# North Atlantic Spring Bloom: coupled physical-biological modelling and variational data assimilation

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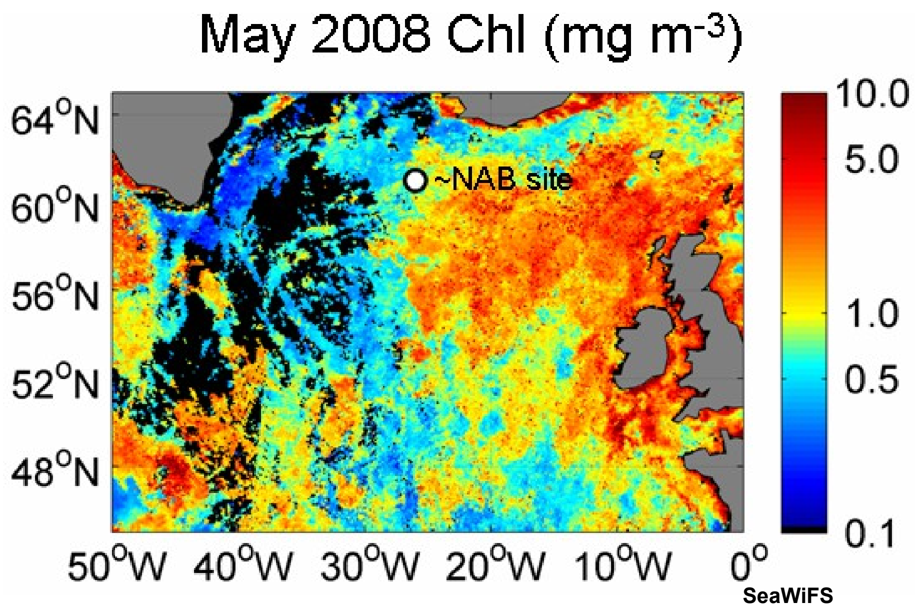
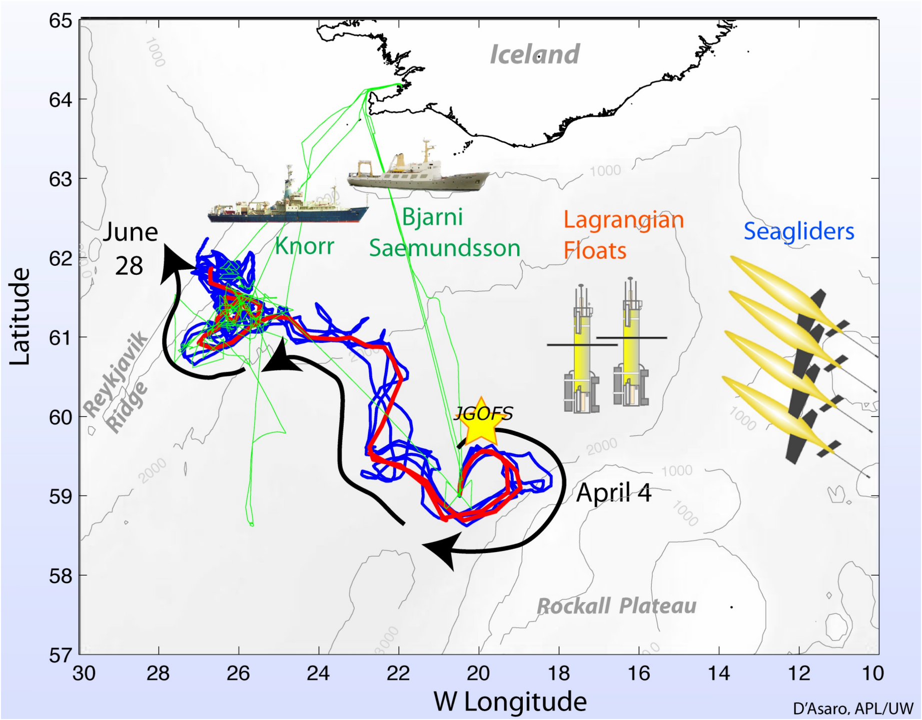
# North Atlantic Spring Bloom

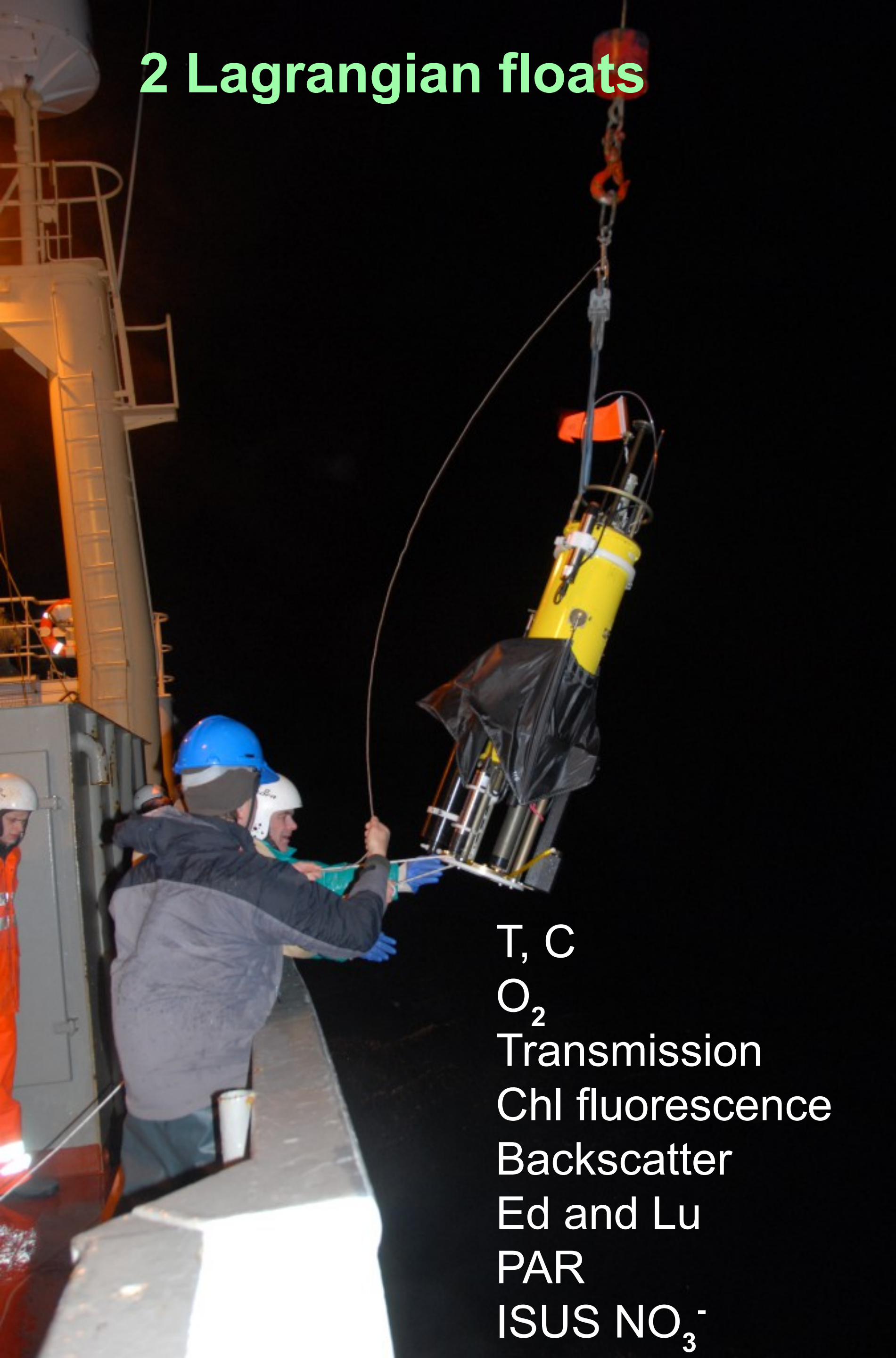
- Photosynthetic Carbon uptake
- Carbon removal (mixed layer pump, aggregate sinking)
- Carbon storage

