A simple theory for ocean carbon chemistry

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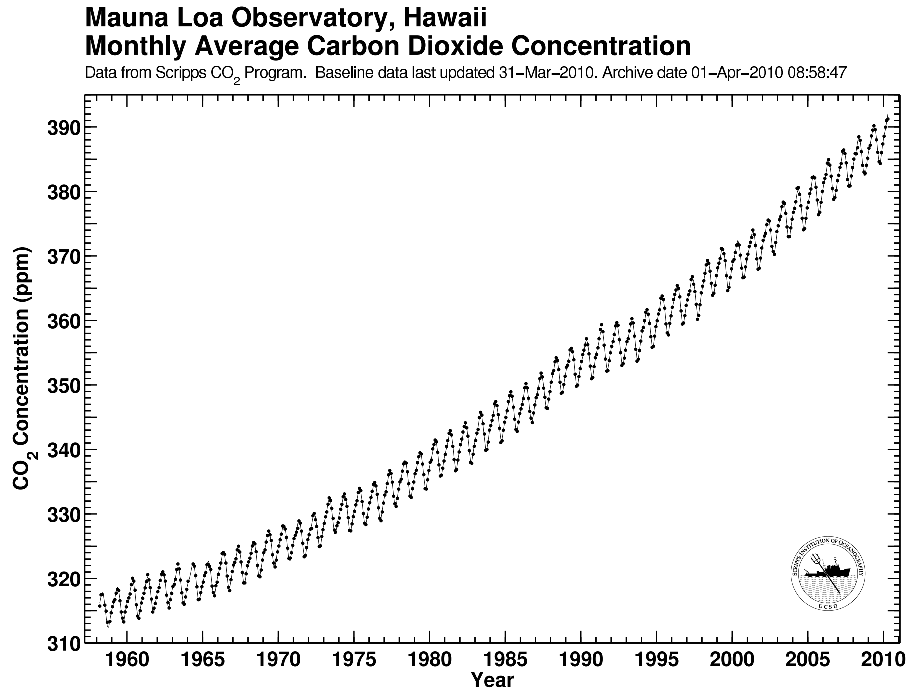
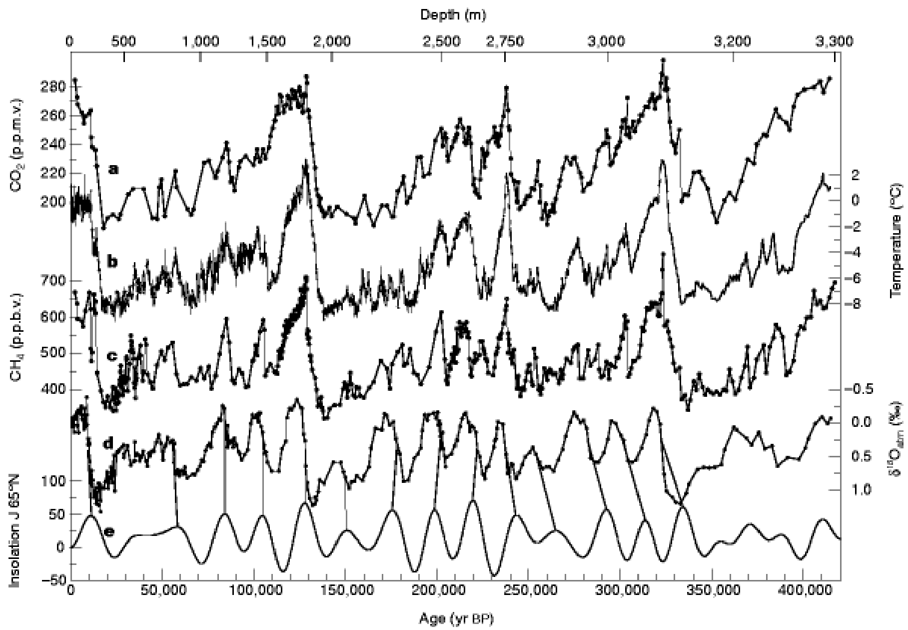
Motivation





