This ecosystem model is mainly based on the NEMURO model which was previously developed and applied to the North Pacific (Yamanaka et al., 2004; Kishi et al., 2007). In this study, we modified and extended the model in order to investigate the dynamics of bioelements, such as nitrogen, silicon and iron in the ocean.

The unit used for each prognostic variable is as follows: for non-diatom small phytoplankton (PS), diatoms (PL), micro-zooplankton (ZS), meso-zooplankton (ZL), predatory zooplankton (ZP), nitrate (NO_3), ammonium (NH_4), small/large particulate organic nitrogen (PON_S, PON_L), dissolved organic nitrogen (DON) in molN l^{-1}; for silicate ($Si(OH)_4$) and biogenic silica (Opal) in molSi l^{-1}; for dissolved iron (Fe_d) and particulate iron (Fe_p) in molFe l^{-1}. The prognostic variables are calculated as a function of time, t, and depth, z. The governing equations for nitrogen, silicon and iron fluxes are listed below.

$$\begin{aligned}\frac{\mathrm{d}[\mathrm{PS}]}{\mathrm{d}t} = {} & (\text{PS photosynthesis}) - (\text{PS respiration}) \\ & - (\text{PS extracellular excretion}) - (\text{PS mortality}) \\ & - (\text{PS grazing by ZS}) - (\text{PS grazing by ZL}),\end{aligned} \tag{A1}$$

$$\begin{aligned}\frac{\mathrm{d}[\mathrm{PL}]}{\mathrm{d}t} = {} & (\text{PL photosynthesis}) - (\text{PL respiration}) \\ & - (\text{PL extracellular excretion}) - (\text{PL mortality}) \\ & - (\text{PL grazing by ZL}) - (\text{PL grazing by ZP}),\end{aligned} \tag{A2}$$

$$\begin{aligned}\frac{\mathrm{d}[\mathrm{ZS}]}{\mathrm{d}t} = {} & (\text{PS grazing by ZS}) - (\text{ZS excretion}) \\ & - (\text{ZS egestion}) - (\text{ZS mortality}) \\ & - (\text{ZS predation by ZL}) - (\text{ZS predation by ZP}),\end{aligned} \tag{A3}$$

$$\begin{aligned}\frac{\mathrm{d}[\mathrm{ZL}]}{\mathrm{d}t} = {} & (\text{PS grazing by ZL}) + (\text{PL grazing by ZL}) \\ & + (\text{ZS predation by ZL}) - (\text{ZL excretion}) \\ & - (\text{ZL egestion}) - (\text{ZL mortality}) \\ & - (\text{ZL predation by ZP}),\end{aligned} \tag{A4}$$

$$\begin{aligned}\frac{\mathrm{d}[\mathrm{ZP}]}{\mathrm{d}t} = {} & (\text{PL grazing by ZP}) + (\text{ZS predation by ZP}) \\ & + (\text{ZL predation by ZP}) - (\text{ZP excretion}) \\ & - (\text{ZP egestion}) - (\text{ZP mortality}),\end{aligned} \tag{A5}$$

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$$\begin{aligned}\frac{\mathrm{d}[\mathrm{NO_3}]}{\mathrm{d}t} = &\ (\text{nitrification}) \\ & - \{(\text{PS photosynthesis}) - (\text{PS respiration})\} \\ & \times R_{\mathrm{newS}} \\ & - \{(\text{PL photosynthesis}) - (\text{PL respiration})\} \\ & \times R_{\mathrm{newL}},\end{aligned} \tag{A6}$$

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$$\begin{aligned}\frac{\mathrm{d}[\mathrm{NH_4}]}{\mathrm{d}t} = &\ (\text{ZS excretion}) + (\text{ZL excretion}) \\ & + (\text{ZP excretion}) + (\text{DON remineralization}) \\ & + (\mathrm{PON_S}\ \text{remineralization}) \\ & + (\mathrm{PON_L}\ \text{remineralization}) \\ & - (\text{nitrification}) \\ & - \{(\text{PS photosynthesis}) - (\text{PS respiration})\} \\ & \times (1 - R_{\mathrm{newS}}) \\ & - \{(\text{PL photosynthesis}) - (\text{PL respiration})\} \\ & \times (1 - R_{\mathrm{newL}}),\end{aligned} \tag{A7}$$

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$$\begin{aligned}\frac{\mathrm{d}[\mathrm{PON_S}]}{\mathrm{d}t} = &\ (\text{PS mortality}) + 0.5(\text{PL mortality}) \\ & + (\text{ZS mortality}) + (\text{ZS egestion}) \\ & - (\mathrm{PON_S}\ \text{remineralization}) \\ & - (\mathrm{PON_S}\ \text{decomposition to DON}) \\ & + (\mathrm{PON_S}\ \text{settlement}) \\ & + (\text{Aggregation of DON to } \mathrm{PON_S}) \\ & - (\text{Aggregation of } \mathrm{PON_S} \text{ to } \mathrm{PON_L}),\end{aligned} \tag{A8}$$

