Ocean Carbon Cycling & Pelagic Ecosystem Dynamics

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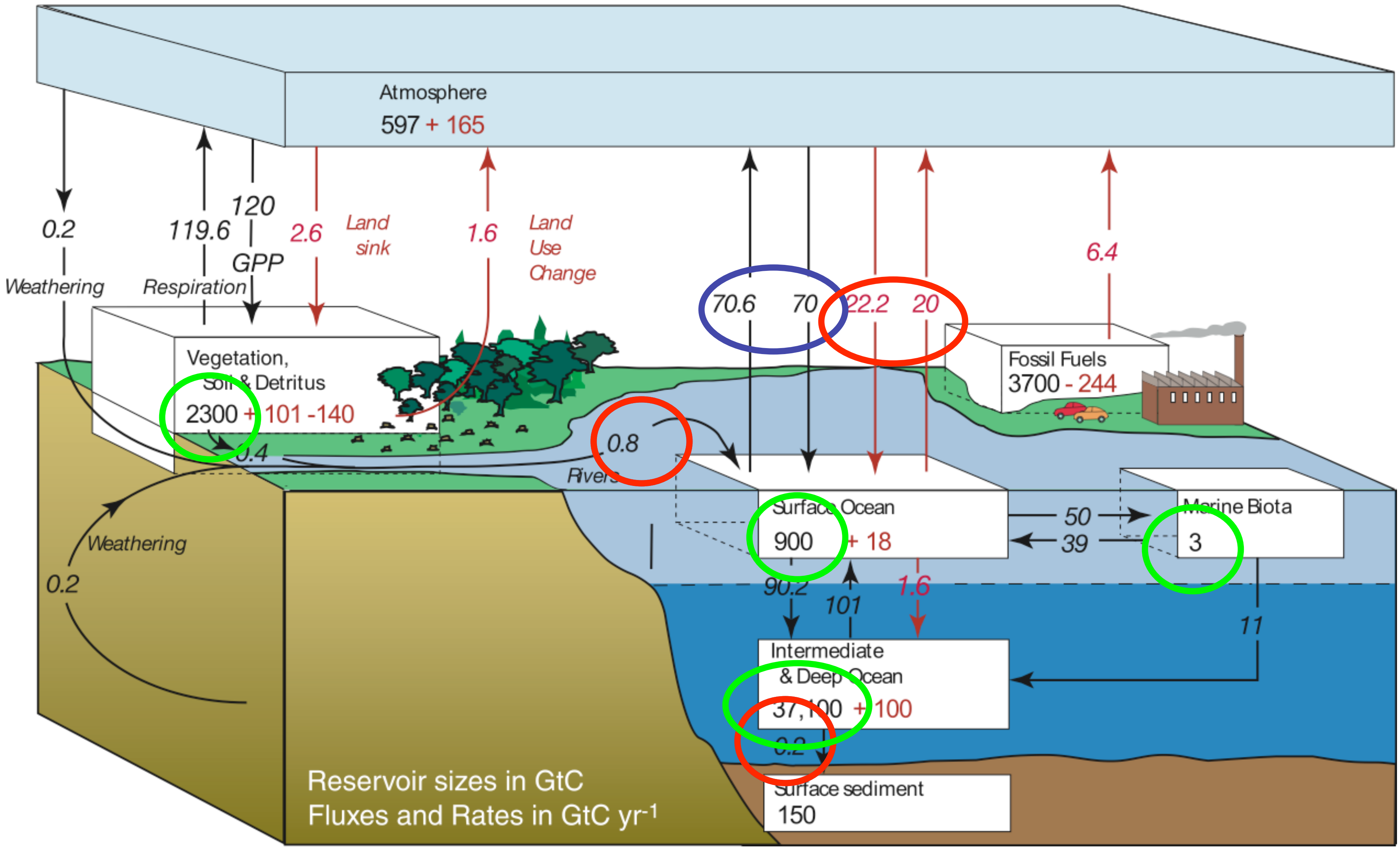
Geography & ICESS
UC Santa Barbara

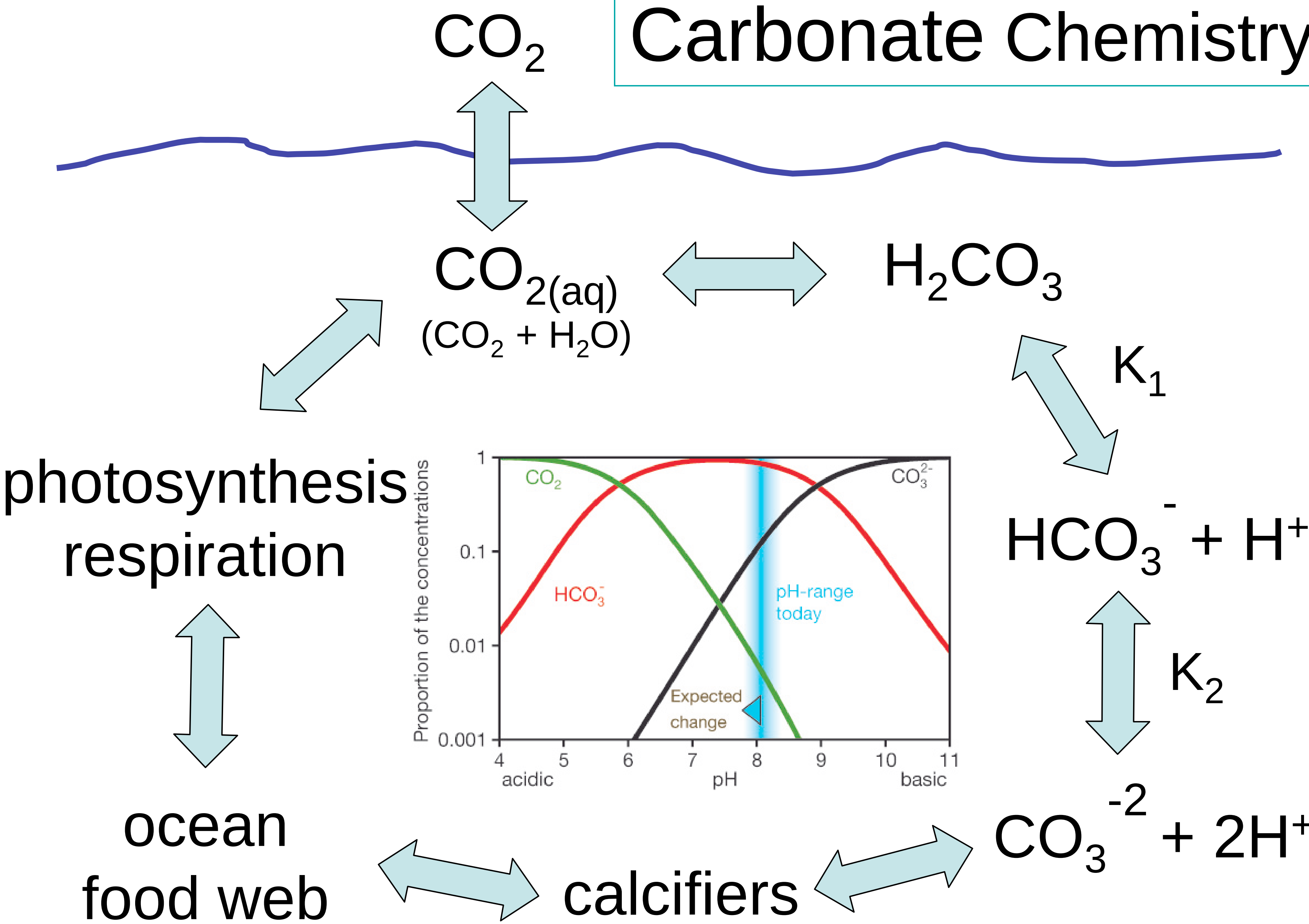
Talk Outline

- Ocean's Role in the Carbon Cycle
  - Buffering capacity of seawater
  - Air-sea flux of CO_2
- The Pumps
  - Solution, Sinking Carbon & $CaCO_3$
  - Anthropogenic CO_2 inventory
- Future Oceans
  - Trends & Predictions
  - Acidification
  - Fe limitations (Tony will talk about this more)


Atmosphere
597 + 165
0.2
Weathering
119.6
Respiration
120
GPP
2.6
Land sink
1.6
Land Use Change
70.6
70
22.2
20
6.4
Fossil Fuels
3700 - 244
Vegetation, Soil & Detritus
2300 + 101 -140
0.4
0.8
Rivers
Surface Ocean
900 + 18
50
39
Marine Biota
3
90.2
101
1.6
11
Intermediate & Deep Ocean
37,100 + 100
0.2
Surface sediment
150
Weathering
0.2
Reservoir sizes in GtC
Fluxes and Rates in GtC yr-1

IPCC [2007]

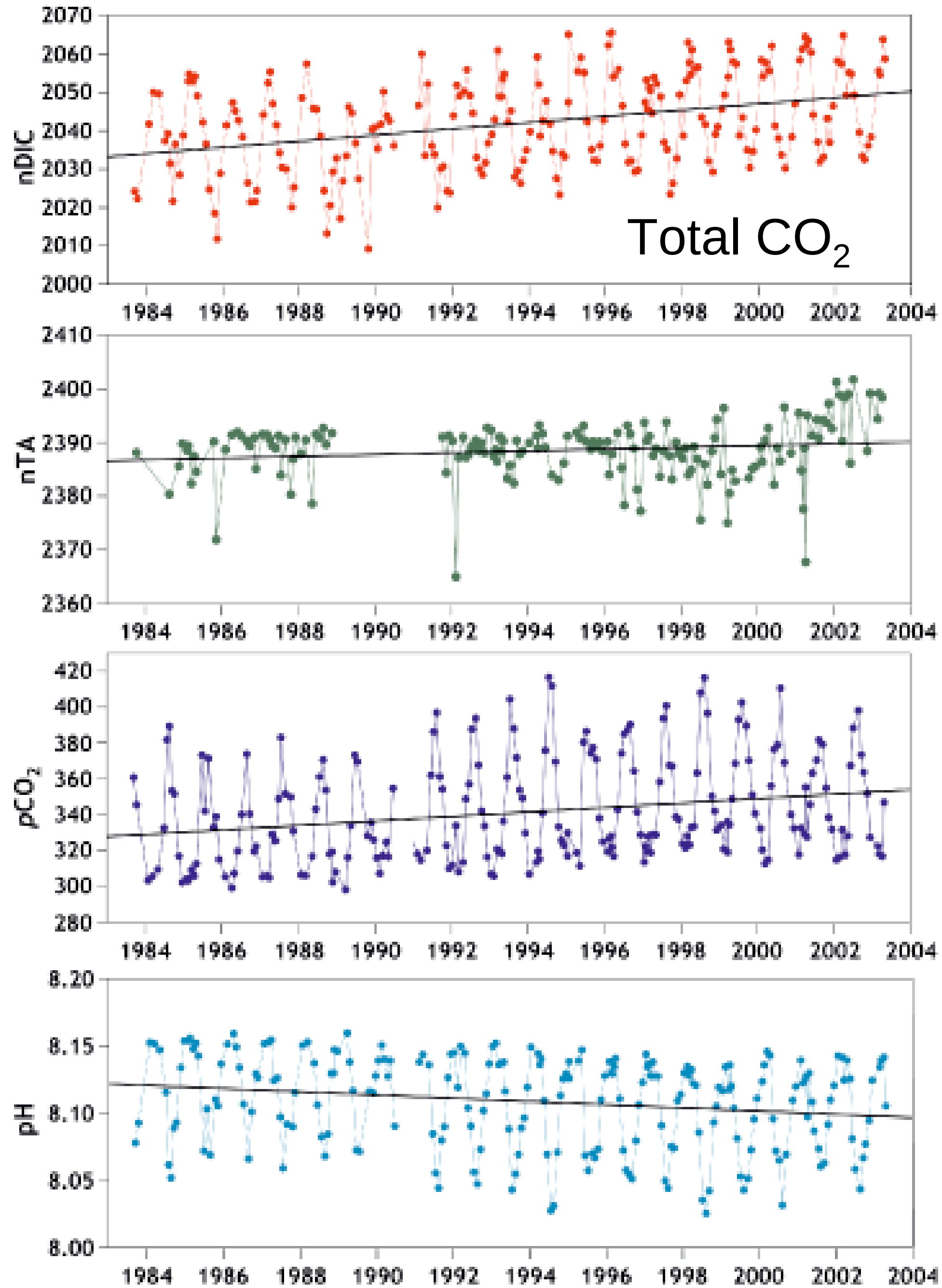
Carbonate Chemistry



Bermuda Atlantic Time Series (BATS)

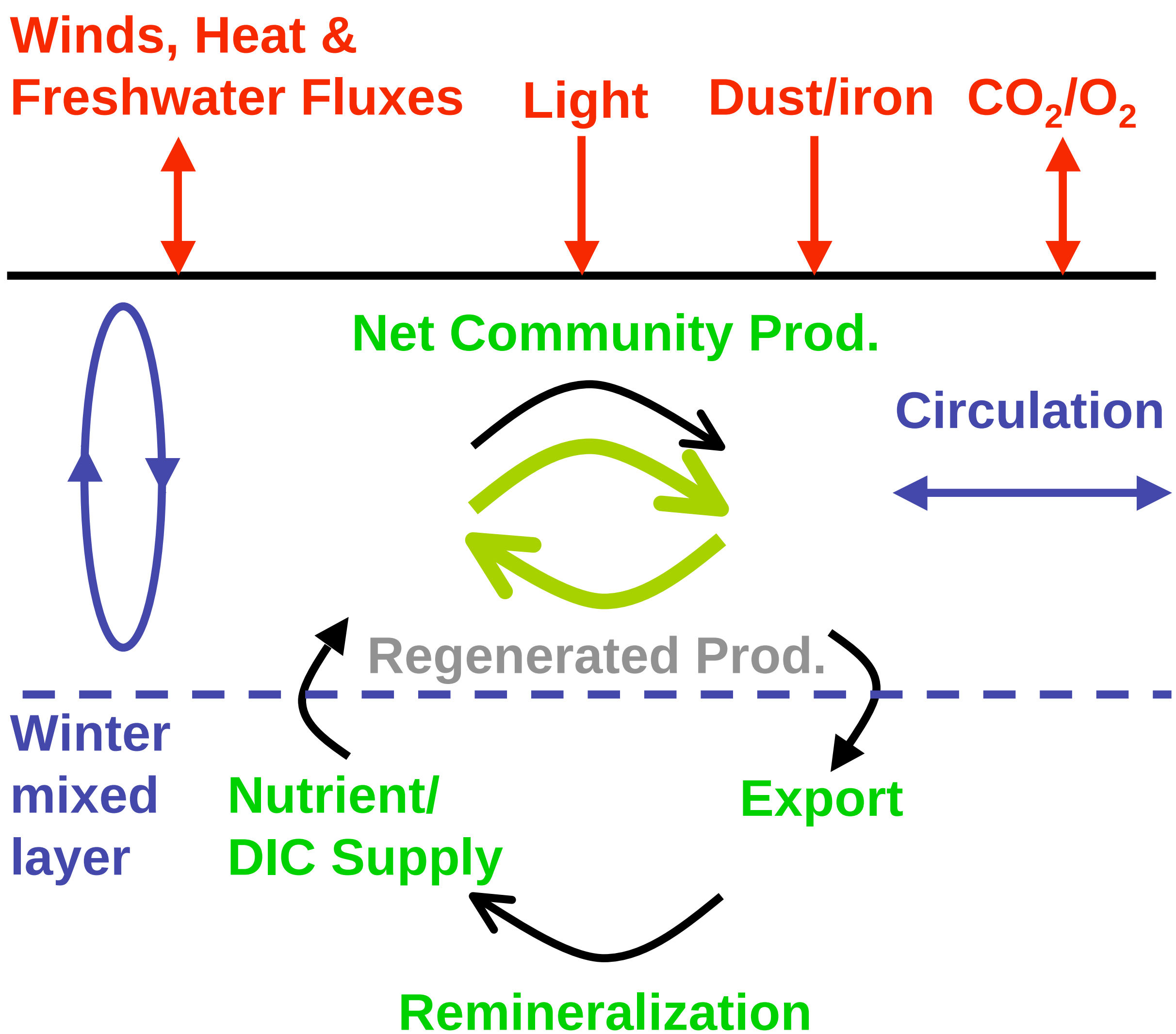
- Surface waters of the Sargasso Sea
- Large seasonal changes due to local production & SST changes
- Total CO_2 and pCO_2 are increasing
- pH is decreasing

Bates [2007] JGR-Oce



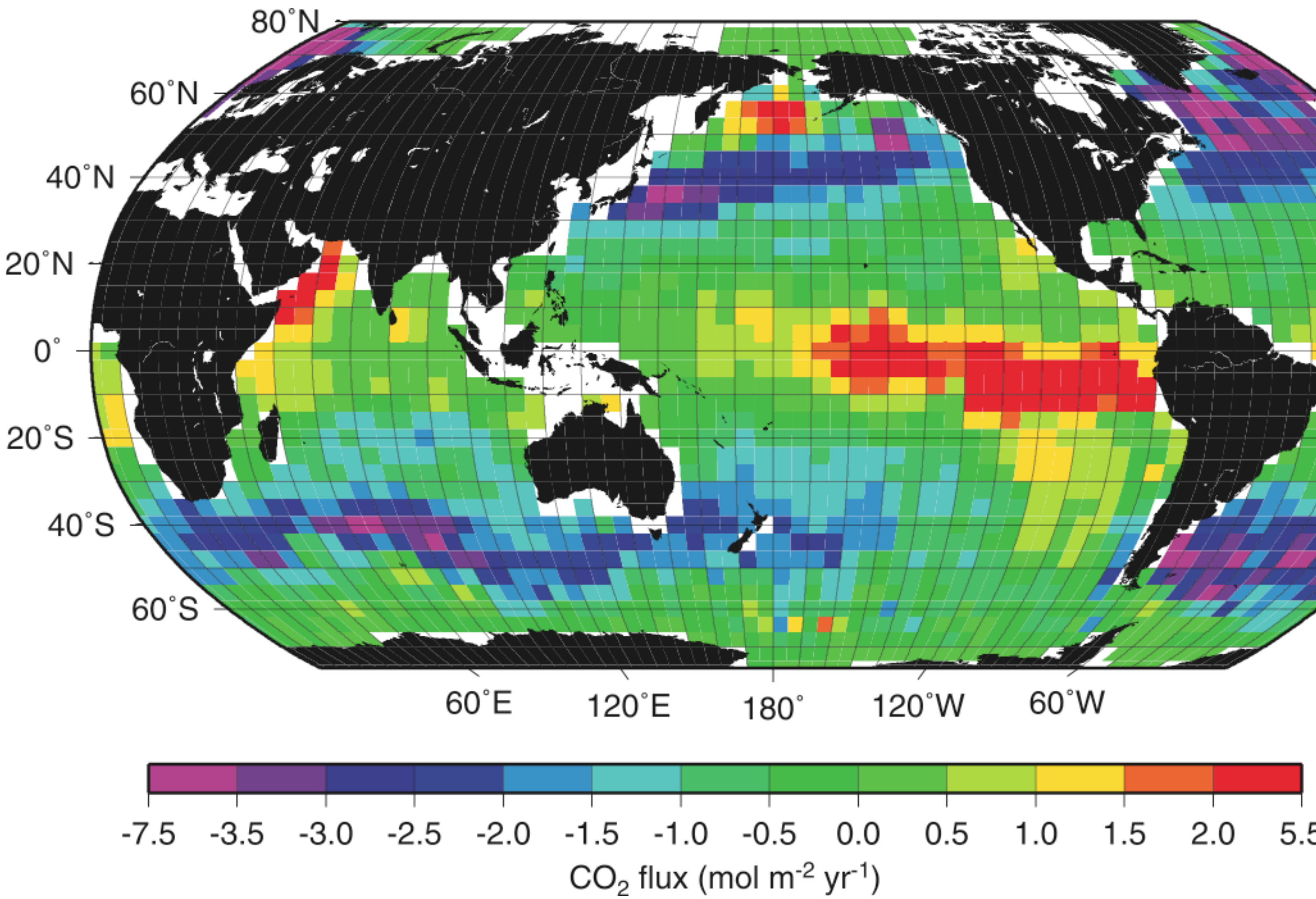
pCO2 = f(Temp., Salinity, DIC, Alkalinity)
+ (+) + -

Physical & Biological Controls



Biology only one factor on surface pCO_2 & air-sea CO_2 flux;

