

Part II: chemical oceanography

- **Processes:** Physical, chemical and biological mechanisms that transfer elements within the ocean and across boundaries with atmosphere and land biosphere
- **Cycling:** Interaction of processes that regulates the global distribution
- **Climate-relevant elements:** CO₂, methane, oxygen, nutrients, trace metal, ...

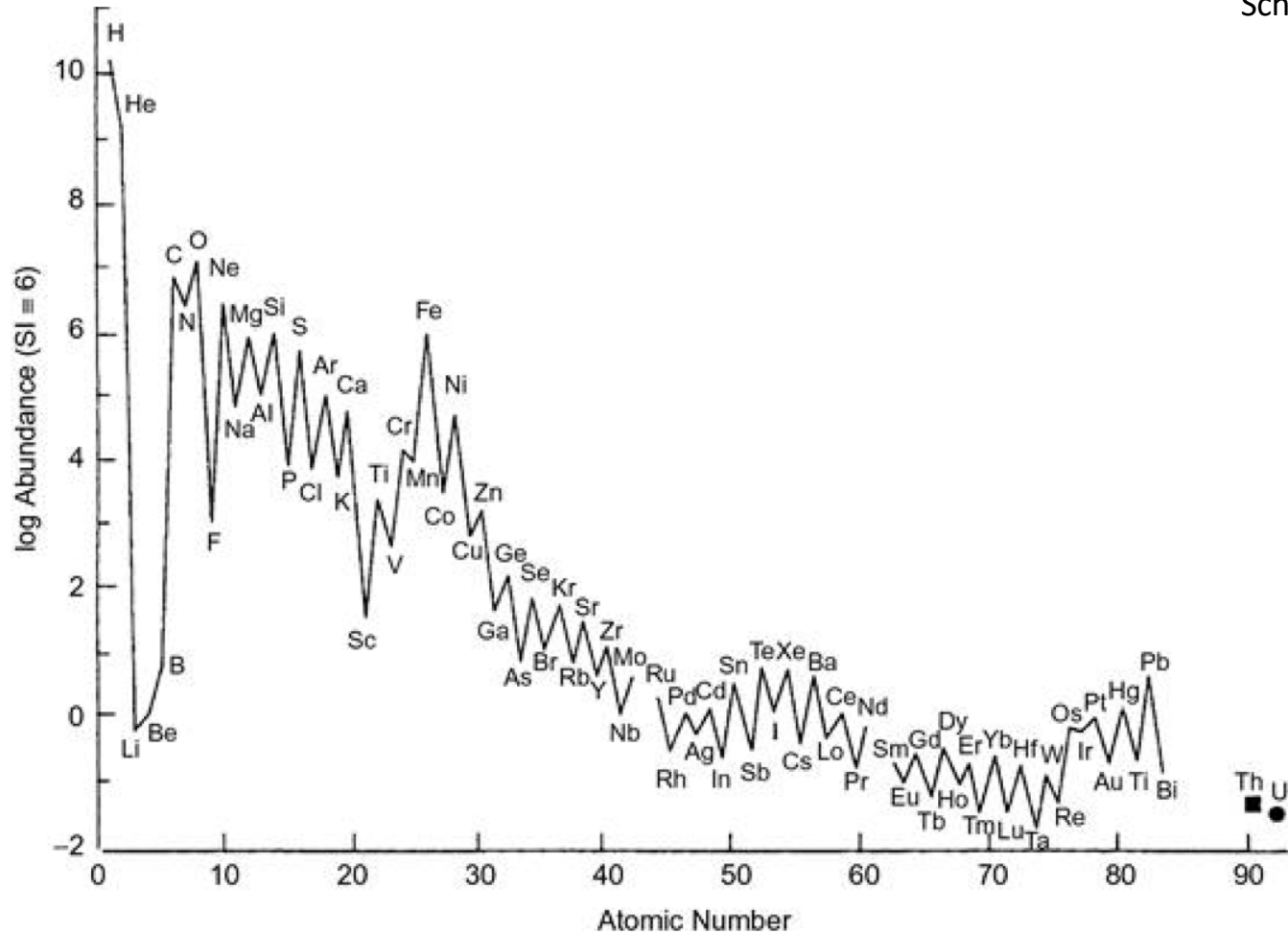
The origin

- 13.7 billion years ago (Ga):
The Big bang
- 12.5 Ga: The Milky Way
galaxy
- 4.57 Ga: The Solar System

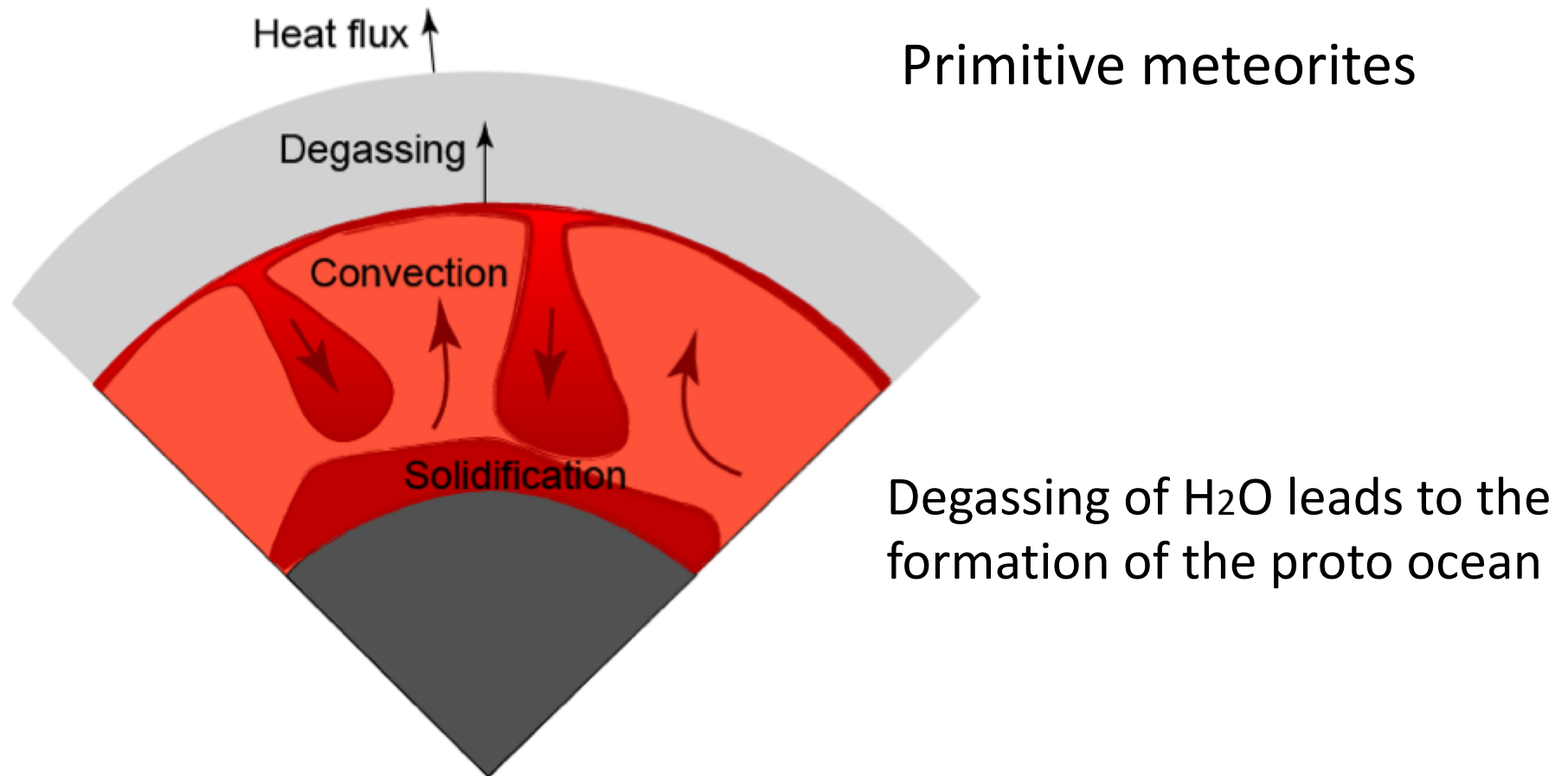
with thanks to L. T. Elkins-Tanton, JPL

Cosmic abundance

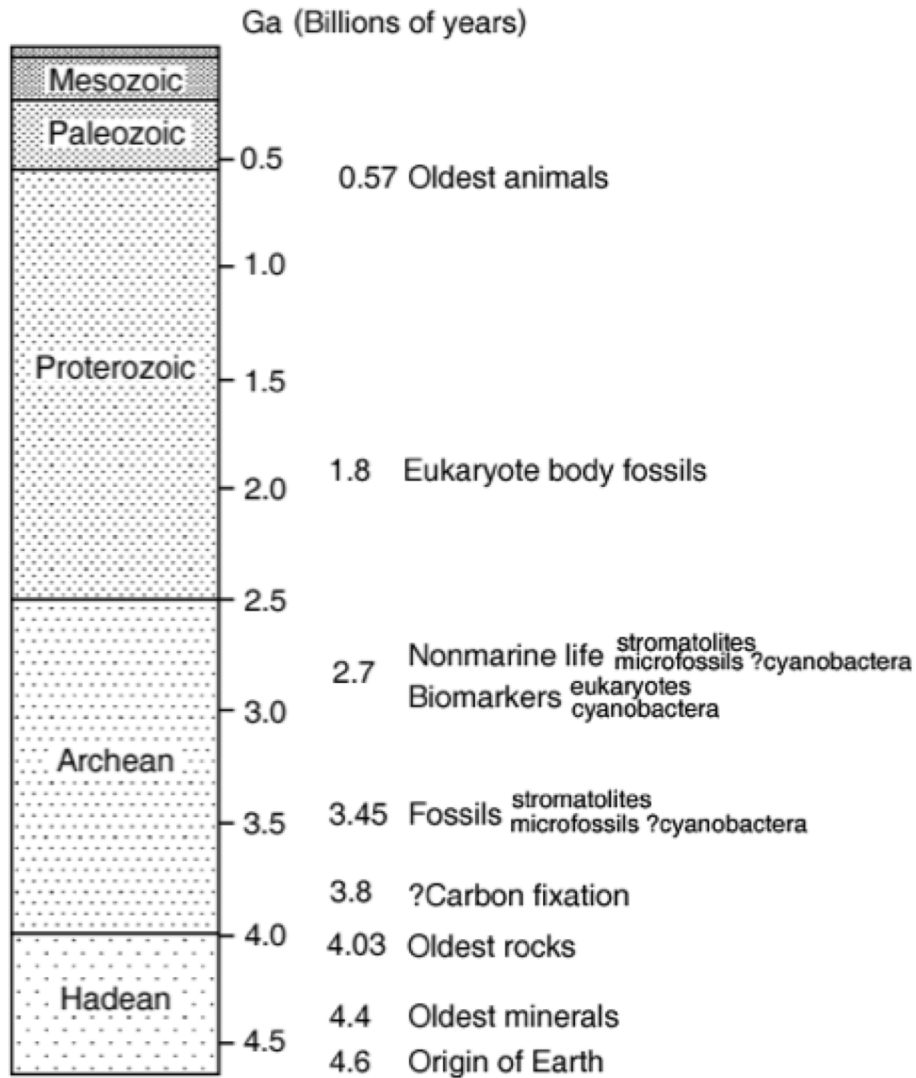
Schlesinger Fig 2.1



Cooling and solidification of the early Earth



Early life

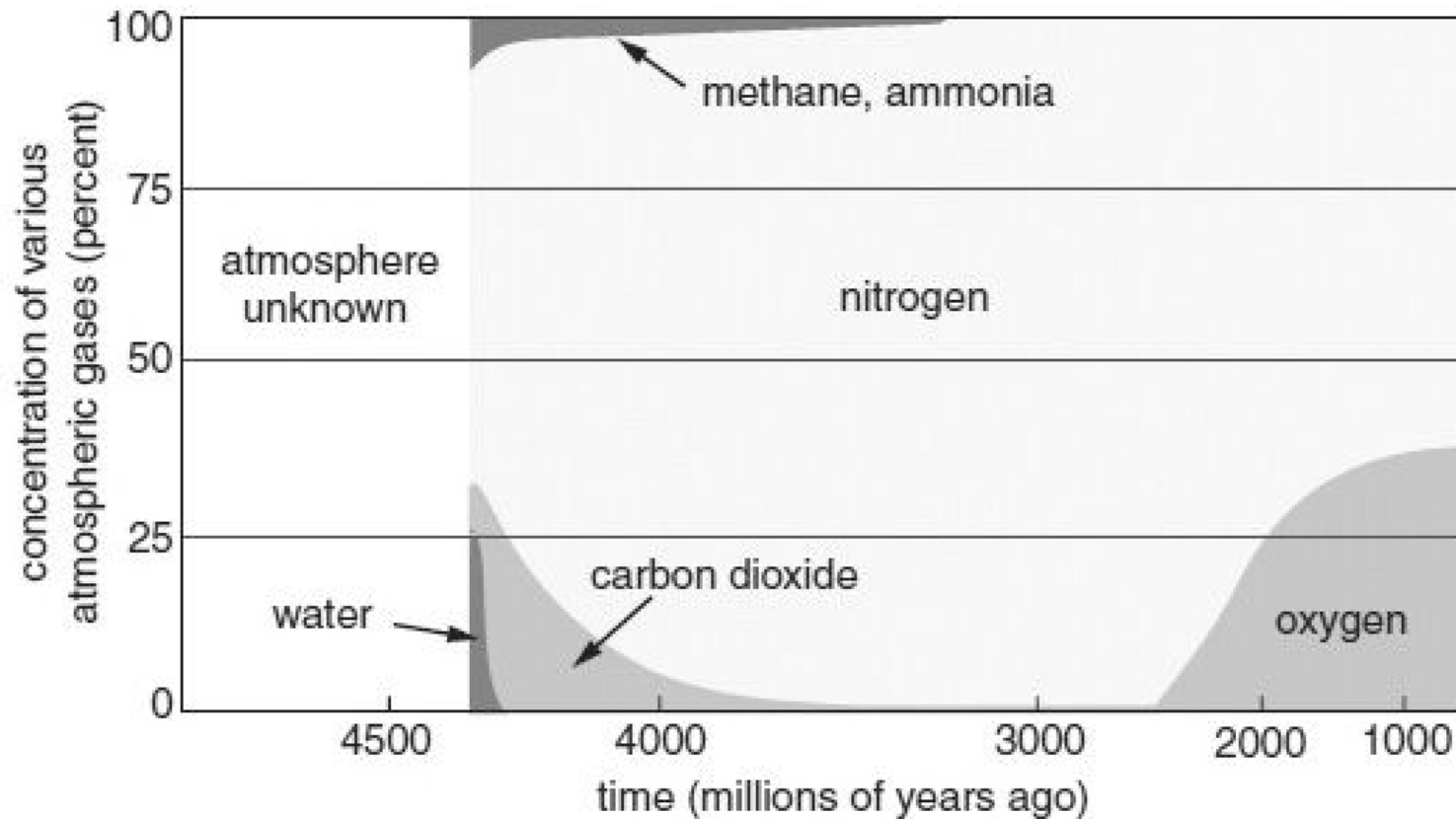


- 0.5 Ga: Cambrian explosion
- 2.5 Ga: Atmospheric oxygen starts to rise
- 3.4-3.8 Ga: Evidences of the earliest life

The Archean Earth

- 4 to 2.5 Ga
- Very low atmospheric oxygen content
 - No ozone layer
 - UV radiation reaching the surface
 - Early life was likely anaerobic and underwater
- CO₂ and CH₄ rich atmosphere
 - Super greenhouse effect
 - Despite the faint young sun, the surface of the Earth was likely warmer than today

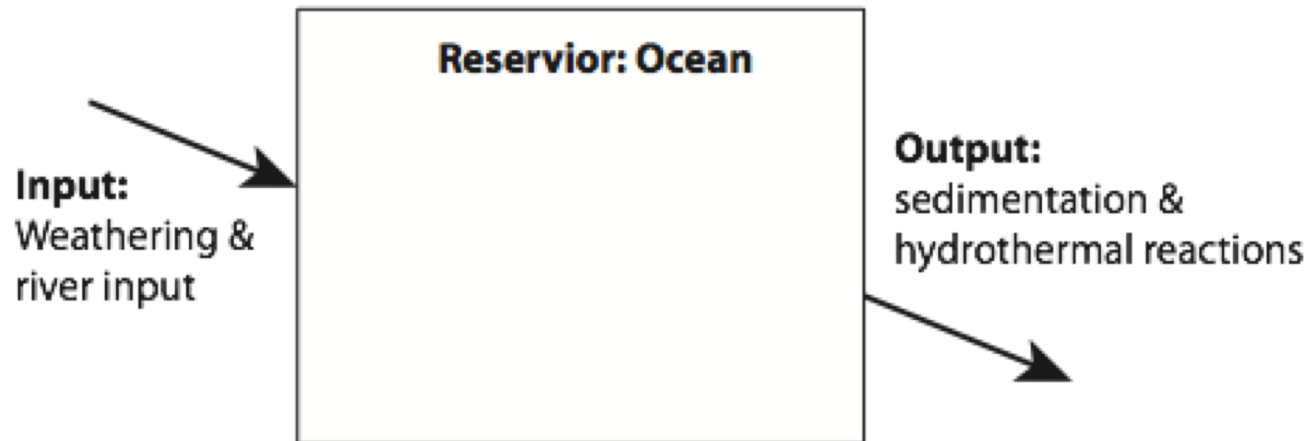
Early Atmosphere



Geochemical balances

- Mass balance
 - Reservoir: ocean
 - Steady-state: (input) = (output)

Steady state of most salt minerals in the ocean

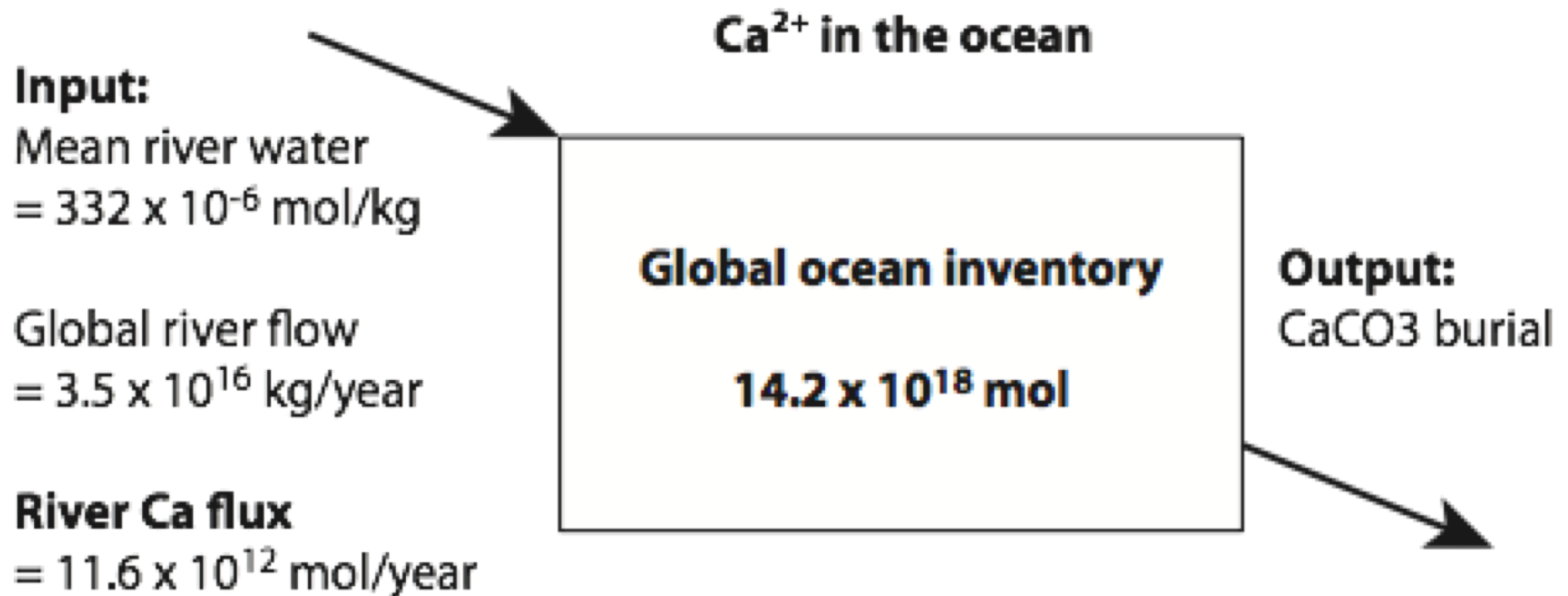


Inventory and flux

$$V \frac{dC}{dt} = (\textit{influx}) - (\textit{outflux})$$

- Inventory: total amount in the reservoir (mol, kg, ...)
- Flux: rate of input or output (mol/s, kg/s, ...)
- Mean Residence Time (MRT) = Inventory / Flux

Some example



$$\text{Residence time} = \frac{14.2 \times 10^{18} \text{ mol}}{11.6 \times 10^{12} \text{ mol/year}} = 1.2 \times 10^6 \text{ years}$$

Mackenzie-Garrels mass balance

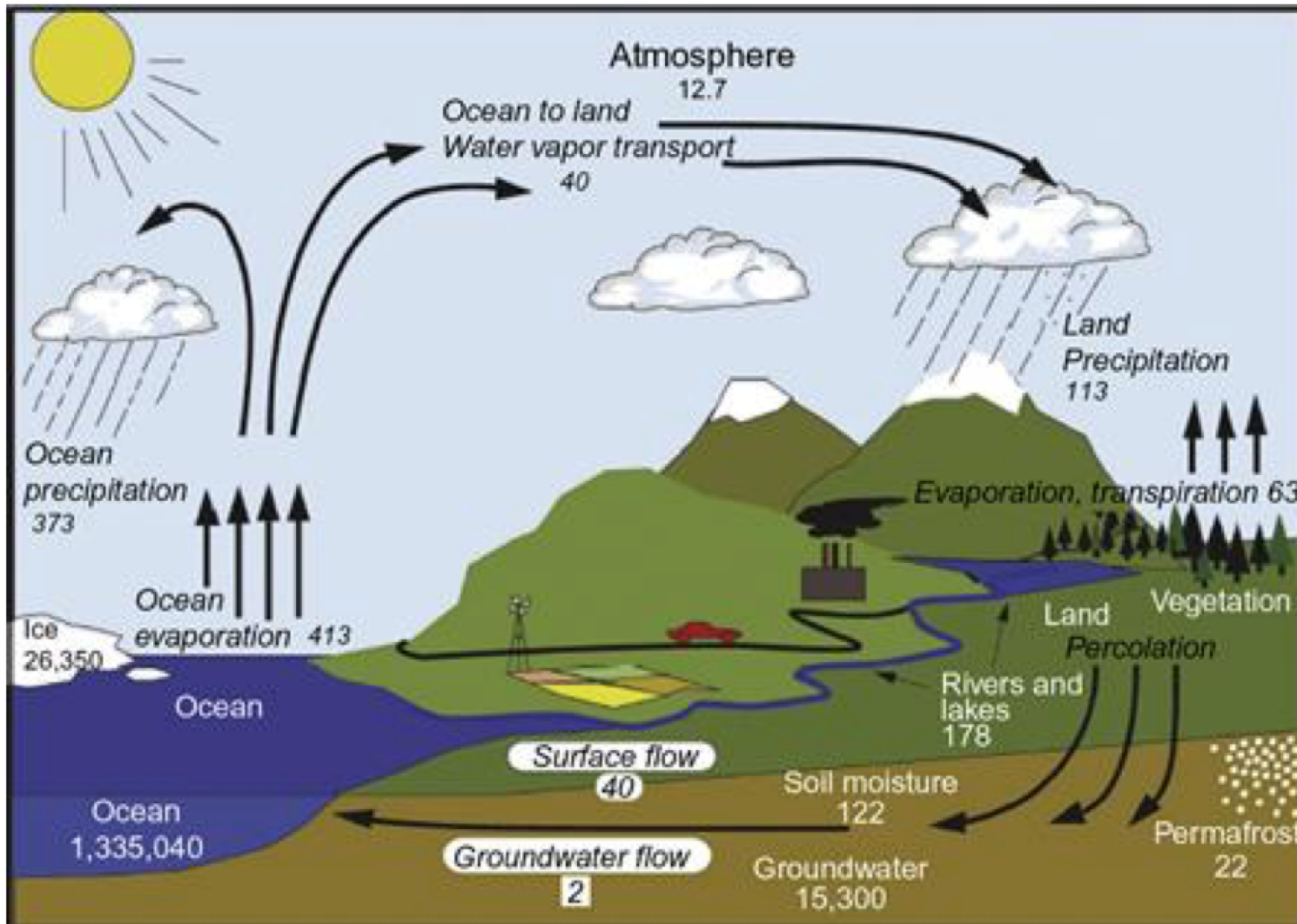
- Mackenzie and Garrels (1966)
- Steady state: (input) = (output)
- Dissolved constituents in the global rivers and the oceans
- Calculate mass balance
- Obtain residence time for each element

Residence time of dissolved constituents in the seawater

Schlesinger Table 9.1

Constituent	Concentration in seawater ^a (g kg ⁻¹)	Chlorinity ratio ^a (g kg ⁻¹)	Concentration in river water ^b (mg/kg)	Mean residence time ^b (10 ⁶ yr)
Sodium	10.78145	0.556492	5.15	75
Magnesium	1.28372	0.066260	3.35	14
Calcium	0.41208	0.021270	13.4	1.1
Potassium	0.39910	0.020600	1.3	11
Strontium	0.00795	0.000410	0.03	12
Chloride	19.35271	0.998904	5.75	120
Sulfate	2.71235	0.140000	8.25	12
Bicarbonate	0.10481	0.005410	52	0.10
Bromide	0.06728	0.003473	0.02	100
Boron	0.02739	0.001413	0.01	10
Fluoride	0.00130	0.000067	0.10	0.05
Water	964.83496	49.800646		0.034

Water cycle : residence time of water molecule in the ocean w.r.t. evaporation $\sim 3.4 \times 10^3$ year



Units in 10^3km or 10^3km/yr

Salinity

- Main source of salt in the ocean is river input.
- Why is ocean much saltier than the rivers?

