The Abdus Salam
International Centre for Theoretical Physics

United Nations
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IAEA
International Atomic Energy Agency

2066-2

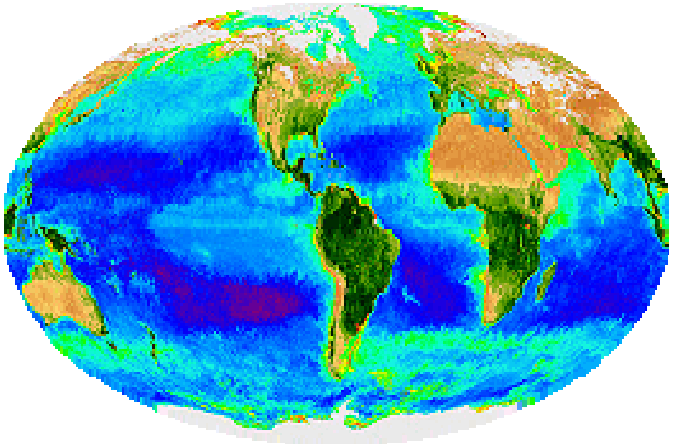
Workshop and Conference on Biogeochemical Impacts of Climate and Land-Use Changes on Marine Ecosystems

2 - 10 November 2009

Phytoplankton and climate change

J.R. Moisan

NASA
U.S.A.



Phytoplankton and Climate Change

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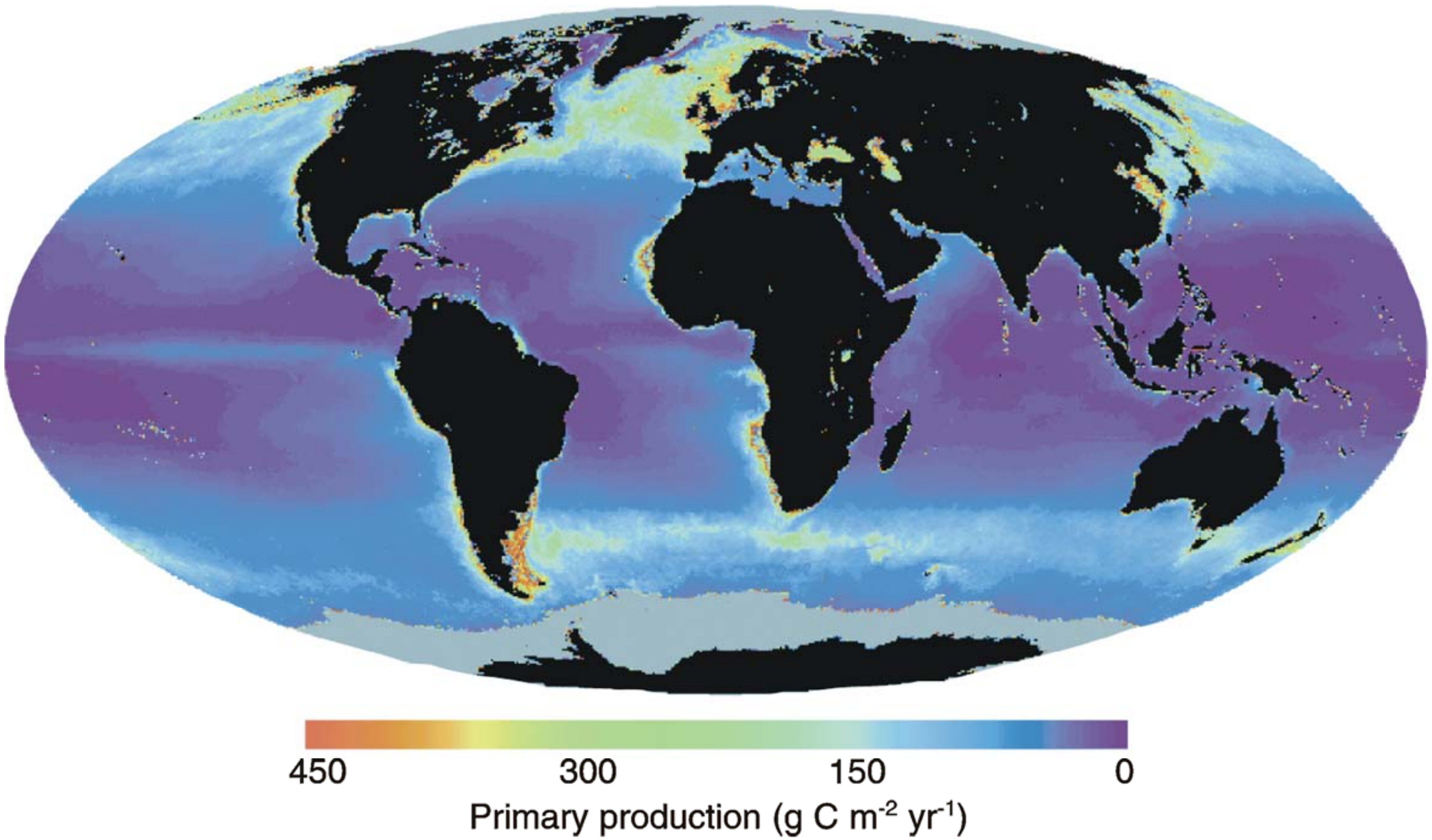
Meditation Time

- Long term meditation for 15 minutes a day can increase your ability to actively focus your brain
  - Similar to a cup of coffee
- Children life in the 'now.'
- Breathing is the first thing to learn in meditation

Breathe in……..Breathe out........

Breathe in……..Breathe out........

Phytoplankton make half of oxygen that you use!!!



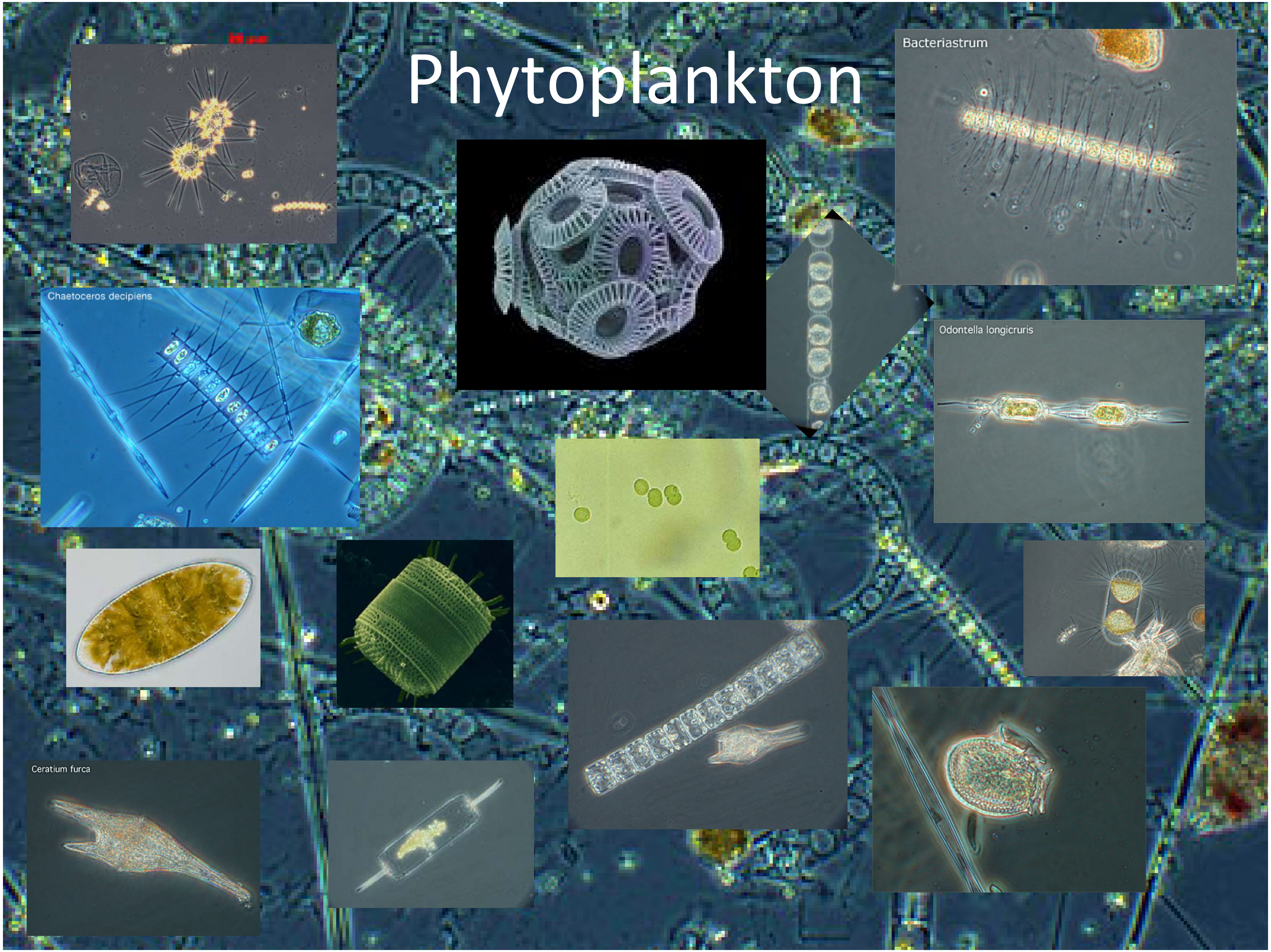
Annual mean

The ocean on earth is like water on a wet football/basketball

Overview

- Phytoplankton
  - Composition, Size Classes, Cellular Processes
  - Functional Types
  - Influence on Climate Processes
    - Ocean Heating, Atmospheric Gases, Clouds
- Climate Change
  - Primary Production/Biomass
  - Species Diversity
  - Succession

Phytoplankton



Worldwide Photoautotroph Species

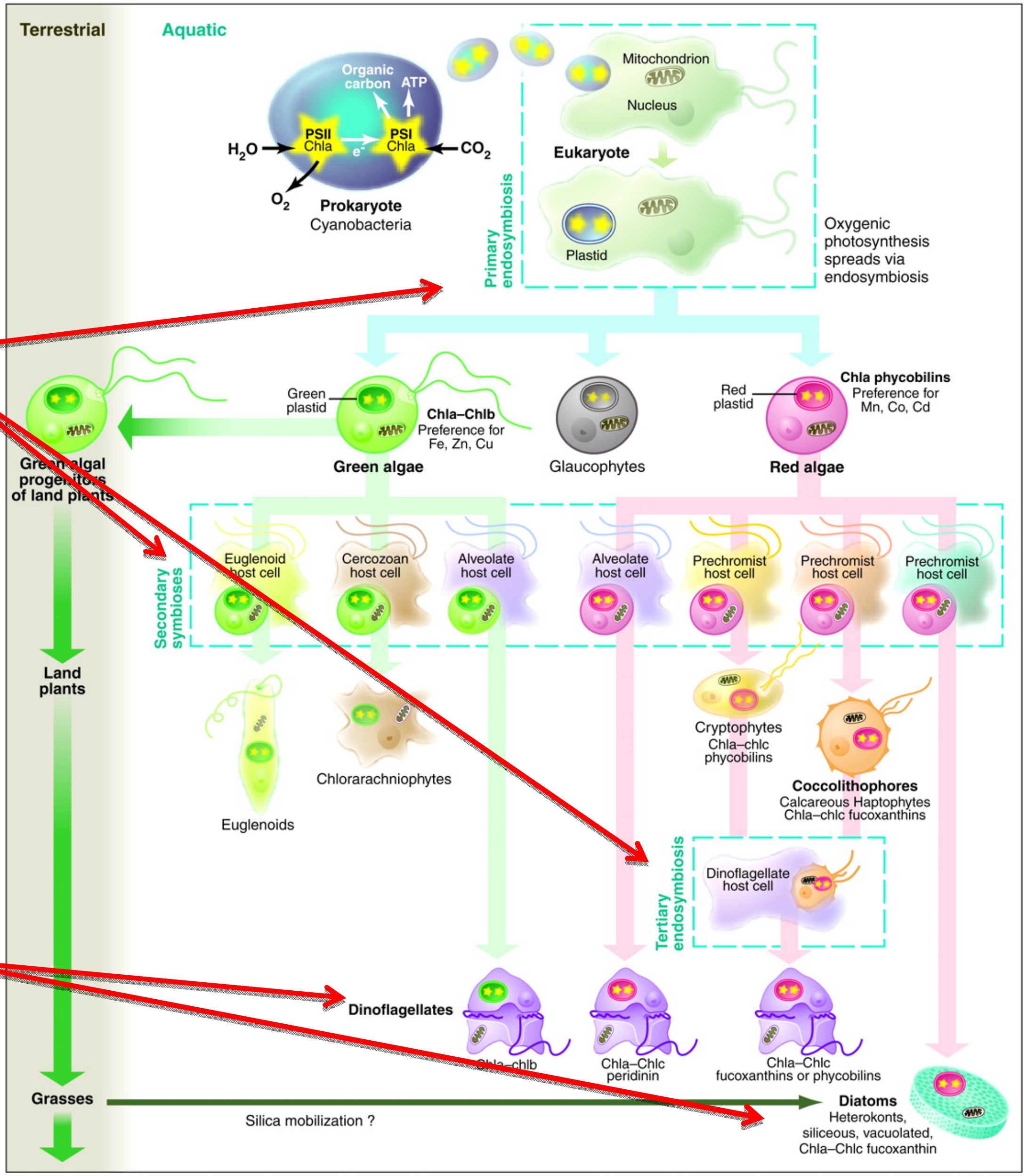
- Bacteria: Cyanobacteria: **150**/1350 spp. [Synechococcus/Prochlorococcus/Trichodesmium]
- DiscicristataEuglenophyta: **30**/1020 spp.
- AlveolataDinoflagellata: **200**/1800 spp. [Dinoflagellates]
- PlantaeEmbryophyta: 272,000 spp. (99% terrestrial)
  Glaucocystophyta: **0**/13 spp.
  Rhodophyta: **6500**/200 spp.
  Chlorophyceae: **100**/2400 spp. [Dunaliellasp.]
  Prasinophyceae: **100**/20 spp. [Prasinophytes: Micromonis sp., picoplankton]
  Ulvophyceae: **1000**/100 spp.
  Charophyceae: **5**/3395 spp.
- CercozoaChlorarachniophyta: **4**/0 spp.
- ChromistaCryptophyta: **100**/100 spp. [Cryptomonads]
  Prymnesiophyta/Haptophytes: **480**/20 spp. [Coccolithophorids&Phaeocystis]
  Bacillariophyta: **5000**/5000 spp. [Diatoms]
  Chrysophyta: **800**/200 spp.
  Dictochophyceae: **2**/0 spp.
  Eustigmatophyceae: **6**/6 spp.
  Phaeophyta: **1497**/3 spp.
  Raphidophyceae: **10**/17 spp.
  Synurophyceae: **0**/250 spp.
  Xanthophyceae (Tribophyceae): **50**/500 spp.
- Symbiotic Fungi Lichens: 13000 spp., 97% terrestrial

Falkowski et al., 2005

The basic pattern of the inheritance of plastids in eukaryotic phytoplankton

3 levels of endosymbiotic engagement

Diatoms and Dinoflagellates are late-comers



Published by AAAS

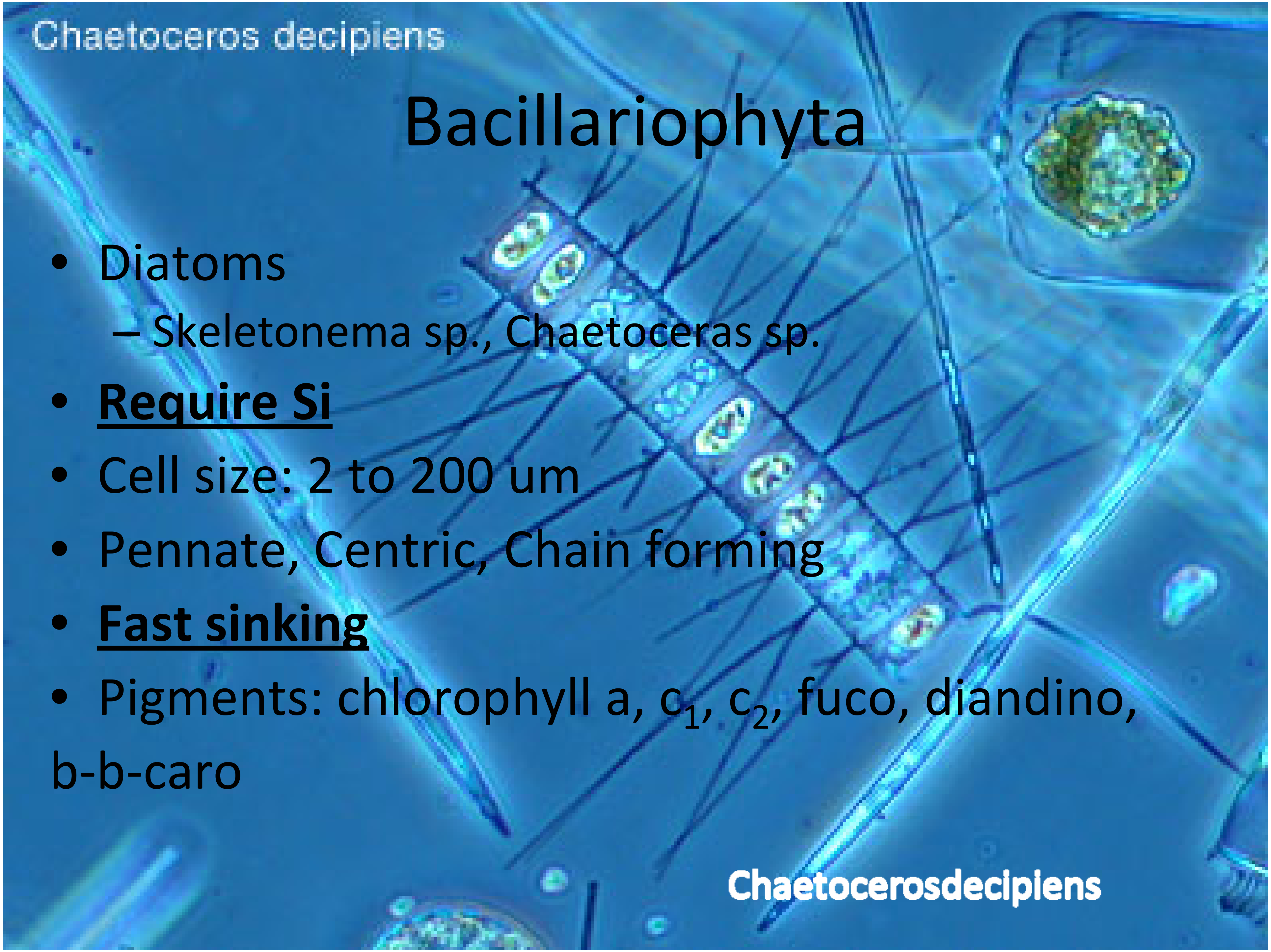
P. G. Falkowski et al., Science 305, 354 -360 (2004)

Science AAAS

Phytoplankton

- Worldwide about 5000 species
- Prokaryotic vs eukaryotic
- Cell size classification
- Pigment differentiation
- Functional types
- Light and nutrient requirements
- Obligate autotrophsvsmixotrophic

Phytoplankton Classes/Functional Types



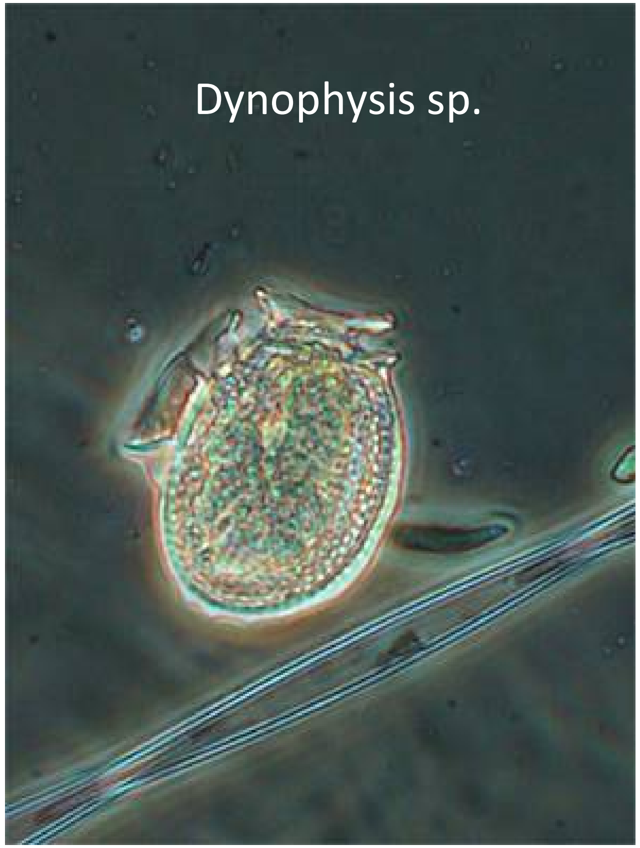
Bacillariophyta

- Diatoms
  - Skeletonema sp., Chaetoceras sp.
- **Require Si**
- Cell size: 2 to 200 um
- Pennate, Centric, Chain forming
- **Fast sinking**
- Pigments: chlorophyll a, c_1, c_2, fuco, diandino,

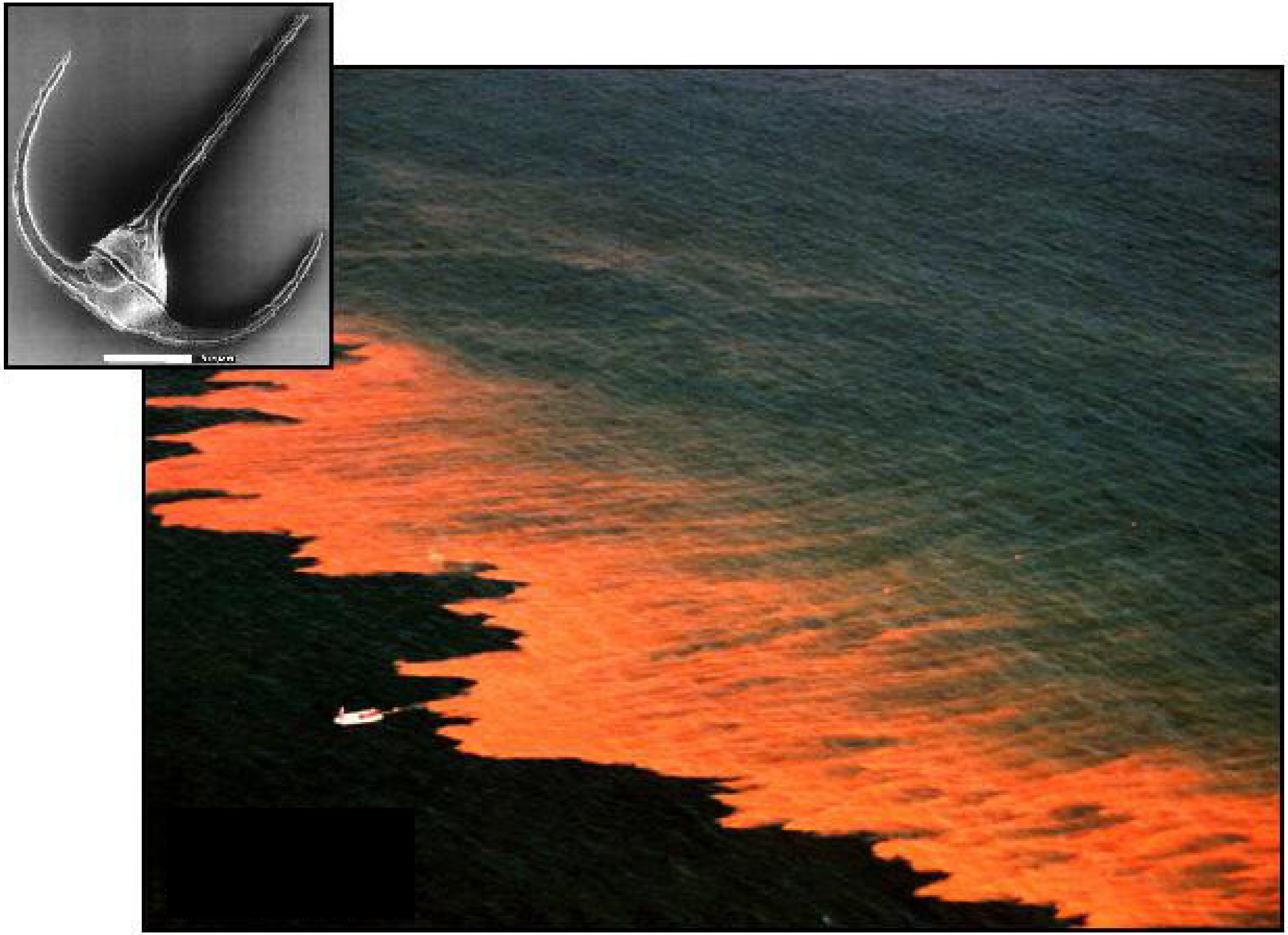
b-b-caro

Dinophyceae

- Dinoflagellates
  - Amphidium sp., Gymnodinium sp.
- Cell Size: 10—200 um
- **Vertical migrators**
- **Sensitive to turbulence**
- Pigments: chlorophyll a, c_2, peridinin, dino, diadino, peridinin
- Some species are toxic (red tides)
- **Complex life cycles (cysts)**
- Not all are phototrophs
  - **mixotrophic and heterotrophic**



Red Tide (non-toxic) Bloom off SIO

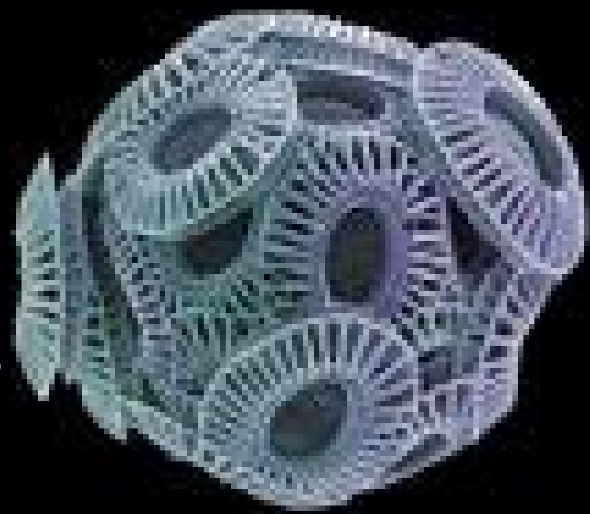


Prymnesiophyceae (Type I)

- Haptophyte: Phaeocystis sp.
- Pigments: Chlorophyll a, c, 19'but, 19'hex, fuco, diadino, carotenoids
- **Complex Life Strategy**
  - small single celled vsmuch larger colonial
- **Produce DMS**
  - cloud nucleation gas

Prymnesiophyceae (Type II)

- Coccolithophores
  - Emiliana sp.
- Produce calcareous plates
  - Carbon cycle importance
- Highly scattering
  - Heat Budget/Radiance Field
- Pigments: Chlorophyll a, c3, 19-hex



Coccolithophorid Bloom in the North Sea

Springer-Verlag Berlin Heidelberg 2005

Cyanophyta

- Cyanobacteria (blue-green algae)
  - Synechococcus sp.
  - Trichodesmium sp.
  - Microcystis sp.
- Size: 0.5—2.0 um
- Some capable of **<u>nitrogen fixation</u>**
- Pigments: Chlorophyll a, caro, Zeazanthin, phycocyanin, phycoerythrin

Prochlorophyta

- Prochlorococcus sp.
- Pigments: Chlorophyll a, DV a, DV b, caro,

zea, phycocyanin, phycoerythrin

- Cell Size: 0.4—0.8 um (**very small**)
- 1988 Sallie (Penny) Chisholm isolated Prochlorococcus (0.6 um)
- Prochlorococcus is thought to be the most abundant photosynthetic organism on Earth and may account for **20%** of global Oxygen production
  - (remember: breath in…..breath out).

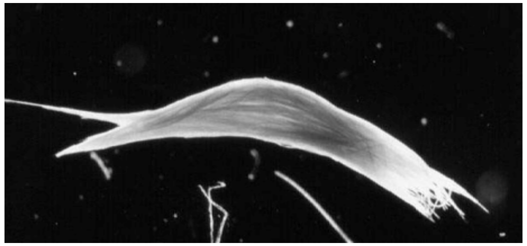
Chlorophyceae

- Chlorophytes: Dunaliella sp.
  - Dunaliella sp. is the “Lab Rat” of phytoplankton physiologists
- Pigments: Chlorophyll a, b, caro, lut, neo, viola, zea
- Cell Size: 1—40 um

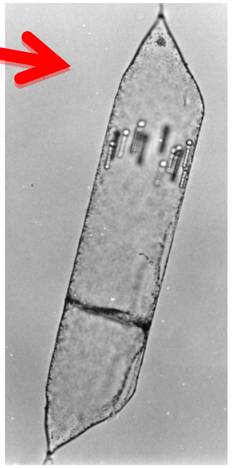
Cryptophyta

- Cryptomonads:
  - Chroomonas sp., Rhodomonas sp.
- Pigments: Chlorophyll a, c2,caro, allo, phycocyanan, phycoerythrin
- Cell Size: **picoplankton**

Diazotrophs and Nitrogen Fixation



- Fixation of N_2 by nitrogenase
- Inhibited by oxygen or presence of fixed nitrogen
- CyanobacteriaTrichodesmium
- Diatom Rhizosolenia (with Richeliaintracellularis)
- Need for Organic N reduced but need for Fe and P remains!
- Vertical migration and dust events



Zehr et al., 2000

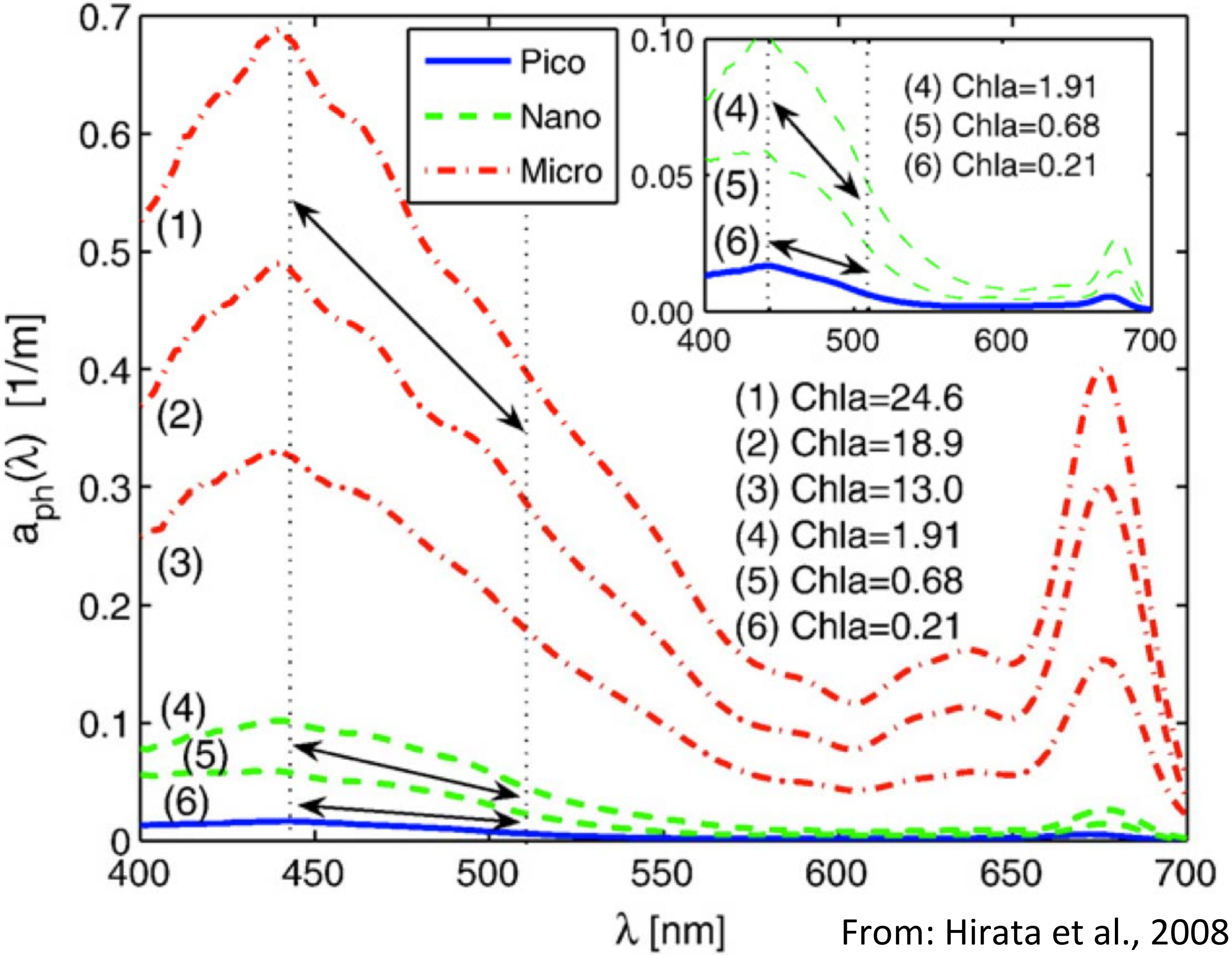
Plankton Size Distribution

- Megaplankton: >20 mm
  - Mesozoans: jellyfish, ctenophores, salps, pelagic Tunicates, cephalopods
- Macroplankton: 2 mm to 20 mm
  - Medusae: copepods, ctenophores, Pteropods, Tunicates, Heteropods
- Mesoplankton: 0.2 mm to 2 mm
  - Copepods, Cladocera, Ostracoda, Chaetognaths
- Microplankton: 20 um to 200 um
  - Most phytoplankton, protozoa, large eukaryotic protists, Foraminifera, ciliates, copeopodnauplii,
- Nannoplankton: 2 um to 20 um
  - small eukaryotic protists, small diatoms, small flagellates, Chrysophyta, Chlorophyta, Xanthophyta
- Picoplankton: 0.2 to 2 um
  - Small eukaryotic protists; bacteria; Chrysophyta
- Femtoplankton: < 0.2 um
  - Marine Viruses

Why is size important?

