New NEMURO-based model incorporating the iron cycle

I am sorry that now is just developed new ecosystem model

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A project under 7 projects in our group

GW Pro.,POMAL CREST

Our group activities for improving marine ecosystem model from the original NEMURO

- Introducing subtropical groups as new 4 components [eNEMURO] *Yoshie-san's invited talk in W4*
- Improving each process(e.g., OU kinetics) and introducing iron cycle as new 3 components [nNEMURO?] *My invited talk in W1*
- Improving physical condition: our high resolution model with 1/6 x 1/4 degrees in global domain *Sumata-san's talk in W9*
- Coupling with small pelagic fish as two-way *Okunishi-san's invited talk in S9*
- Future projection (*Just published in GRL*) & Model Intercomparison Project (MAREMIP) *(Hashioka-san's talk on Oct 29th in Cambridge, UK)*

eNEMURO + nNEMURO? → xNEMURO? (probably, within 5 years)

New NEMURO-based model (nNEMURO)

- Iron cycle in the water column

  Introducing two iron components: dissolved & particulate forms
  (Moore et al., 2004; Moore & Braucher, 2008)

- Nutrients uptake by phytoplankton

  Michaels-Menten → considering acclimation to wide nutrient conditions by Optimal Uptake Kinetics for multi-nutrients
  (Smith & Yamanaka, 2008; Smith et al., 2009)

- Photosynthesis

  Steele (1965) → no considering strong light inhibition (Platt et al., 1980)

- Sinking particles

  Two types of sinking particle, small and large POMs, considering aggregation process (Kriest & Evans., 1999; Aumont & Bopp, 2006)

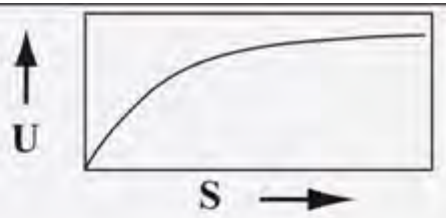
- Optimum parameter estimation by genetic algorithm

  1-D model assimilated to the observed monthly means of NO_3, $Si(OH)_4$, PS, PL, ZS, ZL, ZP at A4, KNOT, Station P, B1(Subtropical)
  (Okunishi et al., in prep.)

Nutrient Uptake: M.-M. → Optimal Uptake

Michaelis-Menten (MM) Equation

$$\text{Uptake Rate, } U(S) = \frac{V_{max}\, S}{[\, K_s + S\,]}$$



Affinity-based Equation *(Aksnes & Egge, MEPS, 1991)*

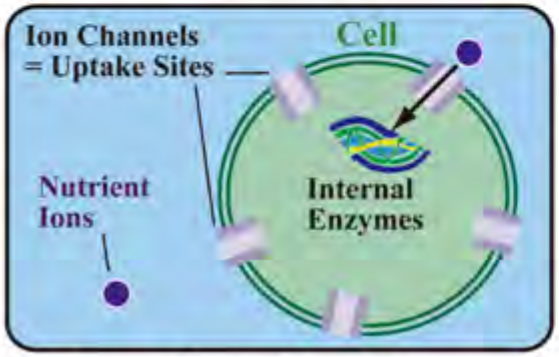
$$V(S) = \frac{1}{[\,(A_s\, S)^{-1} + (V_{max})^{-1}\,]}$$

More general
Reduces to MM as a special case

Optimal Uptake (OU) Equation *(Pahlow, MEPS, 2005)*

Uptake Sites	more sites	=> Greater Affinity, **A** (lower K_S)
Internal Enzymes	more enzymes	=> Greater $\mathbf{V_{max}}$

Both are mostly protein & contain lots of N.



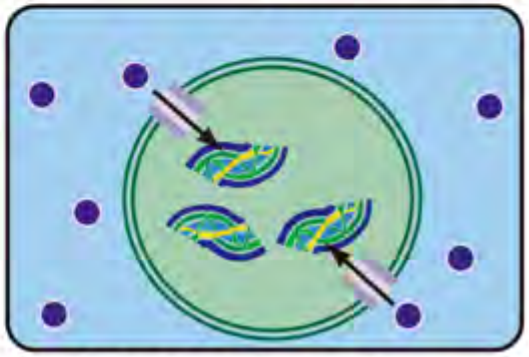
Low Nutrient Conc.

f_A = **fractional allocation of internal N:**

$$A = A_0\, f_A$$

$$V_{max} = V_0\,(1 - f_A)$$

Acclimation



High Nutrient Conc.

Apearent half-saturation "constant" as a function of nutrient

Equations for the Rate of Nutrient Uptake.

The New OU Equation (Pahlow, MEPS, 2005):

$$V_{OU} = \frac{V_0 S}{\left(\frac{V_0}{A_0}\right) + \left(\frac{V_0 S}{A_0}\right)^{0.5} + S}$$

This is like a MM equation with

$$K_S = \left(\frac{V_0}{A_0}\right) + 2\left(\frac{V_0 S}{A_0}\right)^{0.5}$$

This predicts how K_S values (fit to the MM eqn.) should vary with nutrient concentration.

For multi-nutrients, the **limited** nutrient determines Ks for the others

The Classic Michaelis-Menten (MM) Equation:

$$V_{MM} = \frac{V_{max} S}{K_S + S}$$

K_S is called the Half-Saturation "constant".

But it is well-known to vary as a function of:

- Nutrient Concentration
- Species
- Temperature

Does this explain the observed variations in Half-Saturation "constants" as a function of nutrient concentration?

Dependence of K_{NO3} on Nitrate concentration in Field Studies

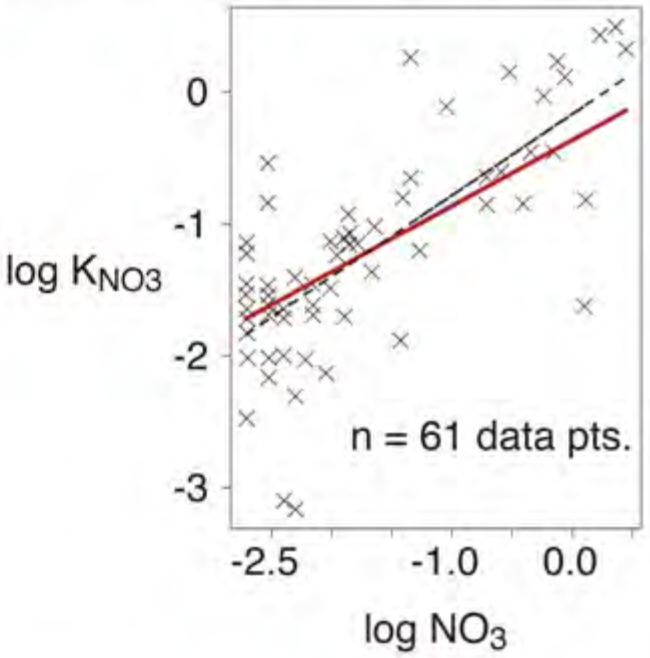
Harrison et al (Limnol. Oceanogr., 1996) N. Atlantic
McCarthy et al (Deep Sea Res. II, 1999) Arabian Sea

which used similar methods.
This provides an independent test,
over wide regions of the ocean,
and over wide ranges of concentration.

Significant relationship (b != 0) at level $p < 10^{-10}$
$r^2 = 0.54$ for the general equation
$r^2 = 0.52$ for the eqn. with b = 0.50

b is not significantly different from 0.50
(ANOVA, $p < 0.119$)
The data is cosistent with OU kinetics.

