Climate forcing from carbon emissions

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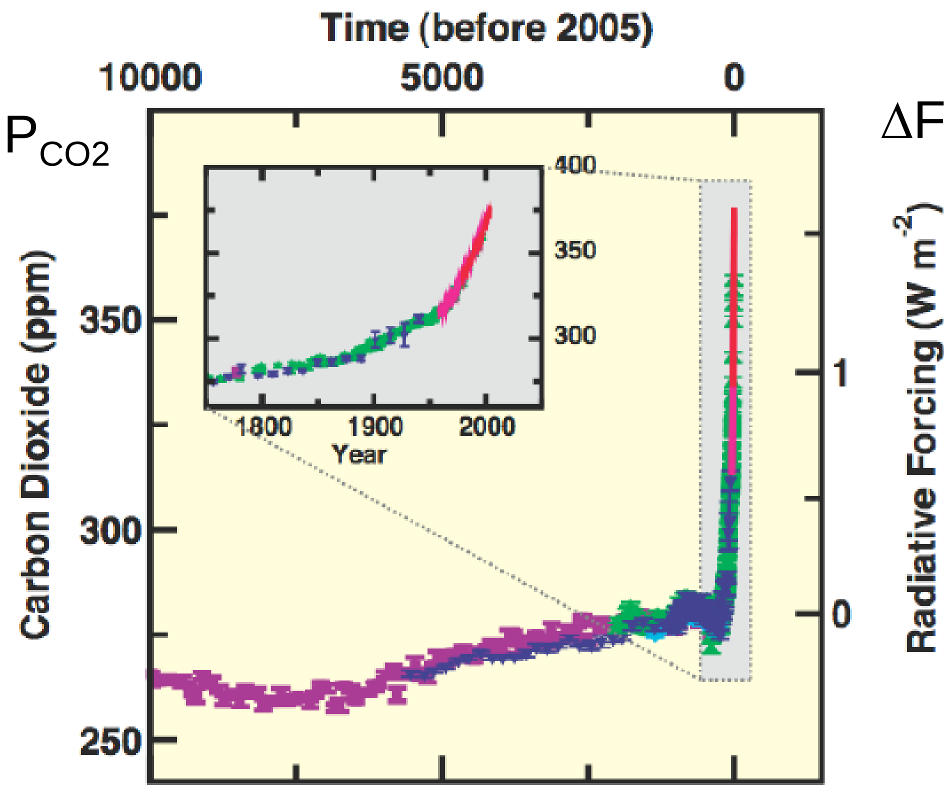
Rising atmospheric carbon dioxide (P_{CO2}): Anthropogenic projection



[*IPCC* 2007]

Aims:

A) Relate emissions to 'steady state' P_{CO2}

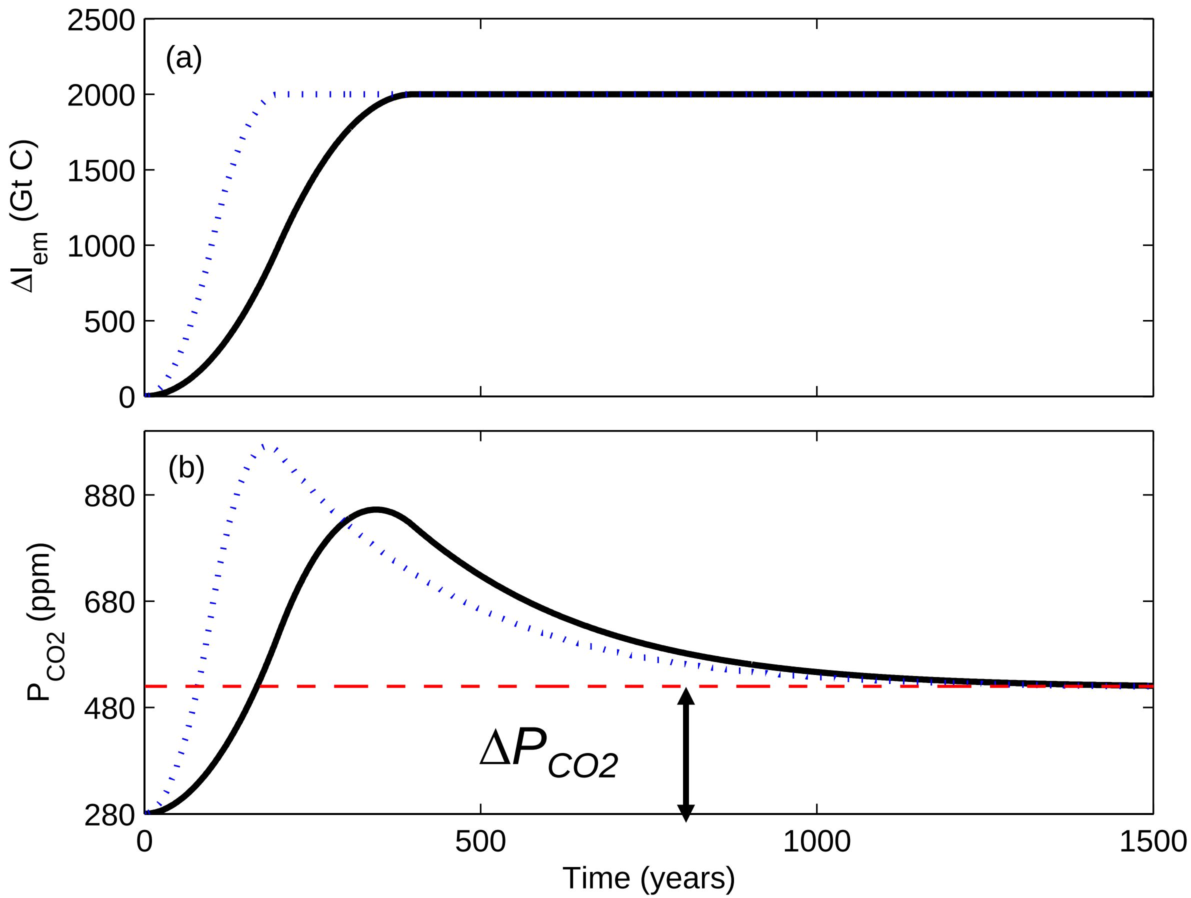
B) Consider radiative forcing

C) Consider feedbacks

– Ignore carbonate and silicate rock weathering

The rise in partial pressure of atmospheric CO_2 (P_{CO2}) causes a radiative forcing (ΔF) which alters climate

