Computational Marine Ecological Modelling report: NPD model

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1 Introduction

Understanding the vertical distribution of phytoplankton has become one of the most exciting research areas because of its highly complex and interdependent nature over other physical and biological factors in aquatic communities. To understand this complex growth of phytoplankton, the advection-reaction-diffusion equation model has been used to investigate phytoplankton species' distribution and competition in a water column. In some of the previous research, gradients of light and nutrients, sinking detritus and seasonality have been considered as an essential set of critical factors to qualitatively and quantitatively describe subsurface biomass of phytoplankton [2],[1],[3]. The main objective of this report is to understand and recreate some results explained in mentioned papers and analyze the effect of change in the initial concentration of phytoplankton overgrowth for future time steps using the NPD model.

1.1 Advection-reaction-diffusion equation

The base of this report is advection-reaction-diffusion equation which is used to calculate advective and diffusive flux across the layers in water column, and can be defined as:

$$\frac{\delta\phi(z,t)}{\delta t} + u\frac{\delta\phi(z,t)}{\delta z} = \frac{\delta}{\delta z}D(z,t)\frac{\delta\phi(z,t)}{\delta z} \tag{1}$$

Where $\phi(z,t)$ is the concentration of a substance (substance/volume) as a function of the vertical position z and time t. The substance is advected with the velocity u and diffuses with the diffusion coefficient D(z; t). The equation 1 can be written in "conservative" form in terms of a advective $J_a(z,t)$ and diffusive $J_d(z,t)$ fluxes:

$$\frac{\delta\phi(z,t)}{\delta t} = -\frac{\delta J(z,t)}{\delta z} \tag{2}$$

where $J(z,t) = J_a(z,t) + J_d(z,t)$ as advective and diffusive flux respectively.
The advective flux is:

$$\delta J_a(z,t) = u\phi(z,t) \tag{3}$$

and diffusive flux is:

$$\delta J_d(z,t) = -D(z,t)\frac{\delta\phi(z,t)}{\delta z} \tag{4}$$

Using 3 and 4 in 2, we can get the main equation mentioned in 1.
Note that the boundary needs special attention where we used no flux condition, meaning that the boundary is closed and no substance is moving across the boundary, which gives $J_1 = 0$ and $J_{n+1} = 0$

1.2 System of equations used for analysis

In our analysis, the focus in mainly on three parameters i.e. phytoplankton (P), nutrients (N) and detritus (D) for which we have considered a system of three equations as:

$$\frac{\delta P}{\delta t} = \mu\sigma_L\sigma_N P - \epsilon P - \gamma P^2 + A_v\frac{\delta^2 P}{\delta z^2} \tag{5}$$

$$\frac{\delta N}{\delta t} = \mu\sigma_L\sigma_N P - \tau D + A_v\frac{\delta^2 N}{\delta z^2} \tag{6}$$

$$\frac{\delta D}{\delta t} = \epsilon P - \gamma P^2 - \tau D - w\frac{\delta D}{\delta z} + A_v\frac{\delta^2 D}{\delta z^2} \tag{7}$$

where P is phytoplankton, N the main limiting nutrient (in our case nitrogen), D detritus (all in units of $mmolNm^3$) and the growth limitation functions for nutrient σ_N and light σ_L are

$$\sigma_N = \frac{N}{k_N + N} \tag{8}$$

$$\sigma_L = \frac{\alpha I(z)}{\sqrt{\mu^2 + \alpha^2 I(z)^2}} \tag{9}$$

With the half-saturation constant k_N, maximum specific growth rate μ and the PI-curve α slope. The irradiance decreases with depth according to

$$I(z,t) = I_0 exp((k_w + k_c \int_0^z (P + D))z) \tag{10}$$

Where I_0 is the surface irradiance, k_w is the attenuation coefficient of water.
Note that advection for nutrients is always zero, and for diffusion for nutrients at the bottom will be:

$$J_d = -av(N_b - N_i)/z \tag{11}$$

Where av is depth-dependent turbulent diffusivity and N_b is nutrients from the bottom layer.
To understand the effect of seasonality in the phytoplankton growth and flux, an additional seasonality factor have been introduced which changes the light intensity over time using the equation as follows:

$$seas = (1 - cos((2 * pi * t)/T)) \tag{12}$$

and after using 12 in 10, we get:

$$I(z,t) = I_0 * seas * exp((k_w + k_c \int_0^z (P + D))z) \tag{13}$$

Where T is the total number of time steps, and t is a one-time step.

