Primary production

= growth of phytoplankton biomass separate from loss terms in differential equations

Hadocc: Primary production

$$
\begin{aligned}
dm_{PP} &= Dm \cdot \frac{DIN}{k_{DIN}^{Dm} + DIN} \cdot \frac{Si}{k_{Si}^{Dm} + Si} \\
&\quad \cdot PP(z, sol_{noon}, dlh, chl_{ttl}, P_m^{Dm}, \alpha^{Dm}) \\
ph_{PP} &= Ph \cdot \frac{DIN}{k_{DIN}^{Ph} + DIN} \cdot PP(z, sol_{noon}, dlh, chl_{ttl}, P_m^{Ph}, \alpha^{Ph})
\end{aligned}
$$

- Realisable growth calculated according to Anderson (1993): parameterises changing spectral distribution.
- Achieved growth amended using multiplicative nutrient limitations
- Effect of iron is to alter maximum growth rate
- No temperature effect

Effects of iron in Diat-HadOCC

$$\Pi = \Pi_{replete} + (\Pi_{deplete} - \Pi_{replete}) \cdot \frac{1}{1 + \frac{FeT}{k_{FeT}}}$$

$$\begin{aligned}
FeT &= FeL + FeF \\
LgT &= FeL + LgF \\
K_{FeL} &= \frac{FeL}{FeF \cdot LgF} \\
B &= K_{FeL} \cdot (LgT - FeT) - 1 \\
FeF &= FeT - LgT \\
&\quad + \frac{1}{2 \cdot K_{FeL}} \cdot \left(B + \sqrt{B^2 - 4 \cdot K_{FeL} \cdot LgT} \right) \\
fe_{adsorp} &= \Pi_{ads}^{FeF} \cdot FeF
\end{aligned}$$

- (Total) dissolved iron (free and complexed) alters the value of five parameters: diatom max growth rate, nd-phytoplankton max growth rate, diatom Si:N ratio, zooplankton base feeding preference for diatoms and zooplankton mortality rate (in CMIP5 runs only the first varied)
- Iron is taken up by diatoms and nd-phyto in a fixed ratio to carbon, and passed through Dm, Ph and Zp in that ratio
- There is no iron in detritus
- The final sink for iron is adsorption of free iron onto (implicit) mineral particles

MEDUSA

$$\theta_{\mathrm{Pn}}^{\mathrm{Chl}} = \frac{\mathrm{Chl_{Pn}} \cdot \xi}{\mathrm{Pn}}$$

$$\hat{\alpha}_{\mathrm{Pn}} = \alpha_{\mathrm{Pn}} \cdot \theta_{\mathrm{Pn}}^{\mathrm{Chl}}$$

$$V_{\mathrm{Pn}^T} = V_{\mathrm{Pn}} \cdot 1.066^T$$

$$J_{\mathrm{Pn}} = \frac{V_{\mathrm{Pn}^T} \cdot \hat{\alpha}_{\mathrm{Pn}} \cdot I}{(V_{\mathrm{Pn}^T}^2 + \hat{\alpha}_{\mathrm{Pn}}^2 \cdot I^2)^{1/2}}$$

$$Q_{\mathrm{N,Pn}} = \frac{\mathrm{N}}{k_{\mathrm{N,Pn}} + \mathrm{N}}$$

$$Q_{\mathrm{Fe,Pn}} = \frac{\mathrm{F}}{k_{\mathrm{Fe,Pn}} + \mathrm{F}}$$

$$\mathrm{PP_{Pn}} = J_{\mathrm{Pn}} \cdot Q_{\mathrm{N,Pn}} \cdot Q_{\mathrm{Fe,Pn}}$$

- C:Chl ratio regulates alpha (initial PI curve slope)
- Phytoplankton maximum growth rate set by temperature
- Realisable growth amended by light availability
- Achieved growth amended using multiplicative nutrient limitations