For the same ΔI_{em}, eventually same steady state P_{CO2}



Air-sea model response to a ΔI_{em}= 2000GtC EMISSION: Same steady state

Carbon in the atmosphere and ocean

CO_2 (Partial pressure, P_{CO2})

ATMOSPHERE

OCEAN

$CO_2 \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- \leftrightarrow CO_3^{2-}$

$C_{DIC} = CO_2 + H_2CO_3 + HCO_3^- + CO_3^{2-}$

Atmospheric carbon inventory:

$I_A = V^{atm} x P_{CO2}$

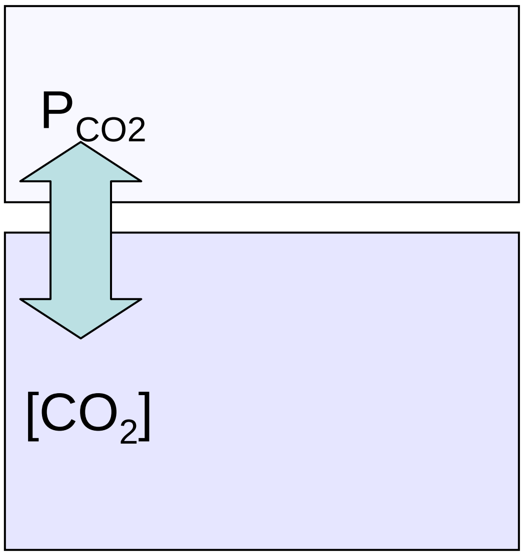
Ocean carbon inventory:

$I_O = V^{ocean} x C_{DIC}$

- A steady state is reached when:

$$P_{CO2} \propto [CO_2]_{ocean}$$

Emissions without ocean chemistry



Special case;

$I_O = V^{ocean} \times [CO_2]$

Steady state when:

$$P_{CO2} \propto [CO_2]$$

Therefore: $P_{CO2} \propto I_A \quad \propto I_O$

Thus P_{CO2} proportional to total air-sea carbon:

$$P_{CO2} \propto (I_O + I_A)$$

And:

$$\delta P_{CO2} \propto \delta(I_O + I_A)$$

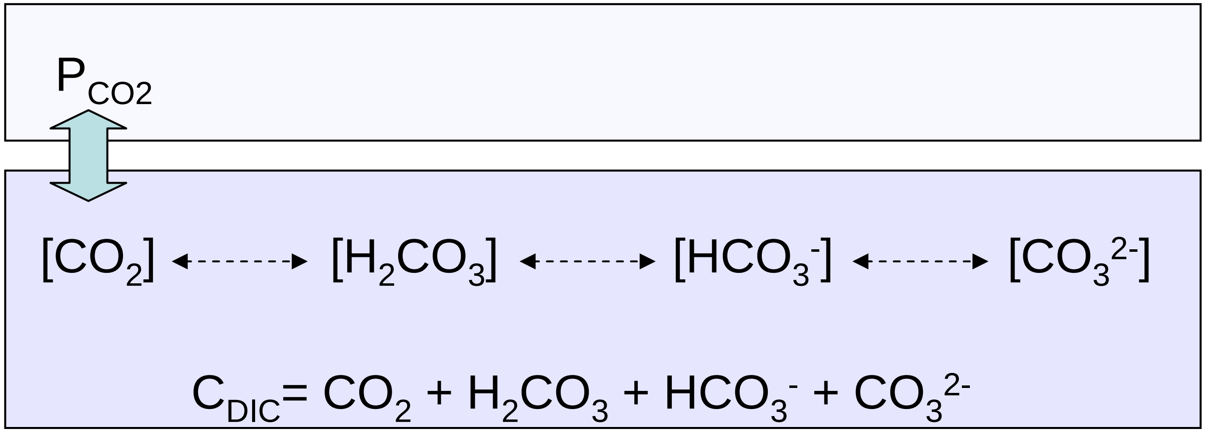
We can make a ratio:

$$\frac{\delta P_{CO2}}{P_{CO2}} = \frac{\delta(I_A + I_O)}{I_A + I_O}$$

Change in air-sea carbon is emission, $\delta I_{em} = \delta(I_A + I_O)$:
Therefore we can write:

$$\delta \ln|P_{CO2}| = \frac{\delta I_{em}}{I_A + I_O}$$

Emissions with ocean chemistry



At steady state:

$$P_{CO2} \propto [CO_2]$$

But:

$$P_{CO2} \not\propto I_A + I_O$$

We must define a **new** inventory, I_B [*Goodwin et al*, 2007], that accounts for the dissociation of CO_2 in seawater

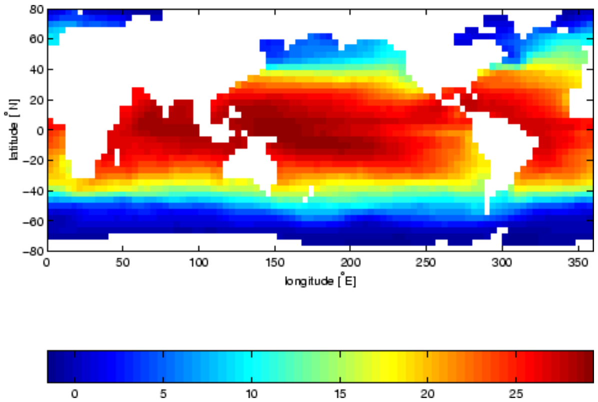
NO OCEAN CHEMISTRY : OCEAN CHEMISTRY

$$I_A + I_O \quad \longleftrightarrow \quad I_B = I_A + \frac{I_O}{B}$$

WHERE: $B = \frac{\delta P_{CO2}}{\delta C_{DIC}} \frac{C_{DIC}}{P_{CO2}}$

$$\delta \ln\left|P_{CO2}\right| = \frac{\delta I_{em}}{I_A + I_O} \quad \longleftrightarrow \quad \boxed{\delta \ln\left|P_{CO2}\right| = \frac{\delta I_{em}}{I_B}}$$

