A1. CARIACO model methods

The ecosystem model equations are similar to those used in Acevedo-Trejos et al. (2016). Most significant changes are that multiple phytoplankton and zooplankton functional types have been added, and that the grazing formulation was expanded to include preferential feeding on certain functional types.

Nitrogen N (and Silicate Si for Diatoms) is assimilated by the phytoplankton types P_i, which are grazed by several zooplankton types Z_j. Mortality of and excretion from plankton, and sloppy feeding by zooplankton contribute to Detritus D. The phytoplankton types include Nanoflagellates P_n, Diatoms P_{dt}, Coccolithophorse, P_c and Dinoflagellates P_{dn}. There are two Zooplankton types split by size class, named Mikrozooplankton Z_μ and Mesozooplankton Z_λ.

ToDo: Highlight in the equations how grazing works, selective feeding, explain difference in R_j between zooplankton types

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\begin{aligned}
\frac{\partial N}{\partial t} &= \kappa \cdot (N_0 - N) + \delta_D^N \cdot D - \sum_{i=1}^{n_P} [\mu_i \cdot U_i(N_0, Si_0) \cdot L_i(PAR) \cdot T_i(SST) \cdot P_i] \\
\frac{\partial Si}{\partial t} &= \kappa \cdot (Si_0 - Si) - \mu_{dt} \cdot U_{dt}(N_0, Si_0) \cdot L_{dt}(PAR) \cdot T_{dt}(SST) \cdot P_{dt} \\
\frac{\partial P_i}{\partial t} &= \mu_i \cdot U_i(N_0, Si_0) \cdot L_i(PAR) \cdot T_i(SST) \cdot P_i - m_i \cdot P_i - \sum_{j=1}^{n_Z} [I_j^{tot} \frac{p_j^i \cdot P_i}{R_j} Z_j] - \frac{v}{M(t)} \cdot P_i - \kappa \cdot P_i \\
\frac{\partial Z_\mu}{\partial t} &= \delta_Z \cdot I_\mu^{tot} \cdot Z_\mu - \mu_\lambda \frac{Z_\mu}{Z_\mu + k_\lambda} Z_\lambda - \kappa_Z \cdot Z_\mu - m_\mu \cdot Z_\mu - g_\mu \cdot Z_\mu^2 \\
\frac{\partial Z_\lambda}{\partial t} &= \delta_Z \cdot I_\lambda^{tot} \cdot Z_\lambda + \delta_\lambda \cdot \mu_\lambda \frac{Z_\mu}{Z_\mu + k_\lambda} Z_\lambda - \kappa_Z \cdot Z_\lambda - m_\lambda \cdot Z_\lambda - g_\lambda \cdot Z_\lambda^2 \\
\frac{\partial D}{\partial t} &= \sum_{j=1}^{n_Z} [(1-\delta_Z) I_j^{tot} \cdot Z_j] + (1-\delta_\lambda) \cdot \mu_\lambda \frac{Z_\mu}{Z_\mu + k_\lambda} Z_\lambda - \sum_{j=1}^{n_Z} [m_j \cdot Z_j] + \sum_{i=1}^{n_P} [m_i \cdot P_i] - \kappa \cdot D - \delta_D^N \cdot D
\end{aligned}
$$

where:

$N_0 =$ Nitrogen concentration right below mixed layer [μM],
$N =$ Nitrogen concentration above mixed layer [μM],
$v =$ sinking rate of P_i [$m\ day^{-1}$],
$M(t) =$ mixed layer depth at time point t [m],
$\kappa = \frac{1}{M(t)} \cdot (h^+(t) + \kappa)$ Constant that parameterizes diffusive mixing across the thermocline,
$h^+(t) = \max\left(0, \frac{d}{dt} M(t)\right)$ Function that describes entrainment and detrainment of material,
$\delta_D^N =$ Remineralization rate of nitrogen component of detritus D [$\mu M d^{-1}$],
$\mu_i =$Growth rate of phytoplankton type i [d^{-1}],

$$U_i = \begin{cases} \min\left(\frac{N}{N+U_i^N}, \frac{Si}{Si+U_i^{Si}}\right), & \text{if P-type is Diatom} \\ \frac{N}{N+U_i^N}, & \text{otherwise} \end{cases}$$ Nutrient uptake of phytoplankton i,

