Ocean ecology in a warmer world and consequences for the carbon cycle

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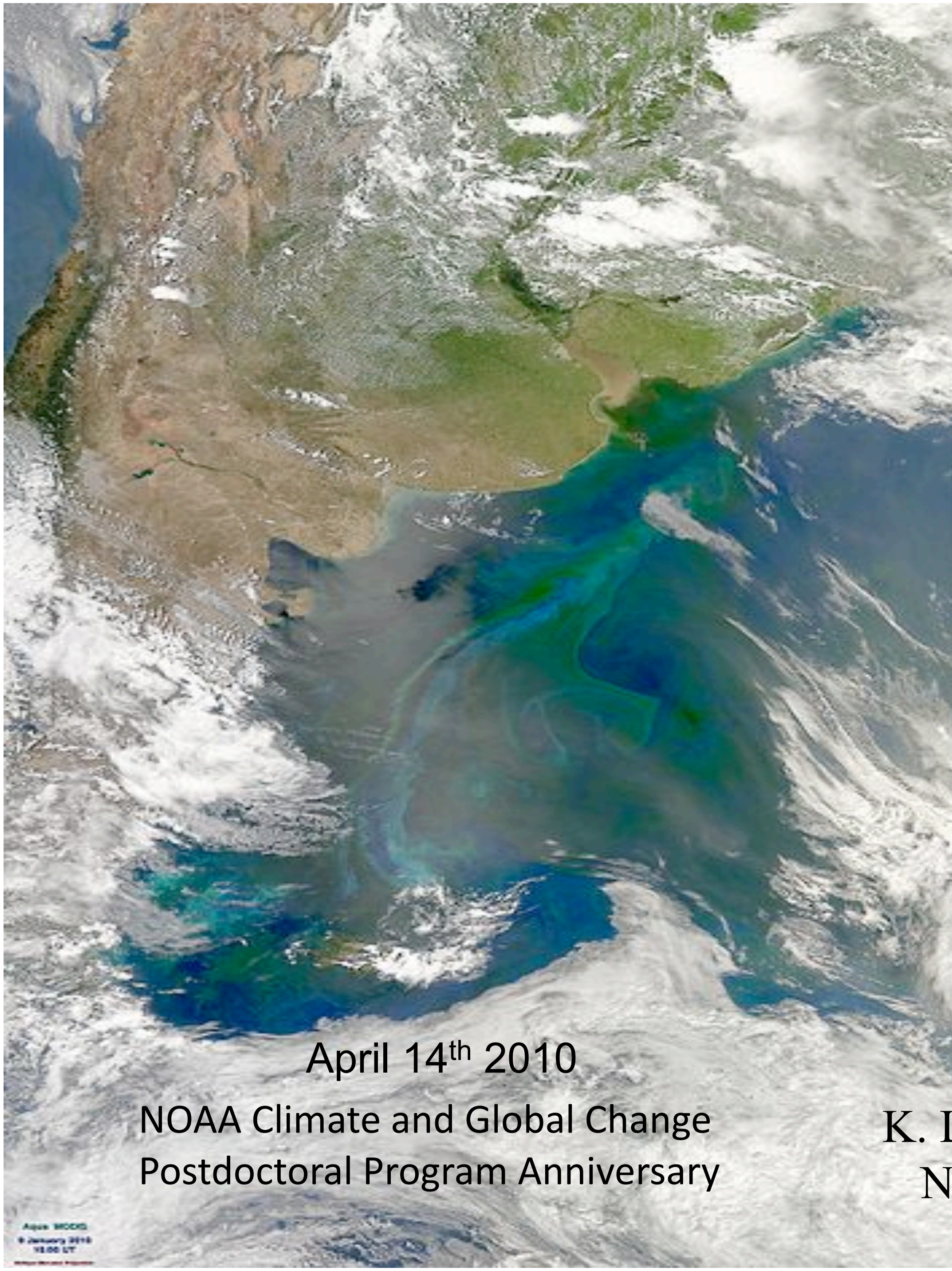


April 14th 2010

NOAA Climate and Global Change Postdoctoral Program Anniversary

Collaborators:

Scott Doney, Ivan Lima (WHOI)

K. Lindsey (NCAR), K. Moore (UC Irvine)
N. Mahowald (Cornell) = CCSM ocean biogeochemistry group

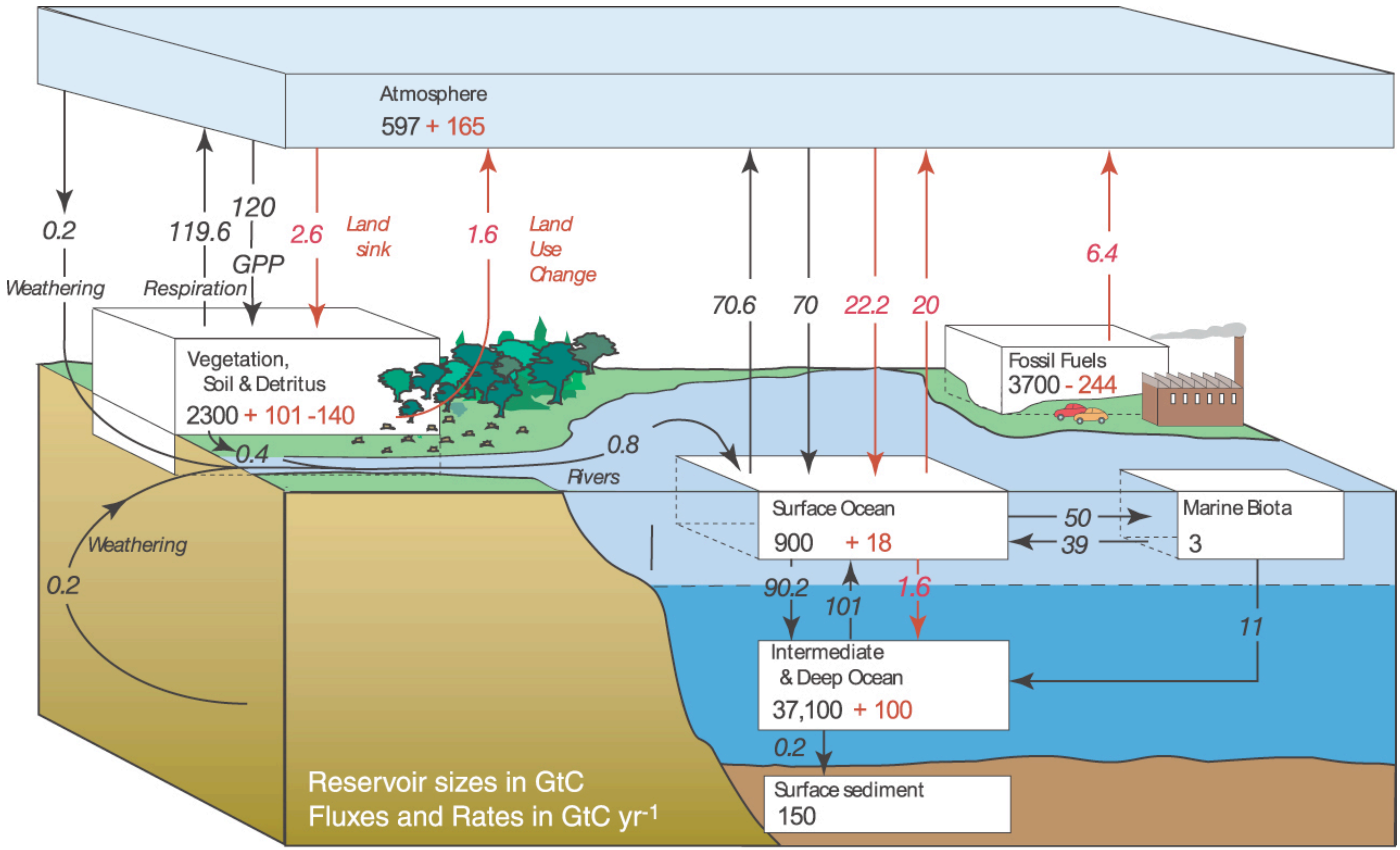
"North-South asymmetry in the response of ocean ecology and biogeochemistry to climate change over the 21st century."

Marinov et al. submitted to Global Biogeochem. Cycles

" Response of ocean phytoplankton community structure to climate change over the 21st century: partitioning the effects of nutrients, temperature and light"