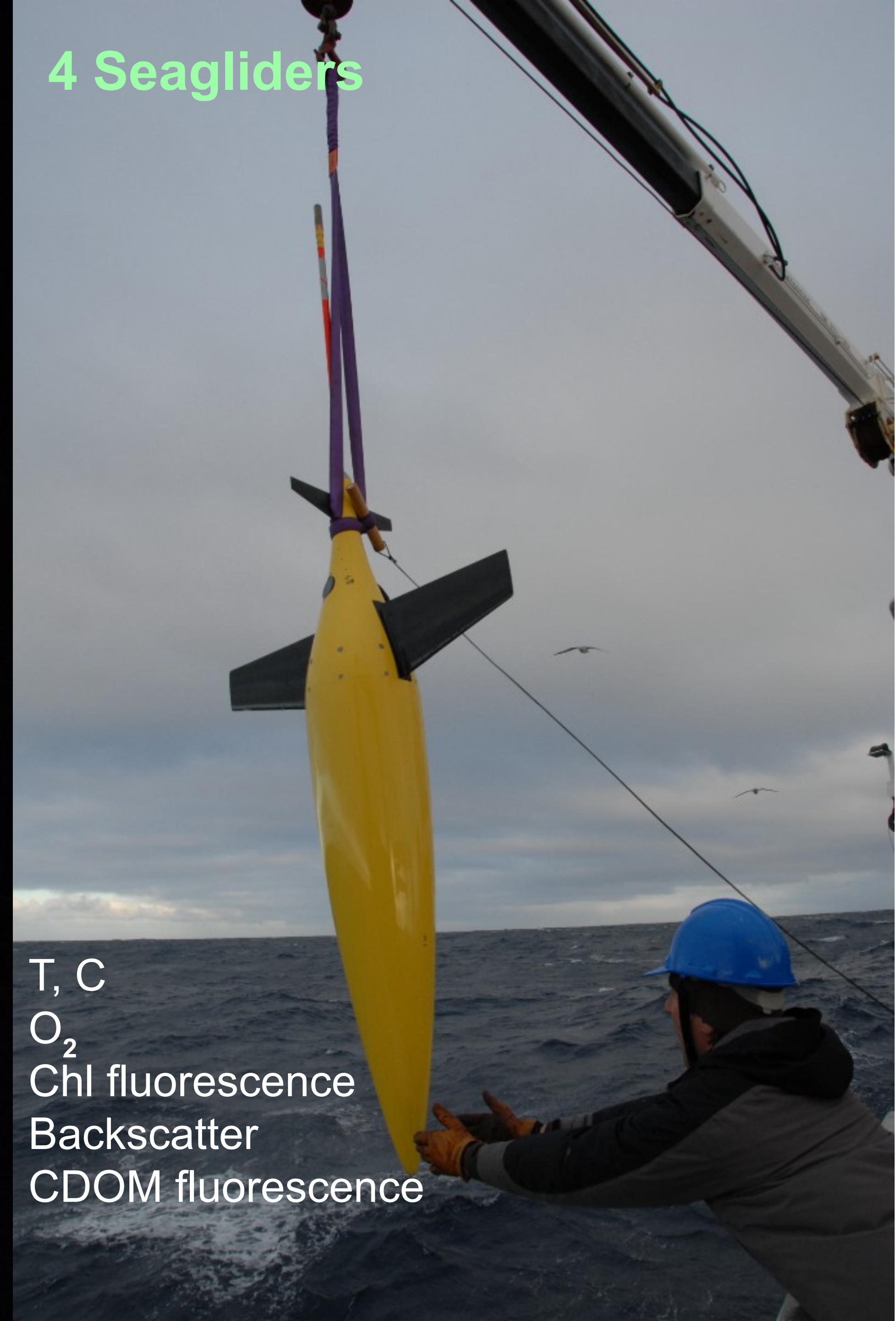
High spatial variability – patchiness:



# Three cruises

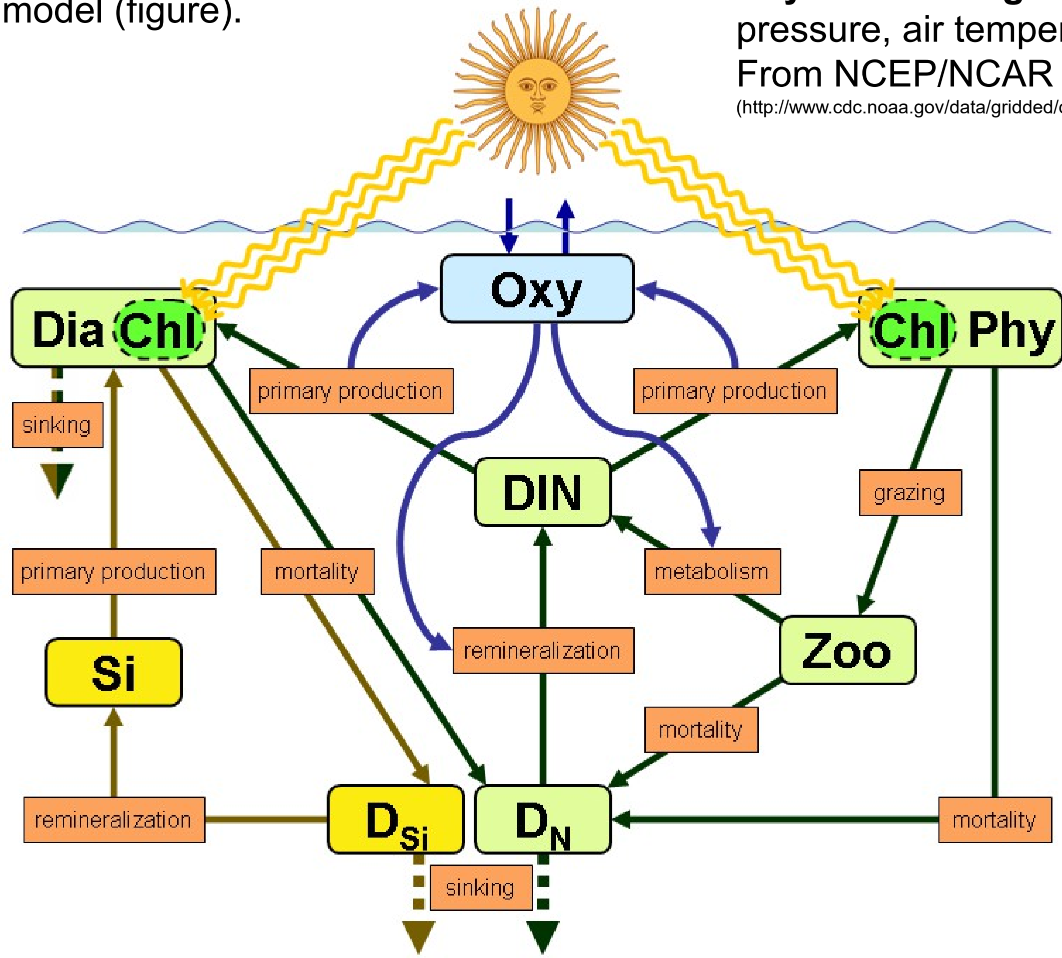

2 Lagrangian floats
T, C
$O_2$
Transmission
Chl fluorescence
Backscatter
Ed and Lu
PAR
ISUS $NO_3^-$


4 Seagliders
T, C
$O_2$
Chl fluorescence
Backscatter
CDOM fluorescence

# GOTM 1-D physical - biological model

**Physical model:** 1D General Ocean Turbulence Model (GOTM), coupled with a biological model (figure).

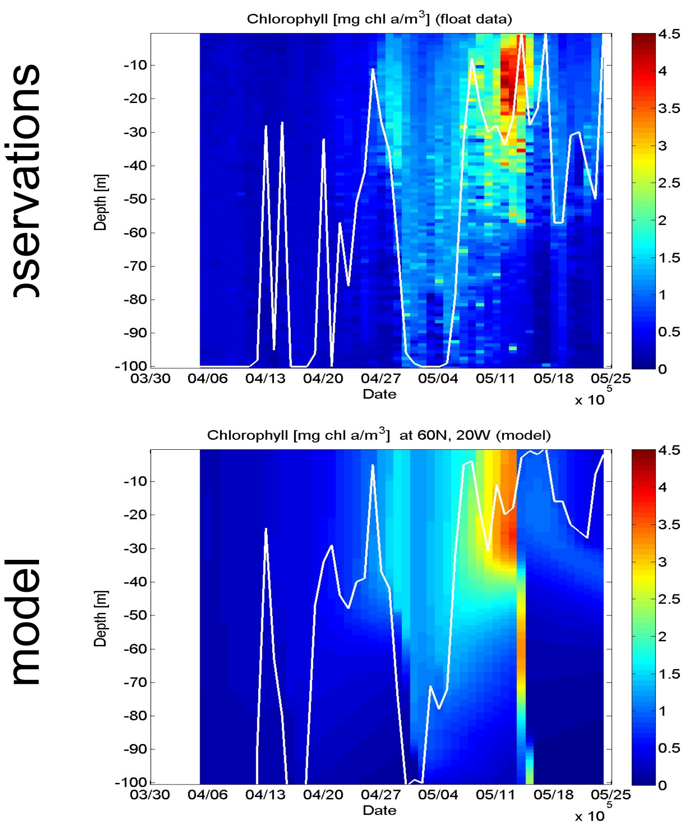
**Physical forcing:** wind speed, air pressure, air temperature and humidity. From NCEP/NCAR Reanalysis
(http://www.cdc.noaa.gov/data/gridded/data.ncep.reanalysis.surfaceflux.html).