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$$\begin{aligned}\frac{\mathrm{d}[\mathrm{PON_L}]}{\mathrm{d}t} = &\ 0.5(\text{PL mortality}) + (\text{ZL mortality}) \\ & + (\text{ZP mortality}) + (\text{ZL egestion}) \\ & + (\text{ZP egestion}) \\ & - (\mathrm{PON_L}\ \text{remineralization}) \\ & - (\mathrm{PON_L}\ \text{decomposition to DON}) \\ & + (\mathrm{PON_L}\ \text{settlement}) \\ & + (\text{Aggregation of DON to } \mathrm{PON_L}) \\ & + (\text{Aggregation of } \mathrm{PON_S} \text{ to } \mathrm{PON_L}),\end{aligned} \tag{A9}$$

$$\frac{d[\mathrm{DON}]}{dt} = (\text{PS extracellular excretion}) + (\text{PL extracellular excretion}) + (\text{PON}_\mathrm{S}\ \text{decomposition to DON}) + (\text{PON}_\mathrm{L}\ \text{decomposition to DON}) - (\text{Aggregation of DON to PON}_\mathrm{S}) - (\text{Aggregation of DON to PON}_\mathrm{L}) - (\text{DON remineralization}), \tag{A10}$$

$$\frac{d[\mathrm{Si(OH)_4}]}{dt} = (\text{Opal dissolution}) - (\text{Opal formation}), \tag{A11}$$

$$\frac{d[\mathrm{Opal}]}{dt} = (\text{Opal egestion by ZL}) + (\text{Opal egestion by ZP}) + (\text{Opal derived from PL mortality}) - (\text{Opal dissolution}) + (\text{Opal settlement}), \tag{A12}$$

$$\frac{d[\mathrm{Fe_d}]}{dt} = \left[\frac{d[\mathrm{NO_3}]}{dt} + \frac{d[\mathrm{NH_4}]}{dt}\right] \times R_\mathrm{FeN} + (\text{Dust dissolution}) + (\mathrm{Fe_p}\ \text{desorption}) - (\mathrm{Fe_d}\ \text{scavenging}), \tag{A13}$$

$$\frac{d[\mathrm{Fe_p}]}{dt} = (\mathrm{Fe_d}\ \text{scavenging}) - (\mathrm{Fe_p}\ \text{desorption}) + (\mathrm{Fe_p}\ \text{settlement}) - (\mathrm{Fe_p}\ \text{burial}). \tag{A14}$$

A2 Formulation of each source/sink process

In the following, the model's source minus sink (sms) equations are listed, and parameter values described below are shown in Table 1.

Photosynthesis of PS is determined by temperature (T, ℃), NH_4, NO_3, Fe_d and photosynthetically active radiation (I, W m^{-2}) to which solar radiation in the model is converted by multiplying by 0.45 as in Fujii et al. (2007), and is expressed as

$$(\text{PS photosynthesis}) = \min(\mu_\mathrm{N}^\mathrm{PS}, \mu_\mathrm{Fe_d}^\mathrm{PS}) L_{f,\mathrm{PS}}(I) \exp(k_\mathrm{PS} T)[\mathrm{PS}], \tag{A15}$$

where $\mu_\mathrm{N}^\mathrm{PS}$ and $\mu_\mathrm{Fe_d}^\mathrm{PS}$ are nitrogen (NH_4 and NO_3) and dissolved iron limited growth rates, respectively, and $L_{f,\mathrm{PS}}(I)$ is a non-dimensional light limiting factor. $\mu_\mathrm{N}^\mathrm{PS}$ and $\mu_\mathrm{Fe_d}^\mathrm{PS}$ are calculated based on the Optimum Uptake (OU) kinetics for nutrients proposed by Smith and Yamanaka (2007) and Smith et al. (2009) as follows:

$$\mu_{\mathrm{N}}^{\mathrm{PS}} = \frac{V_{0,\mathrm{PS}}[\mathrm{NO_3}]}{\dfrac{[\mathrm{NO_3}]}{1-f_{\mathrm{AS}}} + \dfrac{V_{0,\mathrm{PS}}}{f_{\mathrm{AS}} A_{0,\mathrm{NO3,PS}}}} \left(1 - \frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + K_{\mathrm{NH4,PS}}}\right) + \frac{V_{0,\mathrm{PS}}[\mathrm{NH_4}]}{\dfrac{[\mathrm{NH_4}]}{1-f_{\mathrm{AS}}} + \dfrac{V_{0,\mathrm{PS}}}{f_{\mathrm{AS}} A_{0,\mathrm{NH4,PS}}}}, \quad \text{(A16)}$$

$$\mu_{\mathrm{Fe_d}}^{\mathrm{PS}} = \frac{V_{0,\mathrm{PS}}[\mathrm{Fe_d}]}{\dfrac{[\mathrm{Fe_d}]}{1-f_{\mathrm{AS}}} + \dfrac{V_{0,\mathrm{PS}}}{f_{\mathrm{AS}} A_{0,\mathrm{Fe_d,PS}}}}, \quad \text{(A17)}$$