Salinity

- Main source of salt in the ocean is river input.
- Why is ocean much saltier than the rivers?
- Once salt enters the ocean, it remains there for a long period of time (MRT ~ millions of years), so it can accumulate to a higher concentration than the river water. It also explains why salinity is almost uniform (35 psu, or 3.5%wt)

Weathering

- Rocks and Atmosphere

- Breakdown of rocks
- Runoff to the ocean

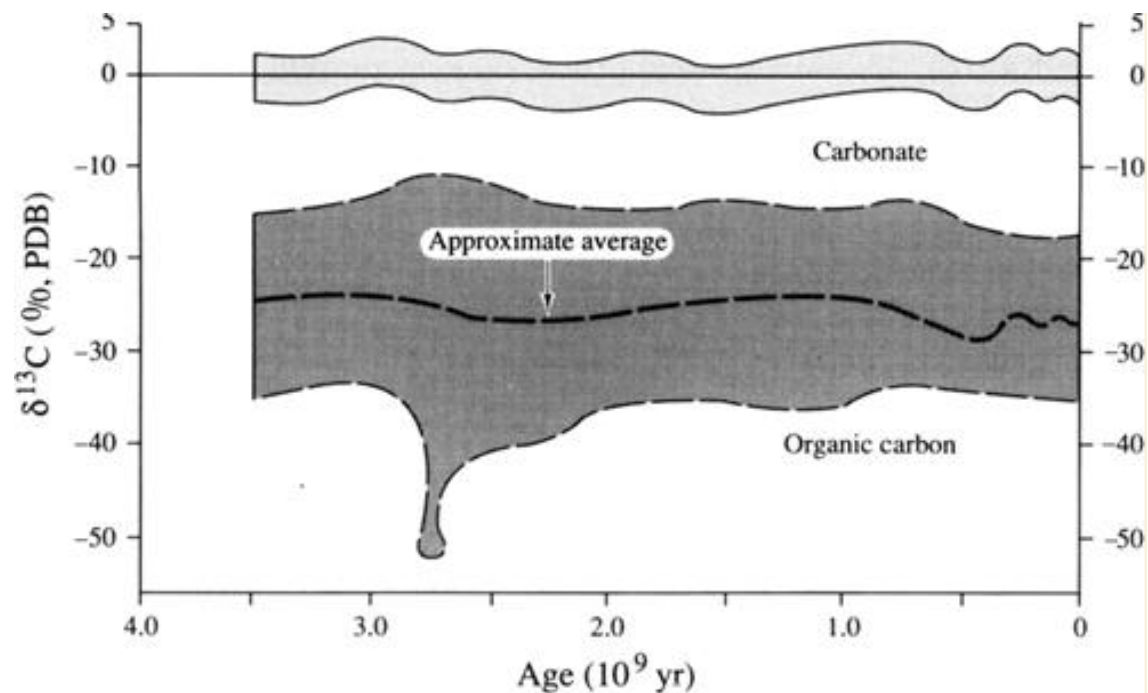


- Source of minerals to the ocean
- Sedimentation

(Igneous rocks) + (CO₂ acid) = (sedimentary rocks) + (salty ocean)

Photosynthesis

- 3.8 Ga: early evidence of photoautotrophs
 - Fossilized organic matter depleted in ^{13}C



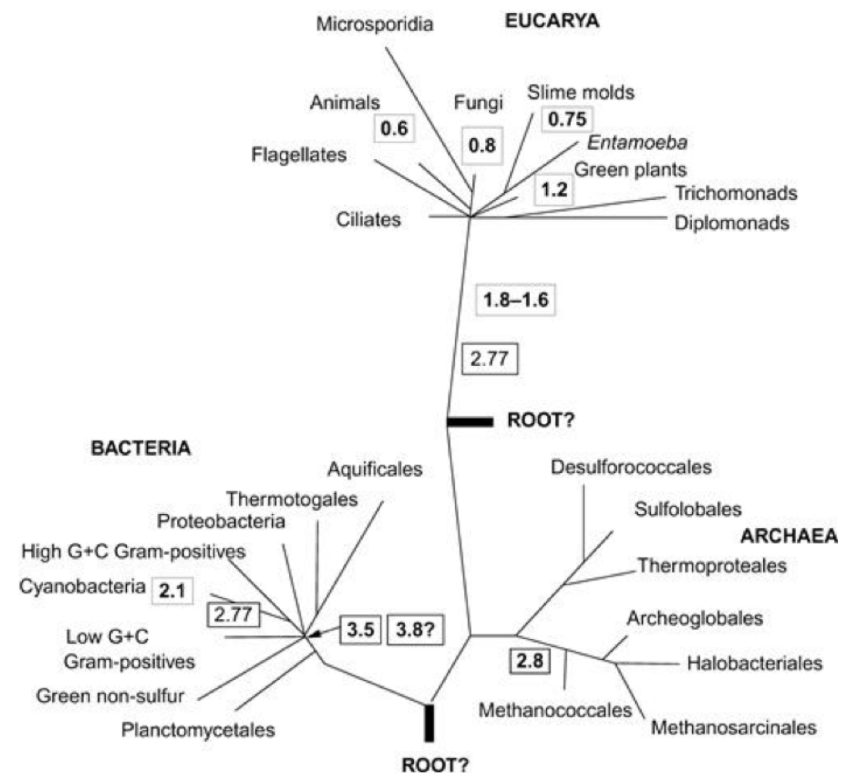
Basic concepts and terms in metabolism

- **Anabolism** = biosynthesis, production of organic matter. There are two types of anabolism. Autotrophy and heterotrophy based on the different **sources of carbon**.
 - **Autotrophy** = biosynthesis based on inorganic matter (like CO₂)
 - **Heterotrophy** = biosynthesis based on organic matter (like eating food)
 - Production of organic matter requires energy. Depending on the **energy source**, we have further classification. (e.g.) **Photoautotrophy, chemoautotrophy**
- **Catabolism** = consumption of organic matter. It destroys organic matter. For example, heterotrophs gaining energy from the organic matter would be **chemoheterotrophy**.

Basic concepts and terms

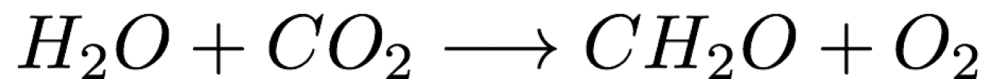
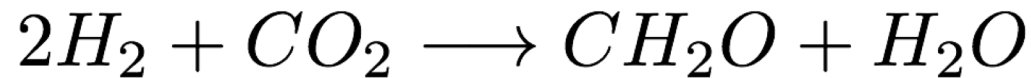
- **Three domains of life**
 - **Archaea**, single-cell microorganism, prokaryote (without cell nucleus) exists in various habitats, genetically distinct from bacteria.
 - **Bacteria**, single-cell microorganism, prokaryote. Very diverse and widely distributed in many habitats.

Eukarya, contains membrane-contained cell nucleus, and there are single-cell (unicellular) and multi-cellular organisms



Early Photosynthetic reactions

- Use sunlight as the energy source to reduce CO₂ into organic molecules



The last reaction eventually become dominant due to the abundance of water and much higher energy yield of O₂, that fundamentally changed chemical environment in the oceans (and atmosphere).

Oxygenation of the atmosphere

- ~2 Ga: atmospheric oxygen starts to increase
- Banded iron formation
 - O_2 -poor Archean ocean well dissolved Fe^{2+}
 - As O_2 is produced and it reacts with Fe
 - Fe^{2+} is oxidized to form iron oxide deposition

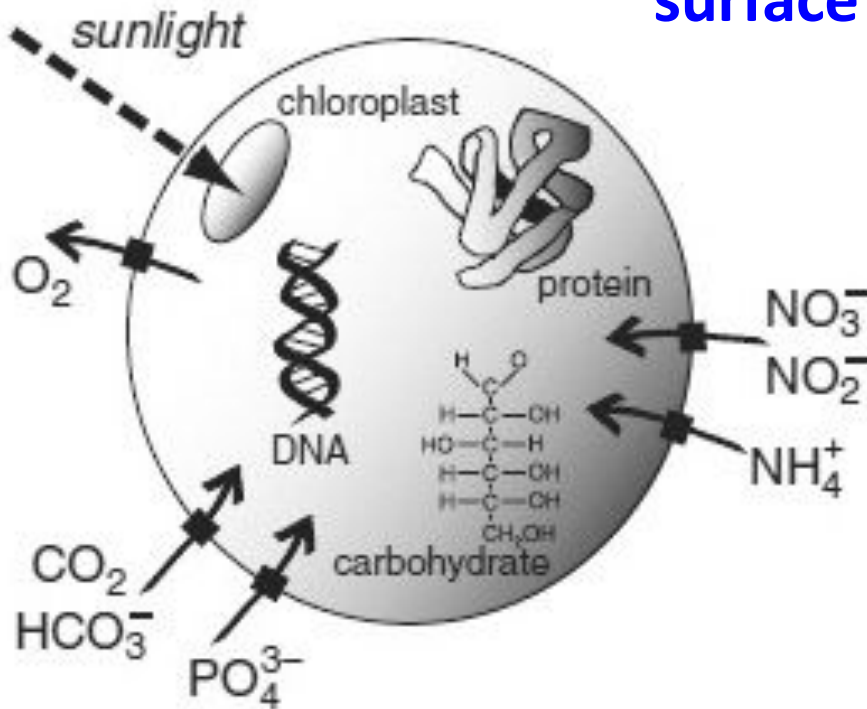


Schlesinger Fig 2.7
Banded iron formation
from South Africa

Photosynthesis

(a) phytoplankton

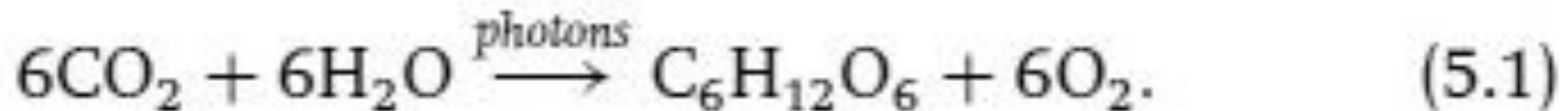
Microscopic plant, drifting in the surface ocean



Responsible for about 50% of photosynthesis on the Earth

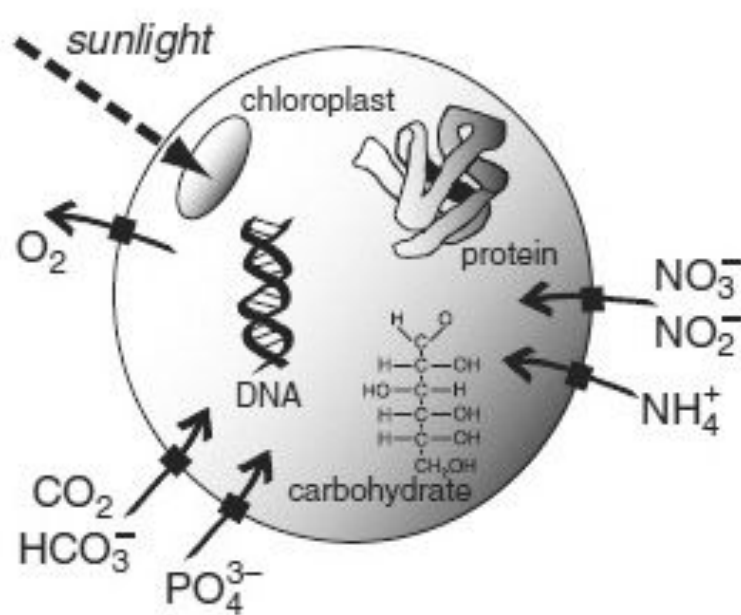
Diverse in size, genetic information, and biogeochemical functions

Harvests light, absorbs CO_2 and nutrients to produce organic material

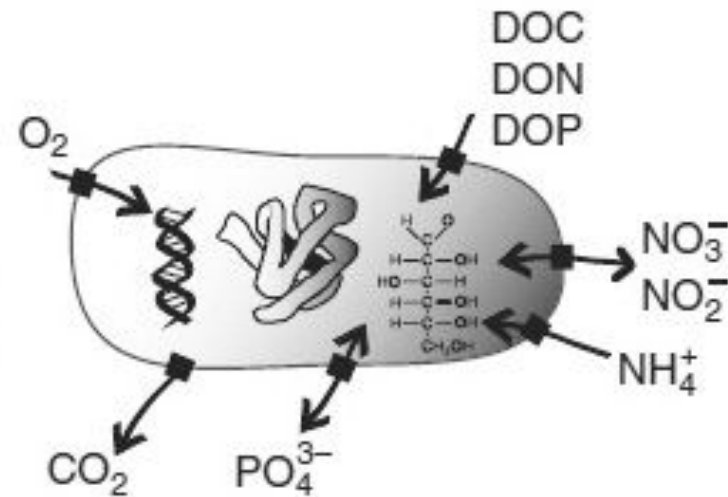


Elemental composition of microbes

(a) phytoplankton

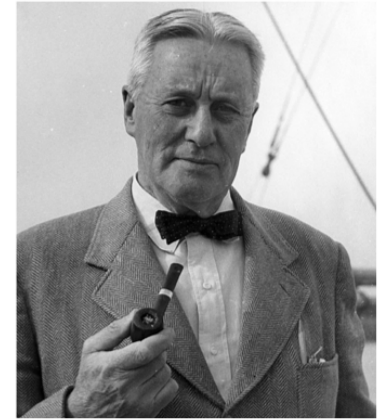


(b) bacteria



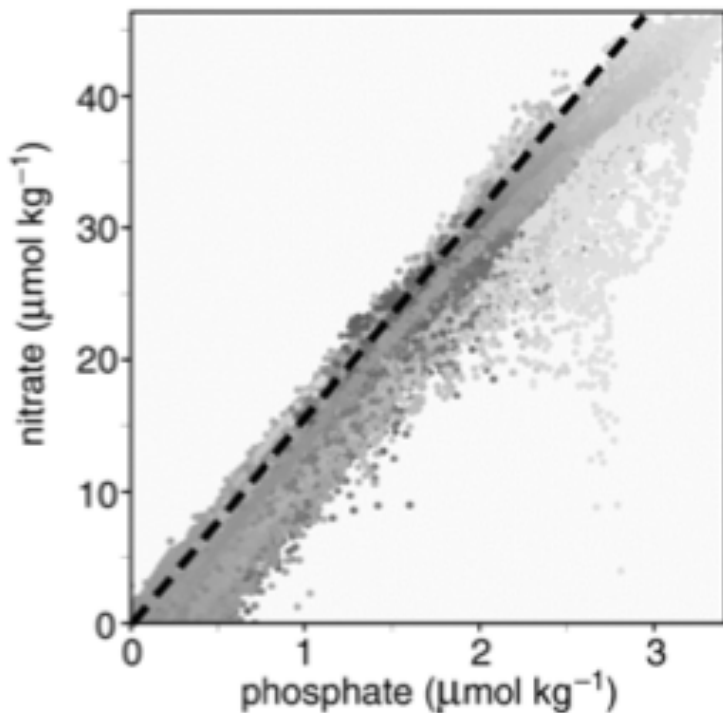
		% cell
Protein	$C_{3.83}H_{6.05}O_{1.25}N$	54.5
Carbohydrate	$C_6H_{10}O_5$	25.5
Lipid	$C_{40}H_{74}O_5$	16.1
Nucleic acid	$C_{9.625}H_{12}O_{6.5}N_{3.75}P$	4.0

Redfield Ratio



Bulk Marine Organic matter
 $P:N:C:O_2 = 1:16:106:-138$

(a) nitrate : phosphate



Same ratio in the seawater

Redfield, (1958)

AMERICAN SCIENTIST

AUTUMN

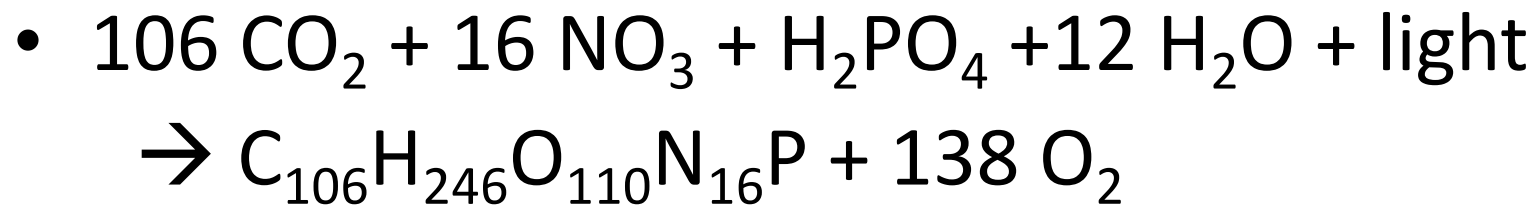
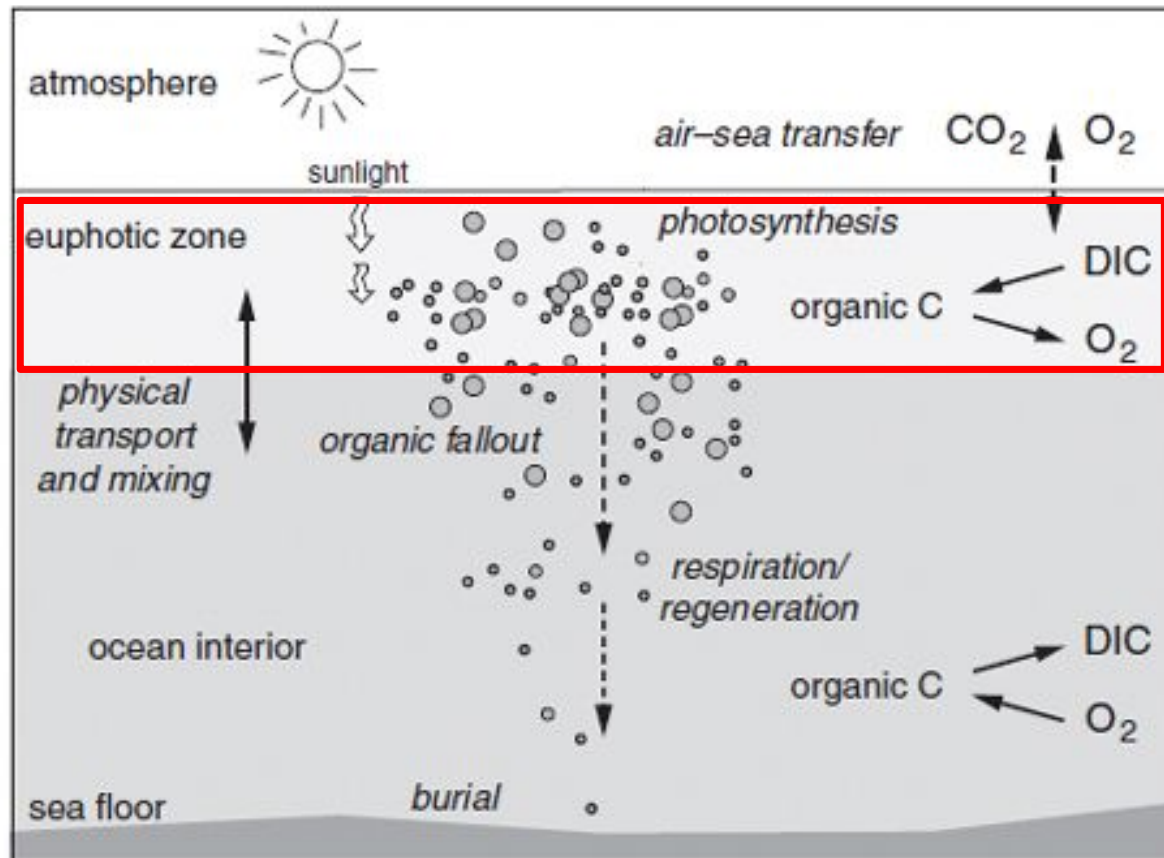
SEPTEMBER 1958

THE BIOLOGICAL CONTROL OF CHEMICAL FACTORS IN THE ENVIRONMENT¹

By ALFRED C. REDFIELD

IT IS a recognized principle of ecology that the interactions of organisms and environment are reciprocal. The environment not only determines the conditions under which life exists, but the organisms influence the conditions prevailing in their environment. The examples on which this principle rests are usually difficult to describe in quantitative terms and are frequently local in their application. In the ocean the principal interactions between organisms and environment are chemical. Because of its unity, its fluid nature, and the intensity of the mixing to which the water is subject their relations can be examined statistically and expressed in quantitative terms.

Photosynthesis



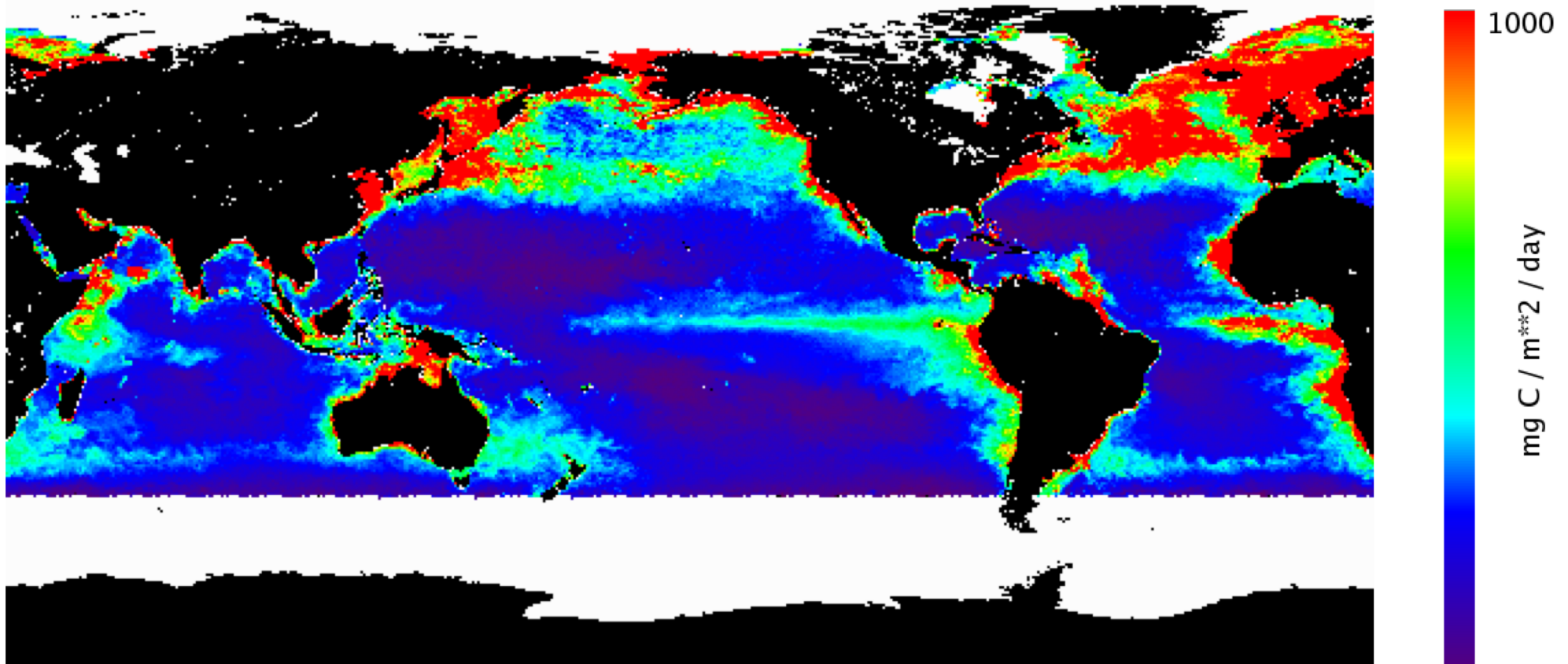
What regulates primary productivity?