1.3 Parameters used:

Quantity	Minimum	Reference	Maximum	Unit
u	0.01	0.04	0.1	$ms{-}1$
N_b	5	50	100	$mmolNm^{-3}$
I_0	100	200	300	Wm^{-2}
k_w	0.025	0.0375	0.05	m^{-1}
k_c	0.03	0.05	0.07	$m^2(mmolN)^{-1}$
μ	0.2	0.5	0.8	$d{-}1$
α	0.01	0.1	0.19	$m^2W^{-1}d^{-1}$
k_N	0.1	0.3	0.5	$mmolNm^{-3}$
ϵ	0.01	0.03	0.05	d^{-1}
γ	0.5	1.5	2.5	$m^3(mmolN)^{-1}d^{-1}$
τ	0.05	0.1	0.15	d^{-1}
av	1	5	9	$(*10^{-5})m^2s^{-1}$
$depth$	100	200	300	$m^3(mmolN)^{-1}d^{-1}$
$time$	10	100	500	d^{-1}
n_{layers}	10	20	30	—

Table 1: Range of parameters)

Where u is sinking velocity, N_b is a nutrient concentration from the bottom, I_0 is solar irradiance at the sea surface, k_w is light penetration length2, k_c is attenuation coefficient of phytoplankton, μ is the maximum specific growth rate, α is initial slope of the PI-curve, k_N is half-saturation constants for nitrogen, ϵ is phytoplankton mortality, γ is grazing parameter, τ is remineralization rate, av is vertical diffusivity, *depth* is the depth of water column, and *time* is to determine the change in flux in the specified time interval.

2 Analysis

Using the equations mentioned in section 1.2 and parameters in section 1.3, a model has been designed to:

- Understand the change in phytoplankton biomass with different parametric values considering the effect of nutrient flux and detritus.

- understands the Effect of seasonality on phytoplankton concentration across the water column.

As a solver function, the $solve_{ivp}$ function is used, which solves an initial value problem for a system of ODEs. This function numerically integrates a system of ordinary differential equations given an initial value.

The initial concentration for phytoplankton and nutrients is 1 and 5, respectively, for all the layers in the water profile. In contrast, the initial detritus value for all layers is taken as 0.

Please note that nutrient flux and light intensity shown in figures are scaled based on phytoplankton concentration and taken as a reference to understand the pattern over the layer in the water column.

2.1 Results from reference model parameters

For initial model, reference values have been used from table 1 and following are the results for this model:

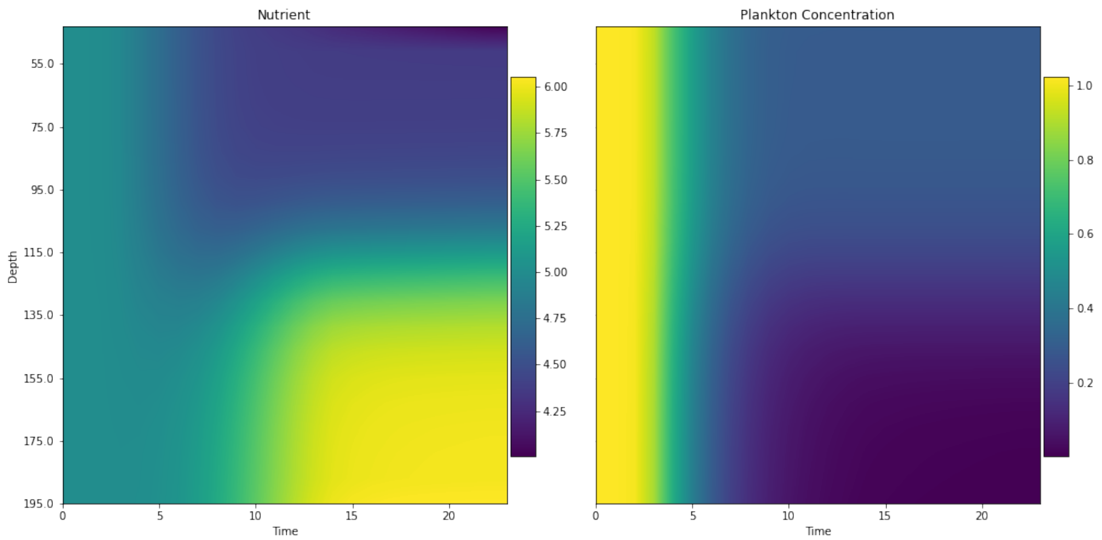


Figure 1: Change in Nutrient and phytoplankton concentration on spatio-temporal domain

