Oakley Court
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MEDUSA

Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification

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History of MEDUSA

- Conceived and developed as part of Oceans 2025 Research Programme
- Focus on the carbon cycle, export production and surface-to-deep ocean connectivity
- Structure created *de novo* but based loosely on developments at NOC by Mike Fasham
- Parameterisation drawn from a mixture of extant NOC models plus literature “best”

Philosophy of MEDUSA

- NPZD is no longer up to the job
- But simplicity (re: formulation, simulation and analysis) is still to be valued
- Intermediate complexity approach favoured
- Basic NPZD structure still (broadly) valid, so increment upwards from this
- Size, silicon and iron were primary motivators for MEDUSA’s double-NPZD structure

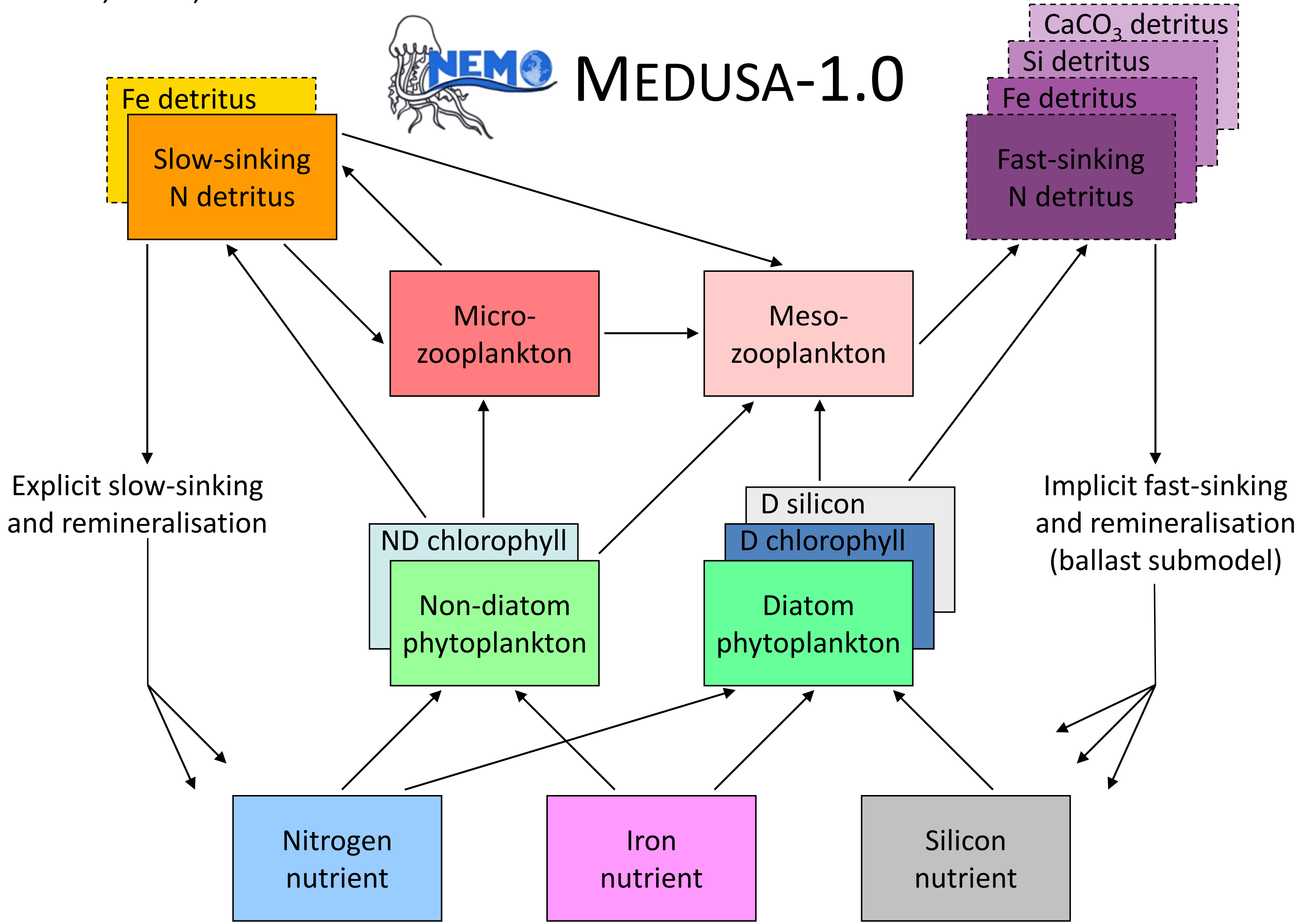
Who’s in?

- Nitrogen: largely a legacy choice (cf. Fasham)
- Silicon: see diatoms
- Iron: now well-established that significant areas of World Ocean in iron stress
- Diatoms: major players in ecosystems; controls on abundance relatively well-understood (fast growth, large size); no (major) mysteries
- Non-diatoms: small phytoplankton are key players in ecosystems, especially oligotrophic ones; modelled as fast-growing generic phytoplankton
- Zooplankton: micro- and meso- added to complement (= eat) corresponding phytoplankton

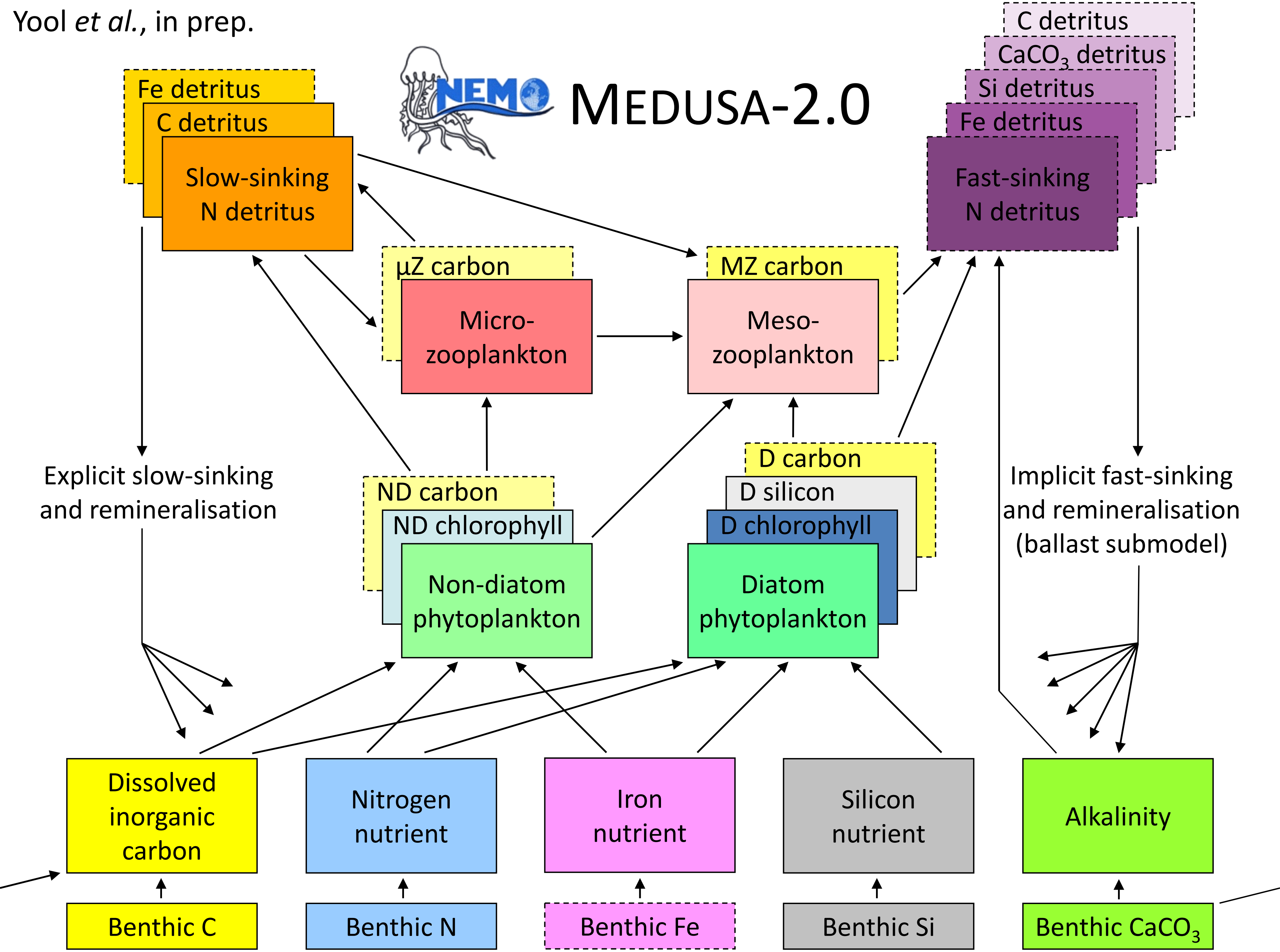
Who's out?

- Phosphorus: largely a legacy choice but there's a good case for choosing it over nitrogen
- Organic nutrients: could be key in oligotrophic systems, but these aren't important in total-flux terms and there are gaps in understanding
- N2-fixers: largely omitted to keep nitrogen cycle simple (i.e. nothing in, nothing out), but controls on them are becoming better known
- Coccolithophorids: omitted purely because of ignorance of controlling factors; also, they are not "in charge" of CaCO3 production in the way that diatoms are of biogenic opal production
- Bacteria: assumed role in remineralisation handled instead via simple rate parameters

Yool *et al.*, *GMD*, 2011



Yool *et al.*, in prep.



$$\frac{\partial Pn}{\partial t} = +\underbrace{[PP_{Pn} \cdot Pn]}_{\text{non-diatom PP}} - \underbrace{[G\mu_{Pn}]}_{\mu\text{zoo graze}} - \underbrace{[Gm_{Pn}]}_{\text{mzoo graze}} - \underbrace{[M1_{Pn}]}_{\text{linear losses}} - \underbrace{[M2_{Pn}]}_{\text{non-lin losses}} \quad (1)$$

$$\frac{\partial Pd}{\partial t} = +\underbrace{[PP_{Pd} \cdot Pd]}_{\text{diatom PP}} - \underbrace{[Gm_{Pd}]}_{\text{mzoo graze}} - \underbrace{[M1_{Pd}]}_{\text{linear losses}} - \underbrace{[M2_{Pd}]}_{\text{non-lin losses}} \quad (2)$$

$$\frac{\partial Chl_{Pn}}{\partial t} = \theta_{Pn}^{Chl} \cdot \xi^{-1} \cdot (+\underbrace{[R_{Pn} \cdot PP_{Pn} \cdot Pn]}_{\text{non-diatom PP}} - \underbrace{[G\mu_{Pn}]}_{\mu\text{zoo graze}} - \underbrace{[Gm_{Pn}]}_{\text{mzoo graze}} - \underbrace{[M1_{Pn}]}_{\text{linear losses}} - \underbrace{[M2_{Pn}]}_{\text{non-lin losses}}) \quad (3)$$

$$\frac{\partial Chl_{Pd}}{\partial t} = \theta_{Pd}^{Chl} \cdot \xi^{-1} \cdot (+\underbrace{[R_{Pd} \cdot PP_{Pd} \cdot Pd]}_{\text{diatom PP}} - \underbrace{[Gm_{Pd}]}_{\text{mzoo graze}} - \underbrace{[M1_{Pd}]}_{\text{linear losses}} - \underbrace{[M2_{Pd}]}_{\text{non-lin losses}}) \quad (4)$$

$$\frac{\partial Pd_{Si}}{\partial t} = +\underbrace{[PP_{Pd_{Si}} \cdot Pd_{Si}]}_{\text{diatom PP}} - \underbrace{[Gm_{Pd_{Si}}]}_{\text{mzoo graze}} - \underbrace{[M1_{Pd_{Si}}]}_{\text{linear losses}} - \underbrace{[M2_{Pd_{Si}}]}_{\text{non-lin losses}} - \underbrace{[DS_{Pd_{Si}}]}_{\text{dissolution}} \quad (5)$$

$$\frac{\partial Z\mu}{\partial t} = +\underbrace{[F_{Z\mu}]}_{\text{all grazing}} - \underbrace{[Gm_{Z\mu}]}_{\text{mzoo graze}} - \underbrace{[M1_{Z\mu}]}_{\text{linear losses}} - \underbrace{[M2_{Z\mu}]}_{\text{non-lin losses}} \quad (6)$$

$$\frac{\partial Zm}{\partial t} = +\underbrace{[F_{Zm}]}_{\text{all grazing}} - \underbrace{[M1_{Zm}]}_{\text{linear losses}} - \underbrace{[M2_{Zm}]}_{\text{non-lin losses}} \quad (7)$$

$$\frac{\partial D}{\partial t} = +\underbrace{[M2_{Pn}]}_{\text{non-diatom losses}} + \underbrace{[(1 - D1_{frac}) \cdot M2_{Pd}]}_{\text{diatom losses}} + \underbrace{[M2_{Z\mu}]}_{\mu\text{zoo losses}} + \underbrace{[(1 - D2_{frac}) \cdot M2_{Zm}]}_{\text{mzoo losses}} + \underbrace{[(1 - \beta_N) \cdot IN_{Z\mu}]}_{\mu\text{zoo egestion}} + \underbrace{[(1 - \beta_N) \cdot IN_{Zm}]}_{\text{mzoo egestion}} - \underbrace{[G\mu_D]}_{\mu\text{zoo graze}} - \underbrace{[Gm_D]}_{\text{mzoo graze}} - \underbrace{[M_D]}_{\text{remin}} - \underbrace{\left[w_g \cdot \frac{\partial D}{\partial z}\right]}_{\text{sinking}} \quad (8)$$

$$\frac{\partial N}{\partial t} = -\underbrace{[PP_{Pn} \cdot Pn]}_{\text{non-diatom PP}} - \underbrace{[PP_{Pd} \cdot Pd]}_{\text{diatom PP}} + \underbrace{[\phi \cdot (G\mu_{Pn} + G\mu_D)]}_{\mu\text{zoo messy feeding}} + \underbrace{[\phi \cdot (Gm_{Pn} + Gm_{Pd} + Gm_{Z\mu} + Gm_D)]}_{\text{mzoo messy feeding}} + \underbrace{[E_{Z\mu}]}_{\mu\text{zoo excretion}} + \underbrace{[E_{Zm}]}_{\text{mzoo excretion}} + \underbrace{[M1_{Pn}]}_{\text{non-diatom losses}} + \underbrace{[M1_{Pd}]}_{\text{diatom losses}} + \underbrace{[M1_{Z\mu}]}_{\mu\text{zoo losses}} + \underbrace{[M1_{Zm}]}_{\text{mzoo losses}} + \underbrace{[M_D]}_{\text{remin}} + \underbrace{[LD_N(k)]}_{\text{fast N detritus remin}} \quad (9)$$

$$\frac{\partial S}{\partial t} = -\underbrace{[PP_{Pd_{Si}} \cdot Pd_{Si}]}_{\text{diatom PP}} + \underbrace{[M1_{Pd_{Si}}]}_{\text{linear losses}} + \underbrace{[(1 - D1_{frac}) \cdot M2_{Pd_{Si}}]}_{\text{non-lin. losses}} + \underbrace{[DS_{Pd_{Si}}]}_{\text{dissolution}} + \underbrace{[(1 - D2_{frac}) \cdot Gm_{Pd_{Si}}]}_{\text{mzoo graze}} + \underbrace{[LD_{Si}(k)]}_{\text{fast Si detritus remin}} \quad (10)$$

$$\frac{\partial F}{\partial t} = -\underbrace{\left[R_{Fe} \cdot \frac{\partial N}{\partial t}\right]}_{\text{coupled to N}} + \underbrace{[F_{atmos}]}_{\text{aeolian}} - \underbrace{[F_{scavenge}]}_{\text{scavenging}} \quad (11)$$

What lies beneath ...

$$\theta^{\mathrm{Chl}}_{\mathrm{Pn}} = \frac{\mathrm{Chl}_{\mathrm{Pn}} \cdot \xi}{\mathrm{Pn}}$$

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

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

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

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

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

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

$$\theta^{\mathrm{Chl}}_{\mathrm{Pd}} = \frac{\mathrm{Chl}_{\mathrm{Pd}} \cdot \xi}{\mathrm{Pd}}$$

$$\hat{\alpha}_{\mathrm{Pd}} = \alpha_{\mathrm{Pd}} \cdot \theta^{\mathrm{Chl}}_{\mathrm{Pd}}$$