- Influences trophic structure
  - Most smaller zooplankton can’t eat larger phytoplankton
- Radiative Transfer/bio-optical consequences
  - Larger cell scatter backwards more than smaller cells
- Sinking rates
  - Big cells sink faster
- Pigment Packaging
- Nutrient Uptake
  - Surface to volume ratios

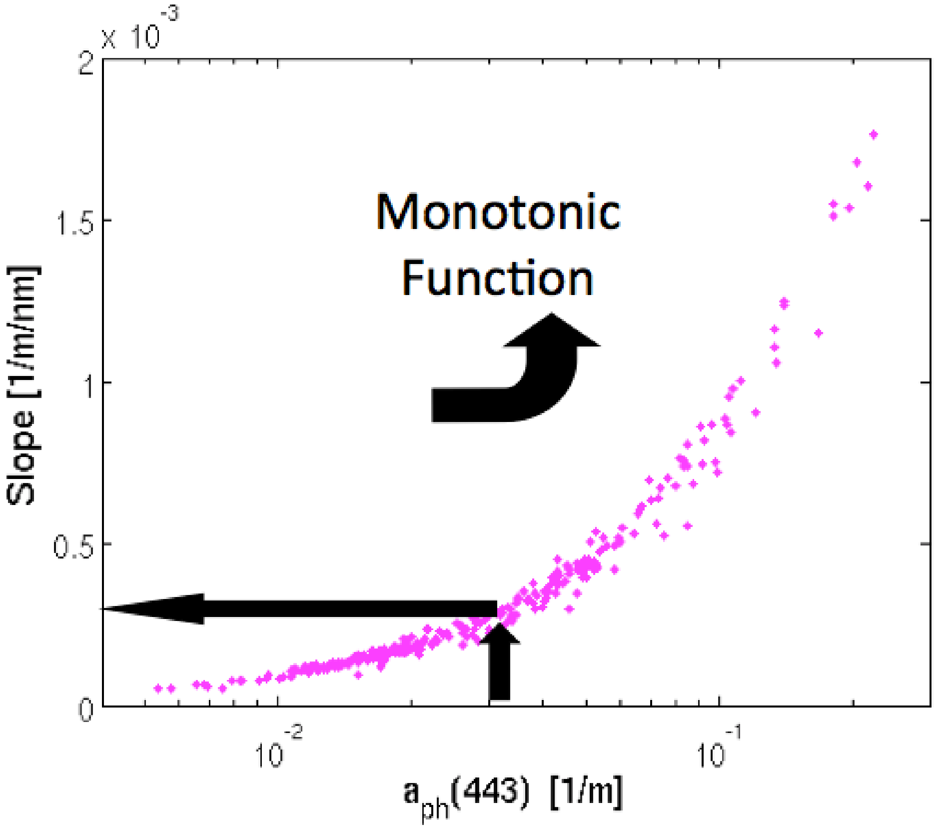
Determining Phytoplankton Size from Space

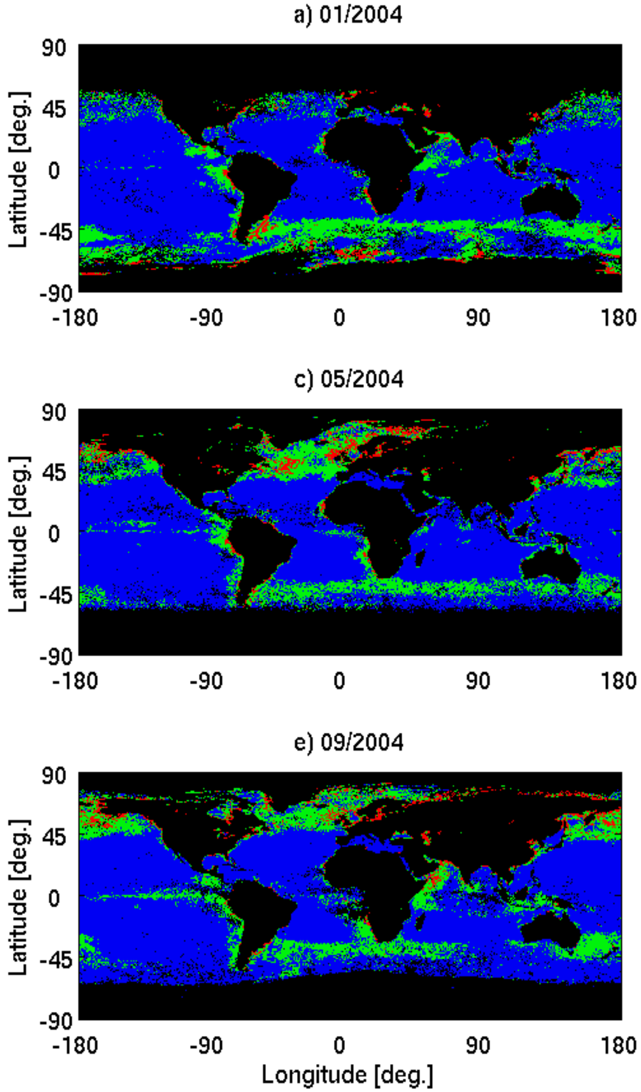


From: Hirata et al., 2008

Dominant size class

Blue: Pico, Green: Nano, Red: Micro

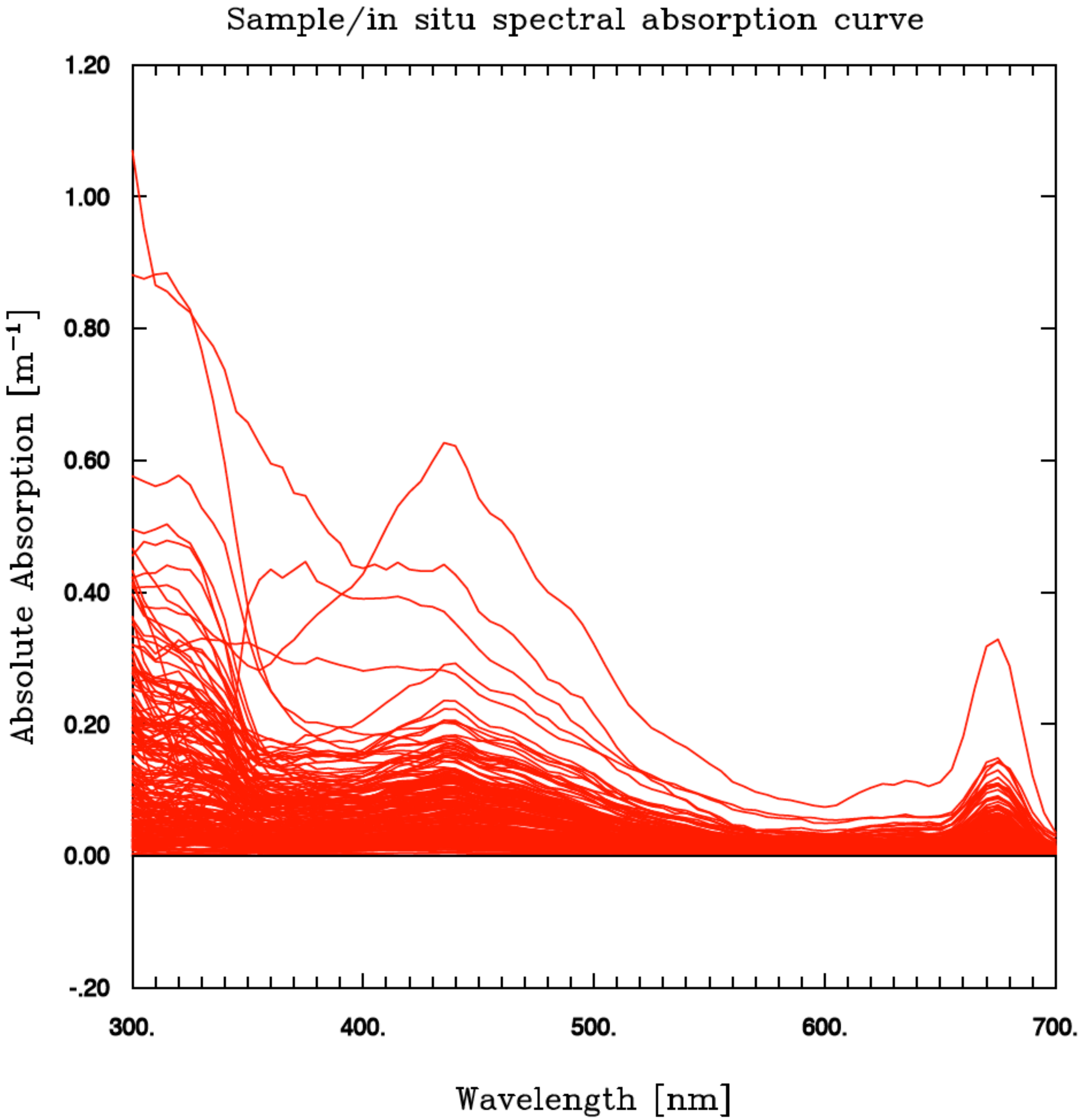




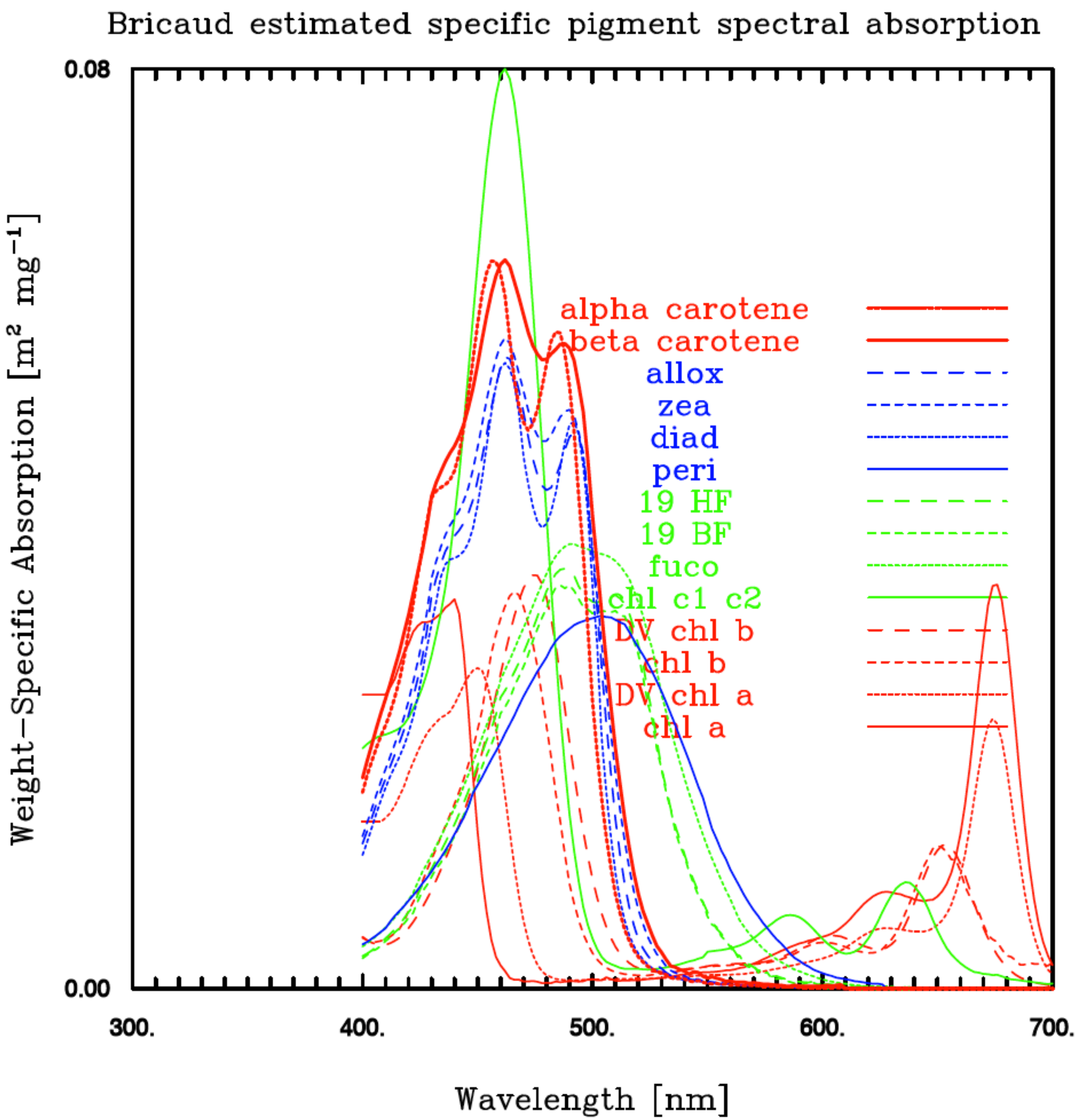
Magnitude of $a_{ph}(443)$ uniquely identifies the absorption slope

Hirata et al., Rem. Sens. Environ., 2008

Phytoplankton Pigment Absorption Spectra



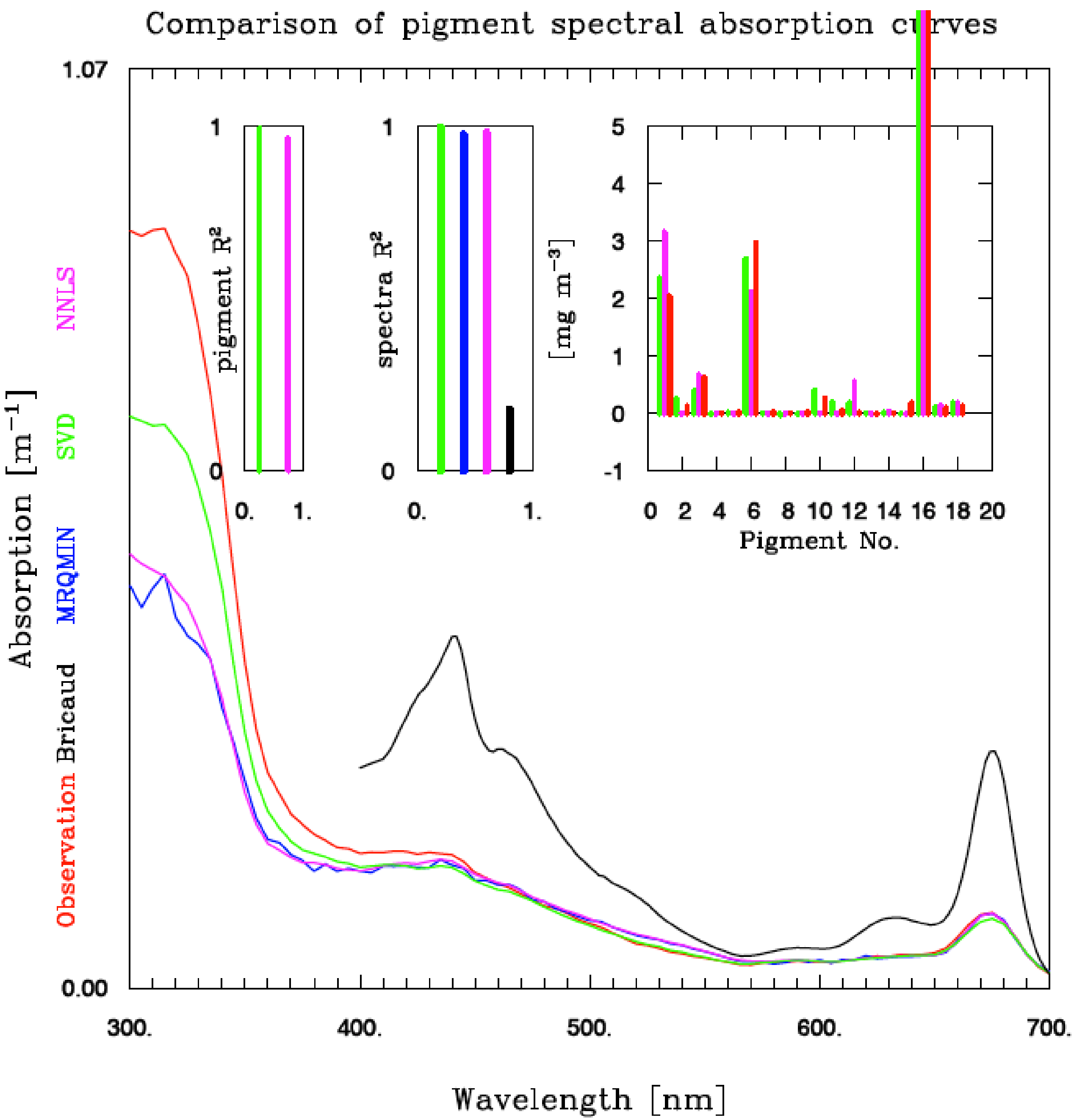
Pigment-specific absorption spectra



Distribution of pigments in algal classes

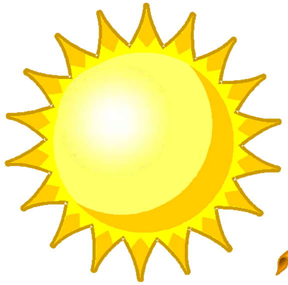
	Chlorophylls										Xanthophylls													
	chl a	chl b	chl c1	chl c2	chl c3	MgDVP	DV a	DV b	β,ε – car	β,β – car	Allo	19 BF	Diadino	Dino	Fuco	19HF	Lut	Neo	Per	Pras	Viola	Zea	P/cyanin	P/erythrin
Cyanophyta	●									●												●	●	●
Prochlorophyta							●	●	●	●												●		
Rhodophyta	●								●													●	•	●
Cryptophyta	●			●					●		●												●	●
Chlorophyceae	●	●							•	●							●	●			●	•		
Prasinophyceae	●	●				●			•	●							•	●		●	●			
Euglenophyta	●	●								●			●					•						
Eustigmatophyta	●									●											●	•		
Bacillariophyta	●		●	●						•			●		●									
Dinophyta	●			●						•			●	●					●					
Prymnesiophyceae	●		●	●	●				•	•		●	●		●	●								
Chrysophyceae	●			●	●					•		●	●		●									
Raphidophyceae	●		●	●						●			●		●									

CSIRO
MARINE RESEARCH



Comparison of pigment spectral absorption curves
1.07
0.00
300.
400.
500.
600.
700.
Wavelength [nm]
Absorption [m^{-1}]
Observation Bricaud MRQMIN SVD NNLS
pigment R^2
spectra R^2
[mg m^{-3}]
Pigment No.

What Drives Change in the Climate System?



Earth's Heat Balance = Warming - Cooling

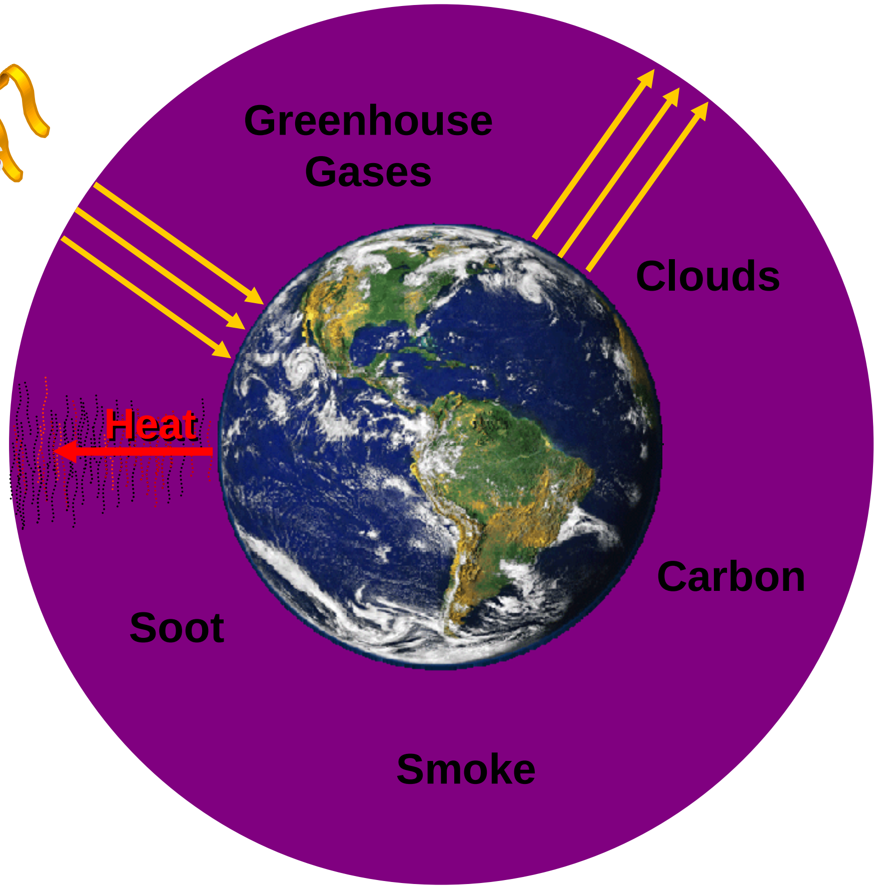
Warming:

Greenhouse gases

Absorbing aerosols

Greenhouse Gases
- •Carbon dioxide CO_2
- •Methane CH_4
- •Water Vapor H_2O
- •Nitrous Oxide N_2O
- •Chloroflorocarbons CFC's
- •Ozone O_3

Absorbing Aerosols
- •Smoke
- •Soot



Cooling:

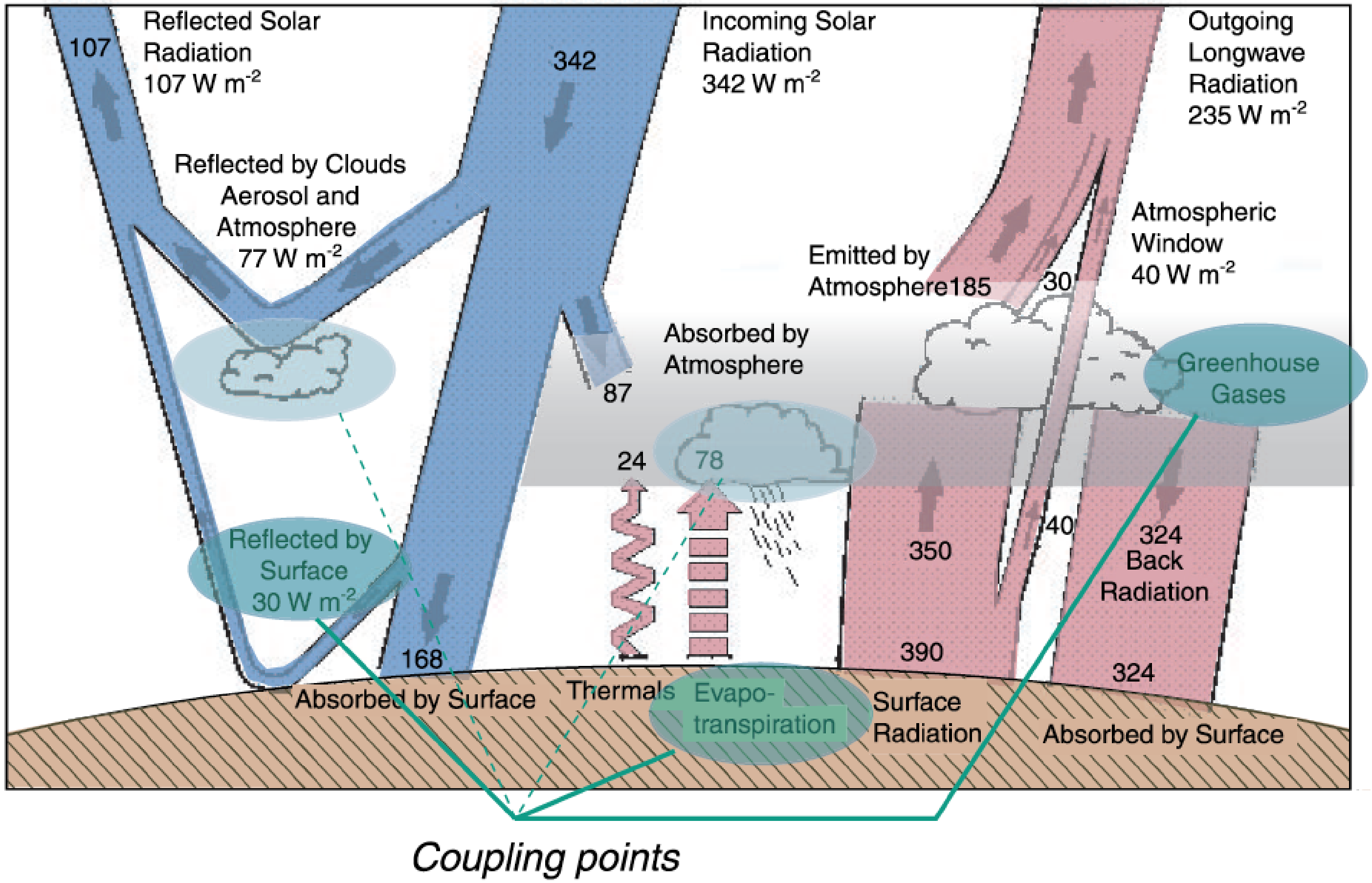
Reflective aerosols

Natural carbon sequestration

Reflective Aerosols
- •Impact on cloud formation
- •Dust
- •Volcanic aerosols SO_2

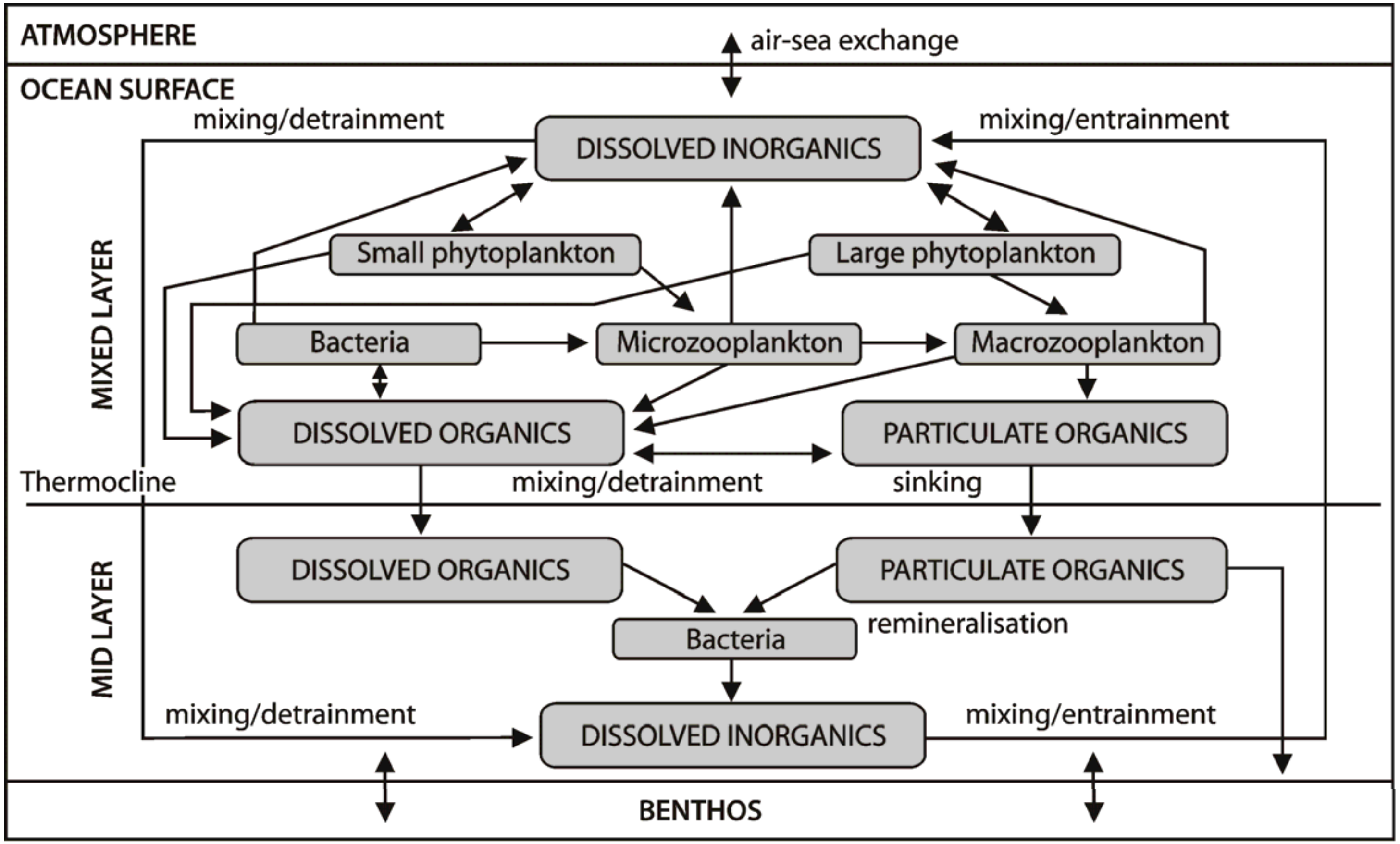
Natural carbon sequestration
- •Forests/Soils
- •Air-sea CO2 equilibrium
- •Ocean Biota

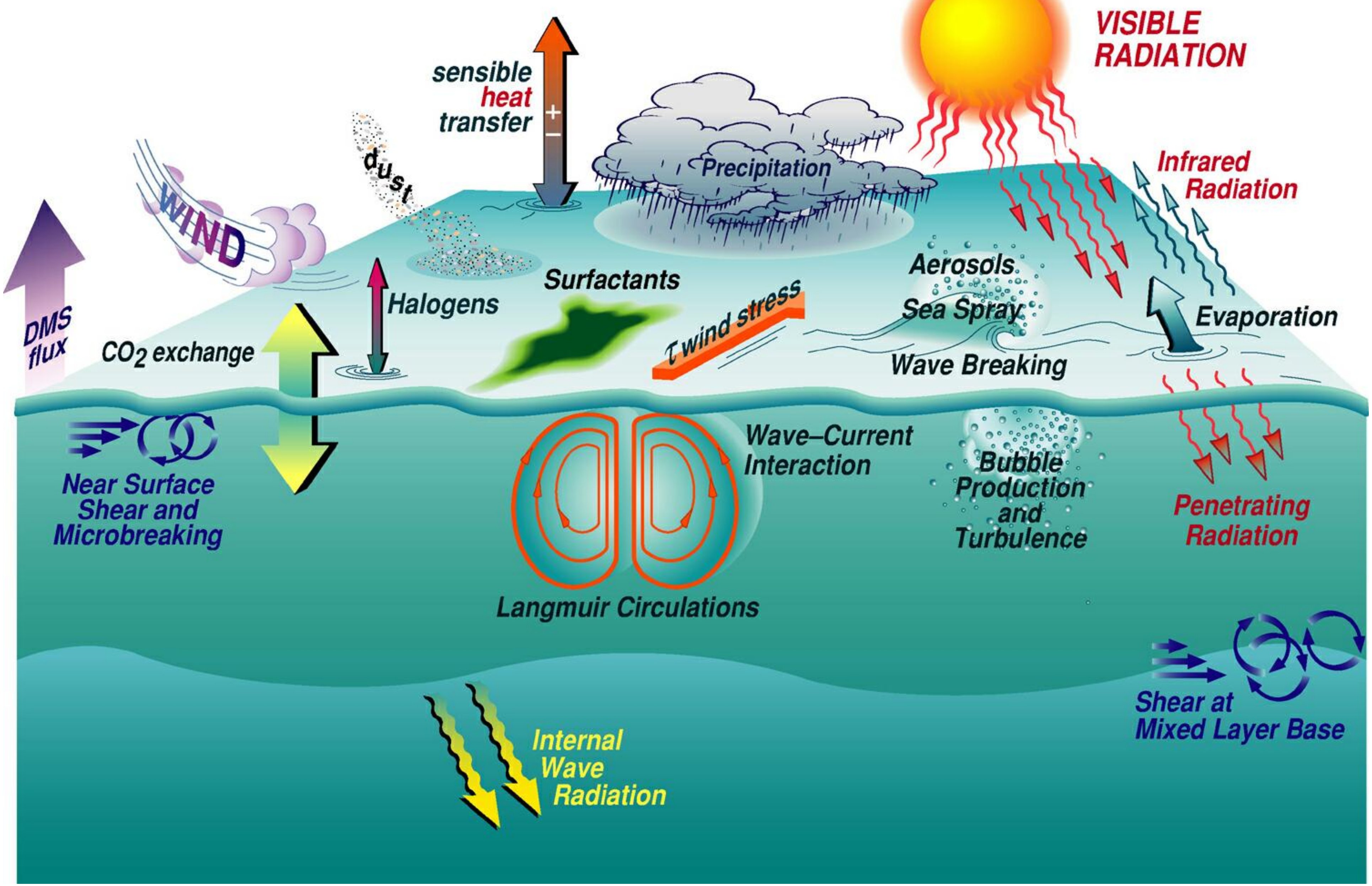
Global Energy Budget



adapted from Kiehl and Trenberth (1997)

