Climate-carbon cycle interaction in the 20th-21st centuries from global climate models simulations

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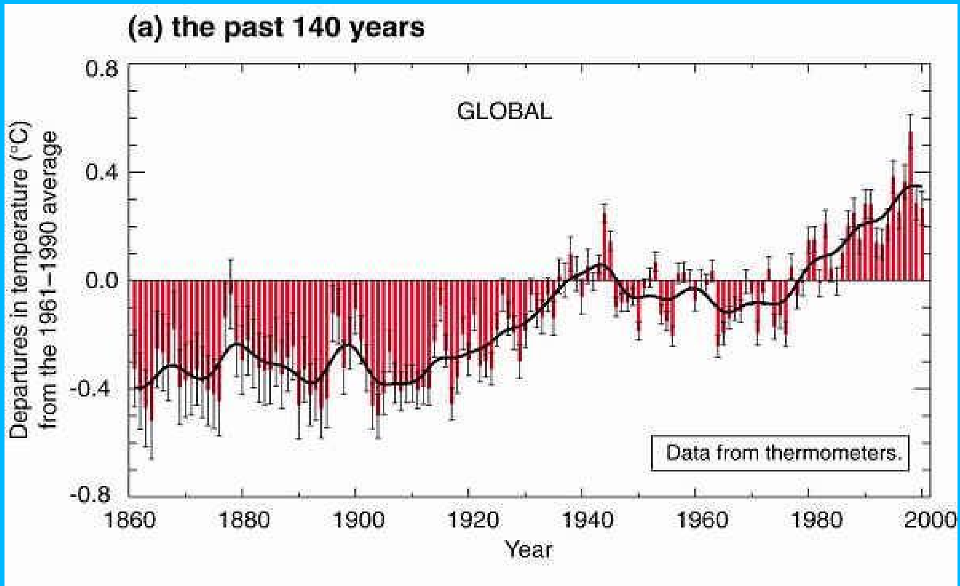
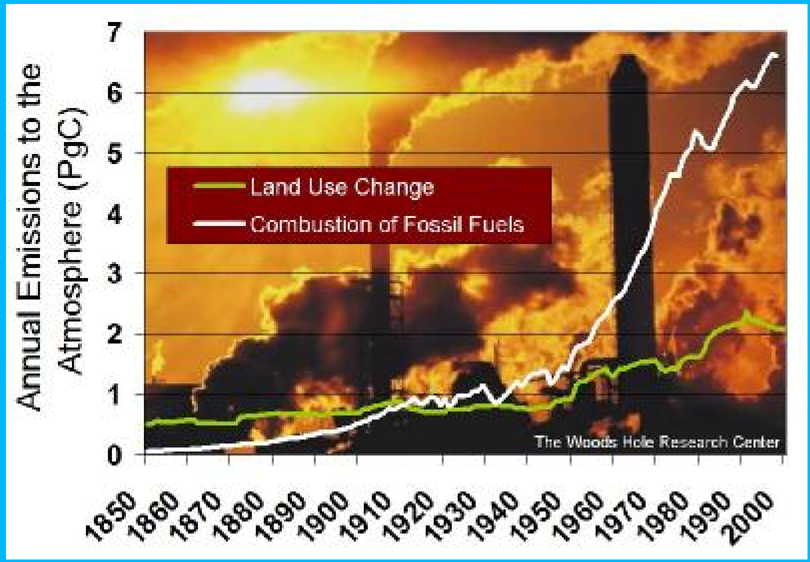
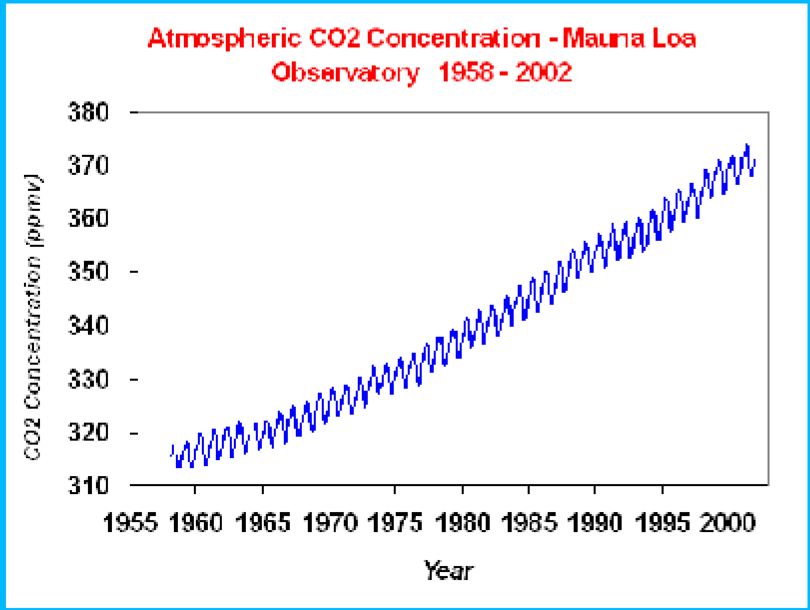
Changes in globally averaged temperature and carbon dioxide during the 20th century

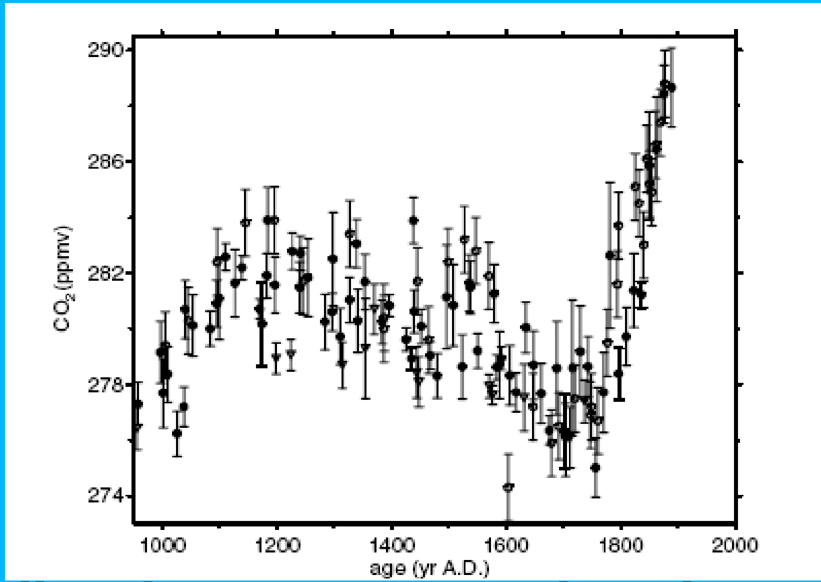


University of East Anglia
Climate Research Unit analysis of instrumental data

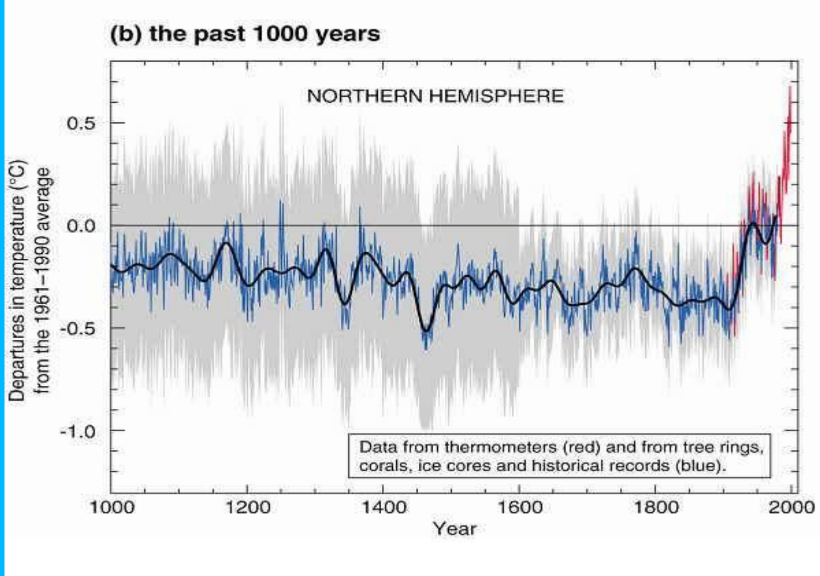




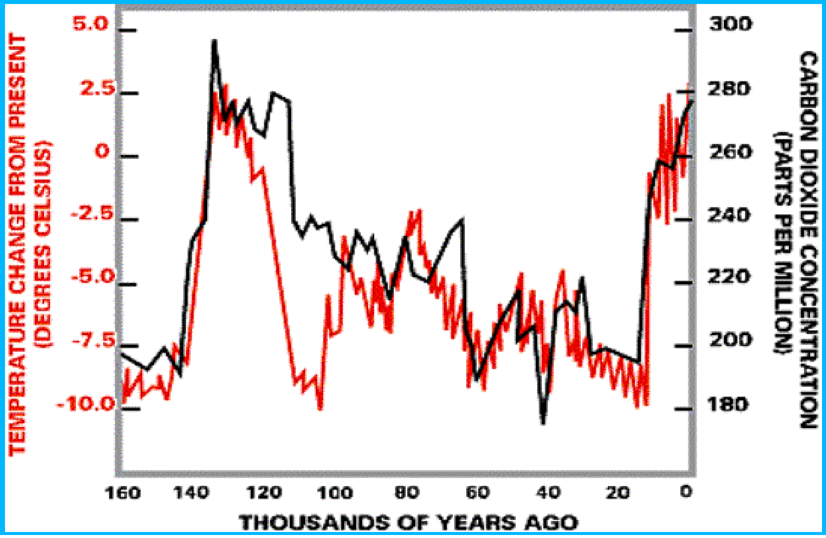
Past changes in atmospheric carbon dioxide



full circles: Dronning Maud Land ice core,
open triangles: South Pole ice core
open circles: Law Dome data
(after Siegenthaler et al [2005])



