Biogeochemical modelling with PISCES

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The Pisces model

- Based on the Aumont et al. (2015) paper (no updated documentation yet)
- Coupled with NEMO ocean model and ROMS-AGRIF/CROCO model
- Not all the model is detailed, only the «most important » processes (subjective choice)
- Different versions of PISCES are available depending on the CROCO version :

PISCESv0 in old ROMS-agrif/earlier CROCO versions

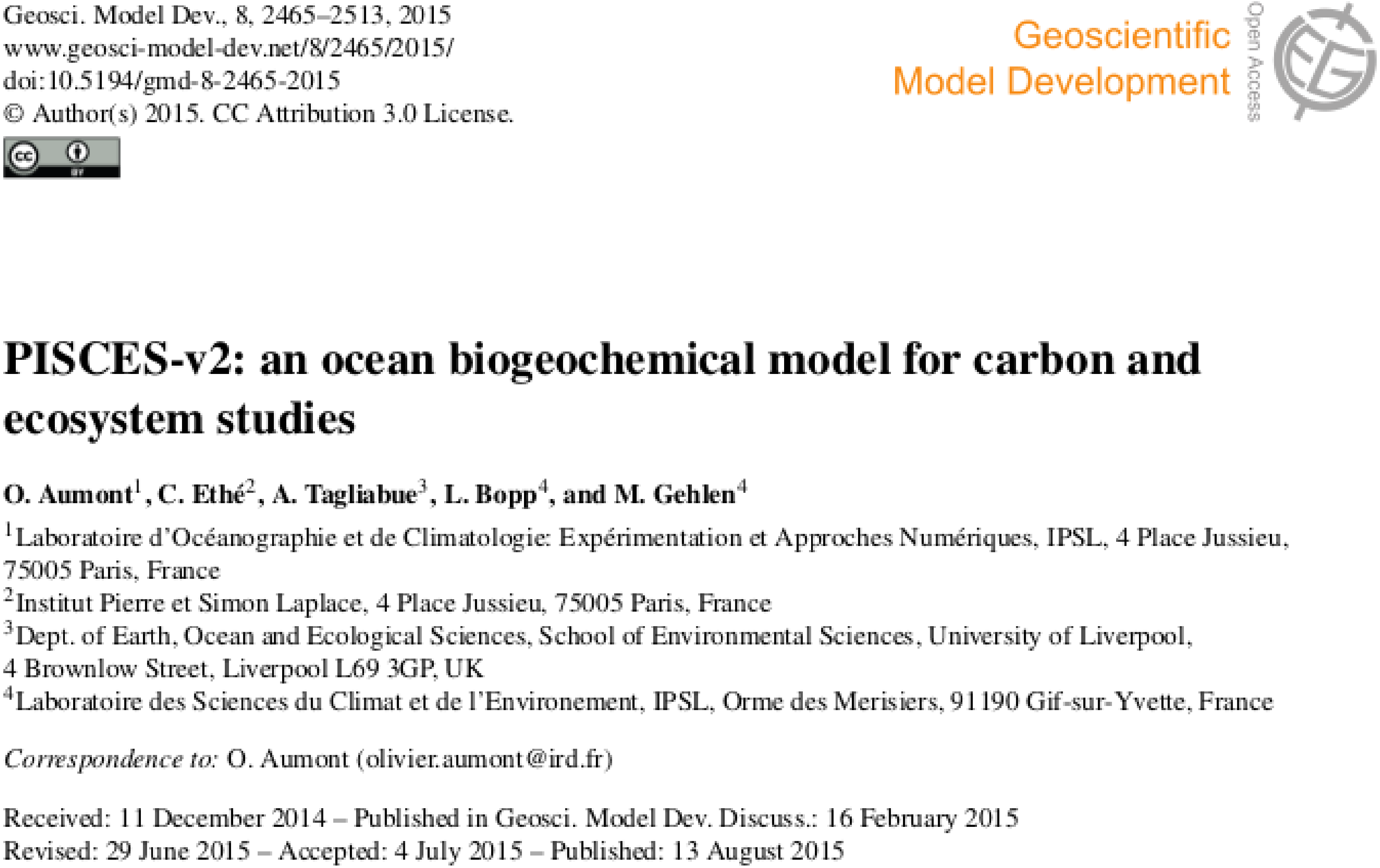
PISCESv2 (in newest CROCO version)

=> detailed description of the common parameterizations of PISCESv0 and PISCESv2

\+ brief overview of the new potentialities of PISCESv2

=> there may be small differences with parameterizations in
Aumont et al. (2015) but the philosophy is the same

The Pisces model



Geosci. Model Dev., 8, 2465–2513, 2015
www.geosci-model-dev.net/8/2465/2015/
doi:10.5194/gmd-8-2465-2015
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Geoscientific Model Development
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PISCES-v2: an ocean biogeochemical model for carbon and ecosystem studies

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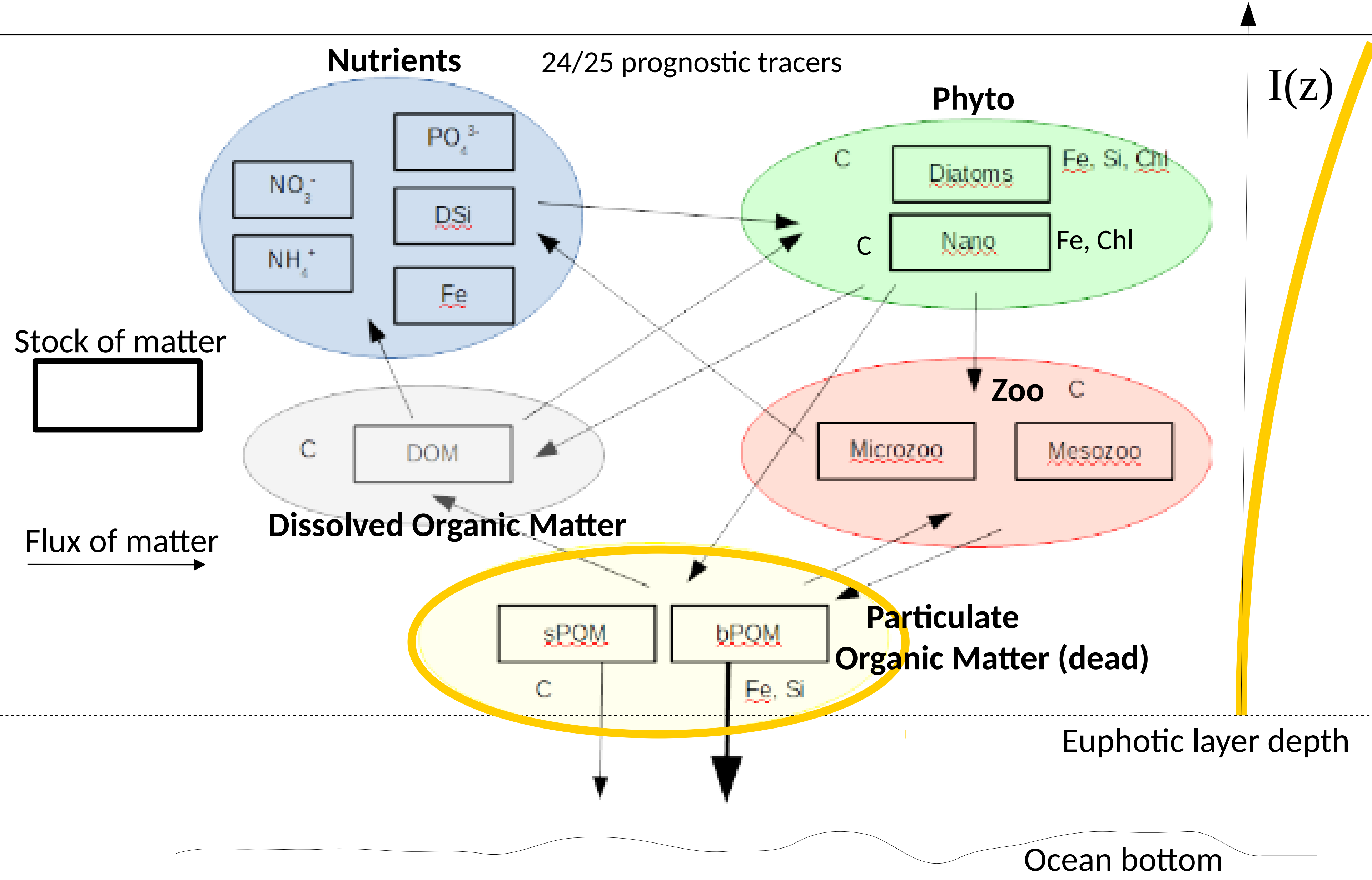
Received: 11 December 2014 – Published in Geosci. Model Dev. Discuss.: 16 February 2015
Revised: 29 June 2015 – Accepted: 4 July 2015 – Published: 13 August 2015

Pisces model structure



Nutrients

24/25 prognostic tracers

NO_3^-

PO_4^{3-}

DSi

NH_4^+

Fe

Phyto

C Diatoms Fe, Si, Chl

C Nano Fe, Chl

Zoo C

Microzoo

Mesozoo

Stock of matter

C DOM

Dissolved Organic Matter

Flux of matter

sPOM

bPOM

C

Fe, Si

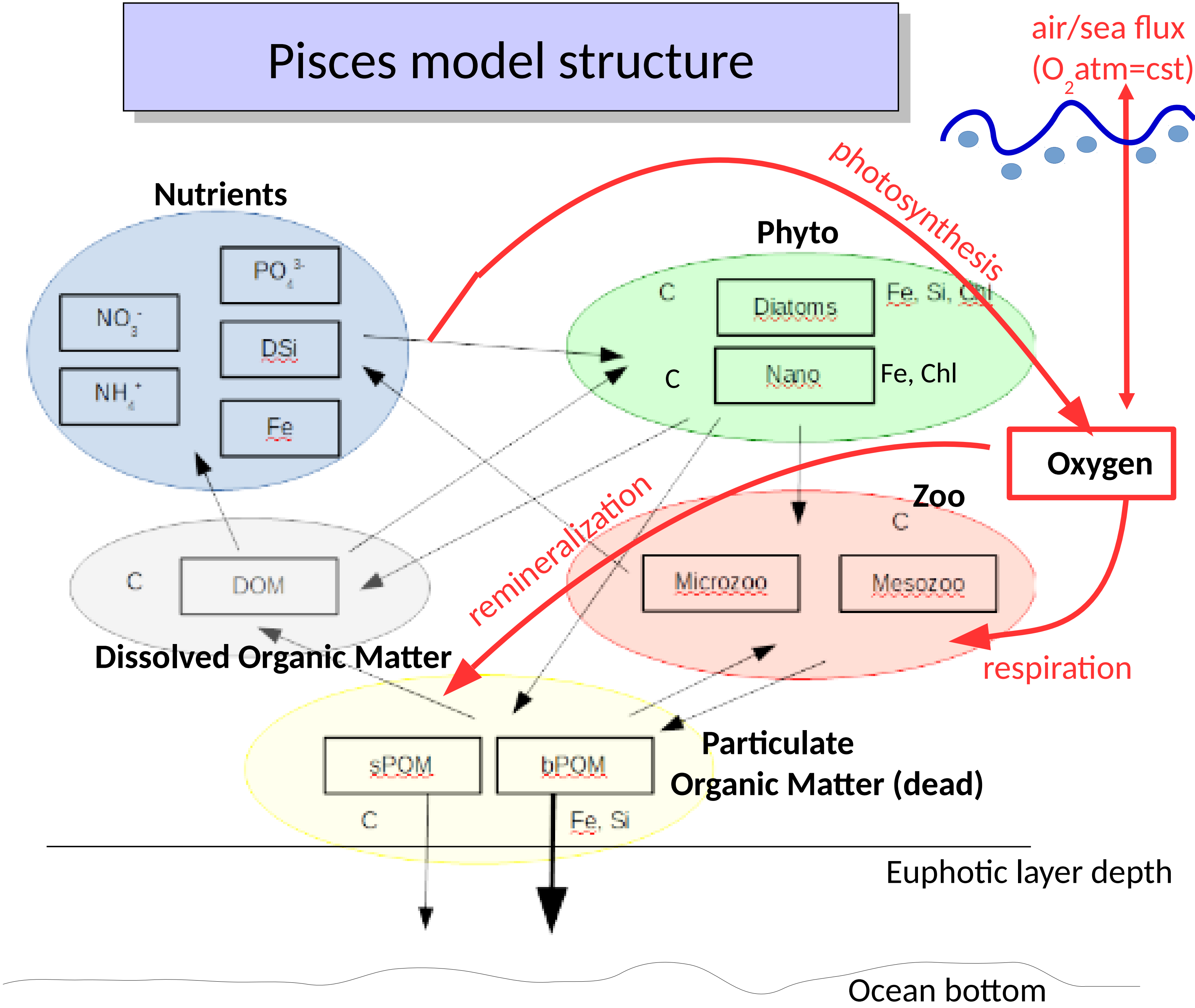
Particulate Organic Matter (dead)

I(z)

Euphotic layer depth

Ocean bottom

Pisces model structure



air/sea flux
(O_2atm=cst)

photosynthesis

Nutrients

NO_3^-

NH_4^+

PO_4^{3-}

DSi

Fe

Phyto

C

Diatoms

Fe, Si, Chl

C

Nano

Fe, Chl

Oxygen

Zoo

C

Microzoo

Mesozoo

respiration

remineralization

C

DOM

Dissolved Organic Matter

sPOM

bPOM

C

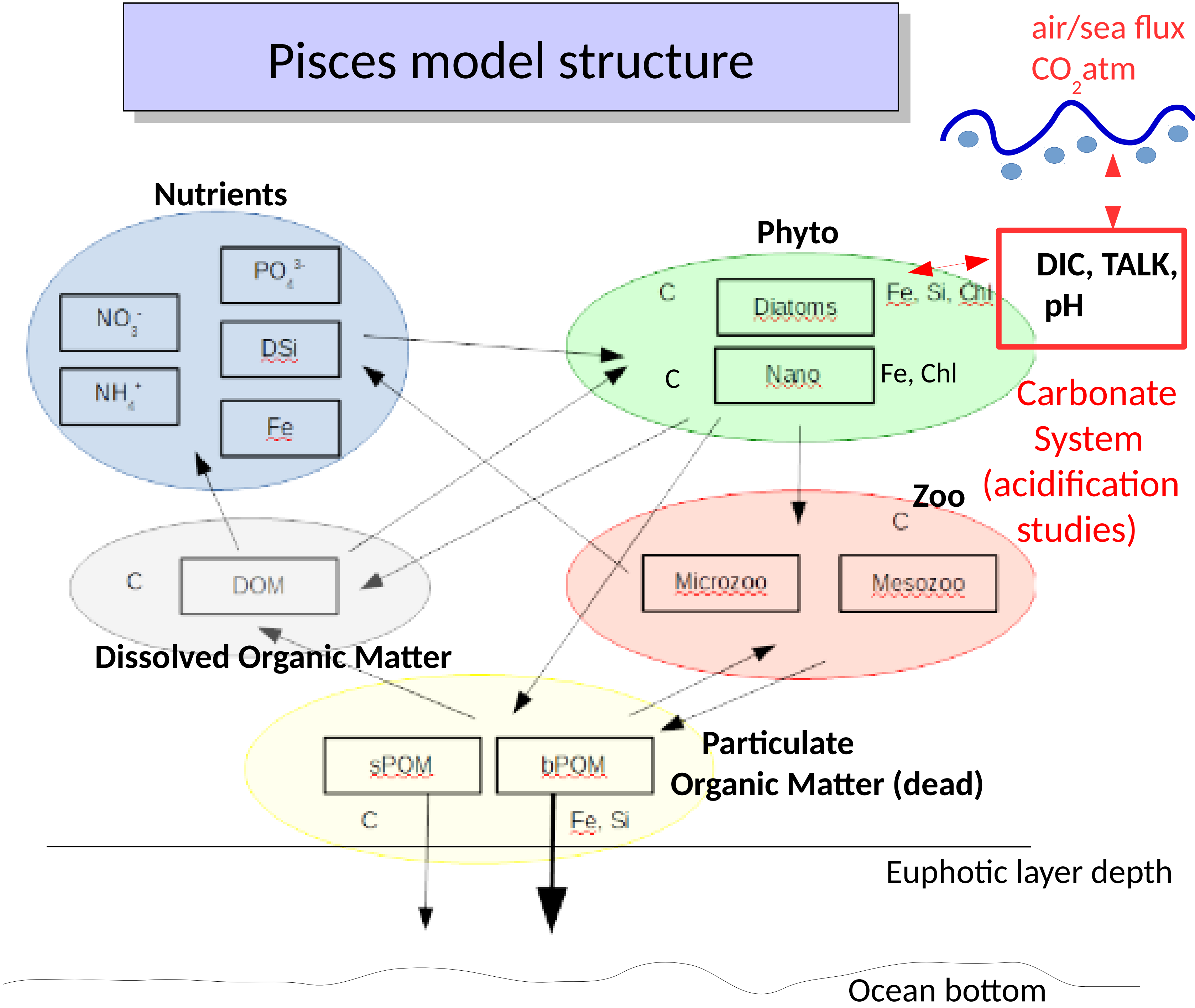
Fe, Si

Particulate
Organic Matter (dead)

Euphotic layer depth

Ocean bottom

Pisces model structure



air/sea flux

CO_2 atm

DIC, TALK, pH

Carbonate System (acidification studies)

Nutrients

NO_3^-

NH_4^+

PO_4^{3-}

DSi

Fe

Phyto

C Diatoms Fe, Si, Chl

C Nano Fe, Chl

Zoo

C

Microzoo

Mesozoo

C DOM

Dissolved Organic Matter

sPOM

bPOM

C

Fe, Si

Particulate Organic Matter (dead)

Euphotic layer depth

Ocean bottom

Equation for Nanophytoplankton (small phytoplankton)

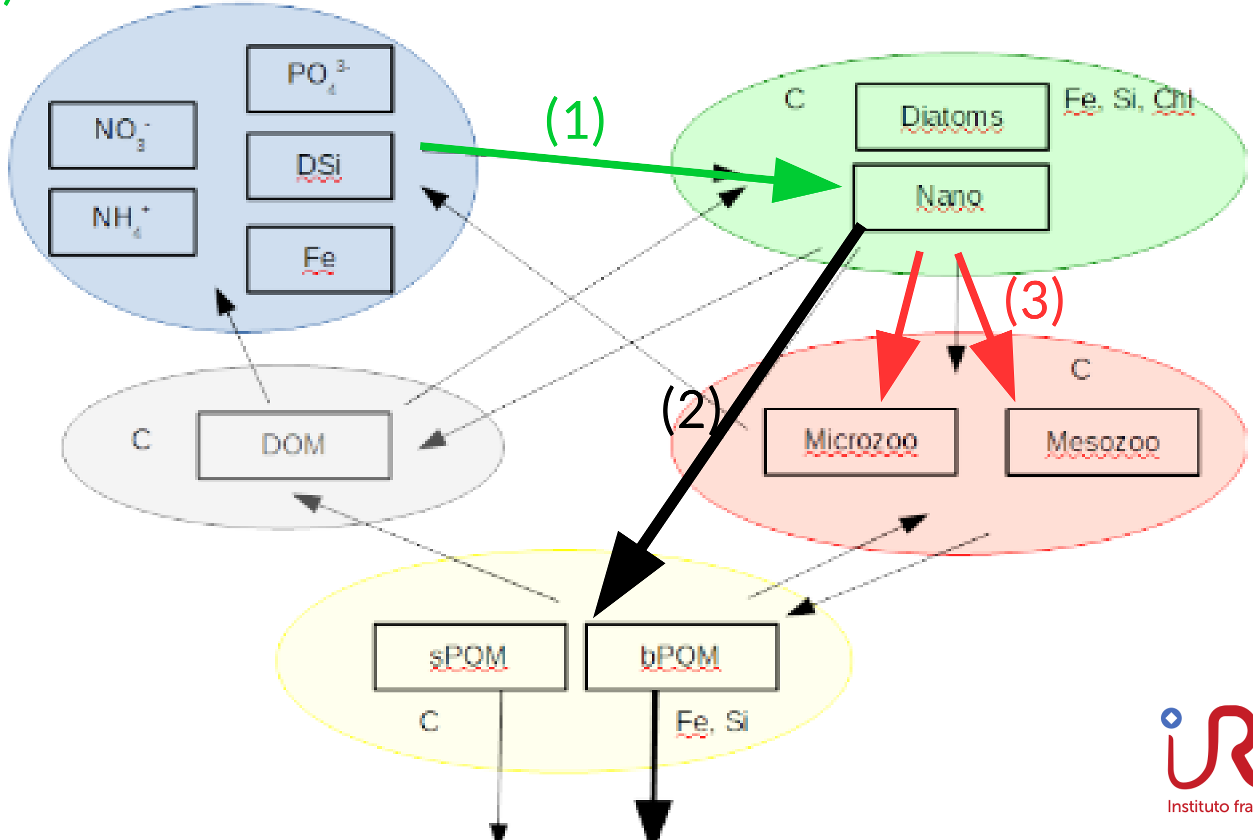
$$\frac{\partial P}{\partial t} = \boxed{(1-\delta^{nano})\mu^{nano}P} - \boxed{m^{nano}\frac{P}{K_{nano}+P}P - w_p^{nano}P^2} - \boxed{g^{micro}(P)Z} - \boxed{g^{micro}(P)M}$$

Production (1)

Linear and quadratic mortality (2)

Grazing by small zoo (Z), (3)

Grazing by big zoo (M), (3)



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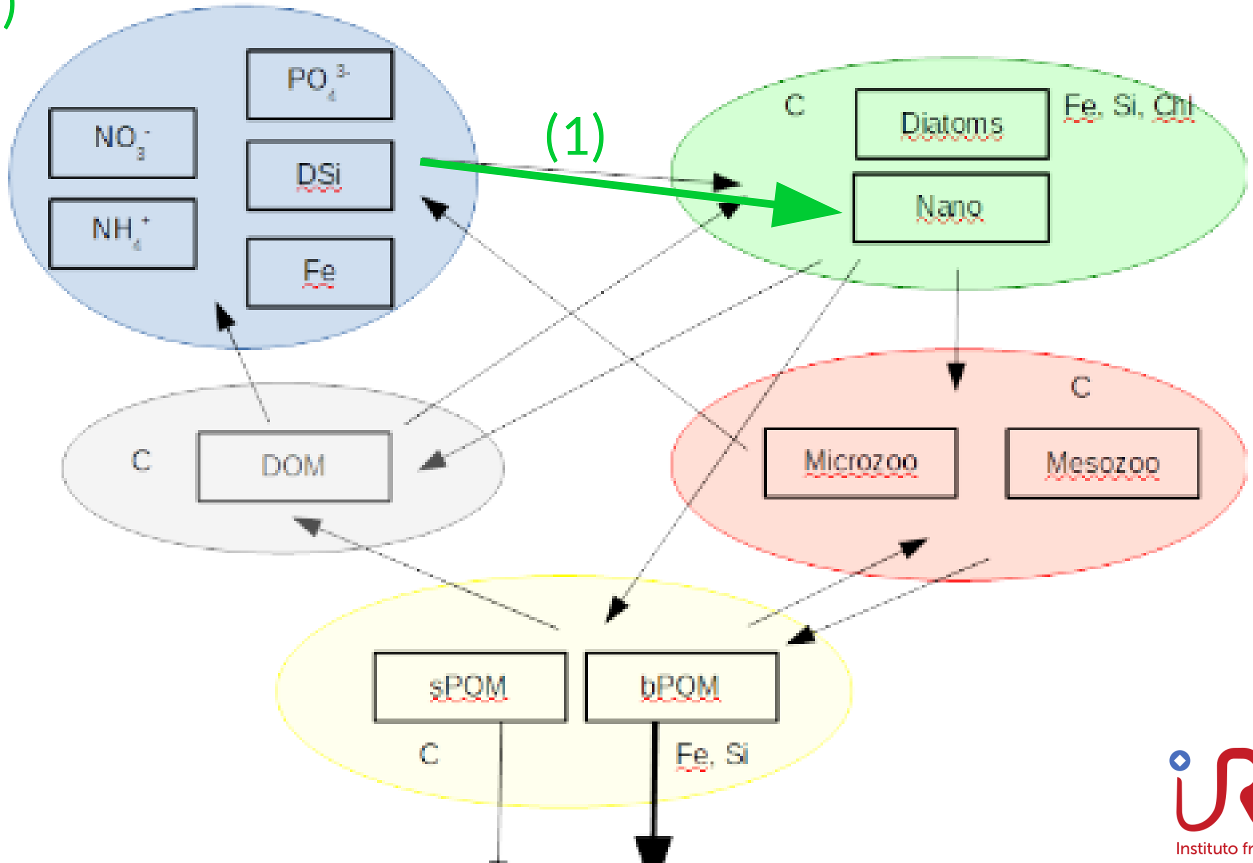
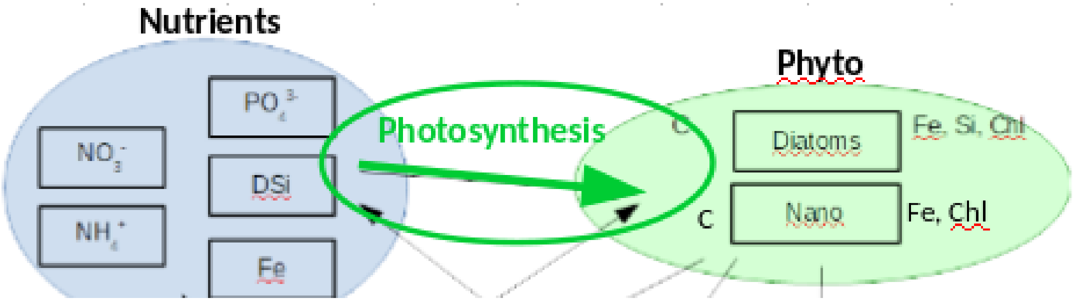
Equation for Nanophytoplankton (small phytoplankton)

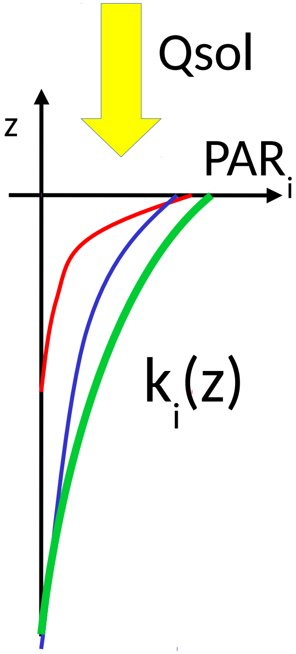
$$\frac{\partial P}{\partial t} = \boxed{(1-\delta^{nano})\mu^{nano}P} - m^{nano}\frac{P}{K_{nano}+P}P - w_p^{nano}P^2 - g^{micro}(P)Z - g^{micro}(P)M$$

Production
(1)



Calculation of PAR (Photosynthetically Available Radiation) to compute photosynthesis





Photosynthesis : transformation of mineral/inorganic matter
into living organic matter

Optical model required to compute the penetration of light in the water column

⇒ 3 wavelengths in PISCES optical model: red, green, blue

⇒ PAR= PAR$_r$ +PAR$_g$+ PAR$_b$, Qsol = solar radiation at the surface of the ocean

	red
Light absorption	$PAR_r(z) = PAR_r(z-dz)\,e^{-k_r dz}$ $PAR_r(0) = \frac{0.43}{3} Q_{sol}$
Absorption coefficient	$k_r = k_{r0} + \chi_{rp} Pig^{e_r}$

$$Pig = \frac{Chl}{r_{pig}}$$

Equation for Nanophytoplankton (small phyto cells)

$$\frac{\partial P}{\partial t} = \boxed{(1-\delta^{nano})\mu^{nano}P} - m^{nano}\frac{P}{K_{nano}+P}P - w_p^{nano}P^2 - g^{micro}(P)Z - g^{micro}(P)M$$

Production

PAR= photosynthetically available radiation

$$\mu^{nano} = \mu_P\left(1 - e^{-\frac{\alpha^P\left(\frac{Chl}{C}\right)^P PAR}{\mu_P L_{lim}^{nano}}}\right)L_{lim}^{nano}$$

$$\mu_P = ab^{cT}$$ =temperature dependent

Equation for Nanophytoplankton (small phyto cells)

$$\frac{\partial P}{\partial t} = \boxed{(1-\delta^{nano})\mu^{nano} P} - m^{nano}\frac{P}{K_{nano}+P}P - w_p^{nano}P^2 - g^{micro}(P)Z - g^{micro}(P)M$$

Production

$$\mu^{nano} = \mu_P\left(1 - e^{-\frac{\alpha^P\left(\frac{Chl}{C}\right)^P PAR}{\mu_P L_{lim}^{nano}}}\right) L_{lim}^{nano}$$

PAR= photosynthetically available radiation

$\mu_P = ab^{cT}$ =temperature dependent

Half-saturation constants

PO4 $$L_{po4}^{nano} = \frac{PO_4}{K_{po4}^{nano} + PO_4}$$

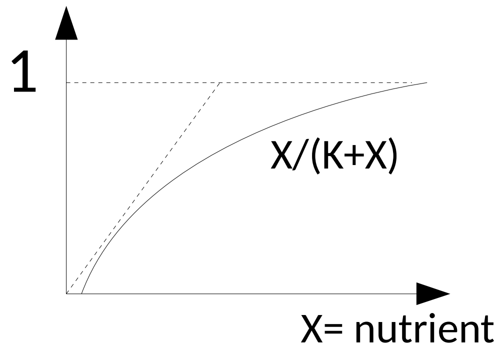
Fe $$L_{fe}^{nano} = \frac{Fe}{K_{Fe}^{nano} + Fe}$$

NO3 $$L_{no3}^{nano} = \frac{K_{nh4}^{nano} NO_3}{K_{no3}^{nano} K_{nh4}^{nano} + K_{nh4}^{nano} NO_3 + K_{no3}^{nano} NH_4}$$

NH4 $$L_{nh4}^{nano} = \frac{K_{no3}^{nano} NH_4}{K_{no3}^{nano} K_{nh4}^{nano} + K_{nh4}^{nano} NO_3 + K_{no3}^{nano} NH_4}$$

preference for NH_4

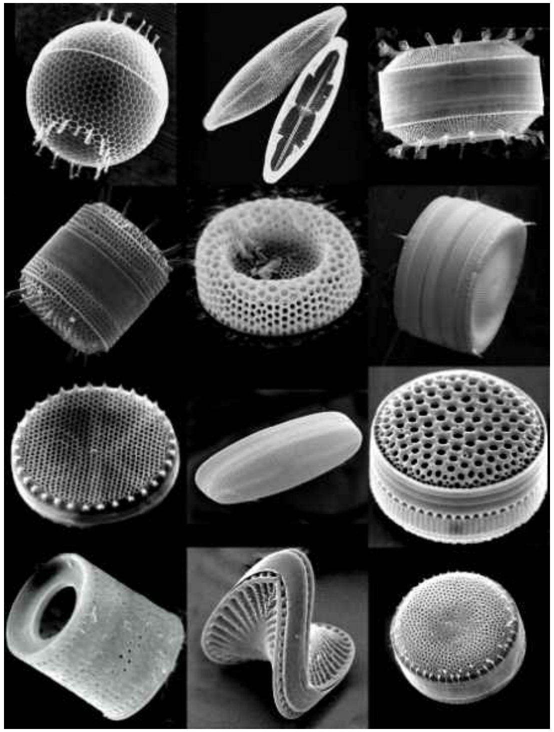
Michaelis-Menten parameterization



$$L_{lim}^{nano} = \min(L_{po4}^{nano}, L_{Fe}^{nano}, L_{no3}^{nano} + L_{nh4}^{nano})$$ min=>limiting nutrient

Equation for Diatoms (big phyto cells)

$$\frac{\partial D}{\partial t} = \underbrace{\boxed{(1-\delta^{diat})\mu^{diat} D}}_{\text{Production}} - m^{diat}\frac{D}{K_{diat}+D}D - w_p^{diat}D^2 - g^{micro}(D)Z - g^{meso}(D)M$$



Diatoms need Silicate for their exoskeleton

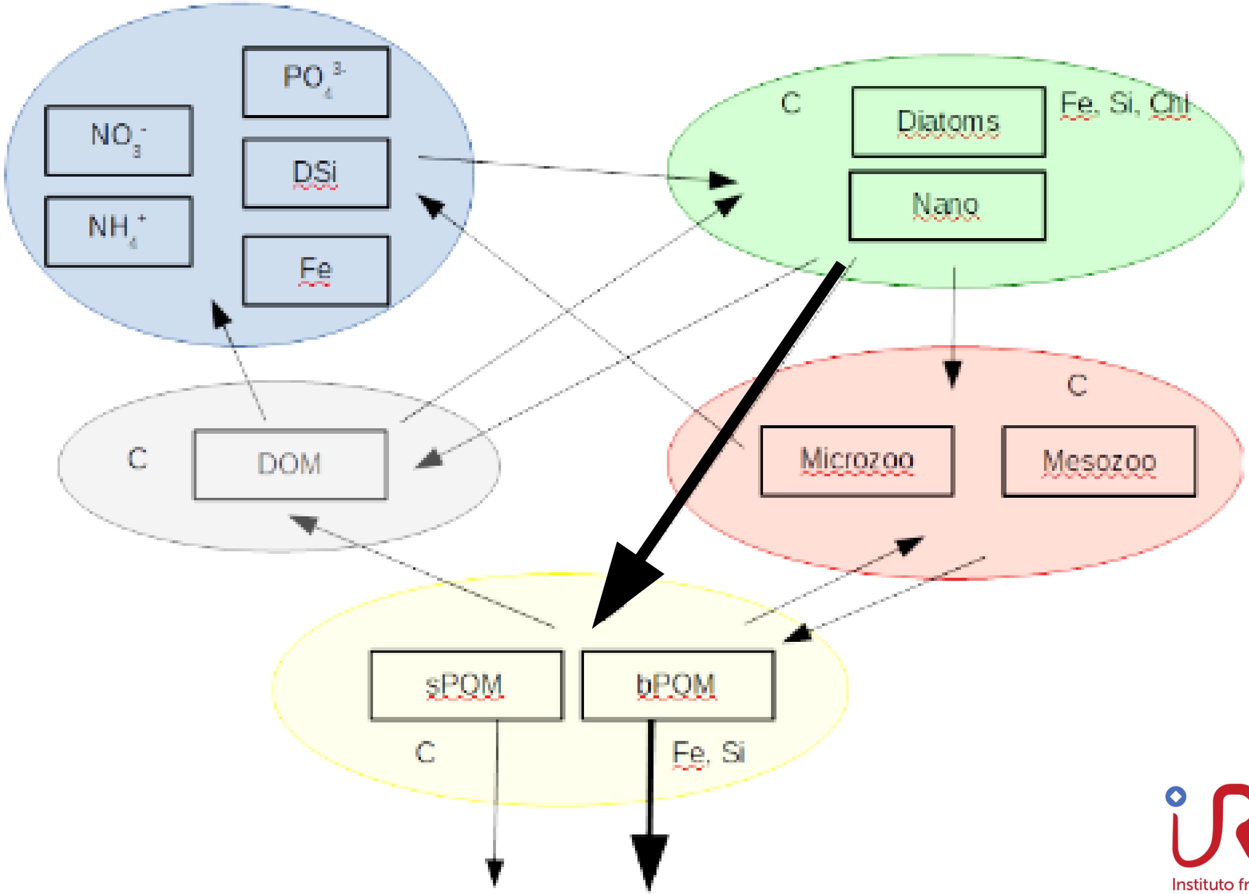
Limiting nutrients : PO4, NO3, NH4, Fe , Silicate (Si)

$$\begin{aligned} \boxed{L_{Si}^{diat}} &= \frac{Si}{K_{Si}^{diat}+Si} \\ L_{lim}^{diat} &= \min(L_{po4}^{diat}, L_{Fe}^{diat}, L_{no3}^{diat}+L_{nh4}^{diat}, \boxed{L_{Si}^{diat}}) \end{aligned}$$

Equation for Diatoms (big phyto cells)

$$\frac{\partial D}{\partial t} = (1-\delta^{diat})\mu^{diat} D - \boxed{m^{diat}\frac{D}{K_{diat}+D}D - w_p^{diat}D^2} - g^{micro}(D)Z - g^{meso}(D)M$$

Mortality



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Equation for Diatoms (big phyto cells)

$$\frac{\partial D}{\partial t} = (1-\delta^{diat})\mu^{diat} D - \boxed{m^{diat}\frac{D}{K_{diat}+D}D - w_p^{diat}D^2} - g^{micro}(D)Z - g^{meso}(D)M$$

Two terms : « linear » and quadratic mortality (= aggregation of cells)

Aggregation increases when nutrient stress increases,
cells become more sticky, and merge into big sinking particles:

$$\boxed{w_p^{diat}} = w_p^{min} + w_p^{max} \times (1 - \boxed{L_{lim}^{diat}})$$

Equation for micro-zooplankton (small cells)

Grazing of phyto (P and D) and small POC

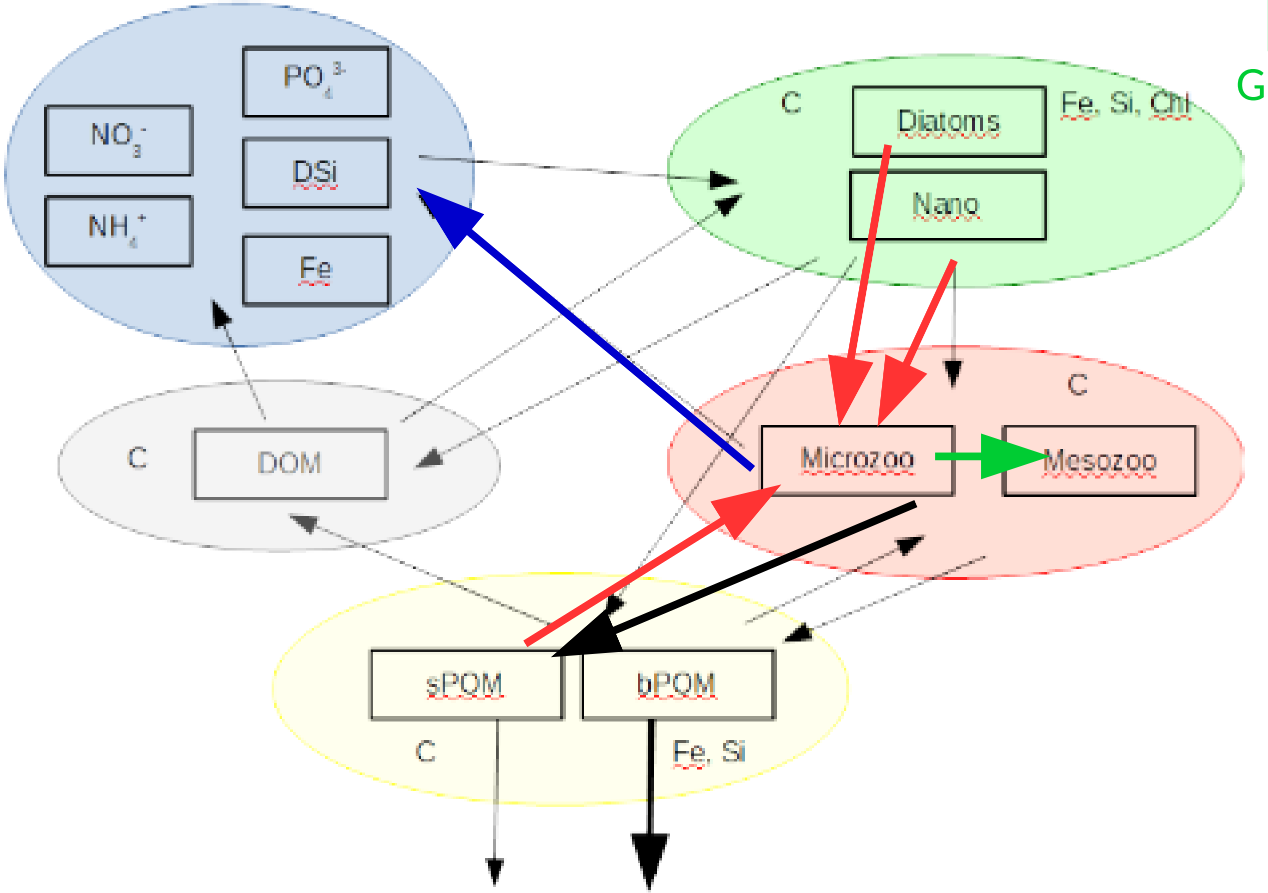
Zoo excretion

$$\frac{\partial Z}{\partial t} = \boxed{e^{micro}(g^{micro}(P) + g^{micro}(D) + g^{micro}(POC_s))Z} - \boxed{r^{micro}\frac{Z}{K_{micro}+Z}Z}$$

$$-\boxed{g^{M}(Z)M} - \boxed{m^{Z} f_{Z}(T)Z^{2}}$$

Grazing by M

Mortality and grazing by higher trophic levels



Equation for micro-zooplankton (small cells)

Grazing of phyto (P and D) and small POC

$$\frac{\partial Z}{\partial t} = \boxed{e^{micro}(g^{micro}(P) + g^{micro}(D) + g^{micro}(POC_s))Z} - r^{micro}\frac{Z}{K_{micro} + Z}Z - g^{M}(Z)M - m^{Z} f_{Z}(T)Z^{2}$$

Grazing efficiency (~0.2-0.3)

Grazing parameters

- p_N=preferential grazing of zoo for species (N) over all species I (= P,D,POCs):

$$g^{micro}(N) = g^{micro}\frac{p_N^{micro}N}{K_G^{micro} + \sum_I (p_I^{micro}I)}$$

$p_{POC} < p_{Dia} < p_{Nano}$ => zoo prefers to graze nanophyto (P), then big phyto (Diatoms), then POC

- grazing coefficient increases with temperature: same dependence as phytoplankton : b^{cT}

Equation for meso-zooplankton (big cells)

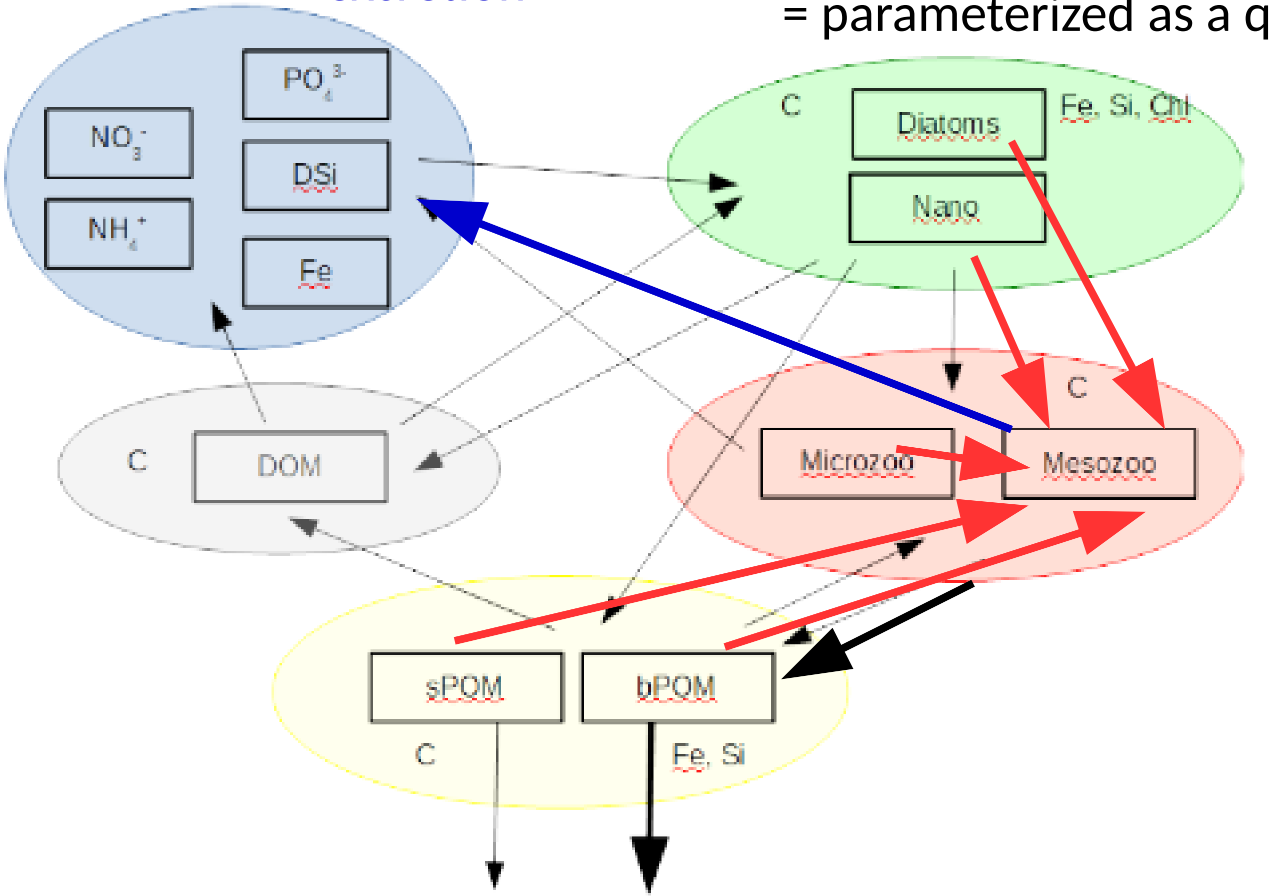
$$\frac{\partial M}{\partial t} = \boxed{e^{meso}(g^{meso}(P)+g^{meso}(D)+g^{meso}(Z)+g^{meso}(POC_s)+g^{meso}(POC_b))M}$$

$$-\boxed{r^{meso}\frac{M}{K_{meso}+M}M}-\boxed{m^{meso}M^2}$$

grazing of P,D,Z,POCs,POCg

excretion

grazing by higher trophic levels (fish larvae, ..)
= parameterized as a quadratic mortality



Equation for meso-zooplankton (big cells)

$$\frac{\partial M}{\partial t} = \boxed{e^{meso}(g^{meso}(P) + g^{meso}(D) + g^{meso}(Z) + g^{meso}(POC_s) + g^{meso}(POC_b))M}$$

$$-\boxed{r^{meso}\frac{M}{K_{meso}+M}M} - \boxed{m^{meso}M^2}$$

grazing of P,D,Z,POCs,POCg

excretion

grazing by higher trophic levels (fish larvae, ..)
= parameterized as a quadratic mortality

- Meso zooplankton grazes on two phyto and two detritus size classes (POCs and POCb)

  - p^{meso}_N=preferential grazing of M for species (N) over all species I (P,D,POCs,POCb):

$$g^{meso}(N) = g^{meso}\frac{p_N^{meso}N}{K_G^{meso} + \sum_I (p_I^{meso} I)}$$

$$p_N^{meso} = \frac{\gamma_N N}{\sum_I (\gamma_I I)}$$

= not a constant (as for micro zoo)

=> Meso zoo easts preferentially the most abundant prey

Equation for dissolved organic matter (DOM) (carbon only : DOM =DOC)

$$
\begin{aligned}
\frac{\partial DOC}{\partial t} = {} & \boxed{\delta^{nano}\mu^{nano}P + \delta^{diat}\mu^{diat}D} + \boxed{(1-\epsilon^{micro})r^{micro}\frac{Z}{K_{micro}+Z}Z} \\
& \boxed{+(1-\epsilon^{meso})r^{meso}\frac{M}{K_{meso}+M}M} + (1-\sigma^{micro}-e^{micro}) \\
& (1-\gamma^{micro})(g^{micro}(P)+g^{micro}(D)+g^{micro}(POC_s))Z \\
& +(1-\sigma^{meso}-e^{meso})(1-\gamma^{meso})(g^{meso}(P)+g^{meso}(D) \\
& +g^{meso}(Z)+g^{meso}(POC_s)+g^{meso}(POC_b))M + \boxed{\lambda^{\star}_{POC}POC_s} \\
& -\boxed{\lambda^{\star}_{DOC}DOC} - \boxed{\Phi^{DOC\rightarrow POC_s}_{agg} - \Phi^{DOC\rightarrow POC_b}_{agg}}
\end{aligned}
$$

Organic exsudation by phyto

Excretion by the 2 zoo

Organic exudation by the 2 zoo (proportional to grazing)

-Denit

Degradation of small POC

Remineralisation of DOC in DIC & NH_4

(-Denit if O_2 low)

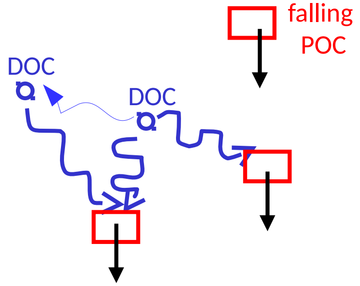
Aggregation of DOC by POC

Equation for dissolved organic matter (DOM)
(carbon only : DOM =DOC)

$$
\begin{aligned}
\frac{\partial DOC}{\partial t} = {} & \boxed{\delta^{nano}\mu^{nano}P + \delta^{diat}\mu^{diat}D} + \boxed{(1-\epsilon^{micro})r^{micro}\frac{Z}{K_{micro}+Z}Z} \\
& \boxed{+(1-\epsilon^{meso})r^{meso}\frac{M}{K_{meso}+M}M} + (1-\sigma^{micro}-e^{micro}) \\
& (1-\gamma^{micro})(g^{micro}(P)+g^{micro}(D)+g^{micro}(POC_s))Z \\
& +(1-\sigma^{meso}-e^{meso})(1-\gamma^{meso})(g^{meso}(P)+g^{meso}(D) \\
& +g^{meso}(Z)+g^{meso}(POC_s)+g^{meso}(POC_b))M + \lambda^{\star}_{POC}POC_s \\
& -\lambda^{\star}_{DOC}DOC - \boxed{\Phi^{DOC\rightarrow POC_s}_{agg} - \Phi^{DOC\rightarrow POC_b}_{agg}}
\end{aligned}
$$

Aggregation of DOC by POC

$$
\begin{aligned}
\Phi^{DOC\rightarrow POC_s}_{agg} &= \phi^{DOC}_1\,\mathrm{sh}\,\boxed{DOC^2} + \phi^{DOC}_2\,\mathrm{sh}\,\boxed{DOC}\,\boxed{POC_s} \\
\Phi^{DOC\rightarrow POC_b}_{agg} &= \phi^{DOC}_3\,\mathrm{sh}\,\boxed{DOC}\,\boxed{POC_b}
\end{aligned}
$$



Aggregation terms: effect of turbulence=> sh= 1/(time scale): 1s in mixed layer,
100s below mixed layer

Φ_i = parameters for probability of encounter of particules

Equation for (small) particulate organic matter (POCs)

Detritus production from grazing

$$
\begin{aligned}
\frac{\partial POC_s}{\partial t} = {} & \boxed{\sigma^{micro}\Big(\sum_N g^{micro}(N)\Big)Z - g^{micro}(POC_s)Z} \\
& + \boxed{(1-0.5R_{CaCO3})\left(m^{nano}\frac{P}{K_{nano}+P}P + w_P^{nano}P^2\right)} \\
& \boxed{+0.5m^{diat}\frac{D}{K_{diat}+D}D + \epsilon^{micro}r^{micro}\frac{Z}{Z_{micro}+Z}Z} - \boxed{\lambda^\star_{POC}POC_s} \\
& - \boxed{w^{POC_s}\frac{\partial POC_s}{\partial z}} + \Phi_{agg}^{DOC\rightarrow POC_s} - \Phi_{agg}^{POC_s\rightarrow POC_b}
\end{aligned}
$$

Production of calcite shells ($RCaCO_3$= proportion of calcifying organisms)

Corpses of dead diatoms and zoo

Degradation of small POC

Sinking of small particules

Equation for (small) particulate organic matter (POCs)

$$
\begin{aligned}
\frac{\partial POC_s}{\partial t} = {} & \boxed{\sigma^{micro}\left(\sum_N g^{micro}(N)\right)Z - g^{micro}(POC_s)Z} \\
& + \boxed{(1-0.5R_{CaCO3})\left(m^{nano}\frac{P}{K_{nano}+P}P + w_P^{nano}P^2\right)} \\
& \boxed{+0.5m^{diat}\frac{D}{K_{diat}+D}D + \epsilon^{micro}r^{micro}\frac{Z}{Z_{micro}+Z}Z} - \boxed{\lambda^{\star}_{POC}POC_s} \\
& - \boxed{w^{POC_s}\frac{\partial POC_s}{\partial z}} + \Phi_{agg}^{DOC\rightarrow POC_s} - \Phi_{agg}^{POC_s\rightarrow POC_b}
\end{aligned}
$$

Sinking velocity

Sinking of small particules

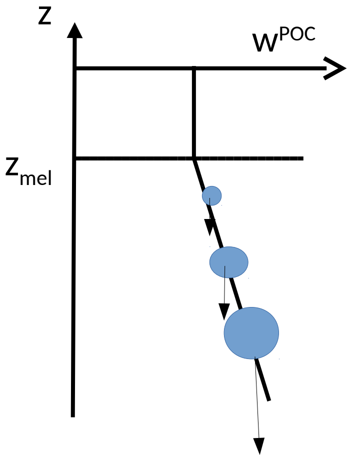
Same equation as vertical advection of dissolved tracer C : - w .∂C/∂z

w = vertical velocity of the fluid

In present case : w^{POCs} = sinking velocity of particules (increases with depth)

$$
w^{POC} = w^{POC}_{min} + (w^{POC}_{max} - w^{POC}_{min})\max(0, \frac{z - z_{mel}}{2000m})
$$

Zmel=max(Zmxl,Ze)



Differences between Nitrogen and Phosphate pools (1)

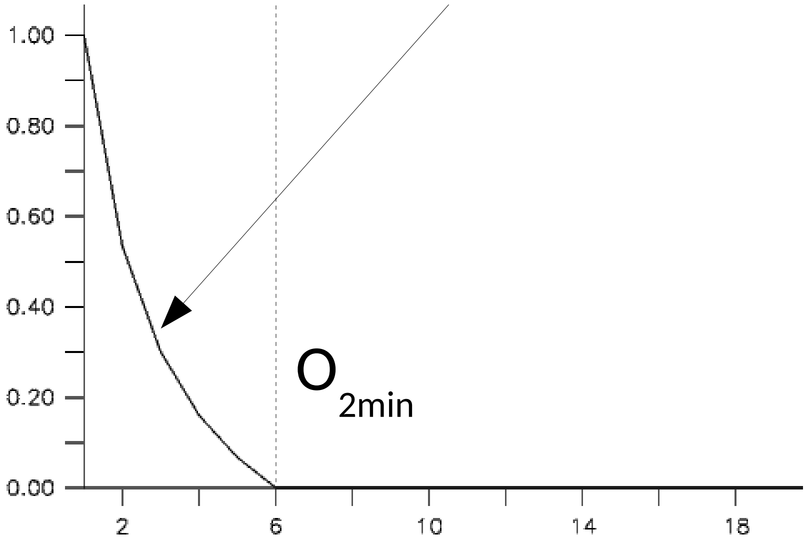
$$\boxed{\left(\frac{\partial NO_3}{\partial t} + \frac{\partial NH_4}{\partial t}\right) - \frac{\partial PO_4}{\partial t} = Nfix - Denit}$$

Nitrogen Fixation
by Trichodesnium

Denitrification: when O_2 reduces,
nitrate is consumed during OM
remineralization instead of O_2

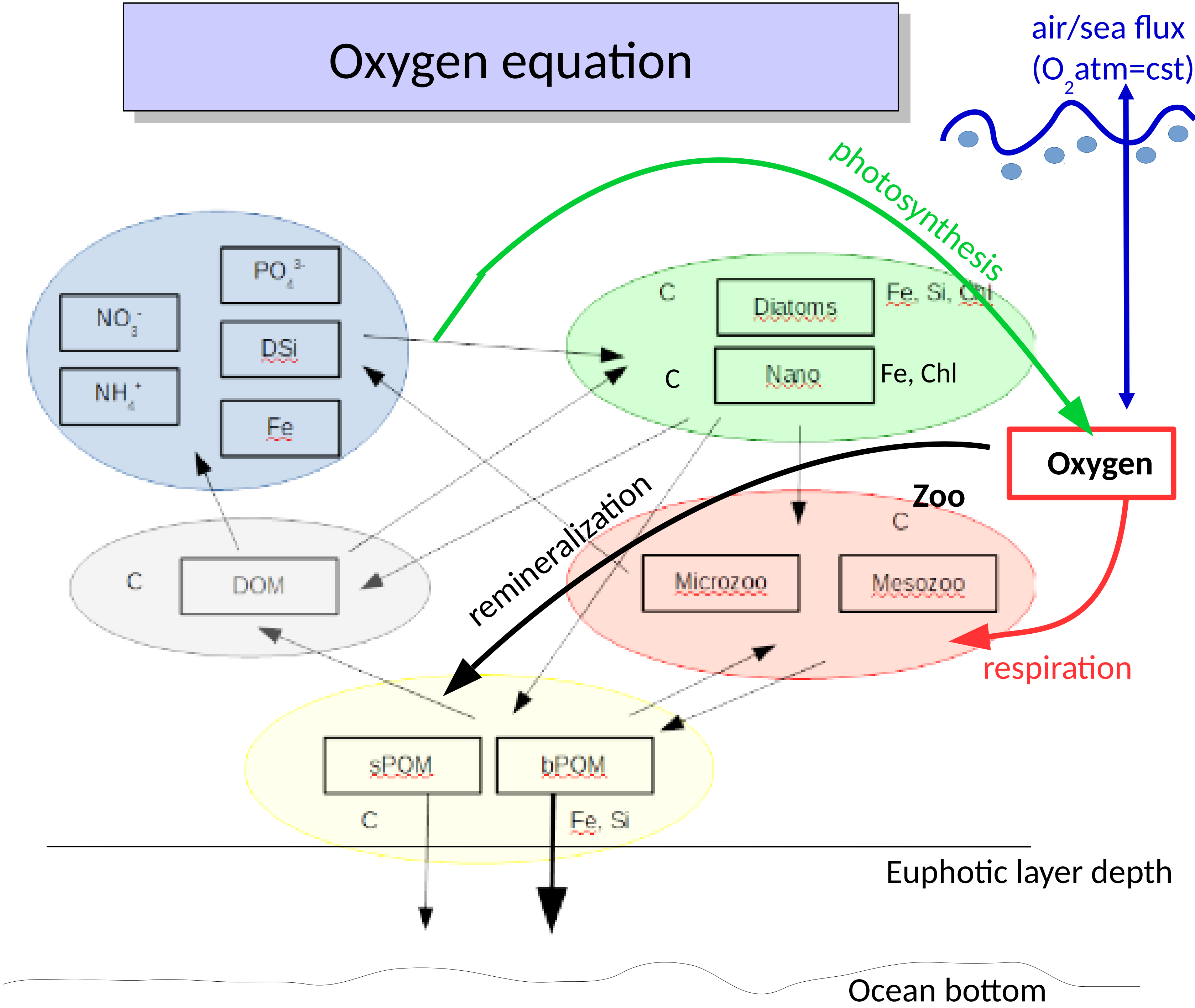
Denitrifcation (Denit term in DOC equation) :

$$Denit = R_{NO3}\lambda^{\star}_{DOC}\boxed{(1-\Delta(O_2))}DOC$$



If *Nfix*=*Denit*=0 => $(NO_3+NH_4)/PO_4$=cst

Oxygen equation



Oxygen equation :

$$\begin{aligned}
\frac{\partial \mathrm{O}_2}{\partial t} = & \boxed{\mathrm{O}_2^{\mathrm{ut}}(\mu^P_{\mathrm{NH}_4}P + \mu^D_{\mathrm{NH}_4}D) + (\mathrm{O}_2^{\mathrm{ut}}+\mathrm{O}_2^{\mathrm{nit}})} \\
& \boxed{(\mu^P_{\mathrm{NO}_3}P+\mu^D_{\mathrm{NO}_3}D) + \mathrm{O}_2^{\mathrm{nit}}N_{\mathrm{fix}}} \\
& \boxed{-\mathrm{O}_2^{\mathrm{ut}}\gamma^Z(1-e^Z-\sigma^Z)\sum_I g^Z(I)Z - \mathrm{O}_2^{\mathrm{ut}}\gamma^M (1-e^M-\sigma^M)\left(\sum_I g^M(I)+\sum_I g^M_{\mathrm{FF}}(I)\right)M} - \boxed{\mathrm{O}_2^{\mathrm{ut}}\gamma^M R^M_{\mathrm{up}}} \\
& -\boxed{\mathrm{O}_2^{\mathrm{ut}}\mathrm{Remin}} - \boxed{\mathrm{O}_2^{\mathrm{nit}}\mathrm{Nitrif}}
\end{aligned}$$

Production by photosynthesis
(new prod., regenerated prod., N fixation)

Respiration by zooplancton
and higher trophic levels
(proportional to grazing)

Consumption of oxygen
by remineralisation of
organic matter

Consumption of oxygen
by nitrification (NH_4->NO_3)

O_2^{ut}, O_2^{nit} = different O/C Redfield ratios for new and regenerated production

At depth (out of euphotic layer) : $\partial_t O_2 \sim -O_2^{ut}$ Remin $-O_2^{Nit}$ Nitrif

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Oxygen equation :

$$\left.\begin{aligned}
\frac{\partial \mathrm{O}_2}{\partial t} &= \mathrm{O}_2^{\mathrm{ut}}(\mu^P_{\mathrm{NH}_4} P + \mu^D_{\mathrm{NH}_4} D) + (\mathrm{O}_2^{\mathrm{ut}} + \mathrm{O}_2^{\mathrm{nit}}) \\
&(\mu^P_{\mathrm{NO}_3} P + \mu^D_{\mathrm{NO}_3} D) + \mathrm{O}_2^{\mathrm{nit}} N_{\mathrm{fix}} \\
&- \mathrm{O}_2^{\mathrm{ut}} \gamma^Z (1 - e^Z - \sigma^Z) \sum_I g^Z(I) Z - \mathrm{O}_2^{\mathrm{ut}} \gamma^M \\
&(1 - e^M - \sigma^M)\left(\sum_I g^M(I) + \sum_I g^M_{\mathrm{FF}}(I)\right) M - \\
&- \mathrm{O}_2^{\mathrm{ut}} \mathrm{Remin} - \mathrm{O}_2^{\mathrm{nit}} \mathrm{Nitrif}
\end{aligned}\right\}$$