Marinov, Doney and Lima, Biogeosciences 2010

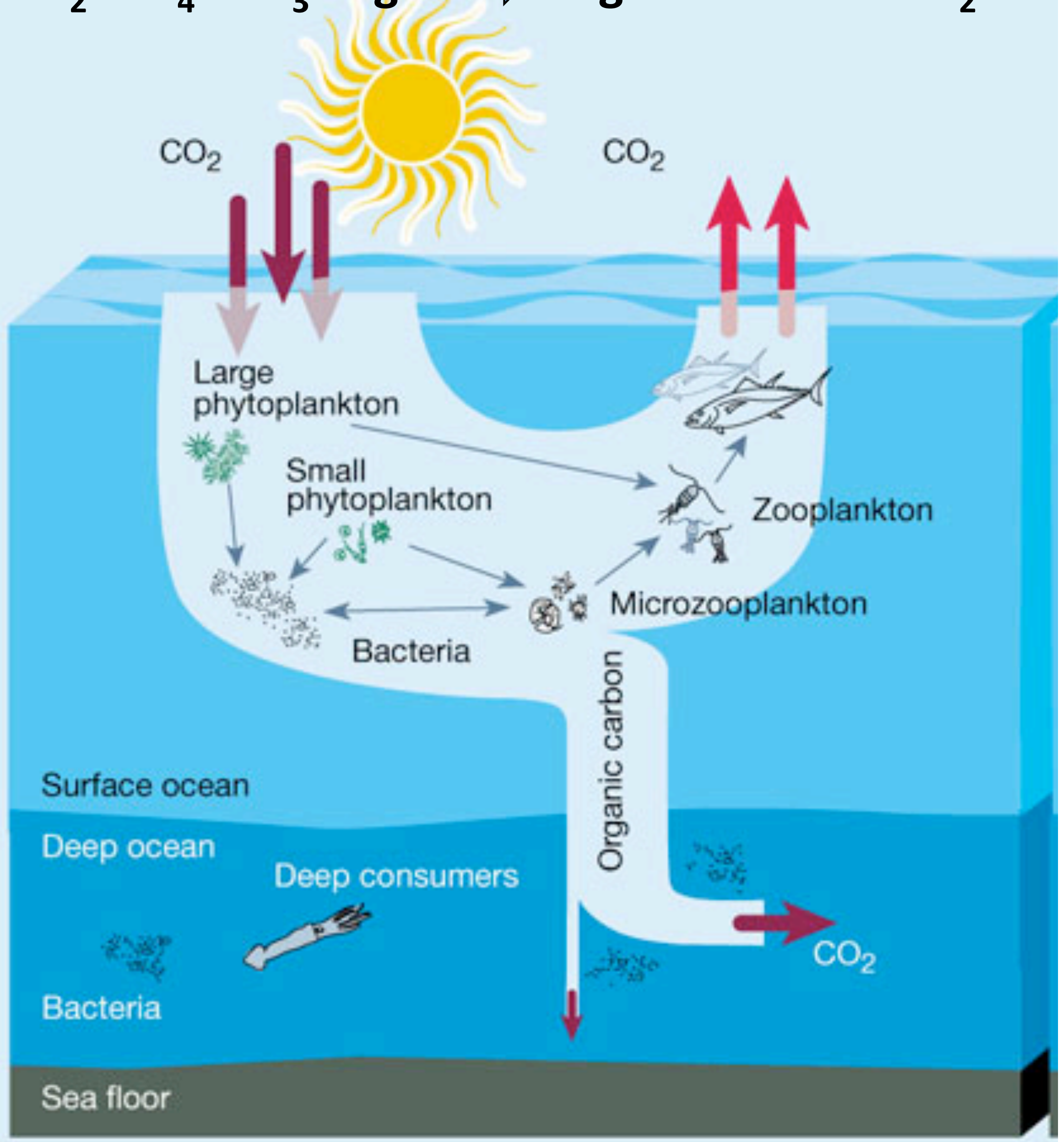
The ocean plays the dominant role in determining atmospheric CO_2 on time scales of centuries and longer



Biological carbon pump

$CO_2 + PO_4 + NO_3 + \text{light} \Rightarrow \text{organic matter} + O_2$

PO_4, CO_2 consumed



PO_4, CO_2 added to the deep

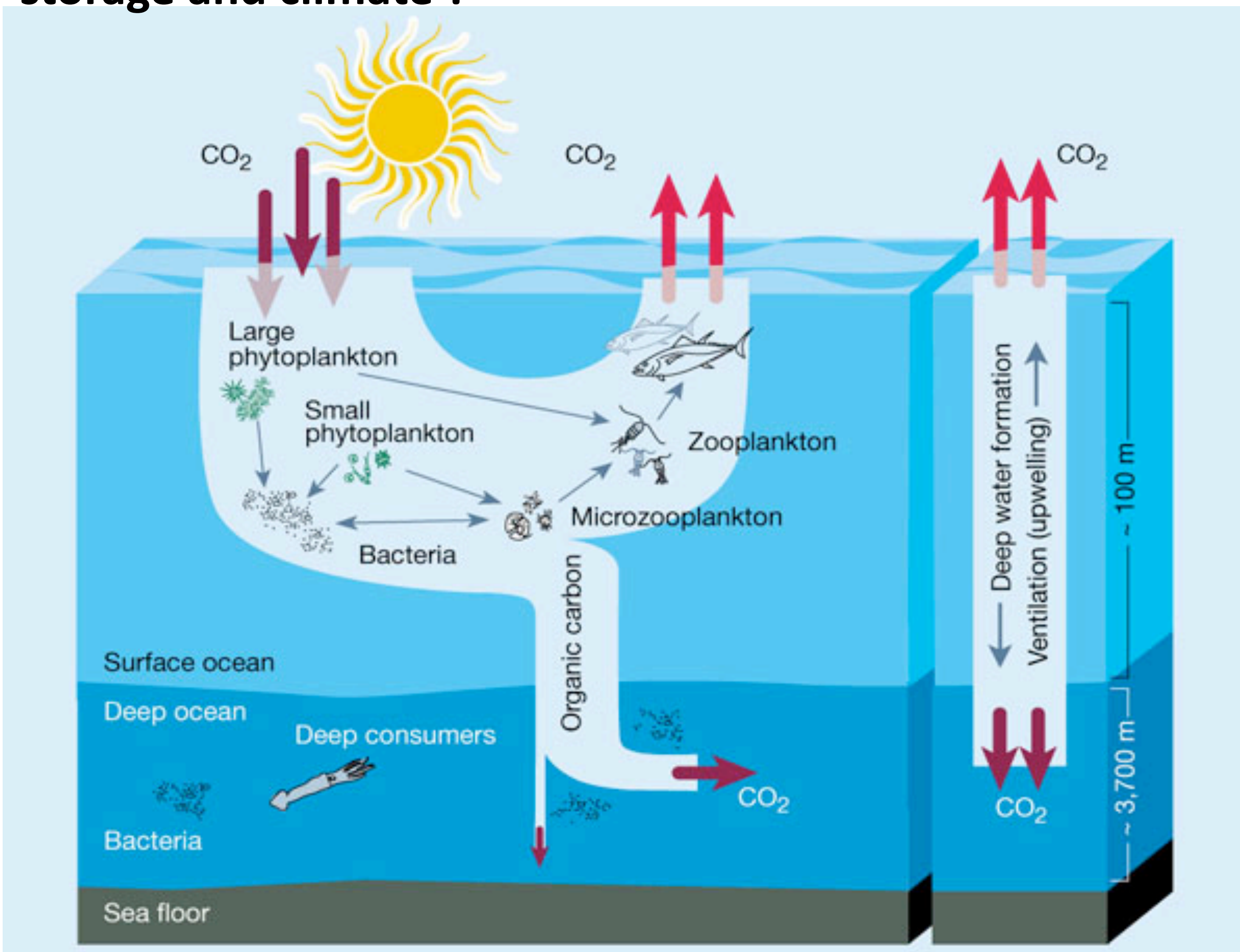
$\text{Organic matter} + O_2 \Rightarrow CO_2 + PO_4 + NO_3$

Store PO_4, CO_2

Ocean Carbon Storage

1. Climate change decreases surface-deep water mixing. This decreases the supply of nutrients to the surface. Temperature and light also change. How will phytoplankton biomass, production and size structure respond ?

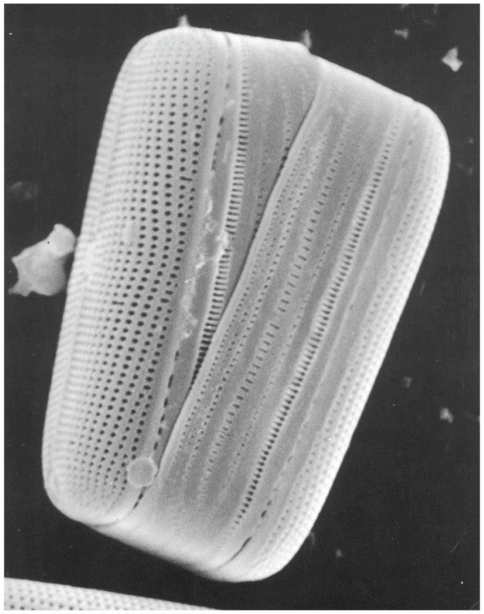
2. What will be the ultimate impact on the biological pump, ocean carbon storage and climate ?



Ocean carbon pumps

nutrients and CO_2 transported down

Types of phytoplankton



(a)

1. Large phytoplankton (ex: Diatoms)

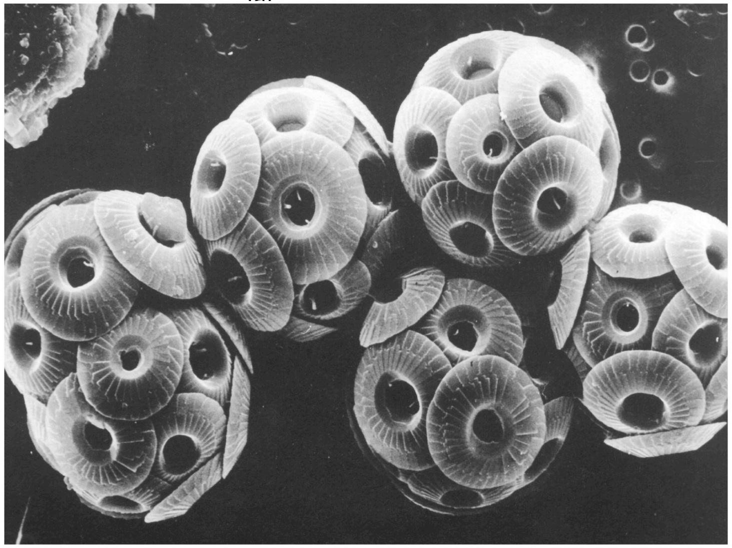
Large photosynthetic phytoplankton, 50 mm wide, with SiO_2 cell walls, eukaryotes

– **Best at exporting Carbon to the deep ocean**

– Low area to volume ratio

2. Small phytoplankton (Nano-pico plankton)

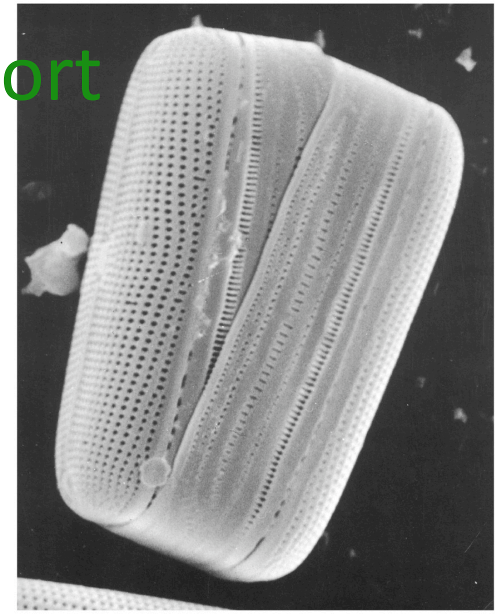
- **get recycled more at surface, less export**
- High area to volume ratio