PlankTOM5 & 10

$$\frac{\delta \mathrm{Chl}}{\delta t} = \left(P^{C}_{\max} \times \left(1 - \exp\left(\frac{-\alpha^{\mathrm{Chl}}\theta^{C}E}{P^{C}_{\max}}\right)\right)\right)^{2} \times \frac{\theta^{C}_{\max}}{\alpha^{\mathrm{Chl}}\theta^{C}E} \times C$$

$$V_I = \left(1\text{-}\exp\left(\frac{-\alpha^{\mathrm{Chl}}\,\theta^{C}\,I}{P^{C}{}_{\max}}\right)\right)$$

$$V_T = \mu_{\max,\,0^\circ} \times Q_{10}{}^{\wedge T/10}$$

$$\rho_{\max} = \rho^{\mathrm{hi}}_{\max} - (\rho^{\mathrm{hi}}_{\max} - \rho^{\mathrm{lo}}_{\max}) \times \frac{(Q - Q_{\min})}{(Q_{\max} - Q_{\min})}$$

$$\frac{\delta \mathrm{Fe}_p}{\delta t} = \rho_{\max} \times \frac{\mathrm{Fe}'}{K_{1/2} + \mathrm{Fe}'} \times C$$

$$V_N = \min\left(\frac{Q - Q_{\min}}{Q_{\mathrm{opt}} - Q_{\min}}, \frac{NO_3}{K_{½,\,NO3} + NO_3}, \frac{SiO_3}{K_{½,\,SiO3} + SiO_3}, \frac{PO_4}{K_{½,\,PO4} + PO_4}, 1\right)$$

$$PP = V_T \times V_I \times V_N$$

- C:Chl ratio regulates alpha (initial PI curve slope)
- Phytoplankton maximum growth rate set by PFT specific μ_{max} and Q_{10}
- Dynamic solution of iron-light limitation on C:Chl:Fe ratios and $P^{C}{}_{max}$
- Achieved growth amended using minimum of nutrient limitations

ERSEM: Carbon

$$photosynthesis = r_{ass} \cdot t \cdot f_i \cdot P^C \left[\cdot \max\left(\frac{[Si]}{h_s}, 1.0 \right) \right]$$

$$t = Q_{10}^{((T-10.0)/10.0)} - Q_{10}^{((T-32.0)/3.0)}$$

$$f_i = \left(1.0 - e^{(-\alpha \cdot I \cdot \theta/(r_{ass} \cdot t))}\right) \cdot e^{(-\beta \cdot I \cdot \theta/(r_{ass} \cdot t))}$$

$$\rho = \theta_{\max} \cdot r_{ass} \cdot t \cdot f_i / (\alpha \cdot I \cdot \theta)$$

$$lysis = \frac{1.0}{n + 0.1} \cdot r_{lysis} \cdot P^C$$

$$exc = photosynthesis \cdot (p_{ex} + (1.0 - n) \cdot (1.0 - p_{ex}))$$

Gross photosynthetic production is a function of maximum assimilation rate (*rass*, defined at 10°C), temperature factor (*t*), light limitation (*fi*, Equation A.5) and phytoplankton (carbon) biomass (*PC*). Photosynthesis is not dependent on external nutrient concentration with the exception of diatoms which are limited by a linear term derived from the external silicate concentration.

Light limitation (*fi*) on phytoplankton growth is assumed to be a function of a variable cell carbon to chlorophyll ratio, modelled after Geider et al (1997).

The proportion of photosynthate directed to chlorophyll synthesis (ρ)

Modelled lysis represents non-resolved mortality processes and is assumed to be
enhanced in nutrient limited situations
Lysis carbon loss is partitioned between particulate and dissolved detritus according
to the ratio of minimal to actual internal nutrient to carbon ratio
Excretion (*exc*) consists of two elements, activity excretion of a fixed proportion
(*pex*) of uptake and nutrient stress excretion of the potential assimilate (*1-pex*), (Excretion is directed exclusively to the
dissolved phase.

ERSEM: Nutrients

$$n = \left[\frac{\left(P^P / P^C\right) - qP^P_{\min}}{qP^P_{\max} - qP^P_{\min}} \cdot \frac{\left(P^N / P^C\right) - qP^N_{\min}}{qP^N_{\max} - qP^N_{\min}} \right]^{0.5}$$

The nutrient limitation factor (*n*) employs 'Droop kinetics' (Droop, 1974). This is a function of the instantaneously calculated internal cell C:N and C:P ratios (*PN/PC, PP/PP*) and the maximum C:N and C:P ratios (*qPmax*), having subtracted the structural content of the cell (*qPmin*) from each. A separate limitation factor is calculated for each phytoplankton group and is constrained between the range 0 - 1.