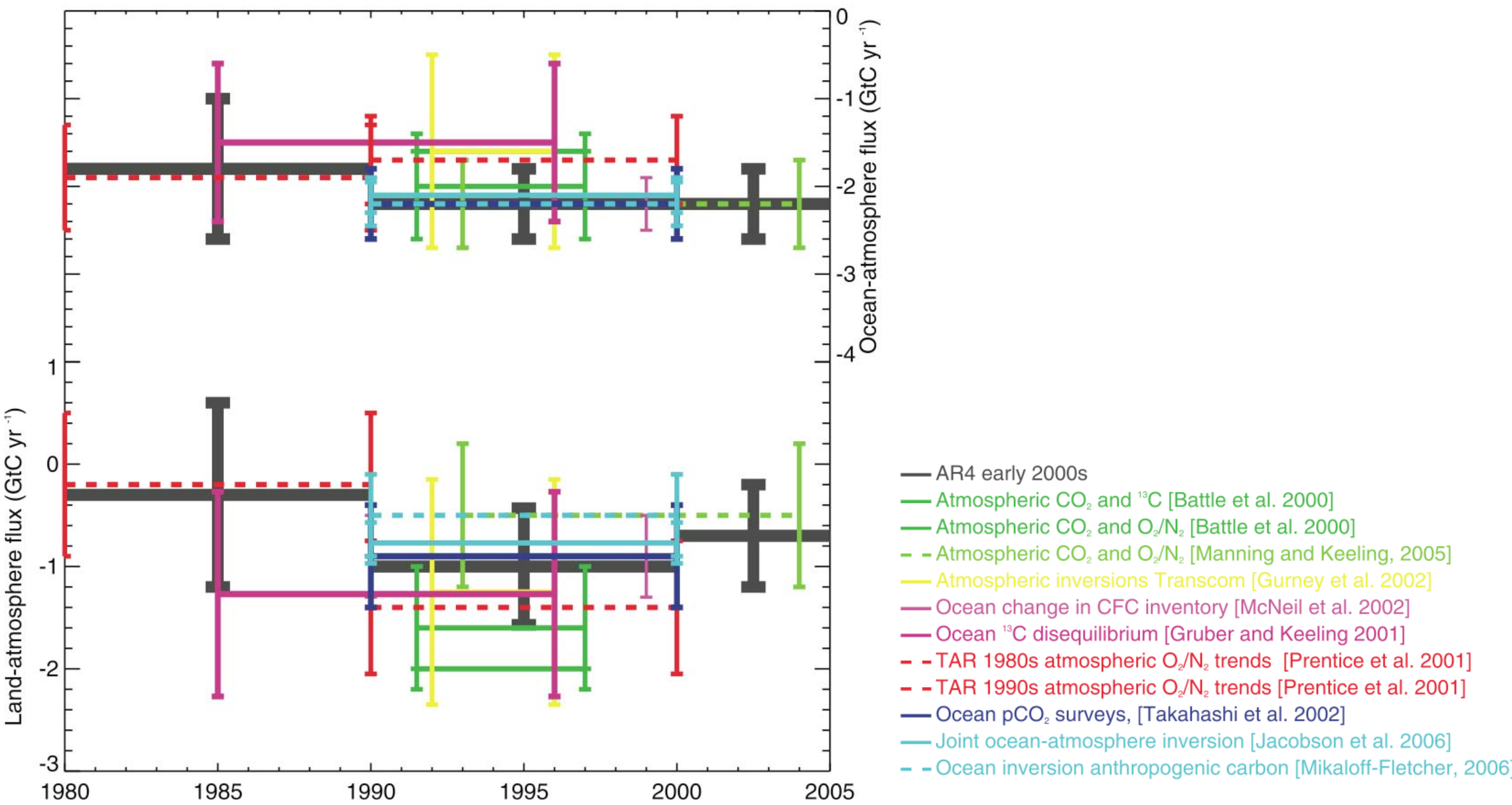
Air-Sea CO_2 Exchange



$F = k(U)\ (CO_{2\text{-}w} - CO_{2\text{-}a})$

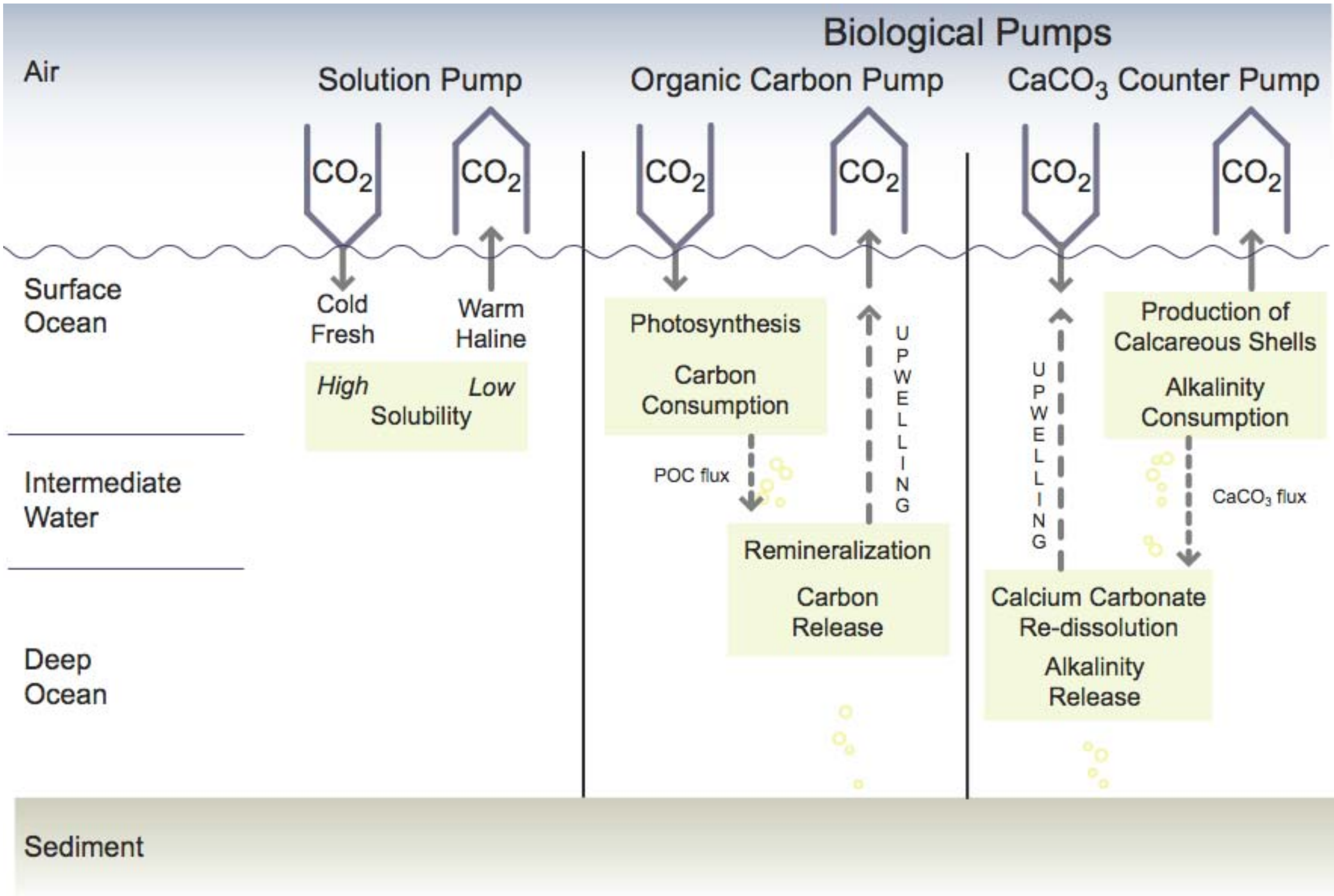
IPCC [2007]

Land- & Ocean-Atmos CO_2 Exchanges

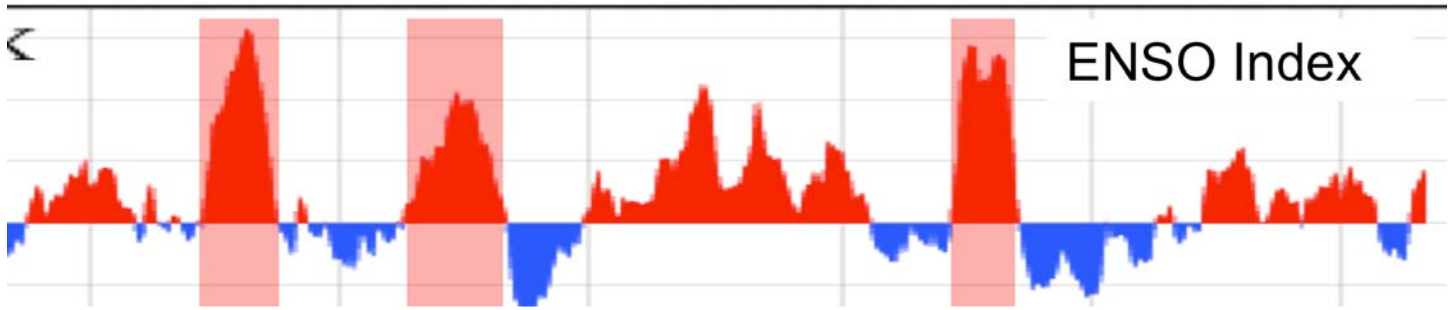


IPCC [2007]

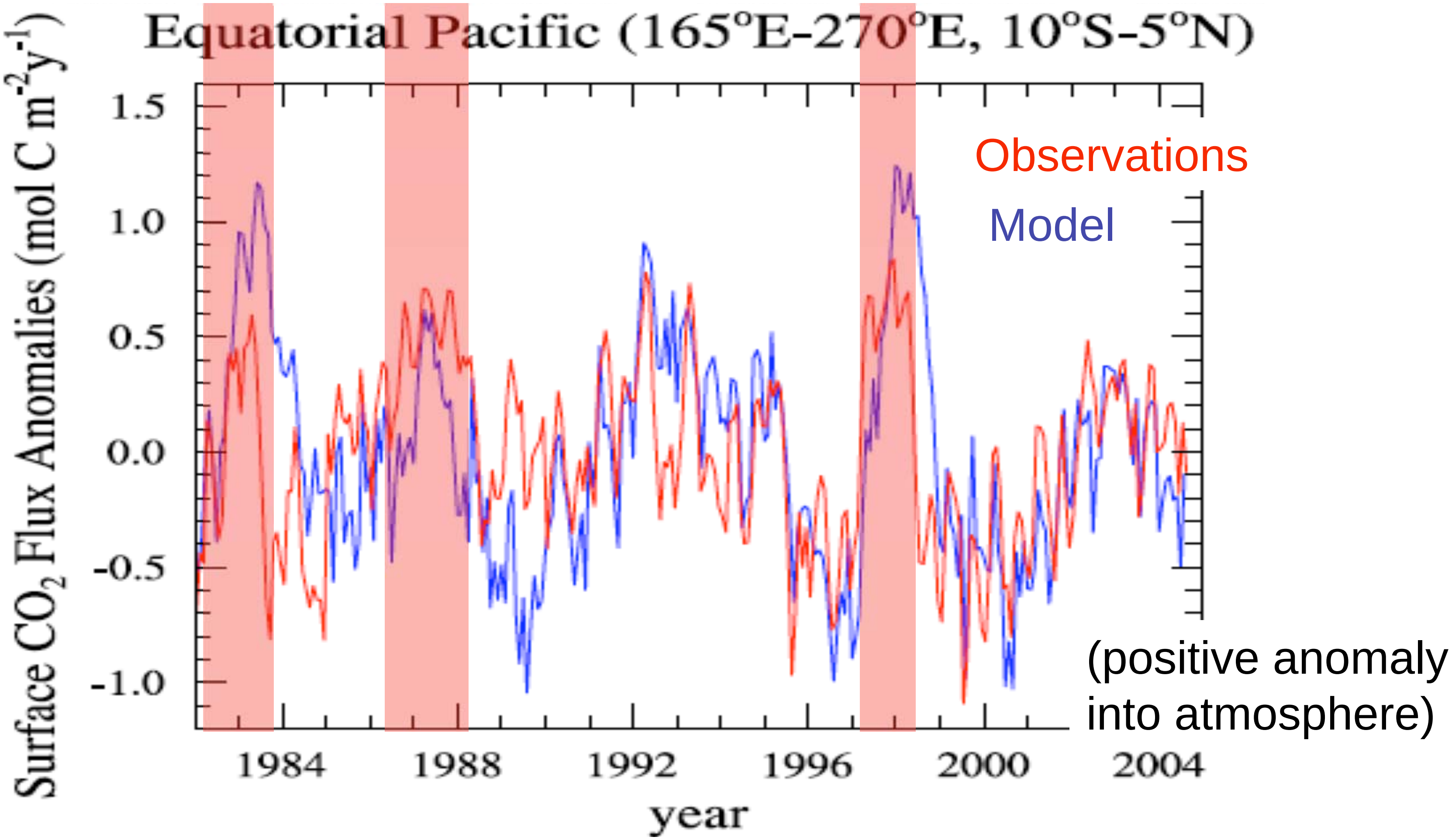
The Pumps



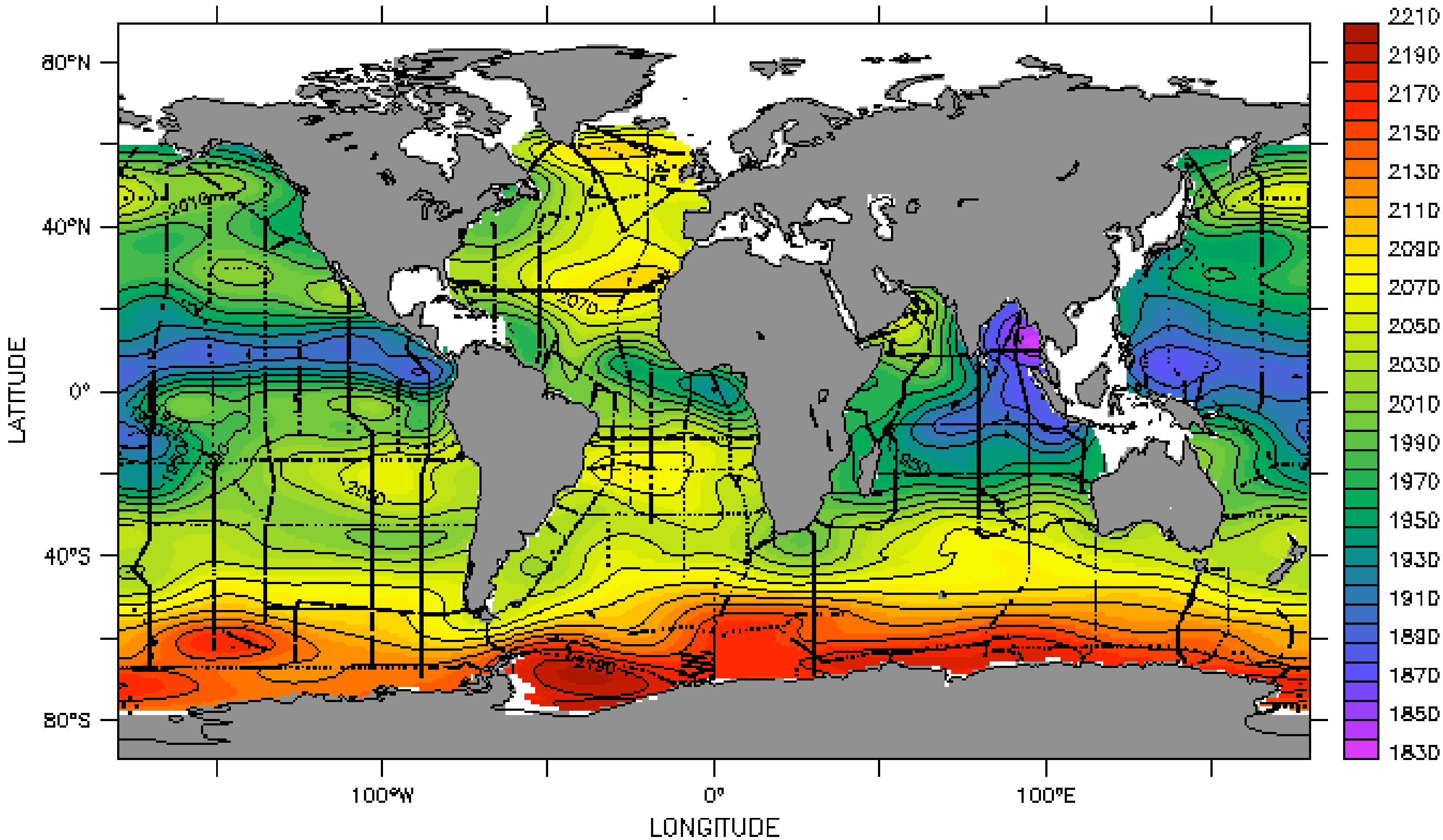
IPCC [2007]



Elevated temperature leads to outgassing of CO_2



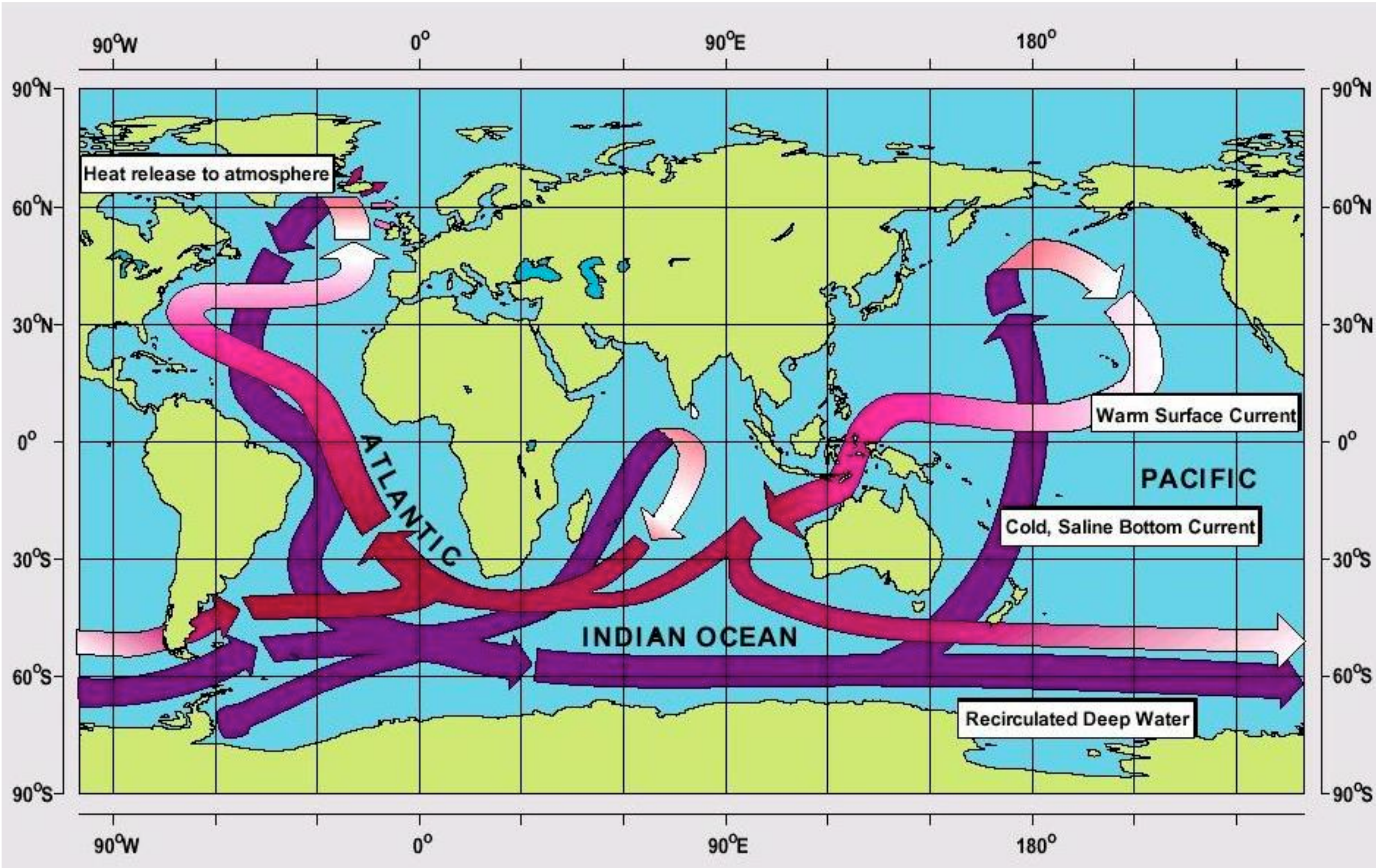
Surface Total CO_2



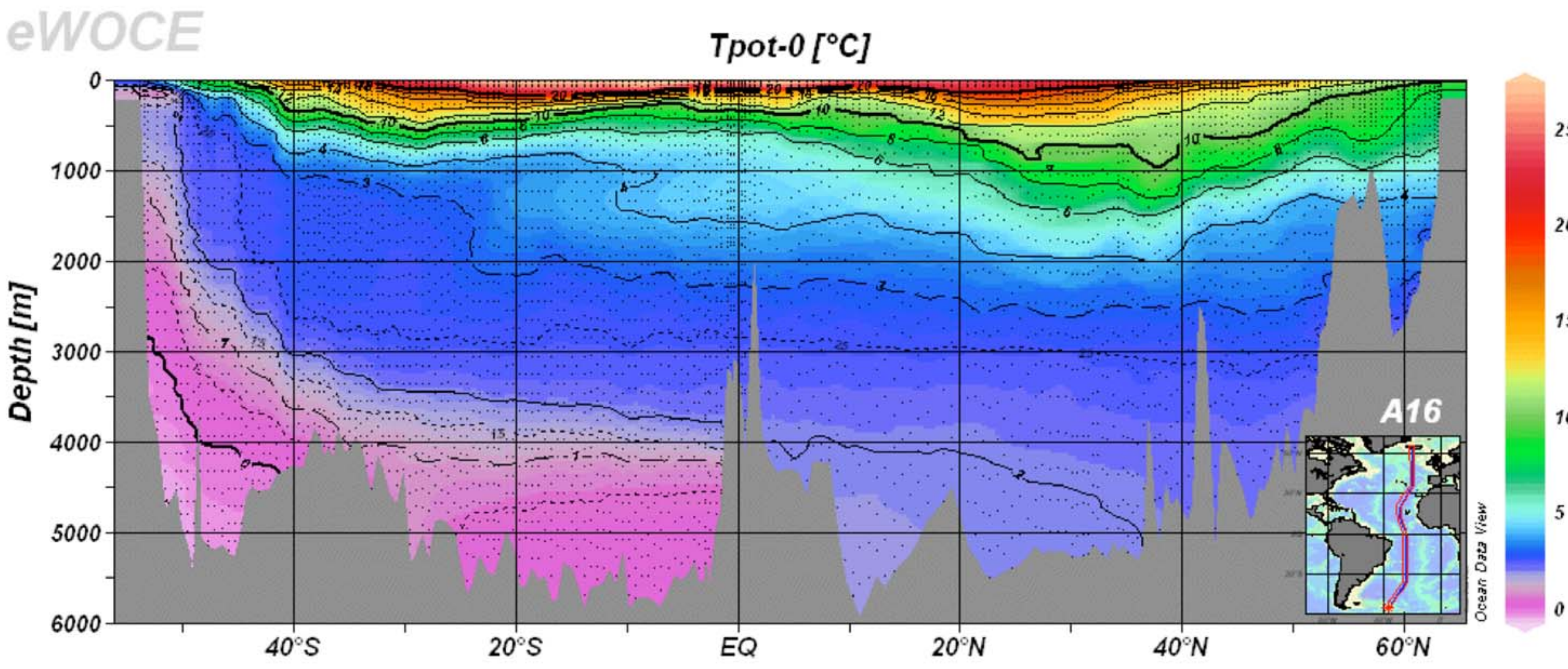
So, where does it go?

GLODAP - cdiac.ornl.gov/oceans/home.html

Conveyor Belt

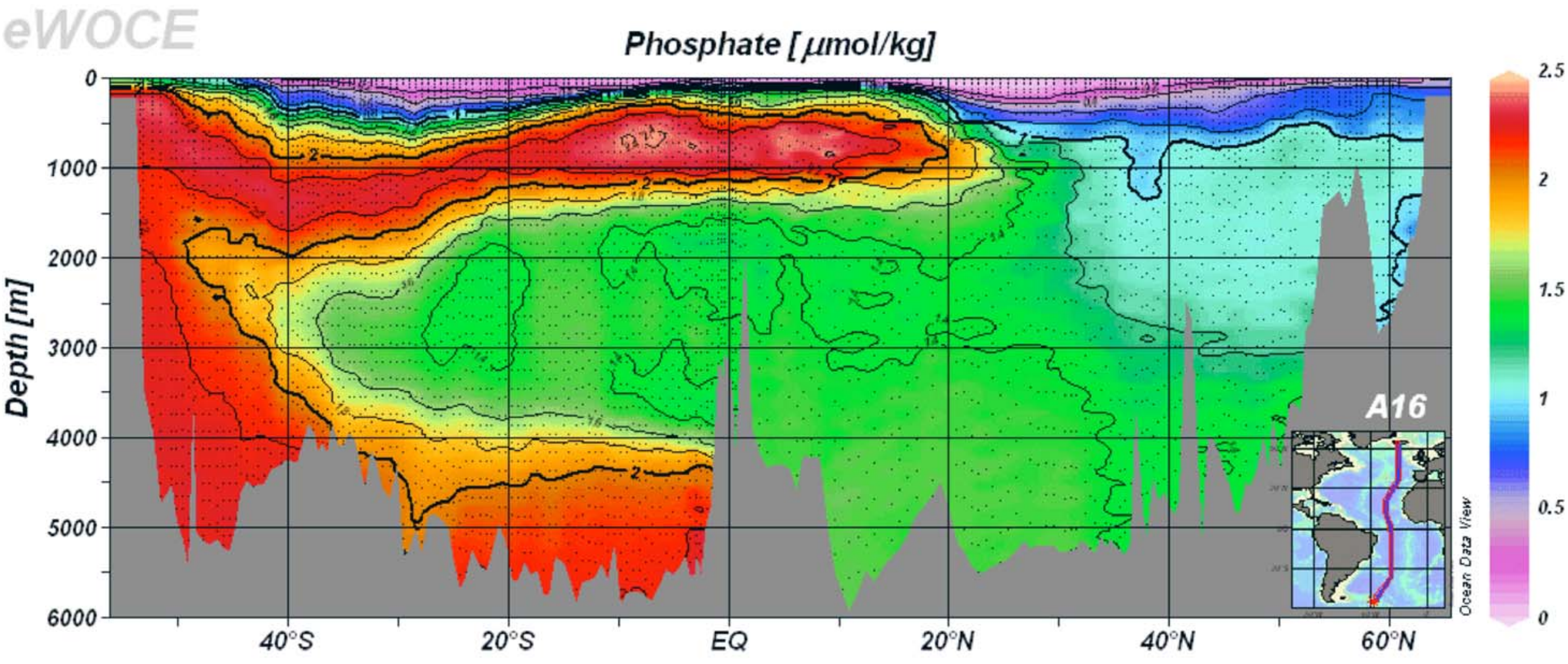


Atlantic Temperature



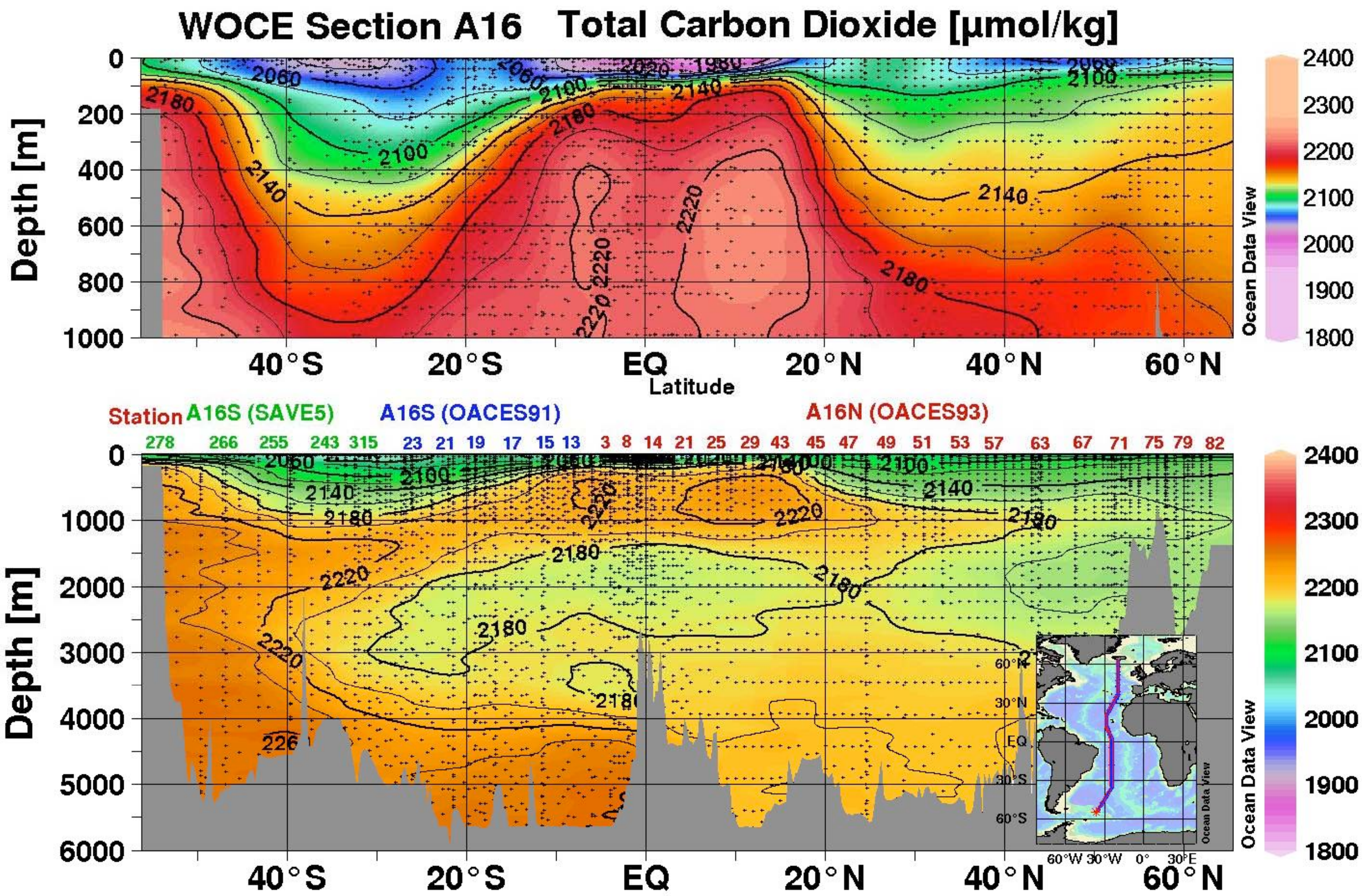
eWOCE gallery – www.ewoce.org

Atlantic Phosphate



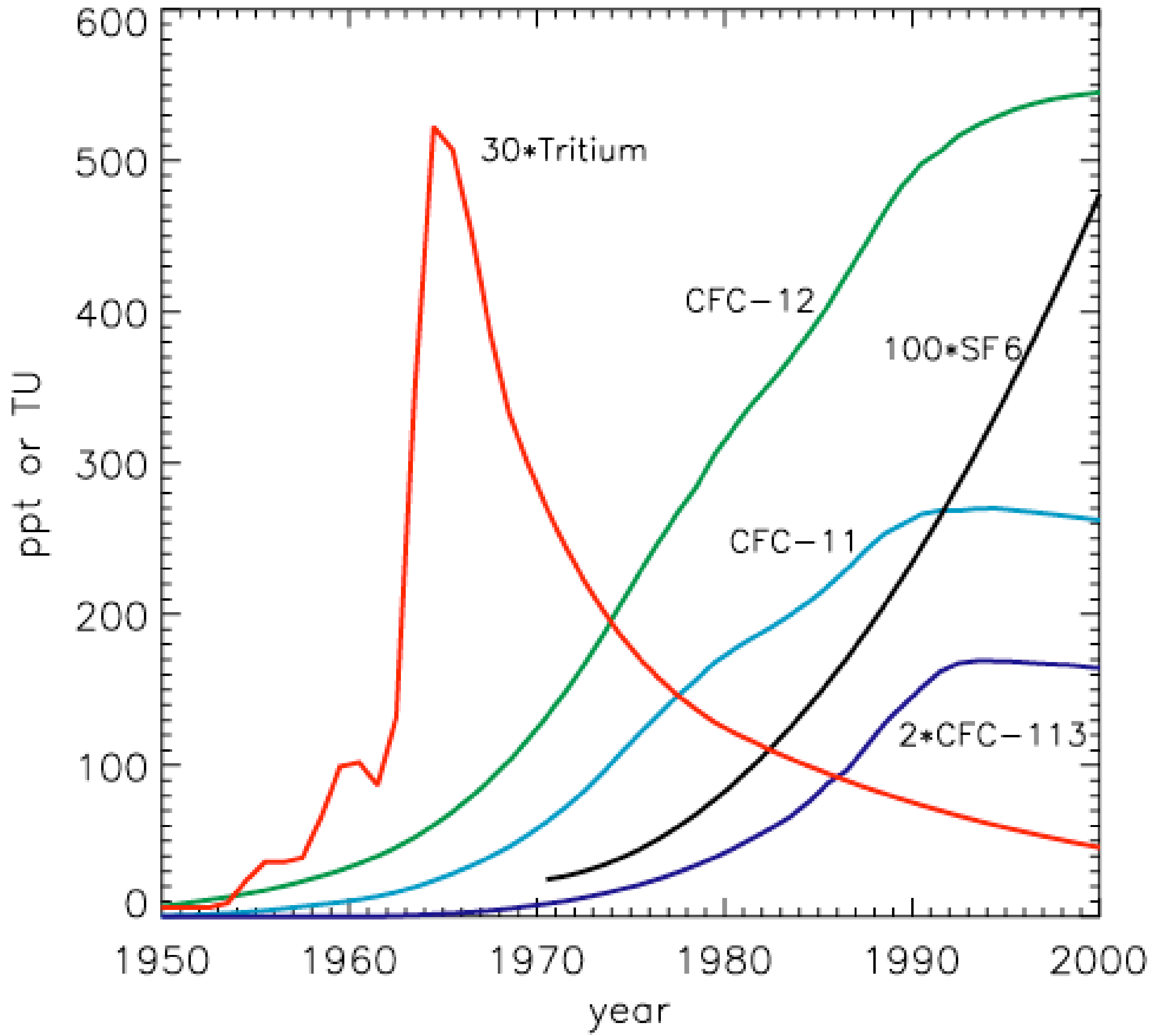
eWOCE gallery – www.ewoce.org

Atlantic Total CO_2



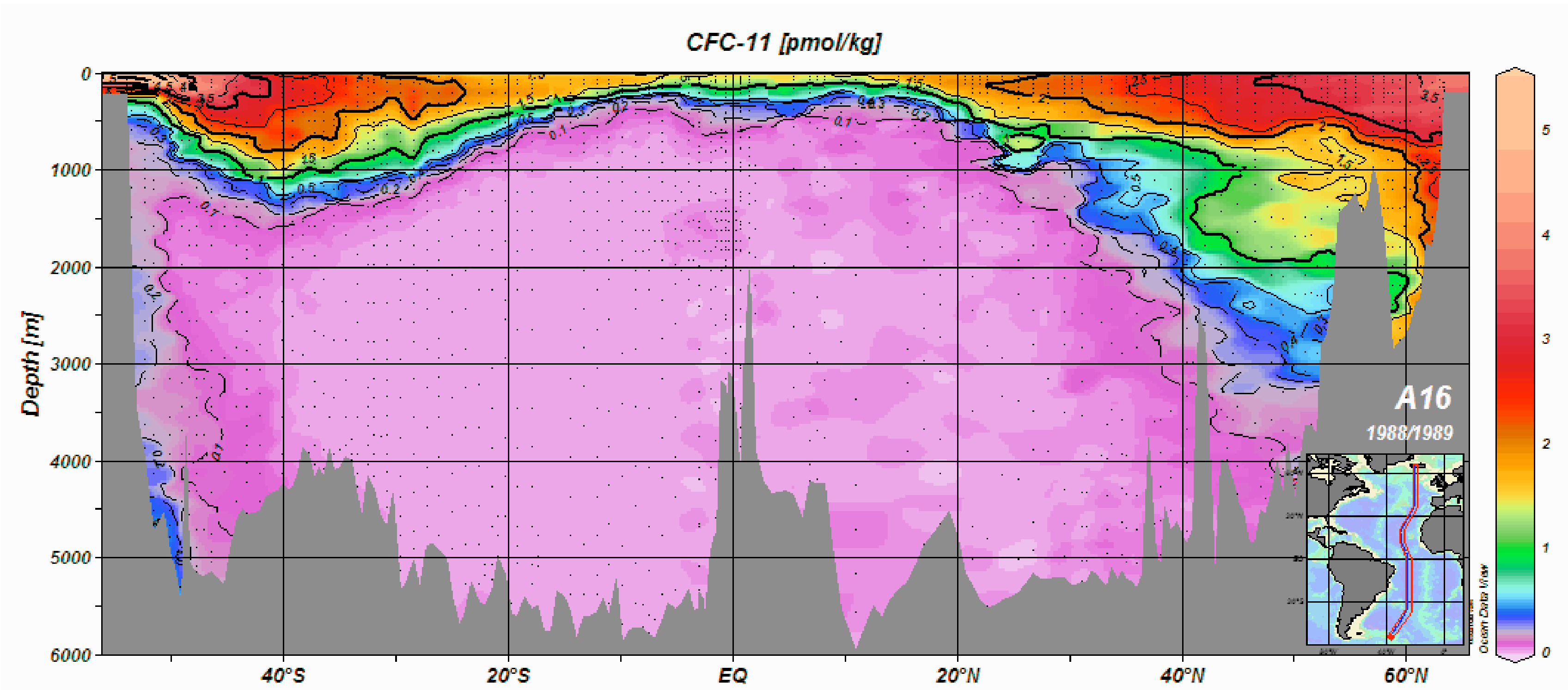
How to separate the anthropogenic fraction?

Transient Tracers



http://www.jhu.edu/~dwaugh1/ttd_tracerages.html

Chlorofluorocarbons

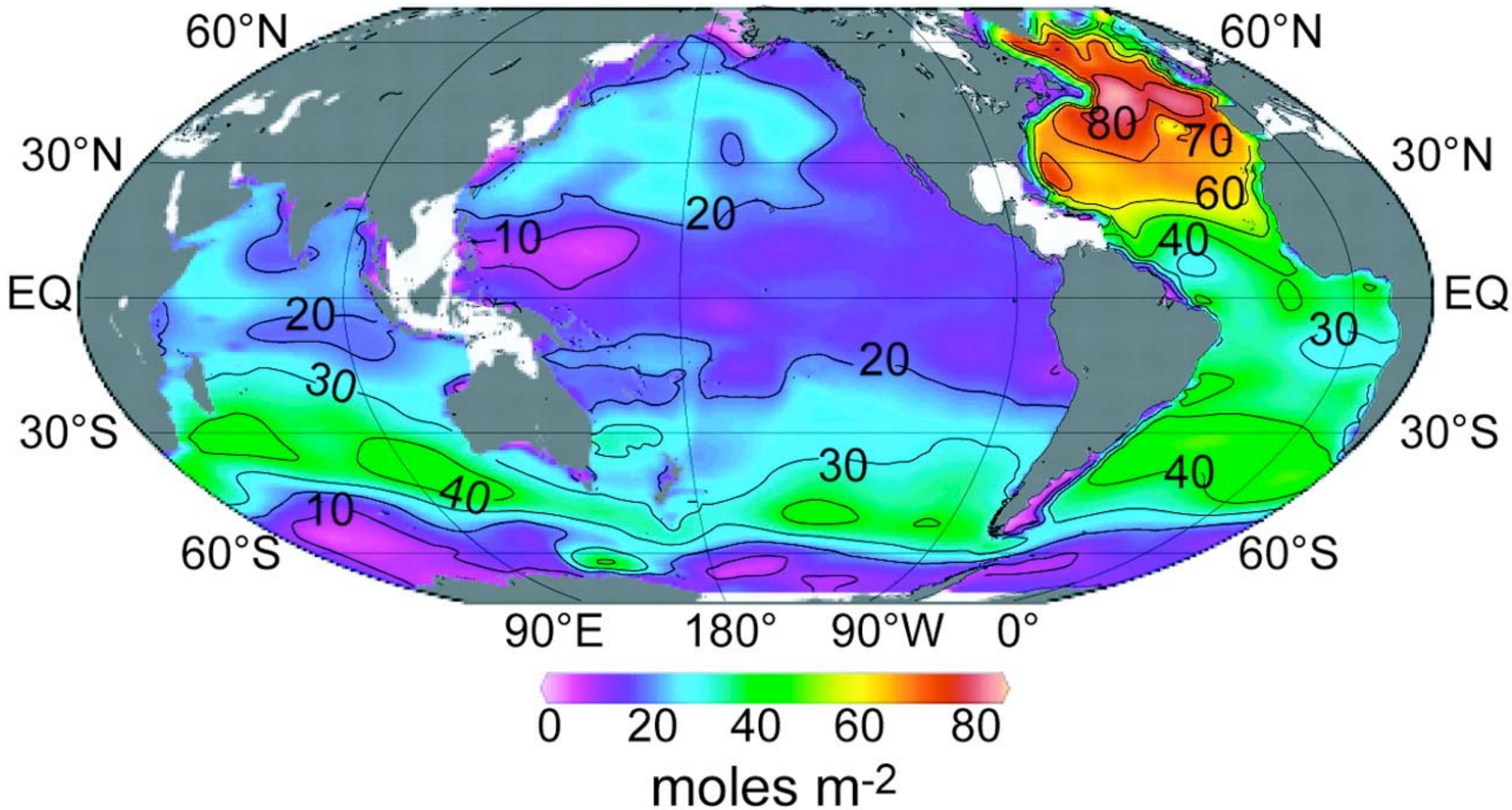


CFC-11 - trichlorofluormethane

Tracer of anthropogenic penetration

eWOCE gallery – www.ewoce.org

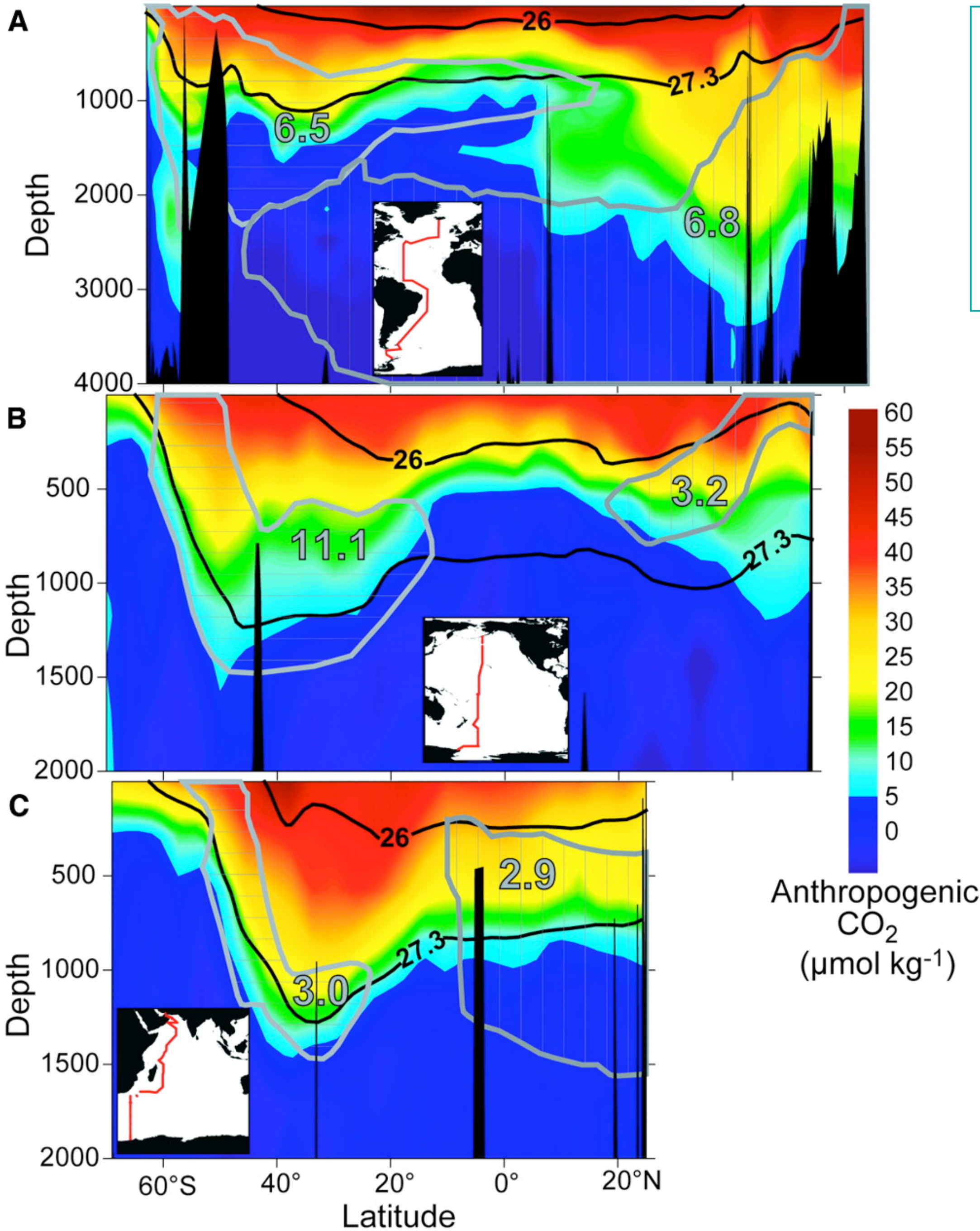
Anthropogenic CO_2



- Total ~ 106 Gt C
- Atlantic ~ 40 Gt C (25% in 15% area)

Sabine et al. *Science* [2004]

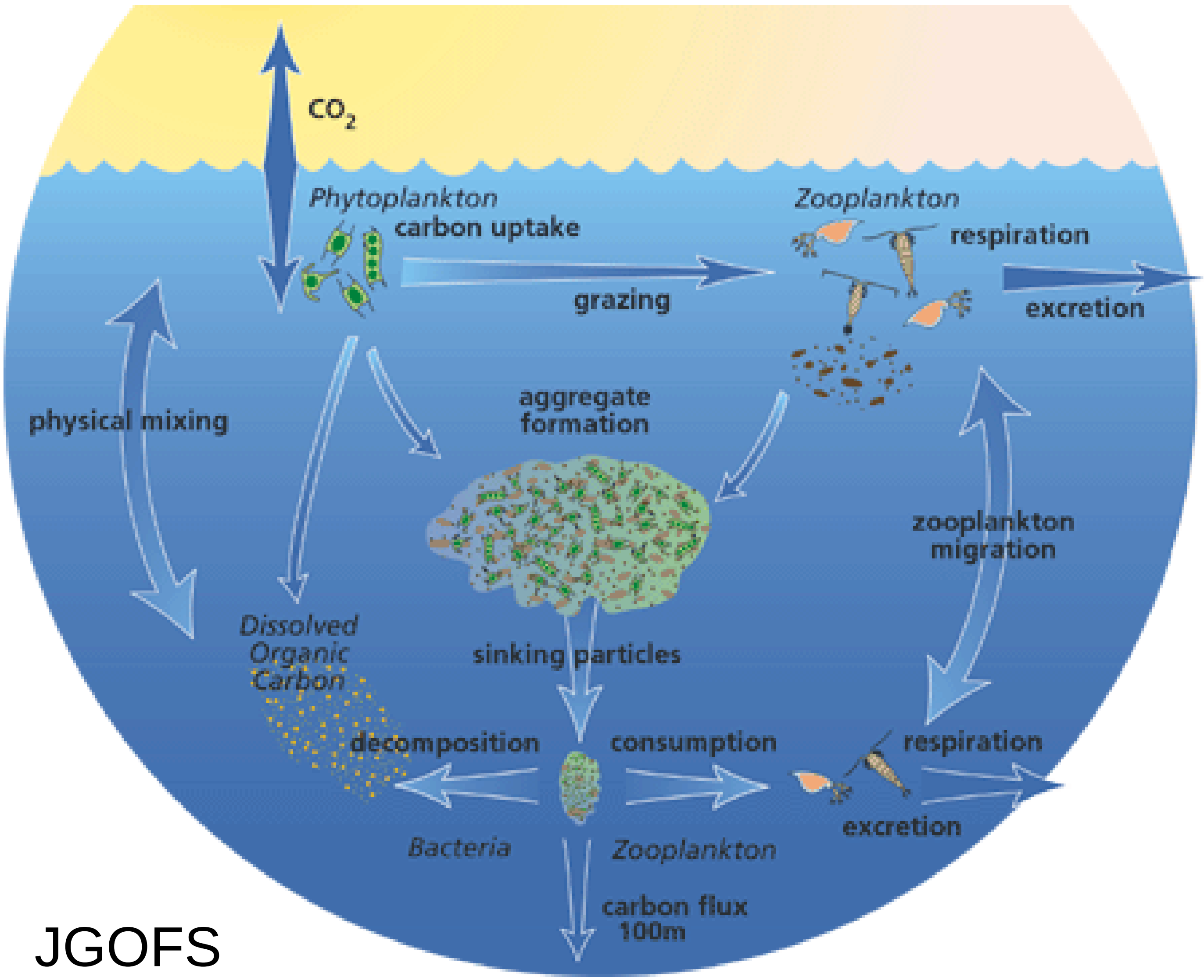
Anthropogenic CO_2



- Half anthropogenic CO_2 found in upper 400 m
- Penetration depth ~ 1 km
- Anthropogenic CO_2 is small fraction of TotalCO_2

Sabine et al. *Science* [2004]

Ocean Biological Pump



JGOFS

Food web processes transfer organic matter to depth

-pathway for rapid C sequestration

Quickly remove C from surface ocean

-turn off bio pump and 200 ppmv increase atm. CO_2

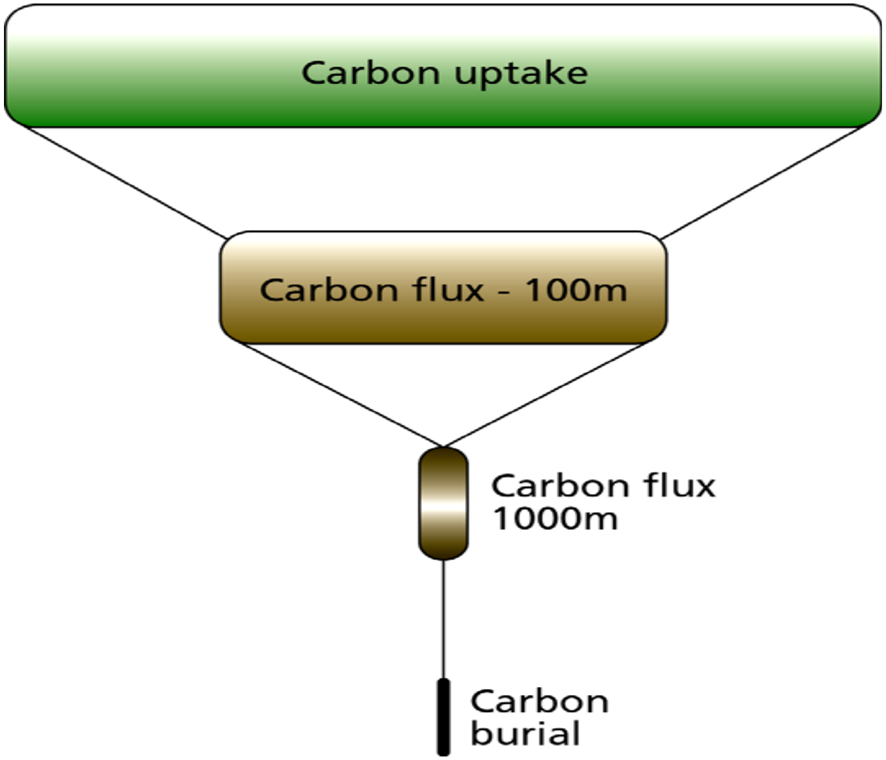
Ocean Biological Pump

Net Primary Production

Sinking particles ~10% NPP

~1% NPP

~0.1%

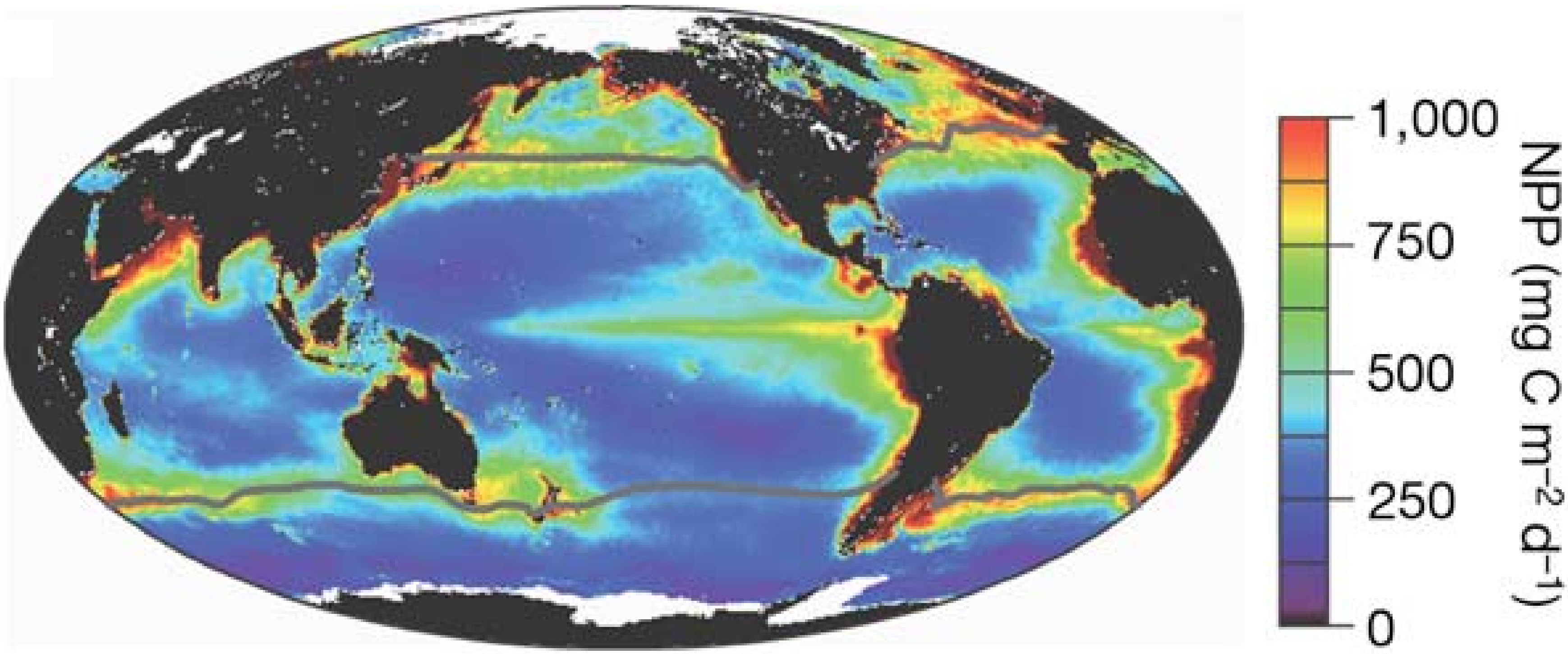


Little anthropogenic CO_2 is sequestered by the biological pump (900 vs. 18 Gt C in surface ocean)

Climate-driven trends in contemporary ocean productivity

Michael J. Behrenfeld[1], Robert T. O'Malley[1], David A. Siegel[3], Charles R. McClain[4], Jorge L. Sarmiento[5], Gene C. Feldman[4], Allen J. Milligan[1], Paul G. Falkowski[6], Ricardo M. Letelier[2] & Emmanuel S. Boss[7]

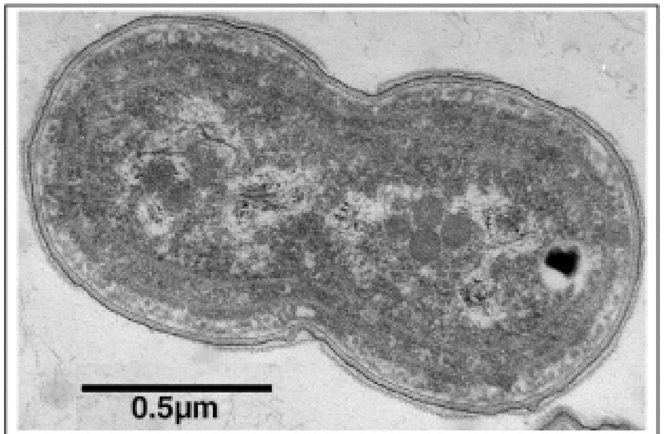
7 December 2006 Vol. 444 Nature



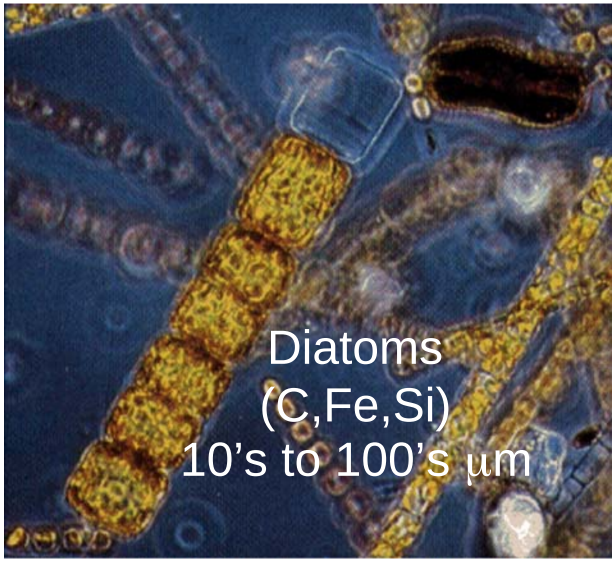
Net primary production = f(Chlorophyll, Light, SST) (VGPM)

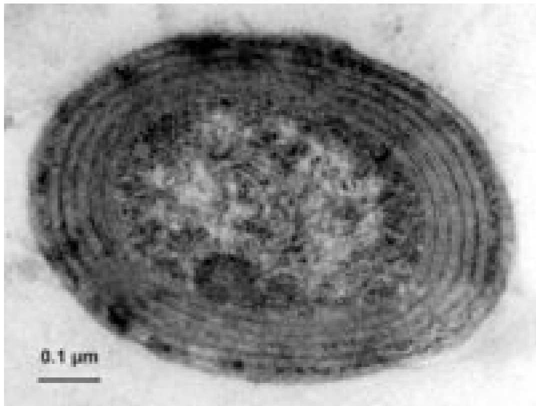
Global mean NPP ~ 55 Pg C / y

Bloom-Formers Differ in Size and BGC Impacts

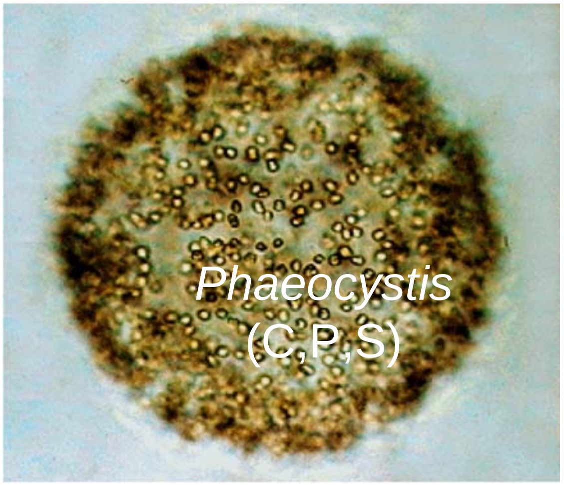


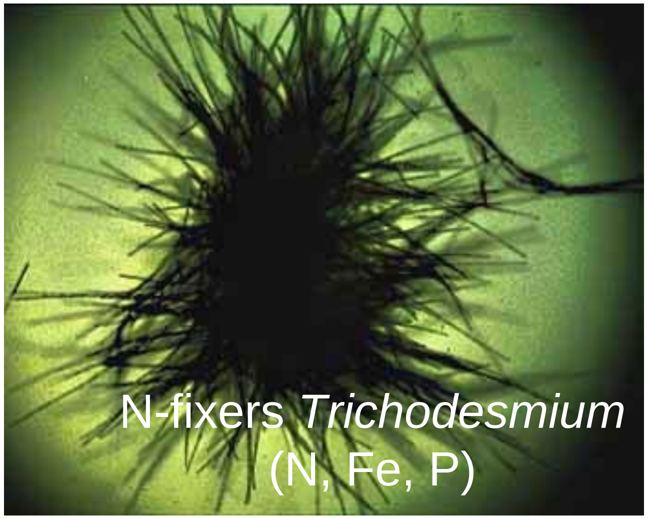
Synechococcus





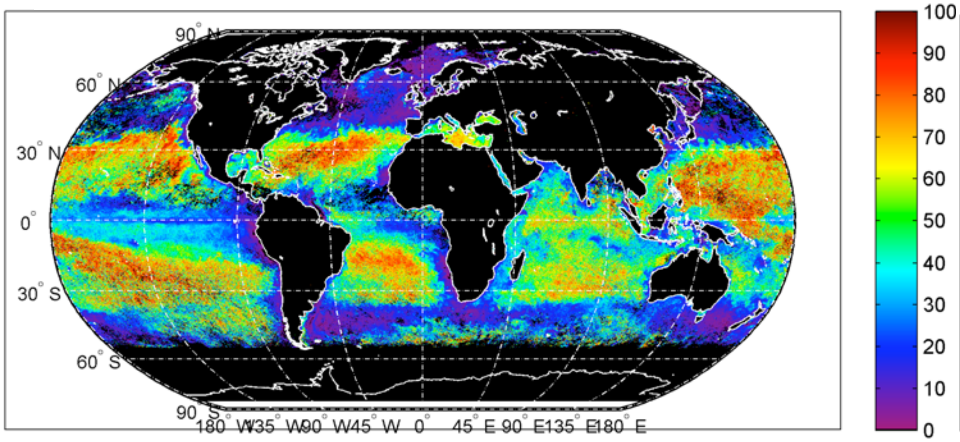
Prochlorococcus



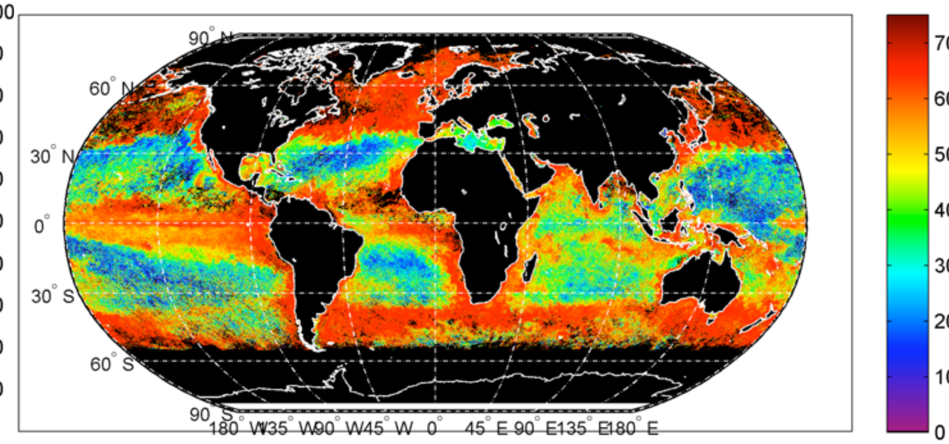


Assessing Particle Size

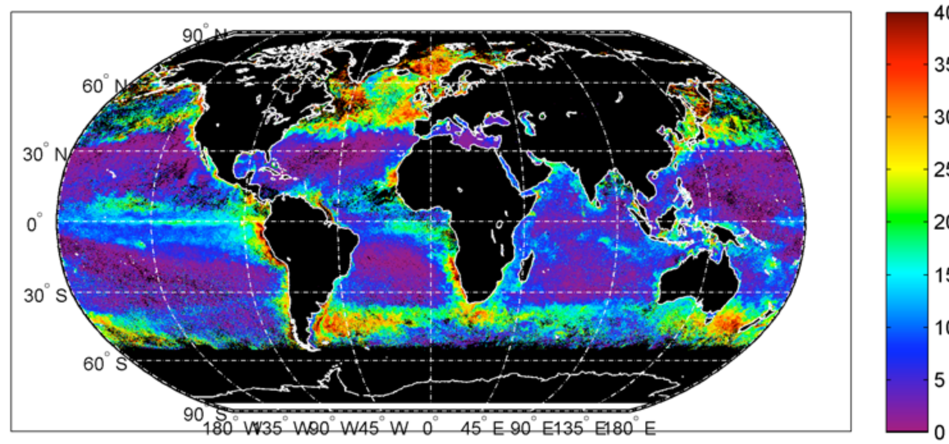
Picoparticles % (0.5 μm to 2 μm)