(a)

- **Coccolithophores**: nanoplankton (~10-100mm) with $CaCO_3$ shells
- **Prochlorococcus** (0.6mm), tiny cyanobacteria, **most plentiful species in the ocean,** dominate bt 40^oS -40^oN, 13-48% of ocean primary production

Types of phytoplankton determine C export



(a)

$$e - ratio = \frac{\text{Export Production (at100m)}}{\text{Total Production (above100m)}}$$

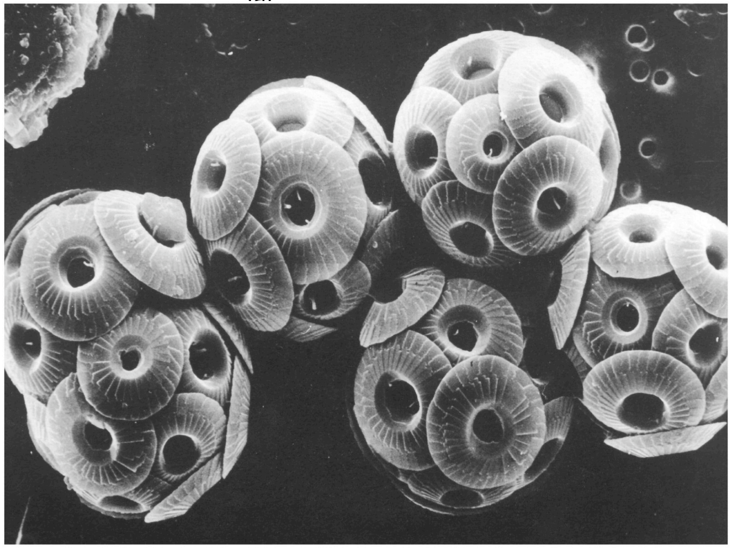
Will a future warmer world have:

1. More Large phytoplankton (Diatoms) ?

- **More carbon export to the deep**
- **Larger e-ratio**
- **Lower atmospheric pCO_2**
- **Negative climate feedback ?**

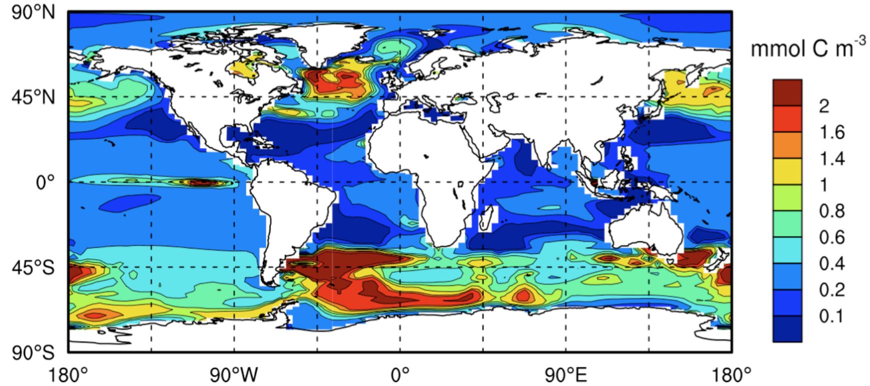
2. More Small phytoplankton ?

- **More surface recycling, less export**
- **smaller e-ratio**
- **higher atmospheric pCO_2**
- **positive climate feedback ?**

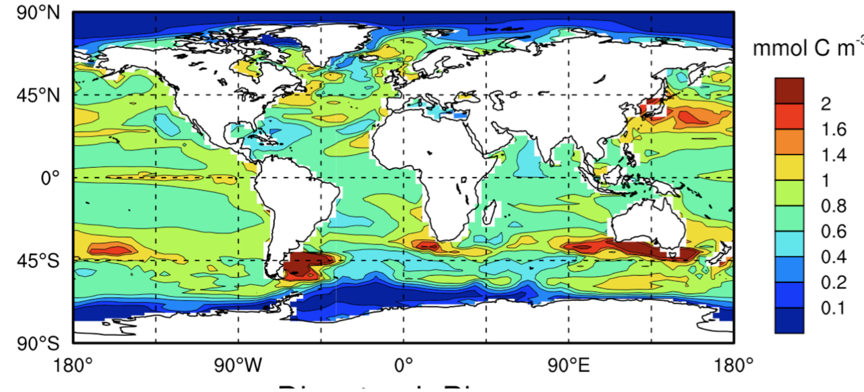


(a)

Diatom Biomass

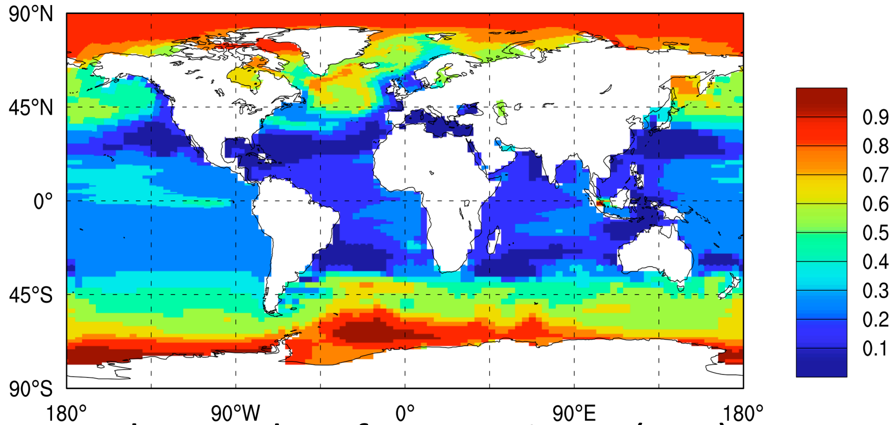


Small Phyto. Biomass

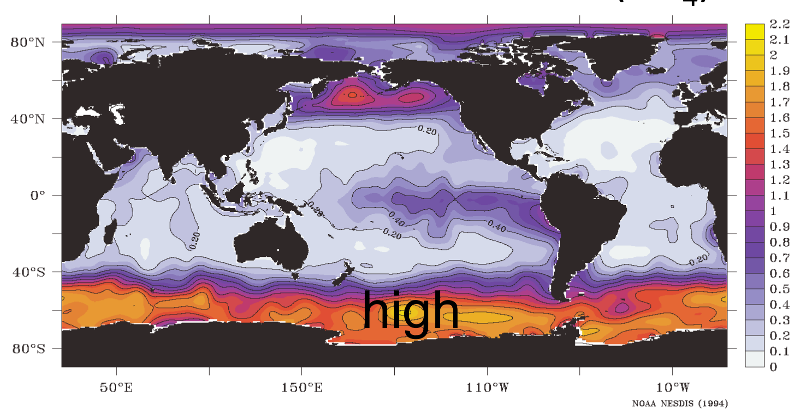


NCAR model (1980-1999)

Diatom relative abundance



Observed surface nutrients (PO_4)



Small phytoplankton: **high area to volume ratio -> better at taking up nutrients in nutrient poor subtropical gyres. Strongly grazed.**

Diatoms: low area to volume -> require higher nutrients to reach their maximal growth rates. Grazed less. Dominant in turbulent conditions or under bloom conditions.

THIS STUDY:

NCAR Model:

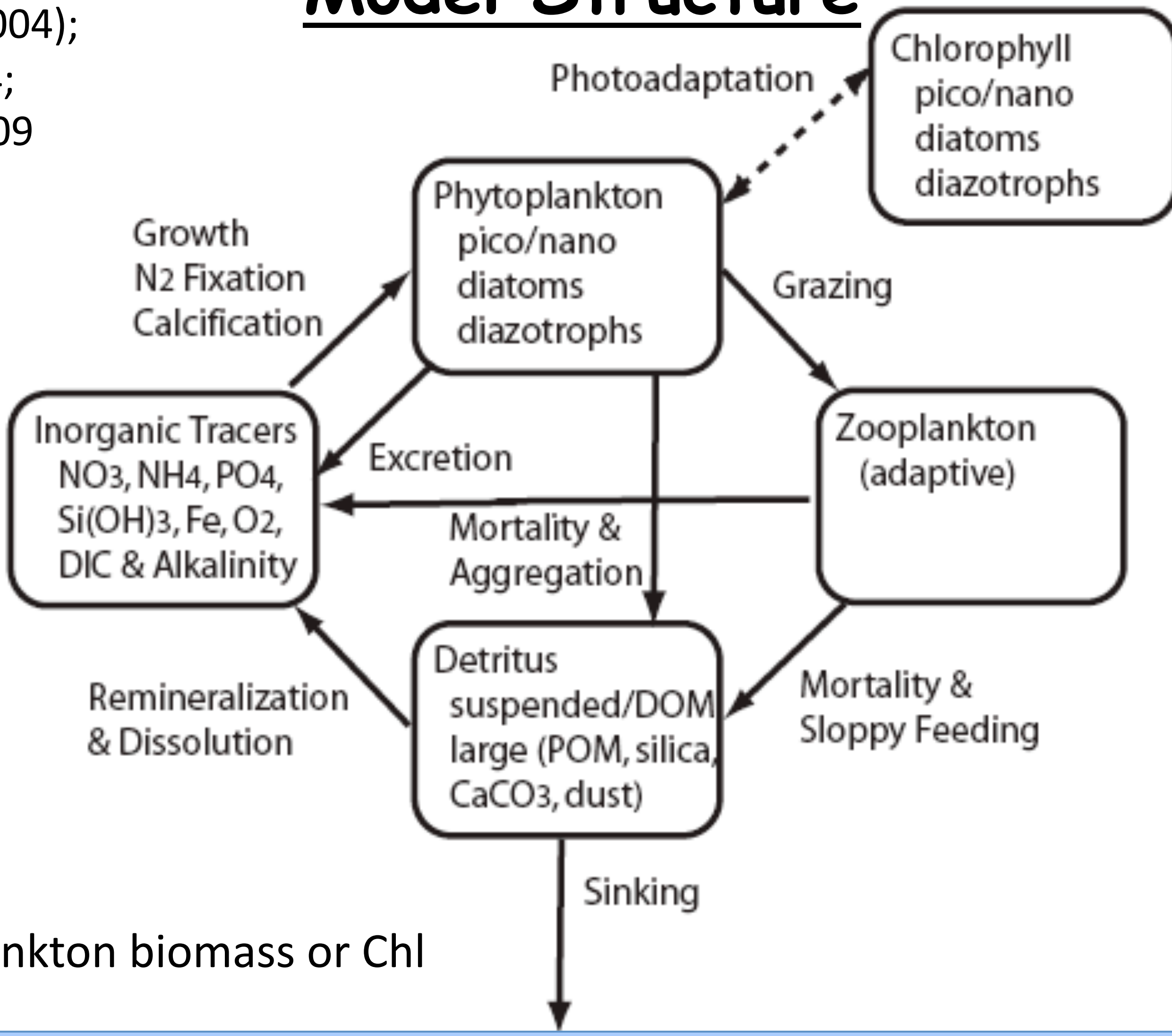
- The Community Climate System Model version 3 (CCSM3) with prognostic marine biogeochemistry and ecosystem dynamics (Moore et al. 2004, 2006) + terrestrial carbon & nitrogen cycles.
- atm/land grid: T31 (~3.75° resolution), 26 atmospheric vertical levels
- ocean grid: gx3v5 (3.6° long, 0.8°-1.8° lat), 25 vertical levels

