Earth System Modeling at GFDL:

Goals, strategies and early results for the carbon system

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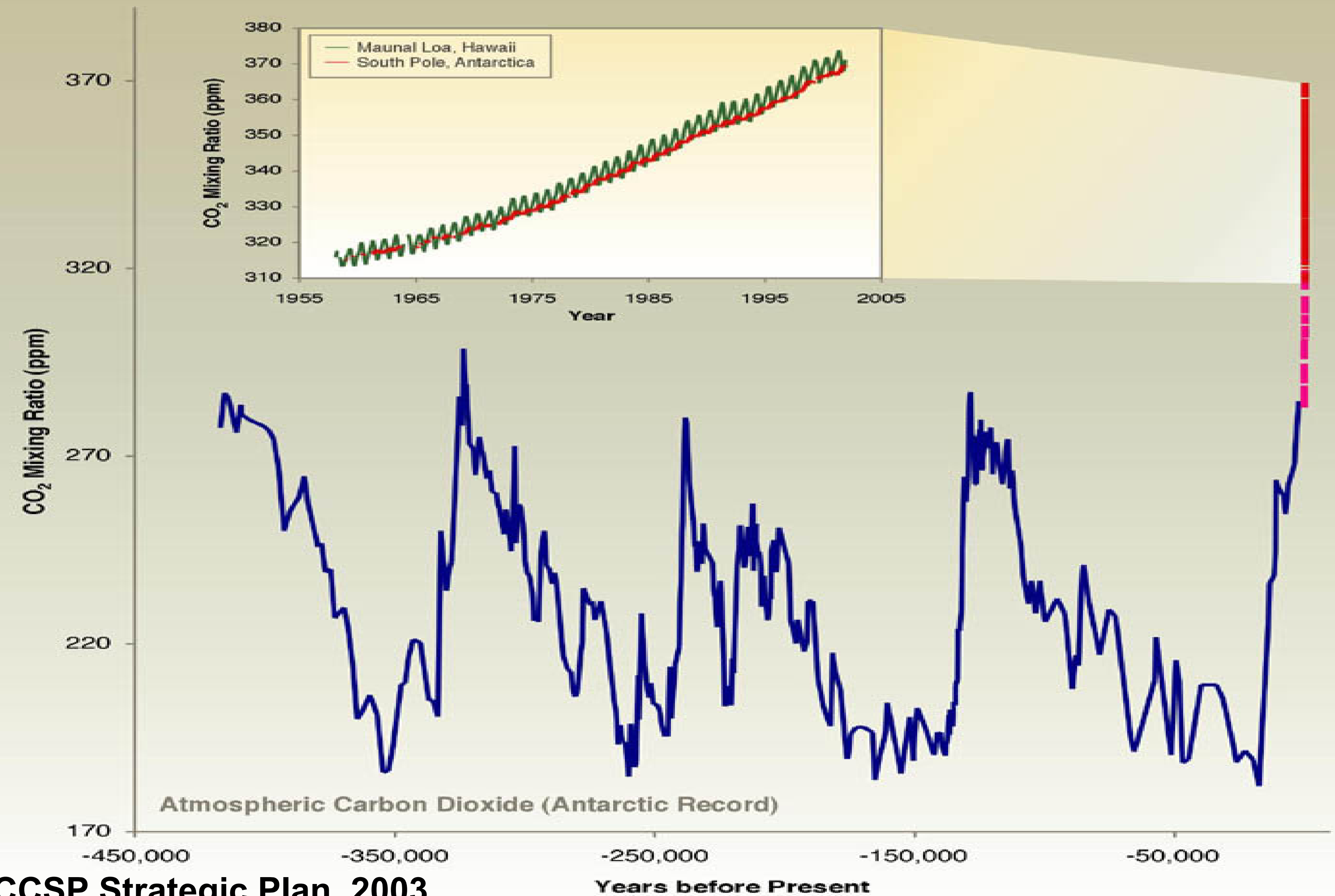
In coordination with researchers at GFDL and PU

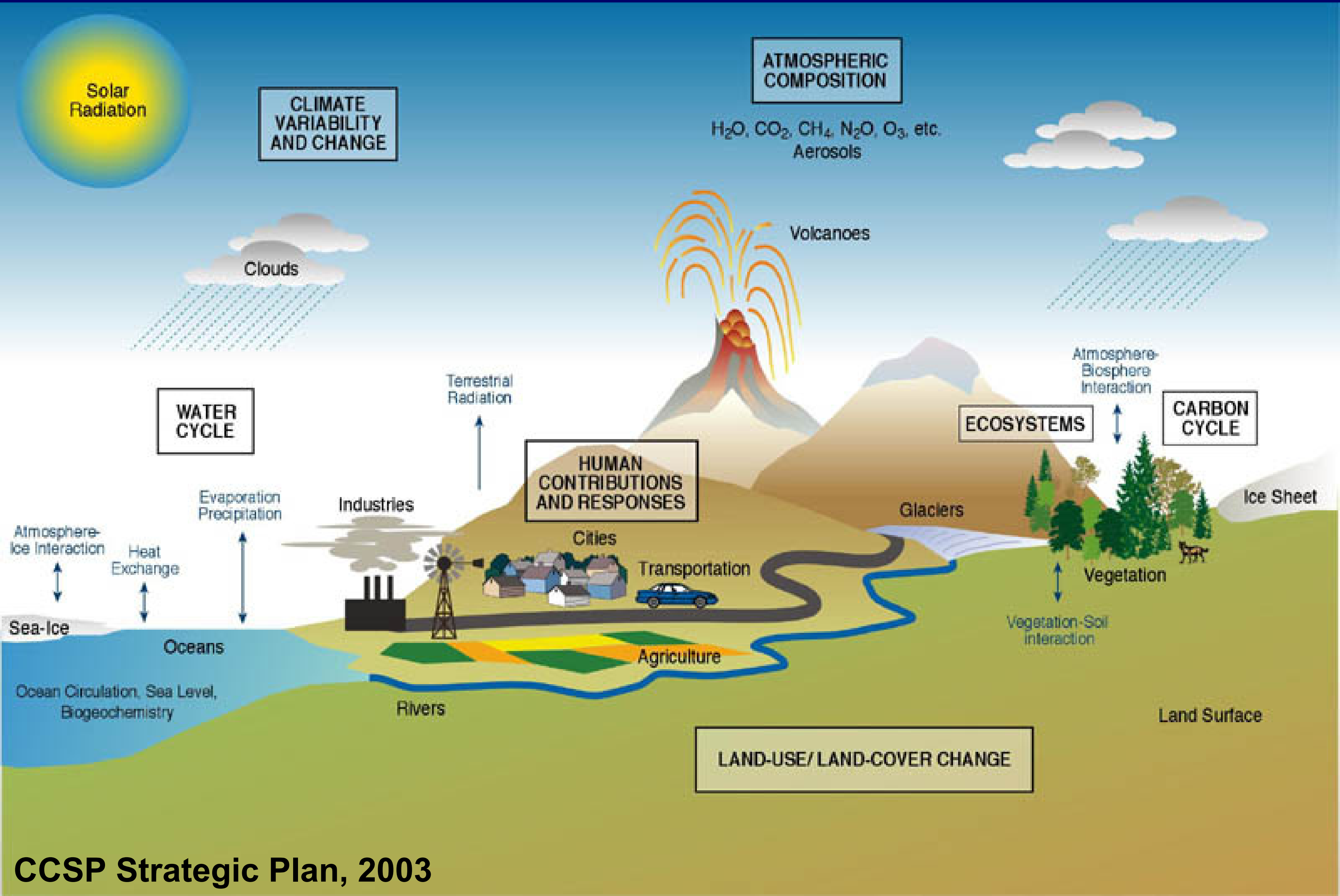
Background

The CO_2 Climate Forcing Question



CCSP Strategic Plan, 2003

Climate Forcing and Feedbacks



CCSP Strategic Plan, 2003

The New Fashion: Earth System Modeling

As a "natural progression" of IPCC style assessments,

The US Climate Change Science Program's Strategic Plan has called for the next generation of climate simulations to include explicit carbon cycling.

…This task involves a daunting synthesis of climate models, terrestrial ecology models and ocean biogeochemistry models.

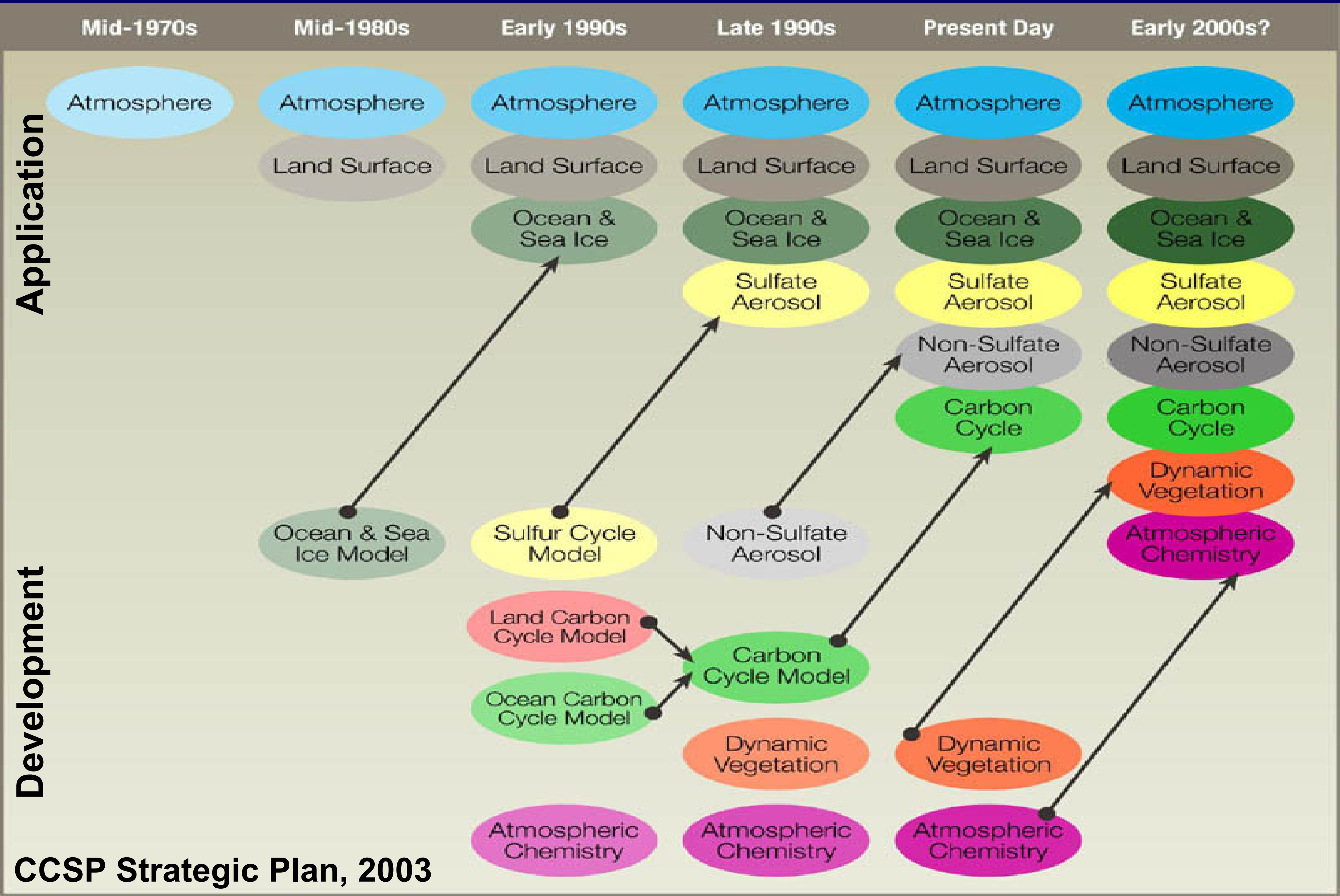
Climate Objectives:

- Simulate the past, present and future climate with dynamic carbon cycles
- Identify modes of variability and key susceptibilities.
- Predict biospheric response to human-induced change.
- Quantify biosphere – climate feedbacks

Biogeochemical Objective:

- Identify biospheric and biogeochemical controls
- Explore relationships between biospheric components
- Quantify the degree to which the biosphere maintains optimal conditions for itself (i.e. the GAIA hypothesis)

Timeline of Model development



CCSP Strategic Plan, 2003

Current Challenges

- The complexity and computational intensity of these models have grown beyond the scope of individual investigators.
- The large climate modeling centers are all involved in incorporating explicit carbon cycling into their models.
- This is a monumental task – no one group has yet succeeded without making large concessions and dubious assumptions.

Centers developing these models

Hadley Centre (UK)

IPSL (France)

NCAR (USA)

GFDL (USA)

MPI (Germany)

JMA-MRI (Japan)

CCSR (Japan)

CCCMA (Canada)

BMRC/CSIRO (Australia)

others???