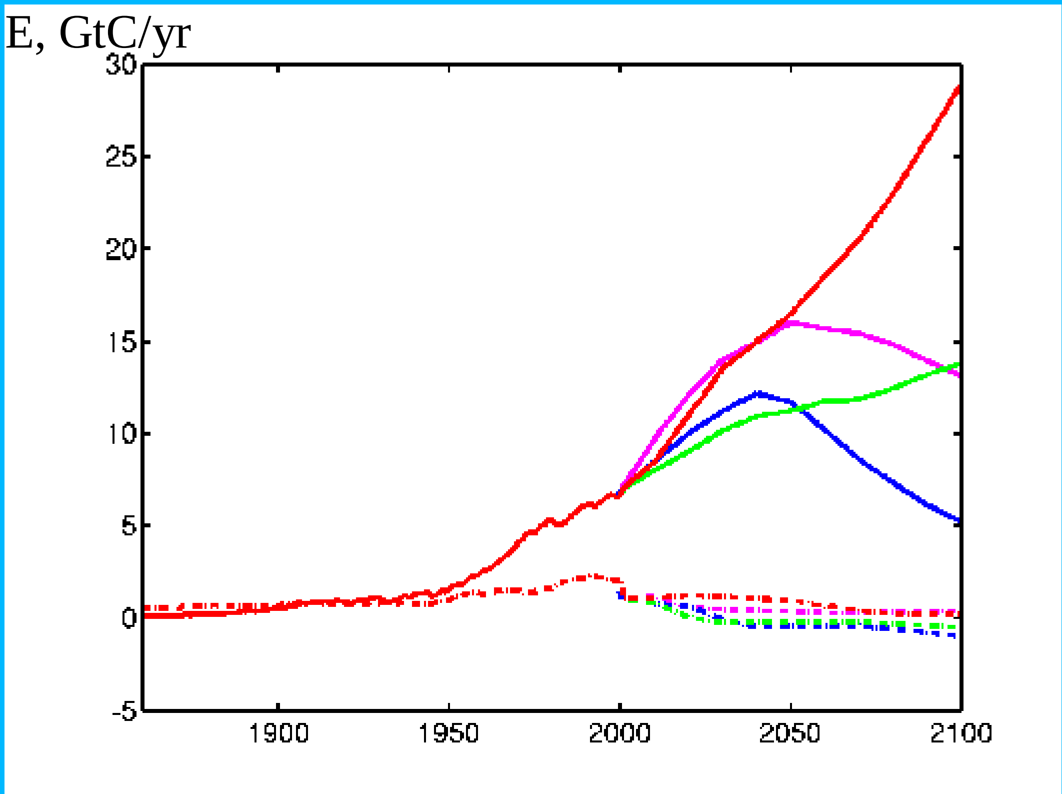
Northern Hemipshere temperature reconstructions (after [IPCC, 2001])



Reconstruction of temperature and CO2 concentration for the last major glaciation cycle based on the Vostok ice core drilling

IPCC Special Report on Emission Scenarios (SRES)

Totally: more than one hundred scenarios depending on future economical, technological, and political developments
Most frequently the so called marker scenarios are used



SRES A2
($2.00*10^3 + 0.23*10^3$ GtC)

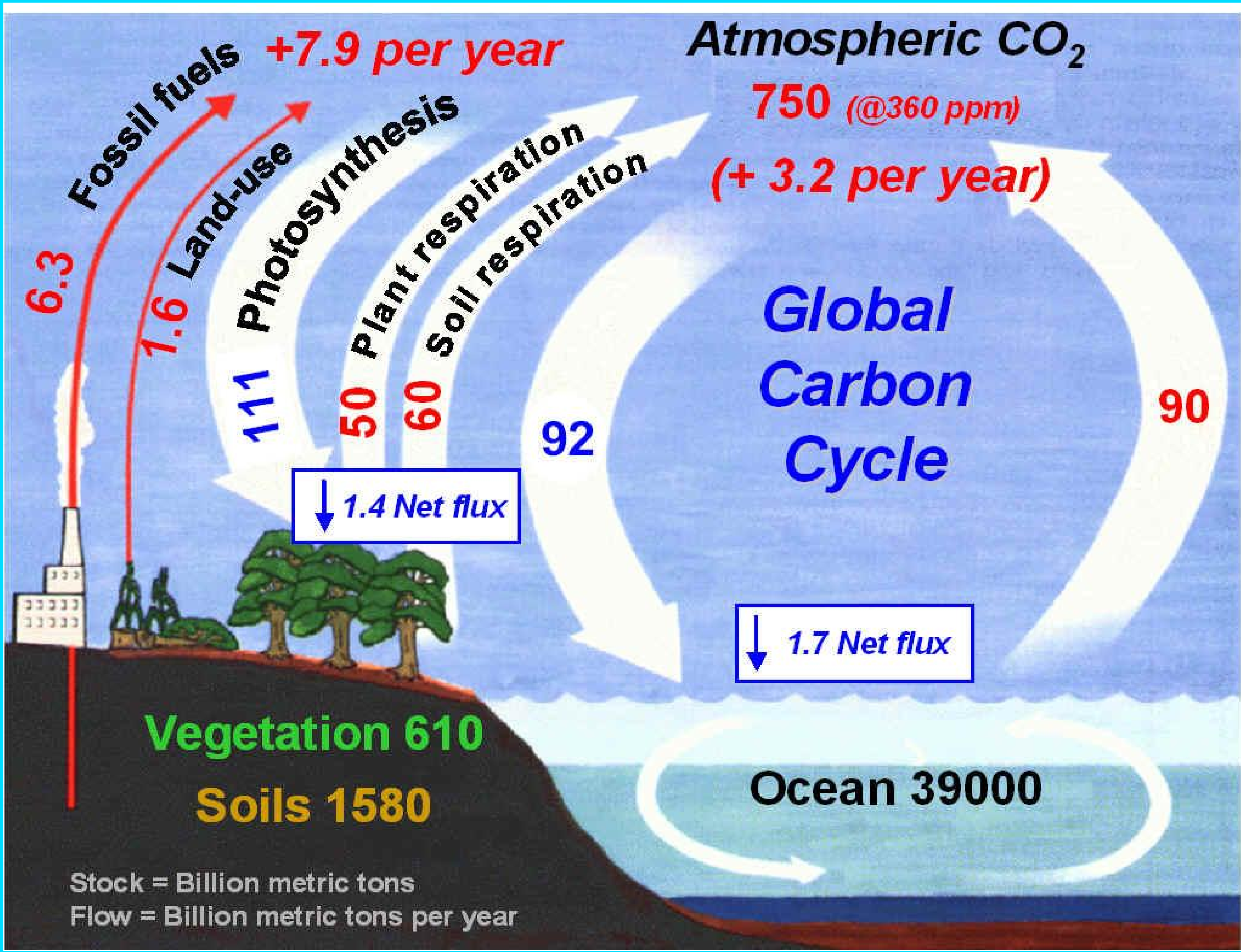
SRES A1B
($1.67*10^3 + 0.31*10^3$ GtC)

SRES B2
($1.38*10^3 + 0.14*10^3$ GtC)

SRES B1
($1.22*10^3 + 0.24*10^3$ GtC)

solid - fossil fuels combustion and industry
dashed – land use
(historical courses of both emissions for 1860-2000 are added)

