Appendix

1 Ecosystem model

The implementation of the ecosystem model is a modification of previous work [1, 2]. The main difference is the introduction of an additional detritus compartment which allows to simulate differing decay time scales of phosphorous and nitrogen. The seven prognostic variables are: nitrate, phosphate, (non-nitrogen-fixing) phytoplankton, zooplankton, two detritus compartments describing nitrogen and phosphorus content and dissolved oxygen. Each prognostic variable C is determined following:

$$\frac{\partial C}{\partial t} = T + sms, \tag{1}$$

where T represents all diffusive and advective transport terms. sms denote the source minus sink terms, which describe the biogeochemical interactions as follows:
Phytoplankton (P) equation:

$$\mathrm{sms}\left(\mathrm{P}\right) = \overline{J}\mathrm{P} - G\left(\mathrm{P}\right)\mathrm{Z} - \mu_{\mathrm{P}}\mathrm{P} \tag{2}$$

Zooplanton (Z) equation:

$$\mathrm{sms}\left(\mathrm{Z}\right) = \gamma_1 G\left(\mathrm{P}\right)\mathrm{Z} - \gamma_2\mathrm{Z} - \mu_{\mathrm{Z}}\mathrm{Z}^2 \tag{3}$$

Nitrogen detritus (D_N) equation:

$$\mathrm{sms}\left(\mathrm{D_N}\right) = \left(1-\gamma_1\right)G\left(\mathrm{P}\right)\mathrm{Z} + \mu_{\mathrm{P}}\mathrm{P} + \mu_{\mathrm{Z}}\mathrm{Z}^2 - \mu_{\mathrm{D_N}}\mathrm{D_N} - w_s\frac{\partial \mathrm{D_N}}{\partial z} \tag{4}$$

Phosphorus detritus (D_P) equation:

$$\mathrm{sms}\left(\mathrm{D}\right) = \left(1-\gamma_1\right)G\left(\mathrm{P}\right)\mathrm{Z} + \mu_{\mathrm{P}}\mathrm{P} + \mu_{\mathrm{Z}}\mathrm{Z}^2 - \mu_{\mathrm{D_P}}\mathrm{D_P} - w_s\frac{\partial \mathrm{D_P}}{\partial z} \tag{5}$$

Nitrate ($\mathrm{NO_3}$) equation:

$$\mathrm{sms}\left(\mathrm{NO_3}\right) = \left(\mu_{\mathrm{D}}\mathrm{D} + \gamma_2\mathrm{Z}\right)\left(1 - 0.8R_{\mathrm{O:N}}\,{r_{sox}}^{NO3}\right) - \overline{J}\mathrm{P} \tag{6}$$

Phosphate ($\mathrm{PO_4}$) equation:

$$\mathrm{sms}\left(\mathrm{PO_4}\right) = \mu_{\mathrm{D}}\mathrm{D} + \gamma_2\mathrm{Z} - \overline{J}\mathrm{P} \tag{7}$$

1.1 Phytoplankton growth

The function $\overline{J} = \overline{J}\left(I, \mathrm{NO_3}, \mathrm{PO_4}\right)$ provides the growth rate of non-diazotrophic phytoplankton determined from irradiance $\left(I\right), \mathrm{NO_3}, \mathrm{PO_4}$,

$$\overline{J}\left(I, \mathrm{NO_3}, \mathrm{PO_4}\right) = min\left(J_I, J_{max}u_{\mathrm{NO3}}, J_{max}u_{\mathrm{PO4}}\right), \tag{8}$$

The maximum growth rate J_{max} is a function of temperature (T):

$$J_{max}(\mathrm{T}) = a \cdot \exp\left(\frac{\mathrm{T}}{T_b}\right) \tag{9}$$

such that growth rates increase by a factor of ten over the temperature range of -2 to 34 °C. We use $a = 0.6\,\mathrm{d}^{-1}$ for the maxium growth rate at 0 °C. Under nutrient-replete conditions, the light-limited growth rate J_I is calculated according to:

$$J_I = \frac{J_{max}\alpha I}{\left[J_{max}^2 + (\alpha I)^2\right]^{1/2}} \tag{10}$$

where α is the inital slope of the photosynthesis vs. irradiance (P-I) curve.