In figure 1, Nutrient concentration tends to increase over time on the bottom layer because of the diffusive flux of nutrients from the bottom layer. However, in contrast, it decreases on the top layer, which supports having fewer nutrients on higher water levels. On the other hand, phytoplankton concentration seems to decrease over time on both the top and bottom layers, but the rate of decline is proportional to the depth of the water column. This is happening significantly since light intensity decreases exponentially in the water column.

Figure 2 is the magnified version of the last time step where it shows the exponential decrease in light intensity with depth, decreasing flux of phytoplankton concentration and increasing nutrient flux. Change has been noticed for 15 different initial phytoplankton concentrations, and the same coloured lines for phytoplankton and nutrients represents initial phytoplankton concentrations. It can be inferred that in the euphotic zone (above 75m of depth), phytoplankton concentration is supported by light intensity and some intake of nutrients. However, below the base of the euphotic zone, a balance is established between organic matter production, the sinking of dead organic material, remineralization, and upward diffusion until 125m of depth. At the deepest levels, flux is reduced to almost zero with little to no reach of light. The change in initial concentration affects the flux at the water surface, but after a certain depth, flux is the same for all the initial concentrations.

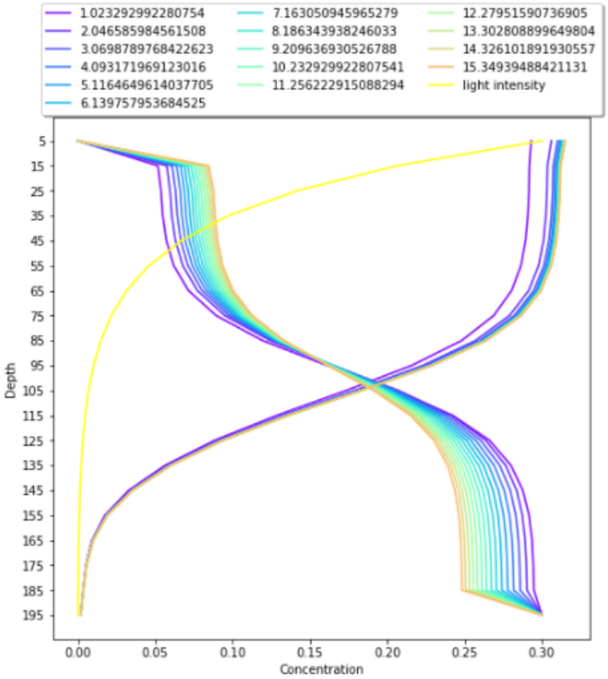


Figure 2: Phytoplankton concentration in water profile for last time step

2.2 Sensitivity analysis on maximum growth rate

In order to understand the effect of parameters on model output, local sensitivity analysis is performed on the maximum growth rate. Maximum growth rate can increase or decrease the duration of survival of phytoplankton on different water depths and infer the potential effects of nutrient loading on phytoplankton biomass and community structure. After performing simulations with low and high growth rates compared to the reference value and keeping all other factors on reference values, the following results have been drawn:

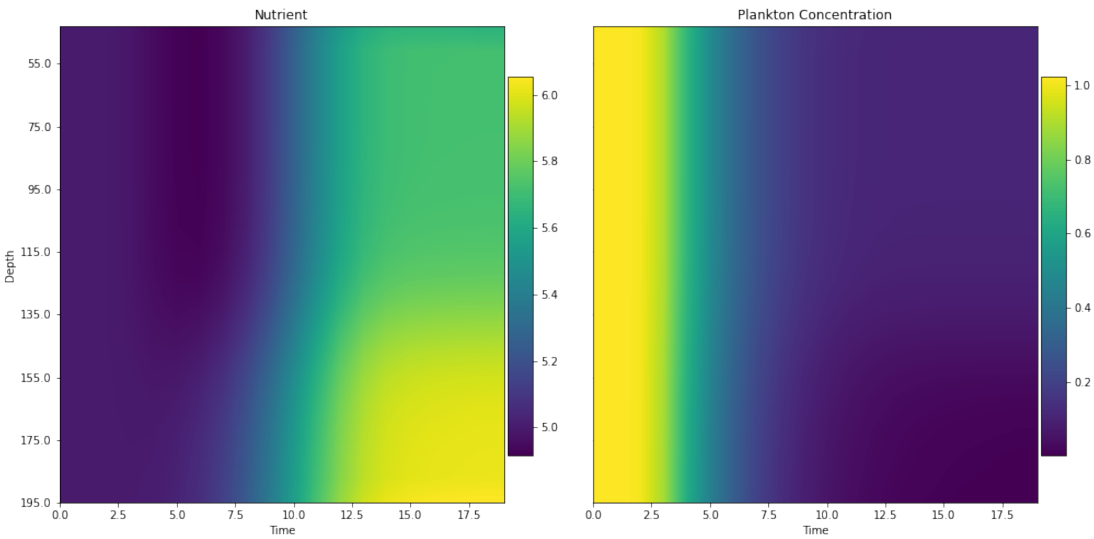


Figure 3: Change in Nutrient and phytoplankton concentration (Using low growth rate of 0.2)

In figure 3 where the maximum growth rate is 0.2, nutrient and phytoplankton concentration flux seems to have decreased significantly in the whole water profile across multiple time steps. It can be inferred that in using the model, regime shift is taking place at deeper depths than the reference model, meaning that nutrient intake is also deficient at depth above 100m (figure 5a), and a balance is established between 100 to 145m. However, In figure 4 where the maximum growth rate is 0.2, the situation is vice versa where flux has