$L_i = \frac{1}{M(t)\cdot k_w} \cdot \left(e^{1-\frac{PAR(t)}{Opt_i^I}} + e^{1-\frac{PAR(t)}{Opt_i^I}\cdot e^{-M(t)\cdot k_w}} \right)$ Light dependence of phytoplankton i,
$T_i = e^{0.063\cdot SST}$ Temperature dependence of phytoplankton i,

$P_i =$ Biomass of phytoplankton type i [μMN],
$m_i =$ Mortality/excretion rate for phytoplankton type i,

$I_j^{tot} = \mu_j^Z \frac{R_j}{R_j+k_j^Z}$ Total intake of zooplankton type j,
$k_j^Z =$ Half saturation constant of zooplankton type j,
$R_j = \sum_i (p_{ij}P_i)$ Total ressource density of zooplankton type j,
$p_j^i =$ Feeding preference of zooplankton type j feeding on phytoplankton type i,
$R_\mu = p_\mu^n P_n + p_\mu^{dn} P_{dn} + p_\mu^c P_c$ Total ressource density of Mikrozooplankton Z_μ,
$R_\lambda = p_\lambda^{dt} P_{dt} + p_\lambda^{dn} P_{dn} + p_\lambda^c P_c$ Total ressource density of Mesozooplankton Z_λ,

$Z_j =$ Biomass of zooplankton type j [μMN],
$\delta_Z =$ Grazing efficiency of zooplankton on phytoplankton (represents sloppy feeding),
$K_Z = \frac{1}{M(t)} \cdot \frac{d}{dt} M(t)$ Mixing term of zooplankton,
$g_i =$ Higher order predation on zooplankton (quadratic),
$m_j =$ Mortality/excretion rate for zooplankton type j,

A1.1. Physical structure:

It is a slab model for now, but might make sense to include depth layering, or euphotic zone depth, etc.. can take some of the cues for slab models from EMPOWER-1.0

A1.2. Phytoplankton growth:

$$\mu_i = \mu_{max_i} \gamma_i^T \gamma_i^I \gamma_i^N$$

where
$\mu_{max_i} =$ maximum growth rate of phytoplankton i,
$\gamma_i^T =$Modification of growth rate by temperature for phytoplankton i,
$\gamma_i^I =$Modification of growth rate by light for phytoplankton i,
$\gamma_i^N =$Modification of growth rate by nutrients for phytoplankton i.

Temperature modification (Fig. **??**a):

$$\gamma_i^T = \frac{1}{\tau_1}(A^T e^{-B(T-T_o)^c})$$

where EPPLEY
...
...

Light modification (Fig. **??**b):

The average photosynthesis within a layer of depth H is

$$V'_{P(H)} = \frac{1}{H} \cdot \int_{z=0}^{H} V_P(z) dz$$

where V_P is photosynthesis as a function of light intensity (specified as the P-I curve). The P-I curve is based on the Smith equation. In both cases a Beer's law attenuation with depth is assumed (parameter k_{PAR}), i.e. $I(z) = I(0) \cdot \exp(-k_{PAR} \cdot z)$, where $I(0)$ is the irradiance entering the layer from above.
By performing a change of variables such that $x = \alpha \cdot I(z)$, the integral above becomes:

$$V'_{P(H)} = \frac{-V_{P_{max}}}{H} \cdot \int_{z=0}^{H} \frac{1}{\sqrt{(V_{P_{max}})^2 + x^2}} dx$$

