Carbon Climate Feedback

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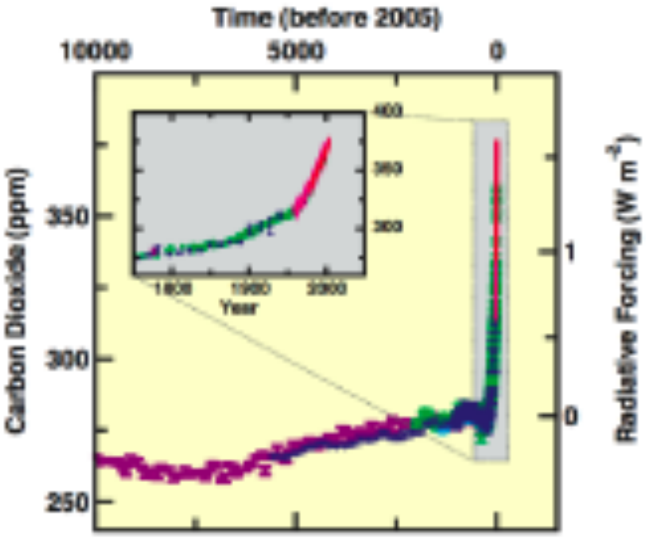
July 31 2013

NCAR ASP Graduate Colloquium: Carbon-Climate Connections in the Earth System

Radiative Forcing (W/m^2)

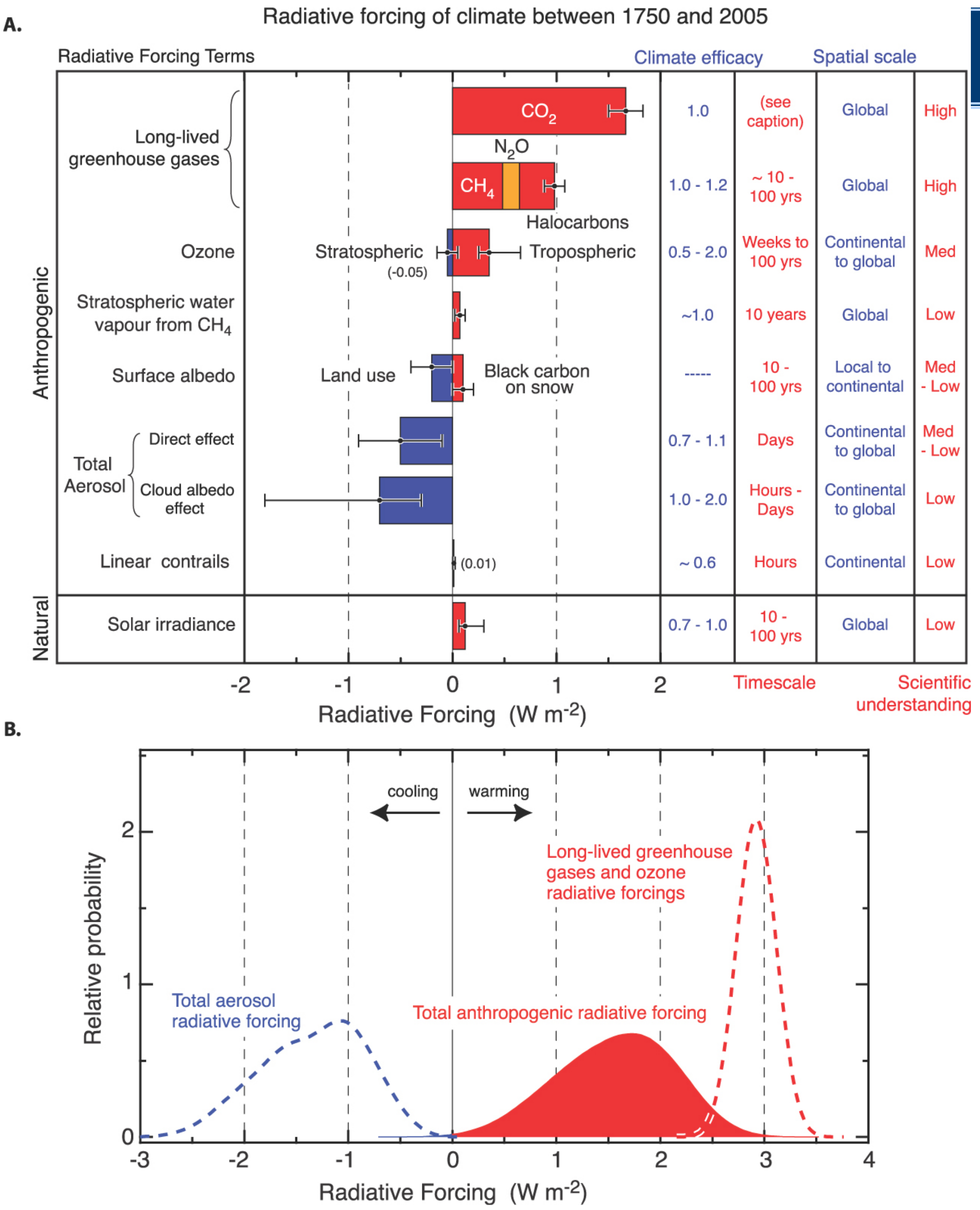
Table 1. Radiative forcings in industrial era. c is CO_2 (ppm), m is CH_4 (ppb), x is CFC-11 (ppb), y is CFC-12 (ppb).