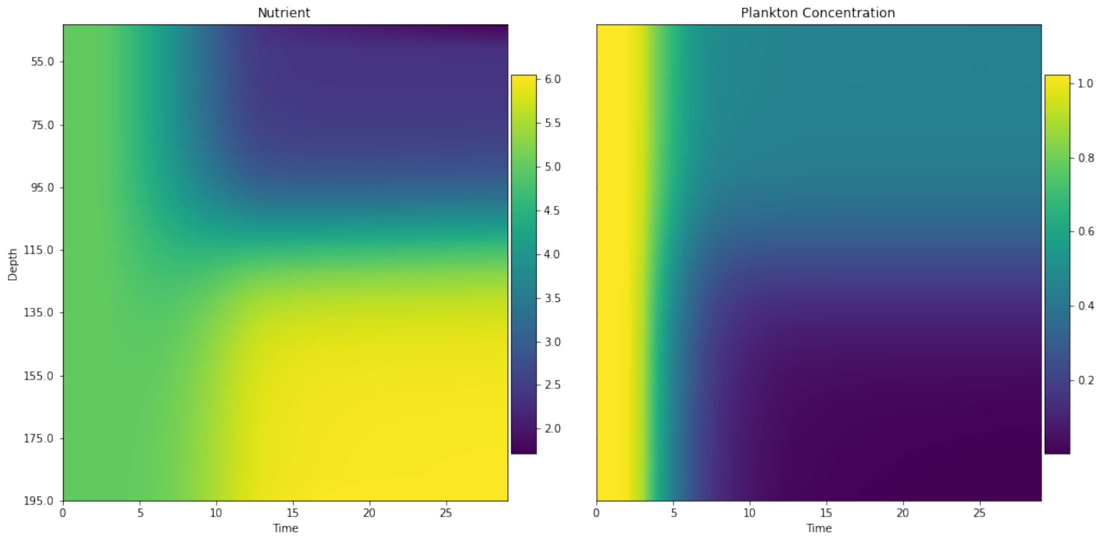
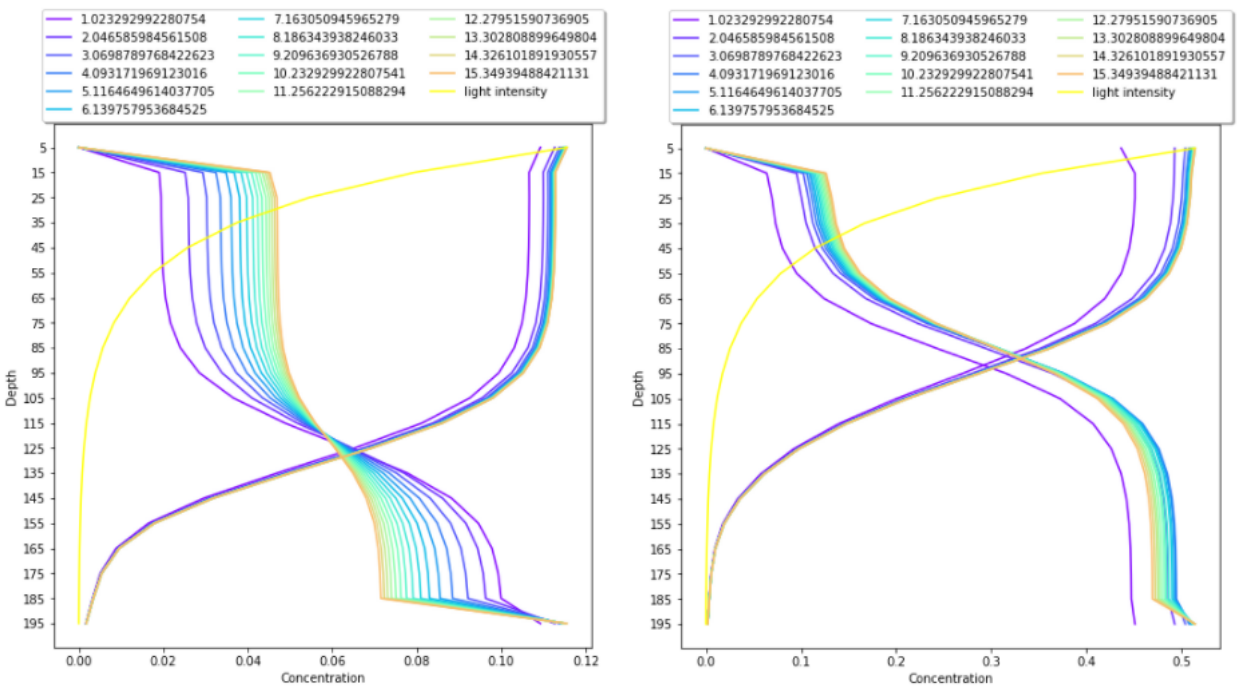


Figure 4: Change in Nutrient and phytoplankton concentration (Using high growth rate of 0.8)



(a) Using low growth rate

(b) Using high growth rate

Figure 5: Phytoplankton concentration in water profile for last time step

increased in the whole water profile, and regime shift is also taking place at shallower depths. In this case, there is a high nutrient flux in the upper layers, and phytoplankton is also sustaining for a more extended period than the reference model(figure 5b).

2.3 Effect of seasonality on phytoplankton concentration

After introducing the seasonality factor in the model (using equation 13), some periodic trends have been analyzed where temporal change can be visualized in figure 6. In the winter season, where light intensity is also very low on the surface, there seems to have less to no phytoplankton concentration in the layers. On the contrary, in summers, phytoplankton also seems to survive at higher depths. In figure 7, the drop in concentration in the balanced layer is less swift, and the increase in concentration is also supporting the extension of the balanced layer in depth.