GCM experiment: how P_{CO2} links to carbon emission



SURFACE

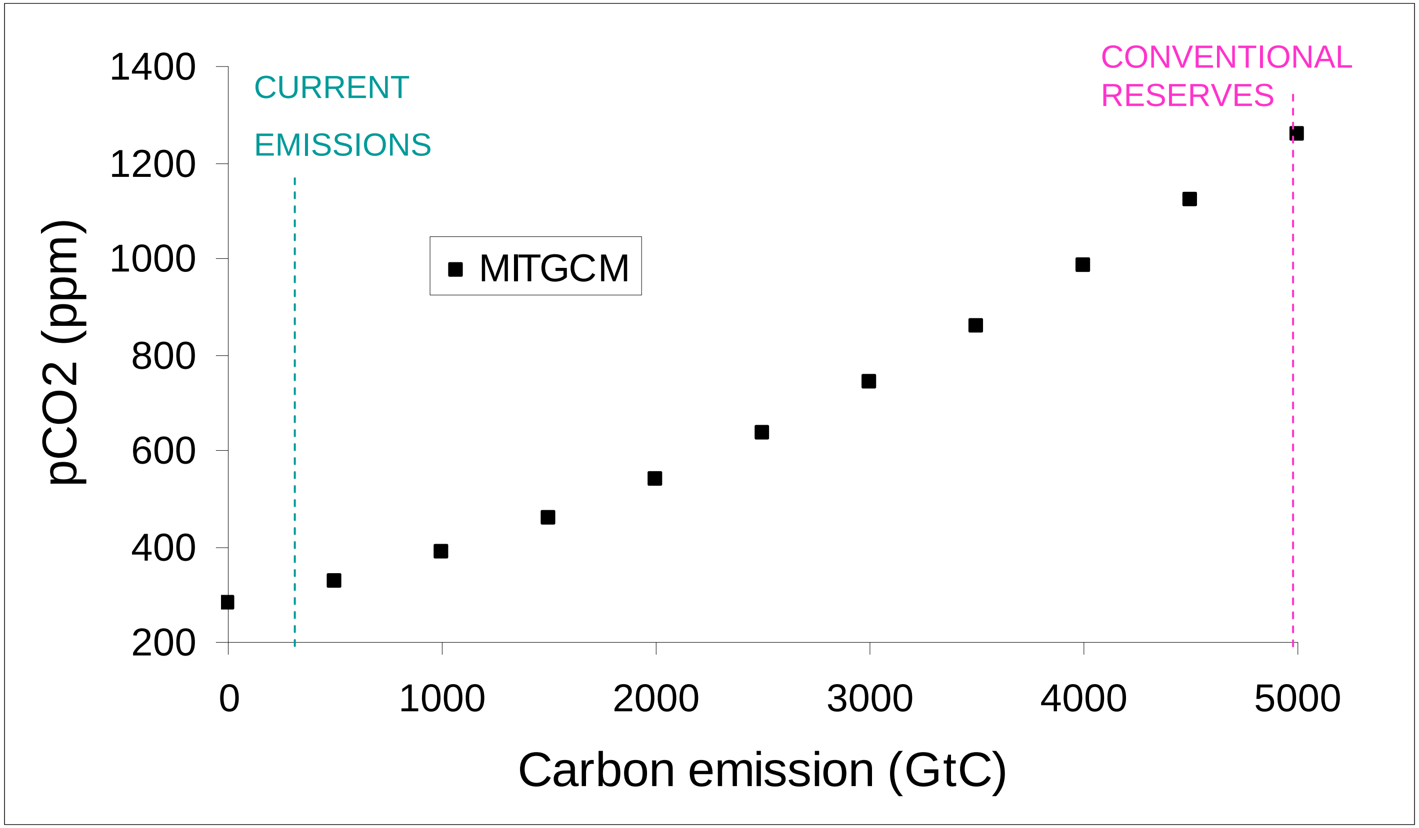
TEMPERATURE

(^{O}C)

MIT GCM

- Realistic circulation
- Realistic carbon cycling
- Monthly mean forcing

- Add carbon to atmosphere over ~500years
- Integrate for ~3000 years for steady state
- Measure final P_{CO2}

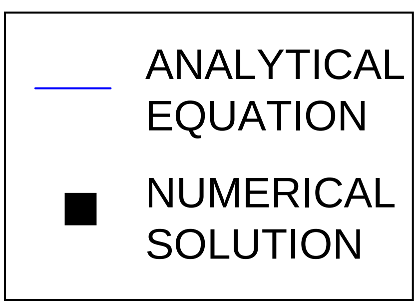


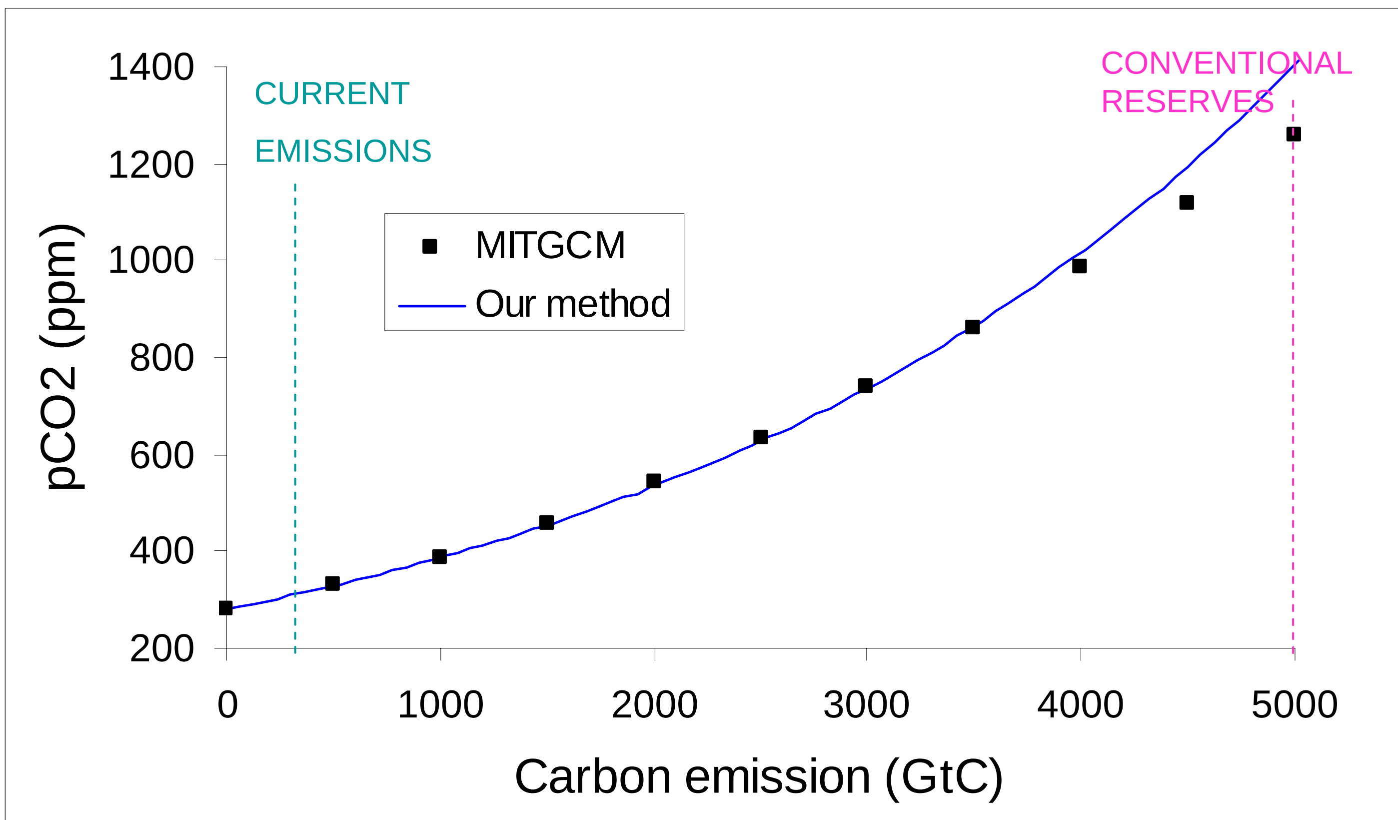
Testing the independent analytical equation