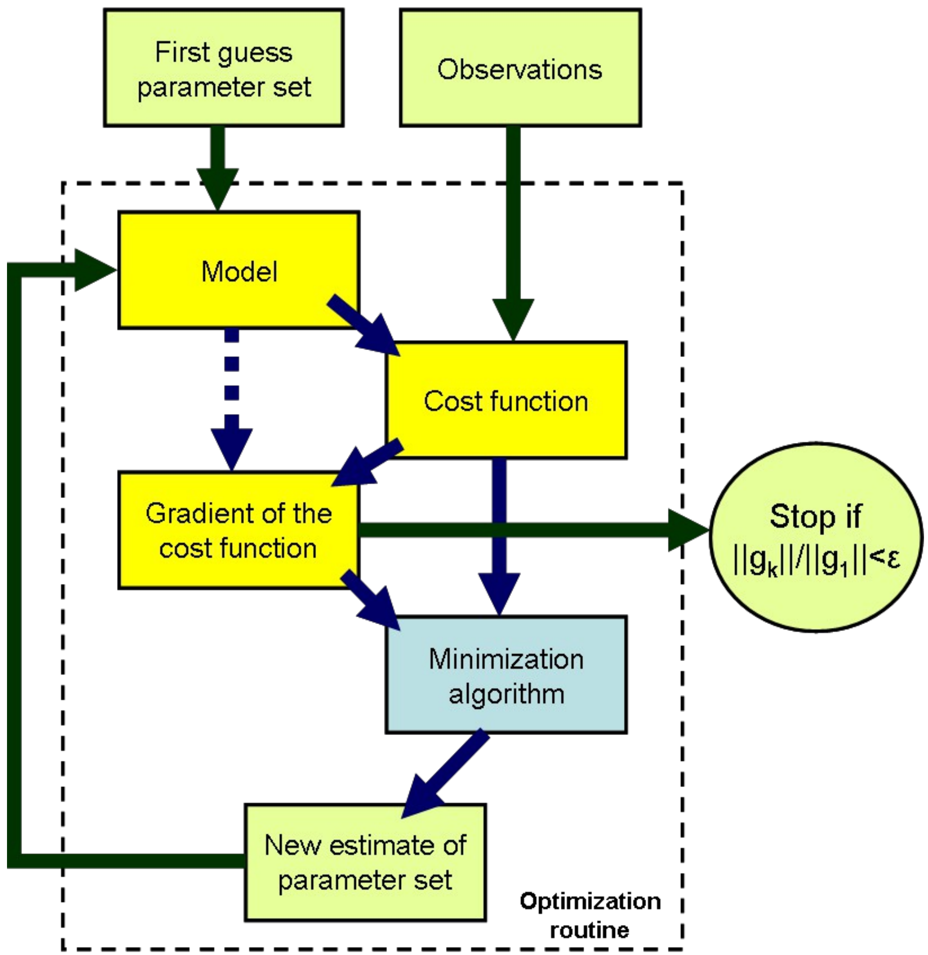
# Data assimilation

**The cost function** – calculates the misfit between model data and observations:

$$F(\bar{p}) = \frac{1}{n}\sum_{i}^{n}\frac{(X_i^{obs} - X_i^{mod}(\bar{p}))^2}{\sigma_i}$$




**Steps involved in the data assimilation procedure:**



# Data assimilation

Before data assimilation:

$\mu_{max}Phy = 0.30$

$\mu_{max}Dia = 0.5$

$g_{max} = 1.0$

**Cost = 4.40**

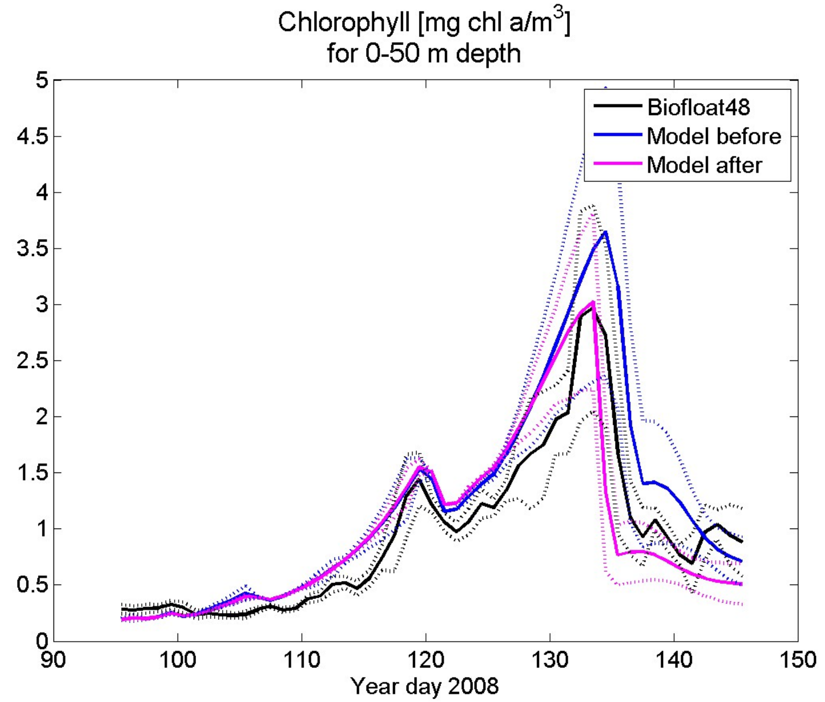
After data assimilation:

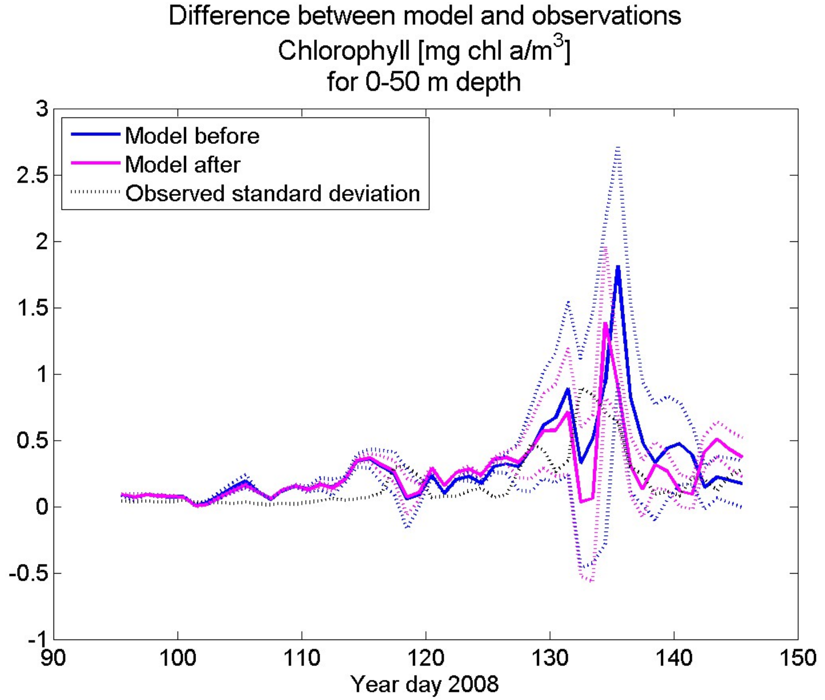
$\mu_{max}Phy = 0.29$

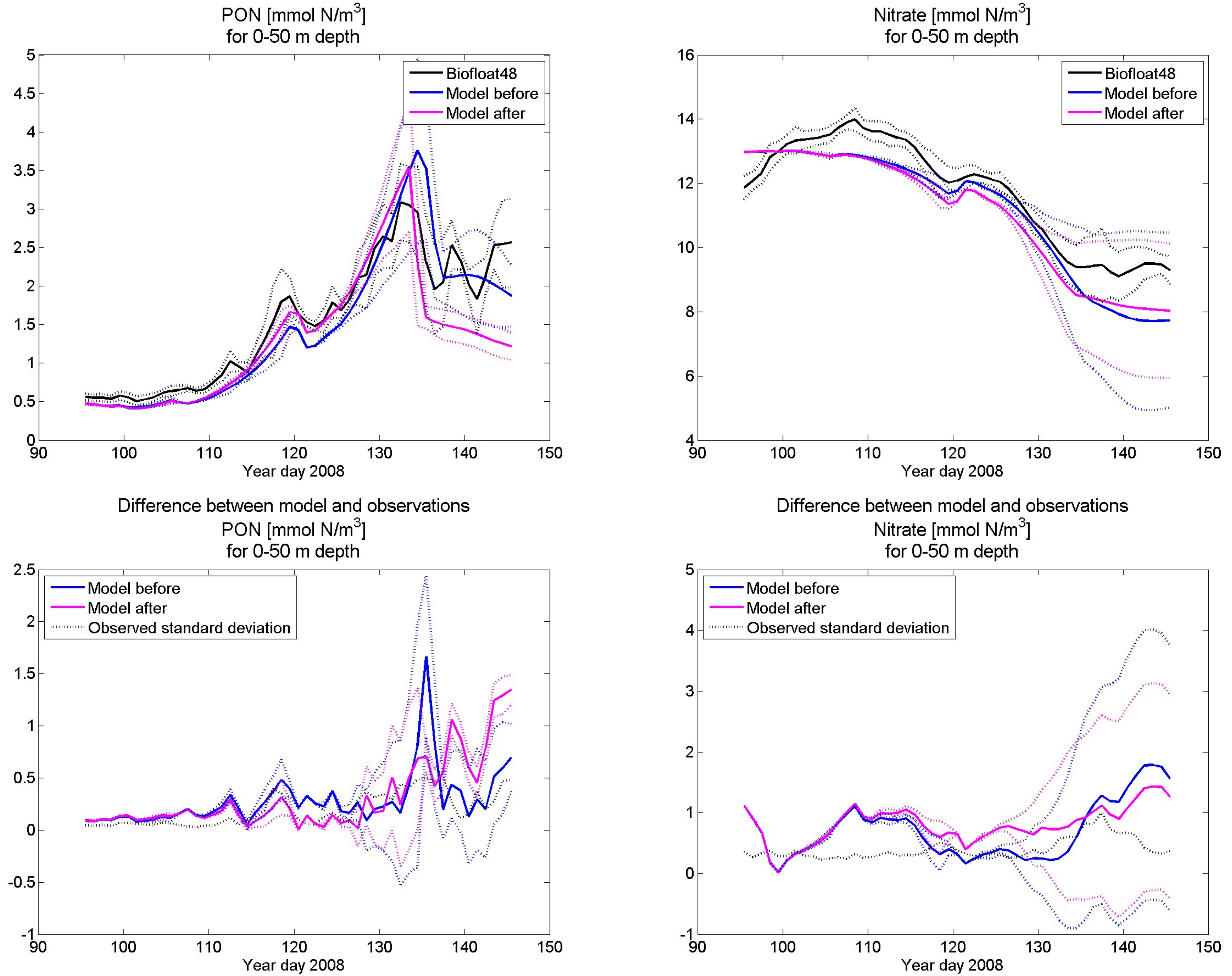
$\mu_{max}Dia = 0.41$

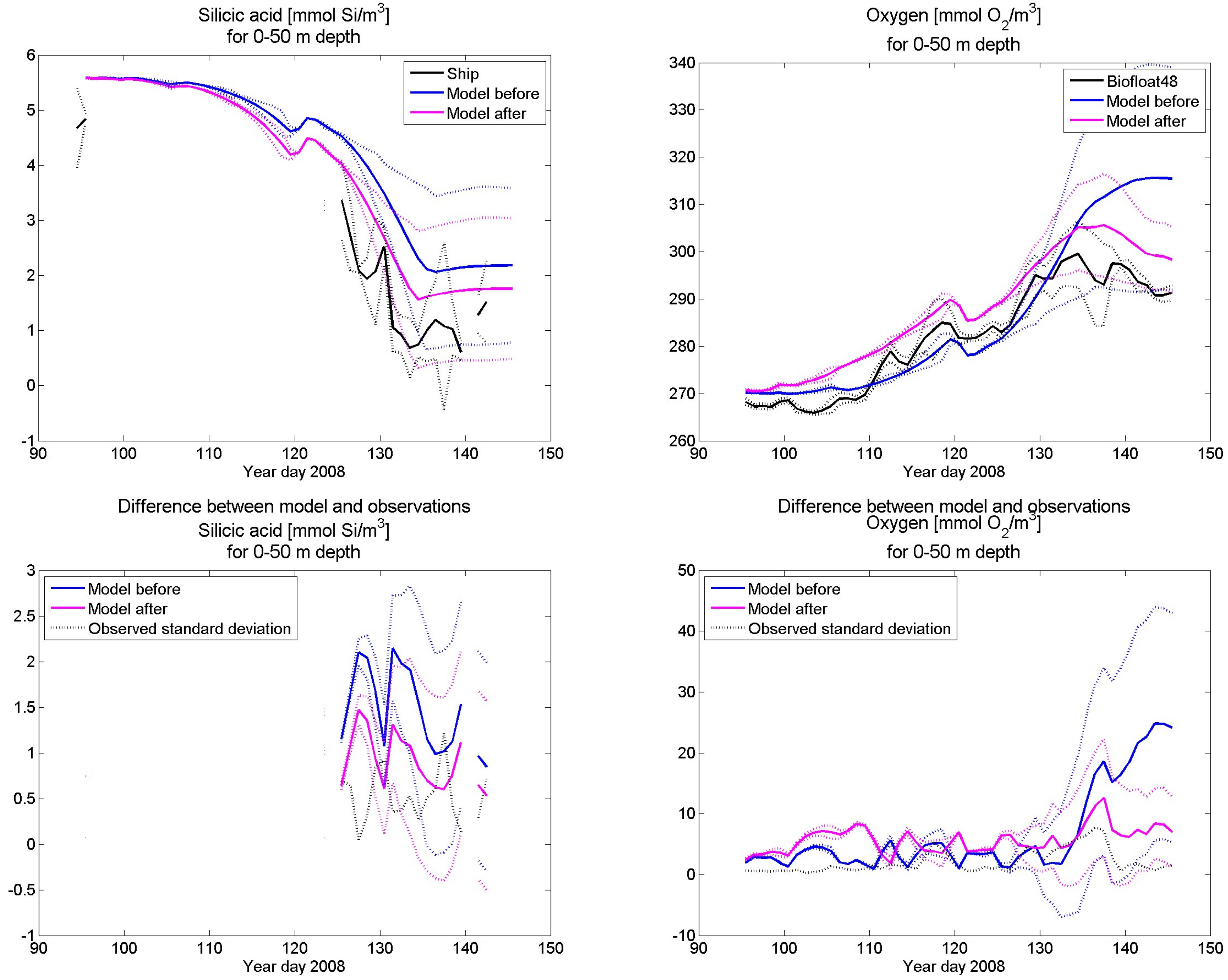
$g_{max} = 1.58$

**Cost = 2.87**

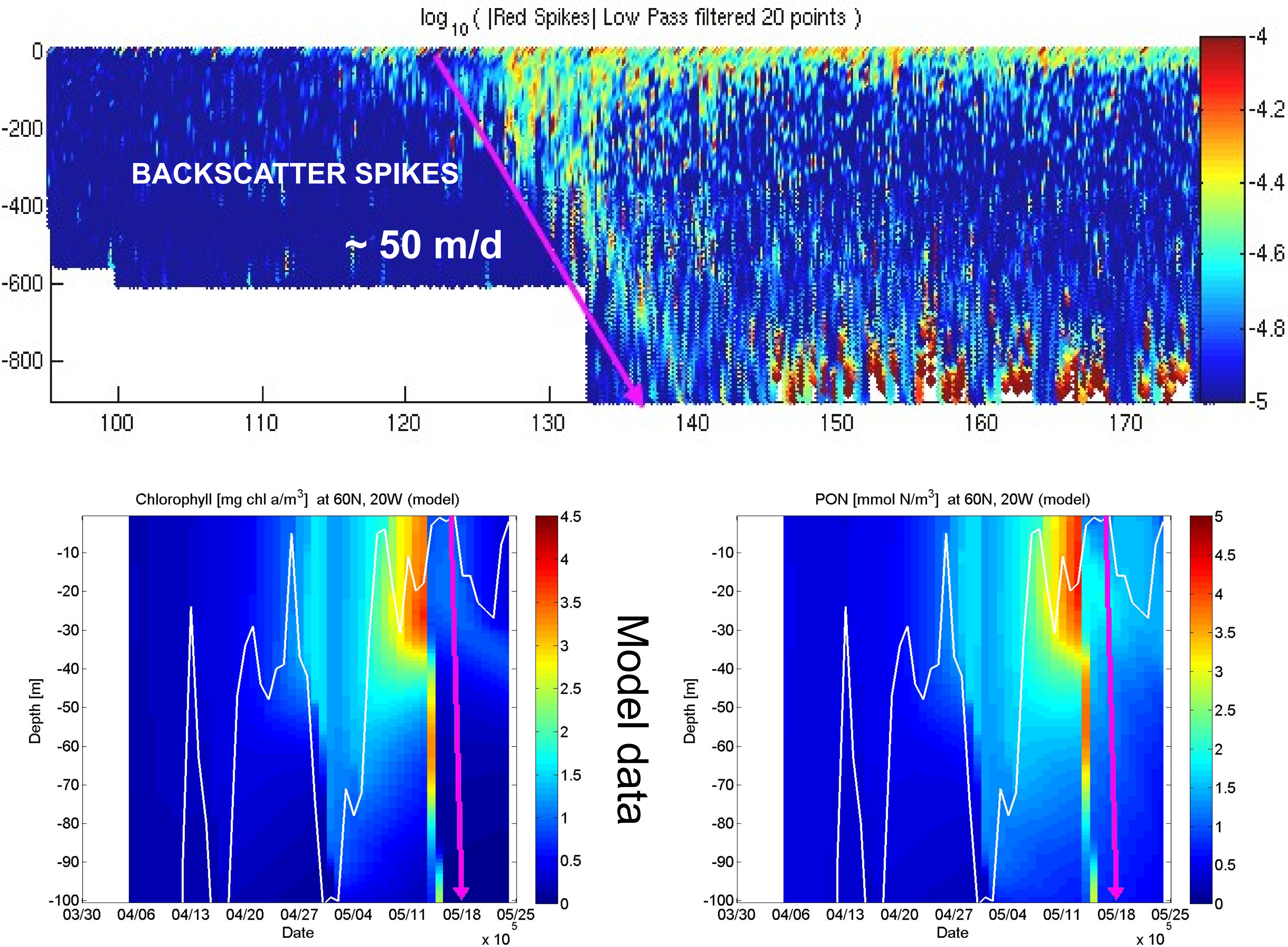


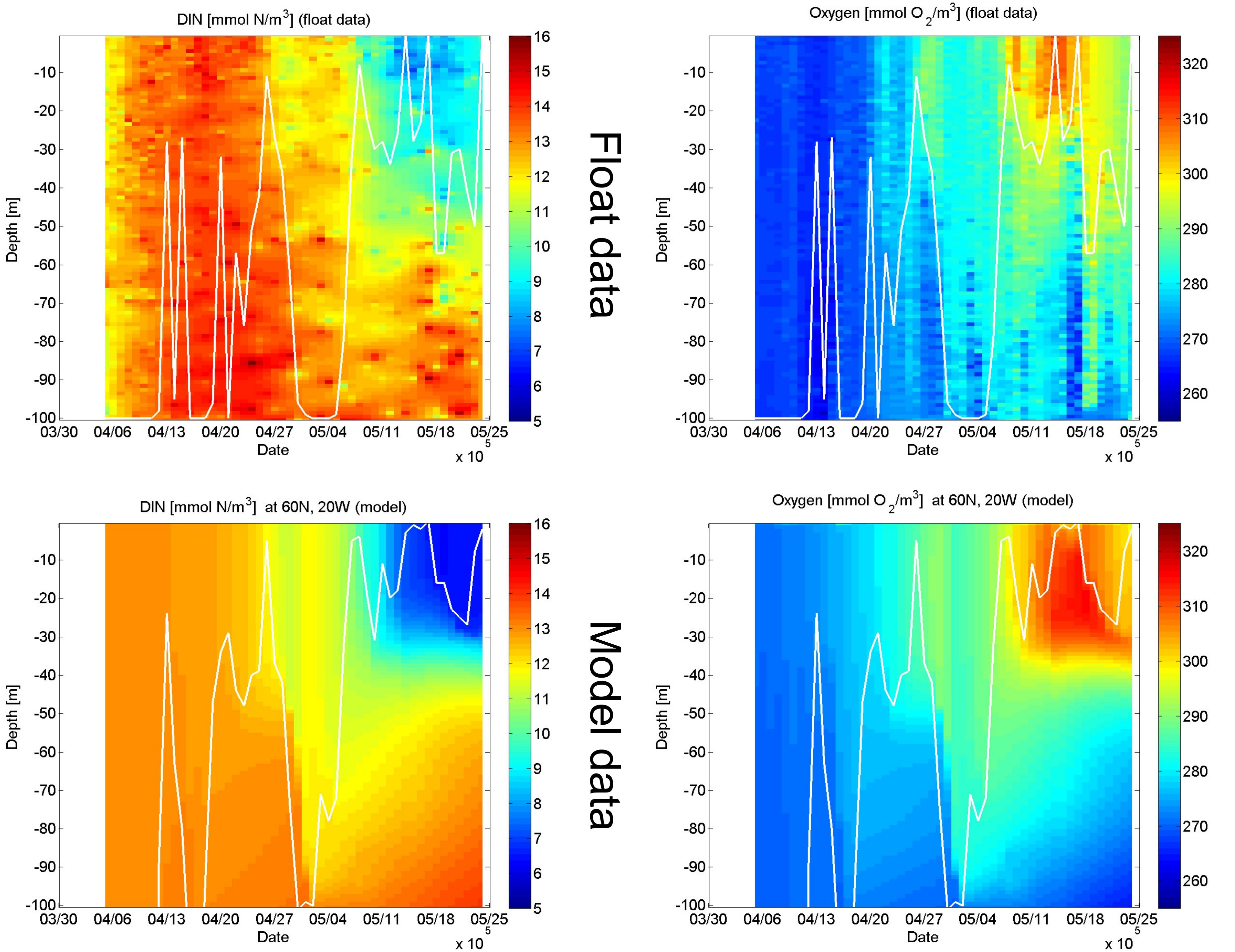

PON [mmol N/m^3]
for 0-50 m depth
Biofloat48
Model before
Model after
Year day 2008
Nitrate [mmol N/m^3]
for 0-50 m depth
Biofloat48
Model before
Model after
Year day 2008
Difference between model and observations
PON [mmol N/m^3]
for 0-50 m depth
Model before
Model after
Observed standard deviation
Year day 2008
Difference between model and observations