Global carbon cycle

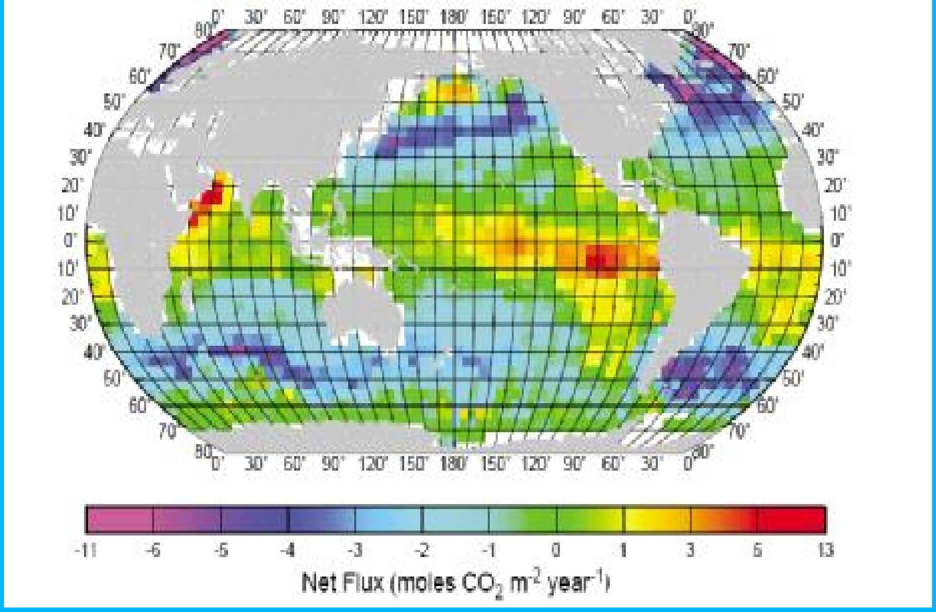


Oceanic uptake of carbon dioxide

$F_{oc} = k\,\alpha\,\Delta pCO_2$

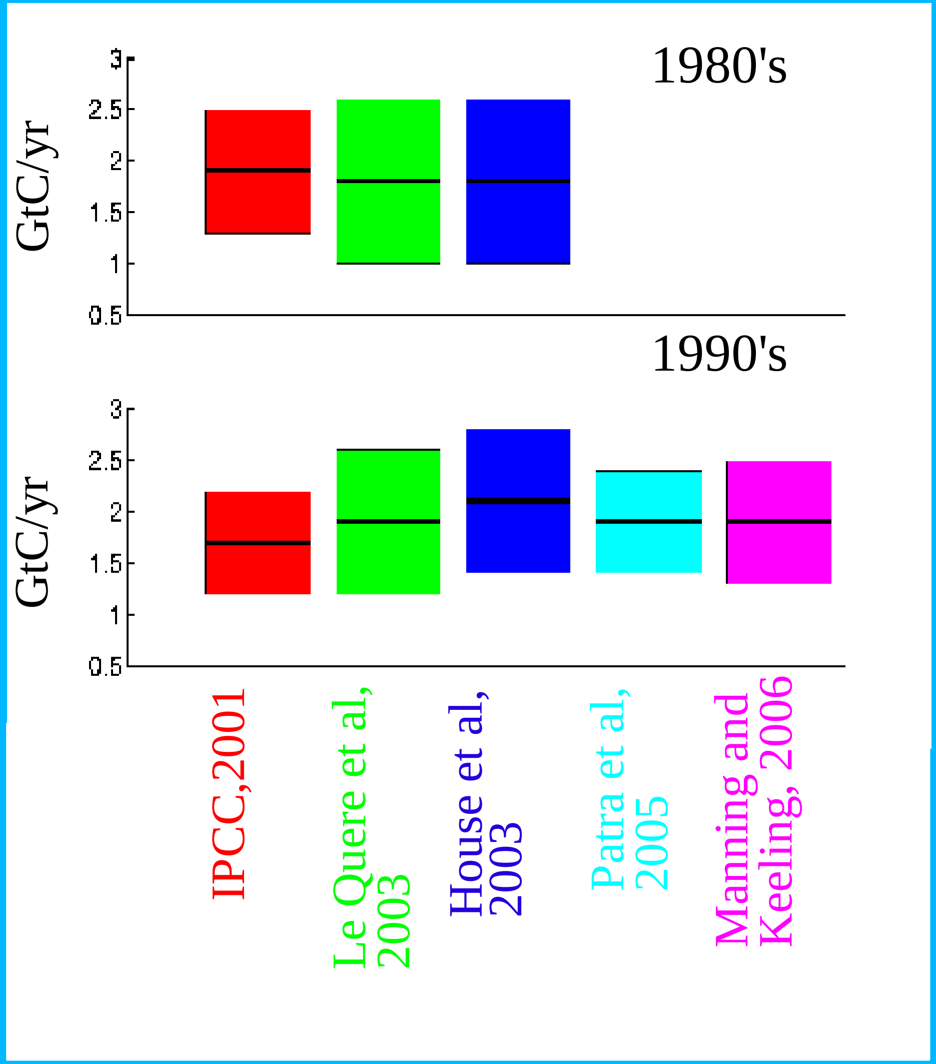
- k - air-sea transfer velocity (depends on wind speed [Wanninkhof, 1992])
- α - solubility of CO_2 in the sea water (supressed in a warmer water)
- ΔpCO_2 - difference of partial pressures of CO_2 between air and water

ΔpCO_2 increase since preindustrial state in the sea water is about ten times smaller than in the air [Bacastow, 1981] ⇒ oceanic uptake has increased since preindustrial period



Mean annual air–sea flux for CO_2 (after Takahashi et al [2002])

Observational estimations of the global oceanic uptake



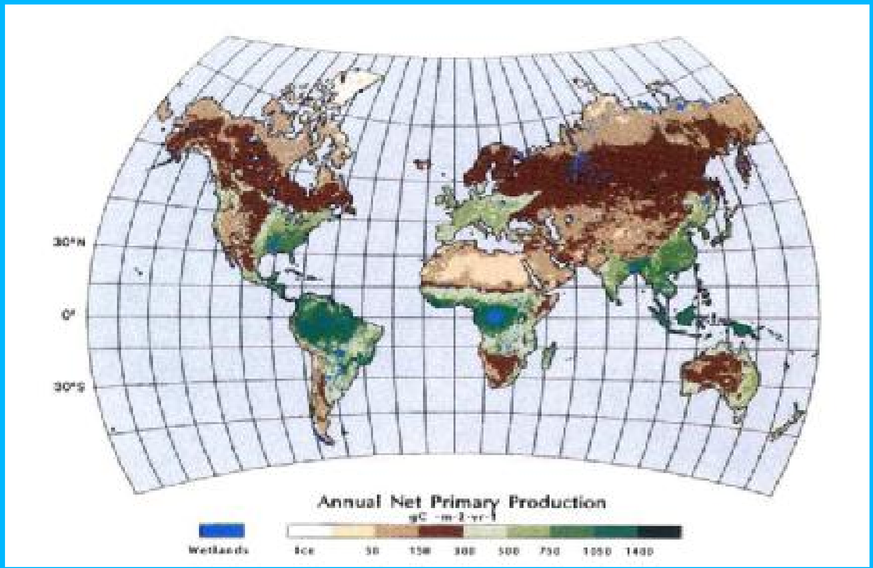
Terrestrial uptake of carbon dioxide

$$F_l = P - R_a - R_h = NPP - R_h\ ,$$

- P - gross photosynthesis (~100-110 Gtc/yr)
- R_a - autotrophic (biota) respiration (~50-60 GtC/yr)
- R_h - heterotrophic (soil) respiration (~50-60 GtC/yr)
- NPP= P - R_a - net primary production (~50-60 GtC/yr)

→ Direct (fertilisation) effect of CO_2 is to enhance the gross photosynthesis

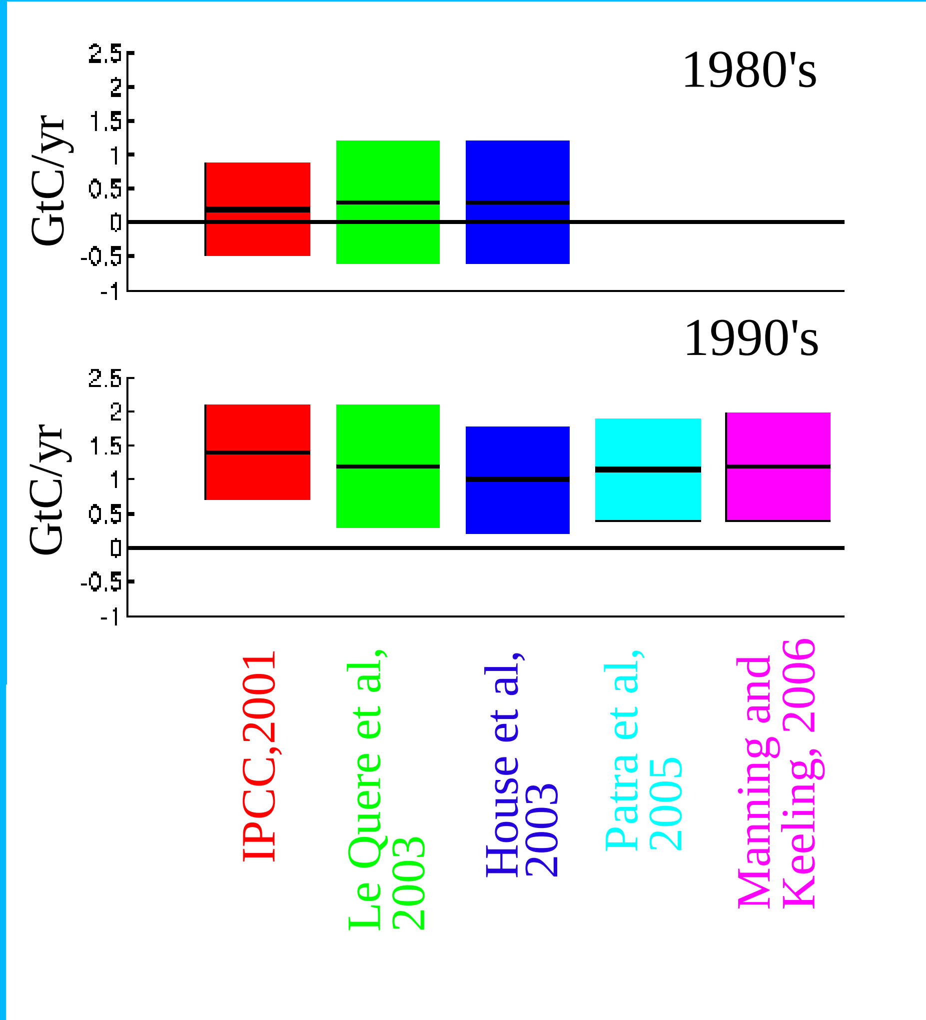
→ Indirect (climate) effect may depend on temperature relationships for P, R_a, and R_h



Annual NPP, after [Melillo et al, 1993]: total 53 GtC

Observational estimations of the global terrestrial uptake

$$F_l' = F_l - E_{lu}$$



Therefore

§ During the late 20th century, more than half of the emitted anthropogenic CO_2 are taken up by the ocean, the soil, and the vegetation

§ The magnitude of future climate change depends critically on the behaviour of these three reservoirs

§ The storage capacity of these reservoirs depends not only on the amount of anthropogenic emissions but also (very likely) on the future climate change (climate-carbon cycle interaction)

Conclusion:

To assess the feedbacks between the carbon cycle and climate change a fully coupled model is needed

Climate-carbon cycle feedback

With a coupled climate-carbon cycle model two simulations forced by the same CO_2 emissions are performed

- coupled (cpl): fully interactive simulation.
- uncoupled (ucpl): carbon cycle is simulated for a prechosen (usually preindustrial), prescribed climate state.

Feedback parameter:

$$f = \Delta pCO_{2,a}^{cpl} / \Delta pCO_{2,a}^{ucpl}$$

Feedback gain:

$$g = f / (f - 1)$$

Feedback intensity:

$$I = \Delta pCO_{2,a}^{cpl} - \Delta pCO_{2,a}^{ucpl}$$

First studies indicate that the carbon-climate feedback is positive

in the year 2100 under SRES A2 scenario:

•Cox et al. [2000] + 250 ppm

•Friedlingstein et al. [2001] + 75 ppm

However, large quantitative discerpancies between these studies lead to the organisation of the Coupled Climate Carbon Cycle Intercomparison Project (C4MIP): participating modelling groups performed simulations forced by the SRES A2 scenario [Friedlingstein et al, 2006]. Totally, 11 models were participating in the project (6 general circulation models and 5 Earth system models of intermediate complexity).

Diagnostics [Friedlingstein et al, 2003]f

$U_X = \int_0^t F_X(\tau)\, d\tau = \beta_X\, \Delta pCO_{2,a} + \gamma_X\, \Delta T_g$, X = l, oc

- β_X - quantifies fertilisation effect,
- γ_X - quantifies climate-carbon cycle feedback.

In the C4MIP simulations [Friedlingstein et al., 2006]

β_l = 0.2-2.8 GtC/ppmv (mean 1.4 GtC/ppmv)
β_{oc} = 0.8-1.6 GtC/ppmv (mean 1.1 GtC/ppmv)

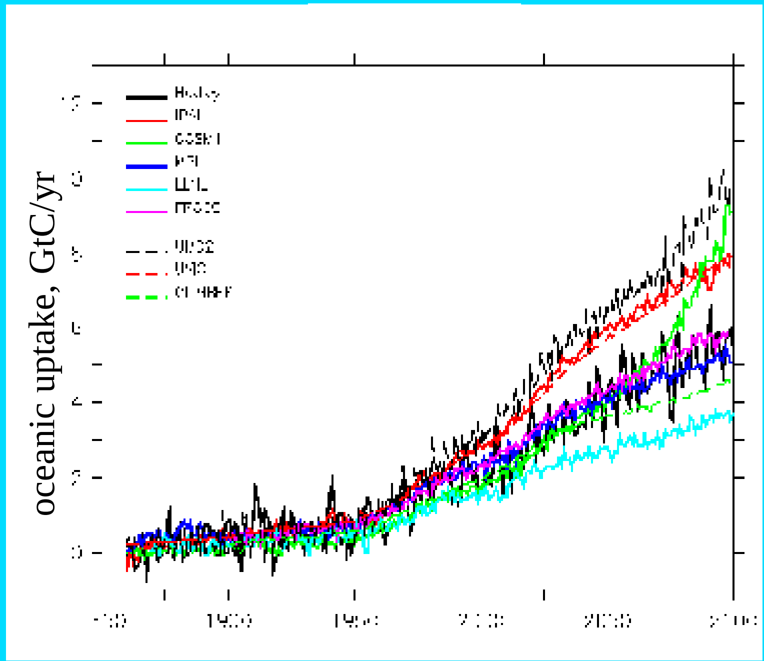
➡ Direct effect of CO_2 build up is to enhance both terrestrial and oceanic uptakes

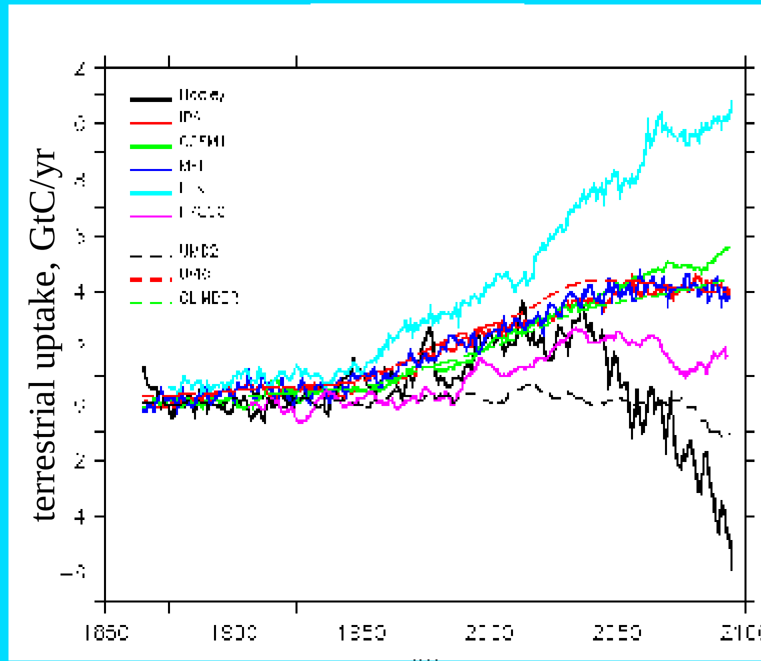
γ_l = - (20-177) GtC/K (mean -79 GtC/K)
γ_{oc} = - (14-67) GtC/K (mean -30 GtC/K)

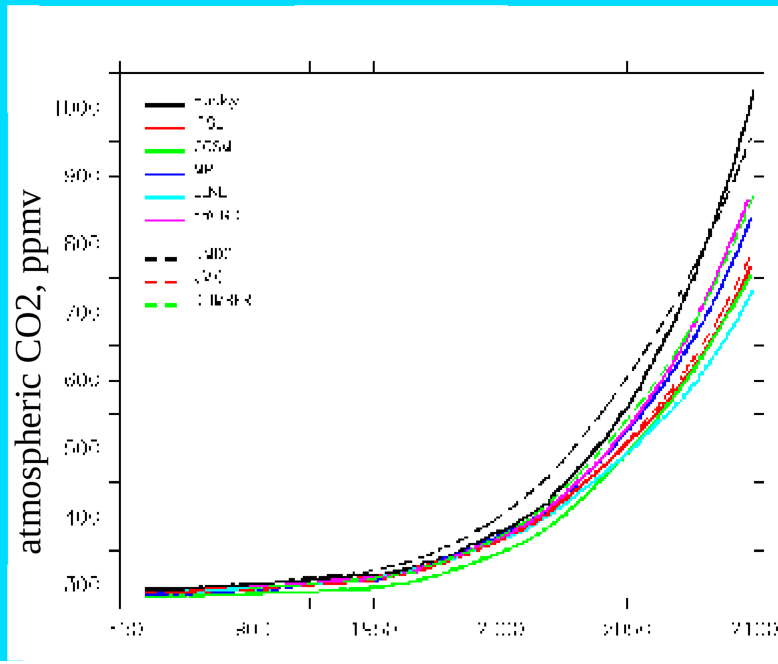
➡ Climatic effect of this build up is to suppress both these uptakes

C4MIP coupled simulations [Friedlingstein et al, 2006]

(11-year running means)

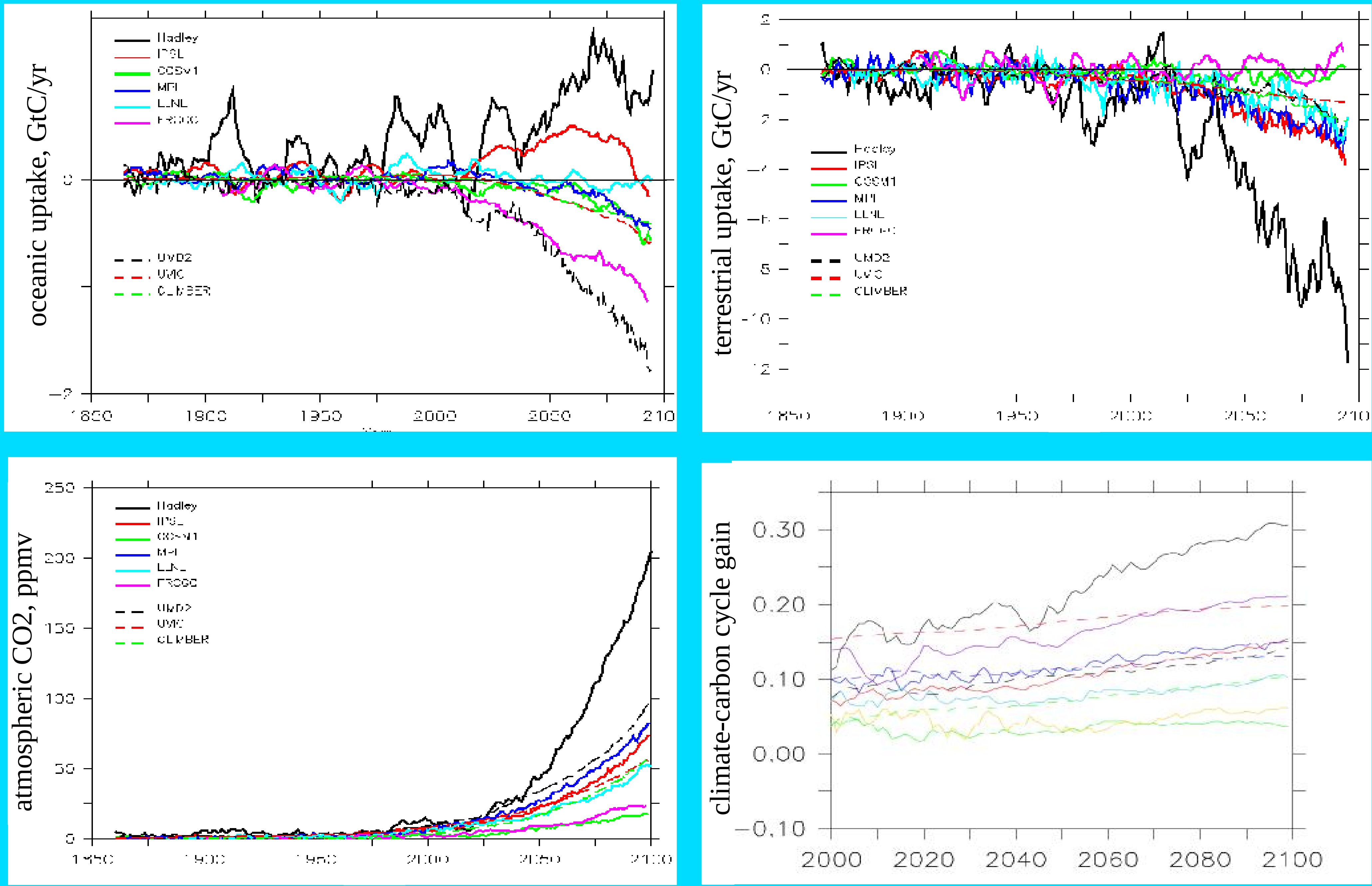






Difference between coupled and uncoupled C4MIP runs

(11-year running means)



IAP RAS CM

<u>Climate compartment</u>: 4.5º*6º, L8 - atmosphere, L4 - ocean, L1 -land. Seasonally resolved
Atmosphere: - 3D quasi-geostrophic large-scale dynamics. Synoptic-scale dynamics is parameterised in terms of the Gaussian ensemble statistics. Linear profiles of temperature in every atmospheric layer are assumed. Interactive hydrological cycle.
Ocean: Prognostic equation for sea surface temperature. Ocean dynamics is treated assuming geostrophy. Universal profiles for characteristic oceanic layers are assumed. Salinity is prescribed.
Sea ice: Diagnostical. Energy conserving.
Land surface: Based on BATS. Vegetation succession is neglected

<u>Carbon cycle compartment</u>: Annual mean. Globally averaged.
Terrestrial carbon cycle:
- Two carbon pools (living vegetation, soil carbon).
- Fertilisation follows Michaelis-Menton law

$$g_f = pCO_{2,a} / (pCO_{2,a} + k_M)$$ k_M - half-saturation constant

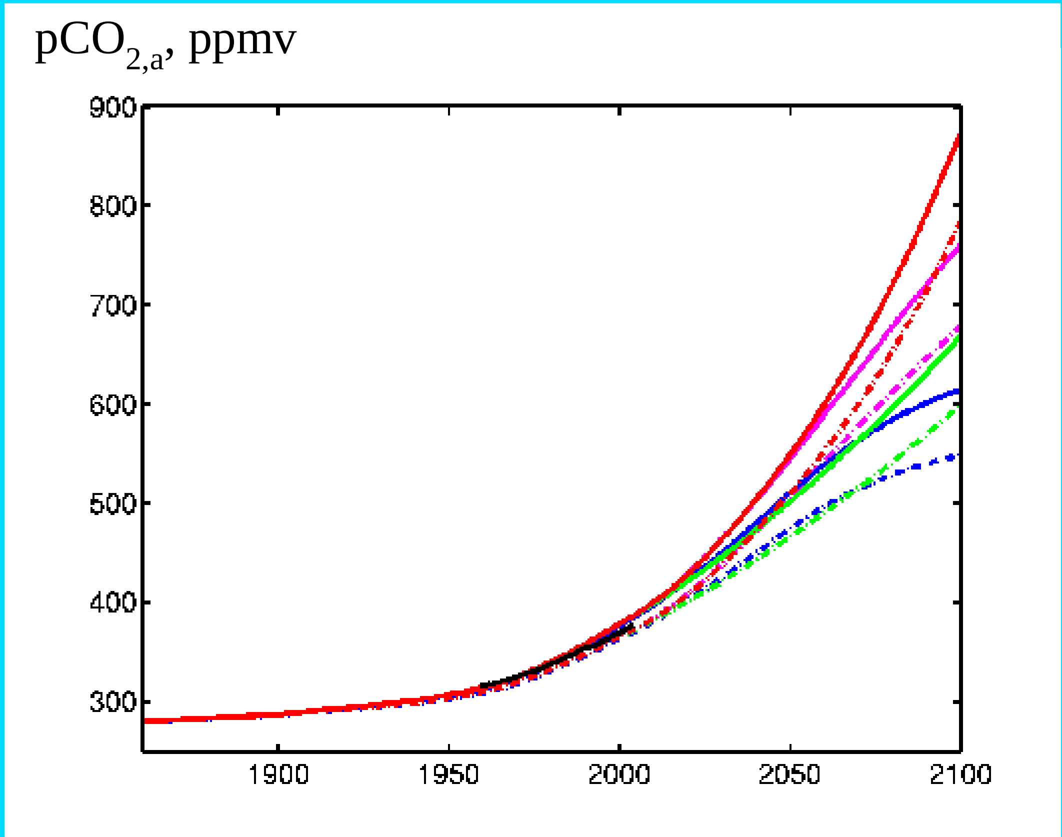
- Temperature dependencies of gross photosynthesis, biota and soil respirations follow

$$Y = Y_0 \, Q_{10,Y}^{\Delta Tg / \Delta To},$$

where $Y = P, R_a, R_h$, ΔT_g - change of globally averaged SAT, $\Delta T_0 = 10$ K, $Y_0 = Y|_{\Delta Tg=0}$
- Agriculture harvesting is proportional to land use emissions

Oceanic carbon cycle: bilinear function of tendencies of globally averaged annual mean sea surface temperature and atmospheric concentration of carbon dioxide

Atmospheric CO_2 content simulated by IAP RAS CM



solid - COUPLED
dashed - UNCOUPLED

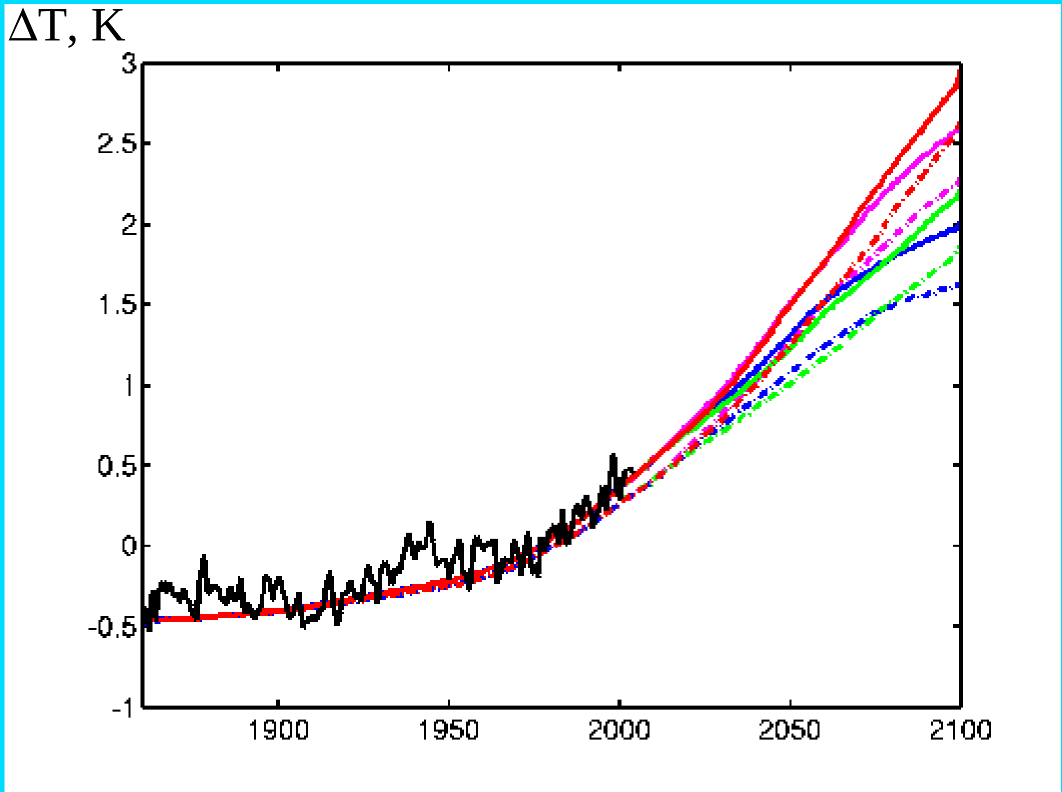
SRES A2
875 ppmv (90 ppmv)