- Evaluate I_B at pre-industrial steady state for MITGCM
- integrate by assuming I_B remains constant [*Goodwin et al*, 2007]:

$$\Delta \ln\left|P_{CO2}\right| = \frac{\Delta I_{em}}{I_B} \quad \Rightarrow \quad P_f = P_i \exp\left(\frac{\Delta I_{em}}{I_B}\right)$$

Compare to model results:





How can CO_2 affect climate?

Add CO_2 → Radiation imbalance, ΔF → Temperature increases, ΔT

How do P_{CO2} levels affect ΔF (and so ΔT)?

$$\Delta F = \alpha \Delta \ln \left| P_{CO2} \right|$$

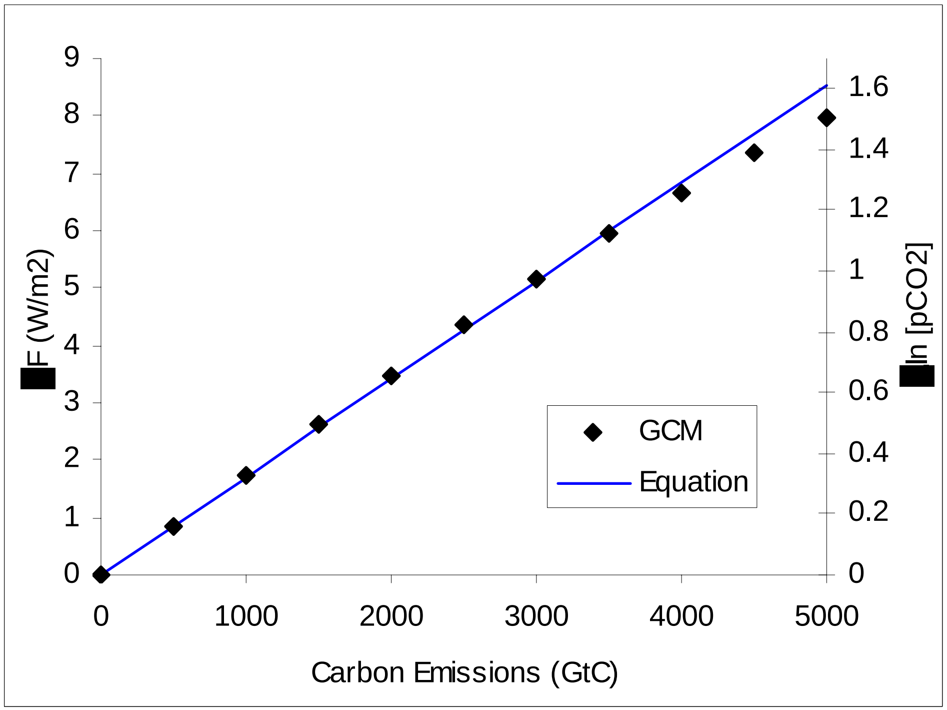
[*Myhre et al*, 1998]

Why logarithmic?

- CO_2 only absorbs at certain wavelengths
- Amount of those wavelengths in atmosphere reduces with increasing P_{CO2}
- An increase in P_{CO2} absorbs set fraction *of what is left* in the atmosphere

Therefore, write equations in log form.

How about Radiative forcing?



From:

$$\Delta F = \alpha \Delta \ln |P_{CO2}|$$

$$\frac{\Delta I_{em}}{I_B} = \Delta \ln |P_{CO2}|$$

We get:

$$\Delta F = \frac{\alpha}{I_B} \Delta I_{em}$$

Using IPCC [2001] α, we find for MITGCM:

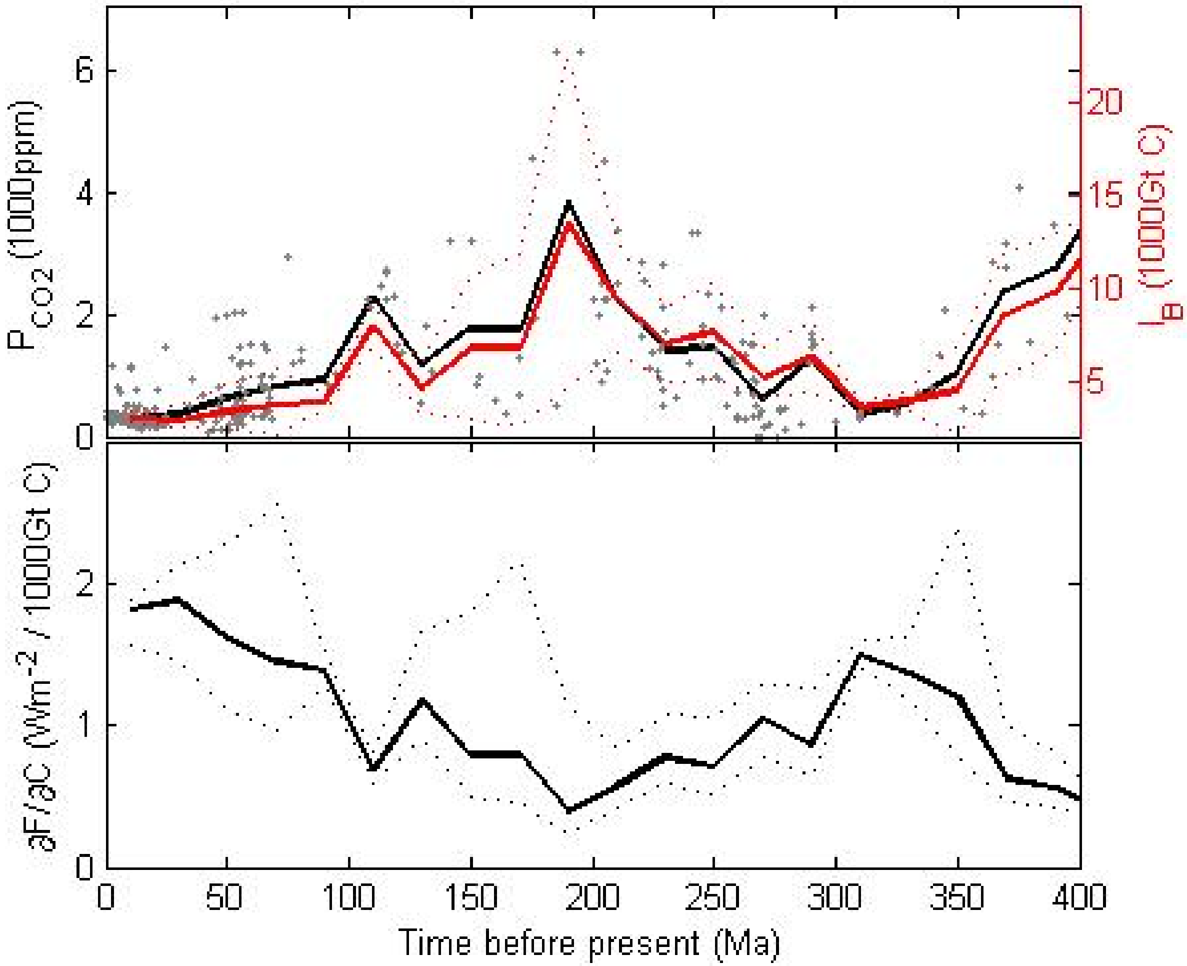
$\Delta F = 1.7 Wm^{-2}$ per 1000Gt C

- The contribution of today's emissions to the climate from 1000 to 5000 years
- cf current forcing ~1.6Wm^{-2} in transient state
- Possibly rising to ~7.5Wm^{-2} lasting for thousands of years

Climate sensitivity of the past

P_{CO2}
(1000ppm)

ΔF for a 1000GtC emission
(Wm^{-2})



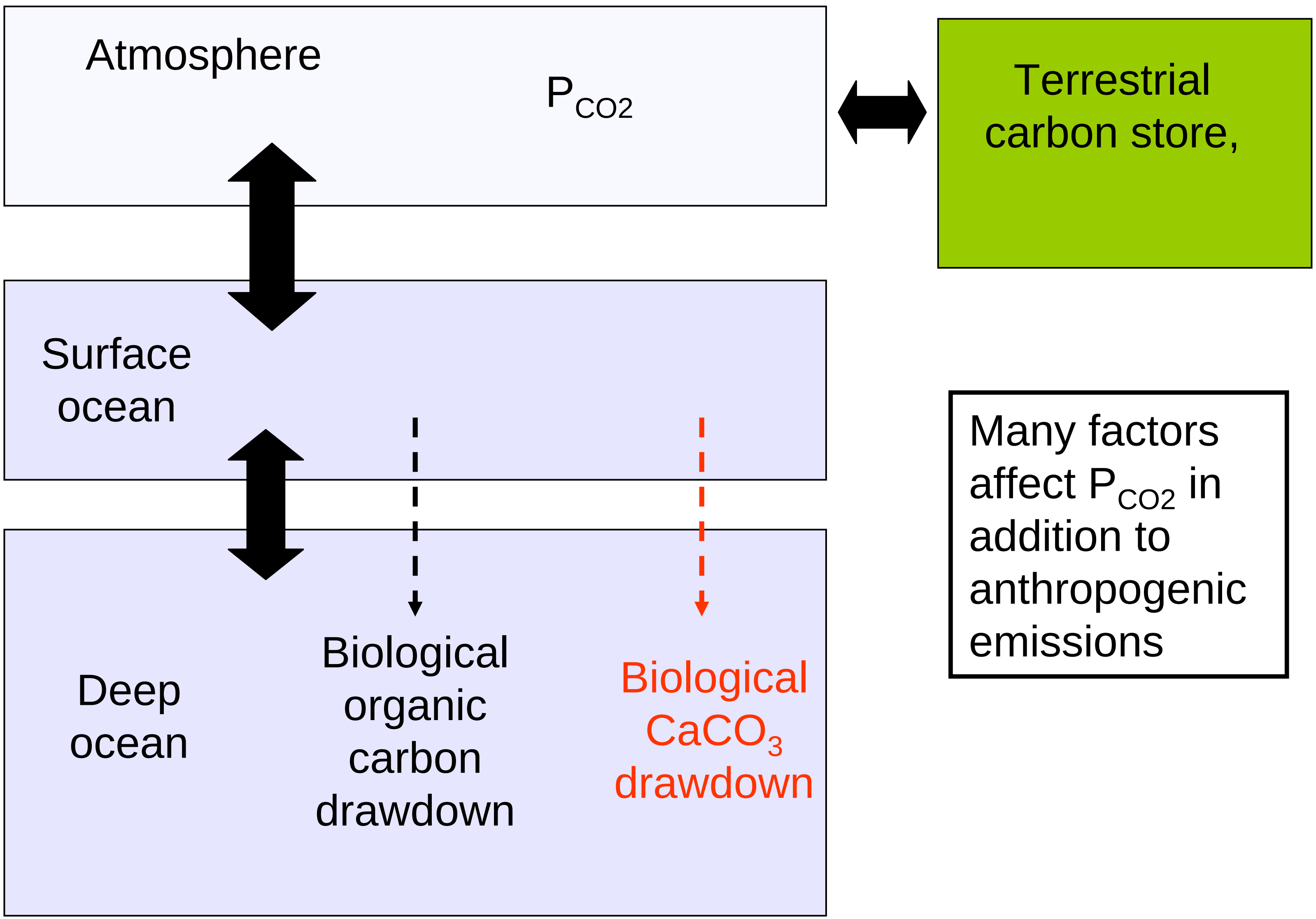
Years BP (Ma)