Gas	Radiative forcing
CO_2	$F = f(c) - f(c_o)$, where $f(c) = 5.04 \ln[c + 0.0005c^2]$
CH_4	$0.04 (\sqrt{m} - \sqrt{m_o}) - [g(m,n_o) - g(m_o,n_o)]$ $g(m,n) = 0.5 \ln[1 + 0.00002(mn)^{0.75}]$
N_2O	$0.14 (\sqrt{n} - \sqrt{n_o}) - [g(m_o,n) - g(m_o,n_o)]$
CFC-11	$F = 0.25 (x - x_o)$
CFC-12	$F = 0.30 (y - y_o)$



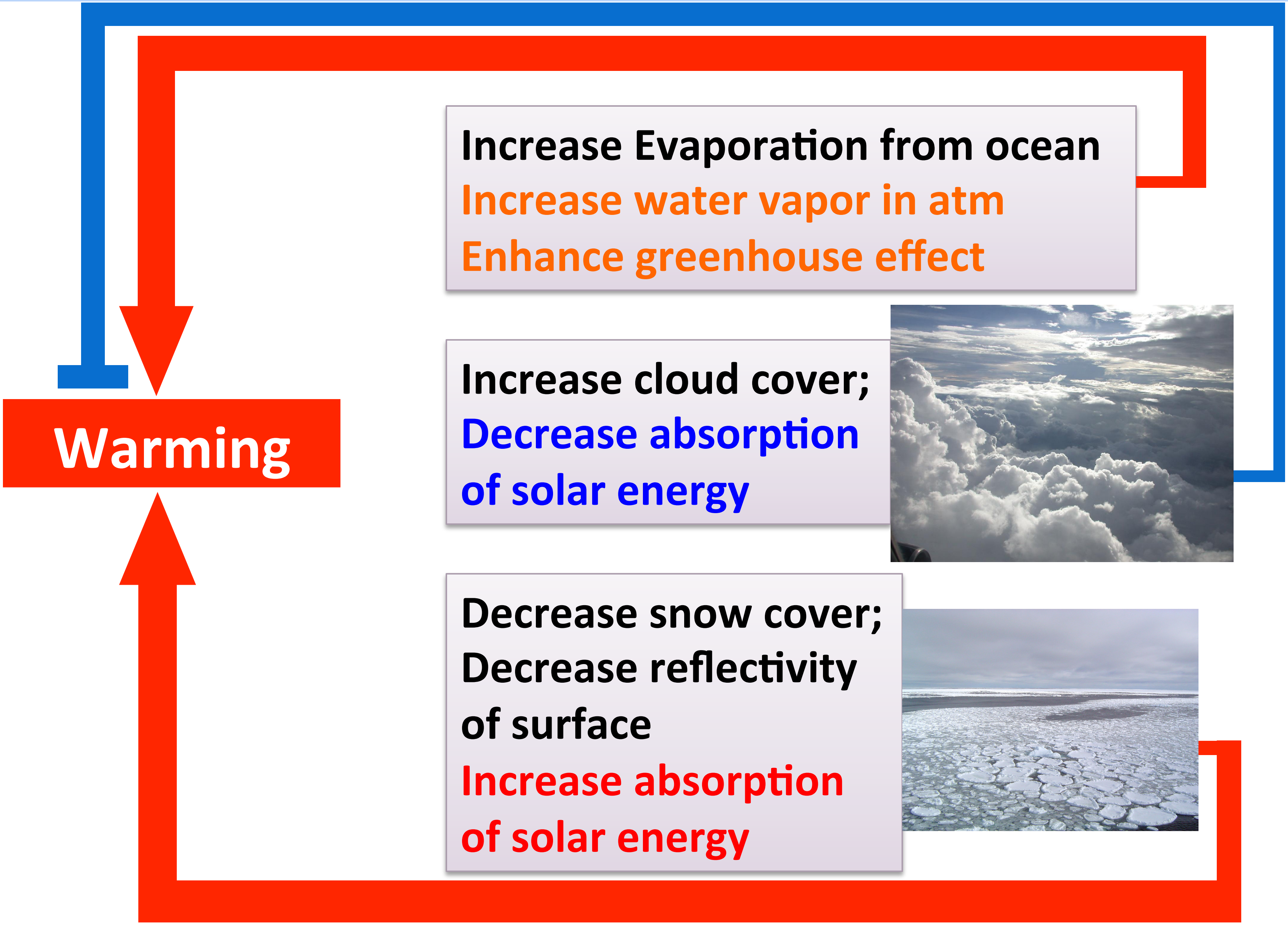
Hansen et al. PNAS 1998

Radiative forcing



Radiative Forcing Terms	Climate efficacy	Timescale	Spatial scale	Scientific understanding
CO_2	1.0	(see caption)	Global	High
N_2O, CH_4, Halocarbons	1.0 - 1.2	~ 10 - 100 yrs	Global	High
Ozone	0.5 - 2.0	Weeks to 100 yrs	Continental to global	Med
Stratospheric water vapour from CH_4	~1.0	10 years	Global	Low
Surface albedo	-----	10 - 100 yrs	Local to continental	Med - Low
Total Aerosol: Direct effect	0.7 - 1.1	Days	Continental to global	Med - Low
Total Aerosol: Cloud albedo effect	1.0 - 2.0	Hours - Days	Continental to global	Low
Linear contrails	~ 0.6	Hours	Continental	Low
Solar irradiance	0.7 - 1.0	10 - 100 yrs	Global	Low

Climate Feedbacks



Warming

Increase Evaporation from ocean
Increase water vapor in atm
Enhance greenhouse effect

Increase cloud cover;
Decrease absorption
of solar energy

Decrease snow cover;
Decrease reflectivity
of surface
Increase absorption
of solar energy