Data (x) compiled from 2 studies

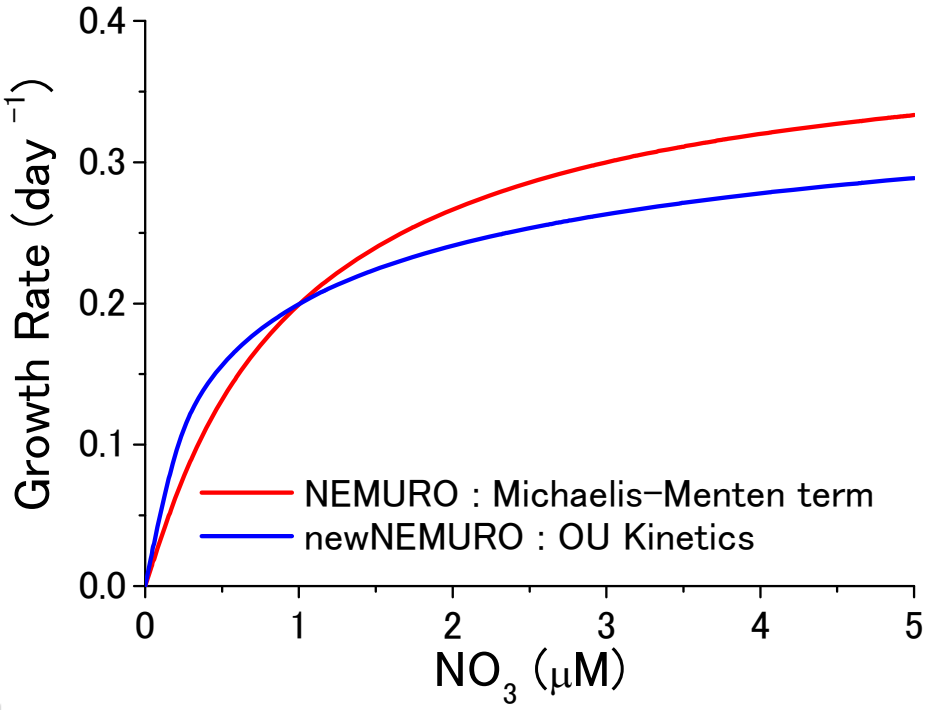


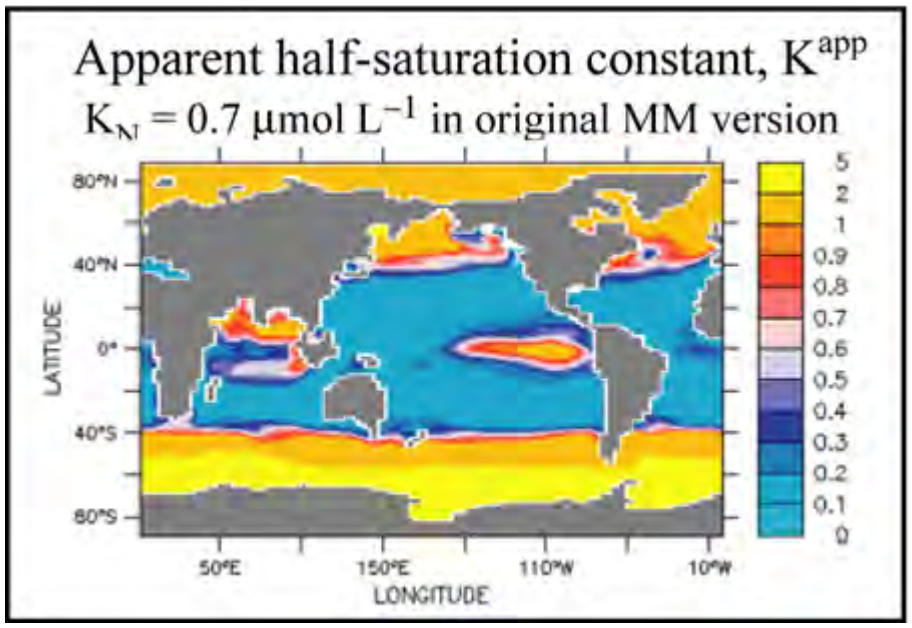
Least-squares fits to the data:

------ log Ks = – 0.17 + 0.62 log NO_3
——— log Ks = – 0.36 + 0.50 log NO_3

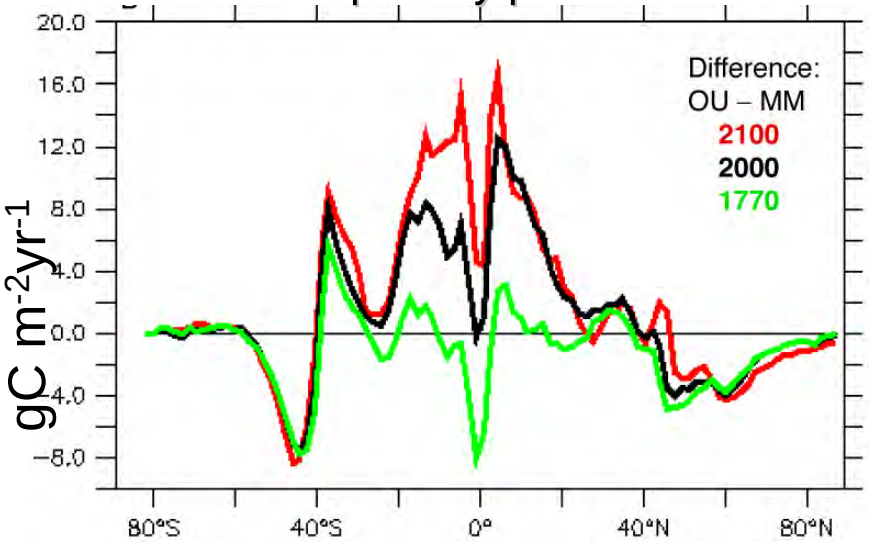
S. L. Smith, Y. Yamanaka, M. Pahlow, A. Oschlies (MEPS, 2009)

OU kinetics permitting acclimation with global warming





Difference of net primary production: OU- MM



Results by an earth system model: UVicESCM

S. L. Smith, Y. Yamanaka, M. Pahlow, A. Oschlies (MEPS, 2009)

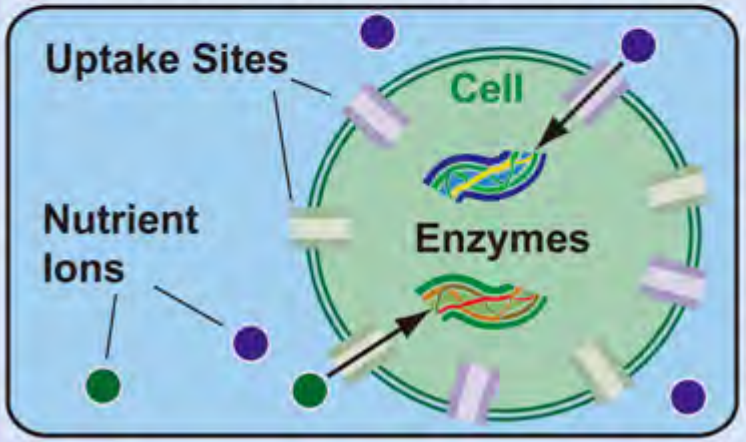
Optimal Uptake for multi-nutrients

Smith and Yamanaka. *Limnology & Oceanography* **52**, 2007

Phytoplankton **maximize uptake of the growth-limiting nutrient,** without reference to concentrations of non-limiting nutrients.

They allocate their internal resources (N) for uptake hardware ***in the same proportion for all nutrients*** based only on the concentration of the growth-limiting nutrient.

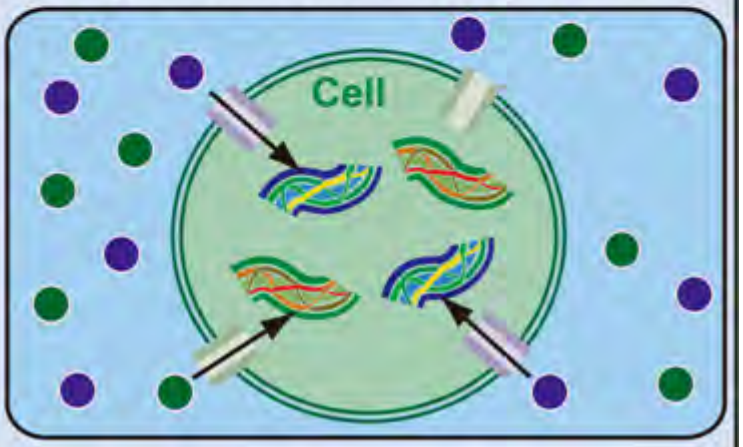
Low Nutrient Concentration



Many uptake sites, few enzymes

for two nutrients, ● & ●, each with its own set of uptake sites & enzymes

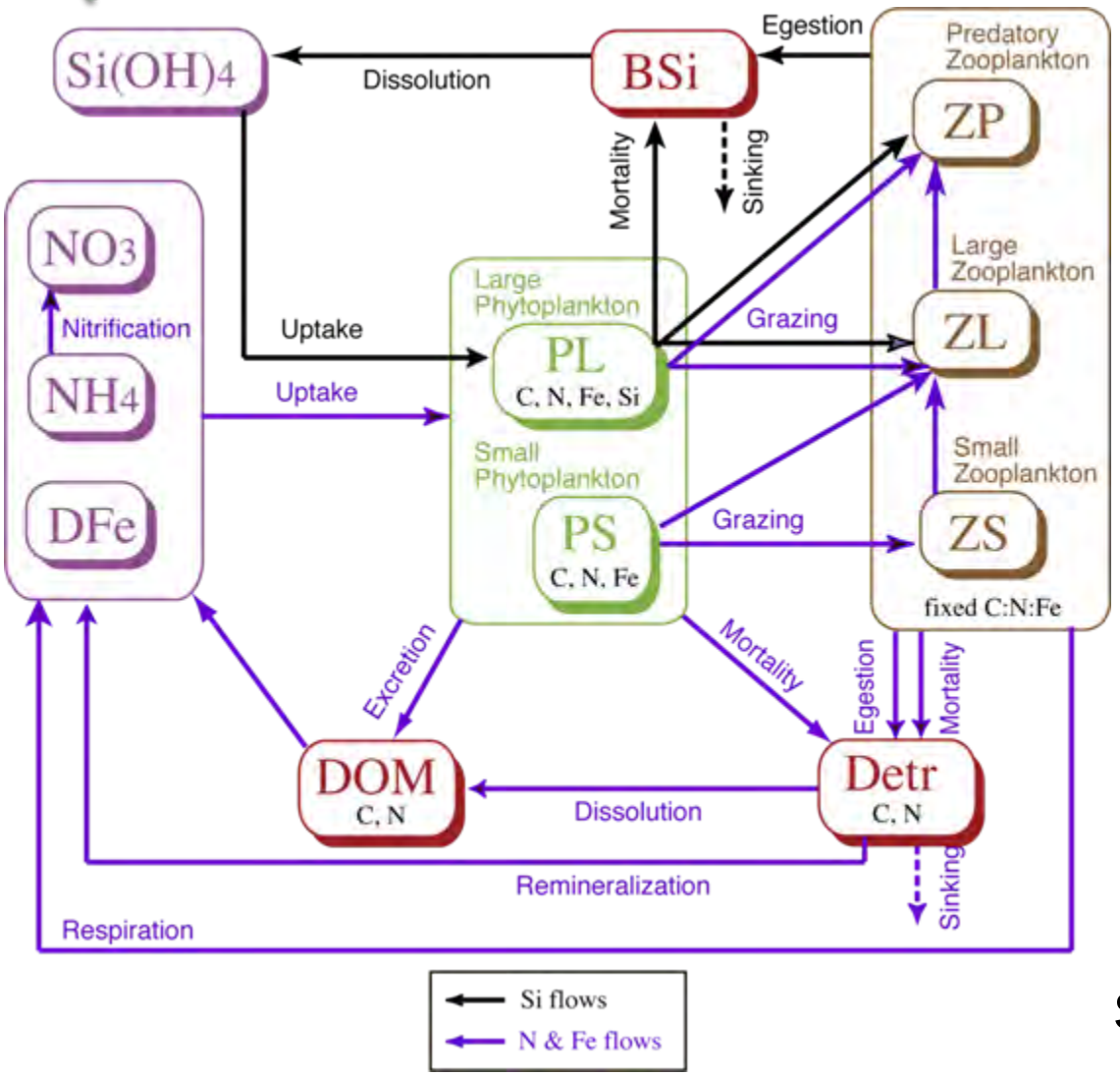
High Nutrient Concentration



Few uptake sites, many enzymes

Above idea supported by simulations of uptake ratio for a couple of chemostat experiments.

