

PISCES biogeochemical model

Olivier AUMONT

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WARNING: This document is not intended to be an exhaustive description of PISCES and is still incomplete

1 Introduction

PISCES is a biogeochemical model which simulates the marine biological productivity and that describes the biogeochemical cycles of carbon and of the main nutrients (P, N, Si, Fe). Historically, this model can be seen as one of the many Monod models by opposition to the quota models, the other big family of ocean biogeochemical model. Thus, it assumes a constant Redfield ratio and phytoplankton growth depends on the external concentration in nutrients. This choice was dictated by the computing cost as describing the internal pools of the different elements requires many more prognostic variables. And PISCES was supposed to be suited for a wide range of spatial and temporal scales, including quasi-steady state simulations on the global scale.

However, when modelling silicate, iron and/or chlorophyll, assuming constant ratios is not justified anymore as these ratios can vary a lot. For instance, the Fe/C ratio can vary by at least an order of magnitude to be compared to the N/C ratio which varies by “only” two times. Thus, in PISCES, a compromise between the two classical families of ocean model was chosen. The elemental ratios of Fe, Si and Chl are prognostically predicted based on the external concentrations of the limiting nutrients like in the quota approach. On the other hand, the phytoplankton growth rates also depends on these external concentrations as in the Monod approach.

Historically, the development of this model started in 1997 with the release of the P3ZD model which was a simple NPZD model with semi-labile DOM. Phytoplankton growth rate was only limited by one nutrient, basically phosphate. However, many deficiencies in this model, especially in the HNLC regions, justified the development, in 1999, of a more complex model including three limiting nutrients (Fe, Si, P), two phytoplankton and two zooplankton size-classes. This model was called HAMOCC5 (*Aumont et al., 2003*) as it was based on HAMOCC3.1 (*Six and Maier-Reimer, 1996*) and used in the LSG model. The embedding of this code in the ocean model OPA required some major changes and improvements, partly because of the much finer vertical resolution. Beside the numerical schemes, these changes were mostly an improved treatment of the optics and the splitting of the particulate organic matter into two different size-classes. All these changes and the major recodings it required lead us to adopt a new name for the model: PISCES. This name can be translated as fishes from latin. It can also be considered as an acronym, but its meaning is much less poetic and will not be

explained here as it is not really essential.

Since 2001, this model has undergone active developments. In 2004, a stable release of the model is made available to the community on the OPA website (www.lodyc.jussieu.fr/opa). It can be freely used and changed by anybody after subscription to the OPA system. Currently, this model is being coupled to OPA only. However, a beta version of the model coupled to ROMS can be obtained by sending an email to this address (aumont@lodyc.jussieu.fr). The rest of this document describes the main aspects of the model. It is still rather incomplete but it is better than nothing ... If you have any comments or suggestions, send me an email (aumont@lodyc.jussieu.fr). I do not promise to take them into account (or even to read the mail) but I'll do my best.

2 Model description

PISCES has currently twenty-four compartments (see figure 1). There are five modeled limiting nutrients for phytoplankton growth: Nitrate and Ammonium, Phosphate, Silicate and Iron. It should be mentioned that phosphate and nitrate+ammonium are not really independent nutrients in PISCES. They are linked by constant Redfield ratios but the nitrogen pool undergoes nitrogen fixation and denitrification. This means that if the latter two processes are set to zero and if the sizes of the nitrogen and phosphorus pools are identical, the distributions of both nutrients should be exactly the same.

Four living compartments are represented: two phytoplankton size-classes/groups corresponding to nanophytoplankton and diatoms, and two zooplankton size classes which are microzooplankton and mesozooplankton. For phytoplankton, prognostic variables are total biomass, the iron, chlorophyll and silicon contents. This means that the Fe/C, Chl/C and Si/C ratios of both phytoplankton groups are fully predicted by the model. For zooplankton, only the total biomass is modeled. For all species, the C/N/P/O₂ ratios are supposed constant and are not allowed to vary. In PISCES, the Redfield ratio -O/C/N/P is set to 172/122/16/1. In addition, the Fe/C ratio of both zooplankton groups is kept constant. No silicified zooplankton is assumed. The bacterial pool is not yet explicitly modeled.

There are three non-living compartments: semi-labile dissolved organic matter, small and big sinking particles. As for the living compartments, the C, N and P pools are not distinctly modeled. Thus, constant Redfield ratios are imposed for C/N/P. However, the iron, silicon and calcite pools of the particles are explicitly modeled. As a consequence, their ratios are allowed to vary. Calcite and biogenic silica are supposed to sink at the speed of the big particles. All the non-living compartments experience aggregation due to turbulence and differential settling.

In addition to the ecosystem model, PISCES also simulates dissolved inorganic carbon, total alkalinity and dissolved oxygen. The latter tracer is also used to define the regions where oxic or anoxic remineralization takes place. The carbon chemistry follows the OCMIP protocols (see the OCMIP website for more information at www.ipsl.jussieu.fr/OCMIP) except that it has been simplified to reduce the computing cost. For instance, alkalinity includes only the carbonate, the borate and the water (H^+ , OH^-).

3 Model equations

The reader should be aware that in the following equations, the conversion ratios between the different elements (Redfield ratios) have been often omitted except when particular parameterizations are defined. All phytoplankton and zooplankton biomasses are in carbon units