Evaluate I_B of GENIE model forced with palaeo constraints from Ridgwell (2005)

$$\frac{\delta F}{\delta I_{em}} = \left(\frac{\alpha}{I_B} \right)$$

The present day has a high climate sensitivity

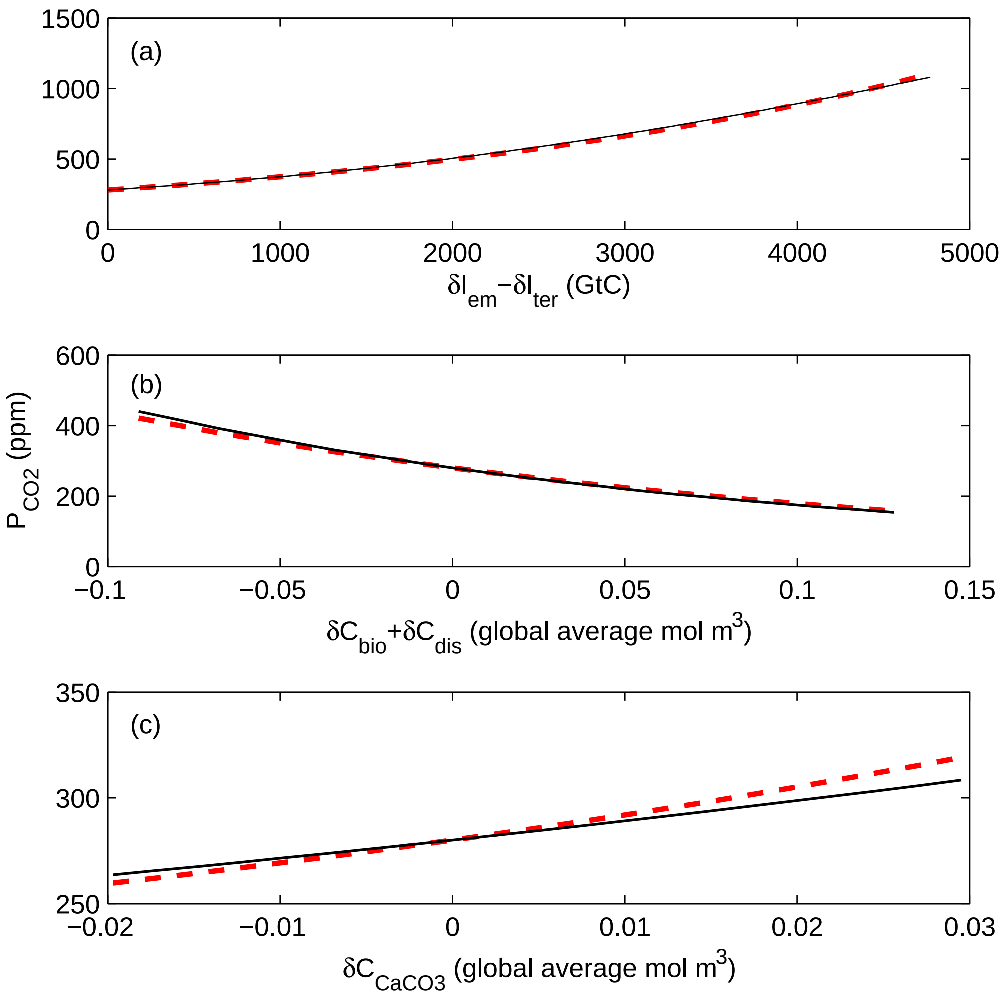
Feedbacks from carbon cycles changes



Many factors affect P_{CO2} in addition to anthropogenic emissions

Testing the independent analytical relations

Evaluate I_B at pre-industrial steady state and plot:



Terrestrial

$$P_f = P_i \exp\left(\frac{-\Delta I_{ter}}{I_B}\right)$$

Soft tissue

$$P_f = P_i \exp\left(\frac{-V\Delta C_{bio}}{I_B}\right)$$

ANALYTICAL EQUATION

NUMERICAL SOLUTION

CaCO3

$$P_f = P_i\left[\frac{I_{O(A-C)}}{I_{O(A-C)} - V\Delta C_{CaCO3}}\right]\exp\left(\frac{-\left(I_A/I_{O(A-C)}\right)\Delta C_{CaCO3}}{I_B}\right)$$

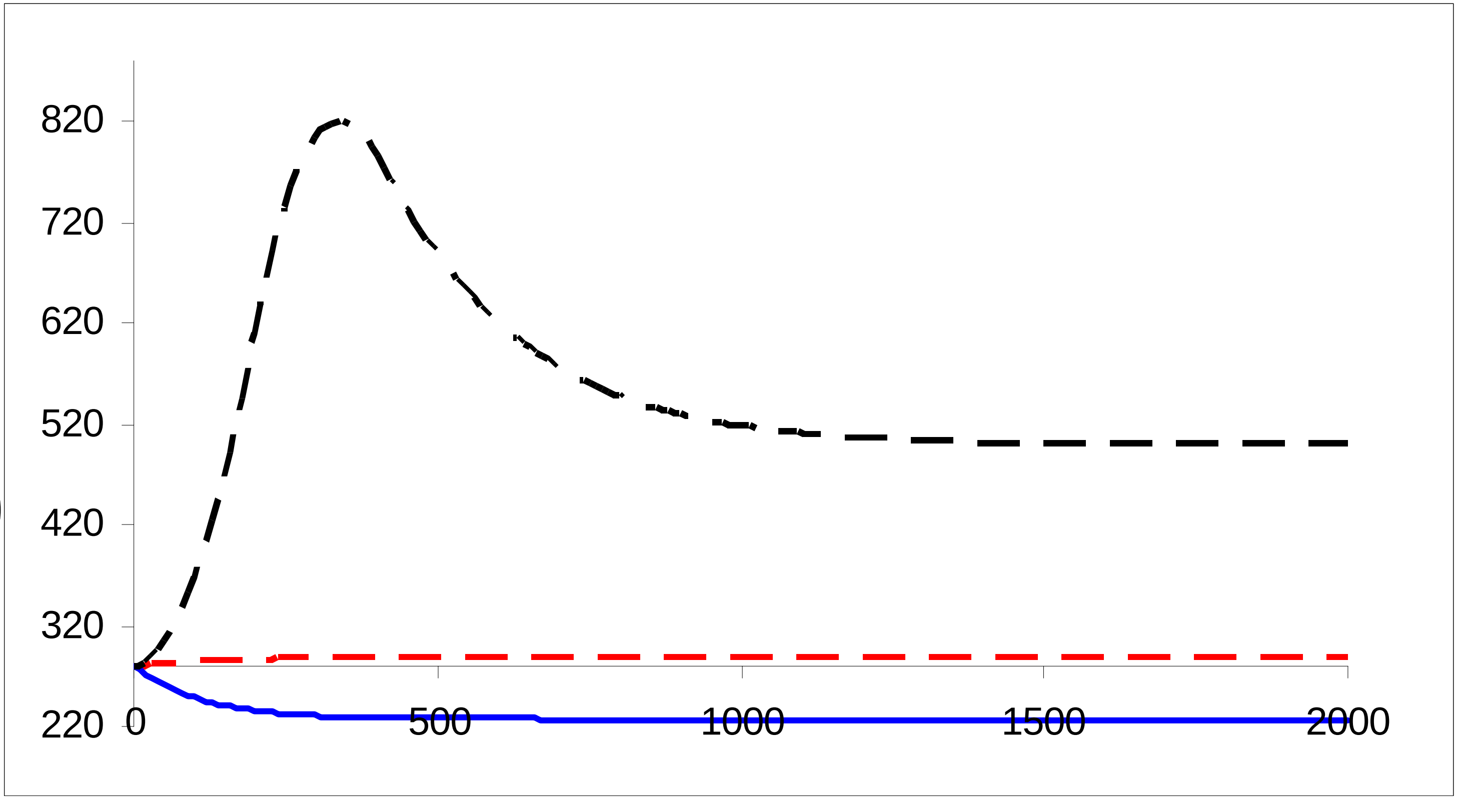
Feedbacks from carbon cycles changes

P_{CO2} over time for:

i) 2000GtC emission,

ii) Change in soft tissue biology,

iii) Change in biological $CaCO_3$ production



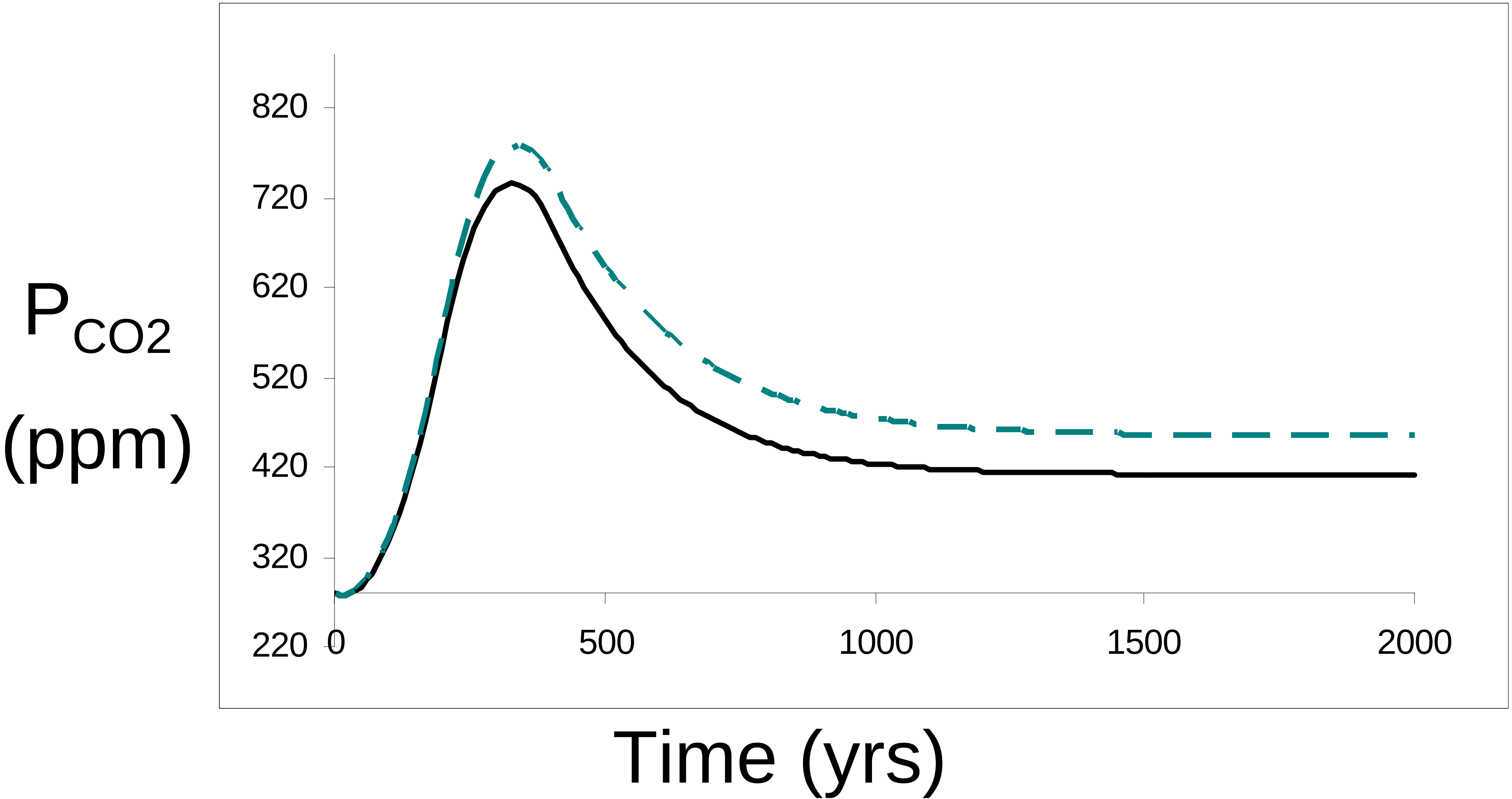
P_{CO2} (ppm)

Time (yrs)