NEMURO + cell quota (variable C:N:Fe:Si ratios in PL &PS)



Now is just
a box model only.

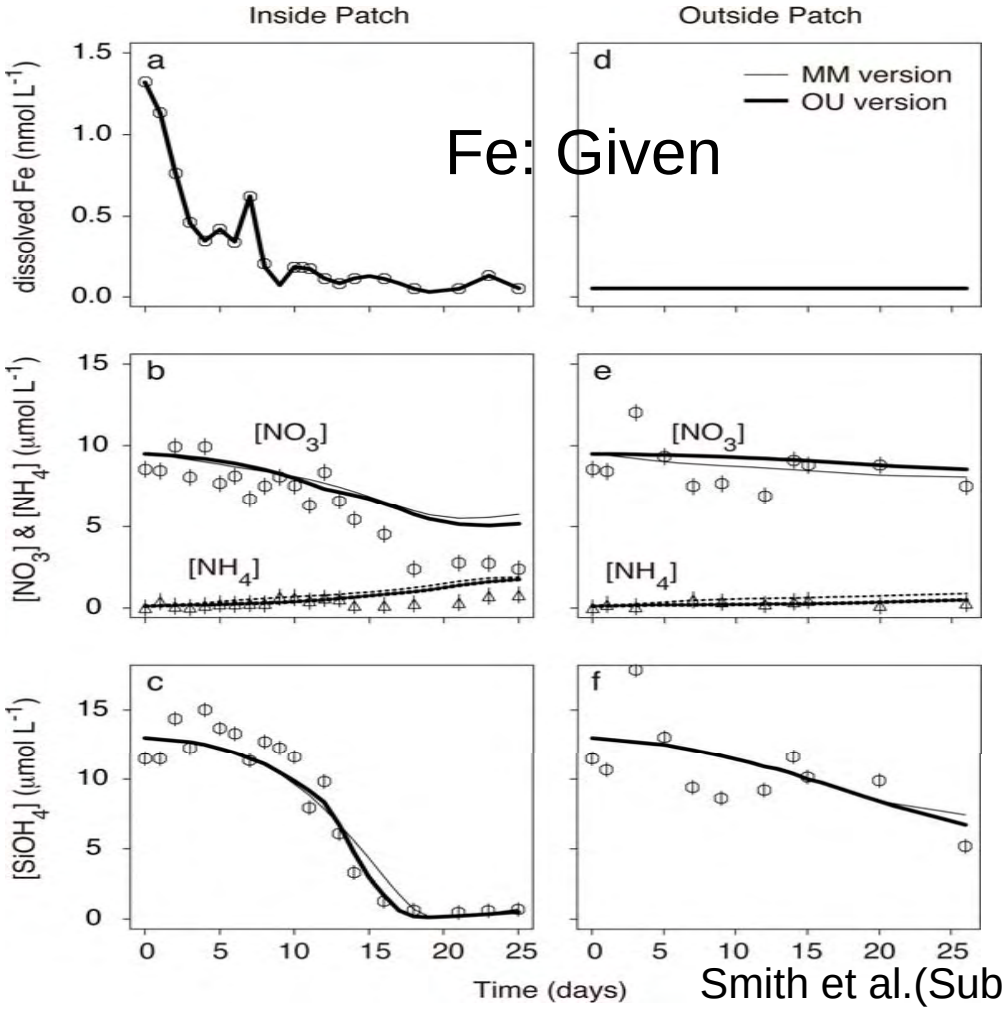
Smith et al.(Submitted)

Applying to SERIES iron fertilization experiments

Specific silicate uptake rate at switching N- to Fe- limitations is

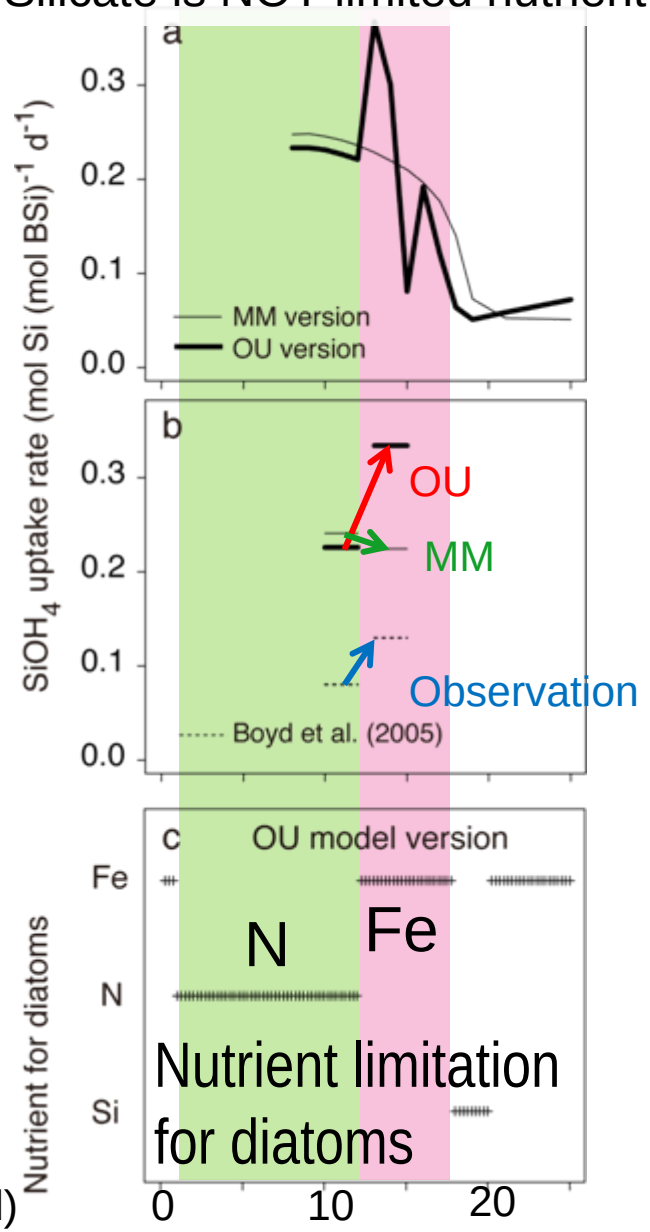
Multi-nutrient OU kinetics: an increase

MM kinetics: a decrease



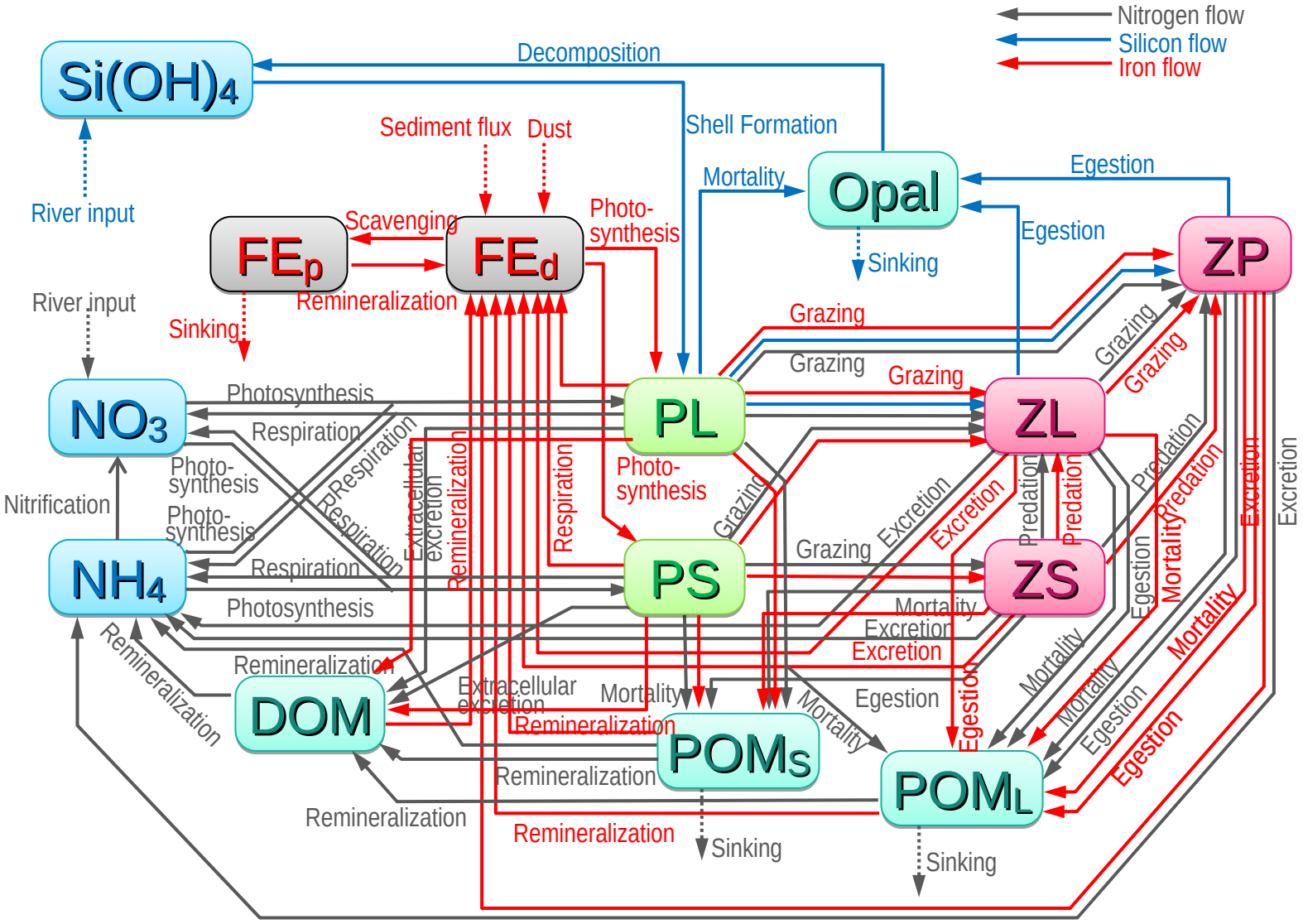
Smith et al.(Submitted)

Silicate is NOT limited nutrient

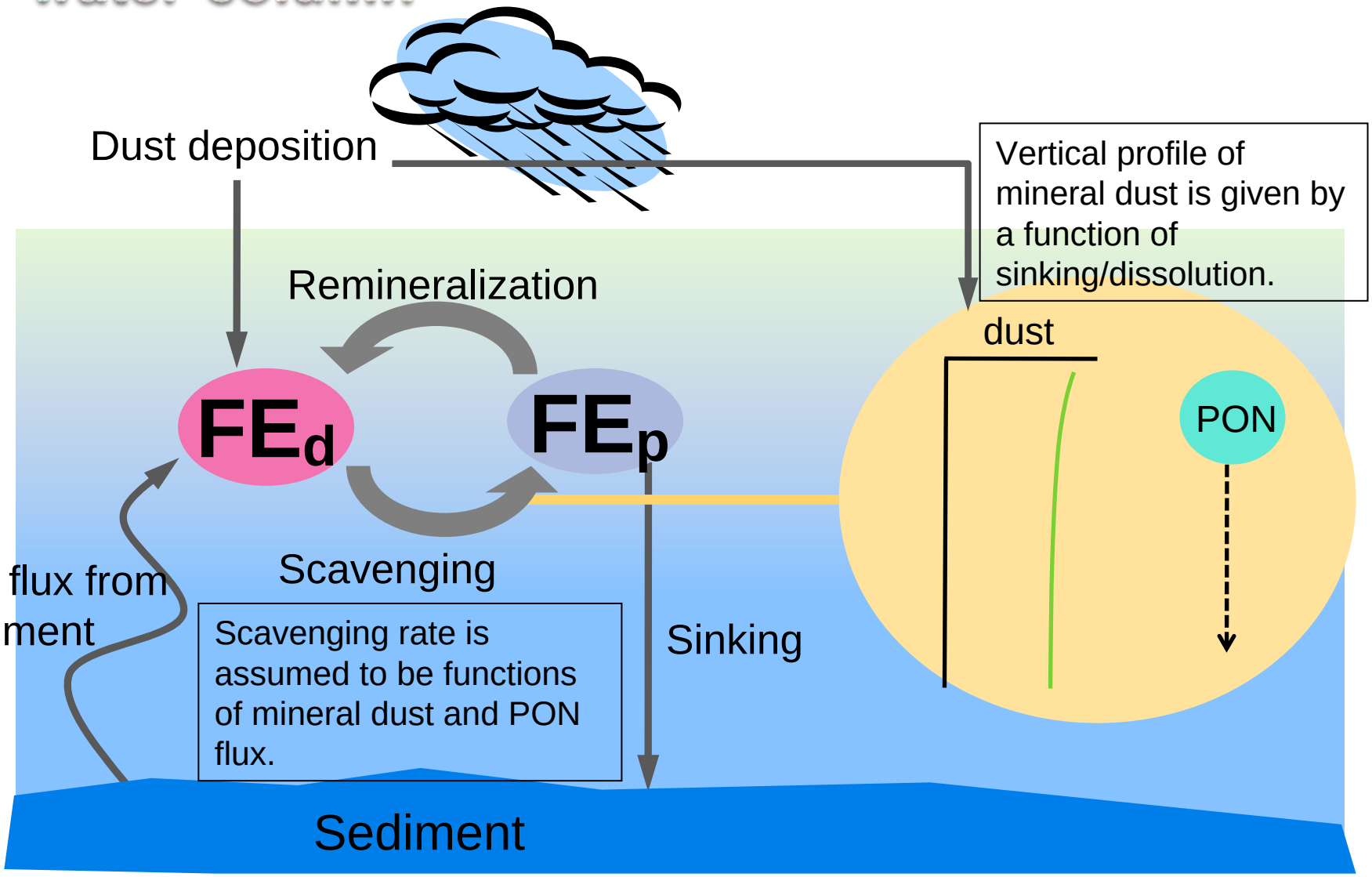


Flow chart of New Model

The original NEMURO has no iron cycle.



Dissolved and particulate iron cycles in the water column



Mainly based on Moore et al.(2004), Moore & Braucher (2008)

Iron flux from dust deposition

$$\mathbf{Flux\_Fe} = \mathbf{DustIN} \times \mathbf{Fe}_{\mathbf{fraction}} \times \alpha_{\mathbf{dissolve}}$$

- Fraction of iron in mineral dust

  $\mathbf{Fe}_{\mathbf{fraction}} = 3.5\%$

  (Duce & Tindall, 1991;Zhu et al., 1997)

- Fraction of iron dissolving

  $\alpha_{\mathrm{dissolve}} = 2.0\%$

  Jickells & Spokes, 2001: 0.8 ~2.1%

  Parekh et al.,2004: 1%

  Moore et al.,2002,2004: 2%

Dust deposition (DustIN) is obtained from climate model (MIROC3.2) experiment as mean value from 1945 to 2005, in which SST and SSS were assimilated to observed value.

Iron flux from sediment

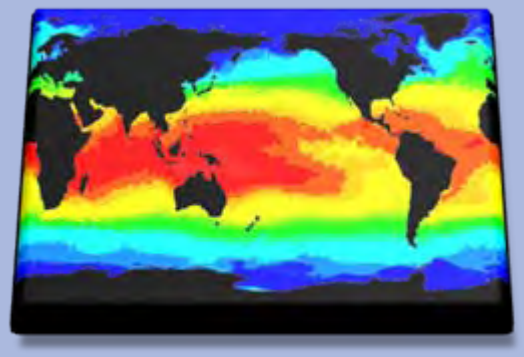
Iron flux from sediment is strongly correlated to organic carbon oxidation in the sediment . (Elrod et al., 2004)

Iron flux from sediment is set to be proportion to sinking POC flux **at the ocean floor** (Moore & Braucher, 2008)

$$\mathbf{Flux\_Fe} = \mathbf{POC\_flux}_{\mathbf{bottom}} \times \mathbf{ß}_{\mathbf{iron}}$$

$\mathbf{ß}_{\mathbf{iron}} = 0.68$ nmolFe/m^2/day

3-D new marine ecosystem model



Eddy permitting OGCM
1/4°x 1/6°x 51 levels

46 years historical run (1959-2004)

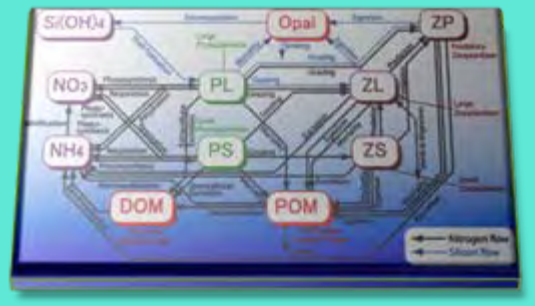
Ocean General Circulation Model
IcedCOCO4.3

Nitrate and silicate input from river runoff
Cunha et al. (2007)
Treguer et al. (1995)

Iron flux from dust deposition
Moore & Braucher (2008)

Iron flux from sedimentary source
Moore & Braucher (2008)

Offline-coupling



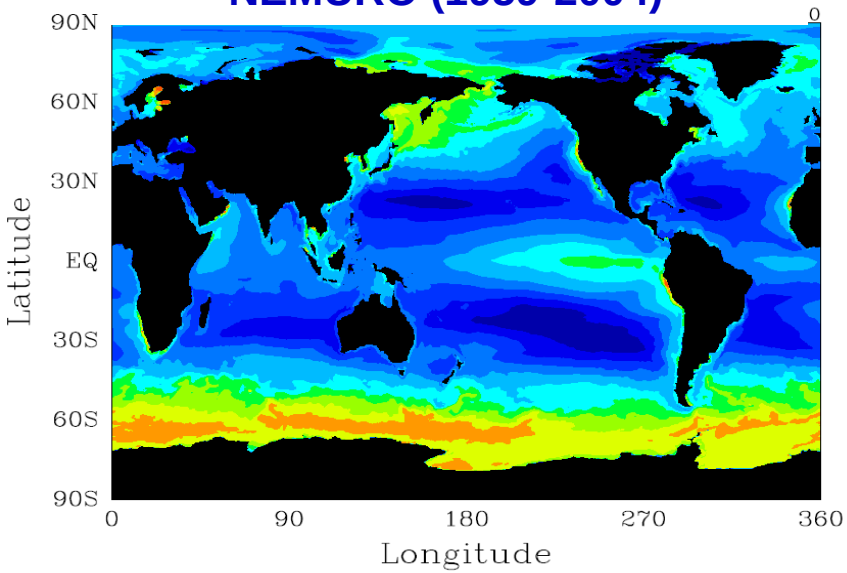
new Ocean Ecosystem Model

- **Nitrogen, Silicon and Iron cycles**
- **2 types of phytoplankton**
- **3 types of zooplankton.**