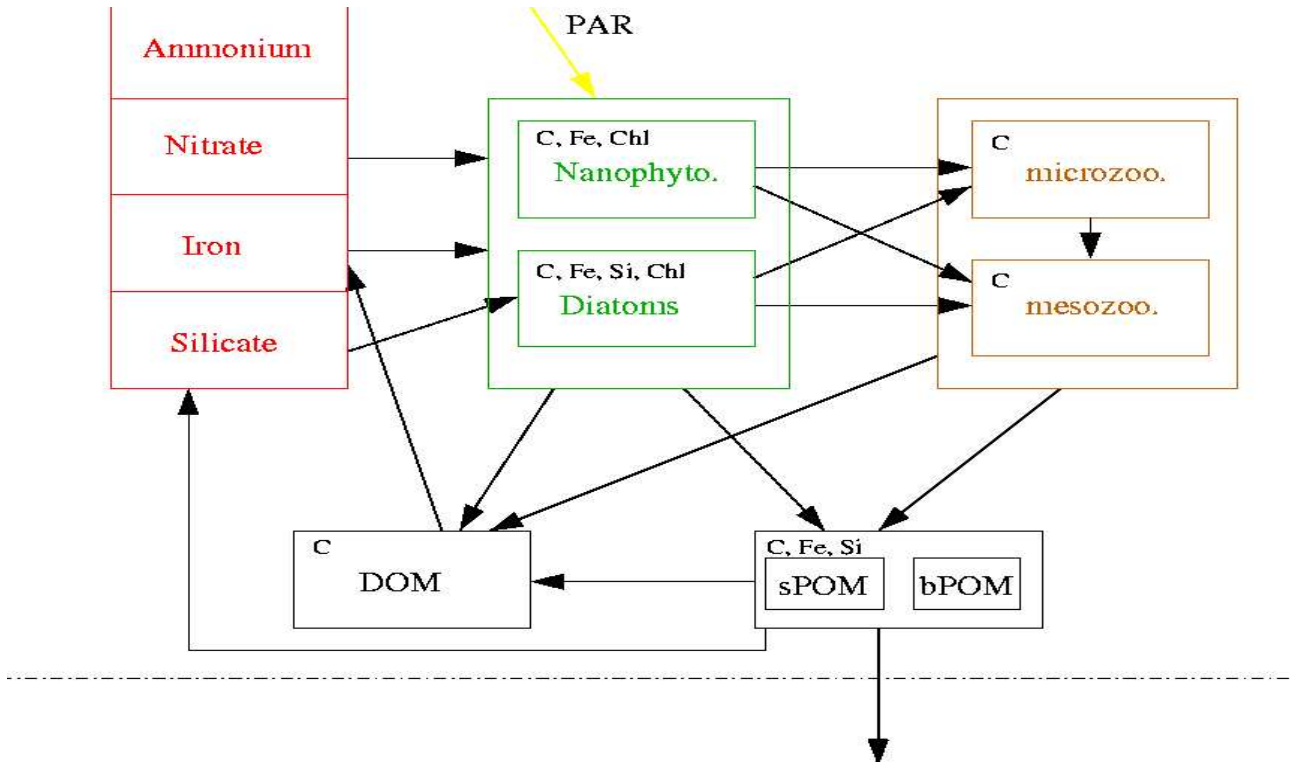


Figure 1: Architecture of PISCES. This figure only shows the ecosystem model omitting thus oxygen and the carbonate system. The element which are explicitly modeled are indicated in the left corner of each box.

except for the silicon, chlorophyll and iron content of phytoplankton. Finally, all parameters and their standard values in PISCES are listed in Table 1 at the end of this section.

3.1 Equation for nanophytoplankton

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

The production terms for nano/picophytoplankton is defined by :

$$\mu^{nano} = \mu_P \left(1 - e^{-\frac{\alpha^P (\frac{Chl}{C})^P PAR}{\mu_P L_{lim}^{nano}}} \right) L_{lim}^{nano} \quad (2)$$

where $\mu_P = ab^{cT}$ and where the limitations terms are defined as follows:

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

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

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

$$\begin{aligned}
L_{nh4}^{nano} &= \frac{K_{no3}^{nano} NH_4}{K_{no3}^{nano} K_{nh4}^{nano} + K_{nh4}^{nano} NO_3 + K_{no3}^{nano} NH_4} \\
L_{lim}^{nano} &= \min(L_{po4}^{nano}, L_{Fe}^{nano}, L_{no3}^{nano} + L_{nh4}^{nano})
\end{aligned} \tag{3}$$

The choice of the half-saturation constants is rather difficult as observations show that they can vary by several orders of magnitude. However, in general, these constants increase with the size of the phytoplankton cell as a consequence of a smaller surface-to-volume ratio (diffusive hypothesis). Thus, diatoms will tend to have larger half-saturation constants than nanophytoplankton. But, in PISCES, phytoplankton is modeled by only two compartments, each of them encompassing thus a large size spectrum. Experiments performed with model have shown that results are especially sensitive to the choice of the iron half-saturation constants, and less to the other constants (with the exception perhaps of silicate). This is not surprising as over most of the ocean, the seawater iron concentrations are close to these constants.

Following these remarks, it appeared not appropriate to keep the iron half-saturations constant. It was then decided to make them vary with the phytoplankton biomass of each compartment. It is assumed that they increase with biomass based on the observations showing that the increase in biomass is generally due to the addition of larger size classes of phytoplankton:

$$\begin{aligned}
P_1 &= \min(P, P_{max}) \\
P_2 &= \max(P, P_{max}) \\
K_{Fe}^{nano} &= \frac{K_{Fe}^{nano,min} P_1 + K_{Fe}^{nano,max} P_2}{P_1 + P_2}
\end{aligned} \tag{4}$$

The distinction between new production based on nitrate and regenerated production based on ammonium is computed as follows:

$$\begin{aligned}
\mu_{no3}^{nano} &= \mu^{nano} \frac{L_{no3}^{nano}}{L_{no3}^{nano} + L_{nh4}^{nano}} \\
\mu_{nh4}^{nano} &= \mu^{nano} \frac{L_{nh4}^{nano}}{L_{no3}^{nano} + L_{nh4}^{nano}}
\end{aligned} \tag{5}$$

The vertical attenuation of PAR is computed using a simplified version of the full spectral model of *Morel and Berthon, 1989*. Only three wave lengths are considered with equal contribution to the total visible at the surface (Red, Green, Blue). The PAR is supposed to be a constant fraction of the total shortwave radiative flux (0.43).

The nanophytoplankton aggregation term w_p^{nano} depends on the shear rate as the main driving force for aggregation is the local turbulence. Rather arbitrarily, this shear rate is set to 1 s^{-1} in the mixed layer and to 0.01 s^{-1} below.