This integral is solved analytically using a trigonometric transformation and then integration by parts, giving:

$$V'_{P(H)} = \frac{V_{Pmax}}{k_{PAR} \cdot H} \cdot \ln\left(\frac{x_0 + \sqrt{(V_{Pmax})^2 + x_0^2}}{x_H + \sqrt{(V_{Pmax})^2 + x_H^2}}\right) \tag{1}$$

Nutrient limitation is determined by the most limiting nutrient:

$$\gamma_j^N = \min(N_i^{lim})$$

where typically $N_i^{lim} = \frac{N_i}{N_i + \kappa_{N_{ij}}}$ (Fig. **??**c) and $\kappa_{N_{ij}}$ is the half saturation constant of nutrient i for phytoplankton j.

When we include the nitrogen as a potential limiting nutrient (EXP2) we modify N_i^{lim} to take into account the uptake inhibition caused by ammonium:

$$N_N^{lim} = \frac{NO_2}{NO_2 + \kappa_{IN}} e^{-\psi NH_4} + \frac{NH_4}{NH_4 + \kappa_{NH4}} \qquad \text{(nsource=1)}$$

$$N_N^{lim} = \frac{NH_4}{NH_4 + \kappa_{NH4}} \qquad \text{(nsource=2)}$$

$$N_N^{lim} = \frac{NO_3 + NO_2}{NO_3 + NO_2 + \kappa_{IN}} e^{-\psi NH_4} + \frac{NH_4}{NH_4 + \kappa_{NH4}} \qquad \text{(nsource=3)}$$

where ψ reflects the inhibition and κ_{IN} and κ_{NH4} are the half saturation constant of $IN = NO_3 + NO_2$ and NH_4 respectively.

A1.2. Zooplankton grazing:

$$g_{jk} = g_{max_{jk}} \frac{\eta_{jk} P_j}{A_k} \frac{A_k}{A_k + \kappa_k^P}$$

where

$g_{max_{jk}} =$ Maximum grazing rate of zooplankton k on phytoplankton j,
$\eta_{jk} =$ Palatibility of plankton j to zooplankton k,
$A_k =$ Palatibility (for zooplankton k) weighted total phytoplankton concentration,
$= \sum_j [\eta_{jk} P_j]$
κ_k^P =Half-saturation constant for grazing of zooplankton k,

A1.3. Inorganic nutrient Source/Sink terms:
S_{N_i} depends on the specific nutrient, and includes the remineralization of organic matter, external sources and other non-biological transformations:

$$\begin{aligned}
S_{PO4} &= r_{DOP} DOP + r_{POP} POP \\
S_{Si} &= r_{POSi} POSi \\
S_{FeT} &= r_{DOFe} DOFe + r_{POFe} POFe - c_{scav} Fe' + \alpha F_{atmos} \\
S_{NO3} &= \zeta_{NO3} NO_2 \\
S_{NO2} &= \zeta_{NO2} NH4 - \zeta_{NO3} NO_2 \\
S_{NH4} &= r_{DON} DON + r_{PON} PON - \zeta_{NO2} NH_4
\end{aligned}$$

where:

r_{DOM_i} =Remineralization rate of DOM for element i, here P, Fe, N,
r_{POM_i} =Remineralization rate of POM for element i, here P, Si, Fe, N,
c_{scav} =scavenging rate for free iron,
Fe' =free iron, modelled as in Parekh et al (2004),
$alpha$ =solubility of iron dust in ocean water,
F_{atmos} =atmospheric deposition of iron dust on surface of model ocean,
$\zeta_{NO3} = \zeta^0_{NO3}(1 - I/I_0)_+$ =oxidation rate of NO_2 to NO_3,
$\zeta_{NO2} = \zeta^0_{NO2}(1 - I/I_0)_+$ =oxidation rate of NH_4 to NO_2 (is photoinhibited),
I_0 =critical light level below which oxidation occurs,

The remineralization timescale r_{DOi} and r_{POi} parameterizes the break down of organic matter to an inorganic form through the microbial loop.

A1.3.1 Fe chemistry: