Dynamical /biogeochemical coupling in models

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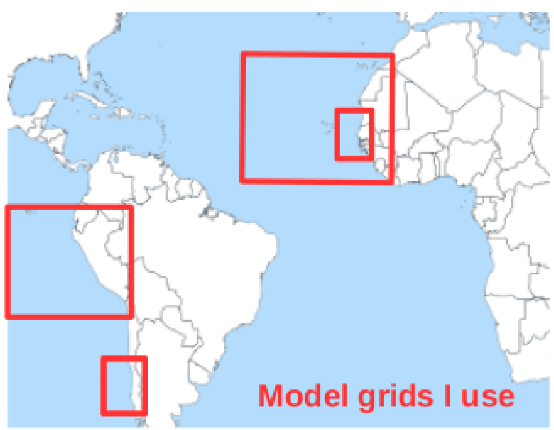
Research interests:

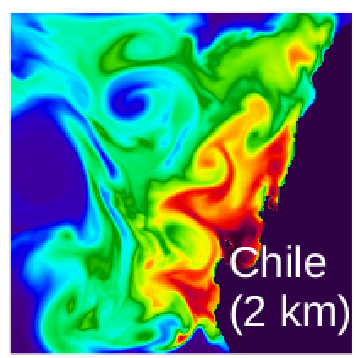
- coastal upwelling systems (Peru, Chile, West Africa)
  from regional scale to the coastal scale (~ 200 m)

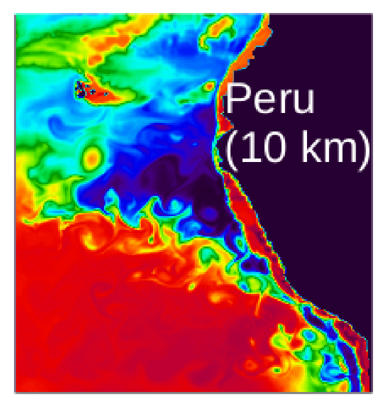
-Impact of physical processes (currents, mixing,…) on productivity, oxygen cycle (oxygen minimum zones),…

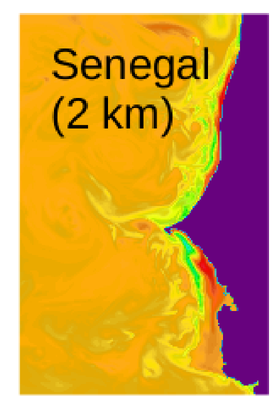
- Time scales: ~ 1 day -> 100 years (climate change)

- Modelling tools: ROMS/CROCO coupled to PISCES (user since 2008)









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Outline of the course

1. Generalities on coupling between ocean dynamics and biogeochemistry (45 min)

2. Modelling using the PISCES model (45 min)

3. Examples of studies based on PISCES model (45 min)

Coupling: dynamics →biogeochemistry

The major role of transport by the fluid

Each biogeochemical tracer C follows the “same” equation:

$$\underbrace{\partial_t C=-u\partial_x C-v\partial_y C-w\partial_z C}_{\text{transport}} \; \underbrace{+\partial_z(K_z\partial_z C)}_{\text{vertical mixing}} \; \underbrace{+ D_h(C)}_{\text{horizontal mixing}} \; + \; \underbrace{S(C)-P(C)}_{\text{Biogeochemistry}}$$

S(C) =sources of C
P(C)= sinks of C

(u,v,w)=velocity of the fluid

w = vertical component (fluid + gravity if C is not fully dissolved)

K_z= vertical mixing coefficient (turbulence)

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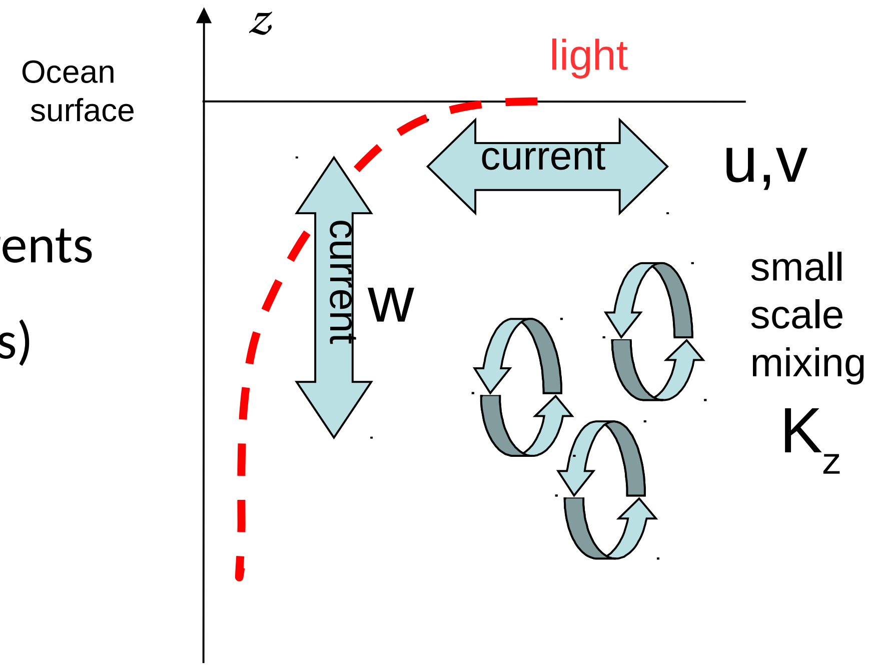
transport acts at all levels of the biogeochemical cycles

Phyto : plant
Plankton : “plant that moves without goal” → (1) **Transport of phytoplankton by the geophysical fluid**

- Horizontal & vertical transport by the currents
- Vertical mixing (up & down displacements)
- Transported in vertical gradient of light



=> small zooplankton, nutrients, dissolved organic matter are transported passively by the geophysical fluid

=> physics of the surface layers of the ocean are very important

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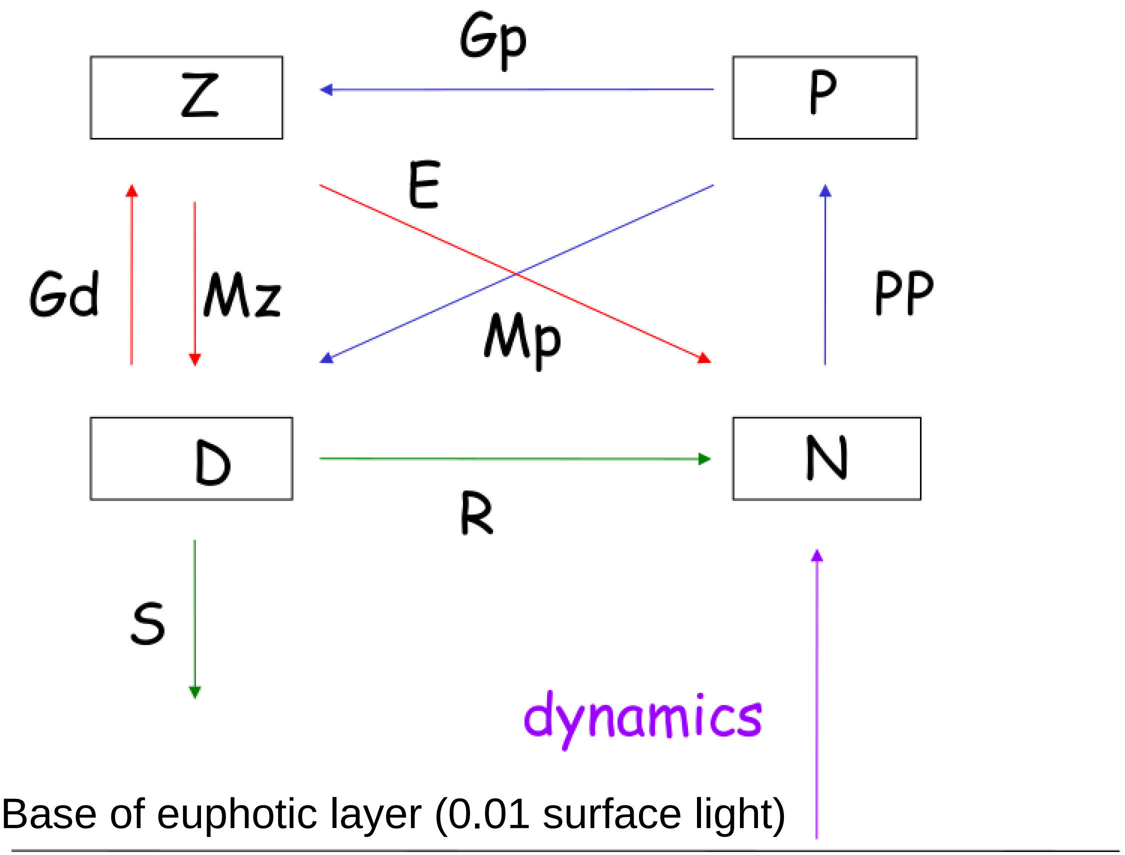
Example of a "simple" NPZD ecosystem