where $V_{0,\mathrm{PS}}$, $A_{0,\mathrm{NO_3,PS}}$, $A_{0,\mathrm{NH_4,PS}}$ and $A_{0,\mathrm{Fe_d,PS}}$ are the potential maximum growth rate of PS, and potential maximum affinity of PS for NO_3, NH_4 and Fe_d, respectively, and f_{AS} represents the fraction of internal resources (nitrogen) allocated to the cellular surface sites of PS. For inhibition of nitrate uptake by ammonium, the parameterization of Vallina and Le Quéré (2008) is used. In this study, $A_{0,\mathrm{NO_3,PS}}$ is optimized, and $A_{0,\mathrm{NH_4,PS}}$, $A_{0,\mathrm{Fe_d,PS}}$ and f_{AS} are expressed as follows:

$$A_{0,\mathrm{NH_4,PS}} = A_{0,\mathrm{NO_3,PS}} \frac{K_{\mathrm{NO_3,PS}}}{K_{\mathrm{NH_4,PS}}}, \quad \text{(A18)}$$

$$A_{0,\mathrm{Fe_d,PS}} = A_{0,\mathrm{NO_3,PS}} \frac{K_{\mathrm{NO_3,PS}}}{K_{\mathrm{Fe_d,PS}}}, \quad \text{(A19)}$$

where $K_{\mathrm{NO_3,PS}}$ (1.0 μmol l^{-1}), $K_{\mathrm{NH_4,PS}}$ (0.1 μmol l^{-1}), $K_{\mathrm{Fe_d,PS}}$ (0.05 nmol l^{-1}) are values of Michaelis-Menten half-saturation constants as estimated in previous studies (Yamanaka et al., 2004; Takeda et al., 2006). Thus, the ratios of affinities for different nutrients, which determine which nutrient will be limiting upon nutrient depletion, are kept consistent with the parameterizations of previous studies. Although with affinity-based kinetics, values of the potential mximum affinity, $A_{0,\mathrm{NH_4,PS}}$ and $A_{0,\mathrm{Fe_d,PS}}$ can be obtained from experimental data, just as half-saturation constants can be obtained by fits to the Michaelis-Menten equation, few estimates of affinity-based parameters exist for large-scale modeling. We therefore calculate initial estimates for potential maximum affinities based on existing estimates of Michaelis-Menten (MM) half saturation constants from previous modeling research.

$$f_{\mathrm{AS}} = \max\left[\left(1 + \sqrt{\frac{\max(A_{0,\mathrm{NO_3,PS}}[\mathrm{NO_3}], A_{0,\mathrm{NH_4,PS}}[\mathrm{NH_4}])}{V_{0,\mathrm{PS}}}}\right)^{-1}, \left(1 + \sqrt{\frac{A_{0,\mathrm{Fe_d,PS}}[\mathrm{Fe_d}]}{V_{0,\mathrm{PS}}}}\right)^{-1}\right]. \quad \text{(A20)}$$

Eq. (A20) for f_{AS} stipulates that acclimation occurs with respect to the limiting nutrient only.

For the non-dimensional light limiting factor of PS, the formula of Platt et al. (1980) is used,

$$L_{f,\mathrm{PS}}(I)=\frac{\left\{1-\exp\left(-\frac{\alpha_{\mathrm{PS}}I}{P_{S,\mathrm{PS}}}\right)\right\}\exp\left(-\frac{\beta_{\mathrm{PS}}I}{P_{S,\mathrm{PS}}}\right)}{\left(\frac{\alpha_{\mathrm{PS}}}{\alpha_{\mathrm{PS}}+\beta_{\mathrm{PS}}}\right)\left(\frac{\beta_{\mathrm{PS}}}{\alpha_{\mathrm{PS}}+\beta_{\mathrm{PS}}}\right)^{\beta_{\mathrm{PS}}/\alpha_{\mathrm{PS}}}}, \qquad \text{(A21)}$$

in which α_{PS}, β_{PS} and $P_{S,\mathrm{PS}}$ denote initial slope of the photosynthesis-irradiance (P-E) curve, photoinhibition index, and potential maximum light-saturated photosynthetic rate under the prevailing condition. F-ratio of PS (R_{newS}) can be defined as

$$R_{\mathrm{newS}}=\frac{\frac{V_{0,\mathrm{PS}}[\mathrm{NO_3}]}{\frac{[\mathrm{NO_3}]}{1-f_{\mathrm{AS}}}+\frac{V_{0,\mathrm{PS}}}{f_{\mathrm{AS}}A_{0,\mathrm{NO_3},\mathrm{PS}}}}\left(1-\frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}]+K_{\mathrm{NH_4},\mathrm{PS}}}\right)}{\frac{V_{0,\mathrm{PS}}[\mathrm{NO_3}]}{\frac{[\mathrm{NO_3}]}{1-f_{\mathrm{AS}}}+\frac{V_{0,\mathrm{PS}}}{f_{\mathrm{AS}}A_{0,\mathrm{NO_3},\mathrm{PS}}}}\left(1-\frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}]+K_{\mathrm{NH_4},\mathrm{PS}}}\right)+\frac{V_{0,\mathrm{PS}}[\mathrm{NH_4}]}{\frac{[\mathrm{NH_4}]}{1-f_{\mathrm{AS}}}+\frac{V_{0,\mathrm{PS}}}{f_{\mathrm{AS}}A_{0,\mathrm{NH_4},\mathrm{PS}}}}}. \qquad \text{(A22)}$$