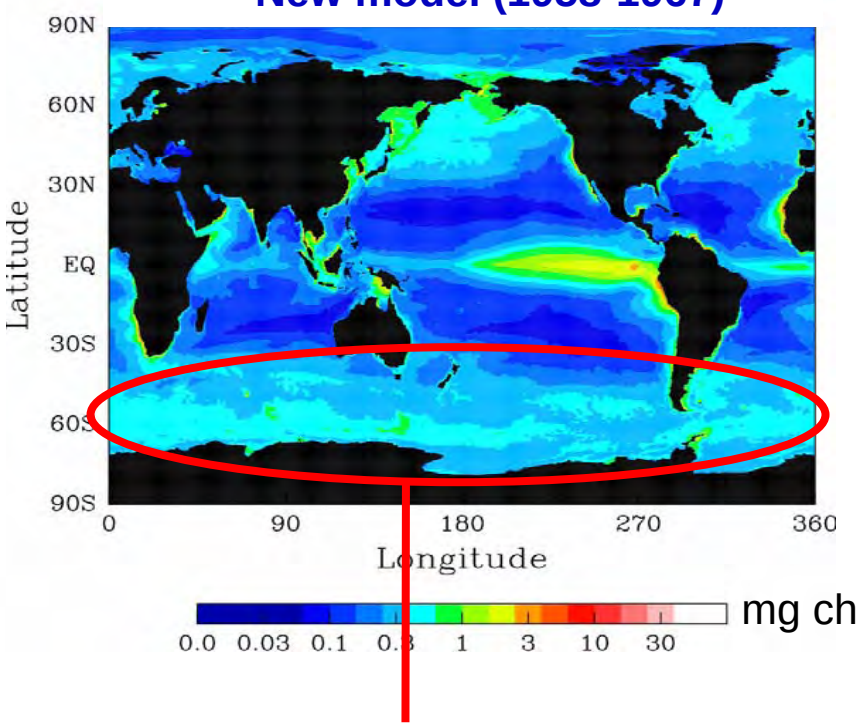
Now integrating from 1959-

Annually averaged chlorophyll-a concentrations of the original, new & SeaWiFS

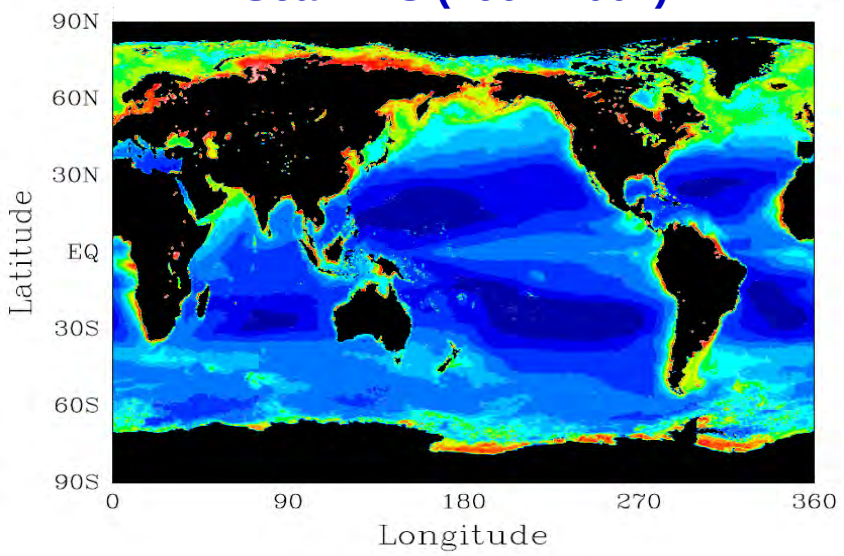
NEMURO (1959-2004)



New model (1958-1967)



SeaWiFS (1997-2007)

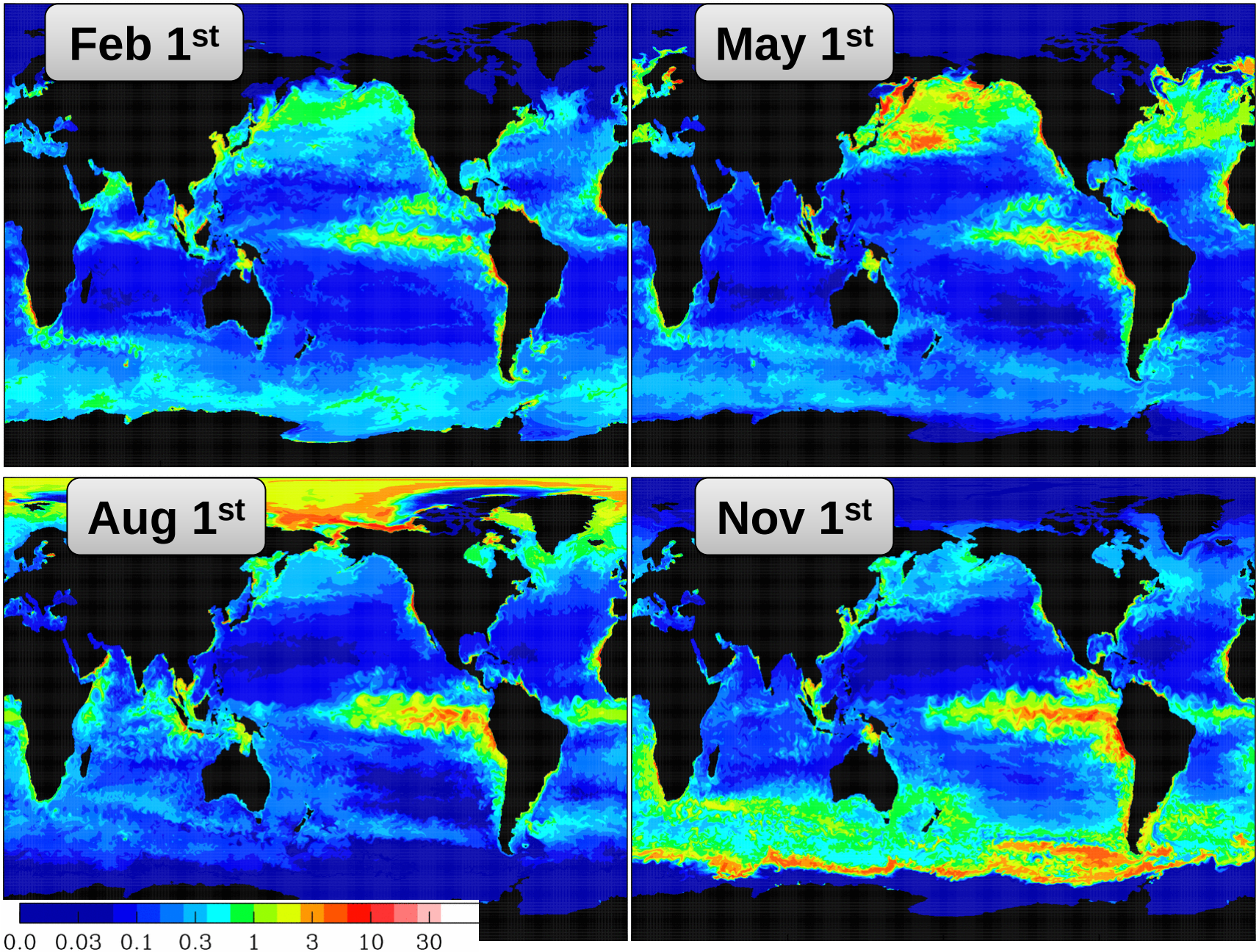


Iron limitation improves chl-a concentration in the Southern Ocean, as the largest problem of original NEMURO.

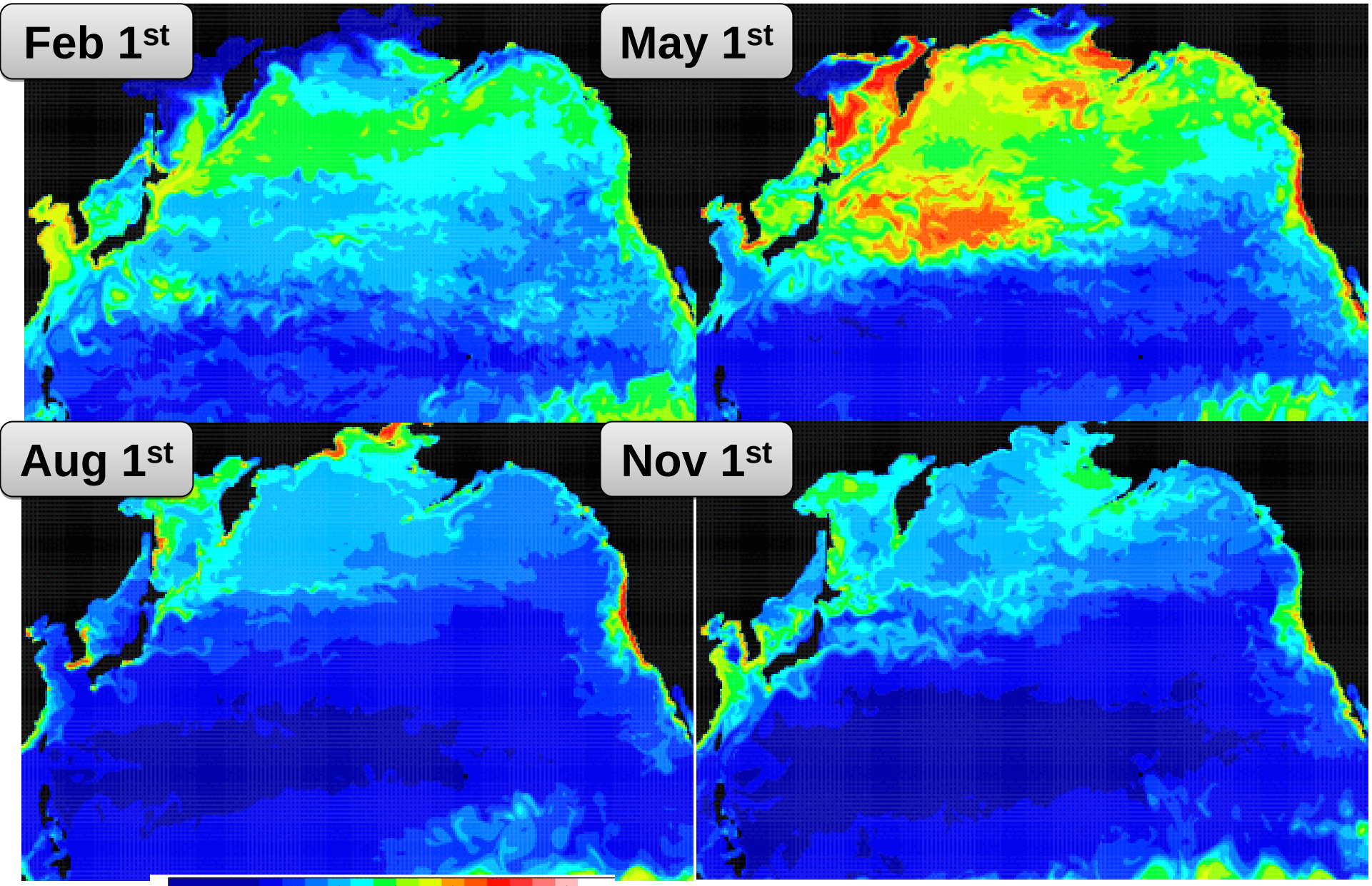
Push!! Animation will start, if you are lucky.