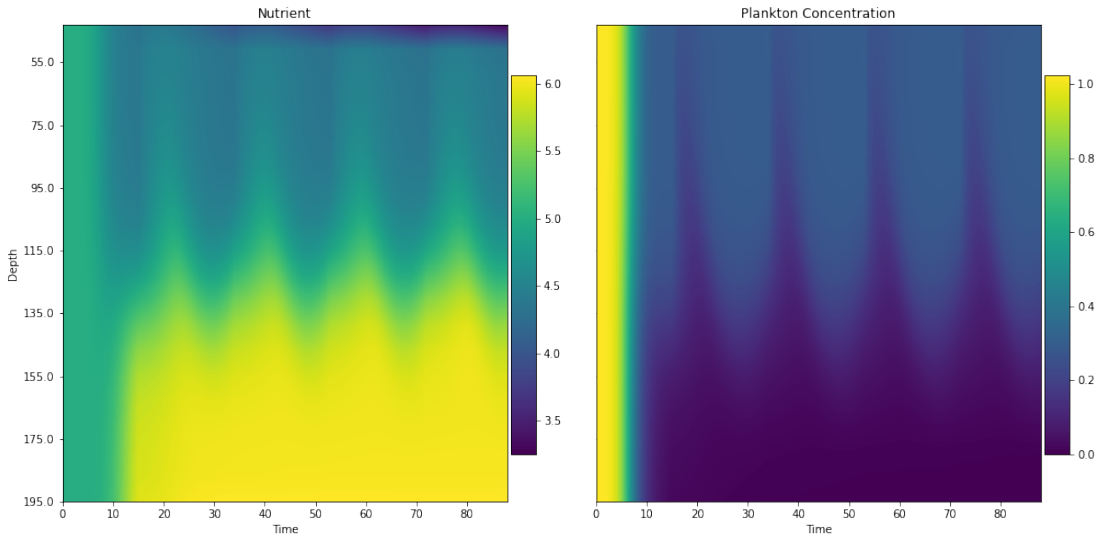


Figure 6: Seasonal Change in Nutrient and phytoplankton concentration (on ref. parameters)

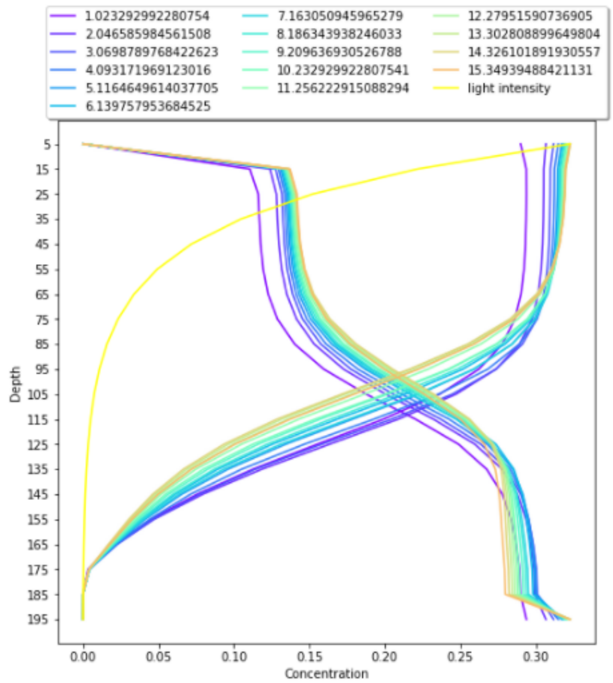


Figure 7: Seasonal effect on phytoplankton concentrations in water profile for last time step(on ref. parameters)

3 Conclusion

The main purpose of this report was to demonstrate how to apply the concept. Based on the assessment of the result, a reference model is a good model concept, considering phytoplankton, a nutrient and sinking dead organic matter in the upper ocean down to the depth of the nutrient maximum. After performing sensitivity analysis on growth rate and exploring the Effect of change in phytoplankton biomass, it can be inferred that the maximum growth rate parameter is highly sensitive and can play a significant role in phytoplankton survival across the whole water column. Furthermore, seasonal variation also controls the plankton growth and nitrogen cycle. It alters the width of the balanced layer with a change in plankton concentration which was not seen in the case of no seasonal variation.

The code can be found in the following link: https://github.com/anshch22/Computational-Marine-Ecological-Modelling

References

[1] Inga Hense Aike Beckmann. Beneath the surface: Characteristics of oceanic ecosystems under weak mixing conditions – a theoretical investigation. 20 September 2007.

[2] Bernd Blasius Alexei B. Ryabov, Lars Rudolf. Vertical distribution and composition of phytoplankton under the influence of an upper mixed layer. 20 September 2007.

[3] Ben Sommeijer Jef Huismana. Population dynamics of sinking phytoplankton in light-limited environments: simulation techniques and critical parameters. 16 May 2002.