Strategy

Simulate global elemental cycles within the atm-ocean-land-ice-river system:

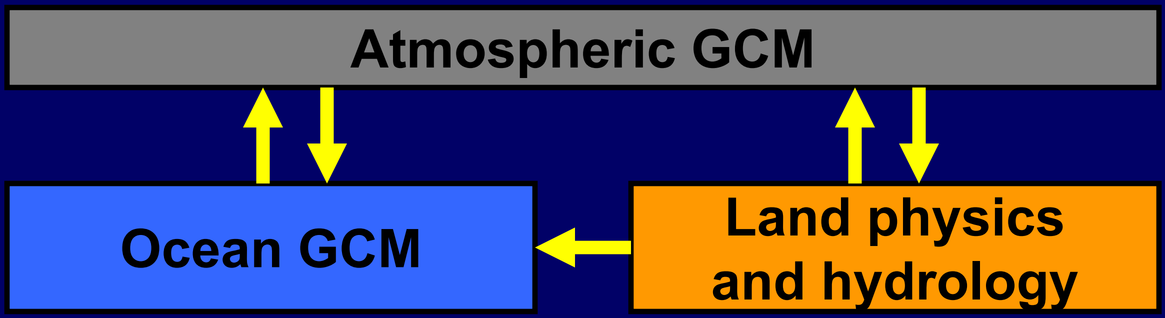
- Carbon (both CO_2 and CH_4)
- Nitrogen
- Dust/Iron
- Sulfur

Include important biospheric processes effecting climate and feedbacks:

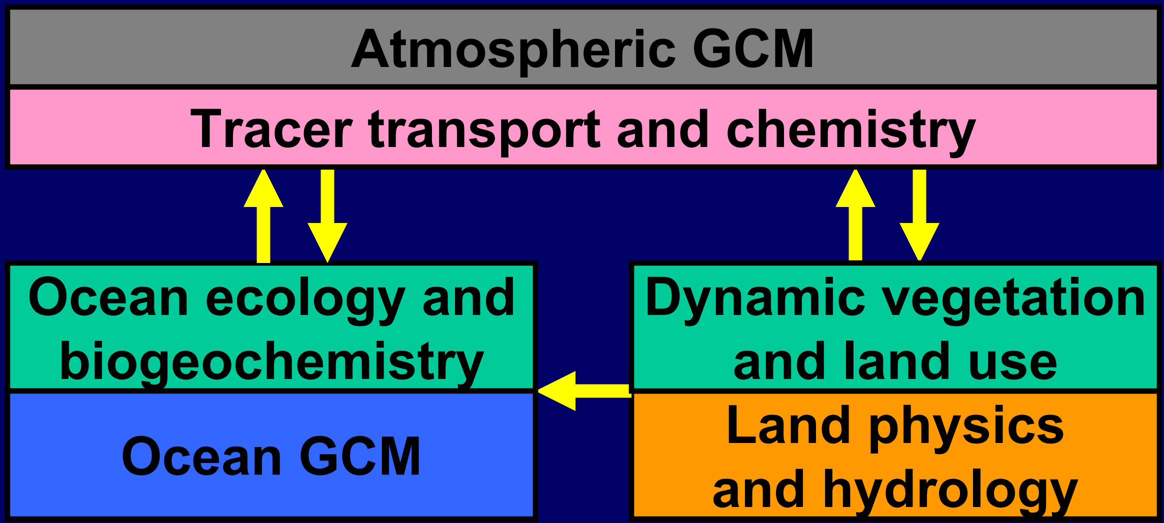
- Ocean radiative bio-feedbacks through Chlorophyll absorption
- Ice radiative bio-feedbacks and gas exchange effects
- Iron transport deposition
- Eutrophication (anoxia and red tide)
- Ecological variability and change
- Atmospheric chemistry and pollution
- Glacial-interglacial cycles
- Human activities such as land use, marine resources

Schematic of an Earth System Model

Climate Model



Earth System Model



Current GFDL climate model

GFDL Climate Model Description

- Coupled model referred to as "CM2.0" and "CM2.1".
  - AM2 atmosphere (2° horizontal, 24 levels)
    - Version CM2.0 uses b-grid
    - Version CM2.1 uses finite volume grid
  - MOM4 ocean model, 1° horizontal, 0.3° at Equator, 50 levels)
  - Sea ice, land, river routing models

- A complete suite of experiments has been conducted for the IPCC 2007 report.

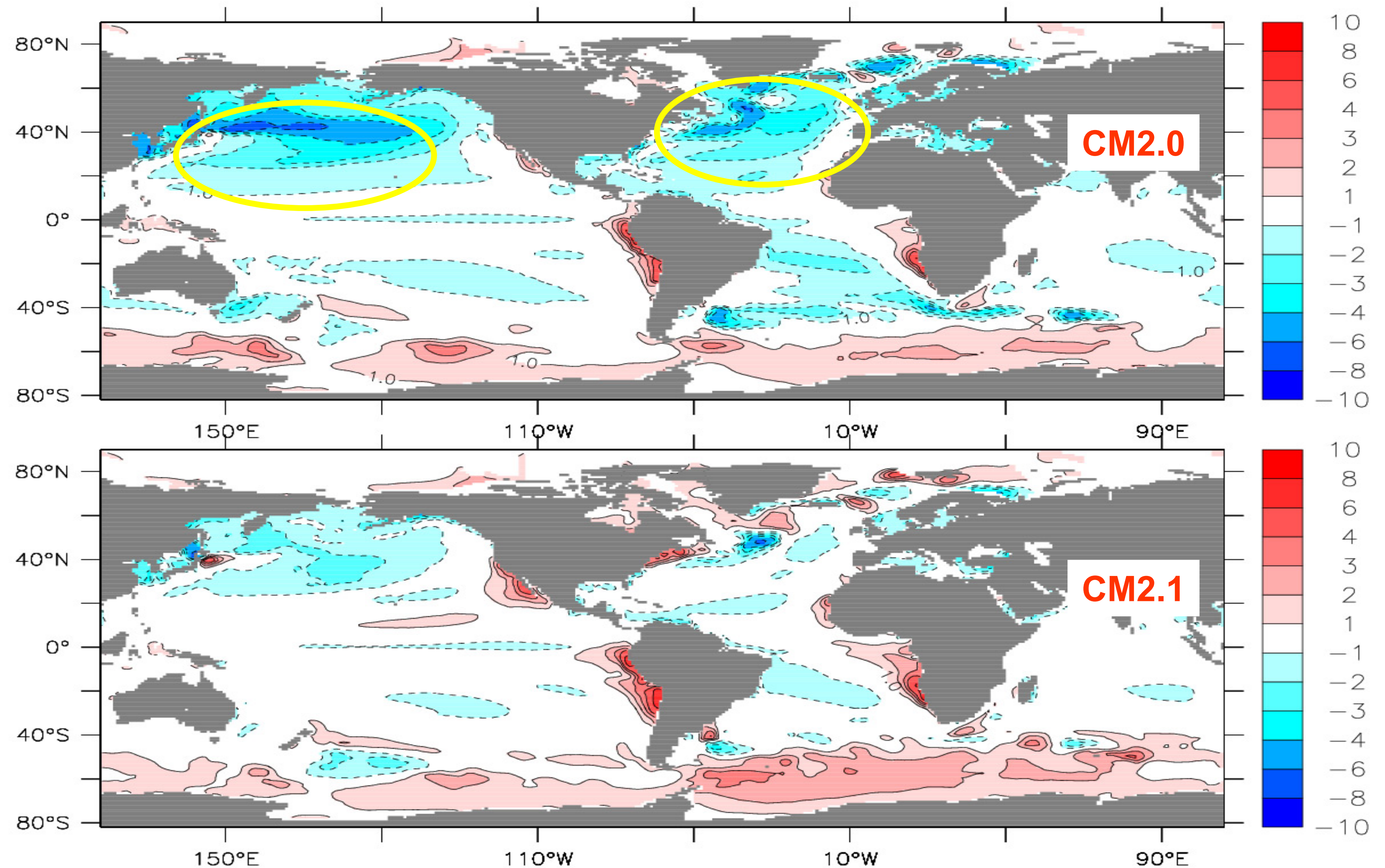
- Detailed descriptions of these models available at:

  http://data1.gfdl.noaa.gov/nomads/forms/deccen/CM2.X/references

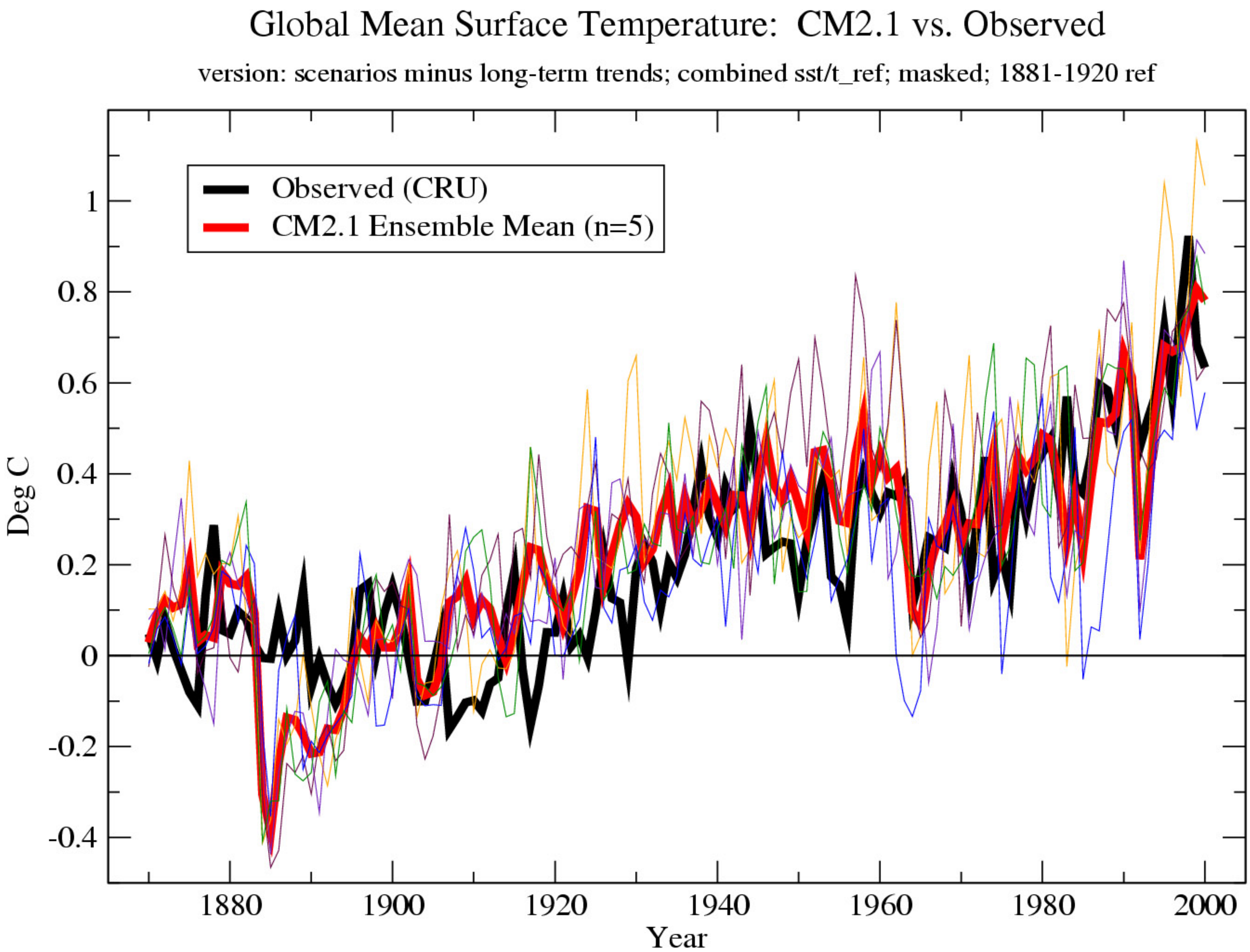
- Model output available at:

  http://data1.gfdl.noaa.gov

Model SST Errors

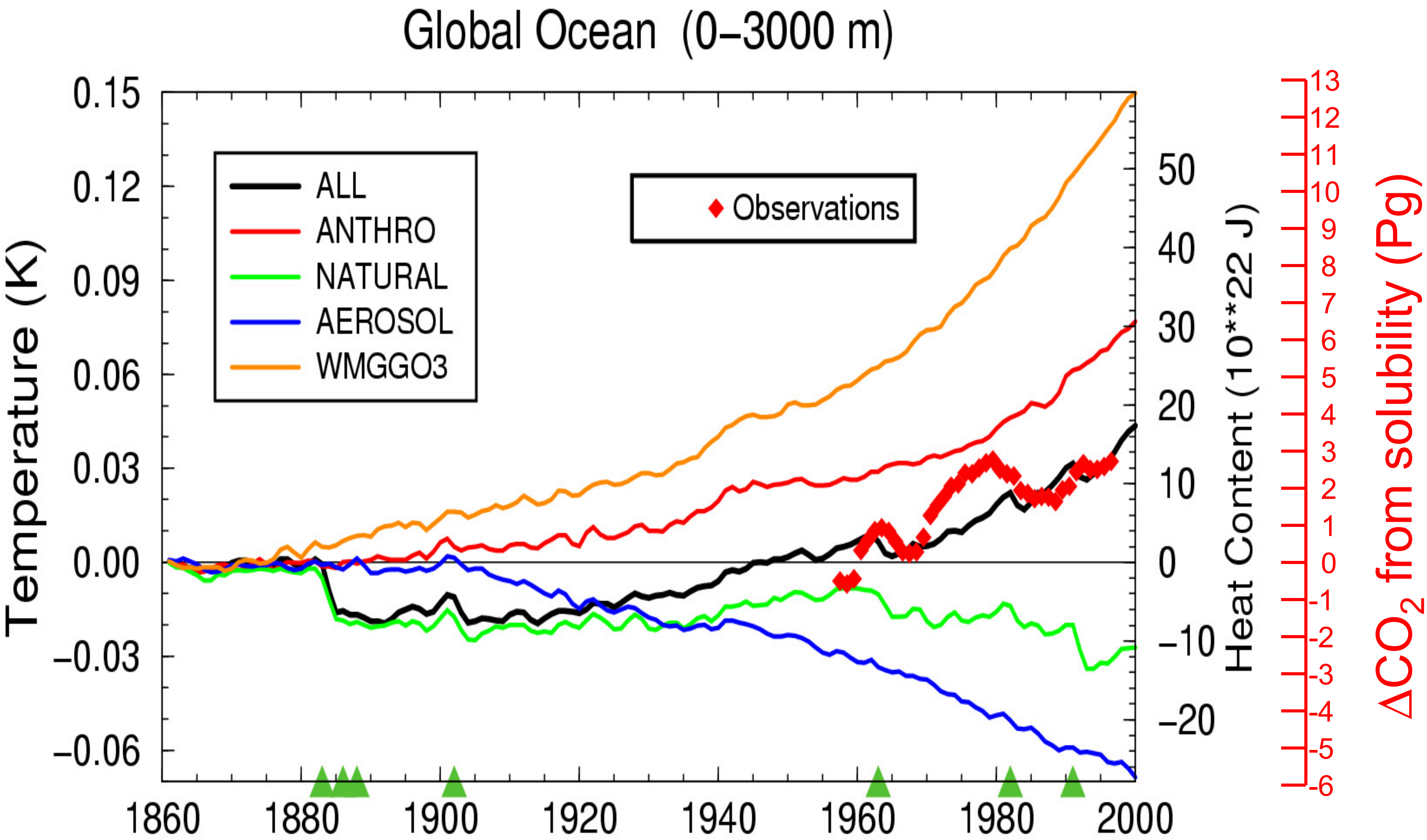


Courtesy of Tom Delworth



Courtesy of Tom Delworth

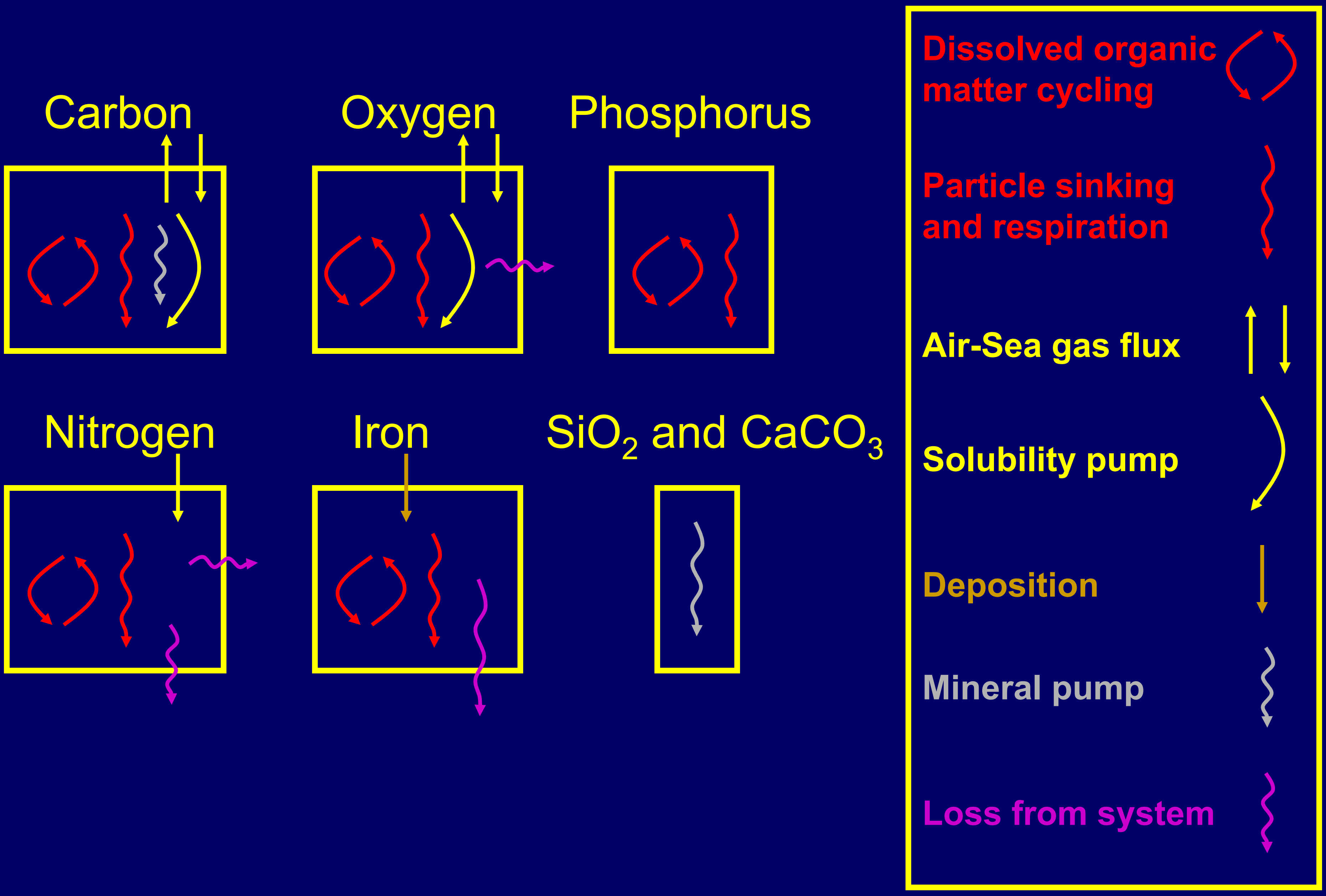
CM2.1 ocean sensitivity to forcing



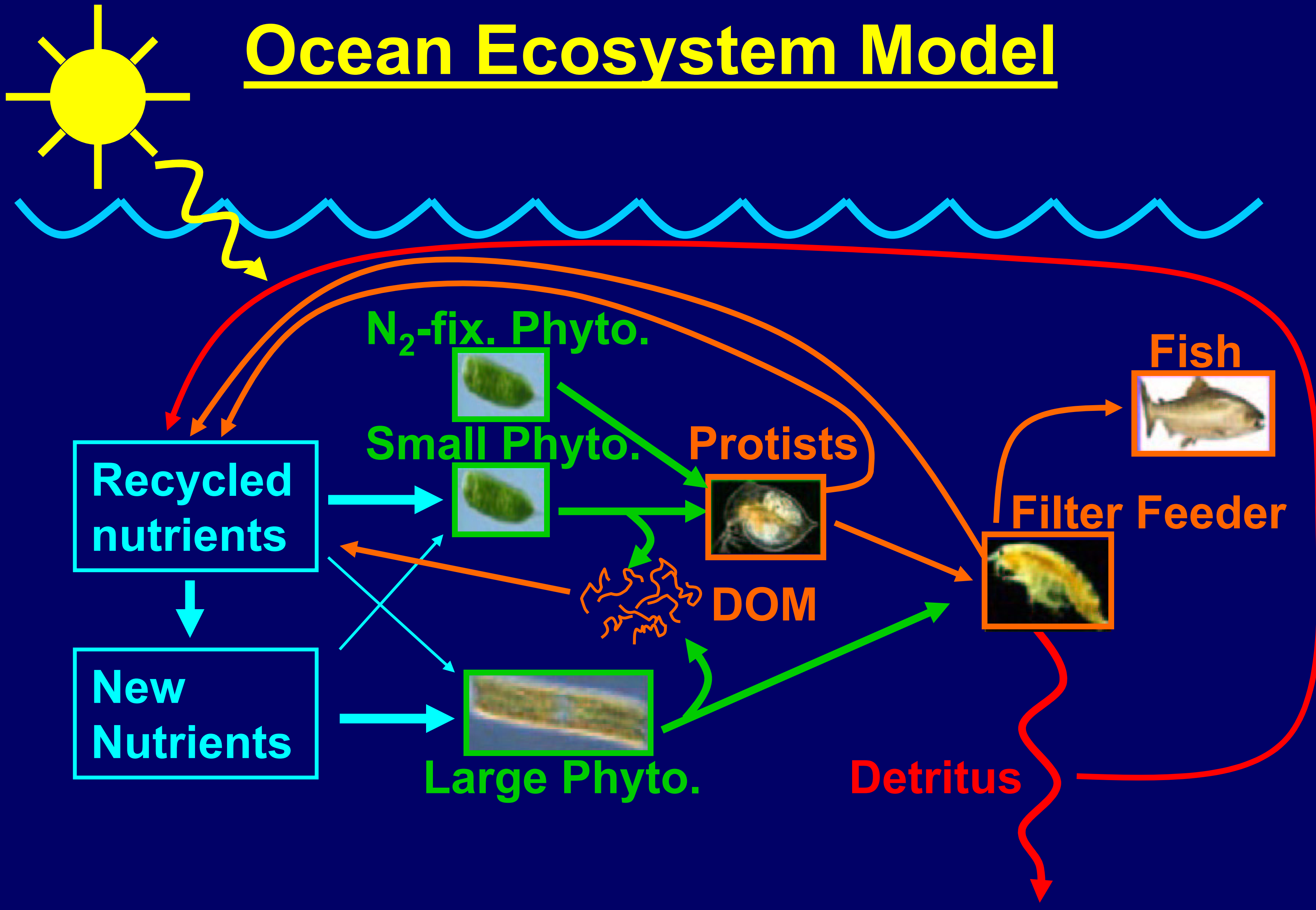
Courtesy of Tom Delworth

GFDL Ocean Biogeochemistry Description

Ocean Biogeochemical Model



Ocean Ecosystem Model



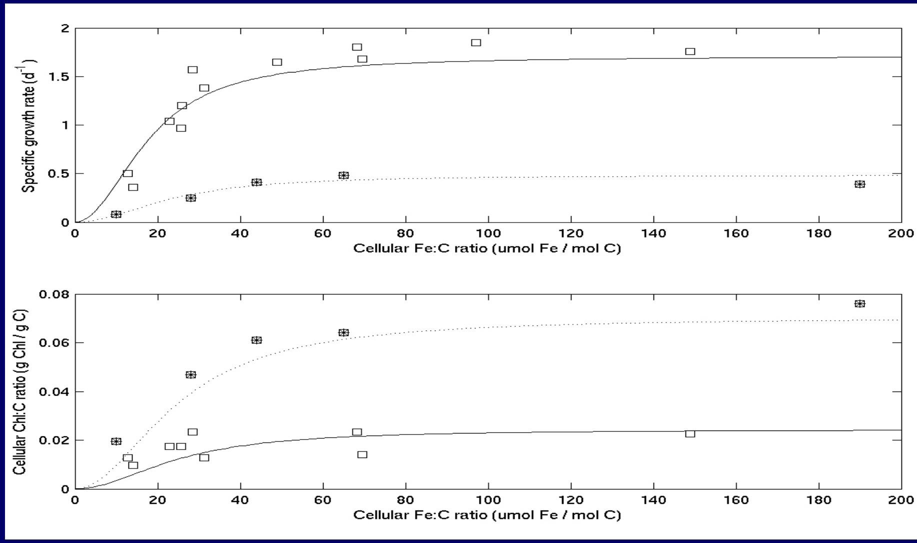
Uptake Components

N-uptake is based on Geider et al. (1997), except for the treatment of iron:

$$Q_{Fe:N} = Fe:N^2 \;/\; (Fe:N_{lim} + Fe:N^2)$$
$$\phi = \phi_{max} /(1 + \phi_{max}\, \alpha\, I_z / (2\, P^C_m))\, Q_{Fe:N}$$
$$\mu_N = P^C_m / (1 + z)\, (1 - \exp(-\alpha I_z \phi / P^C_m))$$

Fe-uptake is proportional to dissolved Fe:

$$Uptake_{Fe} = V_{Fe}\, Lim_{Fe}\, \exp(kT)\, P_N\, (1 - Q_{Fe:N})$$

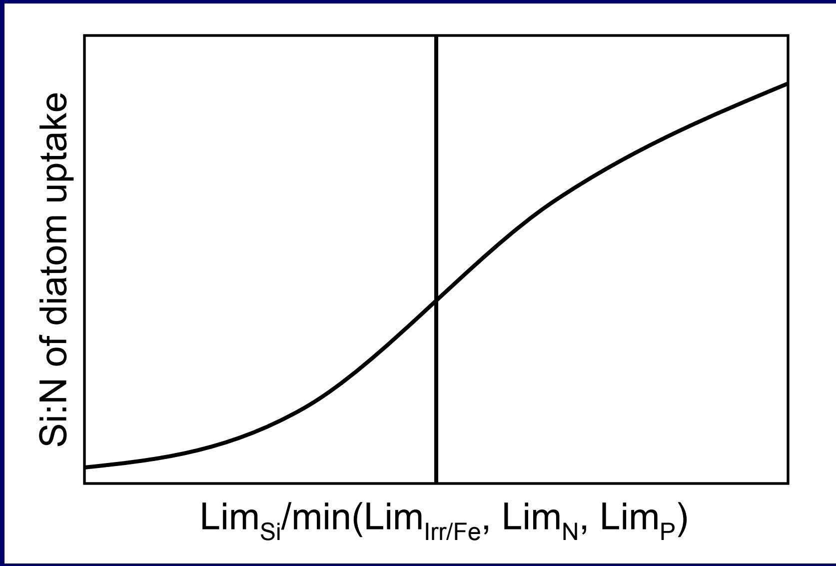


Model fit to Sunda and Huntsman (1997) for *T. Pseudonana* under high (open) and low light (filled):

Diazotrophs have slow growth and high N:P.