For a given radiative forcing RF

At the surface, IF no feedback $RF \rightarrow \Delta T_0^{forcing}$

$$\Delta T_{eqm} = \Delta T_0^{forcing} + \sum_k \Delta T_k^{fdbk}$$

$\Delta T_{eqm} = f_T \cdot \Delta T_0^{forcing}$ f_T is the feedback factor (unitless)

$\Delta T_{eqm} = \dfrac{RF}{f_{RF}}$ f_{RF} is the feedback parameter $(Wm^{-2}K^{-1})$

$\Delta T_{eqm} = cs \cdot RF$ cs is the climate sensitivity $(K/(Wm^{-2}))$

For $2xCO_2$ $RF \sim 3Wm^{-2}$

$$\Delta T_0 = 1.2K$$

$\Delta T_{eqm} \sim 3.2K$ Eqm climate sensitivity

Vostok: Climate sensitivity = 0.75K/(Wm^{-2})

Another way: GAIN

$$g_k = \frac{\Delta T_k^{fdbk}}{\Delta T_{eqm}}$$

$$\Delta T_{eqm} = \Delta T_0^{forcing} + \sum_k g_k \Delta T_{eq}$$

$$= \frac{1}{1 - \sum_k g_k} \Delta T_0^{forcing}$$

g is the gain

Beware: GAIN and FEEDBACK are sometimes interchanged(e.g. papers by Gerard Roe)

Eqm Climate Sensitivity (2xCO2)

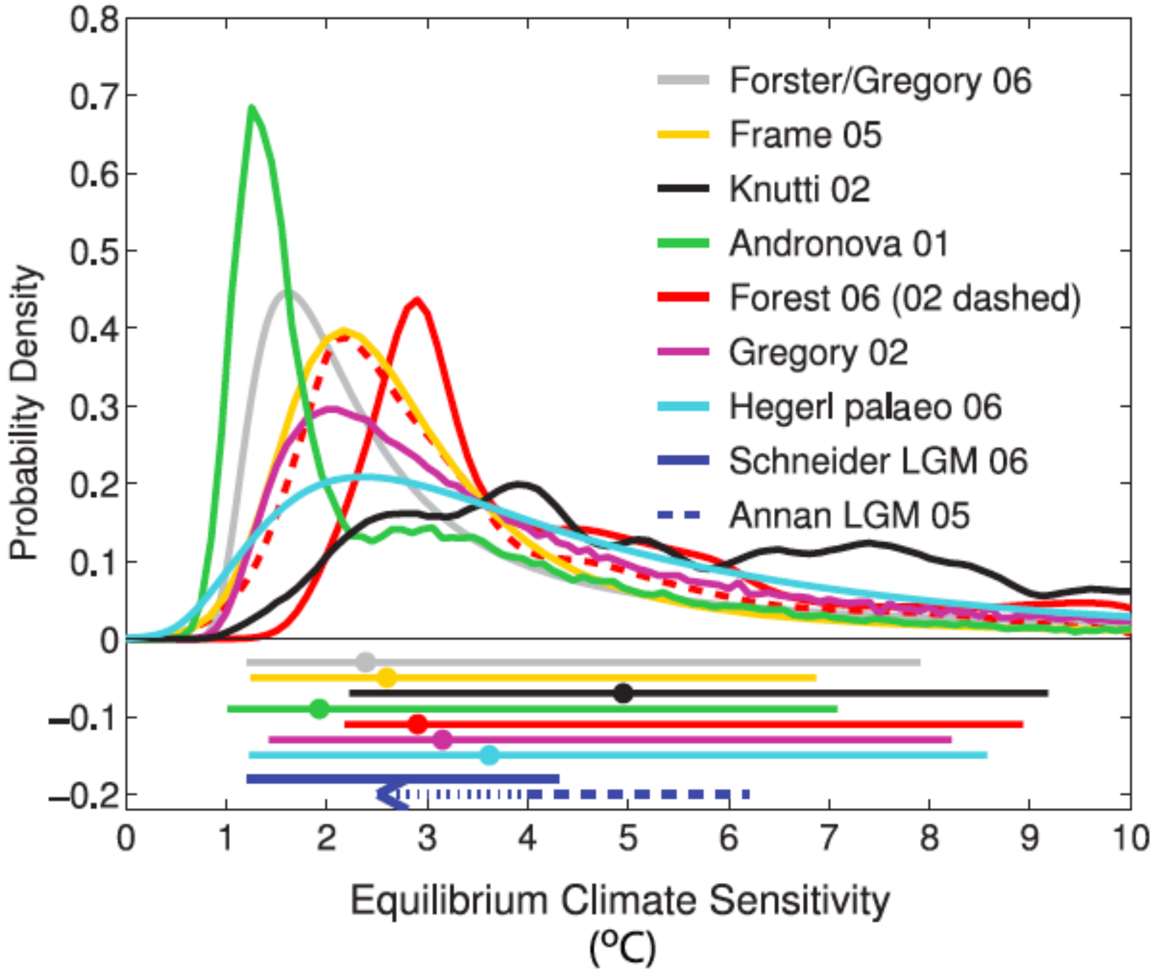


Figure 9.20. *Comparison between different estimates of the PDF (or relative likelihood) for ECS (°C). All PDFs/likelihoods have been scaled to integrate to unity between 0°C and 10°C ECS. The bars show the respective 5 to 95% ranges, dots the median estimate. The PDFs/likelihoods based on instrumental data are from Andronova and Schlesinger (2001), Forest et al. (2002; dashed line, considering anthropogenic forcings only), Forest et al. (2006; solid, anthropogenic and natural forcings), Gregory et al. (2002a), Knutti et al. (2002), Frame et al. (2005), and Forster and Gregory (2006), transformed to a uniform prior distribution in ECS using the method after Frame et al. (2005). Hegerl et al. (2006a) is based on multiple palaeoclimatic reconstructions of NH mean temperatures over the last 700 years. Also shown are the 5 to 95% approximate ranges for two estimates from the LGM (dashed, Annan et al., 2005; solid, Schneider von Deimling et al., 2006) which are based on models with different structural properties. Note that ranges extending beyond the published range in Annan et al. (2005), and beyond that sampled by the climate model used there, are indicated by dots and an arrow, since Annan et al. only provide an upper limit. For details of the likelihood estimates, see Table 9.3. After Hegerl et al. (2006a).*