Climate Simulations:

- Sequential spinup of the model followed by
- 1000 year preindustrial control simulation
- 1870-2099 simulations with prescribed fossil fuel emissions from historical data (1870-1999) and SRES A2 scenario (2000-2099).

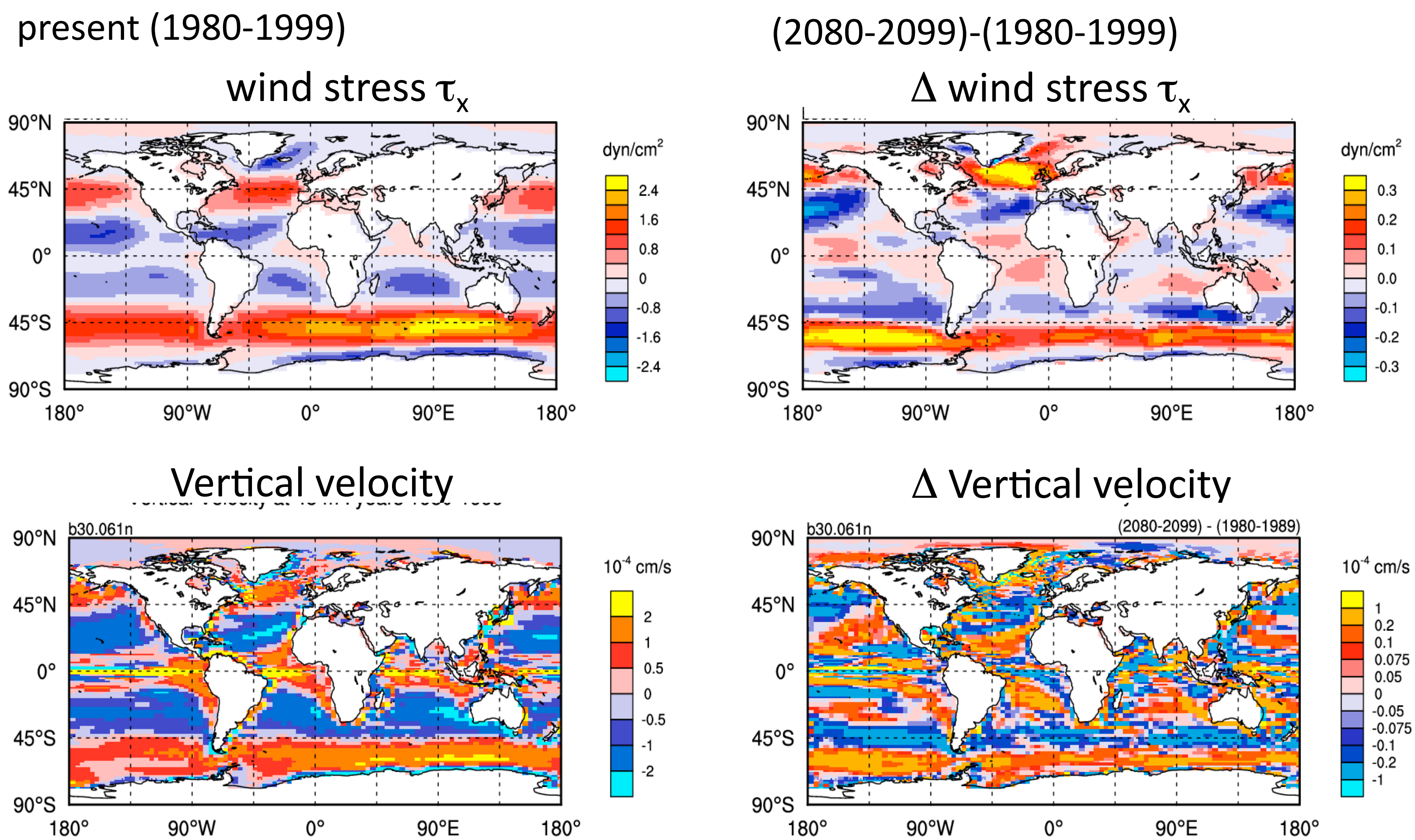
CCSM3 Ocean Ecosystem & Biogeochem Model Structure

Moore et al. (2004);
Lima et al. 2004;
Doney et al. 2009

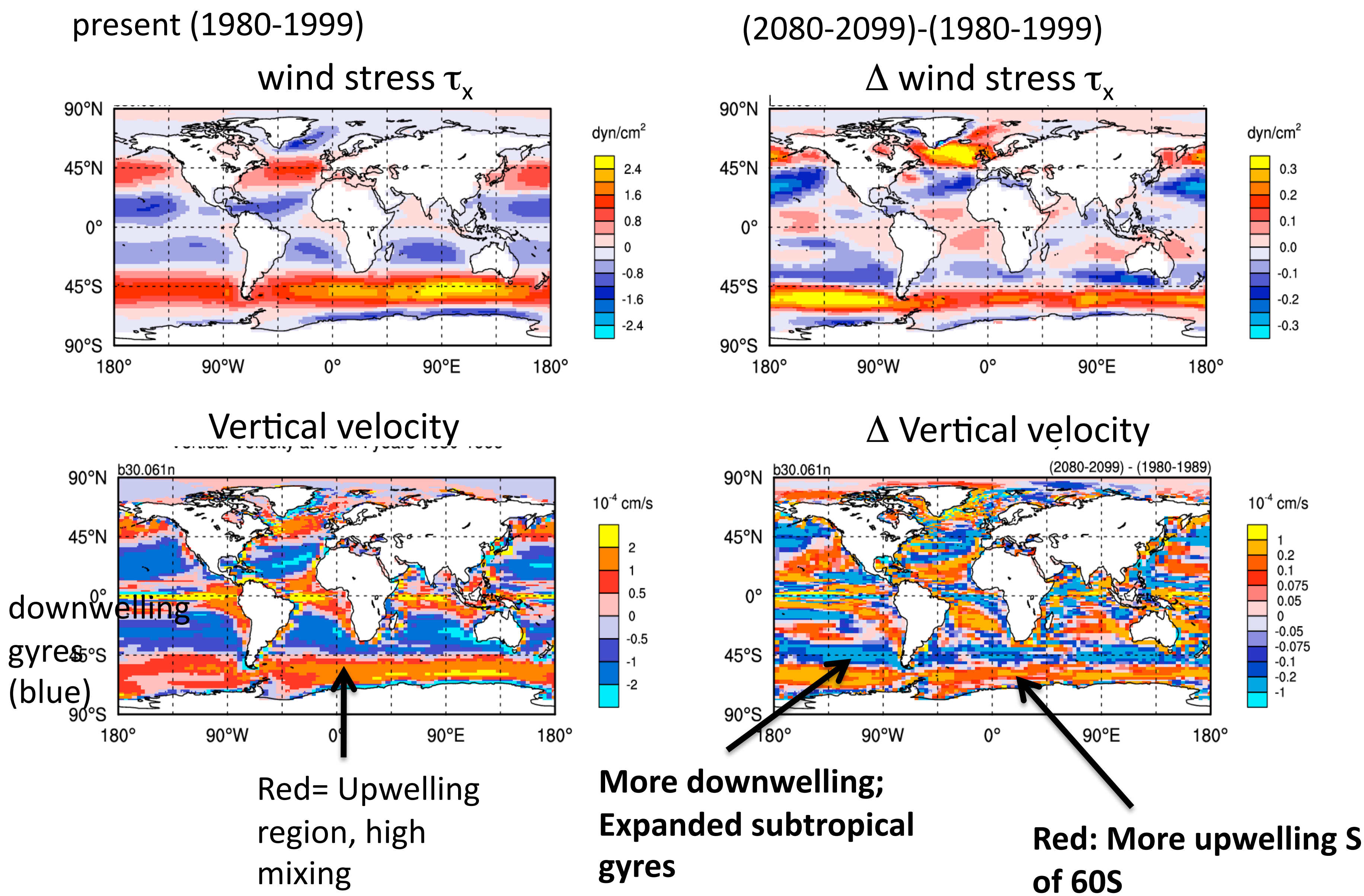


P_x = pytoplankton biomass or Chl

$$\frac{\partial P_x}{\partial t} + \nabla \cdot (\vec{u} P_x) - \nabla \cdot (K \cdot \nabla P_x) = \mu_x \cdot P_x - P_{grazing} - m_x \cdot P_x - P_{aggregation}$$



Southward shift and increase in the intensity of the westerlies: agrees with observations over the past 40 years (**Thompson et al. [2000] and Thompson and Solomon [2002]**)

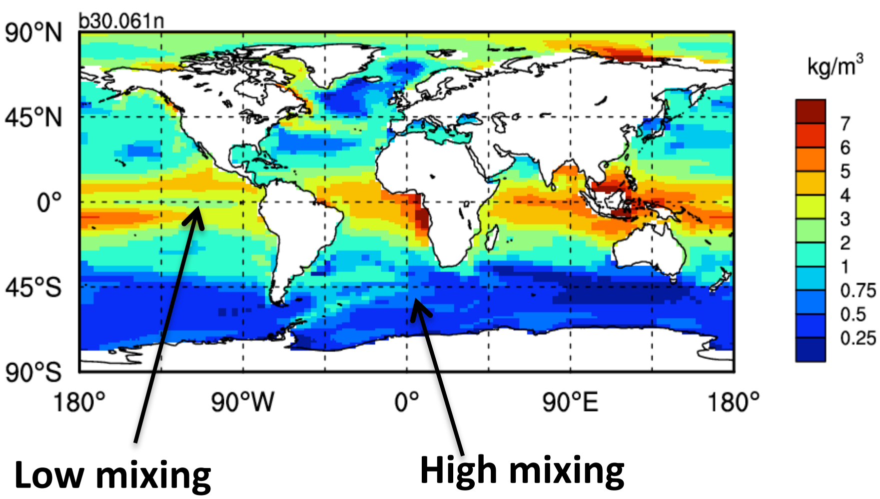


Ecological biomes shift with climate change: ***Subtropical gyres expand as in satellite observations.*** *Subpolar-subtropical boundaries shift poleward. Ice Biome retreats.*

- Increased Stratification with global warming over most of the ocean (due to enhanced temperature and freshening)

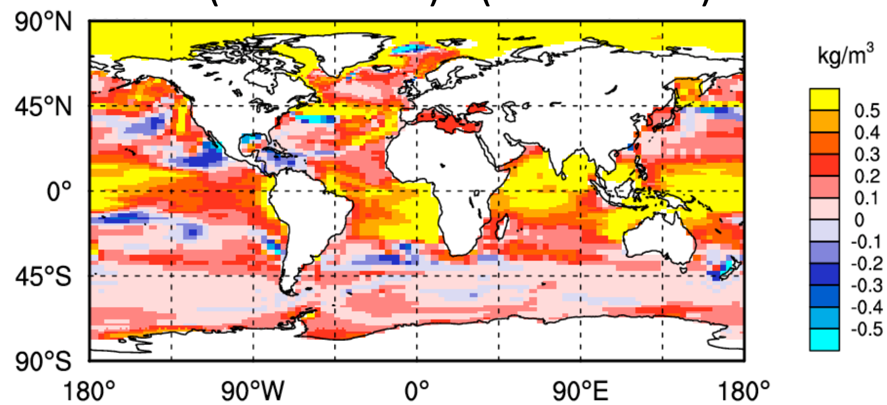
- Less change in Southern Ocean stratification, because of the counteracting impact of stronger winds.

Stratification (1980-1999)

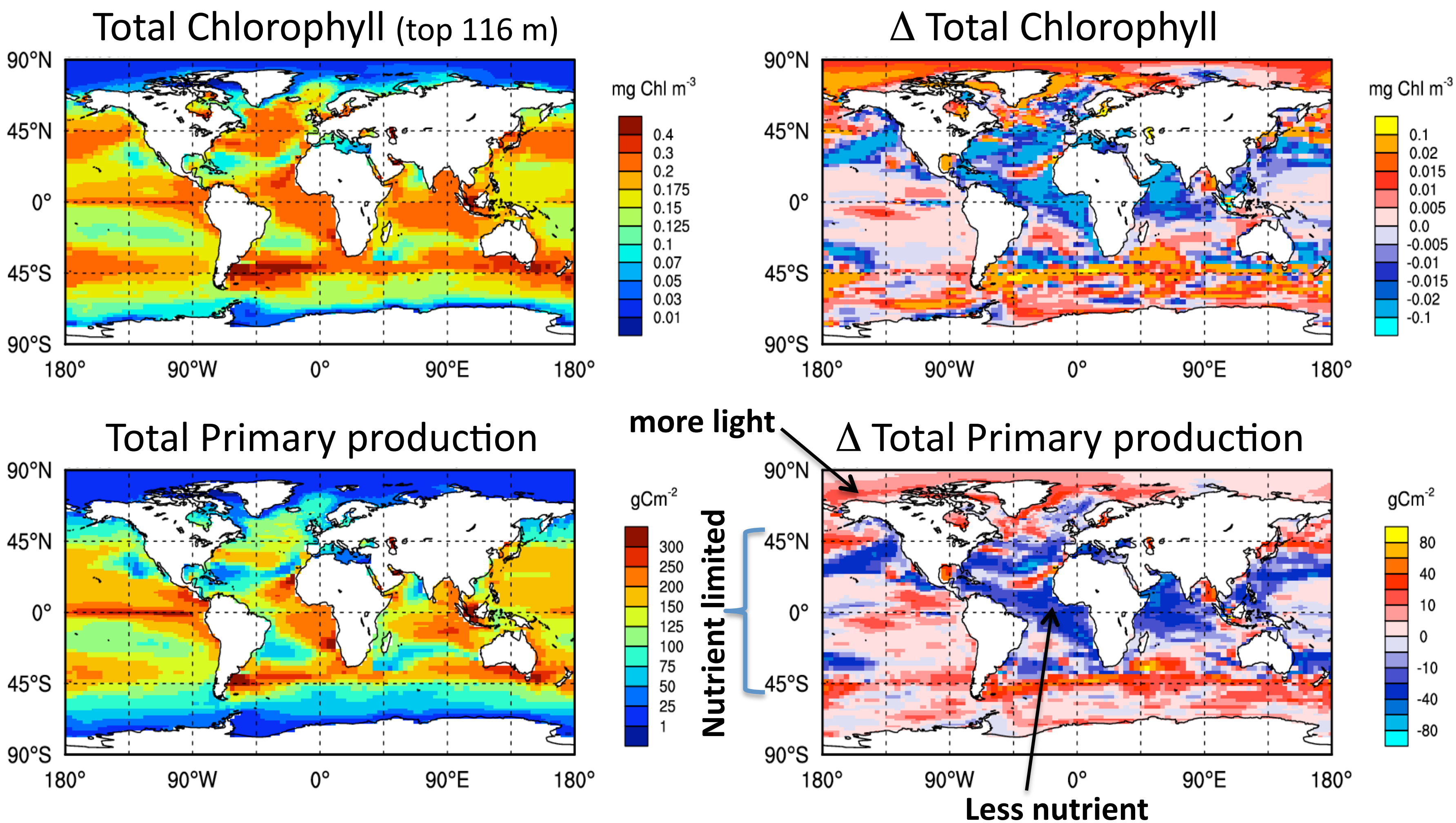


Δ Stratification

Years (2080-2099) - (1980-1999)

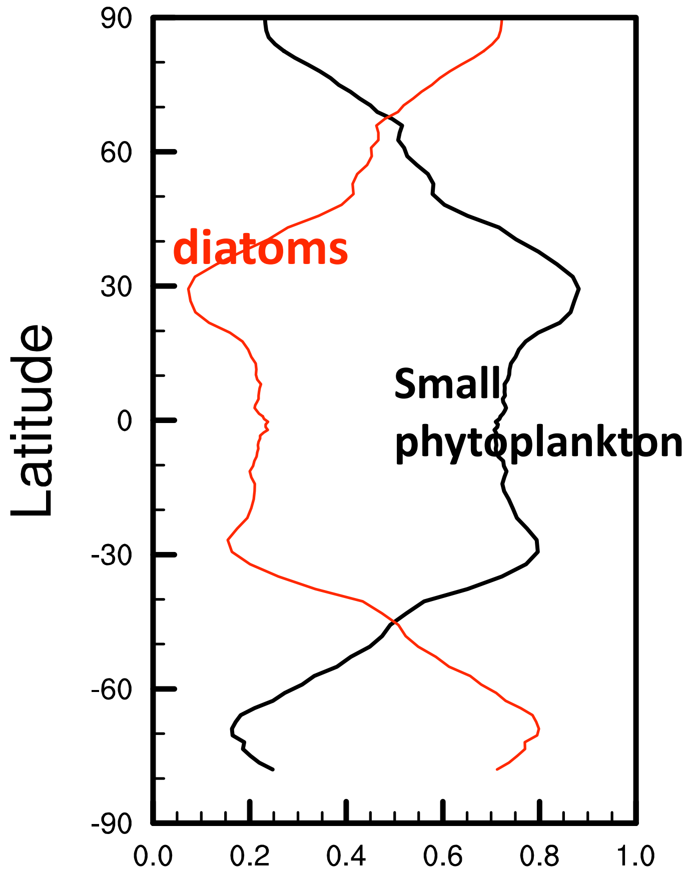


Q: How will ocean ecology respond to these changes in stratification?

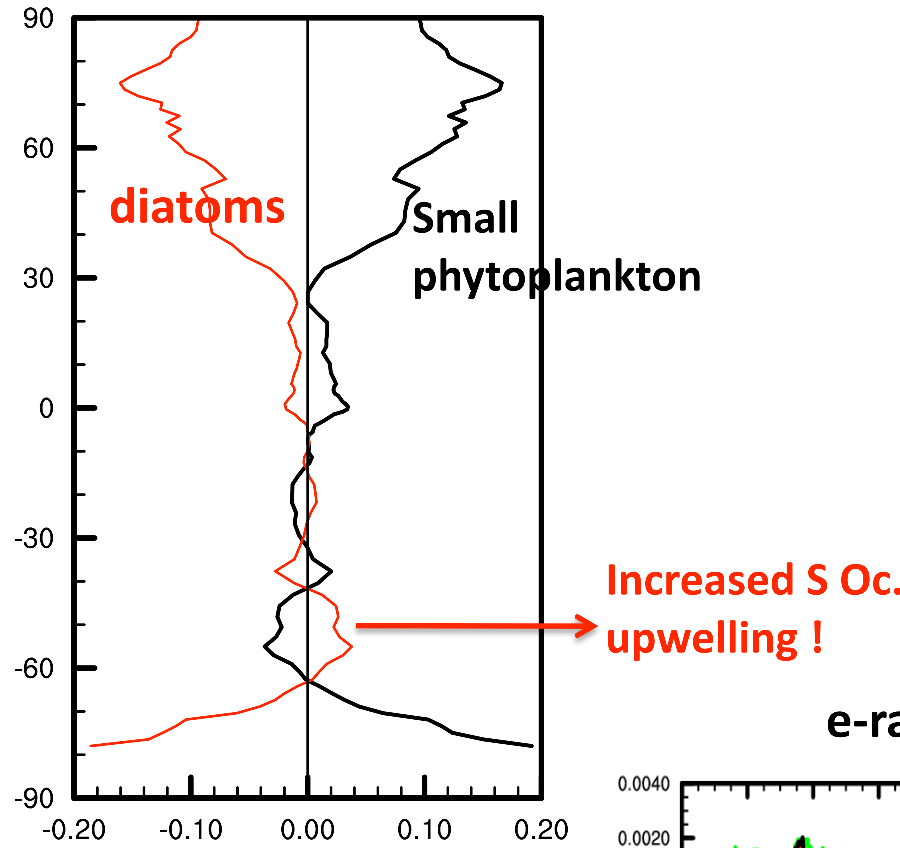


- **Nutrient limited Subtropics**: Climate change decreases vertical nutrient supply to the ocean surface, total phytoplankton chl and productivity.
- **Light limited High latitudes**: Climate change increases light supply to phytoplankton, increasing total chlorophyll and productivity

Decrease in nutrients -> Small phytoplankton displace diatoms in the Northern Hem and global mean. e-ratio decreases.

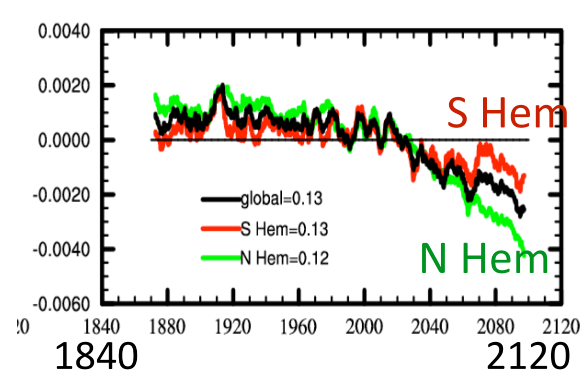


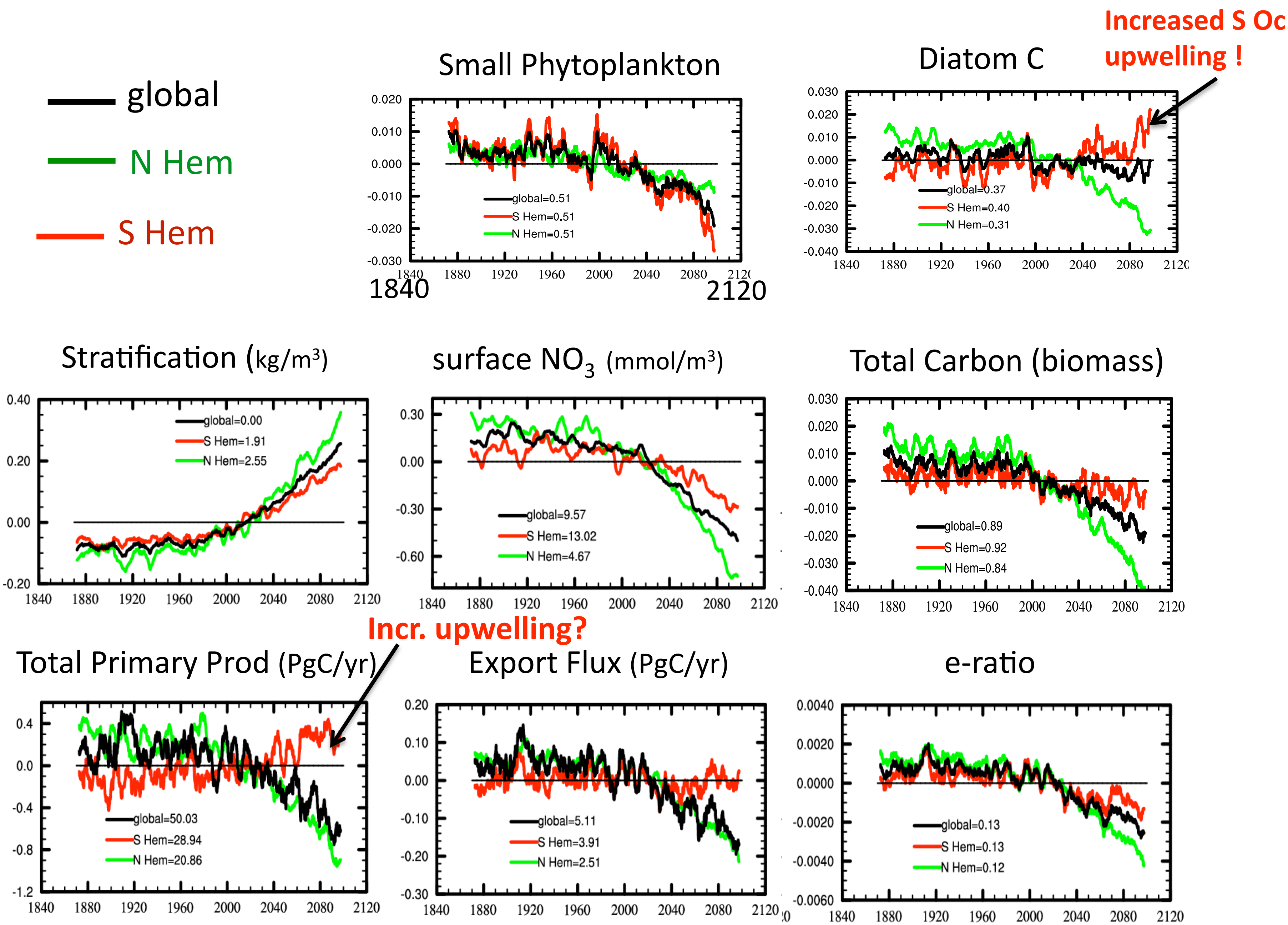
a. Relative Abundance
(at present)



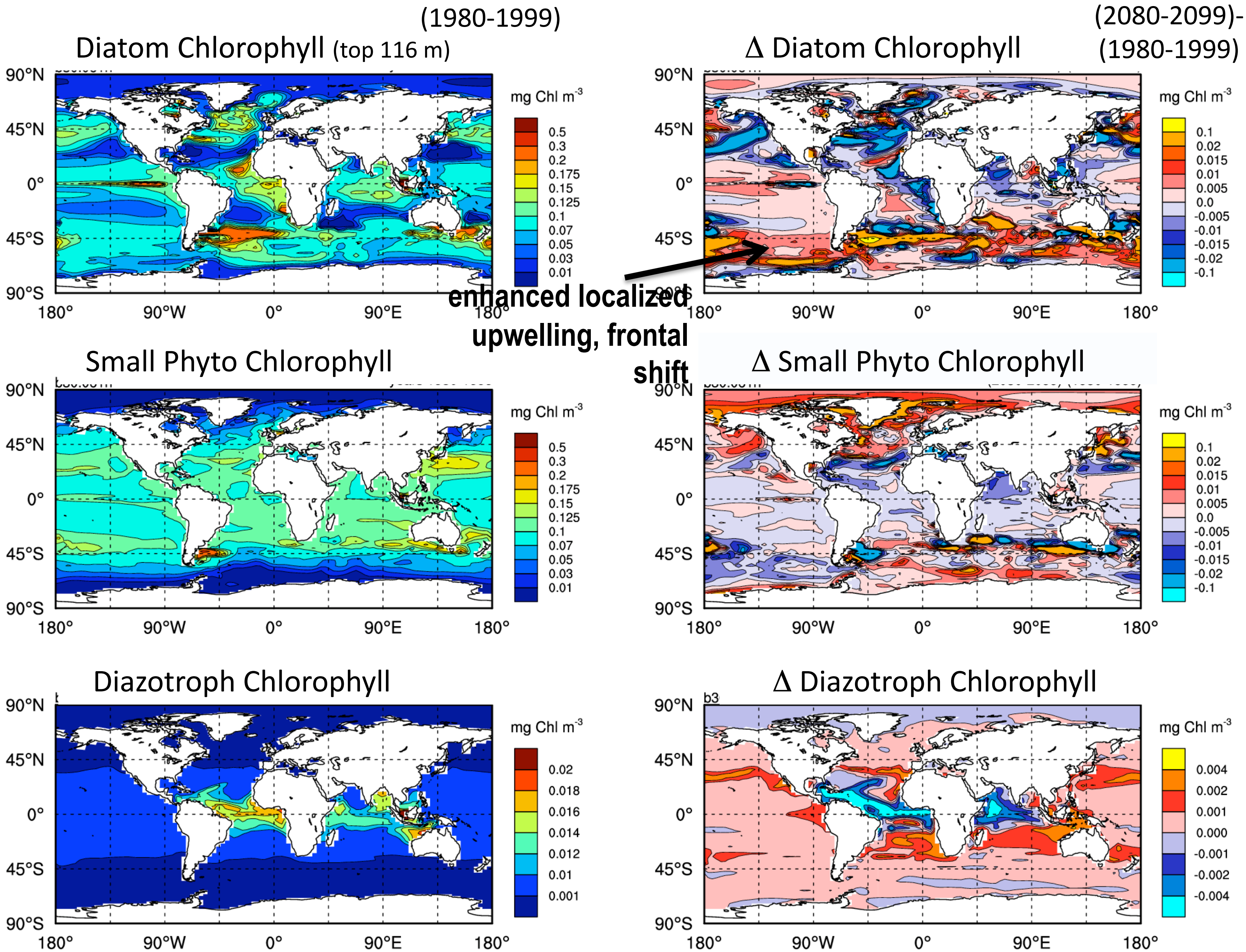
b. Δ Rel Abundance
(change over 100 years)