(1) Phyto

$S(P)=PP$ — Primary Production

$P(P)=Gp+Mp$ — Grazing, Mortality P

(2) Zoo

$S(Z)=Gp+Gd$ — Grazing P, Grazing D

$P(Z)=Mz+E$ — Mortality Z, Excretion

(3) Detritus

$S(D)=Mz+Mp$ — Mortality Z, Mortality P

$P(D)=Gd+S+R$ — Grazing D, Sinking, Remin

(4) Nutrients

$S(N)=R+E$

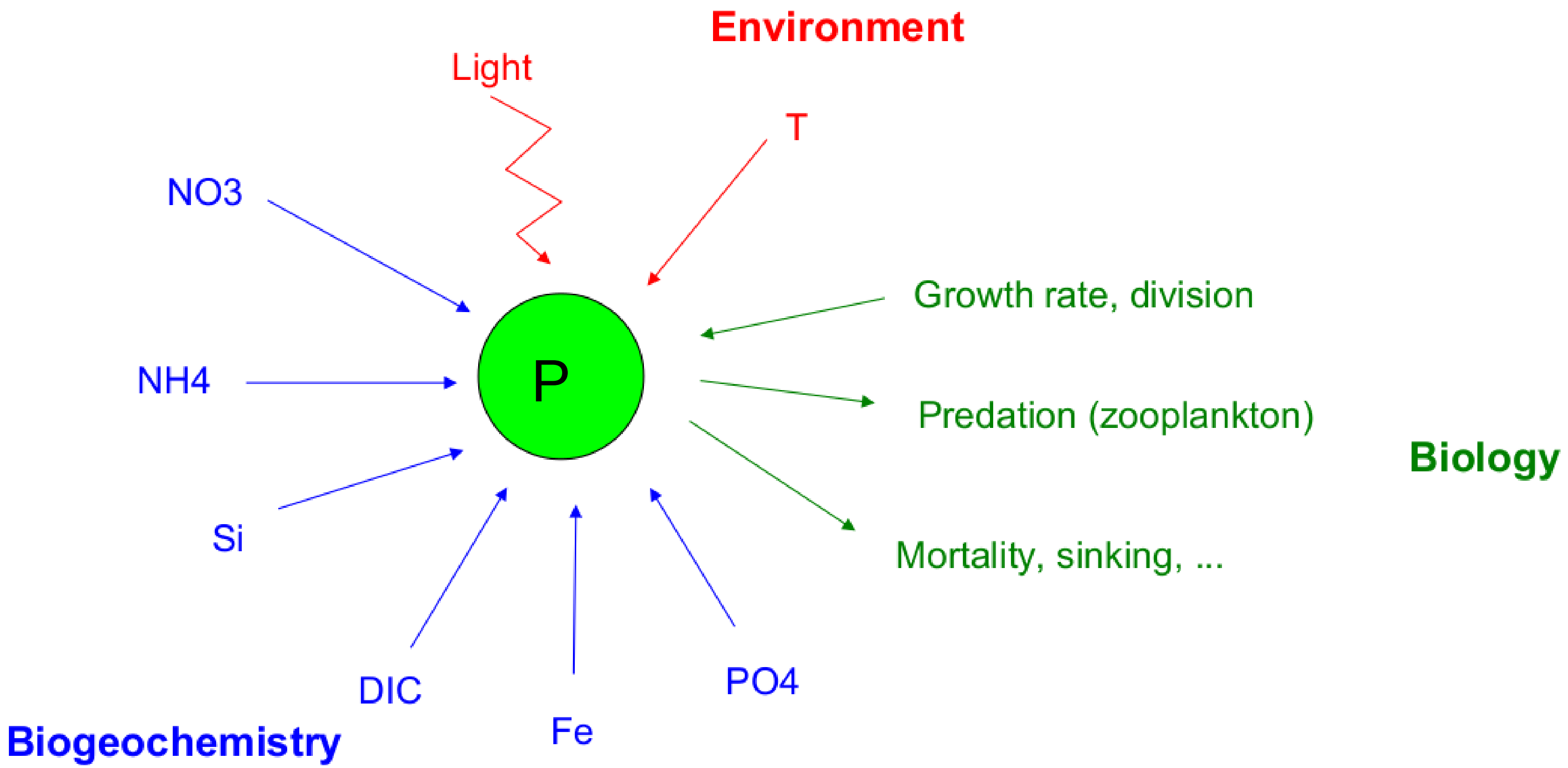
$P(N)=PP$

Conservation:

$$S(P)+S(Z)+S(D)+S(N)-P(P)-P(Z)-P(D)-P(N)=0$$

Dynamics (mixing, currents) bring nutrients in the euphotic layer

Focus on the growth of a phytoplankton cell (P)



Photosynthesis

- Photosynthesis: Process by which autrophic organism use solar energy to produce organic matter

$$106CO_2 + 16\ NO_3^- + HPO_4^{2-} + 122H_2O + 18H^+ + \text{trace elements, light} \dashrightarrow C_{106}H_{263}O_{110}N_{16}P + 138O_2$$

- The ratio between the different chemical elements is called the Redfield ratio
- The amount of organic matter produced by the photosynthesis is called Gross Primary Production

Growth rate

- Growth rate is a function of the environmental and biogeochemical conditions and of the species
- It can be expressed as follows:

$$\mu = gf(T)\,g(E)\,L(N)$$

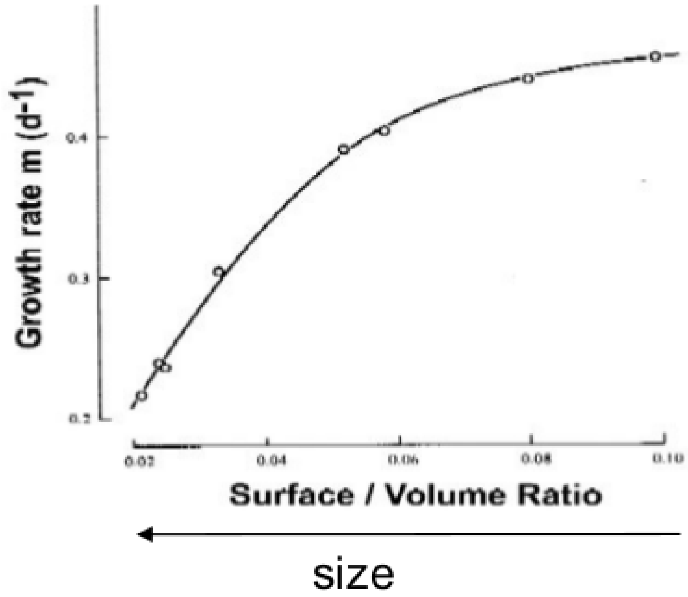
temperature → $f(T)$

Light → $g(E)$

Nutrients → $L(N)$

Growth rate depends on size of P cells

- The specific growth rate varies with species. In general, it tends to decrease with size.



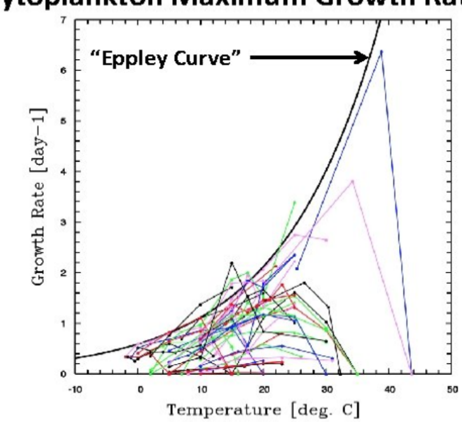
Growth rate depends on temperature

- Growth rate increases with temperature until a critical level
- A relationship for the enveloppe has been proposed for the first time by Eppley (1972) :

$$f(T) = 1.066^T$$

Growth rate increases by 1.9 times every 10°C (Q10).

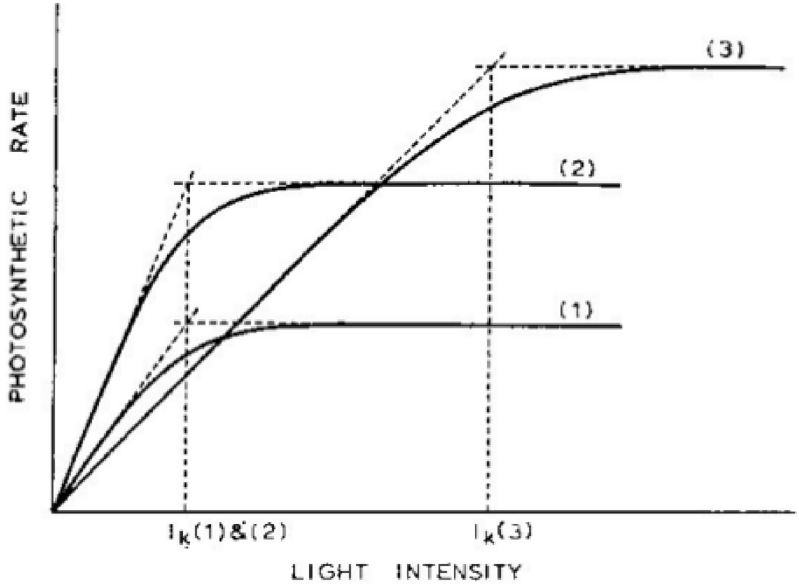
Eppley's relationship is the most commonly used



Eppley, R.W., 1972. Temperature and phytoplankton growth in the sea. Fishery Bull. 70, 1063–1085.

Growth rate depends on light

- Growth rate increases with light until a maximum value at which it saturates or even decreases



α initial slope

μ_{max} maximum growth rate

$I_k = \mu_{max} / \alpha$

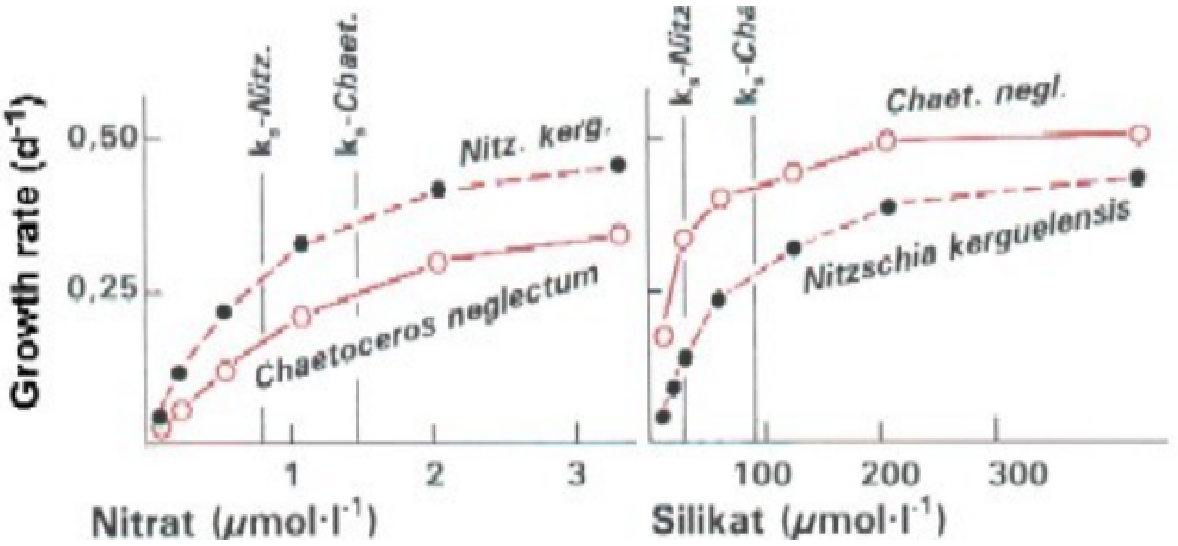
$$\mu = \mu_{max}\left(1 - \exp\left(\frac{-I}{I_k}\right)\right)$$

- I_k is extremely variable between species. For instance, in cyanobacteria, synechococcus spp have a high I_k whereas some prochlorococcus spp have very low I_k.