IPCC AR4

Transient Response

- Fast feedbacks (10 yr)
  - Water vapor, clouds, aerosols, winds → ocean temperature (diffusion)
- Longer term feedbacks (10^2 yr)
  - Glaciers, ocean circulation → ocean temperature
  - Vegetation distribution → water vapor, albedo
  - Carbon cycle: vegetation, ocean biology, uptake
- Still longer term feedbacks ($>10^3$ yr)
  - Ocean sediments
  - Volcanic CO2

Climate Feedback

$$dT = \boxed{\left.\frac{\partial T}{\partial RF}\right|_{ctrl} dRF} \qquad \text{Climate Forcing}$$

$$\left.\begin{aligned}
&+ \left.\frac{\partial T}{\partial WaterVapor}\right|_{ctrl} dWaterVapor \\
&+ \frac{\partial T}{\partial CldCover} dCldCover \\
&+ \frac{\partial T}{\partial CldHt} dCldHt \\
&+ \frac{\partial T}{\partial Albedo} dAlbedo \\
&+ \ldots
\end{aligned}\right\} \text{Climate Feedbacks}$$

Calculating Climate Feedback: AR4

$$
\begin{aligned}
dT = {} & \left.\frac{\partial T}{\partial RF}\right|_{ctrl} dRF \\
& + \left.\frac{\partial T}{\partial WaterVapor}\right|_{ctrl} dWaterVapor \\
& + \frac{\partial T}{\partial CldCover} dCldCover \\
& + \frac{\partial T}{\partial CldHt} dCldHt \\
& + \frac{\partial T}{\partial Albedo} dAlbedo \\
& + \ldots
\end{aligned}
$$

GFDL:

- Example: q=WaterVapor
- Control run; 2xCO2 run: get dq, dCldCover etc.
- Perturbation control run: replace ONLY q with q+dq → dT_q

AR4:

- Define kernel: dT_q/dq from GFDL
- Get dq from each model group
- Feedback parameter
  = dT_q/dq(GFDL) x dq_Modelk