3.2 Equation for diatoms

$$\frac{\partial D}{\partial t} = (1 - \delta^{diat}) \mu^{diat} D - m^{diat} \frac{D}{K_{diat} + D} D - w_p^{diat} D^2 - g^{micro}(D)Z - g^{meso}(D)M \tag{6}$$

The production terms for diatoms are defined as for nanophytoplankton except that the limitations terms also include Si:

$$\begin{aligned}
L_{Si}^{diat} &= \frac{Si}{K_{Si}^{diat} + Si} \\
L_{lim}^{diat} &= \min(L_{po4}^{diat}, L_{Fe}^{diat}, L_{no3}^{diat} + L_{nh4}^{diat}, L_{Si}^{diat})
\end{aligned} \tag{7}$$

The half-saturation constant of iron varies following the same parameterization as for nanophytoplankton (see Eq. 4).

The diatoms aggregation term w_p^{diat} is increased in case of nutrient limitation because it has been shown that the diatoms cells become more sticky in case of nutrient stress:

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

Furthermore as for nanophytoplankton, the aggregation is multiplied by the shear rate.

3.3 Equation for chlorophyll in phytoplankton

$$\begin{aligned} \frac{\partial I^{Chl}}{\partial t} = & \rho_{Chl}^I (1 - \delta^I) \mu^I I - m^I \frac{I}{K_I + I} I^{Chl} \\ & - w_p^I I I^{Chl} - g^{micro}(I) \theta_{Chl}^I Z - g^{meso}(I) \theta_{Chl}^I M \end{aligned} \quad (8)$$

where I is the phytoplankton class and θ_{Chl}^I is the chlorophyll-to-carbon ratio of the considered phytoplankton class. ρ_{Chl}^I represents the ratio of energy assimilated to energy absorbed as defined by *Geider et al. (1996)*:

$$\rho_{Chl}^I = \theta_{Chl,max}^I \frac{144 \mu^I I}{\alpha^I \times PAR \times I^{Chl}} \quad (9)$$

In this equation, 144 is the square of the molar mass of C and is used to convert from mol to mg as the standard unit for Chl is generally in mg Chl/m³.

For the iron content of phytoplankton, a similar approach is used as iron is related to the photosynthetic apparatus. Thus, the equations are exactly equivalent to equation 8. Furthermore, this parameterization predicts an Fe:C ratio whose variations are consistent with the observations: this ratio decreases with light and with the nutrient stress including iron.

3.4 Equation for the silicon content of diatoms

$$\begin{aligned} \frac{\partial D^{Si}}{\partial t} = & (1 - \delta_2) \mu^{diat} \left(\frac{Si}{C} \right)^{opt} D - m^{diat} \frac{D}{K_{diat} + D} D^{Si} \\ & - w_p^{diat} D D^{Si} - (g^{micro}(D) Z + g^{meso}(D) M) \left(\frac{D^{Si}}{D} \right) \end{aligned} \quad (10)$$

Where the $\left(\frac{Si}{C} \right)^{opt}$ ratio is diagnostically defined from *Bucchiarelli et al. (2002)* as:

$$\begin{aligned} F_{Lim}^{Si} &= \min \left(\left(1 - e^{-\frac{\alpha^D (Chl) D PAR}{\mu_D L_{lim}^{diat}}} \right), L_{po4}^{diat}, L_{Fe}^{diat}, L_{no3}^{nano} + L_{nh4}^{nano} \right) \\ \left(\frac{Si}{C} \right)^{opt} &= 0.151 L_{Si}^{diat} (5.4 e^{F_{Lim}^{Si}} + 1.13) \end{aligned} \quad (11)$$

Observations have shown that diatoms in the southern ocean are more heavily silicified than anywhere else. This increase can not be explained only by the light or the iron stress as the

Si:C ratio can reach one, a value outside the range of the diagnostic equation proposed by *bucchiarelli et al. (2002)*. Thus, to mimic this extremely high values in the Southern Ocean which are associated with the highest silicate surface concentrations, we propose the following parameterization:

$$\begin{aligned}\left(\frac{Si}{C}\right)^{opt} &= \left(\frac{Si}{C}\right)^{opt} \left(1 + 3 \left(\frac{\max(0, Si - Si_{min})}{K_{Si}^2 + Si}\right)\right) \\ \left(\frac{Si}{C}\right)^{opt} &= \min\left(1, \left(\frac{Si}{C}\right)^{opt}\right)\end{aligned}\quad (12)$$

In this equation, Si_{min} is a parameter that should be set to a relatively high value, typically 15 $\mu\text{mol/L}$, to restrict the increase to the Southern Ocean.

3.5 Equation for microzooplankton

$$\frac{\partial Z}{\partial t} = e^{micro}(g^{micro}(P) + g^{micro}(D) + g^{micro}(POC_s))Z_1 - r^{micro} \frac{Z}{K_{micro} + Z} Z \quad (13)$$

The grazing on each species N is defined as follows:

$$g^{micro}(N) = g^{micro} \frac{p_N^{micro} N}{K_G^{micro} + \sum_I (p_I^{micro} I)} \quad (14)$$

where p_N^{micro} is the preference microzooplankton has for N and I are all the reservoirs microzooplankton can graze on.

The grazing rate g^{micro} depends on temperature following exactly the same relationship than phytoplankton. It means that we assume a Q_{10} for zooplankton (both micro and mesozooplankton) of about 1.9. We have also adopted this dependency for respiration/mortality.

A special treatment is applied on both types of phytoplankton:

- For nanophytoplankton, a minimum threshold is assumed based on observations showing that below a certain small chlorophyll concentration, grazing ceases. This threshold is generally of the order of 0.03 mg Chl l^{-1} . Thus, for nanophytoplankton, the concentration in the grazing equation (see Eq. 14) is $\max(P - P_{min}, 0)$ instead of P.
- For diatoms, observations show that the biomass increases by the addition of larger cells which escape grazing by microzooplankton. Thus, we assume in PISCES that above a certain concentration, the diatoms excess is unavailable to microzooplankton. The diatoms concentration in Eq. 14 is then $\min(D_{max}, D)$.