Photosynthesis of PL is determined as in that of PS except that PL photosynthesis is also dependent on silicate.

$$(\text{PL photosynthesis})=\min(\mu_{\mathrm{N}}^{\mathrm{PL}},\ \mu_{\mathrm{Si}}^{\mathrm{PL}},\ \mu_{\mathrm{Fe_d}}^{\mathrm{PL}})L_{f,\mathrm{PL}}(I)\exp(k_{\mathrm{PL}}T)[\mathrm{PL}], \qquad \text{(A23)}$$

where $\mu_{\mathrm{N}}^{\mathrm{PL}}$, $\mu_{\mathrm{Si}}^{\mathrm{PL}}$ and $\mu_{\mathrm{Fe_d}}^{\mathrm{PL}}$ are nitrogen (NH_4 and NO_3), $Si(OH)_4$ and Fe_d limited growth rates of PL, respectively, $L_{f,\mathrm{PL}}(I)$ is a non-dimensional light limiting factor for PL. $\mu_{\mathrm{N}}^{\mathrm{PL}}$, $\mu_{\mathrm{Si}}^{\mathrm{PL}}$ and $\mu_{\mathrm{Fe_d}}^{\mathrm{PL}}$ are expressed in the following.

$$\mu_{\mathrm{N}}^{\mathrm{PL}}=\frac{V_{0,\mathrm{PL}}[\mathrm{NO_3}]}{\frac{[\mathrm{NO_3}]}{1-f_{\mathrm{AL}}}+\frac{V_{0,\mathrm{PL}}}{f_{\mathrm{AL}}A_{0,\mathrm{NO_3},\mathrm{PL}}}}\left(1-\frac{[\mathrm{NH_4}]}{[\mathrm{NH_4}]+K_{\mathrm{NH_4},\mathrm{PL}}}\right)+\frac{V_{0,\mathrm{PL}}[\mathrm{NH_4}]}{\frac{[\mathrm{NH_4}]}{1-f_{\mathrm{AL}}}+\frac{V_{0,\mathrm{PL}}}{f_{\mathrm{AL}}A_{0,\mathrm{NH_4},\mathrm{PL}}}}, \qquad \text{(A24)}$$

$$\mu_{\mathrm{Si}}^{\mathrm{PL}}=\frac{V_{0,\mathrm{PL}}[\mathrm{Si(OH)_4}]}{\frac{[\mathrm{Si(OH)_4}]}{1-f_{\mathrm{AL}}}+\frac{V_{0,\mathrm{PL}}}{f_{\mathrm{AL}}A_{0,\mathrm{Si},\mathrm{PL}}}}, \qquad \text{(A25)}$$

$$\mu_{\mathrm{Fe_d}}^{\mathrm{PL}} = \frac{V_{0,\mathrm{PL}}[\mathrm{Fe_d}]}{\dfrac{[\mathrm{Fe_d}]}{1-f_{\mathrm{AL}}} + \dfrac{V_{0,\mathrm{PL}}}{f_{\mathrm{AL}} A_{0,\mathrm{Fe_d},\mathrm{PL}}}}, \tag{A26}$$

where $V_{0,\mathrm{PL}}$, $A_{0,\mathrm{NO3},\mathrm{PL}}$, $A_{0,\mathrm{NH4},\mathrm{PL}}$, $A_{0,\mathrm{Si},\mathrm{PL}}$ and $A_{0,\mathrm{Fe_d},\mathrm{PL}}$ are the potential maximum growth rate of PL, and potential maximum affinity of PL for NO_3, NH_4, $Si(OH)_4$ and Fe_d, respectively and f_{AL} denotes the fraction of internal resources for nutrient uptake allocated to the cellular surface sites of PL. As for PS, the ratios of potential maximum affinities are set based on pre-existing estimates of Michaelis-Menten half-saturation constants, $K_{\mathrm{NO3},\mathrm{PL}}$ (3.0 μmol l^{-1}), $K_{\mathrm{NH4},\mathrm{PL}}$ (0.3 μmol l^{-1}), $K_{\mathrm{SiL},\mathrm{PL}}$ (6.0 μmol l^{-1}), $K_{\mathrm{Fe_d},\mathrm{PL}}$ (0.1 nmol l^{-1}) as follows:

$$A_{0,\mathrm{NH_4},\mathrm{PL}} = A_{0,\mathrm{NO_3},\mathrm{PL}} \frac{K_{\mathrm{NO_3},\mathrm{PL}}}{K_{\mathrm{NH_4},\mathrm{PL}}}, \tag{A27}$$

$$A_{0\mathrm{Si},\mathrm{PL}} = A_{0,\mathrm{NO_3},\mathrm{PL}} \frac{K_{\mathrm{NO_3},\mathrm{PL}}}{K_{\mathrm{SiL},\mathrm{PL}}}, \tag{A28}$$

$$A_{0,\mathrm{Fe_d},\mathrm{PL}} = A_{0,\mathrm{NO_3},\mathrm{PL}} \frac{K_{\mathrm{NO_3},\mathrm{PL}}}{K_{\mathrm{Fe_d},\mathrm{PL}}}, \tag{A29}$$

