

Predictions of carbon fixation during a bloom of *Emiliana huxleyi* is highly sensitive to assumed response to shift in pCO₂



Olivier Bernard
Antoine Sciandra
Sophie Rabouille

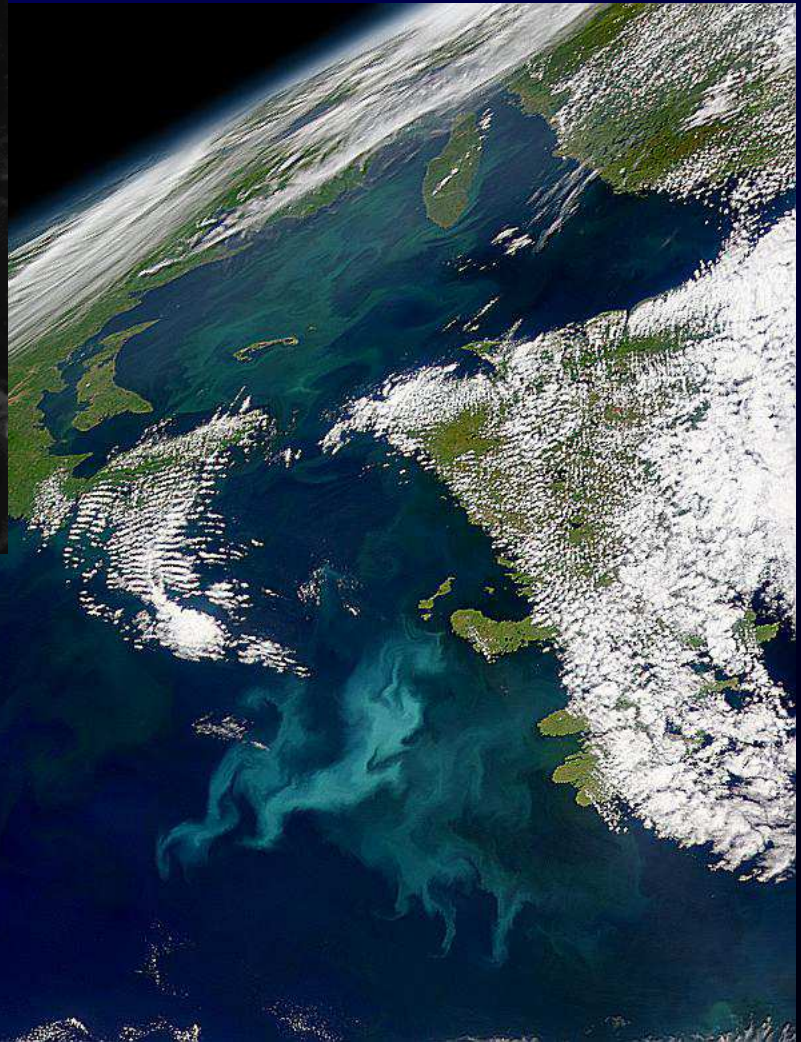
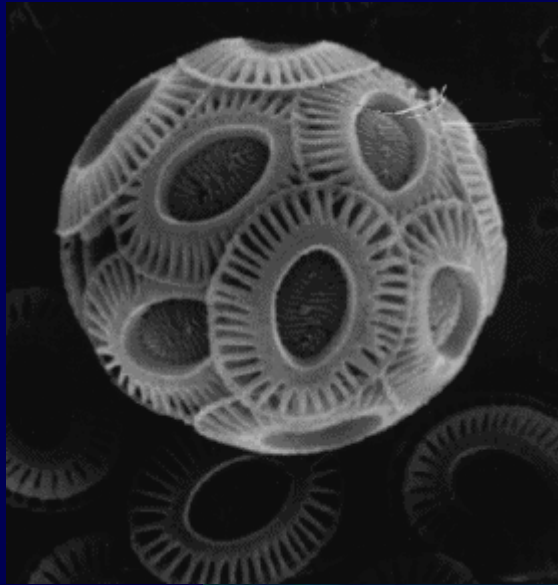


Laboratoire d'Océanographie de
Villefranche/Mer



COMORE Project - Sophia Antipolis

Coccolithophorids play an important role in CO₂ trapping



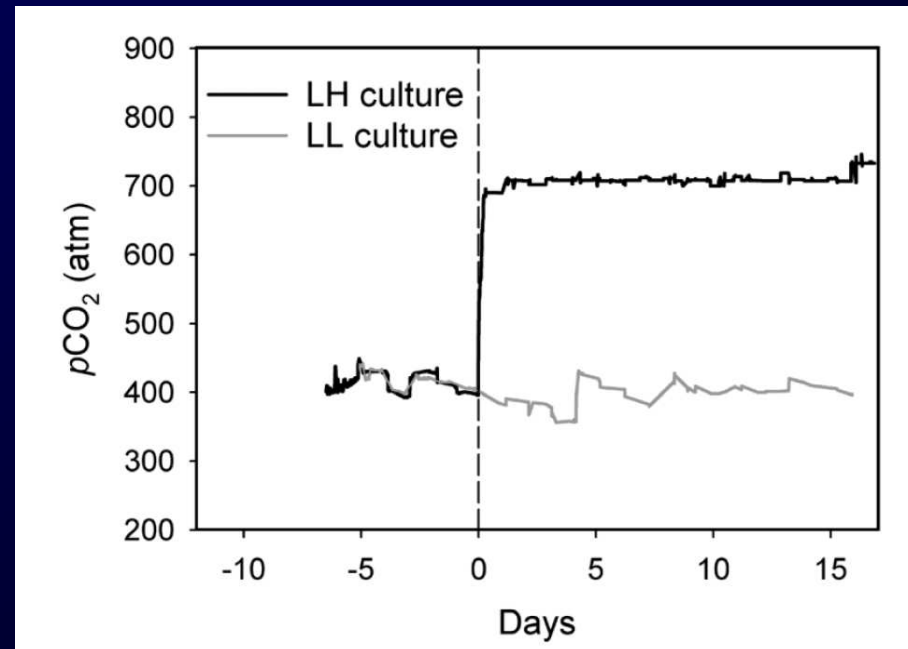
1/3 of the total marine
CaCO₃ production