Climate Feedback 2xCO2

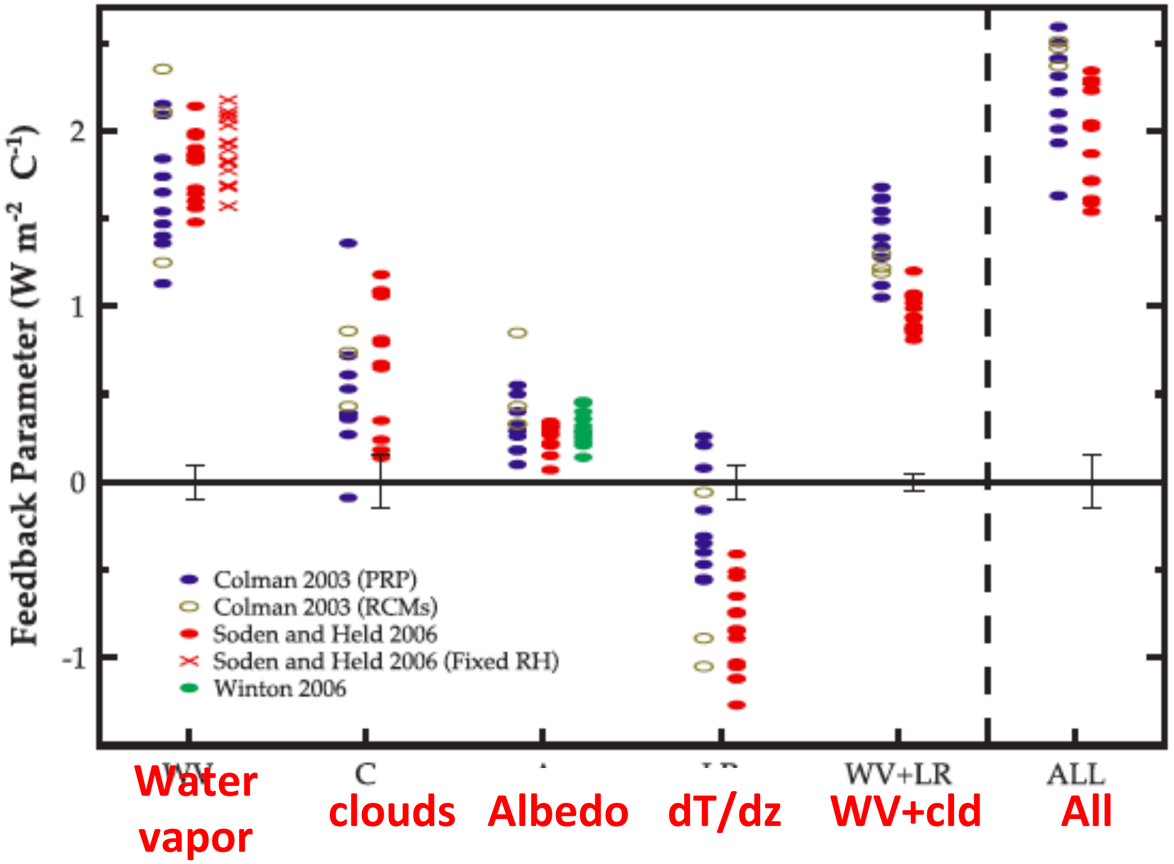


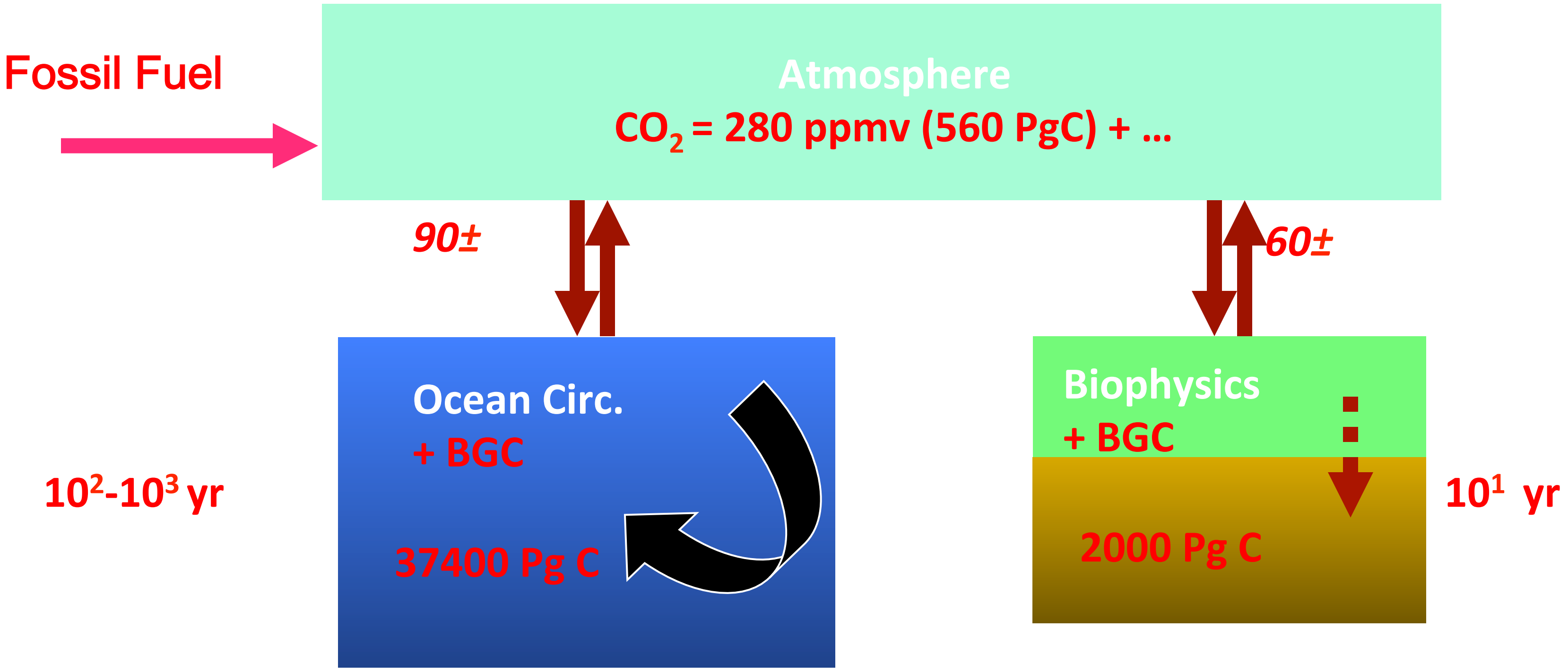
Figure 8.14. *Comparison of GCM climate feedback parameters for water vapour (WV), cloud (C), surface albedo (A), lapse rate (LR) and the combined water vapour plus lapse rate (WV + LR) in units of W m^{-2} °C^{-1}. 'ALL' represents the sum of all feedbacks. Results are taken from Colman (2003a; blue, black), Soden and Held (2006; red) and Winton (2006a; green). Closed blue and open black symbols from Colman (2003a) represent calculations determined using the partial radiative perturbation (PRP) and the radiative-convective method (RCM) approaches respectively. Crosses represent the water vapour feedback computed for each model from Soden and Held (2006) assuming no change in relative humidity. Vertical bars depict the estimated uncertainty in the calculation of the feedbacks from Soden and Held (2006).*

A lot of global climate models

IPCC AR4

Carbon-Climate Feedback:
Will the warming accelerate the warming?

Technical Goal: include interactive carbon dynamics in the climate model. Specify Emission (t), not atm CO_2 (t)



Fossil Fuel

Atmosphere

CO_2 = 280 ppmv (560 PgC) + …

90±

60±

Ocean Circ.

\+ BGC

37400 Pg C

10^2-10^3 yr

Biophysics

\+ BGC

2000 Pg C

10^1 yr

How would CO_2 and climate co-vary?

Suppose there is higher CO2 and warming…

Atm CO_2 would increase because:

- Warming may enhance decomposition
- Increased ocean stratification → more carbon in mixed layer → reduced air-to-sea flux
- ….