Biological Pump Schematic



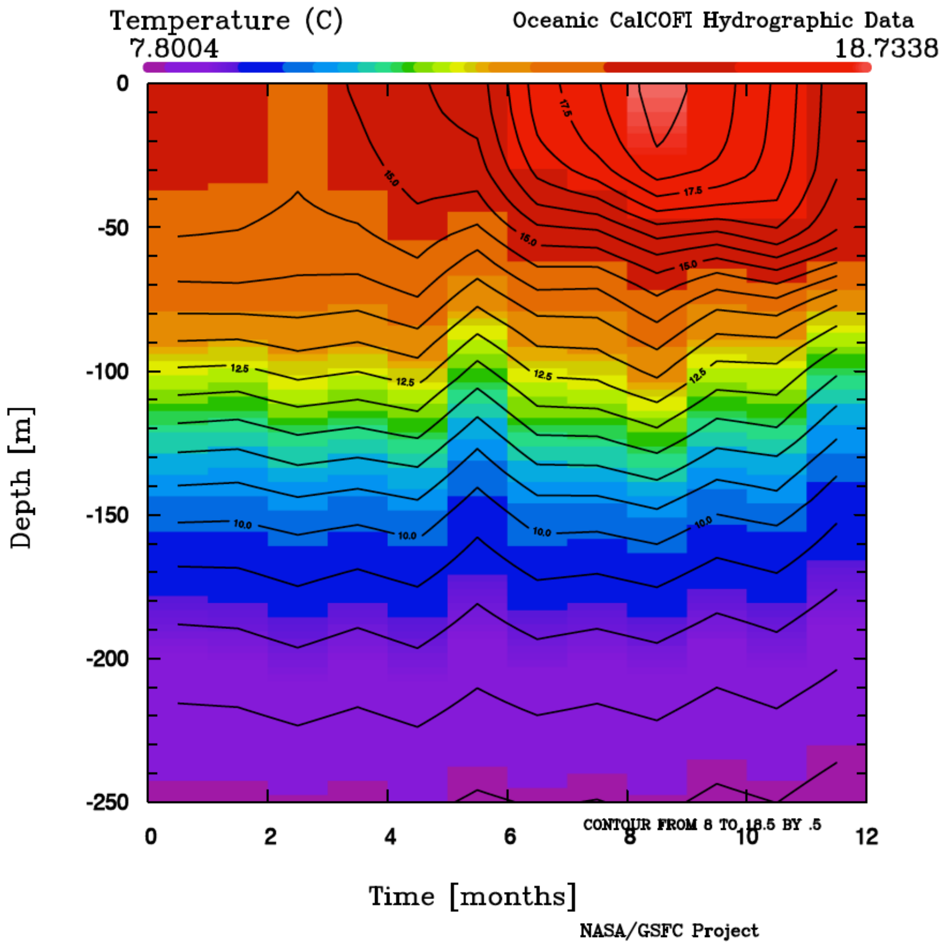

VISIBLE RADIATION
sensible heat transfer
+
–
dust
Precipitation
Infrared Radiation
WIND
DMS flux
Halogens
Surfactants
Aerosols
Sea Spray
Evaporation
τ wind stress
CO_2 exchange
Wave Breaking
Near Surface Shear and Microbreaking
Wave–Current Interaction
Bubble Production and Turbulence
Penetrating Radiation
Langmuir Circulations
Shear at Mixed Layer Base
Internal Wave Radiation

General Equation for Photosynthesis

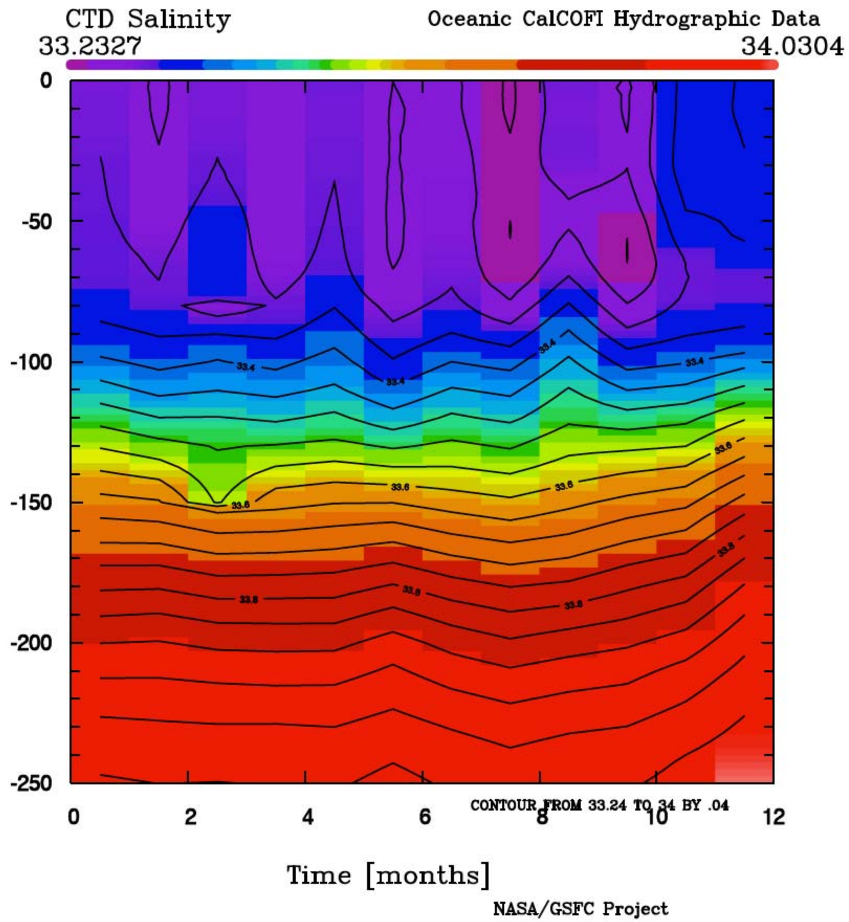
- $106\ CO_2 + 16\ H_2O + H_3PO_4 + 78\ H_2O \rightleftharpoons C_{106}H_{175}O_{42}N_{16}P + 105\ O_2$
- Redfield Equation
  - C:N:P ➔ 106:16:1
  - C:P ➔ 106:1
  - C:N ➔ 16:1