Effect of pCO₂ increase

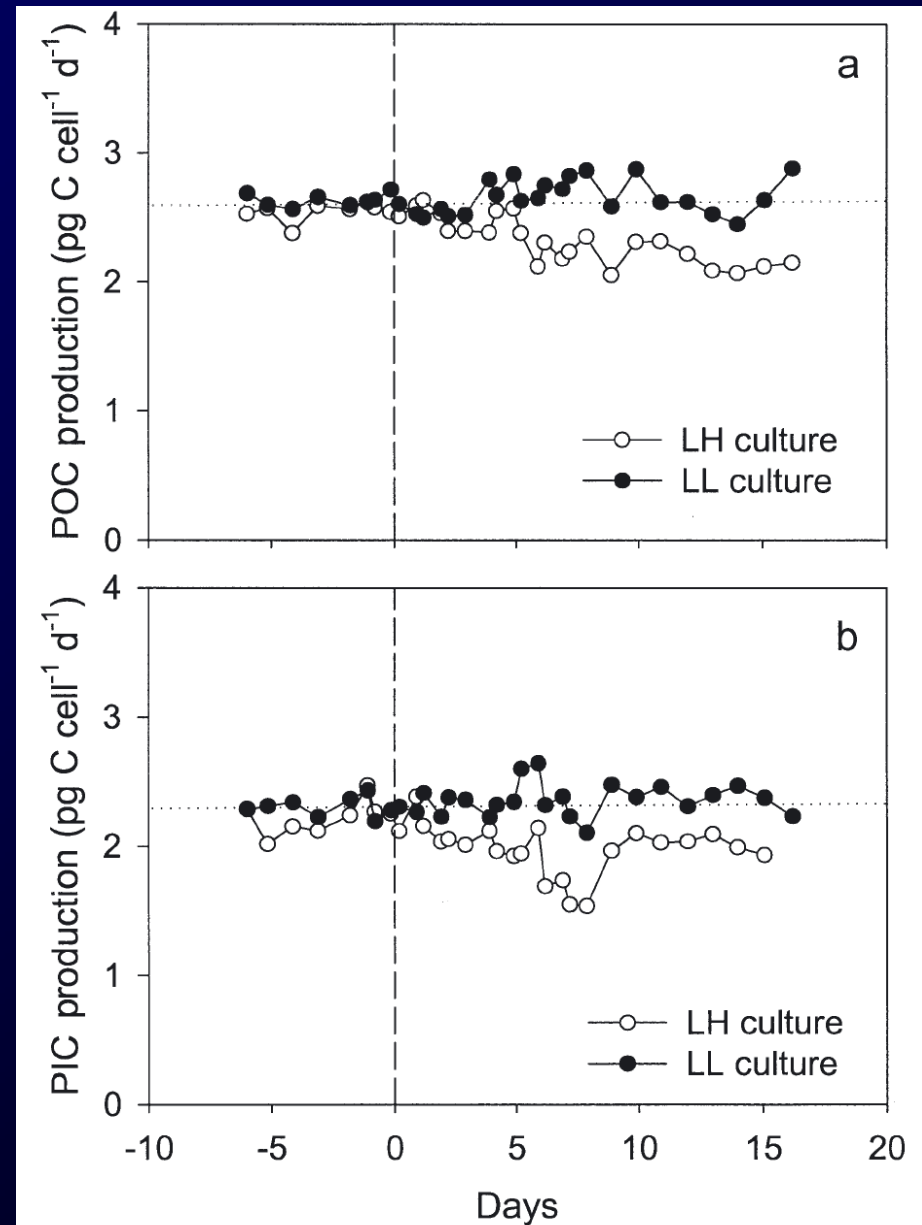
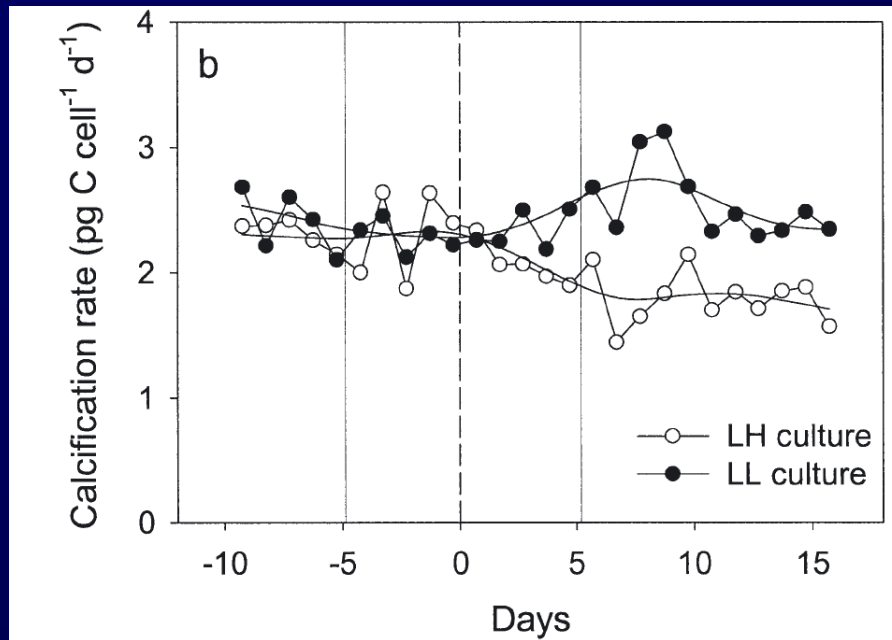
- Underlying mechanisms still to be clarified
- Effect of pCO₂ subject of intense debates
 - Decrease of calcification in *Emiliana huxleyi* (Riebesell et al., 2000), batch experiments
 - Increase in calcification in *E.huxleyi* (Iglesias-Rodriguez et al. 2008), batch experiments
 - Decrease in calcification and photosynthesis *E.huxleyi* (Sciandra et al., 2003) **Chemostat experiments**

Performed experiments

- pH regulation to achieve a dissolved CO₂ concentration corresponding to pCO₂ 415 ppm → 710 ppm



Experimental results



Sciandra et al. 2003

MODEL DESIGN

Model principles

- Integrate both biology and carbonate system dynamics
- Test several possible coupling and regulation mechanisms
- Based on a quota model (Droop like)
- Keep a general (and generic) structure

Simplified point of view

Photosynthesis



Calcification



Coupling ?