- I_k strongly varies with the average received light (photoacclimation)

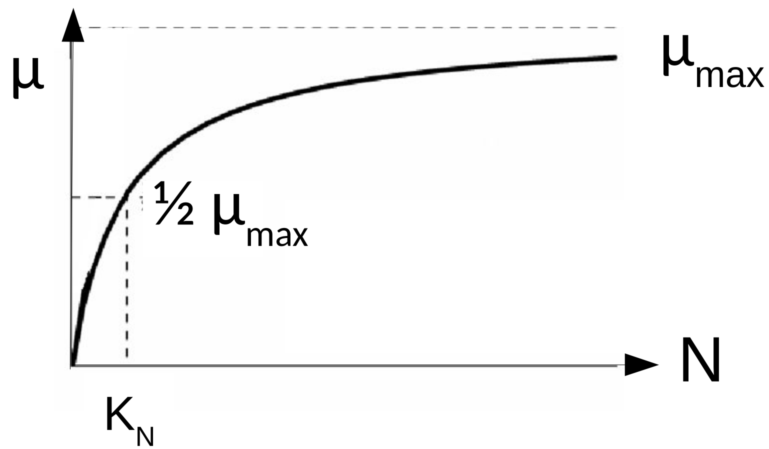
Growth rate depends on nutrients : Monod model (1942)

- Monod model = growth rate is a function of the external concentration of nutrients



$$\mu = \mu_{max} \frac{N}{K_N + N}$$

K_N : half-saturation constant



- K_N increases with size because the S/V ratio decreases.
  S=surface, V=volume

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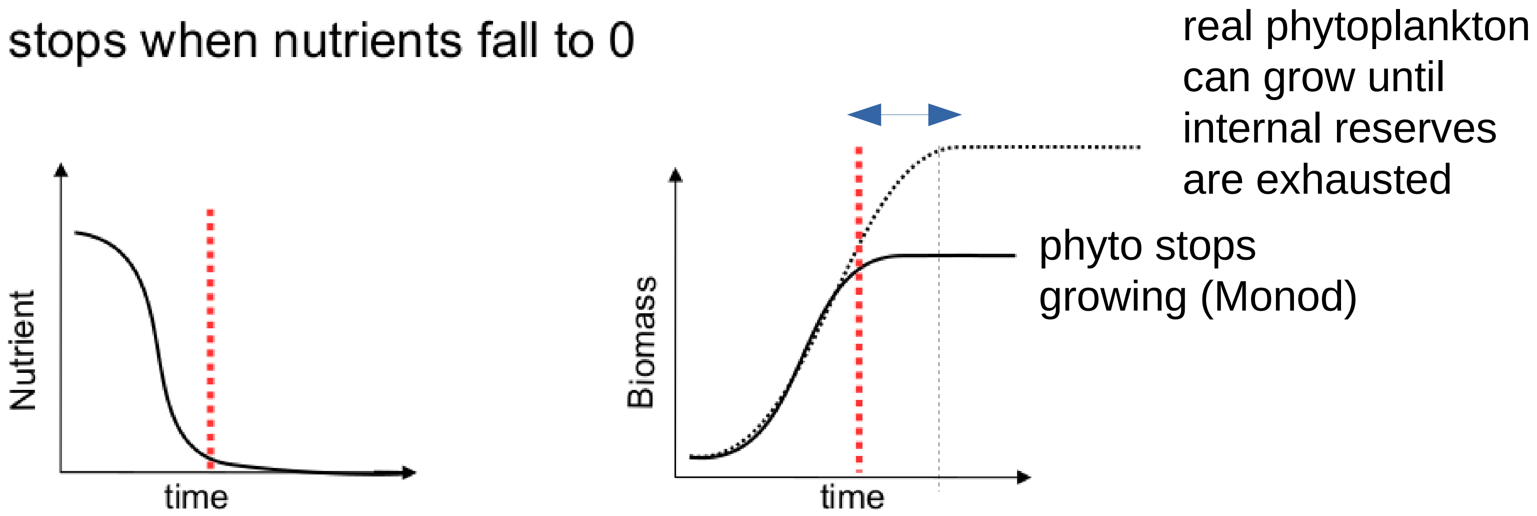
Limitations of the Monod model

- Measured & works best under relatively steady nutrients (or slow change)
- Growth stops when nutrients fall to 0

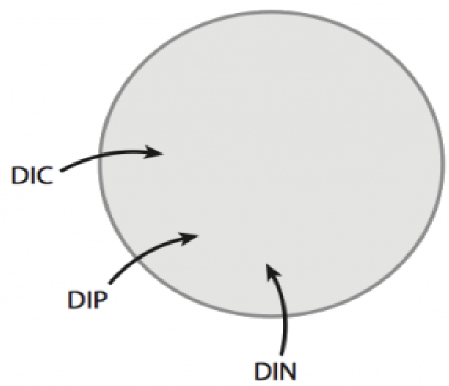


- Assumes constant stoichiometry
- No luxury uptake of transiently elevated nutrients
- Can be difficult to estimate K_N

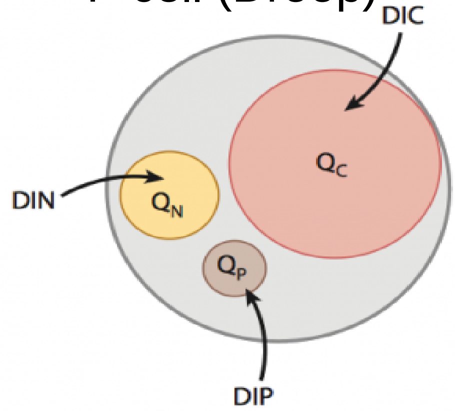
Droop model (1968): Quota model

- Droop model = growth rate is a function of the internal pool of nutrients (quota)
- The internal pool (quota) is a function of the external concentrations of N

P cell (Monod)



P cell (Droop)

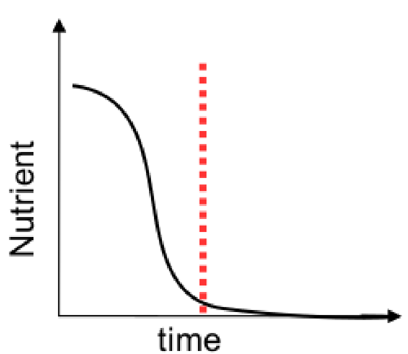


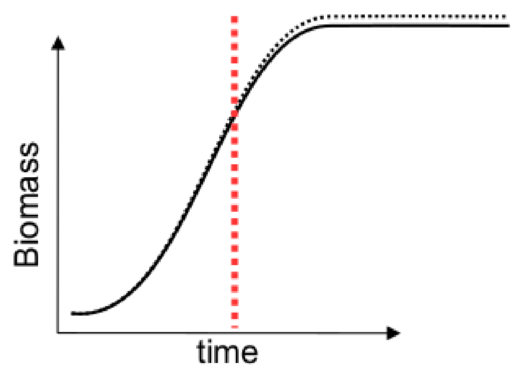
$$\text{growth} = \mu_\infty \left(1 - \frac{Q_{min}}{Q}\right)$$

Q= internal concentration of element (ex N)

$$\frac{dQ_N}{dt} = V_{max}\frac{N}{K_N + N} - \mu Q_N$$

- Generally works better, more physiologically grounded, more general





Internal and external concentrations => more variables in Droop-based models

Back to the Monod model : growth rate depends on several nutrients (ex: N,P,Si, Fe,..)

- Currently, there is no clear consensus on the law which drives growth rate with multiple nutrients. 2 different laws are generally used:

  - The multiplicative law:

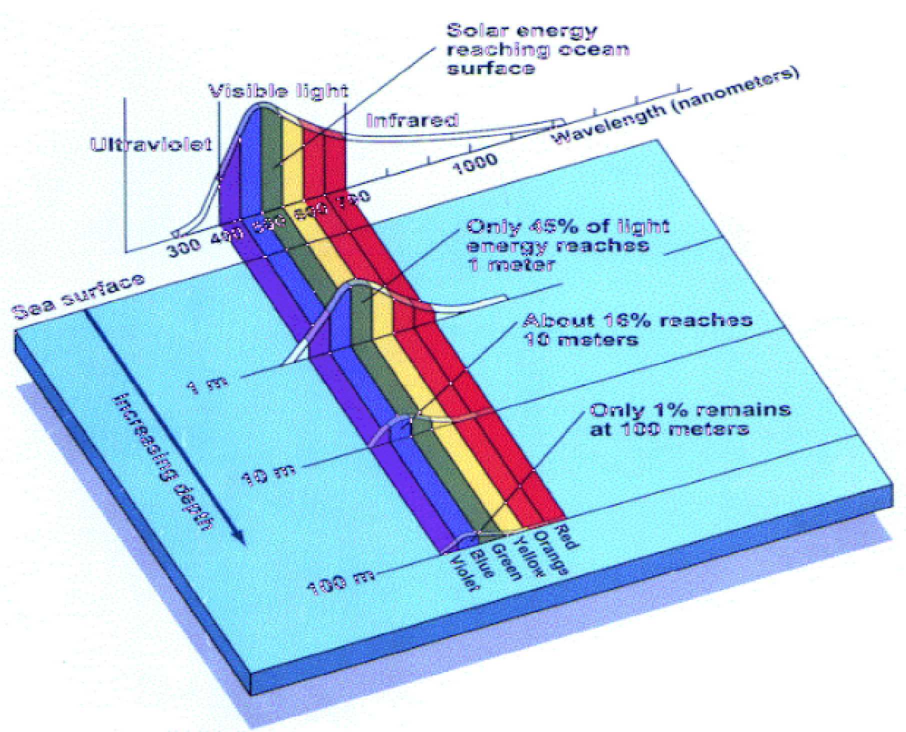
$$\mu = \mu_{max} \frac{N_1}{K_{N_1} + N_1} \frac{N_2}{K_{N_2} + N_2} * \ldots$$

  - The law of the minimum or Liebig's law (1840) :

$$\mu = \mu_{max}\, min\left(\frac{N_1}{K_{N_1} + N_1}, \frac{N_2}{K_{N_2} + N_2}, \ldots \right)$$

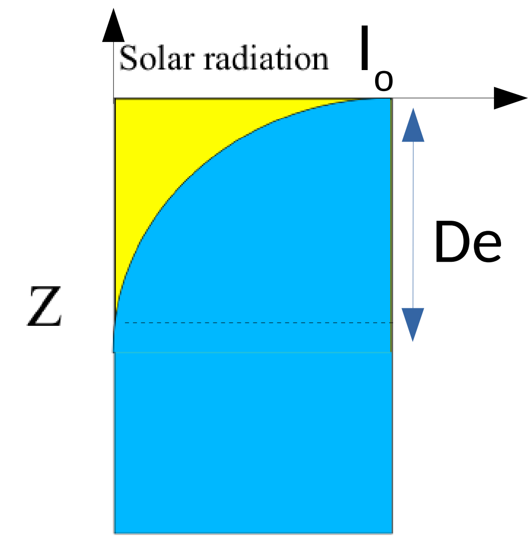
- Many other laws do exist but they are not commonly used.

Growth rate depends on light



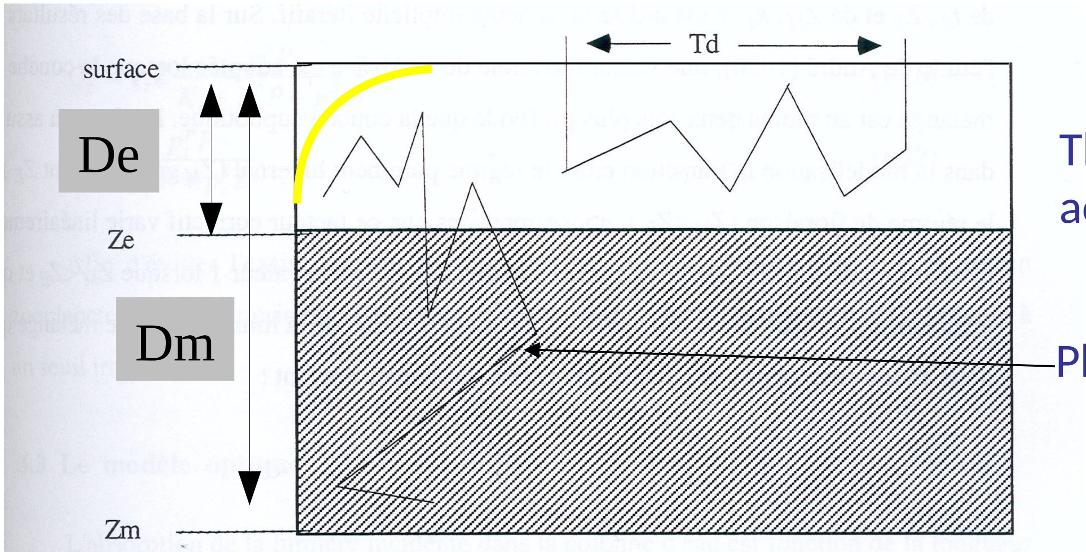
Euphotic zone

$I > 1\% \ I_o$



- Light decreases with depth as (Loi de Beer): $I(z) = I(0)\, e^{-kz}$
- In pure water, the attenuation length is 37m. for a chlorophyll concentation of 0.2 mg Chla/m^3, its value is about 20m.
- Blue light penetrates much deeper than red light which remains trapped in the top 10 to 20m of the ocean.