Nanoparticles % (2 μm to 20 μm)



Microparticles % (20 μm to 30 μm)



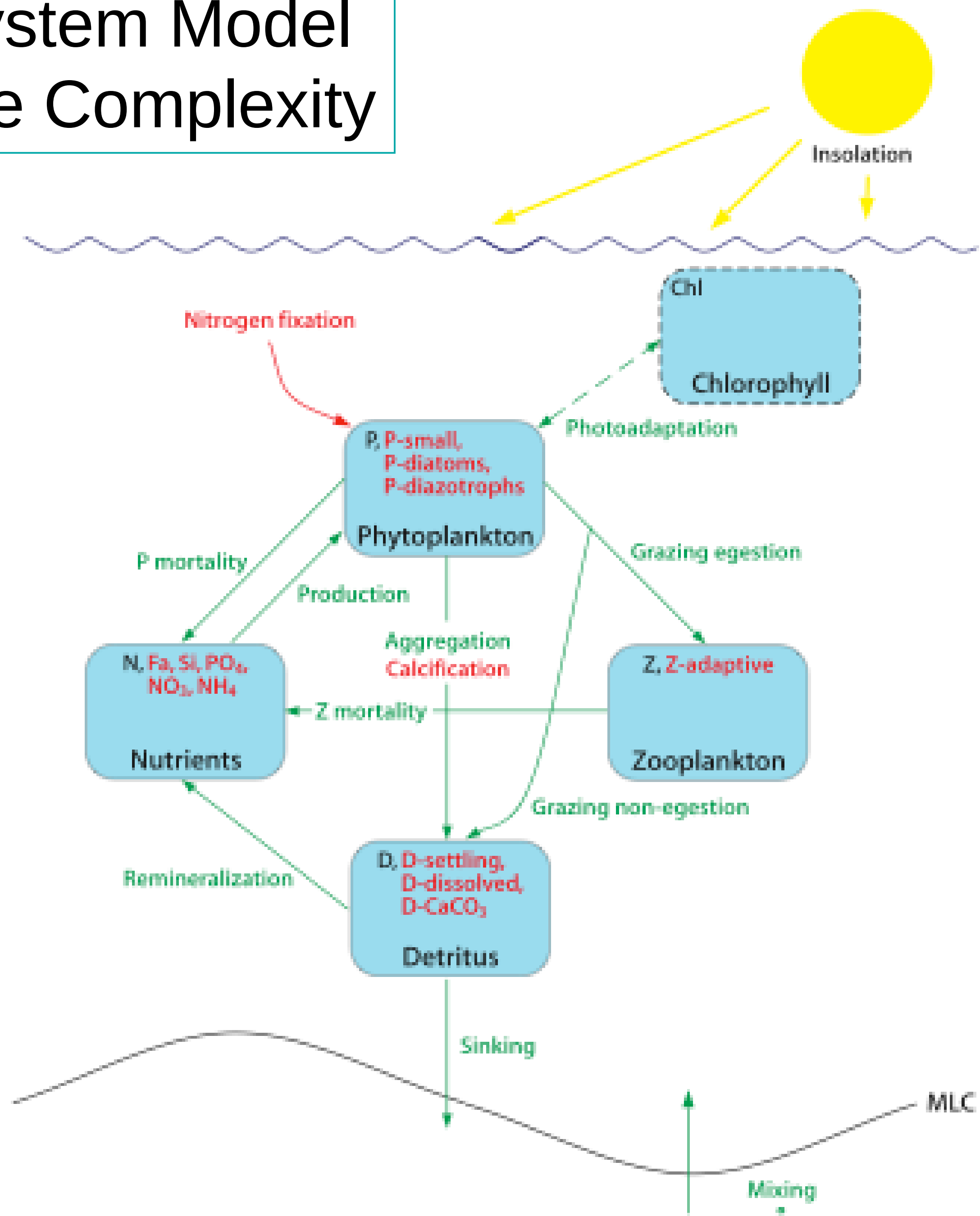
Pico's dominate oligotrophic ocean (>90%)

Nano's in transition regions (65%)

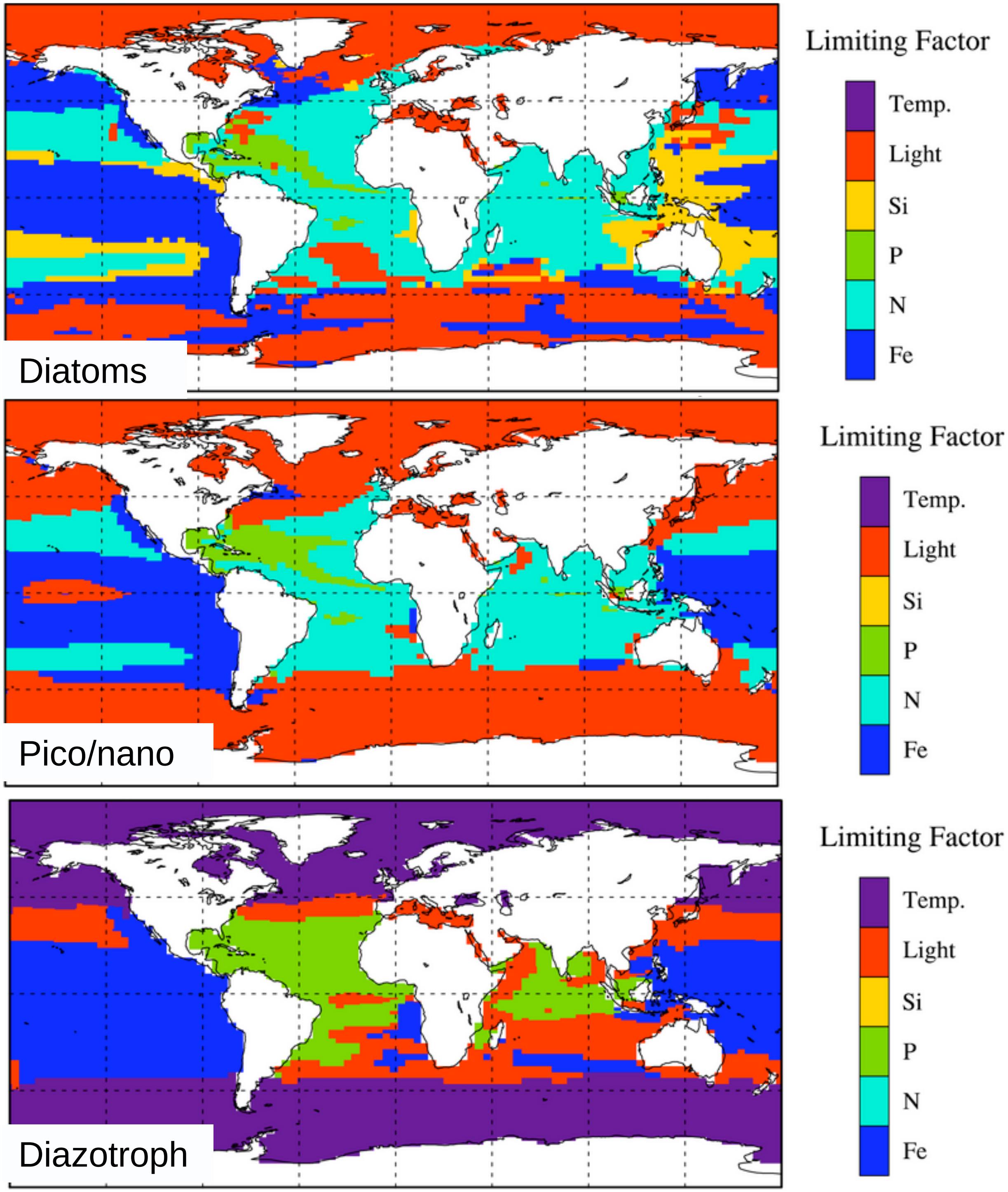
Micro's only found in upwelling zones & high latitudes (<35%)

Tiho Kostadinov (UCSB)

Pelagic Ecosystem Model of Intermediate Complexity



Doney et al. [2004]



Ecological Metrics

Physiological state

- growth rate
- nutrient & light stress

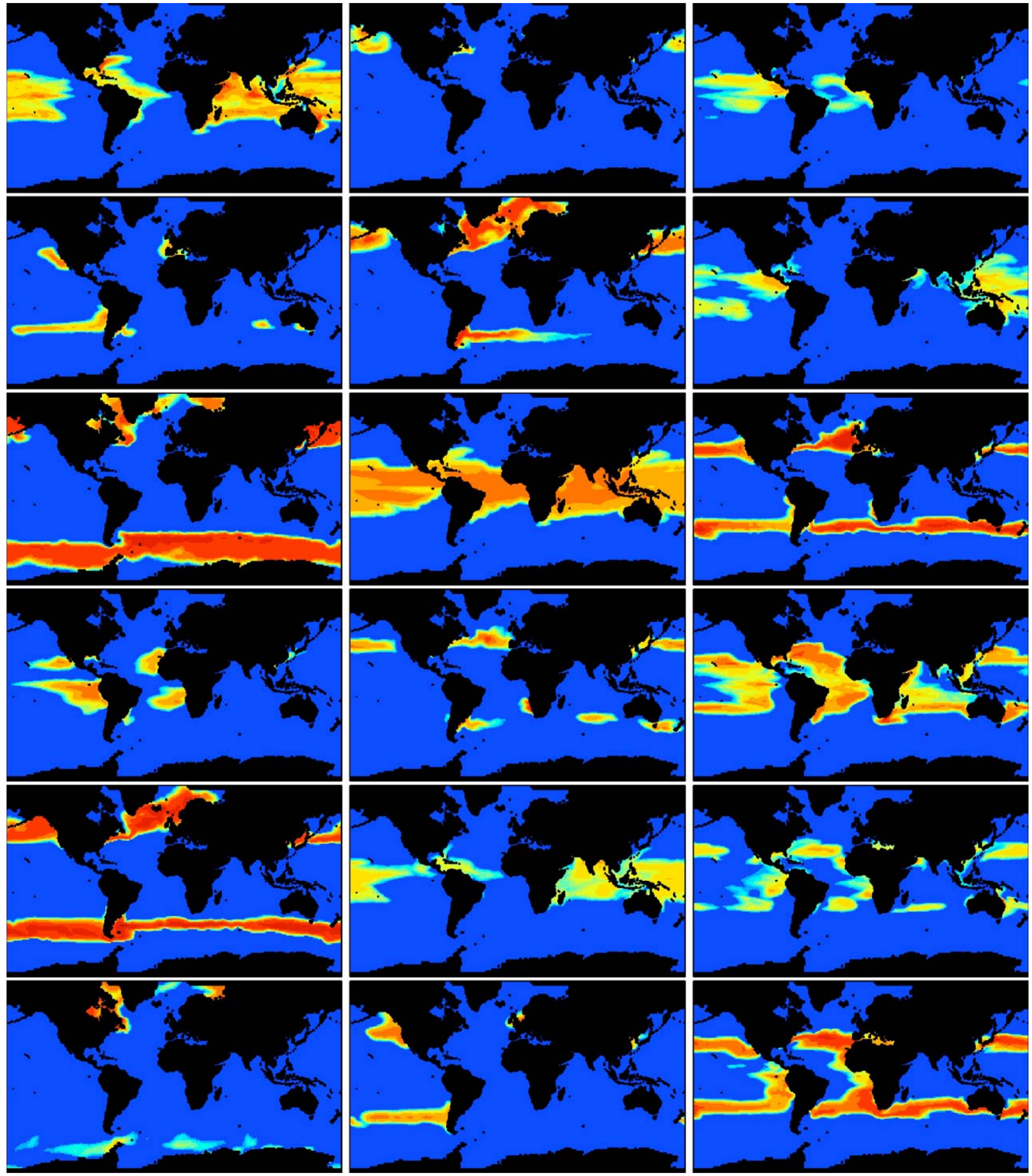
Community structure

- size classes
- BGC functional groups

Doney et al. [2004]

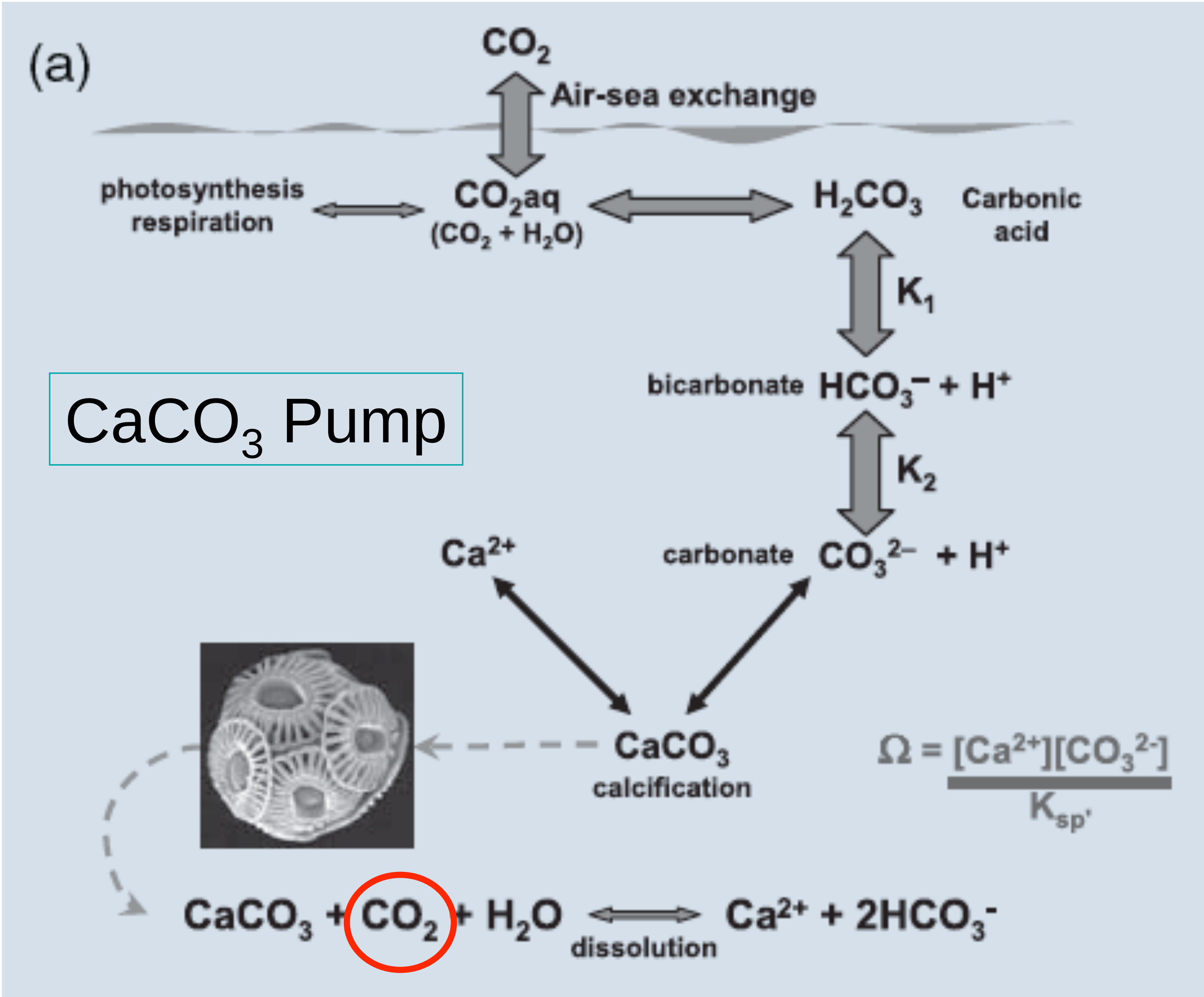
Emergent Biogeography

- Randomly created phytoplankton based on lab observations
- Assessed “who” dominated “which biome”
- Evolutionary approach

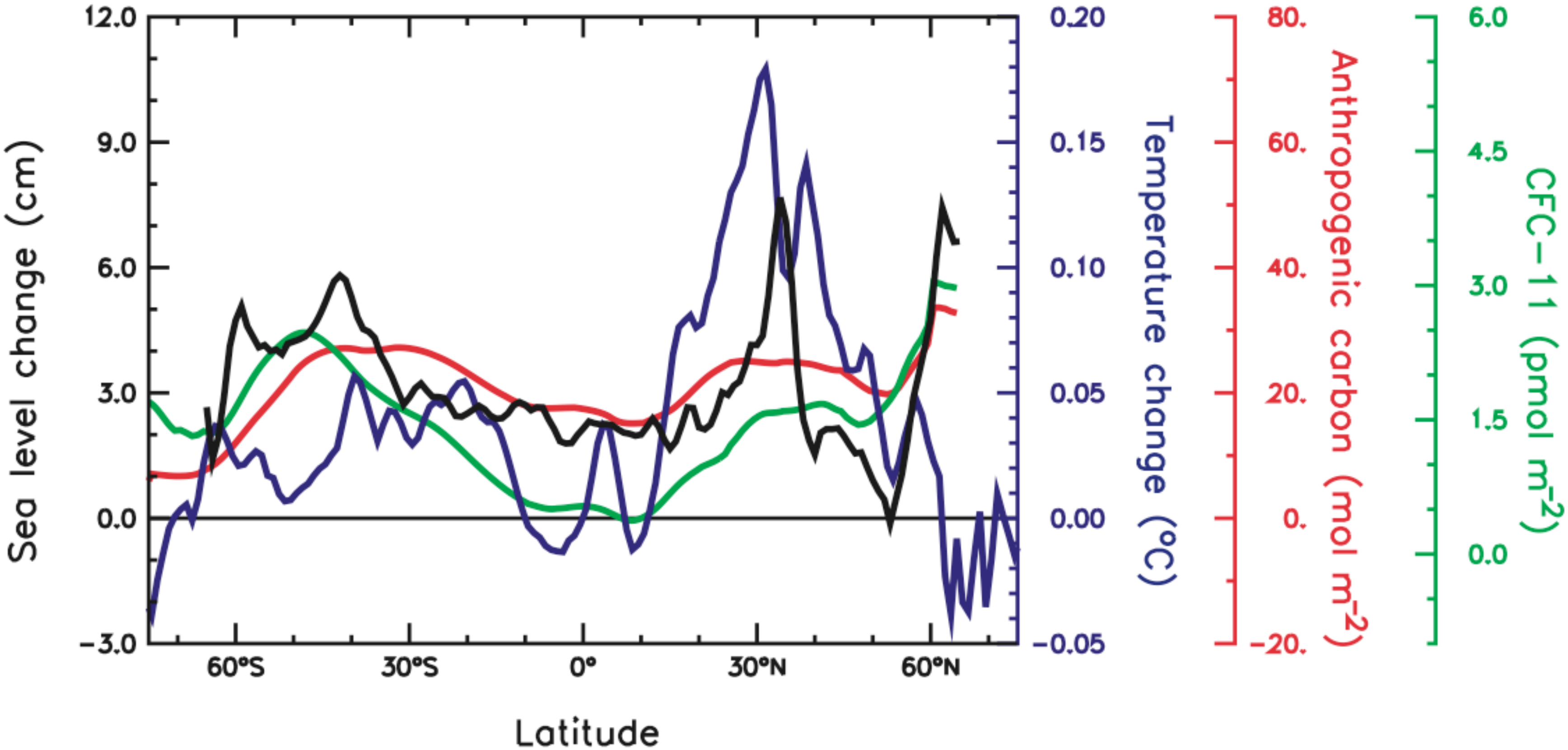


Follows et al. *Science* [2007]

$CaCO_3$ Pump


(a)
CO2
Air-sea exchange
photosynthesis
respiration
CO2aq
(CO2 + H2O)
H2CO3
Carbonic acid
K1
bicarbonate HCO3− + H+
K2
Ca2+
carbonate CO32− + H+
CaCO3
calcification
Ω = [Ca2+][CO32-] / Ksp'
CaCO3 + CO2 + H2O ⟷ Ca2+ + 2HCO3-
dissolution