3.6 Equation for mesozooplankton

$$\begin{aligned}\frac{\partial M}{\partial t} &= e^{meso}(g^{meso}(P) + g^{meso}(D) + g^{meso}(Z) + g^{meso}(POC_s) + g^{meso}(POC_b))M \\ &\quad - r^{meso} \frac{M}{K_{meso} + M} M - m^{meso} M^2\end{aligned}\quad (15)$$

The parametrization for the grazing on multiple resources slightly differs from the one adopted for microzooplankton (compare with equation 14):

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

$$p_N^{meso} = \frac{\gamma_N N}{\sum_I (\gamma_I I)} \quad (16)$$

This parameterization implies that mesozooplankton preferentially grazes on the more abundant prey. This formulation stabilizes the model. This is the reason it has been adopted for the last trophic level of PISCES.

There is one exception to this parameterization of grazing. Grazing on big particles (POC_b) differs from grazing on the other four types of prey. The reason is that it represents flux feeding rather than “conventional” grazing. Flux feeding does not depend on the concentration of the prey but on its flux:

$$g^{meso}(POC_b) = g_{FF}^{meso} w^{POC_b} \frac{POC_b}{K_{POC_b}^{FF} + POC_b} \quad (17)$$

In this equation, there is a michaelis-menten function to avoid an infinite increase of grazing with particles. Thus, for small concentrations of POC_b , flux feeding increases linearly with the flux and then smoothly saturates when concentrations become high. The choice for the parameters in this function is rather arbitrary and difficult.

In the equation for mesozooplankton, the term with a square dependency to mesozooplankton does not depict aggregation but grazing by the higher, non-resolved trophic levels. This term depends on temperature with a Q_{10} of 1.9, exactly like grazing and respiration/mortality.

3.7 Equation for DOC

$$\begin{aligned} \frac{\partial DOC}{\partial t} = & \delta^{nano} \mu^{nano} P + \delta^{diat} \mu^{diat} D + (1 - \epsilon^{micro}) r^{micro} \frac{Z}{K_{micro} + Z} Z \\ & + (1 - \epsilon^{meso}) r^{meso} \frac{M}{K_{meso} + M} M + (1 - \sigma^{micro} - e^{micro}) \\ & (1 - \gamma^{micro}) (g^{micro}(P) + g^{micro}(D) + g^{micro}(POC_s)) Z \\ & + (1 - \sigma^{meso} - e^{meso}) (1 - \gamma^{meso}) (g^{meso}(P) + g^{meso}(D) \\ & + g^{meso}(Z) + g^{meso}(POC_s) + g^{meso}(POC_b)) M + \lambda_{POC}^* POC_s \\ & - \lambda_{DOC}^* DOC - \Phi_{agg}^{DOC \rightarrow POC_s} - \Phi_{agg}^{DOC \rightarrow POC_b} \end{aligned} \quad (18)$$

where the remineralization rate of DOC is parameterized as follows:

$$\lambda_{DOC}^* = \lambda_{DOC} L_{lim}^{bac} 0.7 (Z + M) \min\left(1, \frac{120m}{z}\right)$$

$$L_{Lim}^{bac} = L_{lim}^{nano} \frac{DOC}{K_{DOC}^{bac} + DOC} \quad (19)$$

In the previous equation, $0.7(Z+M)$ is a proxy for the bacterial concentration. This relationship has been constructed from a version of PISCES that includes an explicite description of the bacterial biomass. Above 120m, this proxy is kept constant and set to its value at 120m. The terms Φ denote aggregation processes and are described hereafter (see Equation 21).

3.8 Equation for the two size classes of POC

$$\begin{aligned}
\frac{\partial POC_s}{\partial t} &= \sigma^{micro} \left(\sum_N g^{micro}(N) \right) Z - g^{micro}(POC_s) Z \\
&+ (1 - 0.5 R_{CaCO_3}) \left(m^{nano} \frac{P}{K_{nano} + P} P + w_P^{nano} P^2 \right) \\
&+ 0.5 m^{diat} \frac{D}{K_{diat} + D} D + \epsilon^{micro} r^{micro} \frac{Z}{Z_{micro} + Z} Z - \lambda_{POC}^* POC_s \\
&- w^{POC_s} \frac{\partial POC_s}{\partial z} + \Phi_{agg}^{DOC \rightarrow POC_s} - \Phi_{agg}^{POC_s \rightarrow POC_b} \\
\frac{\partial POC_b}{\partial t} &= \sigma^{meso} \left(\sum_N g^{meso} N \right) M + \epsilon^{meso} r^{meso} \frac{M}{K_{meso} + M} M \\
&+ 0.5 R_{CaCO_3} \left(\frac{P}{K_{nano} + P} P + w_P^{nano} P^2 \right) + 0.5 m^{diat} \frac{D}{K_{diat} + D} D \\
&+ w_P^{diat} D^2 - \lambda_{POC}^* POC_b - w^{POC_b} \frac{\partial POC_b}{\partial z} + \Phi_{agg}^{DOC \rightarrow POC_b} \\
&+ \Phi_{agg}^{POC_s \rightarrow POC_b}
\end{aligned} \tag{20}$$

The fate of mortality and aggregation of nanophytoplankton depends on the proportion of the calcifying organisms (R_{CaCO_3}). We assume that 50% of the organic matter of the calcifiers is associated with the shell. Since calcite is significantly denser than organic matter, 50% of the dying calcifiers biomass is routed to the fast sinking particles. The same is assumed for the mortality of diatoms.