Biogeochemical processes

$$\boxed{- u.\partial_x O_2 \; - v.\partial_y O_2 - w.\partial_z O_2 \quad + \partial_z(K\partial_z O_2) \quad + \mathrm{Diff}_h(O_2) \quad + \quad F_{atm}}$$

Physical processes

3D advection

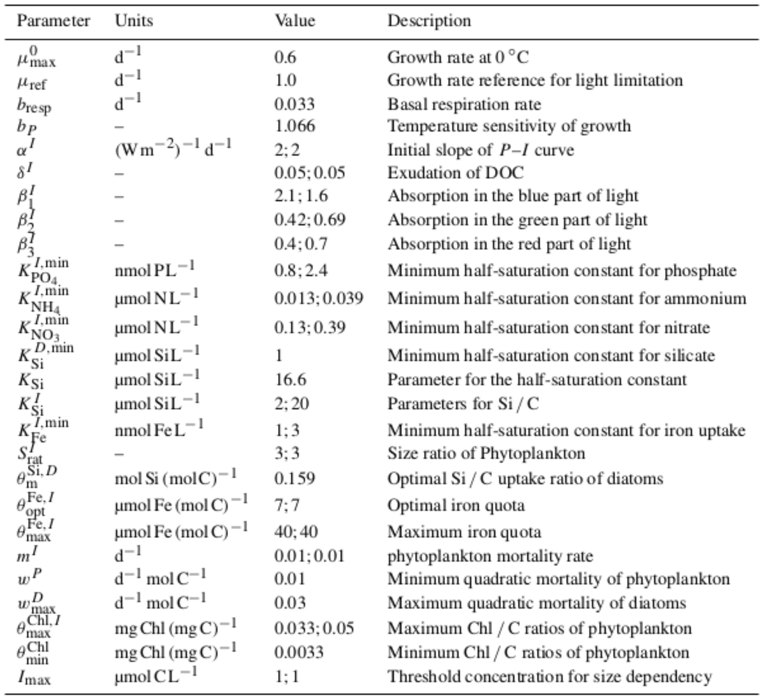
vertical mixing

horizontal mixing

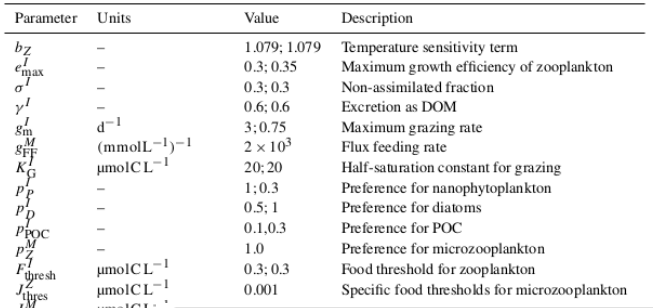
air-sea flux

...same physical terms for all of PISCES tracers

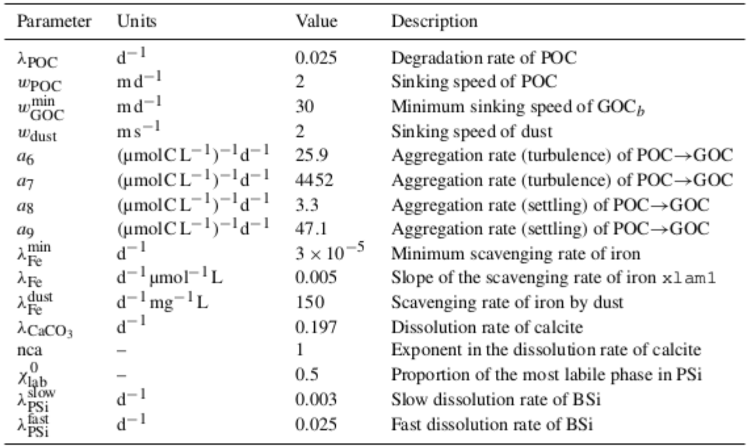
Many parameters in PISCES….



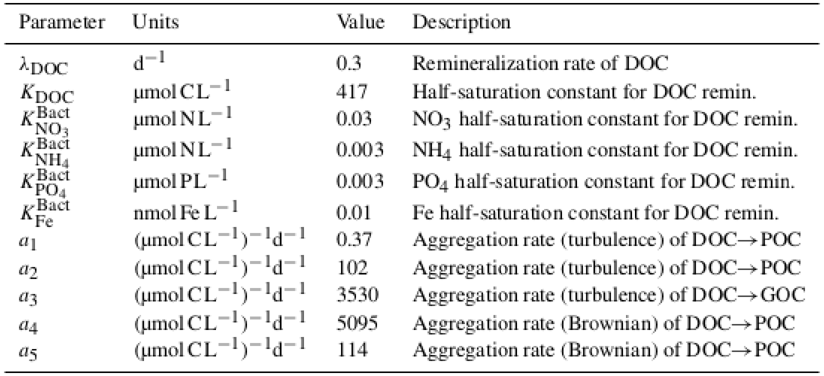
Parameter	Units	Value	Description
$\mu^0_{\max}$	$\mathrm{d^{-1}}$	0.6	Growth rate at 0 °C
μ_{ref}	$\mathrm{d^{-1}}$	1.0	Growth rate reference for light limitation
b_{resp}	$\mathrm{d^{-1}}$	0.033	Basal respiration rate
b_P	–	1.066	Temperature sensitivity of growth
α^I	$(\mathrm{W\,m^{-2}})^{-1}\,\mathrm{d^{-1}}$	2; 2	Initial slope of P–I curve
δ^I	–	0.05; 0.05	Exudation of DOC
β^I_1	–	2.1; 1.6	Absorption in the blue part of light
β^I_2	–	0.42; 0.69	Absorption in the green part of light
β^I_3	–	0.4; 0.7	Absorption in the red part of light
$K^{I,\min}_{\mathrm{PO_4}}$	$\mathrm{nmol\,P\,L^{-1}}$	0.8; 2.4	Minimum half-saturation constant for phosphate
$K^{I,\min}_{\mathrm{NH_4}}$	$\mathrm{\mu mol\,N\,L^{-1}}$	0.013; 0.039	Minimum half-saturation constant for ammonium
$K^{I,\min}_{\mathrm{NO_3}}$	$\mathrm{\mu mol\,N\,L^{-1}}$	0.13; 0.39	Minimum half-saturation constant for nitrate
$K^{D,\min}_{\mathrm{Si}}$	$\mathrm{\mu mol\,Si\,L^{-1}}$	1	Minimum half-saturation constant for silicate
K_{Si}	$\mathrm{\mu mol\,Si\,L^{-1}}$	16.6	Parameter for the half-saturation constant
K^I_{Si}	$\mathrm{\mu mol\,Si\,L^{-1}}$	2; 20	Parameters for Si / C
$K^{I,\min}_{\mathrm{Fe}}$	$\mathrm{nmol\,Fe\,L^{-1}}$	1; 3	Minimum half-saturation constant for iron uptake
S^I_{rat}	–	3; 3	Size ratio of Phytoplankton
$\theta^{\mathrm{Si},D}_{\mathrm{m}}$	$\mathrm{mol\,Si\,(mol\,C)^{-1}}$	0.159	Optimal Si / C uptake ratio of diatoms
$\theta^{\mathrm{Fe},I}_{\mathrm{opt}}$	$\mathrm{\mu mol\,Fe\,(mol\,C)^{-1}}$	7; 7	Optimal iron quota
$\theta^{\mathrm{Fe},I}_{\max}$	$\mathrm{\mu mol\,Fe\,(mol\,C)^{-1}}$	40; 40	Maximum iron quota
m^I	$\mathrm{d^{-1}}$	0.01; 0.01	phytoplankton mortality rate
w^P	$\mathrm{d^{-1}\,mol\,C^{-1}}$	0.01	Minimum quadratic mortality of phytoplankton
$w^D_{\max}$	$\mathrm{d^{-1}\,mol\,C^{-1}}$	0.03	Maximum quadratic mortality of diatoms
$\theta^{\mathrm{Chl},I}_{\max}$	$\mathrm{mg\,Chl\,(mg\,C)^{-1}}$	0.033; 0.05	Maximum Chl / C ratios of phytoplankton
$\theta^{\mathrm{Chl}}_{\min}$	$\mathrm{mg\,Chl\,(mg\,C)^{-1}}$	0.0033	Minimum Chl / C ratios of phytoplankton
$I_{\max}$	$\mathrm{\mu mol\,C\,L^{-1}}$	1; 1	Threshold concentration for size dependency



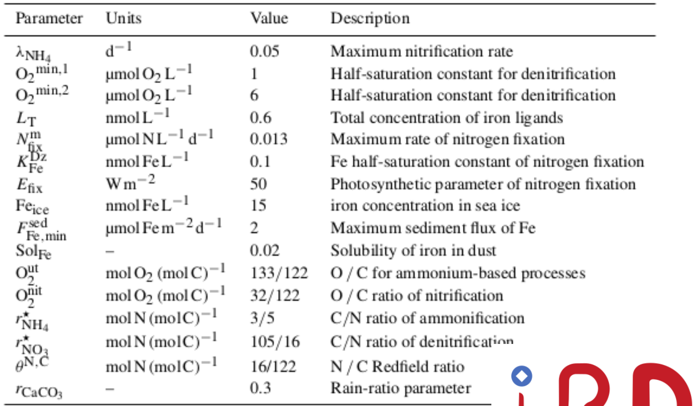
Parameter	Units	Value	Description
b_Z	–	1.079; 1.079	Temperature sensitivity term
$e^I_{\max}$	–	0.3; 0.35	Maximum growth efficiency of zooplankton
σ^I	–	0.3; 0.3	Non-assimilated fraction
γ^I	–	0.6; 0.6	Excretion as DOM
g^I_{m}	$\mathrm{d^{-1}}$	3; 0.75	Maximum grazing rate
g^M_{FF}	$\mathrm{(mmol L^{-1})^{-1}}$	2×10^3	Flux feeding rate
K^I_{G}	$\mathrm{\mu mol C\,L^{-1}}$	20; 20	Half-saturation constant for grazing
p^I_P	–	1; 0.3	Preference for nanophytoplankton
p^I_D	–	0.5; 1	Preference for diatoms
p^I_{POC}	–	0.1,0.3	Preference for POC
p^M_Z	–	1.0	Preference for microzooplankton
F^I_{thresh}	$\mathrm{\mu mol C\,L^{-1}}$	0.3; 0.3	Food threshold for zooplankton
J^Z_{thres}	$\mathrm{\mu mol C\,L^{-1}}$	0.001	Specific food thresholds for microzooplankton
J^M_{thres}	μmolCL		
m^I	(μmol CL		
r^I	$\mathrm{d^{-1}}$		
K_{m}	μmolCL		
ν^I	–		
$\theta^{\mathrm{Fe,Zoo}}$	μmolFe n		



Parameter	Units	Value	Description
λ_{POC}	$\mathrm{d^{-1}}$	0.025	Degradation rate of POC
w_{POC}	$\mathrm{m\,d^{-1}}$	2	Sinking speed of POC
$w^{\min}_{\mathrm{GOC}}$	$\mathrm{m\,d^{-1}}$	30	Minimum sinking speed of GOC$_b$
w_{dust}	$\mathrm{m\,s^{-1}}$	2	Sinking speed of dust
a_6	$\mathrm{(\mu mol C\,L^{-1})^{-1}d^{-1}}$	25.9	Aggregation rate (turbulence) of POC→GOC
a_7	$\mathrm{(\mu mol C\,L^{-1})^{-1}d^{-1}}$	4452	Aggregation rate (turbulence) of POC→GOC
a_8	$\mathrm{(\mu mol C\,L^{-1})^{-1}d^{-1}}$	3.3	Aggregation rate (settling) of POC→GOC
a_9	$\mathrm{(\mu mol C\,L^{-1})^{-1}d^{-1}}$	47.1	Aggregation rate (settling) of POC→GOC
$\lambda^{\min}_{\mathrm{Fe}}$	$\mathrm{d^{-1}}$	3×10^{-5}	Minimum scavenging rate of iron
λ_{Fe}	$\mathrm{d^{-1}\,\mu mol^{-1}\,L}$	0.005	Slope of the scavenging rate of iron `xlam1`
$\lambda^{\mathrm{dust}}_{\mathrm{Fe}}$	$\mathrm{d^{-1}\,mg^{-1}\,L}$	150	Scavenging rate of iron by dust
$\lambda_{\mathrm{CaCO_3}}$	$\mathrm{d^{-1}}$	0.197	Dissolution rate of calcite
nca	–	1	Exponent in the dissolution rate of calcite
χ^0_{lab}	–	0.5	Proportion of the most labile phase in PSi
$\lambda^{\mathrm{slow}}_{\mathrm{PSi}}$	$\mathrm{d^{-1}}$	0.003	Slow dissolution rate of BSi
$\lambda^{\mathrm{fast}}_{\mathrm{PSi}}$	$\mathrm{d^{-1}}$	0.025	Fast dissolution rate of BSi