Atm CO_2 would decrease because:

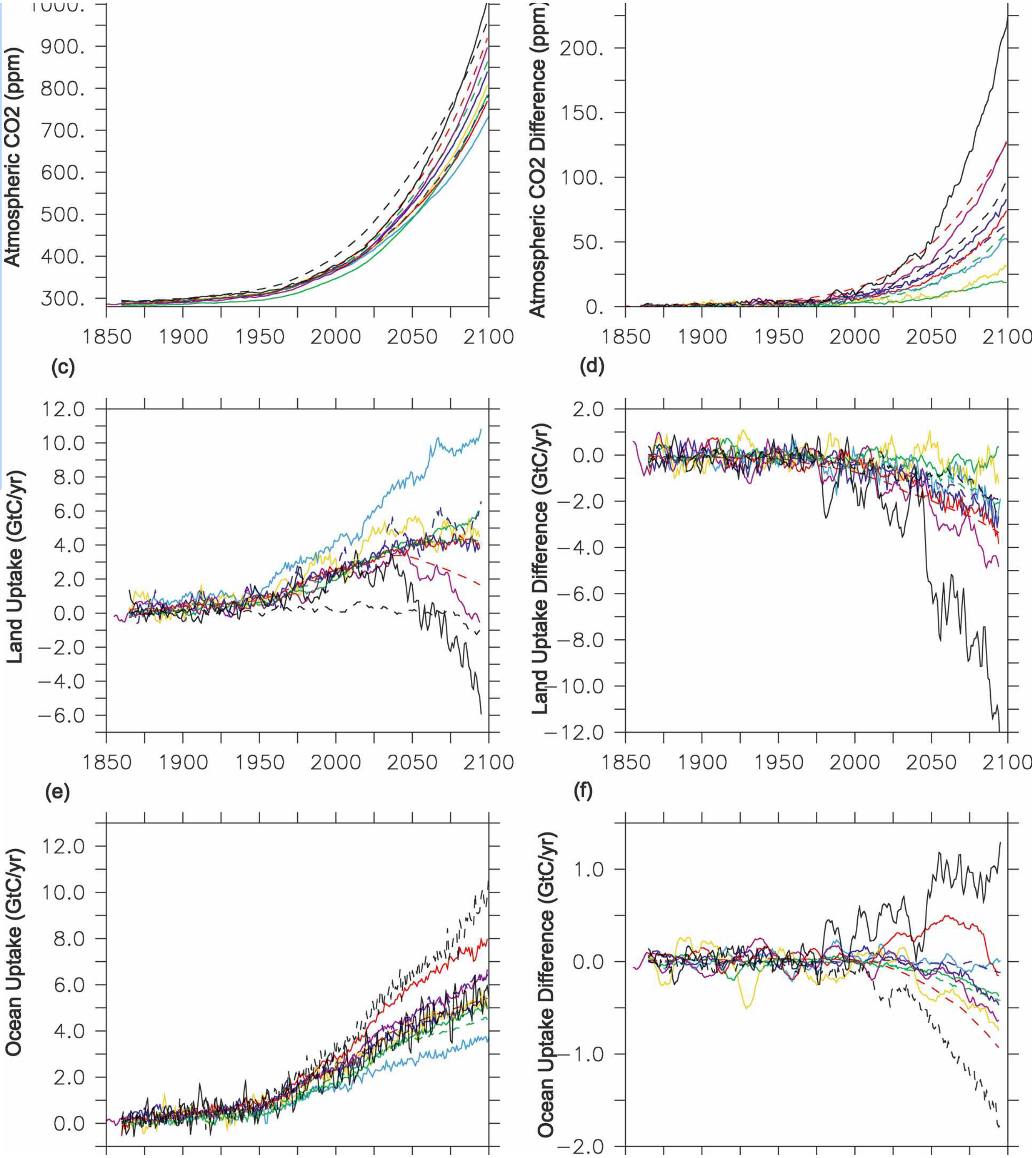
- Higher CO2 may enhance photosynthesis
- Enhanced marine productivity and export

In model, three flavors of CO2:

- CO2_tracer(x,y,z,t)
- CO2_bgc=CO2_tracer(x,y,lowest layer,t)
- CO2_rad=CO2_tracer(x,y,column,t)

Models expts:
BGC coupling,
Radiative coupling

Coupled Carbon Cycle Climate Model Intercomparsion Project



Huge difference in Atm CO2 >200 ppm by 2100!

~100ppm w/o rainforest collapse

Friedlingstein et al 2006

Carbon Climate Feedback

$$\Delta T^{Rad+BGC} = \alpha \bullet m \bullet \Delta CO_2^{Rad+BGC}$$

$$\Delta C_L^{BGC} = \beta_L \bullet m \bullet \Delta CO_2^{BGC}$$

$$\Delta C_O^{BGC} = \beta_O \bullet m \bullet \Delta CO_2^{BGC}$$

$$\Delta C_L^{Rad+BGC} = \beta_L \bullet m \bullet \Delta CO_2^{Rad+BGC} + \gamma_L \bullet \Delta T^{Rad+BGC}$$

$$\Delta C_O^{Rad+BGC} = \beta_O \bullet m \bullet \Delta CO_2^{Rad+BGC} + \gamma_O \bullet \Delta T^{Rad+BGC}$$