Nitrate [mmol N/m^3]
for 0-50 m depth
Model before
Model after
Observed standard deviation
Year day 2008



Silicic acid [mmol Si/m3]
for 0-50 m depth
Ship
Model before
Model after
Year day 2008
Oxygen [mmol O2/m3]
for 0-50 m depth
Biofloat48
Model before
Model after
Year day 2008
Difference between model and observations
Silicic acid [mmol Si/m3]
for 0-50 m depth
Model before
Model after
Observed standard deviation
Year day 2008
Difference between model and observations
Oxygen [mmol O2/m3]
for 0-50 m depth
Model before
Model after
Observed standard deviation
Year day 2008

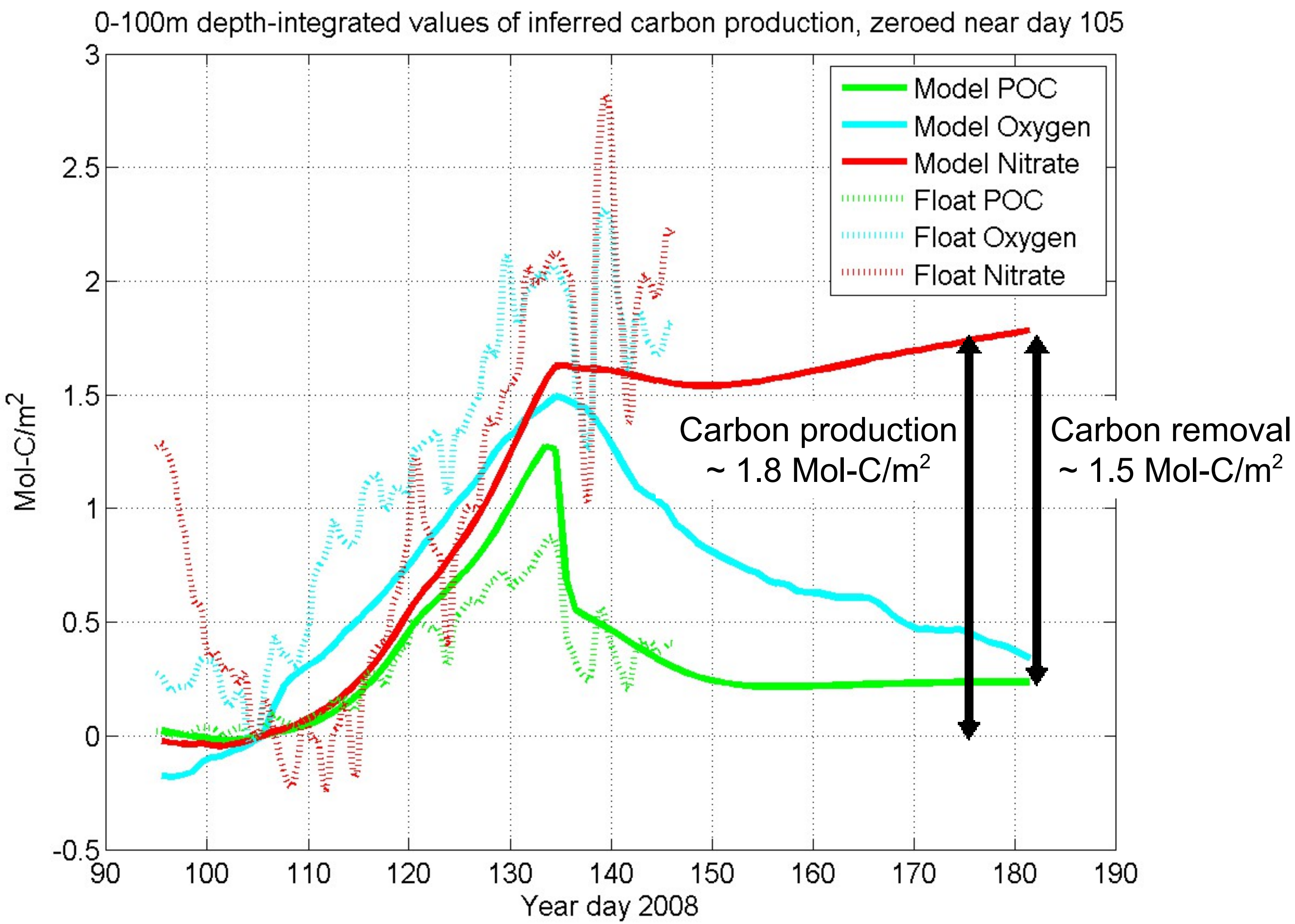


log 10 ( |Red Spikes| Low Pass filtered 20 points )
BACKSCATTER SPIKES
~ 50 m/d
0
-200
-400
-600
-800
100
110
120
130
140
150
160
170
-4
-4.2
-4.4
-4.6
-4.8
-5
Chlorophyll [mg chl a/m3] at 60N, 20W (model)
PON [mmol N/m3] at 60N, 20W (model)
Depth [m]
Date
03/30
04/06
04/13
04/20
04/27
05/04
05/11
05/18
05/25
x 10 5
Model data



DIN [mmol N/m3] (float data)
Oxygen [mmol O2/m3] (float data)
Float data
DIN [mmol N/m3] at 60N, 20W (model)
Oxygen [mmol O2/m3] at 60N, 20W (model)
Model data
Depth [m]
Date
03/30
04/06
04/13
04/20
04/27
05/04
05/11
05/18
05/25
x 10^5
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
5
6
7
8
9
10
11
12
13
14
15
16
260
270
280
290
300
310
320

# Estimating carbon removal



# Summary:

• The use of autonomous platforms in the North Atlantic allowed us to follow the evolution of phytoplankton patches

• We developed an ecosystem model and assimilated data from the platforms to improve the model performance

• The model-based estimate of carbon production during the Spring Bloom is ~ 1.8 Mol-C/$m^2$

• The estimated carbon removal is ~ 1.5 Mol-C/$m^2$

# Thank you

# Biological model

## Sources and sinks of the state variables:

$$\frac{\partial Phy}{\partial t} = \mu_{Phy} Phy - gZoo - m_{Phy} Phy - w_{Phy} \frac{\partial Phy}{\partial z}$$

$$\frac{\partial Dia}{\partial t} = \mu_{Dia} Dia - m_{Dia} Dia - w_{Dia} \frac{\partial Dia}{\partial z}$$

$$\frac{\partial Zoo}{\partial t} = \beta g Zoo - \varepsilon_1 Zoo - \varepsilon_2 Zoo^2$$

$$\frac{\partial Det_N}{\partial t} = (1-\beta) gZoo + m_{Phy} Phy + m_{Dia} Dia + \varepsilon_2 Zoo^2 - r_N Det_N - w_{Det} \frac{\partial Det_N}{\partial z}$$

$$\frac{\partial Det_{Si}}{\partial t} = \frac{Si}{N} m_{Dia} Dia - r_{Si} Det_{Si} - w_{Det} \frac{\partial Det_{Si}}{\partial z}$$

$$\frac{\partial DIN}{\partial t} = r_N Det_N + \varepsilon_1 Zoo - \mu_{Phy} Phy - \mu_{Dia} Dia$$

$$\frac{\partial Si}{\partial t} = r_{Si} Det_{Si} - \frac{Si}{N} \mu_{Dia} Dia$$

$$\frac{\partial Chl_1}{\partial t} = \rho_{Chl_1} \mu_{Phy} Phy - gZoo \frac{Chl_1}{Phy} - m_{Phy} Chl_1 - w_{Phy} \frac{\partial Chl_1}{\partial z}$$

$$\frac{\partial Chl_2}{\partial t} = \rho_{Chl_2} \mu_{Dia} Dia - m_{Dia} Chl_2 - w_{Dia} \frac{\partial Chl_2}{\partial z}$$

$$\frac{\partial Oxy}{\partial t} = r_{Oxy:DIN} (\mu_{Phy} Phy + \mu_{Dia} Dia - r_N Det_N - \varepsilon_1 Zoo)$$

## O2 exchange (surface only):

$$\frac{\partial Oxy}{\partial t} = -K(Oxy - O_{sat}(1+\Delta))$$

$$K = \left(\frac{2}{9} U_{10}^2 + \frac{1}{3} U_{10}\right) \left(\frac{S_C}{600}\right)^{-0.5}$$

$$\Delta = 0.01 \left(\frac{U_{10}}{U_{1ox}}\right)^2$$

## Light equations:

$$f(I) = \frac{\alpha I}{\sqrt{(\mu^{max})^2 + \alpha^2 I^2}}$$

$$I = I_0 \phi e^{-zK_w - \int_0^z K_{Chl}(Chl_1(\eta) + Chl_2(\eta)) d\eta}$$

## Parameters:

| symbol | value | unit | description |
|---|---|---|---|
| $\mu_{Phy}^{max}$ | 0.3 | $d^{-1}$ | maximum small phytoplankton growth rate |
| $\mu_{Dia}^{max}$ | 0.38 | $d^{-1}$ | maximum diatom growth rate |
| $m_{Phy}$ | 0.1 | $d^{-1}$ | small phytoplankton mortality rate |
| $m_{Dia}$ | 0.12 | $d^{-1}$ | diatom mortality rate |
| $k_N$ | 0.7 | $mmolNm^{-3}$ | half-saturation concentration of DIN uptake |
| $k_{Si}$ | 0.71 | $mmolSim^{-3}$ | half-saturation concentration of silicic acid uptake |
| $\alpha_{Phy}$ | 0.017 | $\frac{mmolN}{mgChldW/m^2}$ | initial slope of P-I curve (small phytoplankton) |
| $\alpha_{Dia}$ | 0.028 | $\frac{mmolN}{mgChldW/m^2}$ | initial slope of P-I curve (diatoms) |
| $\theta_{max}$ | 3.84 | $\frac{mgChl}{mgN}$ | phytoplankton maximum Chl:N |
| $\frac{Si}{N}$ | 1.0 | $molSi : molN$ | stoichiometry of diatoms |
| $g_{max}$ | 0.95 | $d^{-1}$ | maximum grazing rate |
| $\lambda$ | 1.0 | $(\frac{mmolN}{m^3})^2$ | zooplankton grazing half-saturation |
| $\beta$ | 0.75 | - | assimilation efficiency of zooplankton |
| $\varepsilon_1$ | 0.067 | $d^{-1}$ | zooplankton excretion rate |
| $\varepsilon_2$ | 0.25 | $(mmolNm^{-3})^{-1}$ | zooplankton mortality rate |
| $r_N$ | 0.1 | $d^{-1}$ | detrital nitrogen remineralization rate |
| $r_{Si}$ | 0.05 | $d^{-1}$ | detrital silicate remineralization rate |
| $w_{Phy}$ | -0.1 | $md^{-1}$ | sinking rate of small phytoplankton |
| $w_{Dia}$ | -0.8, -55.0 | $md^{-1}$ | sinking rates of diatoms |
| $w_{Det}$ | -5.0 | $md^{-1}$ | sinking rate of detritus |
| $I_0$ | | $Wm^{-2}$ | incoming light just below the ocean surface |
| $\phi$ | 0.43 | $-$ | fraction of light that is photosynthetically active |
| $K_w$ | 0.04 | $m^{-1}$ | light attenuation coefficient for water |
| $K_{Chl}$ | 0.016 | $(mgChl)^{-1}m^{-1}$ | light attenuation coefficient for chlorophyll |

## Parametrizations:

$$\rho_{Chl_1} = \frac{\theta_{max} \mu_{Phy} Phy}{\alpha I Chl_1}$$

$$\rho_{Chl_2} = \frac{\theta_{max} \mu_{Dia} Dia}{\alpha I Chl_2}$$

$$\mu_{Phy} = 1.066^T \mu_{Phy}^{max} f(I) \frac{DIN}{k_N + DIN}$$

$$\mu_{Dia} = 1.066^T \mu_{Dia}^{max} f(I) min\left(\frac{Si}{k_{Si} + Si}, \frac{DIN}{k_N + DIN}\right)$$

$$g = g_{max} \lambda Phy (1 - e^{-\lambda Phy}) Zoo$$