- Ocean-atmosphere partitioning of anthropogenic carbon

- Glacial-interglacial problem

Carbon in the ocean

- CO_2 dissolves in seawater: $pCO_2 = \frac{[CO_2]}{K_0}$

- Carbonate chemistry: $CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$, $HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$

- DIC $= [CO_2](0.01mM) + [HCO_3^-](1.8mM) + [CO_3^{2-}](0.2mM)$

Southern Ocean & Carbon Cycle

$\sim \frac{2}{3}$ of deep water originates south of 30°S (Gebbie & Huybers, 2010)
$\rightarrow$ Southern Ocean largely sets whole-ocean properties that determine carbon partitioning (Toggweiler et al., 2003)

Investigate impact of whole-ocean properties on air-sea carbon partitioning

Analytical modelling

Why do analytical modelling if you have computer models?

- Provide more insight
- Aid interpretation of numerical model outcomes
- Save time and effort

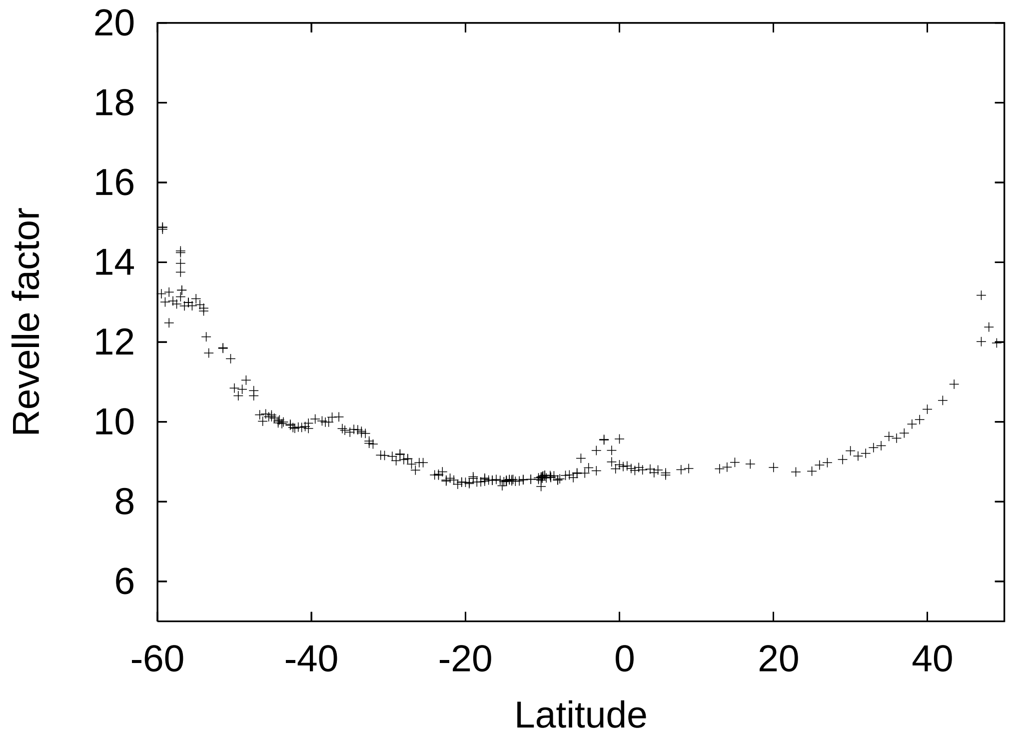
Revelle buffer factor

- $R \equiv \frac{\partial ln(pCO_2)}{\partial ln(C)} \approx 10$ (Bolin & Eriksson, 1959): $pCO_2 \propto C^{10}$

- Defined for estimation of air-sea carbon partitioning

Problems with Revelle factor

Observations of Revelle factor at ocean surface along transect at 170°W

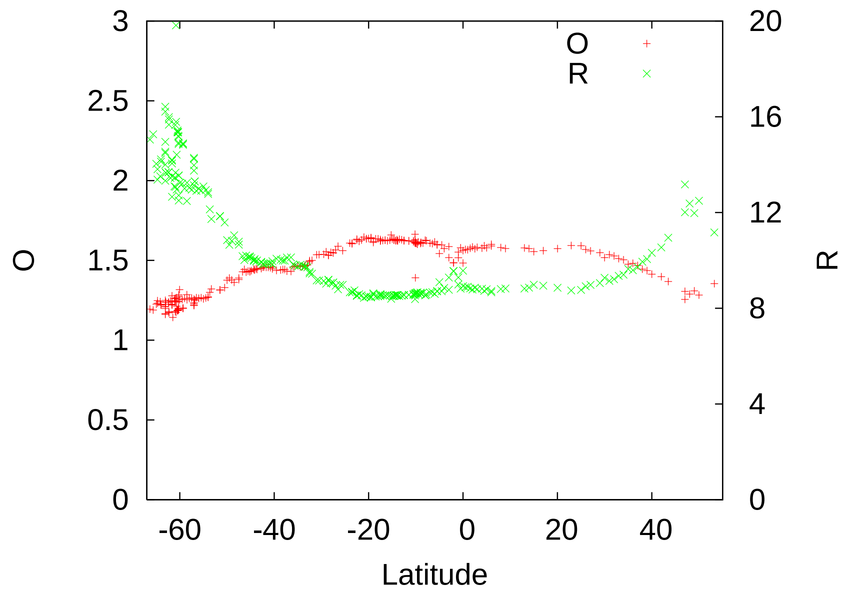


not constant & not transparent: particularly large variation within Southern Ocean!

A new buffer factor

$$O \equiv -\frac{\partial ln(pCO_2)}{\partial ln[CO_3^{2-}]} = 1 + 4\frac{[CO_3^{2-}]}{[HCO_3^-]} \tag{1}$$

O and R along same transect at 170°W



more constant & more transparent: especially in Southern Ocean!

Analysis of numerical simulations of air-sea carbon partitioning

- Goodwin et al. (2007): impact of total carbon
- Omta et al. (2010): impact of ocean temperature

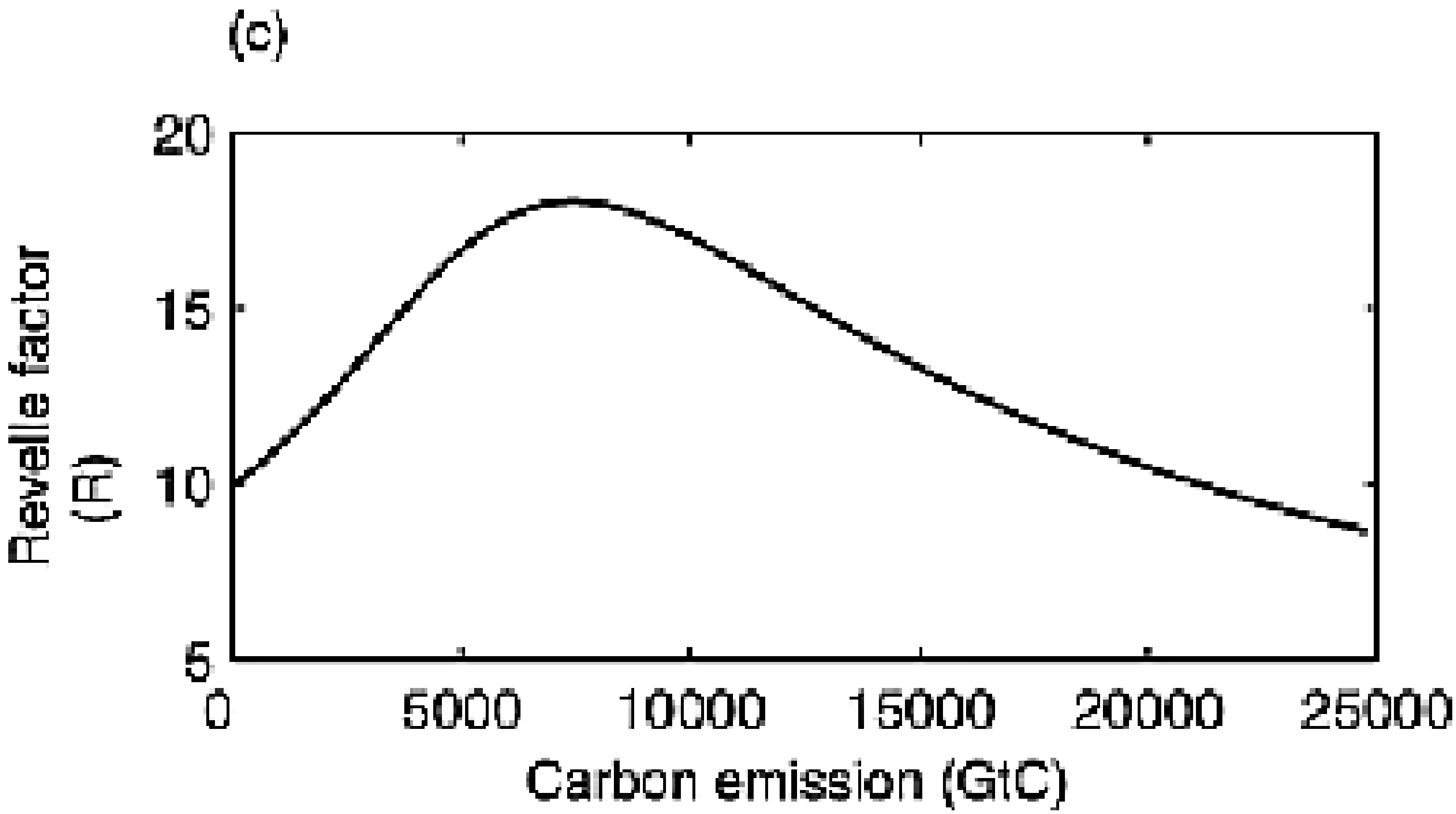
Goodwin et al. (2007) simulations

- Two- and three-box ocean models + atmosphere / MITgcm

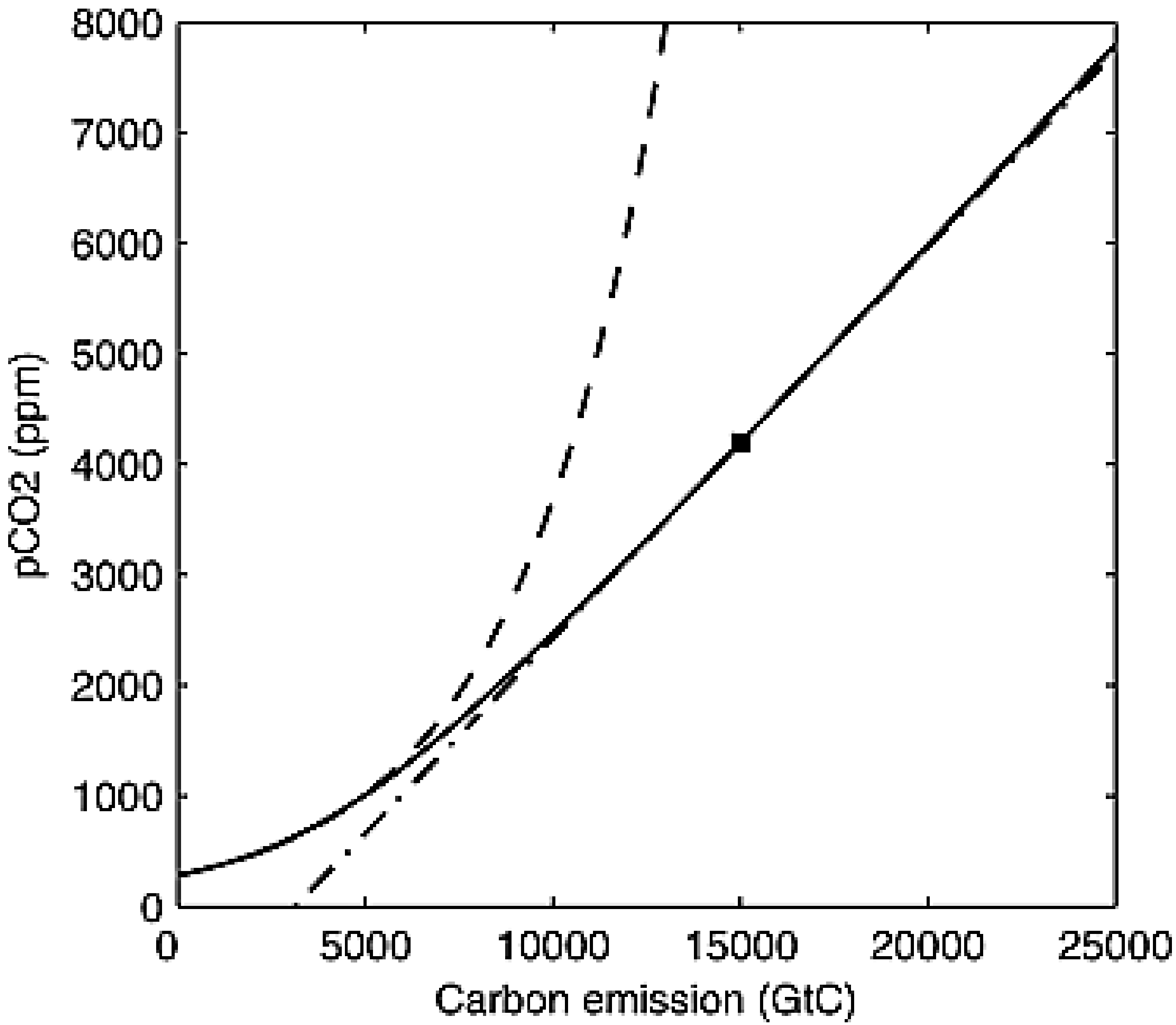
- Put different amounts of carbon in the system

- See how carbon equilibrates between atmosphere and ocean and investigate impact on Revelle factor

Goodwin et al. results: Revelle factor



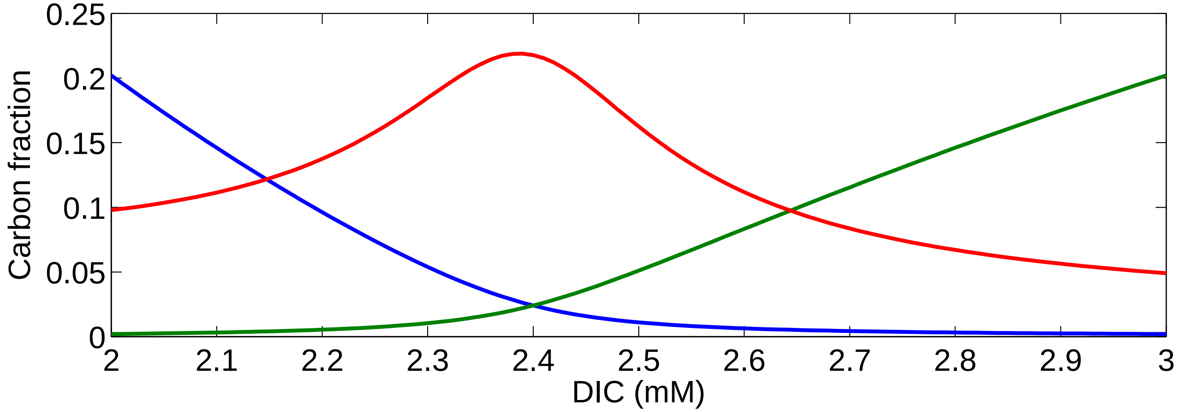
Goodwin et al. results: Carbon uptake



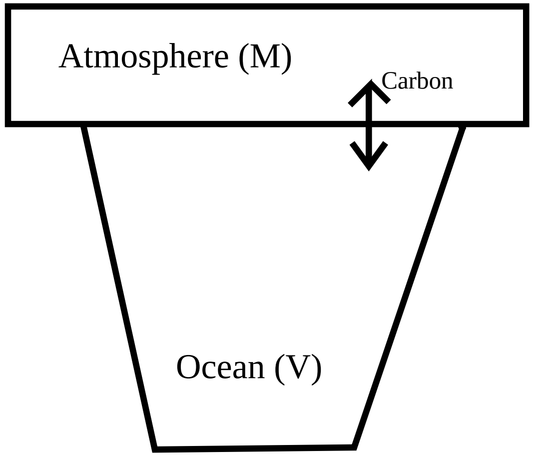
Analysis of R

$$R \equiv \frac{\partial ln(pCO_2)}{\partial ln(C)} = \frac{C}{\frac{[CO_3^{2-}]}{O} + [CO_2]} \qquad (2)$$

R (red) has maximum if both $[CO_3^{2-}]$ (blue) and $[CO_2]$ (green) small!



How to derive air-sea carbon partitioning



Global carbon conservation equation:

$$MpCO_2 + VC = C_t \tag{3}$$

Differentiate conservation equation with respect to C_t

Analysis of air-sea partitioning

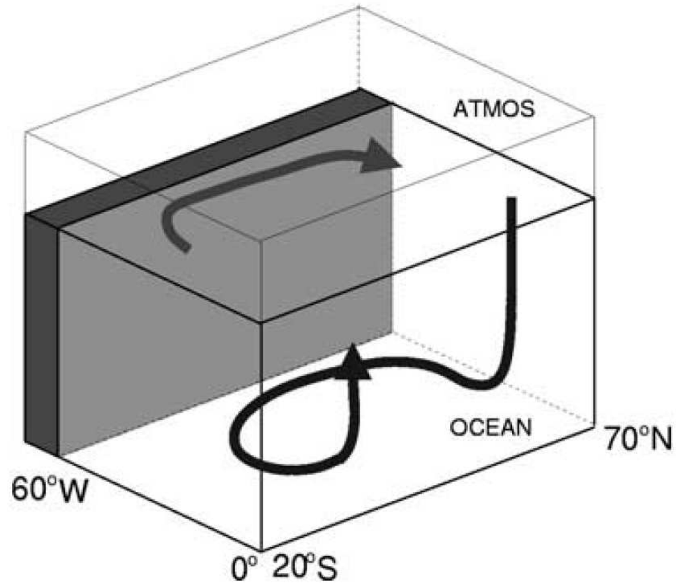
$$\frac{\partial ln pCO_2}{\partial C_t} = \frac{1}{(M + \frac{V}{K_H})pCO_2 + V\frac{[CO_3^{2-}]}{O}} \equiv \frac{1}{I_B} \qquad (4)$$

Current regime: I_B constant $\rightarrow$ exponential dependence of pCO_2 on C_t

High-carbon regime: $I_B \approx (M + \frac{V}{K_H})pCO_2$ $\rightarrow$ linear dependence

In the high-carbon regime, the ocean has lost its buffering capacity, because the CO_3^{2-} ions have been neutralised!

Simulations of temperature impact



- 3°×3° horizontal resolution, 15 levels vertical
- 20000-year spin-up with biogeochemistry
- Change SST in steps of 2°C