Simplified carbonate system modelling

- **The carbonate system**

$$D = [HCO_3^-] + [CO_3^{2-}] + [CO_2]$$

$$CA = [HCO_3^-] + 2[CO_3^{2-}]$$

- **Alkalinity**

$$TA = CA + [B(OH)_4^-] + [OH^-] - [H^+]$$

- **Electroneutrality**

$$\begin{aligned} [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [OH^-] + [Cl^-] + [Br^-] + [F^-] + 2[SO_4^{2-}] + \\ = [Na^+] + [K^+] + 2[Mg^{2+}] + 2[Sr^{2+}] + 2[Ca^{2+}] + [H^+] + \dots \end{aligned}$$

Simplified carbonate system modelling

- **Electroneutrality**

$$CA = \underbrace{\lambda - \lambda_0 + 2[Ca^{2+}]} = [HCO_3^-] + 2[CO_3^{2-}]$$

\approx constant

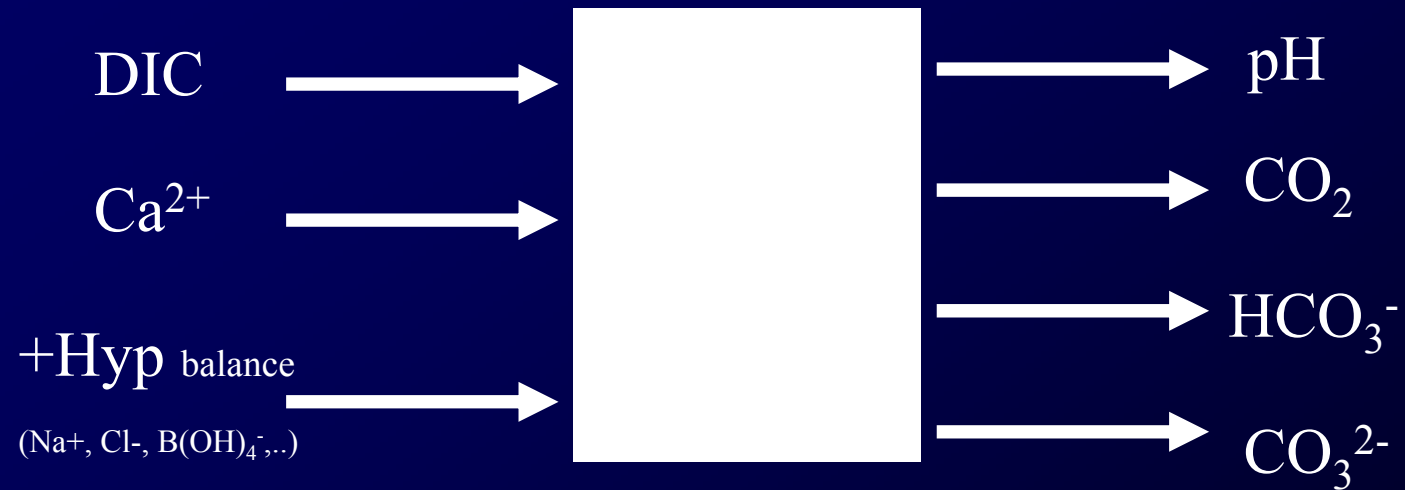
- **Affinity constants**

$$h = [H^+]$$

$$K_1 = \frac{h[HCO_3^-]}{[CO_2]}$$

$$K_2 = \frac{h[CO_3^{2-}]}{[HCO_3^-]}$$

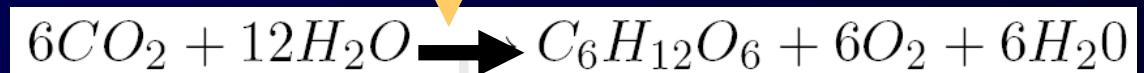
Carbonate system modelling



12 possible models

2. Which processes regulate photosynthesis & calcification?

Photosynthesis

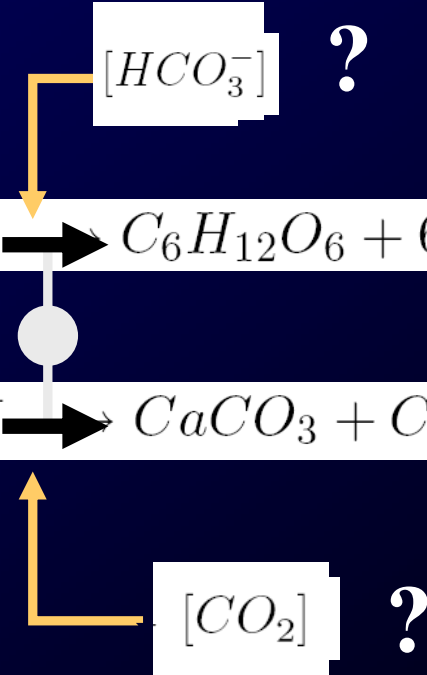


Calcification



$[HCO_3^-]$?

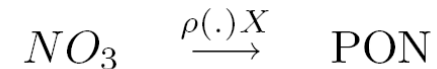
$[CO_2]$?



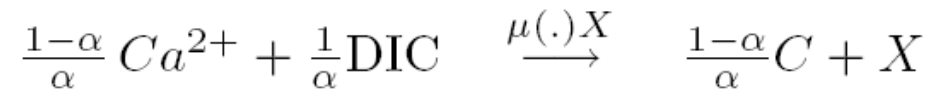
Coupled carbon uptake model

- Mass flows

Nitrogen uptake



Carbon uptake



- Model equations

$$\dot{NO}_3 = d(NO_{3in} - NO_3) - \rho(NO_3)X$$

$$\dot{Q} = \rho(NO_3) - \mu(Q, Dp)Q$$

$$\dot{X} = -dX + \mu(Q, Dp)X$$

$$\dot{C} = -dC + \frac{1-\alpha}{\alpha} \mu(Q, Dp)X$$

$$\dot{\text{DIC}} = d(\text{DIC}_{in} - \text{DIC}) - \frac{1}{\alpha} \mu(Q, Dp)X - K_{La}(\psi(\text{Ca}^{2+}, \text{DIC}) - K_{Hp}\text{CO}_2)$$

$$\dot{Ca}^{2+} = d(Ca_{in}^{2+} - Ca^{2+}) - \frac{1-\alpha}{\alpha} \mu(Q, Dp)X$$

$$Dp = \frac{[HCO_3^-]}{[CO_3^{2-}] + [CO_2]}$$

Carbon fixation specific rate

Hypothesis: $\mu(Q, Dp)$ is an increasing function of Q and Dp

Example: Droop with regulation by Dp

$$\mu(Q, Dp) = \bar{\mu} \left(1 - \frac{k_Q}{Q}\right) \frac{Dp}{Dp + k_{Dp}} - R$$

In the analysis $\mu(Q, Dp)$ is left generic !