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

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

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

$$Q_{\mathrm{Si}} = \frac{\mathrm{S}}{k_{\mathrm{Si}} + \mathrm{S}}$$

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

$$R_{\mathrm{Si:N}} = \frac{\mathrm{Pd}_{\mathrm{Si}}}{\mathrm{Pd}}$$

$$R_{\mathrm{N:Si}} = \frac{\mathrm{Pd}}{\mathrm{Pd}_{\mathrm{Si}}}$$

If $R_{\mathrm{Si:N}} \le R^0_{\mathrm{Si:N}}$ then

$$\mathrm{PP}_{\mathrm{Pd}} = 0$$

else if $R^0_{\mathrm{Si:N}} < R_{\mathrm{Si:N}} < (3 \cdot R^0_{\mathrm{Si:N}})$ then

$$\mathrm{PP}_{\mathrm{Pd}} = (J_{\mathrm{Pd}} \cdot Q_{\mathrm{N,\,Pd}} \cdot Q_{\mathrm{Fe,\,Pd}}) \cdot \left(U_\infty \cdot \frac{R_{\mathrm{Si:N}} - R^0_{\mathrm{Si:N}}}{R_{\mathrm{Si:N}}}\right)$$

else if $R_{\mathrm{Si:N}} \ge (3 \cdot R^0_{\mathrm{Si:N}})$ then

$$\mathrm{PP}_{\mathrm{Pd}} = (J_{\mathrm{Pd}} \cdot Q_{\mathrm{N,\,Pd}} \cdot Q_{\mathrm{Fe,\,Pd}})$$

If $R_{\mathrm{Si:N}} < (3 \cdot R^0_{\mathrm{Si:N}})^{-1}$ then

$$\mathrm{PP}_{\mathrm{Pd}_{\mathrm{Si}}} = (J_{\mathrm{Pd}} \cdot Q_{\mathrm{Si}})$$

else if $(3 \cdot R^0_{\mathrm{Si:N}})^{-1} \le R_{\mathrm{Si:N}} < (R^0_{\mathrm{Si:N}})^{-1}$ then

$$\mathrm{PP}_{\mathrm{Pd}_{\mathrm{Si}}} = (J_{\mathrm{Pd}} \cdot Q_{\mathrm{Si}}) \cdot \left(U_\infty \cdot \frac{R_{\mathrm{N:Si}} - R^0_{\mathrm{N:Si}}}{R_{\mathrm{N:Si}}}\right)$$

else if $R_{\mathrm{Si:N}} \ge (R^0_{\mathrm{Si:N}})^{-1}$ then

$$\mathrm{PP}_{\mathrm{Pd}_{\mathrm{Si}}} = 0$$

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

where X is Pn, Pd, Zμ or D.

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

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

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

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

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

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

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 ...