- $106 \text{ CO}_2 + 16 \text{ NO}_3 + \text{H}_2\text{PO}_4 + 12 \text{ H}_2\text{O} + \text{light}$
→ $\text{C}_{106}\text{H}_{246}\text{O}_{110}\text{N}_{16}\text{P} + 138 \text{ O}_2$
- H_2O (and CO_2) molecules are always available in the surface ocean
- In modern ocean, marine photosynthesis generates about the same amount of O_2 as the land biosphere.
- **Nutrients** (such as N and P) can be limiting photosynthesis
- **Light** can be limiting photosynthesis

Pattern of global ocean productivity

SeaWiFS-based productivity estimates (Behrenfeld and Falkowski 1997)

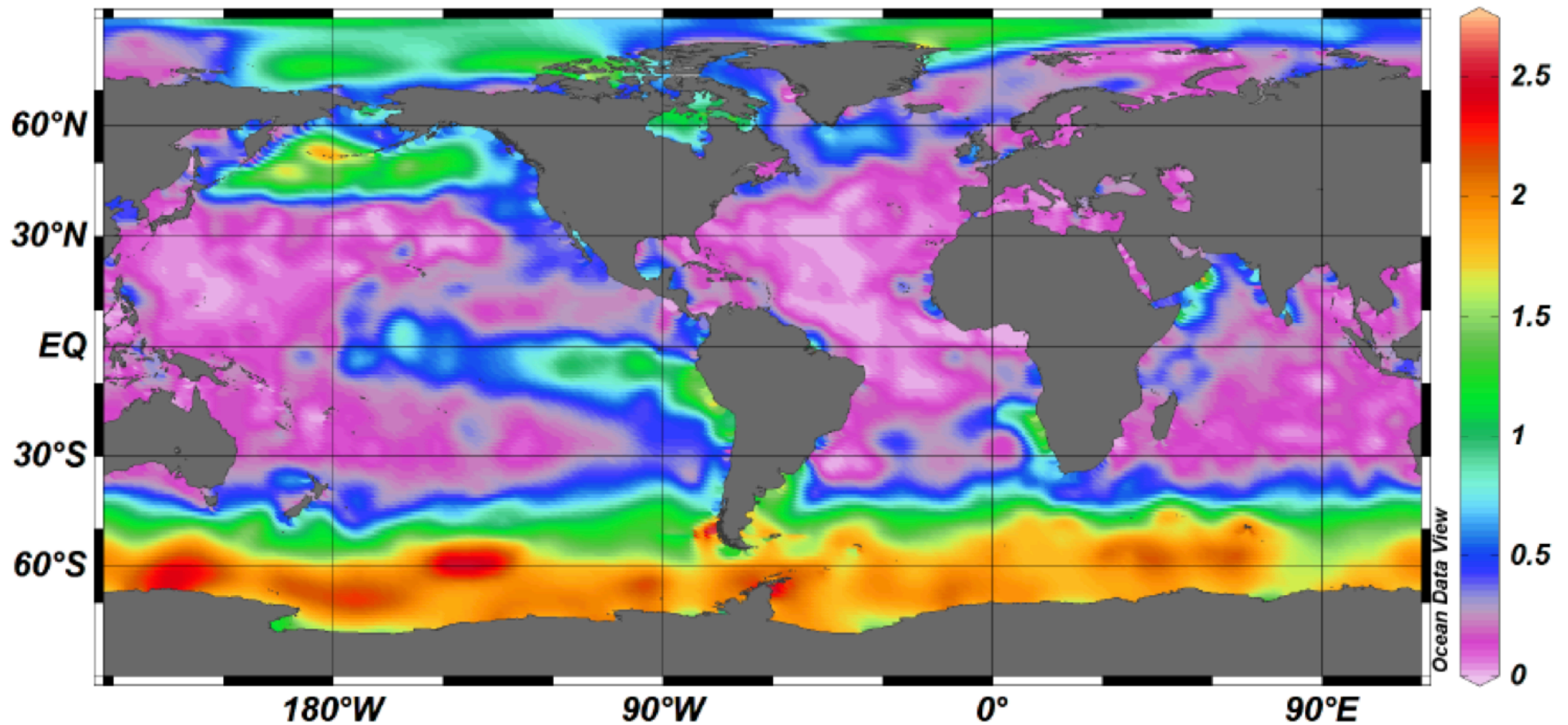
June 2004



- High productivity: high latitudes (summer hemisphere), tropics, coastal regions
- Low productivity: subtropics, high latitudes (winter hemisphere)

Surface nutrient distribution

Phosphate [$\mu\text{mol/l}$] @ Depth [m]=0



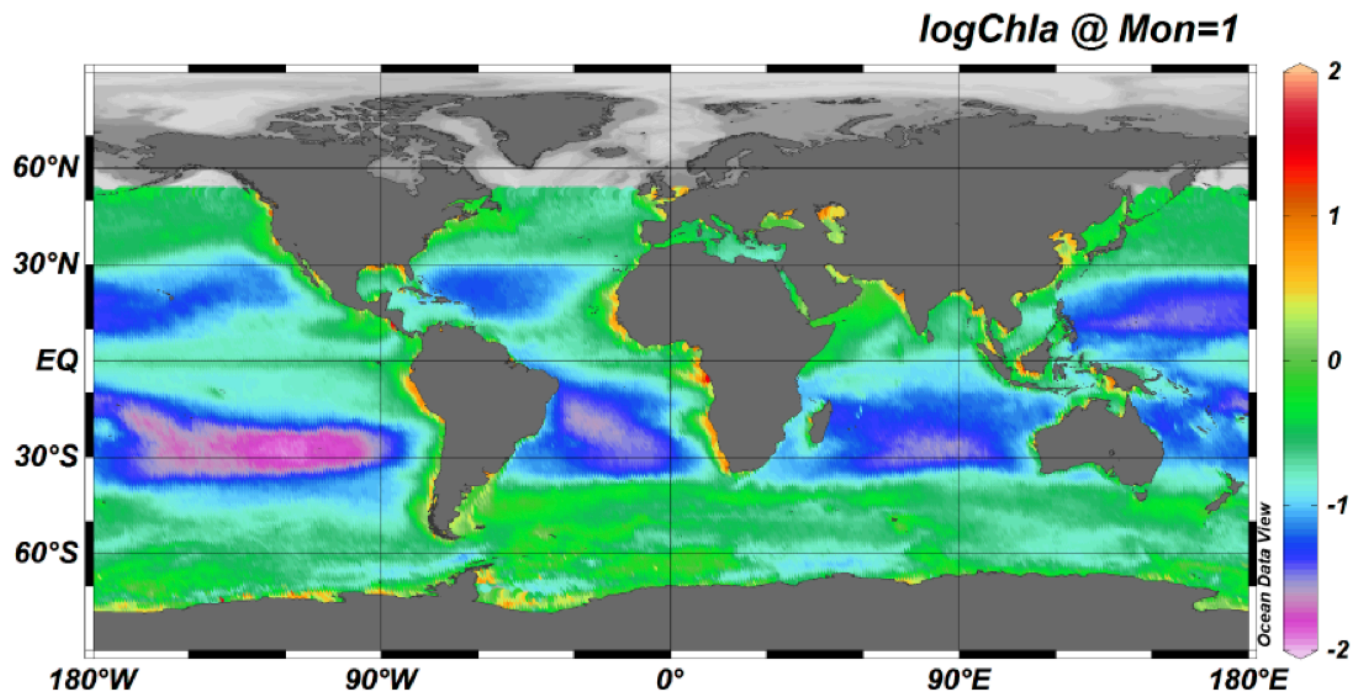
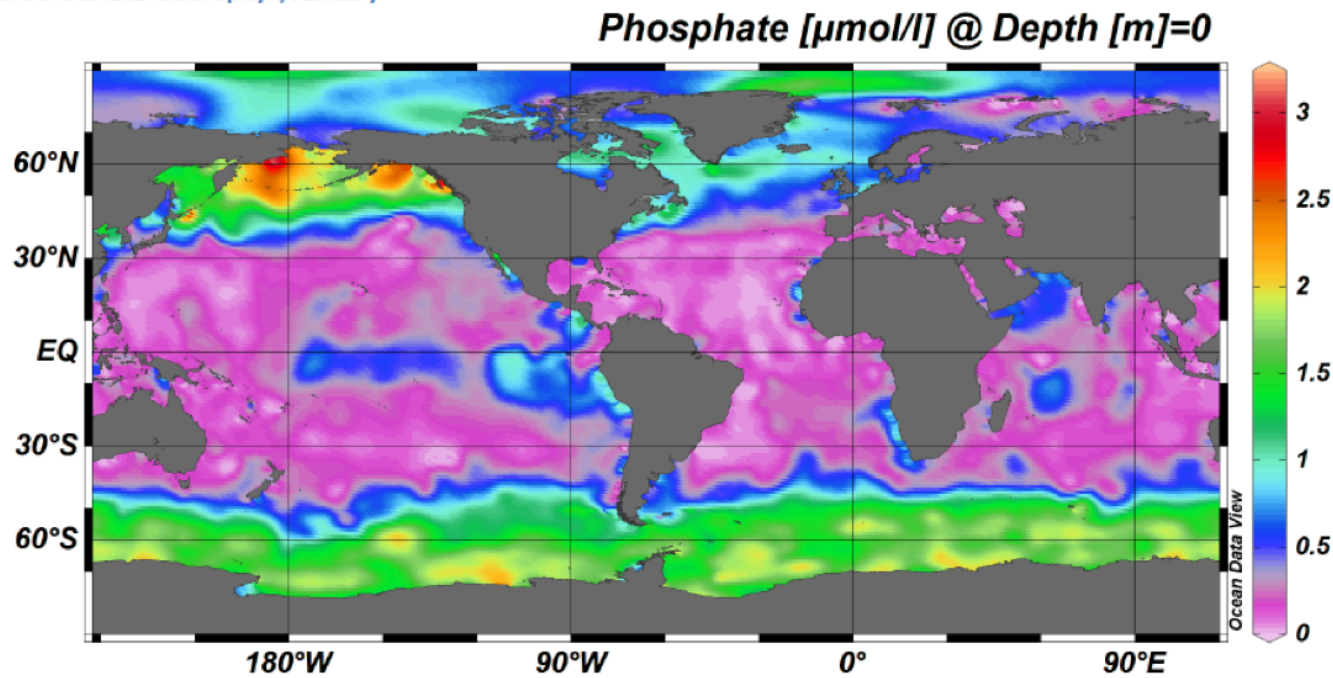
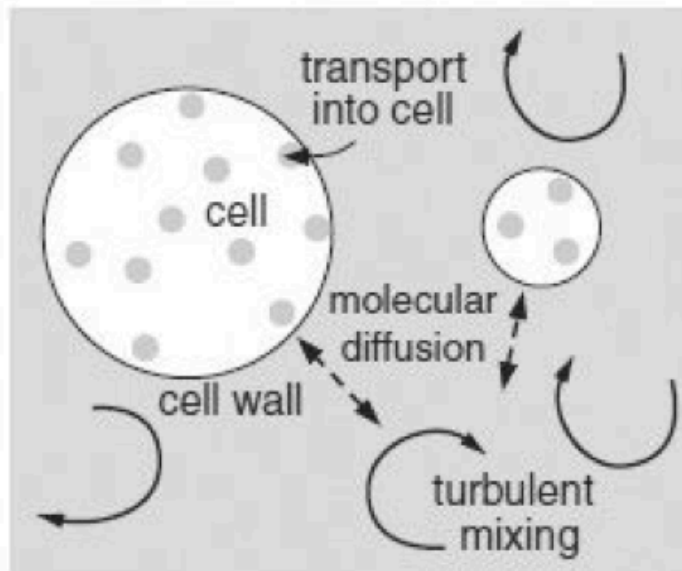


Figure 9. Surface Chlorophyll, January

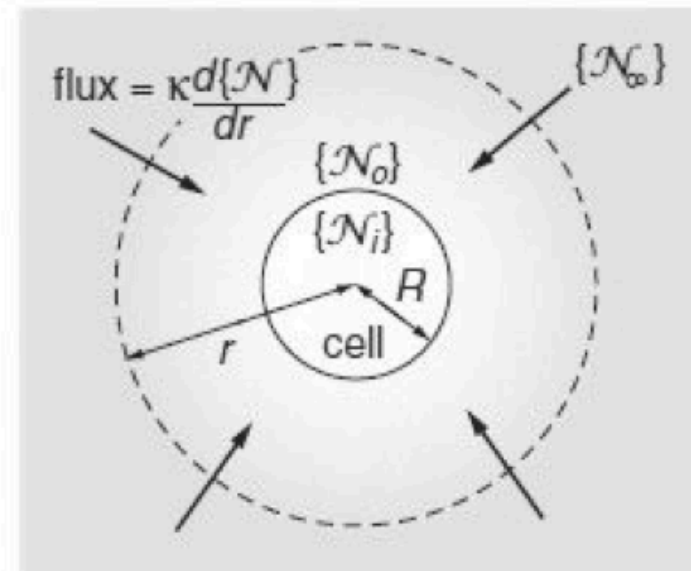


Nutrient uptake kinetics

(a) nutrient uptake by a cell



(b) nutrient diffusion



- Nutrient in the ambient water diffuses towards the plankton cell surface (*rate limiting under low N condition*)
- Nutrient transporter takes in the nutrient across the membrane (*rate limiting under high N condition*)

Two regimes of nutrient uptake

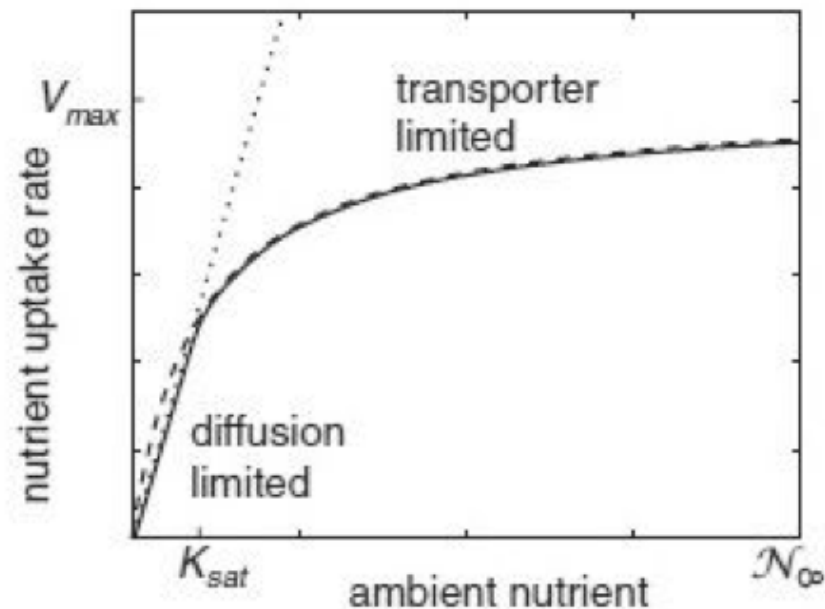
Low nutrient level \rightarrow diffusion

$$\text{uptake of } \mathcal{N} = 4\pi R\kappa\{\mathcal{N}_\infty\}.$$

High nutrient level \rightarrow transporter enzyme kinetics

$$\text{uptake of } \mathcal{N} = V_{max} \frac{\{\mathcal{N}_\infty\}}{K_{sat} + \{\mathcal{N}_\infty\}}.$$

(d) generic uptake response

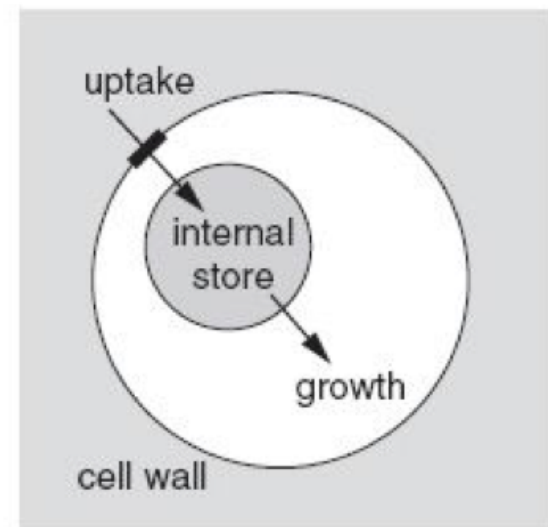


The role of cell size

Consider **low N**, thus diffusion-limited regime,
(per cell N uptake) is proportional to R , but
(per unit volume N uptake) is proportional to R^{-2}

→ Smaller cell size is more advantageous in low N condition
(because it has less biomass per surface area)

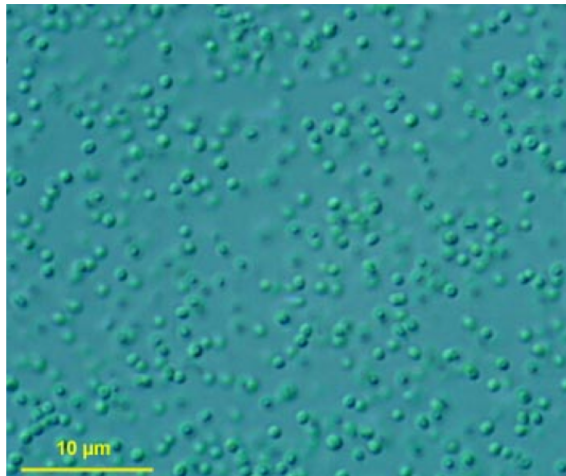
→ Larger plankton can store N internally and use it when
needed: e.g. phytoplankton bloom



Pico-phytoplankton

- Tiny ($< 1\mu\text{m}$) single-cell photosynthesizing bacteria
- Prokaryotes
- Take up nutrients efficiently at very low levels
- Easily grazed and recycled

Prochlorococcus



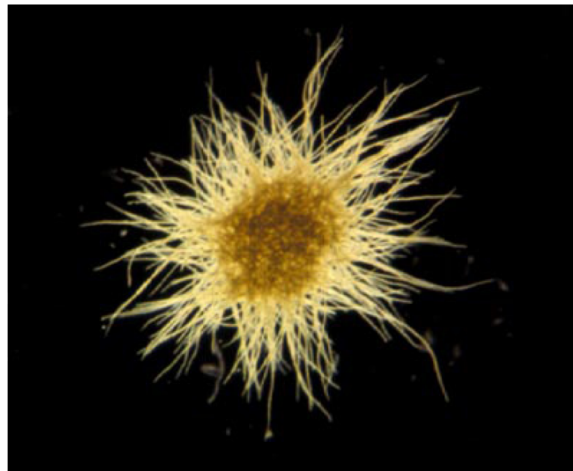
Synechococcus



Diazotrophs

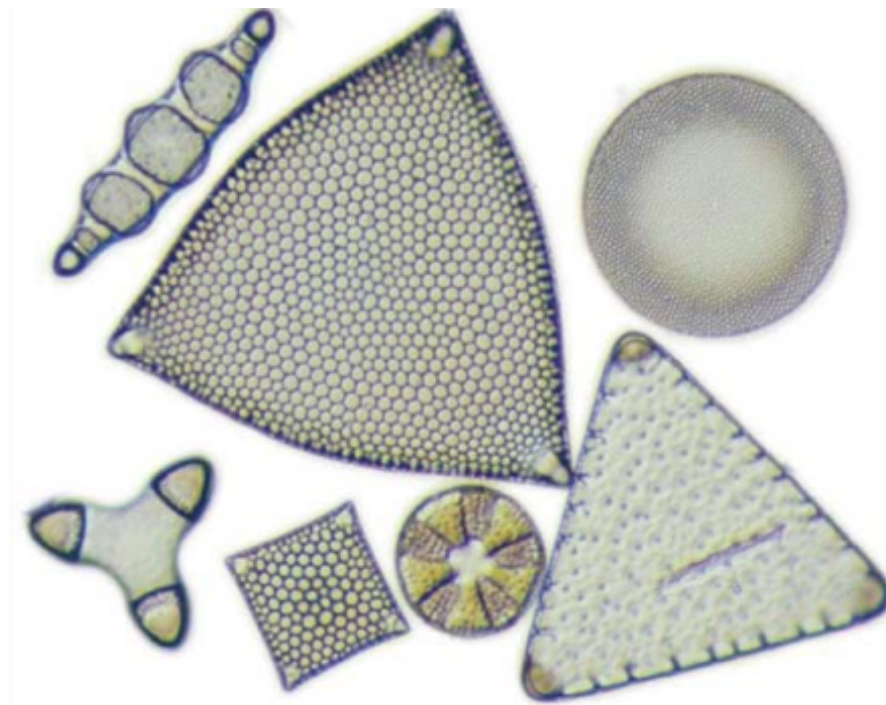
- Nitrogen fixing bacteria
- Can utilize N_2 as a nitrogen source

Trichodesmium



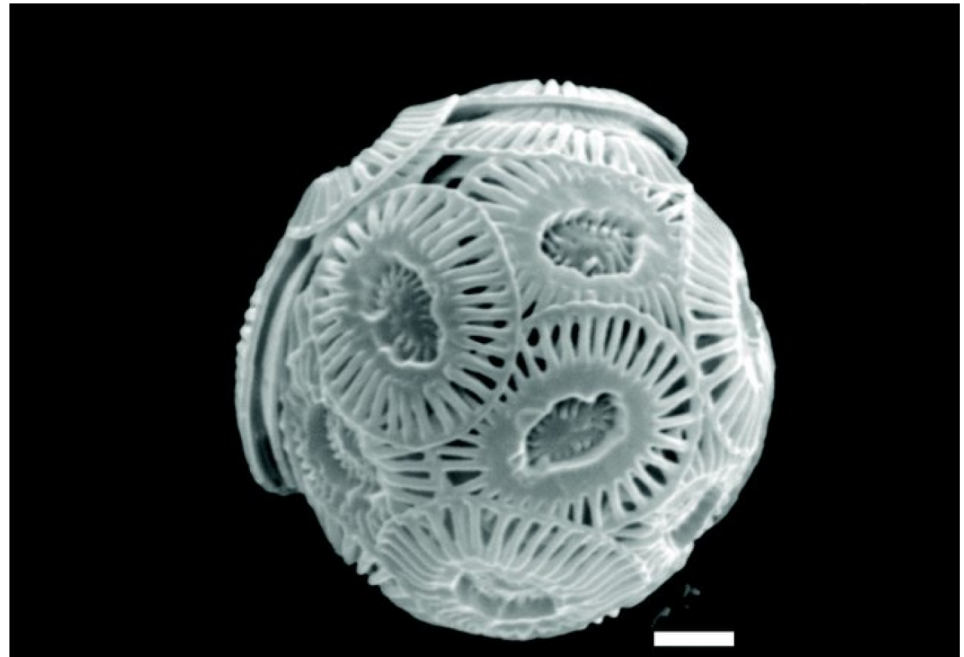
Diatom

- Large (2 to 200 μm) photosynthetic eukaryotes
- Can grow quickly and form blooms
- Silica-based shells (frustles) \rightarrow Sinkers
- Abundant in upwelling regions (e.g. equator, southern ocean)



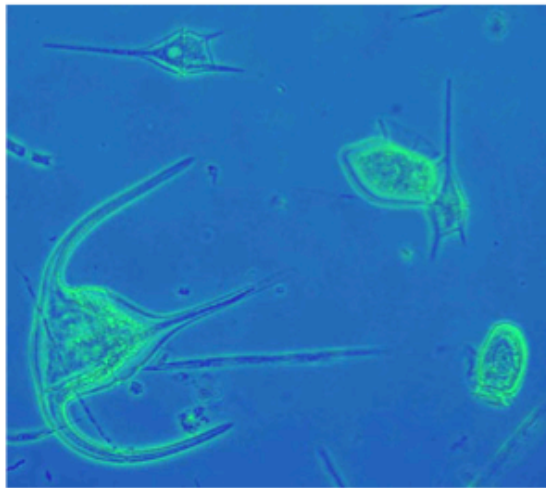
Coccolithophorids

- Calcium carbonate shells
- CaCO_3 cycling
- Sinkers



Flagellates

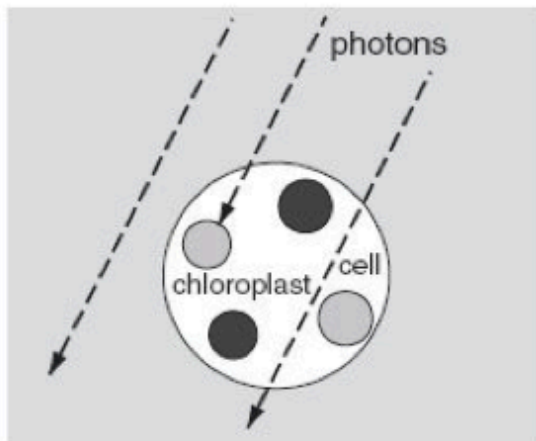
- Motile
- Mixotroph
- Can grow rapidly and bloom → HABs