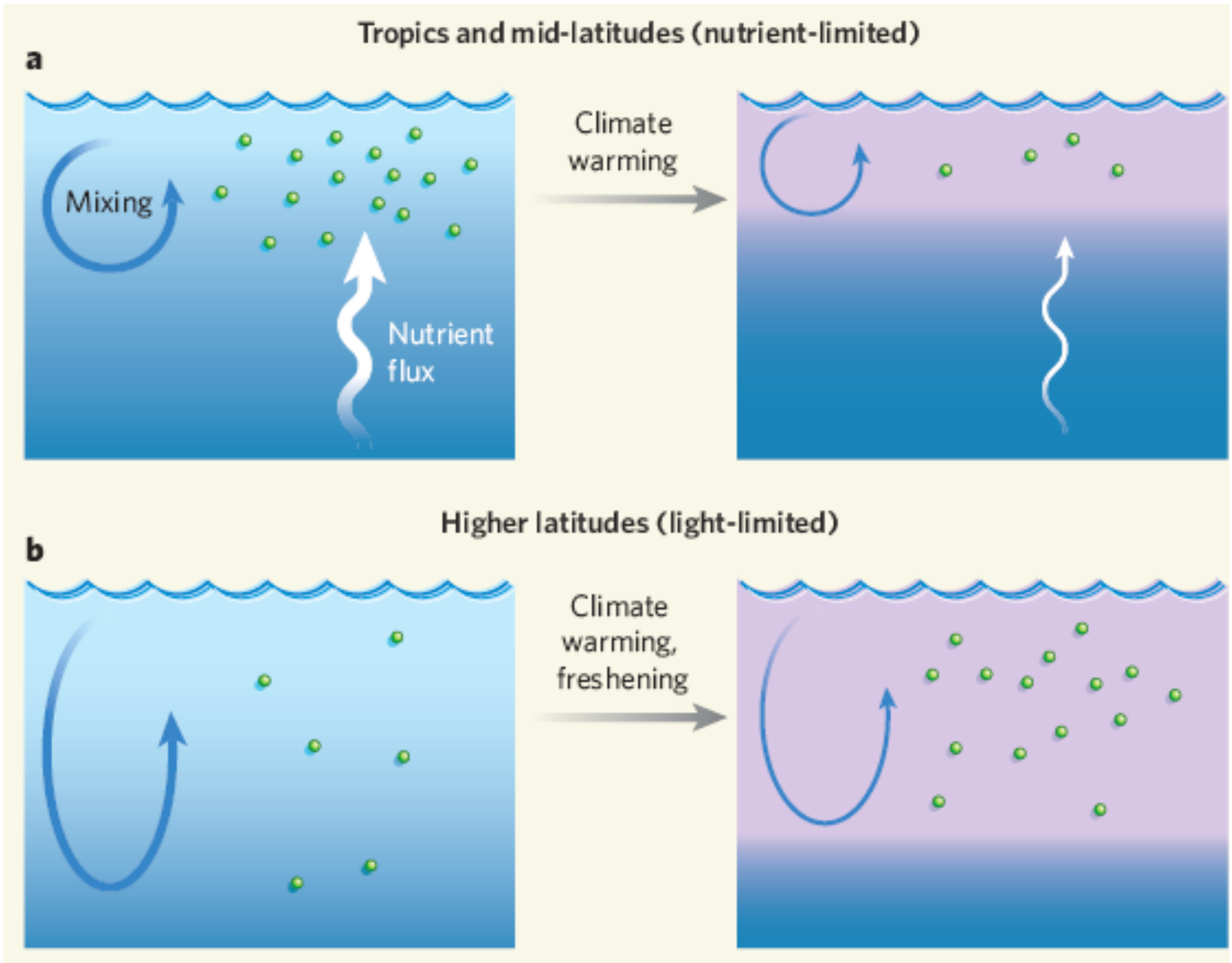
Surface Ocean Change



- Changes for the upper 700 m of the ocean
- Pre-industrial to 1990's

IPCC [2007]

Pelagic Ecosystem Responses to Warming



Climate-driven trends in contemporary ocean productivity

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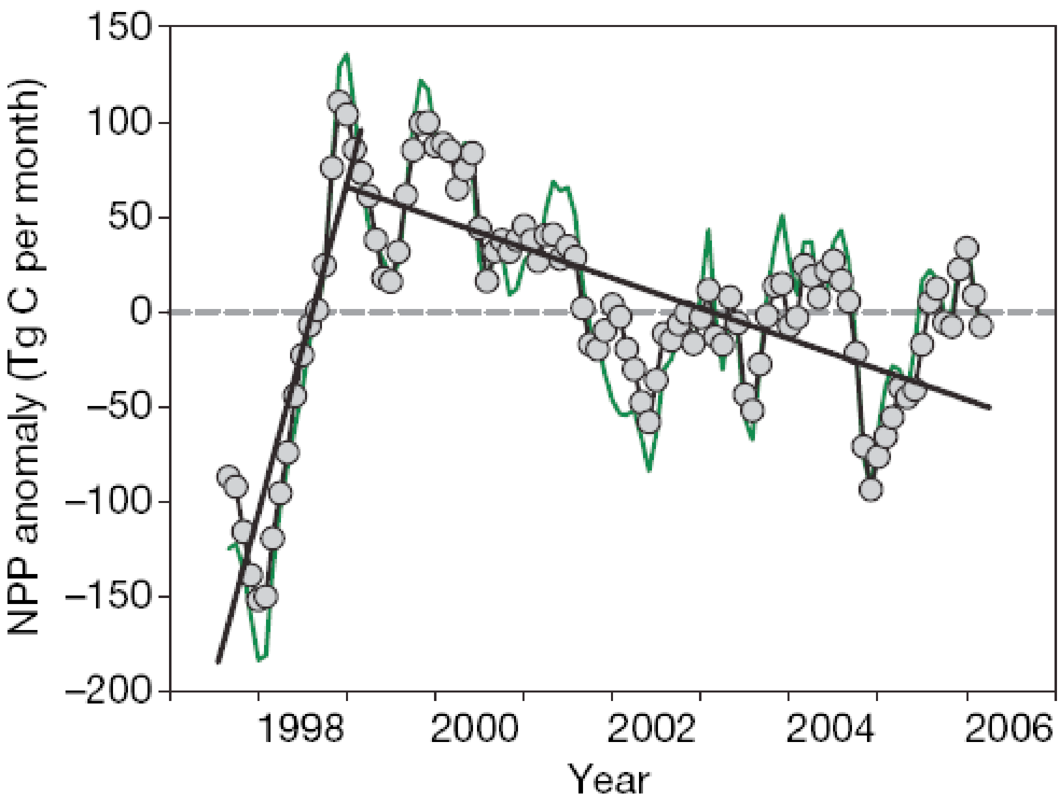
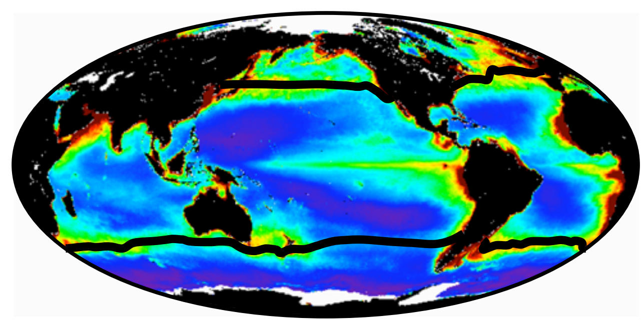


Tidbits

- Based on Vertically Generalized Production Model (VGPM)
- Initial increase = 1,930 TgC/yr
- Subsequent decrease = 190 TgC/yr
- Global trends dominated by changes in permanently stratified ocean regions (ann. ave. SST < 15^{o}C)



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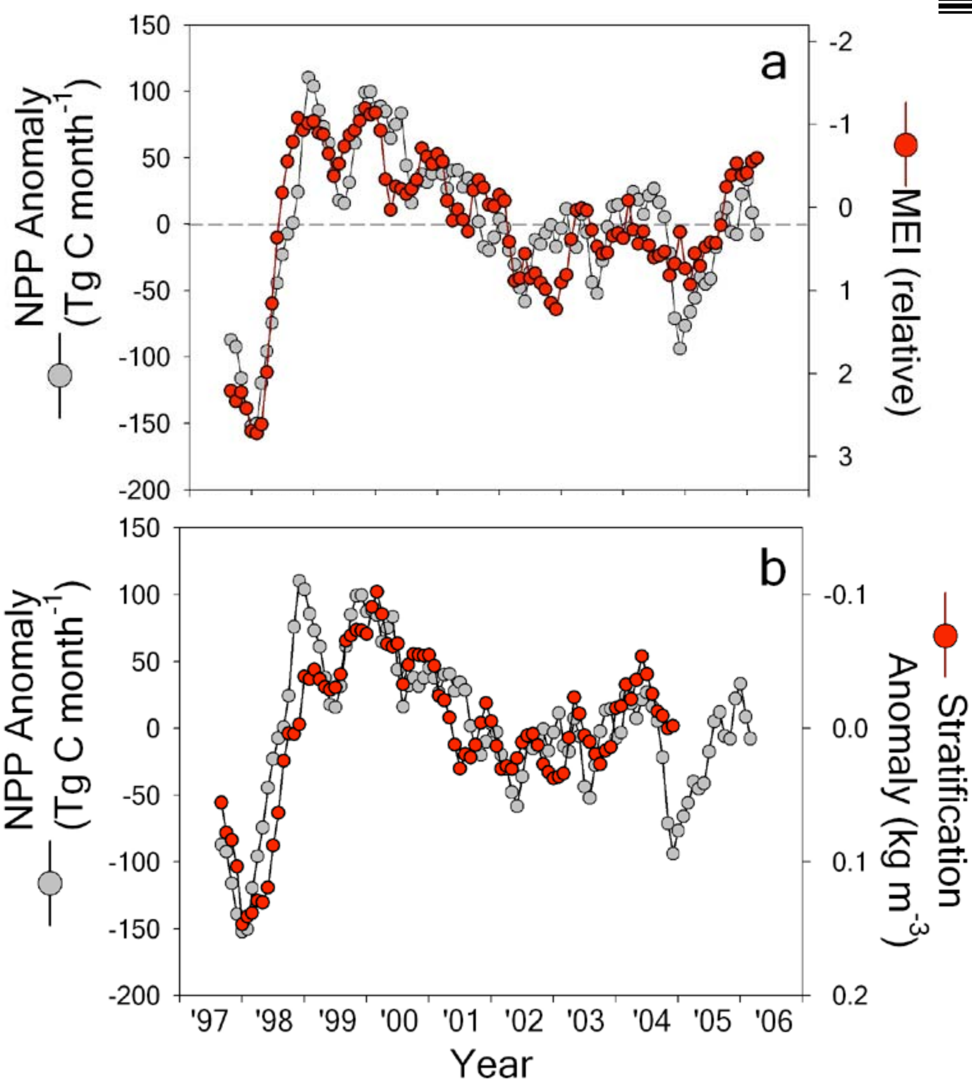
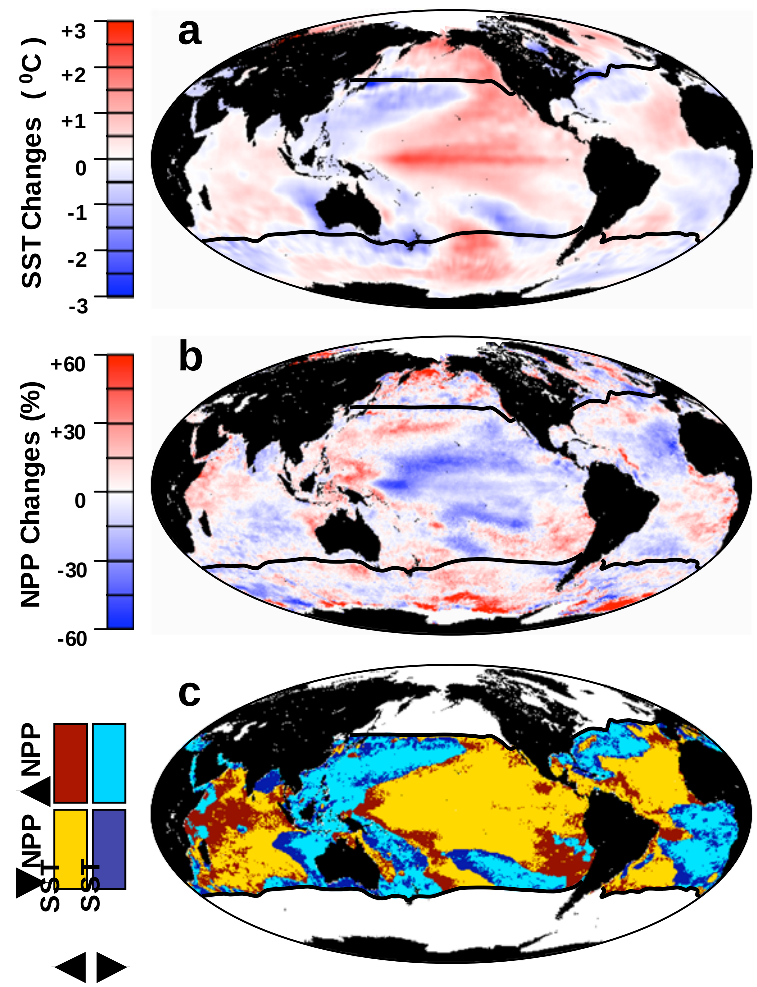


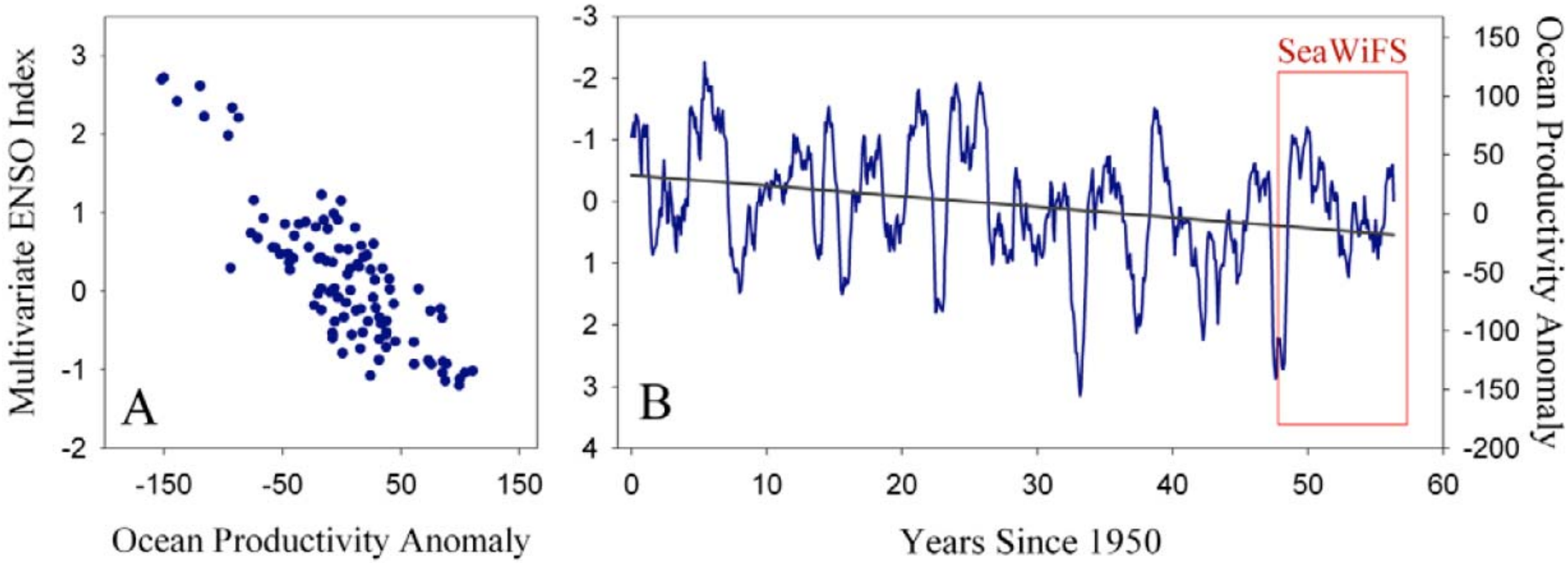


Science Features

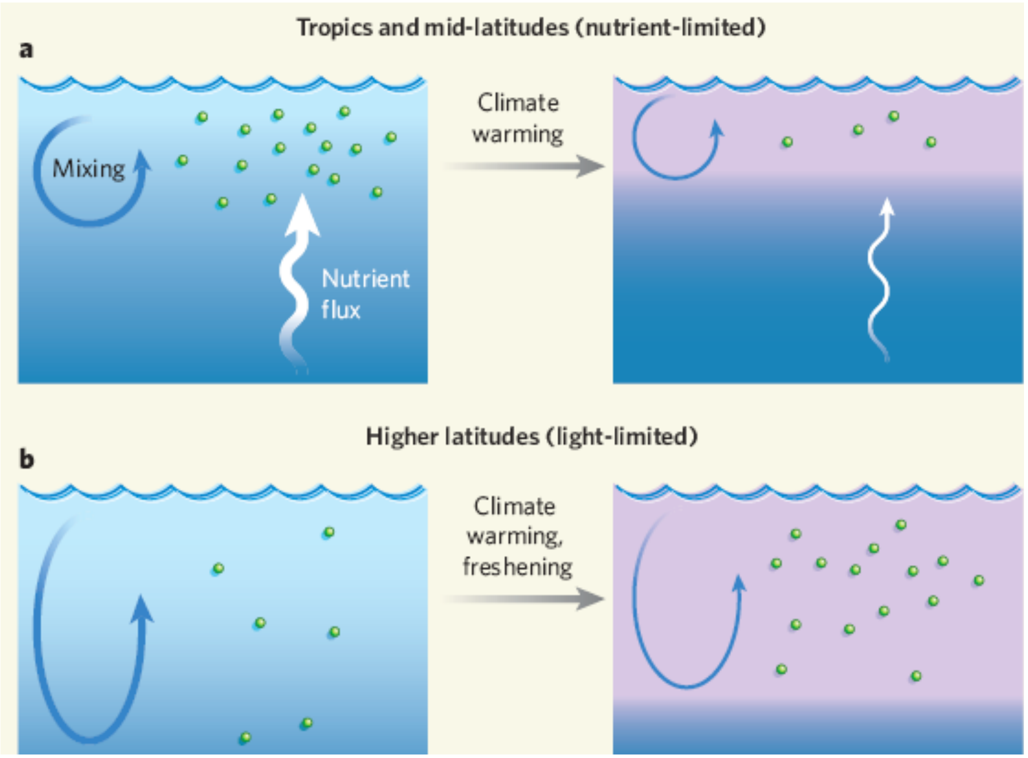
Ocean Productivity – Climate Linkages Imprinted in Satellite Observations

M. J. Behrenfeld and D. A. Siegel

Decrease in tropical / subtropical NPP of ~ 0.01 Gt C / decade



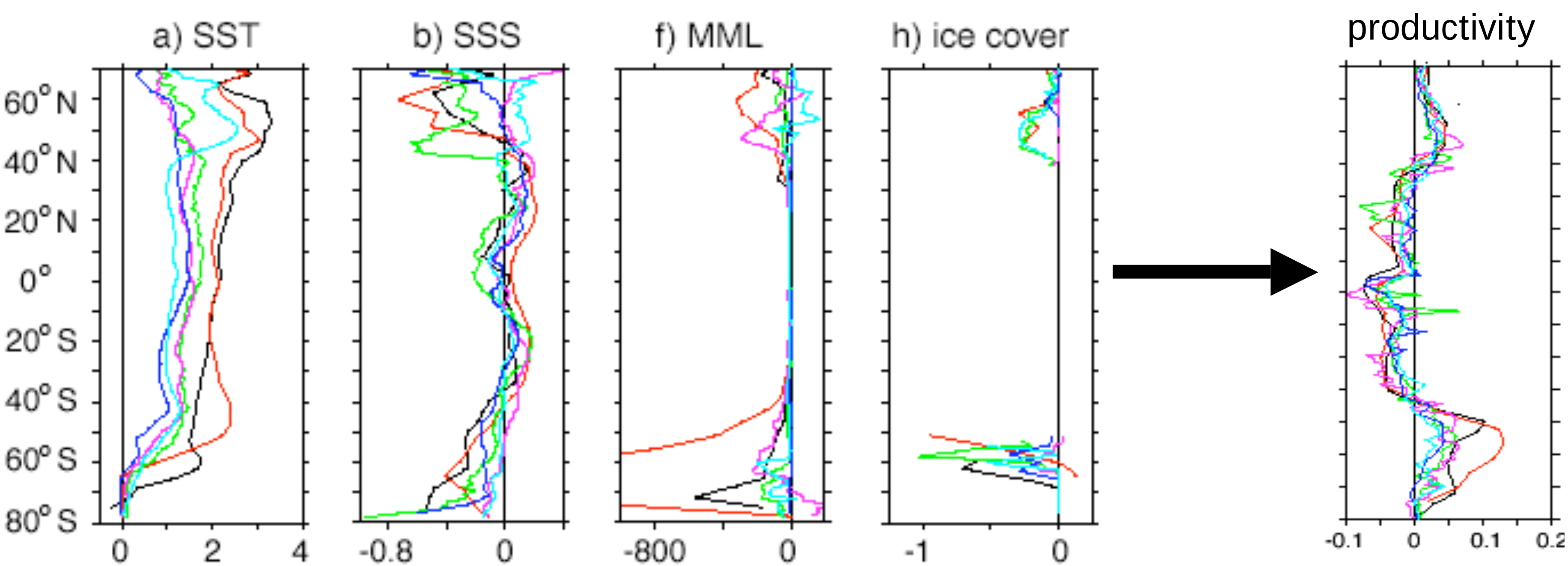
IGBP Newsletter [2007]