Oceanic Climatology

Temperature

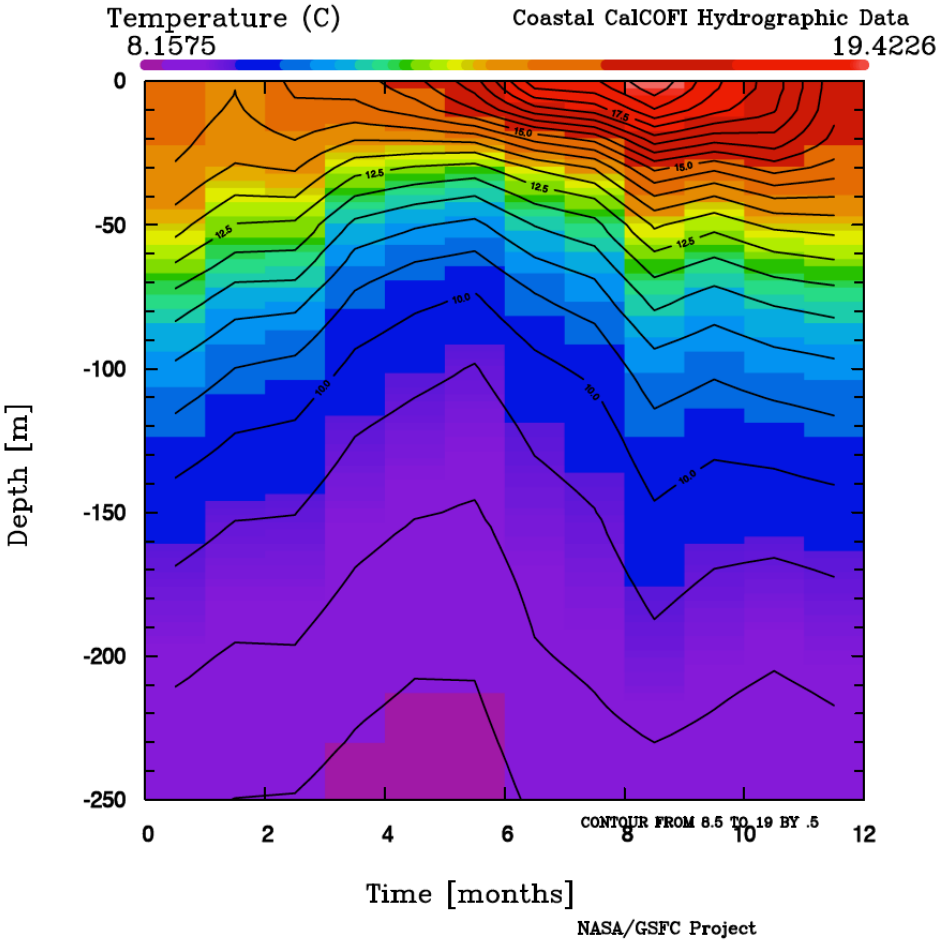


Salinity

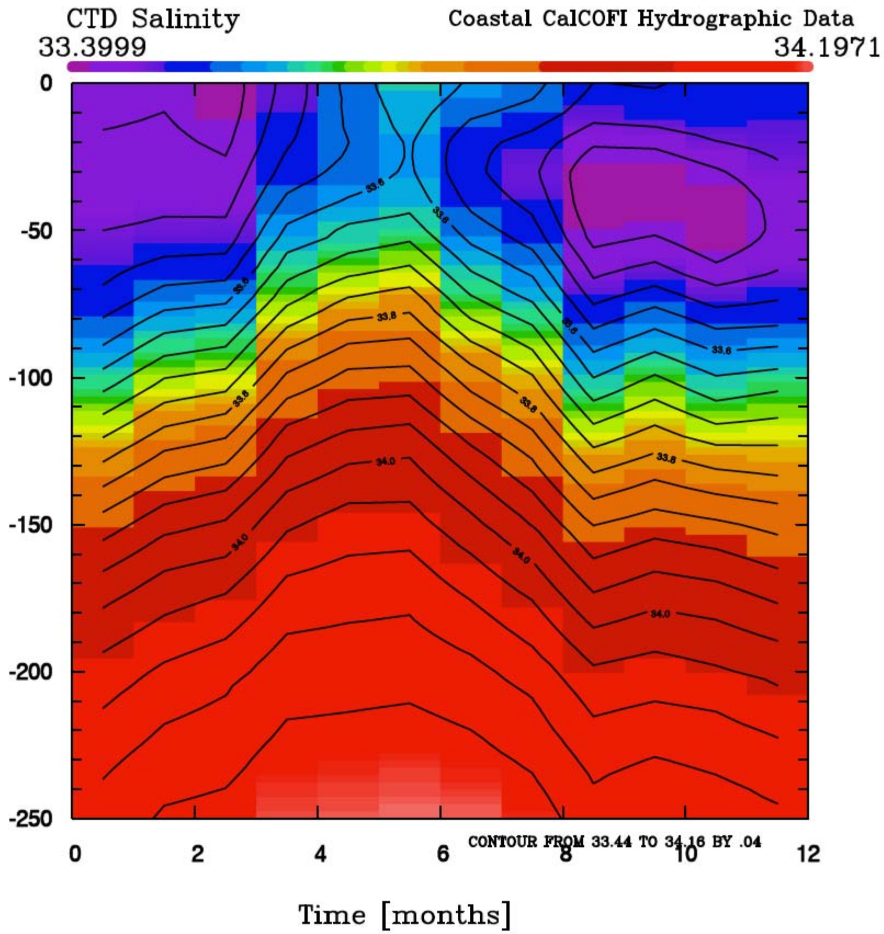


Coastal Upwelling Climatology

Temperature

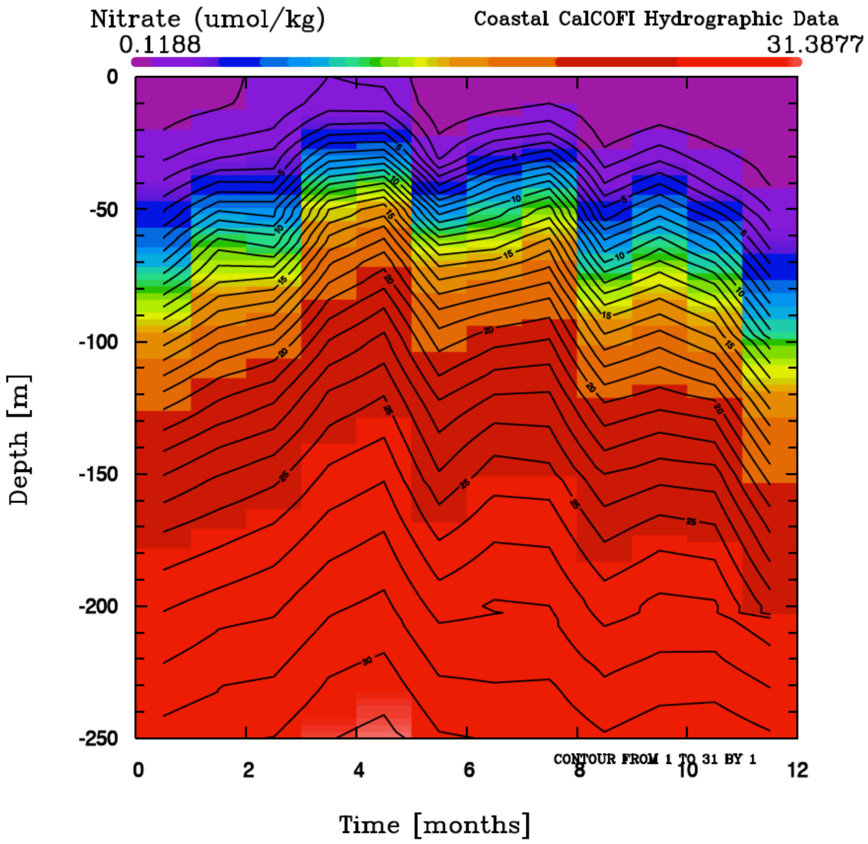


Salinity

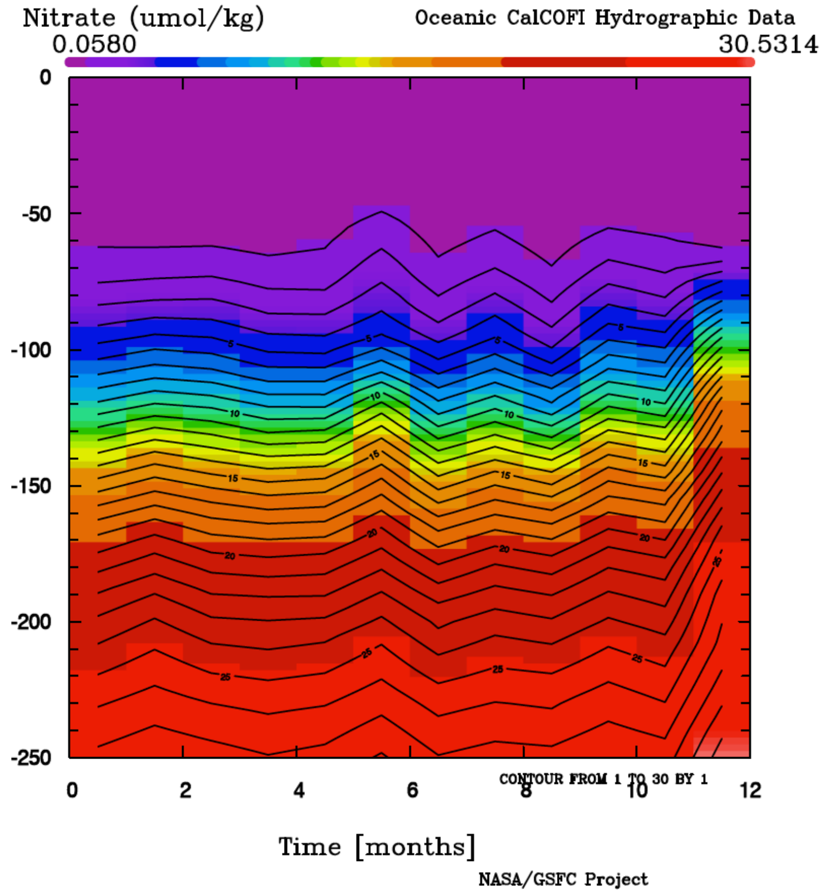


Nitrate Climatology

Coastal Ocean

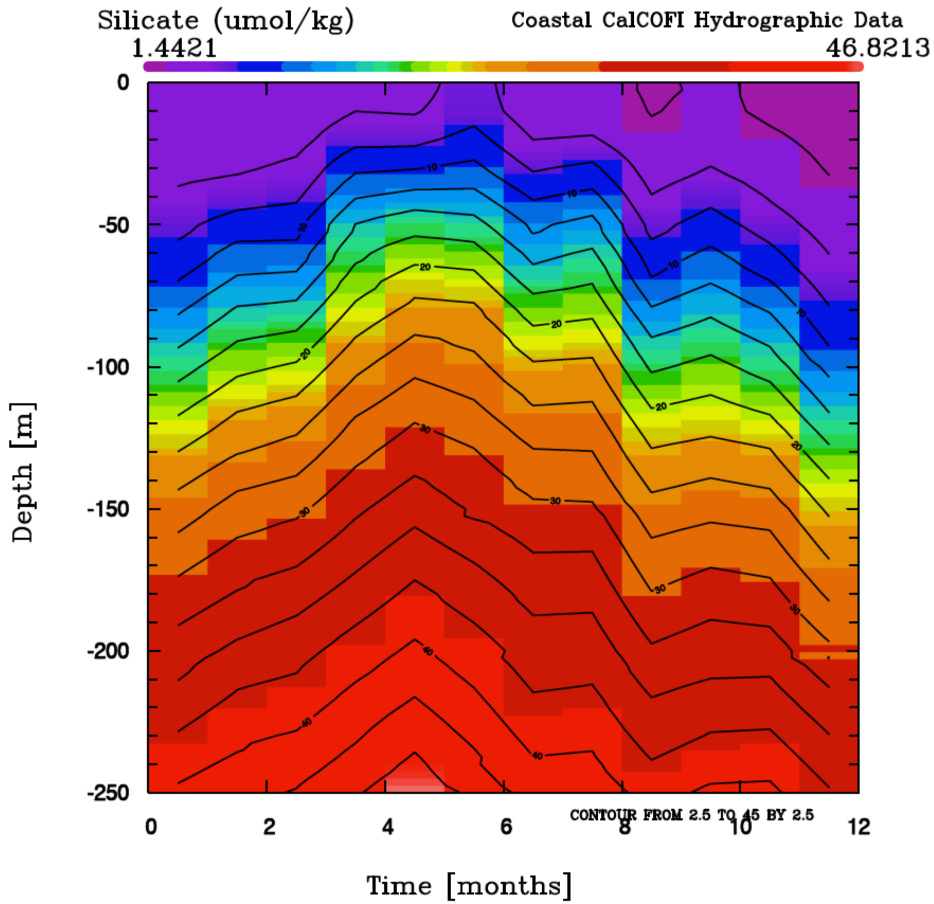


Open Ocean

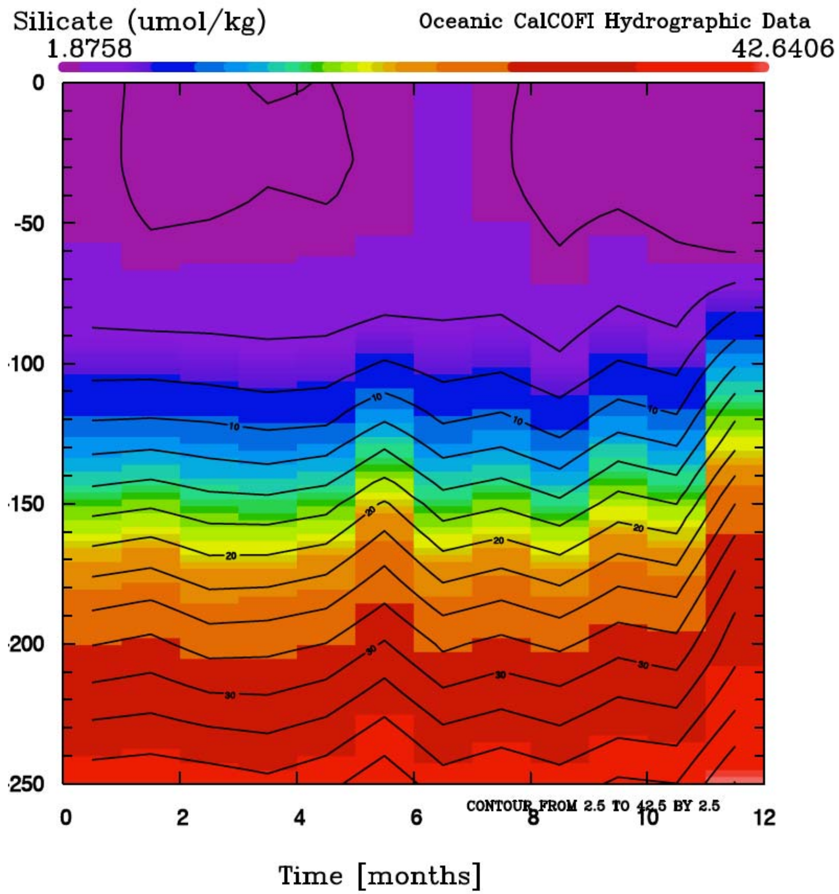


Silicate Climatology

Coastal Ocean

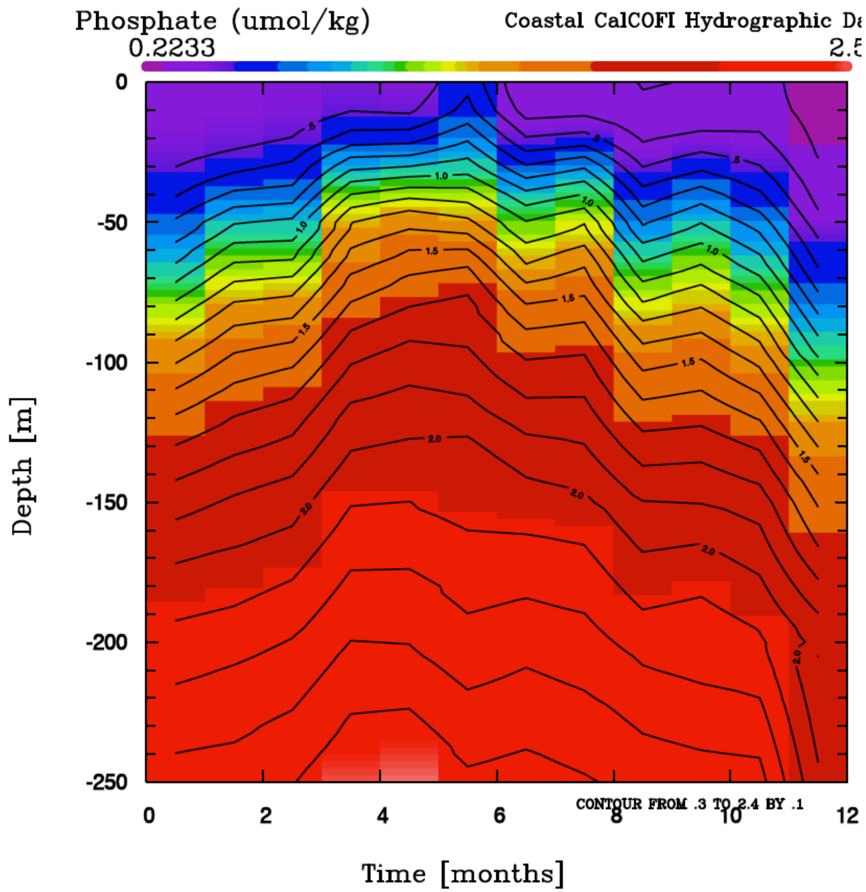


Open Ocean

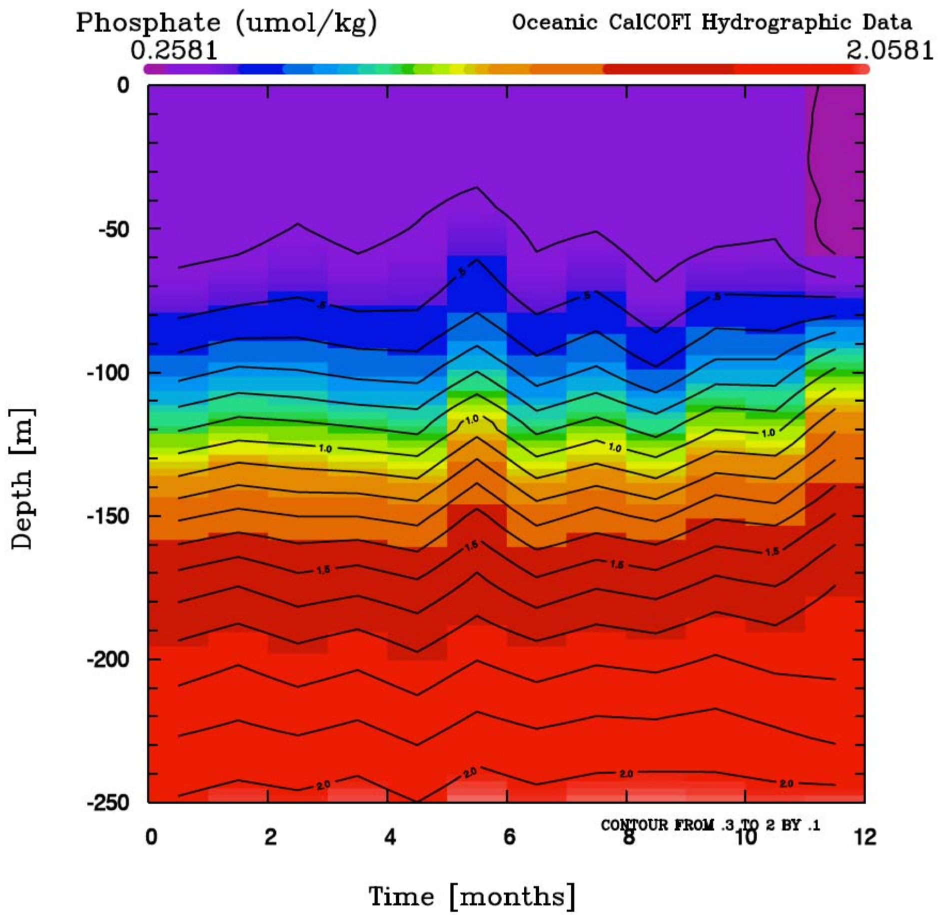


Phosphate Climatology

Coastal Ocean

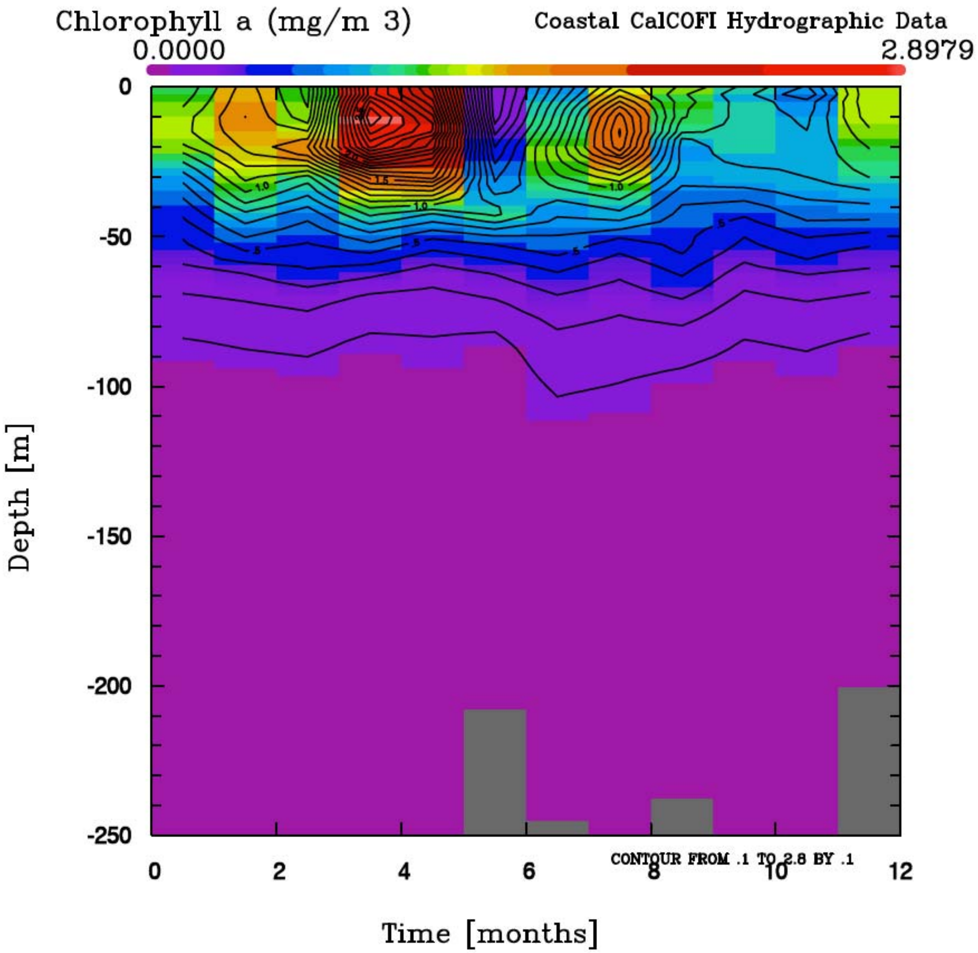


Open Ocean

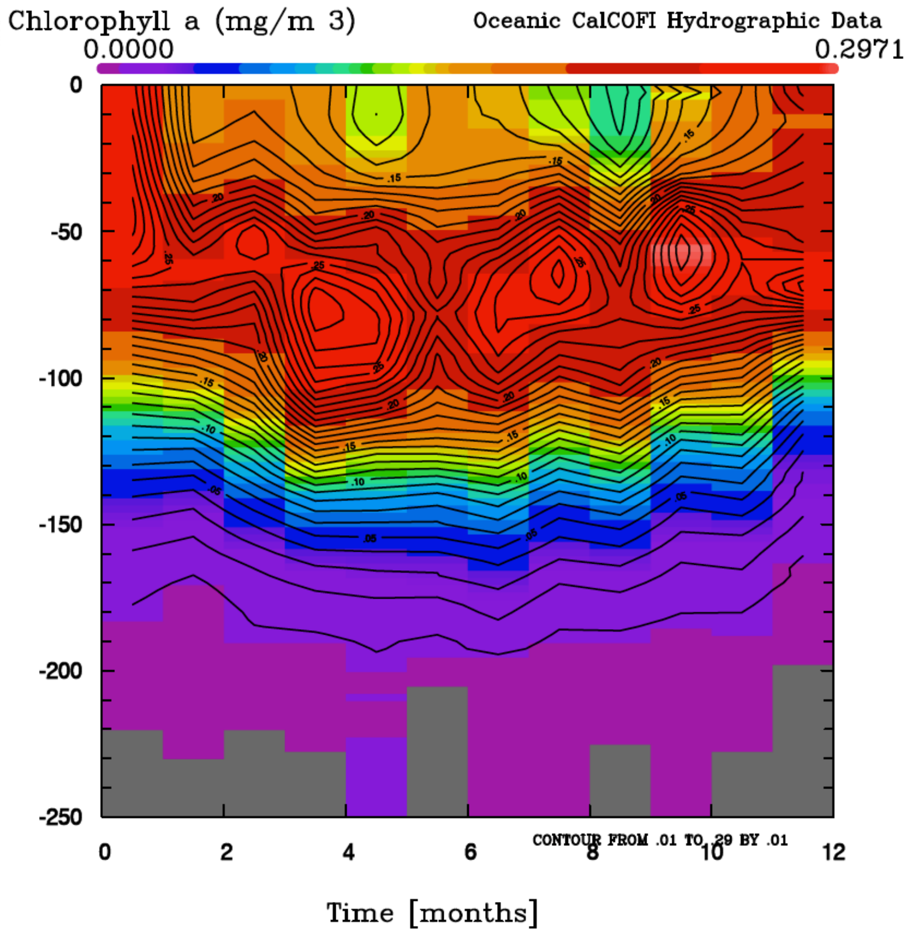


Chlorophyll a Climatology

Coastal Ocean

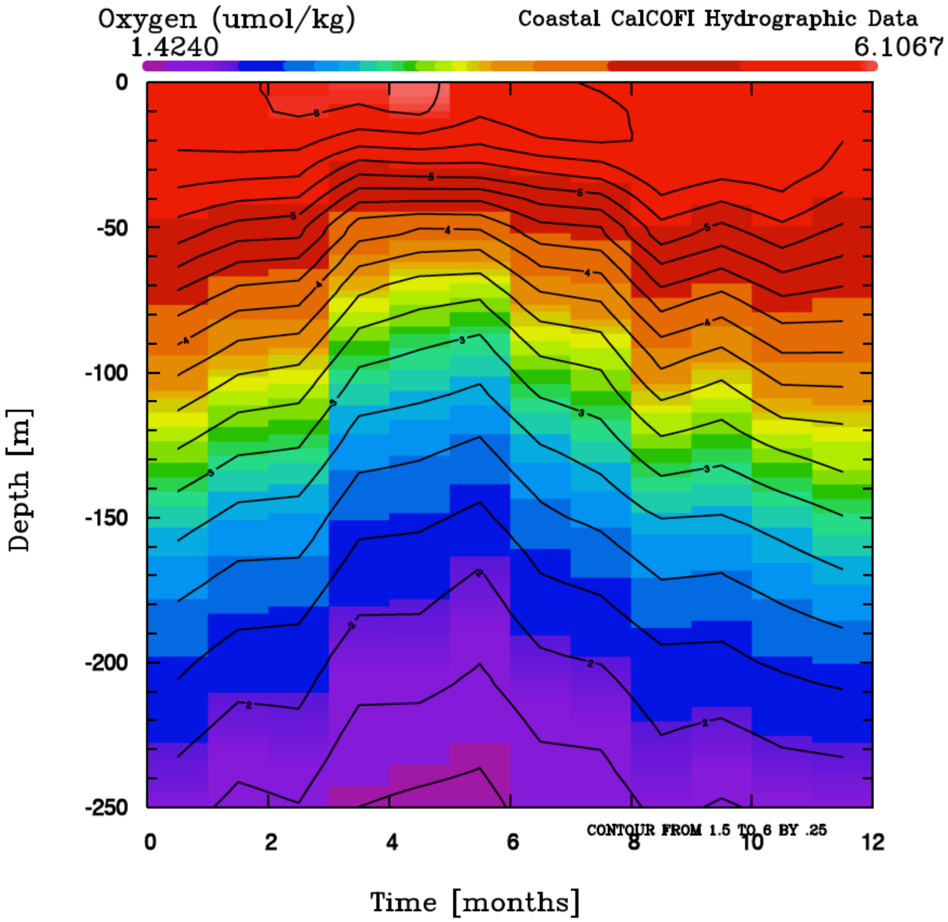


Open Ocean

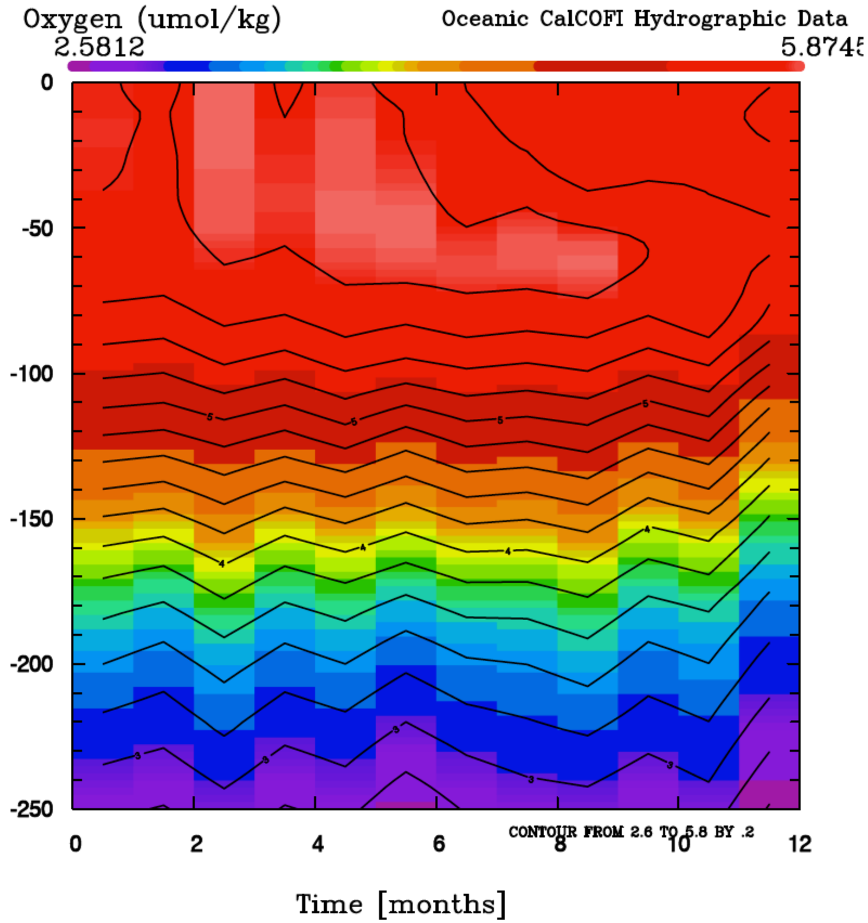


Oxygen Climatology

Coastal Ocean

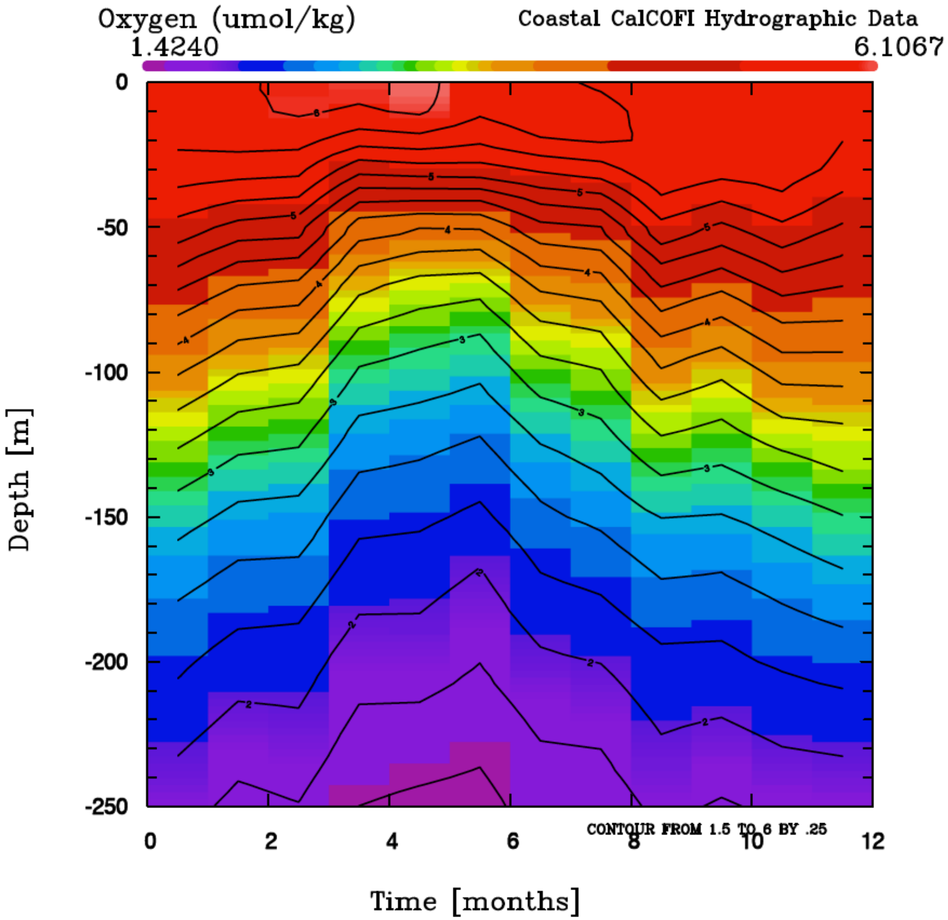


Open Ocean

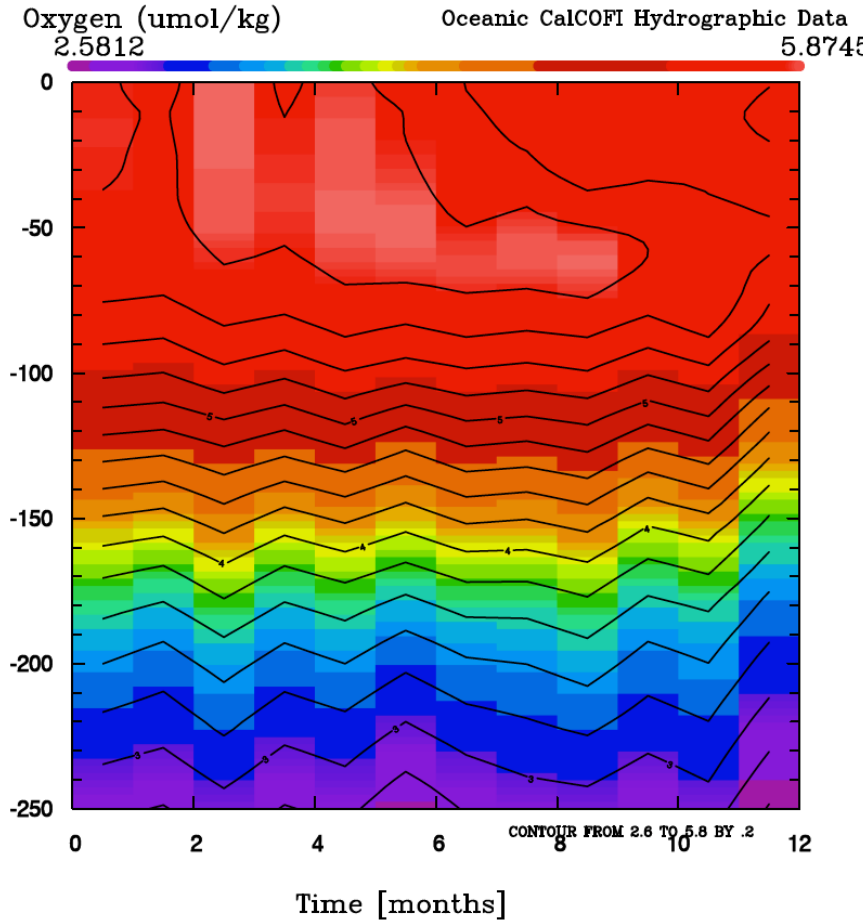


Oxygen Climatology

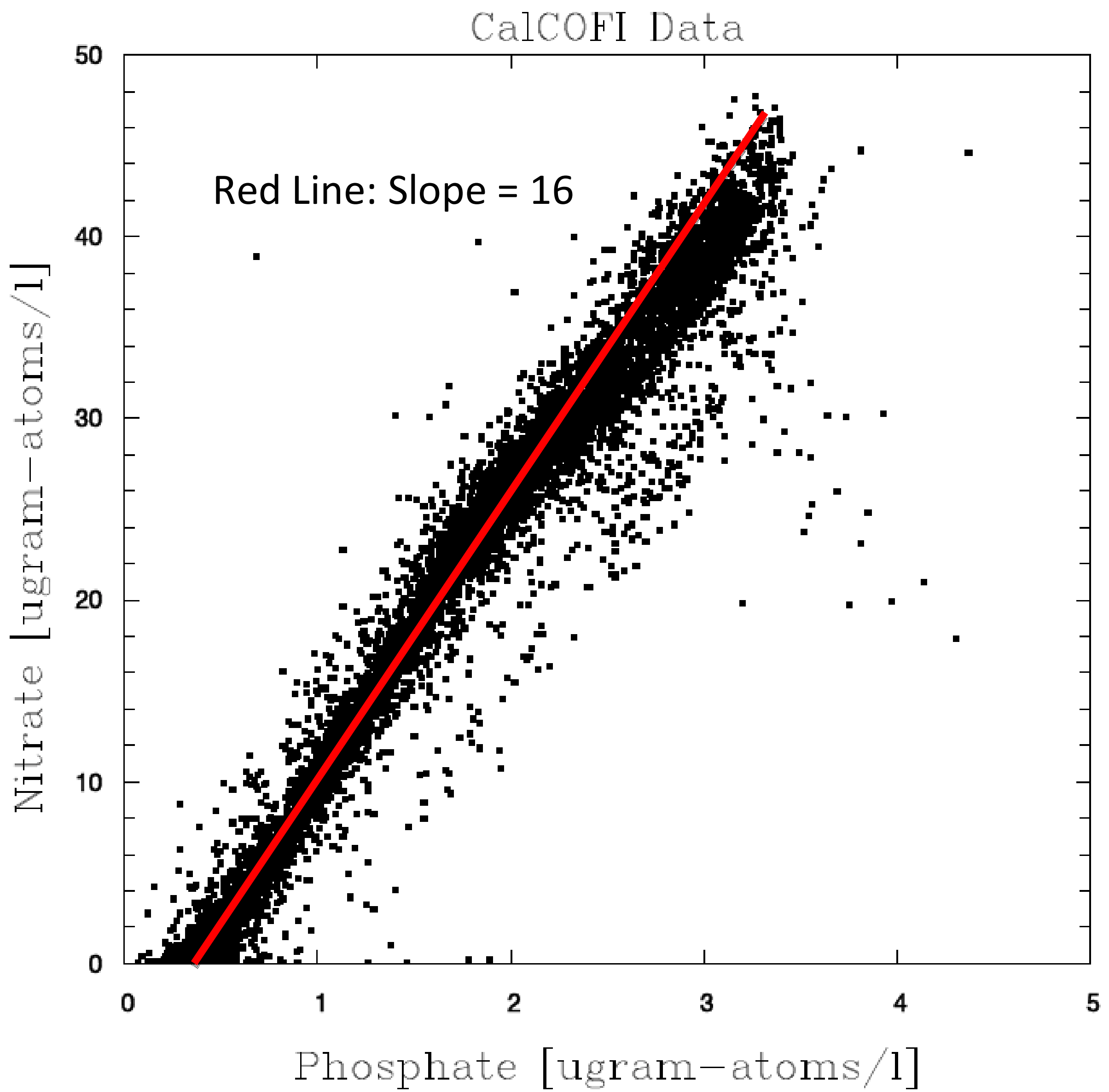
Coastal Ocean



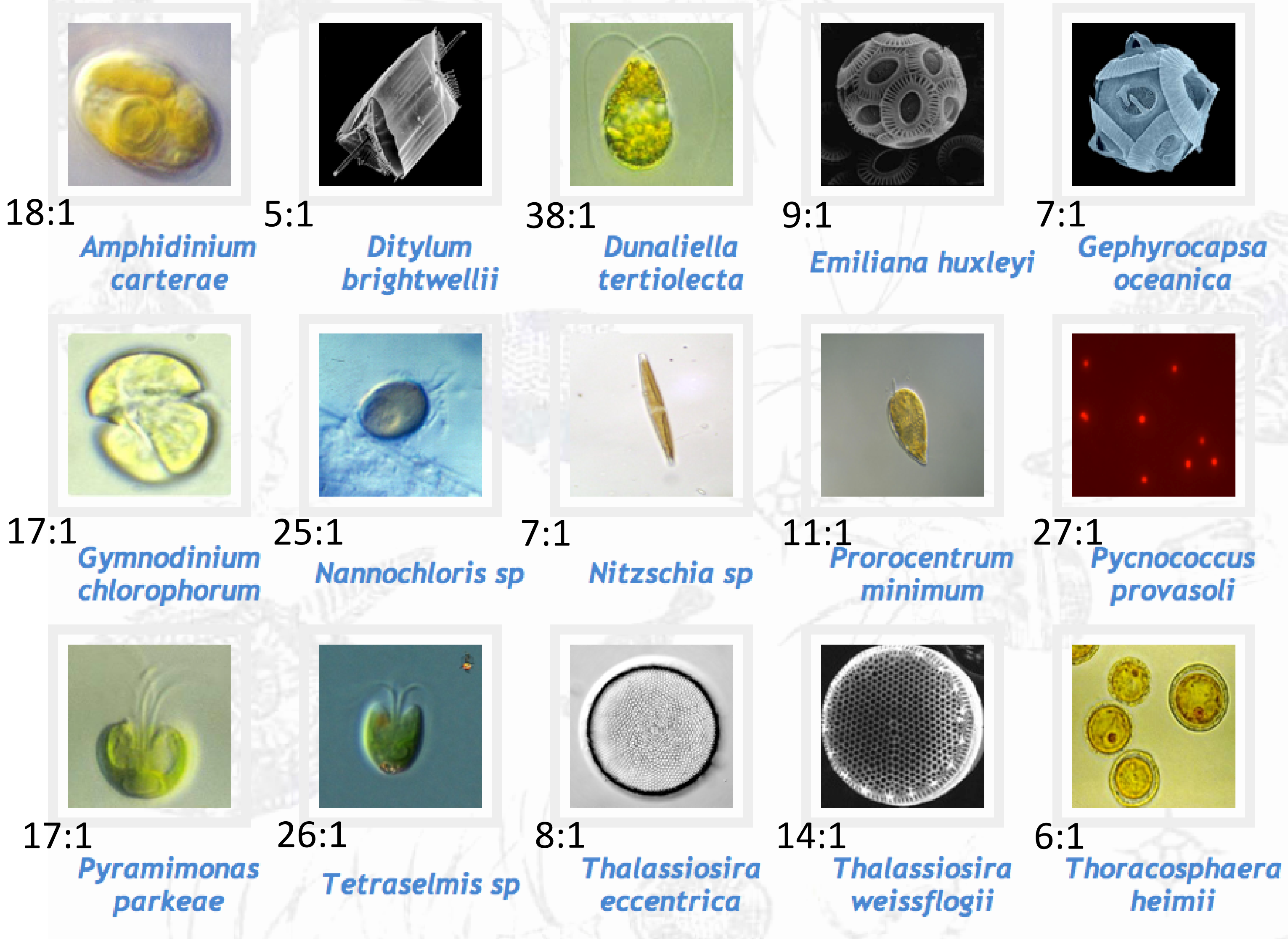
Open Ocean



CalCOFI N:P Relationship

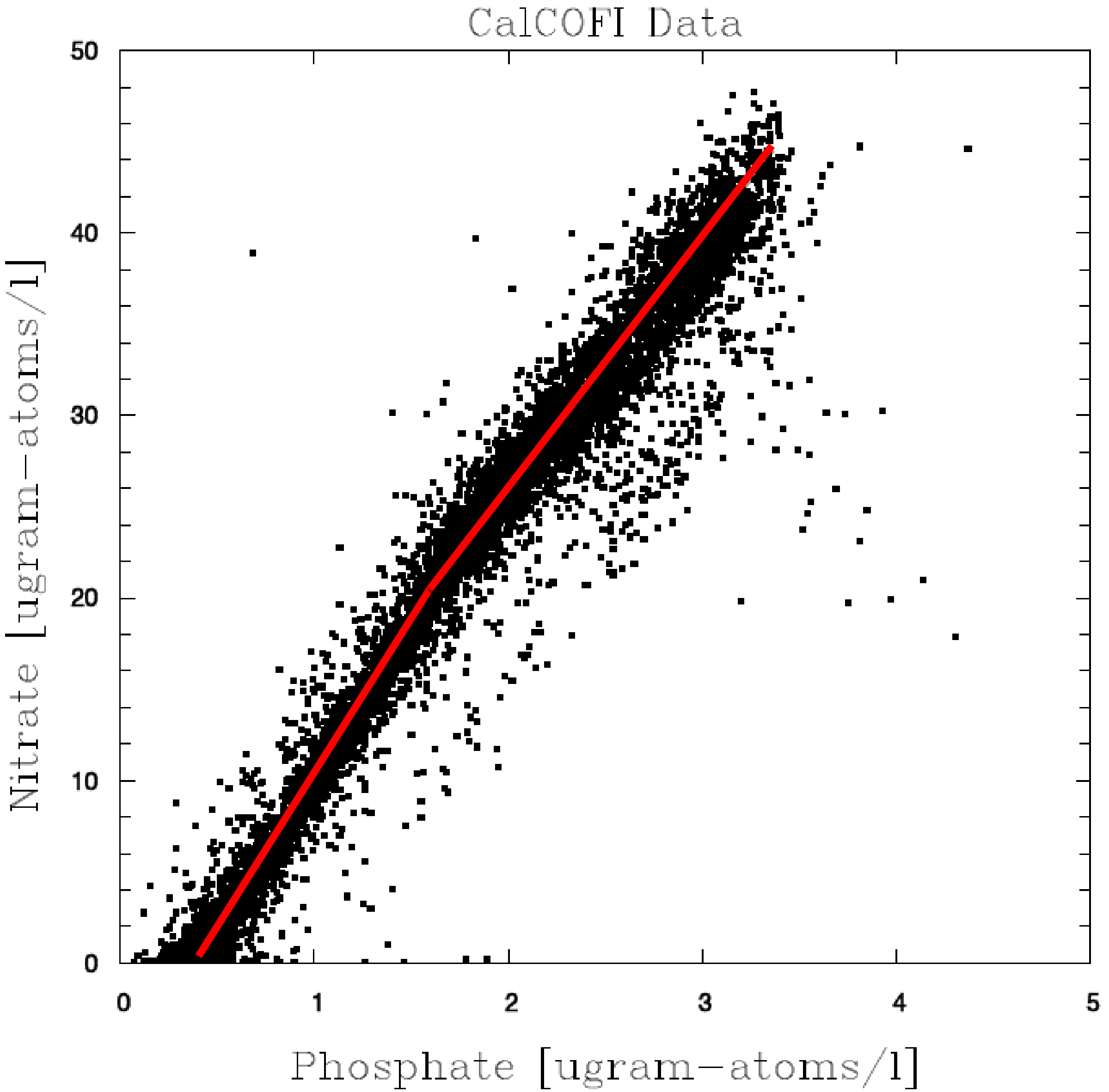


Species-specific Redfield N:P Ratios

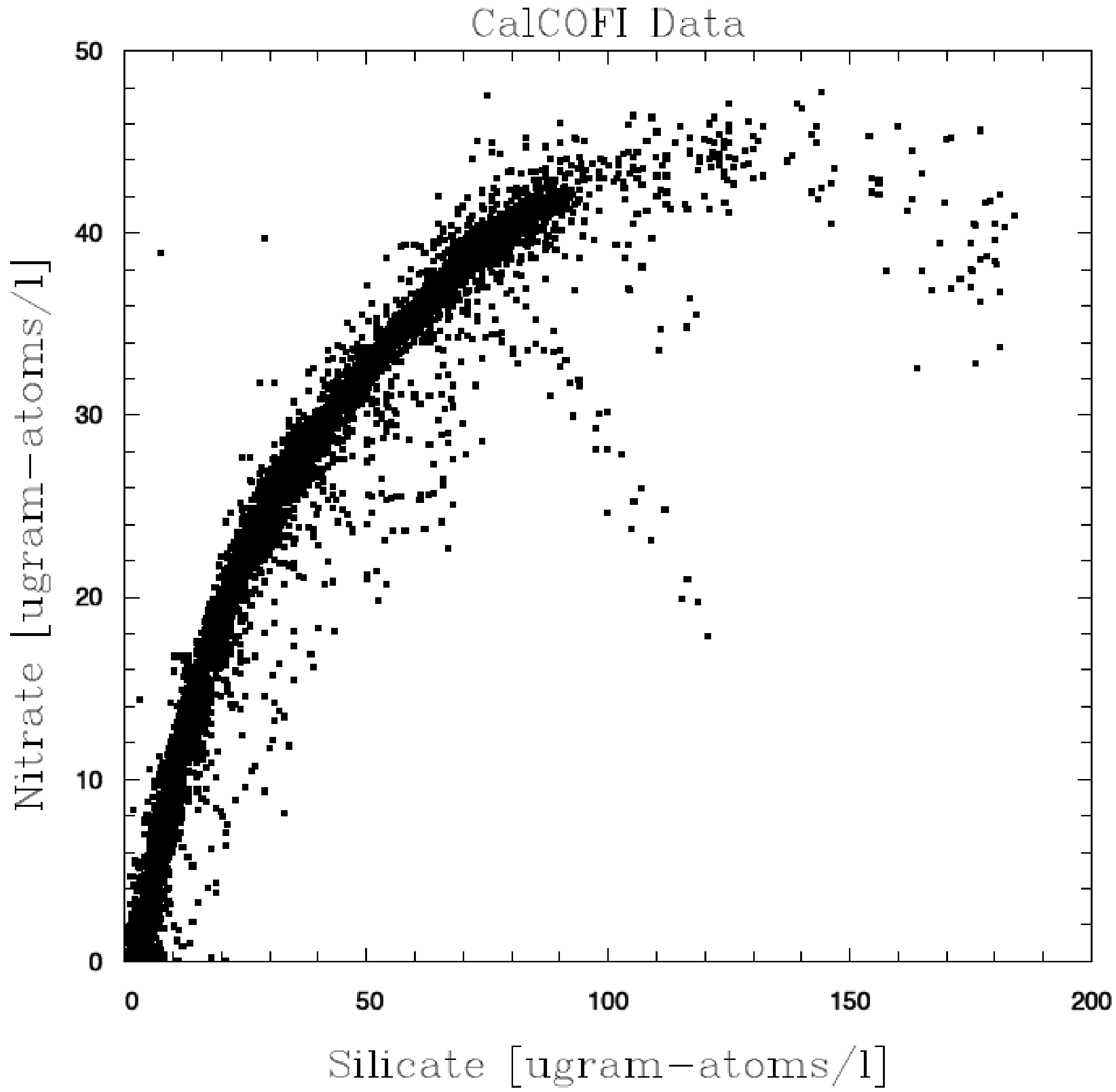


http://www.marinebiology.edu/Phytoplankton/phyto.htm

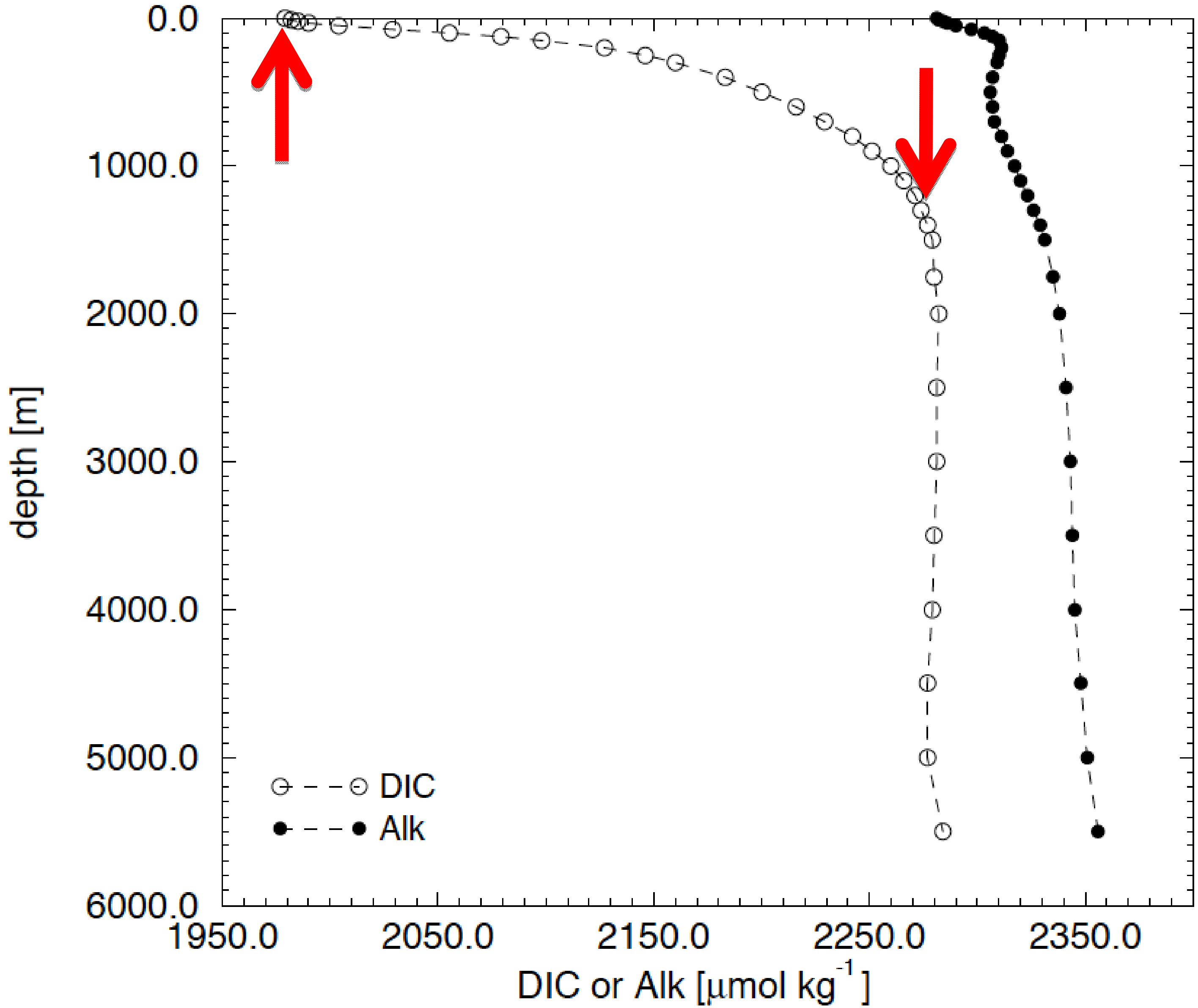
CalCOFI N:P Relationship



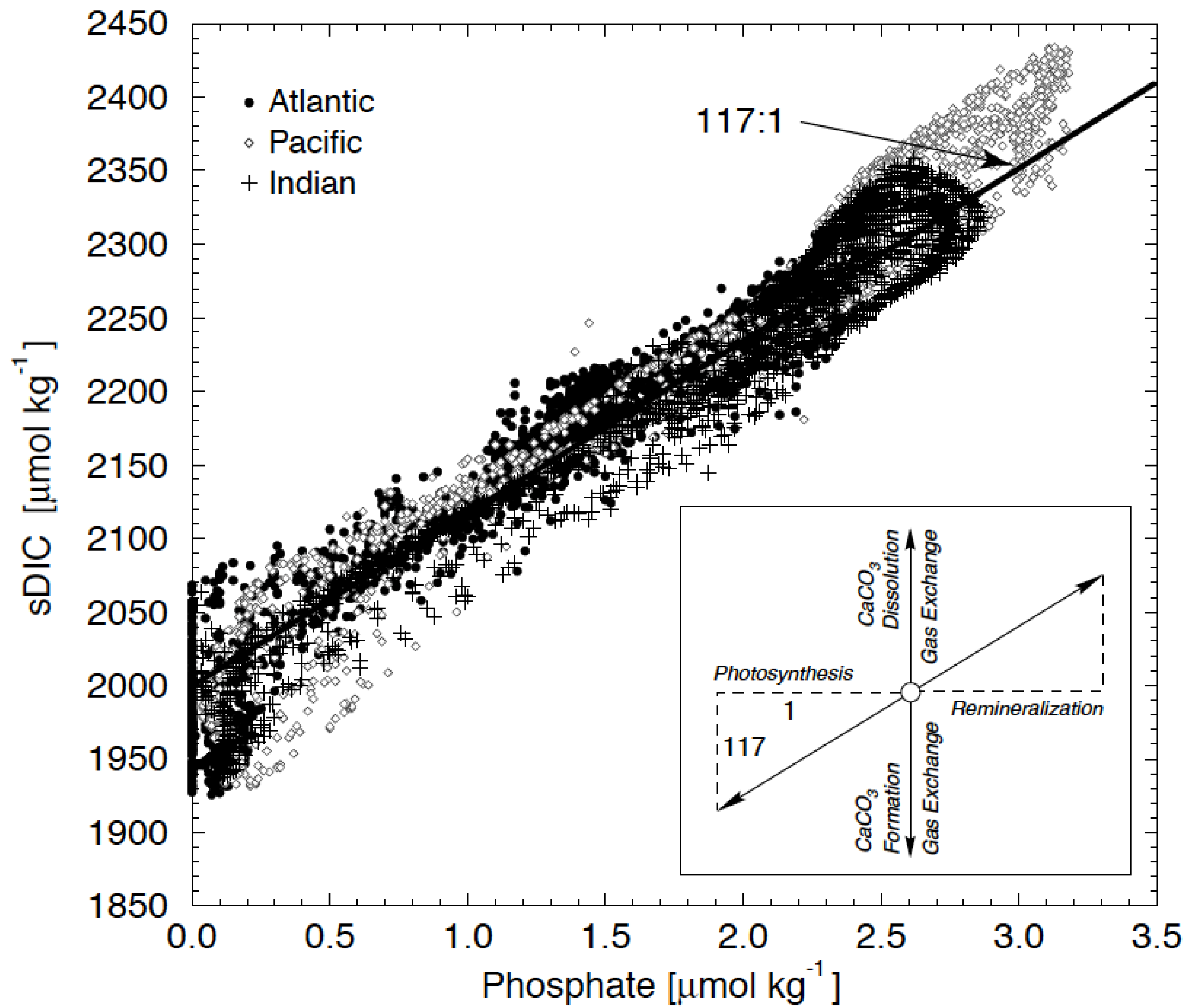
CalCOFIN:Si Relationship



Depth-Dependence of Dissolved Inorganic Carbon



Property-Property plot of sDIC and PO4