Growth limitation by light and mixing



The deeper the mixed layer, the less active is photosynthesis

Phyto cell spends more time in the dark

Doubling time scale for phytoplan kton celle : 1-2 days

Typical velocity in mixed layer : 1000 m/day=> time scale to cross the mixed layer (100m) ~2 hours

=> light used by planktonic cells to grow = $(1/De)\int I(z)dz \times (De/Dm)$

=> if Dm>De => limitation of growth by light

the deeper the mixed layer , the less active is photosynthesis

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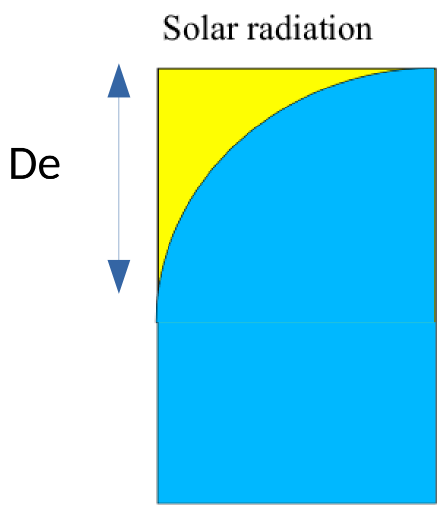
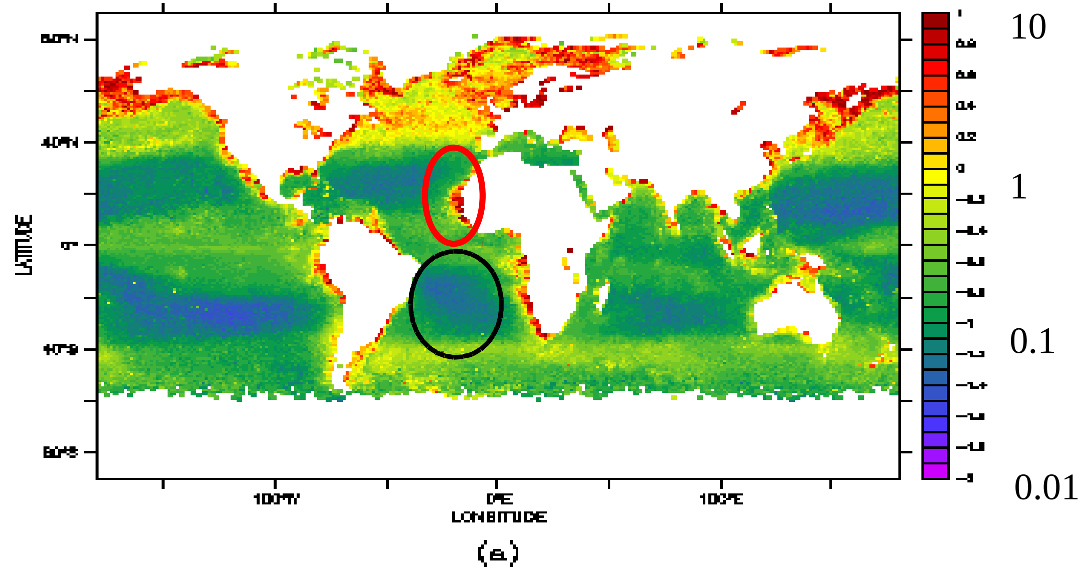
Chlorophyll and euphotic depth

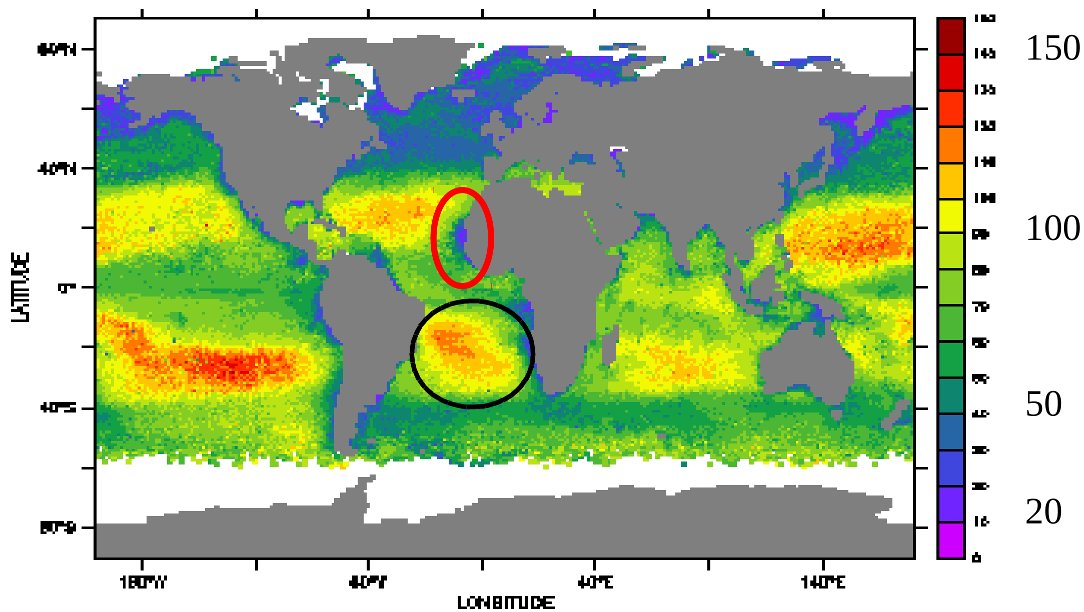
Euphotic zone

$I > 1\% \, I_o$



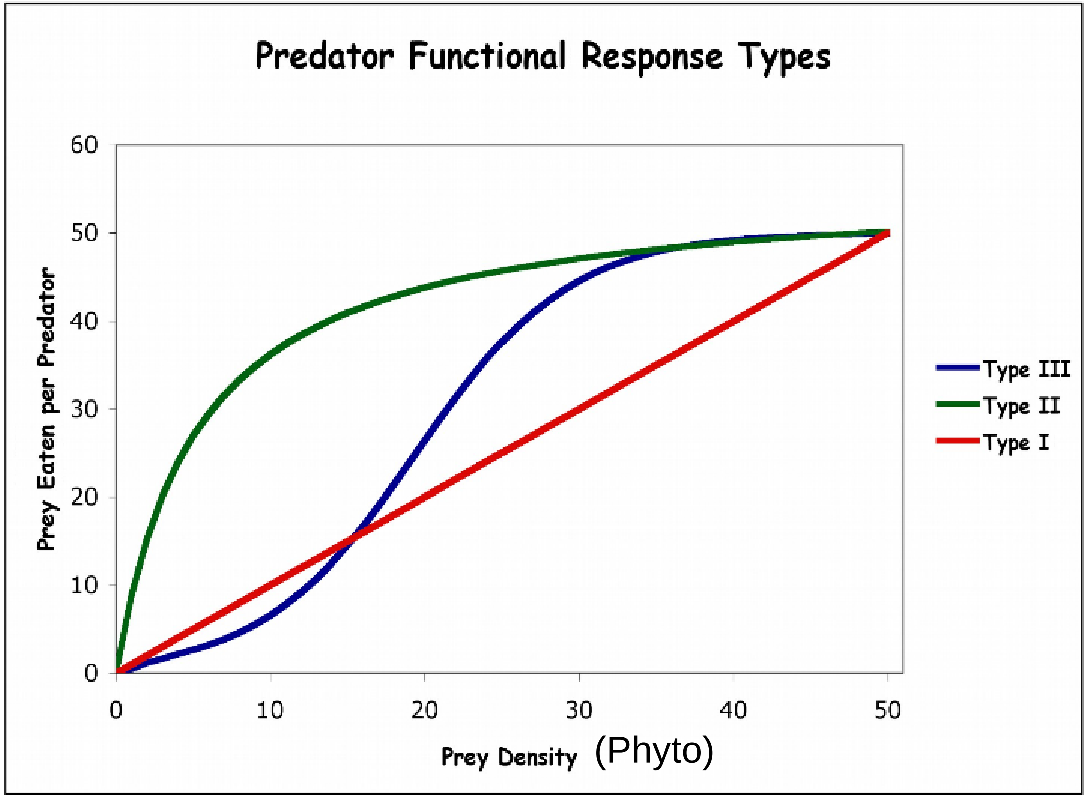
Chlorophyll (mg/m^3)





De profondeur de la couche euphotique (m)

Predation of phytoplankton by zooplankton (grazing)



(Phyto)

- Holling Type I

$$G_p = gP$$

- Holling Type II

$$G_p = g \frac{P}{K_z + P} Z$$

- Holling Type III

$$G_p = g \frac{P^2}{K_z^2 + P^2} Z$$

Holling type III: slower growth when zoo is starved

More complex with several preys (ex: nanoP, diatoms, particulate matter)
=> definition of preferences

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Mortality of P,Z

- Mortality in models does not necessarily represent senescence. It may model :
  - senescence
  - viral attacks
  - aggregation/sinking
  - predation by unresolved higher trophic levels (e.g. fish)

- Numerous formulations exist but the two most common expressions are:

$$M = m_p P \qquad\qquad M = m_p P^2$$

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Representing the sinking particles in models

- If bacterial degradation and sinking are the only active processes

D=detritus=particules

$$\frac{\partial D}{\partial t} = \underbrace{-\lambda D}_{\text{Remineralization}} - \overbrace{\frac{\partial vD}{\partial z}}^{\text{Sinking}}$$

v= sinking velocity

Remineralization
(λ^{-1}=remin time scale~1 month)

- Specific cases : at equilibrium: $\partial_t D=0$, with F=v.D the vertical flux of particles