Feedbacks from carbon cycles changes

Feedbacks combine in a non-linear way to alter P_{CO2}

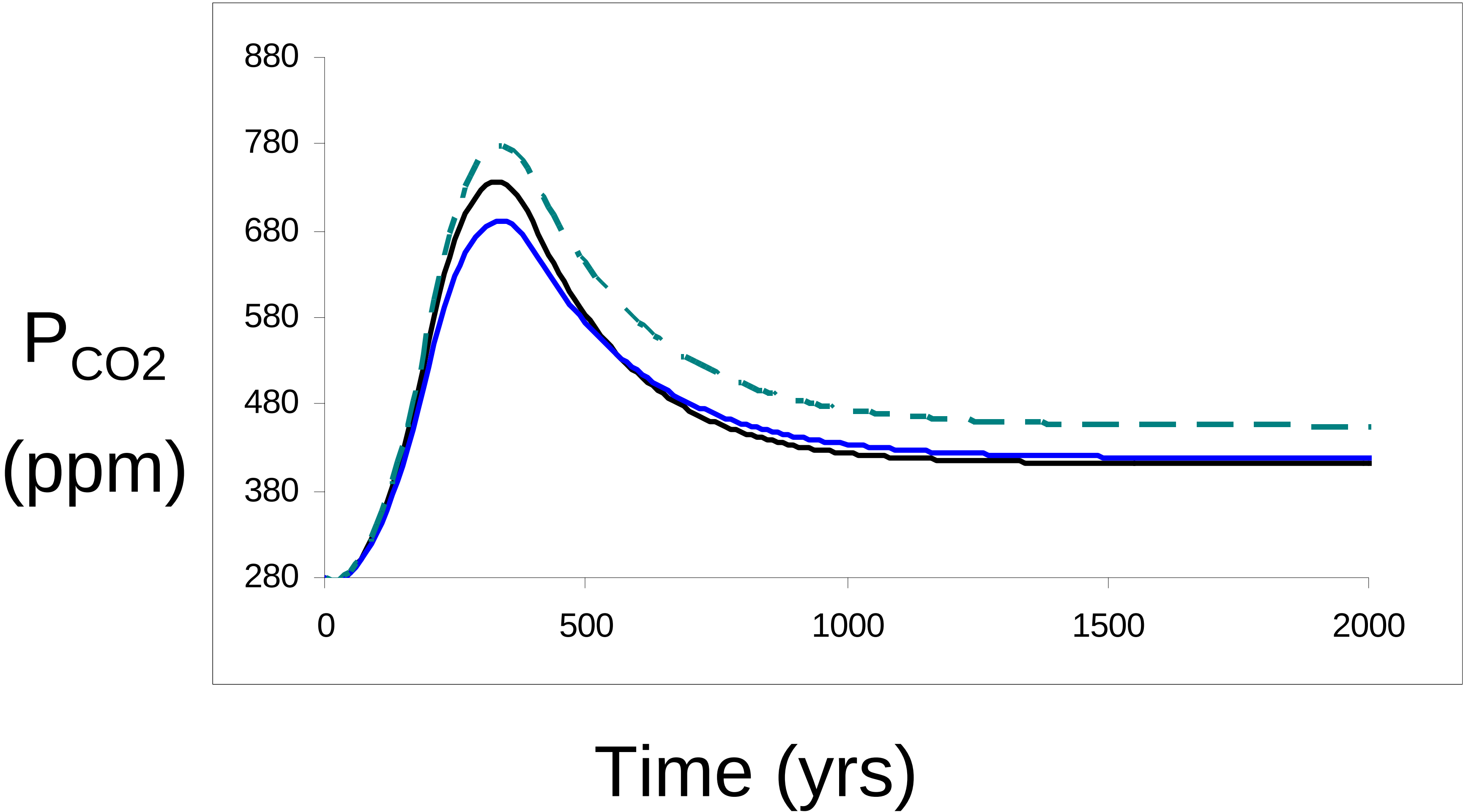
$$\left(\Delta P_{CO2}\right)_{overall} \neq \left(\Delta P_{CO2}\right)_{EMISSION} + \left(\Delta P_{CO2}\right)_{SOFT-TISSUE} + \left(\Delta P_{CO2}\right)_{CaCO3}$$



Feedbacks from carbon cycles changes

Maths predicts:

$$\left(\frac{P_{CO2}}{P_0}\right)_{overall} = \left(\frac{P_{CO2}}{P_0}\right)_{EMISSION} \times \left(\frac{P_{CO2}}{P_0}\right)_{SOFT-TISSUE} \times \left(\frac{P_{CO2}}{P_0}\right)_{CaCO3}$$

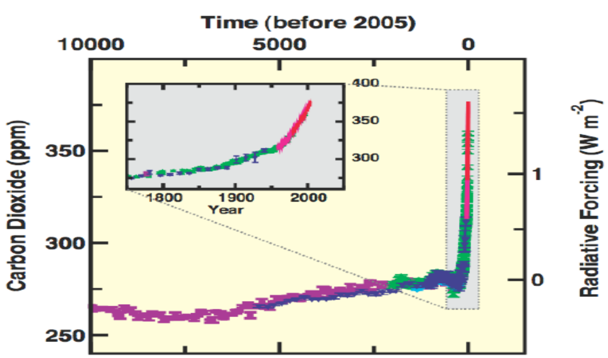


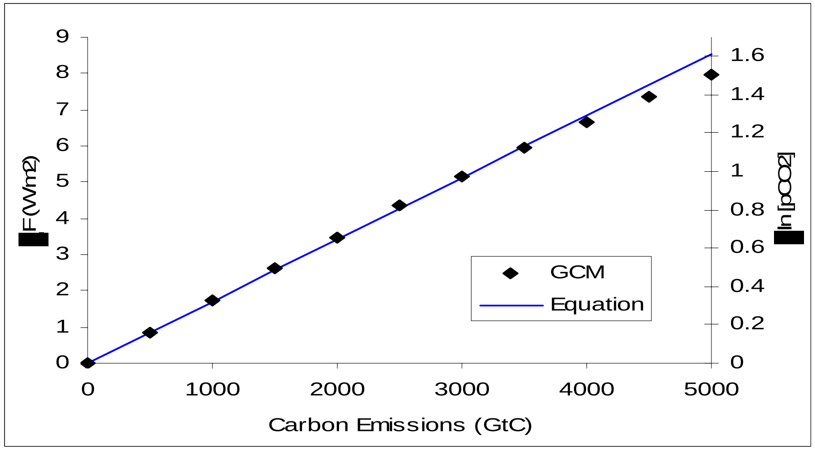
Conclusions

- Analytical link to numerical models: insight into non-linear feedbacks

$$\left(\frac{P_{CO2}}{P_0}\right)_{overall} = \left(\frac{P_{CO2}}{P_0}\right)_{EMISSION} \times \left(\frac{P_{CO2}}{P_0}\right)_{SOFT-TISSUE} \times \left(\frac{P_{CO2}}{P_0}\right)_{CaCO3}$$

- Can compare future steady state forcing to present transient levels:





- Present climate sensitivity to carbon perturbations is large: 1.7Wm^{-2} per 1000Gt C for thousands of years

Why should we assume I_B remains constant?

I_B can be expressed in terms of a carbon 'buffer factor', *B*:

$$B = \frac{\delta[CO_2]}{[CO_2]} \frac{C_{DIC}}{\delta C_{DIC}}$$

By writing:

$$I_B = I_A + \frac{I_O}{B}$$

While *B* increases as P_{CO2} increases; they have opposing effects on the value of I_B. Causing: $\Delta I_B << I_B$

VALID UNTIL ~ 5000GtC