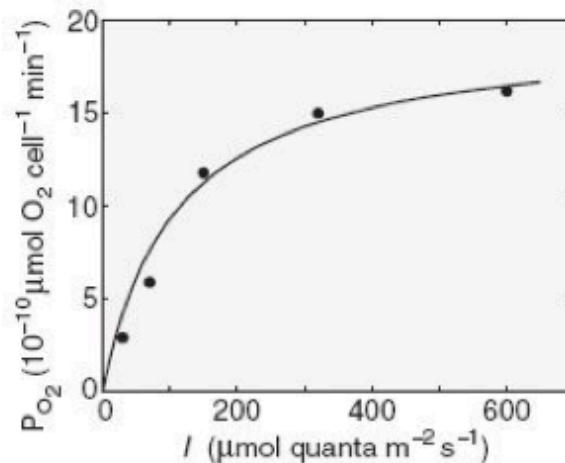
Light

- Phytoplankton has chlorophyll pigment, light harvesting mechanism
 - Under low light condition, phytoplankton increase chlorophyll to capture more photons
 - Under high light condition, phytoplankton reduce chlorophyll

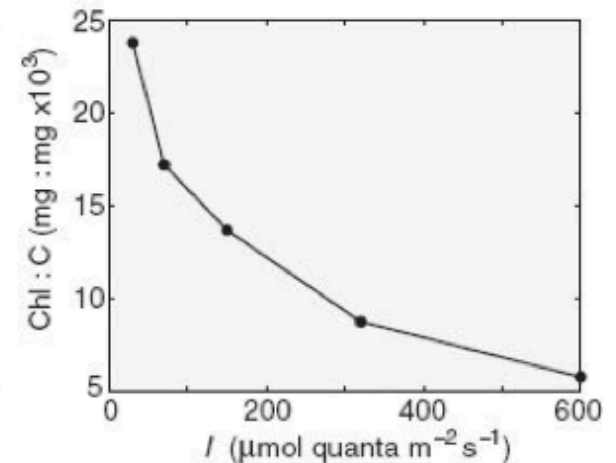
(a) photons being absorbed



(b) O₂ production vs. irradiance



(c) Chl : C ratio vs. irradiance



Variation of light with depth

- Seawater is an excellent absorber of light

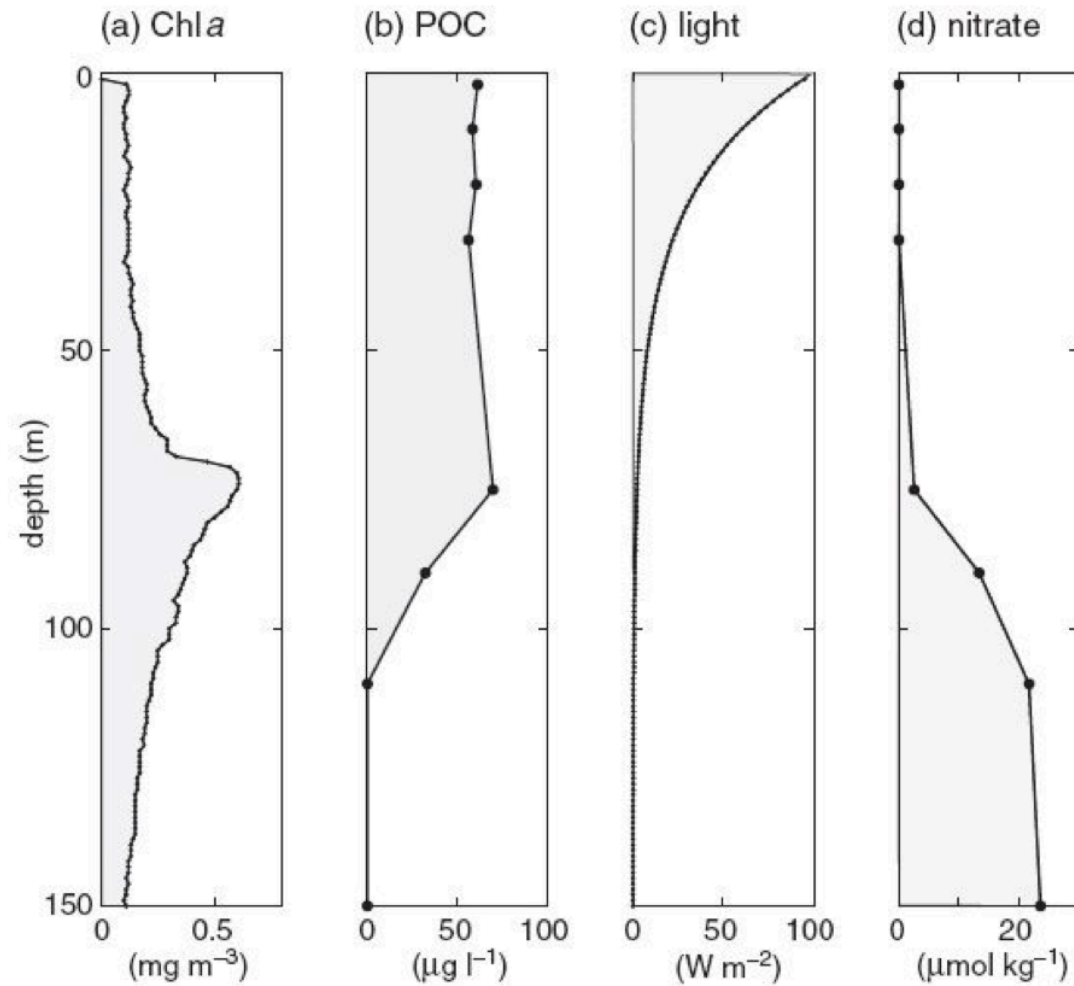
How deep can the solar radiation reach?

- Depends on the particle concentration in the seawater
- Light intensity has an exponential decay with depth

$$I = I_0 e^{-\frac{z}{Z_\lambda}}$$

- Red light (longer wavelength) is more readily absorbed into the seawater
- Blue light penetrates deeper and scattered by water molecule
- For typical open ocean condition, Z_λ is about 20m for blue light, and is only a few meters for red light
- The clearest water, N depleted water from the subtropical open ocean, has a deep dark blue color, almost black

A typical vertical profiles

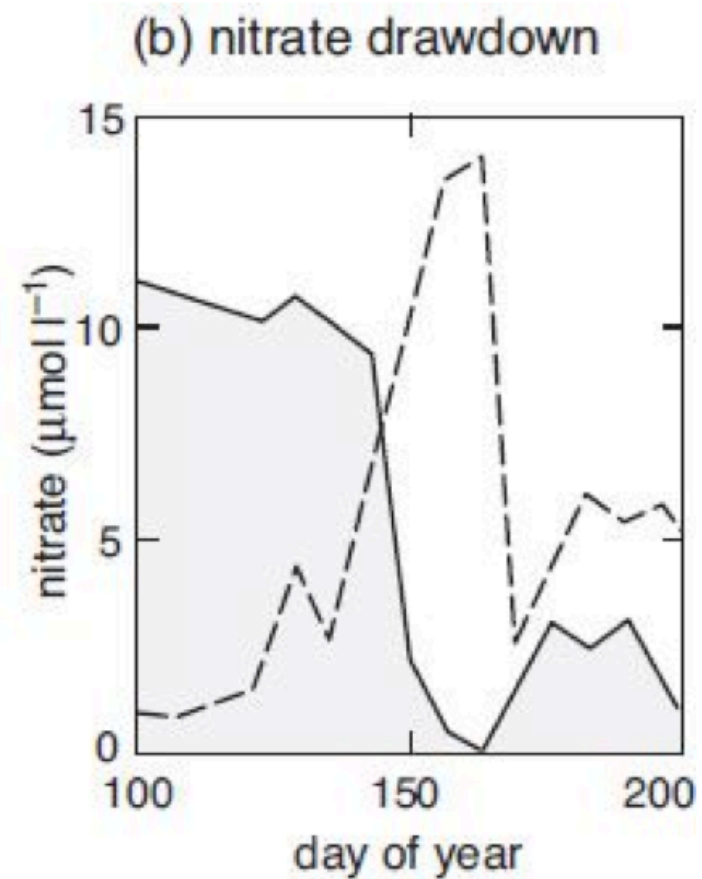
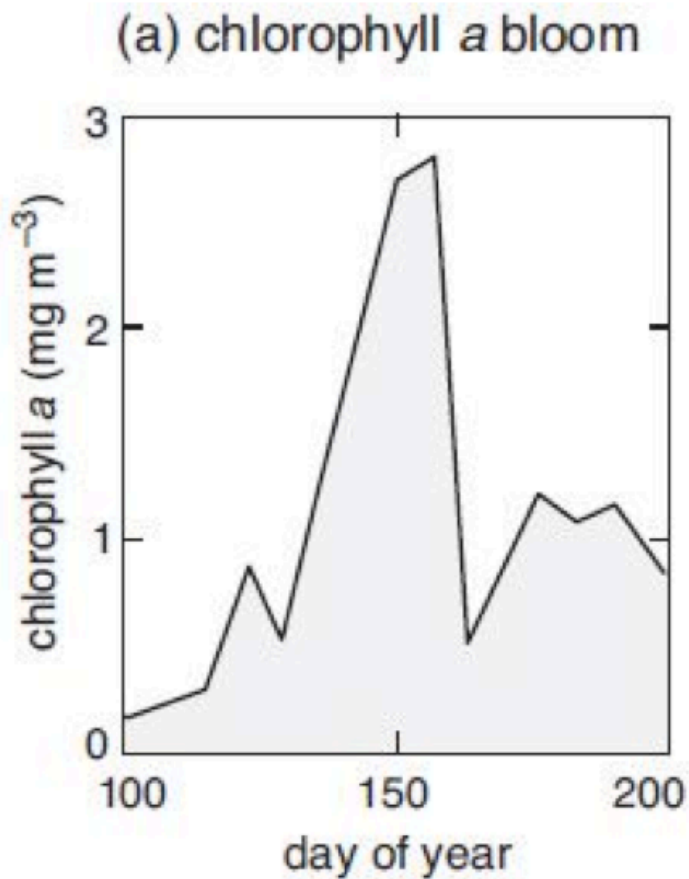


Chla = Chlorophyll-a, common pigment

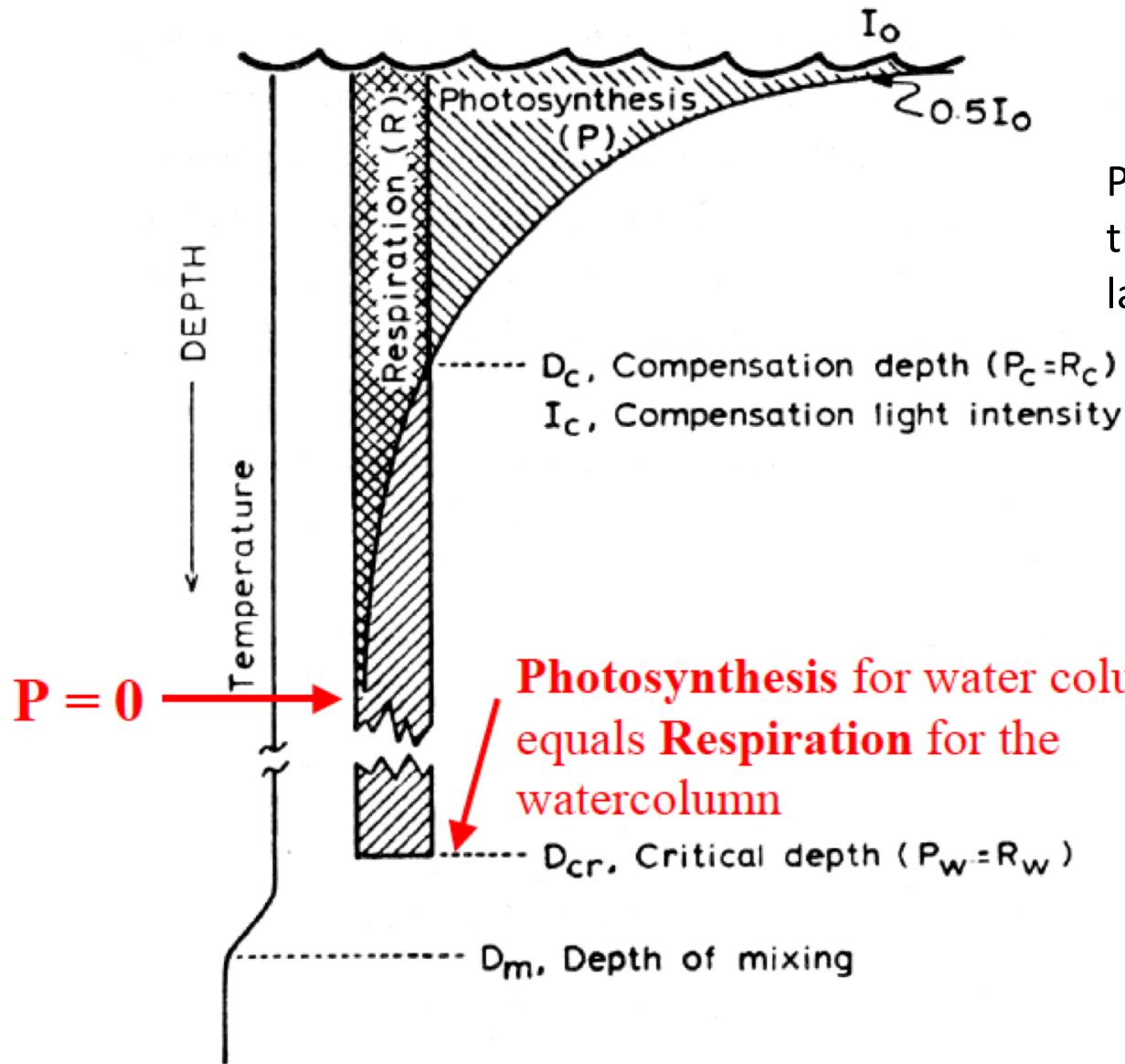
POC = Particulate Organic Carbon ~ biomass + detritus in particle form

Seasonal cycle of photosynthesis

- North Atlantic bloom



Sverdrup Hypothesis: A theory for spring bloom



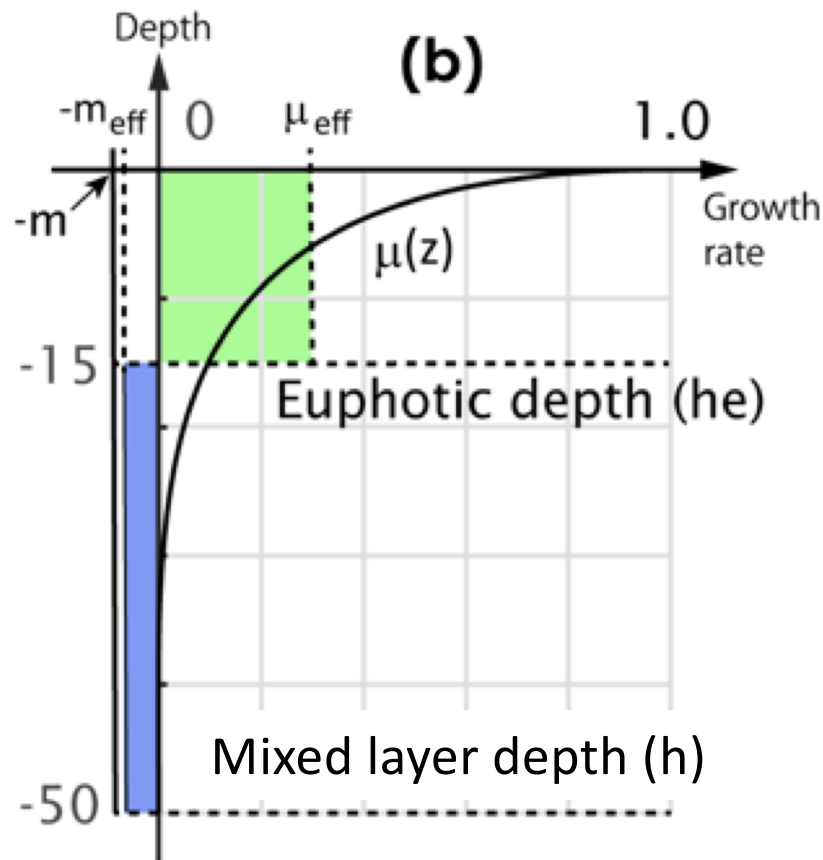
Plankton is vertically transported through the depth of the mixed layer

If $MLD < \text{critical depth}$, the vertically integrated photosynthesis exceeds respiration in the mixed layer.

Critical depth theory (Sverdrup theory)

- Simple 2 layer model

$$\frac{\partial P}{\partial t} = \mu P - mP$$



Kida and Ito (2017)

Assume there is a strong turbulence so that phytoplankton is well mixed down to the mixed layer depth (h)

Light is only available above the euphotic depth (h_e).

Mortality (m) is constant throughout the mixed layer.

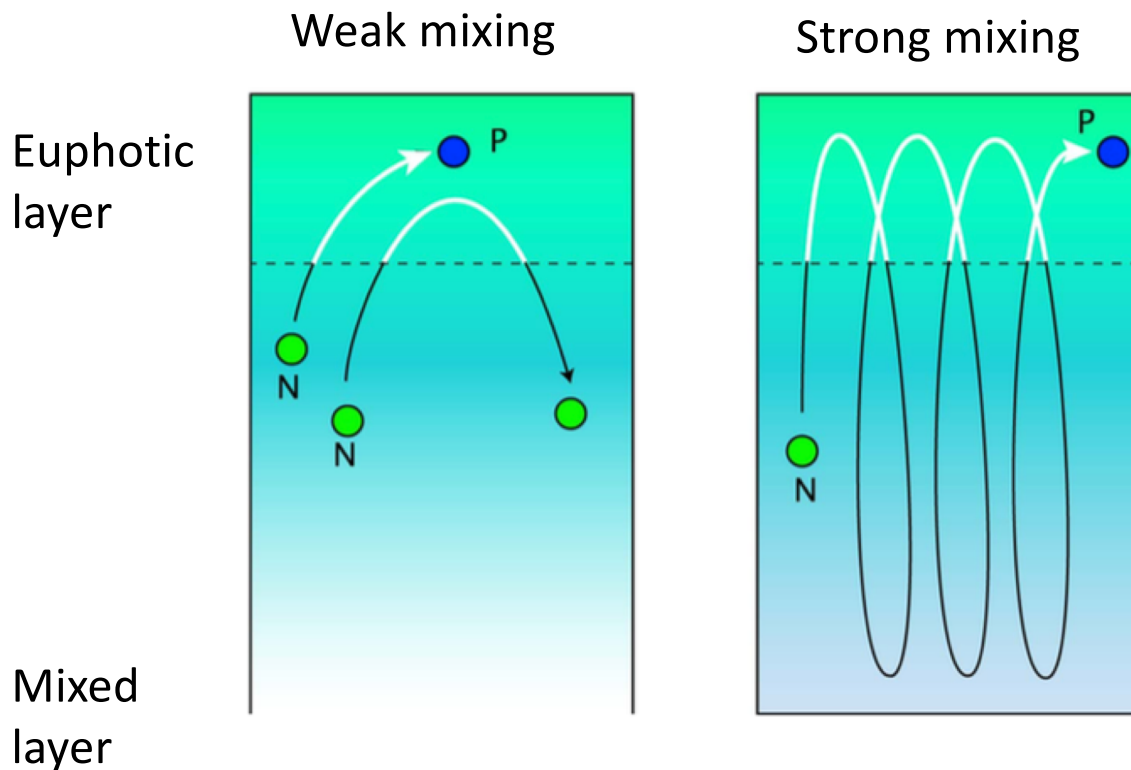
Then we have the critical depth (h_c)

$$h_c = \frac{\mu_{eff} h_e}{m}$$

Critical turbulence theory

Observational data often show phytoplankton bloom before the mixed layer shoals.

Can phytoplankton bloom occur with a deep mixed layer?

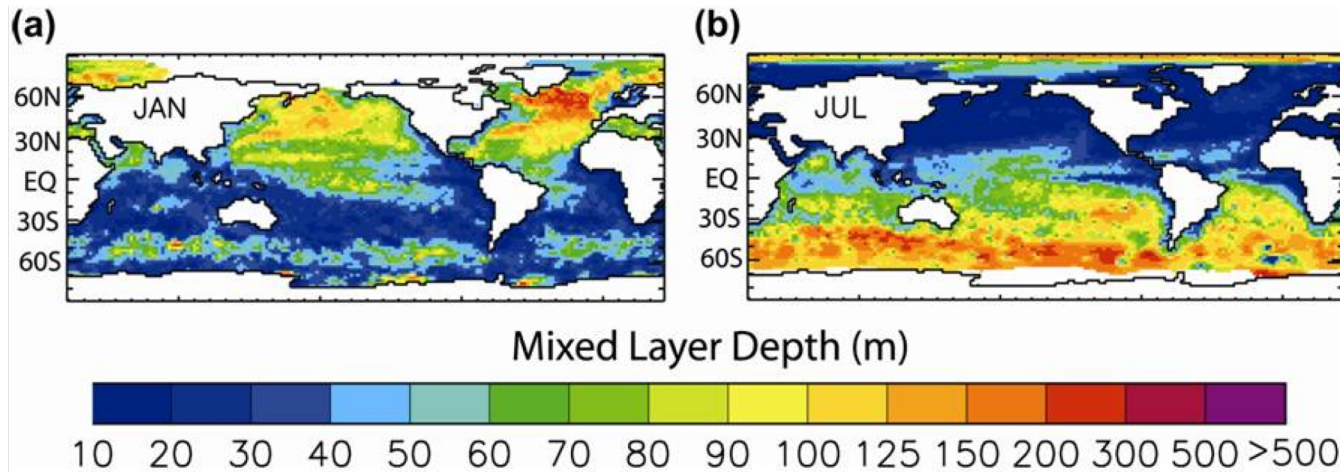


If the mixed layer turbulence weakens, it is possible for some water parcel to remain in the euphotic layer long enough to trigger a bloom

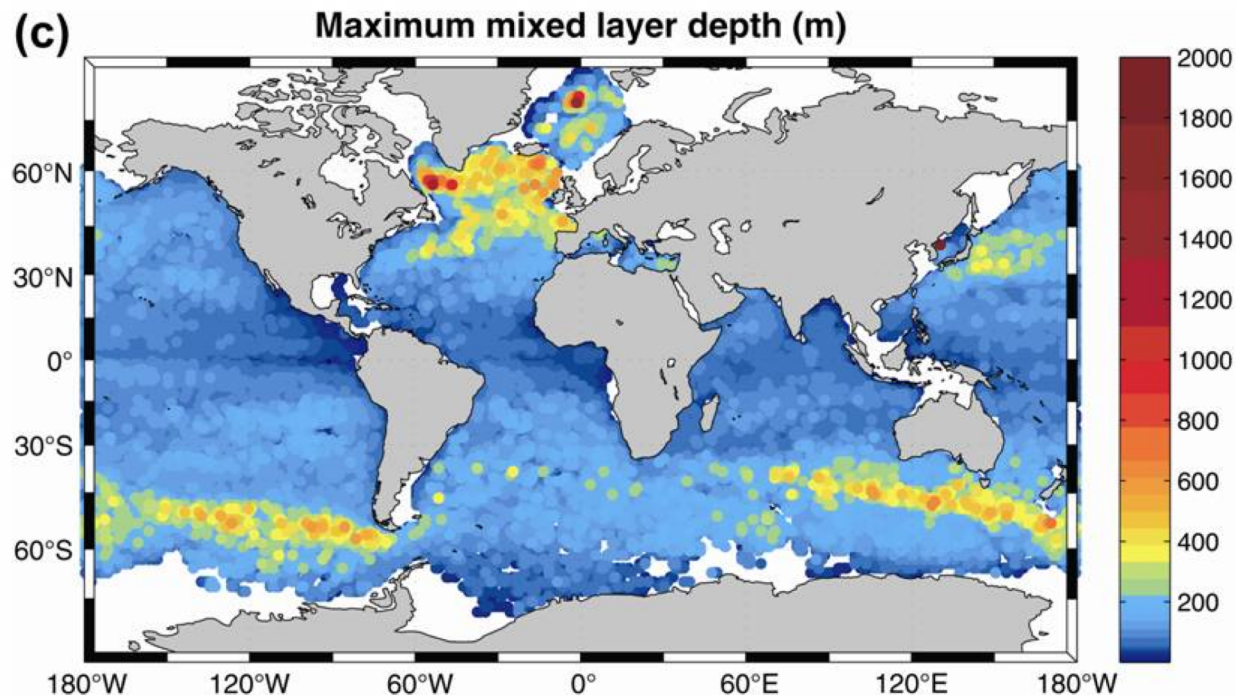
Kida and Ito (2017)