  - If v and λ are constant :

$$F = vD = F(\tilde{z})\, e^{-\frac{\lambda}{v}(z-\tilde{z})}$$

  - If λ is constant and v = Az

v increases with depth
as particles get bigger
(aggregation)

$$F = vD = F(\tilde{z}) \left(\frac{z}{\tilde{z}}\right)^{(-b)}$$

where $b = \frac{\lambda + A}{A}$

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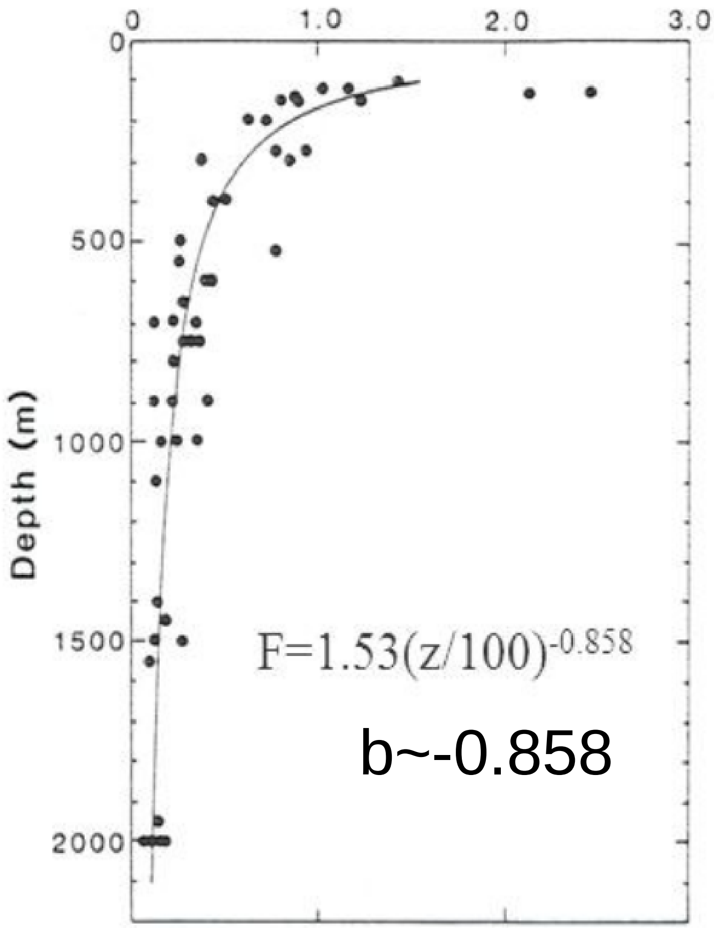
Observed vs modeled vertical flux

The “Martin” curve (Martin et al., 1987)

$$F = vD = F\left(\tilde{z}\right)\left(\frac{z}{\tilde{z}}\right)^{\left(-b\right)}$$

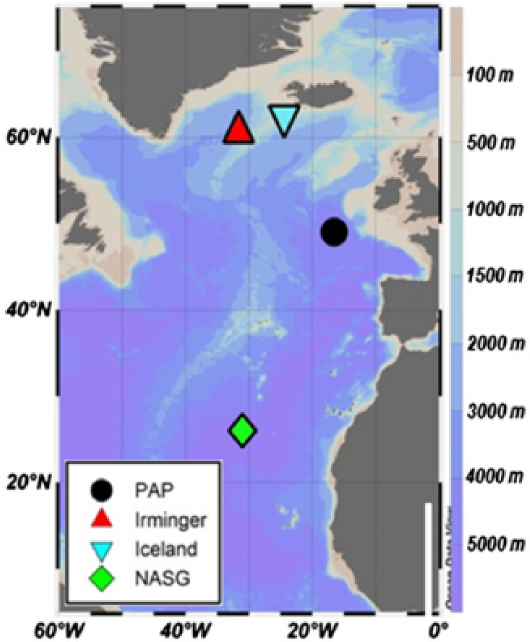
$$b = \frac{\lambda + A}{A}$$

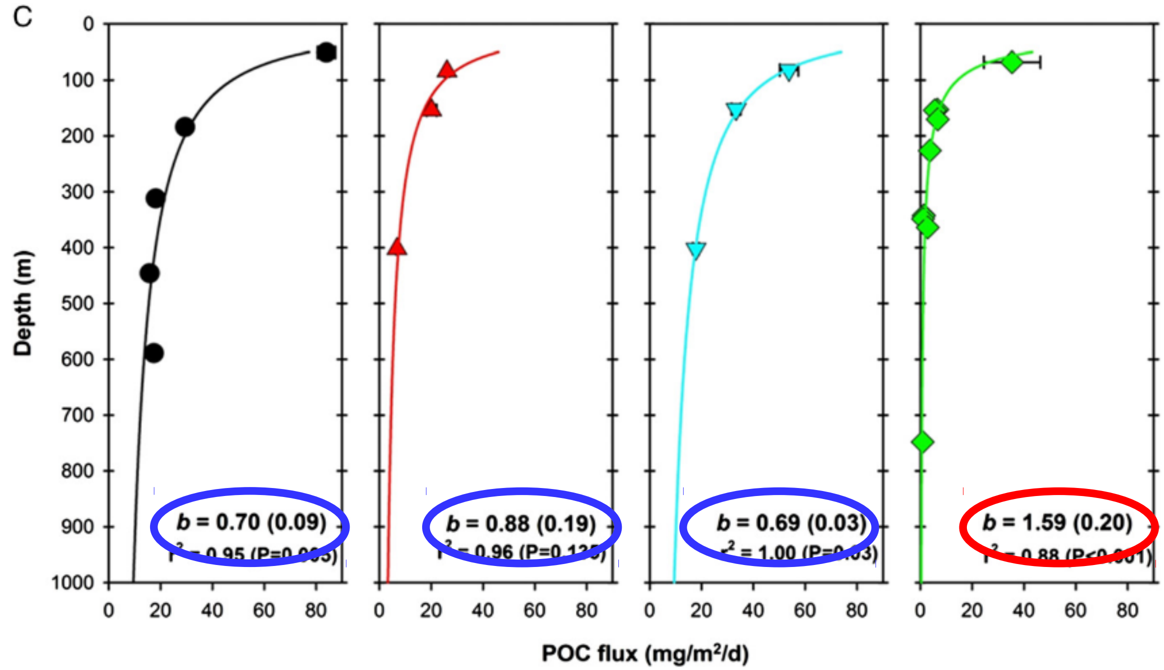
F(z)=v.D

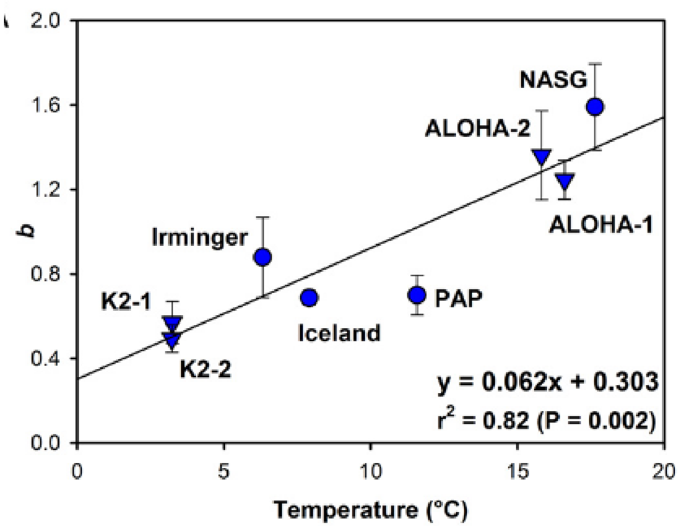


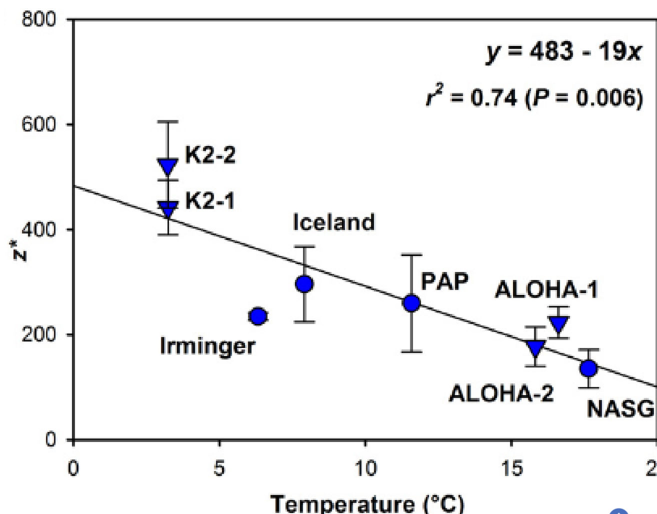
b~-0.858

Spatial variability of Particule Organic Carbon flux



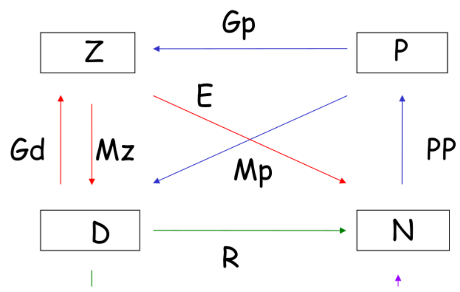






b and z* depend on temperature (0-500m)

A “simple” set of 4 nonlinear equations …

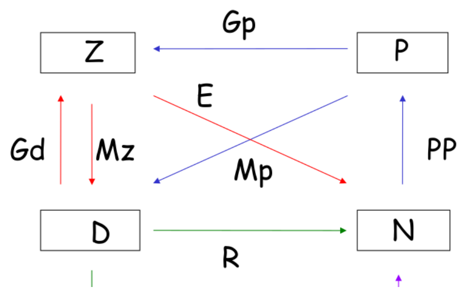


Grazing of P

production

$$(S-P)(P) = \mu_{max} L_{NUT} L_I P - g \frac{pP}{K_z + pP + (1-p)D} Z - m_p P$$

A “simple” set of 4 nonlinear equations…



Grazing of P

production

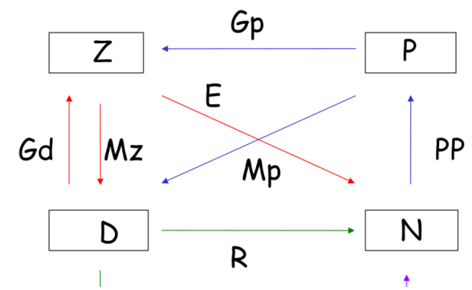
$$(S-P)(P)=\mu_{max} L_{NUT} L_I P - g \frac{pP}{K_z + pP + (1-p)D} Z - m_p P$$

assimilated grazing of P and D

P mortality

$$(S-P)(Z)=ga \frac{pP + (1-p)D}{K_z + pP + (1-p)D} Z - m_z Z^2$$

A "simple" set of 4 nonlinear equations ...