Parameter	Units	Value	Description
λ_{DOC}	$\mathrm{d^{-1}}$	0.3	Remineralization rate of DOC
K_{DOC}	$\mathrm{\mu mol\,C\,L^{-1}}$	417	Half-saturation constant for DOC remin.
$K^{\mathrm{Bact}}_{\mathrm{NO_3}}$	$\mathrm{\mu mol\,N\,L^{-1}}$	0.03	$\mathrm{NO_3}$ half-saturation constant for DOC remin.
$K^{\mathrm{Bact}}_{\mathrm{NH_4}}$	$\mathrm{\mu mol\,N\,L^{-1}}$	0.003	$\mathrm{NH_4}$ half-saturation constant for DOC remin.
$K^{\mathrm{Bact}}_{\mathrm{PO_4}}$	$\mathrm{\mu mol\,P\,L^{-1}}$	0.003	$\mathrm{PO_4}$ half-saturation constant for DOC remin.
$K^{\mathrm{Bact}}_{\mathrm{Fe}}$	$\mathrm{nmol\,Fe\,L^{-1}}$	0.01	Fe half-saturation constant for DOC remin.
a_1	$\mathrm{(\mu mol\,C\,L^{-1})^{-1}d^{-1}}$	0.37	Aggregation rate (turbulence) of DOC→POC
a_2	$\mathrm{(\mu mol\,C\,L^{-1})^{-1}d^{-1}}$	102	Aggregation rate (turbulence) of DOC→POC
a_3	$\mathrm{(\mu mol\,C\,L^{-1})^{-1}d^{-1}}$	3530	Aggregation rate (turbulence) of DOC→GOC
a_4	$\mathrm{(\mu mol\,C\,L^{-1})^{-1}d^{-1}}$	5095	Aggregation rate (Brownian) of DOC→POC
a_5	$\mathrm{(\mu mol\,C\,L^{-1})^{-1}d^{-1}}$	114	Aggregation rate (Brownian) of DOC→POC



Parameter	Units	Value	Description
$\lambda_{\mathrm{NH_4}}$	$\mathrm{d^{-1}}$	0.05	Maximum nitrification rate
$\mathrm{O_2}^{\min,1}$	$\mathrm{\mu mol\,O_2\,L^{-1}}$	1	Half-saturation constant for denitrification
$\mathrm{O_2}^{\min,2}$	$\mathrm{\mu mol\,O_2\,L^{-1}}$	6	Half-saturation constant for denitrification
L_{T}	$\mathrm{nmol\,L^{-1}}$	0.6	Total concentration of iron ligands
$N^{\mathrm{m}}_{\mathrm{fix}}$	$\mathrm{\mu mol\,N\,L^{-1}\,d^{-1}}$	0.013	Maximum rate of nitrogen fixation
$K^{\mathrm{Dz}}_{\mathrm{Fe}}$	$\mathrm{nmol\,Fe\,L^{-1}}$	0.1	Fe half-saturation constant of nitrogen fixation
E_{fix}	$\mathrm{W\,m^{-2}}$	50	Photosynthetic parameter of nitrogen fixation
$\mathrm{Fe_{ice}}$	$\mathrm{nmol\,Fe\,L^{-1}}$	15	iron concentration in sea ice
$F^{\mathrm{sed}}_{\mathrm{Fe,min}}$	$\mathrm{\mu mol\,Fe\,m^{-2}\,d^{-1}}$	2	Maximum sediment flux of Fe
$\mathrm{Sol_{Fe}}$	–	0.02	Solubility of iron in dust
$\mathrm{O^{ut}_2}$	$\mathrm{mol\,O_2\,(mol\,C)^{-1}}$	133/122	O / C for ammonium-based processes
$\mathrm{O^{nit}_2}$	$\mathrm{mol\,O_2\,(mol\,C)^{-1}}$	32/122	O / C ratio of nitrification
$r^{\star}_{\mathrm{NH_4}}$	$\mathrm{mol\,N\,(mol\,C)^{-1}}$	3/5	C/N ratio of ammonification
$r^{\star}_{\mathrm{NO_3}}$	$\mathrm{mol\,N\,(mol\,C)^{-1}}$	105/16	C/N ratio of denitrification
$\theta^{\mathrm{N,C}}$	$\mathrm{mol\,N\,(mol\,C)^{-1}}$	16/122	N / C Redfield ratio
$r_{\mathrm{CaCO_3}}$	–	0.3	Rain-ratio parameter

Aumont et al., 2015

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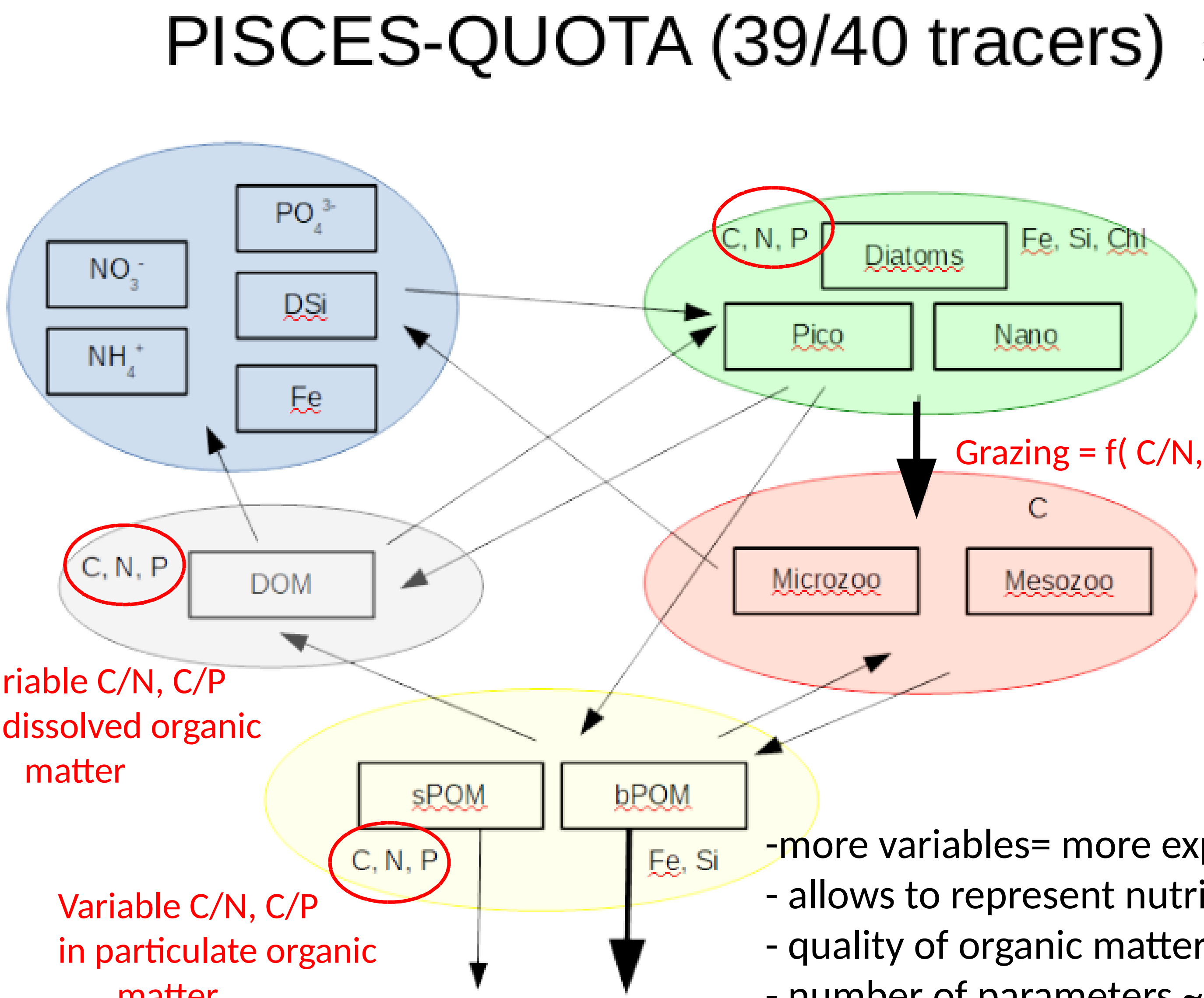
More sophisticated PISCESv2 options : PISCES-quota



24/25 in PISCES std

Variable C/N, C/P
in phytoplancton cells
~ "health of phyto"

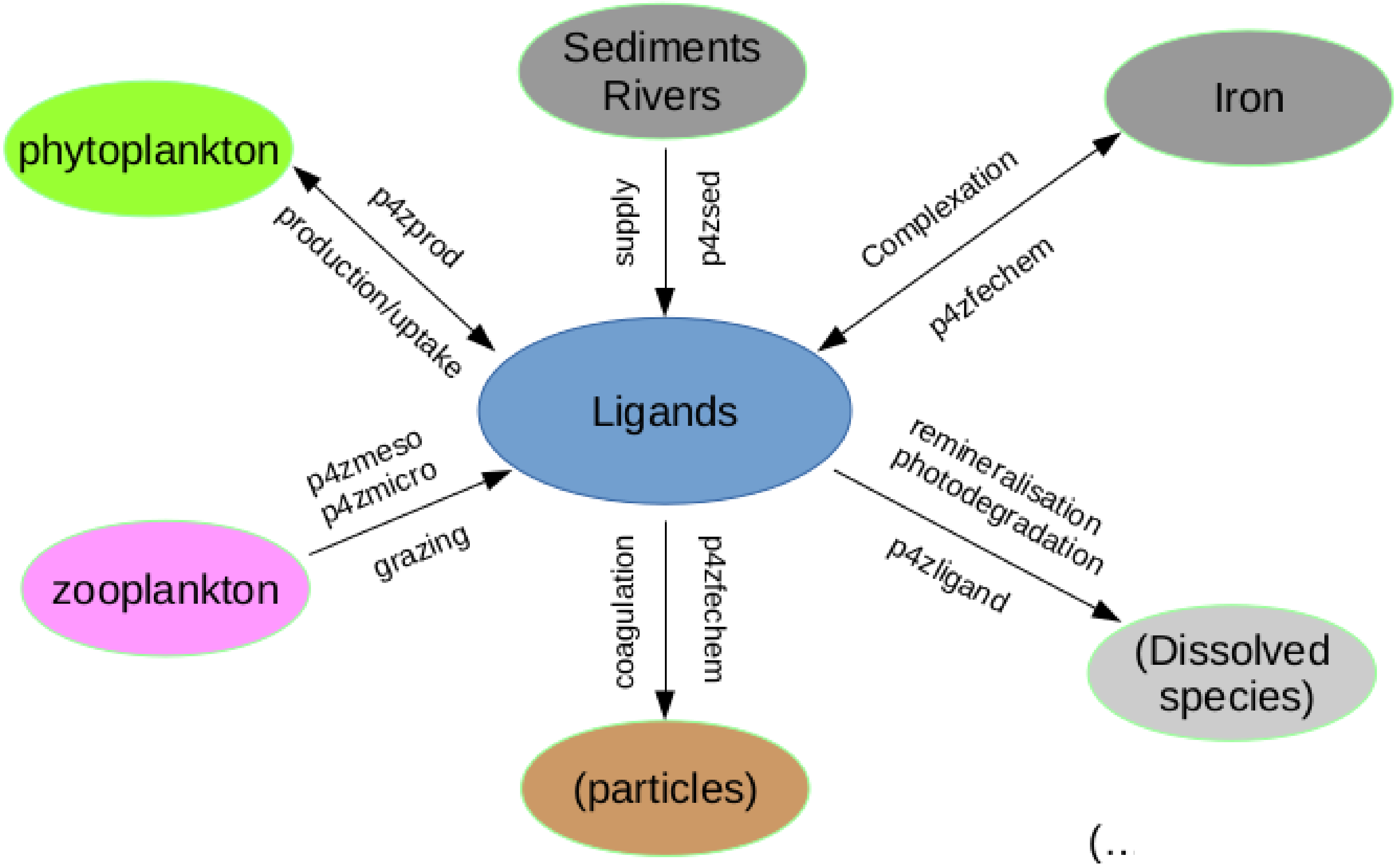
Grazing = f(C/N, C/P in phyto)

