Supplementary Material

# CESM model equations

The equations listed below are written for the small phytoplankton functional group or class in CESM. The equations for diatoms are similar in form, with some minor exceptions noted below; small phytoplankton and diatom function groups utilize different parameter values (see parameters in Table in Section 2 of Supplementary Material).

The change in small phytoplankton carbon biomass over time (left side of equation 1) is the net result of phytoplankton growth (first term on the right side), grazing, mortality, and aggregation.

|  |  |
| --- | --- |
|  | (1) |

Equation 2 describes the light limitation for the phytoplankton growth.

|  |  |
| --- | --- |
|  | (2) |

Equation 3 describes the nutrient and temperature limitation.

|  |  |
| --- | --- |
|  | (3) |

Equation 4 describes Liebig’s law of the minimum for overall nutrient limitation.

|  |  |
| --- | --- |
|  | (4) |

For the diatom functional group, the nutrient limitation equation (Equation 4) includes an additional uptake term for silicate associated with diatom test formation.

Equations 5-7: Nitrogen limitation as Michaelis-Menten form with ammonia inhibition of nitrate uptake.

|  |  |
| --- | --- |
|  | (5) |

|  |  |
| --- | --- |
|  | (6) |

|  |  |
| --- | --- |
|  | (7) |

Equation 8-9: Nutrient limitation as Michaelis-Menten form for phosphate and iron.

|  |  |
| --- | --- |
|  | (8) |

|  |  |
| --- | --- |
|  | (9) |

The diatom functional group incorporates a similar Michaelis-Menten like equation for Si uptake.

Equation 10: Temperature limitation on maximum growth.

|  |  |
| --- | --- |
|  | (10) |

Equation 11: Depth dependence of light (PAR).

|  |  |
| --- | --- |
|  | (11) |

Equation 12: Grazing (Holling’s type III functional response).

|  |  |
| --- | --- |
|  | (12) |

Grazing is the dominate phytoplankton loss-term during moderate to bloom phytoplankton biomass conditions (Behrenfeld et al., 2013).

Equation 13: Linear mortality with temperature term.

|  |  |
| --- | --- |
|  | (13) |

Equation 14: Aggregation with either linear or quadratic term.

|  |  |
| --- | --- |
|  | (14) |

The mortality and aggregation terms reflect different biological processes (e.g. viral lysis and programmed cell death for the mortality term); for diagnostic purposes, however, the two terms are sometimes combined into a single, non-grazing loss term. The relative contribution of the aggregation term increases with biomass, however, the linear mortality term tends to dominate non-grazing loss except at low temperatures because of the temperature function.

The aggregation term for diatoms incorporates an additional lower limit on aggregation based a linear function of diatom biomass with a small minimum rate parameter.

To keep simulated phytoplankton biomass levels from going to zero in the upper ocean, the loss terms incorporate minimum threshold biomass values, 0.001 mmol C/m3 for small phytoplankton and 0.02 mmol C/m3 for diatoms. The threshold values are applied in the depth range 0-100 m and decline linearly to zero at 200 m.

The routing of the carbon losses associated with the non-ingested grazing, mortality, and aggregation terms is functional group dependent, with a larger fraction of the diatom carbon loss routed towards sinking detrital material with the remainder routed into zooplankton growth, remineralization into dissolved inorganic carbon, and a small leakage flux of organic carbon into semi-labile dissolved organic carbon pool.

Equation 15: Chlorophyll to carbon ratio.

|  |  |
| --- | --- |
|  | (15) |

# The ingested fraction (*zingest*=0.3) of the grazed carbon *Gsp* and *Gdiat* (Equation 12) is routed to the single zooplankton class, where time rate of change equation for zooplankton carbon biomass, *ZC*, is given by:

|  |  |
| --- | --- |
|  | (16) |

where *Zloss* is a closure term that addresses zooplankton mortality and, implicitly, grazing by higher trophic levels; carnivores are not modeled explicitly. The *Zloss* term includes linear and power-law elements proportional to *ZC* and (*ZC)*1.4 ,effectively mortalityand carnivory. Similar to phytoplankton, a minimum threshold value of 0.2 mmol C/m3 is incorporated for zooplankton biomass in the upper ocean.