Snap shots of chlorophyll-*a* in 1968

mg chl/m^3

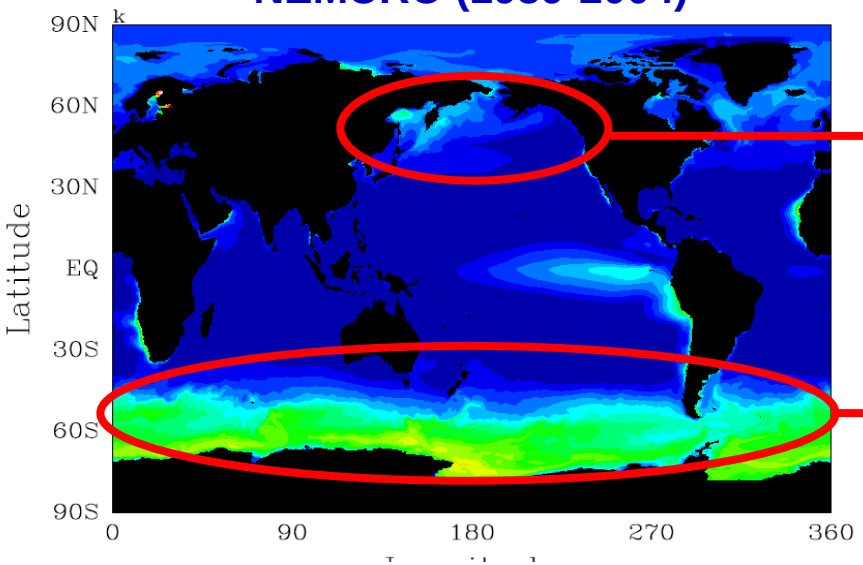


Seasonal chlorophyll-a in NEW model

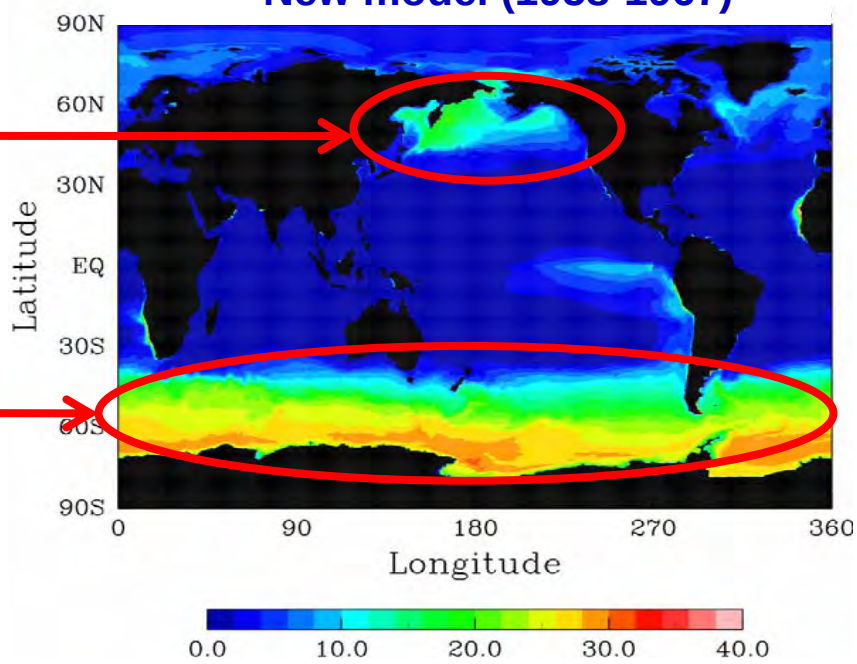


Surface nitrate concentrations of the original, new & SeaWiFS

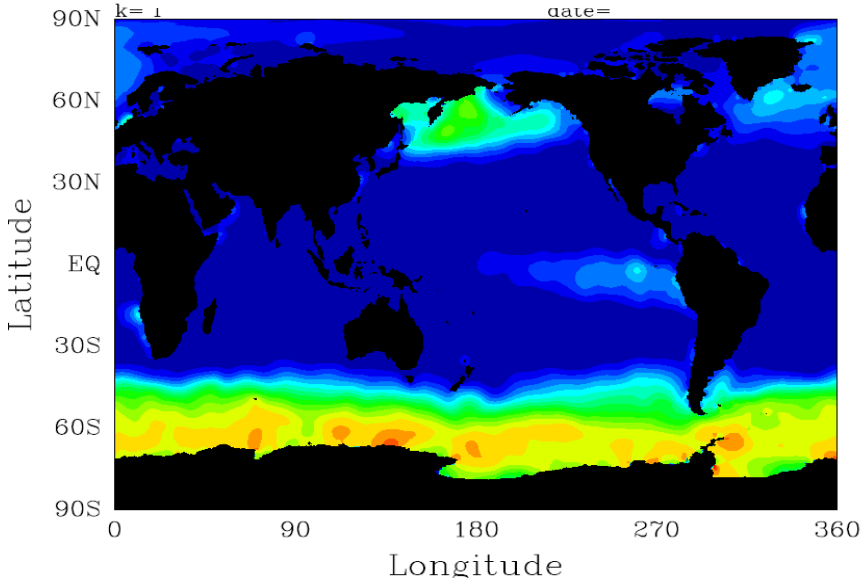
NEMURO (1959-2004)



New model (1958-1967)



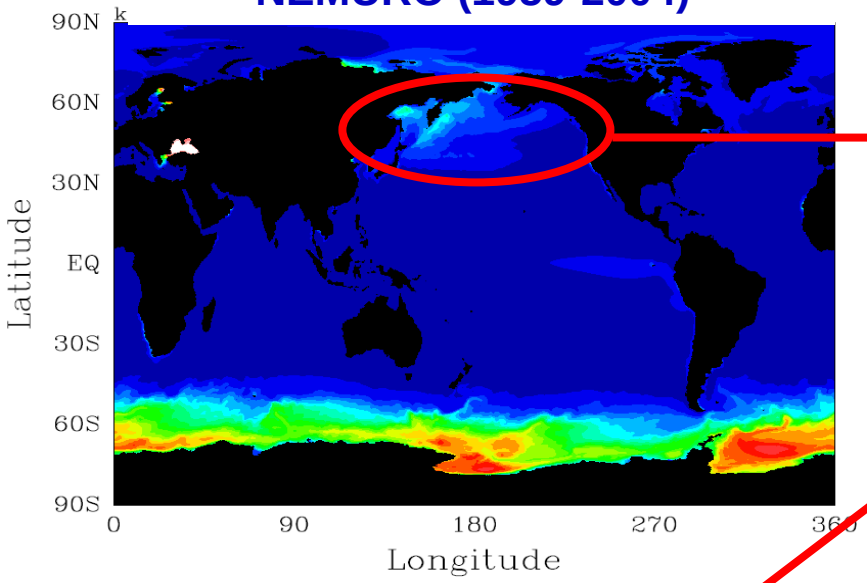
Observation (WOA05)



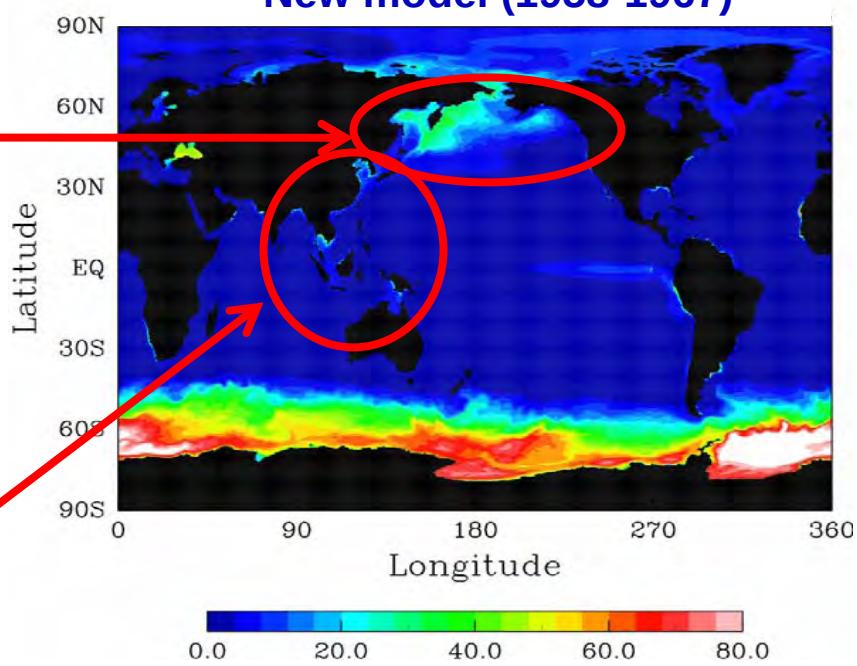
Depletion of surface nitrate in HNLC regions is also improved by iron limitation.