Grazing of P

production

$$(S-P)(P)=\mu_{max} L_{NUT} L_I P - g\frac{pP}{K_z+pP+(1-p)D}Z - m_p P$$

assimilated grazing of P and D

P mortality

$$(S-P)(Z)=ga\frac{pP+(1-p)D}{K_z+pP+(1-p)D}Z - m_z Z^2$$

unassimilated grazing of P&D

$$(S-P)(D)=g(1-a)\frac{pP+(1-p)D}{K_z+pP+(1-p)D}Z + m_z Z^2 + m_p P$$

$$-g\frac{(1-p)D}{K_z+pP+(1-p)D}Z - v\frac{\partial}{\partial z}D - t_d D$$

remin

sinking

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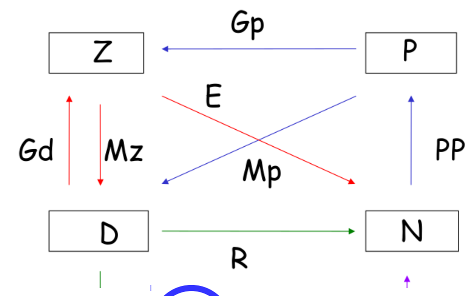
A “simple” set of 4 nonlinear equations … with many parameters



Grazing of P

production

$$(S-P)(P)=\mu_{max} L_{NUT} L_I P - g \frac{pP}{K_z + pP + (1-p) D} Z - m_p P$$

assimilated grazing of P and D

P mortality

$$(S-P)(Z)=g a \frac{pP + (1-p) D}{K_z + pP + (1-p) D} Z - m_z Z^2$$

unassimilated grazing of P&D

$$(S-P)(D)=g(1-a) \frac{pP + (1-p) D}{K_z + pP + (1-p) D} Z + m_z Z^2 + m_p P$$

$$-g \frac{(1-p) D}{K_z + pP + (1-p) D} Z - v \frac{\partial}{\partial z} D - t_d D$$

remin

sinking

$$(S-P)(N)=-m_{max} L_{NUT} L_I P + t_d D$$

uptake of production

Many parameters values needed to constrain the model

μ_{max}, K_N, K_I, m_p phytoplancton

g, K_z, p, a, m_z zooplancton

v, t_d détritus

Difficult estimation

- lab experiments, species dependant, equilibrium state
- large variability: non constant
- agregate many processes
- inverse methods (data assimilation)
- empirical estimation (repeating 10,20,..,100s of experiments with different parameter values)

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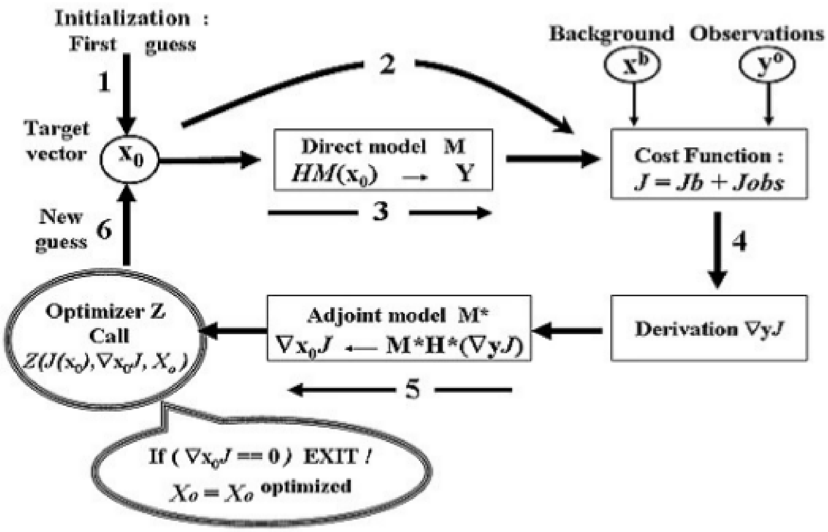
Optimizing parameters values using data assimilation

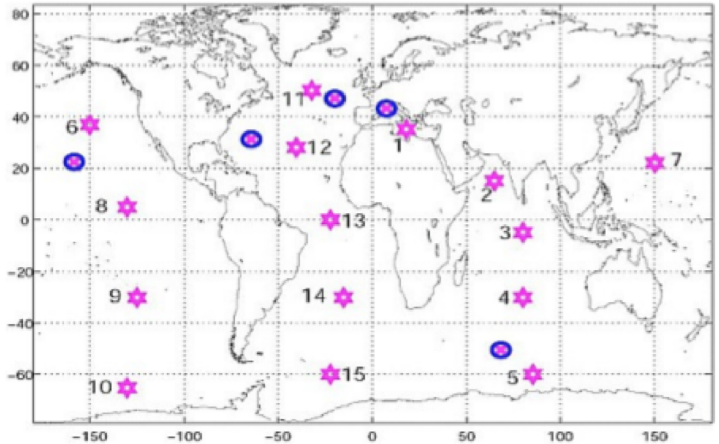
Variational assimilation



Example: Simultaneous assimilation at 5 1-D stations: Chla, NO3, POC et Si

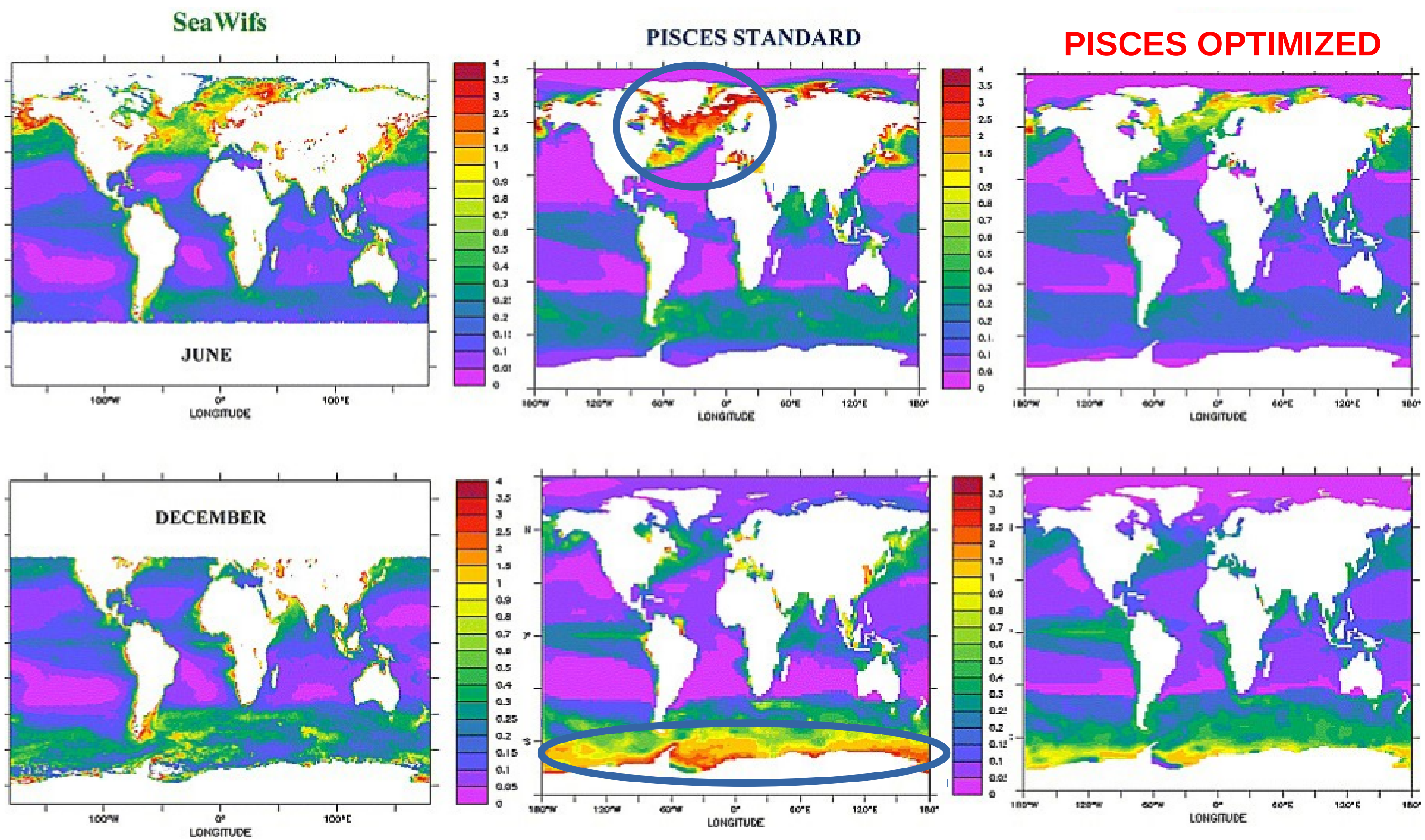
=data used in the assimilation process

45 optimized parameters



Kane et al., 2011

Optimizing parameters values using data assimilation



Kane et al., 2011

- complex variational algorithm
- are “1D” stations really representative of the 3D system?
- what should be done with non assimilated variables?
- some parameters are not well constrained
- physics are assumed to be “perfect” and model-data misfit is assumed to be only due to parameters values => physical model bias impacts optimized parameter values

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Coupling: dynamics →biogeochemistry

(major role of transport by the fluid)

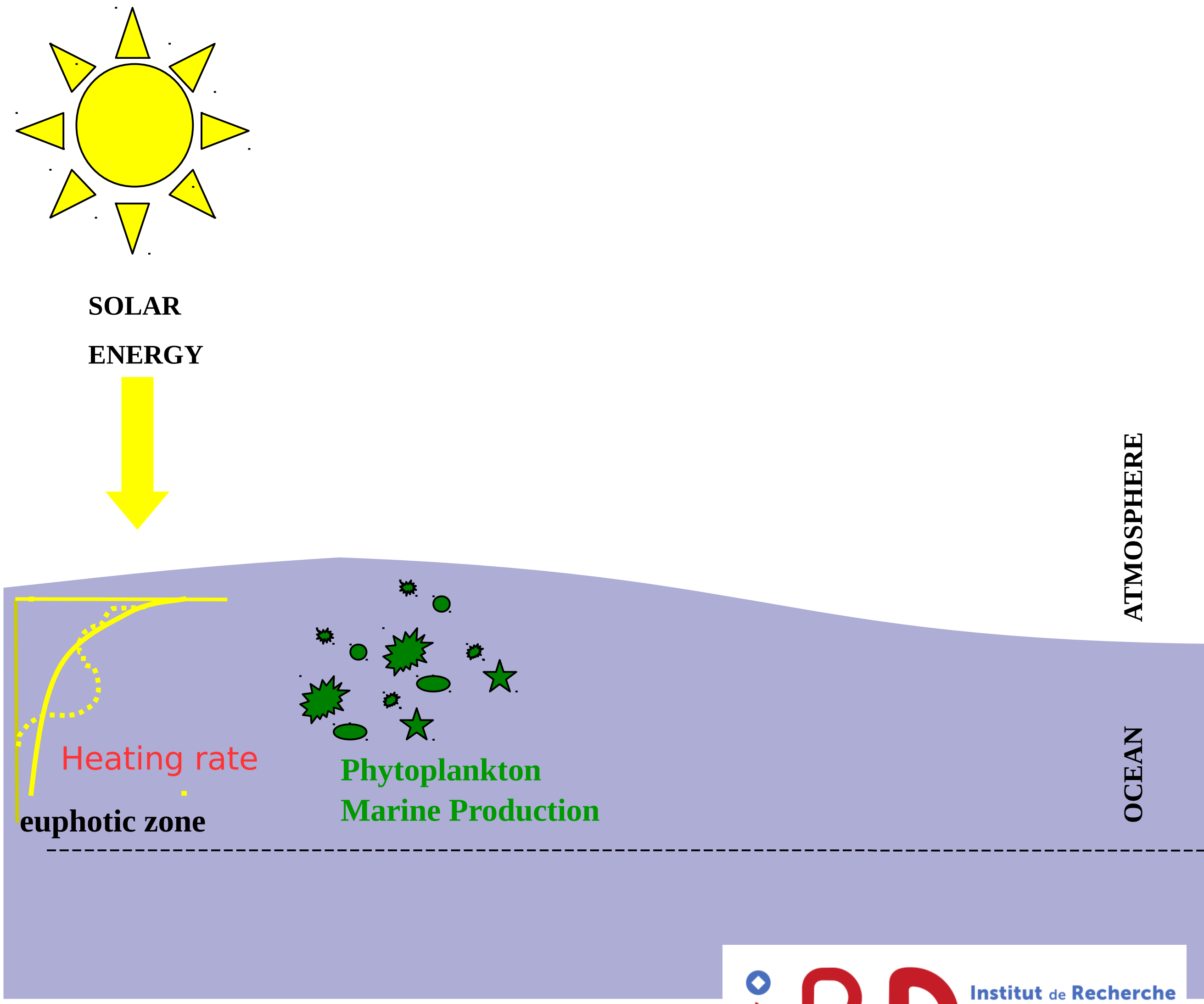
but also...