Seasonality of the surface mixed layer

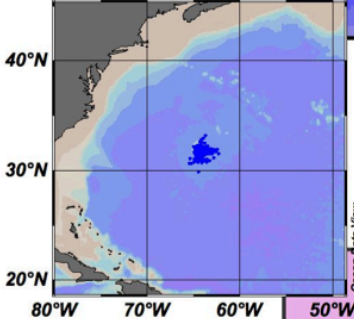
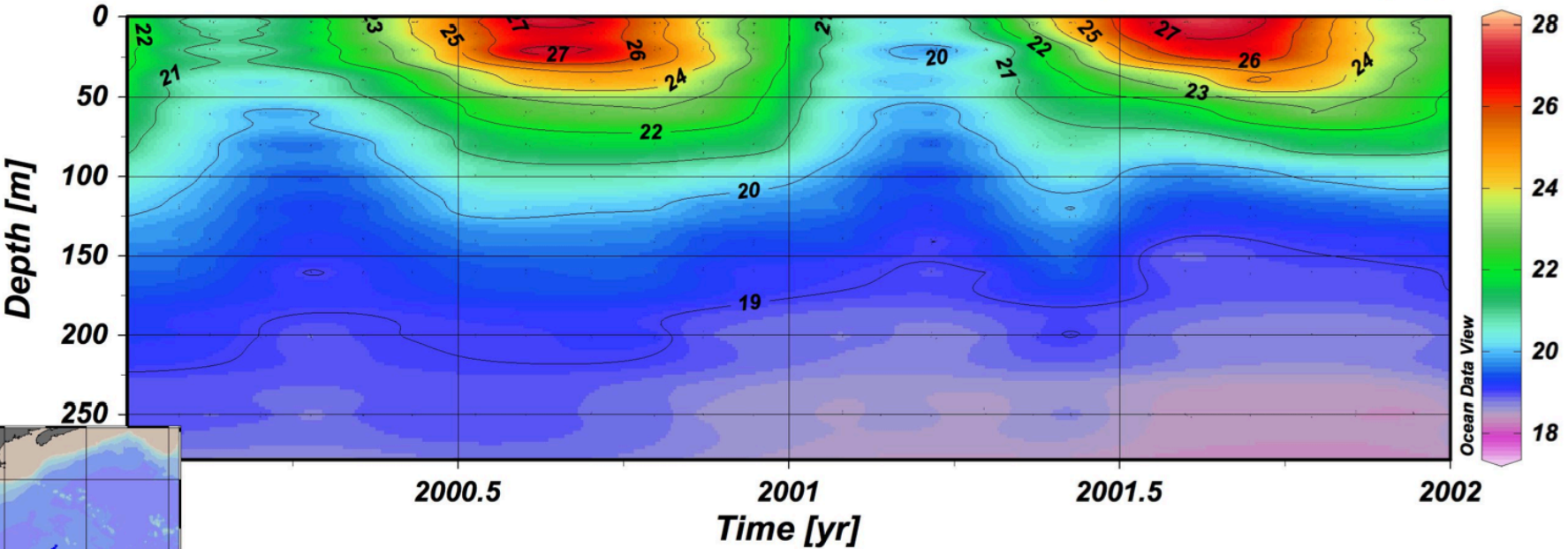
NH winter



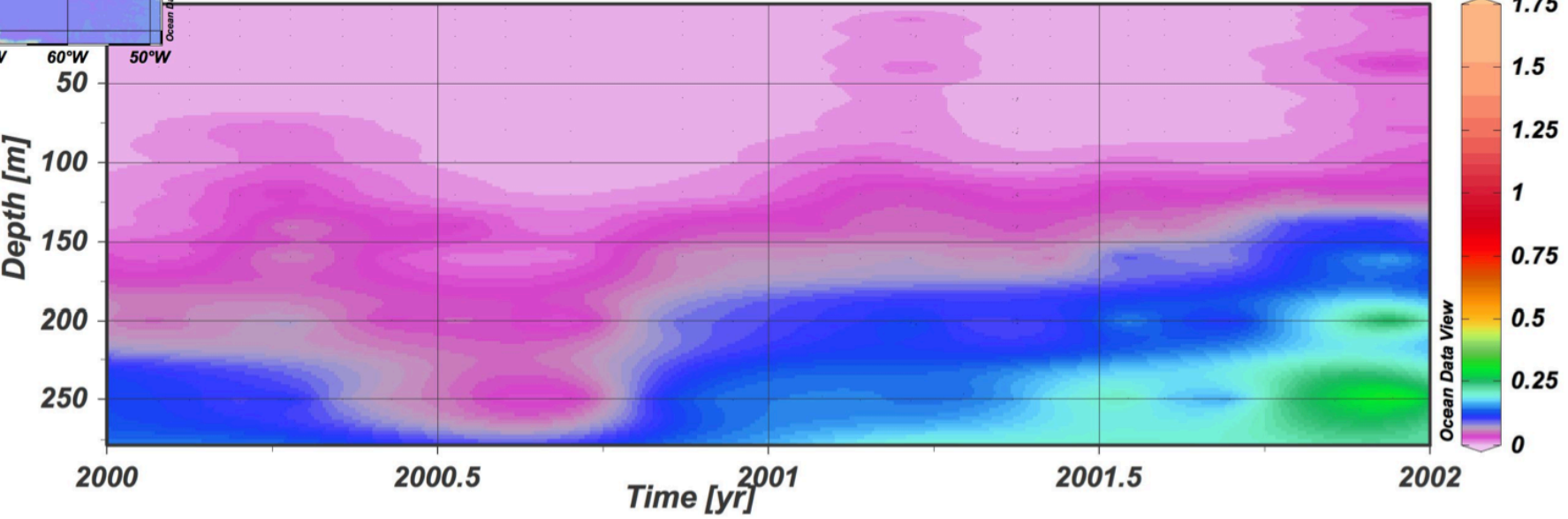
NH summer



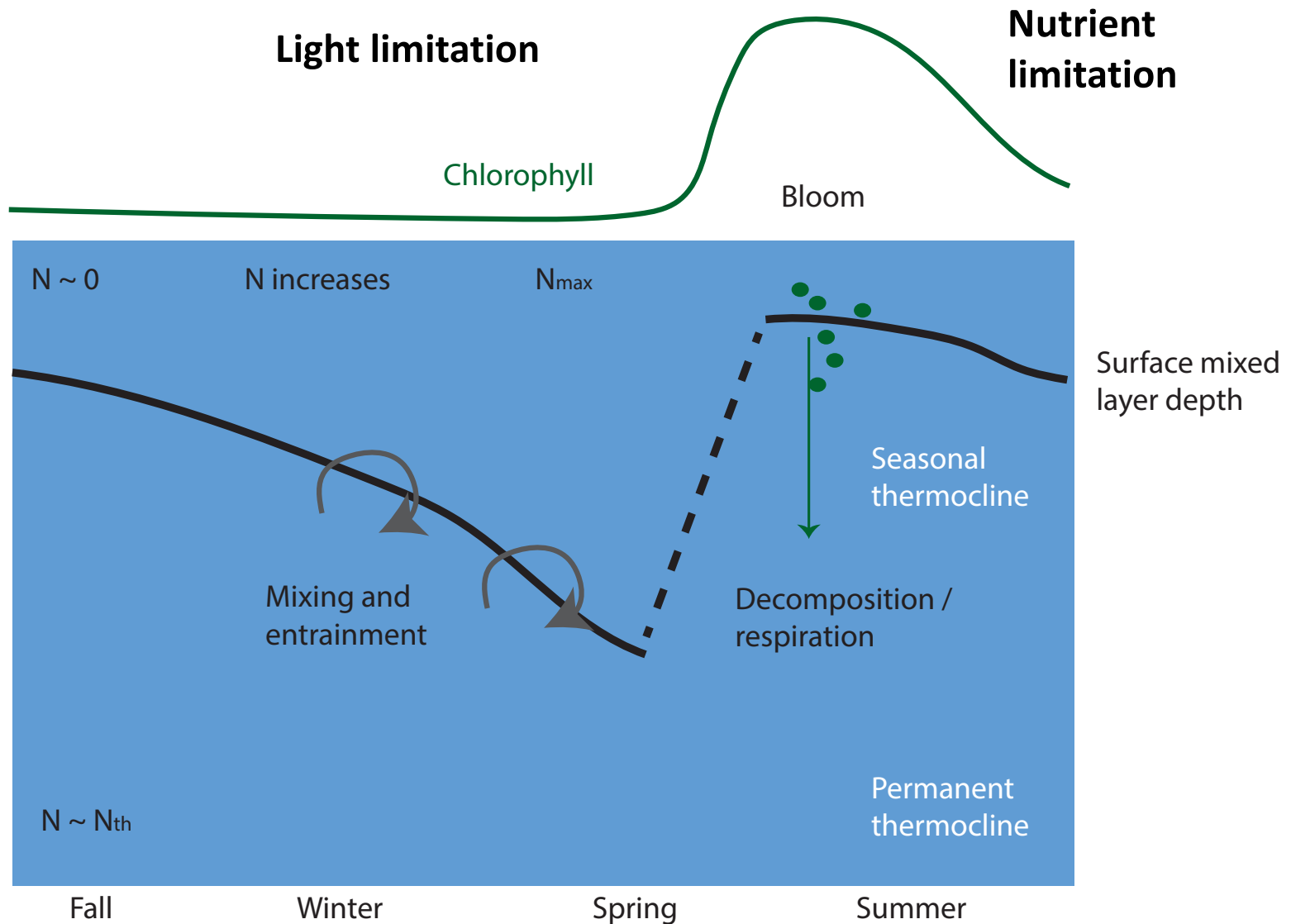
Temperature ITS-90 [C]



Phosphate (micromol/kg)



Seasonal progression



Large scale distribution of nutrients

- Vertical gradient
 - Surface water is generally depleted with nutrients (uptake)
 - Deep water is enriched in nutrients (remineralization/respiration)
- Horizontal gradient
 - Relatively new deep water (e.g. NADW) contains less nutrient
 - Relatively old deep water (e.g. NPDW) contains high nutrient

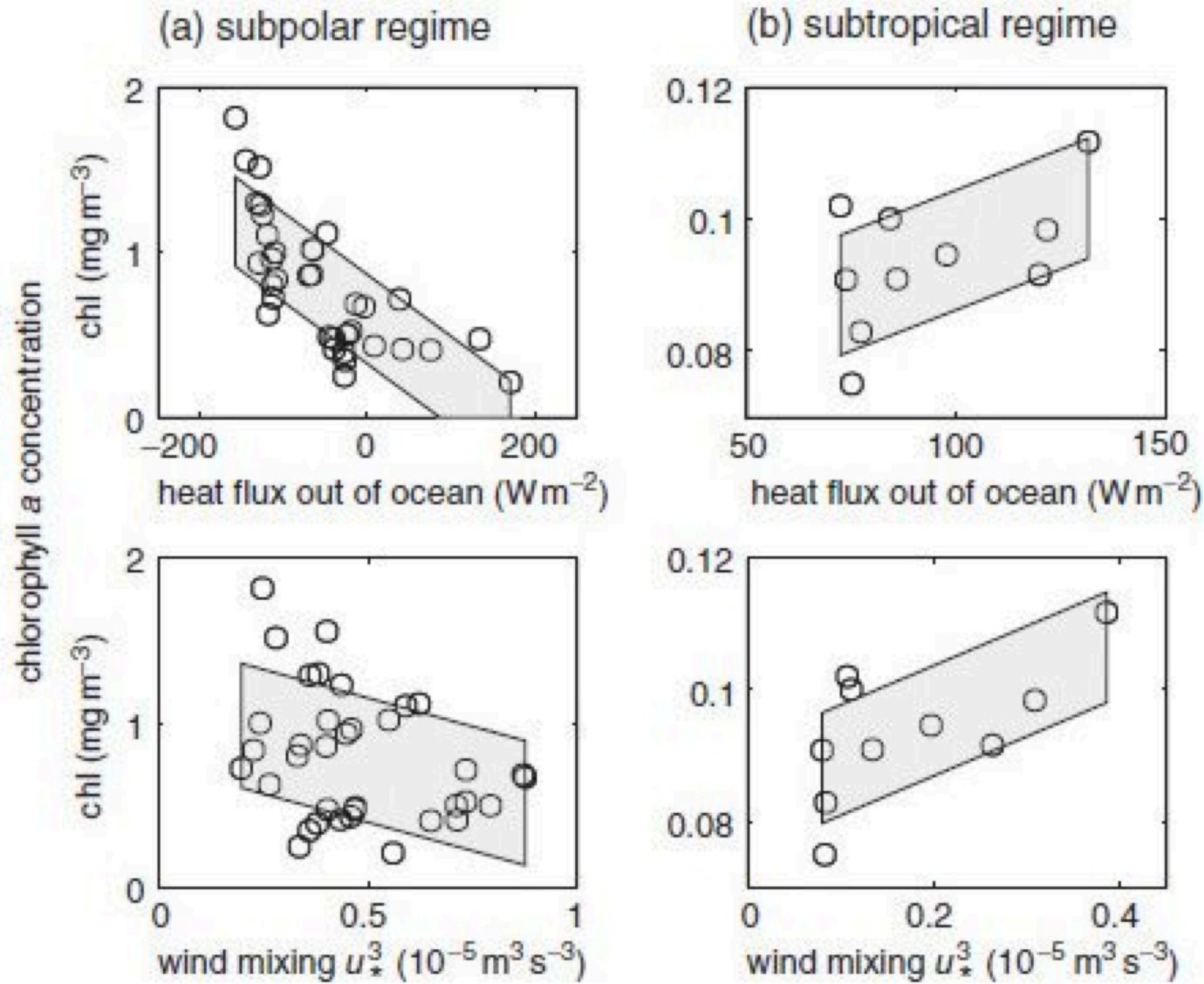
Subpolar productivity

- Strong seasonality
 - Spring/summer blooms
- Light limited
 - Upper ocean stratification regulates productivity
 - Spring/summer shoaling of the mixed layer
 - Wind-induced mixing (prefers weak wind)

Subtropical productivity

- Relatively weak seasonality
- Macro-nutrient (N,P) limited
 - Upwelling supply of nutrient regulates productivity
 - Winter-time deepening of mixed layer
 - Wind-induced mixing (tropical storm, episodic wind events etc)
 - Ocean eddies induce episodic upwelling events

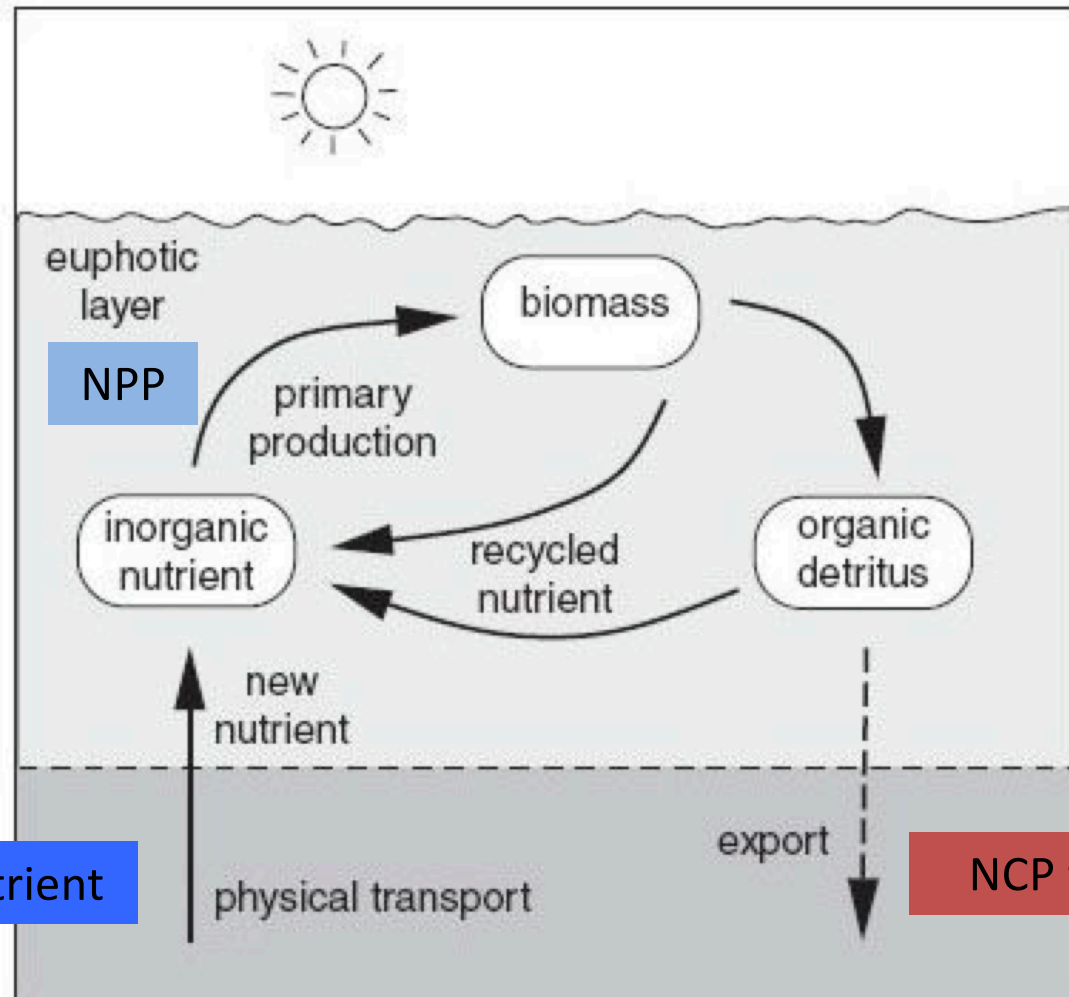
Subtropical vs subpolar productivity



GPP, NPP and NCP

- GPP (**Gross Primary Production**)
 - Total amount of photosynthesis
- NPP (**Net Primary Production**) = $GPP - R_a$
 - R_a is the autotrophic respiration
 - Subtract plant respiration
- NCP (**Net Community Productin**) = $NPP - R_h$
 - R_h is the heterotrophic respiration
 - This is the total amount of biological C fixation

GPP, NPP and NCP



Observing ocean productivity

- Ship-based, in-situ measurements
 - Carbon-14 (^{14}C) incubation
 - Nutrient mass balance
 - Oxygen mass balance
- Satellite ocean color data
- Marine particles

Ship-based, in-situ measurement of biological productivity

- C-14 incubation experiment
 - Steeman-Nielsen (1952)
 - Most of C atom has the atomic mass of 12
 - C-14 is radioactive → a marker to track the flow of C
 - Add radiocarbon to the bottle containing water sample
 - During photosynthesis, carbon is assimilated into the organic matter

$$\text{C uptake} = (\text{total C in bottle}) \times \left(\frac{{}^{14}\text{C in particle}}{{}^{14}\text{C added}} \right) \times 1.05$$

Ship-based, in-situ measurement of biological productivity

- Is C-14 measuring gross or net primary productivity?
 - Strong photosynthesis during day
 - Weak photosynthesis / respiration at night
 - 12 hour incubation under light
 - 12 hour incubation in dark
 - Total 24 hours (light+dark) C-14 incubation ~ NPP per day
 - Remember $NPP = GPP - R_a$
 - R_a (autotrophic respiration = phytoplankton respiration)

HW: calculating NPP

- NPP (mgC/m^3) can be measured at each standard depths (5m, 25m, 45m, 75m, 100m, 125m, 150m, 175m).
- We want to know the vertically integrated NPP per unit area for the water column ($\text{gC}/\text{m}^2/\text{day}$).

$$\begin{aligned}\overline{NPP} &= \int_{-200}^0 NPP(z) dz \\ &= NPP_1 \Delta z_1 + NPP_2 \Delta z_2 + NPP_3 \Delta z_3 + \dots\end{aligned}$$

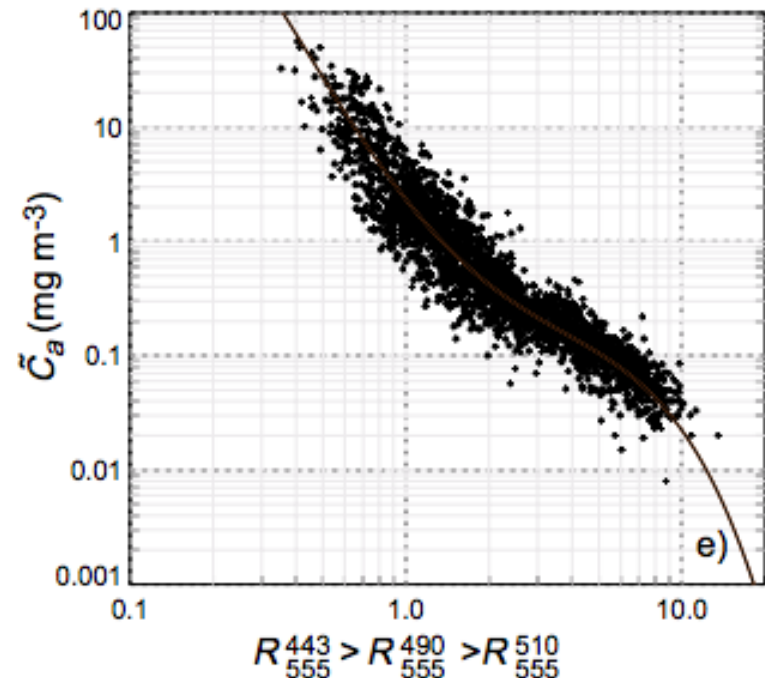
Measuring chlorophyll from space

- Remote sensing reflectance (λ) = the ratio between reflected and incident solar radiation (normalized for solar angle, sun-earth distance, and atmospheric absorption)
- SeaWiFS sensors (412, 443, 490, 510, 555, 670, 765, 865nm wave lengths)
 - Standard algorithm for SeaWiFS is chl_oc4

$$C_a = 10.0 \left(0.366 - 3.067R_{4S} + 1.930R_{4S}^2 + 0.649R_{4S}^3 - 1.532R_{4S}^4 \right)$$

$$R_{4S} = \log_{10} (R_{555}^{443} > R_{555}^{490} > R_{555}^{510})$$

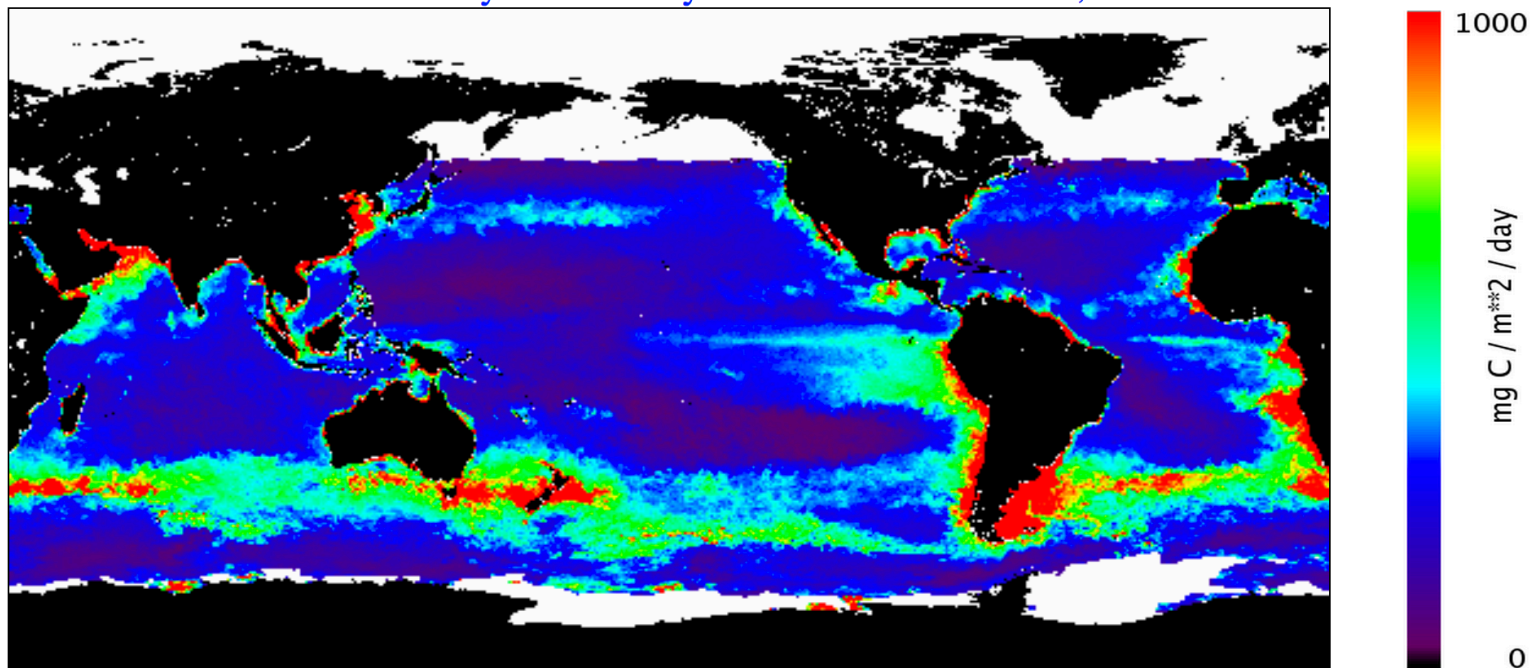
O'Reilly et al., (2000)