The Si:N uptake ratio is:

$$Si:N = (Si:N_{max} - Si:N_{min}) Si:N_{lim} / (Si:N_{max} + Si:N_{lim}) + Si:N_{min}$$



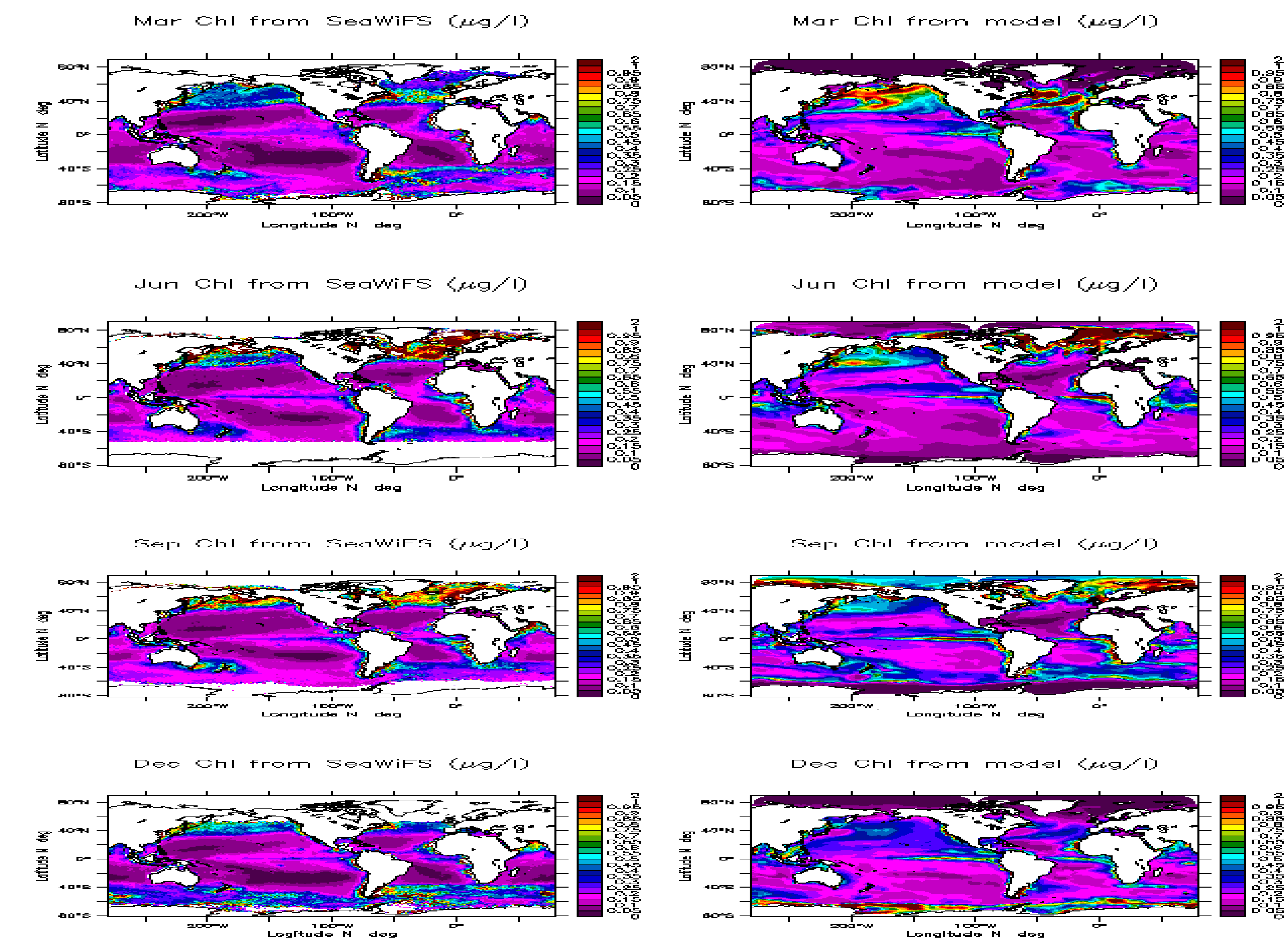
$CaCO_3$ production is a fraction of small Phytoplankton production.

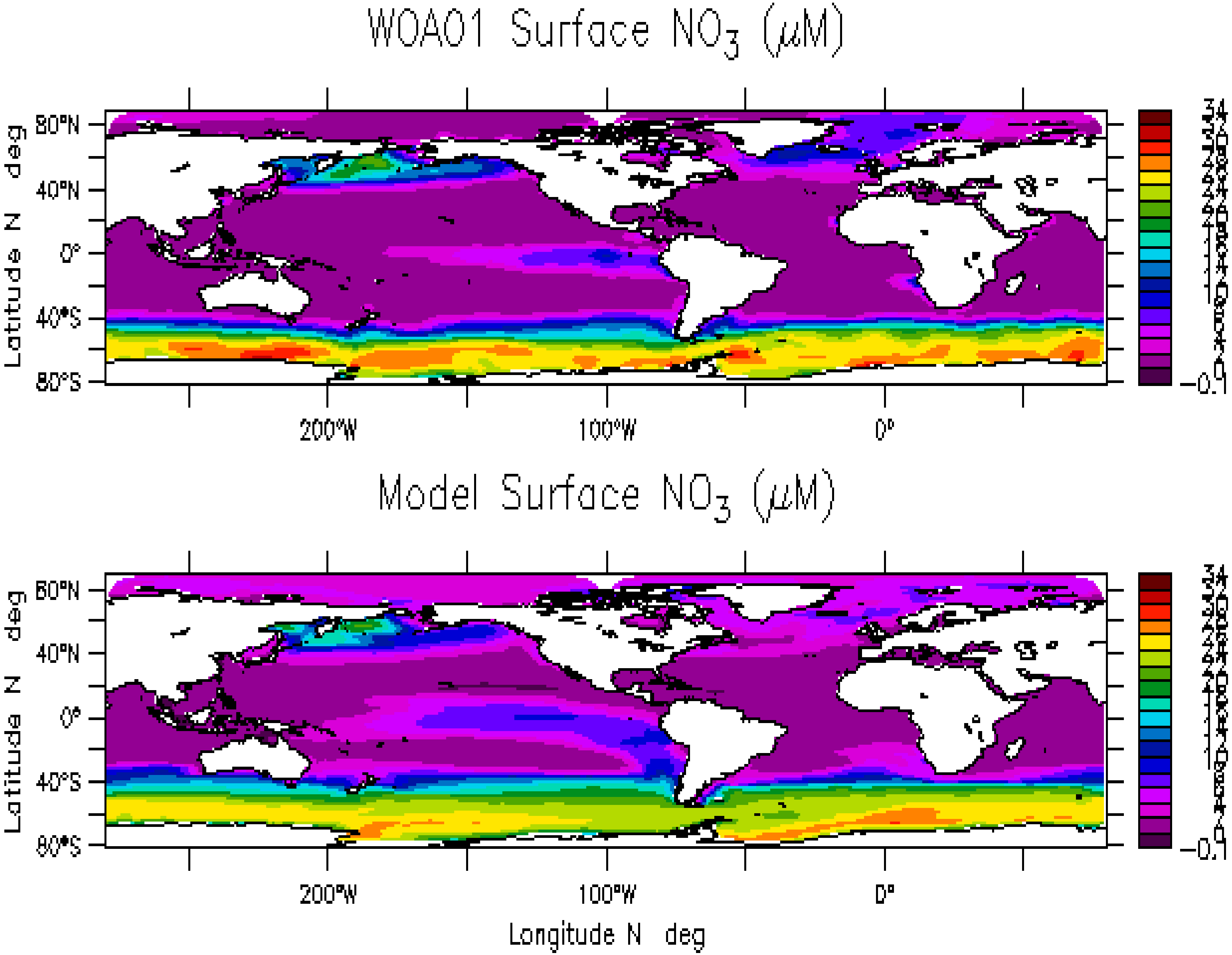
Recycling Components

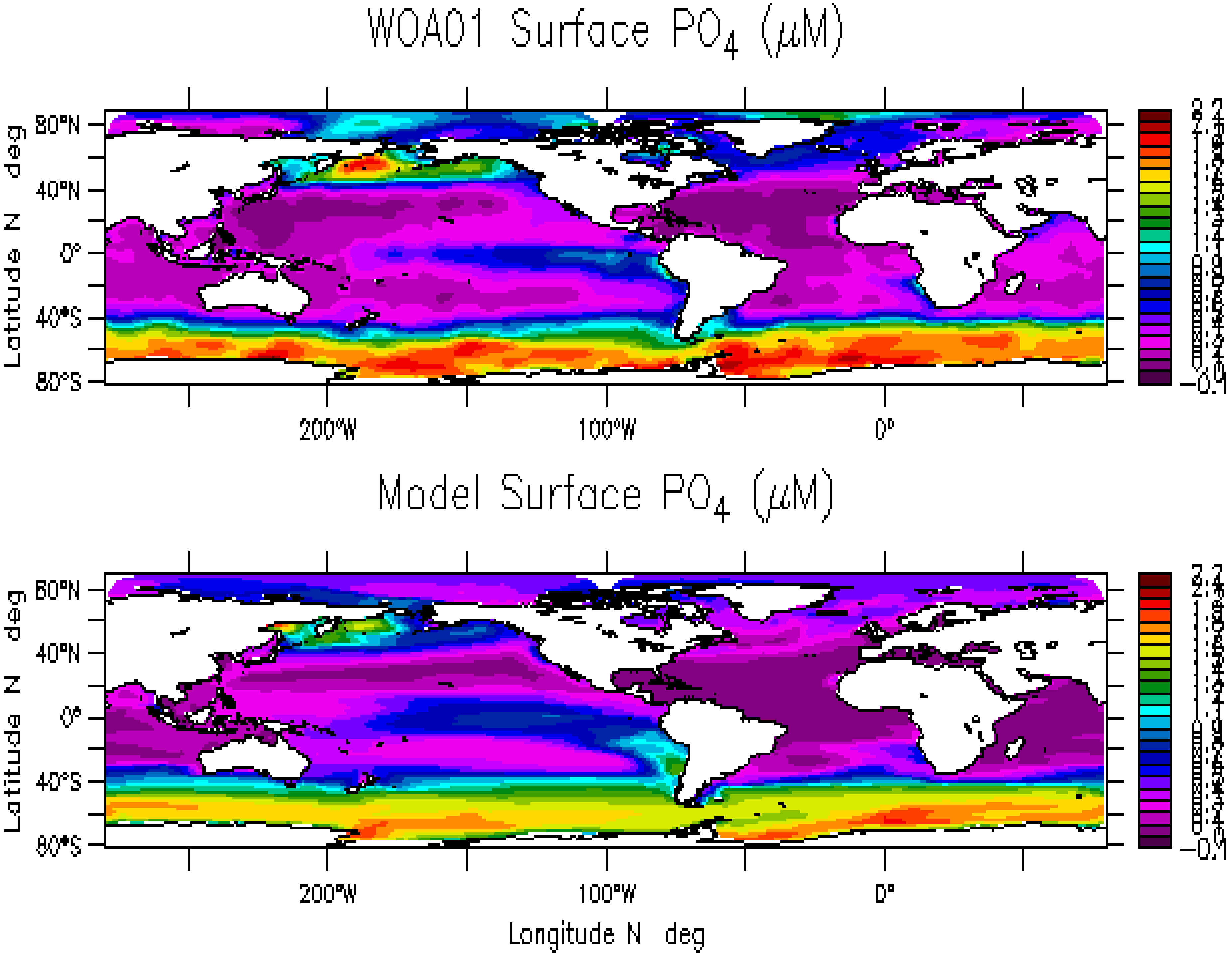
- Grazing of $P_S \propto P_S^2$
- Grazing of P_L and $P_{Di} \propto P^{4/3}$
- Detritus production a function of P_S, P_L, and P_{Di} grazing and T
- Grazing threshold prevents phytoplankton extinction
- Dissolved Fe adsorbs onto sinking organic particles
- Sinking detritus protected from remineralization by mineral after Klaas and Archer (2002)
- Semilabile DON (t_{remin} = 18 yr), Semilabile DOP (t_{remin} = 4 yr; Abell et al., 2000), and Labile DOM (t_{remin} = 3 mo) produced as constant fractions of grazing.

