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

\[ C_n - C_s = (Q_n - Q_s) \tau / 2 \]
Key carbon cycle observations: Radiocarbon ($^{14}$C)

Levin and Hessheimer, 2001
Direct response of the global carbon cycle to the anthropogenic perturbation

- Emissions from burning of fossil fuels and cement production
- Changes in landuse and land management

CO2

Atmosphere

Ocean

Landbiosphere
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 Atlantic: 0.42 PgC yr$^{-1}$

*Sabine et al., 2004*
Mid- and long-term response of carbon cycle to direct perturbation

Atmosphere fraction after pulse injection at $t=0$

Ocean dominated uptake

2000 PgC

Effect of ocean chemistry

6 PgC

Si + CaCO$_3$ weathering

time constant:

~30kyr

~0.15

~0.05

100kyr

Years

0 200 400 600 800 1000 1200

Hoos et al., 2001

Archer, 2005
Stabilization of atmospheric CO$_2$

No climate feedbacks

**Figure 10.21.**

- **(a)** Cumulative emissions for the period from 2000 to 2100 (to stabilize atmospheric CO$_2$ concentration at 450 ppm, etc.) as simulated by three trajectories and the use of a dynamic ocean model (Joos et al., 2001; Plattner et al., 2001; see Table 8.3 for model details) and the BERN2.5CC carbon cycle EMIC (Joos et al., 2001; Plattner et al., 2001; triangles) for the three stabilisation scenarios without accounting for the climate-carbon cycle feedback. As detailed above, the climate-carbon cycle models. As detailed above, the climate-carbon cycle feedback will have an impact on the estimate of the projected CO$_2$ concentration for. (d) The difference between (b) and (c) showing the impact of the climate-carbon cycle feedback highlighted in the C$_4$F$_8$ suite of simulations covering carbon cycle uncertainty, even including the upper bound, which is based on rather extreme assumptions here compared to the TAR.

- **(b)** Uncoupled emissions required to achieve stabilisation. In this case, the higher the stabilisation scenario, the larger the climate change, the larger the emission reduction relative to the case without climate-carbon cycle feedback reduces the land and ocean uptake of carbon.

**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.

**IPCC AR4, 2007**

**Siegenthaler and Oeschger, 1978**
Carbon cycle - climate system feedbacks

- Emissions from burning of fossil fuels and cement production
- Changes in land use and land management
- CO2
  - Atmosphere
  - Ocean
  - Landbiosphere
- Climate
Basic terrestrial carbon cycle - climate system feedbacks
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

- Coupled land
- Uncoupled land
- Coupled ocean
- Uncoupled ocean
- Coupled atmosph.
- Uncoupled atmosph.

Climate feedback:
- Atmospheric
- Land biosphere
- Carbon content

Year

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

kgC m\(^{-2}\)

Raddatz et al., 2006
Coupled Carbon Cycle - Climate Model Simulation Experiments (C⁴MIP):

Predicted atmospheric CO₂ concentration

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

Decadal averages, smoothed
C4MIP simulations: Reproduction of atmospheric CO₂ increase

- 11 models,
- historical CO₂ emissions from fossil fuels and land use change

Uncoupled simulation

Coupled simulation

Observations (MLO+SPO)
Coupled Carbon Cycle - Climate Model Simulation Experiments (C⁴MIP)

11 models,
SRES-A2 emission profile

Decadal averages, smoothed

C⁴MIP Simulations, Friedlingstein et al., 2006
Coupled Carbon Cycle - Climate Model Simulation Experiments ($C^4$MIP):

Climate feedback effects on global uptake by land and ocean

11 models, SRES-A2 emission profile

Decadal averages, smoothed
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 C⁴MIP models

blue: uncoupled simulation
red: coupled simulation
Global CO₂ budget over the next 100 years: Based on C⁴MIP results

A2-SRES Emissions

Decadal averages, smoothed

C⁴MIP 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 “CO₂ fertilization”:
    \[ \beta = \frac{\Delta NPP}{NPP_0} = \frac{\Delta C}{C_0} = 0.2 - 0.6 \]
    - Strong climate feedback

- Carbon cycle - climate feedback gain, range of C^4MIP models:
  - 4 - 20% (10 models),
  - 31% (HadCM3LC)
Climate feedbacks: Implications for atmospheric CO₂ 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)

*Jones et al., 2006*
Vulnerability of carbon pools (100yr time scale)

1 PgC release ⇒ ~0.25 ppm atmospheric CO₂ increase (100yr time scale)

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, CH4,...)
- 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