Surface slicate concentrations of the original, new & SeaWiFS

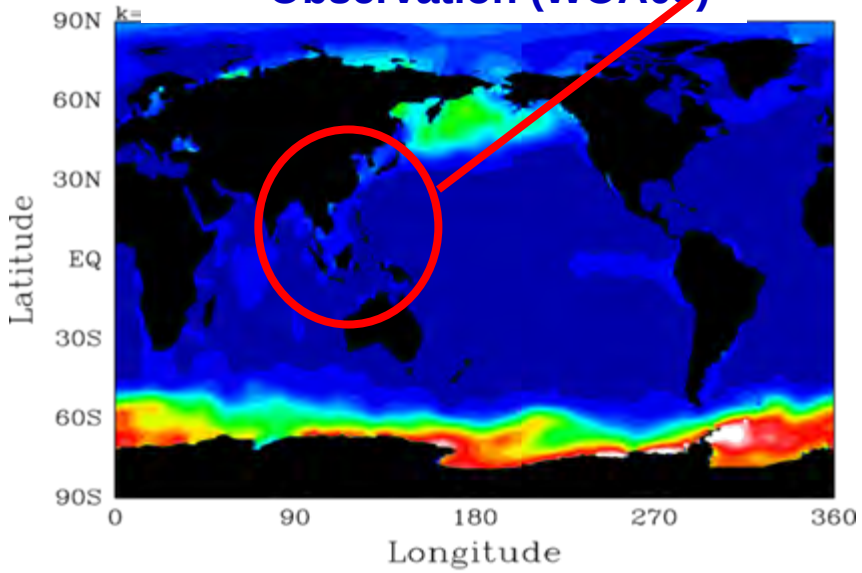
NEMURO (1959-2004)



New model (1958-1967)

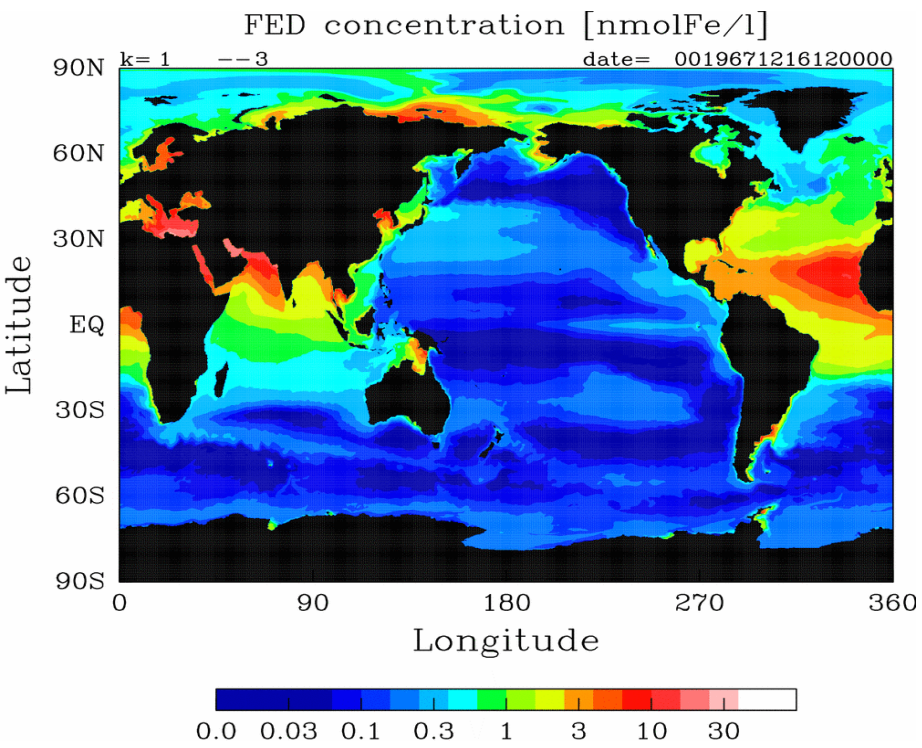


Observation (WOA05)



- Depletion of surface silicate in the North Pacific Ocean is improved by iron limitation.
- Silicate concentration over the continental shelf can be reproduced by introduction of river flux

Surface dissolved iron concentration of NEW model



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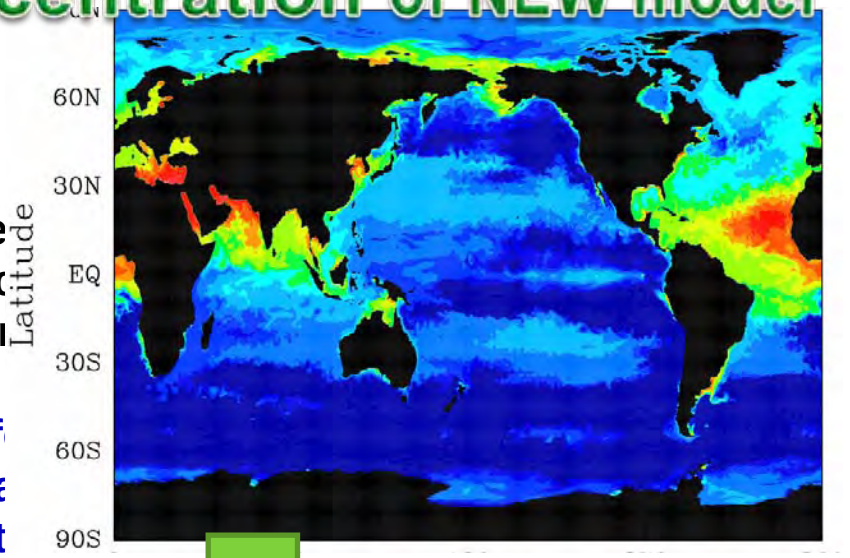
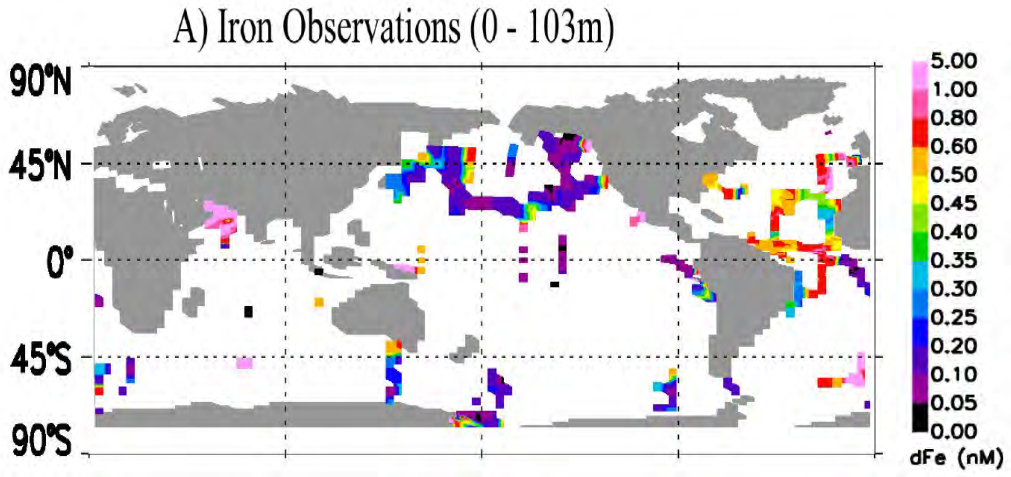
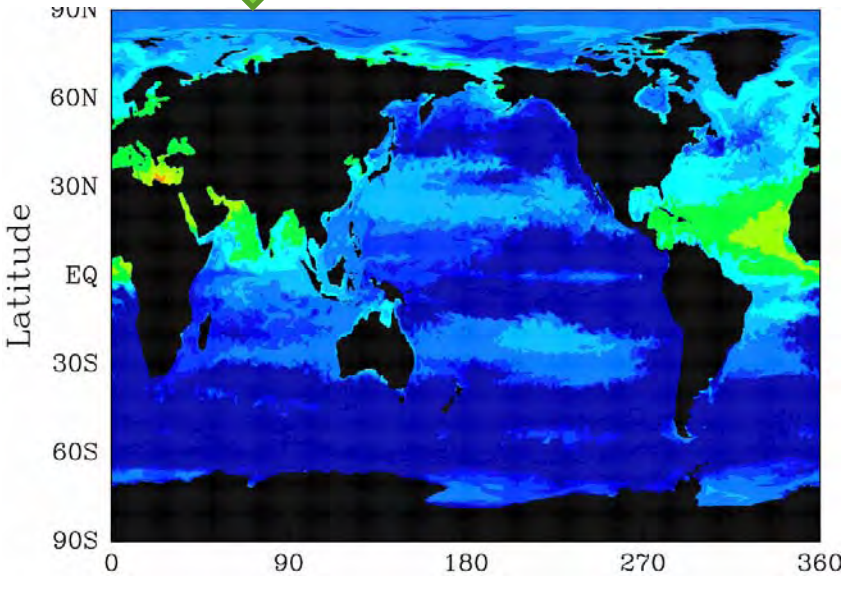