$$m = PgC / ppm$$

$$\alpha = K / ppm$$

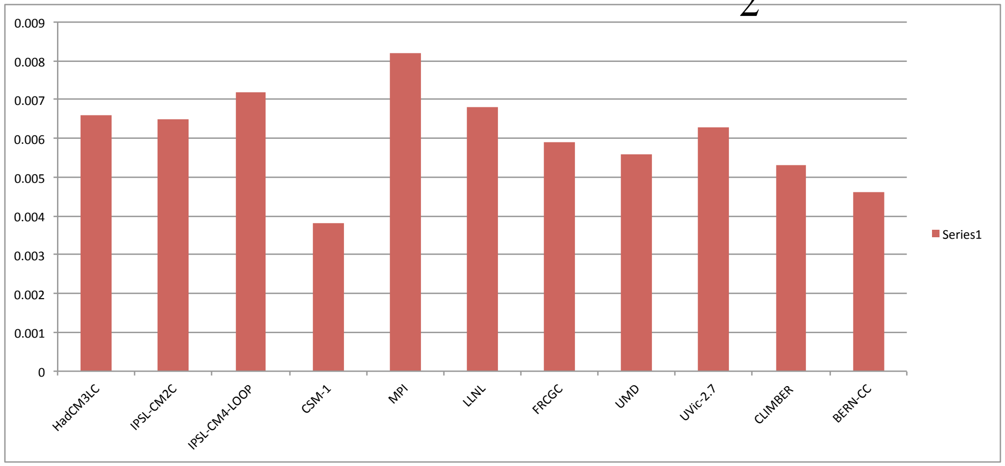
$$\beta = PgC / ppm$$

$$\gamma = PgC / K$$

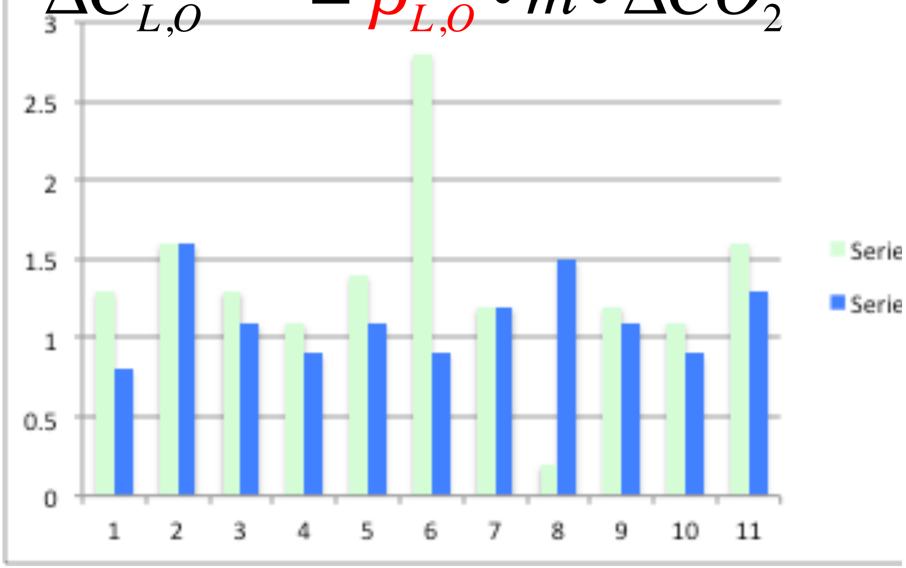
Friedlingstein et al. J Climate 2006

alpha, beta, gamma

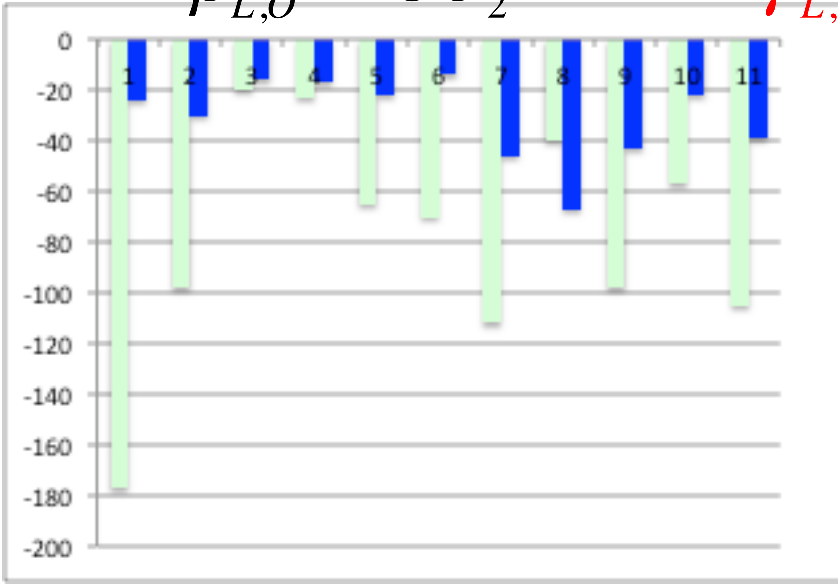
$$\Delta T^{Rad+BGC} = \alpha \bullet m \bullet \Delta CO_2^{Rad+BGC}$$