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

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

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

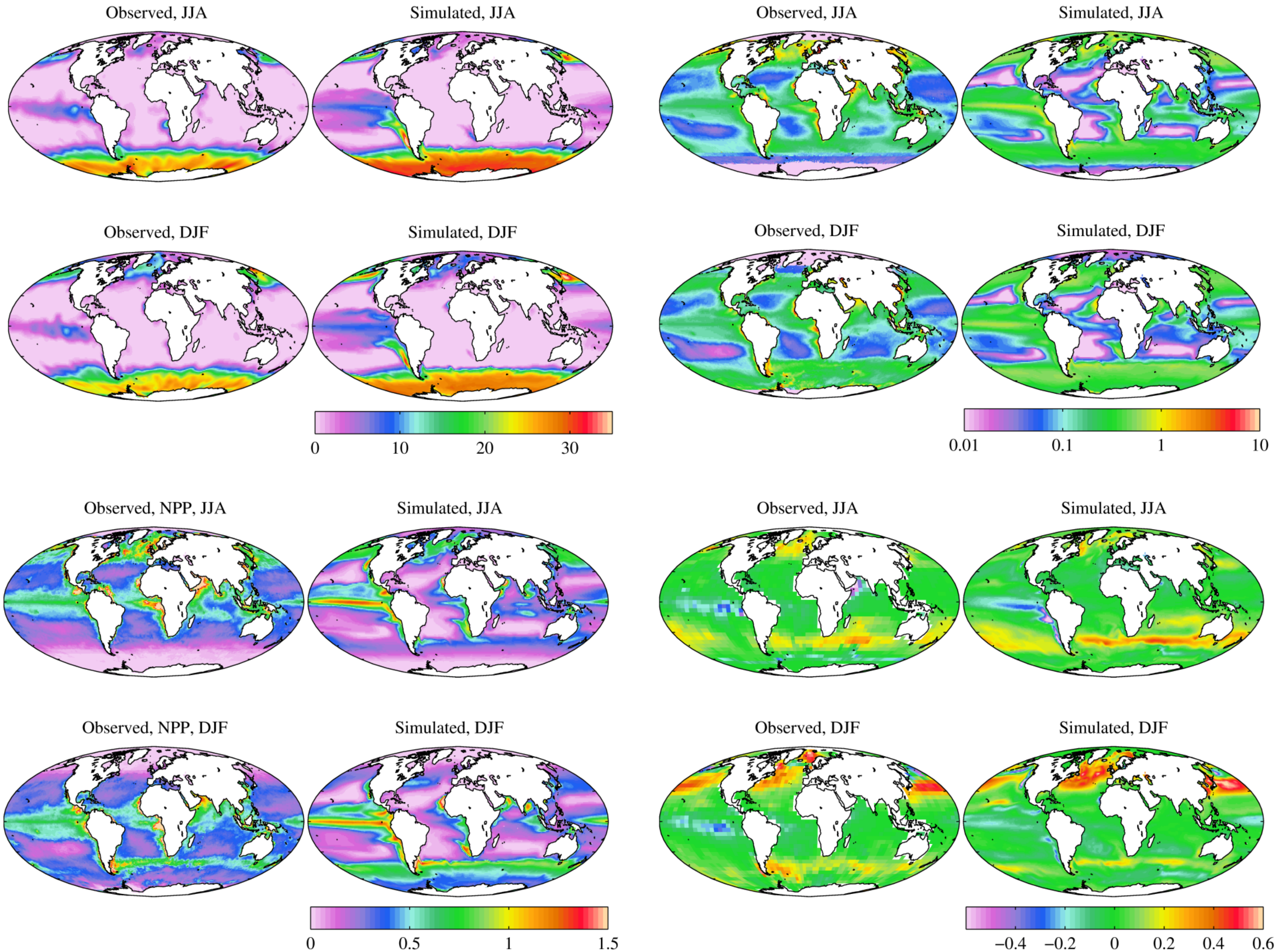
(Some) Guts of MEDUSA

- Multiplicative nutrient limitation
- Temperature dependent growth / remin.
- Submodel regulating diatom N, Si uptake
- Fasham-esque prey switching
- N:C balancing of zooplankton diet
- Aeolian / benthic supply of iron
- Concentration-dependent Fe scavenging
- $[CO_3^-]$-dependent calcification rate
- Ballast-driven export flux and remin.

MEDUSA-2; 1860-2005 simulation

DIN

Chlorophyll



Primary production

Air-sea CO_2 flux

Happy / Not happy

- We're happy(-ish) with the overall performance of MEDUSA
- However, specific weaknesses are:
  - significantly elevated Southern Ocean nutrients (NEMO partially to blame)
  - silicic acid too low away from the SO
  - chlorophyll too low in oligotrophic gyres
  - production a little on the low side
  - long-term drifts in nutrient fields
- And we have no good, systematic way of altering parameterisations to address these issues

Where next?

- Flynn & Fasham style intracellular pools
- Treatment of larger non-diatoms
- Inclusion of missing N-cycle processes (e.g. denitrification, implicit N2-fixation)