Variable C/N, C/P
in dissolved organic
matter

Variable C/N, C/P
in particulate organic
matter

-more variables= more expensive than PISCES std
- allows to represent nutrient stocks in cells
- quality of organic matter for zoo and fish
- number of parameters ~ PISCES std

More sophisticated PISCESv2 options : Ligands for Fe

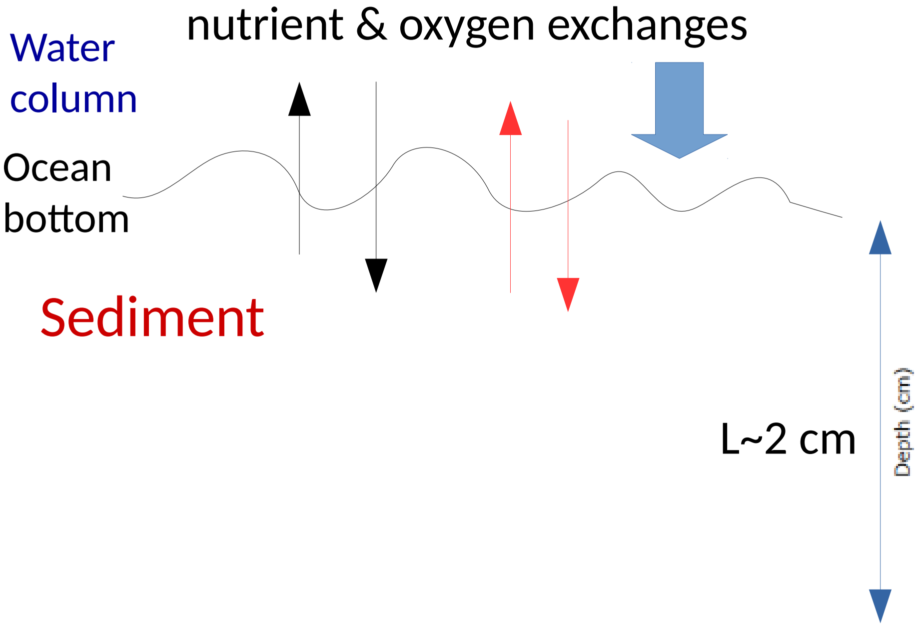


- Dissolved Fe assimilated by phyto mostly in its complexed for with ligands (L)

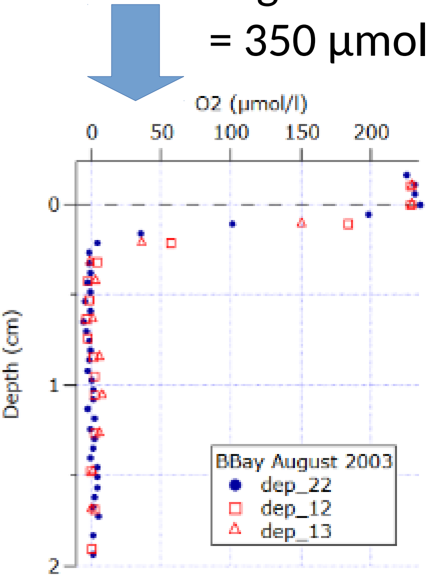
- ligand concentration is constant in previous version v0,v1

=> prognostic equation for1 ligand concentration in v2 if chosen (other version with more L)

More sophisticated PISCESv2 options : sediment module



Organic matter sedimentation rate = 350 µmolC/cm²/year



- In the default configuration, exchanges with the sediments are modeled based on a simple metamodel proposed by Middelburg et al. (1996):

$$F_{sed} = F(NO_3, O_2, Z, \ldots)$$

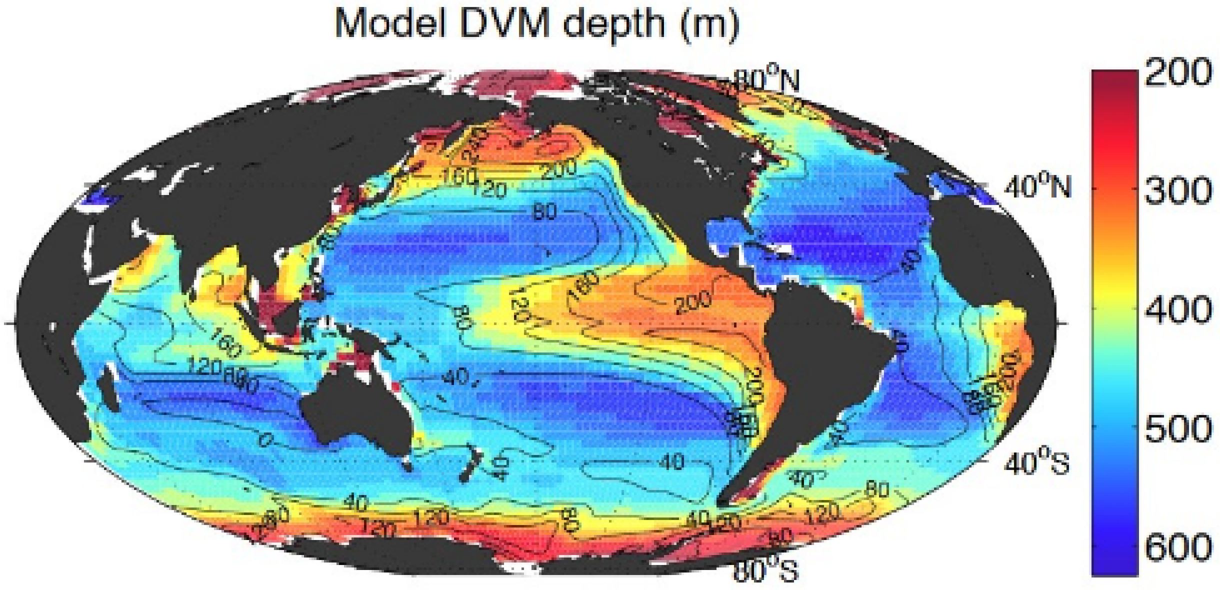
New process model : new chemical species : Sulfate, FeS,... dissolved and precipitate

=> long integration time (~100s of years) to reach equilibirum
=> very new in CROCO (not yet used), soon in West Africa (Senegal) (P.-A. Auger, IRD/LOPS)

More sophisticated PISCESv2 options : diurnal vertical migration of zooplankton (Gorgues et al., 2019)

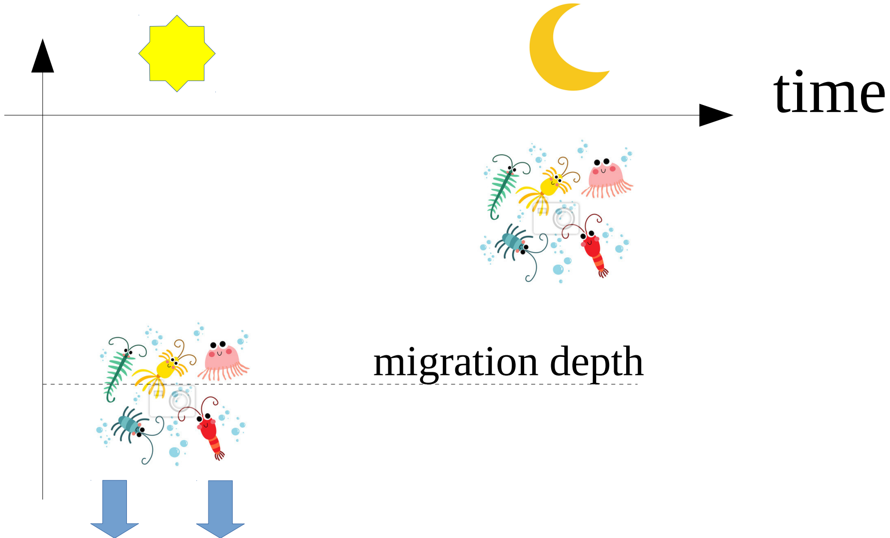
- Not a prognostic parameterization !
- DVM parameterization is activated by `ln_dvm_meso = .true.`
- Migration depth is parameterized according to Bianchi et al. (2013)

$$Z_{mig} = F(O2, Chl, T)$$

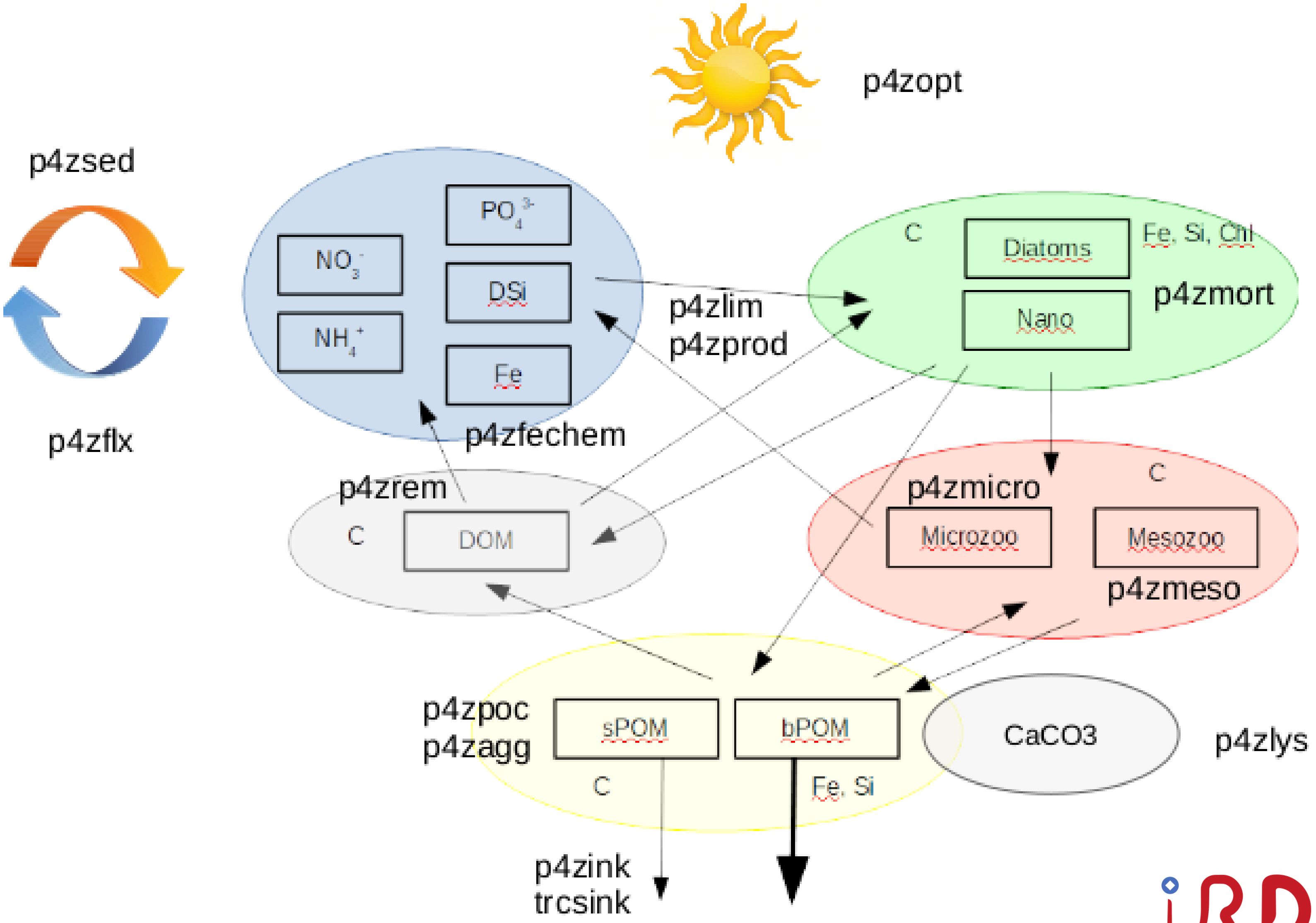

Model DVM depth (m)

More sophisticated PISCESv2 options : diurnal vertical migration of zooplankton

- A constant fraction of mesozoo is prescribed to migrate (`xfracmig`). Microzoo is not migrating
- Organisms are assumed to be at the surface at night and at the migration depth during daytime
- Organisms are supposed to respire, excrete DOM and inorganic nutrients and egest fecal pellets in both habitats (function of daylength and temperature)



Model structure and routine names



p4zopt

p4zsed

p4zflx

NO_3^-

NH_4^+

PO_4^{3-}

DSi

Fe

p4zfechem

p4zlim
p4zprod

C

Diatoms

Fe, Si, Chl

Nano

p4zmort

p4zrem

C

DOM

p4zmicro

C

Microzoo

Mesozoo

p4zmeso

p4zpoc
p4zagg

sPOM

bPOM

C

Fe, Si

CaCO3

p4zlys

p4zink
trcsink

End of part 2