SRES A1B
762 ppmv (83 ppmv)

SRES B2
669 ppmv (69 ppmv)

SRES B1
615 ppmv (67 ppmv)

Change in globally averaged annual surface air temperature



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SRES A2
3.38 K (0.31 K)

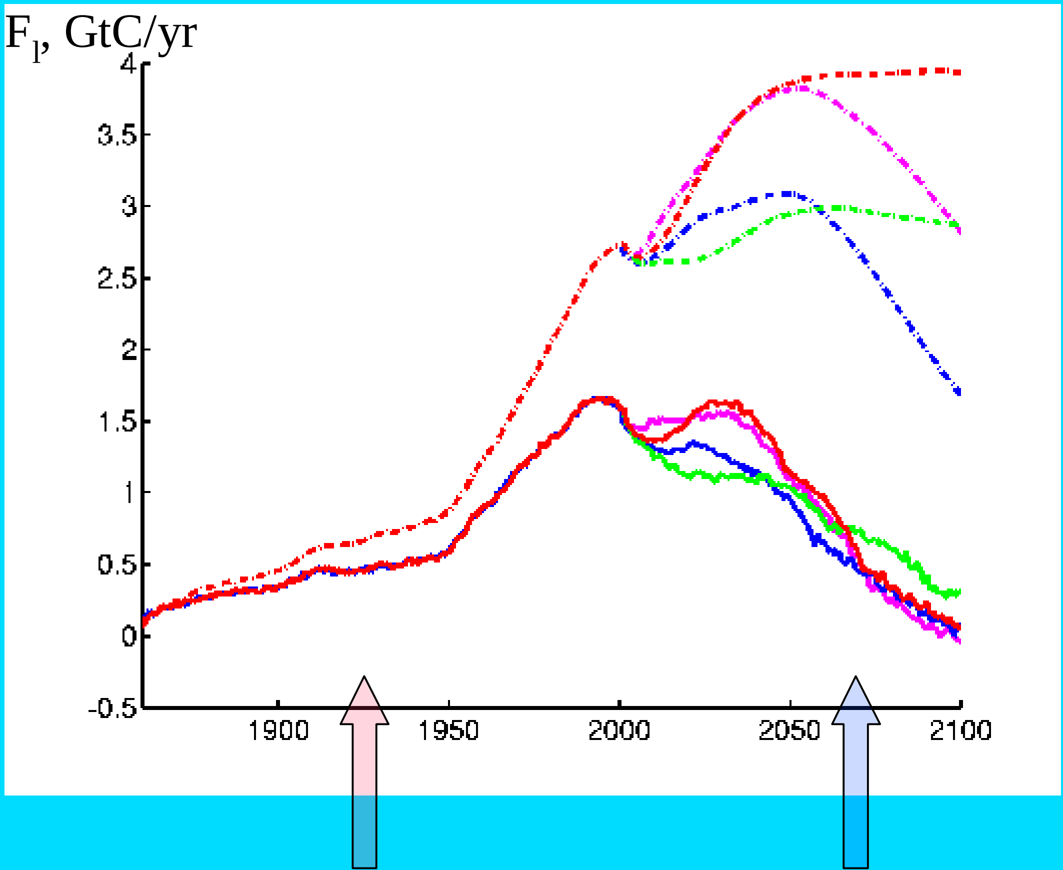
SRES A1B
3.05 K (0.34 K)

SRES B2
2.65 K (0.34 K)

SRES B1
2.43 K (0.35 K)

observed
(CRU UEA)

Terrestrial uptake of CO_2 (excluding land use emissions)



solid -COUPLED
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SRES A2

SRES A1B

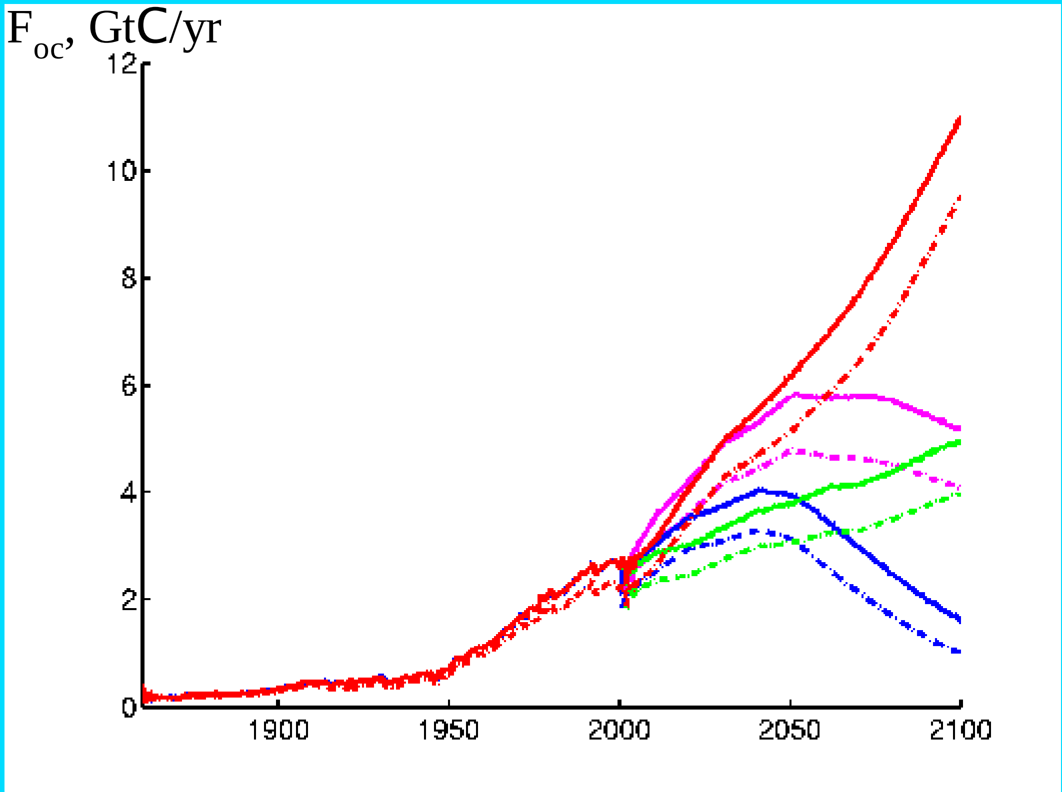
SRES B2

SRES B1

Effect of the direct fertilisation dominates

Climate-carbon cycle feedback dominates

Oceanic uptake of CO_2



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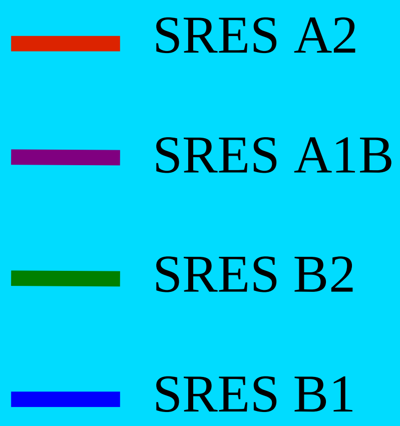
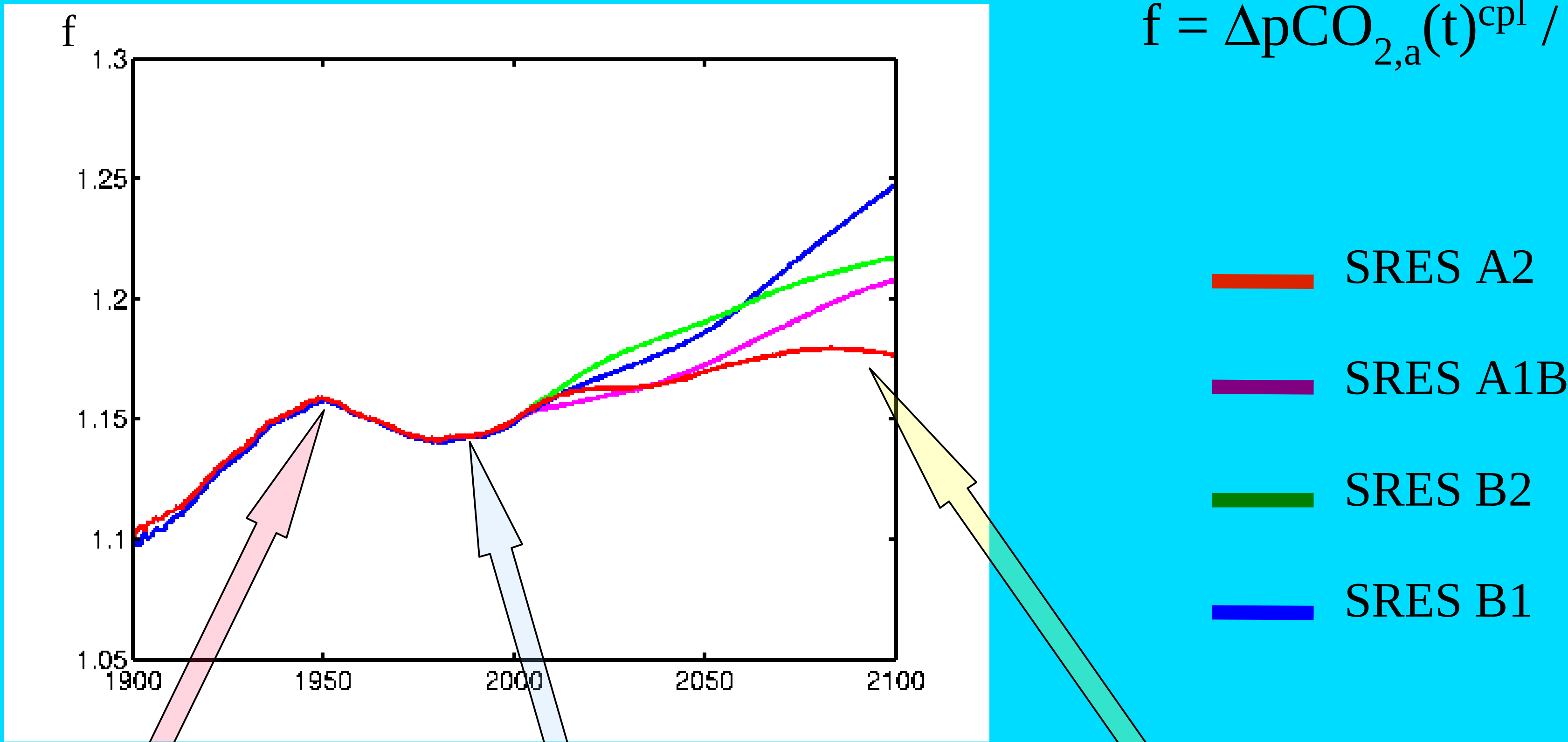


Parameter of climate-carbon cycle interaction

$$f = \Delta pCO_{2,a}(t)^{cpl} / \Delta pCO_{2,a}{}^{ucpl}(t)$$

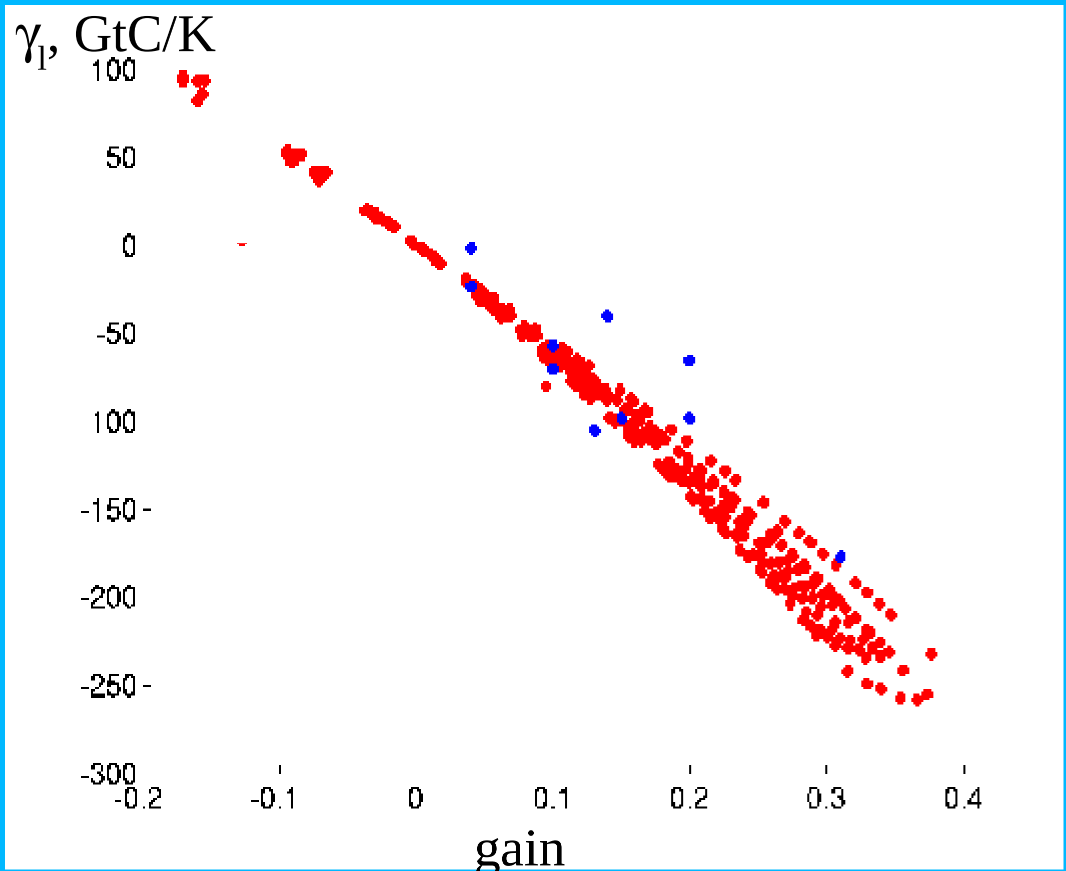


Rapid growth of anthropogenic emissions of CO_2

Climate starts to adjust to these rapid emissions

Additional radiative forcing of CO_2 due to climate-carbon cycle interaction begins to saturate

IAP RAS CM simulations with perturbed climate and carbon cycle



red: IAP RAS CM simulations
blue: C4MIP simulations

Emission scenario: SRES A2

In every simulation a subset of the governing parameters for climate and terrestrial carbon cycle modules has been perturbed based on the corresponding published values.

Therefore:
Moderate negative climate-carbon cycle feedback can not be ruled out based on the present knowledge. However, positive feedback is more probable than negative one.

Conclusions:

➔ Currently, the Earth carbon cycle is forced by strong anthropogenic emissions

➔ In addition, the carbon cycle responds to build up of carbon dioxide in atmosphere and to climate changes via changes in intensities of oceanic uptake of CO_2, living biota primary production, and soil respiration

➔ Coupled climate-carbon cycle models are needed to properly simulate the past and future state of the system

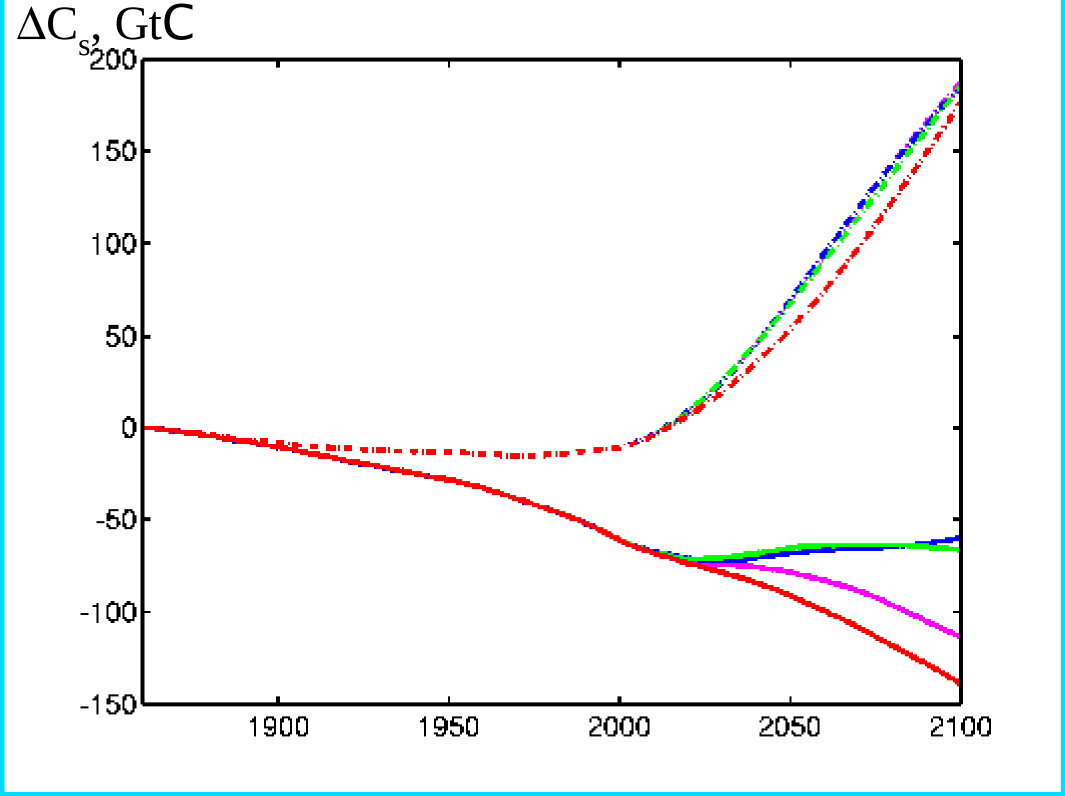
➔ The most models exhibit positive feedback between climate and carbon cycle: CO_2-driven climate changes increase atmopsheric storage of carbon dioxide. The latter, in turn, enhance the respective climatic response. Some models attribute this feedback to the terrestrial compartment while others trace it to the oceanic module.