From chlorophyll to NPP

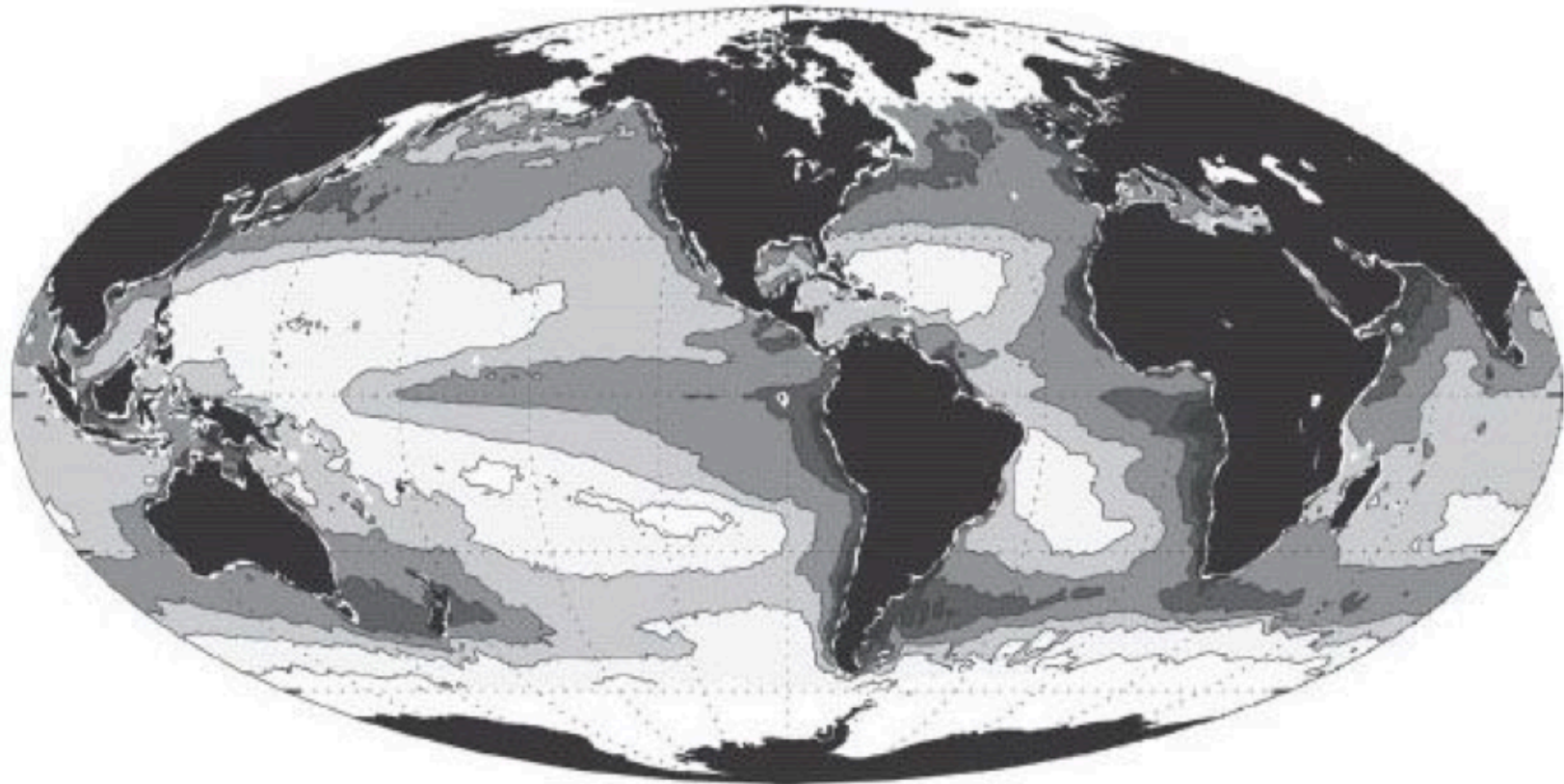
- Chlorophyll-based satellite estimate (Behrenfeld and Falkowski 1997)
 - Photosynthesis = function of chlorophyll, available light and SST
 - Chl → a proxy for biomass
 - SST → a factor controlling the growth rate

Monthly Net Primary Production: December , 2002



Global, satellite based map of NPP

primary production (mol C m⁻² y⁻¹)

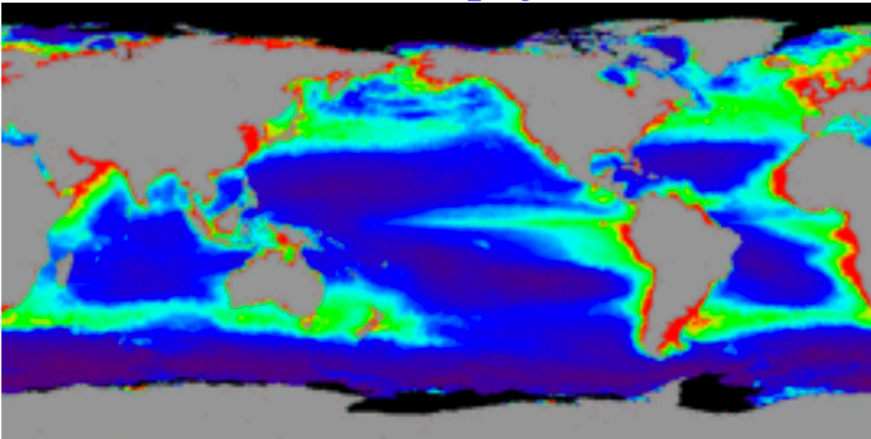


Issues with satellite-based productivity

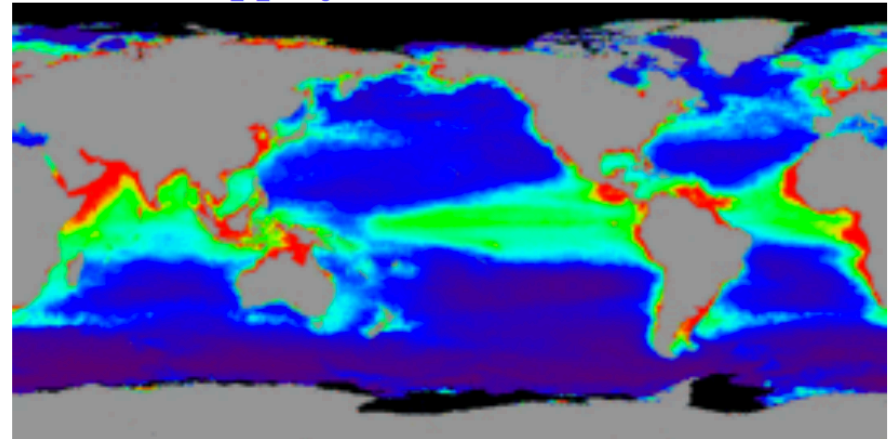
- Many models exist relating chlorophyll and NPP
 - Note: satellite productivity is NOT observation!
 - These models are calibrated fit to observed NPP (i.e. C-14 incubation data)
 - Regional adaptations are often necessary

Annual Net Primary Production for 2003

VGPM (chlorophyll based)



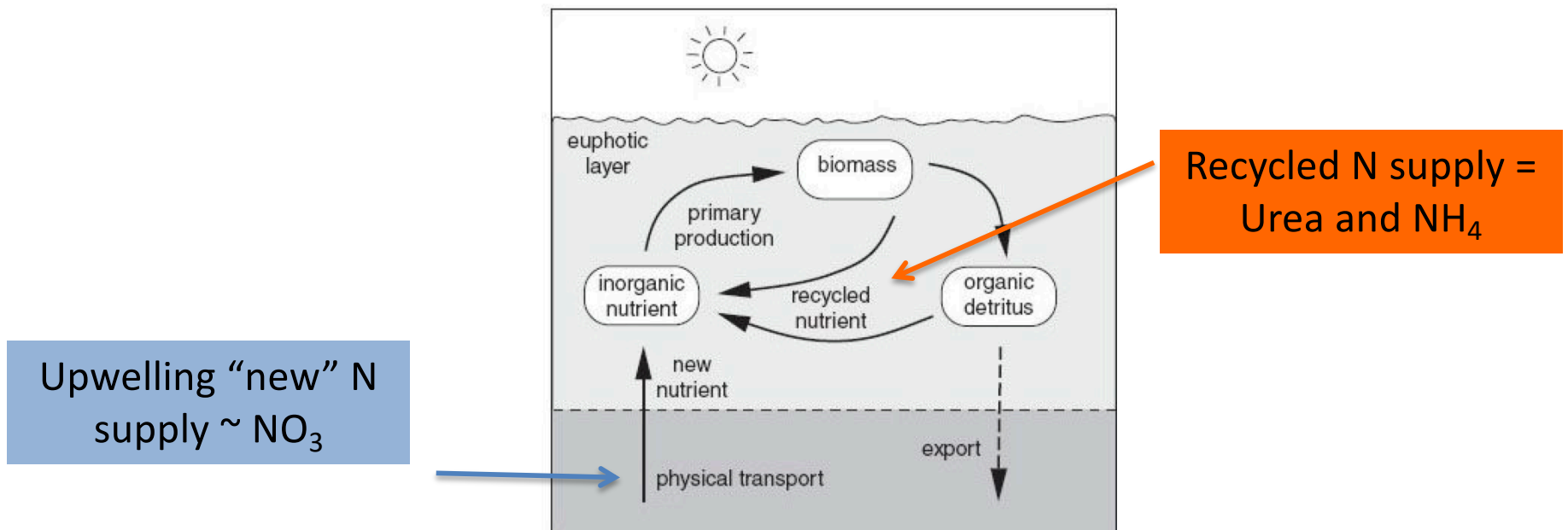
Eppley (VGPM variant)



OSU Ocean Productivity products

Nitrogen mass balance

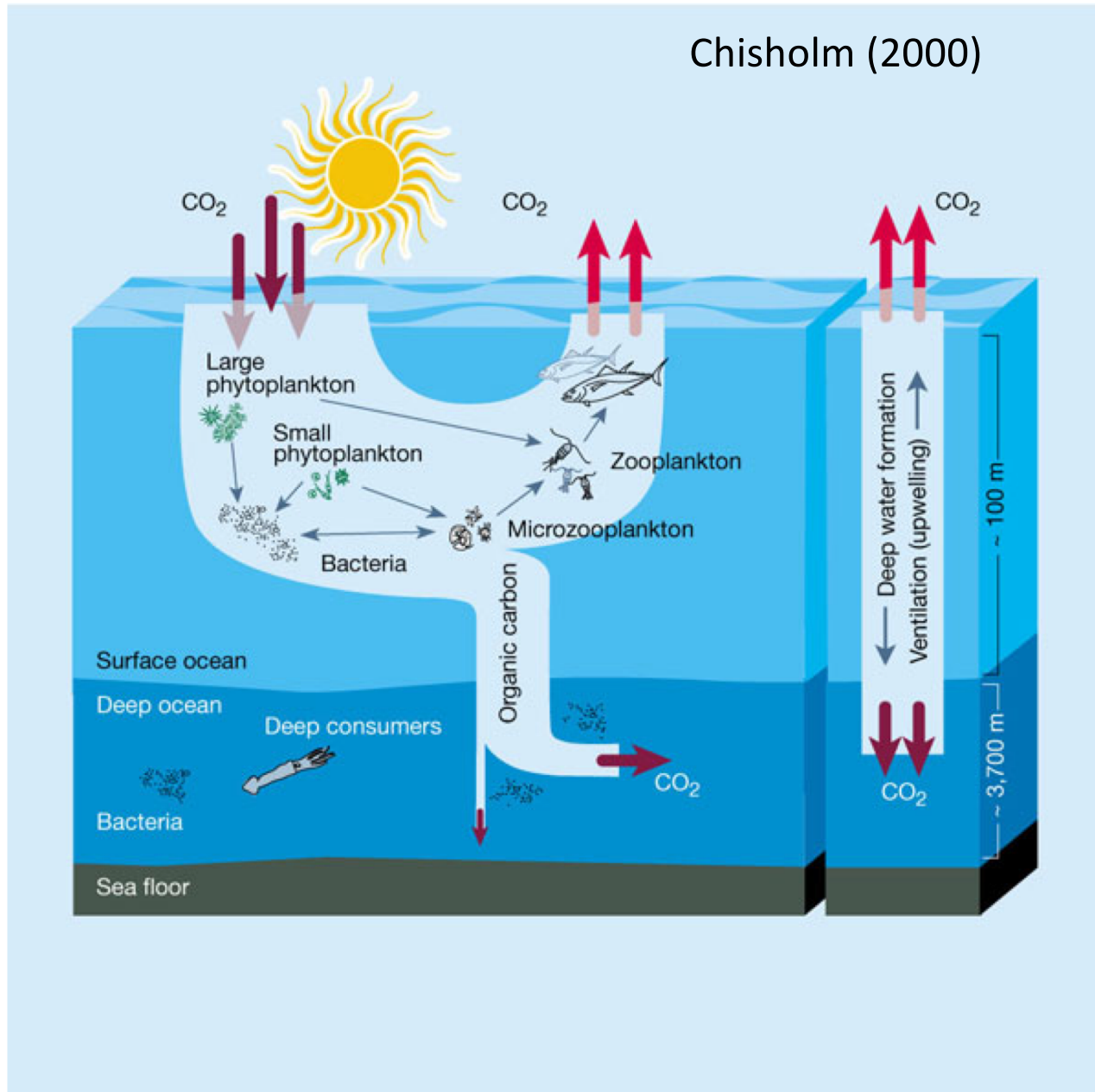
- Different forms of nitrogen available for phytoplankton
 - Urea and ammonium (NH_4) are produced by the decomposition of organic matter. They are readily available for uptake, therefore strongly depleted
 - Nitrate (NO_3) is often depleted in the surface, but enriched at depths



“New” and “Recycled” production

- Nitrogen source
 - **Recycled production** uses Urea and NH_4 supplied by the decomposition of organic matter within the surface mixed layer
 - **New production** uses NO_3 supplied by the entrainment or upwelling from thermocline
 - Considering the vertical N mass balance, **New production** is approximately equal to **Export production** and **NCP**

Nutrient and carbon cycling



Global marine NPP
~ 50 PgC/year

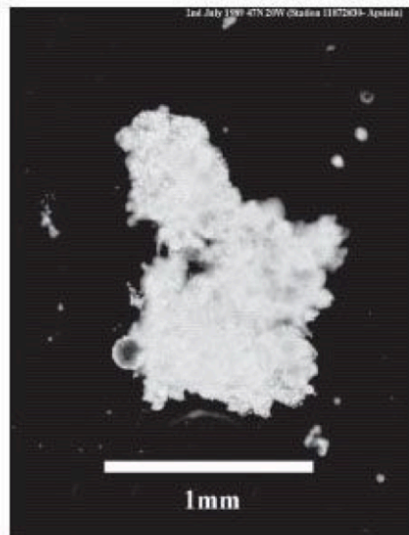
Global average e Ratio
~ 0.3

Export production ~
 $50 \times 0.3 = 15$ PgC/year

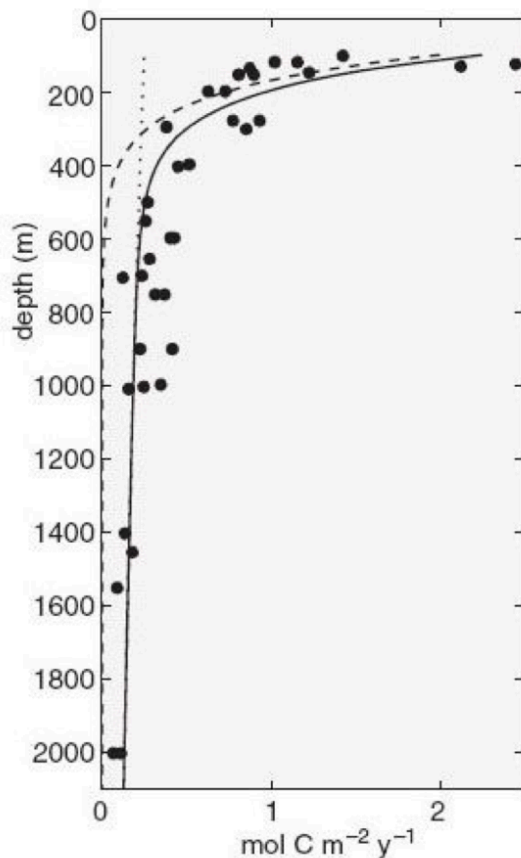
Recycled production ~
 $50 - 15 = 35$ PgC/year

Vertical profile of sinking particles

(a) marine snow



(b) sinking flux of POC



“Martin curve”

Composition of sinking particle

(Sinking particle) = (Organic matter) + (mineral particles)

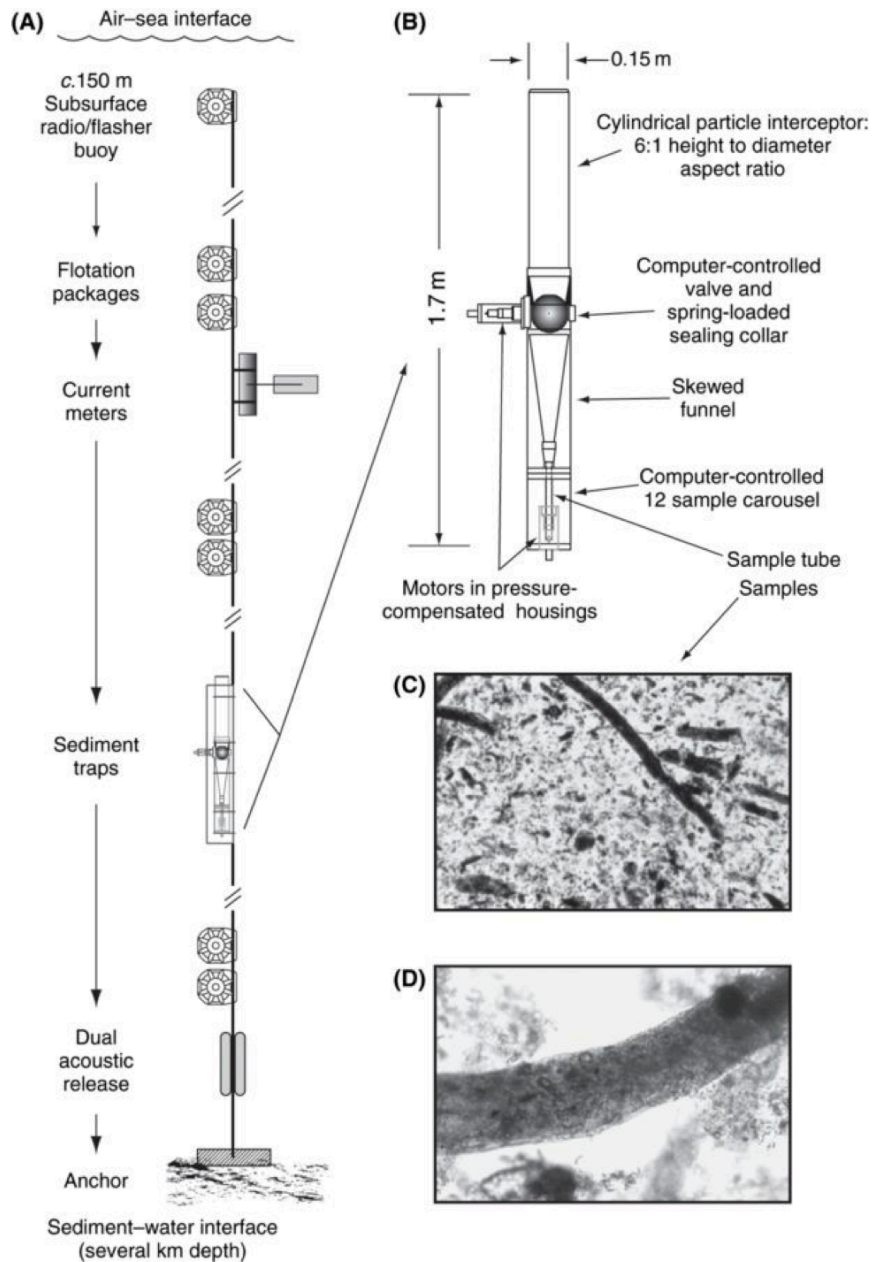
Globally, about 6% of sinking C out of euphotic layer is CaCO₃ (the rest is organic C).

Also globally, the ratio of Si:CaCO₃ is about 2:1 (Sarmiento et al., 2002)

Attenuation of sinking particle

Approximately only 5% of particle remains at 1000m depth

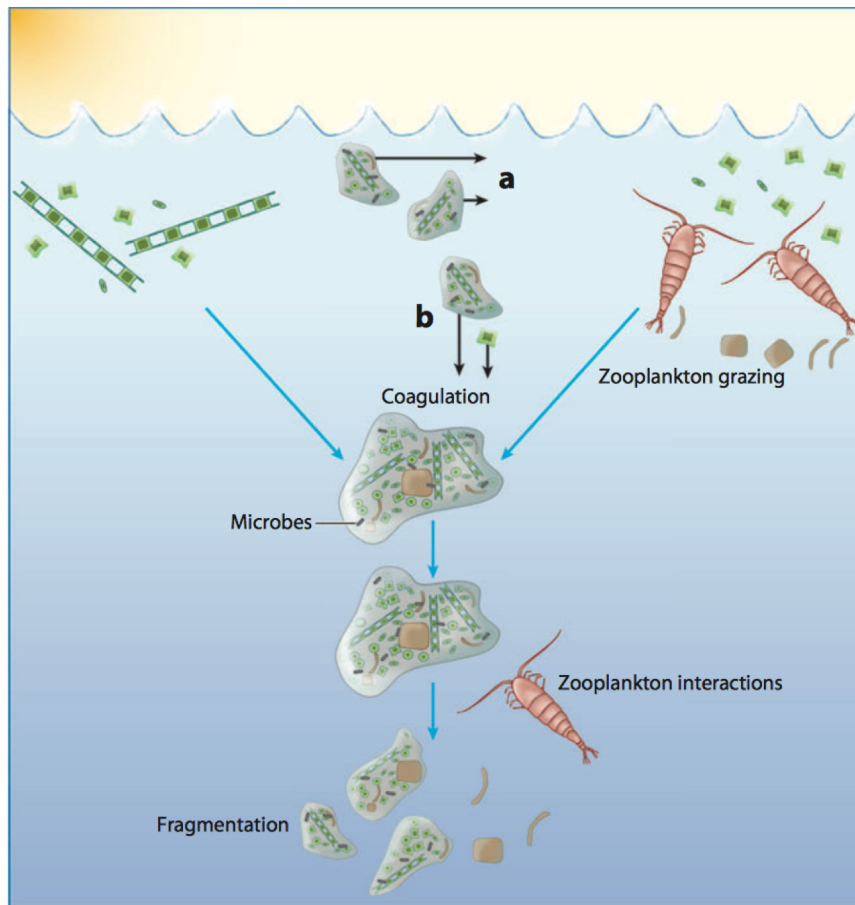
Measuring marine particles by sediment traps



Sediment trap
= Rain gauge like instrument
that captures falling particles
in the water

Sinking organic matter

Burd and Jackson (2009)



Larger particle sinks faster

Aggregation: physical and biological processes that transfers material to a larger particles.

Fragmentation: physical and biological processes that breaks apart particles into smaller sizes.

e Ratio measures the fraction of NPP that is exported across the base of euphotic zone

Figure 1

Particle aggregation processes and how they affect particles in the marine environment. Biological aggregation (e.g., fecal pellet production) and physical aggregation by (a) shear and (b) differential sedimentation form large, heterogeneous, rapidly settling particles in the surface waters. In deeper waters, fragmentation and repackaging of this material by zooplankton are the dominant processes that affect aggregate sizes and properties. Microbes decompose material throughout the water column.

$$e \text{ Ratio} = \frac{C_{\text{export}}}{NPP}$$

Particle size spectrum

Jackson et al., (1997)

Burd and Jackson (2009)

The abundance of particle as a function of size (diameter)

There are much more smaller particle than larger ones.
Observations show power law relationship.

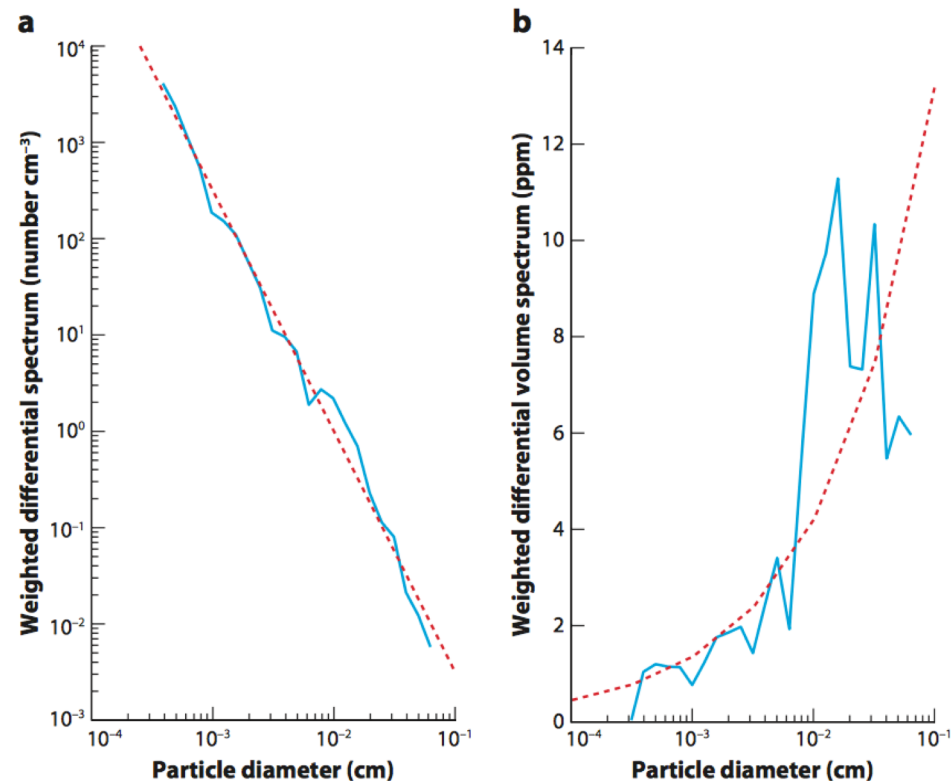


Figure 2

Different representations of particle size distributions: (a) the size-weighted particle size spectrum [$dn(d)$] and (b) the weighted volume spectrum [$dV(d)n(d)$]. The advantage of the weighted spectrum is that the area under the curve of the weighted volume spectrum is proportional to the conserved volume for particles in that size range. The dashed line shows the best fit power-law spectrum in (a) and the weighted volume spectrum using that power law in (b). Data are from Monterey Bay (Jackson et al. 1997).

Respiration at depth

- As measured by O_2 in dark bottles of water samples at depth

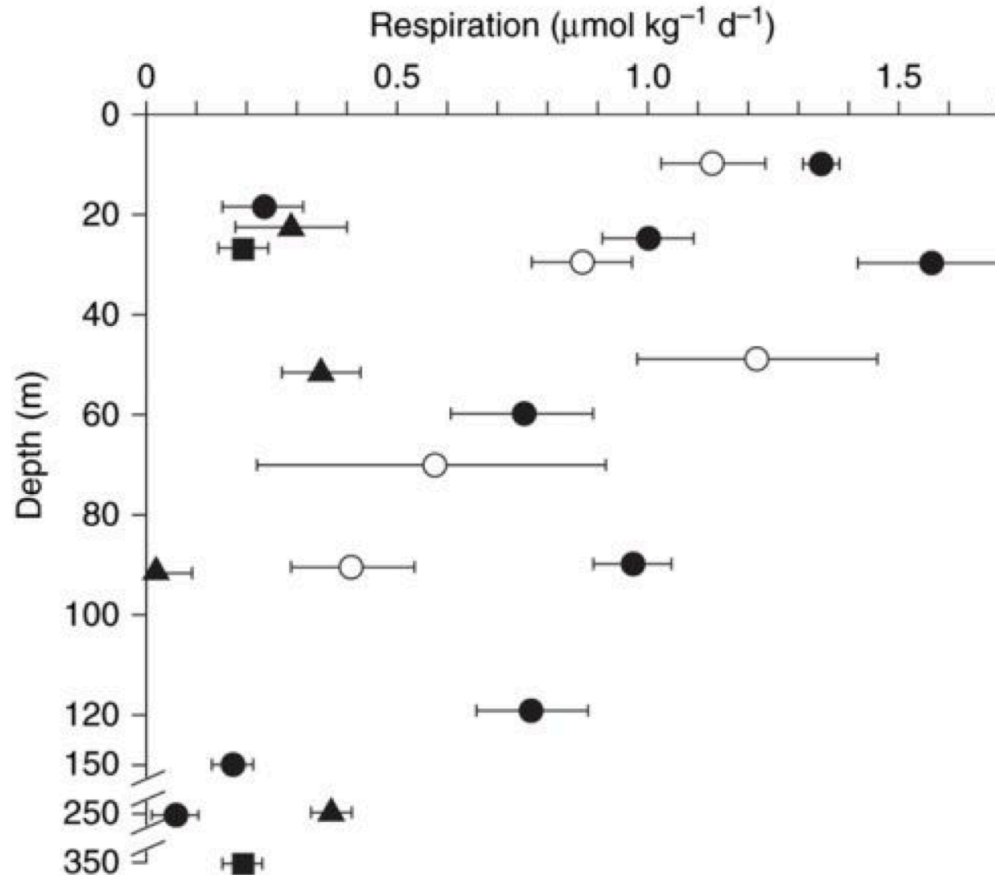
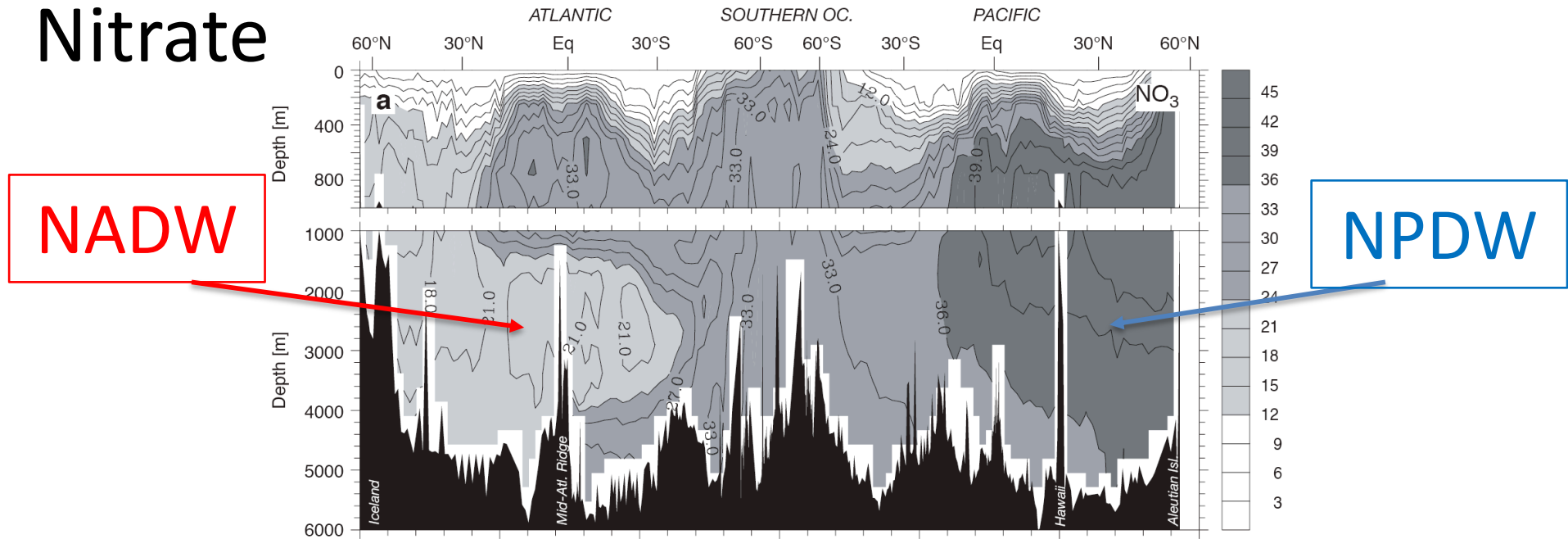


Figure 6.7. Measurements of *in vitro* changes in oxygen concentration in dark bottles containing samples taken from different depths in the ocean from the subtropical North Pacific. Samples from different depths were incubated in bottles either on deck or *in situ*. Symbols indicate different casts. Redrawn from Williams and Purdie (1991).

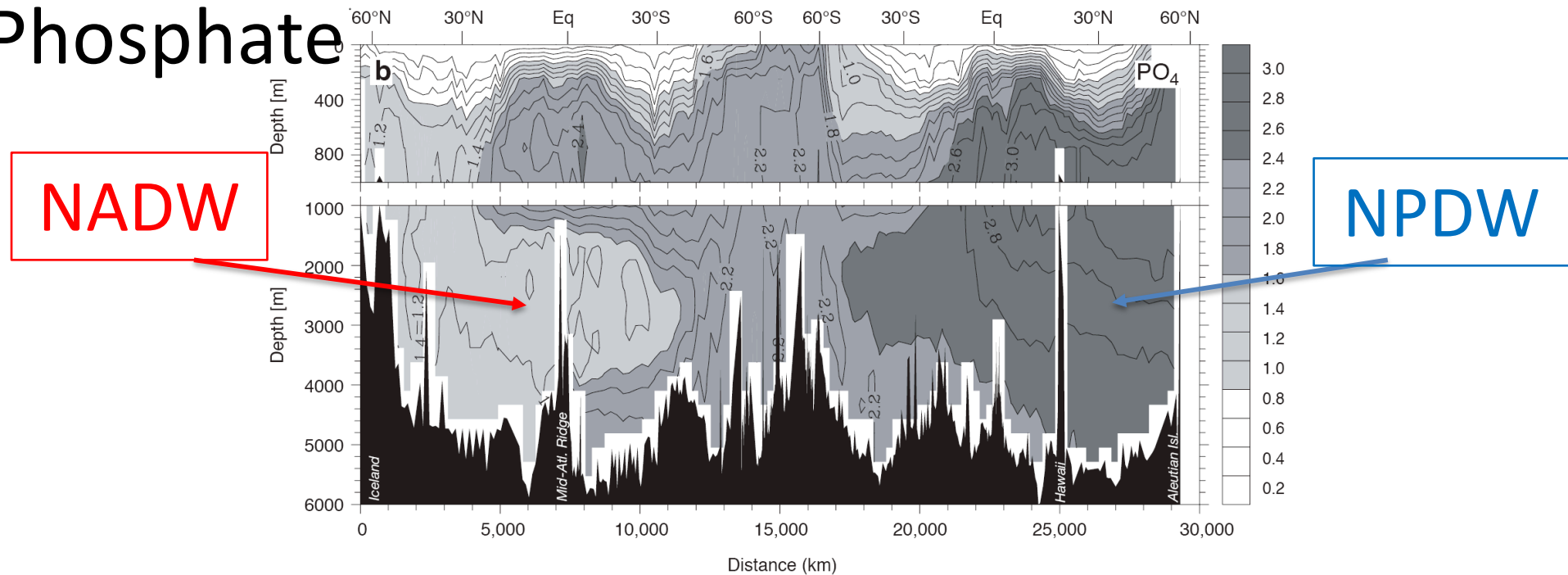
Large scale distribution of nutrients

- Vertical gradient
 - Surface water is generally depleted with nutrients (uptake)
 - Deep water is enriched in nutrients (remineralization/respiration)
- Horizontal gradient
 - Relatively new deep water (e.g. NADW) contains less nutrient
 - Relatively old deep water (e.g. NPDW) contains high nutrient

Nitrate

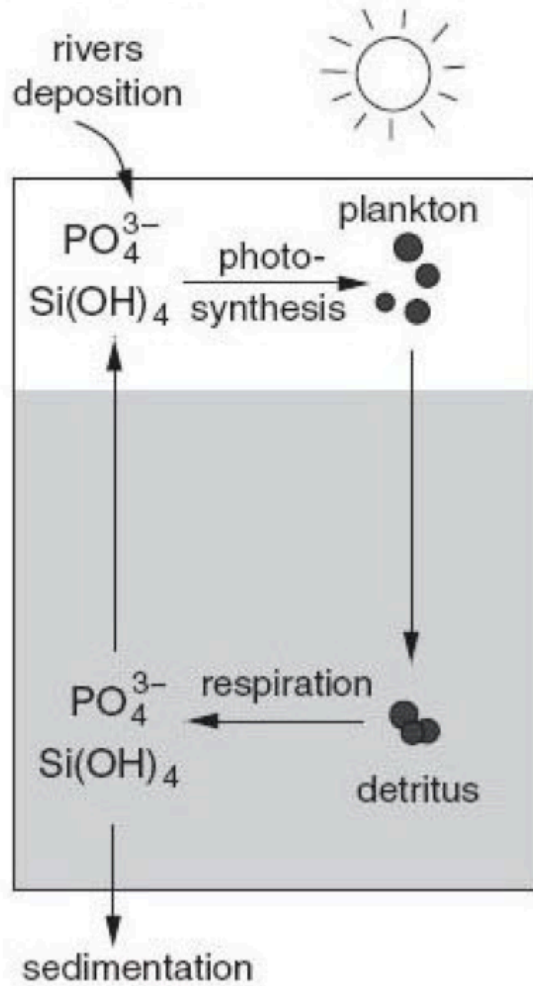


Phosphate

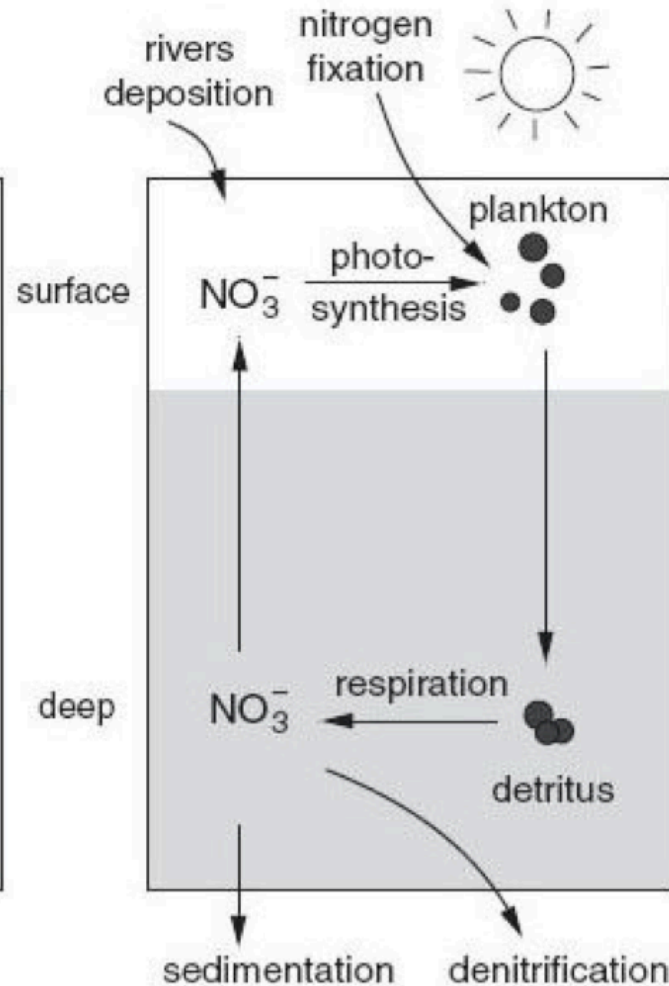


Contrasting different nutrient cycling

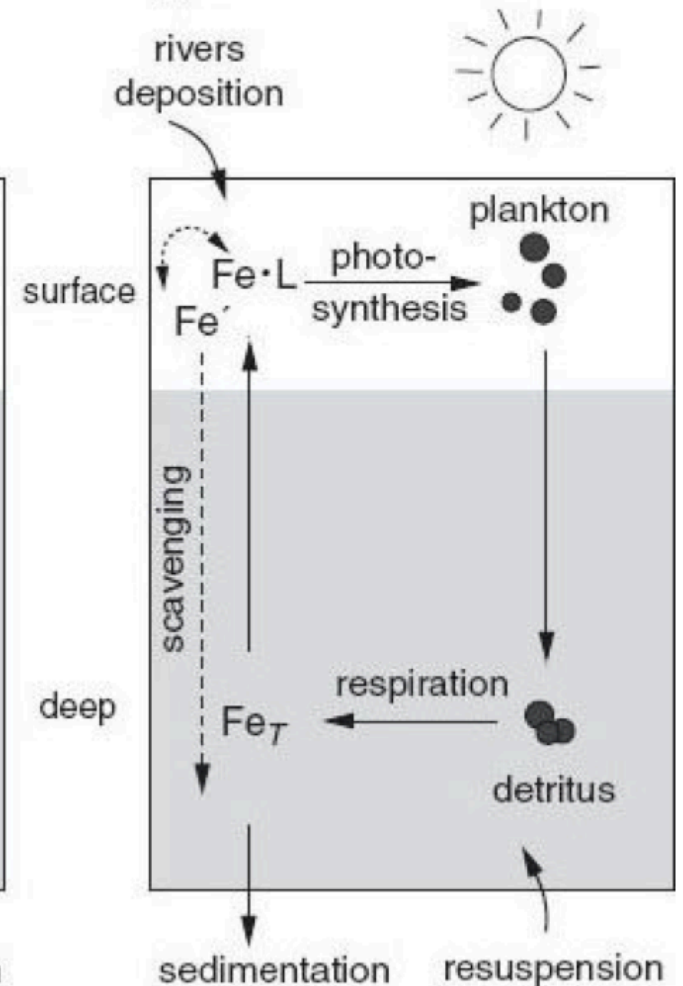
(a) phosphorus and silica



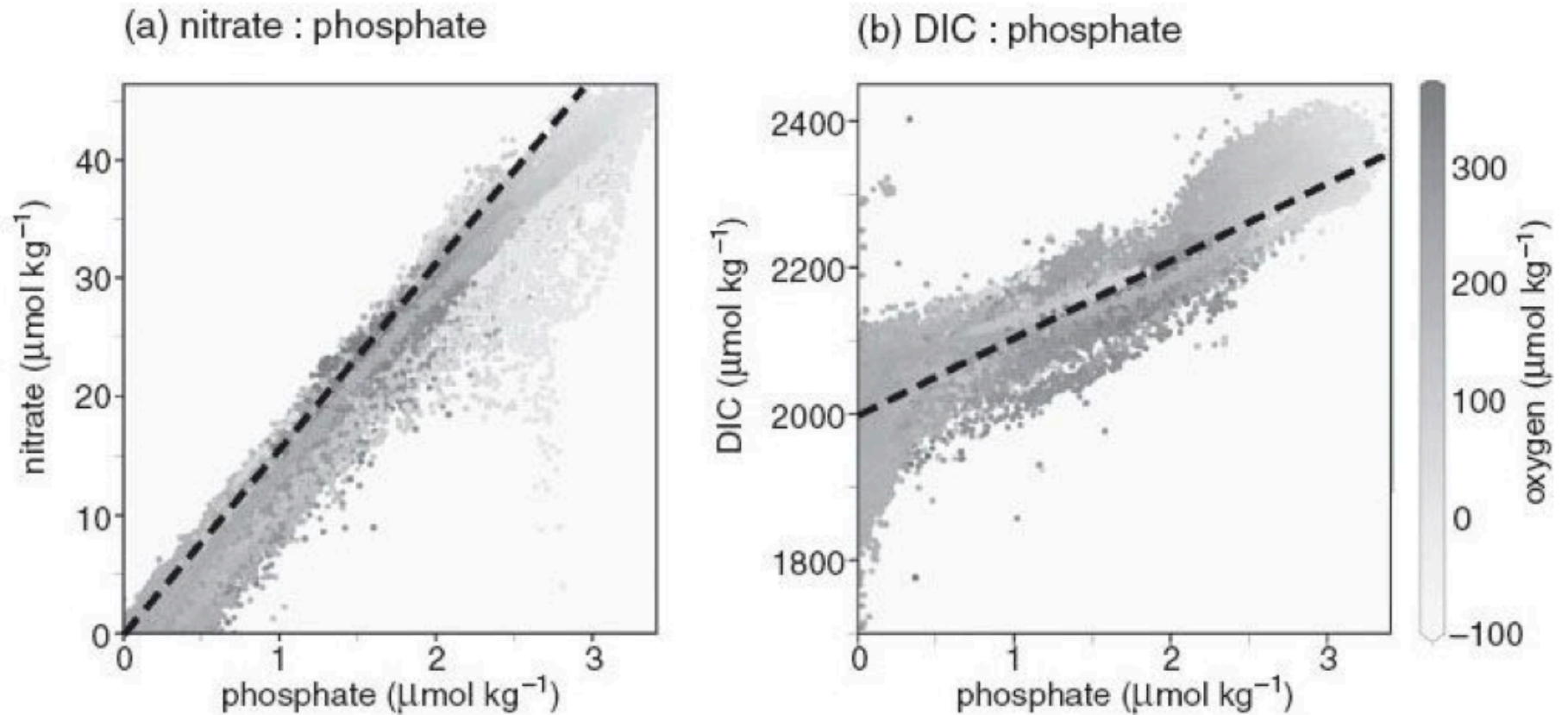
(b) nitrogen



(c) iron



Redfield ratio

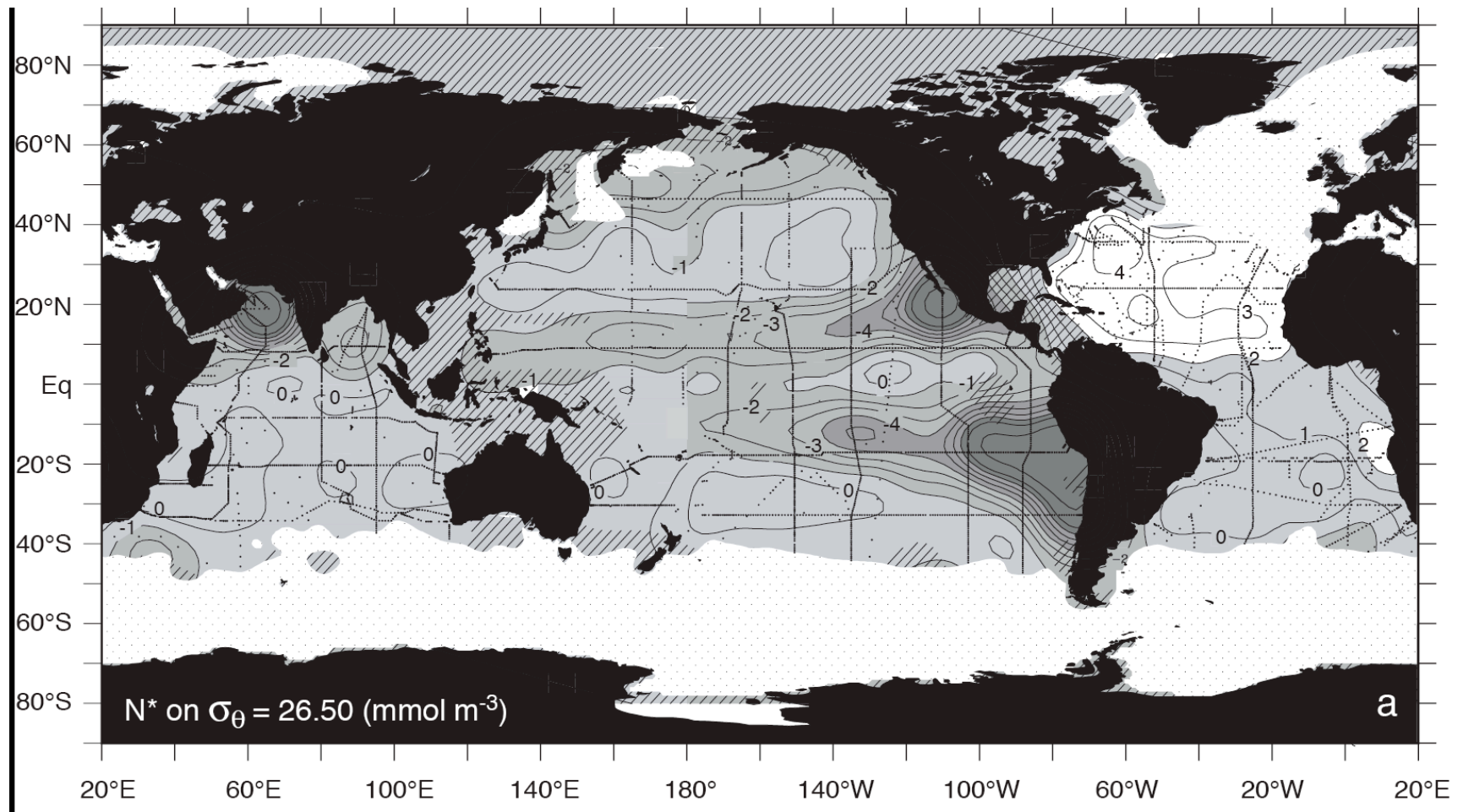


When organic matter decomposes in the deep water, it releases inorganic nutrient and carbon dioxide to the deep water.