Coupling: biogeochemistry → dynamics

Coupling: biogeochemistry → physics

1. Direct effects

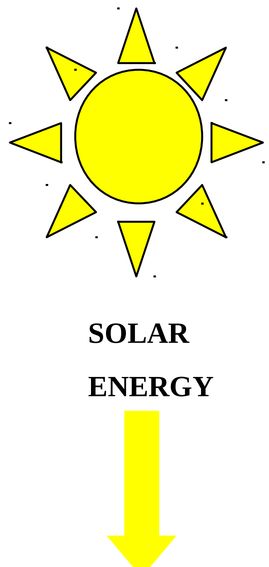
Absorption of SW/solar radiation:
heating concentrated where chlorophyll is present
(at the surface or at depth in case of deep chlorophyll maximum)
=> temperature change
=> density change
=> circulation change



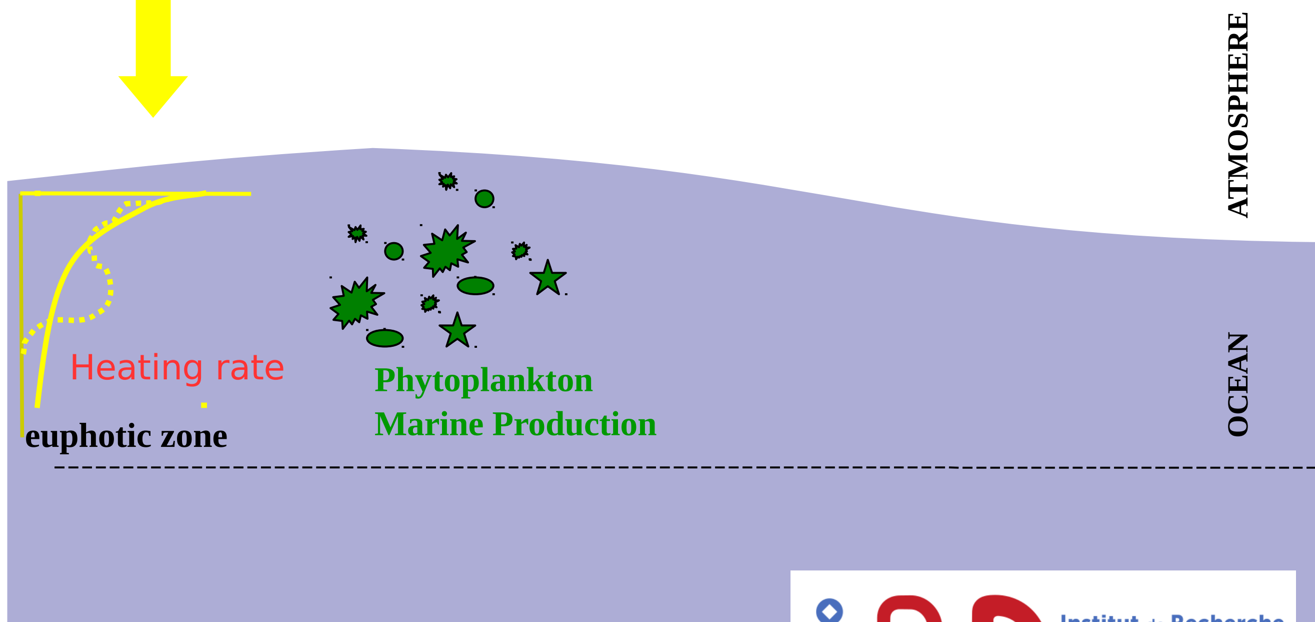
Coupling: biogeochemistry → physics

1. Direct effects

Absorption of SW/solar radiation:
heating concentrated where there is chlorophyll
(at the surface or at depth in case of deep chlorophyll maximum)
=> temperature change
=> density change
=> circulation change



=> this effect is not represented in all models:
often neglected but can be important in some regions



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Coupling: biogeochemistry → physics

1. Direct effects

Absorption of SW/solar radiation:
heating concentrated where there is chlorophyll
(at the surface or at depth in case of deep chlorophyll maximum)
=> temperature change
=> density change
=> circulation change

2. Indirect effects in ocean/atm/BGC models

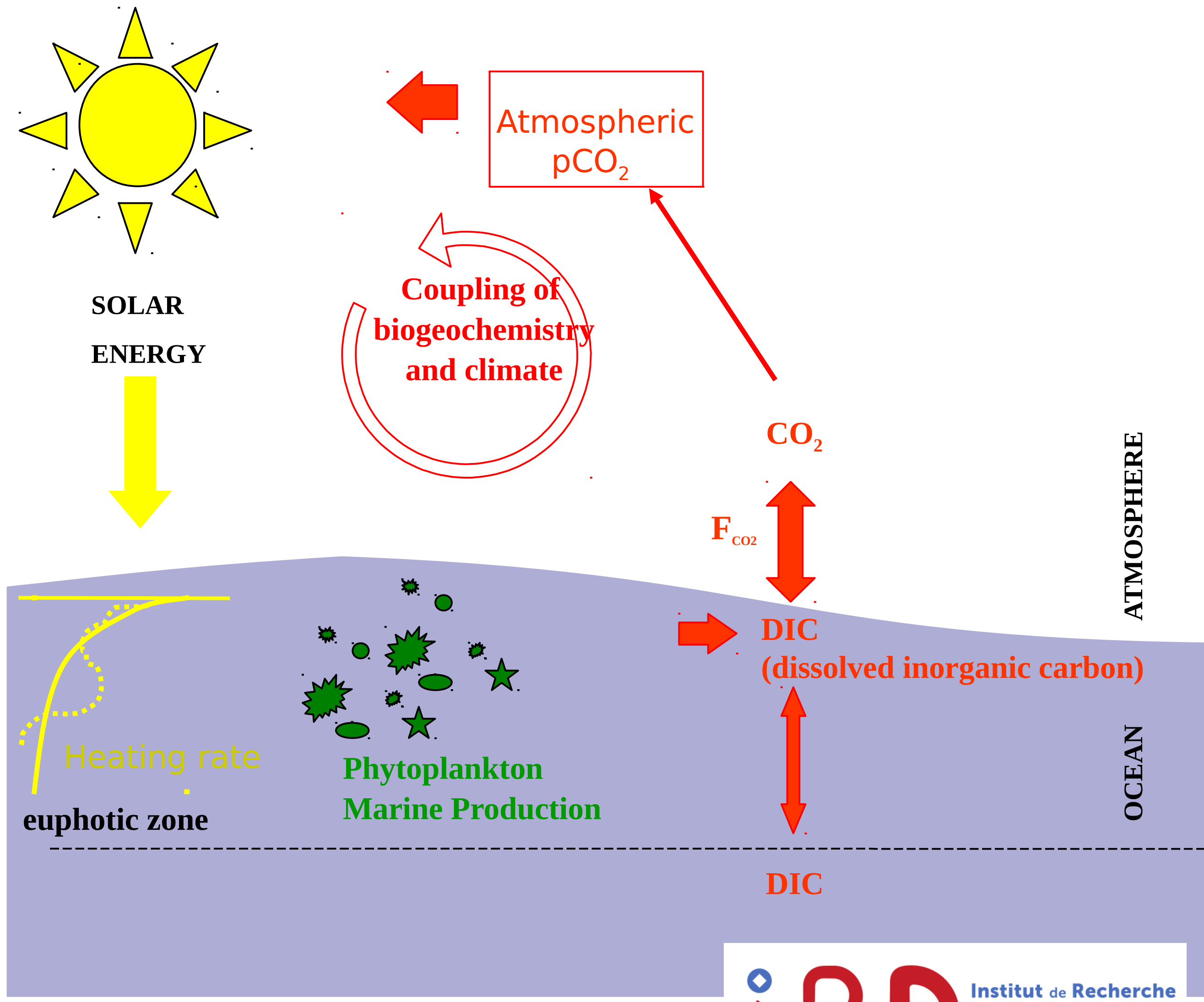
changes air/sea fluxes of CO_2 (temp. dependent)

=> Greenhouse effect

=> Change of atmospheric infrared heat fluxes

=> temperature change

=> ocean circulation change



A few useful concepts/tools in biogeochemistry

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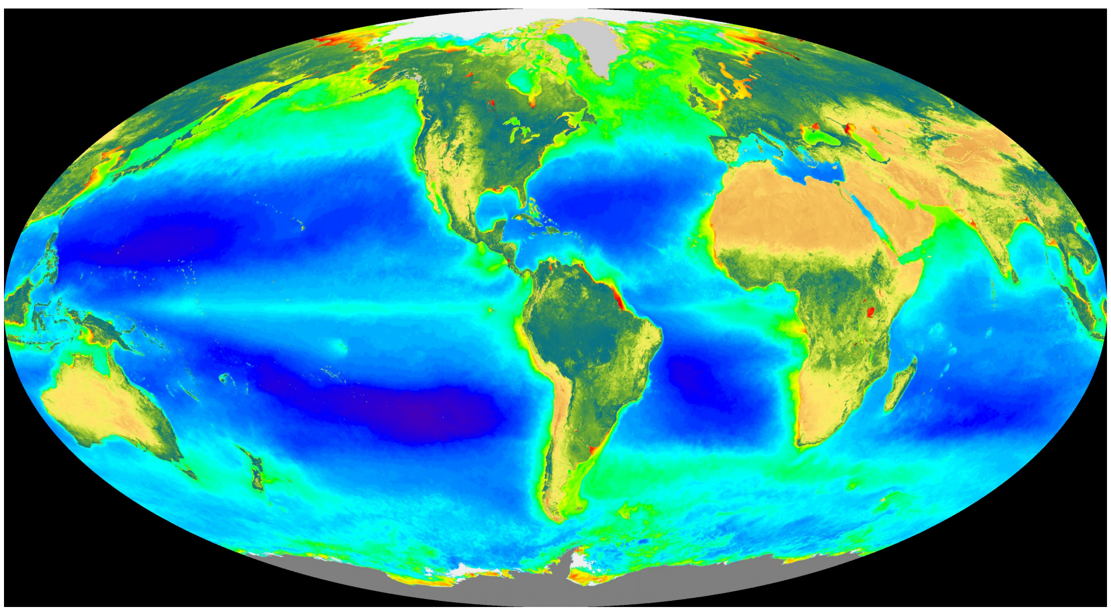
Measure of surface chlorophyll : “sea color”

- measure with captors on satellites
-CZCS (80s), SeaWiFS (1997-2003), Meris (2002-..), Modis (2002-..),…
-passive measurements: retrodiffused light
-Chl : algorithm, reflectance ratio = $R(\lambda_1)/R(\lambda_2)$
-recent algorithms : different pigments can be identified : surface organic matter

-problem 1: measure of Chl in the mixed layer=> sub-surface Chl maximum not seen
-problem 2: no measurements when there are clouds!