Eq. (A30) for f_{AL} stipulates that acclimation occurs with respect to the limiting nutrient only.

$$f_{\mathrm{AL}} = \max\left[\left(1+\sqrt{\frac{\max(A_{0,\mathrm{NO_3},\mathrm{PL}}[\mathrm{NO_3}], A_{0,\mathrm{NH_4},\mathrm{PL}}[\mathrm{NH_4}])}{V_{0,\mathrm{PL}}}}\right)^{-1}, \left(1+\sqrt{\frac{A_{0\mathrm{Si},\mathrm{PL}}[\mathrm{Si(OH)_4}]}{V_{0,\mathrm{PL}}}}\right)^{-1}, \left(1+\sqrt{\frac{A_{0,\mathrm{Fe_d},\mathrm{PL}}[\mathrm{Fe_d}]}{V_{0,\mathrm{PL}}}}\right)^{-1}\right]. \tag{A30}$$

For the non-dimensional light limiting factor of PL, the formula of Platt et al. (1980) is also used,

$$L_{f,\mathrm{PL}}(I) = \frac{\left\{1-\exp\left(-\dfrac{\alpha_{\mathrm{PL}} I}{P_{S,\mathrm{PL}}}\right)\right\}\exp\left(-\dfrac{\beta_{\mathrm{PL}} I}{P_{S,\mathrm{PL}}}\right)}{\left(\dfrac{\alpha_{\mathrm{PL}}}{\alpha_{\mathrm{PL}}+\beta_{\mathrm{PL}}}\right)\left(\dfrac{\beta_{\mathrm{PL}}}{\alpha_{\mathrm{PL}}+\beta_{\mathrm{PL}}}\right)^{\beta_{\mathrm{PL}}/\alpha_{\mathrm{PL}}}}. \tag{A31}$$

F-ratio of PL (R_{newL}) is defined as follows:

$$R_{\mathrm{newL}} = \frac{\dfrac{V_{0,\mathrm{PL}}[\mathrm{NO_3}]}{\dfrac{[\mathrm{NO_3}]}{1-f_{\mathrm{AL}}} + \dfrac{V_{0,\mathrm{PL}}}{f_{\mathrm{AL}} A_{0,\mathrm{NO_3,PL}}}} \left(1 - \dfrac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + K_{\mathrm{NH_4,PL}}}\right)}{\dfrac{V_{0,\mathrm{PL}}[\mathrm{NO_3}]}{\dfrac{[\mathrm{NO_3}]}{1-f_{\mathrm{AL}}} + \dfrac{V_{0,\mathrm{PL}}}{f_{\mathrm{AL}} A_{0,\mathrm{NO_3,PL}}}} \left(1 - \dfrac{[\mathrm{NH_4}]}{[\mathrm{NH_4}] + K_{\mathrm{NH_4,PL}}}\right) + \dfrac{V_{0,\mathrm{PL}}[\mathrm{NH_4}]}{\dfrac{[\mathrm{NH_4}]}{1-f_{\mathrm{AL}}} + \dfrac{V_{0,\mathrm{PL}}}{f_{\mathrm{AL}} A_{0,\mathrm{NH_4,PL}}}}}. \tag{A32}$$

Light intensity at the depth z used in Eqs. (A21) and (A31) is represented as follows:

$$I = I_0 \exp(-\int_0^z \kappa \mathrm{d}z), \tag{A33}$$

$$\kappa = \alpha_1 + \alpha_2([\mathrm{PS}] + [\mathrm{PL}]), \tag{A34}$$

where I_0 is the irradiance at the sea surface, imposed as a boundary condition, and κ is the light extinction coefficient.

The formulae used for respiration, extracellular excretion and mortality of phytoplankton, PS and PL, and mortality of zooplankton, ZS, ZL and ZP are the same as the previous model and read:

$$(\text{PS respitation}) = R_{\mathrm{PS0}} \exp(k_{\mathrm{RS}} T)[\mathrm{PS}], \tag{A35}$$

$$(\text{PL respitation}) = R_{\mathrm{PL0}} \exp(k_{\mathrm{RL}} T)[\mathrm{PL}], \tag{A36}$$

$$(\text{PS extracellular excretion}) = \gamma_{\mathrm{S}}(\text{PS photosynthesis}), \tag{A37}$$

$$(\text{PL extracellular excretion}) = \gamma_{\mathrm{L}}(\text{PL photosynthesis}), \tag{A38}$$

$$(\text{PS mortality}) = M_{\mathrm{PS0}} \exp(k_{\mathrm{MS}} T)[\mathrm{PS}]^2, \tag{A39}$$

$$(\text{PL mortality}) = M_{\mathrm{PL0}} \exp(k_{\mathrm{ML}} T)[\mathrm{PL}]^2, \tag{A40}$$

$$(\text{ZS mortality}) = M_{\mathrm{ZS0}} \exp(k_{\mathrm{MZS}} T)[\mathrm{ZS}]^2, \tag{A41}$$

$$(\text{ZL mortality}) = M_{\mathrm{ZL0}} \exp(k_{\mathrm{MZL}} T)[\mathrm{ZL}]^2, \tag{A42}$$

$$(\text{ZP mortality}) = M_{\mathrm{ZP0}} \exp(k_{\mathrm{MZP}} T)[\mathrm{ZP}]^2, \tag{A43}$$

