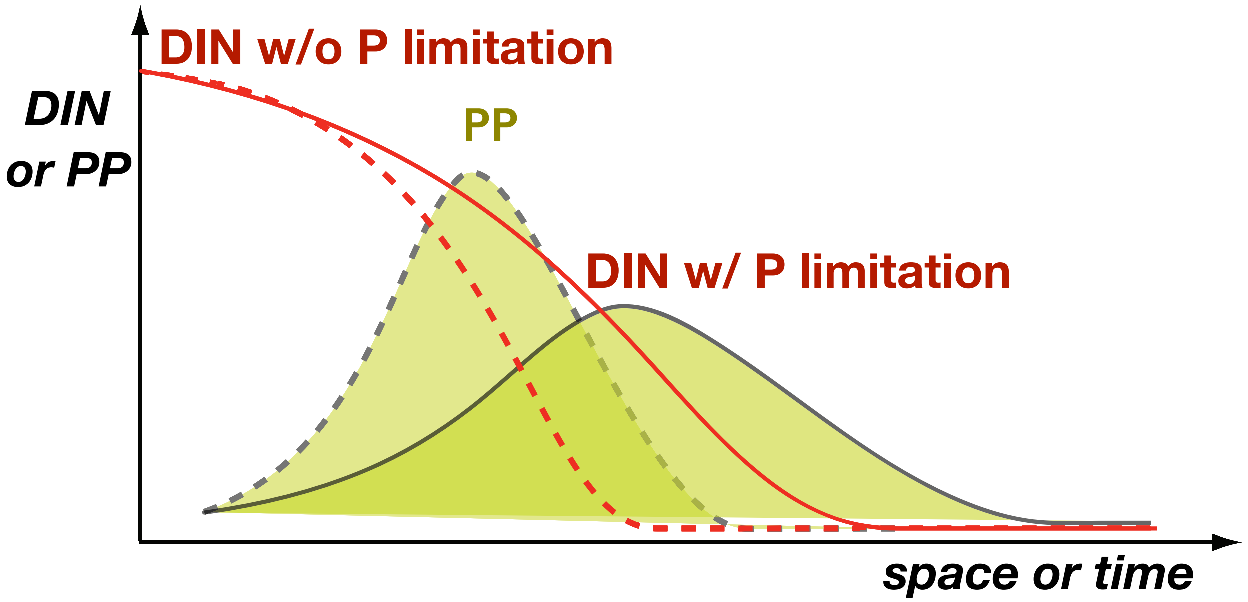

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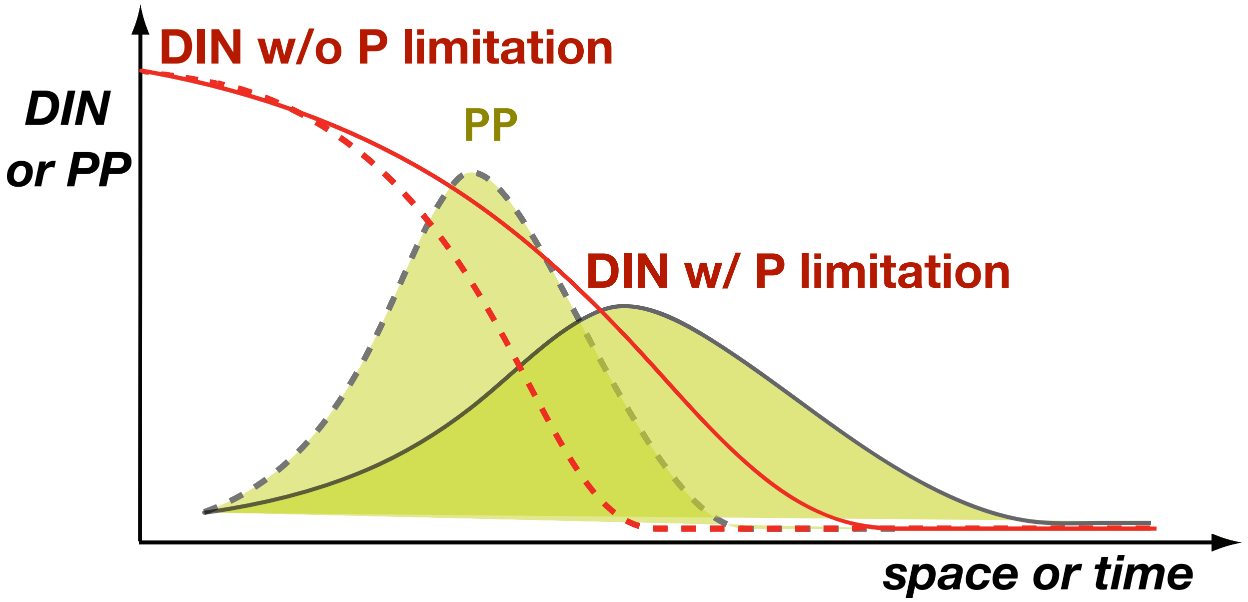
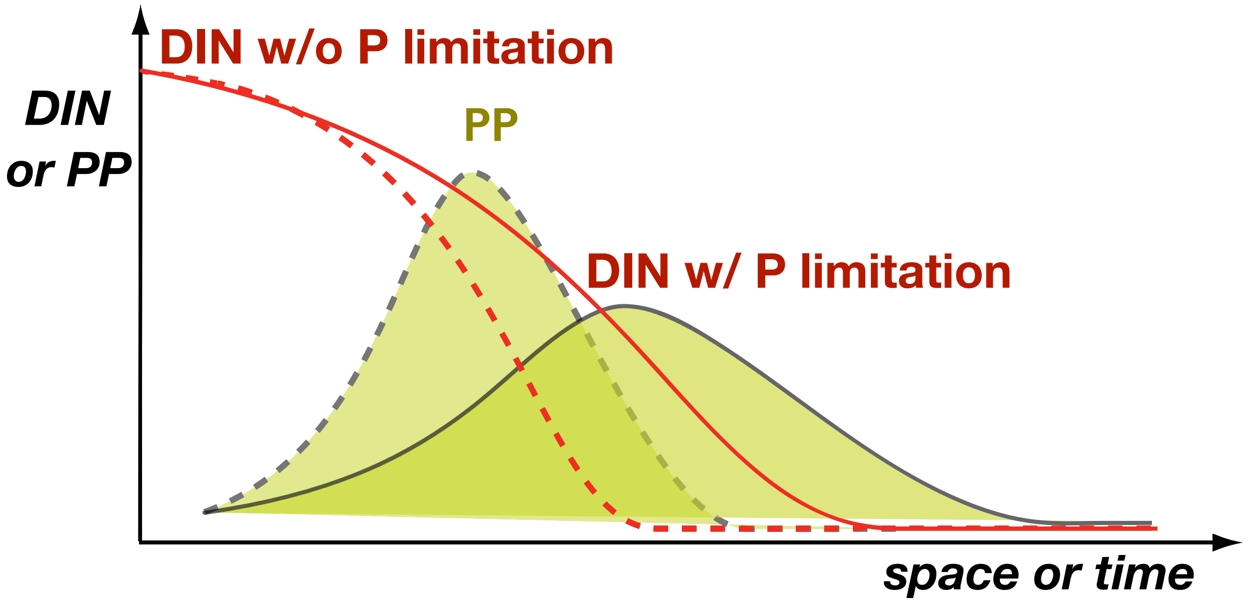
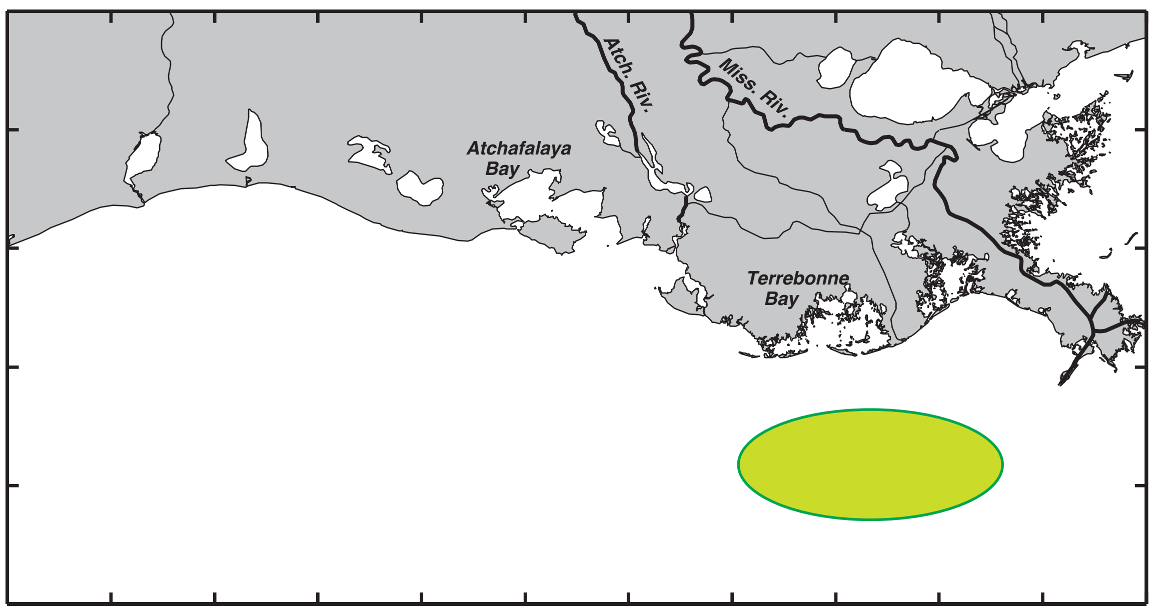


Implications of P limitation

- delays utilization of DIN and induces spatial shift
- reduces magnitude of PP peak but results in elevated PP in larger area/over longer time period





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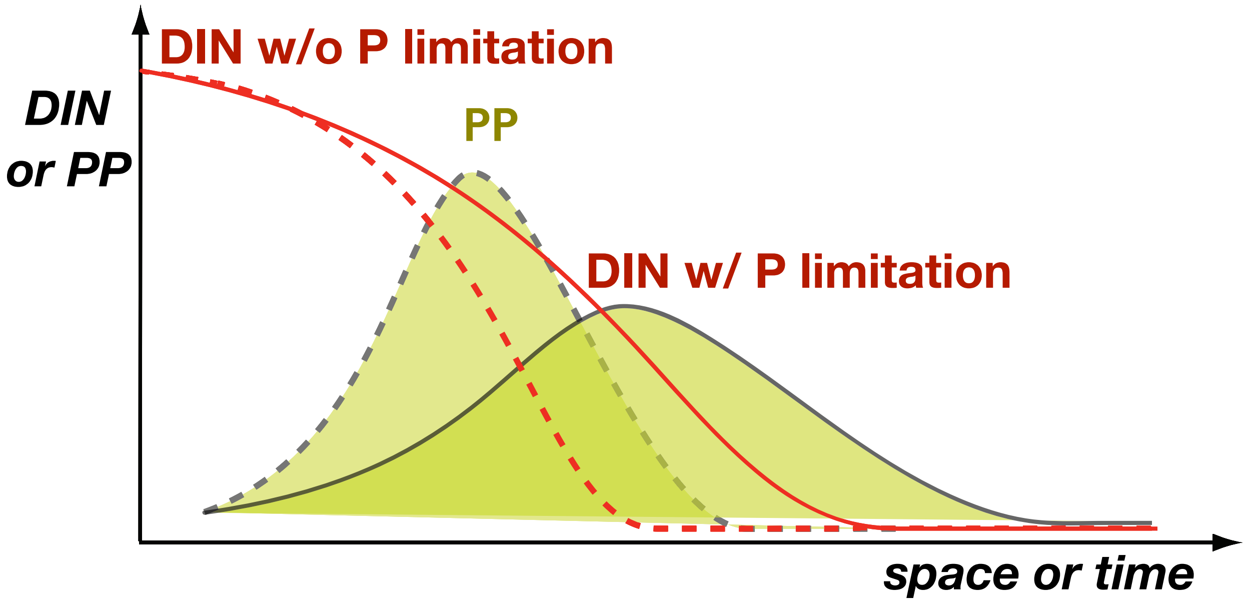

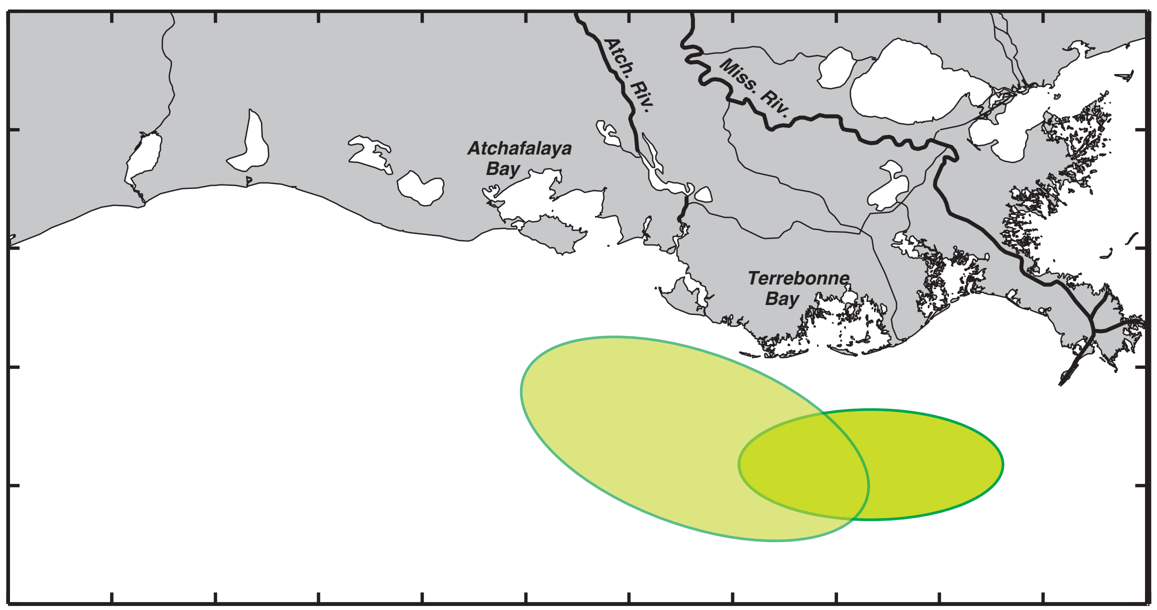

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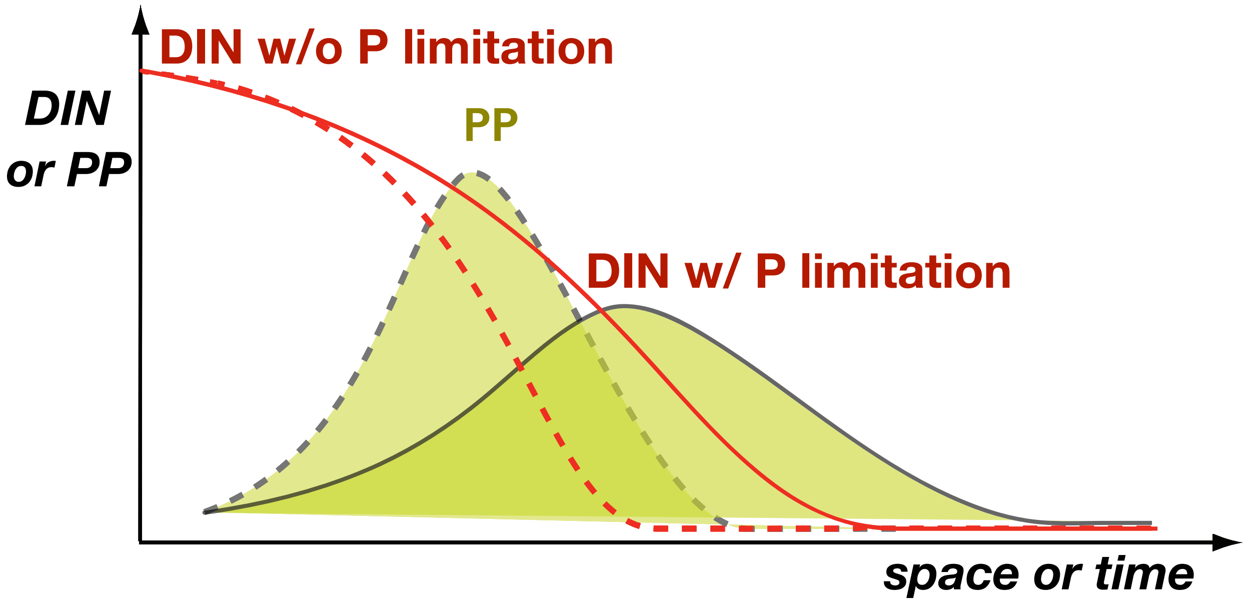

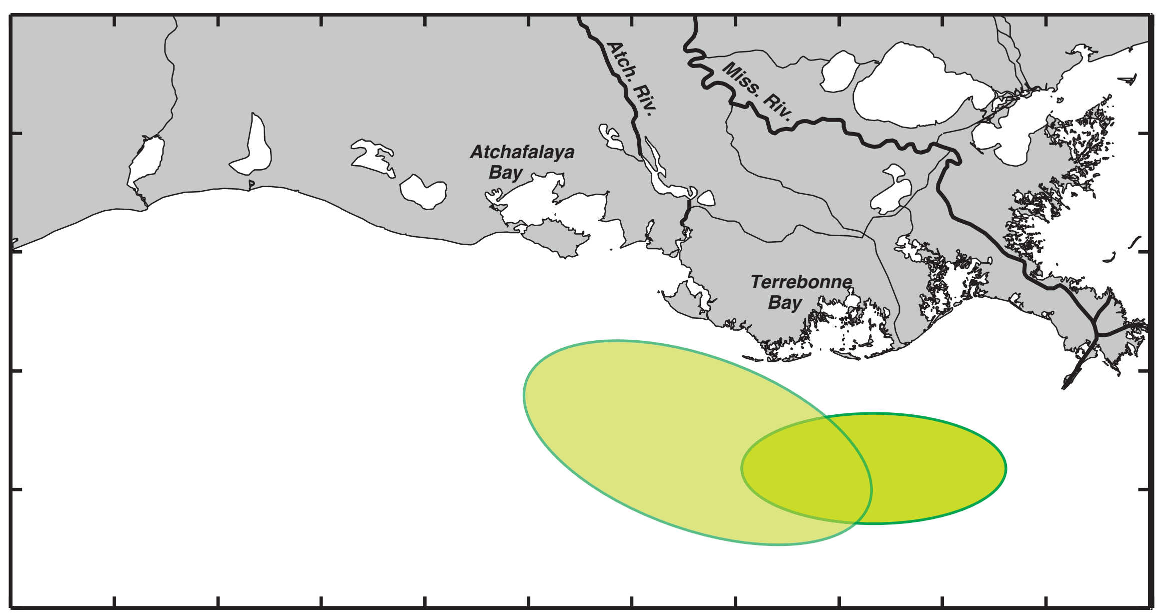

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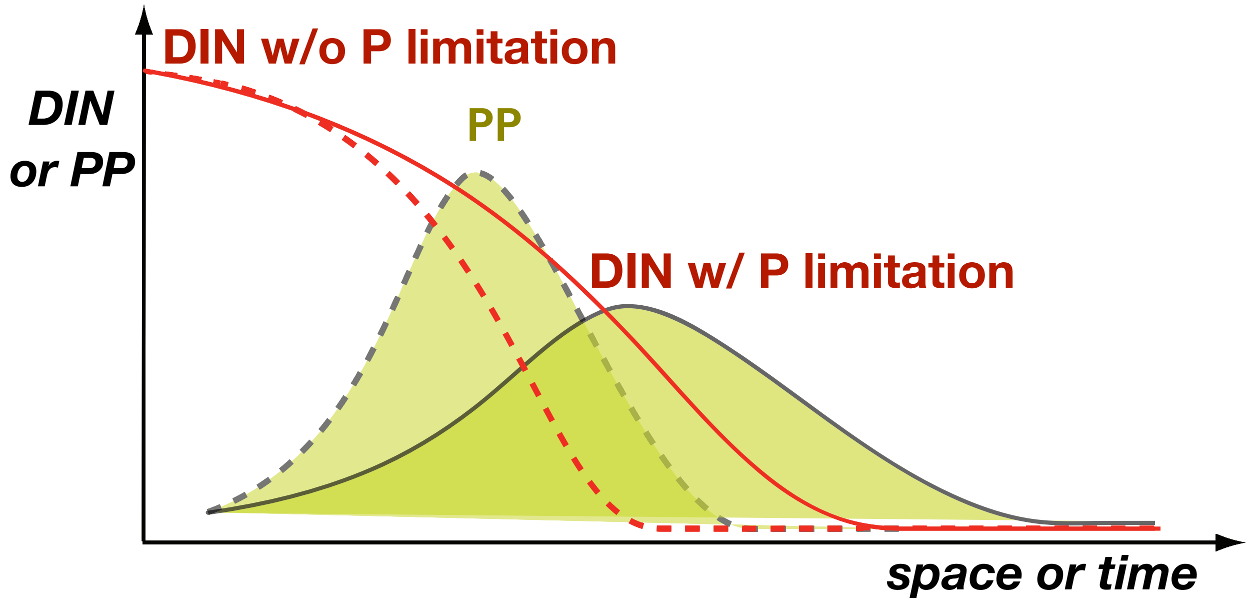
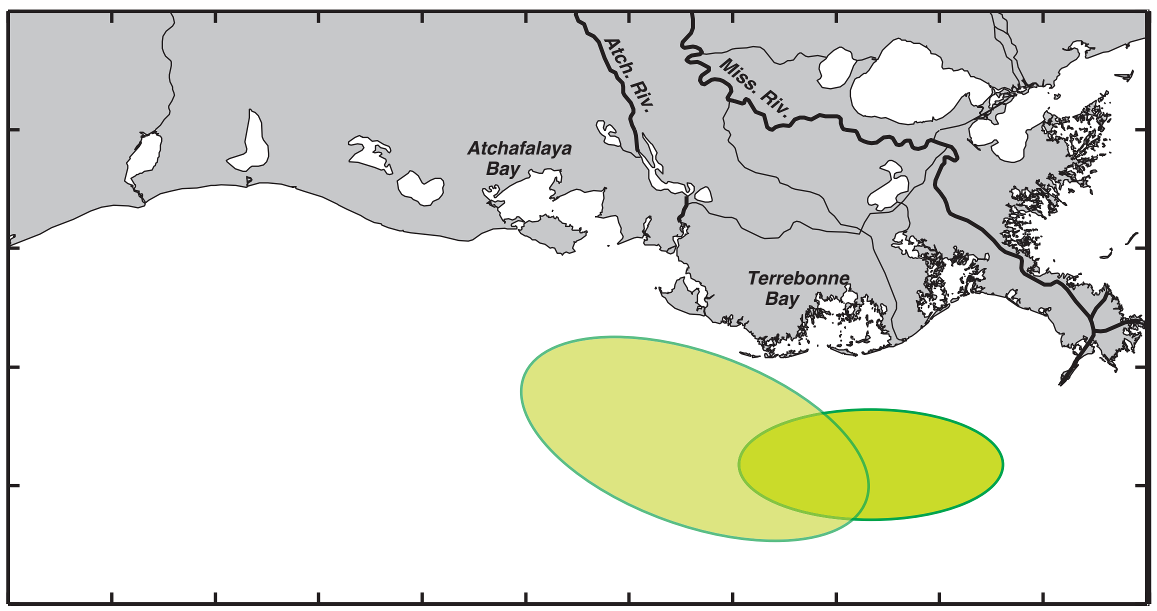
And hypoxia?