- 1 image/day
- 1km resolution
-composites of several days because of clouds

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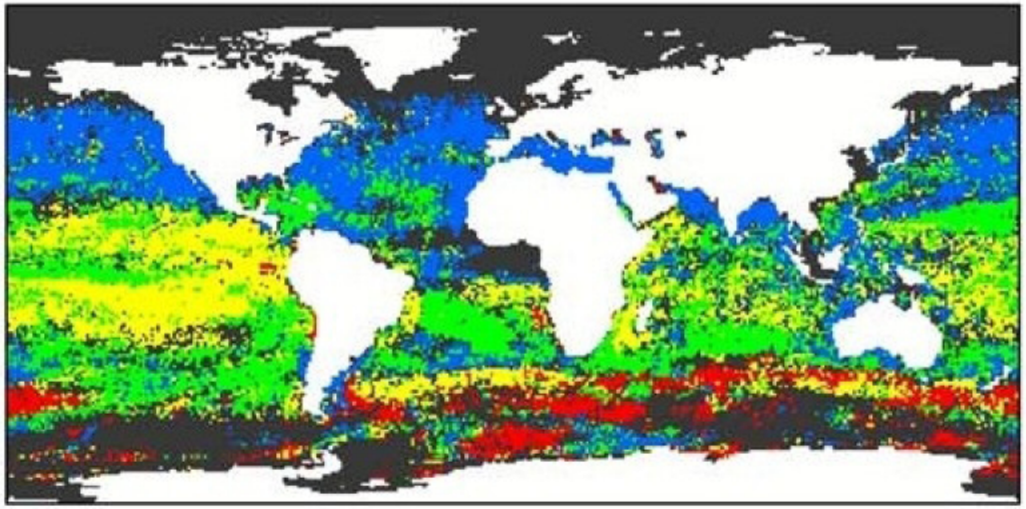
Global phytoplankton community structure from satellite

Interpretation of ocean color observations =>different functional types of phyto

PHYSAT algorithm



January: dominant functional types from SeaWifS (Alvain et al, 2005)

red - diatoms
Green - *Prochlorococcus*
yellow - *Synechococcus*-like
blue - includes coccolithophores

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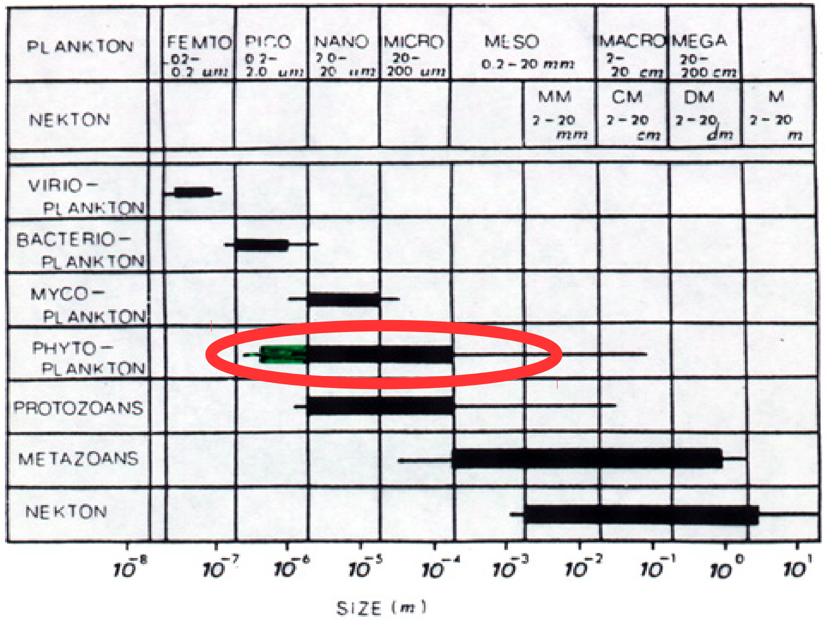
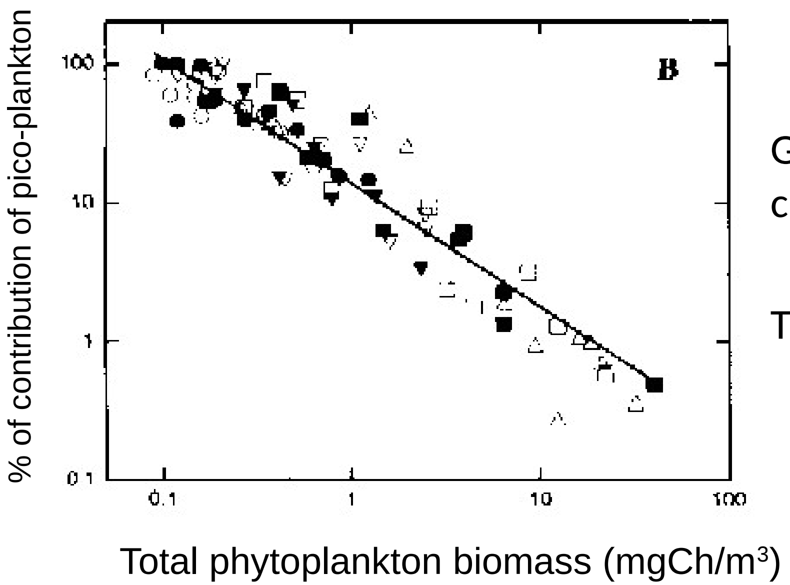
Heterogeneity of plankton : size classes



Phytoplankton size covers at least 2 orders of magnitude

- picophyto : 0.5-2 µm
- nanophyto : 2-10/20 µm
- microphyto : 20-200 µm
- colonies : several mm to 1 cm



Generally, increase in biomass occurs with appearance of size classes of bigger species

The mean size of the cell increases with biomass

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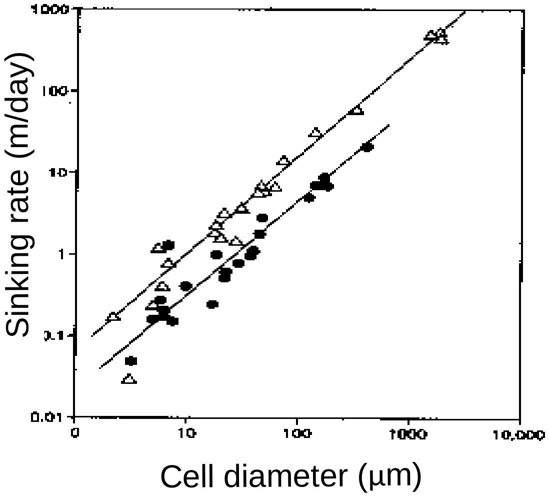
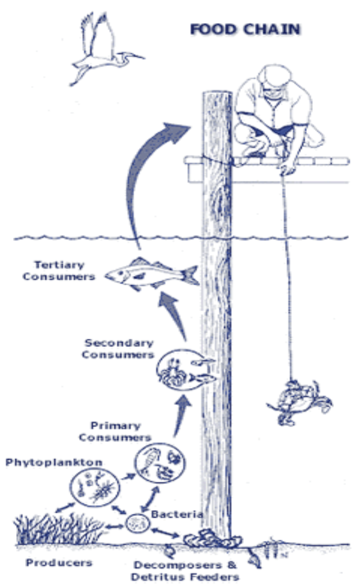
importance of phytoplankton size classes

- **For biogeochemical cycles :**



- big cells export carbon to the deep ocean more efficiently (sinking)
- big cells often form blooms (e.g. diatoms in upwelling systems)

- **For trophic chains:**



- big cells generate shorter trophic chains (*e.g*. fish feed on phyto)
- 10-20% of the energy of a trophic level is transferred to the next
- The shorter the chain, the more efficient the transfer of energy to higher predators

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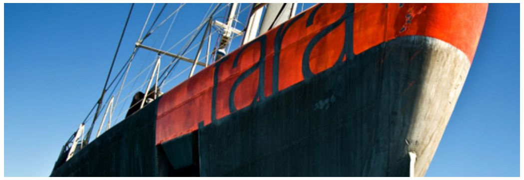
phytoplankton groups and species

- There are **5000** species of phytoplankton. This number increases all the time, particularly since the progress in genetics (for example TARA cruise)



- two types of species: bacteries (procaryotes) and alguae (eucaryotes).
  Eucaryotes form 8 groups, each with several sub-groups.

- The notion of groups and species is essential. For example, different species have different biogeochemical roles, growth and reproduction strategies, ...

- A few examples : ...

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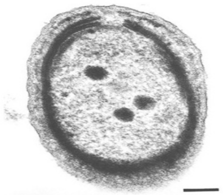
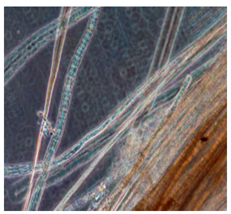
Groups of phytoplankton : examples (1)

Cyanobacteria



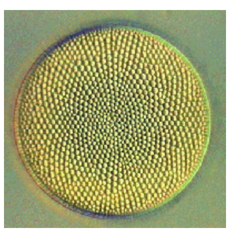


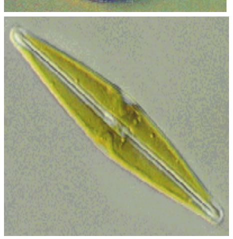
Small cells (< 1 µm), but form colonies, filaments, aggregates

- Contribute strongly to primary production, especially in regions deprived of nutrients (subtropical gyres)
- In tropical areas, *Trichodesmium spp.* can fix atmospheric nitrogen N2

(=>parameterized in PISCESv2)

Diatoms





Cells (5 - >100 µm), form filaments, aggregates

- 2 types : penned (long) et centred (round, cylindrical shapes)
- Contribute strongly to primary production in mid-lat, high- lat blooms, and eastern border upwelling systems
- **silicate** is needed for their skelleton (frustul)

(=>parameterized in PISCESv2)

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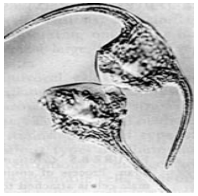
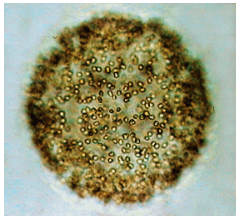
Groups of phytoplankton : examples (2)

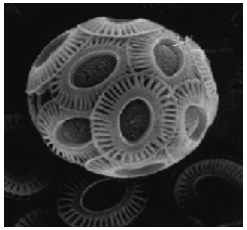
Dinoflagellates



- Cells (5 – 2000 µm), sometimes colonies
- Have two flagels and can migrate vertically (**complex for modelling!**)
- Hate turbulence, can be mixotrophs (graze on phytoplancton and do have chlorophyll to do photosynthesis)
- Abundant in summer and fall blooms (low wind conditions)
- Some species are toxic and form the infamous “red tides”

Prymnesiophytes





Cells (< 20 µm)

- Form important blooms (need a lot of light)
- Phaeocystis : form gelatineous colonies and produce DMS (sulfur compound which has a climatic effect= aerosol for clouds formation)
- Coccolithophores : have a “shell” ($CaCO_3$)
  blooms can be identified from space

End of the first course

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