e-ratio



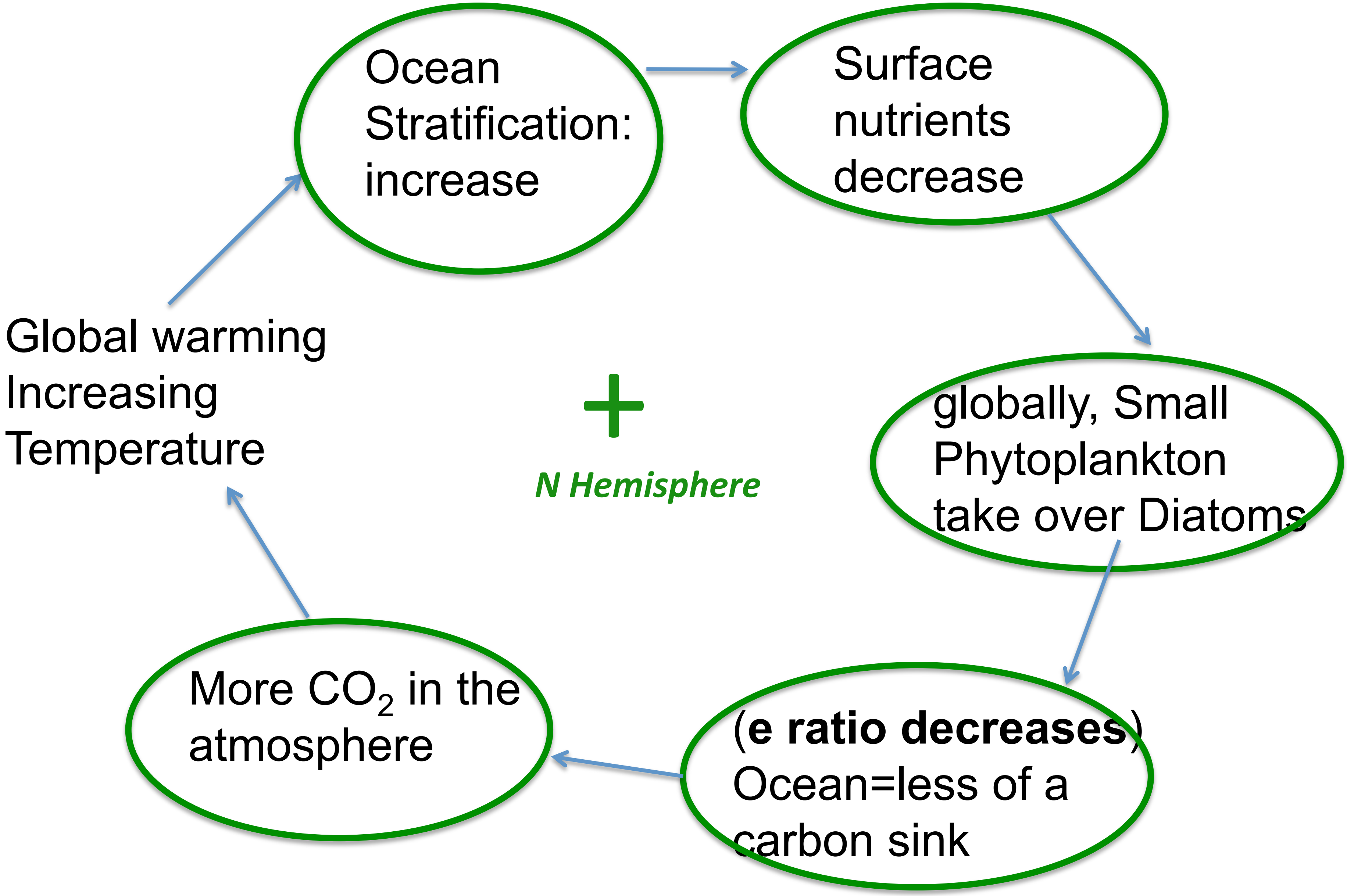


Different ecosystem responses to climate change in the N and S Hemisphere !



(1980-1999)
Diatom Chlorophyll (top 116 m)
(2080-2099)-
(1980-1999)
Δ Diatom Chlorophyll
enhanced localized
upwelling, frontal
shift
Small Phyto Chlorophyll
Δ Small Phyto Chlorophyll
Diazotroph Chlorophyll
Δ Diazotroph Chlorophyll
mg Chl m-3
0.5
0.3
0.2
0.175
0.15
0.125
0.1
0.07
0.05
0.03
0.01
0.1
0.02
0.015
0.01
0.005
0.0
-0.005
-0.01
-0.015
-0.02
-0.1
0.02
0.018
0.016
0.014
0.012
0.01
0.001
0.004
0.002
0.001
0.000
-0.001
-0.002
-0.004
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°

A small positive Phytoplankton-climate feedback (ocean becomes less of a sink for carbon)



IMPACTS OF CLIMATE CHANGE:

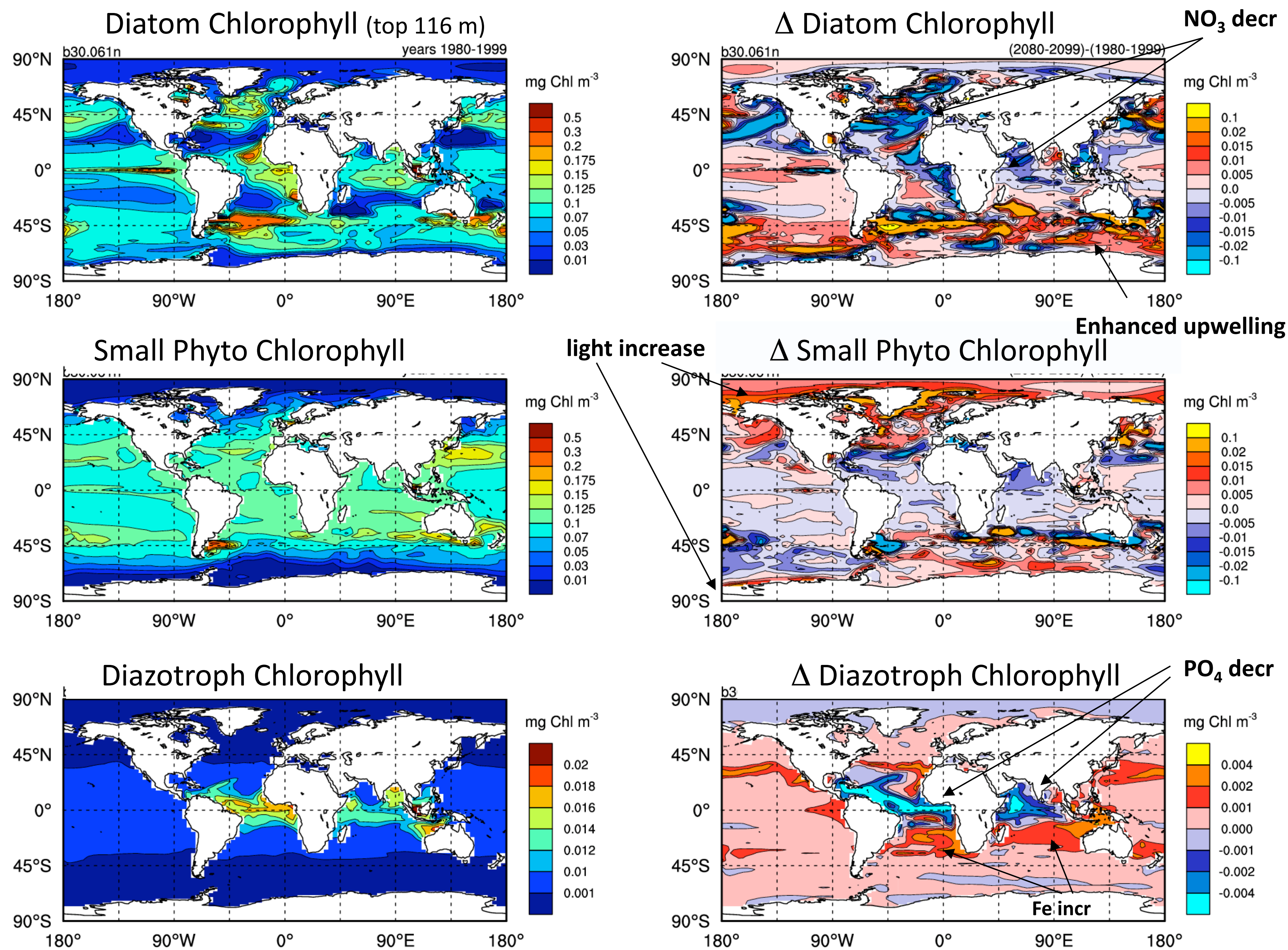
1. Ecological biomes shift with climate change; shifts larger in the Northern Hemisphere: ***Ice Biome retreats. Subtropical gyres expand as in satellite observations.*** *Subpolar-subtropical boundaries shift poleward.*

2.

- ***Stratifying effects of warmer temp and a stronger hydrological cycle dominate the ecosystem response (Chl decrease) in the Northern Hemisphere.***
- ***Destratifying effects of increasing wind strength result in minimal ecosystem changes in the S Hemisphere.***

3. In the global mean diatom relative abundance decreases with climate change. Diatoms are displaced by small phytoplankton. e-ratio decreases.

Less efficient biological pump: less carbon export to the deep ocean !