P

$$uptake_{required} = productivity \cdot qP^P_{\max} + qP^P_{\max} \cdot P^C - P^P$$

$$uptake = MIN\left(uptake_{required}, a_p \cdot PO_4 \cdot P^C\right)$$

N – two forms

$$uptake_{required} = productivity \cdot qP^N_{\max} + qP^N_{\max} \cdot P^C - P^N$$

$$uptake = MIN\left(uptake_{required}, \left(a_{no3} \cdot NO_3 \cdot P^C\right) + \left(a_{nh4} \cdot NH_4 \cdot P^C\right)\right)$$

The required nutrient uptake is calculated as a combination of uptake commensurate with carbon productivity and uptake necessary to address any internal shortfall of nutrients. Actual uptake is constrained by a maximum uptake dependent on an affinity parameter (*a*) and external nutrient concentration. where productivity is given by (*uptake – excretion – respiration*), *qPmax* is the maximum internal nutrient : carbon ratio and *ap* the affinity for nutrient

Zooplankton grazing

= form of function relating prey abundance to zooplankton ingestion

Grazing: HadOCC

$$
\begin{aligned}
food &= R_{b2n}^{Ph} \cdot Ph + R_{b2n}^{Dt} \cdot Dt \\
grz_{ttl} &= \frac{g_{max} \cdot R_{b2n}^{Zp} \cdot Zp \cdot (food - food_{min})^2}{(g_{sat})^2 + (food - food_{min})^2} \\
ph_{grz} &= grz_{ttl} \cdot \frac{Ph}{food} \\
dt_{grz} &= grz_{ttl} \cdot \frac{Dt}{food}
\end{aligned}
$$

- Generic grazer eats phytoplankton and detritus
- No preference or "switching"
- Phyto/detritus ingested in proportion to its abundance (in biomass units, allowing for different C:N)
- Holling Type 3 functional form
- 77% of grazed material enters gut; remainder is "messy feeding", 90% of which becomes detritus, 10% DIN or DIC

Grazing: Diat-HadOCC

$$food = dprf_{Dm} \cdot R^{Dm}_{b2n} \cdot Dm + dprf_{Ph} \cdot R^{Ph}_{b2n} \cdot Ph + dprf_{Dt} \cdot (R^{DtN}_{b2n} \cdot DtN + R^{DtC}_{b2c} \cdot DtC)$$

$$dm_{grz} = \frac{dprf_{Dm} \cdot Dm \cdot g_{max} \cdot R^{Zp}_{b2n} \cdot Zp}{g_{sat} + food}$$

$$dmsi_{grz} = \frac{dprf_{Dm} \cdot DmSi \cdot g_{max} \cdot R^{Zp}_{b2n} \cdot Zp}{g_{sat} + food}$$

$$ph_{grz} = \frac{dprf_{Ph} \cdot Ph \cdot g_{max} \cdot R^{Zp}_{b2n} \cdot Zp}{g_{sat} + food}$$

$$dtn_{grz} = \frac{dprf_{Dt} \cdot DtN \cdot g_{max} \cdot R^{Zp}_{b2n} \cdot Zp}{g_{sat} + food}$$

$$dtc_{grz} = \frac{dprf_{Dt} \cdot DtC \cdot g_{max} \cdot R^{Zp}_{b2n} \cdot Zp}{g_{sat} + food}$$

- Generic grazer eats diatoms, nd-phytoplankton and detritus
- Fasham-style “switching” grazer: dynamic preferences based on (non-equal) base prefs and abundances
- Holling Type 2 functional form
- 77% of grazed material enters gut; remainder is “messy feeding”, 90% of which becomes detritus, 10% DIN or DIC

HadOCC: Secondary production

$$
\begin{aligned}
assim_N &= f_{ingst} \cdot (\beta^{Dm} \cdot dm_{grz} + \beta^{Ph} \cdot ph_{grz} + \beta^{Dt} \cdot dtn_{grz}) \\
assim_C &= f_{ingst} \cdot (\beta^{Dm} \cdot R_{c2n}^{Dm} \cdot dm_{grz} + \beta^{Ph} \cdot R_{c2n}^{Ph} \cdot ph_{grz} \\
&\quad + \beta^{Dt} \cdot dtn_{grz}) \\
grz_{Zp} &= MIN\left(assim_N, \frac{assim_C}{R_{c2n}^{Zp}}\right)
\end{aligned}
$$

