Constraints from long-term observations on the future of the global carbon cycle

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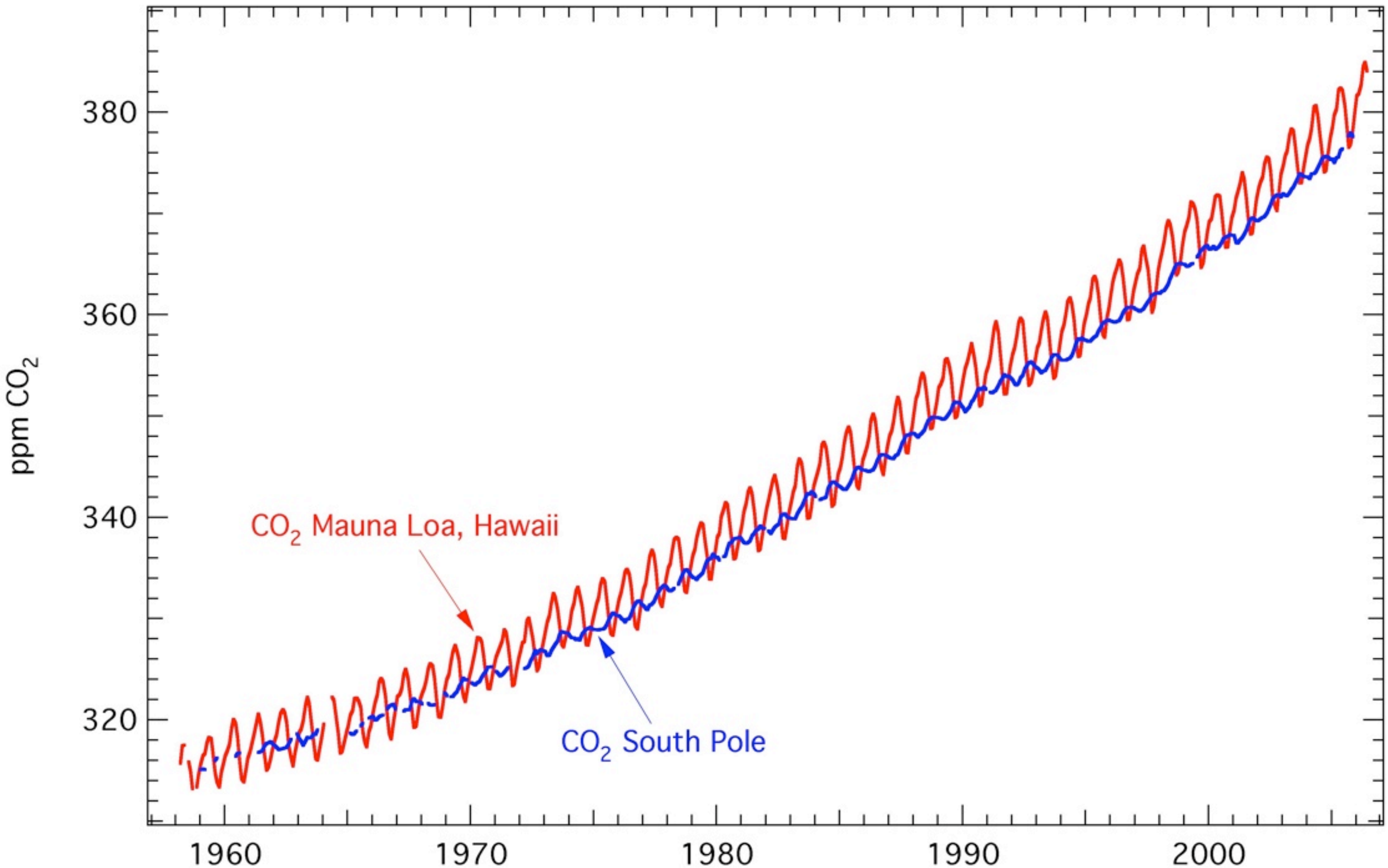
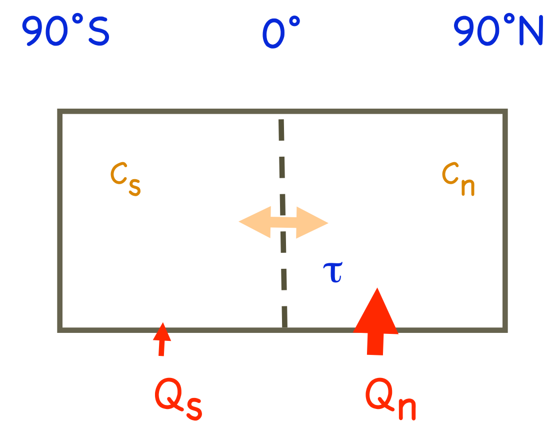
Anthropogenic Perturbation of the Global Carbon Cycle

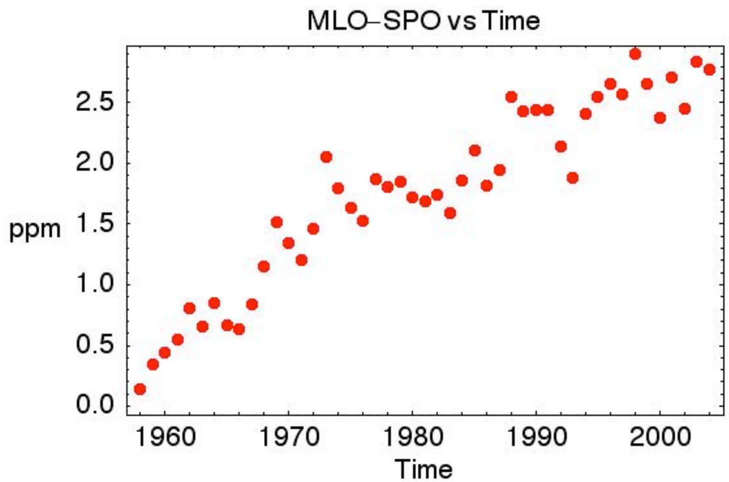


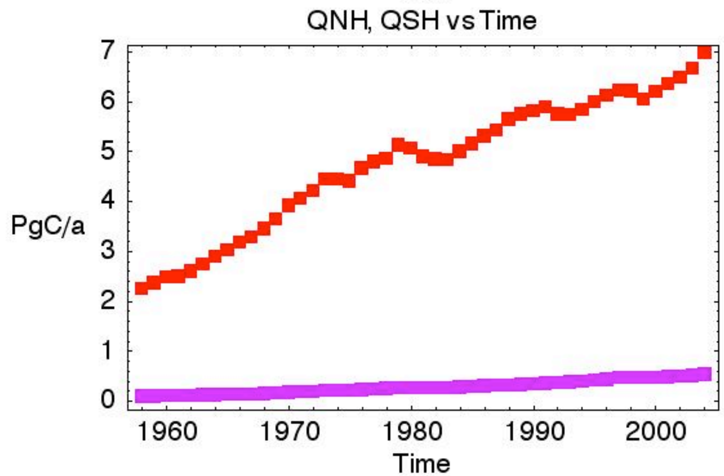
Keeling et al., 2005, updated

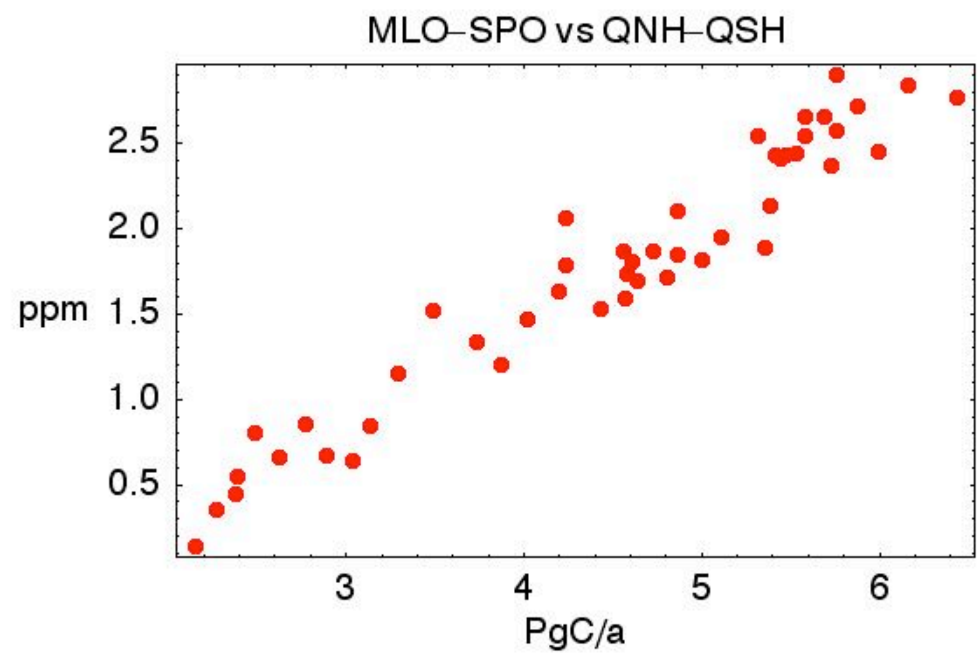
Interhemispheric CO_2 concentration gradient tracks fossil fuel emissions



$$c_n - c_s = (Q_n - Q_s)\,\tau/2$$







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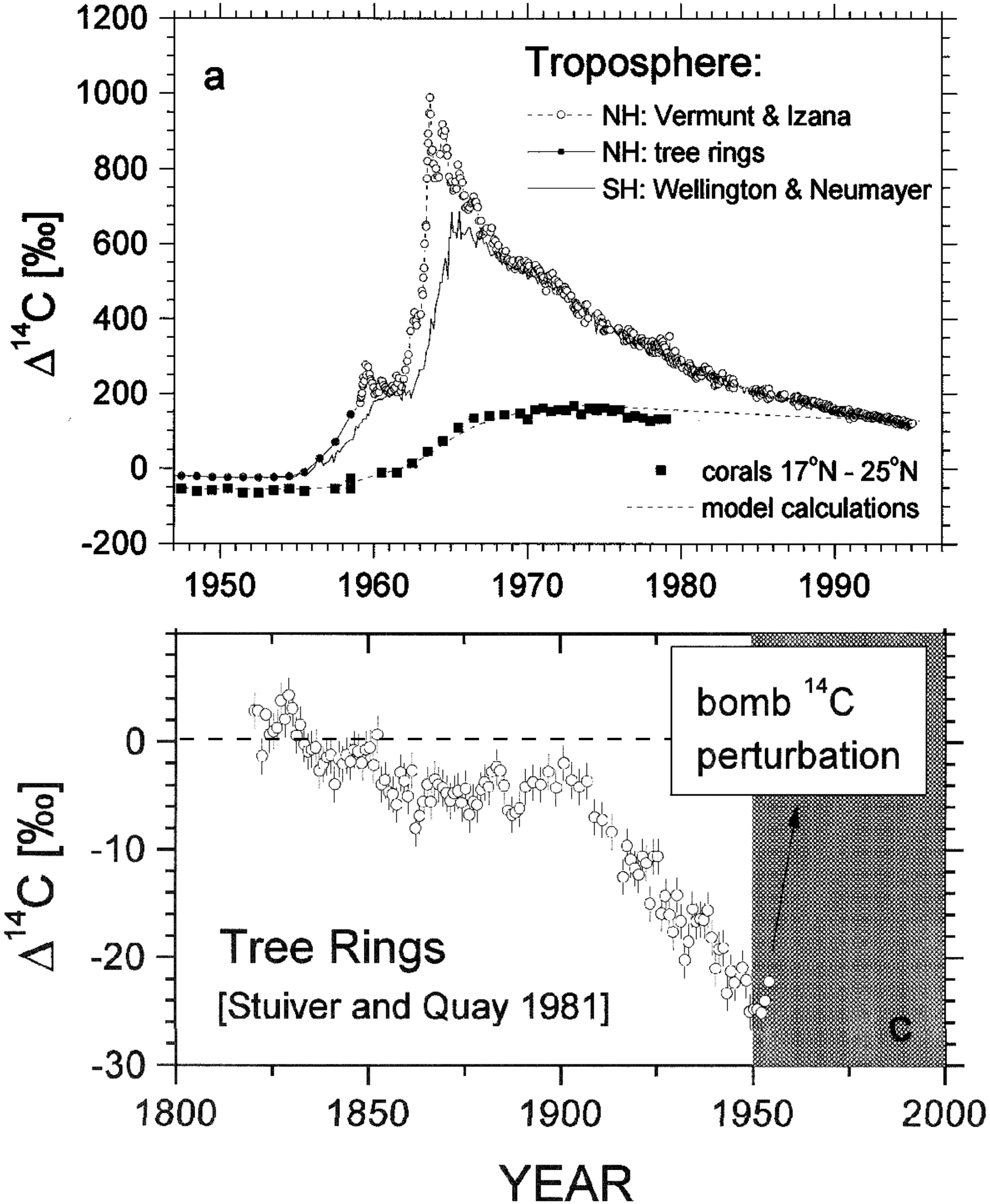
Key carbon cycle observations: Radiocarbon (^{14}C)



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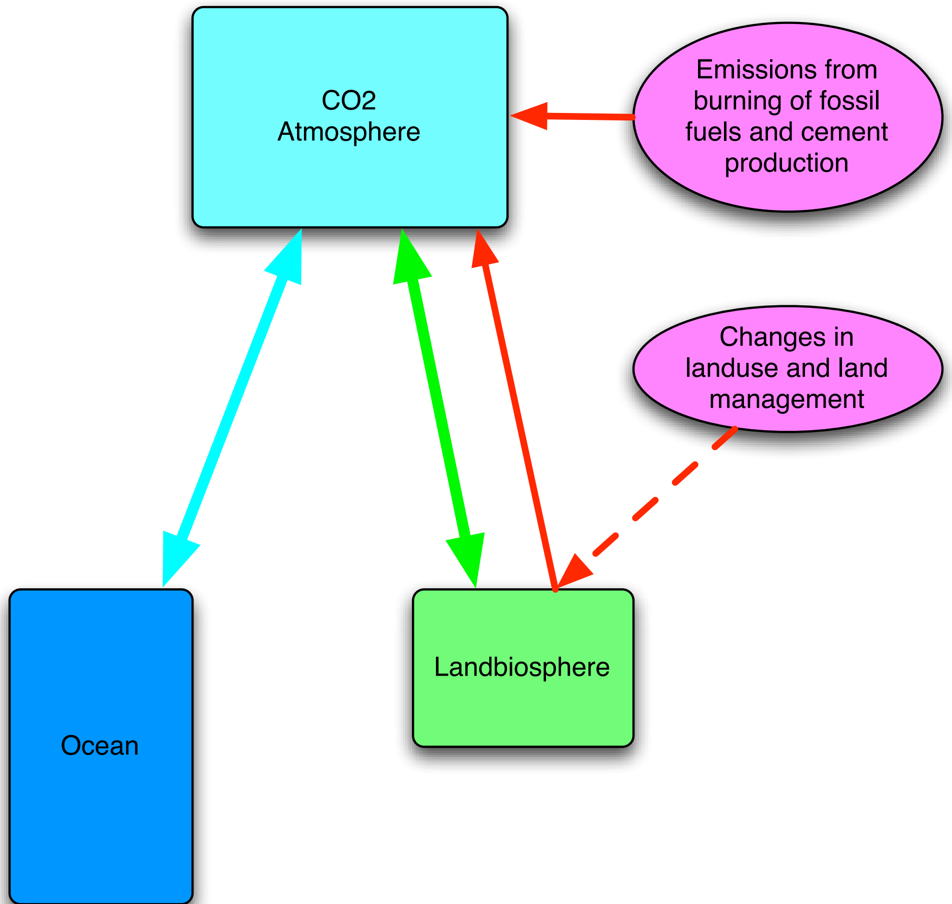
Levin and Hessheimer, 2001

Direct response of the global carbon cycle to the anthropogenic perturbation



Observed anthropogenic CO_2 inventory in word ocean (~ mid 1990s)

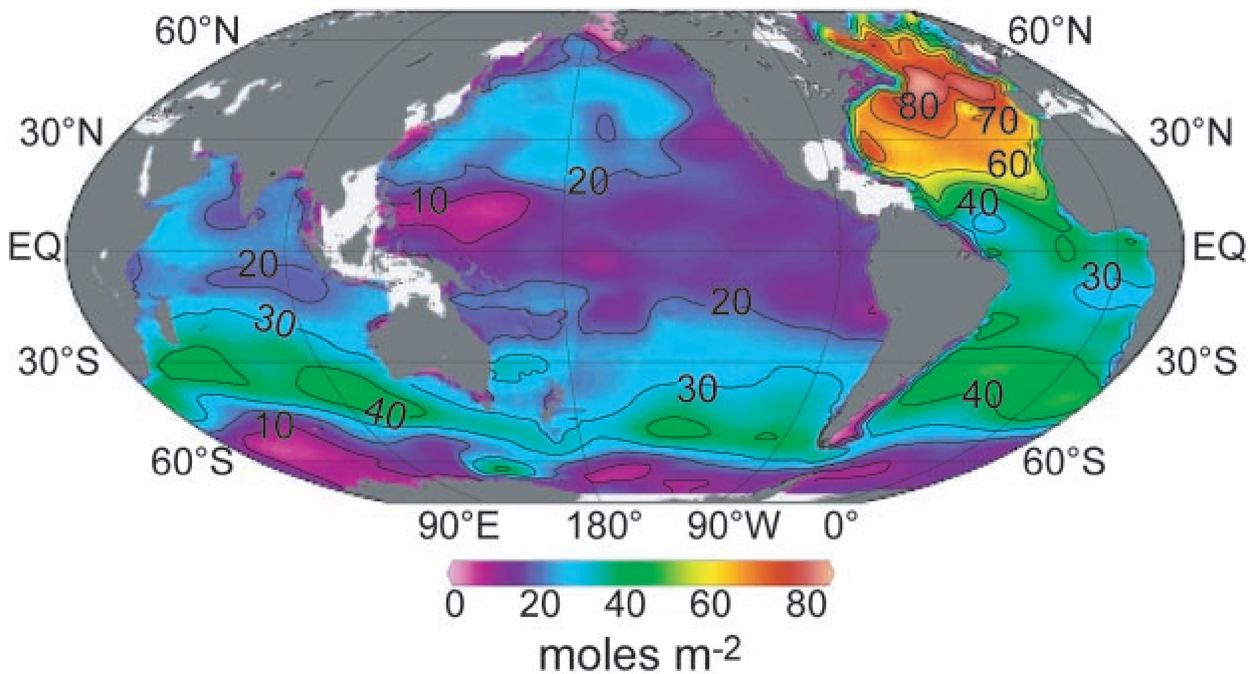


Fig. 1. Column inventory of anthropogenic CO_2 in the ocean (mol m^{-2}). High inventories are associated with deep water formation in the North Atlantic and intermediate and mode water formation between 30° and 50°S. Total inventory of shaded regions is 106 ± 17 Pg C.

Inventories
Global:
118 PgC
North Atlantic:
27 PgC

Estimated uptake rates (1980-2000):
Global:
1.85 PgC yr^{-1}
North Atlantc:
0.42 PgC yr^{-1}

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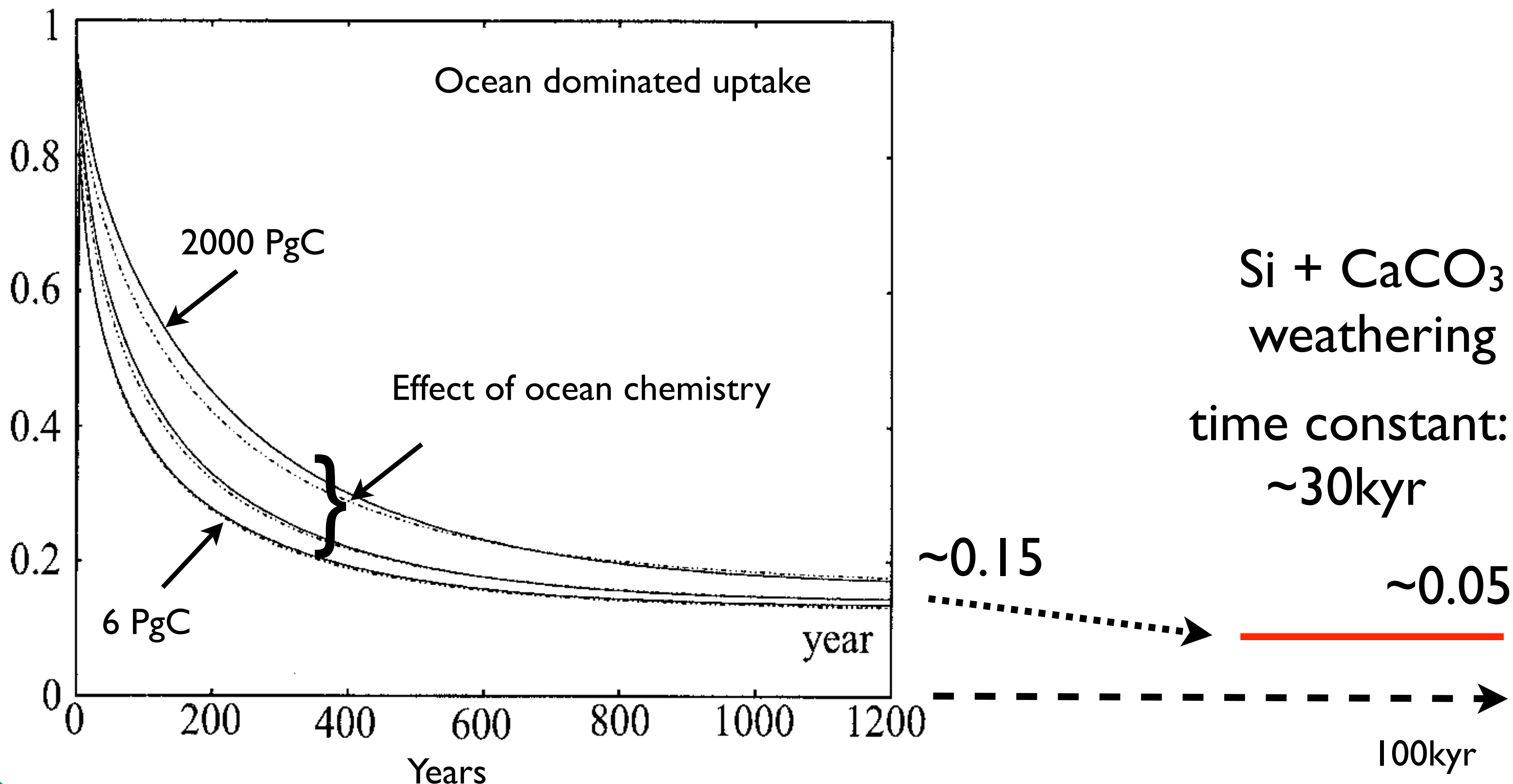
Sabine et al., 2004

Mid- and long-term response of carbon cycle to direct perturbation

Atmosphere fraction after pulse injection at t=0



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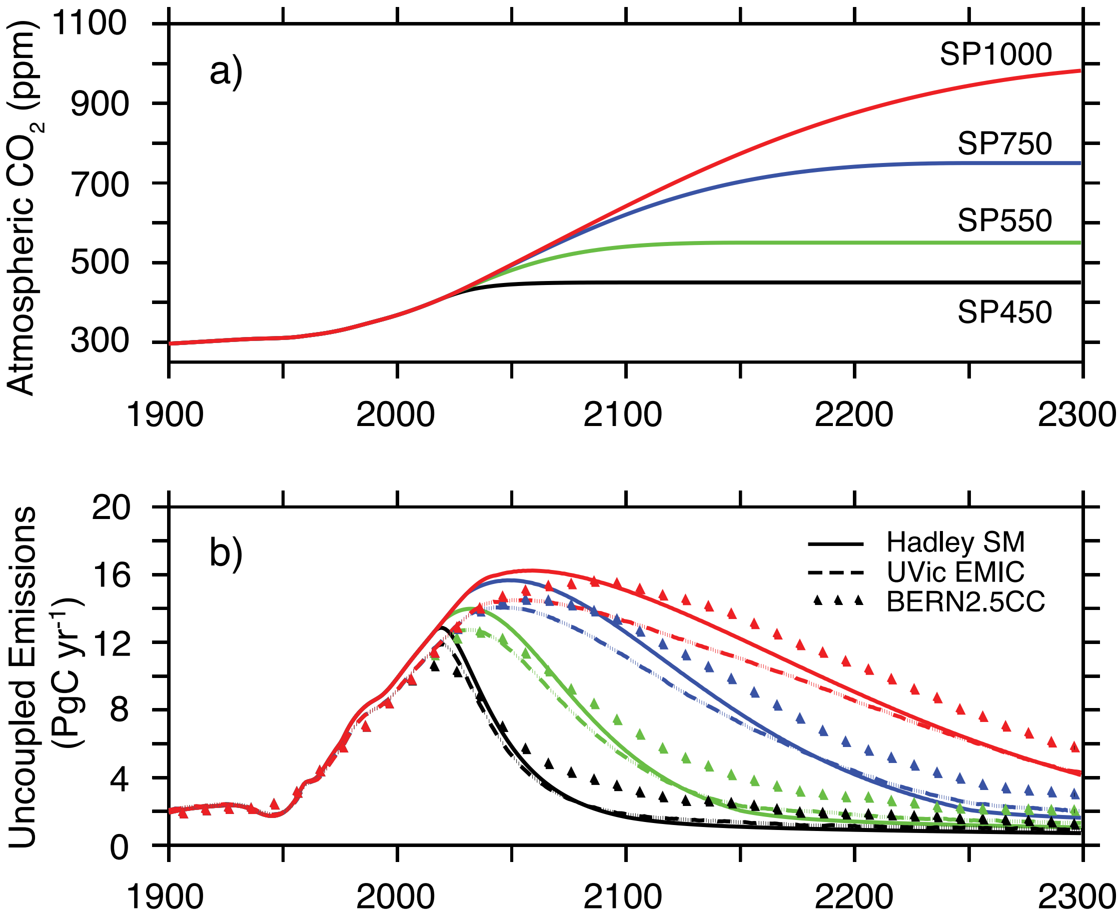
Hoos et al., 2001

Archer, 2005

Stabilization of atmospheric CO_2
No climate feedbacks



IPCC AR4, 2007

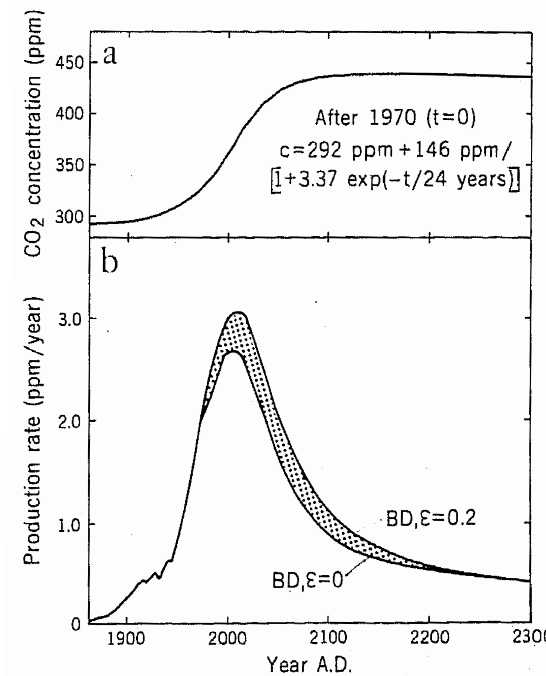


Fig. 6. Carbon dioxide production rates as observed up to 1970, and as permitted after 1970 for an increase of the atmospheric excess in a prescribed way (a) to a maximum of 50 percent.

Siegenthaler and Oeschger, 1978

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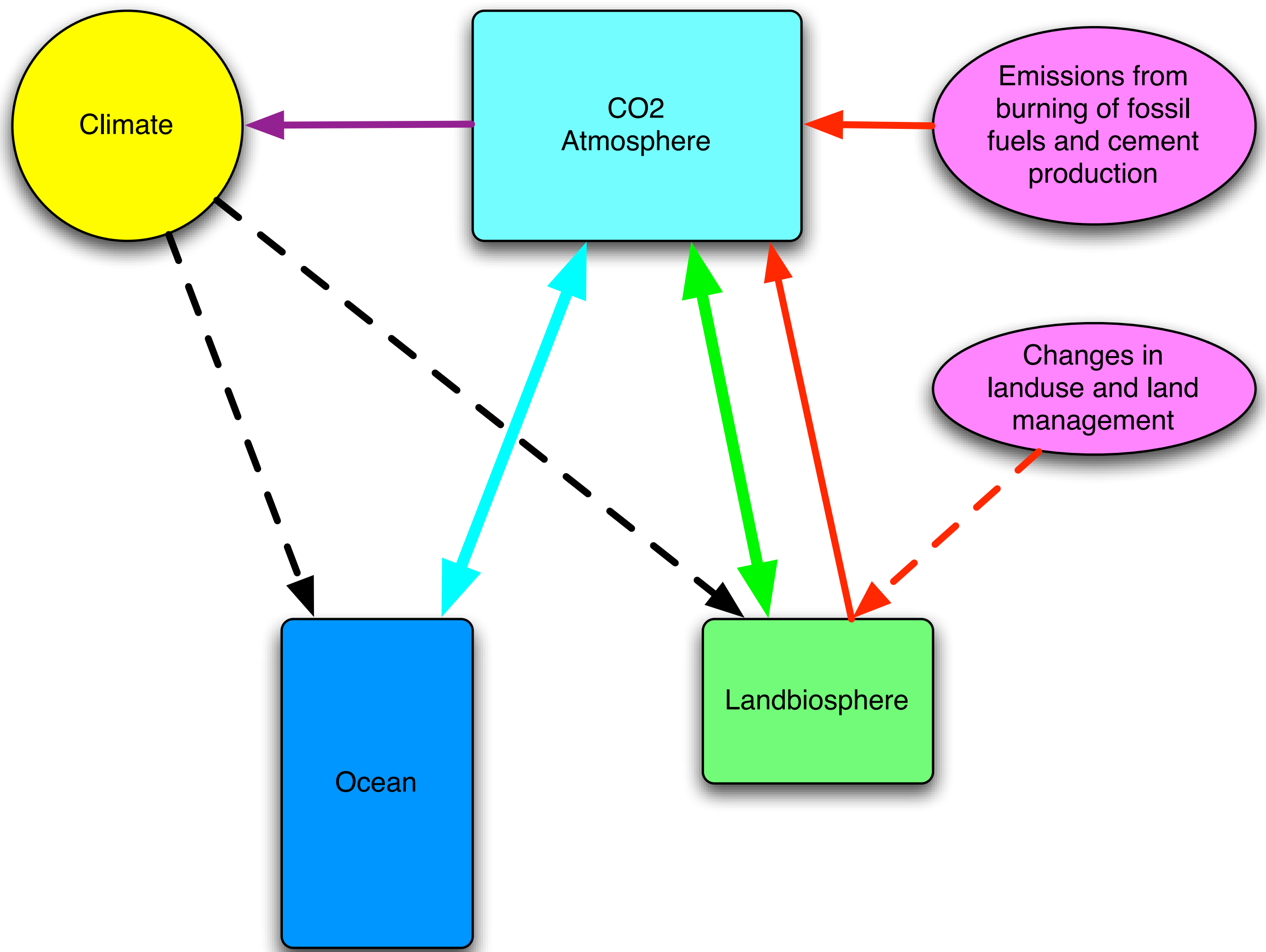
Carbon cycle - climate system feedbacks



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Basic terrestrial carbon cycle - climate system feedbacks

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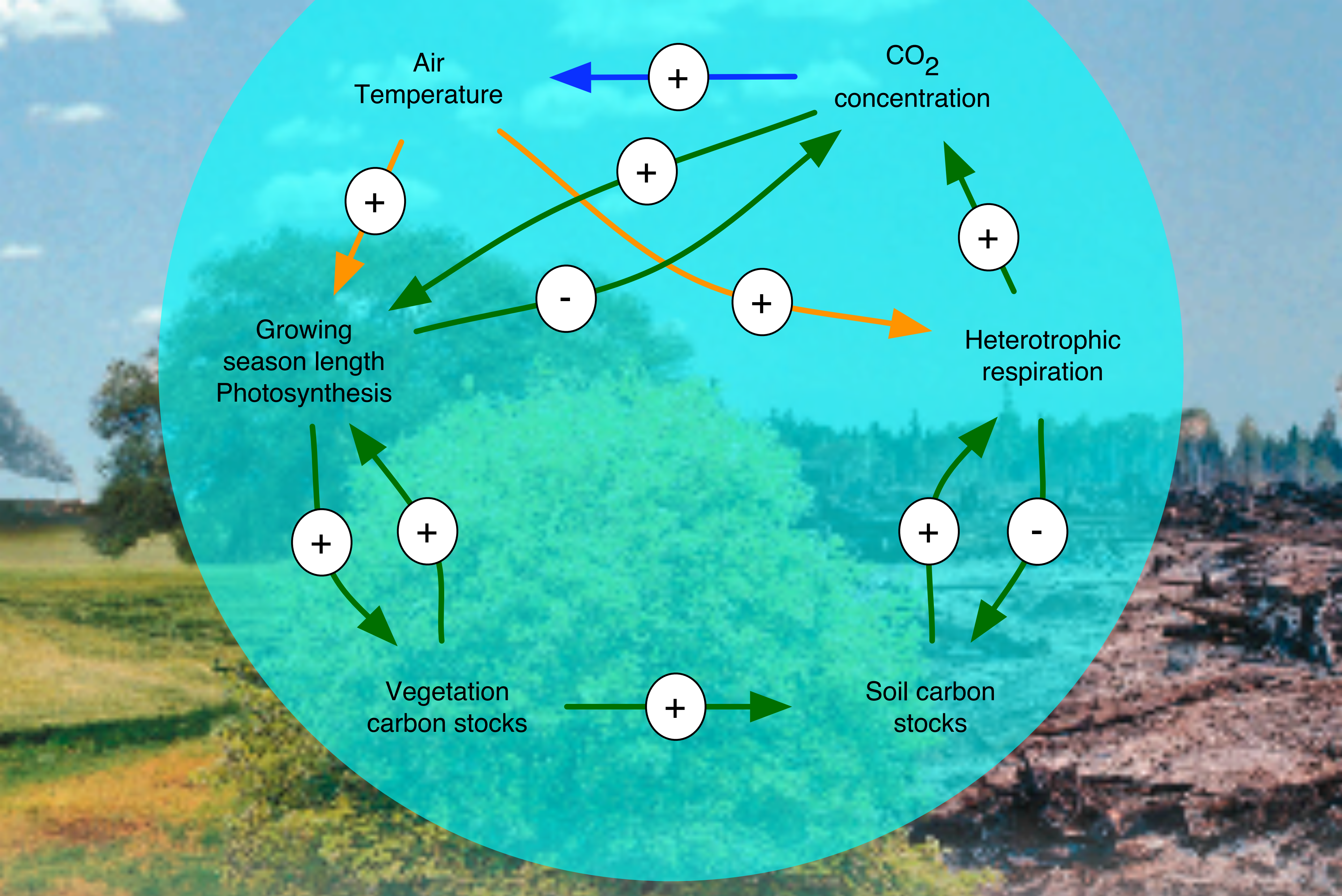
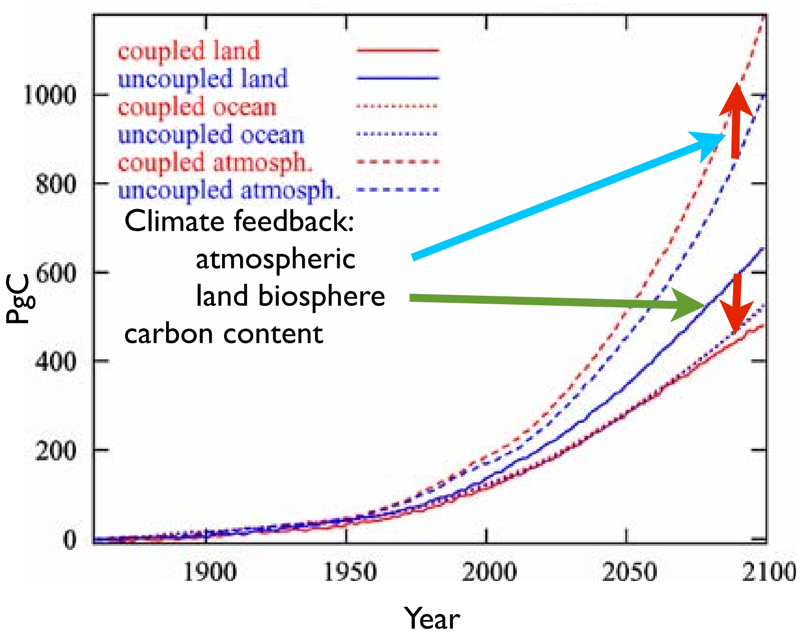


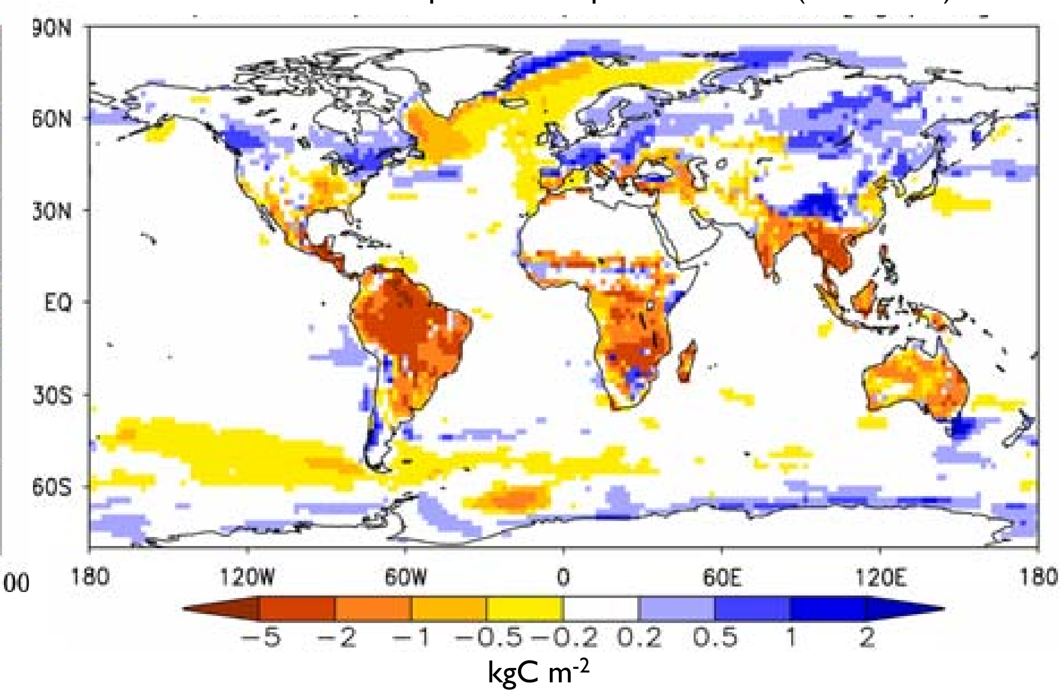
Basic terrestrial carbon cycle - climate system feedbacks

Model simulation of coupled carbon cycle - climate system

Simulated global carbon stock increases in atmosphere, ocean and land biosphere



Carbon uptake by land and ocean
Difference coupled - uncoupled simulation (2070-2100)



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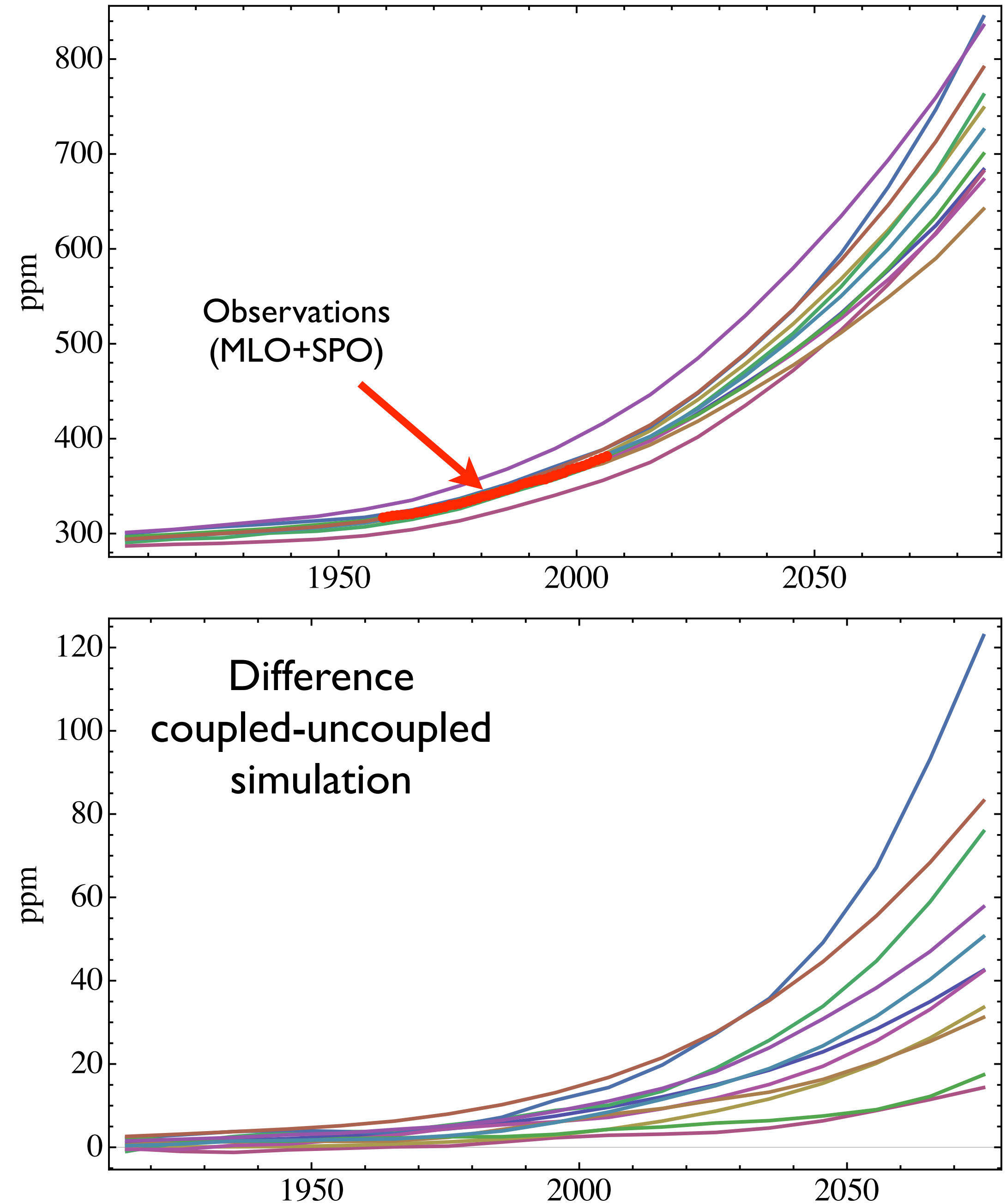
Raddatz et al., 2006

Coupled Carbon Cycle - Climate Model Simulation Experiments (C⁴MIP):

Predicted atmospheric CO_2 concentration

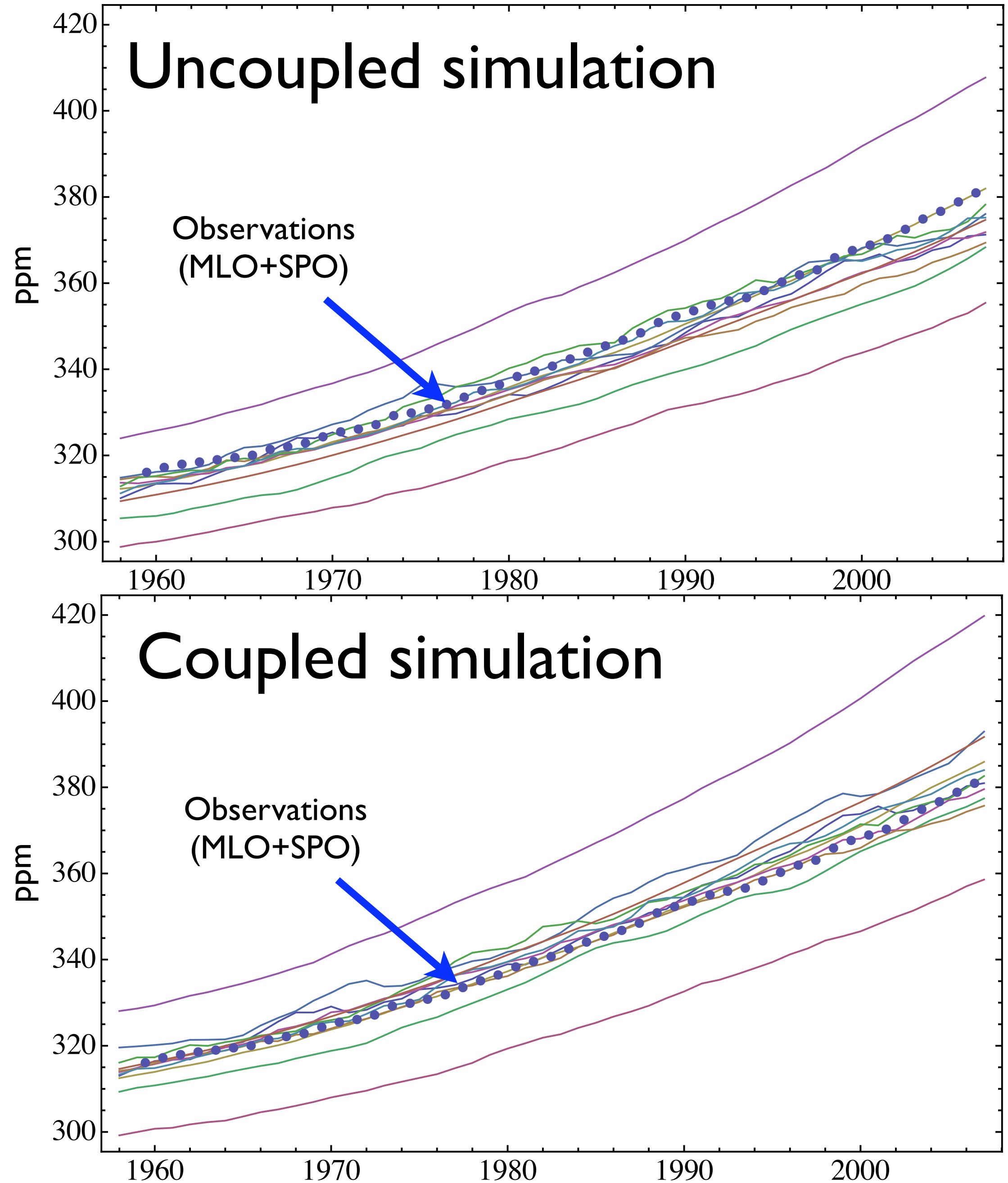


11 models,
historical emissions
after 2000: SRES-A2 emission profile

Decadal averages, smoothed

C⁴MIP Simulations, Friedlingstein et al., 2006

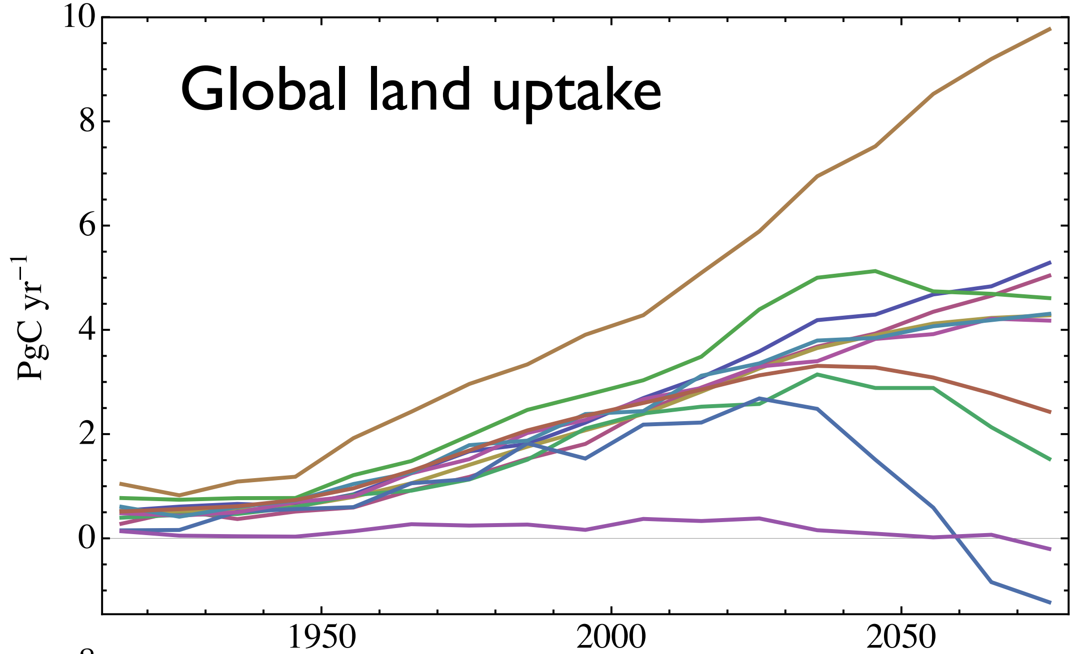
C4MIP simulations: Reproduction of atmospheric CO_2 increase

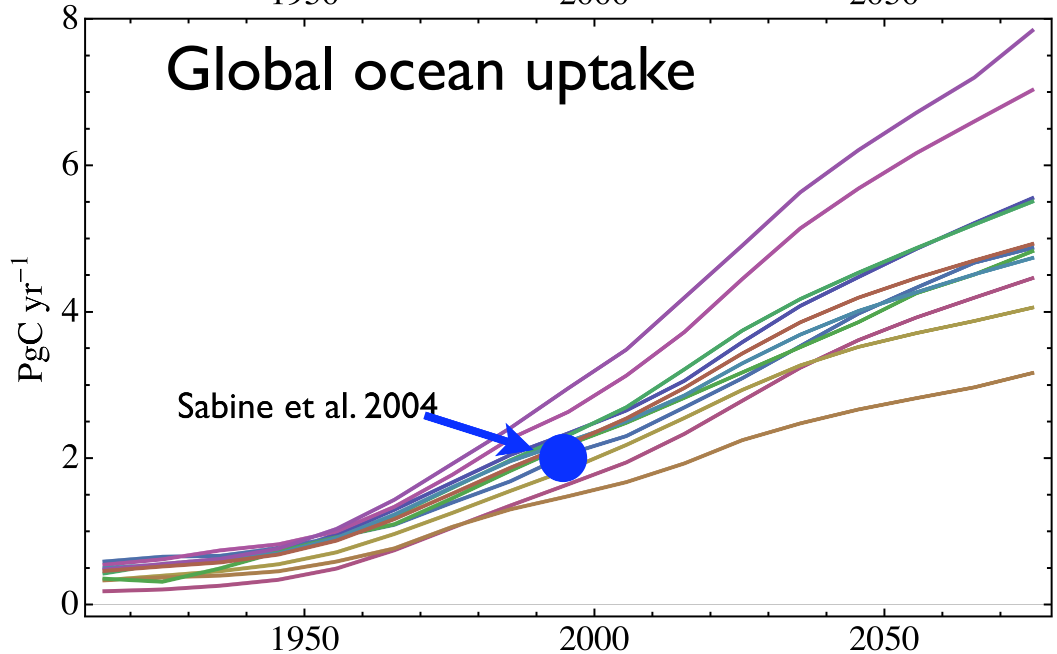


- 11 models,
- historical CO_2 emissions from fossil fuels and land use change

C[4]MIP Simulations, Friedlingstein et al., 2006

Coupled Carbon Cycle - Climate Model Simulation Experiments (C^4MIP)





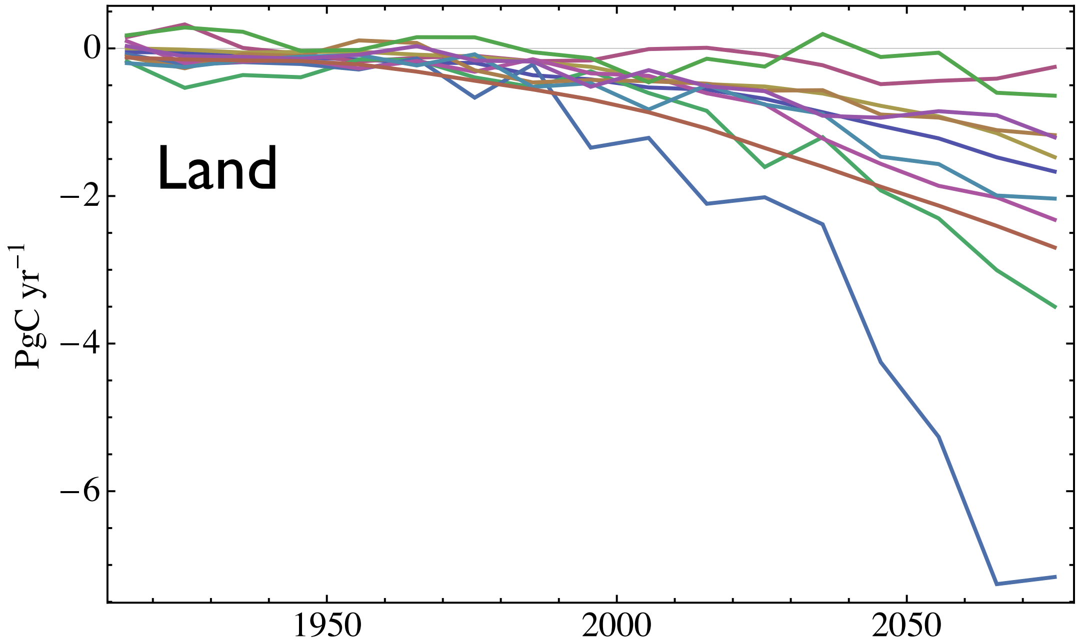
11 models,
SRES-A2 emission profile

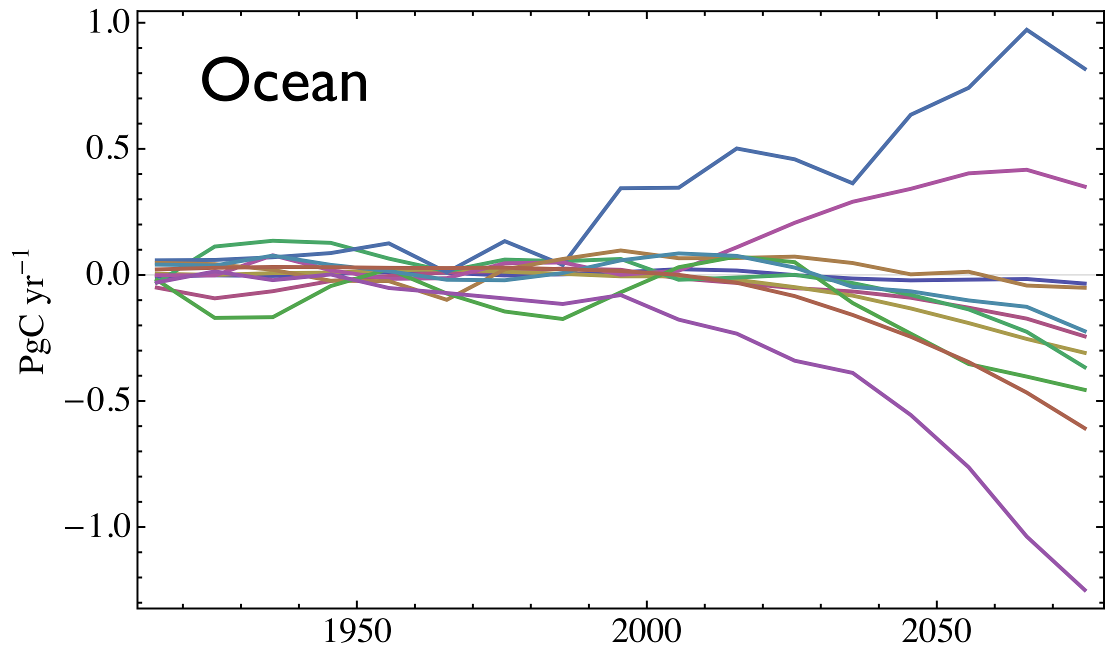
Decadal averages, smoothed

C^4MIP Simulations, Friedlingstein et al., 2006

Coupled Carbon Cycle - Climate Model Simulation Experiments (C^4MIP):

Climate feedback effects on global uptake by land and ocean



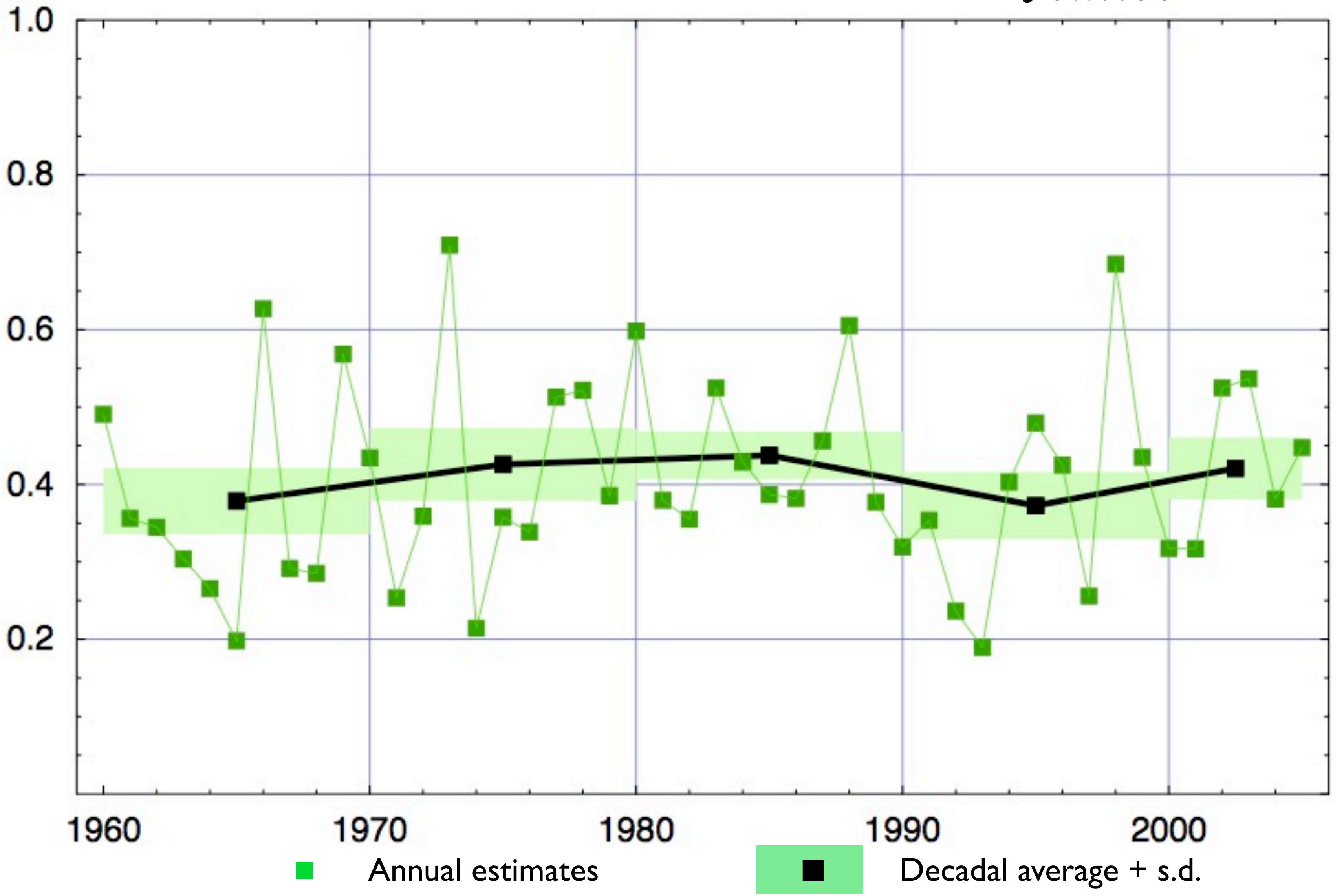


11 models,
SRES-A2 emission profile

Decadal averages, smoothed

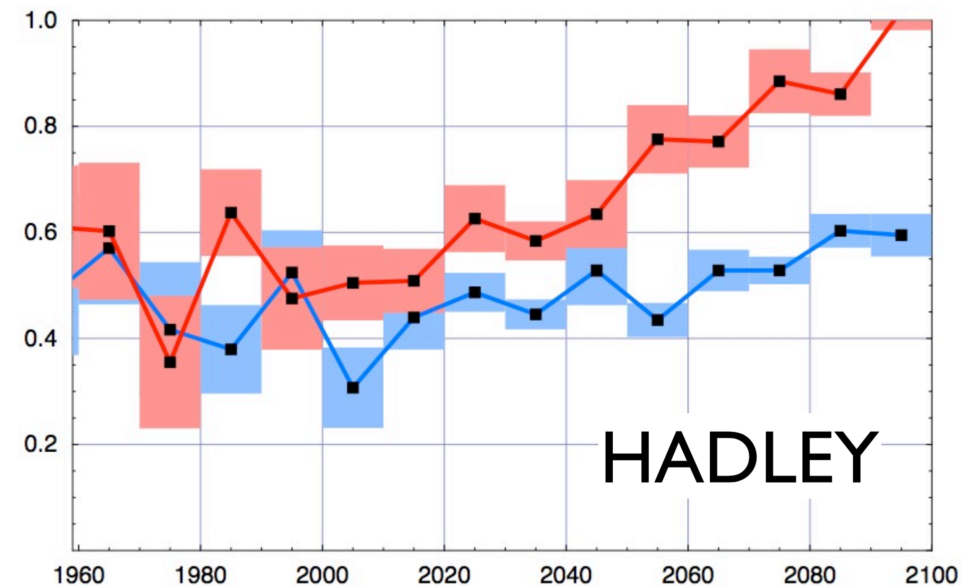
C^4MIP Simulations, Friedlingstein et al., 2006

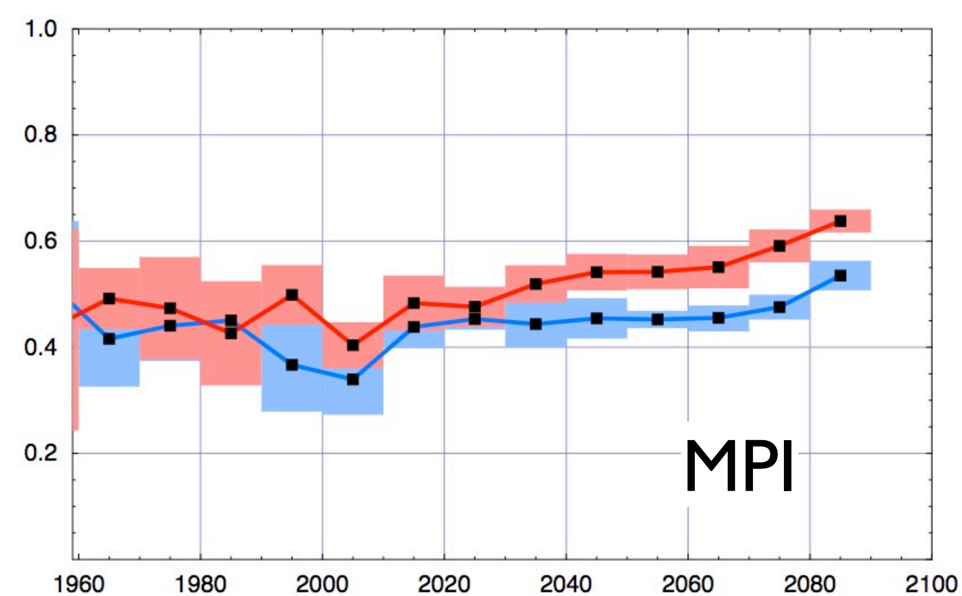
Observed airborne fraction: $\frac{\Delta N_{atm}}{Q_{emiss}}$



When can we expect to see a clear climate feedback signal on global carbon cycle?

Decadal average airborne fraction simulated by C^4MIP models





blue: uncoupled simulation
red: coupled simulation

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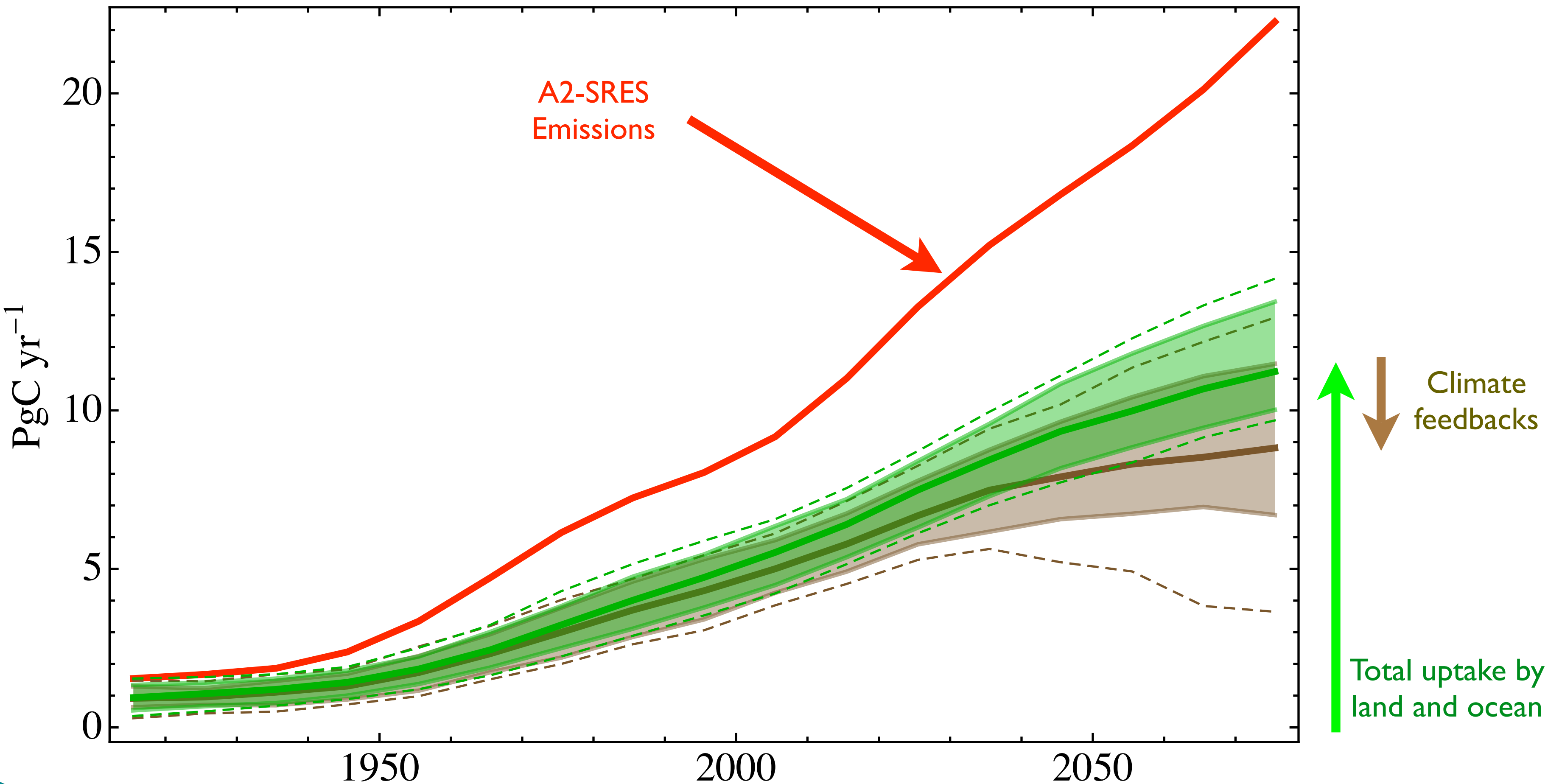
Global CO_2 budget over the next 100 years: Based on C[4]MIP results



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Decadal averages, smoothed

C[4]MIP Simulations, Friedlingstein et al., 2006

Carbon cycle in the 21st century: Lessons from C^4MIP simulation experiments

- Ocean:
  - Uncertainty due to different mixing and circulation characteristics
  - Relatively small climate feedback
- Land:
  - Models assume substantial "CO_2 fertilization":

    Effective $$\beta = \frac{\frac{\Delta NPP}{NPP_0}}{\frac{\Delta C}{C_0}} = 0.2 - 0.6$$
  - Strong climate feedback
- Carbon cycle - climate feedback gain, range of C^4MIP models:
  - 4 - 20% (10 models),
  - 31% (HadCM3LC)

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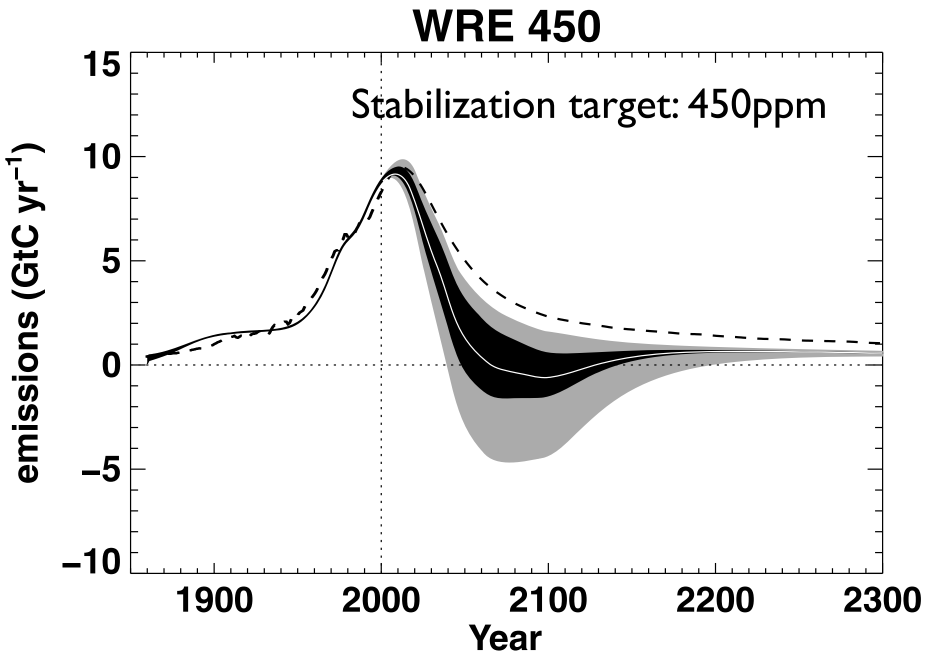
Climate feedbacks: Implications for atmospheric CO_2 stabilization

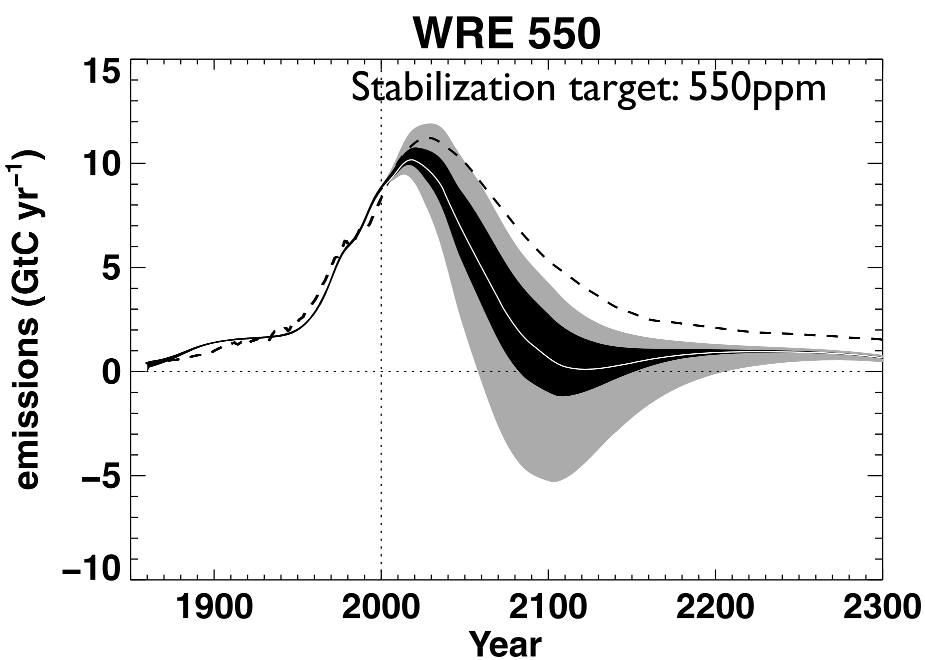
Standard HadCM3LC climate sensitivity: 3 K

Uncertainty range from climate sensitivity 1.5 - 4.5 K

Uncertainty range from climate sensitivity + carbon cycle model parameters

Emission profiles of Wigley, 1996 (no feedbacks)





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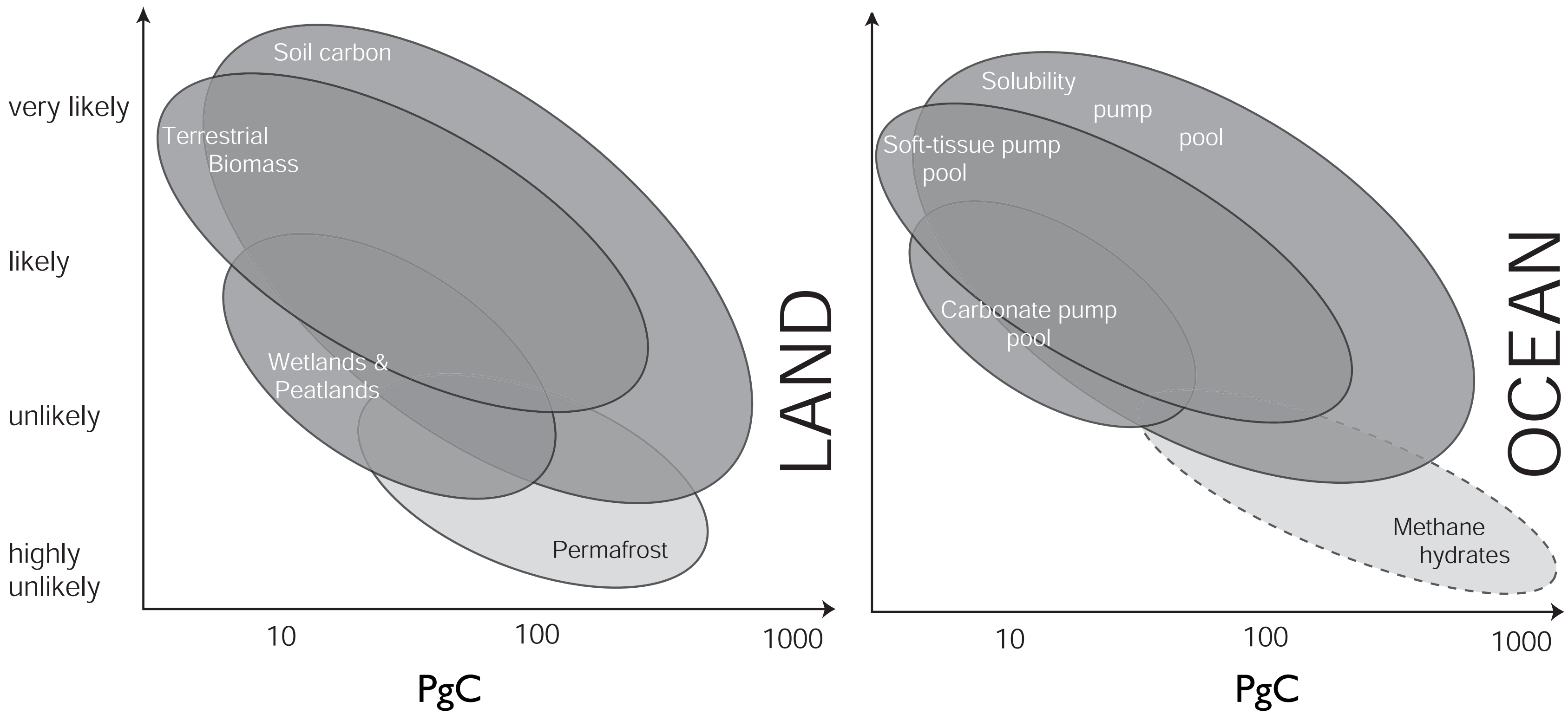
Jones et al., 2006

Vulnerability of carbon pools (100yr time scale)



1 PgC release ⇒

~0.25 ppm atmospheric CO_2 increase (100yr time scale)

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Gruber et al., 2006

Conclusions

- Currently observed (~linear) dynamics will change
- Present records do not yet exhibit enough information for quantification or validation of non-linear dynamics
- Current models exhibit still large differences ->
  Indication of insufficient process knowledge
- Many vulnerable pools and biogeochemical processes not yet represented in current Earth system models (a.o. permafrost, wetlands, fire, nutrients, ozone, CH_4,...)
- Effects of changes in land use and management not yet included
- Comprehensive assessment: Biogeochemical + biophysical feedbacks!
- 100yr time scale carbon cycle - climate feedbacks:
  positive, ~20% effect

Thank you