Like for DOC, the Φ terms represent aggregation processes. In PISCES, differential sedimentation and turbulence coagulation mechanisms are considered. Differential sedimentation is omitted for DOC as this term is almost negligible compared to turbulence.

$$\begin{aligned}
\Phi_{agg}^{DOC \rightarrow POC_s} &= \phi_1^{DOC} \text{sh } DOC^2 + \phi_2^{DOC} \text{sh } DOC POC_s \\
\Phi_{agg}^{DOC \rightarrow POC_b} &= \phi_3^{DOC} \text{sh } DOC POC_b \\
\Phi_{agg}^{POC_s \rightarrow POC_b} &= \phi_1^{POC_s} \text{sh } POC_s^2 + \phi_2^{POC_s} \text{sh } POC_b POC_s \\
&+ \phi_3^{POC_s} POC_s^2 + \phi_4^{POC_s} POC_b POC_s
\end{aligned} \tag{21}$$

In these equations, sh is the shear rate. It is set to 1 s^{-1} in the mixed layer and to 0.01 s^{-1} elsewhere. The coefficients ϕ were obtained by integrating the standard curvilinear kernels for collisions over the size range of each organic matter pool.

The degradation rate λ_{POC}^* depends on temperature with a Q_{10} of about 1.9.

Furthermore, many observations have shown that the mean sinking speed of the particulate organic matter increases with depth. This increase is parameterized in PISCES as follows:

$$w^{POC} = w_{min}^{POC} + (w_{max}^{POC} - w_{min}^{POC}) \max\left(0, \frac{z - z_{mel}}{2000m}\right) \tag{22}$$

This equation is used only for big POC. The parameters in this equation have been adjusted using a model of aggregation/disaggregation with multiple size classes. We have not included yet a ballasting effect due to the higher density of biogenic silica or calcite.

3.9 Equation for biogenic silica

$$\begin{aligned}
\frac{\partial BSi}{\partial t} = & m^{diat} \frac{D}{K_{diat} + D} D^{Si} + w_P^{diat} D D^{Si} \\
& + (g^{micro}(D)Z + g^{meso}(D)M) \left(\frac{D^{Si}}{D} \right) - \lambda_{BSi}^* BSi \\
& - w^{POC_b} \frac{\partial BSi}{\partial z}
\end{aligned} \tag{23}$$

The dissolution rate of BSi depends on in situ temperature and on saturation following the parameterization proposed by *Ridgwell et al., 2003*:

$$\begin{aligned}
Si_{eq} &= 10^{6.44 - \frac{968}{T+273.15}} \\
Si_{sat} &= \frac{Si_{eq} - Si}{Si_{eq}} \\
\lambda_{BSi}^* &= \lambda_{BSi} \left[0.225 \left(1 + \frac{T}{15} \right) Si_{sat} + 0.775 \left(\left(1 + \frac{T}{400} \right)^4 Si_{sat} \right)^9 \right]
\end{aligned} \tag{24}$$

3.10 Equations for particulate organic iron

To make the document clearer, the equations are not detailed here. The reader could refer to the equations for particulate organic carbon (see Equations 20) as the sources and sinks are pretty much the same as for PFe.

3.11 Equation for calcite

$$\begin{aligned}
\frac{\partial CaCO_3}{\partial t} = & R_{CaCO_3} (0.5(\sigma^{micro} g^{micro}(P) + \sigma^{meso} g^{meso}(P)M) + w_P^{nano} P^2 \\
& + m^{nano} \frac{P}{K_{nano} + P} P) - \lambda_{CaCO_3}^* CaCO_3 - w^{POC_b} \frac{\partial CaCO_3}{\partial z}
\end{aligned} \tag{25}$$

In this equation, the rain ratio R_{CaCO_3} is variable. The proportion of calcifying phytoplankton is generally very low in oligotrophic regions. When the nanophytoplankton blooms, the dominant species are often calcifiers. To mimic these very general considerations, we propose the following parameterizations which is similar to that of *Moore et al. (2003)*:

$$R_{CaCO_3} = R_{CaCO_3}^* L_{lim}^{nano} \max \left(0.0001, \frac{T}{2+T} \right) \max \left(1, \frac{P}{2} \right) \tag{26}$$

The rain ratio is not allowed to fall below 0.01 and to exceed 0.8.

Only half of the grazed shells is routed to sinking calcite. The rest is supposed to dissolve in the acidic guts of zooplankton. This dissolution is still highly debated. However, observations tend to show that a significant proportion of the sinking shells is lost in the upper ocean, whether during grazing or by other mechanisms.

The dissolution rate constant is defined as follows:

$$\begin{aligned}
\Delta CO_3 &= \max(0, CO_3_{sat}^{2-} - CO_3^{2-}) \\
\lambda_{CaCO_3}^* &= \lambda_{CaCO_3} \frac{\Delta CO_3}{K_{CaCO_3} + \Delta CO_3}
\end{aligned} \tag{27}$$

This means that no dissolution is allowed in case of oversaturation. On the other hand, dissolution increases with the undersaturation.

3.12 Equations for the different modeled nutrients

$$\begin{aligned} \frac{\partial PO_4}{\partial t} = & -\mu^{nano} P_1 - \mu^{diat} P_2 + \lambda_{DOC}^* DOC \\ & + (1 - \sigma^{micro} - e^{micro}) \gamma^{micro} (g^{micro}(P) + g^{micro}(D) + g^{micro}(POC_s)) Z_1 \\ & + (1 - \sigma^{meso} - e^{meso}) \gamma^{meso} (g^{meso}(P) + g^{meso}(D) + g^{meso}(Z) \\ & + g^{meso}(POC_s)) M \end{aligned} \quad (28)$$

$$\frac{\partial NO_3}{\partial t} = -\mu_{no3}^{nano} P_1 - \mu_{no3}^{diat} P_2 + Nitrif - Denit \quad (29)$$

$$\begin{aligned} \frac{\partial NH_4}{\partial t} = & -\mu_{nh4}^{nano} P_1 - \mu_{nh4}^{diat} P_2 + \lambda_{DOC}^* DOC \\ & - Nitrif + Nfix \\ & + (1 - \sigma^{micro} - e^{micro}) \gamma^{micro} (g^{micro}(P) + g^{micro}(D) + g^{micro}(POC_s)) Z_1 \\ & + (1 - \sigma^{meso} - e^{meso}) \gamma^{meso} (g^{meso}(P) + g^{meso}(D) + g^{meso}(Z) \\ & + g^{meso}(POC_s)) M \end{aligned} \quad (30)$$