CI models: Coupled Inorganic carbon uptake

•3 models

CI- HCO_3^- , CI- CO_2 , CI- CO_3^{2-}

$$\dot{S}_1 = d(S_{1in} - S_1) - \rho(S_1)X$$

$$\dot{Q} = \rho(S_1) - \mu(Q, Dp)Q$$

$$\dot{X} = -dX + \mu(Q, Dp)X$$

$$\dot{C} = -dC + \frac{1-\alpha}{\alpha}\mu(Q, Dp)X$$

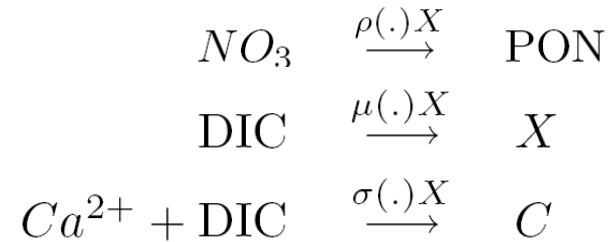
$$\dot{D} = d(D_{in} - D) - \frac{1}{\alpha}\mu(Q, Dp)X - K_L a(\psi(S_2, D) - K_{HP}CO_2)$$

$$\dot{S}_2 = d(S_{2in} - S_2) - \frac{1-\alpha}{\alpha}\mu(Q, Dp)X$$

Uncoupled carbon uptake model

- Mass flows

Nitrogen uptake
Photosynthesis
Calcification



- Model equations

$$\dot{NO}_3 = d(NO_{3in} - NO_3) - \rho(NO_3)X$$

$$\dot{Q} = \rho(NO_3) - \mu(Q, Dp)Q$$

$$\dot{X} = -dX + \mu(Q, Dp)X$$

$$\dot{C} = -dC + \sigma(Dc)X$$

$$\dot{DIC} = d(DIC_{in} - DIC) - \mu(Q, Dp)X - \sigma(Dc)X - K_{La}(\psi(Ca^{2+}, DIC) - K_{HP}CO_2)$$

$$\dot{Ca}^{2+} = d(Ca_{in}^{2+} - Ca^{2+}) - \sigma(Dc)X$$

$$Dc = [HCO_3^-]$$

$$Dp = [CO_3^{2-}]$$

$$Dc = [CO_2]$$

MATHEMATICAL MODEL STUDY

Results analysis

variables	CI			UI									
	HCO ₃ ⁻	CO ₂	CO ₃ ²⁻	HCO ₃ ⁻	HCO ₃ ⁻	HCO ₃ ⁻	CO ₂	CO ₂	CO ₂	CO ₃ ²⁻	CO ₃ ²⁻	CO ₃ ²⁻	
Photosynthesis													
Calcification													
DIC	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗	↗
Dp*	↗	↗	↘	↗	↗	↗	↗	↗	↗	↘	↘	↘	↘
Dc*	↗	↗	↘	↗	↗	↘	↗	↗	↘	↗	↗	↘	↘
X*	↗	↗	↘	↗	↗	↗	↗	↗	↗	↘	↘	↘	↘
Q*	↘	↘	↗	↘	↘	↘	↘	↘	↘	↗	↗	↗	↗
S ₁ *	↘	↘	↗	↘	↘	↘	↘	↘	↘	↗	↗	↗	↗
C*	↗	↗	↘	↗	↗	↘	↗	↗	↘	↘	↗	↗	↘
Ca ₂ ⁺	↘	↘	↗	↘	↘	↗	↘	↘	↗	↗	↘	↘	↗
$\frac{C^*}{X^*}$	→	→	→	↗	↗	↘	↗	↗	↘	↗	↗	↗	↘
pH*	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘	↘
CA	↘	↘	↗	↘	↘	↗	↘	↘	↗	↗	↘	↘	↗
TA	↘	↘	↗	↘	↘	↗	↘	↘	↗	↗	↘	↘	↗
Φ*	↗	↗	↘	↗	↗	↘*	↗	↗	↘*	↘	↘	↘	↘
Φ _p *	↗	↗	↘	↗	↗	↗	↗	↗	↗	↘	↘	↘	↘
Φ _c *	↗	↗	↘	↗	↗	↘	↗	↗	↘	↘	↘	↘	↘
$\frac{\Phi_p^*}{\Phi_c^*}$	→	→	→	↘	↘	↗	↘	↘	↗	↘	↘	↘	↗

○
Experimental
Observations
Sciandra et al.
2003

Consequences

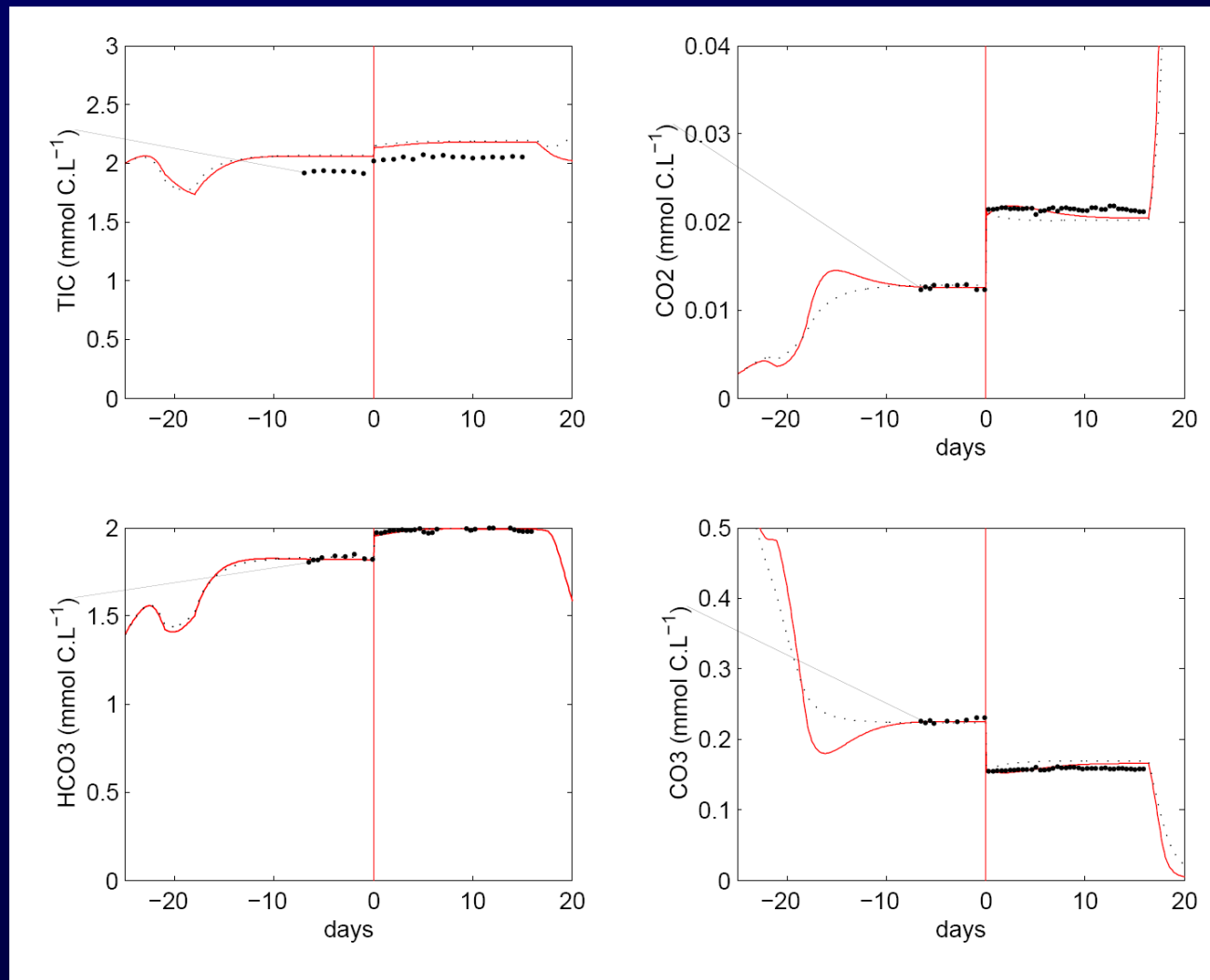
- From this analysis 4 models can explain data from Sciandra et al. 2003:

Photosynthesis regulated by CO_3^{2-} !!!!

 This is not the classical hypothesis for N-replete experiments

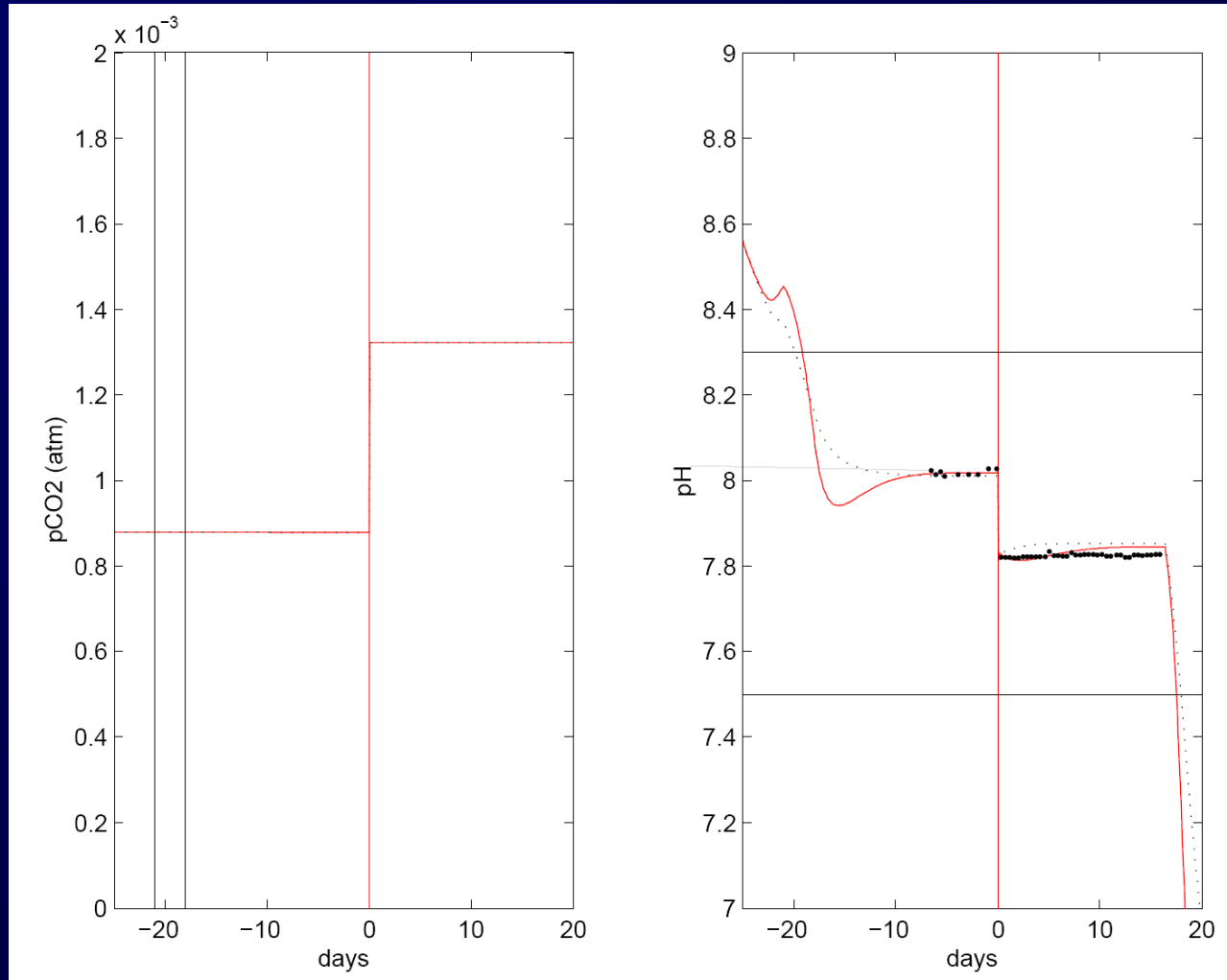
Remark: pH can play the same role in the model than CO_3^{2-}