$$
\begin{aligned}
grz_{DtN} &= (1 - f_{ingst}) \cdot (1 - f_{messy}) \cdot (dm_{grz} + ph_{grz} \\
&\quad + dtn_{grz}) + f_{ingst} \cdot ((1 - \beta^{Dm}) \cdot dm_{grz} \\
&\quad + (1 - \beta^{Ph}) \cdot ph_{grz} + (1 - \beta^{Dt}) \cdot dtn_{grz}) \\
grz_{DtC} &= (1 - f_{ingst}) \cdot (1 - f_{messy}) \cdot (R_{c2n}^{Dm} \cdot dm_{grz} + R_{c2n}^{Ph} \cdot ph_{grz} \\
&\quad + dtc_{grz}) + f_{ingst} \cdot ((1 - \beta^{Dm}) \cdot R_{c2n}^{Dm} \cdot dm_{grz} \\
&\quad + (1 - \beta^{Ph}) \cdot R_{c2n}^{Ph} \cdot ph_{grz} + (1 - \beta^{Dt}) \cdot dtc_{grz}) \\
grz_{dtsi} &= dmsi_{grz} \\
grz_{DIN} &= (1 - f_{ingst}) \cdot f_{messy} \cdot (dm_{grz} + ph_{grz} \\
&\quad + dtn_{grz}) + MAX\left(0, assim_N - \frac{assim_C}{R_{c2n}^{Zp}}\right) \\
grz_{DIC} &= (1 - f_{ingst}) \cdot f_{messy} \cdot (R_{c2n}^{Dm} \cdot dm_{grz} + R_{c2n}^{Ph} \cdot ph_{grz} \\
&\quad + dtc_{grz}) + MAX(0, assim_C - assim_N \cdot R_{c2n}^{Zp})
\end{aligned}
$$

- C:N of assimilatable gut contents calculated, compared to zooplankton C:N
- As much of assimilatable material as C:N will allow is assimilated, excess of C or N excreted as DIC or DIN
- Non-assimilatable material egested as detrital-N and detrital-C
- All grazed diatom silicate passes unchanged through gut, becomes detrital-Si

MEDUSA

$$\mathrm{Gm}_X = \frac{g_{\mathrm{m}} \cdot p_{\mathrm{m}X} \cdot X^2 \cdot \mathrm{Zm}}{k_{\mathrm{m}}^2 + \mathrm{Fm}}$$

where X is Pn, Pd, Zμ or D.

$$\mathrm{Fm} = (p_{\mathrm{mPn}} \cdot \mathrm{Pn}^2) + (p_{\mathrm{mPd}} \cdot \mathrm{Pd}^2) + (p_{\mathrm{mZ\mu}} \cdot \mathrm{Z\mu}^2) + (p_{\mathrm{mD}} \cdot \mathrm{D}^2)$$

$$\mathrm{Gm}_{\mathrm{Pd_{Si}}} = R_{\mathrm{Si:N}} \cdot \mathrm{Gm}_{\mathrm{Pd}}$$

$$\mathrm{IN}_{\mathrm{Zm}} = (1-\phi) \cdot (\mathrm{Gm}_{\mathrm{Pd}} + \mathrm{Gm}_{\mathrm{Pn}} + \mathrm{Gm}_{\mathrm{Z\mu}} + \mathrm{Gm}_{\mathrm{Pd}})$$

$$\mathrm{IC}_{\mathrm{Zm}} = (1-\phi) \cdot ((\theta_{\mathrm{Pd}} \cdot \mathrm{Gm}_{\mathrm{Pd}}) + (\theta_{\mathrm{Pn}} \cdot \mathrm{Gm}_{\mathrm{Pn}}) + (\theta_{\mathrm{Z\mu}} \cdot \mathrm{Gm}_{\mathrm{Z\mu}}) + (\theta_{\mathrm{D}} \cdot \mathrm{Gm}_{\mathrm{D}}))$$

- Fasham-esque
- Prey items assigned “preference” (= nominally equal)
- This permits “switching” between prey types depending upon abundance
- Prey defined by size; microzoo take small items (non-diatoms and slow detritus), mesozoo can additionally take large items (i.e. eat everything!)
- This results in total ingested N and C