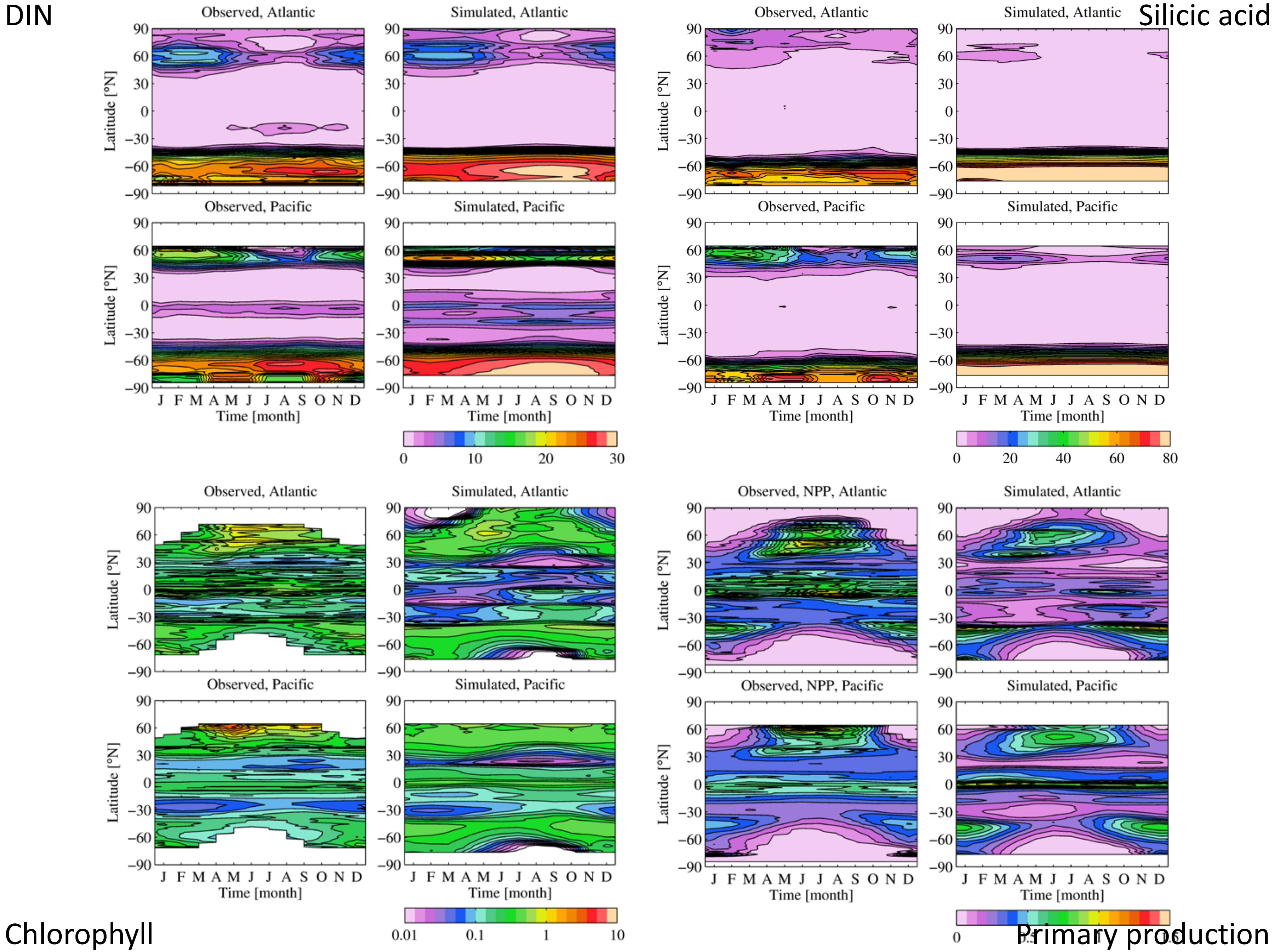
- General upgrades to formulations and parameters