Biogeochemical model

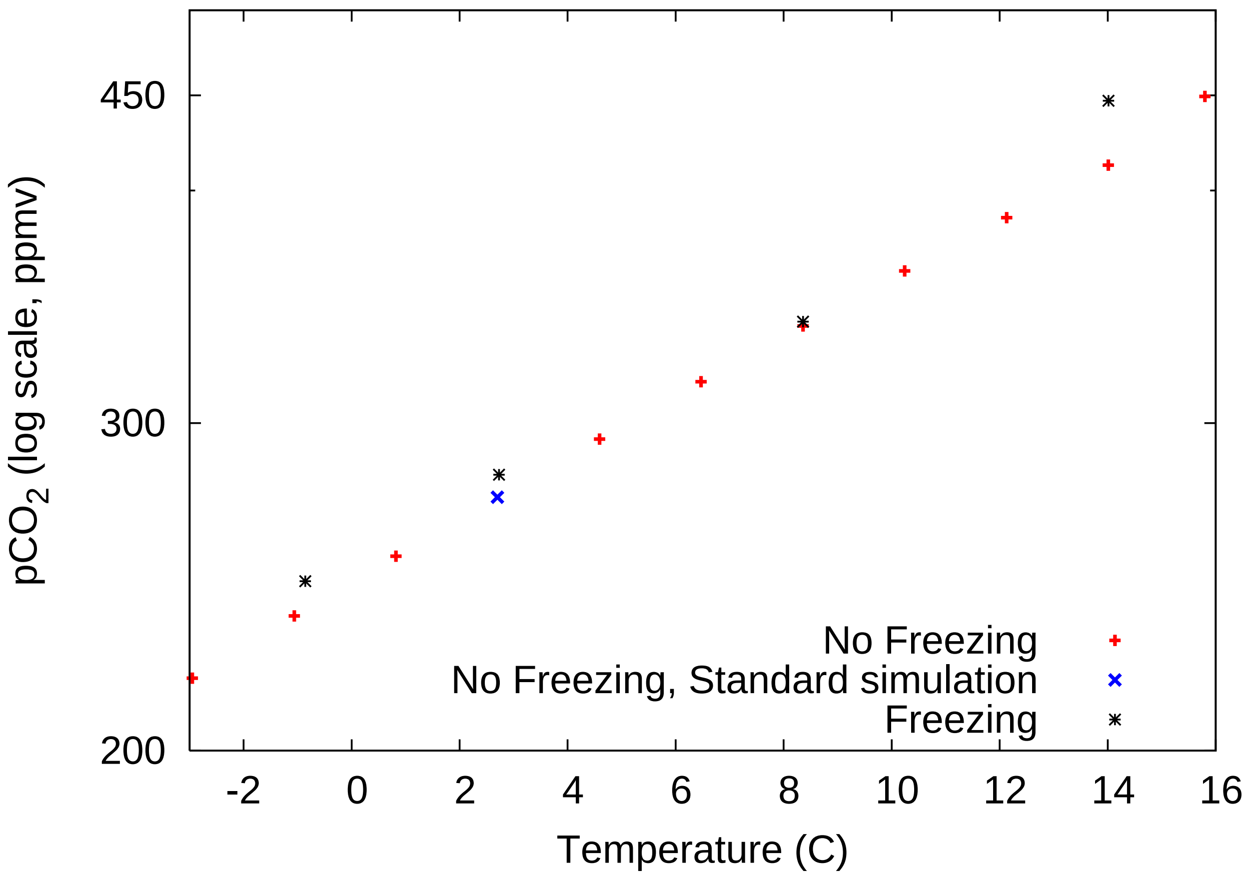
- Productivity depends on light and phosporus
- $\frac{1}{3}$ of net production is exported, remineralised according to empirical power law
- Fixed carbon:phosphorus stoichiometry & fixed rain ratio

Dependence of air-sea carbon partitioning on temperature: analytical calculation

Carbon conservation equation, differentiate with respect to T:

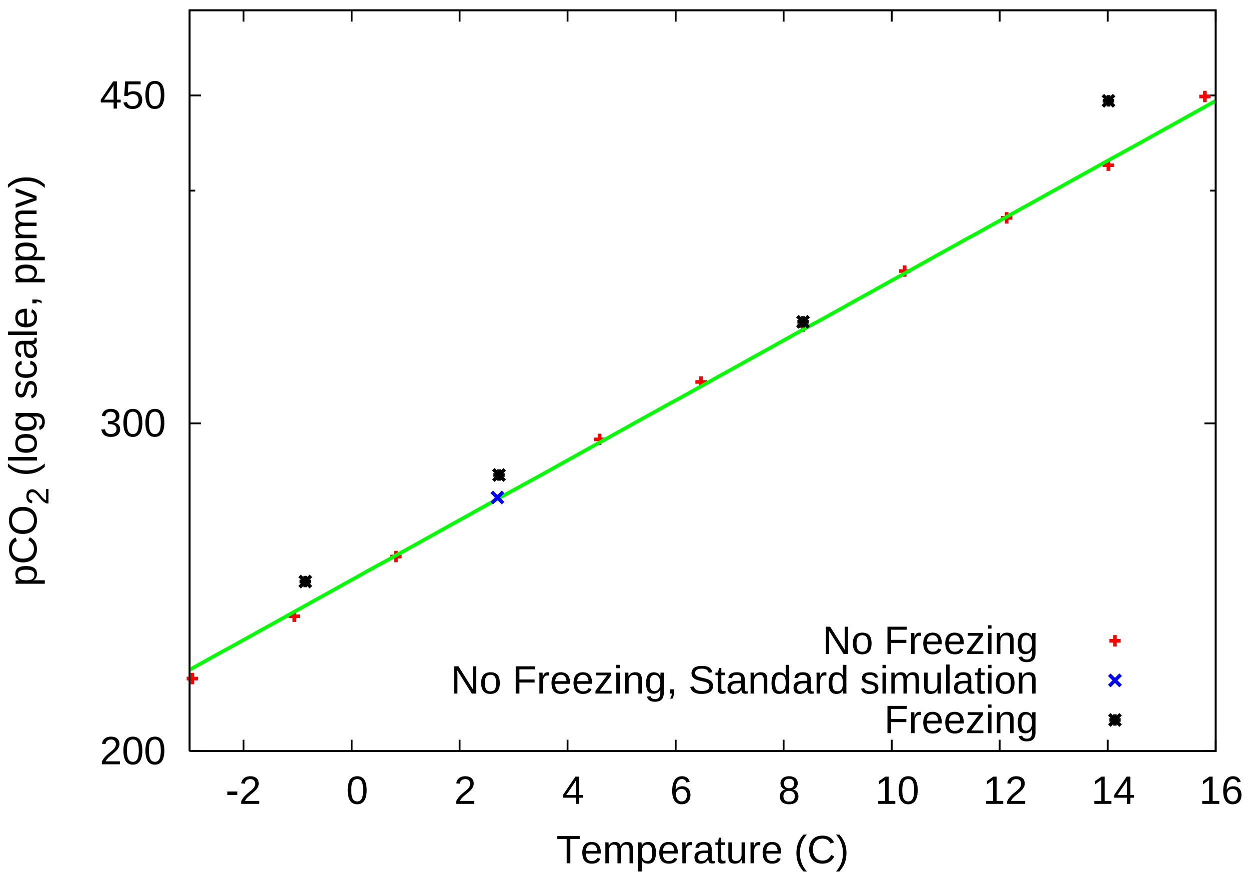
$$\frac{dpCO_2}{dT} = \frac{(a + \frac{bO[CO_2]}{[CO_3^{2-}]})pCO_2}{1 + \frac{MpCO_2O}{[CO_3^{2-}]V} + \frac{O[CO_2]}{[CO_3^{2-}]}} \approx 0.038pCO_2 \quad (5)$$

Comparison of theory with simulations



$$\frac{dln(pCO_2)}{dT} \approx 0.038 \quad (6)$$

Comparison of theory with simulations



$$\frac{dln(pCO_2)}{dT} \approx 0.038 \quad (7)$$

Conclusions

We have developed a new theoretical framework that:

- Theory predicts behaviour of full 3-D coupled flow/biogeochemical model $\rightarrow$ you can think of climate problems without performing simulation
- Provides insight: explains different carbon regimes
- Appears applicable to analyse impact of different water masses (e.g., AABW) on carbon partitioning