➔ However, perturbing governing parameters of a coupled climate-carbon cycle system, one may obtain moderate negative climate-carbon cycle feedback

➔ In the IAP RAS CM simulations, direct effect of fertilisation on terrestrial primary production dominates till the late 20th century while late in the 21st century the biota's response on climatic change is most important. This is exhibited in some of the C4MIP runs as well.

➔ As a whole, climate-carbon cycle feedback is expected to be intensified during the 21st century. However, it can be weakened under the most agressive scenarios in the late 21st century.

Change of soil carbon stock



solid -COUPLED
dashed - UNCOUPLED

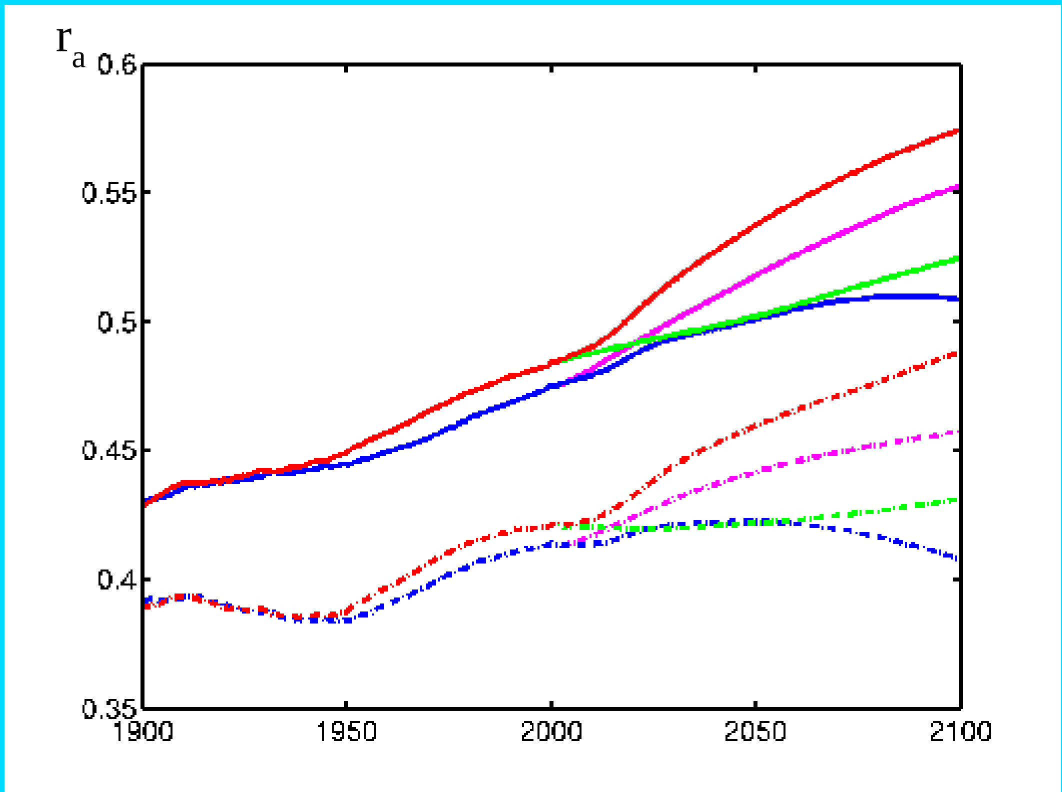
SRES A2

SRES A1B

SRES B2

SRES B1

Atmospheric storage of the anthropogenic carbon dioxide emissions



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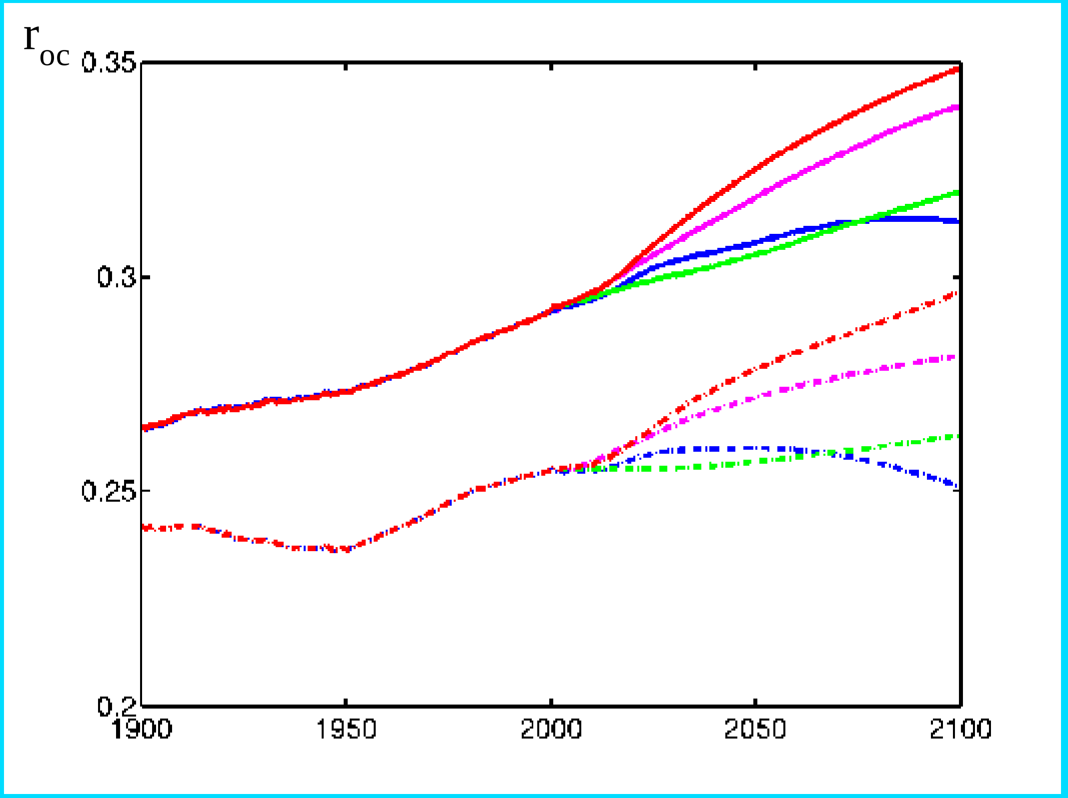
SRES A2

SRES A1B

SRES B2

SRES B1

Oceanic storage of antropogenic carbon dioxide emissions



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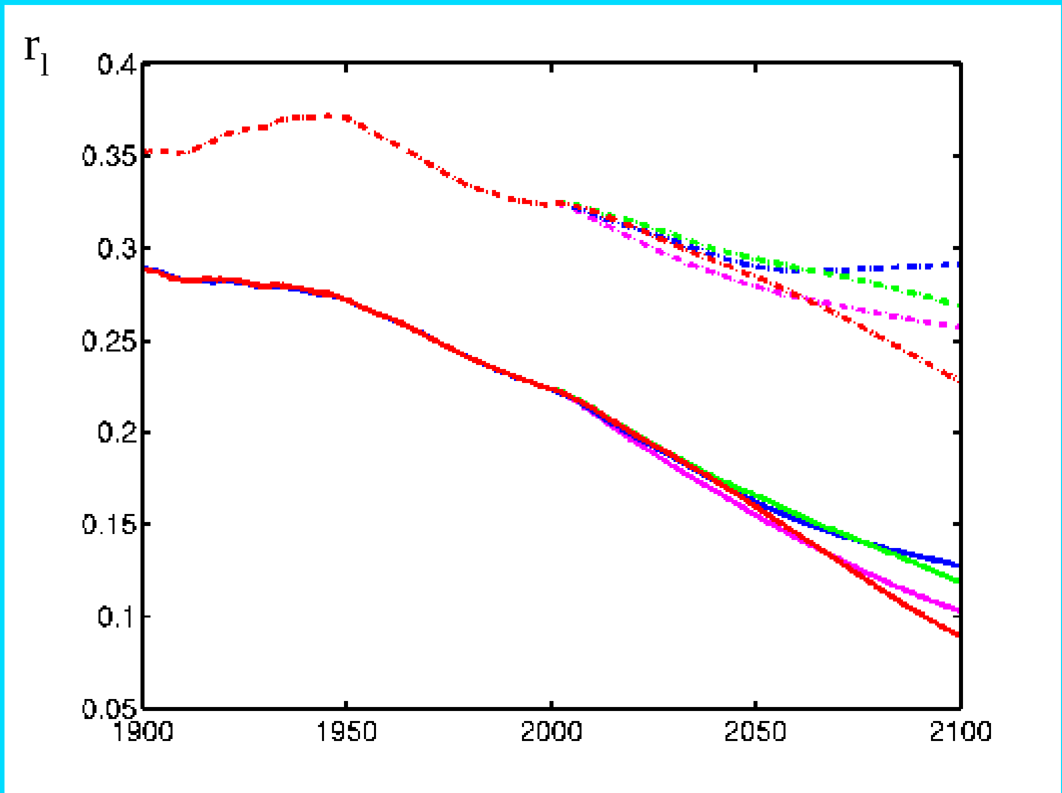
SRES A2

SRES A1B

SRES B2

SRES B1

Terrestrial storage of anthropogenic carbon dioxide emissions



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dashed - UNCOUPLED

SRES A2

SRES A1B

SRES B2

SRES B1