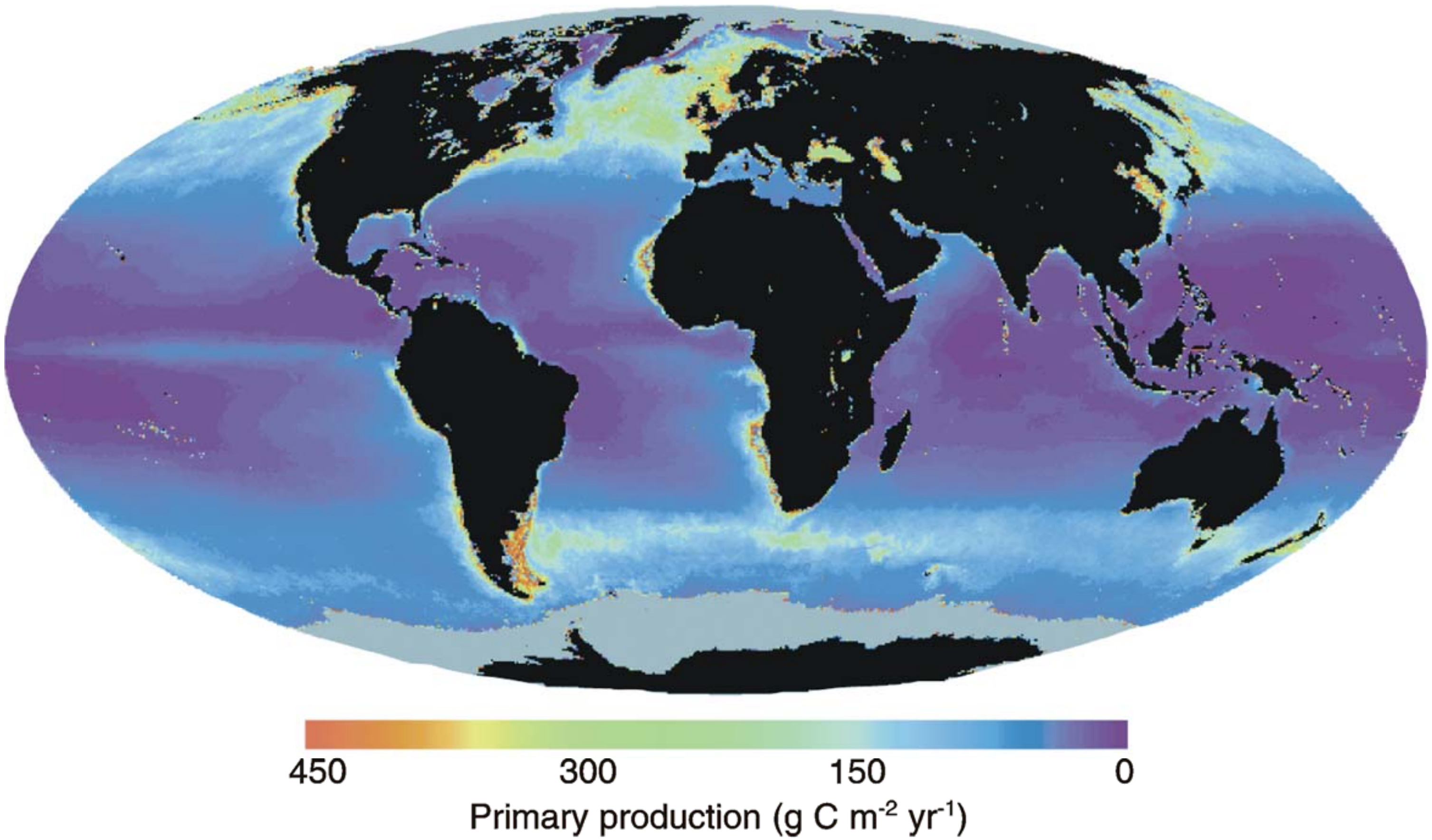
Variations on the Carbon Pump

- Standard: Nitrogen limited Ocean

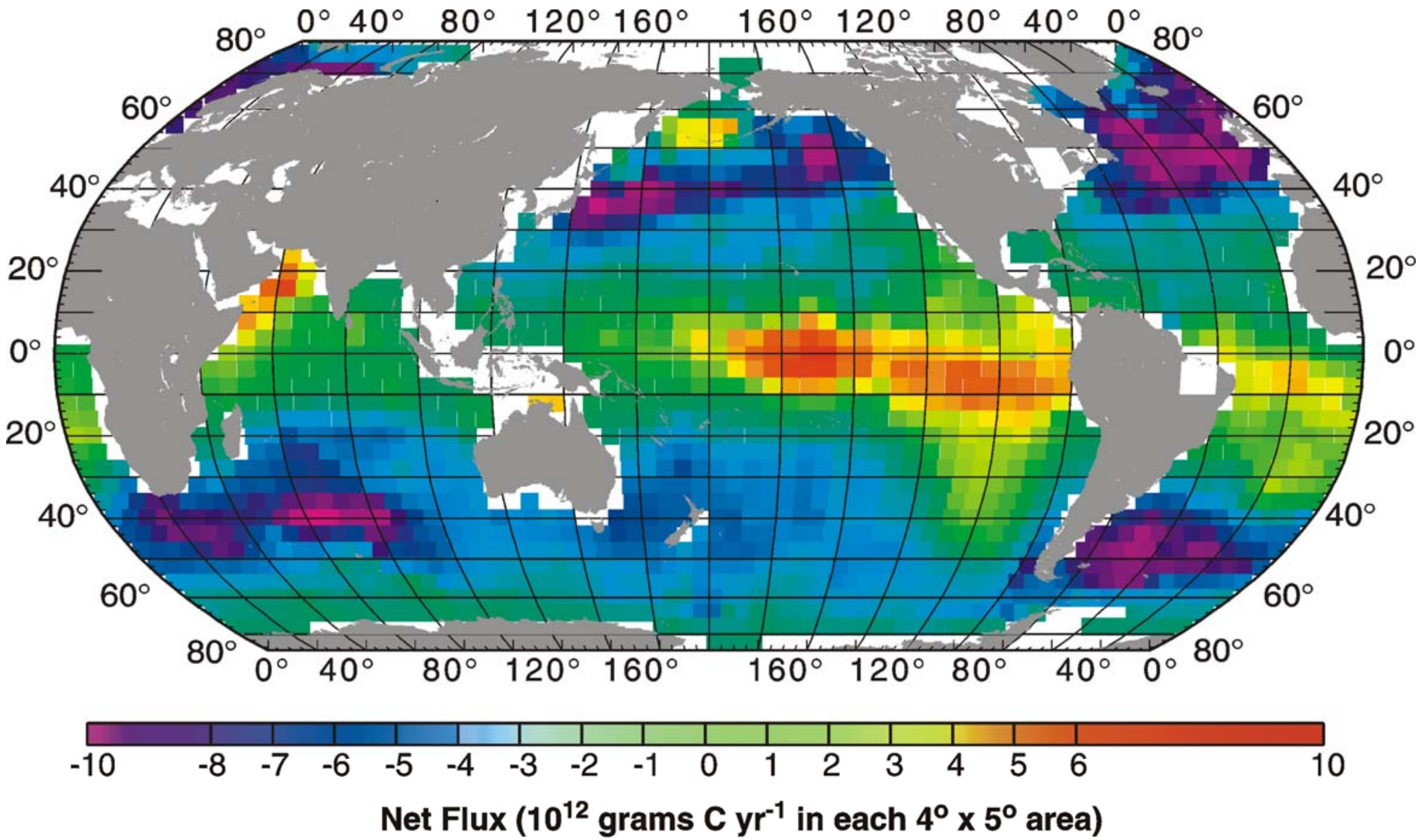
- Steady-Fe inputs: Iron input driven, Phosphate—limited?

- Periodic-Fe events: Dust/iron events, diatom blooms drive pulses of carbon sink events

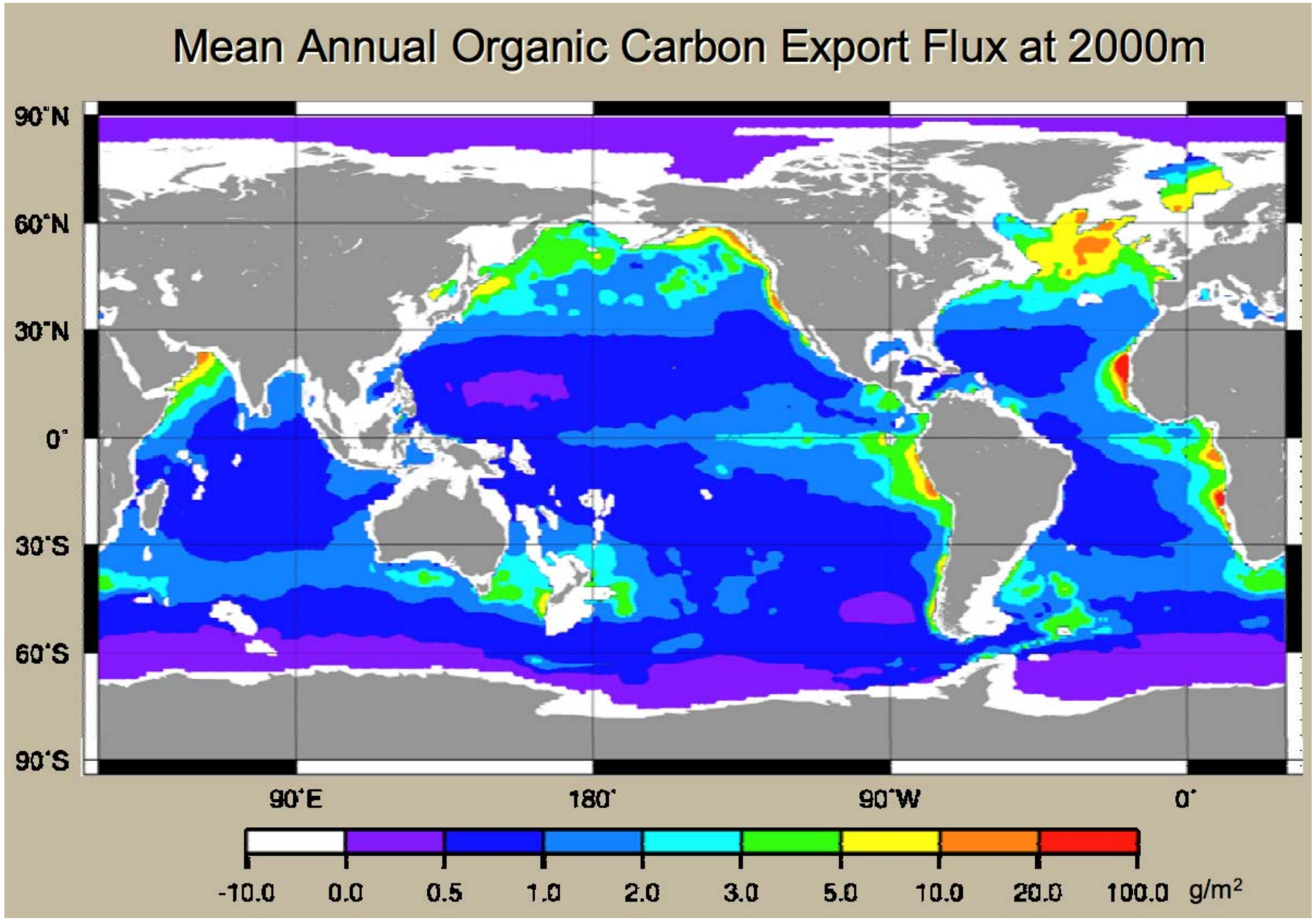
Annual Mean Ocean Primary Productivity



Annual Mean air-sea CO2 Flux

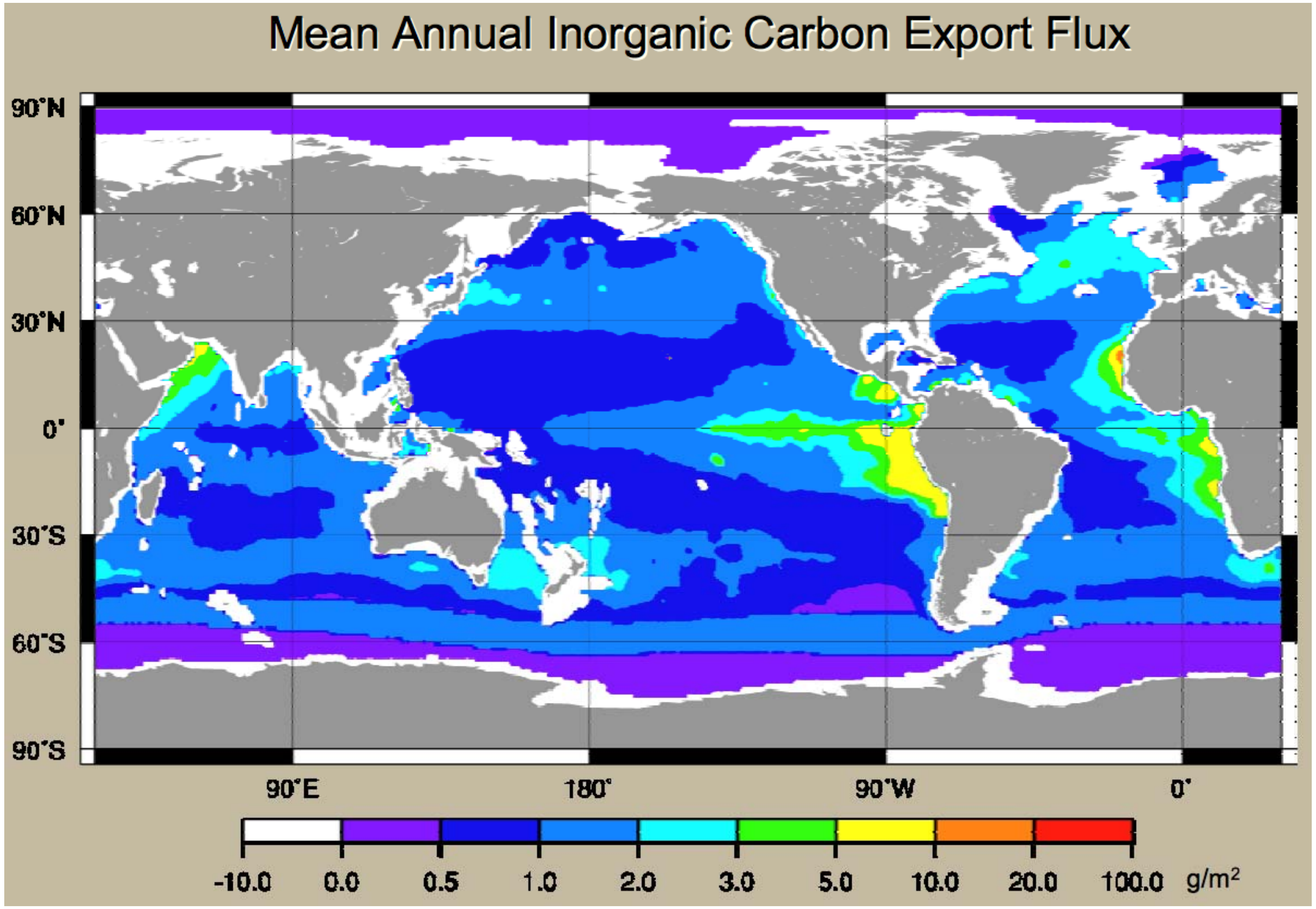


Mean Annual Organic Carbon Export

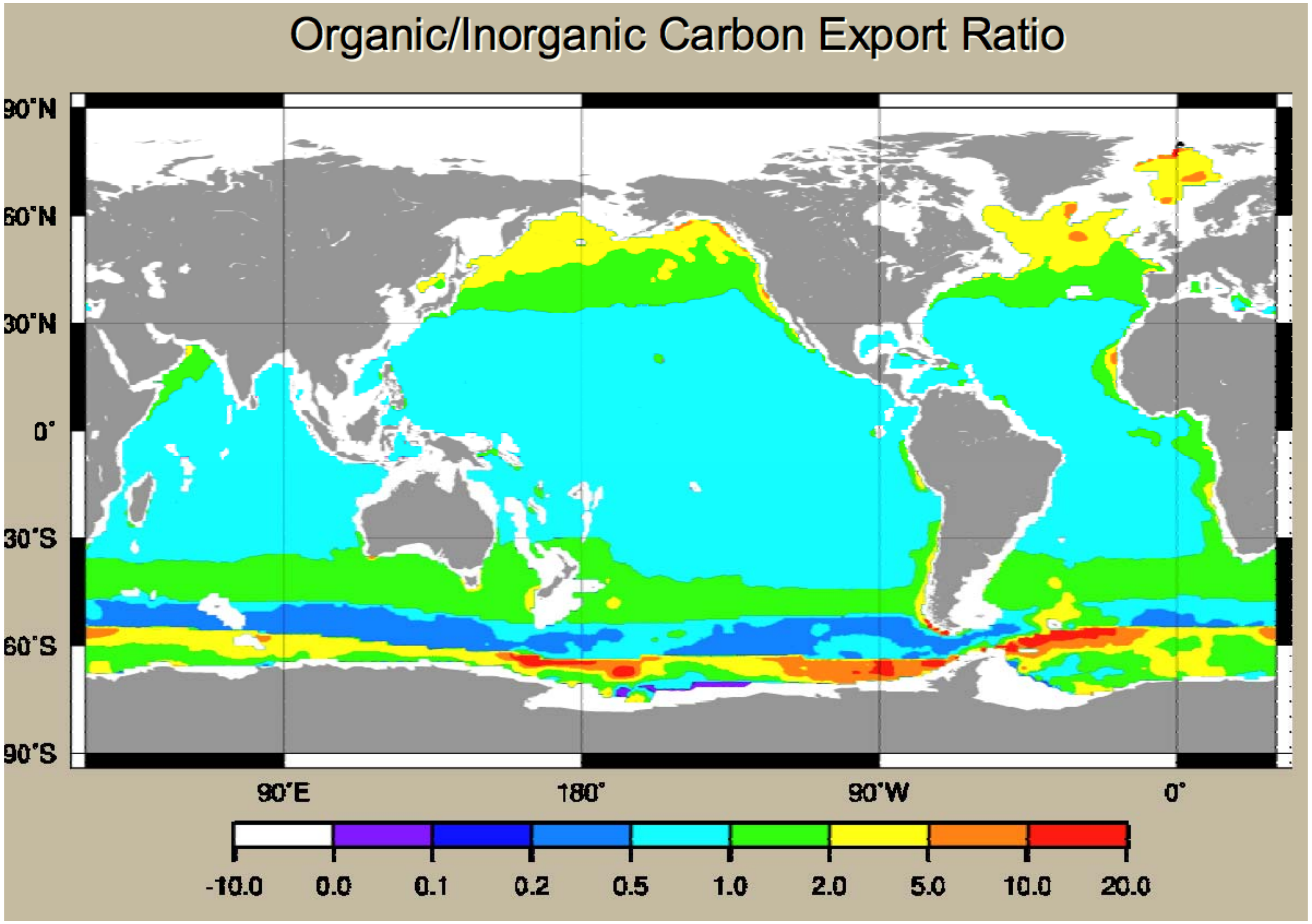


From SusHonjo WHOI

Mean Annual Inorganic Carbon Export



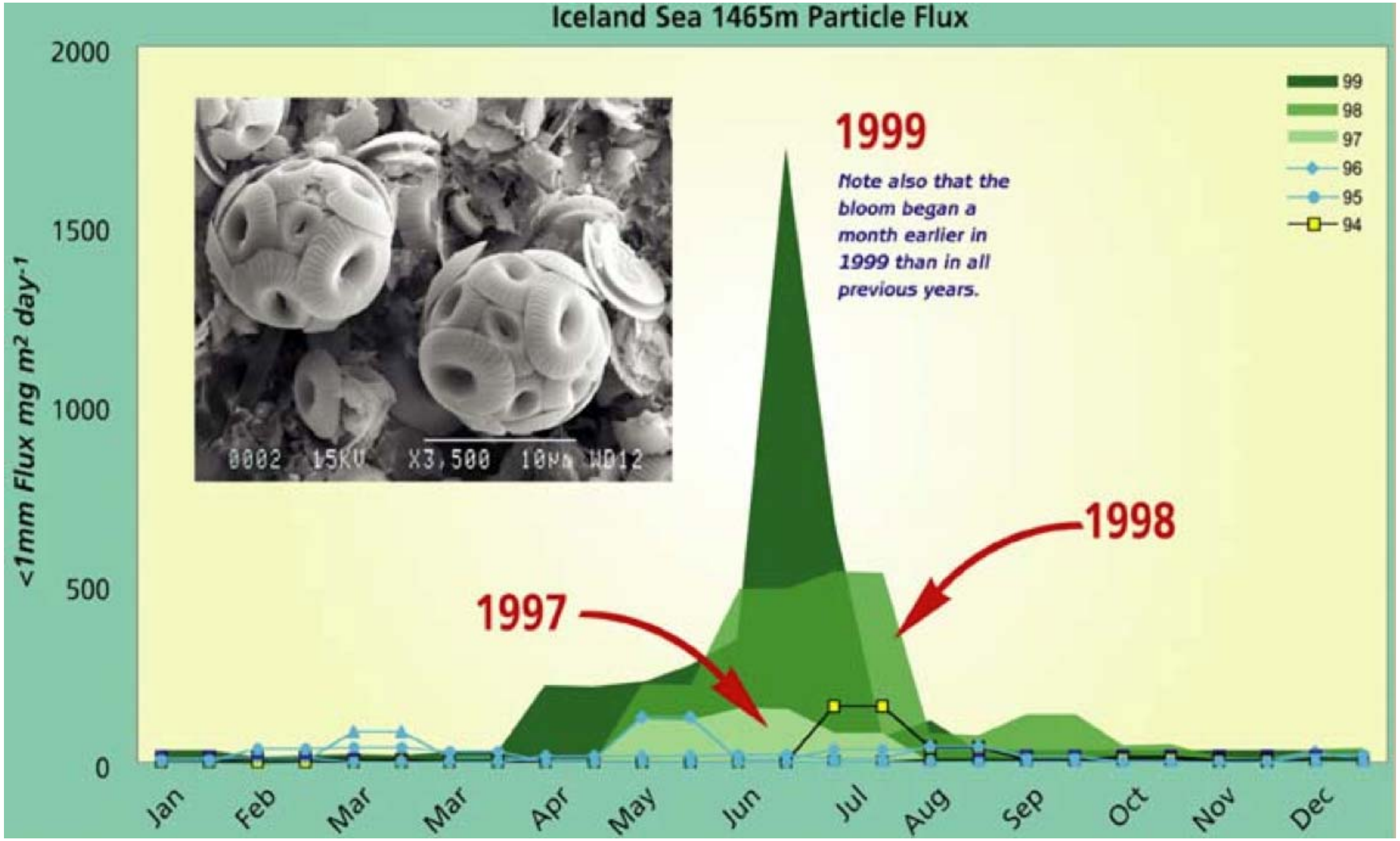
Organic/Inorganic Carbon Export Ratio



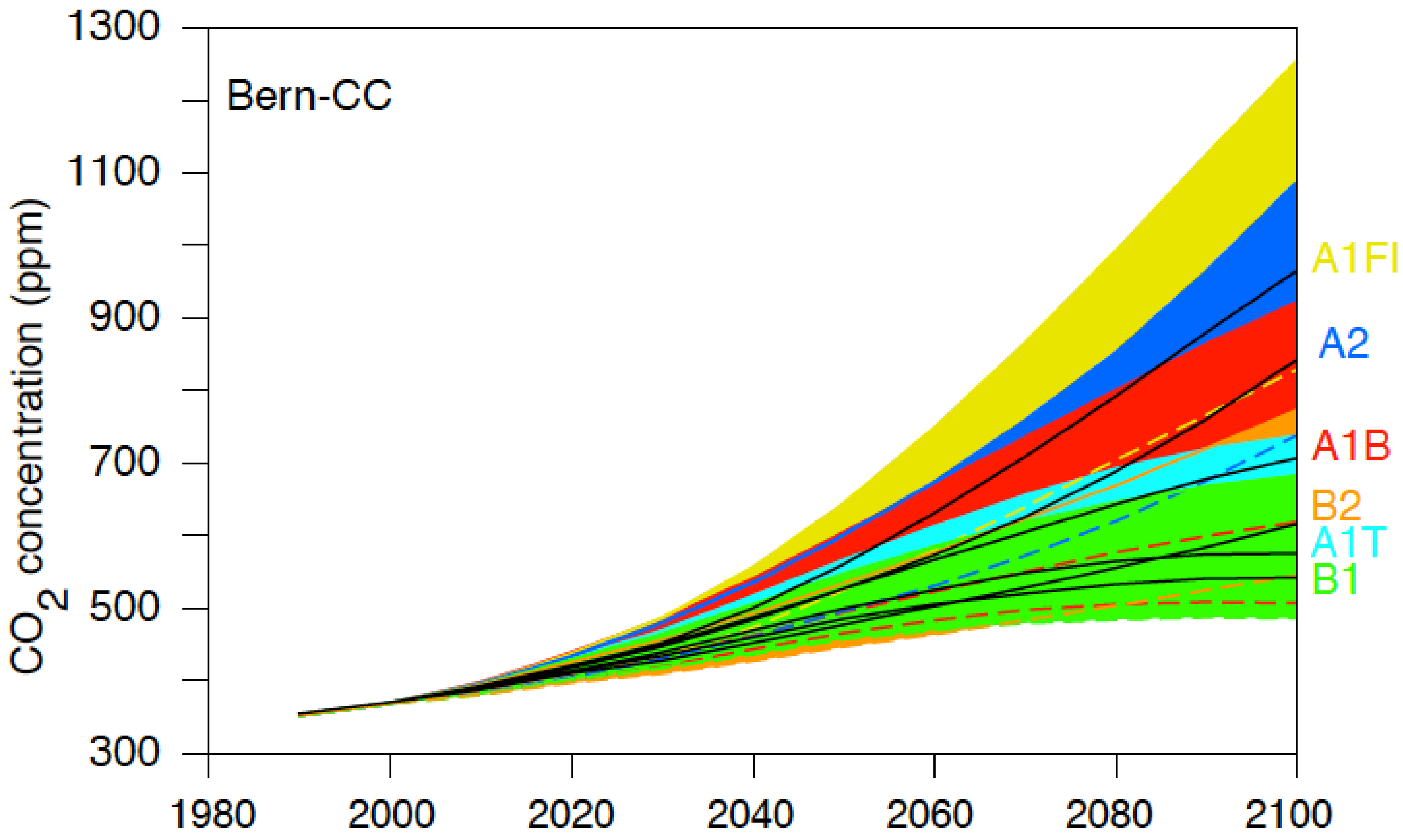
Integrated Global C Export to Deep Ocean

Global Export to the Ocean's Interior
>2 km over 301 Mkm²

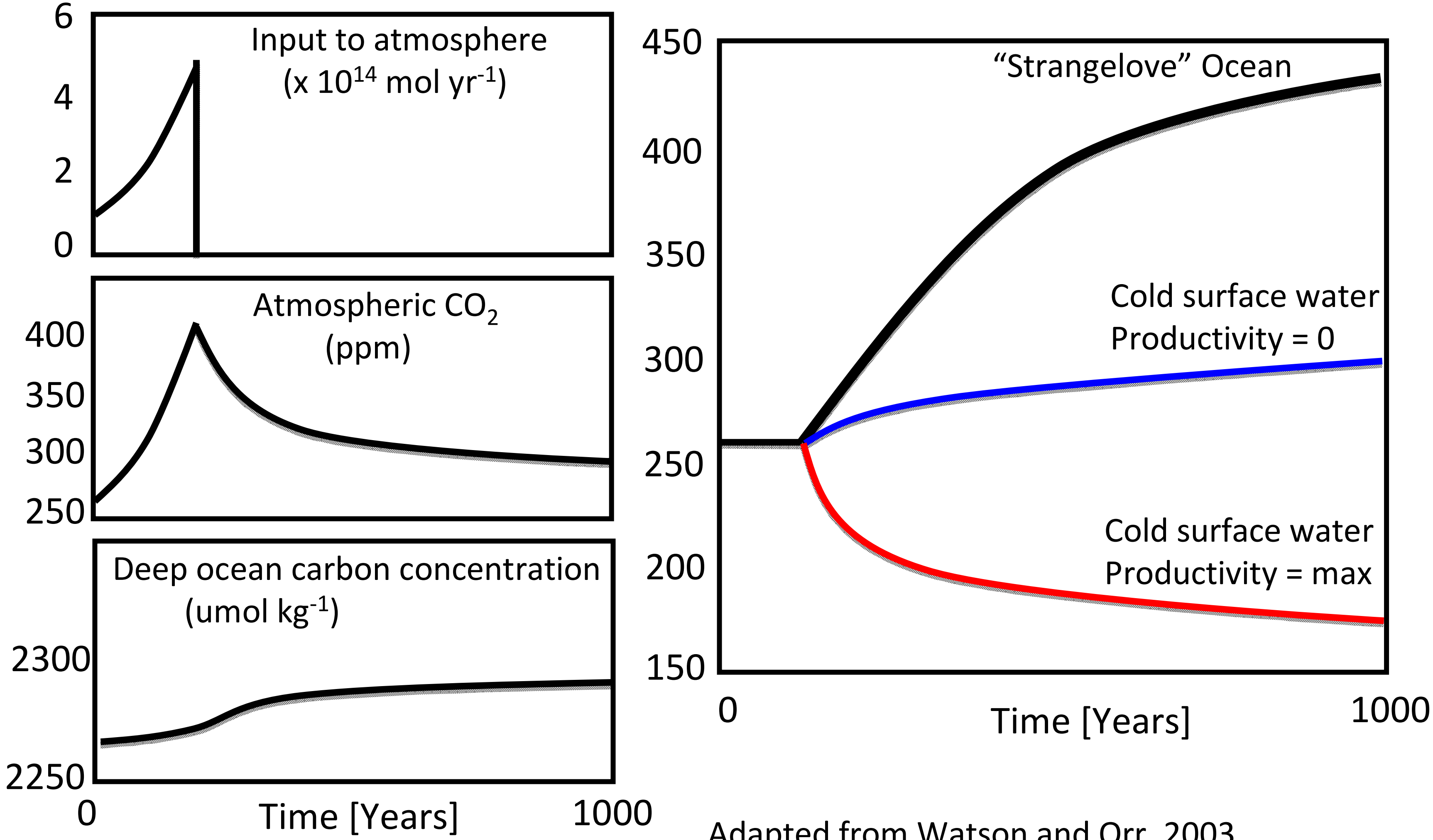
C_{org}	:	36.2 Tmol C yr^{-1}	(434 Tg yr^{-1})
C_{inorg}	:	33.8 Tmol C yr^{-1}	(406 Tg yr^{-1})
Si_{bio}	:	34.6 Tmol C yr^{-1}	(969 Tg yr^{-1})
Ca	:	33.8 Tmol C yr^{-1}	


Iceland Sea 1465m Particle Flux
<1mm Flux mg m² day⁻¹
2000
1500
1000
500
0
Jan
Feb
Mar
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
99
98
97
96
95
94
1999
Note also that the bloom began a month earlier in 1999 than in all previous years.
1998
1997
0002 15KV X3,500 10µm WD12

IPCC Model Predictions



Simple ocean-atmosphere CO2 model

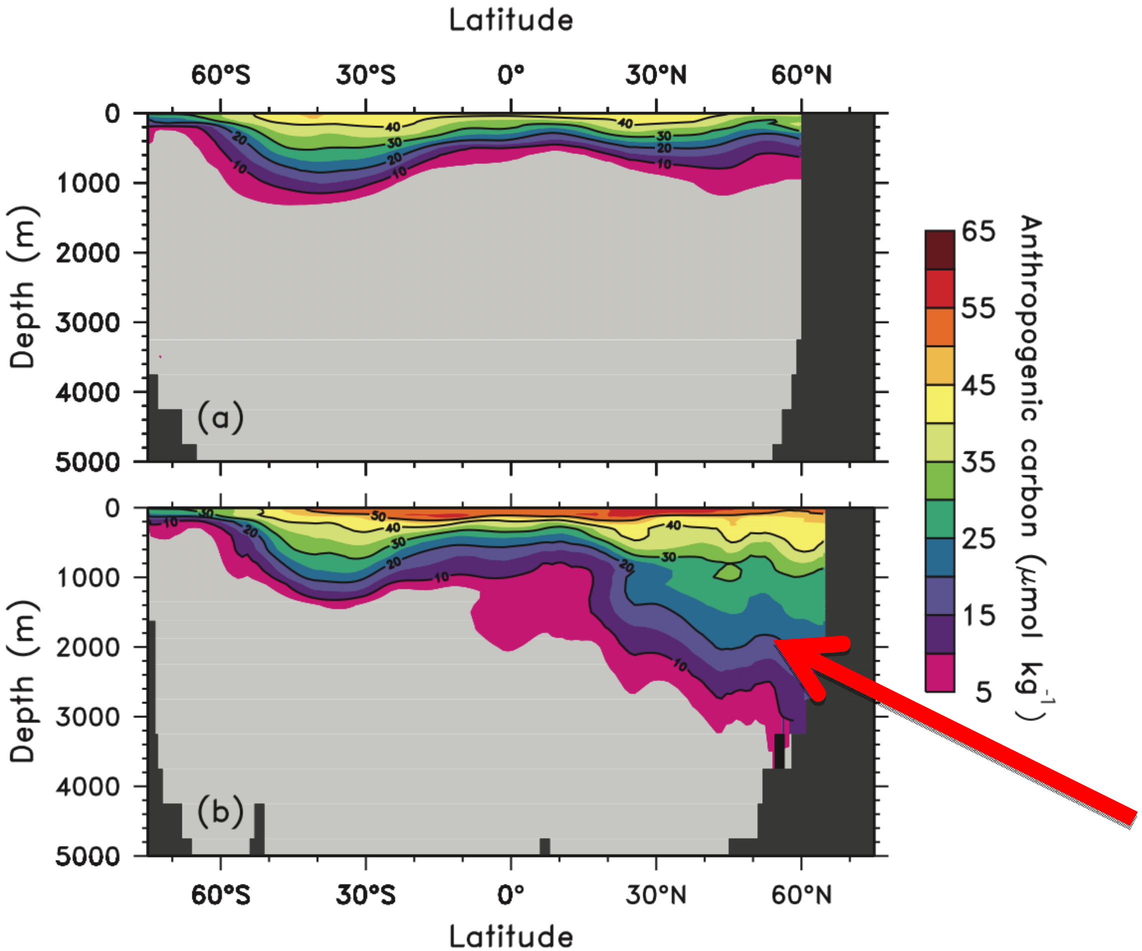


Adapted from Watson and Orr, 2003
using results from Sarmiento and Toggweiler, 1984