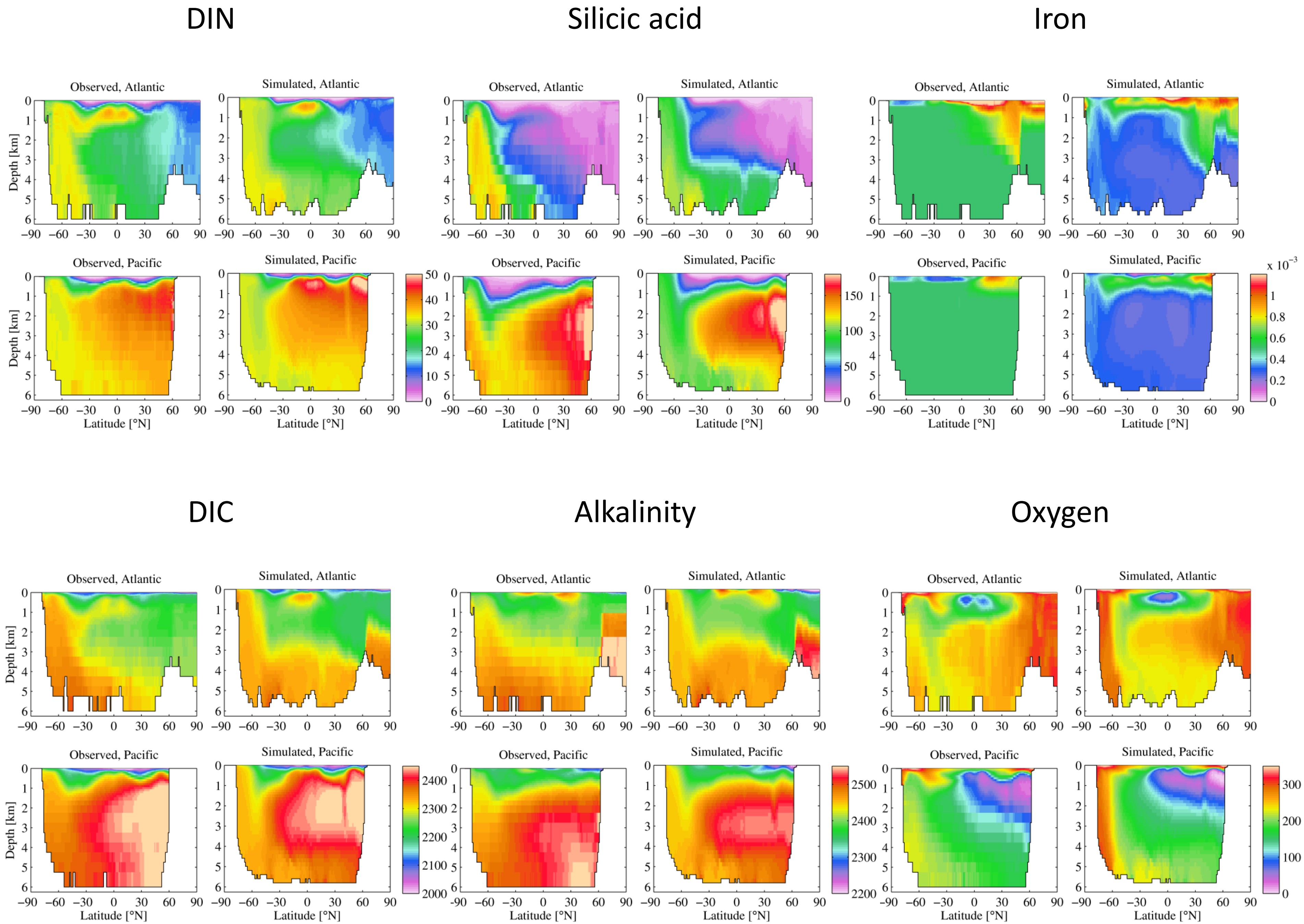
The bigger picture ... as I see it; 1

- iMARNET shouldn't shy away from nutrient-only and NZPD models – we "know" they're wrong, but are our models objectively better than them?
- Alongside developing a new marine BGC component for NERC's ESM strategy, iMARNET should think – clearly and early – about the broader rules that should guide ecosystem model architecture
- Can we learn anything from other communities, for instance terrestrial ecology and JULES?

The bigger picture … as I see it; 2

- Modelling internal physiology and cellular economics will provide valuable constraints on parameterisations (cf. trade-offs)
- Allometry in physiology and ecology (e.g. Mark Baird, Ben Ward) is the way to bump-up model granularity (i.e. not the original Darwin model)
- Diverse or poorly-understood groups (e.g. coccolithophorids) should only be added very carefully until the situation improves
- Sooner or later we're going to have to engage more fully with the fish people


DIN
Silicic acid
Chlorophyll
Primary production
Observed, Atlantic
Simulated, Atlantic
Observed, Pacific
Simulated, Pacific
Observed, NPP, Atlantic
Observed, NPP, Pacific
Latitude [°N]
Time [month]
J F M A M J J A S O N D
90 60 30 0 −30 −60 −90
0 10 20 30
0 20 40 60 80
0.01 0.1 1 10


DIN
Silicic acid
Iron
DIC
Alkalinity
Oxygen
Observed, Atlantic
Simulated, Atlantic
Observed, Pacific
Simulated, Pacific
Depth [km]
Latitude [°N]
−90 −60 −30 0 30 60 90
0 1 2 3 4 5 6
0 10 20 30 40 50
0 50 100 150
x 10^−3
0 0.2 0.4 0.6 0.8 1
2000 2100 2200 2300 2400
2200 2300 2400 2500
0 100 200 300