GFDL Ocean Biogeochemistry Results

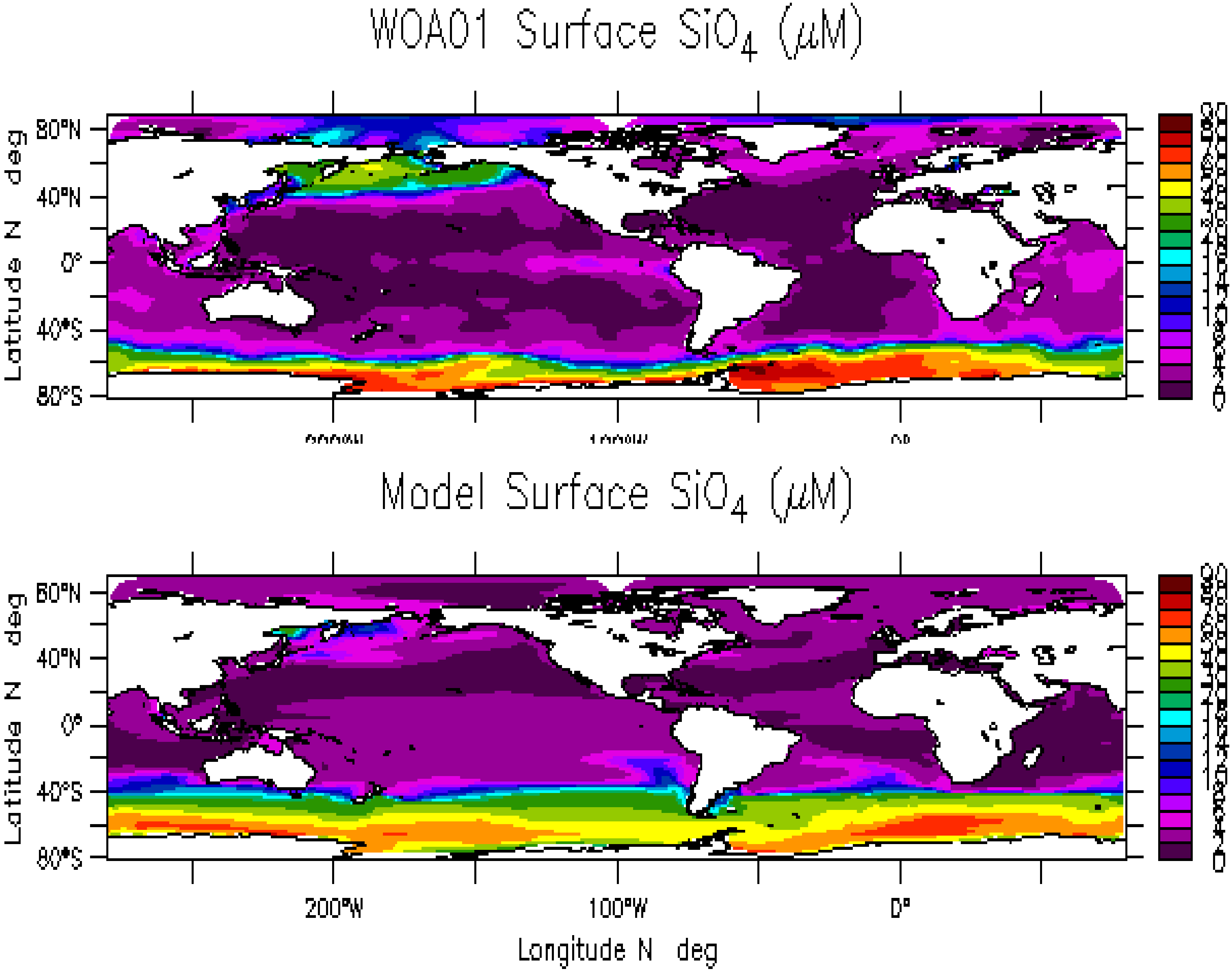
(NCAR/NCEP Reanalysis)

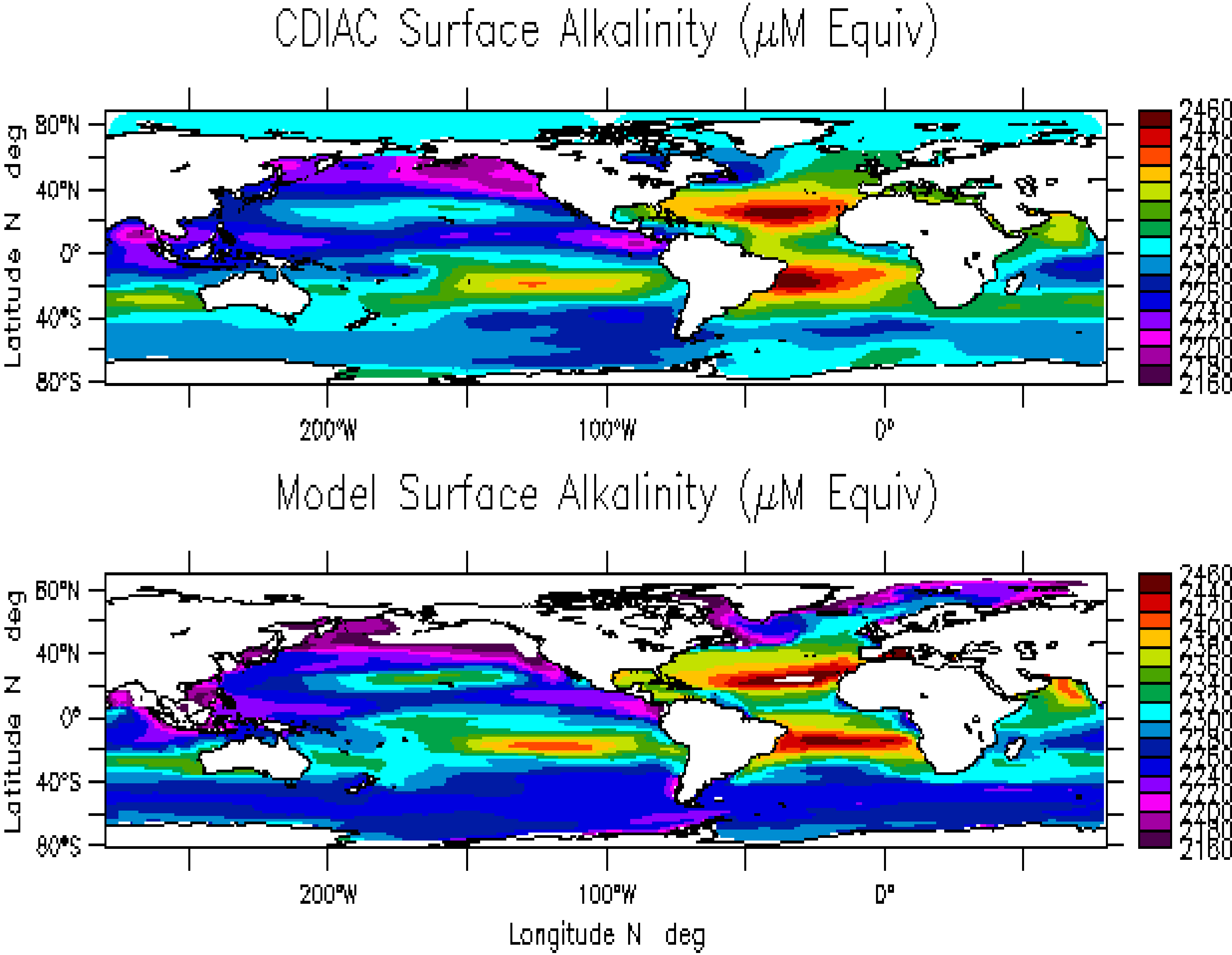

Mar Chl from SeaWiFS (μg/l)
Mar Chl from model (μg/l)
Jun Chl from SeaWiFS (μg/l)
Jun Chl from model (μg/l)
Sep Chl from SeaWiFS (μg/l)
Sep Chl from model (μg/l)
Dec Chl from SeaWiFS (μg/l)
Dec Chl from model (μg/l)
Latitude N deg
Longitude N deg
200°W
100°W
0°
40°N
0°
40°S


WOA01 Surface NO3 (μM)
Model Surface NO3 (μM)
80°N
40°N
0°
40°S
80°S
200°W
100°W
0°
Latitude N deg
Longitude N deg
34
-0.1