Bug fixed
@ 16th October



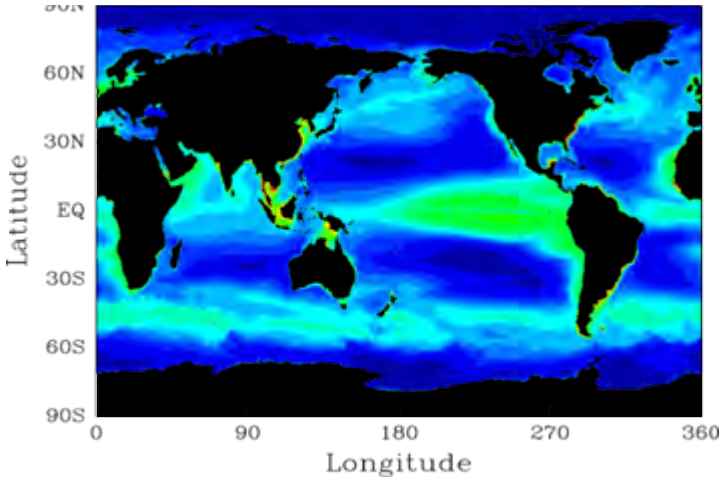


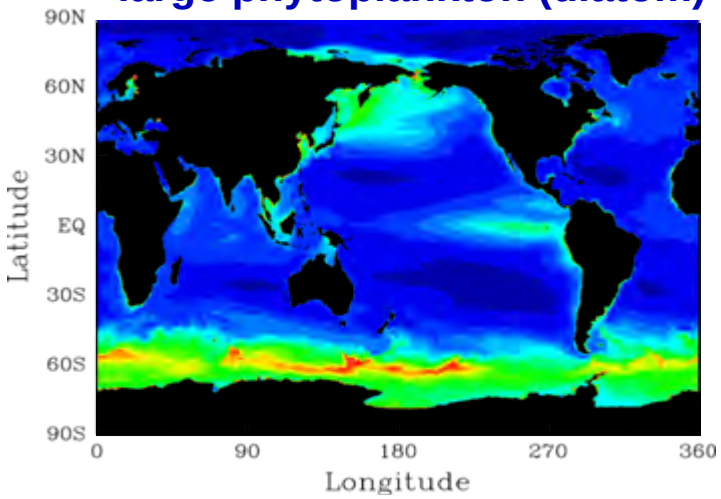
Annually averaged ditoms and other biomass of the original & new

small phytoplankton (coccolith, etc.)

large phytoplankton (diatom)

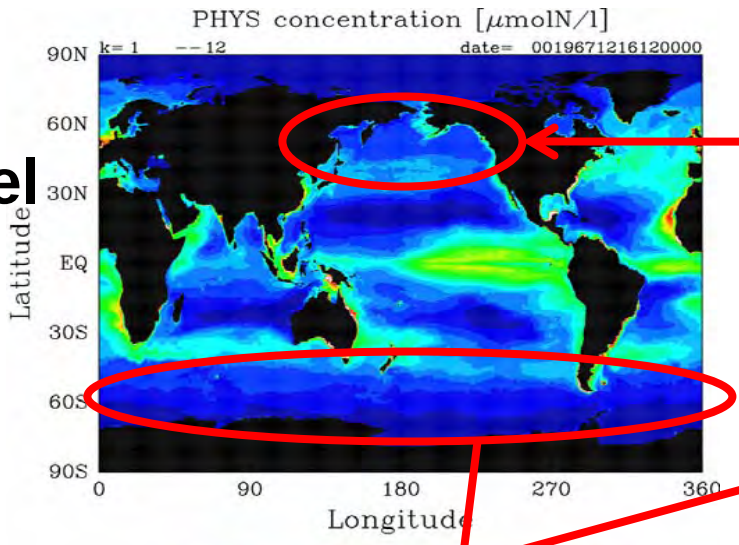
NEMURO
(1959-2004)

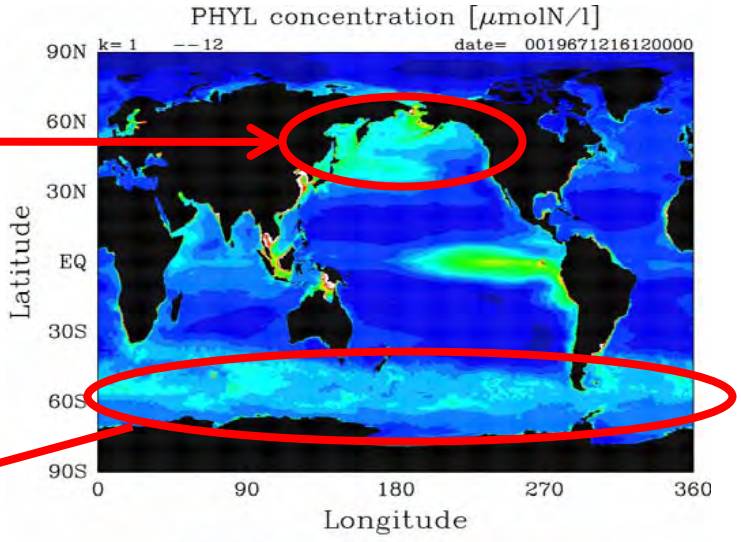




Diatom dominates in the subarctic North Pacific

New model
(1958-1967)

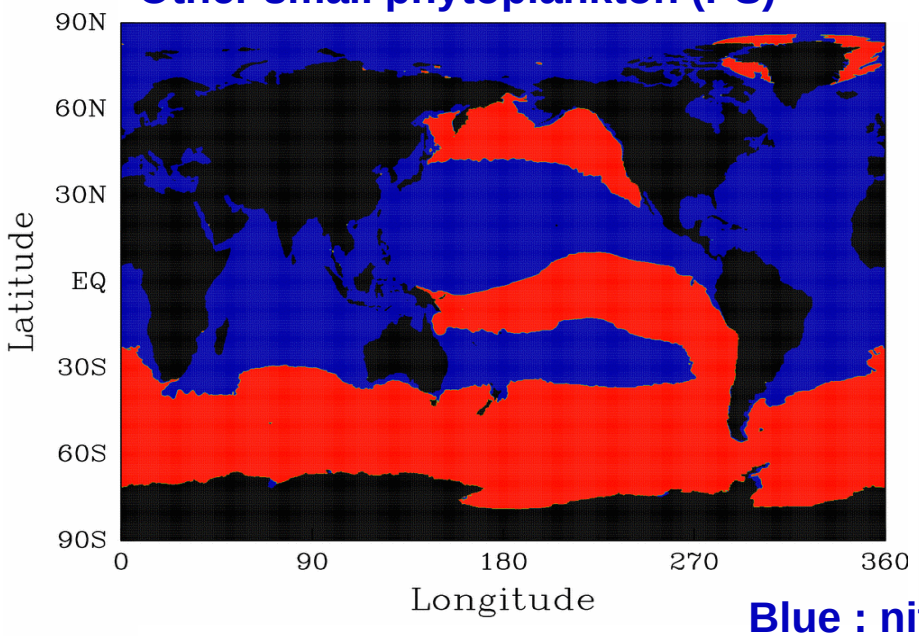




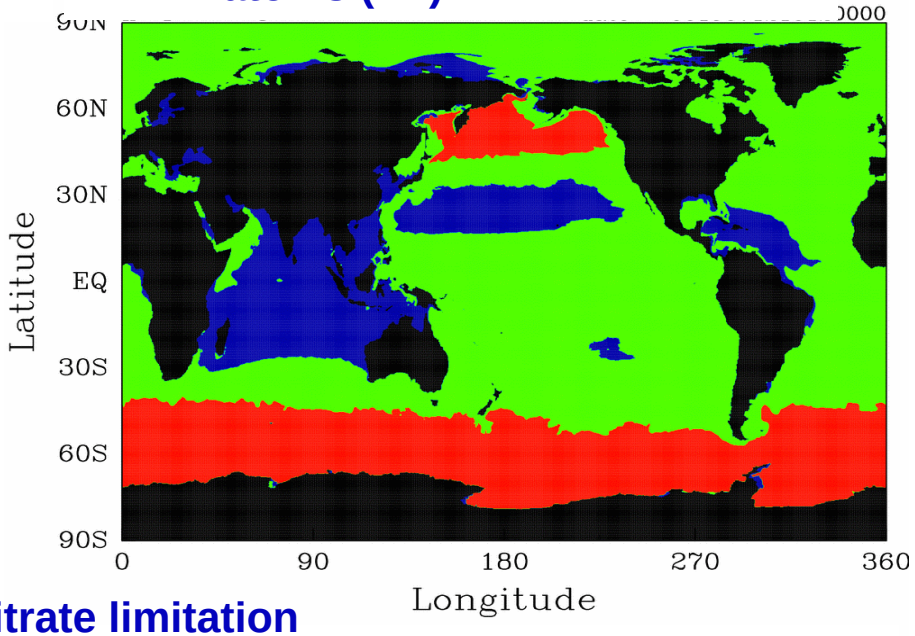
Improved phytoplankton biomass in the Southern Ocean

Nutrient limitation on phytoplankton growth rate

Other small phytoplankton (PS)



Diatoms (PL)



Blue : nitrate limitation
Green : silicate limitation
Red : iron limitation

- **The model adequately represents difference of limiting nutrient for each area.**
- **Iron limitation in HNLC regions (the subarctic North Pacific, the Equatorial Pacific, the Southern Oceans)**

Summary of my talk

- Now is just developed new ecosystem model based on NEMURO, to introducing iron cycle, the optimal uptake of multi-nutrient kinetics, two size of POMs with tuning by genetic algorism.
- The new model greatly improved its model performance compared with the original NEMURO.

- We could provide huge results of case studies, changing iron inputs according to your suggestions, as collaboration with you.