$$\frac{\partial Si}{\partial t} = -(1 - \delta^{diat}) \mu^{diat} \left(\frac{Si}{C} \right) D + \lambda_{BSi}^* BSi \quad (31)$$

$$\begin{aligned} \frac{\partial Fe}{\partial t} = & -(1 - \delta^{nano}) \mu_{Fe}^{nano} P - (-1 - \delta^{diat}) \mu_{Fe}^{diat} D + \left(\frac{Fe}{C} \right)^{zoo} \\ & \left((1 - \epsilon^{micro}) r^{micro} \frac{Z}{K_{micro} + Z} Z + (1 - \epsilon^{meso}) r^{meso} \frac{M}{K_{meso} + M} M \right) \\ & + (1 - e^{micro} - \sigma^{micro}) \left[\left(\frac{P^{Fe}}{P} \right) g^{micro}(P) + \left(\frac{D^{Fe}}{P} \right) g^{micro}(D) \right. \\ & + \left. \left(\frac{PFe_s}{POC_s} \right) g^{micro}(POC_s) \right] Z \\ & + (1 - e^{meso} - \sigma^{meso}) \left[\left(\frac{P^{Fe}}{P} \right) g^{meso}(P) + \left(\frac{D^{Fe}}{P} \right) g^{meso}(D) \right. \\ & + \left. \left(\frac{PFe_s}{POC_s} \right) g^{meso}(POC_s) + \left(\frac{Fe}{C} \right)^{zoo} g^{meso}(Z) \right] M \\ & + \lambda_{POC}^* PFe_s - \lambda_{scav} \min(0, Fe - Fe_{sol}) \end{aligned} \quad (32)$$

In the latter equation, some additional terms are added in the code to ensure iron conservation during grazing. These terms are needed because of the differences in the $\frac{Fe}{C}$ ratios of the preys and of the grazers. However, to keep the equations as clear as possible, they are not included here.

Nitrification (Nitrif) corresponds to the conversion of ammonium to nitrate due to the bacterial activity. It is assumed to be photoinhibited and reduced in suboxic waters:

$$Nitrif = \lambda_{NH_4} \frac{1}{1 + PAR} (1 - \Delta(O_2)) NH_4 \quad (33)$$

When the waters become suboxic, nitrate instead of oxygen is consumed during the remineralization of organic matter:

$$Denit = R_{NO_3} \lambda_{DOC}^* (1 - \Delta(O_2)) DOC \quad (34)$$

where

$$\Delta(O_2) = \min\left(1, 0.4 \frac{6 - O_2}{O_2^{min} + O_2}\right)$$

Finally, nitrogen fixation is parameterized in PISCES in a very crude way as follows:

$$\begin{aligned} Nfix_{pot} &= \mu^P \max(0, \mu_P - \mu_P(20^\circ C))(1 - L_{no3}^{nano} - L_{nh4}^{nano})L_{fe}^{diat} \\ Nfix &= \frac{\int_{A,t} Denit}{\int_{A,t} Nfix_{pot}} Nfix_{pot} \end{aligned} \quad (35)$$

where $\int_{A,t}$ means spatial and temporal integration over a year and the ocean area.

This very crude parameterization is based on the following assumptions:

- Nitrogen fixation is restricted to warm waters above 20°C
- Nitrogen fixation is restricted to area with insufficient nitrogen
- Nitrogen fixation requires iron
- To ensure N conservation in the ocean, annual total nitrogen fixation should balance denitrification.

Thus, from the last point of this list of hypotheses, this means that the maximum rate of nitrogen fixation is diagnosed from denitrification.

Finally, the scavenging rate of iron is made dependant upon the particulate load of the seawater as follows:

$$\lambda_{Fe}^* = \lambda_{Fe}^{min} + \lambda_{Fe}(POC_s + POC_b + CaCO_3 + BSi) \quad (36)$$

Implicitly, in this equation, it is assumed that the affinity of iron for the different types of particles is the same.

Table 1: Model coefficients with their standard values in PISCES

Parameter	Units	Value	Description
Phytoplankton			
a	day^{-1}	0.66	Growth rate at 0°C
b	–	1.066	Temperature sensitivity of growth
c	$degC$	1	Temperature dependence of growth
α	$(W m^{-2})^{-1} d^{-1}$	4	initial slope of P-I curve
δ	–	0.05,0.05	exsudation of DOC
K_{po4}	$\mu mol P l^{-1}$	0.0008,0.004	Half-saturation constant for phosphate
K_{nh4}	$\mu mol N l^{-1}$	0.013,0.065	Half-saturation constant for ammonium
K_{no3}	$\mu mol N l^{-1}$	1.3,0.26	Half-saturation constant for nitrate
K_{si}^{diat}	$\mu mol Si l^{-1}$	2	Half saturation constant for silicate
K_{Fe}^{min}	$nmol Fe l^{-1}$	0.02,0.1	Minimum half-saturation constant for iron
K_{Fe}^{max}	$nmol Fe l^{-1}$	0.06,0.3	Maximum half-saturation constant for iron
P_{max}	$\mu mol C l^{-1}$	1	Maximum concentration of small nanophytoplankton
D_{max}	$\mu mol C l^{-1}$	0.5	Maximum concentration of small diatoms