Diatom Chlorophyll (top 116 m)
b30.061n
years 1980-1999
mg Chl m-3
0.5
0.3
0.2
0.175
0.15
0.125
0.1
0.07
0.05
0.03
0.01
Δ Diatom Chlorophyll
NO3 decr
(2080-2099)-(1980-1999)
0.1
0.02
0.015
0.01
0.005
0.0
-0.005
-0.01
-0.015
-0.02
-0.1
Enhanced upwelling
Small Phyto Chlorophyll
light increase
Δ Small Phyto Chlorophyll
Diazotroph Chlorophyll
0.02
0.018
0.016
0.014
0.012
0.01
0.001
Δ Diazotroph Chlorophyll
PO4 decr
0.004
0.002
0.001
0.000
-0.001
-0.002
-0.004
Fe incr
90°N
45°N
0°
45°S
90°S
180°
90°W
0°
90°E
180°

" Response of ocean phytoplankton community structure to climate change over the 21st century: partitioning the effects of nutrients, temperature and light" Marinov, Doney and Lima, Biogeosciences 2010

= complicated function (Temp, Nutrients, Light): $\nu \frac{N}{N+K_x^N} \cdot 2^{\left(\frac{T-30^o C}{10^o C}\right)} \cdot \left[1-\exp\left(\frac{-\alpha_x \cdot \theta_x^c \cdot I_{PAR}}{\mu_{ref} V_x T_f}\right)\right]$

$$\frac{D(Diat_C)}{Dt} = \mu_{diat} \cdot Diat_C - m_D Diat_C - Diat_{graze} - Diat_{agg}$$

$$\frac{D(S_C)}{Dt} = \mu_{sp} \cdot S_C - m_s S_C - S_{graze} - S_{agg}$$

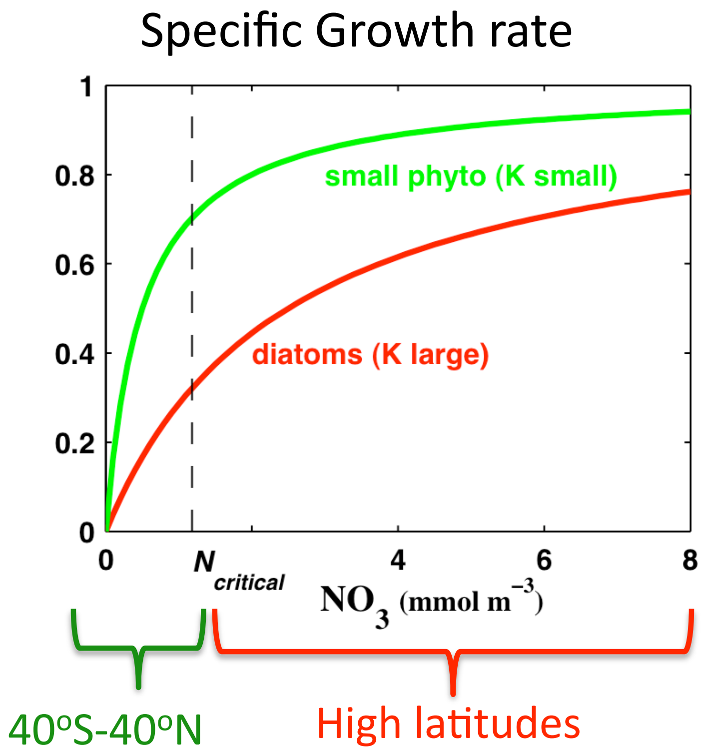
$$S_{graze} = u^S \cdot 2^{(T-30)/10} \cdot \frac{{S_C}^2}{{S_C}^2 + g^2} \cdot Z_C$$

$$\frac{D(Diaz_C)}{Dt} = \mu_{diaz} Diaz_C - m_{diaz} Diaz_C - Diaz_{graze}$$

- Can we predict the behavior of the system with climate change based on these equations? What are the separate impacts of changes in nutrients, light and temperature on the plankton growth rates and biomass?

- Will changes in nutrients, light, temperature affect more the diatom or small phytoplankton ? Is this behavior universal or highly model dependent ?

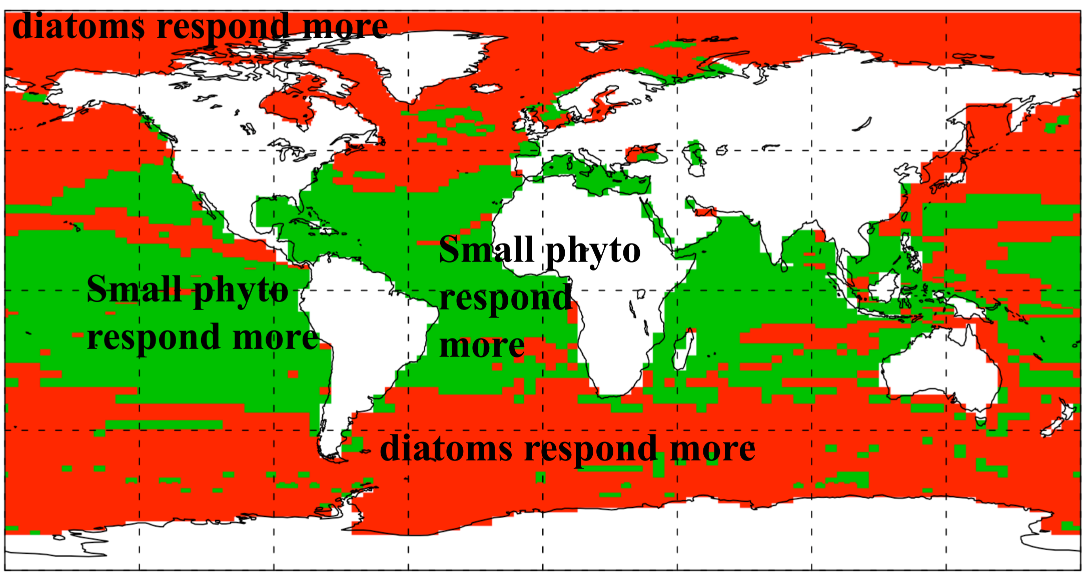
Critical Nutr Hypothesis



Theoretical analysis of the phytoplankton growth equation:

$$\frac{DP_x}{Dt} = \left(r \cdot \frac{N}{N + K_x^N} \right) P_x - m_x \cdot P_x$$

Sp. Growth rate



40°S - 40°N: low nutrient region

small phytoplankton respond more than diatoms to nutrient change

high latitudes: high nutrient zone

diatoms respond more than small phytoplankton to nutrient change

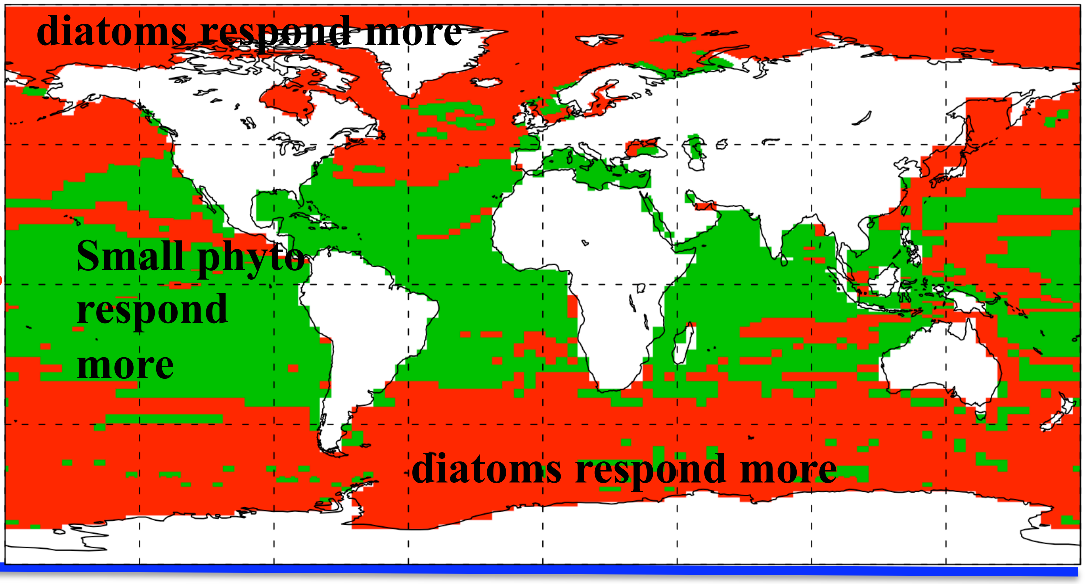
Results:

• I propose an analytical framework to understand the impact of global warming (via changes in nutrients, light and temperature) on phytoplankton growth rates and the competition between phytoplankton (Marinov et al.,2010)

• Hypothesis: Climate driven changes in light, whether positive or negative and changes in temperature have a stronger impact on small phytoplankton than on diatom growth rate. (holds in NCAR model, GFDL?)

***<u>Critical nutrient hypothesis</u>**: In the 40S-40N biome, small phytoplankton respond more than diatoms to changes in nutrients. The opposite is the case in high nutrient high latitudes.*

(holds in the NCAR, GFDL models. generalize?)



Future research :

- *Can we see the critical nutrient threshold in existing size structure data (satellite) ? How can one test that ? Ideas ?*
- ***What are the implications of my hypotheses for future changes in export production, surface recycling and the global carbon cycle?***

And more broadly:

- ***Does ecological diversity matter for biogeochemical cycling of nutrients and carbon, and for atmospheric pCO_2? Does it matter (for climate) whether we have 100 species or 2?***
- ***What is the overall magnitude of the ecology – climate change feedback?***

Advertise, advertise, advertise …

- ***Websites are important !***

  https://climate.sas.upenn.edu

- ***Utube ?***

  Irina's "60s talk": Water and future climate change

Looking for a grad student and postdoc !

- ***Research direction 1:*** ***How will future changes in ocean phytoplankton affect ocean carbon storage and ultimately climate? Quantify ecology-climate feedbacks.***

- ***Research direction 2:*** ***How will future changes in ocean ventilation affect ocean carbon storage and atmospheric pCO_2? Quantify biogeochemistry-climate feedbacks (NOAA –GCC grant. Thank you NOAA!)***