Incursion of Anthropogenic Carbon

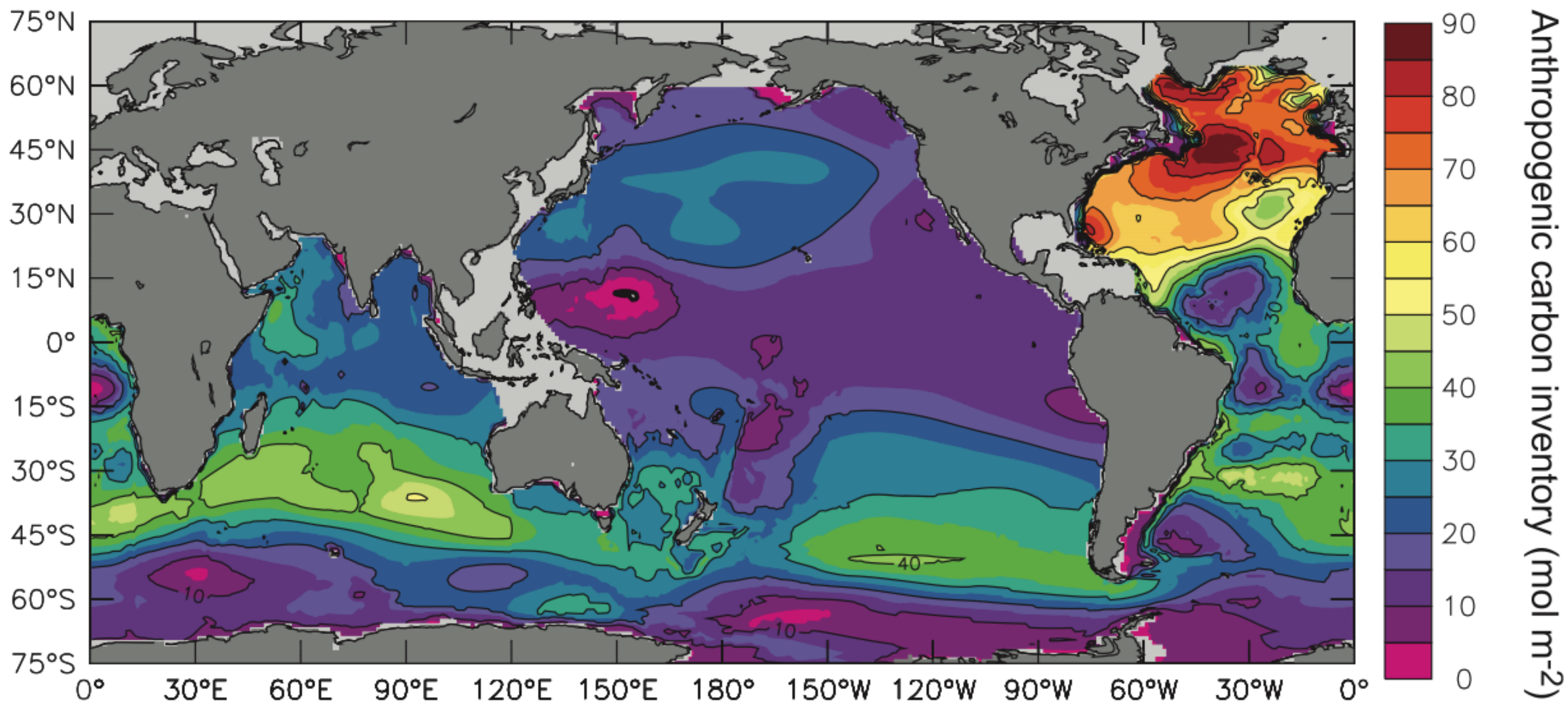
Pacific Ocean

Atlantic Ocean

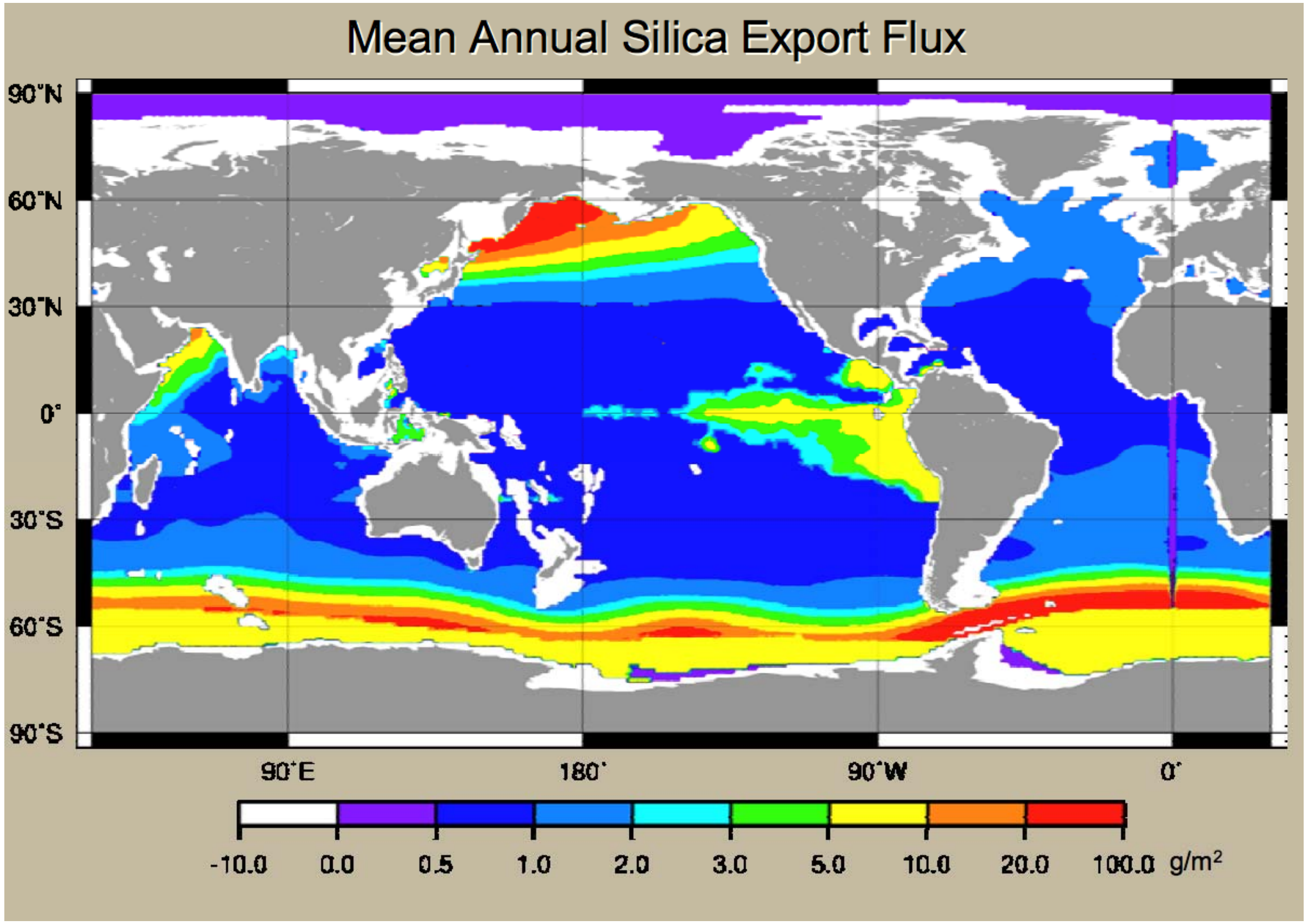


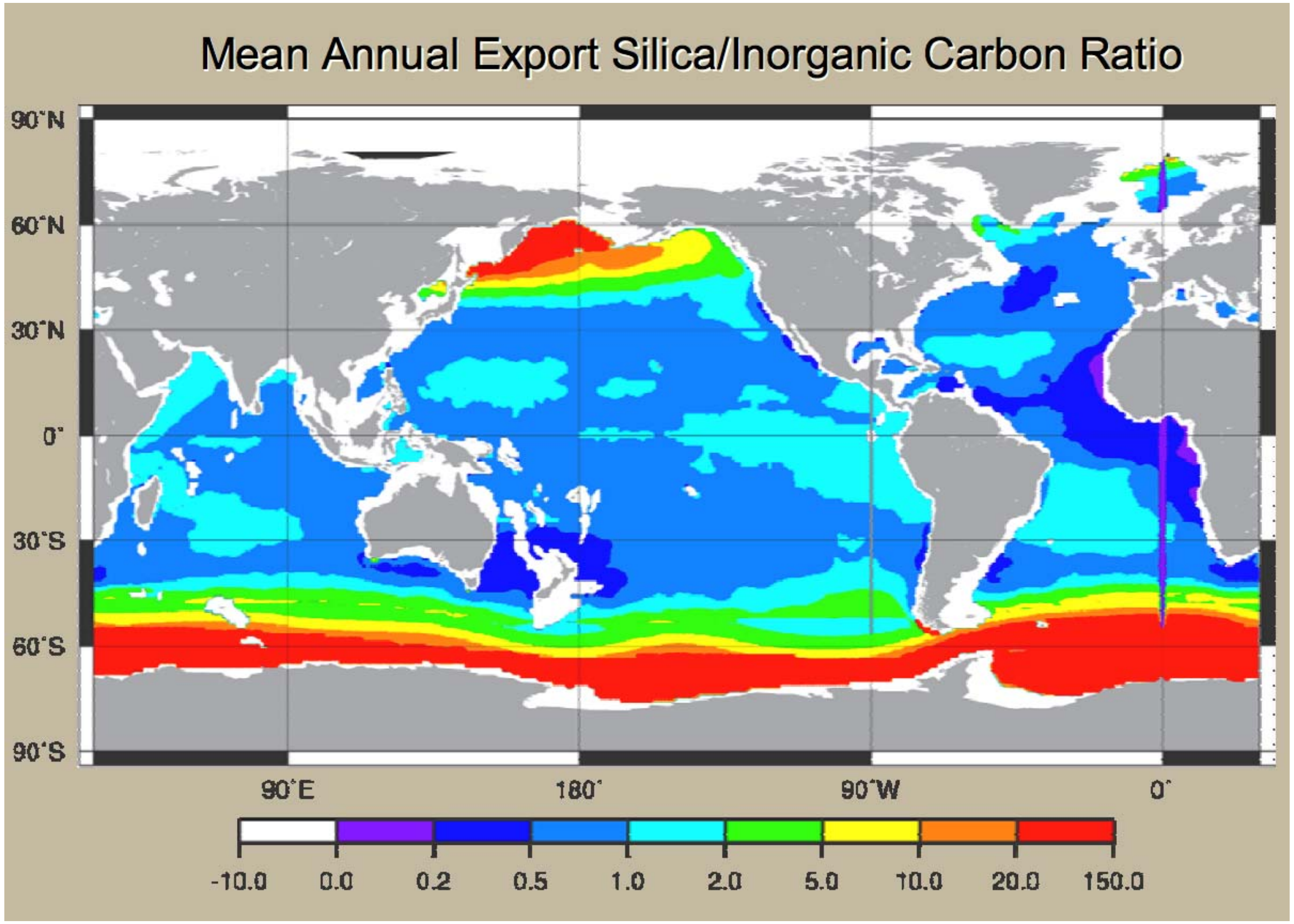
Deep-Water Formation Zone

Sabine et al., 2004 Science

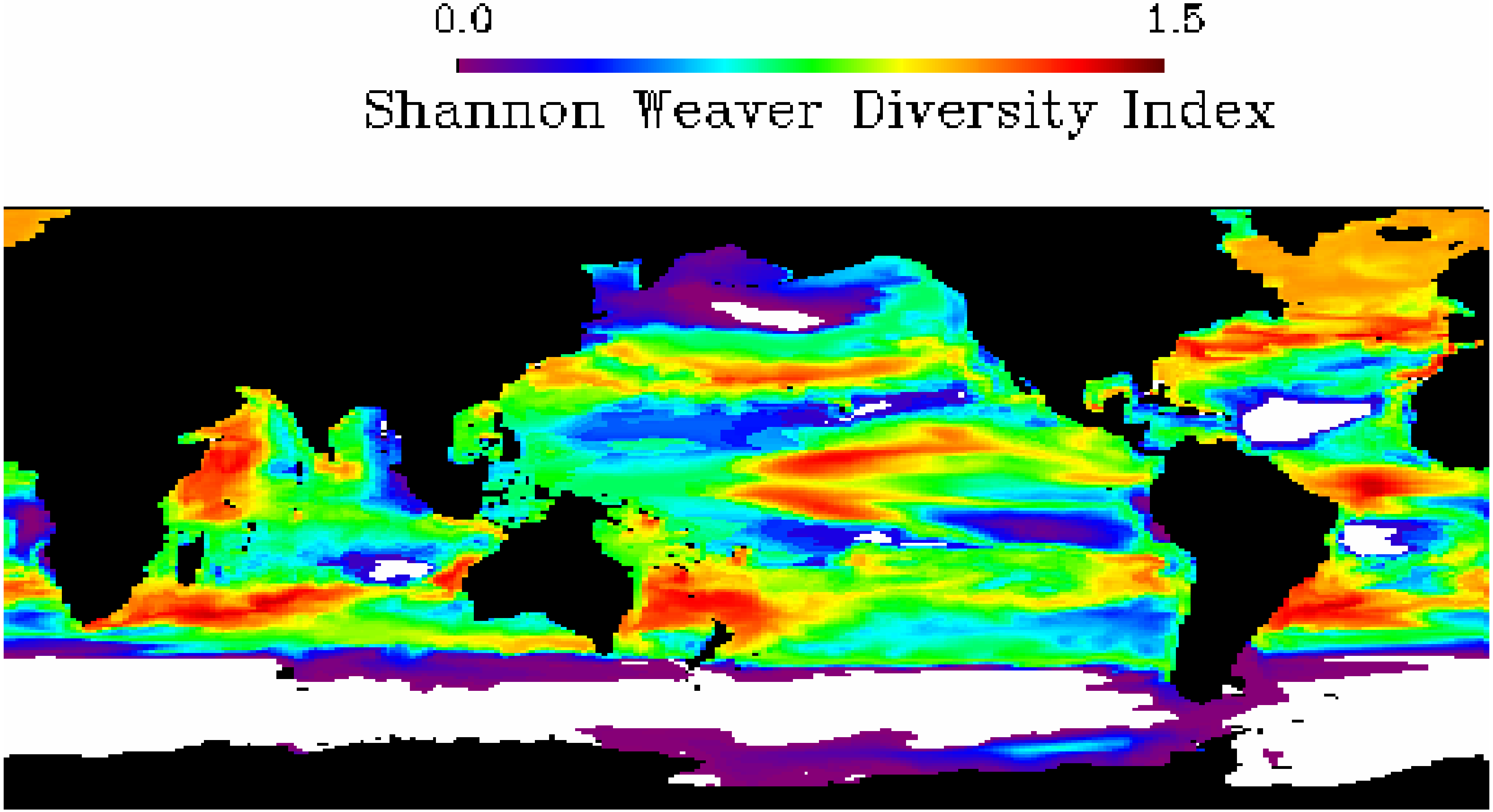


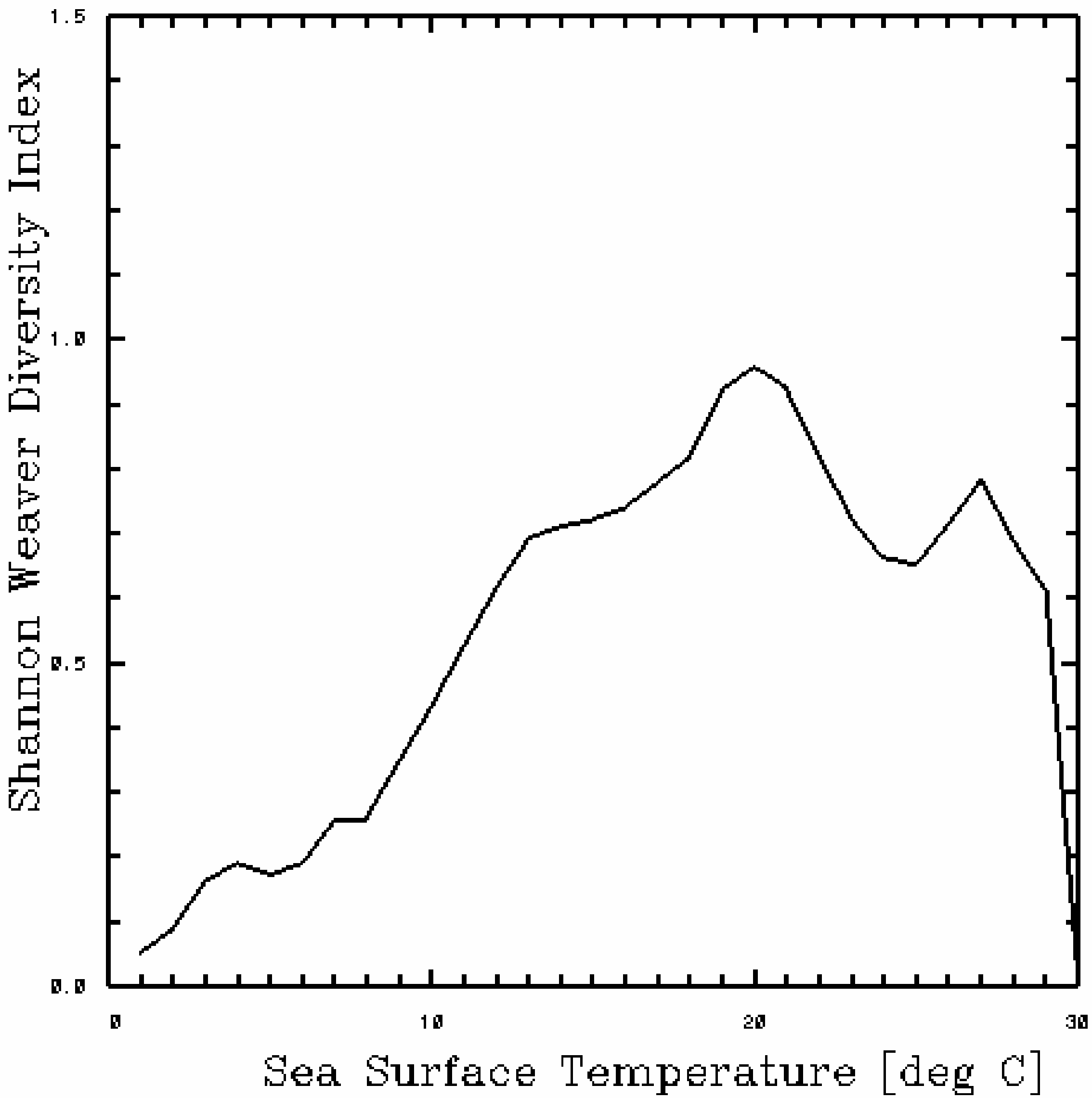
Sabine et al., 2004 Science


Mean Annual Silica Export Flux
90°N
60°N
30°N
0°
30°S
60°S
90°S
90°E
180°
90°W
0°
-10.0
0.0
0.5
1.0
2.0
3.0
5.0
10.0
20.0
100.0
g/m2

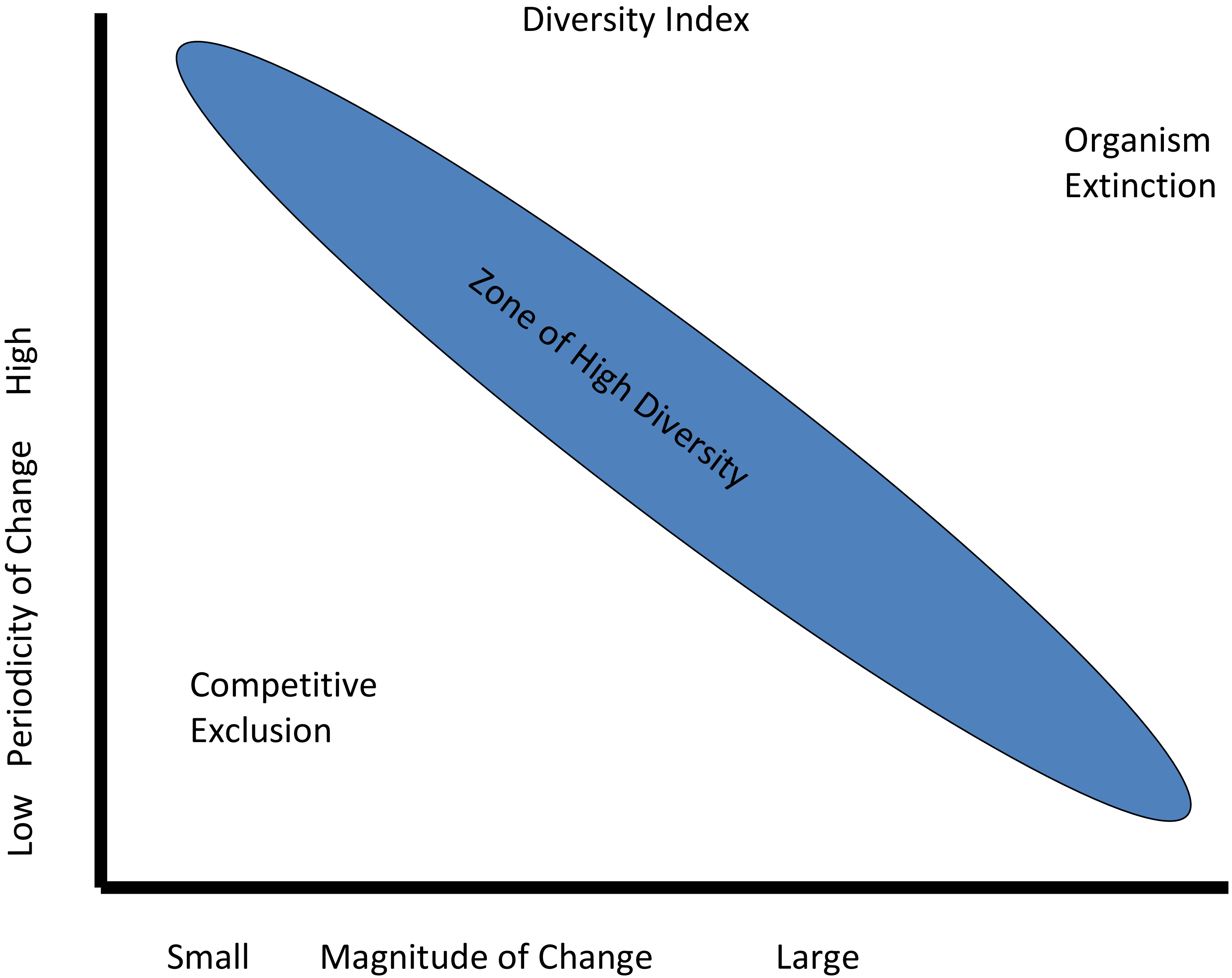

Mean Annual Export Silica/Inorganic Carbon Ratio
90°N
60°N
30°N
0°
30°S
60°S
90°S
90°E
180°
90°W
0°
-10.0
0.0
0.2
0.5
1.0
2.0
5.0
10.0
20.0
150.0

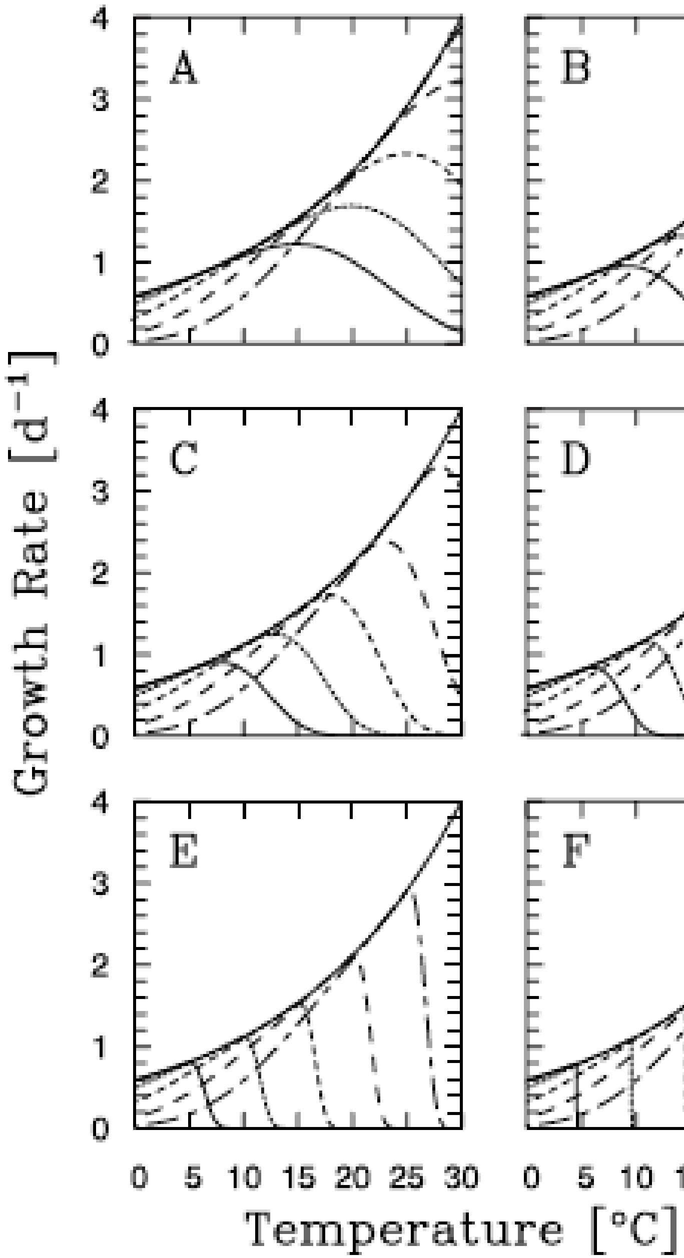
Phytoplankton Diversity



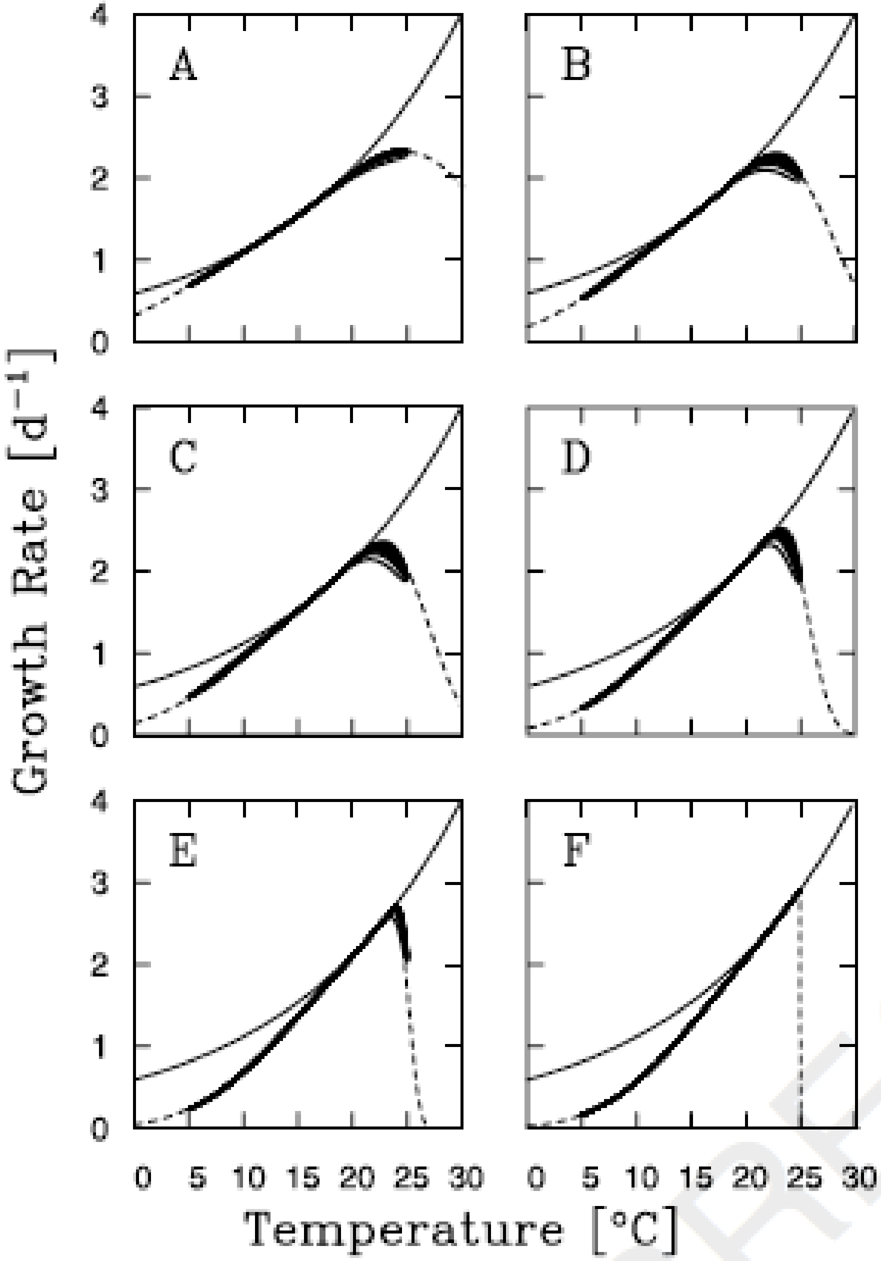


1.5
1.0
0.5
0.0
Shannon Weaver Diversity Index
0
10
20
30
Sea Surface Temperature [deg C]

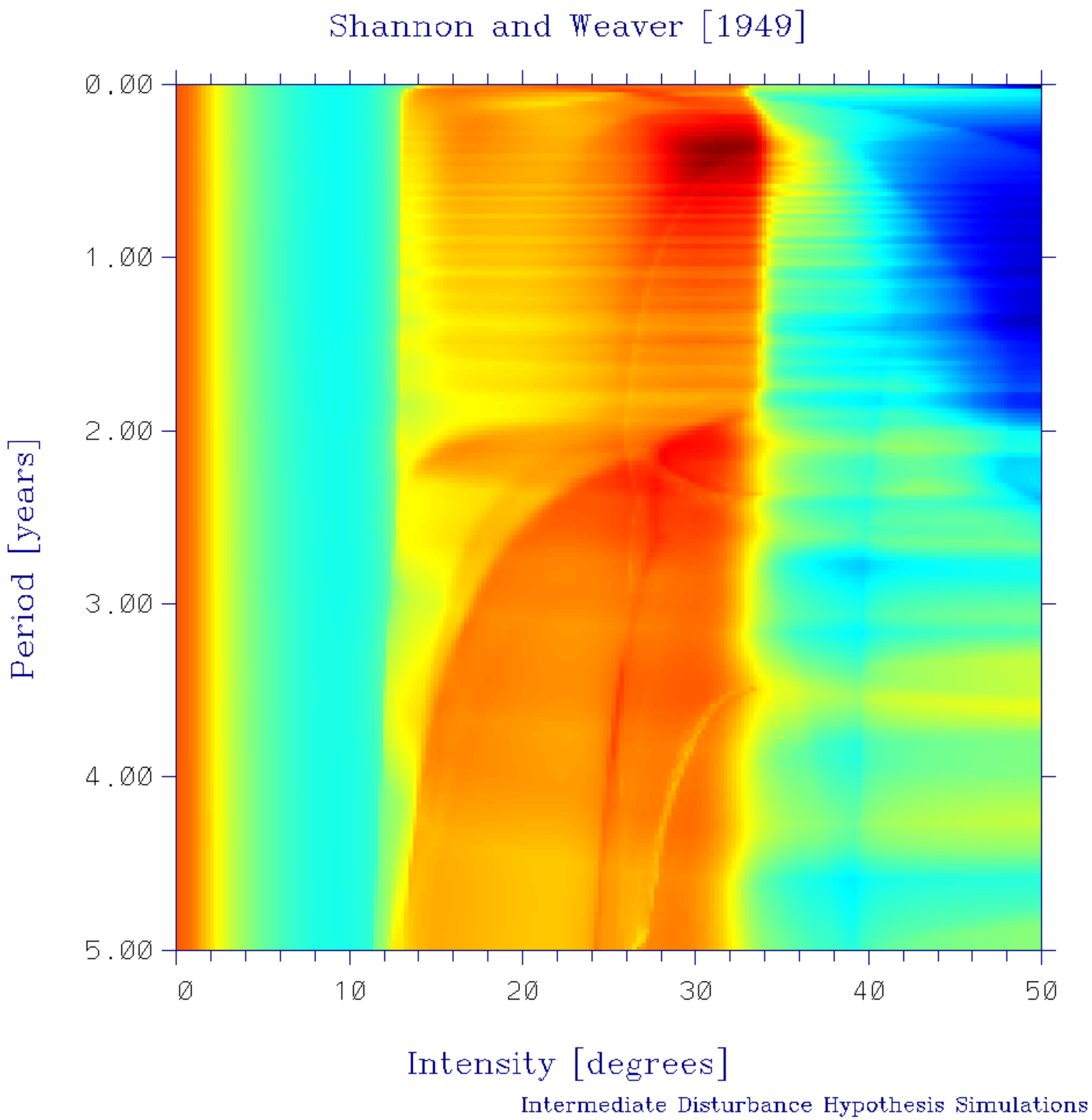

Diversity Index
Organism
Extinction
Zone of High Diversity
Competitive
Exclusion
High
Periodicity of Change
Low
Small
Magnitude of Change
Large