As in the previous model, grazing and predation by zooplankton are derived from the formulae:

$$\begin{aligned}(\text{PS grazing by ZS}) = G_{\mathrm{RmaxS}} &\max[0, 1 - \exp\{\lambda_{\mathrm{S}}(\mathrm{PS}^*_{ZS} - [\mathrm{PS}])\}] \\ &\times \exp(k_{\mathrm{GS}} T)[\mathrm{ZS}],\end{aligned} \tag{A44}$$

$$(\text{PS grazing by ZL}) = G_{\text{RmaxL,PS}} \max[0, 1 - \exp\{\lambda_{\text{L}}(\text{PS}^*_{\text{ZL}} - [\text{PS}])\}] \times \exp(k_{\text{GL}} T)[\text{ZL}], \quad \text{(A45)}$$

$$(\text{PL grazing by ZL}) = G_{\text{RmaxL,PL}} \max[0, 1 - \exp\{\lambda_{\text{L}}(\text{PL}^*_{\text{ZL}} - [\text{PL}])\}] \times \exp(k_{\text{GL}} T)[\text{ZL}], \quad \text{(A46)}$$

$$(\text{ZS predation by ZL}) = G_{\text{RmaxL,ZS}} \max[0, 1 - \exp\{\lambda_{\text{L}}(\text{ZS}^*_{\text{ZL}} - [\text{ZS}])\}] \times \exp(k_{\text{GL}} T)[\text{ZL}], \quad \text{(A47)}$$

$$(\text{PL grazing by ZP}) = G_{\text{RmaxP,PL}} \max[0, 1 - \exp\{\lambda_{\text{P}}(\text{PL}^*_{\text{ZP}} - [\text{PL}])\}] \times \exp\{-\Psi_{\text{PL}}([\text{ZS}] + [\text{ZL}])\} \exp(k_{\text{GP}} T)[\text{ZP}], \quad \text{(A48)}$$

$$(\text{ZS predation by ZP}) = G_{\text{RmaxP,ZS}} \max[0, 1 - \exp\{\lambda_{\text{P}}(\text{ZS}^*_{\text{ZP}} - [\text{ZS}])\}] \times \exp(-\Psi_{\text{ZS}}[\text{ZL}]) \exp(k_{\text{GP}} T)[\text{ZP}], \quad \text{(A49)}$$

$$(\text{ZL predation by ZP}) = G_{\text{RmaxP,ZL}} \max[0, 1 - \exp\{\lambda_{\text{P}}(\text{ZL}^*_{\text{ZP}} - [\text{ZL}])\}] \times \exp(k_{\text{GP}} T)[\text{ZP}]. \quad \text{(A50)}$$

Excretion and egestion for ZS, ZL and ZP are also the same as in the previous model and read:

$$(\text{ZS excretion}) = (\alpha_{\text{ZS}} - \beta_{\text{ZS}})(\text{PS grazing by ZS}), \quad \text{(A51)}$$

$$(\text{ZL excretion}) = (\alpha_{\text{ZL}} - \beta_{\text{ZL}})\{(\text{PS grazing by ZL}) + (\text{PL grazing by ZL}) + (\text{ZS predation by ZL})\}, \quad \text{(A52)}$$

$$(\text{ZP excretion}) = (\alpha_{\text{ZP}} - \beta_{\text{ZP}})\{(\text{PL grazing by ZP}) + (\text{ZS predation by ZP}) + (\text{ZL predation by ZP})\}, \quad \text{(A53)}$$

$$(\text{ZS egestion}) = (1 - \alpha_{\text{ZS}})(\text{PS grazing by ZS}), \quad \text{(A54)}$$

$$(\text{ZL egestion}) = (1 - \alpha_{\text{ZL}})\{(\text{PS grazing by ZL}) + (\text{PL grazing by ZL}) + (\text{ZS predation by ZL})\}, \quad \text{(A55)}$$

$$(\text{ZP egestion}) = (1 - \alpha_{\text{ZP}})\{(\text{PL grazing by ZP}) + (\text{ZS predation by ZP}) + (\text{ZL predation by ZP})\}. \quad \text{(A56)}$$

As in the previous model, decomposition and remineralization of PON_S, PON_L, DON and Opal and nitrification are formulated as follows:

$$(\text{PON}_\text{S} \text{ remineralization}) = V_{\text{PA0S}} \exp(k_{\text{PAS}} T)[\text{PON}_\text{S}], \quad \text{(A57)}$$

$$(\text{PON}_\text{S} \text{ decomposition to DON}) = V_{\text{PD0S}} \exp(k_{\text{PDS}} T)[\text{PON}_\text{S}], \quad \text{(A58)}$$

$$(\text{PON}_\text{L} \text{ remineralization}) = V_{\text{PA0L}} \exp(k_{\text{PAL}} T)[\text{PON}_\text{L}], \quad \text{(A59)}$$

$$(\text{PON}_\text{L} \text{ decomposition to DON}) = V_{\text{PD0L}} \exp(k_{\text{PDL}} T)[\text{PON}_\text{L}], \quad \text{(A60)}$$

$$\text{(DON remineralization)} = V_{\text{DA0}} \exp(k_{\text{DA}} T)[\text{DON}], \quad \text{(A61)}$$

$$\text{(Opal dissolution)} = V_{\text{Opal}} \exp(k_{\text{Opal}} T)[\text{Opal}], \quad \text{(A62)}$$

$$\text{(Nitrification)} = V_{\text{Nit0}} \exp(k_{\text{Nit}} T)[\text{NH}_4], \quad \text{(A63)}$$