Model simulations

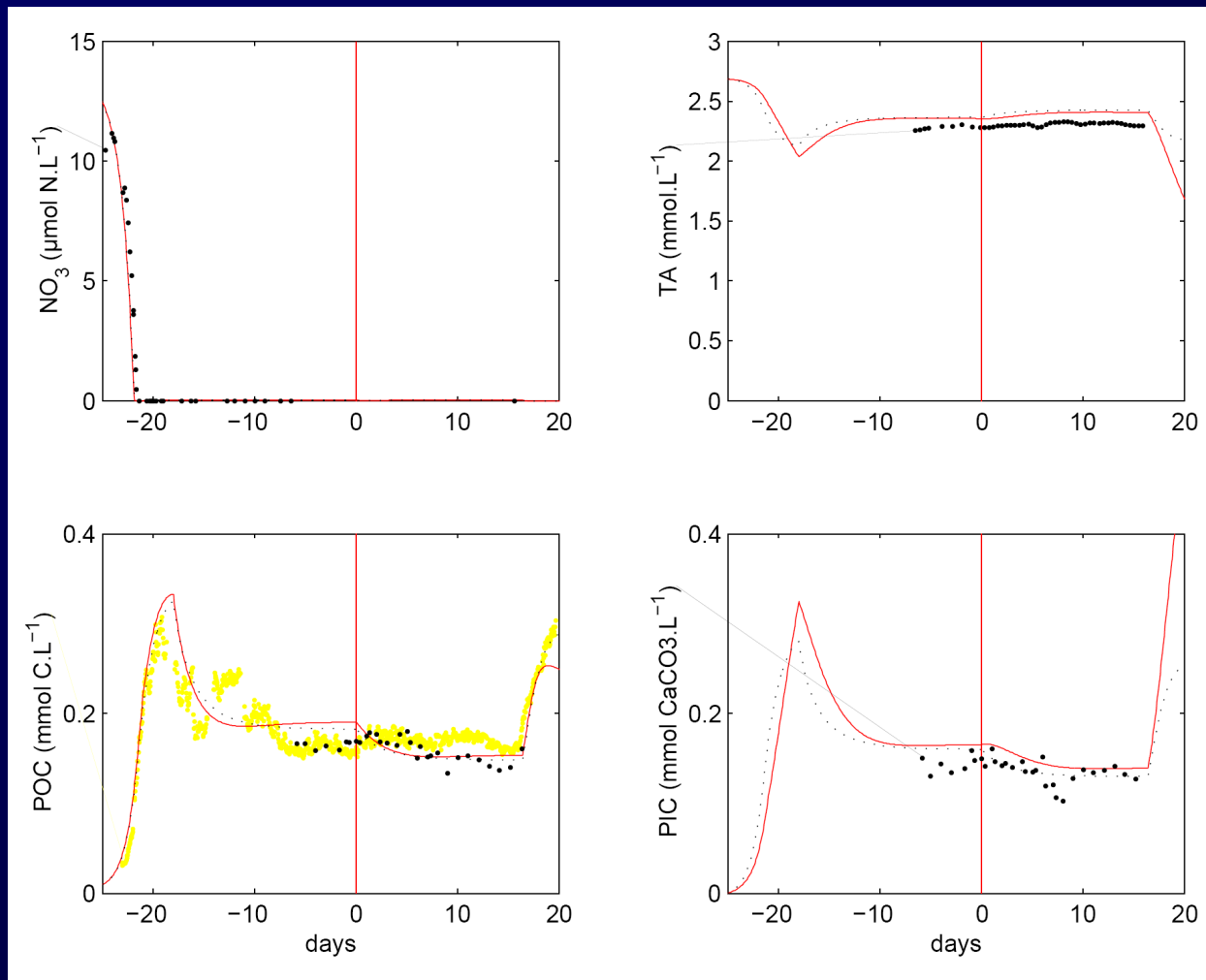


model CI- CO_3^{2-} (-), UI- CO_3^{2-} - HCO_3^- (...) and data

Model simulations



Model simulations



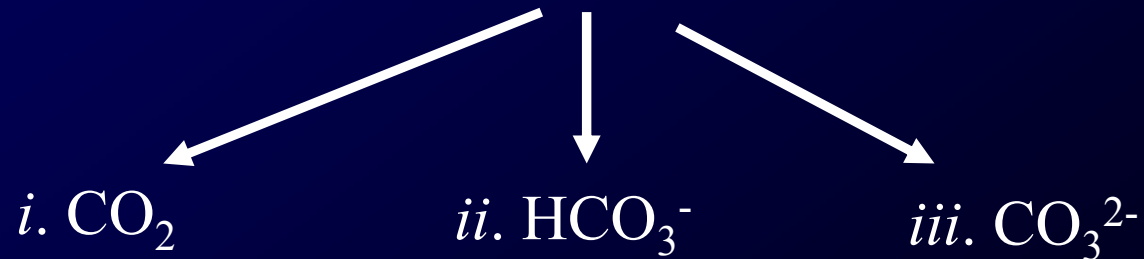
model Cl-CO_3^{2-} (-), UI-CO_3^{2-} - HCO_3^- (...) and data