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$$\mathrm{Gm}_X = \frac{g_\mathrm{m} \cdot p_{\mathrm{m}X} \cdot X \cdot \mathrm{Zm}}{k_{\mathrm{m}} + \mathrm{Fm}}$$

where X is everything smaller

$$\mathrm{Fm} = (p_{\mathrm{mPn}} \cdot \mathrm{Pn}) + (p_{\mathrm{mPd}} \cdot \mathrm{Pd}) + (p_{\mathrm{mZ\mu}} \cdot \mathrm{Z\mu}) + (p_{\mathrm{mD}} \cdot \mathrm{D})$$ etc.

$$\mathrm{Gm}_{\mathrm{Pd_{Si}}} = R_{\mathrm{Si:N}} \cdot \mathrm{Gm}_{\mathrm{Pd}}$$

$$\mathrm{IC}_{\mathrm{Zm}} = (1-\phi) \cdot (\mathrm{Gm}_{\mathrm{Pd}} + \mathrm{Gm}_{\mathrm{Pn}} + \mathrm{Gm}_{\mathrm{Z\mu}} + \mathrm{Gm}_{\mathrm{Pd}})$$

$$\mathrm{I^{Fe}}_{\mathrm{Zm}} = (1-\phi) \cdot ((\theta_{\mathrm{Pd}} \cdot \mathrm{Gm}_{\mathrm{Pd}}) + (\theta_{\mathrm{Pn}} \cdot \mathrm{Gm}_{\mathrm{Pn}}) + (\theta_{\mathrm{Z\mu}} \cdot \mathrm{Gm}_{\mathrm{Z\mu}}) + (\theta_{\mathrm{D}} \cdot \mathrm{Gm}_{\mathrm{D}}))$$

- Michaelis-Menten-esque
- Prey items assigned “preference”
- Prey defined by size; microzoo prefer small items (non-diatoms and slow detritus), mesozoo and macrozoo prefer large items (everybody eats everything smaller)
- $g_m=g_{max}*Q_{10}$^(T/10)
- C:N:P:Fe ratio zooplankton fixed

ERSEM –Zoo

$$uptake = r_{ass} \cdot \frac{F_{tot}^{C}}{\left(F_{tot}^{C} + h\right)} \cdot t \cdot Z^{C}$$

Consumer uptake is of a Michaelis-Menten form function of maximal assimilation rate (*rass*), temperature (*t*, Equation A.1), total food available (*Ftot*), *h* (the amount of food where uptake is 0.5 the maximum rate) and the consumer biomass (*Z*).

$$F_{tot}^{C} = \sum^{F=1-n} p_{f} \cdot F^{C} \cdot \frac{F^{C}}{F^{C} + Z_{\min\ food}}$$

Ftot is given by the sum, for each food source (*F*), of a function governed by the available fraction of that food source (*pf*)
See foodmatrix

$$flux = p_{f} \cdot F^{C} \cdot \frac{F^{C}}{\left(F^{C} + Z_{\min\ food}\right)} \cdot \frac{uptake}{F_{tot}^{C}}$$

Table A.1 Parameters describing the relative prey availability for each consumer defining the trophic structure of the model.

to / from	Heterotrophs	Microzoos	Mesozoos
Bacteria	1.0	0.5	-
Picophytoplankton	1.0	0.5	-
Flagellates	0.25	1.0	0.5
Diatoms	-	0.25	1.0
Dinoflagellates	-	0.25	1.0
Heterotrophic flagellates	0.2	1.0	0.5
Microzooplankton	-	0.2	0.5
Mesozooplankton	-	-	0.2

Zooplankton assimilation

= what do the zooplankton get from what they eat?; what happens to what they don't get?

HadOCC: Mortality and closure

$$
\begin{aligned}
dm_{mort} &= \Pi^{Dm}_{mort} \cdot Dm^2 \\
dmsi_{mort} &= \Pi^{Dm}_{mort} \cdot Dm \cdot DmSi \\
ph_{mort} &= \Pi^{Ph}_{mort} \cdot Ph^2 & (Ph > ph_{min}) \\
&= 0 & (Ph < ph_{min}) \\
zp_{lin} &= \Pi^{Zp}_{lin} \cdot Zp \\
zp_{mort} &= \Pi^{Zp}_{mort} \cdot Zp^2
\end{aligned}
$$

- Zooplankton has quadratic loss-term (as do the autotrophs)
- For zooplankton this function represents "swarming" of their implicit predators (for autotrophs, viral attack)
- Two-thirds of zooplankton mortality goes to DIN/DIC, the rest to detritus (but only 1% of autotroph mortality goes to DIN/DIC)