N*: decoupling between N and P

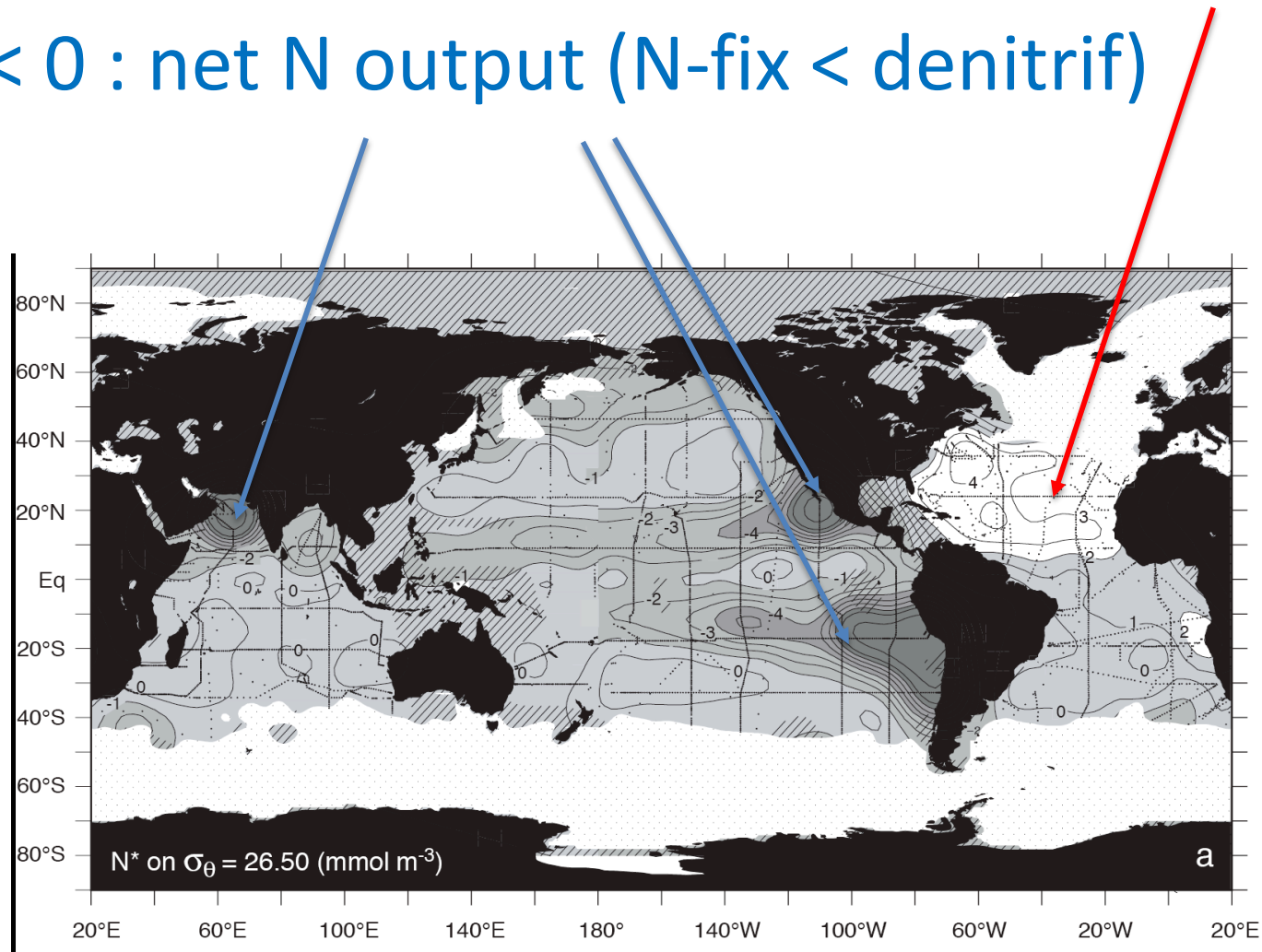
- $N^* = \text{NO}_3 - 16 \cdot \text{PO}_4 + \text{const.}$

Sarmiento and Gruber 2006



N^* : decoupling between N and P

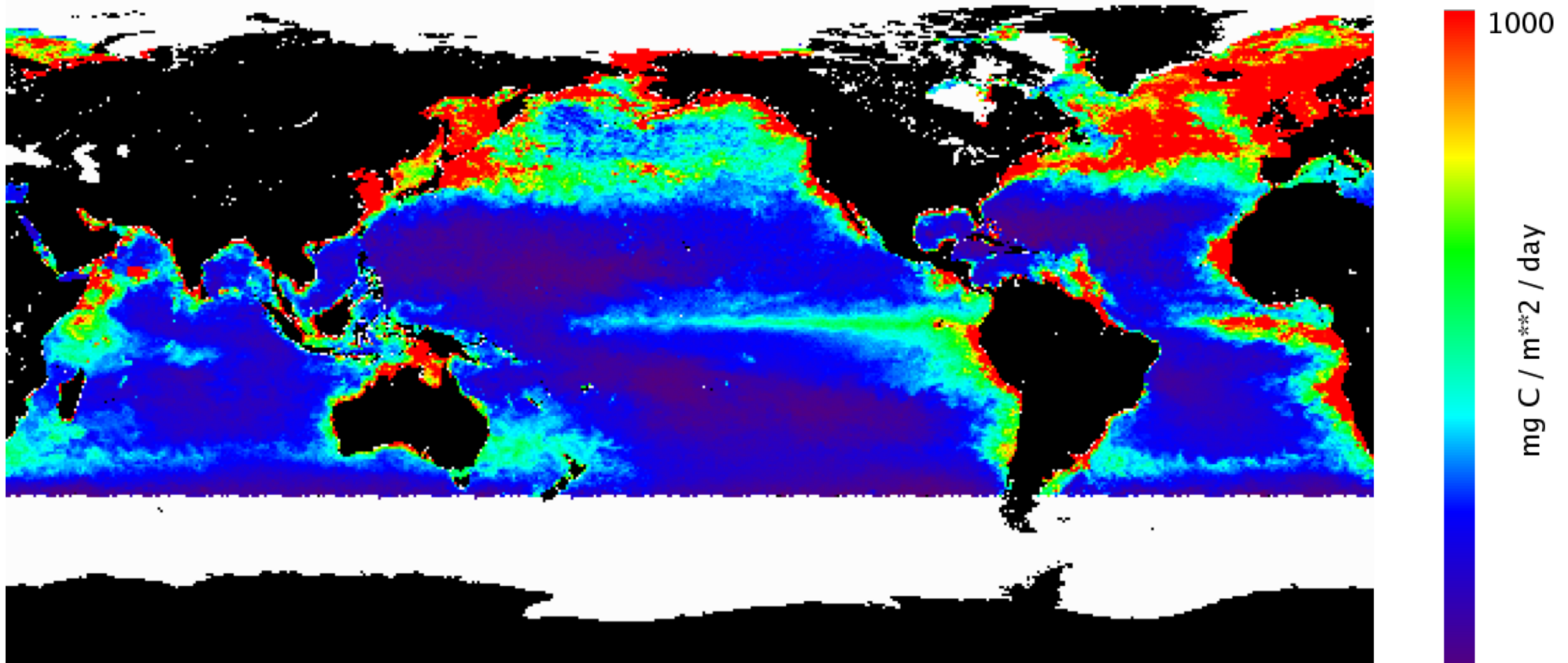
- $N^* > 0$: net N input (N-fix > denitrif)
- $N^* < 0$: net N output (N-fix < denitrif)



Pattern of global ocean productivity

SeaWiFS-based productivity estimates (Behrenfeld and Falkowski 1997)

June 2004

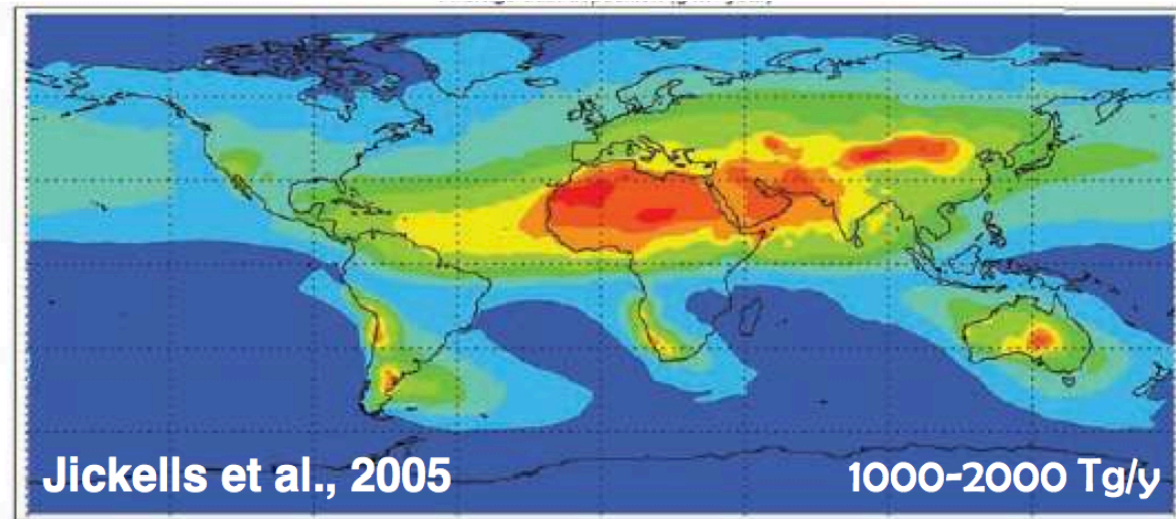


- High productivity: high latitudes (summer hemisphere), tropics, coastal regions
- Low productivity: subtropics, high latitudes (winter hemisphere)
- Compare North Atlantic and North Pacific.

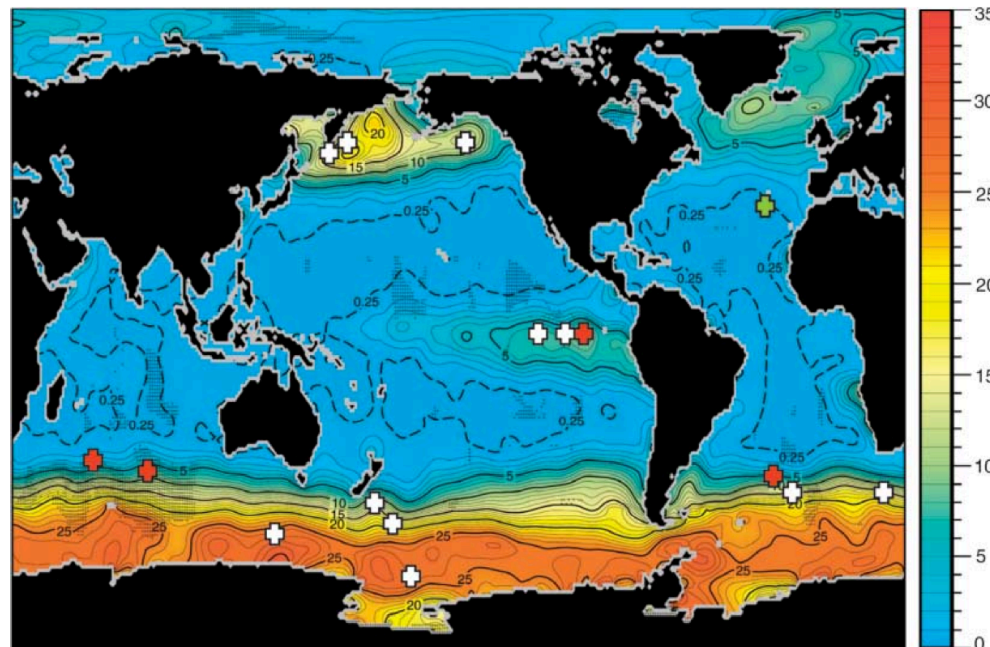
Micro-nutrient

- Phytoplankton also needs trace elements such as iron as necessary nutrients
 - Sources/sinks of iron in the oceans are not fully understood
 - Iron can be released from mineral dust depositing in the surface ocean
 - Other sources include continental shelf sediment and hydrothermal sources
 - Iron in oxygenated seawater forms Fe-oxides and sink out from the water column (Precipitation)
 - Iron is also particle-reactive, and is absorbed into particles that sink out (Scavenging)
 - Dissolved iron concentration is very low (a factor of 1,000 smaller than phosphorus) in the seawater

Fe limitation of marine productivity



Dust deposition to the surface ocean



Surface nitrate concentration highlighting the High-Nutrient-Low-Chlorophyll regions.

(cross) Sites of meso-scale Fe addition experiments
Boyd et al., (2007)

Nutrients in the mineral dust

- **Mineralogical composition**
 - Clay (illite, kaolinite)
 - Carbonates (calcite, dolomite)
 - **Phosphates** (apatite)
 - **Fe oxides** (hematite, goethite)

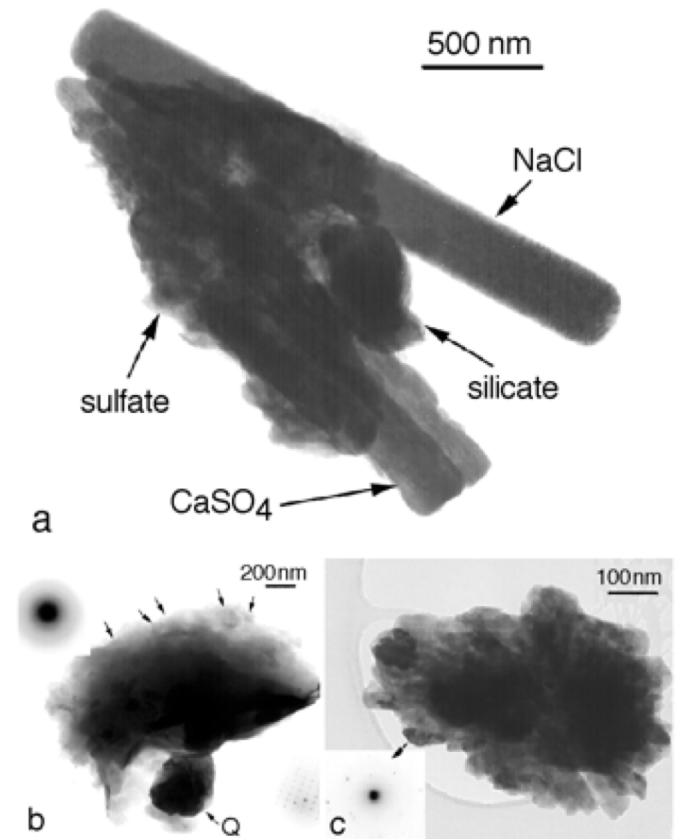
- What is **bioavailable** is the **water-soluble fraction**

(Fe input into the surface water)

= (1) mass of dust deposition

x (2) fraction of total Fe in the dust

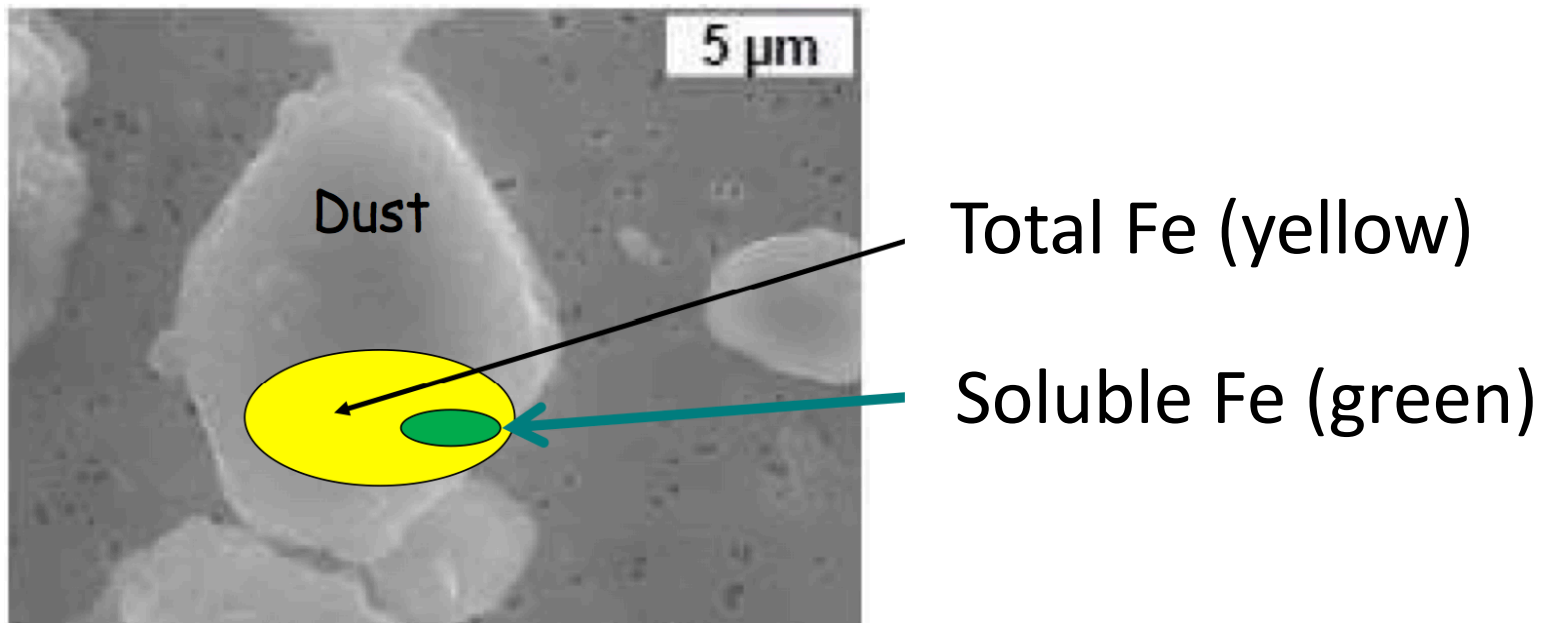
x (3) soluble fraction of Fe



TEM images of marine aerosols
Buseck et al., (1999)

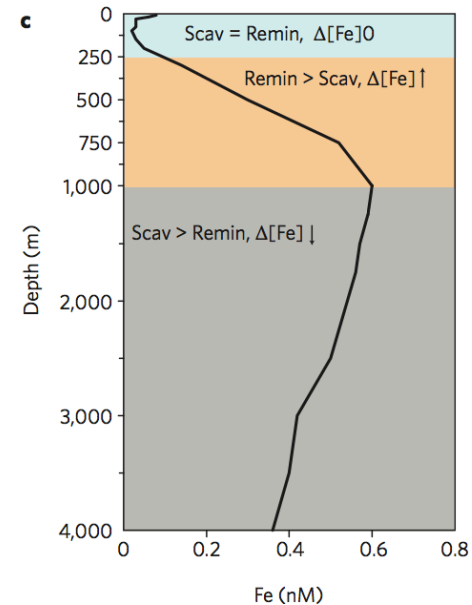
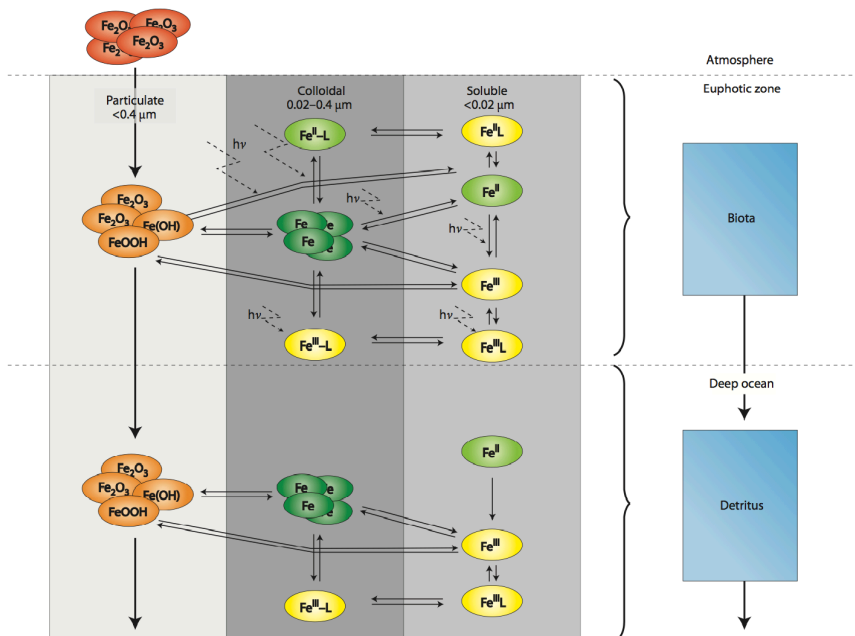
Soluble Fe fraction

- Mechanisms for mobilization of Fe are not well known
- Observed soluble Fe fraction \rightarrow 0.001% to 90%
- In order to satisfy the Fe demand of marine phytoplankton, we need about 0.5% to 2% solubility



Fe chemistry in the seawater

- What happens to the mineral Fe after its deposition over the surface ocean?
 - Hydrolysis reactions
 - Scavenging onto particles
 - Binding with organic ligands
 - Photochemical reactions

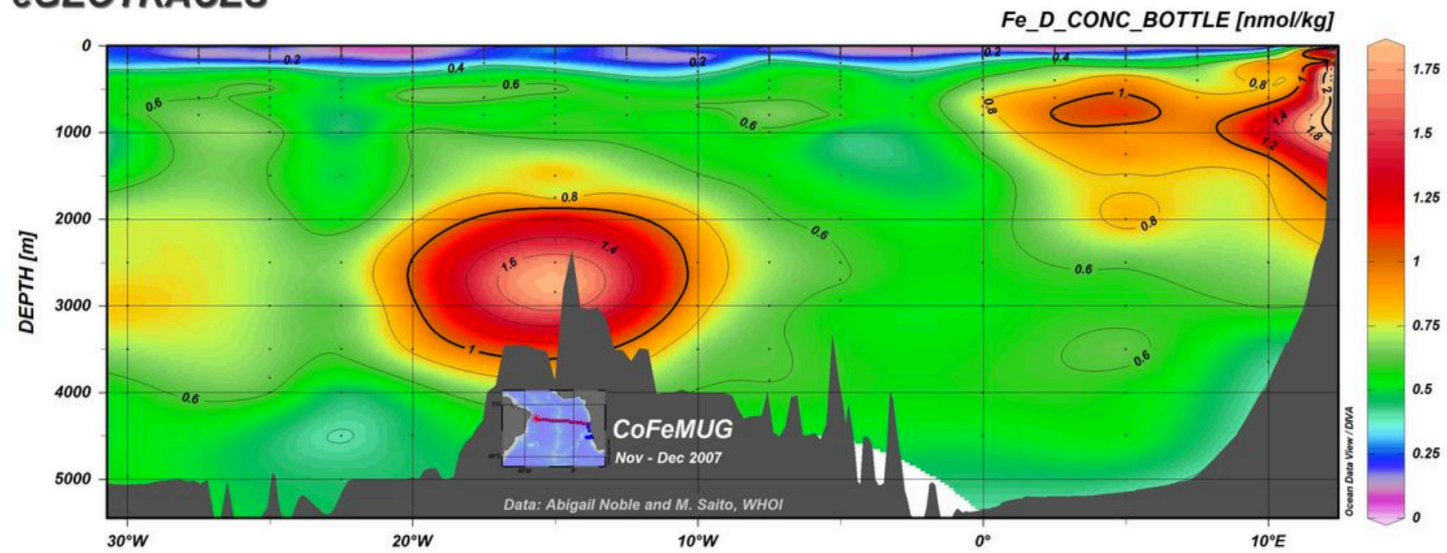


Boyd and Ellwood (2010) Nat. Geosci.

Large-scale distribution of Fe

Fe

eGEOTRACES



O₂

eGEOTRACES