SIMULATION OF A BLOOM OF *E.HUXLEYI*

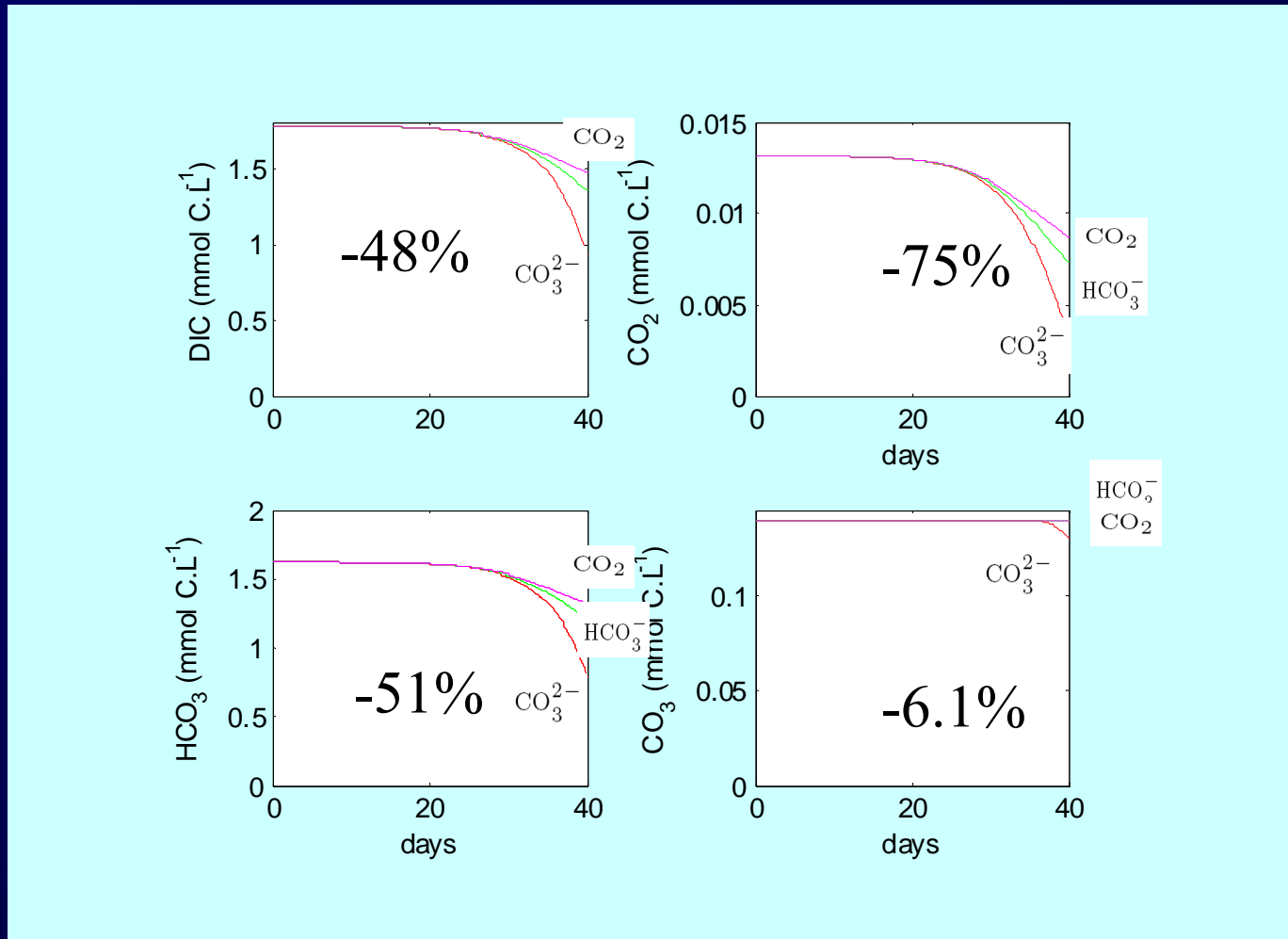
Hypotheses

- Caricature and academic
- Homogeneous mixed layer (10 m), strong stratification
- Simulation of a very intense bloom ($p\text{CO}_2$ drops to 100 ppm)
- 3 possible *scenarii*

Calcification and photosynthesis are regulated by:

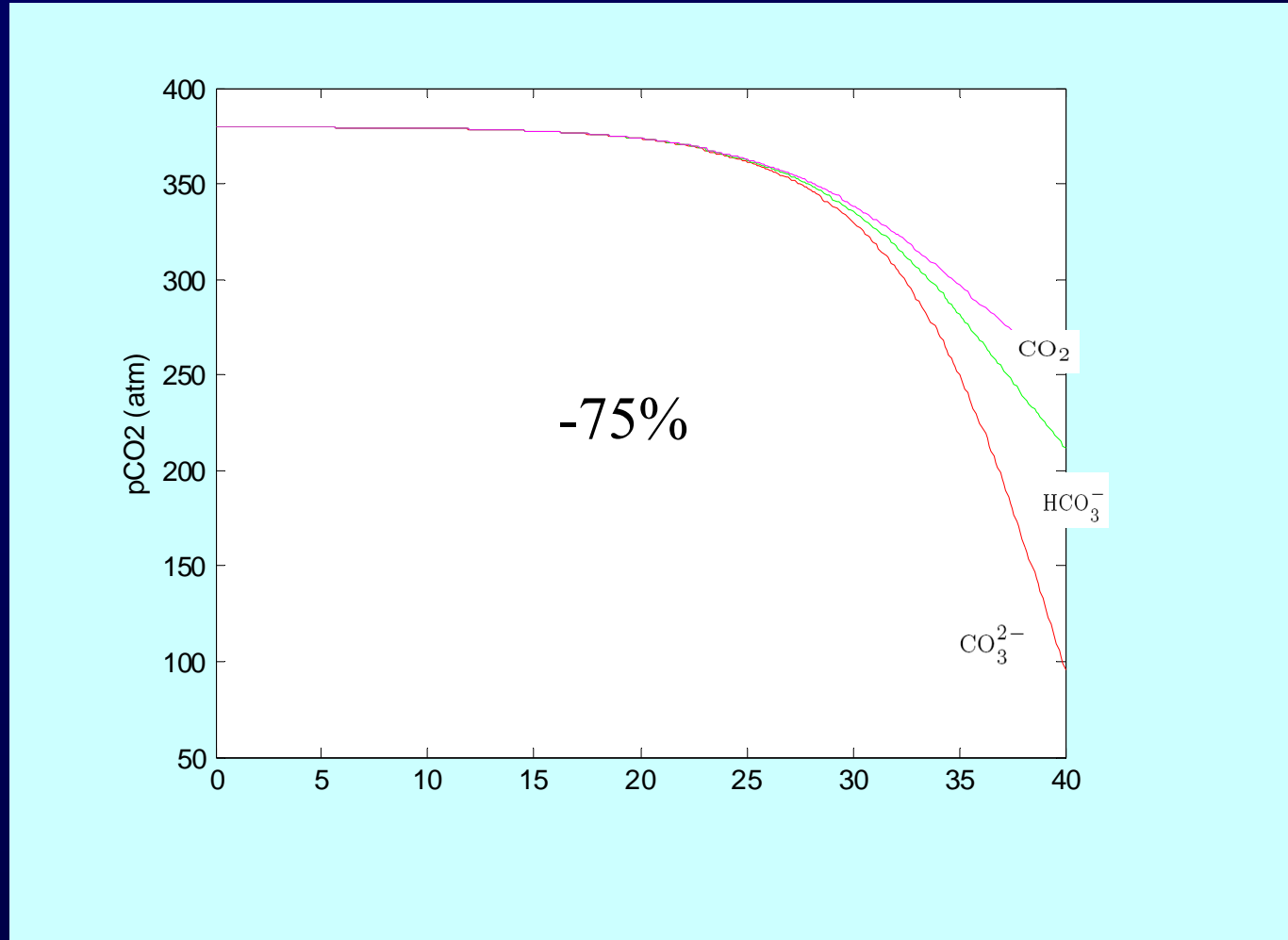


Simulations of the 3 models



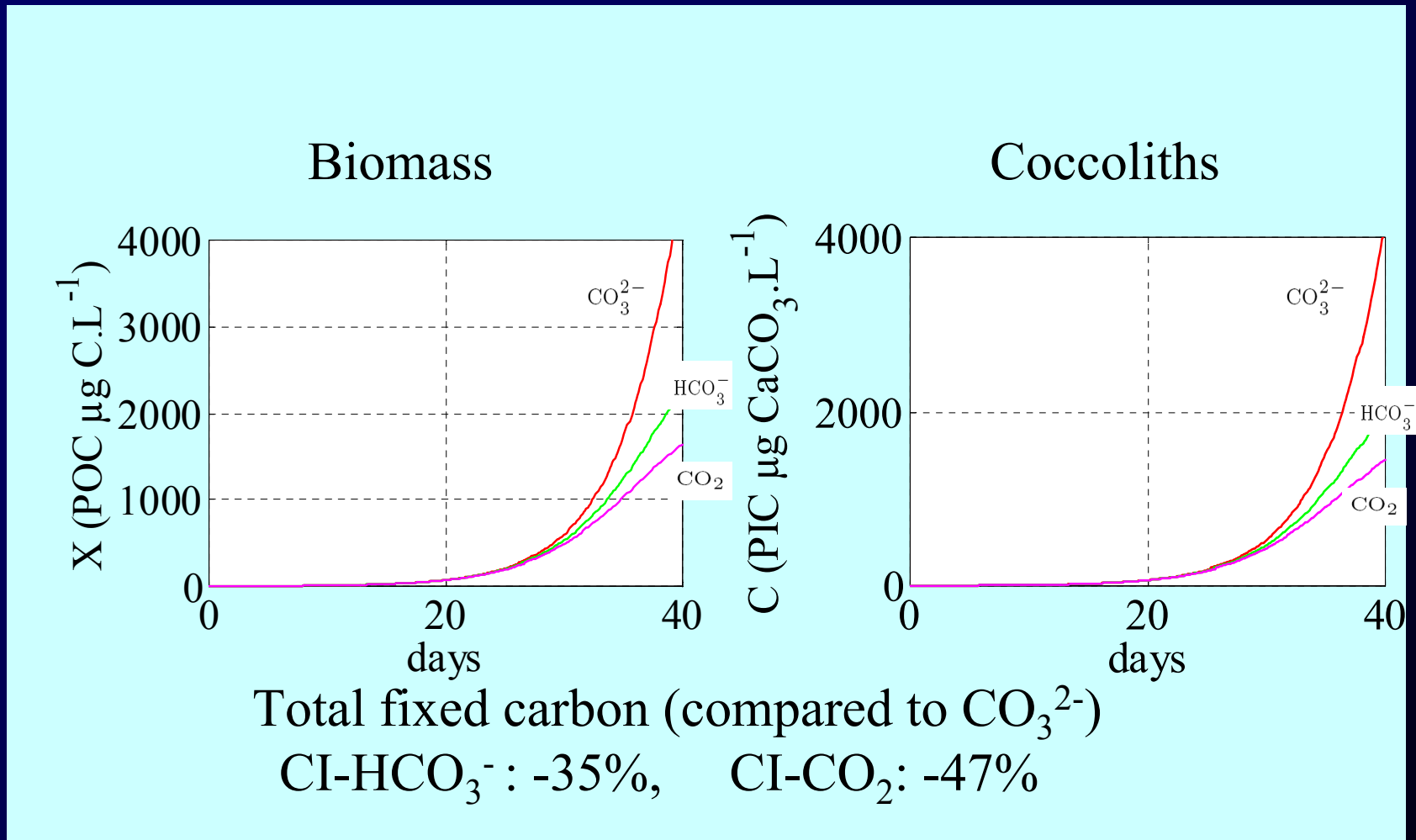
Decrease of DIC and Alkalinity (but CO₃²⁻ less affected)

Simulations of the 3 models



Decrease of pCO₂ during the bloom

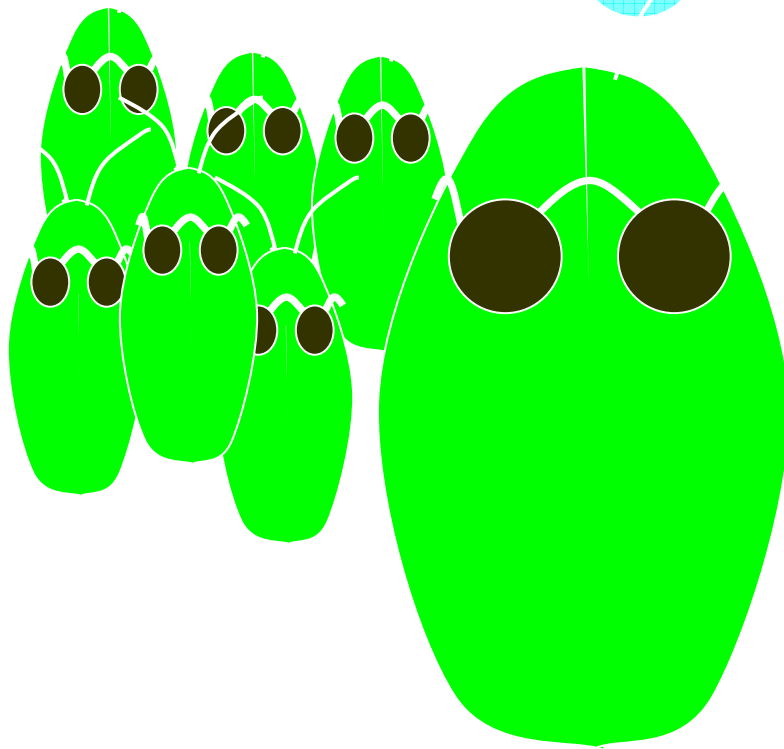
Simulations of the 3 models



Models where growth and calcification are related to CO_3^{2-} or HCO_3^- show a strong slow down of the bloom.

CONCLUSION

- Transient and local phenomenon: cells may experience a broad range of $p\text{CO}_2$ values.
- Quantitative simulations can differ by up to 50% on carbon fluxes predictions
- For intense blooms, the right modelling of the regulating factor is capital



$$\begin{cases} \dot{x}_1 = u(s_i - x_1) - \rho(x_1)x_2 \\ \dot{x}_2 = (\mu(x_3) - u)x_2 \\ \dot{x}_3 = \rho(x_1) - \mu(x_3)x_3 \end{cases}$$