Although PON is divided into two classes in the present model, the specific decomposition and remineralization rates are assumed to be the same.

The equations for the biogenic opal (Opal) are also the same as in the previous model, except for settling.

$$\begin{aligned}\text{(Opal formation)} = \{&\text{(PL photosynthesis)} - \text{(PL respiration)} \\ &- \text{(PL extracellular excretion)}\} \times R_{\text{SiN}},\end{aligned} \quad \text{(A64)}$$

$$\text{(Opal derived from PL mortality)} = \text{(PL mortality)} \times R_{\text{SiN}}, \quad \text{(A65)}$$

$$\text{(Opal egestion by ZL)} = \text{(PL grazing by ZL)} \times R_{\text{SiN}}, \quad \text{(A66)}$$

$$\text{(Opal egestion by ZP)} = \text{(PL grazing by ZP)} \times R_{\text{SiN}}. \quad \text{(A67)}$$

R_{SiN} is determined by the surrounding dissolved iron concentration because in the iron deficient condition diatoms tend to uptake the silicate and nitrate in higher Si:N ratio than that in the iron rich condition (e.g., Takeda, 1998). That is simply formulated as follows:

$$R_{\text{SiN}} = \begin{cases} R_{\text{SiNH}} & ([\text{Fe}_{\text{d}}] \geq \text{Fe}^{*}_{\text{SiN}}) \\ R_{\text{SiNL}} & ([\text{Fe}_{\text{d}}] < \text{Fe}^{*}_{\text{SiN}}) \end{cases}. \quad \text{(A68)}$$

The aggregation processes between DON, PON_{S} and PON_{L} due to turbulence and differential settling are considered based on the parameterization propopsed by Aumont and Bopp (2006) as follows:

$$\text{(Aggregation for DON to PON}_{\text{S}}) = \phi_1^{\text{DON}} \text{sh}[\text{DON}]^2 + \phi_2^{\text{DON}} \text{sh}[\text{DON}][\text{PON}_{\text{S}}], \quad \text{(A69)}$$

$$\text{(Aggregation for DON to PON}_{\text{L}}) = \phi_3^{\text{DON}} \text{sh}[\text{DON}][\text{PON}_{\text{L}}], \quad \text{(A70)}$$

$$\begin{aligned}\text{(Aggregation for PON}_{\text{S}} \text{ to PON}_{\text{L}}) = {}&\phi_1^{\text{PONs}} \text{sh}[\text{PON}_{\text{S}}]^2 + \phi_2^{\text{PONs}} \text{sh}[\text{PON}_{\text{S}}][\text{PON}_{\text{L}}] \\ &+ \phi_3^{\text{PONs}} [\text{PON}_{\text{S}}]^2 + \phi_4^{\text{PONs}} [\text{PON}_{\text{S}}][\text{PON}_{\text{L}}].\end{aligned} \quad \text{(A71)}$$

In (A69) to (A71), sh depicts the shear rate which was set at 1 s^{-1} in the mixed layer and at 0.01 s^{-1} elsewhere.

The sinking of particles is described as follows:

$$(\mathrm{PON_S}\ \text{settlement}) = -w^{\mathrm{PONS}} \frac{\partial[\mathrm{PON_S}]}{\partial z}, \quad \text{(A72)}$$

$$(\mathrm{PON_L}\ \text{settlement}) = -\frac{\partial (w^{\mathrm{PON_L}}[\mathrm{PON_L}])}{\partial z}, \quad \text{(A73)}$$

$$(\text{Opal settlement}) = -\frac{\partial (w^{\mathrm{Opal}}[\mathrm{Opal}])}{\partial z}. \quad \text{(A74)}$$

The sinking speed of $\mathrm{PON_L}$, $w^{\mathrm{PON_L}}$, increases with depth as in Aumont and Bopp (2006) and reads:

$$w^{\mathrm{PON_L}} = w_{\min}^{\mathrm{PON_L}} + (w_{\max}^{\mathrm{PON_L}} - w_{\min}^{\mathrm{PON_L}}) \times (\frac{z - z_{\mathrm{MLD}}}{2000}). \quad \text{(A75)}$$

where z_{MLD} is the depth of the mixed layer. So far, the sinking rate of Opal (w^{Opal}) is the same as that of $\mathrm{PON_L}$, and thus Opal settles at the same sinking speed as $\mathrm{PON_L}$.