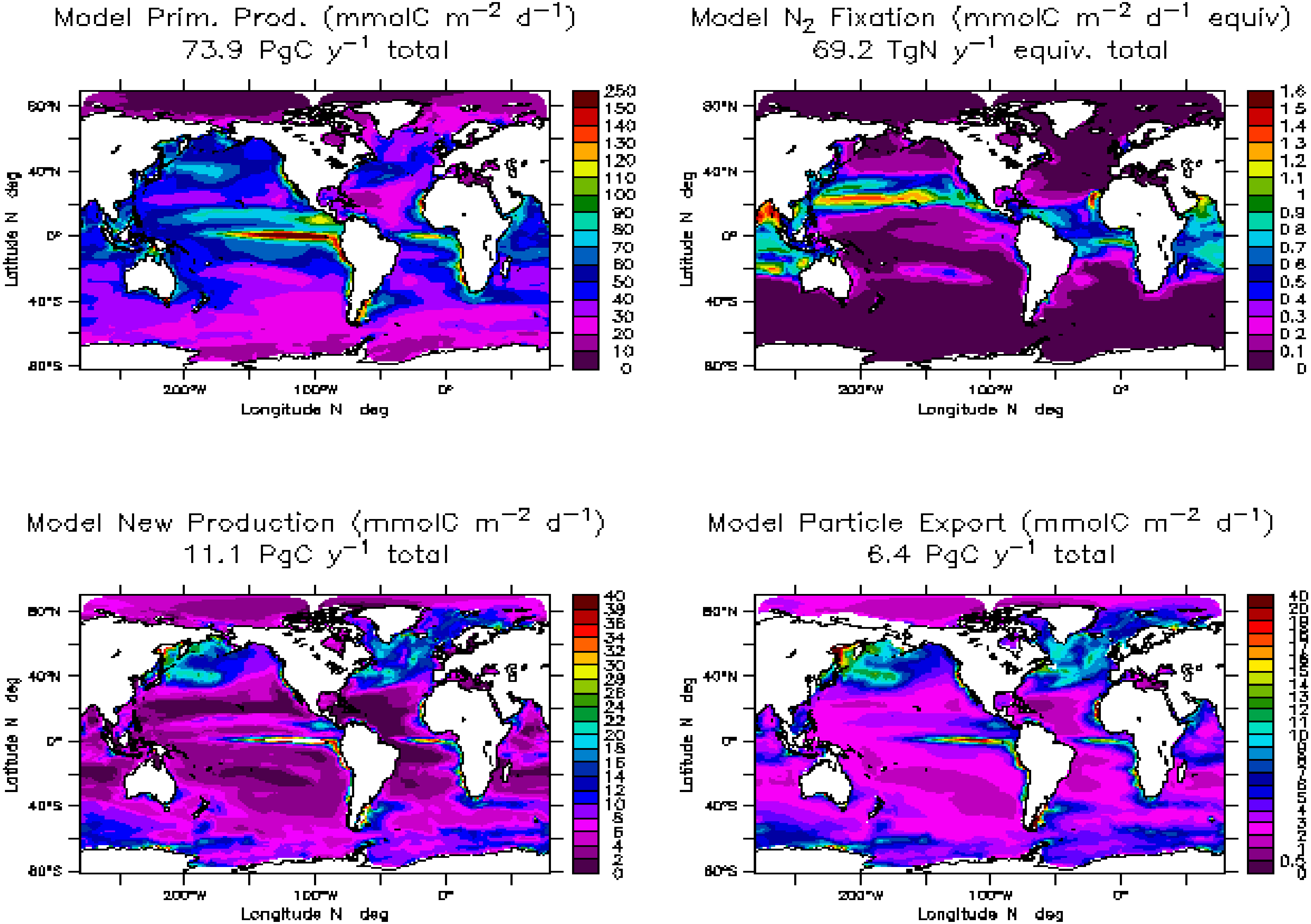


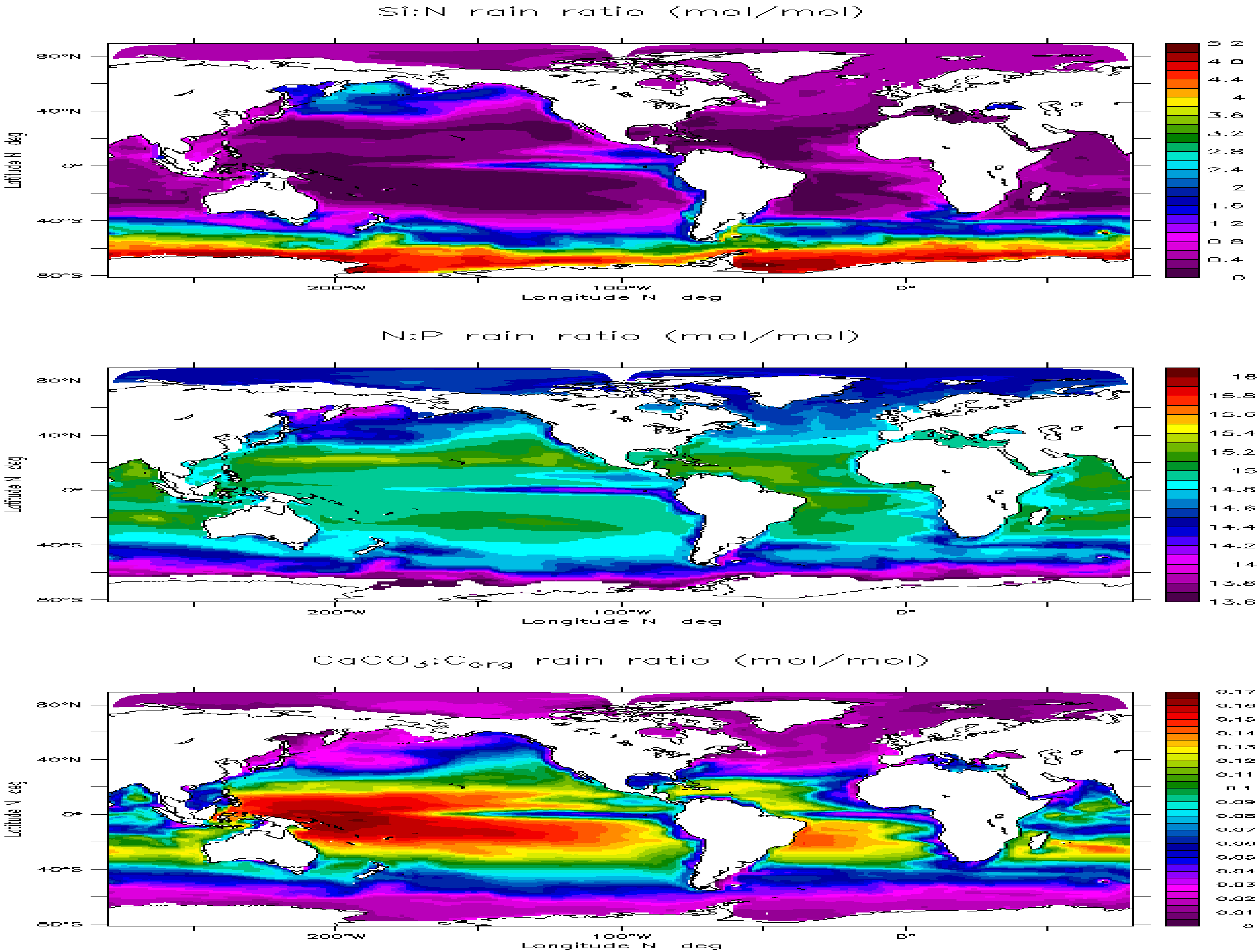
WOA01 Surface PO4 (μM)
Model Surface PO4 (μM)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
2.2
-0.1

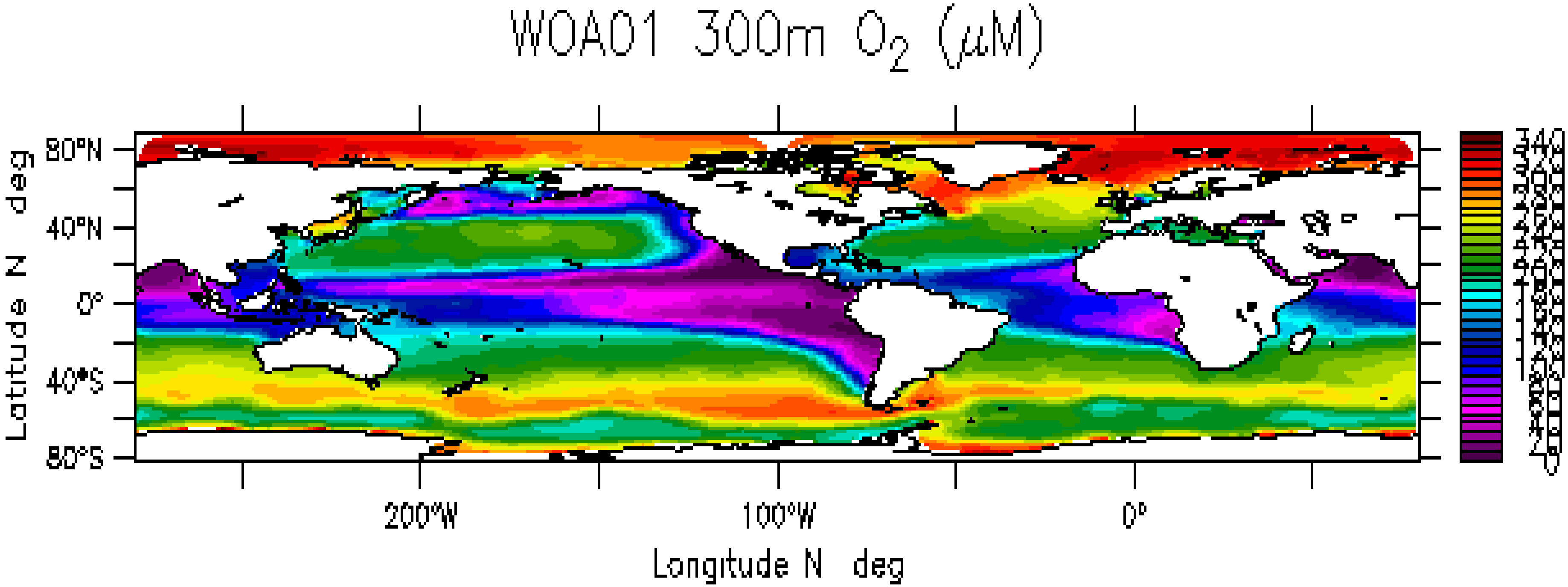

WOA01 Surface SiO4 (μM)
80°N
40°N
0°
40°S
80°S
Latitude N deg
Model Surface SiO4 (μM)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg

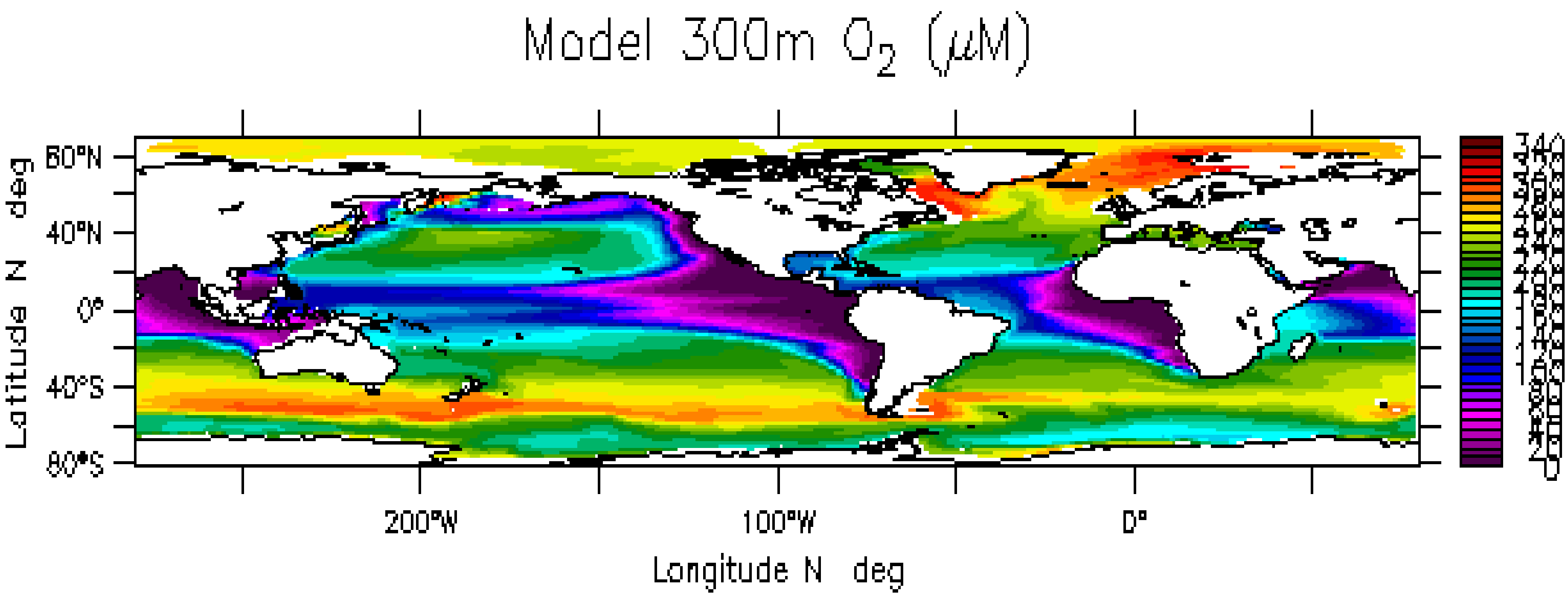


CDIAC Surface Alkalinity (μM Equiv)
Model Surface Alkalinity (μM Equiv)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
2460
2160

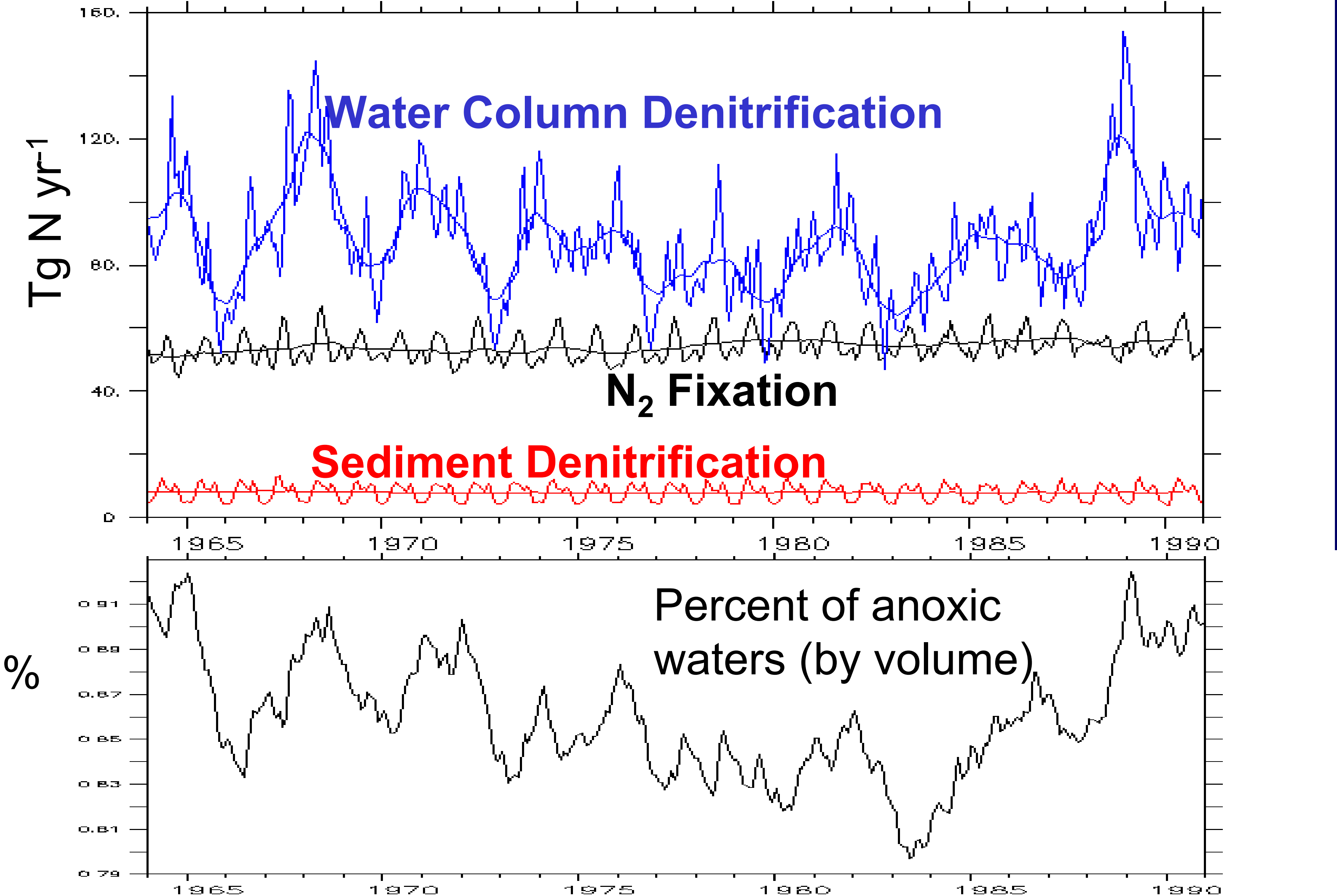

Model Prim. Prod. (mmolC m−2 d−1)
73.9 PgC y−1 total
Latitude N deg
Longitude N deg
Model N2 Fixation (mmolC m−2 d−1 equiv)
69.2 TgN y−1 equiv. total
Latitude N deg
Longitude N deg
Model New Production (mmolC m−2 d−1)
11.1 PgC y−1 total
Latitude N deg
Longitude N deg
Model Particle Export (mmolC m−2 d−1)
6.4 PgC y−1 total
Latitude N deg
Longitude N deg

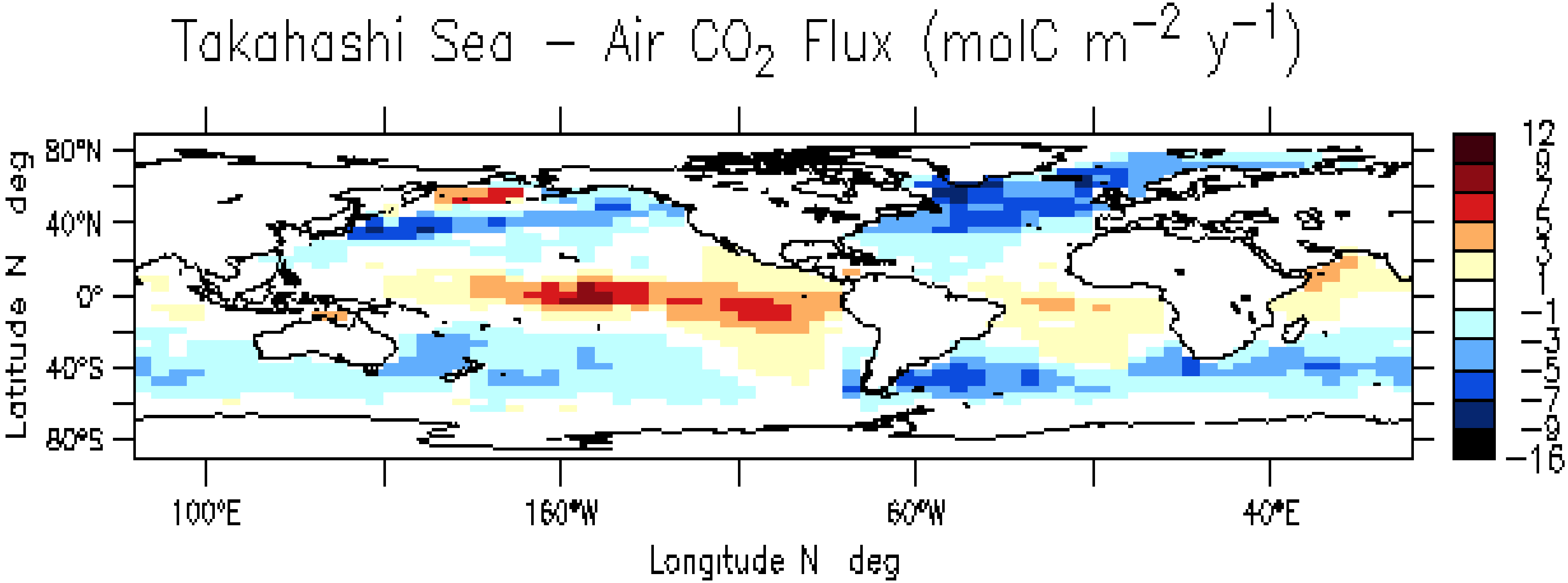

Si:N rain ratio (mol/mol)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
5.2
4.8
4.4
4
3.6
3.2
2.8
2.4
2
1.6
1.2
0.8
0.4
0
N:P rain ratio (mol/mol)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
16
15.8
15.6
15.4
15.2
15
14.8
14.6
14.4
14.2
14
13.8
13.6
CaCO3:Corg rain ratio (mol/mol)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

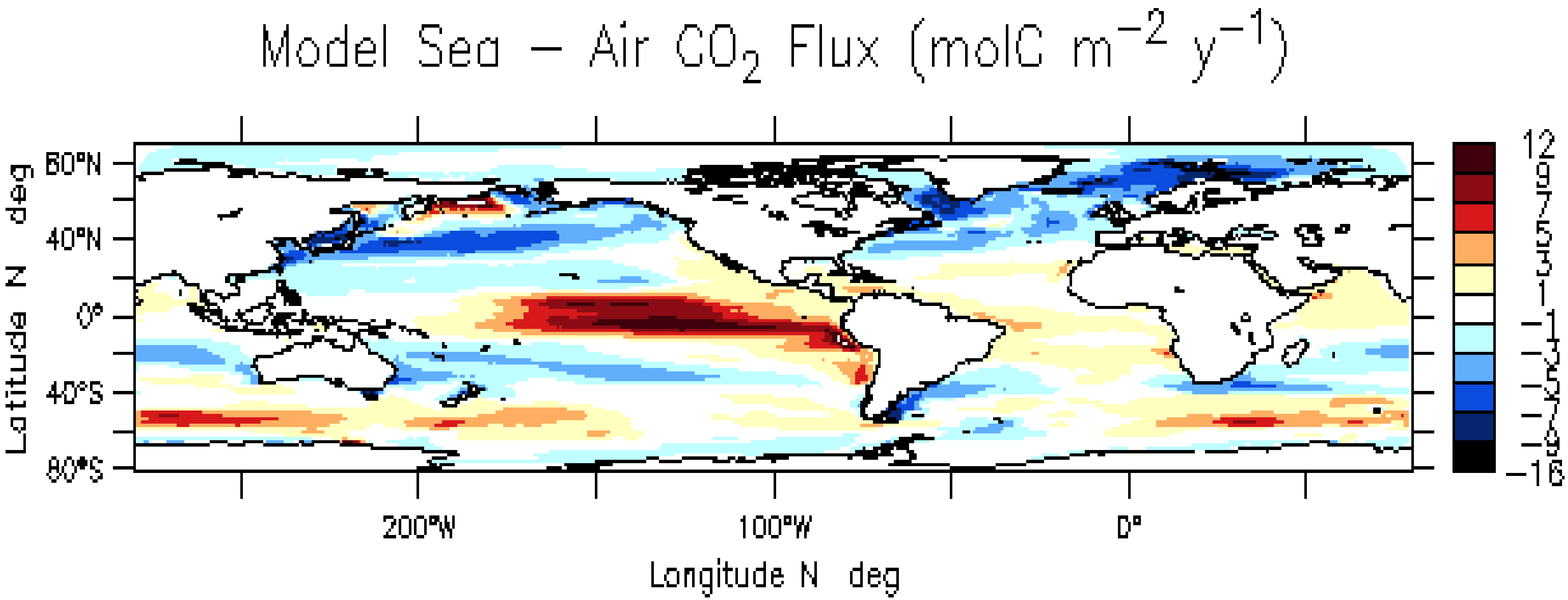

WOA01 300m O_2 (μM)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
340
0


Model 300m O_2 (μM)
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
340
0

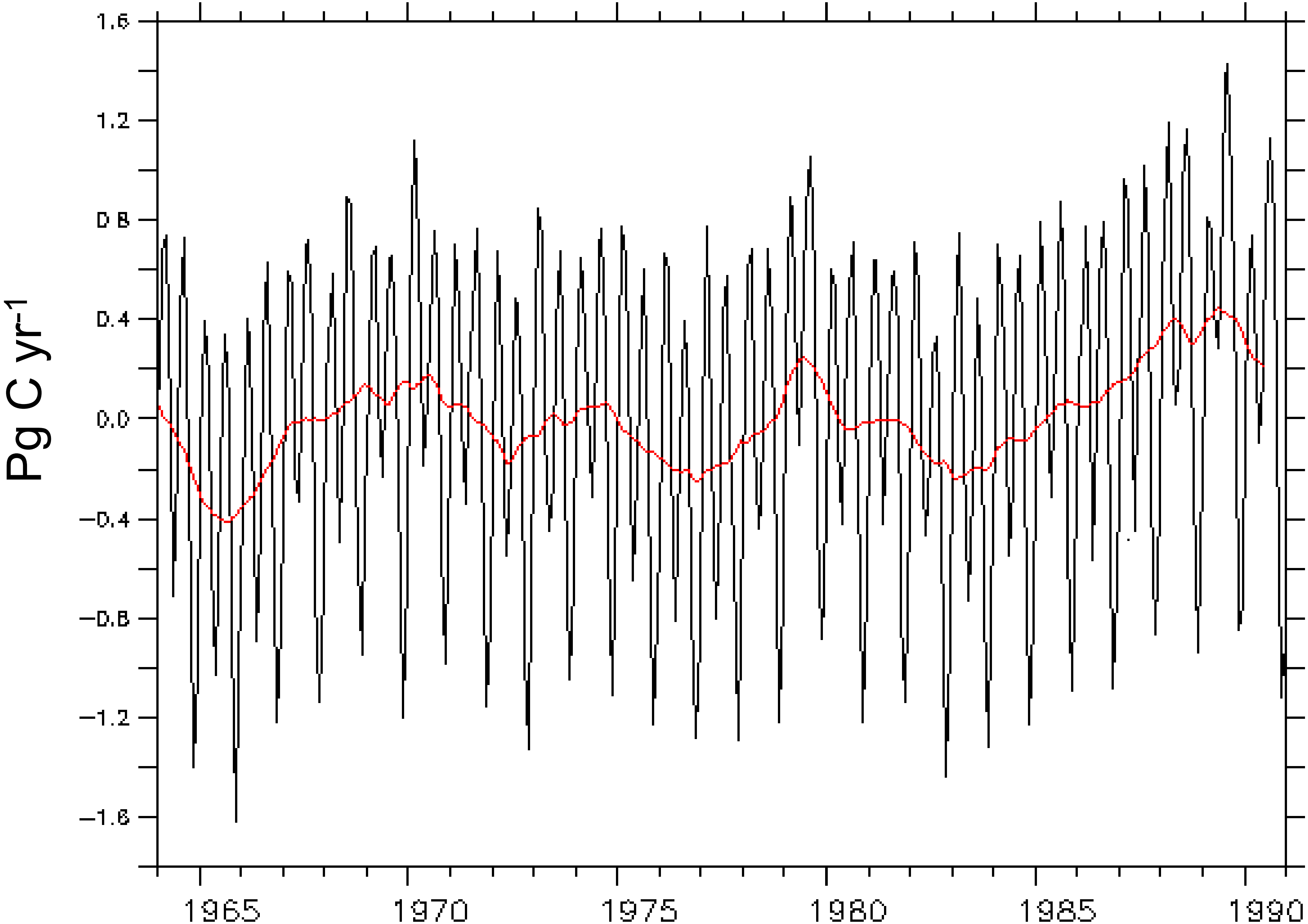
Global variability in Nitrogen Cycling



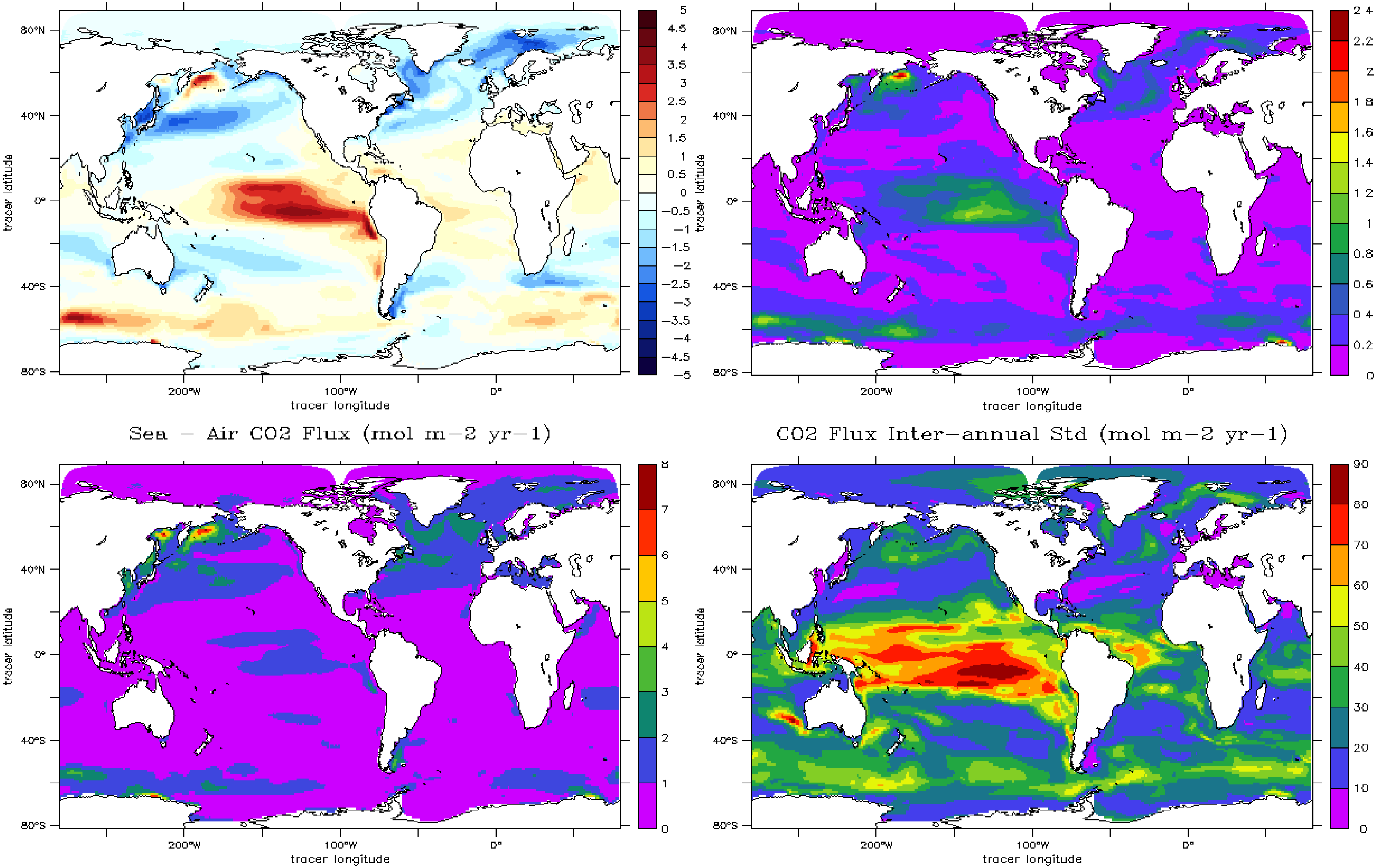

Takahashi Sea - Air CO_2 Flux (molC m^{-2} y^{-1})
80°N
40°N
0°
40°S
80°S
Latitude N deg
100°E
160°W
60°W
40°E
Longitude N deg
12
9
7
5
3
1
-1
-3
-5
-7
-9
-16


Model Sea - Air CO_2 Flux (molC m^{-2} y^{-1})
80°N
40°N
0°
40°S
80°S
Latitude N deg
200°W
100°W
0°
Longitude N deg
12
9
7
5
3
1
-1
-3
-5
-7
-9
-16

Global Sea-Air CO_2 Flux



Global Sea-Air CO_2 Flux Variability



Sea – Air CO2 Flux (mol m−2 yr−1)

CO2 Flux Inter−annual Std (mol m−2 yr−1)

CO2 Flux Std (mol m−2 yr−1)

CO2 Flux % Inter−annual

Summary of reanalysis results

- Large scale WOA01 and SeaWiFS patterns are reproduced though the Southern Ocean is too low in surface nutrients.
- Many areas of improvement remain:
    - Eq. Pacific HNLC region larger than observations
    - Eq. Pacific chlorophyll and production also in excess.
    - North Atlantic subtropical gyre is too far south
    - North Atlantic spring bloom terminates too early
- Global Sea-Air variability in CO_2 fluxes consistent with expectations from radiative forcing
- Intermittently ice-covered regions do not out-gas significant levels of CO_2 in this model.
- Water column denitrification varies significantly on inter-annual time-scales.

Current Challenges

Practical development issues

Model Complexity:

- Composed of 10^6 lines of code and scripts
- Includes 10^3 parameter options
- Includes 10^2 restart and initialization files
- Written by 10^1-10^2 people
- Incomplete documentation
- Code is constantly changing

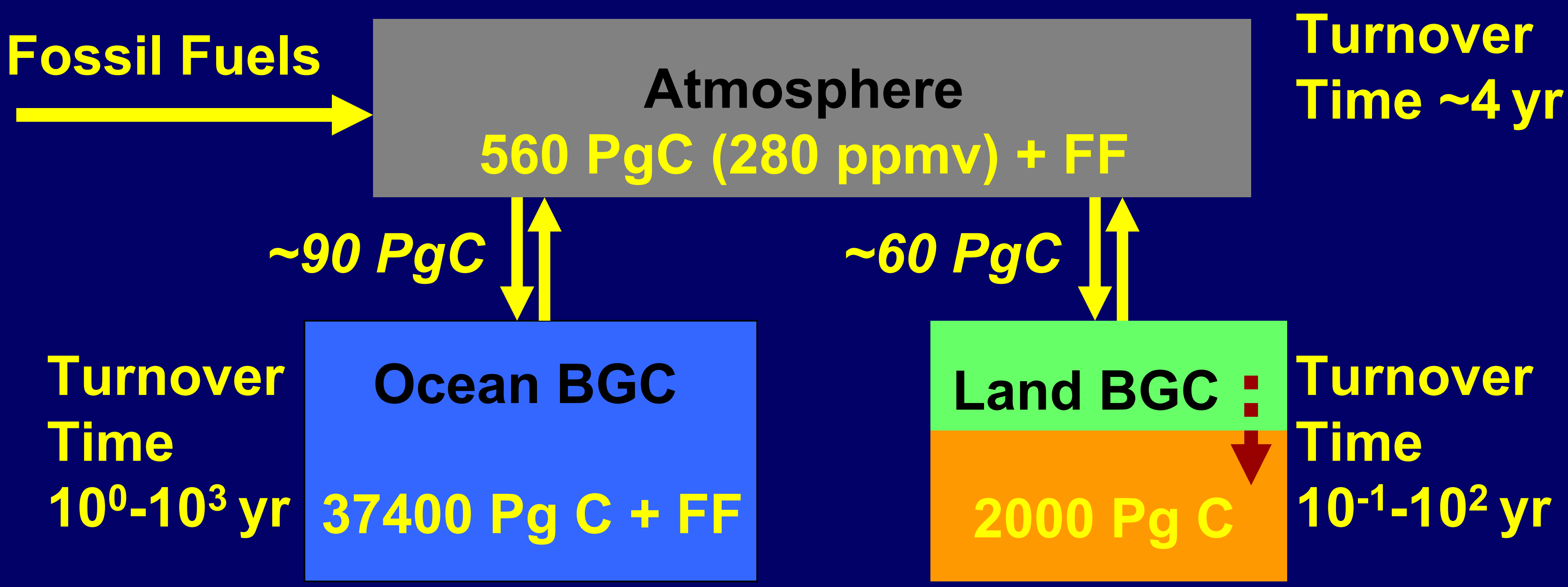
Model speed:

- Code retrieval and compilation takes 3 hours
- Input retrieval for short runs takes up to 2 hours
- Model runs 6 years per day on 126 processors
- Output retrieval of model year takes 2 hours
- Computer system glitches increase time by 1.2-2

Model size:

- Monthly output for a model year is 16Gb

How to initialize the carbon system?



…equilibrium takes 10^3-10^4 yrs…

…running 1000 years takes >6 months

Options to initialize the carbon system

- Run the model out for a very long time
- Perform short runs with drift and always reference to a control
- Run until the drift becomes small relative to the anthropogenic increase
- Run until the drift becomes smaller than the natural variability
- Accelerate the carbon system towards equilibrium
  - Correction via drift extrapolation
  - Inverse methods
  - Correction via solubility and biological pump separation

Is a steady state ever achieved?

- Short term solar and volcanic forcings vary on the order of 5W m^{-2}:

  CO_2 solubility variability ≈ 1 Pg C yr^{-1}
- Long term radiative budget has ~1W m^{-2} heat uptake in standard climate run:

  CO_2 solubility outgassing ≈ 2 Pg C $decade^{-1}$
- Nitrogen cycle has long time-scale variability

When is the model “good enough”?

- Is the model constructed robustly?
  - Nitrate, Silicate and Fe at mode water formation
  - Timing of blooms relative to sea ice cover
- How does one assess model fidelity?
  - Cruise data is sparse, both temporally and geographically
  - Data information can seem contradictory
- What to do when biospheric dynamics degrades climate?
  - Example: Current run turns the Amazon to a desert.

When is the model "good enough"?

- Analogy with GFDL's CM2 development :
  - SST < 10° C away from Levitus
  - NADW > 10 Sv
  - El Nino (1 yr < trop. osc. < 5yr)

- Examples of ESM options:
  - Control run dCO_{2atm}/dt less than 2 Pg C/decade?
  - Vegetation type (Rainforest/desert/savanna/etc) agreement with observations?
  - Surface nutrient agreement with observations?
  - Surface CO_2 flux agreement with observations?
  - Land NPP, Ocean NPP?
  - Others?

Which processes must be simulated?

- Physical pathways are simplified – e.g. no explicit rivers, estuaries or sediments.
  - Are these neglected processes important to CO_2 radiative feedbacks?
- Biogeochemistry has long time scales that cannot be simulated.
  - What do we need to know about longer timescales?
  - How is our lack of information affecting our understanding?
- Biology is far more complex than we can simulate computationally.
  - What susceptibilities need to be represented?

Can the Earth be modeled as a single system, or do different goals require different models?

- Hard: Climate goals only require processes with climate feedbacks:
  - “Importance” defined radiatively in $W\ m^{-2}$
  - Land albedo, transpiration and CO_2 exchange
  - Ocean CO_2 exchange (and perhaps Chl)
  - CH_4 cycle?
- Harder: Biogeochemical goals require ecosystem complexity:
  - Terrestrial Ecology
  - Ocean Ecosystems
  - Rivers, sediments, sea ice
- Hardest: Human impact goals require getting all the rest right:
  - Human health
  - Water supplies
  - Agriculture
  - Fisheries
  - Susceptibility to Catastrophe

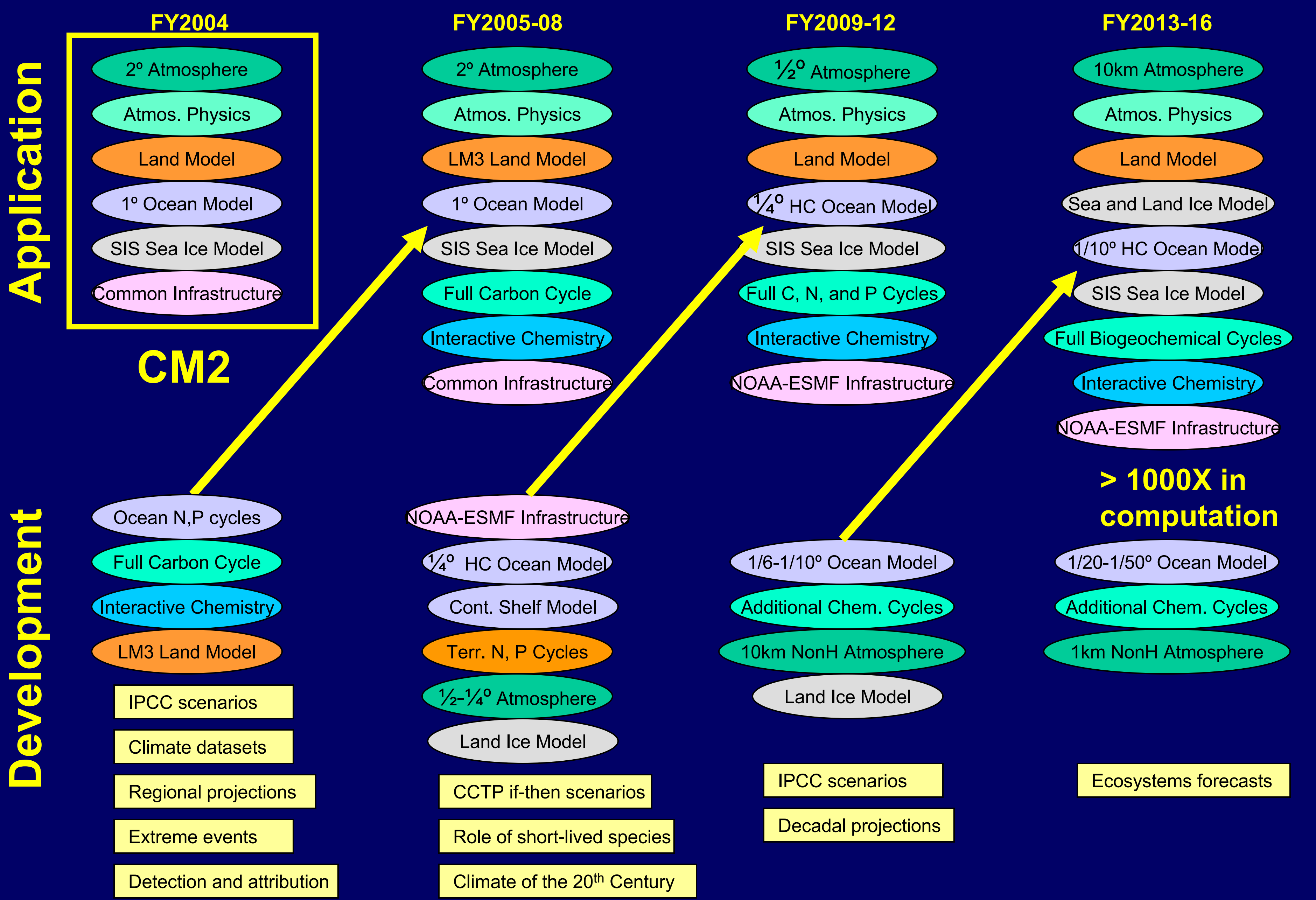
How to address ecologically-forced degradation in physical simulation?

- Until very recently, global climate models had to an artificial “flux adjustment” at the air-sea interface to keep the climate stable and representative…
- What types ESM tunings are advisable?
  - Should CO_2 fluxes be adjusted to reproduce atmospheric concentrations over time?
  - Should ecological feedbacks be tuned to compensate for poor-physics (Amazon example).

Short-term Earth System Modeling Plans

- Code synchronization with climate group
- Address current issue of Amazon fidelity degradation
- Spinup to quasi steady state.
- Run IPCC scenarios of 1860-2100 to quantify:
    - Ecosystem feedbacks on atmospheric CO_2
    - Climate feedbacks on ecosystems
- Assess CO_2 fluxes under various CO_2 emissions, land use and mitigation scenarios.

Long-term Earth System Modeling Plans



How can data “improve models”?

- Provide boundary and initial conditions
  - WOCE, NCEP, GLODAP, etc.
- Data synthesis => Improved theory => implementation
  - Effect of mineral on organic flux
- Data - Model comparison => flaws in models => refutation of model => new theory => implementation
  - HNLC – EqPac - IronEx I – IronEx II – Fe in models