Table 1 – continued on next page

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Parameter	Units	Value	Description
m_P	d^{-1}	0.03	phytoplankton mortality rate
w_P	$d^{-1} mol C^{-1}$	0.01	Quadratic mortality of phytoplankton
w_P^{max}	$d^{-1} mol C^{-1}$	0.02	Maximum quadratic mortality of diatoms
K_P	$\mu mol C l^{-1}$	0.1	Half-saturation constant for mortality
$\theta_{chl,max}$	$mg Chl mg C^{-1}$	0.033,0.05	Maximum Chl/C ratios of phytoplankton
$\theta_{fe,max}$	$\mu mol Fe mol C^{-1}$	10,15	Maximum Fe/C ratios of phytoplankton
K_{Si}^2	$\mu mol Si l^{-1}$	5	Half saturation constant for Si/C increase
Si_{min}	$\mu mol Si l^{-1}$	15	Si concentration for Si/C increase
Zooplankton			
ϵ	–	0.35,0.35	Zooplankton growth efficiency
σ	–	0.3,0.3	Fecal pellets production
g	d^{-1}	4,1	Maximum grazing rate
g_{FF}^{meso}	m^{-1}	$7.1 \cdot 10^{-4}$	Maximum flux feeding rate
$K_{POC_b}^{FF}$	$\mu mol C l^{-1}$	0.01	Half saturation constant for flux feeding
K_G	$\mu mol C l^{-1}$	20,18	Half-saturation constant for grazing
p_P^{micro}, γ_P	–	0.6,0.2	Preferences for nanophytoplankton
p_D^{micro}, γ_D	–	0.4,1	Preferences for diatoms
$p_{POC}^{micro}, \gamma_{POC}$	–	0.,0.2	Preferences for POC _s
γ_Z	–	1.	Preference for microzooplankton
P_{min}	$\mu mol C l^{-1}$	0.1	Minimum available concentration of nanophytoplankton
m^{meso}	$(\mu mol C l^{-1})^{-1} d^{-1}$	0.02	Mesozooplankton mortality
r	d^{-1}	0.03,0.004	Excretion rate
K	$\mu mol C l^{-1}$	0.1	Half-saturation constant for excretion
ϵ	–	0.5,0.5	
$\left(\frac{Fe}{C}\right)^{zoo}$	$\mu mol Fe mol C^{-1}$	3	Fe/C ratio of zooplankton
Organic matter			
λ_{DOC}	d^{-1}	0.06	Remineralization rate of DOC
K_{DOC}^{bac}	$\mu mol C l^{-1}$	417	Half-saturation constant for DOC remin.
λ_{POC}	d^{-1}	0.015	Degradation rate of POC
w_{min}	$m d^{-1}$	3,50	Minimum sinking speed of POC
w_{max}	$m d^{-1}$	200	Maximum sinking speed of POC _b
$\Phi_1^{DOC}, \Phi_2^{DOC}$	$(mol C l^{-1})^{-1}$	80,698	Aggregation rates for DOC \rightarrow POC _s
Φ_3^{DOC}	$(mol C l^{-1})^{-1}$	10500	Aggregation rates for DOC \rightarrow POC _b
$\Phi_1^{POC_s}, \Phi_2^{POC_s}$	$(mol C l^{-1})^{-1}$	940,10540	Aggregation rates for POC _s \rightarrow POC _b
$\Phi_3^{POC_s}, \Phi_4^{POC_s}$	$(mol C l^{-1})^{-1}$	0.66,0	Aggregation rates for POC _s \rightarrow POC _b
λ_{Fe}^{min}	d^{-1}	310^{-5}	scavenging rate of iron
λ_{Fe}	$d^{-1} \mu mol^{-1} l$	0.005	scavenging rate of iron
λ_{CaCO_3}	d^{-1}	0.03	Dissolution rate of calcite
λ_{BSi}	d^{-1}	0.015	Dissolution rate of BSi
λ_{NH_4}	d^{-1}	0.05	Maximum nitrification rate
O_2^{min}	$\mu mol O_2 l^{-1}$	1	Half saturation constant for denitrification
Stoichiometric ratios			
R_{NO_3}	$mol C mol N^{-1}$	-0.8	C/N ratio of denitrification

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Parameter	Units	Value	Description
R_{CaCO_3}	–	0.2	Maximum rain ratio

4 Model structure

The model is being coded in mixed fortran 77/90. Even if very few capabilities of the fortran 90 are used, it will not compile with a F77-only compiler (like the gnu g77 compiler). To activate PISCES, the cpp key `key_trc_pisces` should be declared at the compilation. The biogeochemical code do not include any other cpp keys.

Only the subroutines that compute the biological or chemical sources and sinks are considered to be part of PISCES. Thus, this excludes the computation of the advection-diffusion equation (the transport of the tracers), as it is not specific to PISCES. There are two types of subroutines: The initialization of the tracers and of the parameters and the computation of the various biogeochemical sources and sinks. The latter PISCES subroutines are called from within the ocean model timeloop. There is no need for them to be called at the same frequency than the computation of the advection-diffusion terms or of the dynamics. However, the biological time step should be small enough, typically one hour, to avoid major instabilities, which occur when the sources and sinks become larger than the tracer concentrations. Such instabilities could be avoided by the use of an implicate scheme, which is not implemented yet.

The objective here is not to precisely detail the PISCES code but rather to list the different subroutines and to briefly describe their role. All the subroutines that compute the biogeochemical sources/sinks are called from `p4zprg` which is then the main PISCES subroutine.

p4zbio.F: Computation of the new tracer concentrations by summing up all the different sources and sinks.

p4zche.F: Computation of the various chemical constants.

p4zday.F: Computation of the day length.

p4zdiat.F: Computation of the mortality terms of diatoms.

p4zflx.F: Air-sea fluxes of CO₂ and O₂.

p4zint.F: Time interpolation of various terms (dust deposition, growth rate, ...).

p4zlim.F: Co-limitations by the different nutrients.

p4zlys.F: Calcite dissolution

p4zmeso.F: Sources and sinks of mesozooplankton (mortality, grazing, ...)

p4zmicro.F: Sources and sinks of microzooplankton.

p4znano.F: Computation of the various mortality terms of nanophytoplankton.

p4zopt.F: Optical model and computation of the euphotic depth.

p4zprod.F: Growth rate of the two phytoplankton groups.

p4zrem.F: Remineralization of organic matter, dissolution of biogenic silica, scavenging.

p4zsed.F: Top and bottom boundary conditions of the biogeochemical tracers (deposition, sedimentary losses, ...).

p4zsink.F: Aggregation of organic matter, computation of the particles sinking speeds.

p4zsink2.F: Sinking of the various particle compartments, based on the MUSCL advection scheme.