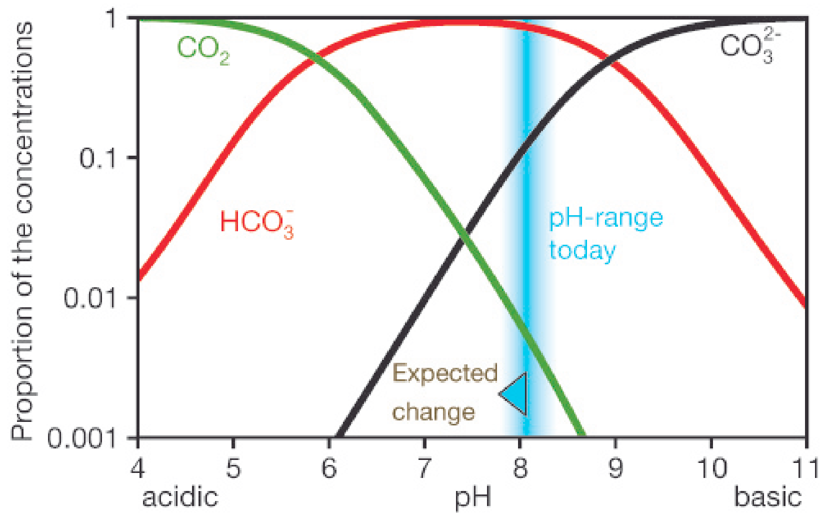


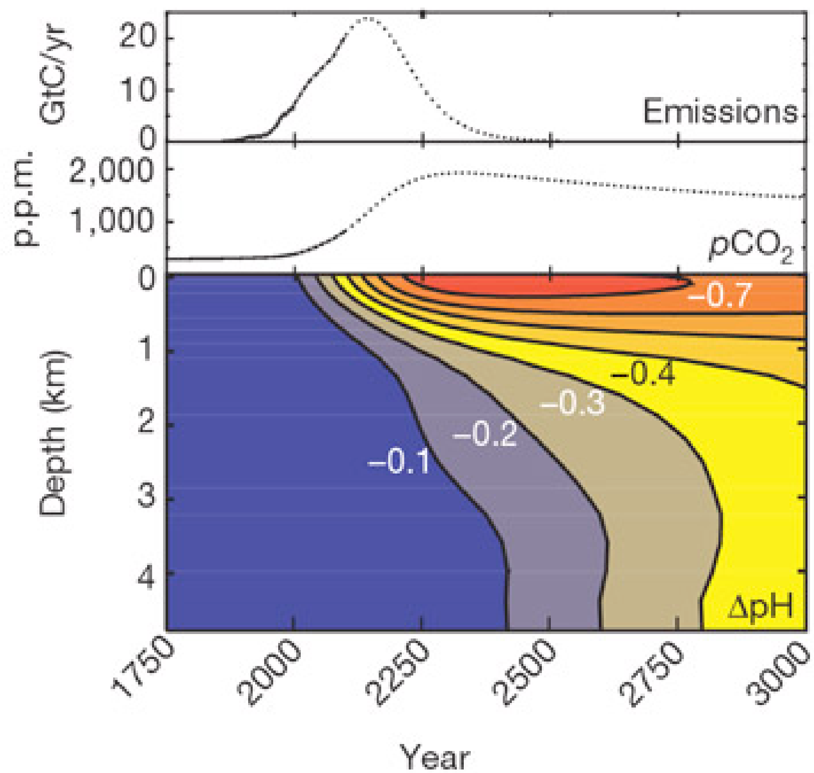
-stratification alters mixed layer depth (light) and nutrient supply

-primary productivity lower in subtropics, higher in subpolar gyres

Doney, Nature (2006); Sarmiento et al., Global Biogeo. Chem. (2004)







Acidification

Increasing CO_2:

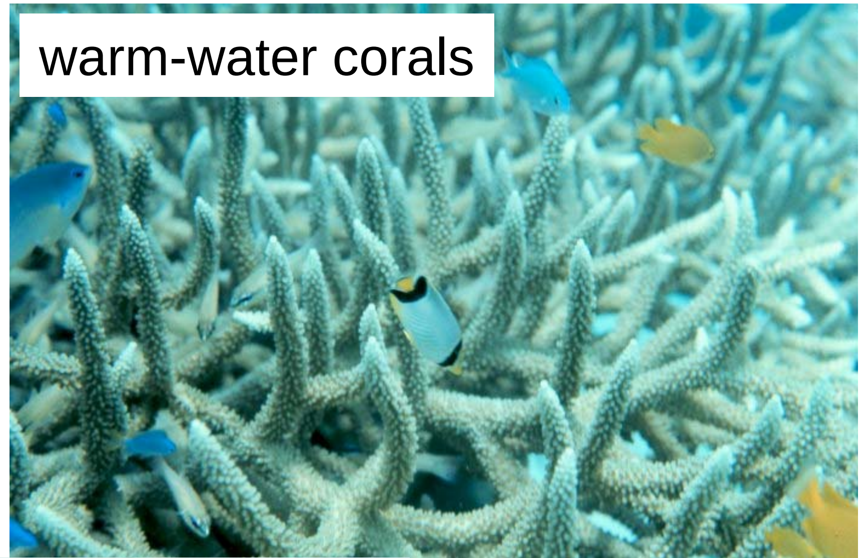
- Increases acidity (lowers pH)
- Lowers $CaCO_3(s)$ saturation state "Ω"

Multiple forms of $CaCO_3$: aragonite, calcite, Mg-calcite with different

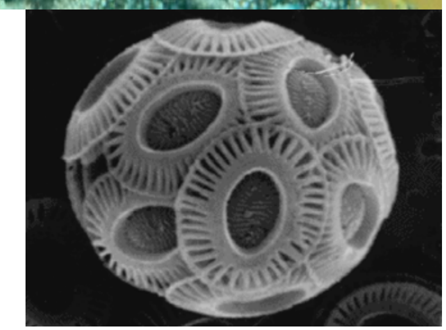
Calderia & Wickett, Nature [2003]

Biological Impacts

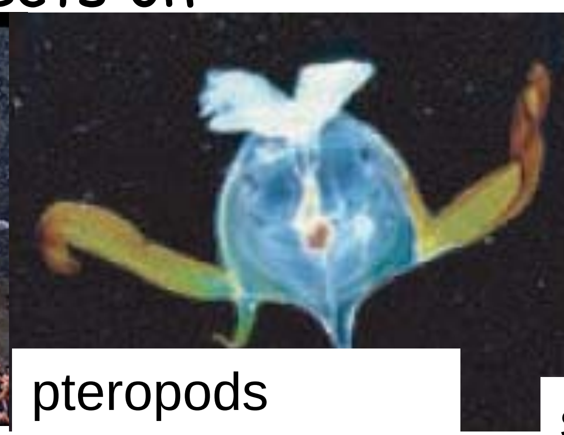
- Shell forming plants & animals
  - reduced shell formation (calcification)
  - lower reproduction & growth rates
- Habitat loss (reefs)
- Less food for predators
  - humans, fish, whales
- Possible negative effects on


warm-water corals

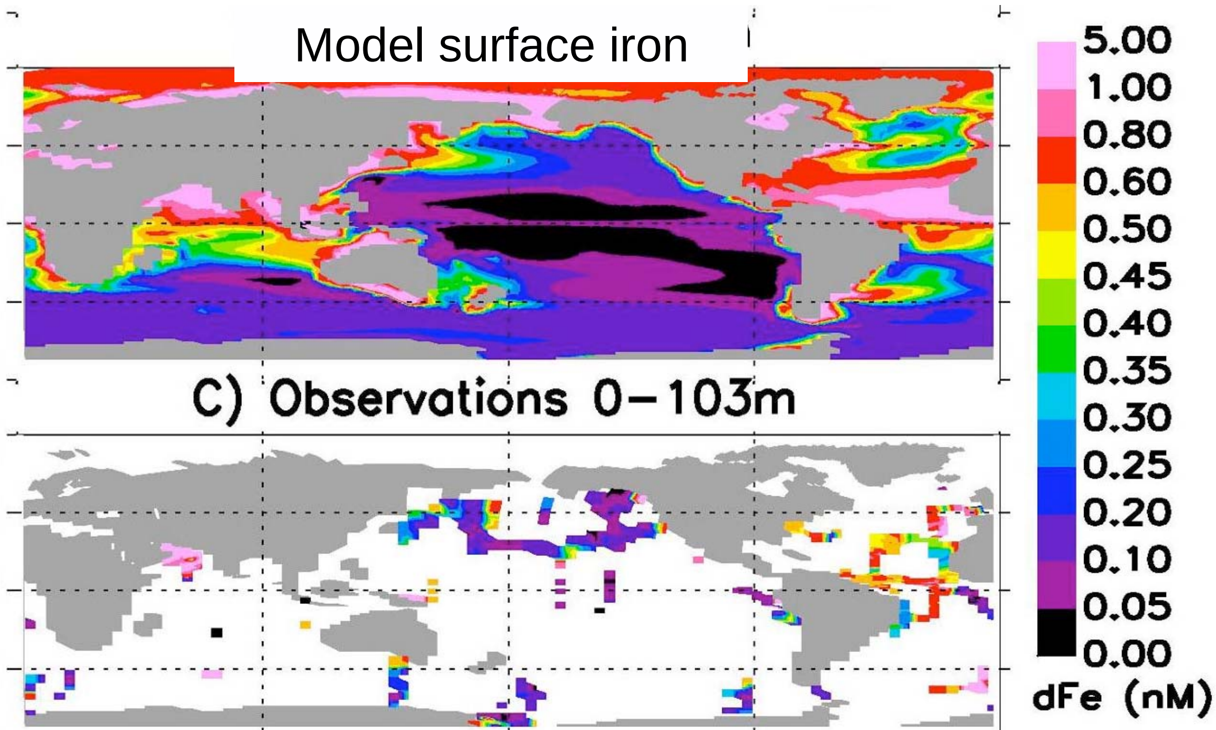

lobsters, crabs

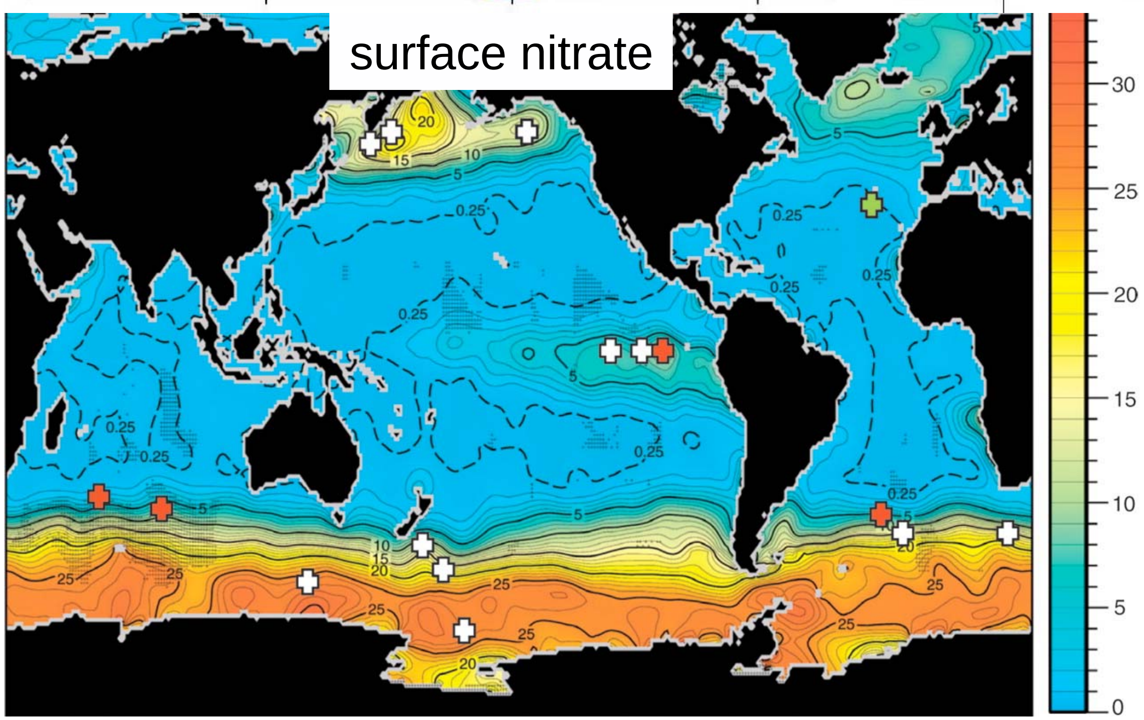

some plankton


cold-water corals


pteropods planktonic snails


scallops, clams, oysters





High Nutrient-Low Chlorophyll (HNLC) Regions

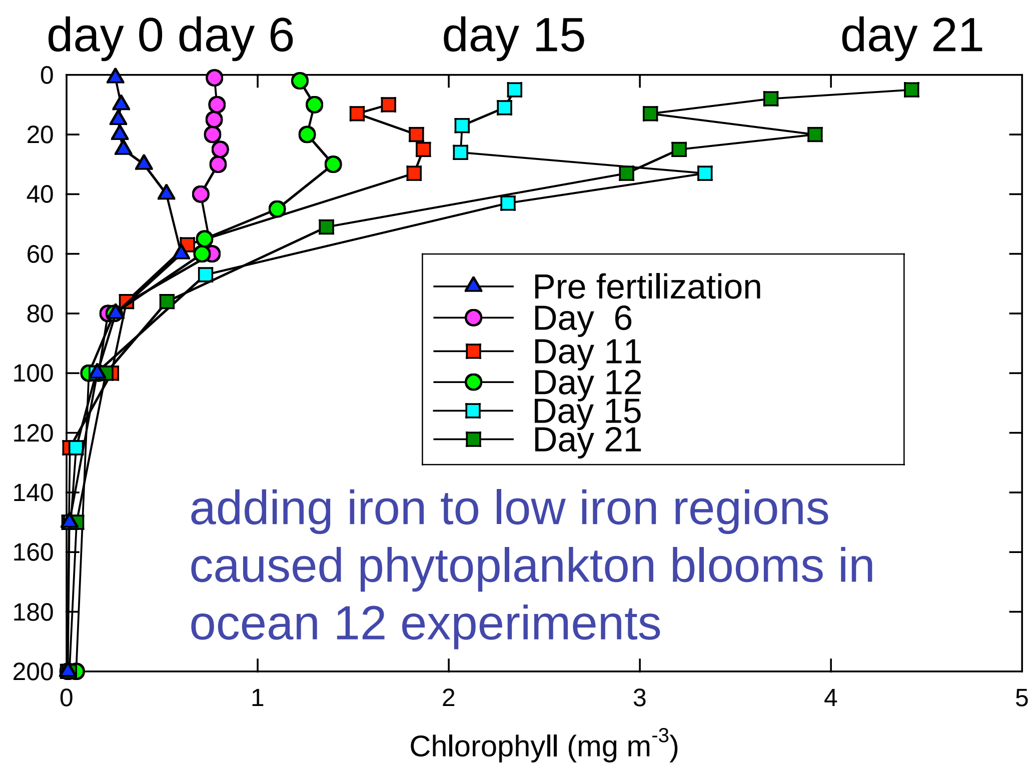
HNLC regions

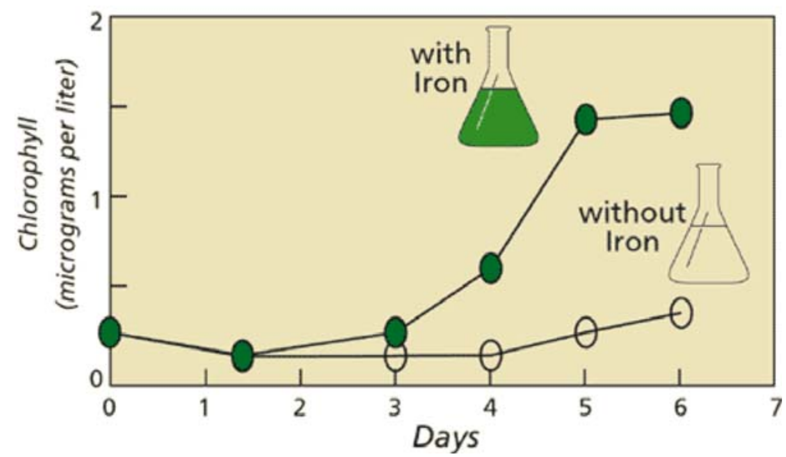
- -low iron
- -available macronutrients

Major iron sources

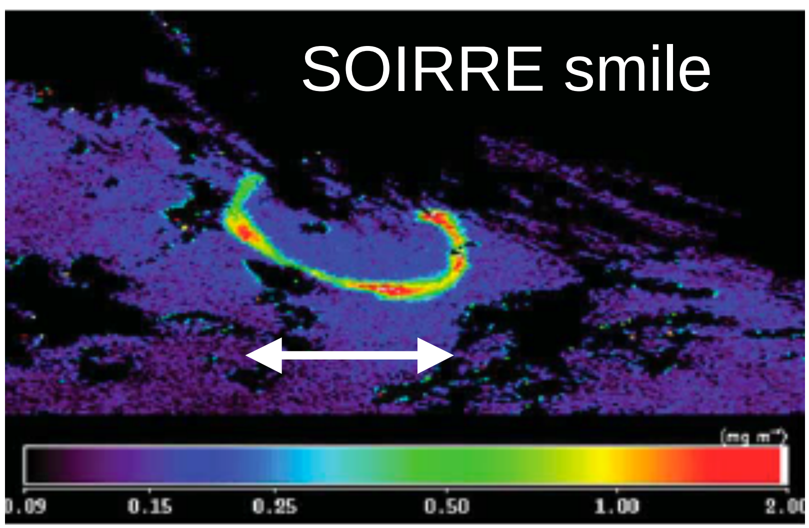
- -atmospheric dust transported via the atmosphere
- -continental shelf sediments

Iron Fertilization





- Efficacy & C storage time
- Verification & additionality
- Other greenhouse gases
- Ecological consequences, low oxygen zones, ...
- Legal, economic & political framework



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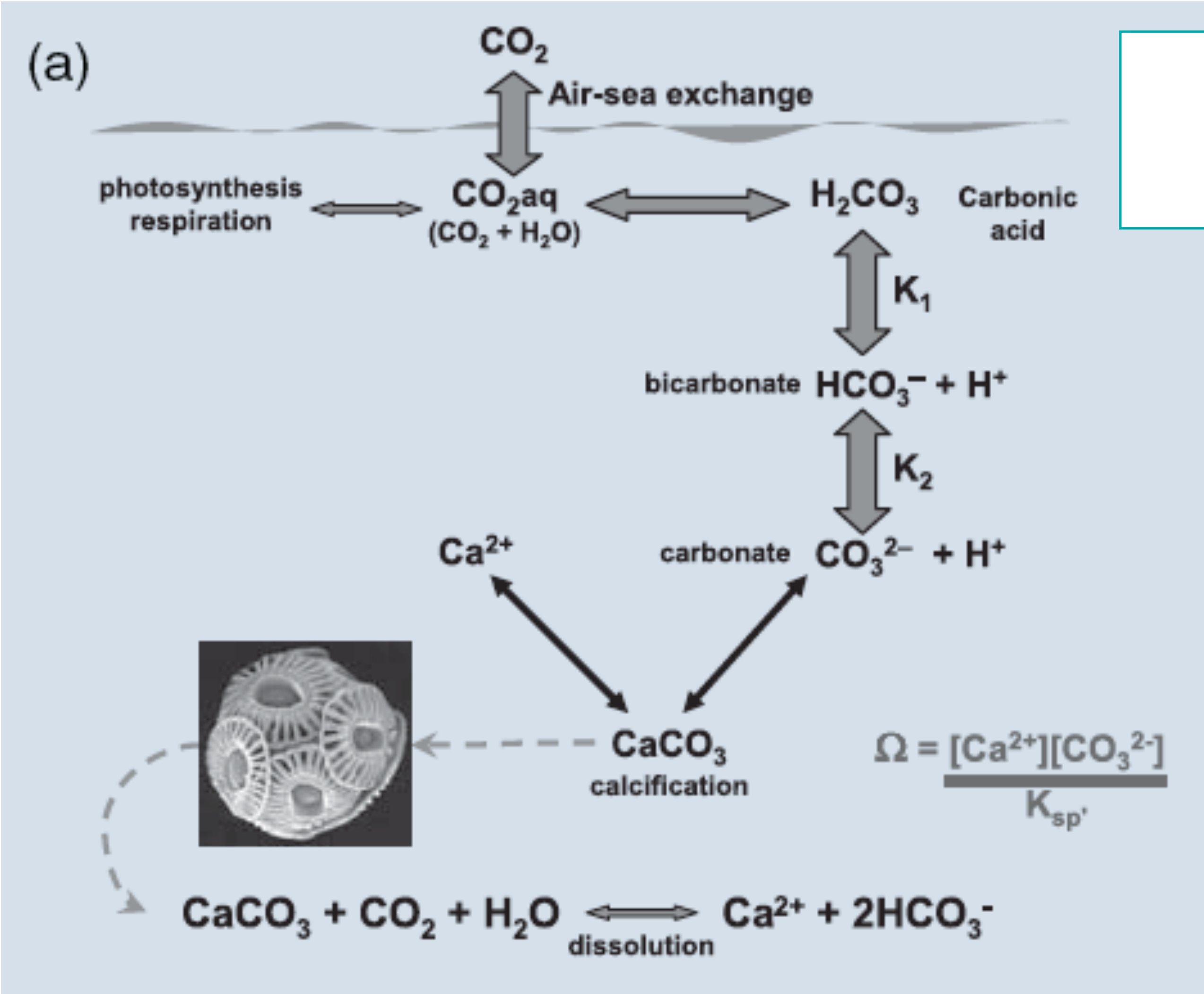
  – Air-sea flux of CO_2
- The Pumps
  – Solution, Sinking Carbon & $CaCO_3$
  – Anthropogenic CO_2 inventory
- Future Oceans
  – Trends & Predictions
  – Acidification
  – Fe limitations (Tony will talk about this more)

Where Are We Going?