The formulae used for $\mathrm{Fe_d}$ and $\mathrm{Fe_p}$ are basically derived from the parameterization of Moore et al. (2004) and Moore and Braucher (2008). In terms of $\mathrm{Fe_p}$ desorption, we considered Arrhenius type temperature dependency. The settlement of $\mathrm{Fe_p}$ differs from the previous researches treating that as instantaneously sinking matter. However, dust is treated as instantaneously sinking matter as in the previous researches.

$$(\text{Dust dissolution}) = \begin{cases} 0.01\alpha F_{0,\mathrm{Fe\_dust}} / \Delta z_s - \left(\frac{\partial F_{\mathrm{Fe\_soft\_dust}}}{\partial z} + \frac{\partial F_{\mathrm{Fe\_hard\_dust}}}{\partial z} \right) & \text{(top-most layer)} \\ -\left(\frac{\partial F_{\mathrm{Fe\_soft\_dust}}}{\partial z} + \frac{\partial F_{\mathrm{Fe\_hard\_dust}}}{\partial z} \right) & \text{(elsewhere),} \end{cases} \quad \text{(A76)}$$

where $F_{0,\mathrm{Fe\_dust}}$ is the dust-derived iron flux as the boundary condition and calculated using iron content (C_{iron}) of 3.5% in dust, iron atomic weight ($A_{w,\mathrm{Fe}}$) and prescribed dust flux ($F_{0,\mathrm{dust}}$). α is the % solubility of iron in dust, and ΔZ_s is the thickness of the model's top-most layer. All the soluble iron is treated as bioavailable one. As in the previous researches, left dust-derived iron flux is separated into two components, relatively labile ($F_{\mathrm{Fe\_soft\_dust}}$) and refractory ($F_{\mathrm{Fe\_hard\_dust}}$) components, and the dissolutions at a given depth (z) are considered with different length scale ($\delta_{\mathrm{soft\_dust}}, \delta_{\mathrm{hard\_dust}}$) as follows:

$$F_{\mathrm{Fe\_soft\_dust}}(z) = F_{0,\mathrm{Fe\_dust}}(1-0.01\alpha)(1-f_{\mathrm{hard}})e^{-\frac{z}{\delta_{\mathrm{soft\_dust}}}}, \qquad \text{(A77)}$$

$$F_{\mathrm{Fe\_hard\_dust}}(z) = F_{0,\mathrm{Fe\_dust}}(1-0.01\alpha)f_{\mathrm{hard}}e^{-\frac{z}{\delta_{\mathrm{hard\_dust}}}}. \qquad \text{(A78)}$$

Dust is also treated as above in the model to reduce the computational cost of running the model, but the dust flux at a given depth is involved in the below scavenging process.

The scavenging of Fe_d, desorption and settlement of Fe_p are formulated as follows:

$$(\mathrm{Fe_d\ scavenging}) = \begin{cases} f_{\mathrm{Fe_p}}\lambda_{\mathrm{scav}}(F_{\mathrm{POC}}+F_{\mathrm{dust}})[\mathrm{Fe_d}] & ([\mathrm{Fe_d}] < C_{\mathrm{ligand}}(0.6\mathrm{nM})) \\ f_{\mathrm{Fe_p}}\{\lambda_{\mathrm{scav}}(F_{\mathrm{POC}}+F_{\mathrm{dust}})[\mathrm{Fe_d}] + \gamma_{\mathrm{high}}([\mathrm{Fe_d}]-C_{\mathrm{ligand}})\}[\mathrm{Fe_d}] & ([\mathrm{Fe_d}] \geq C_{\mathrm{ligand}}(0.6\mathrm{nM}))' \end{cases}$$

(A79)

$$(\mathrm{Fe_d\ burial}) = \begin{cases} (1-f_{\mathrm{Fe_p}})\lambda_{\mathrm{scav}}(F_{\mathrm{POC}}+F_{\mathrm{dust}})[\mathrm{Fe_d}] & ([\mathrm{Fe_d}] < C_{\mathrm{ligand}}(0.6\mathrm{nM})) \\ (1-f_{\mathrm{Fe_p}})\{\lambda_{\mathrm{scav}}(F_{\mathrm{POC}}+F_{\mathrm{dust}})[\mathrm{Fe_d}] + \gamma_{\mathrm{high}}([\mathrm{Fe_d}]-C_{\mathrm{ligand}})\}[\mathrm{Fe_d}] & ([\mathrm{Fe_d}] \geq C_{\mathrm{ligand}}(0.6\mathrm{nM}))' \end{cases}$$

(A80)

$$(\mathrm{Fe_p\ desorption}) = \lambda_{\mathrm{desorption}} \exp\left\{-A_E\left(\frac{1}{T}-\frac{1}{T_{\mathrm{ref}}}\right)\right\}[\mathrm{Fe_p}], \qquad \text{(A81)}$$

$$(\mathrm{Fe_p\ settlement}) = -w_{\mathrm{Fep}}\frac{\partial[\mathrm{Fe_p}]}{\partial z}. \qquad \text{(A82)}$$

In A79 and A80, F_{POC} and F_{dust} represent the flux of POC and dust at a given depth, respectively, and C_{ligand} is the prescribed total ligand concentration (0.6nM). F_{POC} is converted from PON flux with R_{CN}.