MEDUSA

$$\theta_{\mathrm{Fm}} = \frac{\mathrm{IC}_{\mathrm{Zm}}}{\mathrm{IN}_{\mathrm{Zm}}}$$

$$\theta^*_{\mathrm{Fm}} = \frac{\beta_{\mathrm{N}} \cdot \theta_{\mathrm{Zm}}}{\beta_{\mathrm{C}} \cdot k_{\mathrm{C}}}$$

if $\theta_{\mathrm{Fm}} > \theta^*_{\mathrm{Fm}}$ then N is limiting and ...

$$F_{\mathrm{Zm}} = \beta_{\mathrm{N}} \cdot \mathrm{IN}_{\mathrm{Zm}}$$

$$E_{\mathrm{Zm}} = 0$$

$$R_{\mathrm{Zm}} = (\beta_{\mathrm{C}} \cdot \mathrm{IC}_{\mathrm{Zm}}) - (\theta_{\mathrm{Zm}} \cdot F_{\mathrm{Zm}})$$

else if $\theta_{\mathrm{Fm}} < \theta^*_{\mathrm{Fm}}$ then C is limiting and ...

$$F_{\mathrm{Zm}} = \frac{\beta_{\mathrm{C}} \cdot k_{\mathrm{C}} \cdot \mathrm{IC}_{\mathrm{Zm}}}{\theta_{\mathrm{Zm}}}$$

$$E_{\mathrm{Zm}} = \mathrm{IC}_{\mathrm{Zm}} \cdot \left(\frac{\beta_{\mathrm{N}}}{\theta_{\mathrm{Fm}}} - \frac{\beta_{\mathrm{C}} \cdot k_{\mathrm{C}}}{\theta_{\mathrm{Zm}}} \right)$$

$$R_{\mathrm{Zm}} = (\beta_{\mathrm{C}} \cdot \mathrm{IC}_{\mathrm{Zm}}) - (\theta_{\mathrm{Zm}} \cdot F_{\mathrm{Zm}})$$

- Zooplankton food C:N calculated
- Given different assimilation efficiencies for N and C, “ideal” food C:N calculated
- The difference between this and actual ingested C:N is used to proportion N and C to zooplankton growth, excretion and respiration

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- Zooplankton food C:Fe calculated
- maximum GGE is based on observations
- GGE decreases when total respiration < basal respiration or when zoo are Fe limited

ERSEM

$$loss_{inorg}^{N,P} = MAX\left(0, \left(qZ^{N,P} - qZ_{\max}^{N,P}\right) \cdot Z^{C} \cdot c^{N,P}\right)$$

Ingestion of nutrients via predation is derived according to the nutrient to carbon ratio for that food source.

Loss of nutrients via excretion and mortality follow carbon, with the appropriate N:C ratio applied.

Additionally any excess nutrient content over the maximum internal nutrient to carbon ratio (*qmax*) is excreted directly to the inorganic pool

Closure terms

= what regulates zooplankton abundance at the top of the modelled food chain?

HadOCC: Mortality and closure

$$
\begin{aligned}
dm_{mort} &= \Pi^{Dm}_{mort} \cdot Dm^2 \\
dmsi_{mort} &= \Pi^{Dm}_{mort} \cdot Dm \cdot DmSi \\
ph_{mort} &= \Pi^{Ph}_{mort} \cdot Ph^2 && (Ph > ph_{min}) \\
&= 0 && (Ph < ph_{min}) \\
zp_{lin} &= \Pi^{Zp}_{lin} \cdot Zp \\
zp_{mort} &= \Pi^{Zp}_{mort} \cdot Zp^2
\end{aligned}
$$

- Zooplankton has quadratic loss-term (as do the autotrophs)
- For zooplankton this function represents “swarming” of their implicit predators (for autotrophs, viral attack)
- Two-thirds of zooplankton mortality goes to DIN/DIC, the rest to detritus (but only 1% of autotroph mortality goes to DIN/DIC)

MEDUSA

$$M2_{Z\mu} = \mu_{2,Z\mu} \cdot \frac{Z\mu}{k_{Z\mu} + Z\mu} \cdot Z\mu$$

$$M2_{Zm} = \mu_{2,Zm} \cdot \frac{Zm}{k_{Zm} + Zm} \cdot Zm$$

- All plankton have density-dependent loss terms
- Microzoo are eaten by mesozoo
- Mesozoo are not eaten by anyone explicitly but experience higher density-dependent losses
- In Yool et al. (2011) alternative forms of this loss were explored