# CESM model parameters

| Parameter | Value | Unit | Definition |
| --- | --- | --- | --- |
|  | 0.3 | mmol C m2 (mg Chl W d)-1 | Initial slope of P-I curve for diatoms |
|  | 0.34 | mmol C m2 (mg Chl W d)-1 | Initial slope of P-I curve for small phytoplankton |
|  | 30 | °C | Reference temperature |
|  | 273.16 | K | Zero point for Celcius |
|  | 2 |  | Temperature dependence factor |
|  | 4.8 | d-1 | Max. phyto. C-specific growth rate at *Tref* |
|  | 0.5 | mmol N m-3 | Small phyto. NO3 half saturation coefficient |
|  | 0.01 | mmol N m-3 | Small phyto. NH4 half saturation coefficient |
|  | 3 × 10-5 | mmol Fe m-3 | Small phyto. Fe half saturation coefficient |
|  | 0.01 | mmol PO4 m-3 | Small phyto. PO4 half saturation coefficient |
|  | 2.5 | mmol N m-3 | Diatom NO3 half saturation coefficient |
|  | 0.1 | mmol N m-3 | Diatom NH4 half saturation coefficient |
|  | 0.8 × 10-4 | mmol Fe m-3 | Diatom Fe half saturation coefficient |
|  | 0.1 | mmol PO4 m-3 | Diatom PO4 half saturation coefficient |
|  | 1.0 | mmol SiO3 m-3 | Diatom Si half saturation coefficient |
|  | 0.15 | d-1 | Small phyto. linear mortality rate |
|  | 0.15 | d-1 | Diatom linear mortality rate |
|  | 0.0035 | (mmol C)-1 m3 d-1 | Small phyto. quadratic mortality rate |
|  | 0.0035 | (mmol C)-1 m3 d-1 | Diatom quadratic mortality rate |
|  | 0.75 | d-1 | Max. aggregation rate for small phyto. |
|  | 0.75 | d-1 | Max. aggregation rate for diatoms |
|  | 0.01 | d-1 | Min. aggregation rate for diatoms |
|  | 2.50 | d-1 | Max. zoo. growth rate on small phyto. at *Tref* |
|  | 1.95 | d-1 | Max. zoo. growth rate on diatoms at *Tref* |
|  | 3 × 10-2 | m-1 (mg Chl)-1 m3 | Chlorophyll attenuation coefficient |
|  | 4 × 10-2 | m-1 | Water attenuation coefficient |
|  | 0.45 |  | PAR fraction of total irradiance |
|  | 1.00 | mmol C m-3 | Zoo. grazing coefficient for small phyto. |
|  | 0.8367 | mmol C m-3 | Zoo. grazing coefficient for diatoms |

# *Cphyto* Calculation

# *Cphyto* was calculated with the method described by Graff et al. (2015). bbp 700 was converted to bbp 470 with the equation below:

and then *Cphyto* was calculated as:

# Relationship between d*µ*/dt and *r*

Equation 8 in Behrenfeld and Boss (2018) predicts a relationship between r and d*µ*/ dt.

According to DRH, the loss rate (*l*) is tightly coupled with division rate (*µ*), and non-zero values of specific accumulation rate may arise because of short temporal lags between *l* and *µ* as division rate evolves either from episodic events or gradual seasonal changes. Therefore, if the temporal lag between loss and division is approximately constant there should be a linear relationship between r and dµ/dt. However, in reality it is unrealistic that temporal lag between loss and division will be constant throughout the year. In our case (Supplementary Figure 8), the float data did not show a very good linear relationship, which means the lag between division and loss is not constant. Furthermore, in some cases the sign of the relationship is inconsistent with the equation above (r and dµ/dt should have the same sign, so either in 1st or 3rd quadrant), indicating that this relationship did not fully hold for the entire dataset.

# Supplementary Figures

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# Supplementary Figure 1. Mixed layer depth and mixed layer d*µ*/dt and *r* from Argo floats, satellite, and model simulation in region D1.

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# Supplementary Figure 2. Mixed layer depth and mixed layer d*µ*/dt and *r* from Argo floats, satellite, and model simulation in region D2.



# Supplementary Figure 3. Mixed layer depth and mixed layer d*µ*/dt and *r* from Argo floats, satellite, and model simulation in region D3.



# Supplementary Figure 4. Mixed layer depth and mixed layer d*µ*/dt and *r* from Argo floats, satellite, and model simulation in region D4.



**Supplementary Figure 5.** Monthly climatologies of *Chl-a* profile from Argo measurements in each region.



**Supplementary Figure 6.** Monthly climatologies of *Cphyto* profile from Argo measurements in each region.



**Supplementary Figure 7.** Monthly climatologies of *r* profile from Argo measurements in each region.



**Supplementary Figure 8.***r* versus *dµ/dt* from Argo measurements in each region (with color indicating the month)



**Supplementary Figure 9.** The time rate change of *MLD* (d *MLD*/dt), time rate change of normalized *Cphyto* (1/ *Cphyto*\*d *Cphyto*/dt), and phytoplankton net accumulation rate *r* in the mixed layer from satellite measurements. A five-point moving mean was applied to all three parameters. The color shadings represent the four phases of the seasonal phytoplankton biomass dynamics described by the “Disturbance and Recovery Hypothesis (DRH)”. Periods with phytoplankton phenology that did not have all the characteristics matching any DRH phase were left blank, without any color shading.



**Supplementary Figure 10.** The time rate change of *MLD* (d *MLD*/dt), time rate change of normalized *Cphyto* (1/ *Cphyto*\*d *Cphyto*/dt), and phytoplankton net accumulation rate *r* in the mixed layer from CESM outputs. A five-point moving mean was applied to all three parameters. The color shadings represent the four phases of the seasonal phytoplankton biomass dynamics described by the “Disturbance and Recovery Hypothesis (DRH)”. Periods with phytoplankton phenology that did not have all the characteristics matching any DRH phase were left blank, without any color shading.