A
B
C
D
E
F
Growth Rate [d⁻¹]
0
1
2
3
4
0 5 10 15 20 25 30
Temperature [°C]



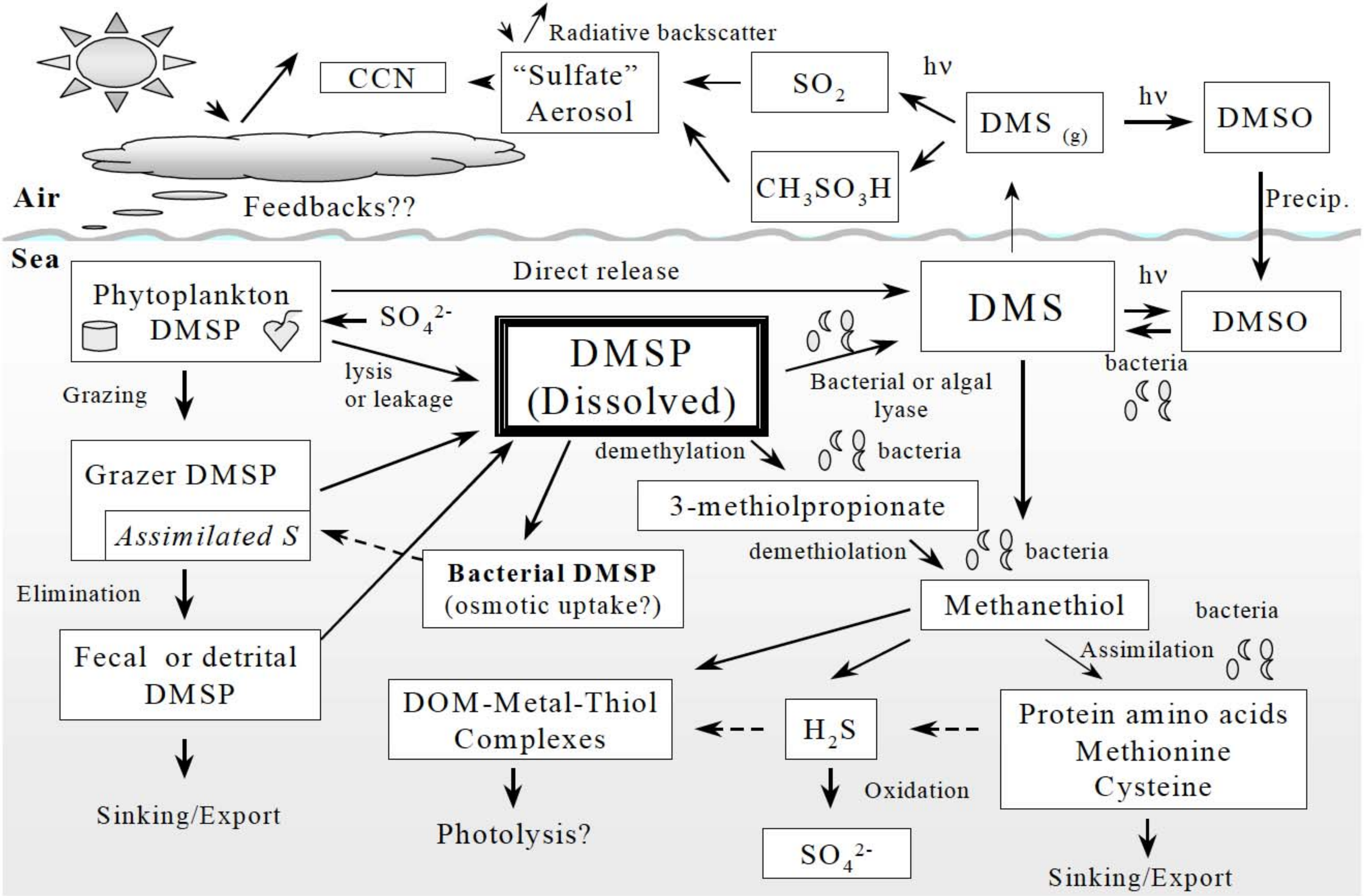
A
B
C
D
E
F
Growth Rate [d⁻¹]
0
1
2
3
4
0 5 10 15 20 25 30
Temperature [°C]


Shannon and Weaver [1949]
0.00
1.00
2.00
3.00
4.00
5.00
Period [years]
0
10
20
30
40
50
Intensity [degrees]
Intermediate Disturbance Hypothesis Simulations

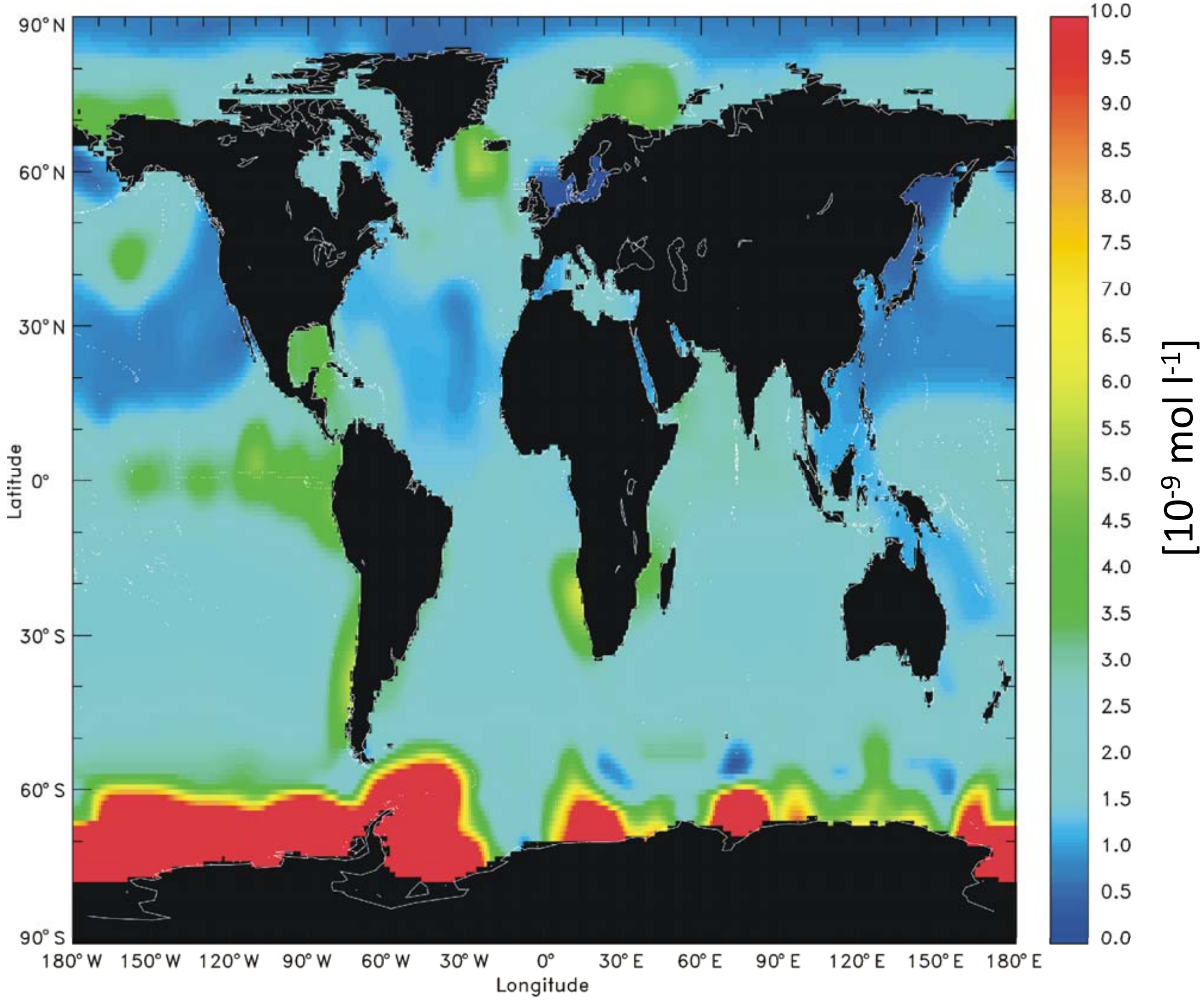
Atmospheric Gases and Aerosols

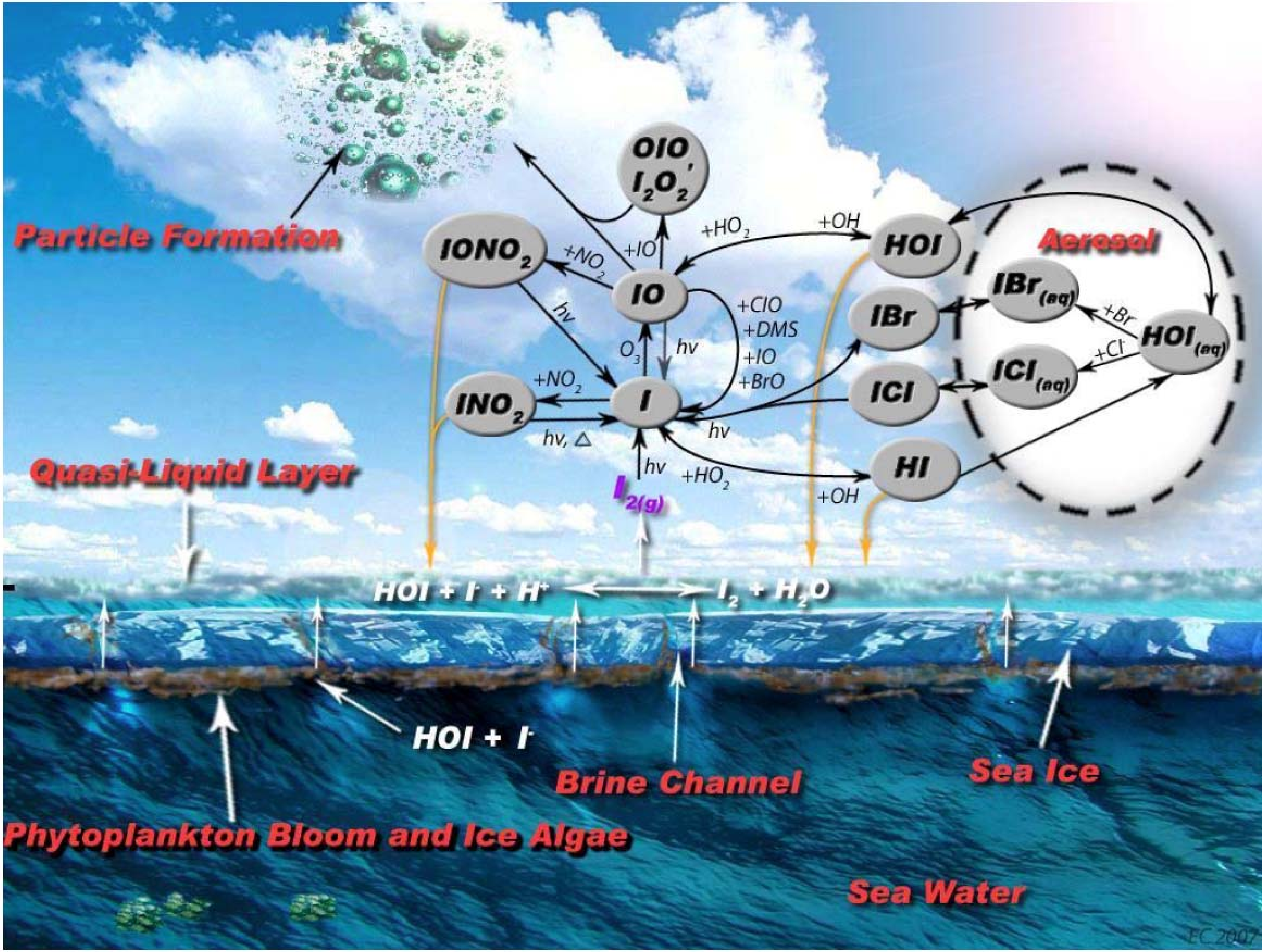
- DMS
  - Claw Hypothesis
  - R. J. Charlson, J. E. Lovelock, M. O. Andreae, S. G. Warren, Nature 326, 655 (1987)
  - > 700 papers
  - Full analysis on this feedback has yet to be done
- Iodate
  - Phytoplankton source
  - New production link
  - Tropospheric ozone depletion link

Gases


Radiative backscatter
CCN
"Sulfate" Aerosol
SO2
hν
DMS (g)
hν
DMSO
CH3SO3H
Air
Feedbacks??
Precip.
Sea
Phytoplankton DMSP
Direct release
DMS
hν
DMSO
SO4 2-
DMSP (Dissolved)
lysis or leakage
Bacterial or algal lyase
bacteria
Grazing
Grazer DMSP
Assimilated S
demethylation
bacteria
3-methiolpropionate
demethiolation
bacteria
Bacterial DMSP (osmotic uptake?)
Elimination
Methanethiol
bacteria
Assimilation
Fecal or detrital DMSP
DOM-Metal-Thiol Complexes
H2S
Protein amino acids Methionine Cysteine
Sinking/Export
Photolysis?
Oxidation
SO4 2-
Sinking/Export

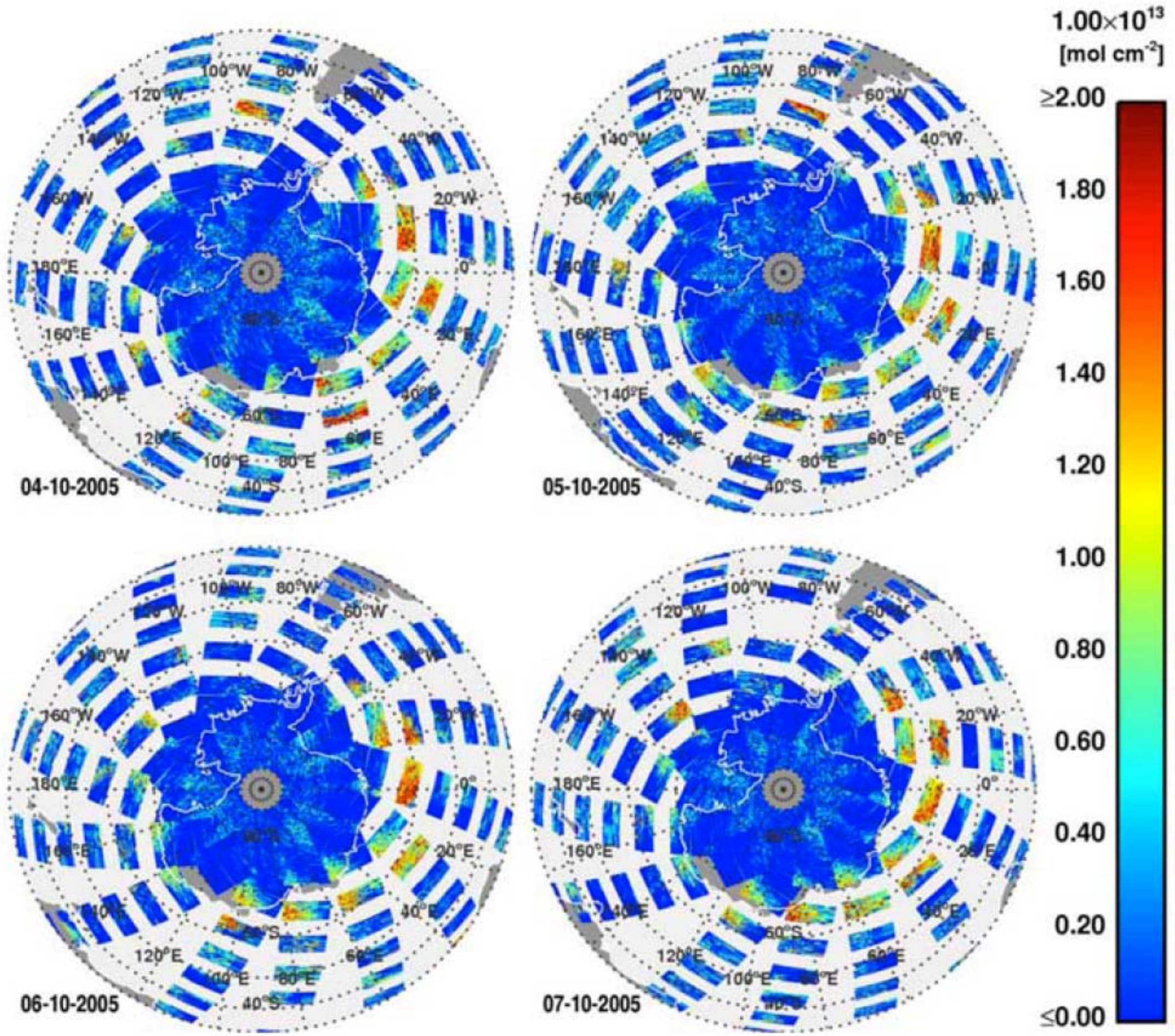
Annual Mean Surface Ocean DMS



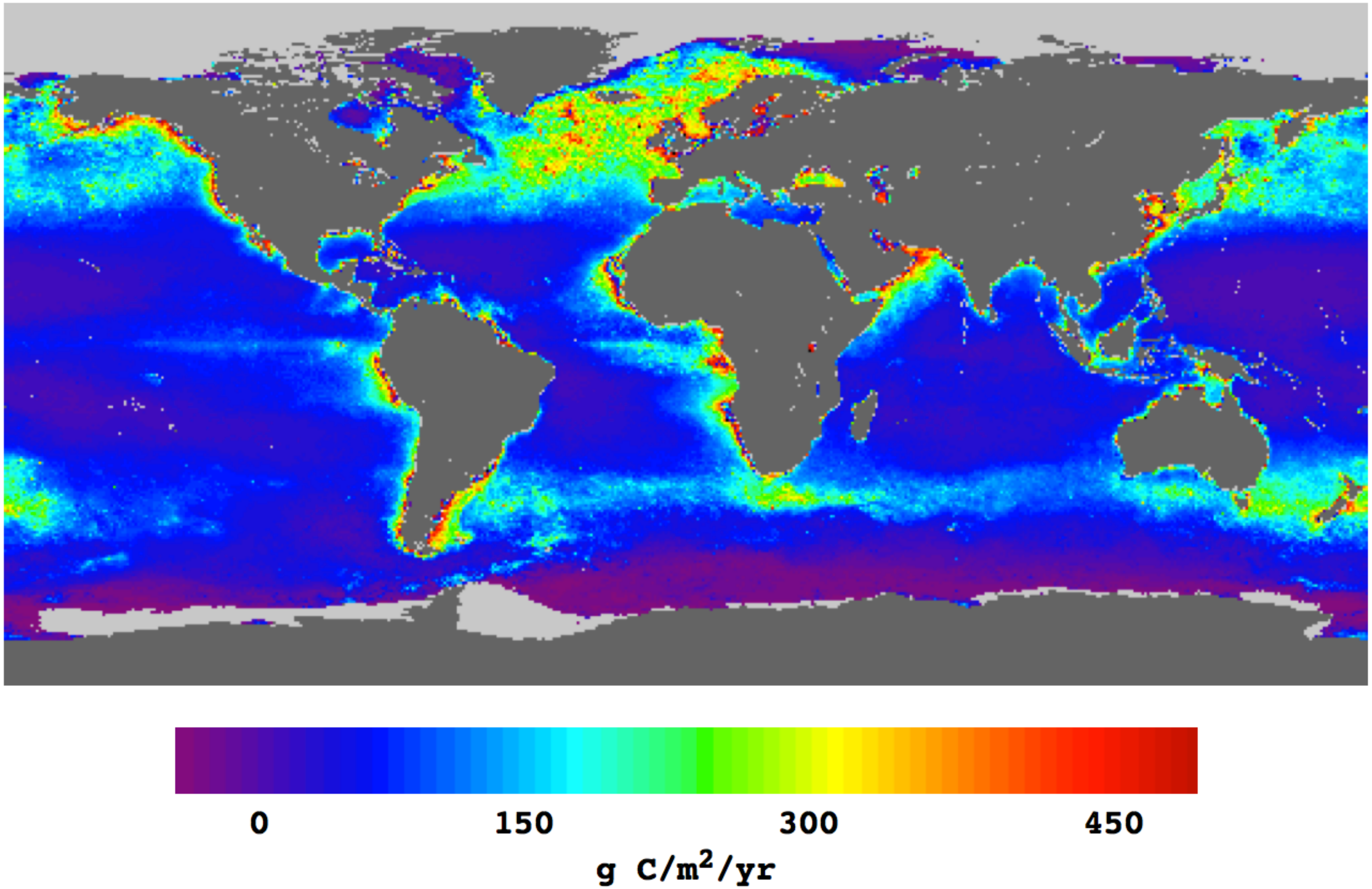


Particle Formation
OIO, I2O2
IONO2
+NO2
+IO
IO
+HO2
+OH
HOI
Aerosol
IBr(aq)
IBr
+Br
HOI(aq)
+ClO
+DMS
+IO
+BrO
hv
O3
+Cl
ICl(aq)
+NO2
INO2
I
ICl
hv, △
hv
hv
+HO2
HI
+OH
Quasi-Liquid Layer
I2(g)
HOI + I- + H+
I2 + H2O
HOI + I-
Brine Channel
Sea Ice
Phytoplankton Bloom and Ice Algae
Sea Water
EC 2007

IO from Space (SCIAMACHY)



Annual Global Primary Production



Behrenfeld and Falkowski, 1997 P_b^{opt} algorithm

Comparison of Global Estimates of PP

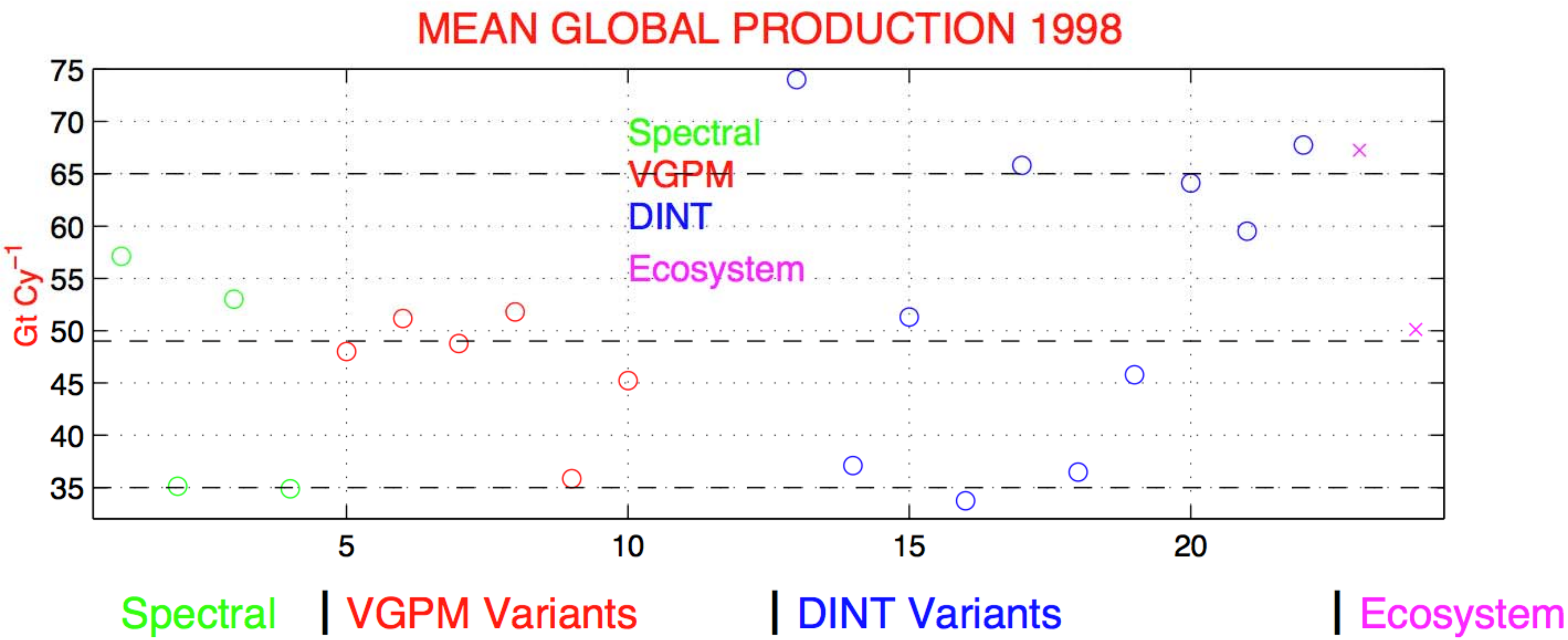
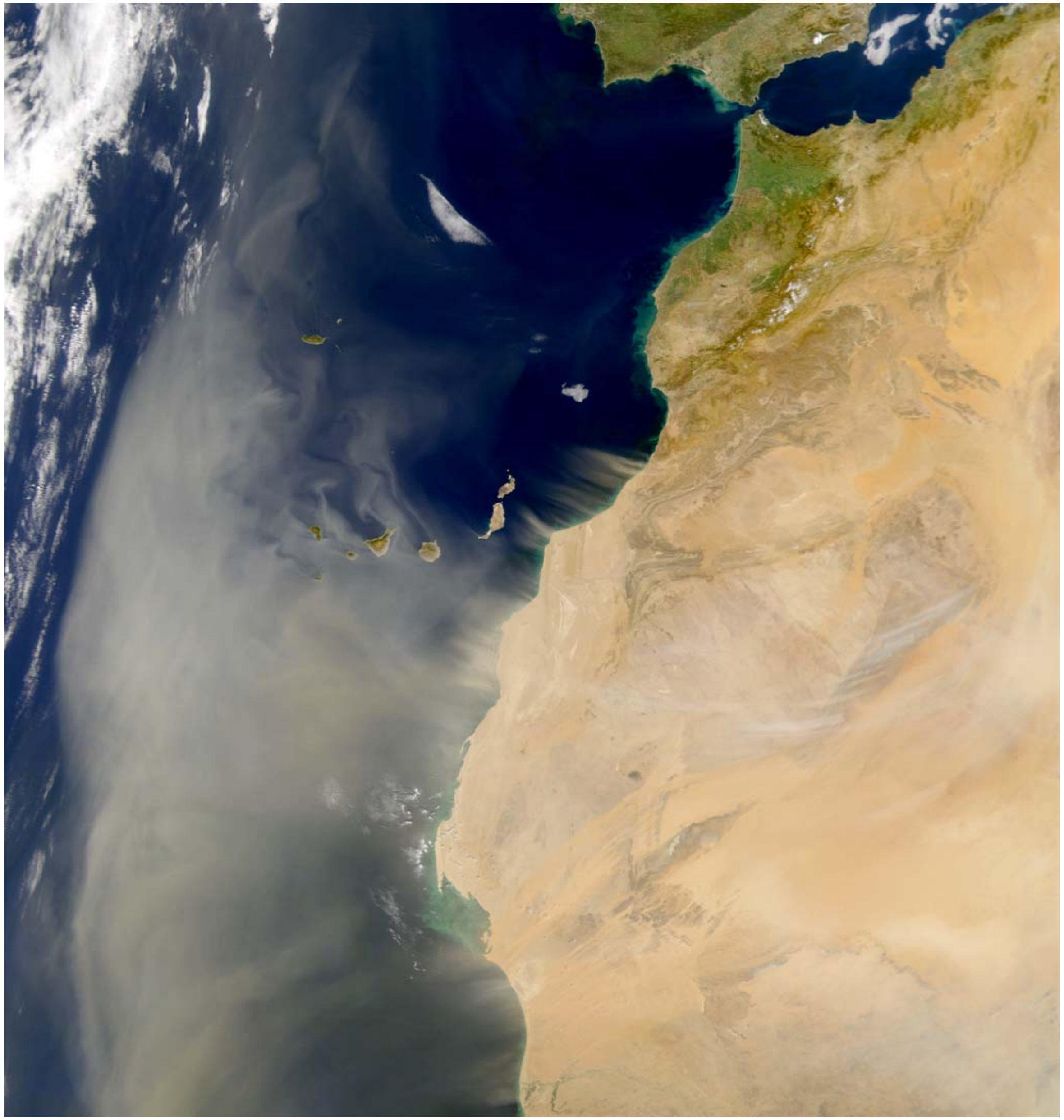


Figure from Carr et al.,

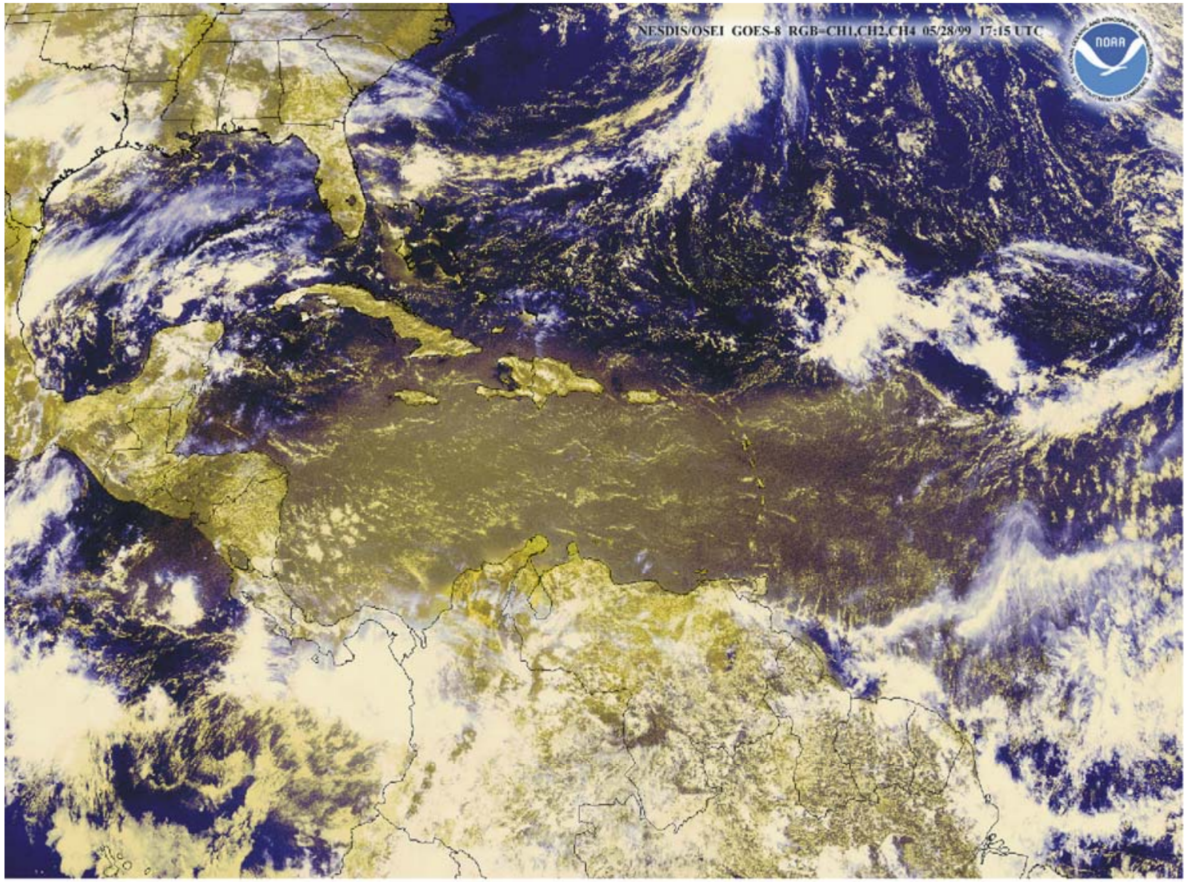
Dust

- Variability linked to climate variability
- Important source of Fe to oceans
- Has broad ocean-reaching length scales
- Possible feedbacks with DMS/clouds