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- All plankton have linear loss terms
- Microzoo and mesozoo are eaten by macrozoo
- top zoo are not eaten by anyone explicitly but experience observed losses
- density dependent loss is not used because it suppresses lower trophic level variability

ERSEM

$$mortality = ((1.0 - eO_2) \cdot r_{mortox} + r_{mort}) \cdot Z^C$$

$$eO_2 = (1 + h_{\mathrm{oxmort}}) \left(\frac{O_{\mathrm{rel}}}{(O_{\mathrm{rel}} + h_{\mathrm{oxmort}})} \right)$$

Mortality loss consists of two terms, mortality triggered by low oxygen conditions and a linear loss term.

All zooplankton classes are cannibalistic

In addition Micro zoo eat HNANS

Mesozoo eat Microzoo and HNAN’s

ERSEM – Bacteria

$$uptake = MIN\left(r_{ass} \cdot t \cdot eO_2 \cdot n \cdot B, R^{C}_{DOM}\right)$$

$$eO_2 = \frac{O_{rel}}{\left(O_{rel} + h_{ox}\right)}$$

$$n = MIN\left(\frac{\left(NH_4 + R^{N}_{DOM}\right)}{\left(NH_4 + R^{N}_{DOM} + h_N\right)}\right),\left(\frac{\left(PO_4 + R^{P}_{DOM}\right)}{\left(PO_4 + R^{P}_{DOM} + h_P\right)}\right)$$

Bacterial uptake is a function of potential assimilation rate (*rass*), temperature (*t*,), a limitation if low oxygen conditions apply (*eO2*), limitation due to the nutrient quotient of the food source and the availability of inorganic nutrients to make up any shortfall (*n*) and bacterial biomass (*B*), constrained by the total amount of available substrate, dissolved organic matter (*RDOM*).

$$respiration = uptake \cdot \left(r_{resp} \cdot O_{rel} + r_{respox} \cdot \left(1.0 - O_{rel}\right)\right) + r_{basal} \cdot t \cdot B^{C}$$

Respiration loss consists of two terms, a temperature dependent rest respiration and an activity respiration which contains a variable component dependent on the ambient oxygen saturation, where *rresp* is the proportion of uptake respired in oxygen replete situations and *rrespox* that in oxygen deficient situations.

$$mortality = r_{mort} \cdot t \cdot B^{C}$$

Mortality is given by a temperature dependent rate, and is directed to the dissolved organic fraction.

$$loss^{N,P} = \left(qB^{N,P} - qB^{N,P}_{\max}\right) \cdot B^{C}$$

Bacterial nutrient uptake of dissolved organic nutrients is simply calculated from the carbon uptake flux and the nutrient to carbon ratio of the substrate.

$$uptake^{N,P} = \left(qB^{N,P} - qB^{N,P}_{\max}\right) \cdot B^{C} \cdot \frac{N}{\left(N + h^{N,P}\right)}$$

In the case of **internal nutrient deficiency**, uptake is moderated by a half rate constant (*h*), where N may be either ammonia or phosphate

Calcification

= how do models represent the production of calcium carbonate by the plankton?

HadOCC: Carbonate pump

$$ccfrmtn = R^{Ph}_{cc2pp} \cdot ph_{PP}$$

$$\begin{aligned} xprt_{cc} &= \sum_n (\, ccfrmtn_n \cdot \Delta_n \,) \\ ccdsltn &= \frac{xprt_{cc}}{\Delta_{dsl}} && (\, valid\ lyrs \,) \\ &= 0 && (\, other\ lyrs \,) \\ crbnt &= ccdsltn - ccfrmtn \end{aligned}$$

- CaCO3 is produced in a fixed ratio to organic production
- In Diat-HadOCC only production by non-diatoms is considered, and fixed ratio has been adjusted to globally compensate
- CaCO3 does not sink with organic detritus, but is instantly moved to below the prescribed lysocline and re-dissolved evenly between that and the sea-floor
- If sea-floor is shallower than lysocline, it is re-dissolved in the bottom layer