- We are still discovering…
  - Just learning who the players are (ex. *Archea*)
  - The genomics revolution (who, what & function)
  - Trace nutrients & their bioavailability
- Feedbacks
  - Sulfur cycle & atmospheric chemistry
  - Acidification & food web dynamics
  - Implications for higher trophic levels???
- Future…
  - More anthropogenic CO_2 will end up in the sea


Thank You!!

More Seawater Chemistry



Increasing CO_2:

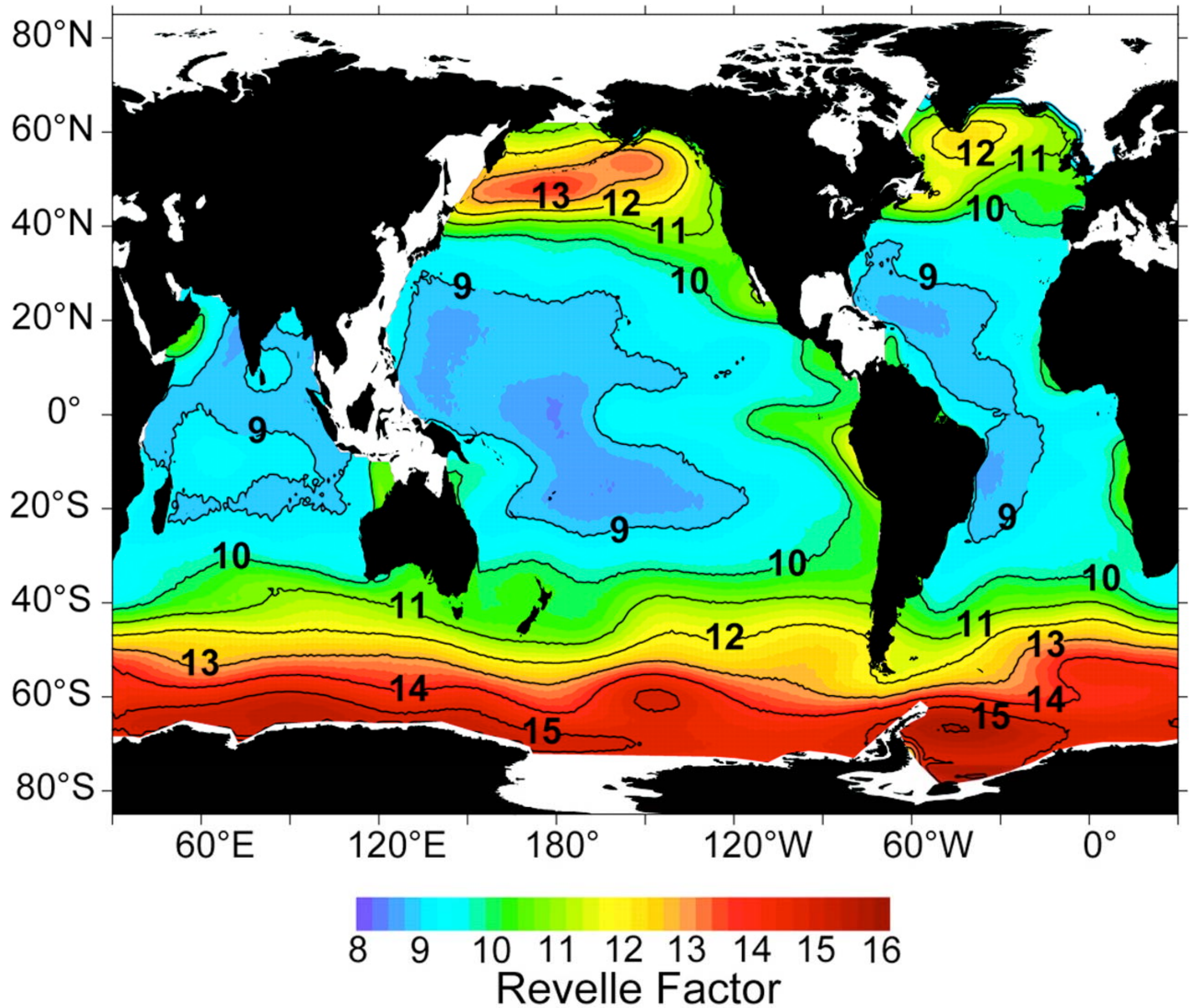
- Increases acidity (lowers pH)
- Lowers $CaCO_3(s)$ saturation state "Ω"

Multiple forms of $CaCO_3$: aragonite, calcite, Mg-calcite with different

$$\Omega = [Ca^{2+}][CO_3^{2-}] / K_{sp}$$

$$\Delta[CO_3^{2-}] = [CO_3^{2-}]_{obs} - [CO_3^{2-}]_{sat}$$

Revelle Factor



- High Revelle factor corresponds to low buffering capacity

Sabine et al. *Science* [2004]

Response of ocean ecosystems to climate warming

J. L. Sarmiento,[1] R. Slater,[1] R. Barber,[2] L. Bopp,[3] S. C. Doney,[4] A. C. Hirst,[5] J. Kleypas,[6] R. Matear,[7] U. Mikolajewicz,[8] P. Monfray,[3] V. Soldatov,[9] S. A. Spall,[10] and R. Stouffer[11]

GLOBAL BIOGEOCHEMICAL CYCLES, VOL. 18, GB3003, doi:10.1029/2003GB002134, 2004

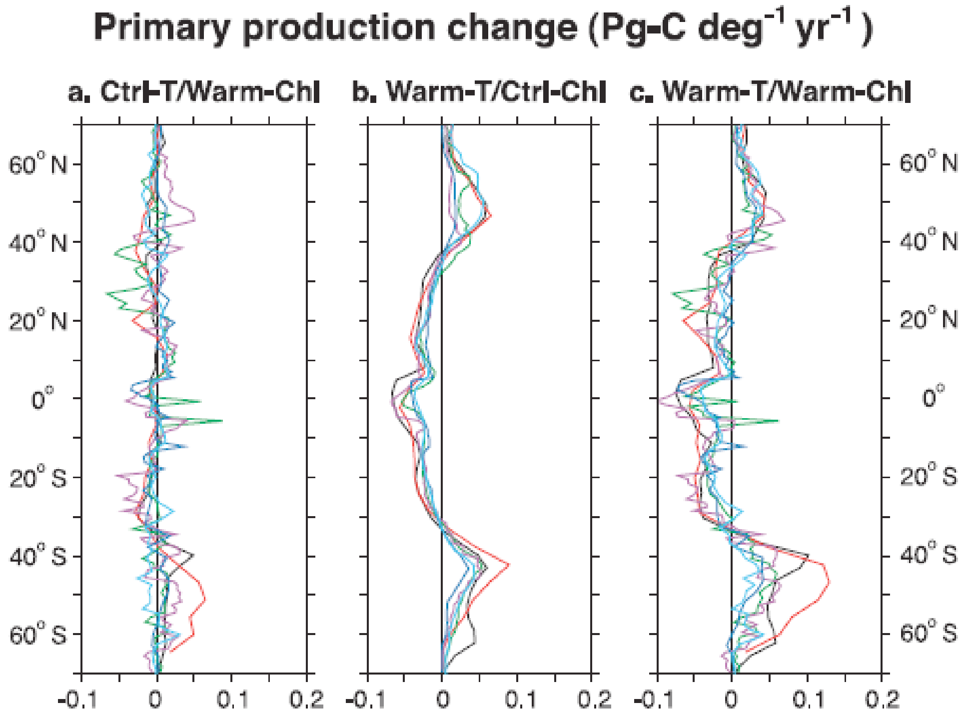


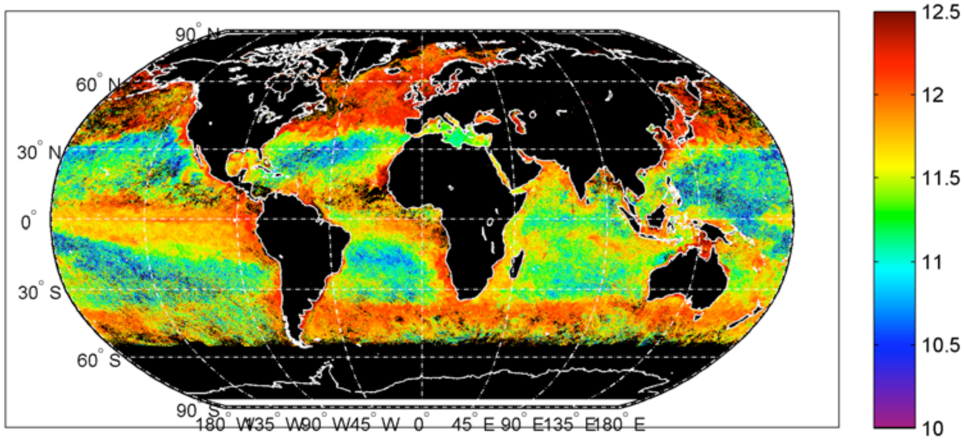
Figure 10. Zonally integrated response of primary production calculated with the *Behrenfeld and Falkowski* [1997] algorithm using chlorophyll calculated from the empirical model (equation (2)). The figure shows the difference between the warming and the control simulation for each of the six AOGCMs averaged over the period 2040 to 2060 (except for MPI, which is for the period 2040 to 2049). (a) The increase in primary production that occurs in response to the chlorophyll change only, with temperature kept constant at the control scenario. (b) The increase in primary production that occurs in response to the temperature increase only, with chlorophyll kept constant at the control scenario. (c) The increase in primary production that occurs in response to the combined effect of the chlorophyll change and temperature increase. See color version of this figure at back of this issue.

Tidbits

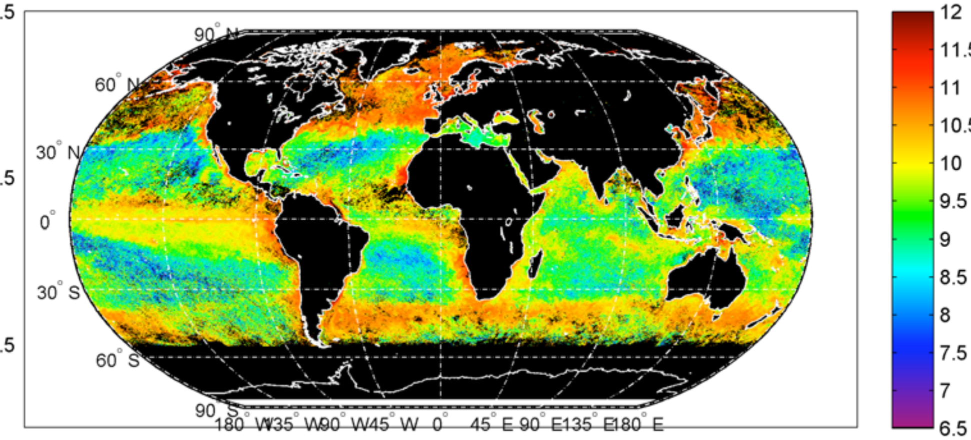
- Six different coupled climate models
- Ocean biological responses to climate warming from industrial revolution to 2050
- Marginal sea-ice biome area decreases 42% (N) and 17% (S)
- Expansion of low production permanently stratified ocean by 4% (N) to 9.4% (S)
- Subpolar gyre biome expands 16% (N) and 7% (S)
- Stratification decreases nutrient supply and thus productivity in permanently stratified oceans
- Stratification, extended growing season, and sea ice retreat enhance production at high latitudes
- Significant shifts in community composition

Partitioning Number Concentration

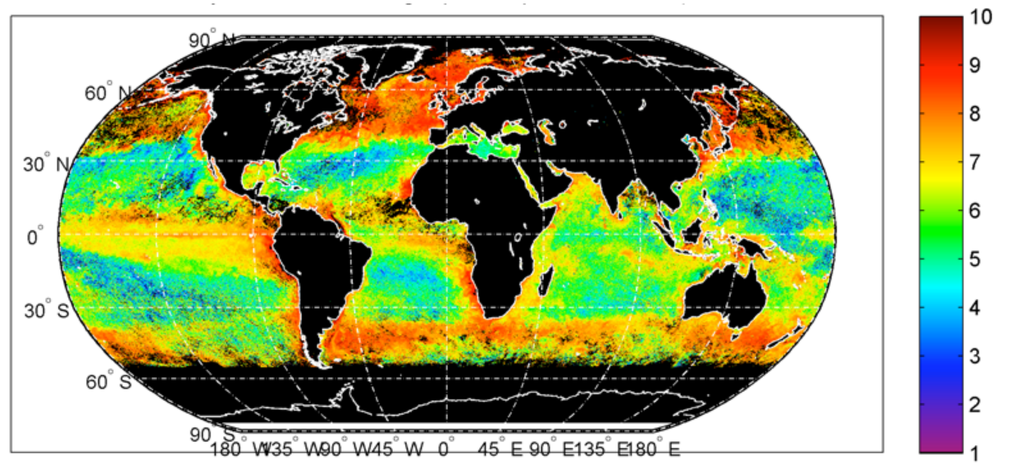
Picoplankton, # m^{-3} (0.5 μm to 2 mm)



Nanoplankton, # m^{-3} (2 μm to 20 μm)



Microplankton, # m^{-3} (20 μm to 30 μm)



Pico's vary ~100 times

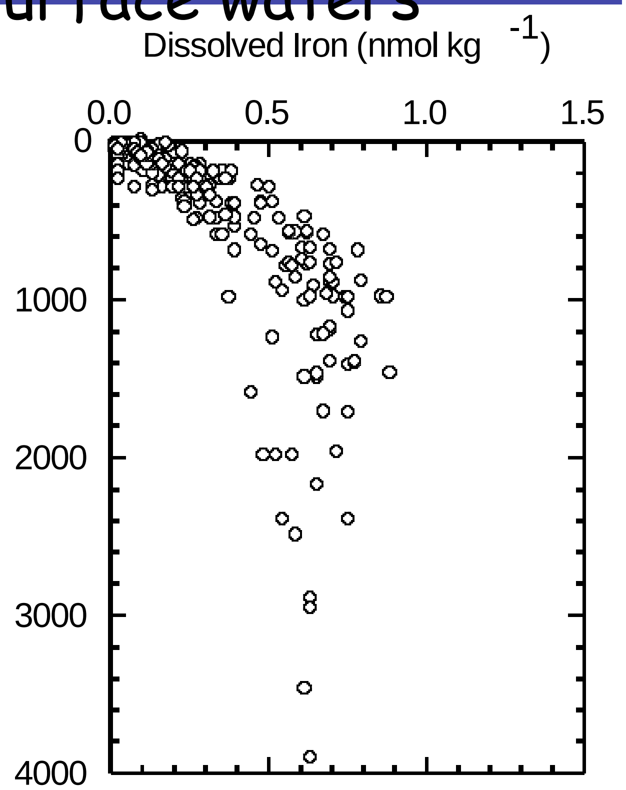
Nano's vary ~ 10,000 times

Micro's vary ~ 10^6 times

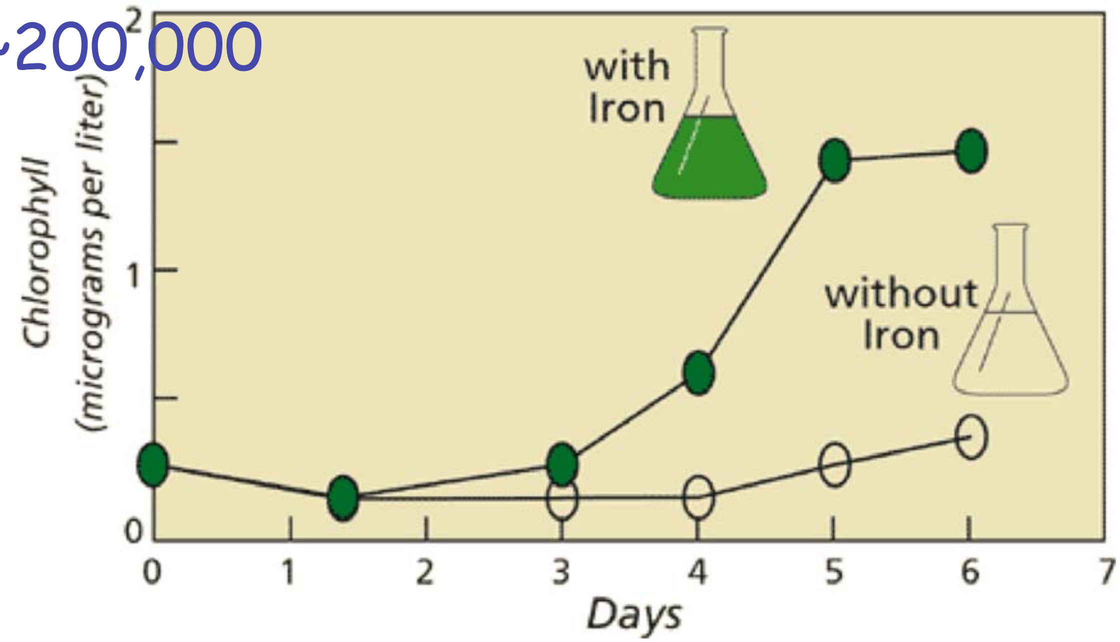
log10(particles/m^3)

Iron Fertilization History

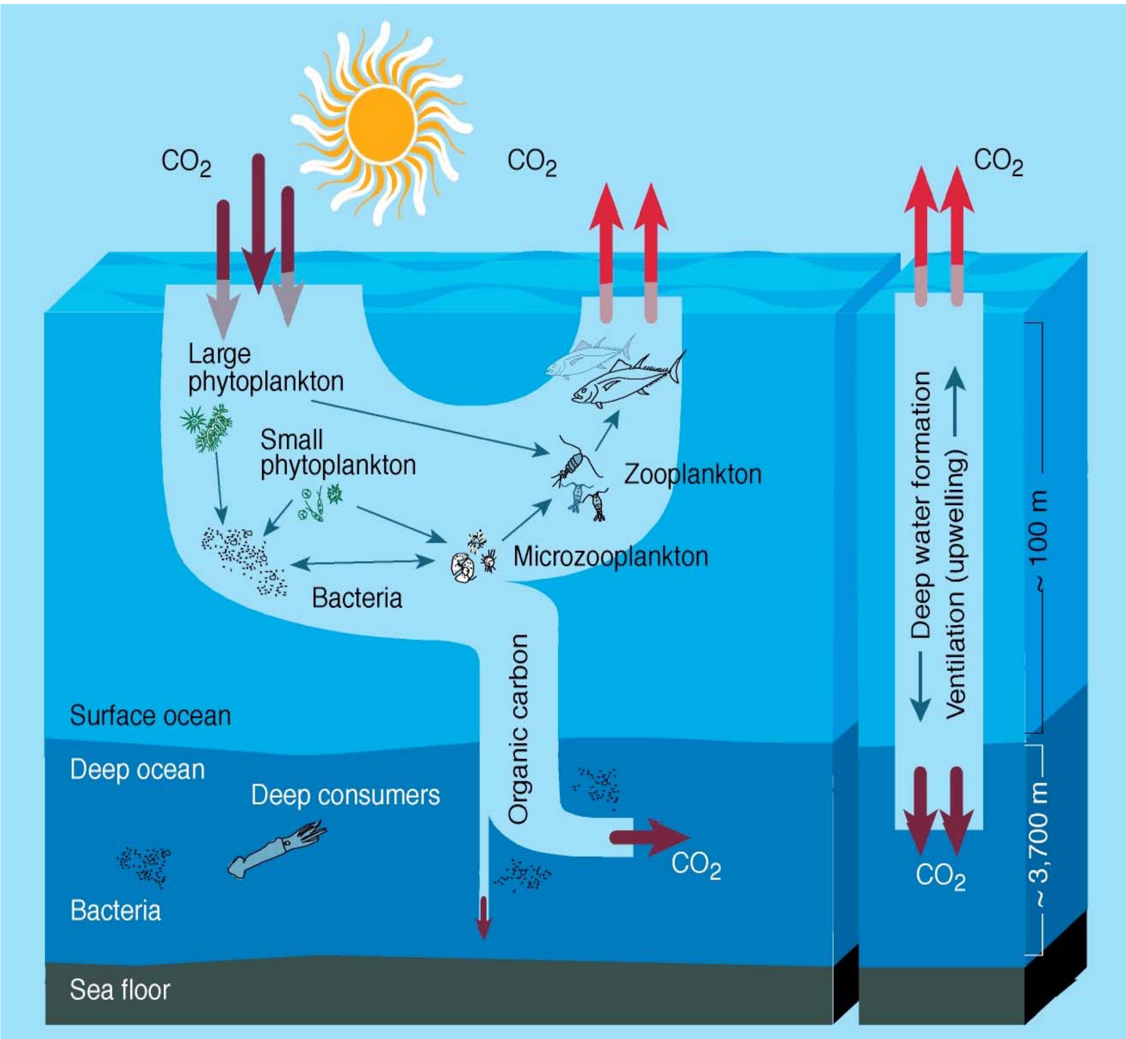
Late 80's- Iron conc. shown to be very low in many surface waters



Adding iron can stimulate phytoplankton growth in these waters plankton carbon/iron ratio ~200,000



Ocean Biological Pump



Food web processes transfer organic matter to depth

-pathway for rapid C sequestration

Quickly remove C from surface ocean & atmosphere

-turn off bio pump and 200 ppmv increase atm. CO_2