Nutrient limitation is represented by the product of J_{max} and the nutrient uptake rates $u_{\mathrm{NO3}} = \mathrm{NO_3}/\left(k_{\mathrm{NO3}} + \mathrm{NO_3}\right)$ and $u_{\mathrm{PO4}} = \mathrm{PO_4}/\left(k_{\mathrm{PO4}} + \mathrm{PO_4}\right)$, with $k_{\mathrm{PO4}} = k_{\mathrm{NO3}} R_{\mathrm{PO4:NO3}}$ providing the respective nutrient uptake rates.

1.2 Grazing

Zooplankton grazing of (non-nitrogen-fixing) phytoplankton $G(\mathrm{P})$ is parameterized using a Holling type III function:

$$G(\mathrm{P}) = \frac{g\epsilon \mathrm{P}^2}{g + \epsilon \mathrm{P}^2} \tag{11}$$

1.3 Sinking of Detritus

The rate of sinking of Detritus w_s is a linear function of depth z but can not exceed a maximum value of w_{Dmax}:

$$w_s = w_s(z) = \min\left(w_{\mathrm{D0}} + m_w\, z, w_{\mathrm{Dmax}}\right). \tag{12}$$

1.4 Ecosystem model parameters

Parameter	Symbol	Value	Units
Phytoplankton (P) Coefficients			
Initial slope of P-I curve	α	0.025	$\mathrm{day}^{-1}/(\mathrm{W\,m}^{-2})$
Maximum growth rate	a	0.6	day^{-1}
E-folding temperature of biotic rates	$\mathrm{T_b}$	15.65	°C
Half-saturation constant for N uptake	k_{NO3}	0.5	$\mathrm{mmol\,m}^{-3}$
Specific mortality rate of (non nitrogen-fixing) phytoplankton	μ_{P}	0.03	day^{-1}
Zooplankton (Z) Coefficients			
Assimilation efficiency	γ_1	0.75	
Maximum grazing rate	g	2.0	day^{-1}
Prey capture rate	ϵ	1.0	$(\mathrm{mmol\,m}^{-3})^{-2}\,\mathrm{day}^{-1}$
(Quadratic) mortality	μ_{Z}	0.2	$(\mathrm{mmol\,m}^{-3})^{-2}\,\mathrm{day}^{-1}$
Excretion	γ_2	0.03	day^{-1}
Detrital (D) Coefficients			
Detrital nitrogen remineralization rate	$\mu_{\mathrm{D_N}}$	0.05	day^{-1}
Euphotic layer detrital phosphorus remineralization rate	$\mu_{\mathrm{D_Ps}}$	0.1	day^{-1}
Detrital phosphorus remineralization rate	$\mu_{\mathrm{D_P}}$	0.05	day^{-1}
Sinking speed at surface	w_{D0}	7	$\mathrm{m\,day}-1$
Increase of sinking speed with depth	m_w	0.04	day^{-1}
Maximum sinking speed in water column	w_{Dmax}	40	$\mathrm{m\,day}-1$

References

[1] A. Oschlies and V. Garçon, 1999: An eddy-permitting coupled physical-biological model of the North Atlantic. Part I: Sensitivity to advection numerics and mixed layer physics. *Global Biogeochem. Cycles*, **13**.

[2] A. Schmittner, A. Oschlies, X. Giraud, M. Eby, and H.L. Simmons, 2005: A global model of the marine ecosystem for long term simulations: sensitivity to ocean mixing, buoyancy forcing, particle sinking and dissolved organic matter cycling. *Global Biogeochem. Cycles*, **19**.