MEDUSA

$$fo(\Omega_{calcite}) = (\Omega_{calcite} - 1)^{\eta} \cdot r_0$$

$$\begin{aligned} T_{CaCO_3}(k+1) = & \; T_{CaCO_3}(k) + \\ & ((\theta_{Pd} \cdot D1_{frac} \cdot M2_{Pd}) + \\ & (\theta_{Zm} \cdot D2_{frac} \cdot M2_{Zm})) \cdot \\ & \delta z(k) \cdot fo(\Omega_{calcite}) \end{aligned}$$

- CaCO3 is only considered important if it is exported
- "Production" here is synonymous with export
- CaCO3 export is calculated using a "rain ratio" and the production of organic C in fast-sinking detritus
- The "rain ratio" of fast-sinking detritus is a function of local calcite saturation state (local-3D or local-surface)

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- both coccolithophore attached and detrital $CaCO_3$ are modelled
- Coccolithophore $CaCO_3$:C is fixed
- detrital $CaCO_3$ export is explicitly modelled in fast-sinking detritus

ERSEM

$$\frac{dDIC}{dt} = RR \cdot (gutdiss \cdot grazedP2 + deadP2 + sedimentingP2)$$

$$RR = RR_0 \cdot \min(Nlim_{P2}, 1 - Plim_{P2}) \cdot \frac{\max(T,0)}{\max(T,0)+2} \cdot (\Omega_{cal} - 1)^n$$

In some ways analogous to MEDUSA

Fraction of P2 (flagellates) is assume to be coccolithophores

Calcite produced as a function of the exported component of P2 (i.e. grazing and particulate matter generated by lysis)

Calcite production is depending on Temperature, nutrient limitation and, optionally, saturation state

Sinks with a constant rate

Fate of detritus

= how do models deal with detritus and its remineralisation down the water column?

HadOCC: Detritus: sinking & remin

- Explicit slow-sinking detritus (10m/d)
- HadOCC: Fixed C:N ratio (7.5 cf 6.625 in phyto, 5.625 in zoop)
- Diat-HadOCC: separate state variables for N, C and Si
- For det-N and det-C: specific remineralisation rate varies as reciprocal of depth (gives Martin-style power-law), but is "capped"
- Det-C: constant specific remin rate

HadoCC: Detritus: at the sea-floor

- All detrital material reaching the sea-floor is instantly remineralised to DIN, DIC, or Si
- Newly-remineralised material spread evenly over lowest three layers
- (Sinking diatoms that hit the sea-floor die instantly, becoming det-N and det-C in the bottom layer; their diatom-silicate becomes det-Si in bottom layer)

MEDUSA

- Two size-classes of detritus: small, slow-sinking and large, fast-sinking
- Small represented explicitly (separate N and C components), large represented implicitly
- Small has a sinking rate and temperature-dependent remineralisation rate
- Large (N, Si, Fe, C, CaCO3) fed into ballast-type scheme

PlankTOM5 & 10

- Two size-classes of detritus: small, slow-sinking and large, ballasted
- Both size-classes have variable C:Fe
- Small has a fixed sinking rate and both temperature-dependent remineralisation rate
- Sinking speed of large detritus is ballasted based on C:$CaCO_3$:Si composition

ERSEM

- three size-classes of detritus: small, slow-sinking and large, defined by fixed sinking rates (0.1,1 and 10m per day)
- All size-classes have variable C:N:P:Si)
- POM Remineralisation to DOM
- explicit consumption of DOM by heterotrophic bacteria
- No ballast parameterisations

MEDUSA

- In ballast scheme, inorganic minerals – opal and $CaCO_3$ – "protect" a fraction of organic material
- This fraction changes down the water column as opal and $CaCO_3$ dissolve
- Opal dissolves everywhere, $CaCO_3$ only below calcite CCD
- Remineralisation of "unprotected" organic material is an e-folding scheme

PlankTOM5 & 10

- Drag equation is solved off-line giving sinking speed as a function of particle density
- large detritus density is calculated from observed fecal pellet porosities of C, $CaCO_3$, SiO_2
- Opal dissolution = f(T)
- $CaCO_3$ dissolution = f(CO_3)
- Remineralisation = f(T, O_2)

ERSEM

- Opal dissolution = constant rate
- $CaCO_3$ dissolution = f($CaCO_{3\ saturation}$)
- POM / DOM Remineralisation = by bacteria
- Addition recycling of DON, DOP via constant rate