Besides the subroutines listed above, several subroutines realize the model initialization. We will only discuss the initialization of the parameters necessary to PISCES. The tracers concentrations are excluded here as their initialization highly depends on the ocean model. Of course, all the initializing subroutines are called only once at the beginning of the simulation.

trclsm.F, trclsm.pisces.h: Reading of the namelist which sets the biological parameters.

trcini.F, trcini.pisces.h: Reading of the boundary conditions (dust deposition, sediment mobilization, ...), initialization of various biogeochemical parameters.

PISCES requires specific dynamical variables to work properly. Thus, if a coupling with a new dynamical model is undertaken, the following dynamical parameters should be absolutely passed to PISCES: Temperature, salinity, mixed layer depth, sea ice concentration, short wave radiation at the ocean surface, wind speed (or at least, wind stress).

In this document, all the model equations and parameterizations adopted in PISCES have been described. Of course, the notation chosen to write in the equations is not identical to that of the fortran code. To ease the manipulation of the code and of the namelist, Table 2 displays the translation between the equation and the code notations for the parameters of the namelist (thus, those that can be changed without recompiling the model). Table 3 lists all the model tracers and their indices in the code.

Table 2: Translation between the fortran code and the model equations

Equation name	Code name	Description
Phytoplankton		
α	pislope, pislope2	Initial slope of the PI curve
δ	excret	Excretion of DOC
K_{po4}	concnh4, concdnh4	Half-saturation constant for Phosphate
K_{nh4}	concnh4, concdnh4	Half-saturation constant for ammonium
K_{no3}	conc0, conc1	Half-saturation constant for nitrate
K_{si}^{diat}	xksil	Half saturation constant for silicate
K_{Fe}^{min}	conc2, conc3	Minimum half-saturation constant for iron
m_P	mprat, mprat2	phytoplankton mortality rate
w_P	wchl	Quadratic mortality of phytoplankton
w_P^{max}	wchld	Maximum quadratic mortality of diatoms
K_P	xkmort	Half-saturation constant for mortality
$\theta_{chl,max}$	chlcnm, chlcdm	Maximum Chl/C ratios of phytoplankton
$\theta_{fe,max}$	fecnm, fecdm	Maximum Fe/C ratios of phytoplankton
K_{Si}^2	xksi2	Half saturation constant for Si/C increase

Table 2 – continued on next page

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Equation name	Code name	Description
Zooplankton		
ϵ	epsher, epshe2	Zooplankton growth efficiency
σ	sigma1, sigma2	Fecal pellets production
g	grazrat, grazrat2	Maximum grazing rate
K_G	xkgraz, xkgraz2	Half-saturation constant for grazing
p_P^{micro}, γ_P	zprefp, xprefp	Preferences for nanophytoplankton
p_D^{micro}, γ_D	zprefd, xprefd	Preferences for diatoms
$p_{POC}^{micro}, \gamma_{POC}$	zprefc, xprefpoc	Preferences for POC _s
γ_Z	xprefz	Preference for microzooplankton
m^{meso}	mzrat2	Mesozooplankton mortality
r	resrat, resrat2	Excretion rate
K	xkmort	Half-saturation constant for excretion
$\left(\frac{Fe}{C}\right)^{zoo}$	ferat3	Fe/C ratio of zooplankton
Organic matter		
λ_{DOC}	xremik	Remineralization rate of DOC
K_{DOC}^{bac}	xkdoc	Half-saturation constant for DOC remin.
λ_{POC}	xremip	Degradation rate of POC
w_{min}	wsbio, wsbio2	Minimum sinking speed of POC
λ_{Fe}	xlam1	scavenging rate of iron
λ_{BSi}	xsirem	Dissolution rate of BSi
λ_{NH_4}	nitrif	Maximum nitrification rate
O_2^{min}	oxymin	Half saturation constant for denitrification
Stoichiometric ratios		
R_{CaCO_3}	caco3r	Maximum rain ratio

Table 3: Description of the model indices

PISCES indices	Units	Description
jpgdic	$mol\ C\ l^{-1}$	Dissolved inorganic carbon
jptal	$eq\ l^{-1}$	Total alkalinity
jpoxy	$mol\ O_2\ l^{-1}$	dissolved oxygen
jpgcal	$mol\ C\ l^{-1}$	Calcite
jppo4	$mol\ C\ l^{-1}$	Phosphate
jppoc	$mol\ C\ l^{-1}$	Small particulate organic carbon
jpgsil	$mol\ Si\ l^{-1}$	silicate
jpgphy	$mol\ C\ l^{-1}$	Nanophytoplankton
jpgzoo	$mol\ C\ l^{-1}$	Microzooplankton
jpgdoc	$mol\ C\ l^{-1}$	Semi-labile dissolved organic carbon
jpgdia	$mol\ C\ l^{-1}$	Diatoms
jpgmes	$mol\ C\ l^{-1}$	Mesozooplankton
jpgbsi	$mol\ Si\ l^{-1}$	Silicon content of the diatoms

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PISCES indices	Units	Description
jpfer	$mol\ Fe\ l^{-1}$	Dissolved iron
jpgbfe	$mol\ Fe\ l^{-1}$	Iron in the big particles
jpgoc	$mol\ C\ l^{-1}$	Big particulate organic carbon
jpsfe	$mol\ Fe\ l^{-1}$	Iron in the small particles
jpgdfe	$mol\ Fe\ l^{-1}$	Iron content of the diatoms
jpgdsi	$mol\ Si\ l^{-1}$	Sinking biogenic silica
jpgnfe	$mol\ Fe\ l^{-1}$	Iron content of the nanophytoplankton
jpgnch	$kg\ Chl\ l^{-1}$	Chlorophyll of the nanophytoplankton
jpgdch	$kg\ Chl\ l^{-1}$	Chlorophyll of the diatoms
jpgno3	$mol\ C\ l^{-1}$	Nitrate
jpgnh4	$mol\ C\ l^{-1}$	Ammonium