A1. CARIACO model description

NPZD models are simplified marine ecosystem models that can be adapted to different physical settings and food web structures. For this model, the basic structure is inspired by the models of Fasham (1990) as it was adapted by Anderson et al. (2015). The pyhsical setting of the model uses a zero-dimensional slab structure as originally presented in Evans and Parslow (1985) and adapted from Acevedo-Trejos et al. (2015) where the ecosystem is described within a seasonally varying surface mixed layer above a deep homogenous layer. The code structure is the PhytoMFTM model written in the open source programming language Python, which provides a flexible framework for NPZD-type models with multiple functional types of phytoplankton and zooplankton. The model code and all statistical scripts are available publicly on Github (`https://github.com/ben1post/BennyPhD`).

The model framework was adapted to the setting of the CARIACO time-series at $10.5°$ N, $64.67°$ W in the Cariaco basin of the coast of Venezuela. The data includes phytoplankton species counts and two size-classes of zooplankton, which were included in the model as the 4 most prominent phytoplankton types, and 2 zooplankton types. The phytoplankton types include Nanoflagellates P_n, Diatoms P_{dt}, Coccolithophores, P_c and Dinoflagellates P_{dn}. There are two Zooplankton types split by size class, named Mikrozooplankton Z_μ and Mesozooplankton Z_λ. Nitrogen N (and Silicate Si for Diatoms) is assimilated by the phytoplankton types P_i, which are grazed by the zooplankton types Z_j. Mortality of and excretion from phytoplankton and zooplankton, and sloppy feeding by zooplankton contribute to Detritus D. In addition to the linear mortality of P_i and
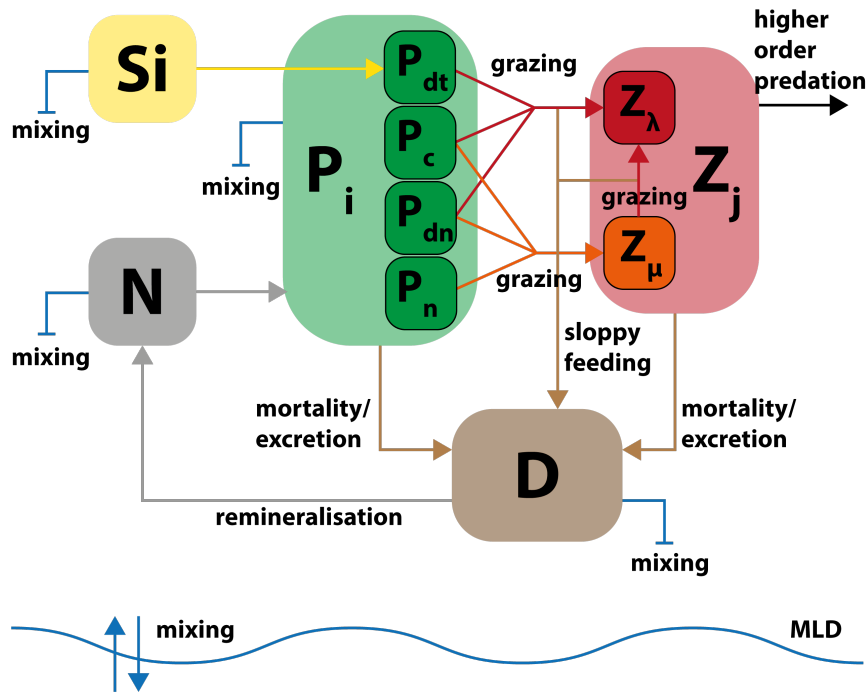

Figure 1: Model schematics of CARIACO model.

Z_j, there is an additional quadratic mortality term acting on Z_j, which represents higher-order predation on zooplankton.

A1.1 Physical setting

The ecosystem component of the model is set within a zero-dimensional physical environment. The water column is divided into a 2-layer structure. A depth variable layer (e.g. the thermo- and/or pycnocline) separates a well-mixed surface layer containing the ecosystem component from a homogenous deep ocean. Concentrations of nutrients are averaged across the mixed layer, and remain constant below. There is no lateral advection, but vertical mixing is modeled as a function of mixed layer depth (MLD) over time $M(t)$. Temperature depth profiles have been used to reconstruct the MLD at the investigated location. The derivative of MLD over time is given as $h(t) = dM(t)$. Exchange between the two layers is described by the two processes of turbulent diffusion and entrainment or detrainment caused by a shallowing or deepening of MLD. Adapted from Fasham (1993), the effects of entrainment and detrainment on nutrients, phyto- plankton and detritus are given by the term $h^+(t) = max[h(t), 0]$. Zooplankton is assumed to be able to maintain themselves within the mixed layer depth, therefore entrainment and detrainment of Z_j are described by $h(t)$. Diffusive mixing between the layers has been parameterized with a constant factor k. The entire diffusion term is thus

$$\kappa = \frac{k + h^+(t)}{M(t)} \tag{1}$$

In addition to the MLD interpolated from time series data, the model is externally forced with sea surface temperature (SST) taken from in situ data and interpolated from monthly to daily values and photosynthetically active radiation (PAR) from 8-day averaged SeaWIFs satellite data.