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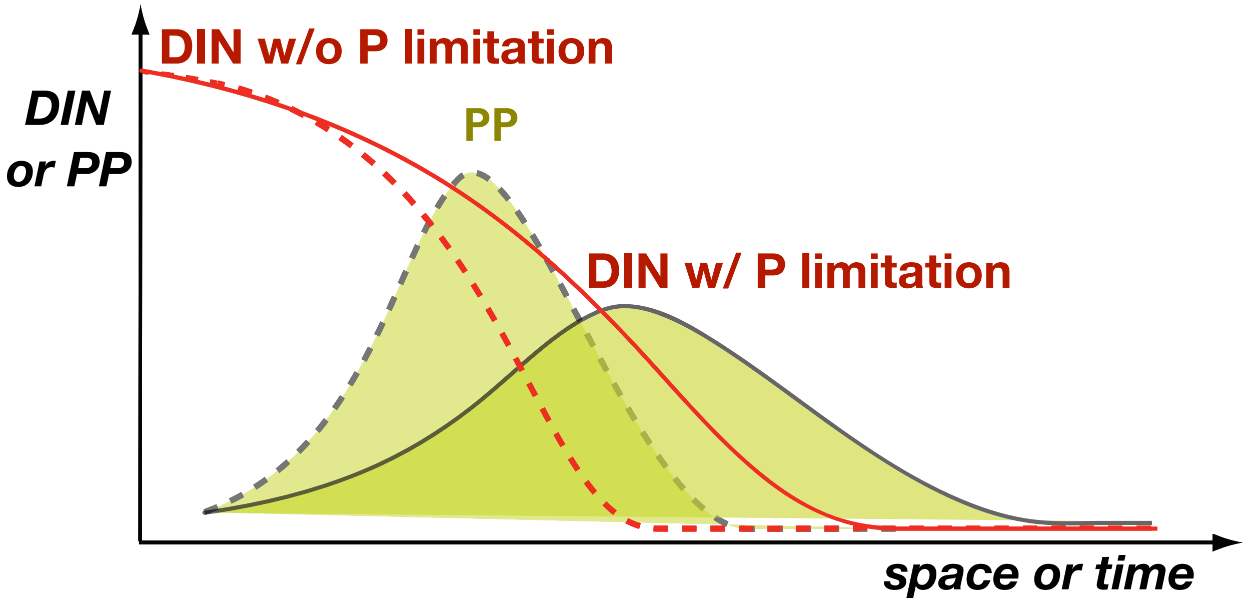
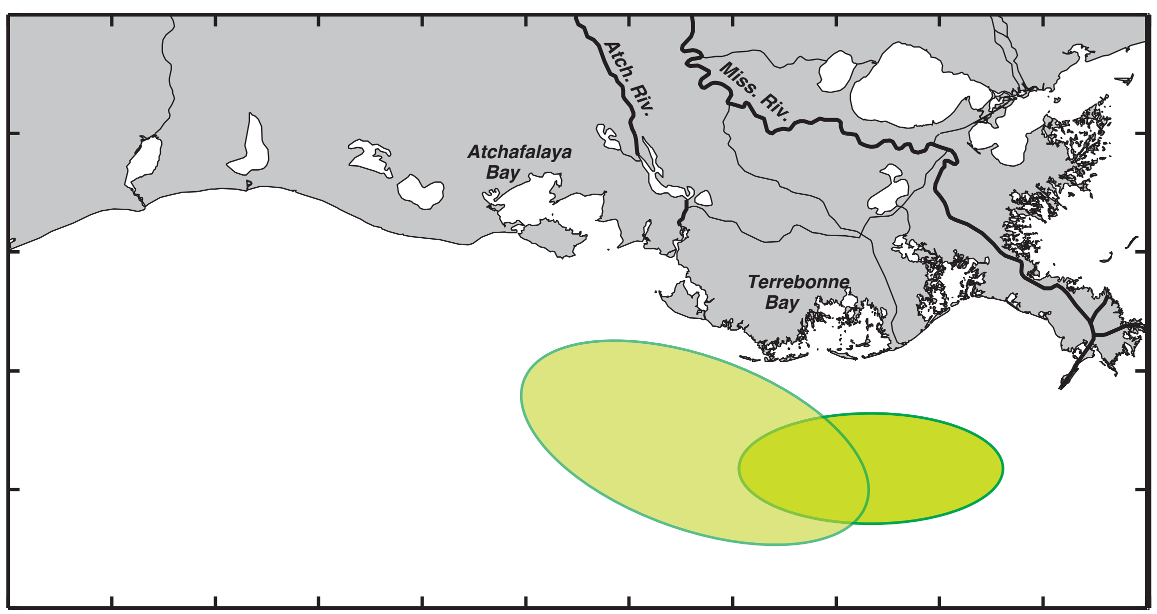
- could intensify (Pearl 2004: Neuse River estuary; Conley et al. 2009: Baltic Sea)





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And hypoxia?

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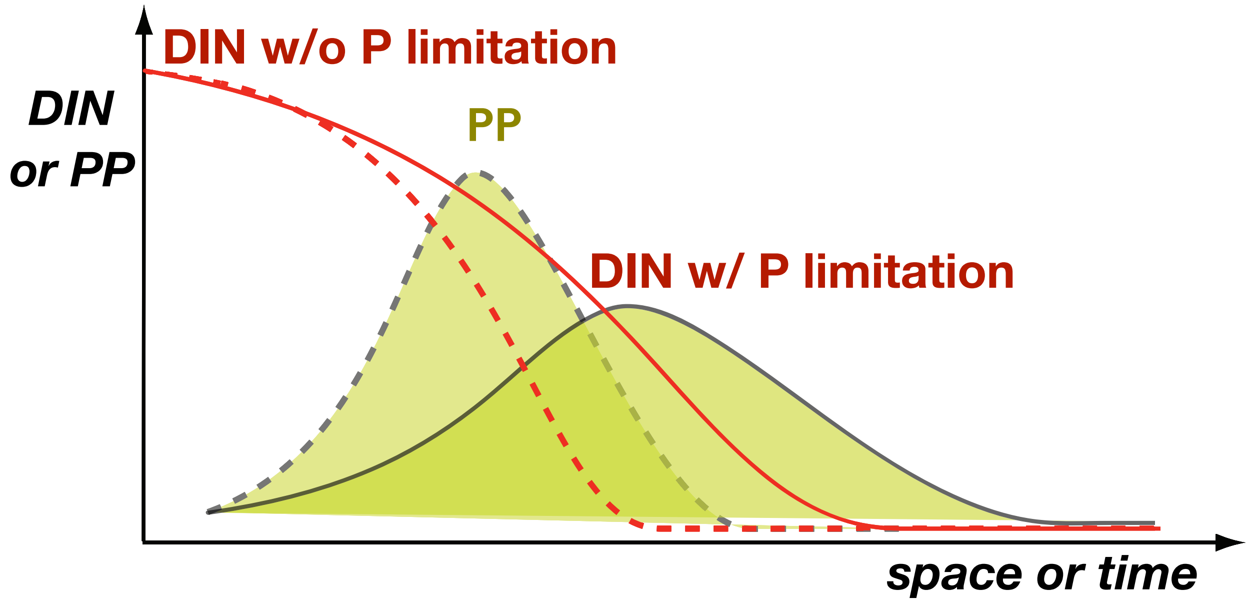
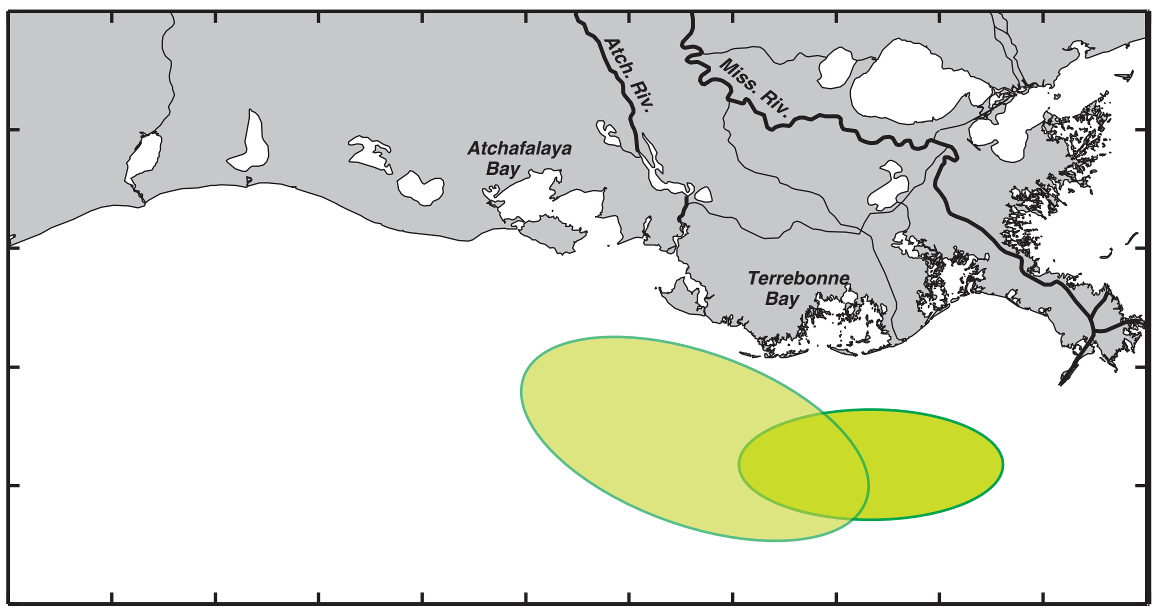
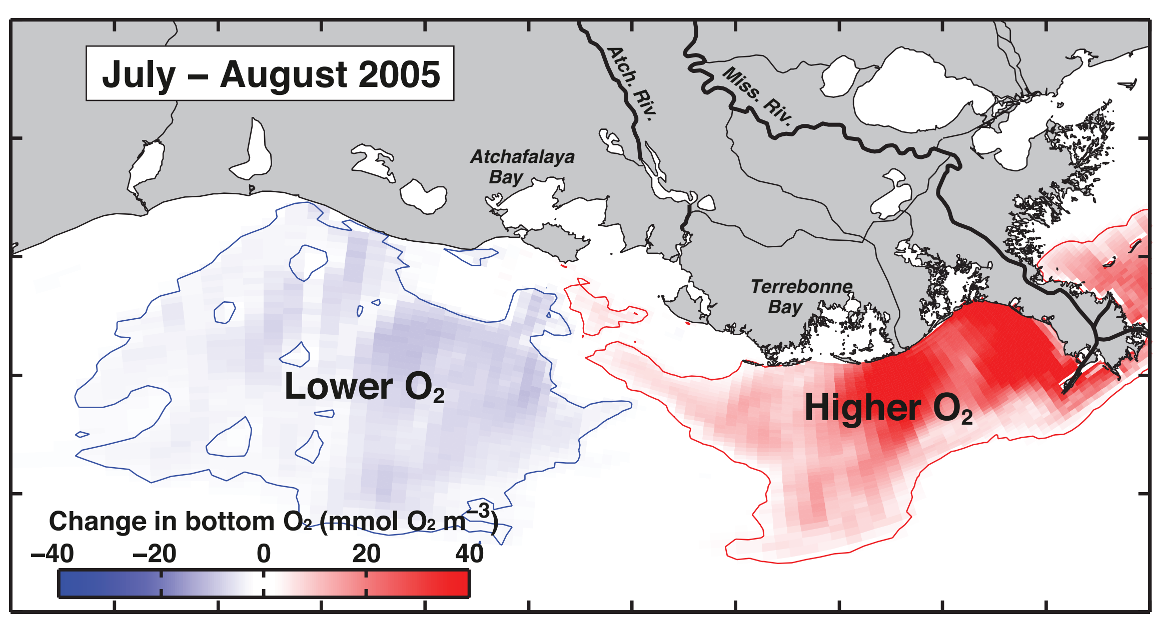
- could be reduced (Laurent & Fennel 2014)







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And hypoxia?

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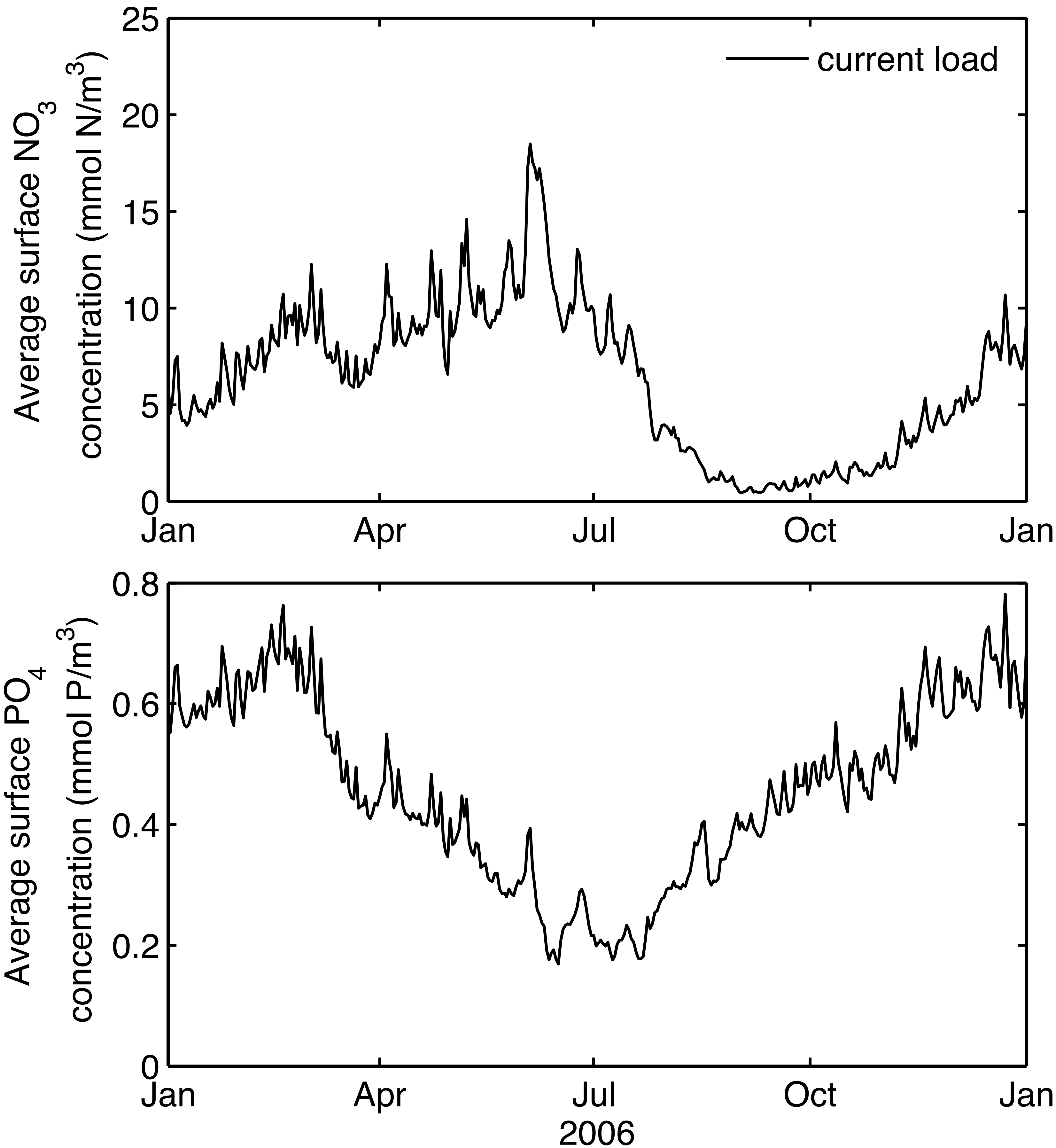
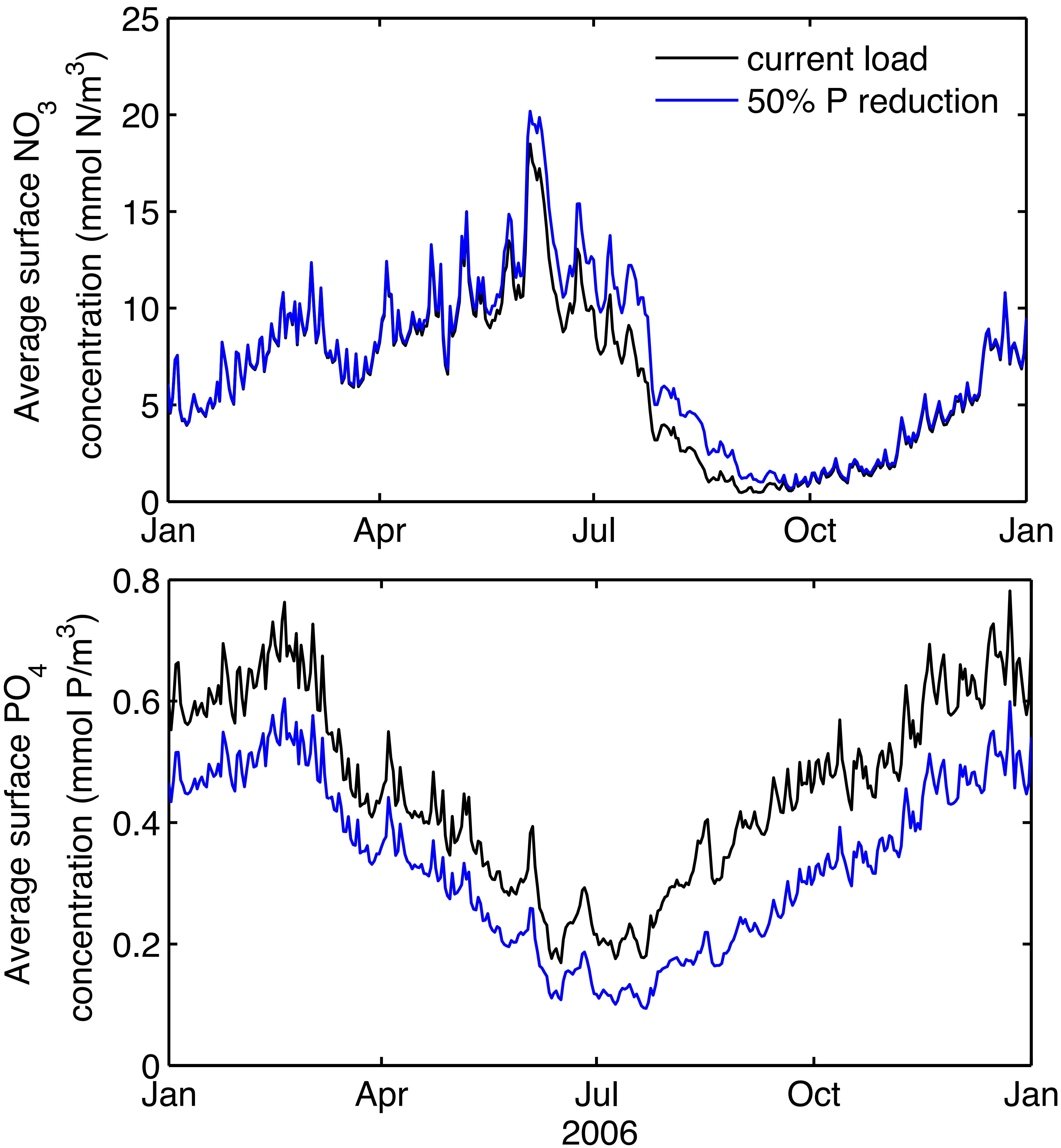
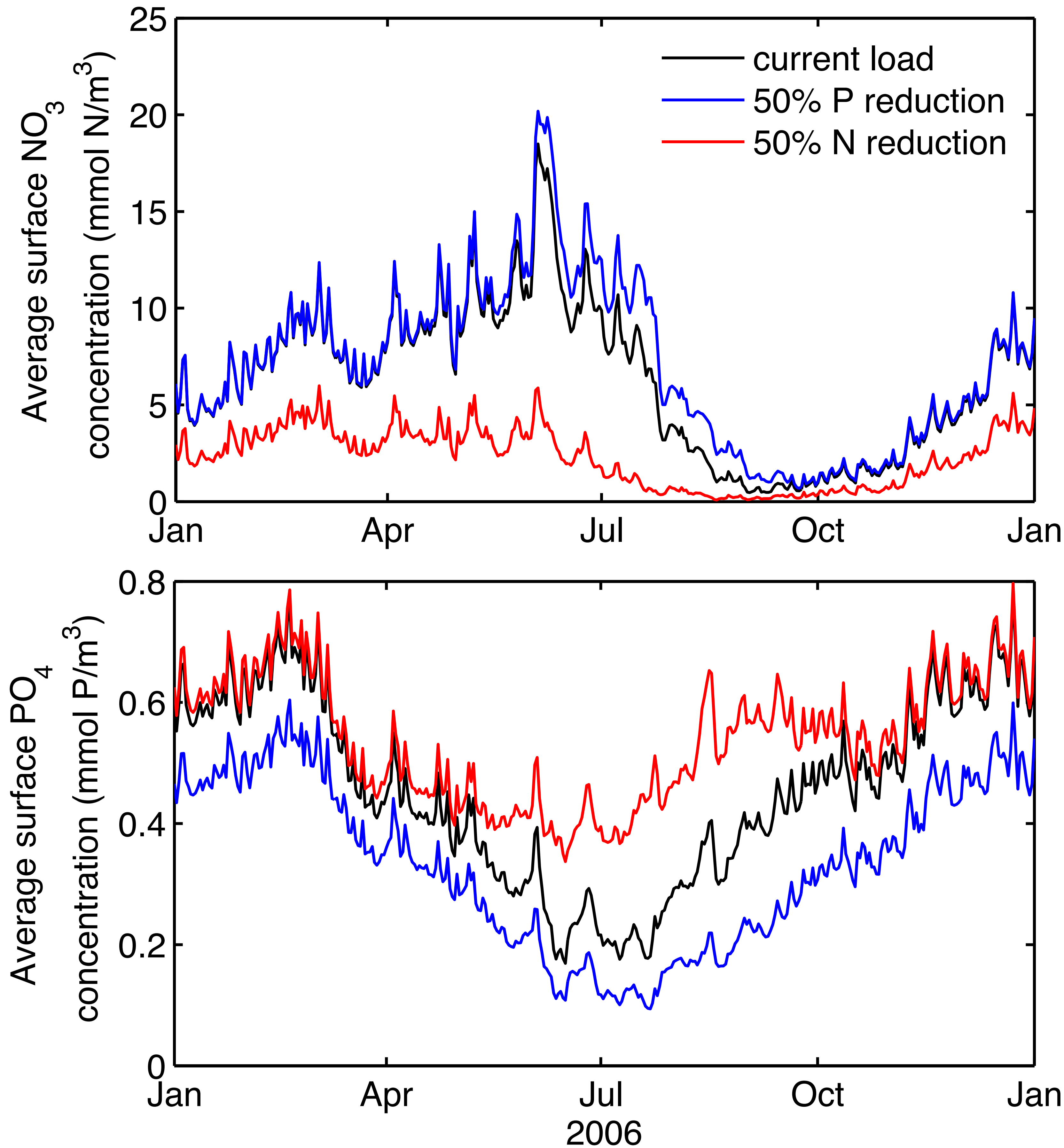
Laurent & Fennel *Elementa* (2014)

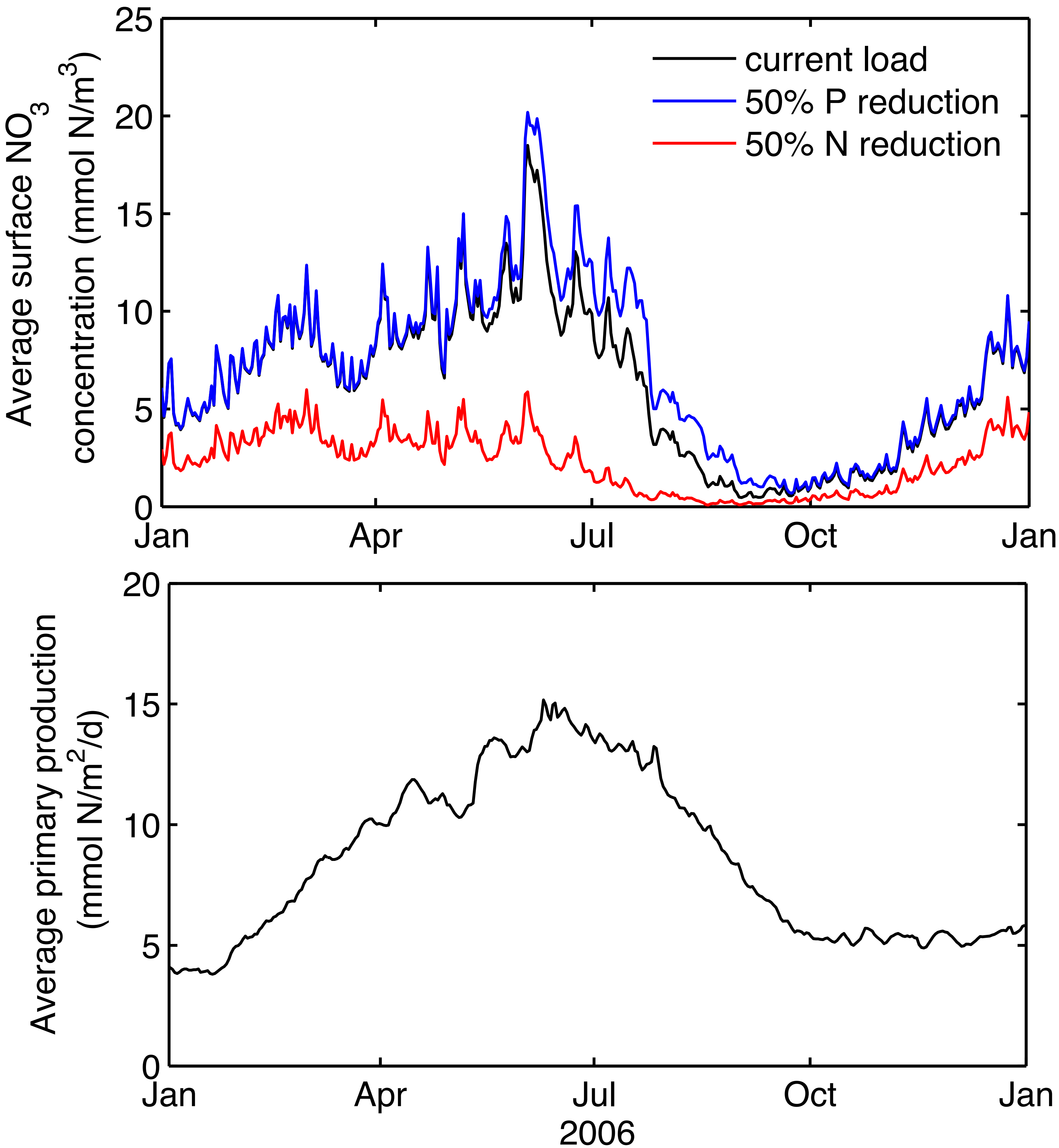


current load
Average surface NO_3 concentration (mmol N/m^3)
25
20
15
10
5
0
Jan
Apr
Jul
Oct
Jan
Average surface PO_4 concentration (mmol P/m^3)
0.8
0.6
0.4
0.2
0
Jan
Apr
Jul
Oct
Jan
2006



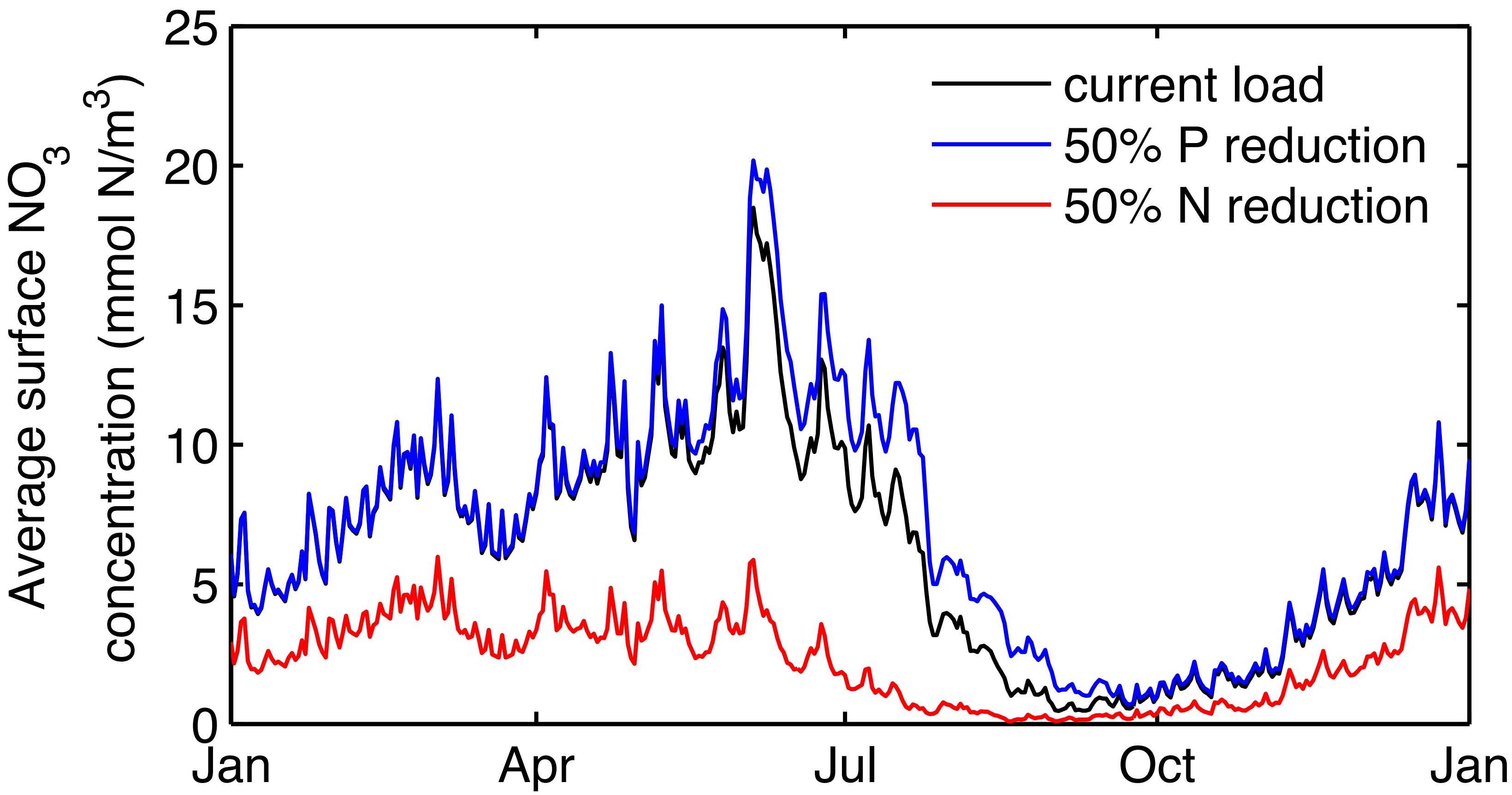
25
20
15
10
5
0
Average surface NO3
concentration (mmol N/m3)
current load
50% P reduction
Jan
Apr
Jul
Oct
Jan
0.8
0.6
0.4
0.2
0
Average surface PO4
concentration (mmol P/m3)
Jan
Apr
Jul
Oct
Jan
2006

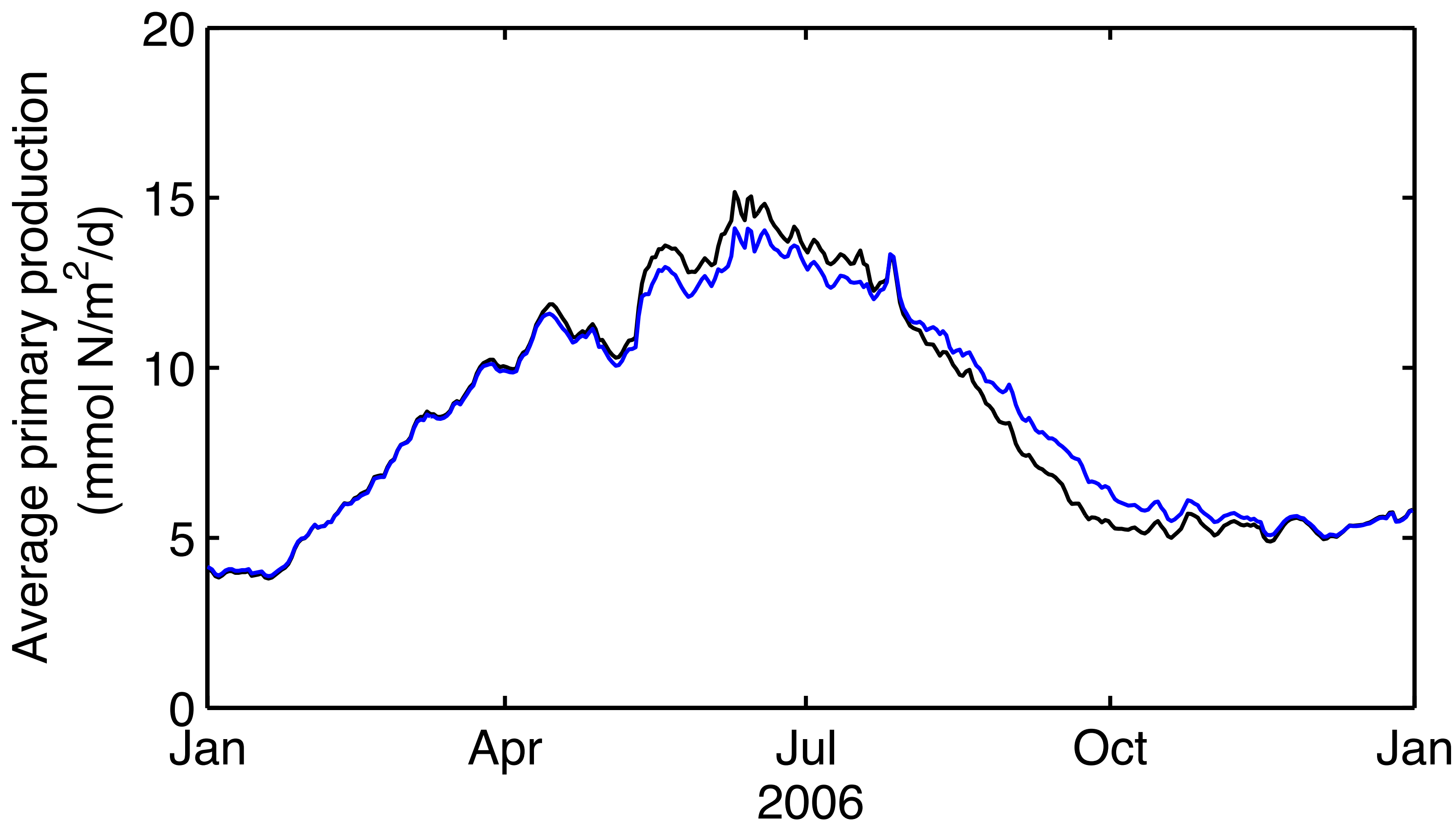

current load
50% P reduction
50% N reduction
Average surface NO3
concentration (mmol N/m3)
Average surface PO4
concentration (mmol P/m3)
0
5
10
15
20
25
0
0.2
0.4
0.6
0.8
Jan
Apr
Jul
Oct
Jan
2006



Annual PP (shelf-wide average):

33.1 mol O_2 /m^2 /yr

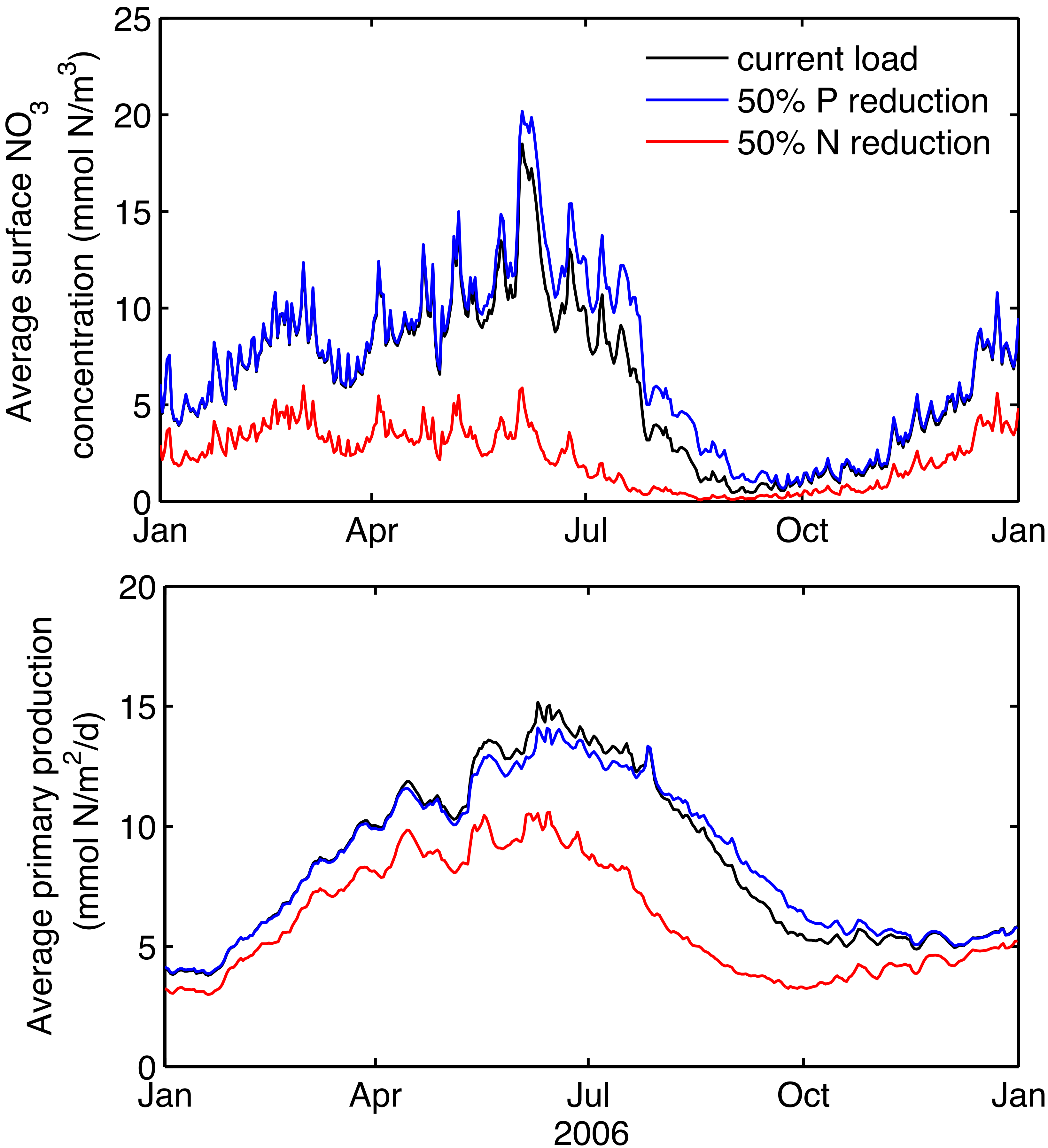




Annual PP (shelf-wide average):

33.1 mol O_2 /m^2 /yr

33.3 mol O_2 /m^2 /yr



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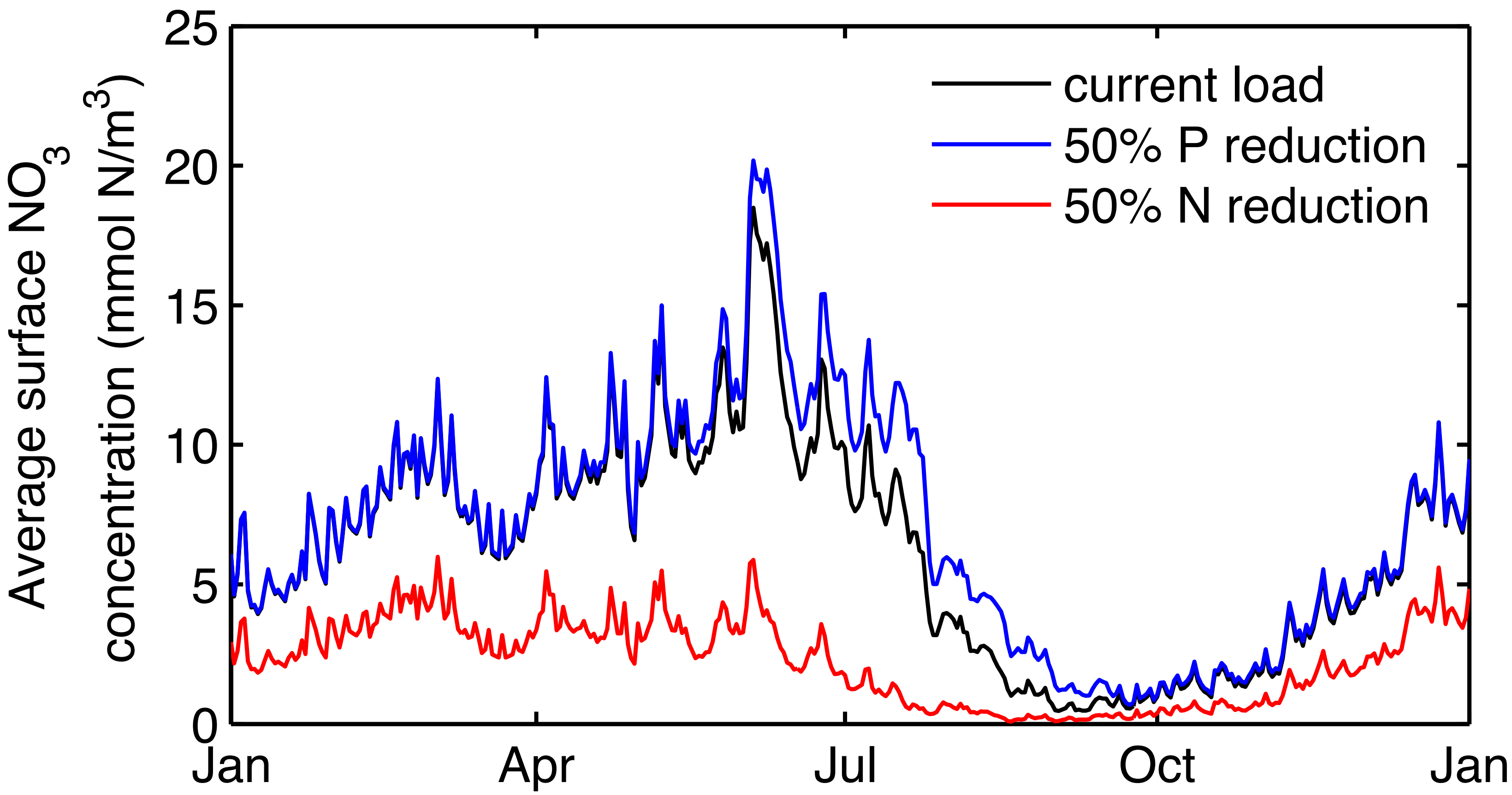

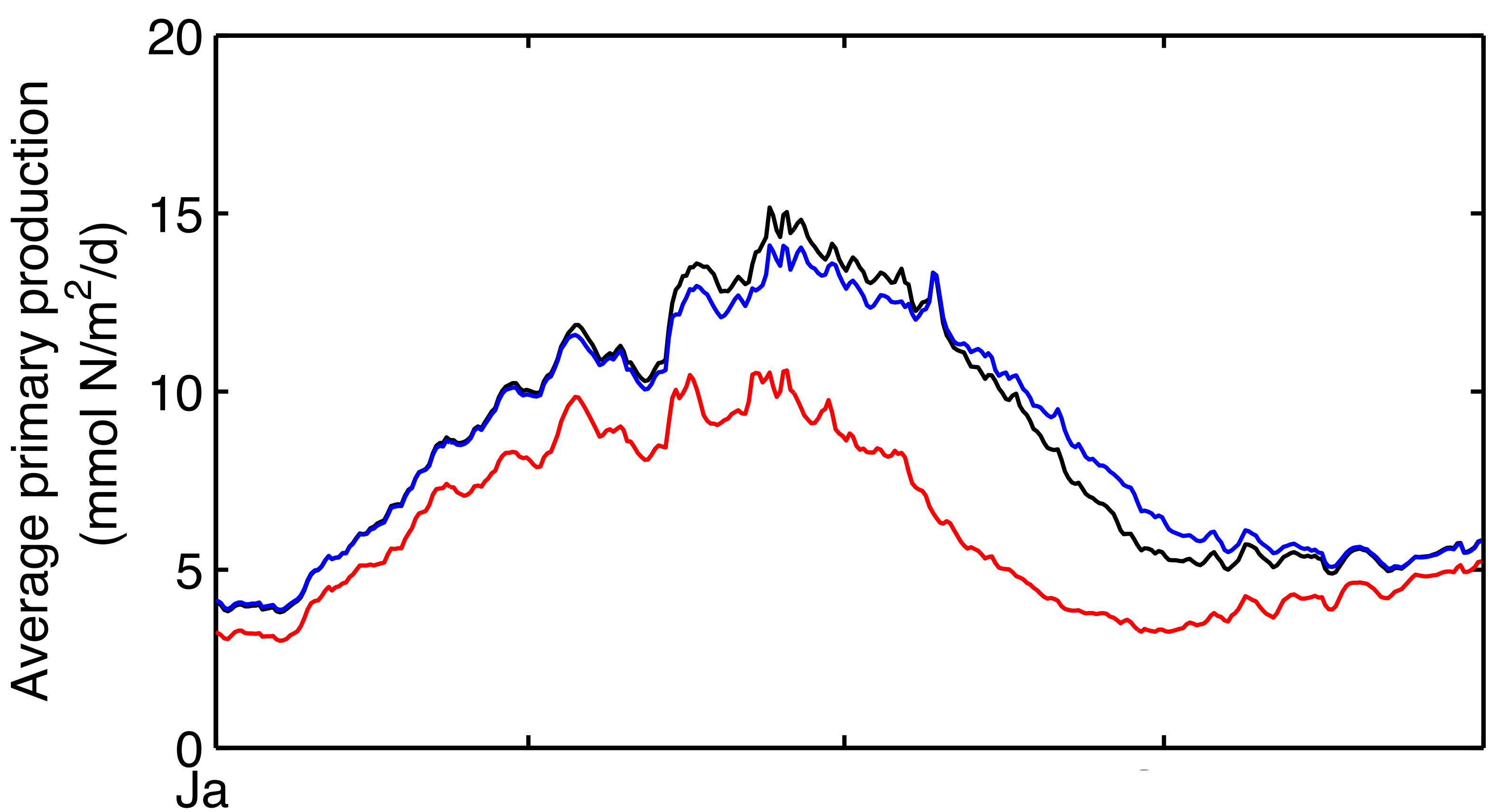

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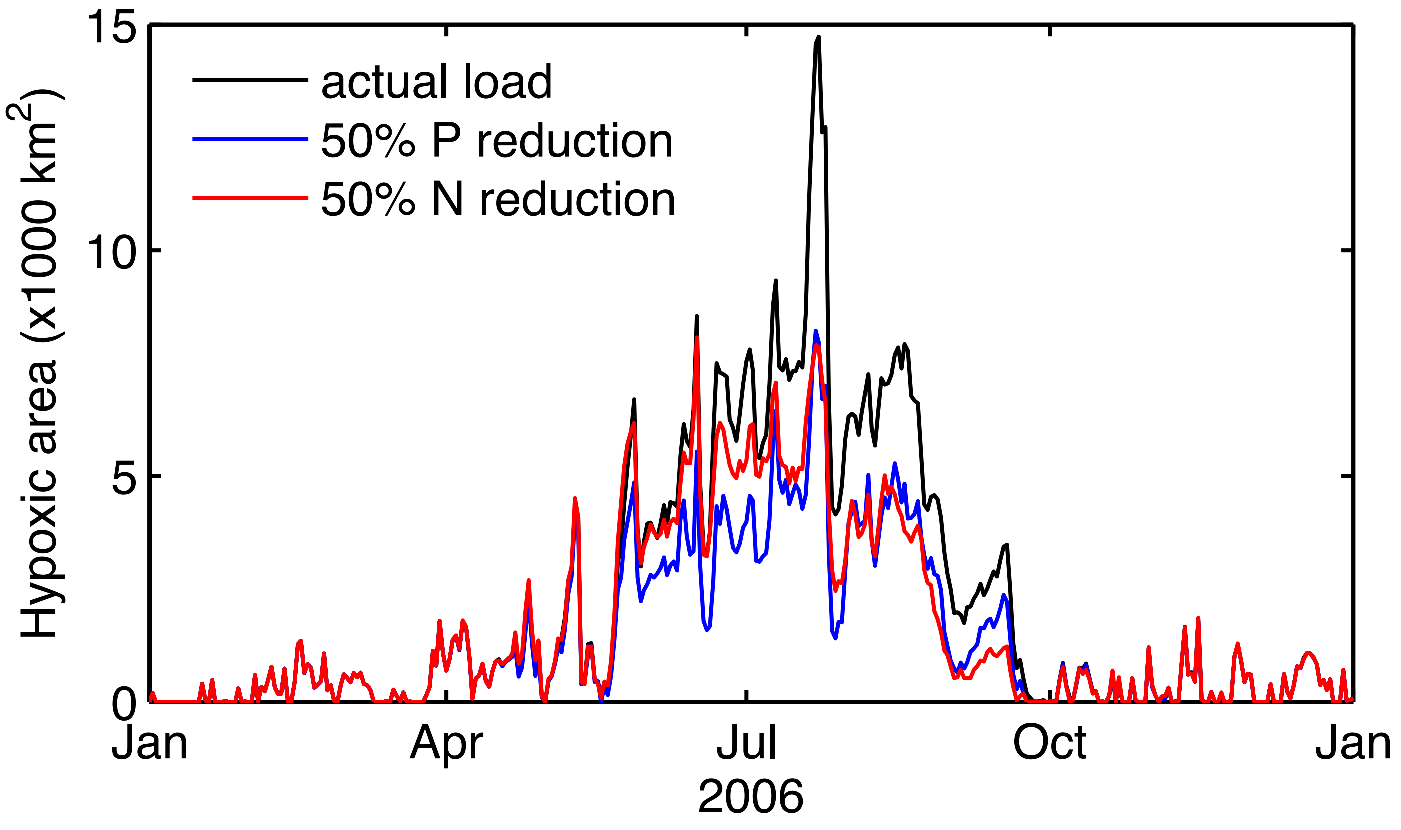
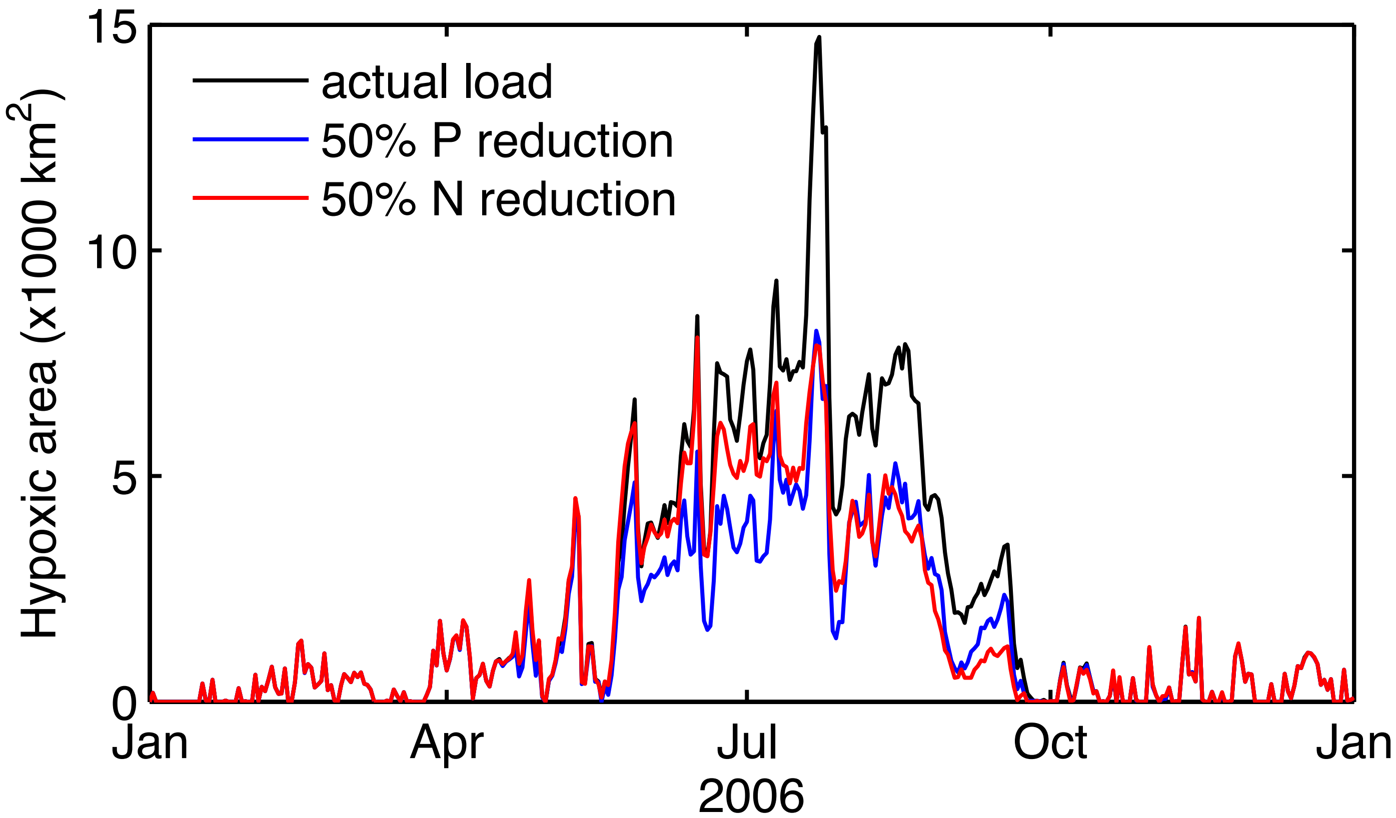
Model results consistent with N as *ultimate* limiting nutrient and P as limiting in a *proximate* sense.



actual load
50% P reduction
50% N reduction
Hypoxic area (x1000 km^2)
15
10
5
0
Jan
Apr
Jul
Oct
Jan
2006

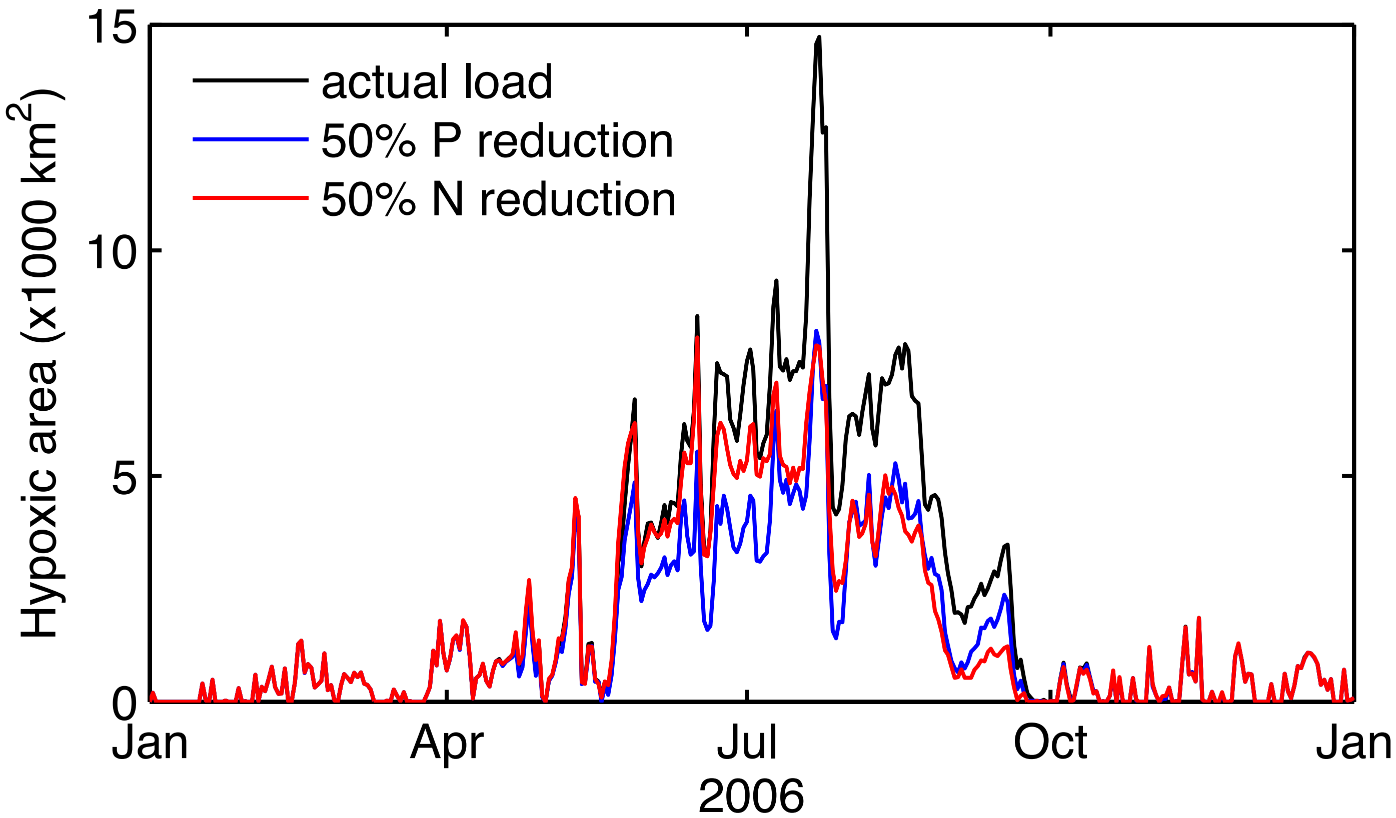


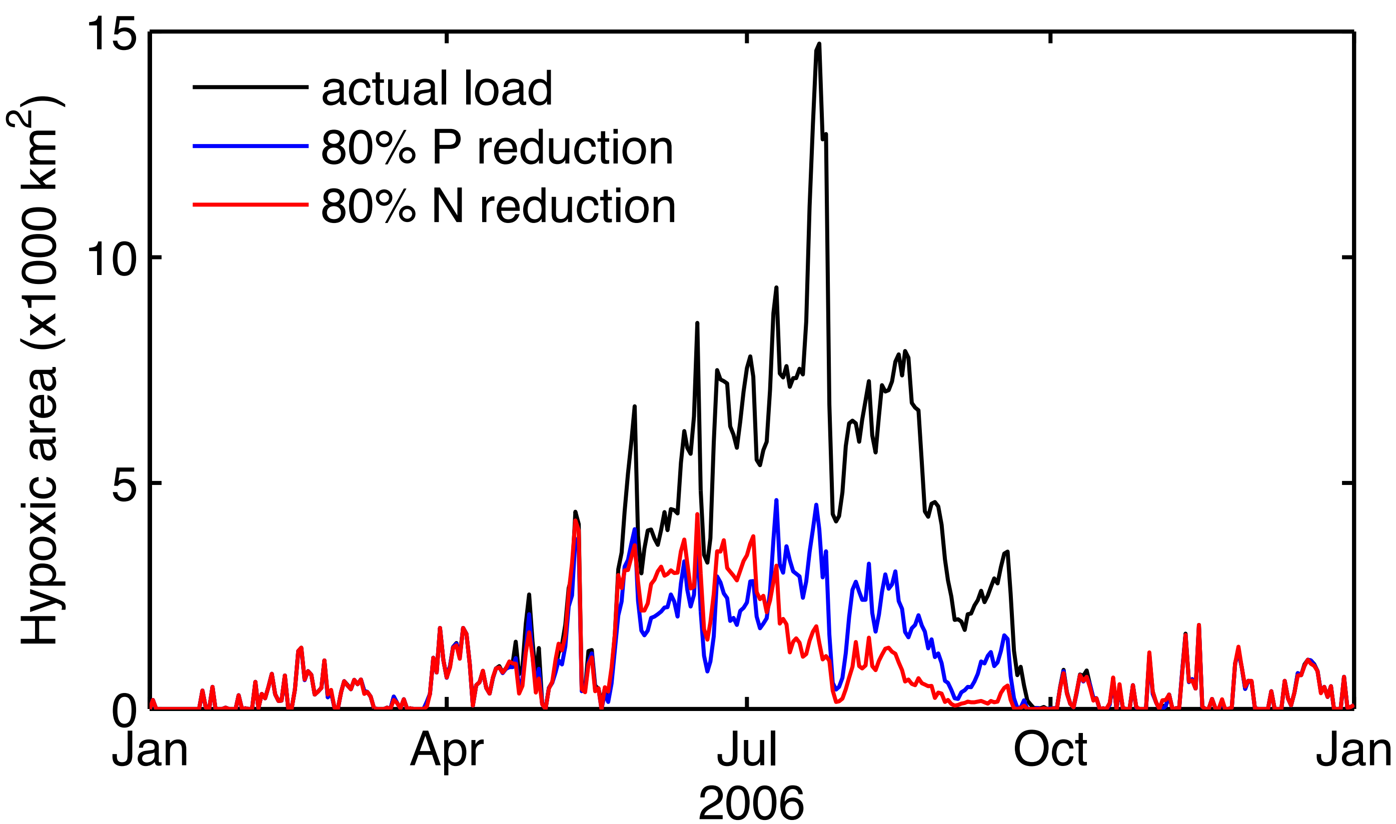
Integrated hypoxic area (H):

Current load: 2.2 x10^3 km^2 yr

50% P reduction: 1.43 x10^3 km^2 yr

50% N reduction: 1.62 x10^3 km^2 yr





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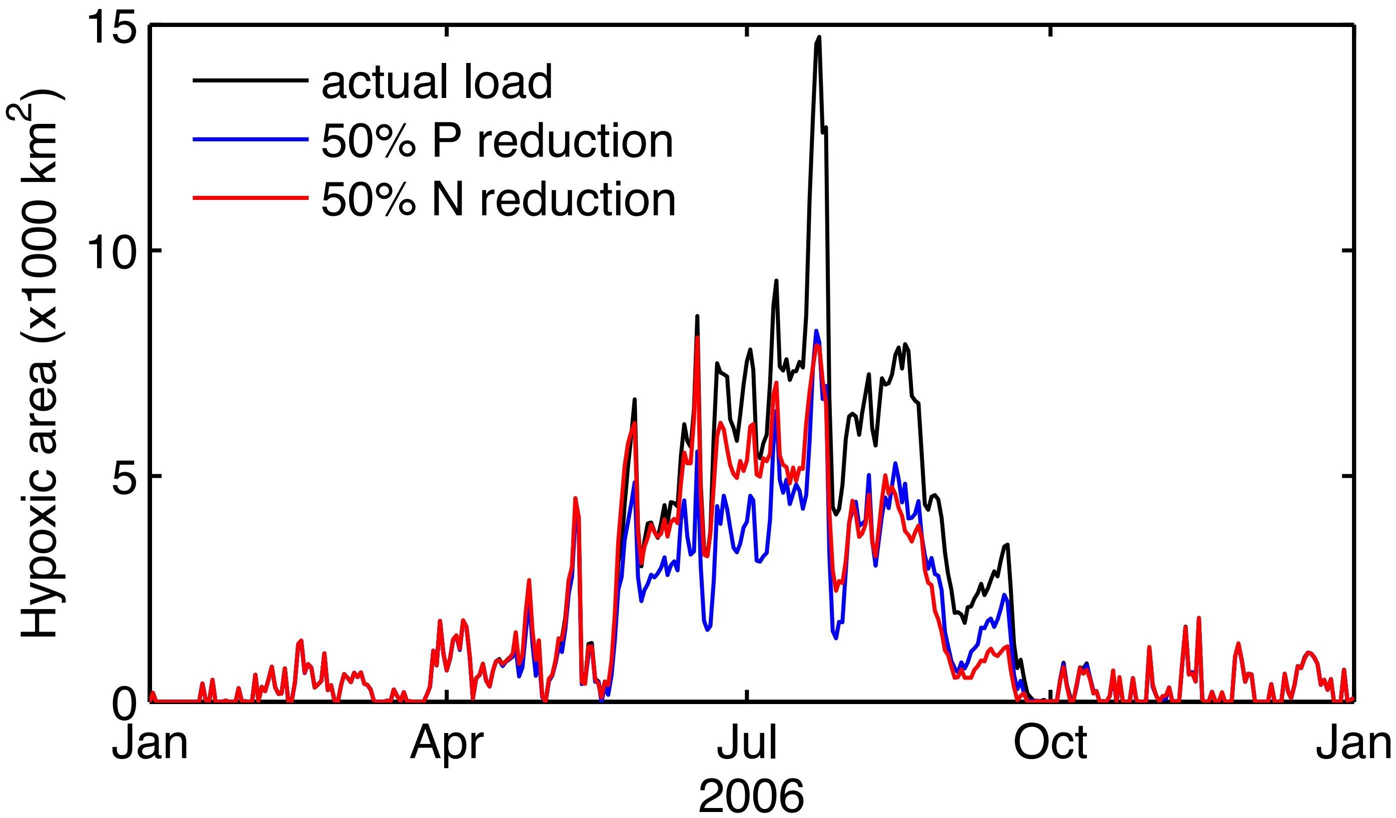

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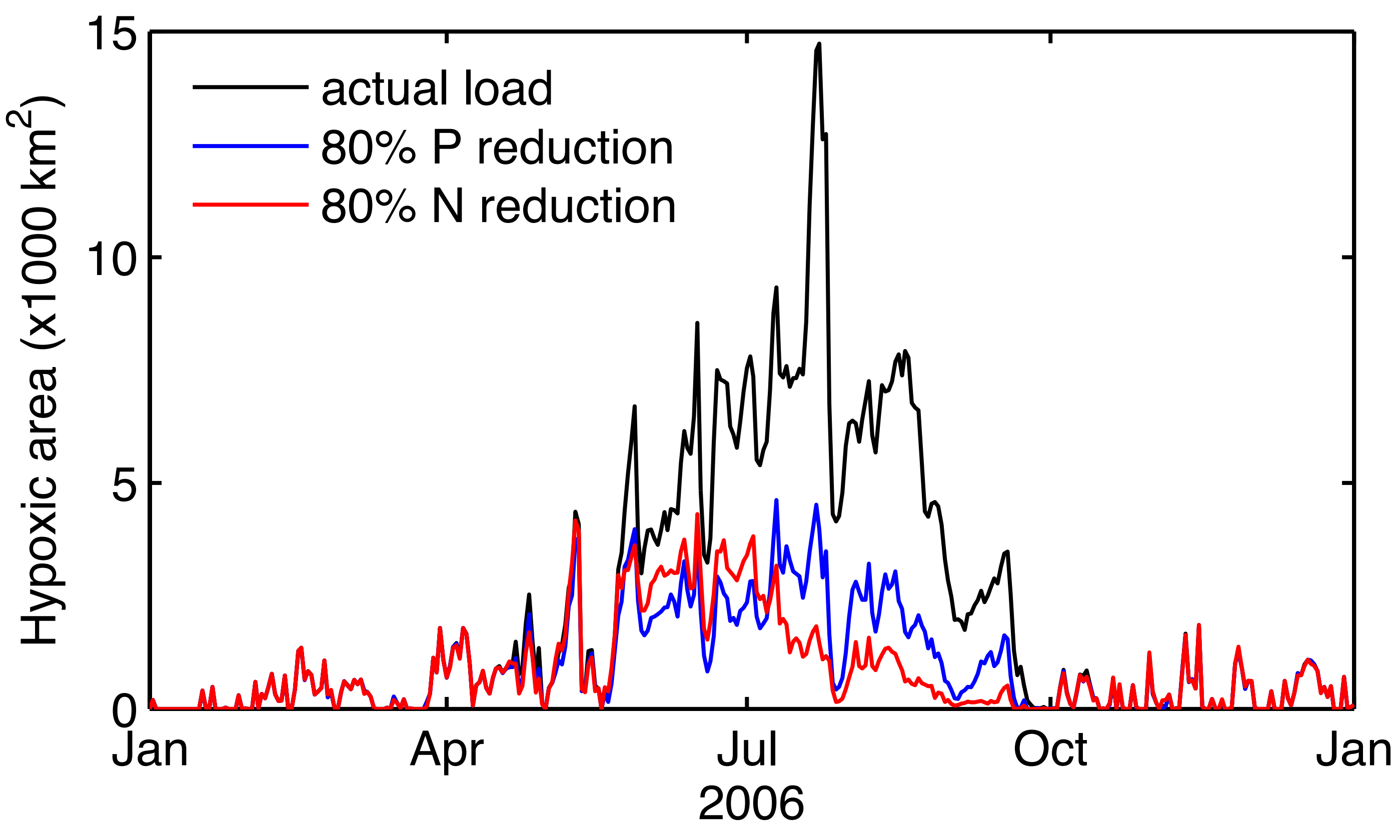
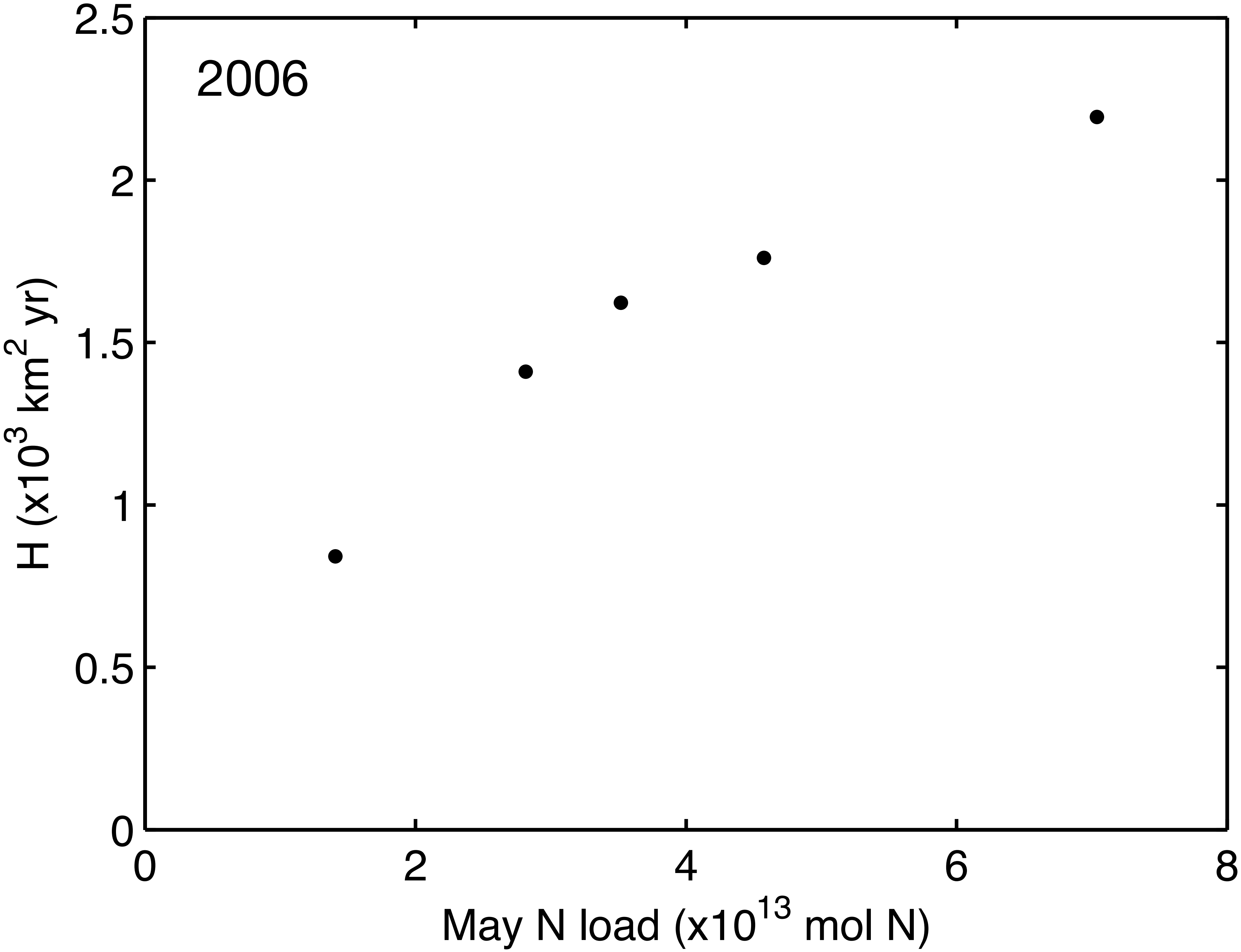
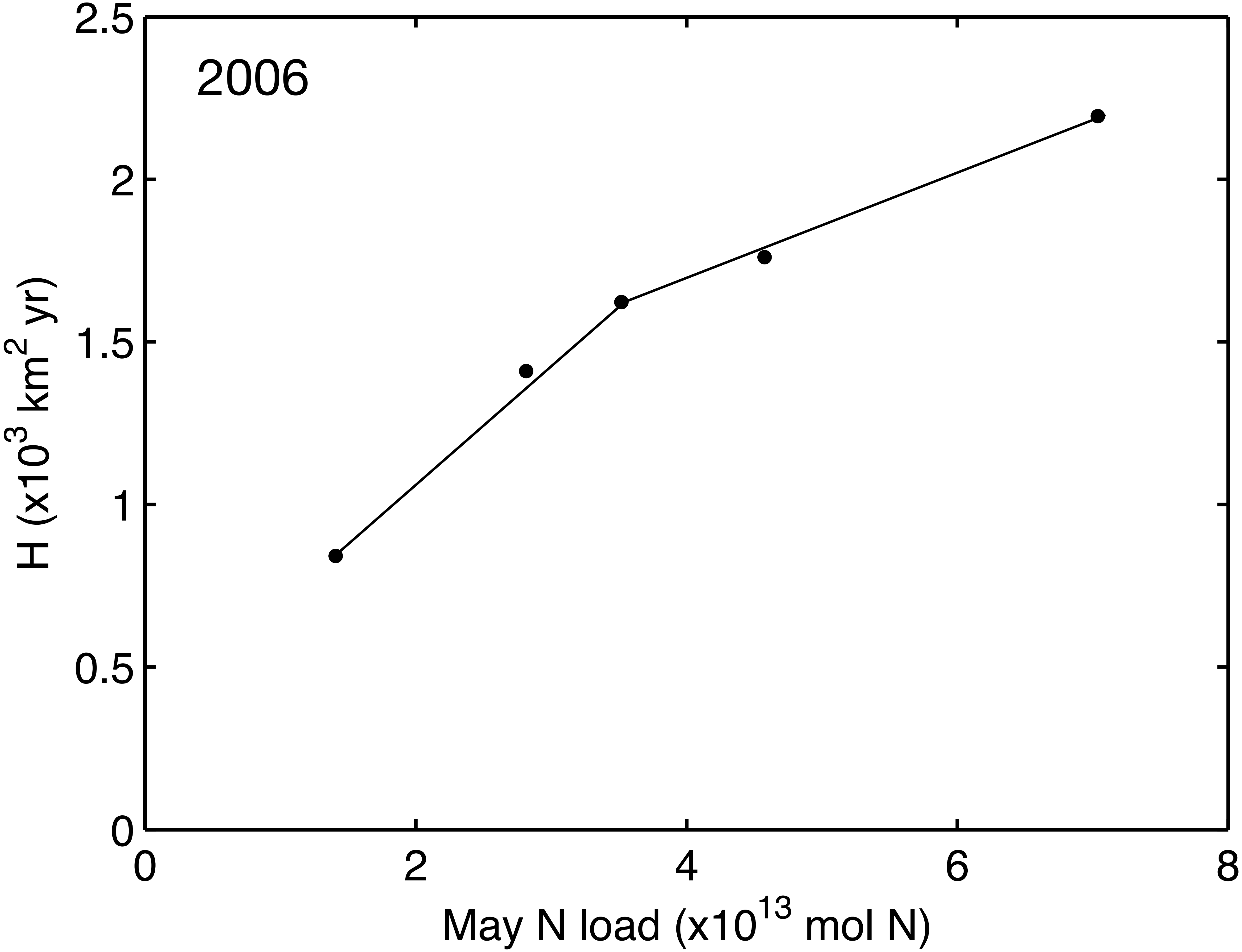


80% P reduction: **0.98** x10^3 km^2 yr

80% N reduction: **0.84** x10^3 km^2 yr



current P load



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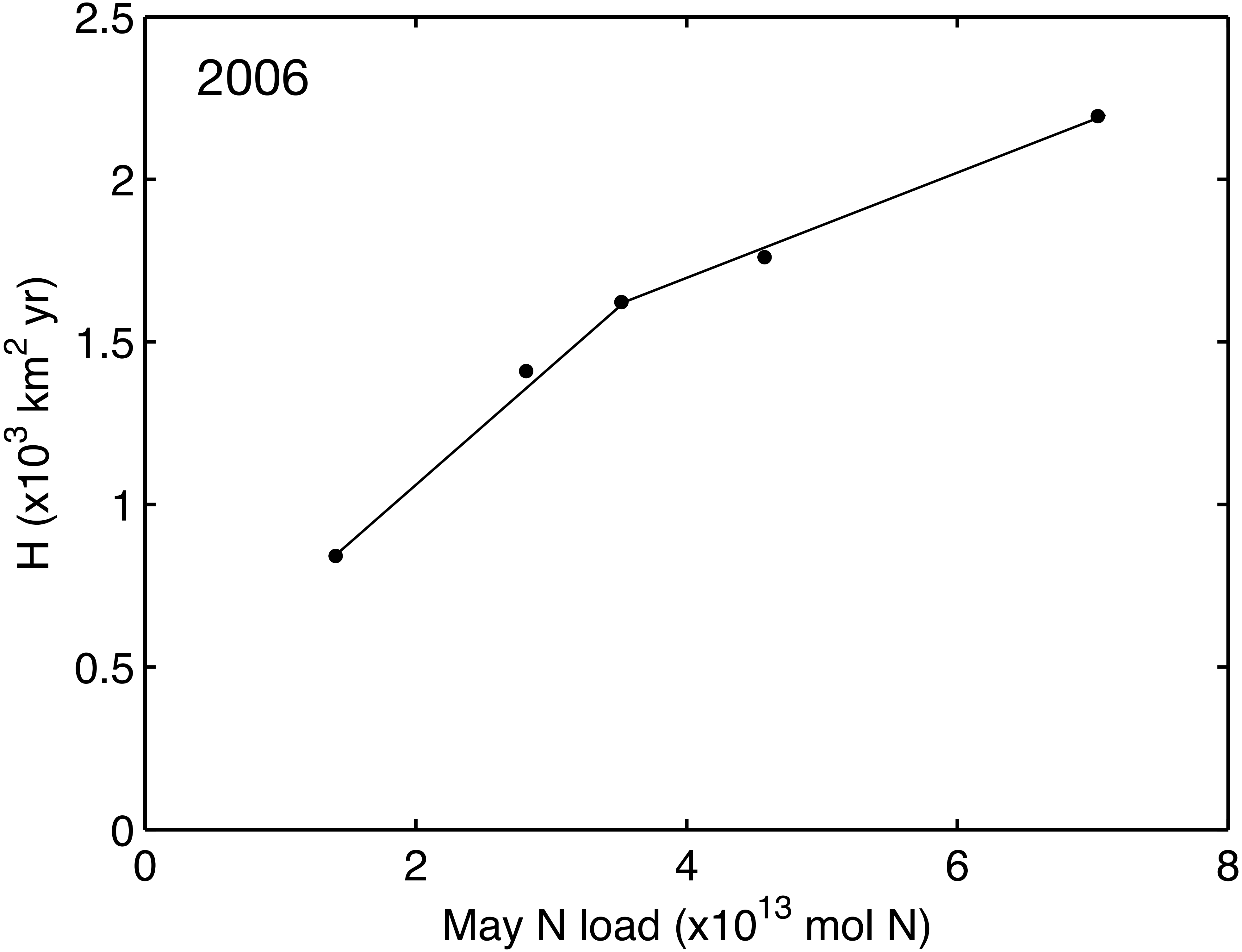

current P load

Sensitivity: S = ΔH(%) / Δload(%)

For S = 1 a 10% reduction in nutrient load will lead to 10% reduction in H.

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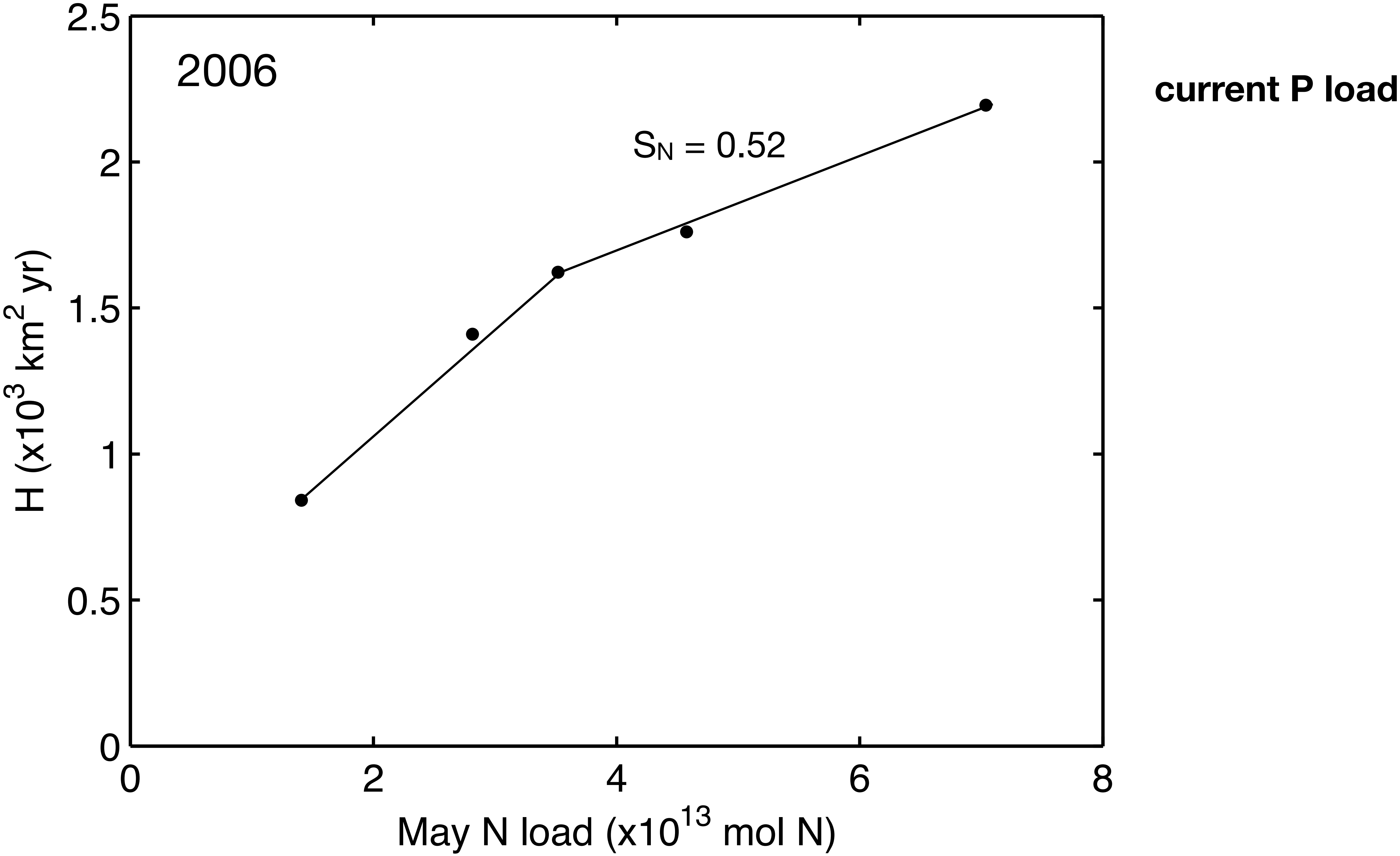

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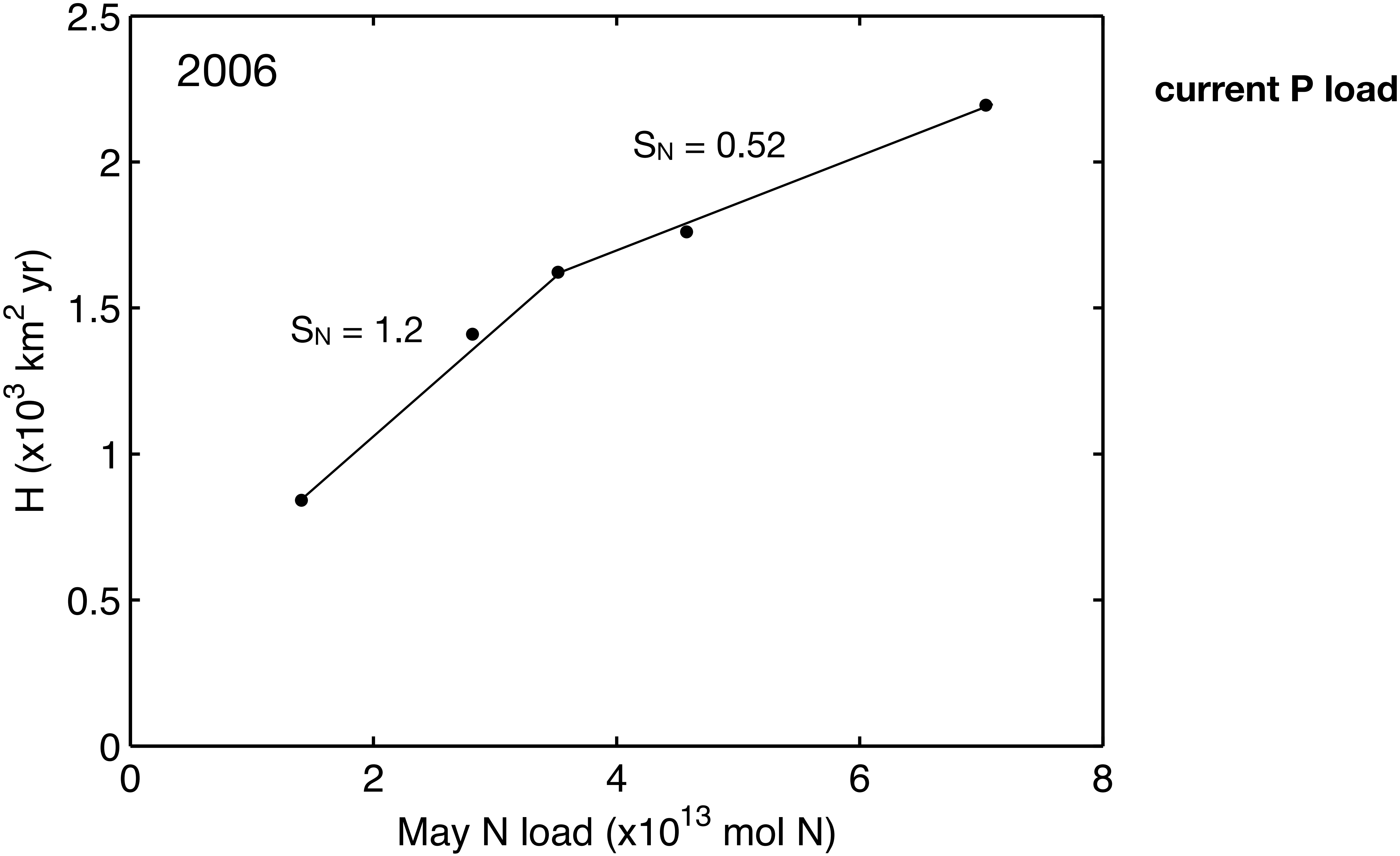

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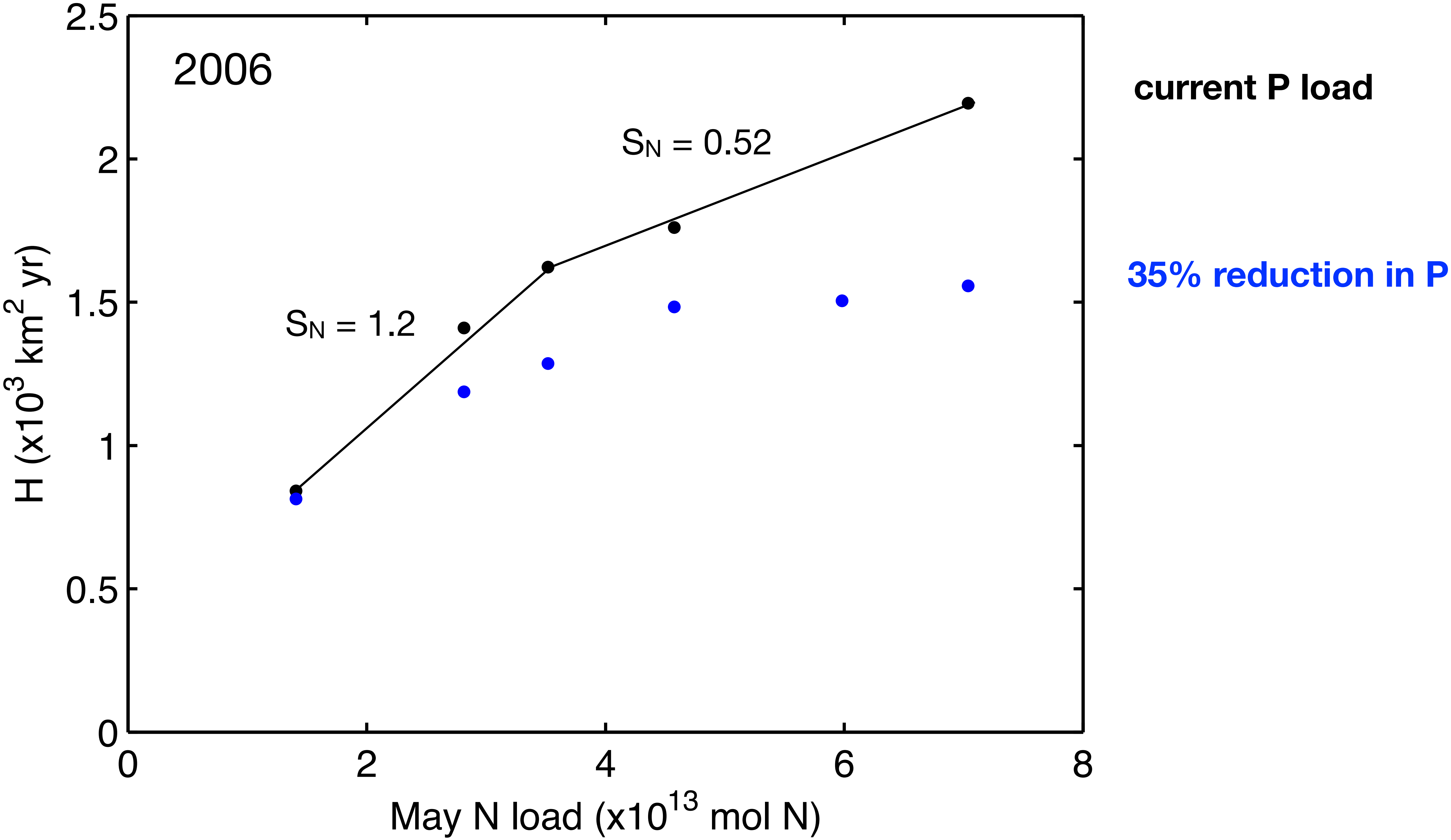

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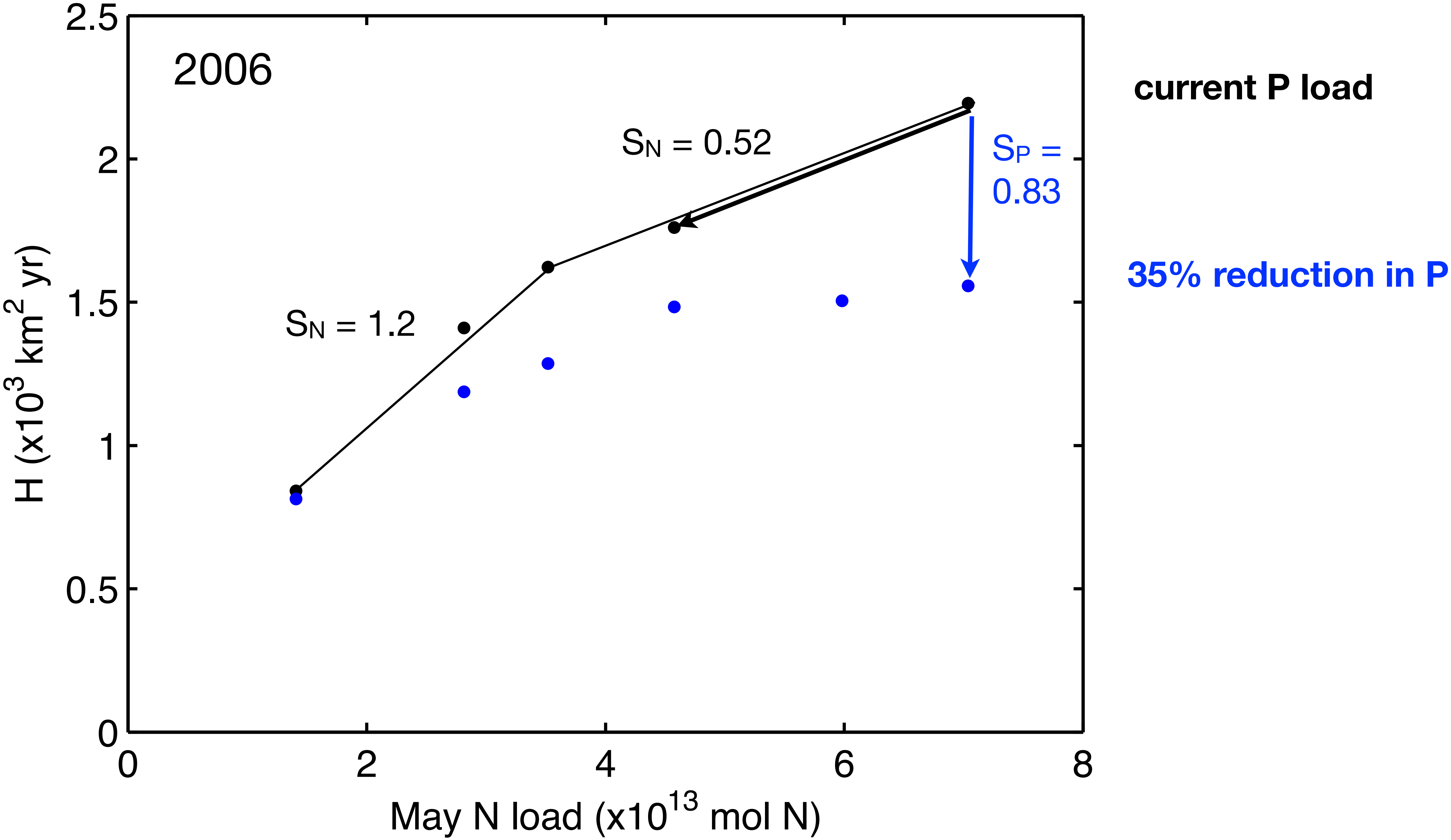

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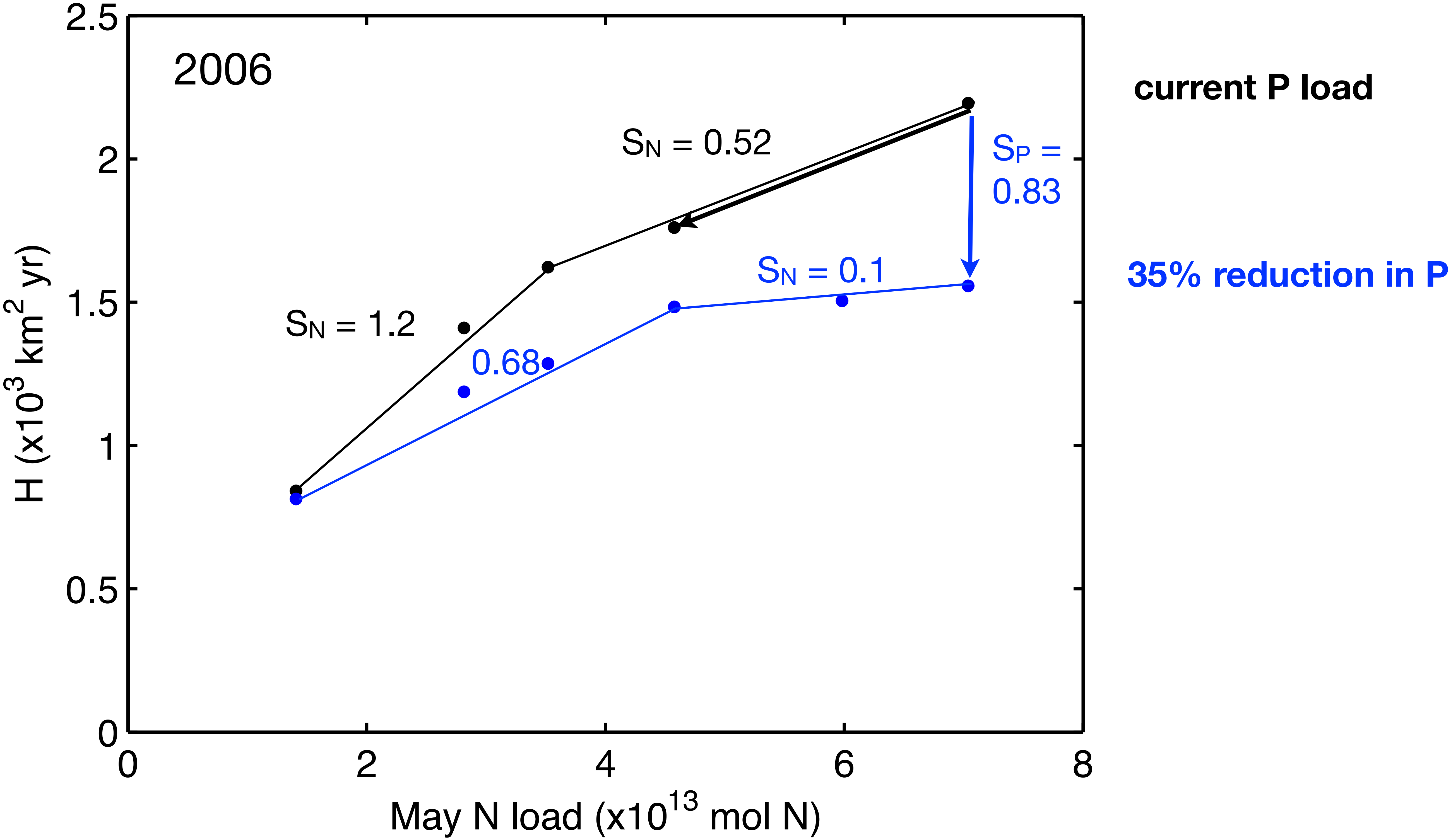

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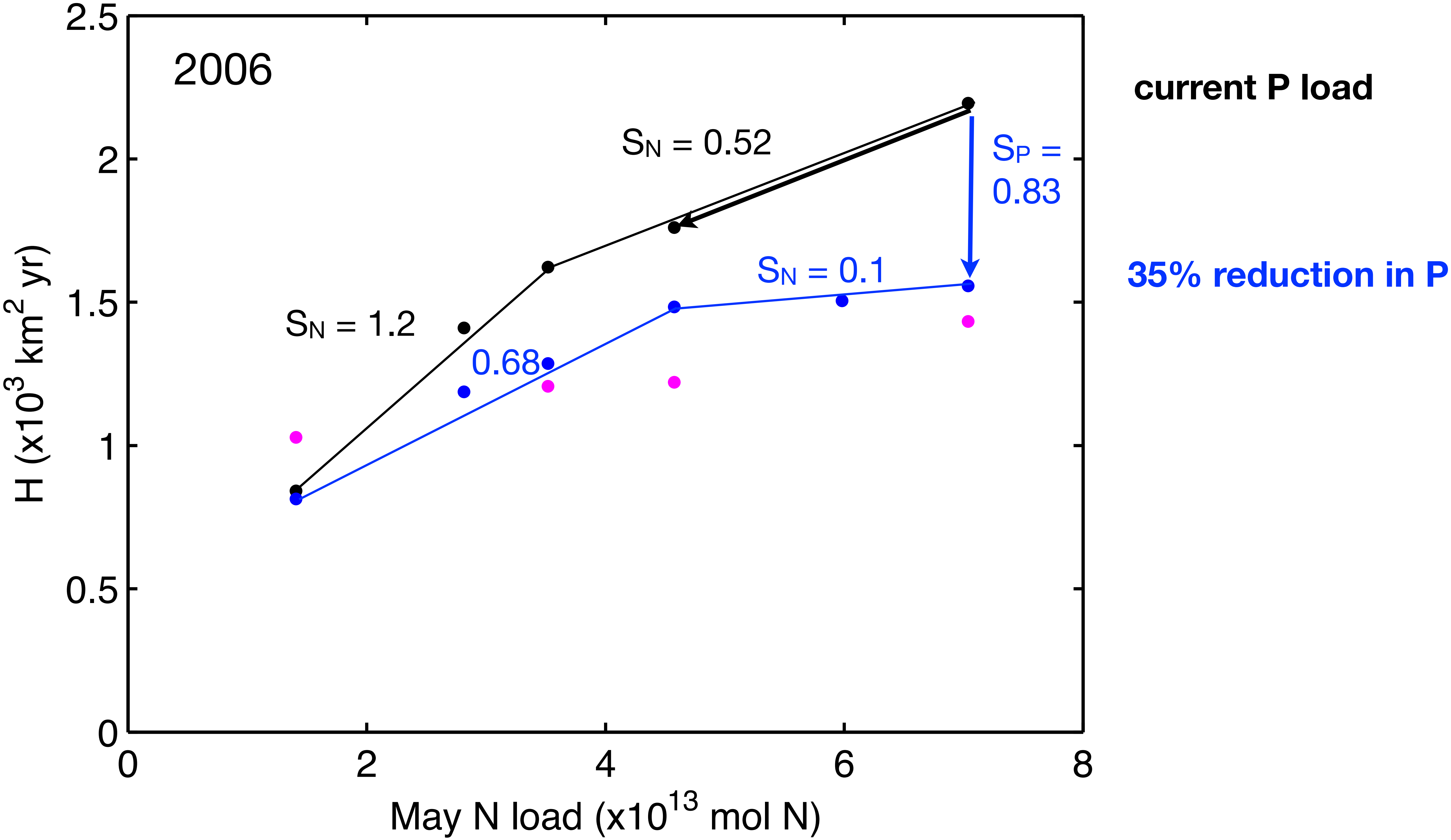

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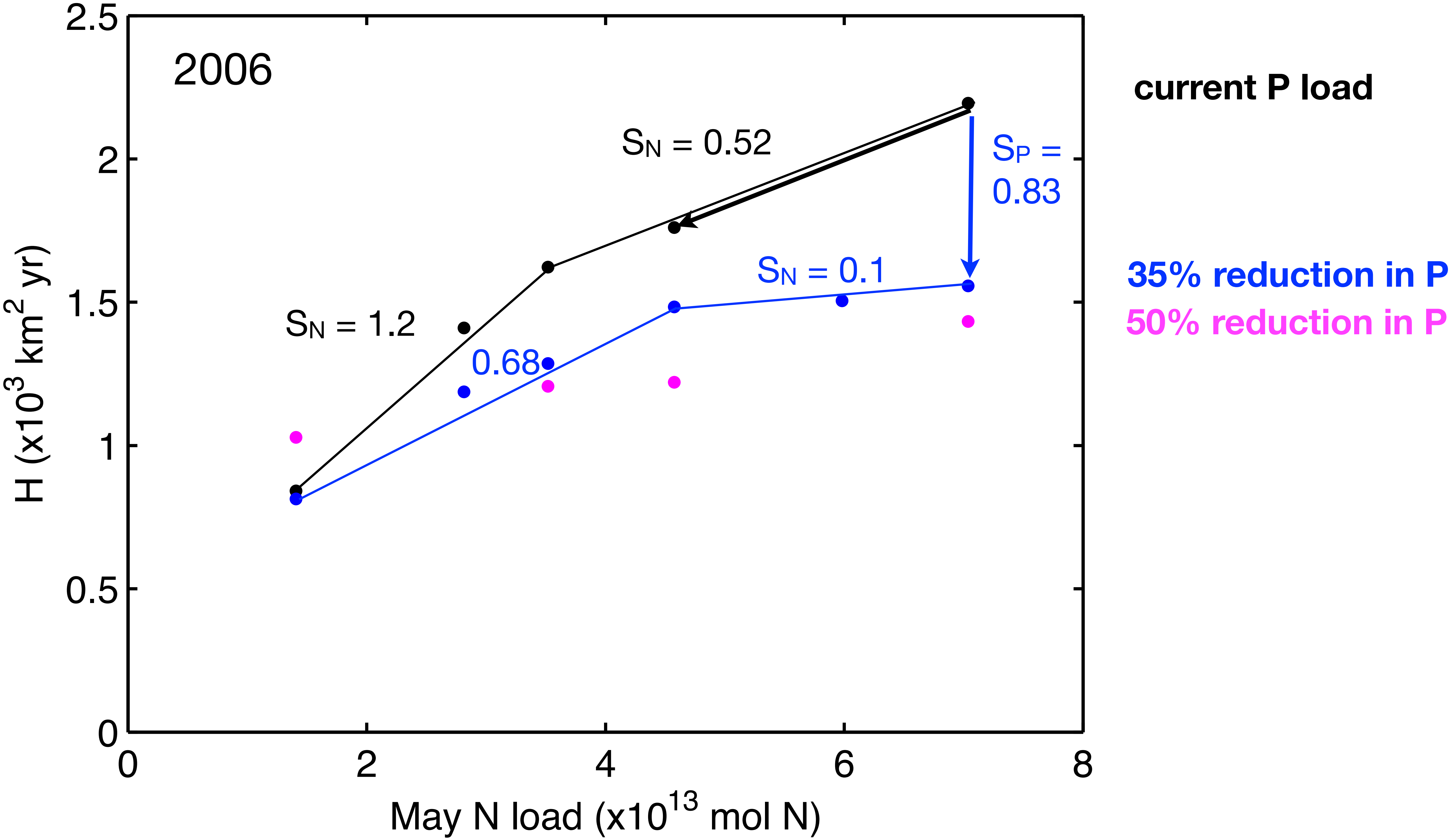

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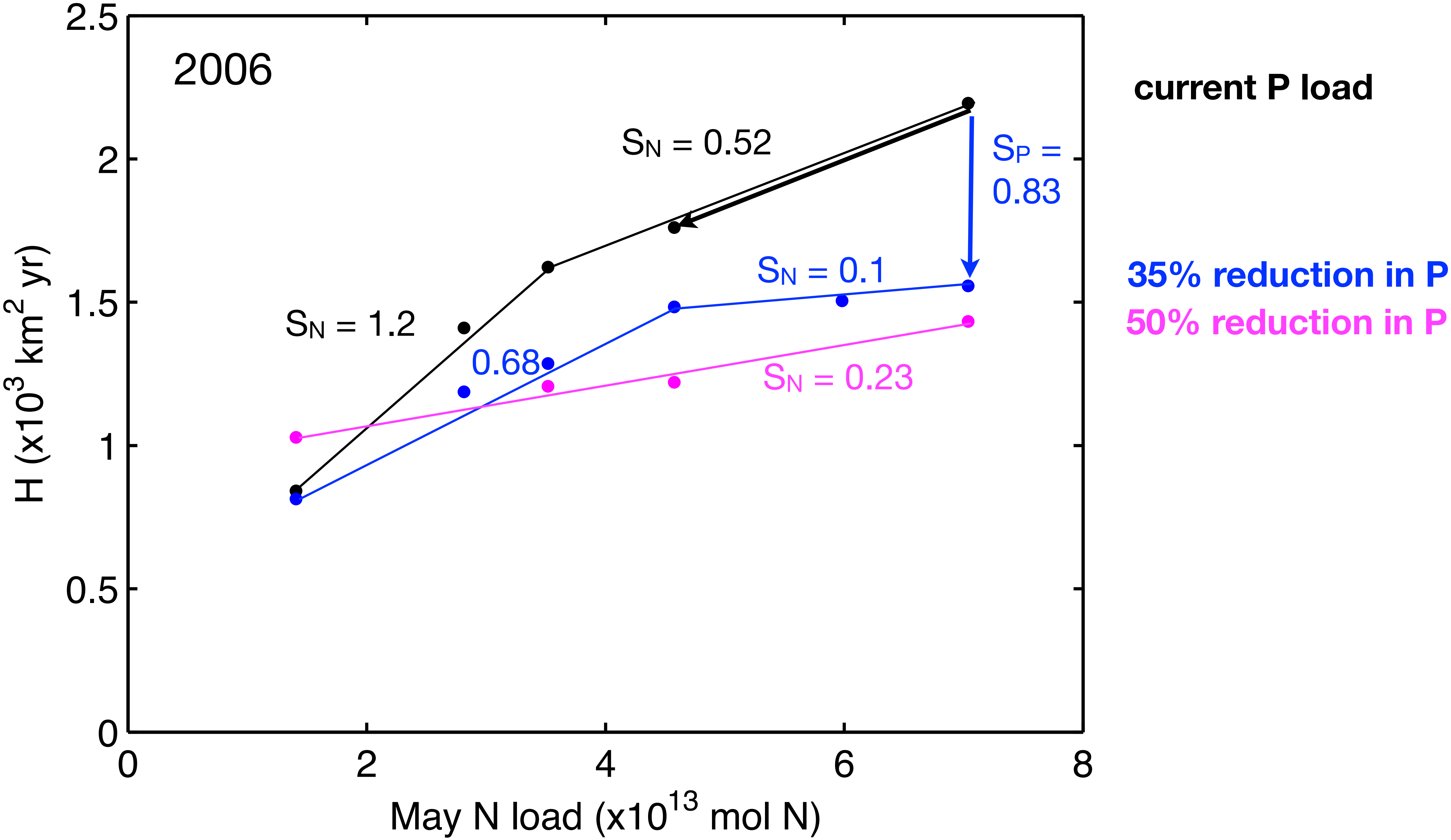

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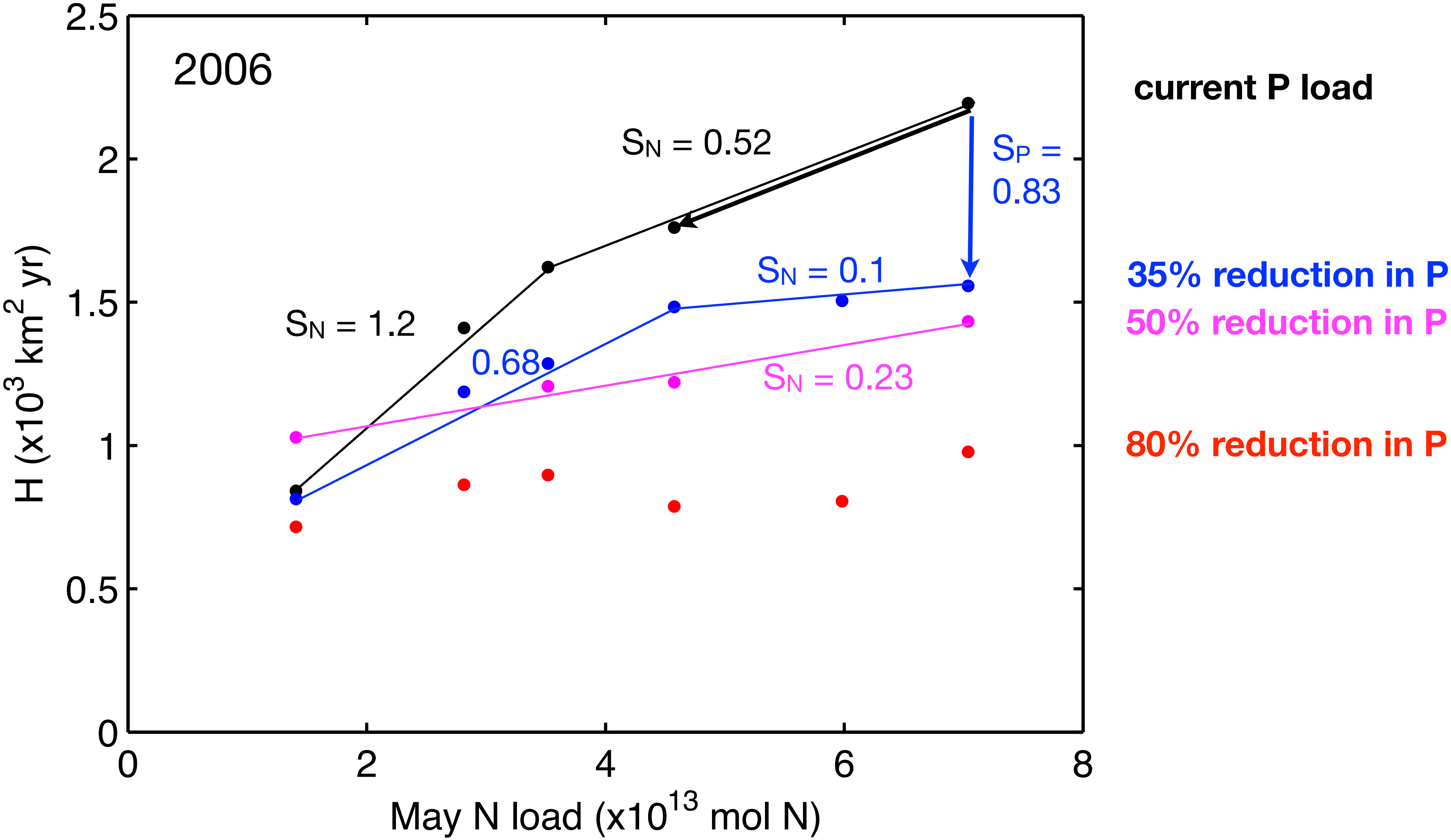

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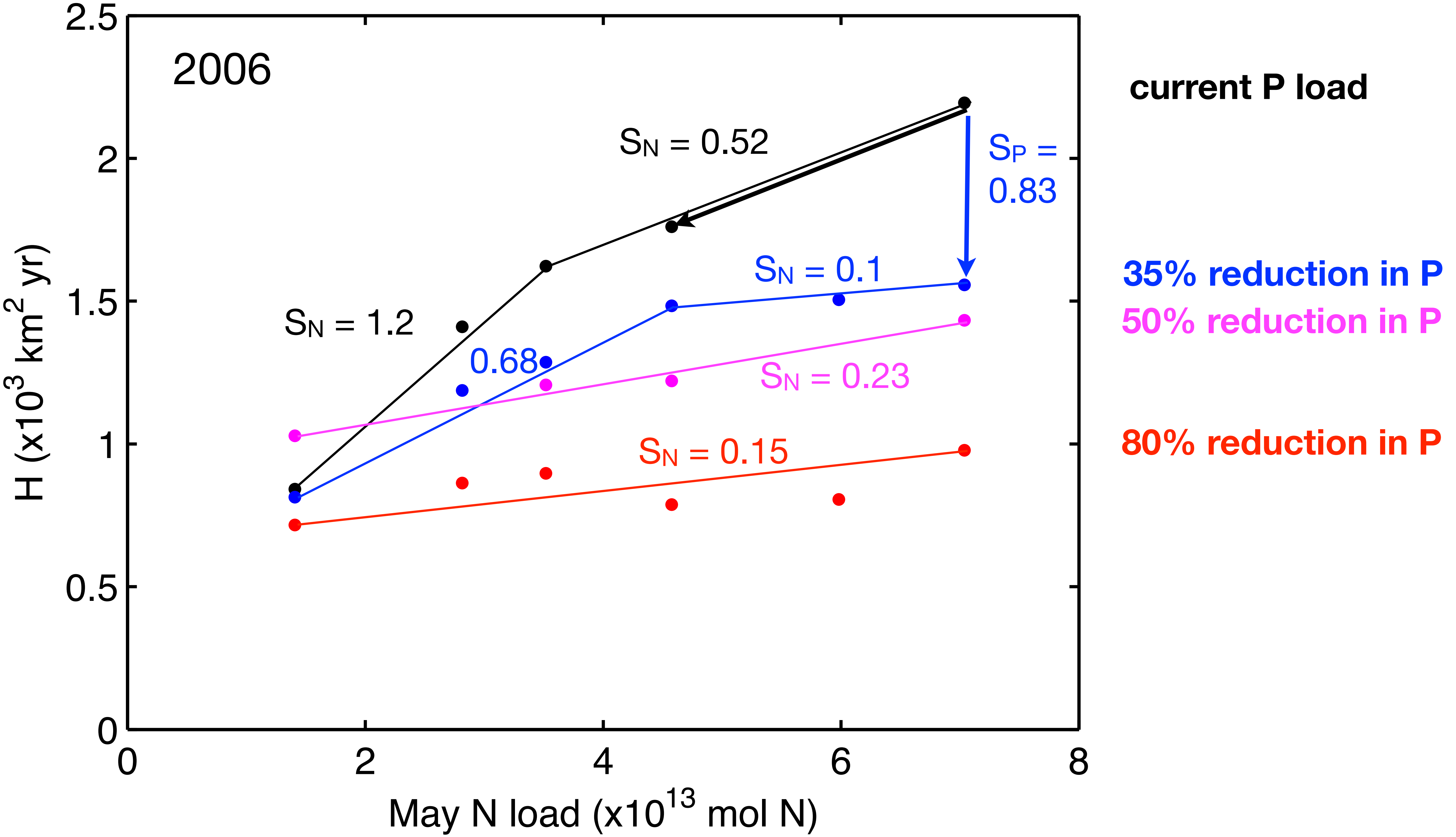

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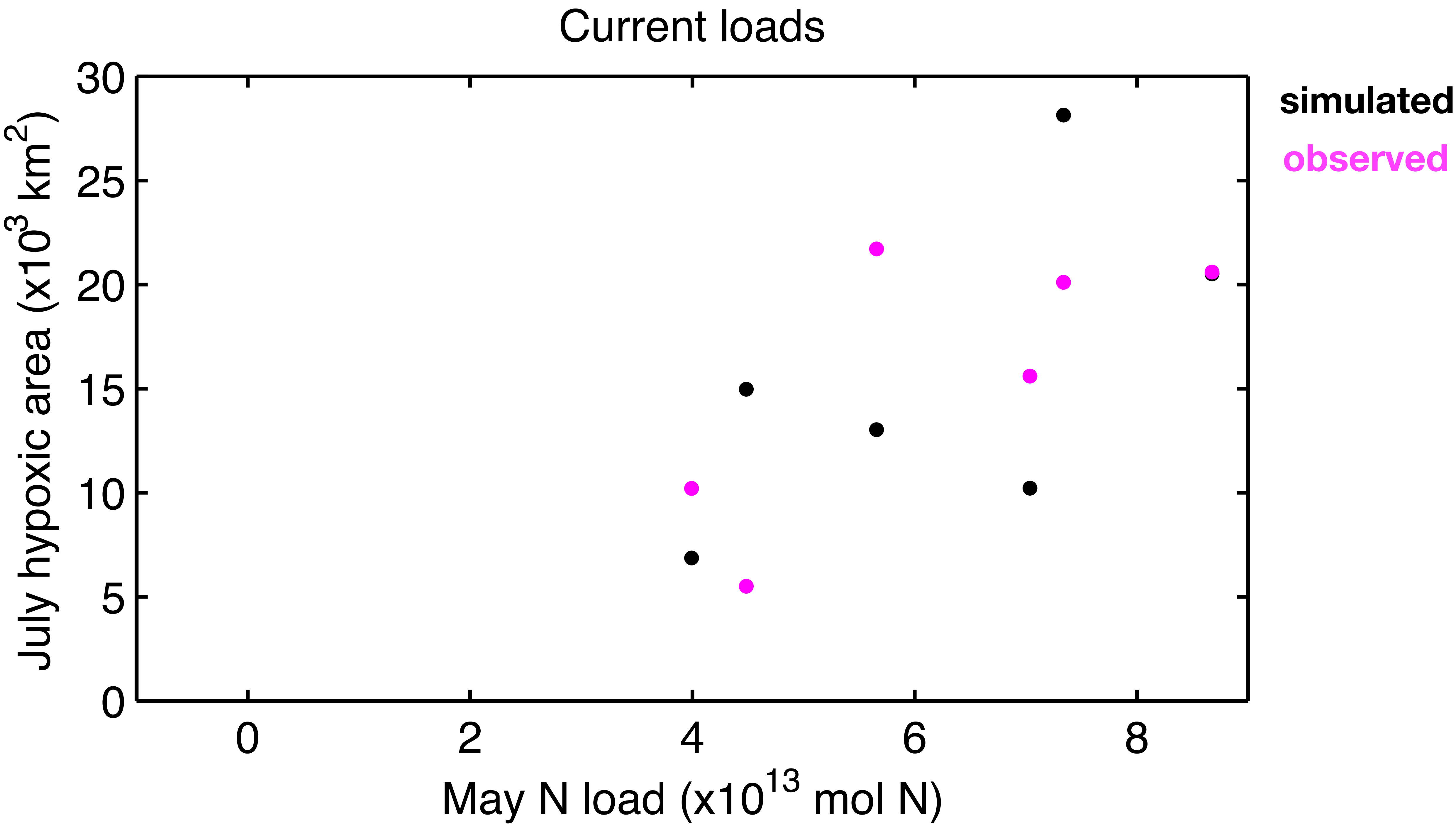
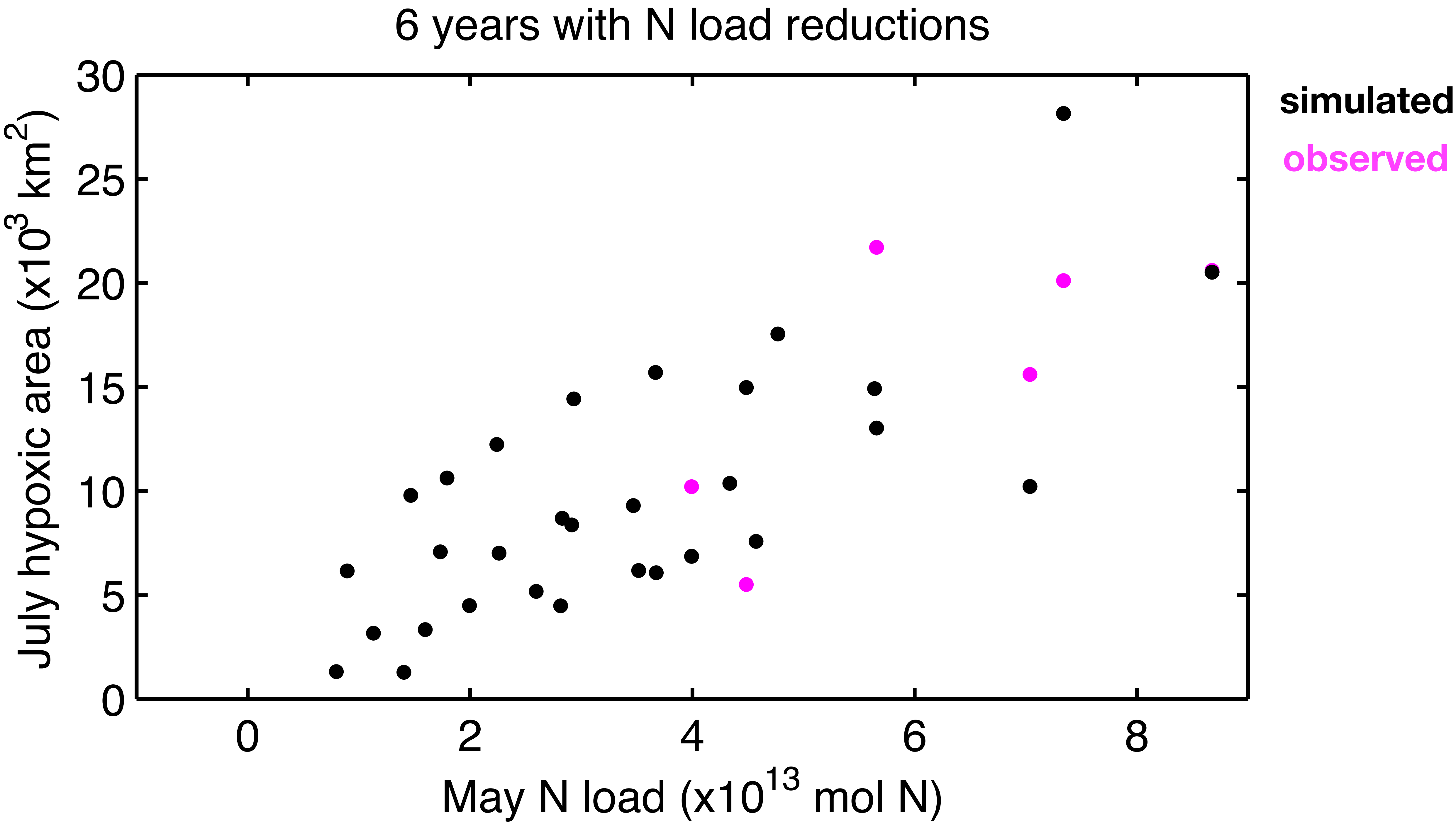
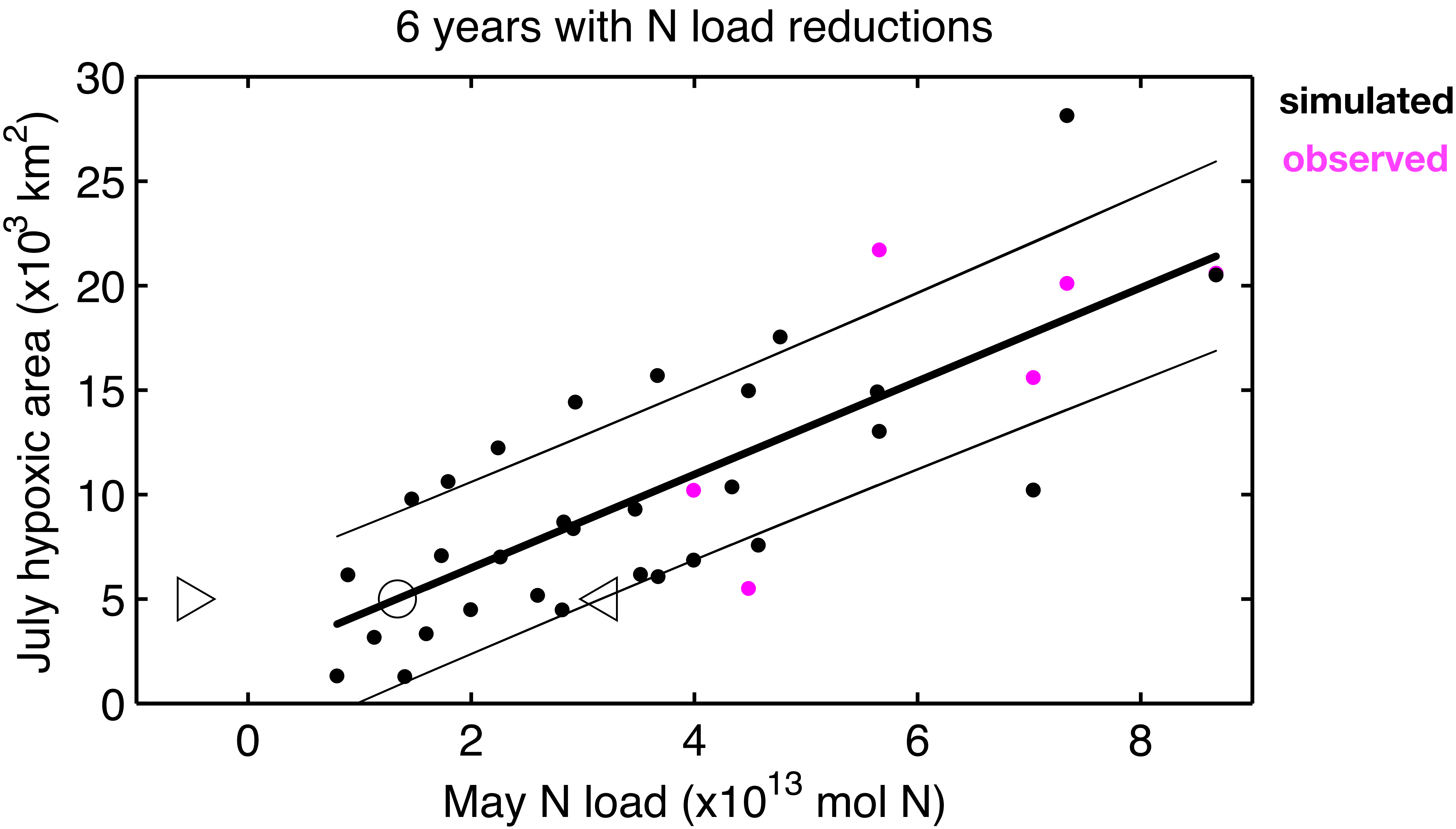


Current loads
July hypoxic area (x10^3 km^2)
30
25
20
15
10
5
0
0
2
4
6
8
May N load (x10^13 mol N)
simulated
observed


6 years with N load reductions
simulated
observed
July hypoxic area (x10^3 km^2)
May N load (x10^13 mol N)
0
5
10
15
20
25
30
0
2
4
6
8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simulated
observed
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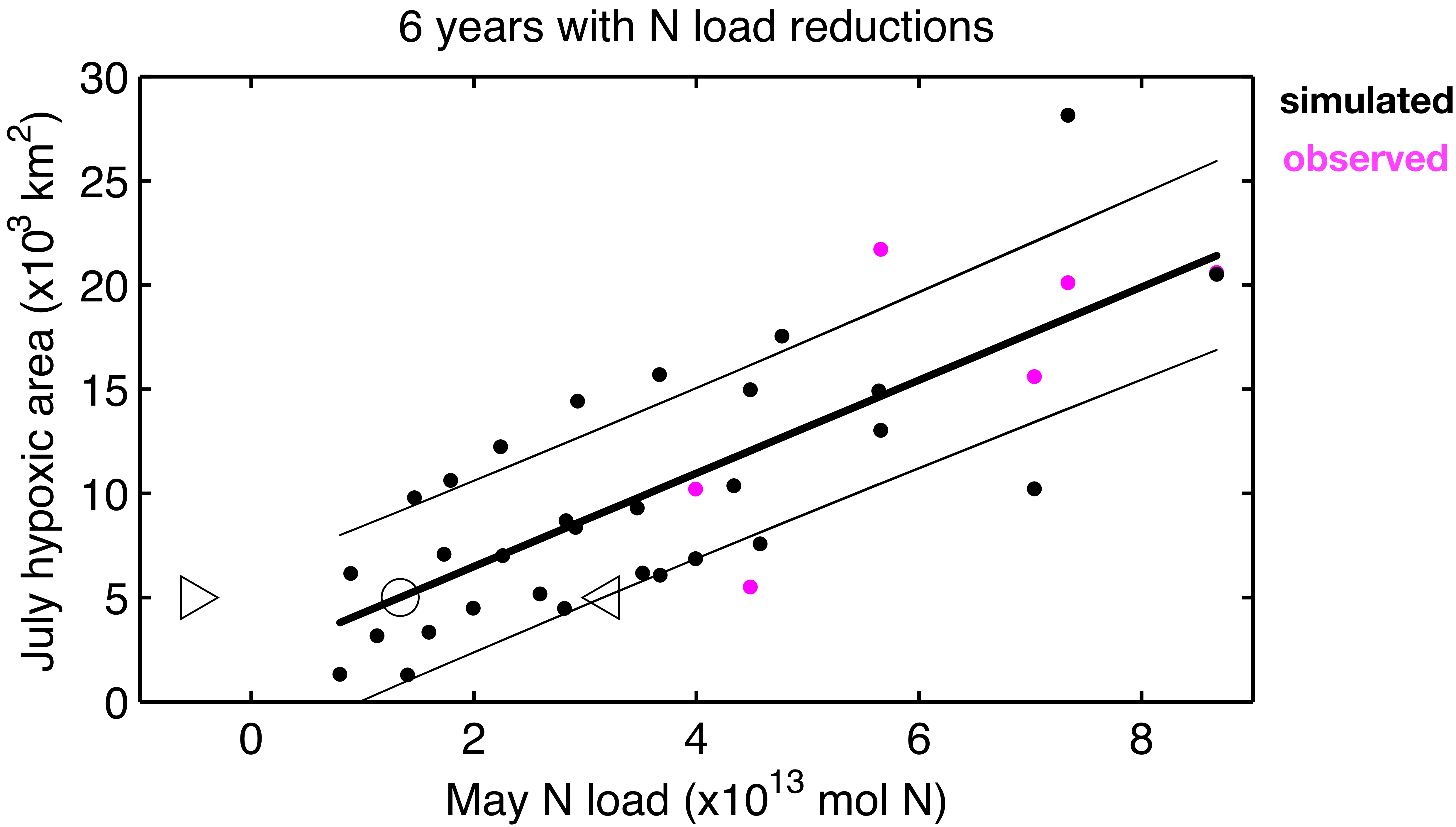
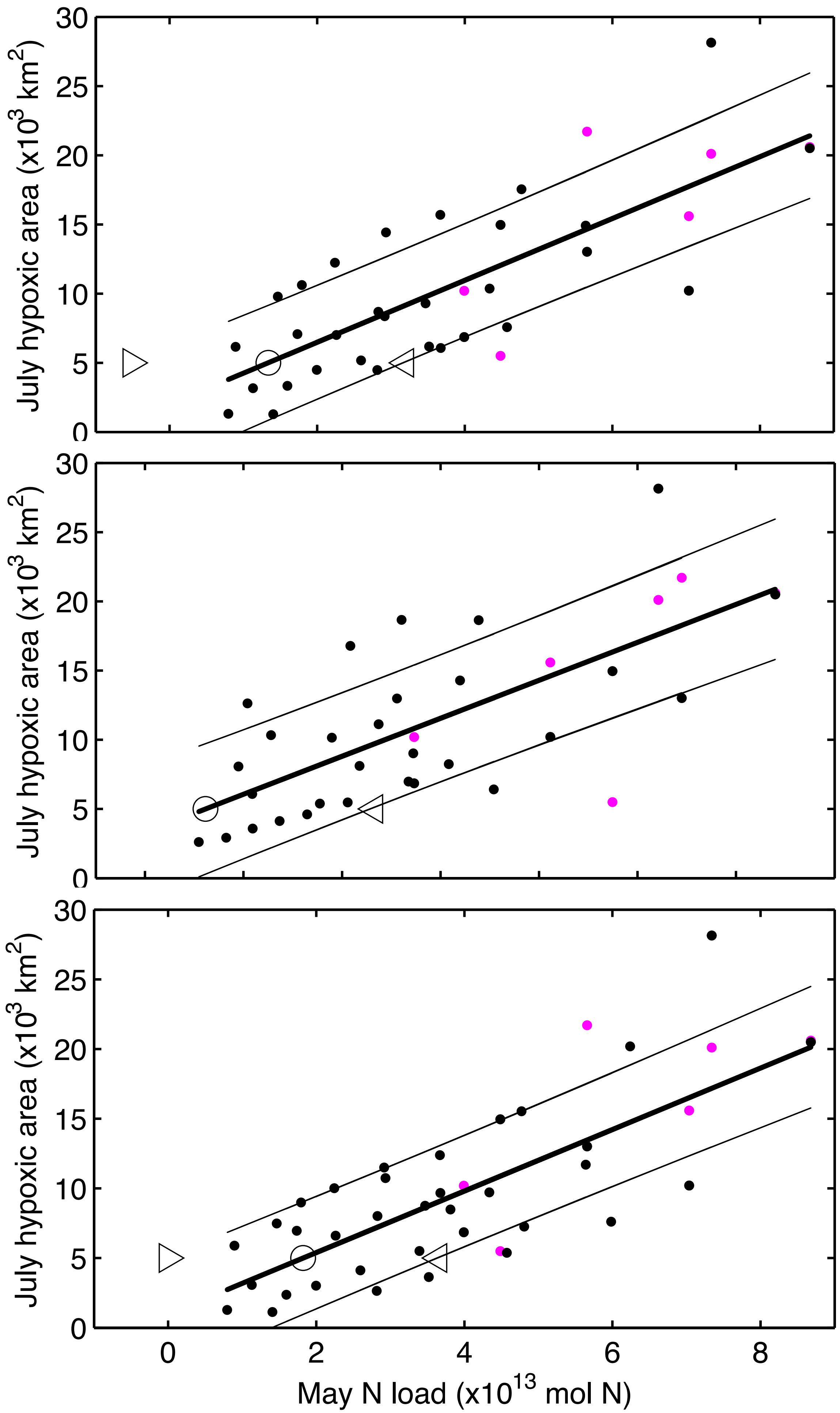
30
25
20
15
10
5
0
0
2
4
6
8



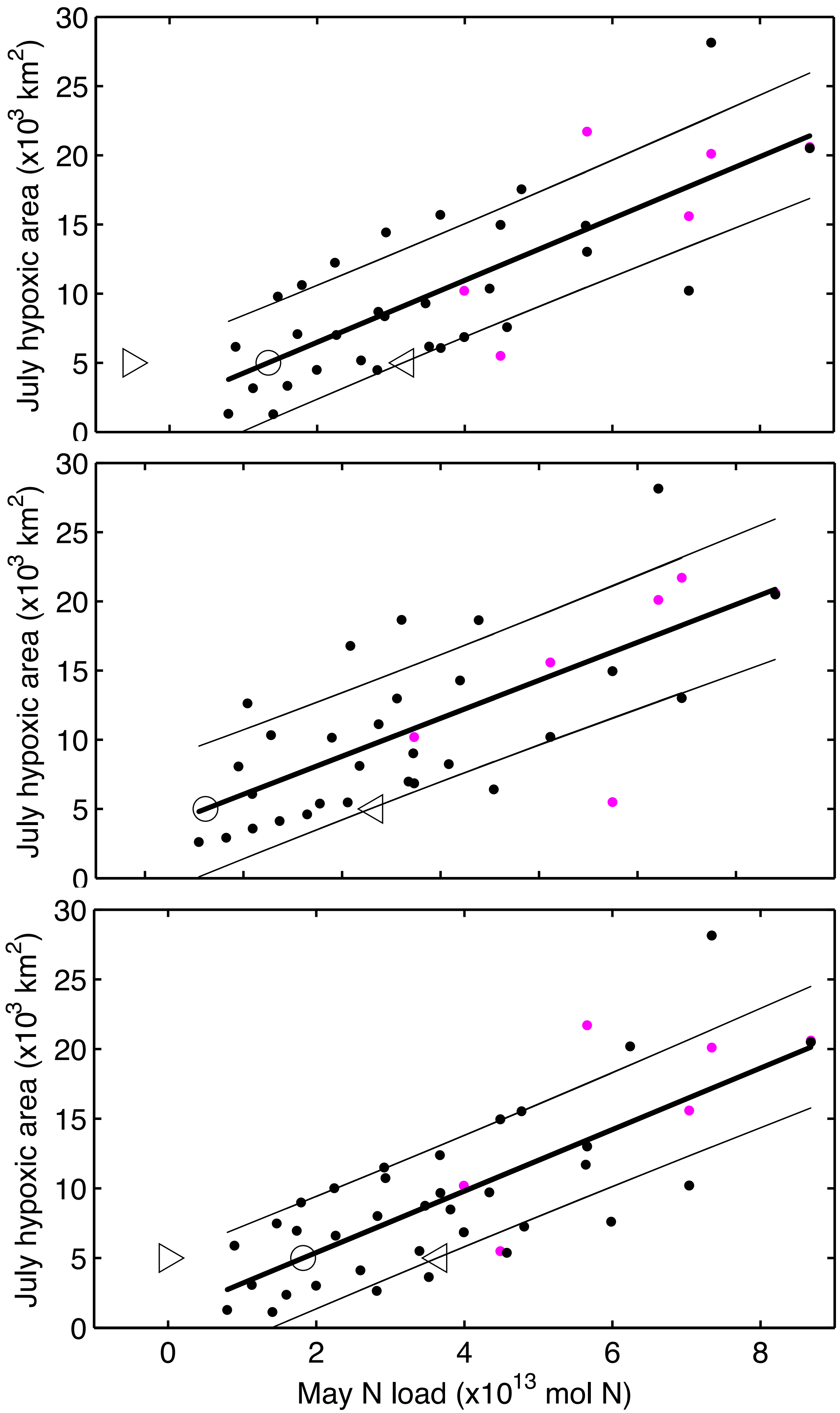
Need 78% +/- 30% N load reduction to reach 5,000 km^2.



78% +/- 30% N load reduction

87% +/- 36% P load reduction

71% +/- 29% N & P load reductions



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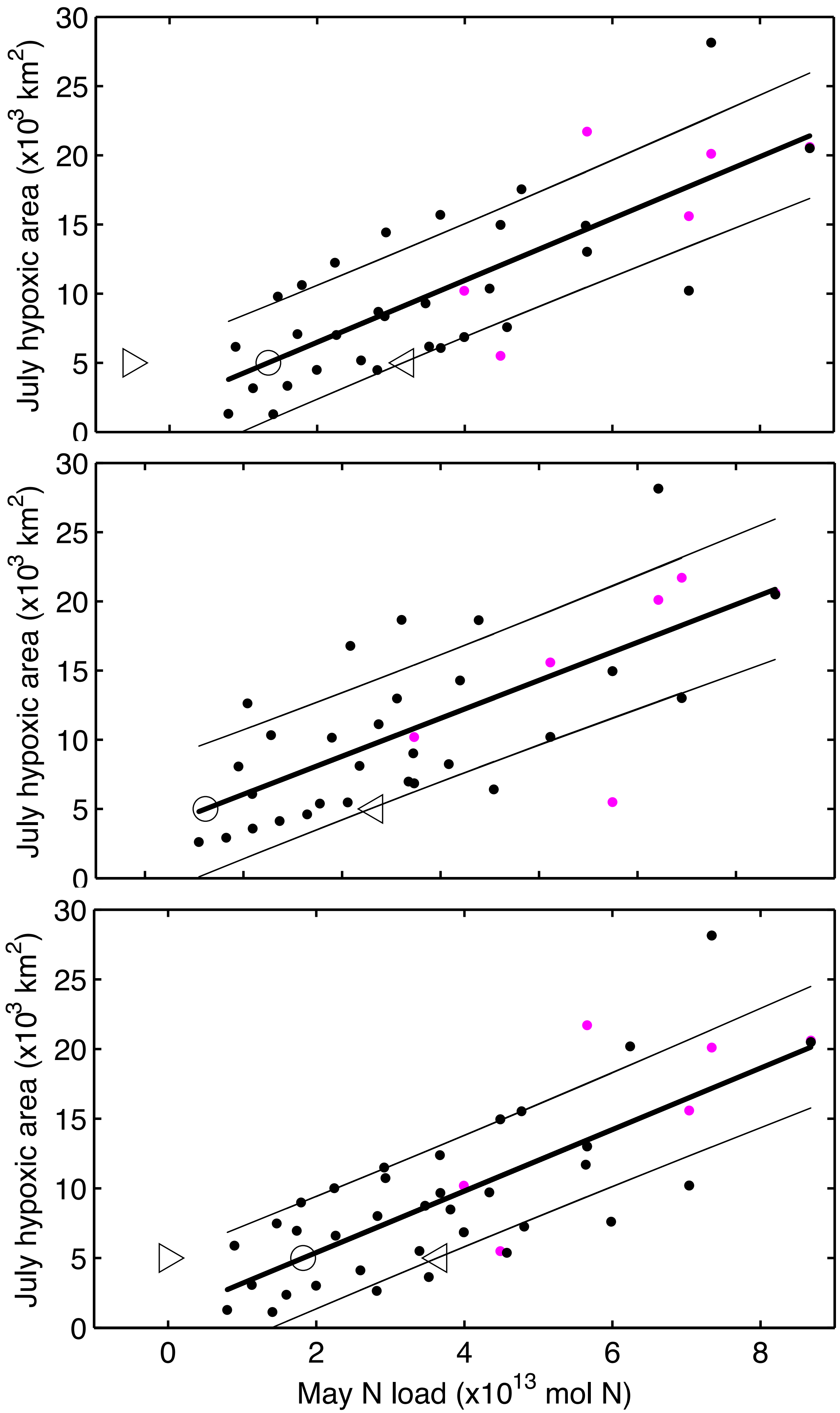
best strategy



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next best

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best strategy

Previous estimates to reach 5,000 km^2 hypoxic area

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Are these ROMS results robust? What do the other models predict?