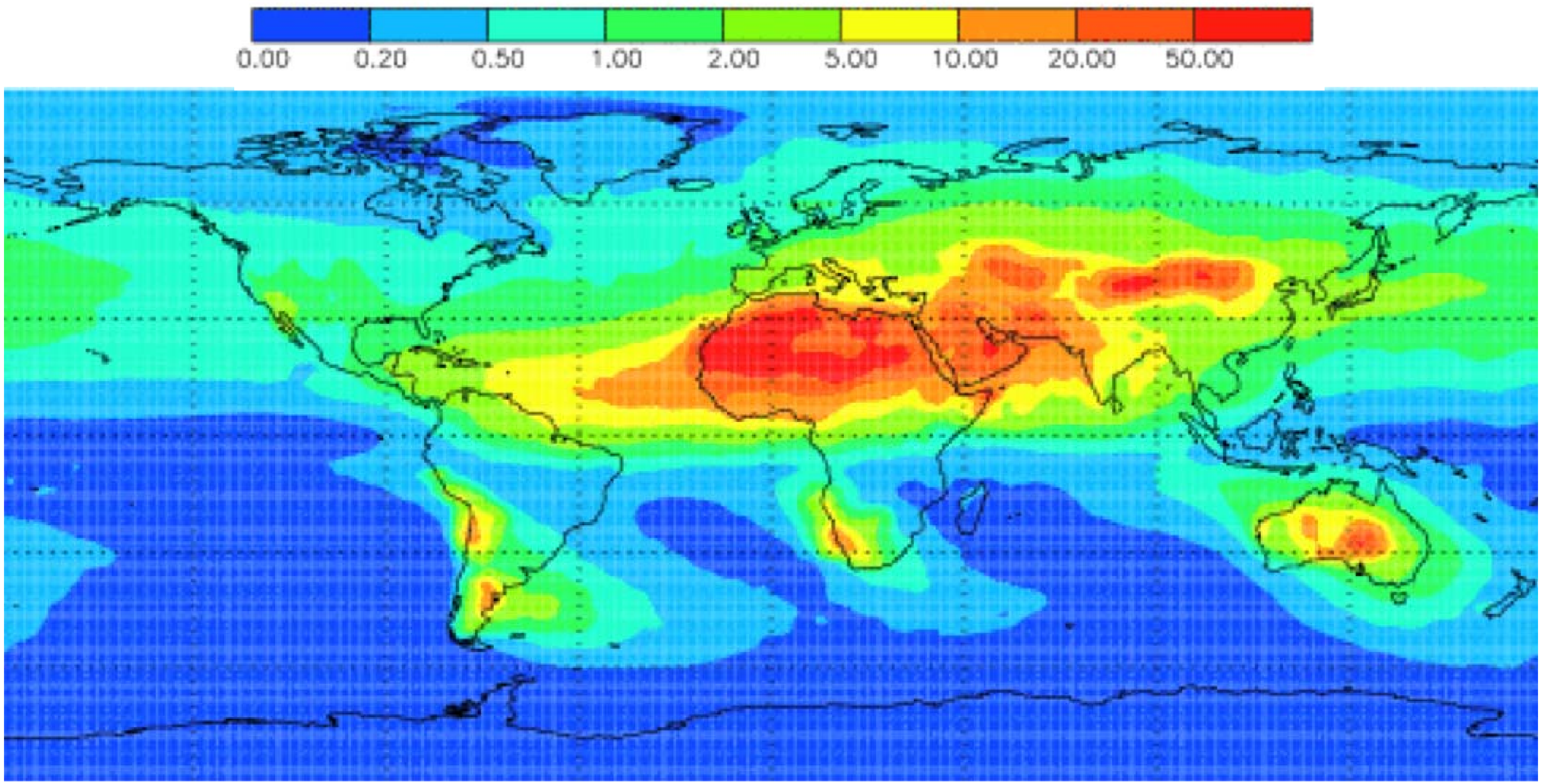
Dust over the Canary Islands



NOAA GOES Image (28 May, 1999) of Dust from Africa

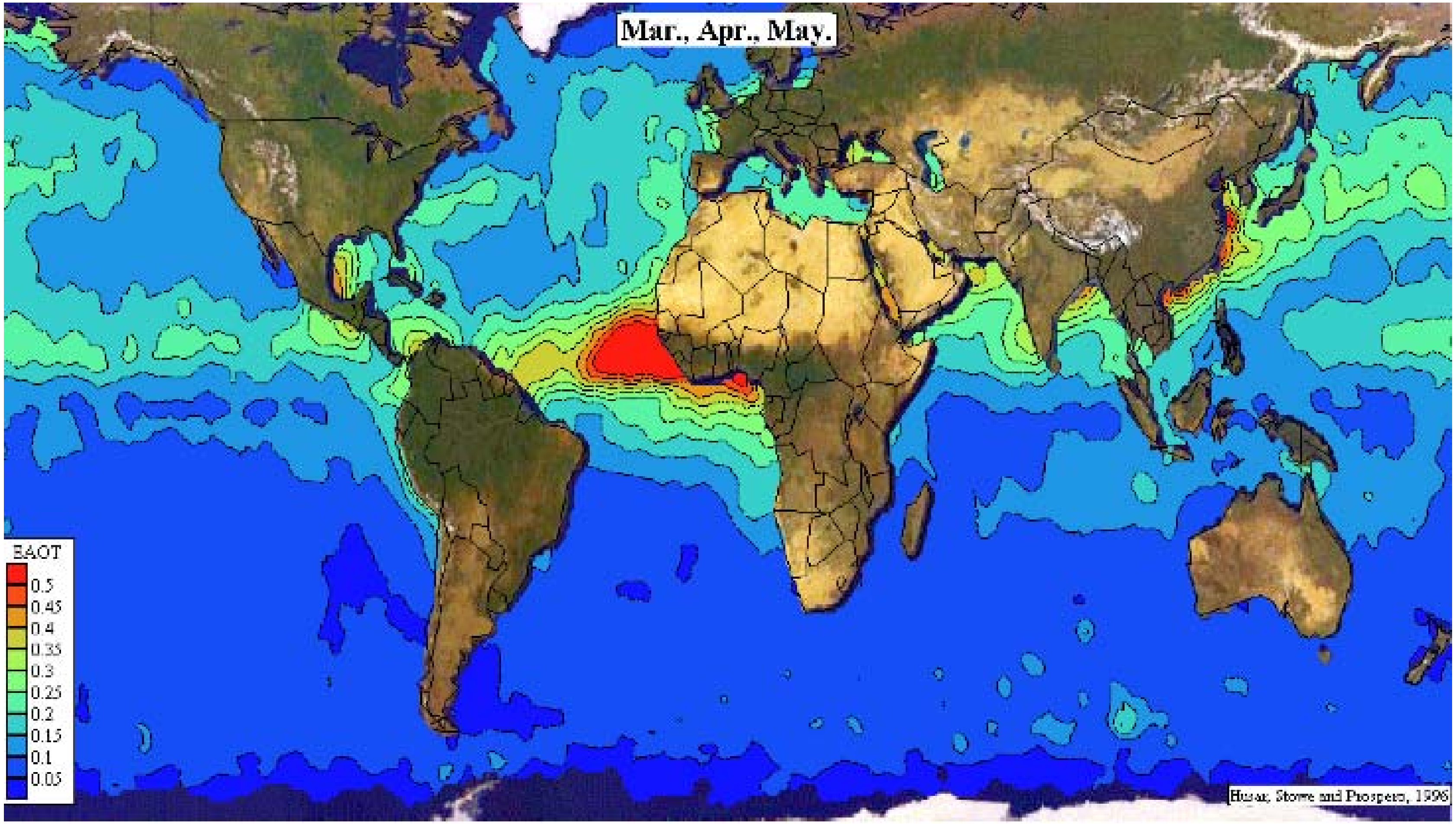


Simple Average Dust Deposition [g m^{-2} $year^{-1}$]



Mahowald, et al., 1995

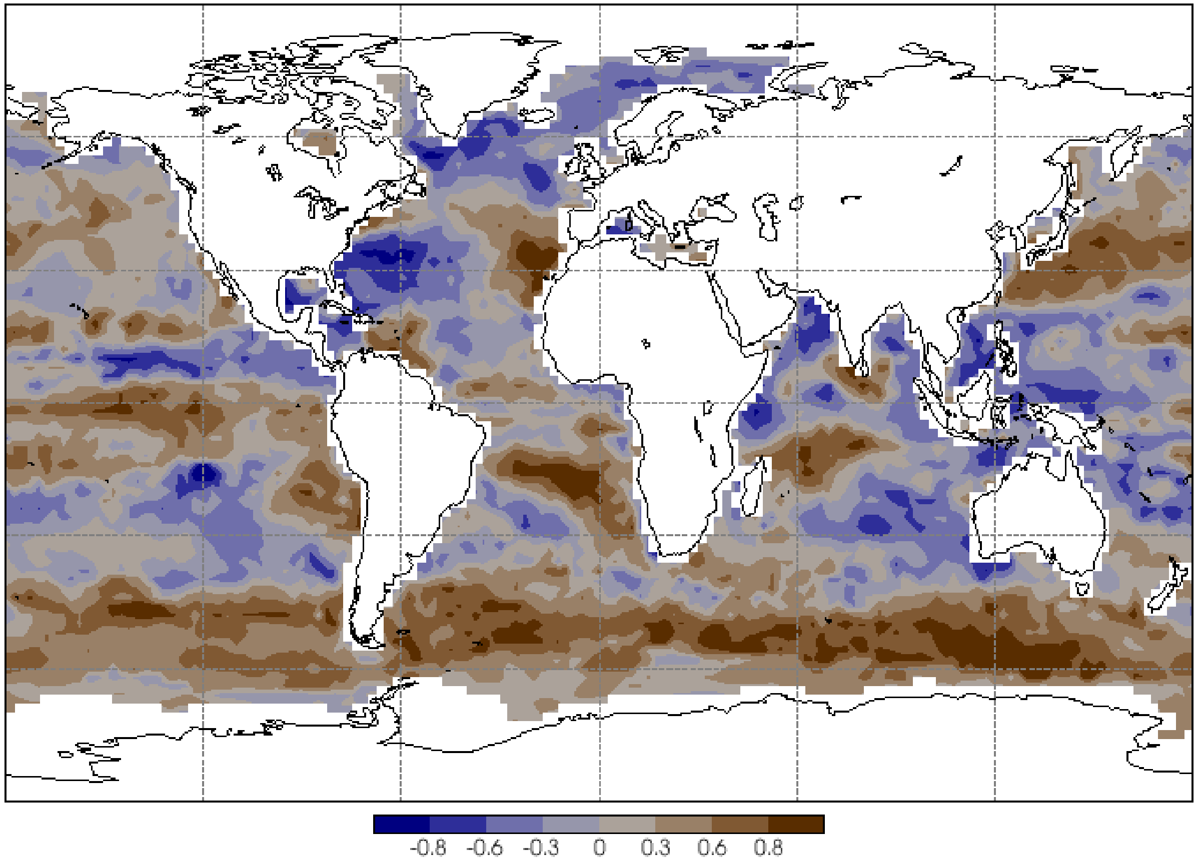
AVHRR annual mean aerosol optical depth for spring (March/April/May) 1989-1991



Husar et al, 1997

Correlation Coefficients

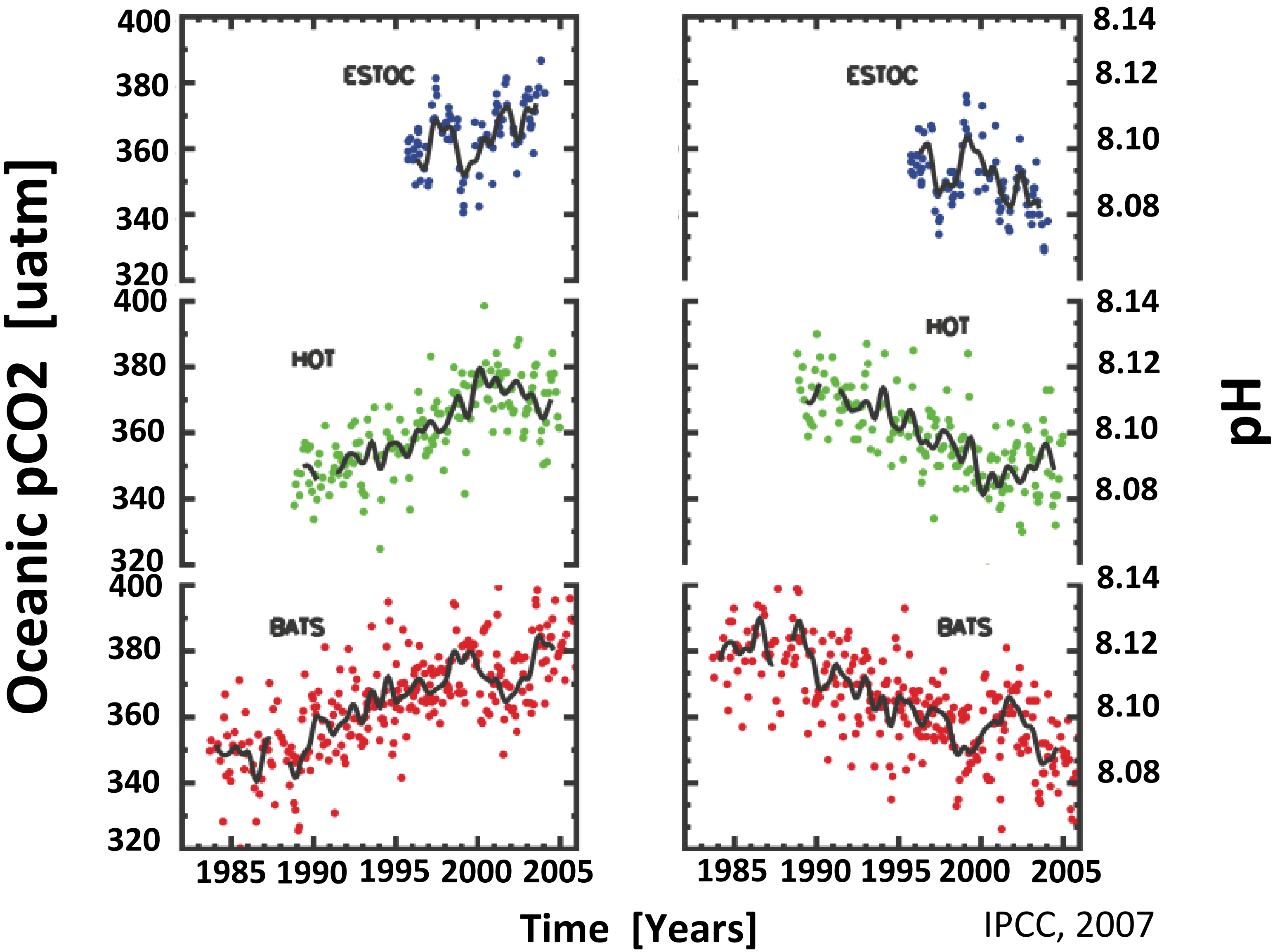
Climatology of Dust Deposition and SeaWiFS Chlorophyll



Acidification

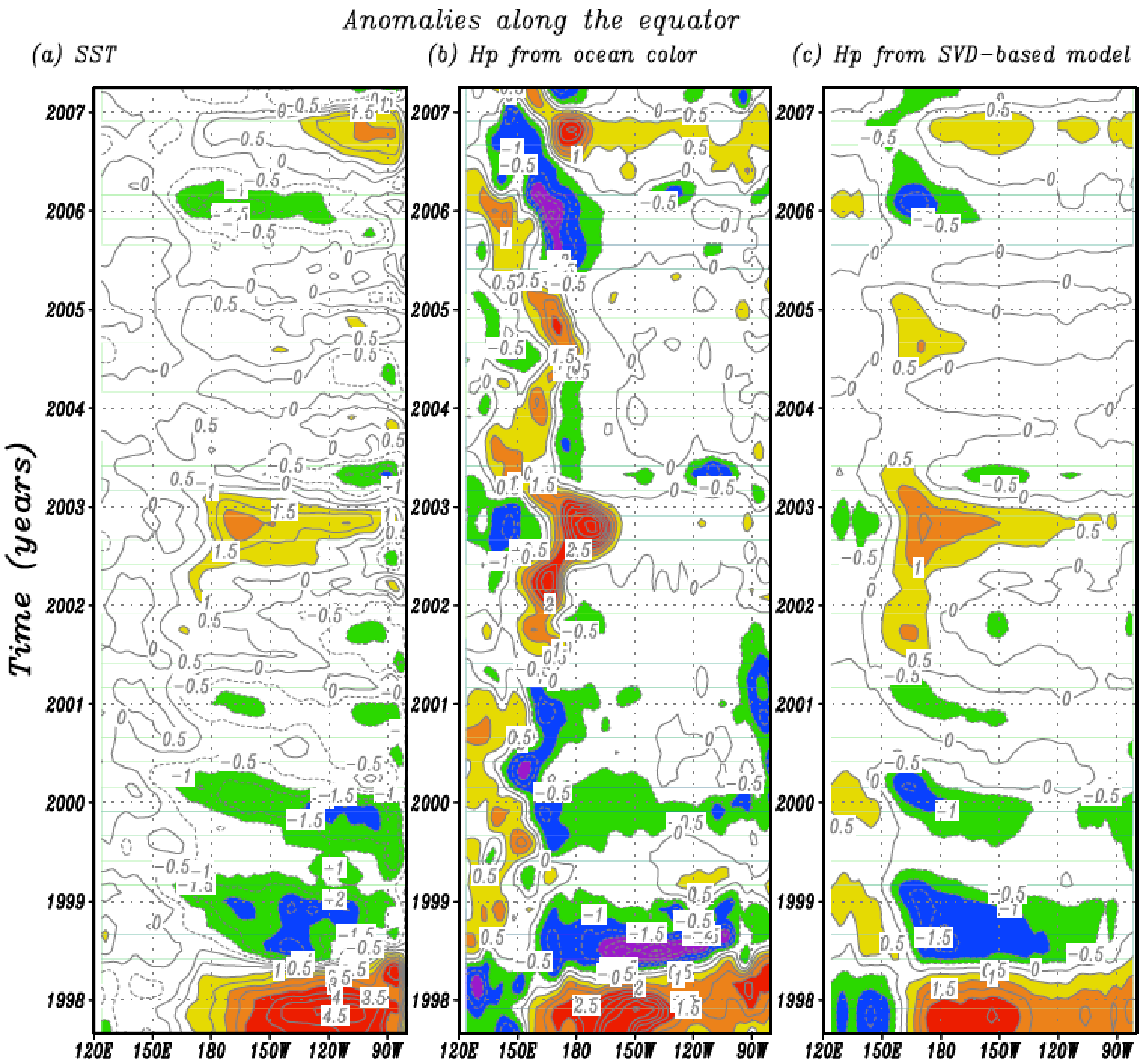
- Changes in the CCD
- Impact on Coccolithophoresseems most likely
- Impact on efficiency of carbon pump
- Unknown impact on diatoms (some like it hot)

Ocean Time Series pCO2 and pH Observations

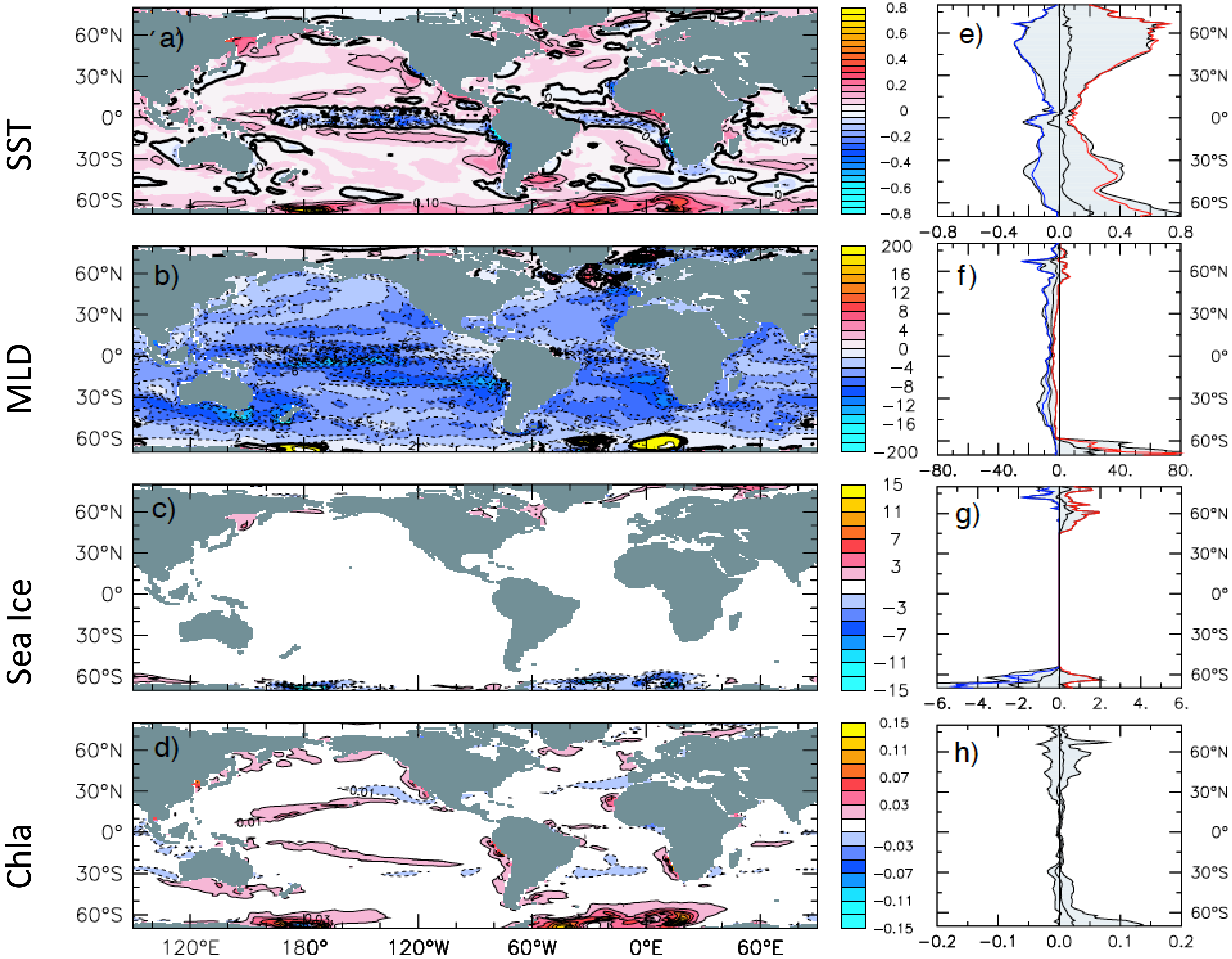


IPCC, 2007

Phytoplankton and ENSO forcing



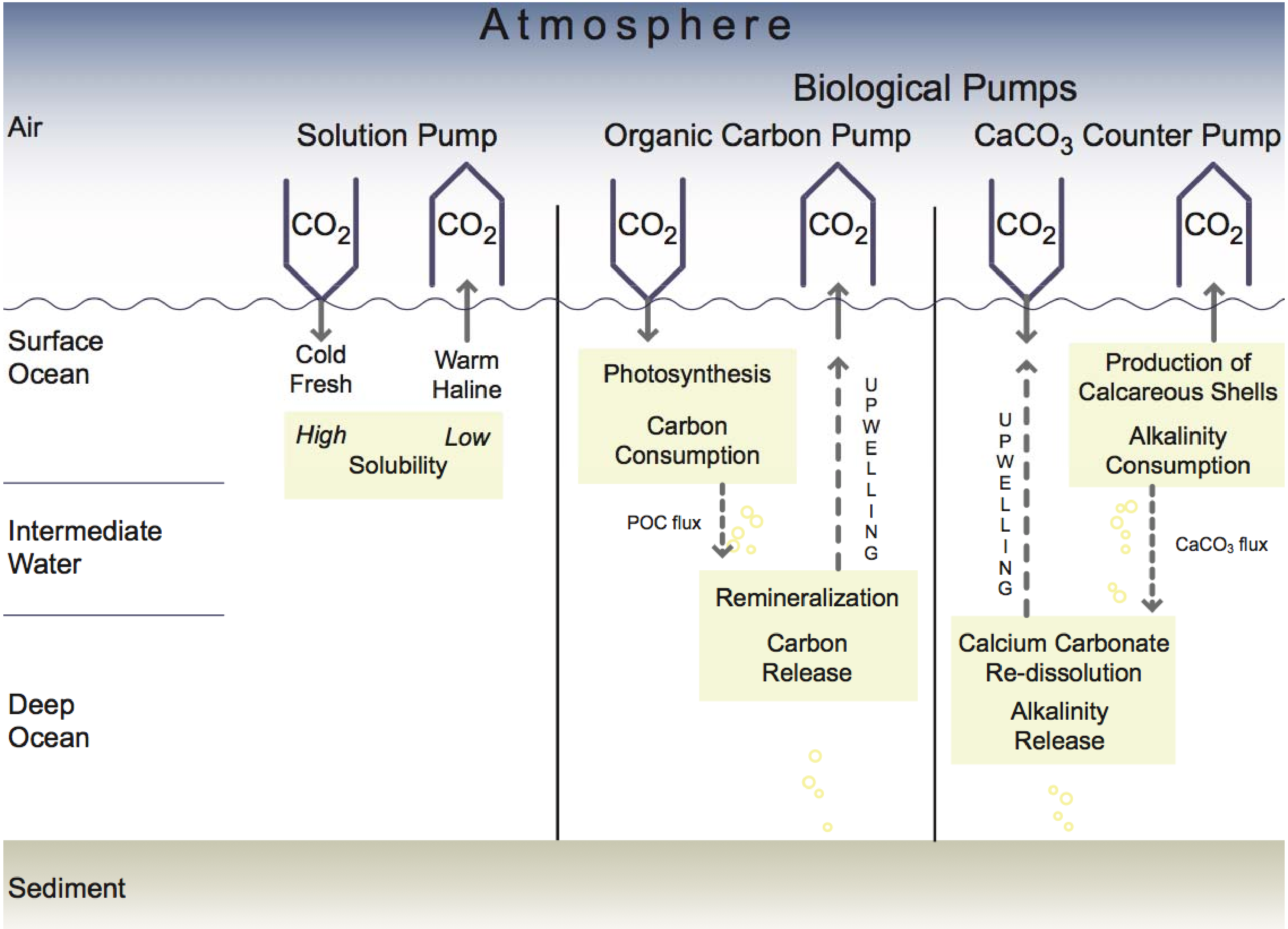
Zhang et al., GRL 2009: Ocean biologically induced forcing can have significant effects on ENSO behaviors, including its amplitude, oscillation periods and seasonal phase locking



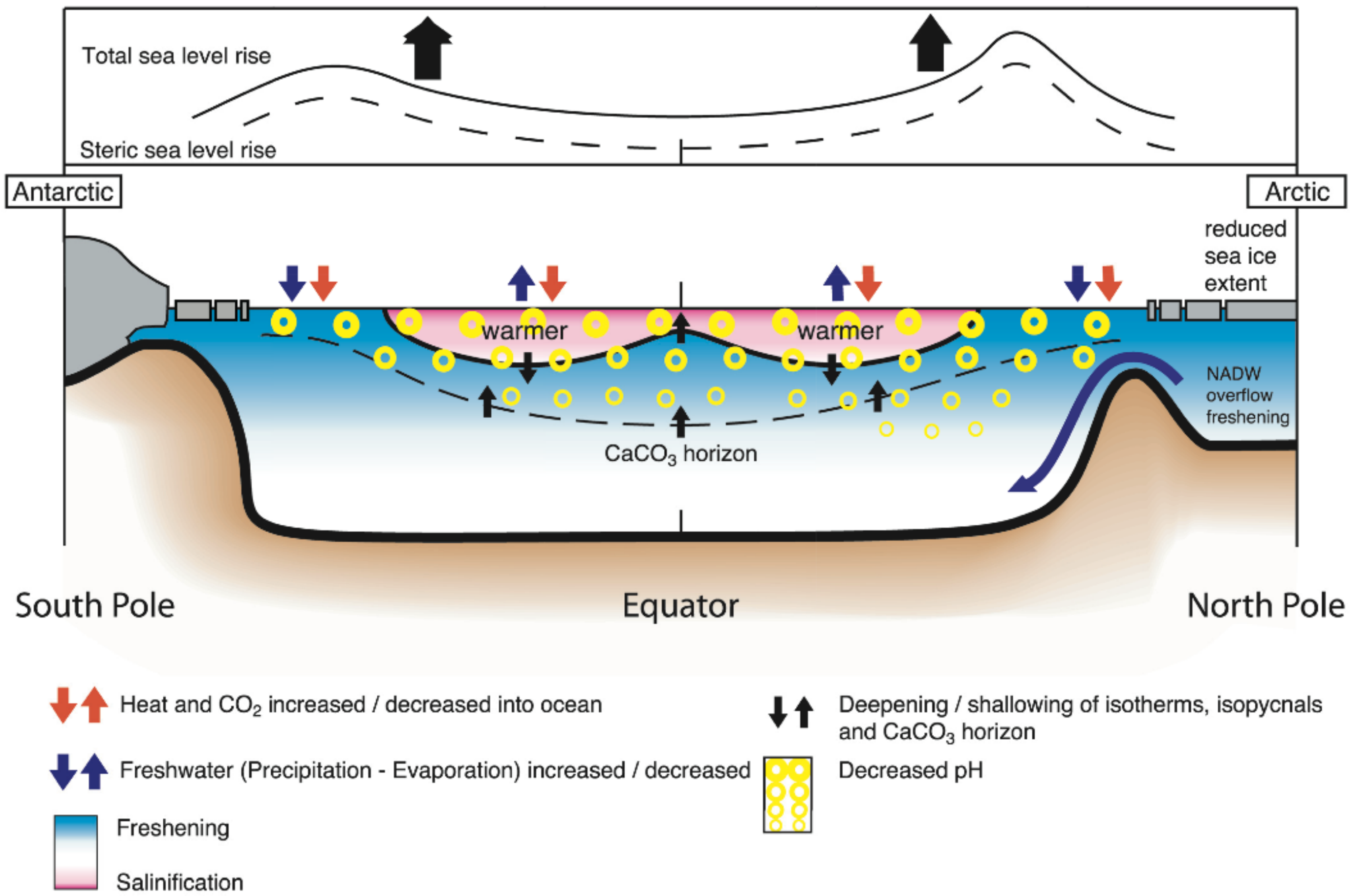
Manizza et al., 2009 GRL

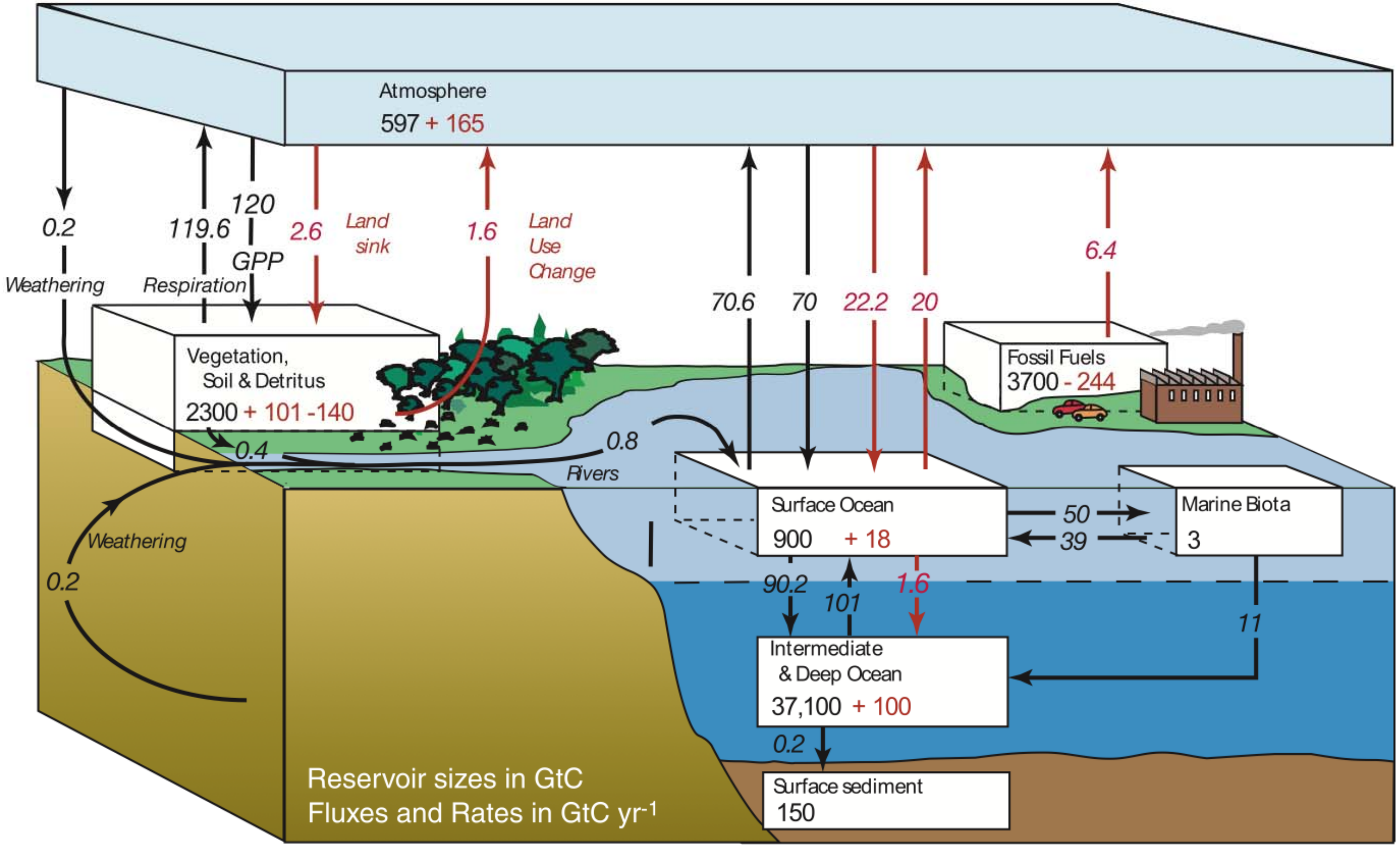
Impact is that SST variability is amplified by 10%

IPCC report Risk Summary



IPCC Ocean Change Summary




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
Vegetation, Soil & Detritus
2300 + 101 -140
Fossil Fuels
3700 - 244
0.4
0.8
Rivers
Surface Ocean
900 + 18
50
39
Marine Biota
3
Weathering
0.2
90.2
101
1.6
11
Intermediate & Deep Ocean
37,100 + 100
0.2
Surface sediment
150
Reservoir sizes in GtC
Fluxes and Rates in GtC yr-1

Ciao