A1.2 Phytoplankton

Phytoplankton growth is a function of light (PAR), temperature (SST) and nutrients. These factors are assumed to independently limit growth, so that (exemplary for P_d, i.e. diatoms) the growth term is

$$\mu_d = \mu_d^{max} \cdot U_d(N, Si) \cdot L_d(PAR) \cdot T_d(SST) \tag{2}$$

where μ_d is the maximum growth rate per day and $T(PAR)$ is Eppley's formulation for temperature dependent growth (Eppley, 1972), given as $T(SST) = e^{0.063*SST}$ with temperature in $°C$. The light-limiting term $L(PAR)$ represents the integrated photosynthesis within the mixed layer as a function of incident irradiance at the surface I_0. Light attenuation is calculated using the Lambert- Beer law with irradiance at depth z equal to

$$I(z) = I_0 \cdot e^{-k_{PAR} \cdot z} \tag{3}$$

Here, k_{PAR} is calculated as the sum of the constant attenuation coefficient of water k_w and the self-shading of phytoplankton k_c with the unit μM^{-1} multiplied by total phytoplankton biomass P, i.e. $k_{PAR} = k_w + k_c P$. This model uses the Smith PI curve as a basis for the calculation, with V_P representing the photosynthetic rate, α, the initial slope of the PI curve and V_p^{Max}, the maximum photosynthetic rate

$$V_p = \frac{\alpha \cdot I \cdot V_p^{Max}}{\sqrt{(V_p^{Max})^2 + \alpha^2 \cdot I^2}} \tag{4}$$

Combining equation (2) and (3) as presented in Anderson et al. (2015), the integrated photosynthesis $\bar{V}_p$ over depth z is calculated as

$$\bar{V}_p(z) = \frac{V_p^{Max}}{k_{PAR} \cdot z} \cdot \ln\left(\frac{\alpha \cdot I_0 + \sqrt{(V_p^{Max})^2 + (\alpha \cdot I_0)^2}}{\alpha \cdot I(z) + \sqrt{(V_p^{Max})^2 + (\alpha \cdot I(z))^2}} \right) \tag{5}$$

where $\bar{V}_p$ equals the light-limiting term L in the growth equation (2).

Nutrient limited growth of the phytoplankton community is described via a Monod equation.

$$U(N) = \frac{N}{k_N + N} \tag{6}$$

For diatoms P_d the nutrient limiting term depends on both nitrogen and silicate concentration within the upper layer. According to Liebig's law of the minimum, always the lower nutrient availability limits Diatom growth:

$$U_d(N, Si) = min\left(\frac{N}{k_d^N + N}, \frac{Si}{k_d^{Si} + Si} \right) \tag{7}$$

All other phytoplankton types are nutrient-limited only by available Nitrogen as in equation (6). Phytoplankton mortality and excretion are parameterized as a linear constant rate mo. With G_μ as grazing by Microzooplankton and G_λ as grazing by Mesozooplankton (defined below), the equations for all phytoplankton types P_i can now be written as

$$\frac{dP_i}{dt} = \mu_i \cdot P_i - mo_i \cdot P - G_\mu(P_i) - G_\lambda(P_i) - \kappa \cdot P_i \tag{8}$$

A1.3 Zooplankton

Two zooplankton types are resolved in the model according to size-class, Microzooplankton Z_μ and Mesozooplankton Z_λ. Following Anderson et al. (2015) the grazing of, for example, Z_λ on diatoms P_d is formulated as follows

$$G_\lambda(P_d) = \left(\frac{\mu_\lambda^Z \cdot \phi_d^\lambda \cdot P_d}{(k_\lambda^Z)^2 + \phi_d^\lambda \cdot P_d + \phi_c^\lambda \cdot P_c + \phi_{df}^\lambda \cdot P_{df} + \phi_n^\lambda \cdot P_n + \phi_\mu^\lambda \cdot Z_\mu} \right) \cdot Z_\lambda \tag{9}$$

$\phi_d^\lambda = \rho_d^\lambda P_d$, $\phi_c^\lambda = \rho_c^\lambda P_c$, $\phi_{df}^\lambda = \rho_{df}^\lambda P_{df}$, $\phi_n^\lambda = \rho_n^\lambda P_n$, $\phi_\mu^\lambda = \rho_\mu^\lambda Z_\mu$

with μ_λ^Z as the maximum grazing rate, k_λ^Z as the half saturation constant of grazing, ϕ_d^λ as the density dependent feeding preference of Z_λ feeding on P_d, defined as $\rho_d \cdot P_d$, with ρ_d^λ as the feeding preference coefficient.

A1.x Solving method

The system of differential equations was solved numerically using the fourth-order Runge-Kutta method in the odeint function of the scipy package in python 3.7.

Physical forcing is interpolated ... Taken from the regimes ... etc.