$$\Delta C_{L,O}^{BGC} = \beta_{L,O} \bullet m \bullet \Delta CO_2^{BGC}$$



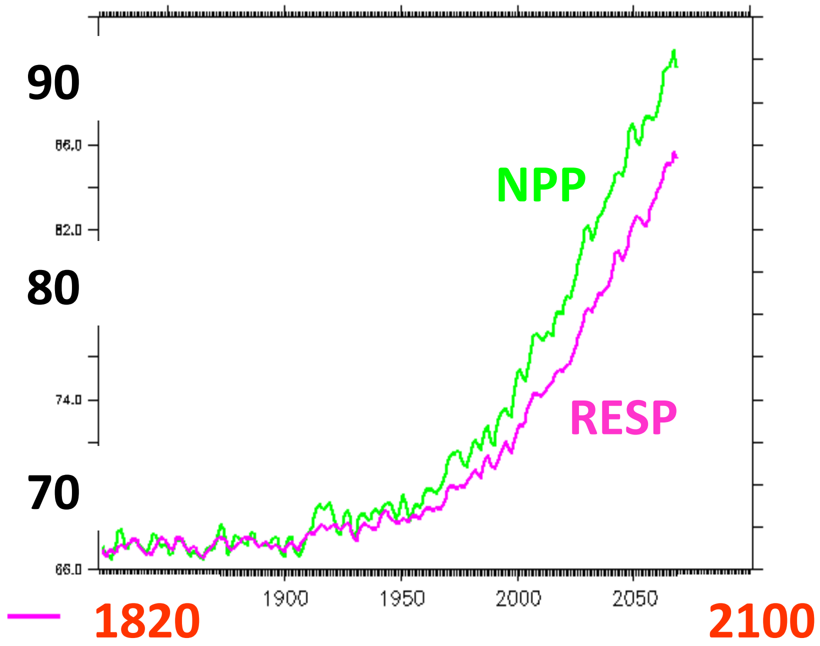
$$\Delta C_{L,O}^{Rad+BGC} = \beta_{L,O} \bullet \Delta CO_2^{Rad+BGC} + \gamma_{L,O} \bullet \Delta T^{Rad+BGC}$$



Carbon Climate Feedback:

- **Land > ocean**
- **Uncertainty: land > ocean**

Critical Parameters for Land Sink



$$\frac{\partial M_{veg}}{\partial t} = NPP - \frac{M_{veg}}{\tau_{veg}}$$

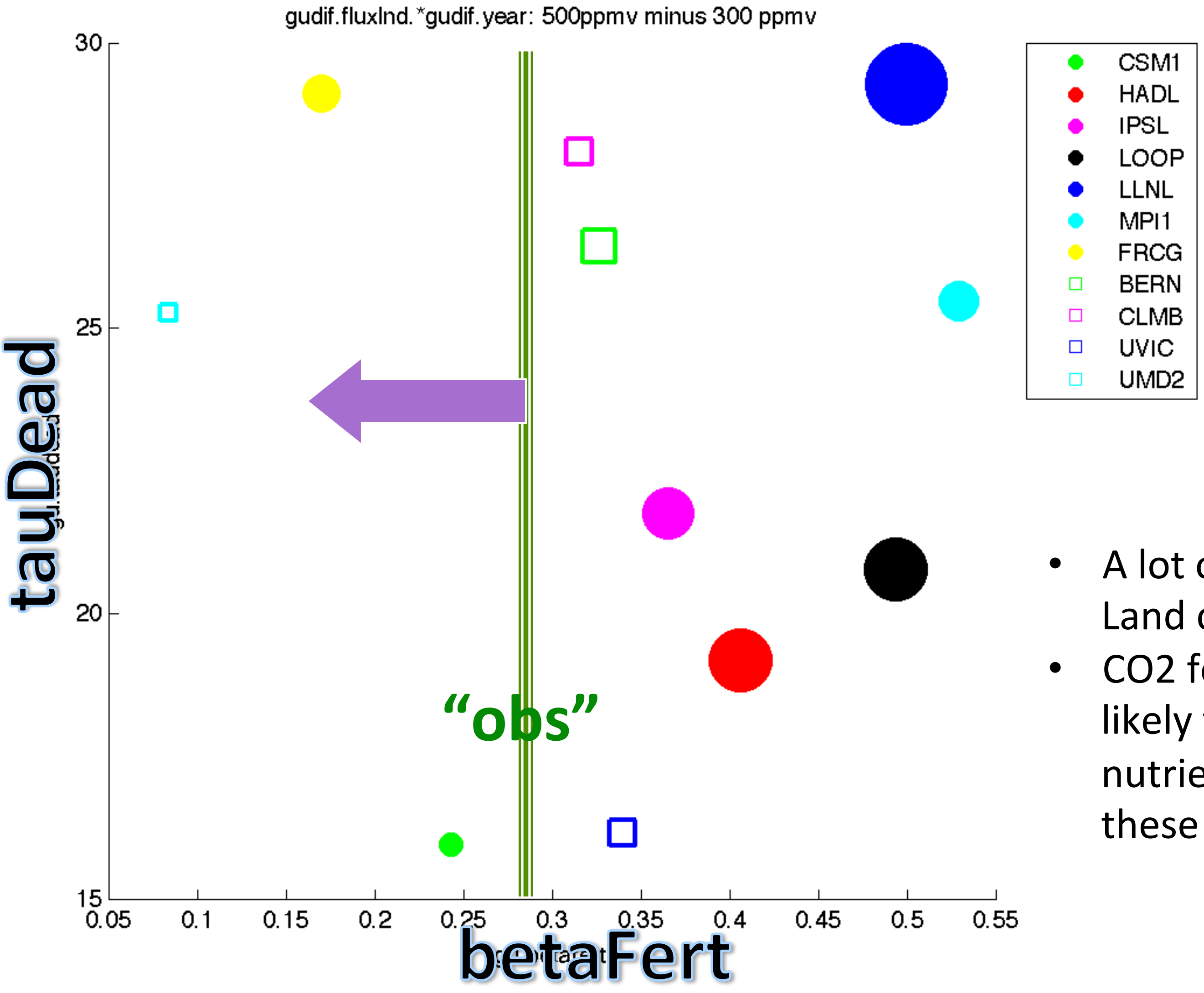
$$\frac{\partial M_{soil}}{\partial t} = \frac{M_{veg}}{\tau_{veg}} - (1-\gamma)\frac{M_{soil}}{\tau_{soil}} - \underbrace{\gamma\frac{M_{soil}}{\tau_{soil}}}_{Het\,\mathrm{Re}sp}$$

BGC run (no carbon climate fdbk):

$$\beta\_fert = \frac{NPP_{600} - NPP_{300}}{NPP_{300}}$$

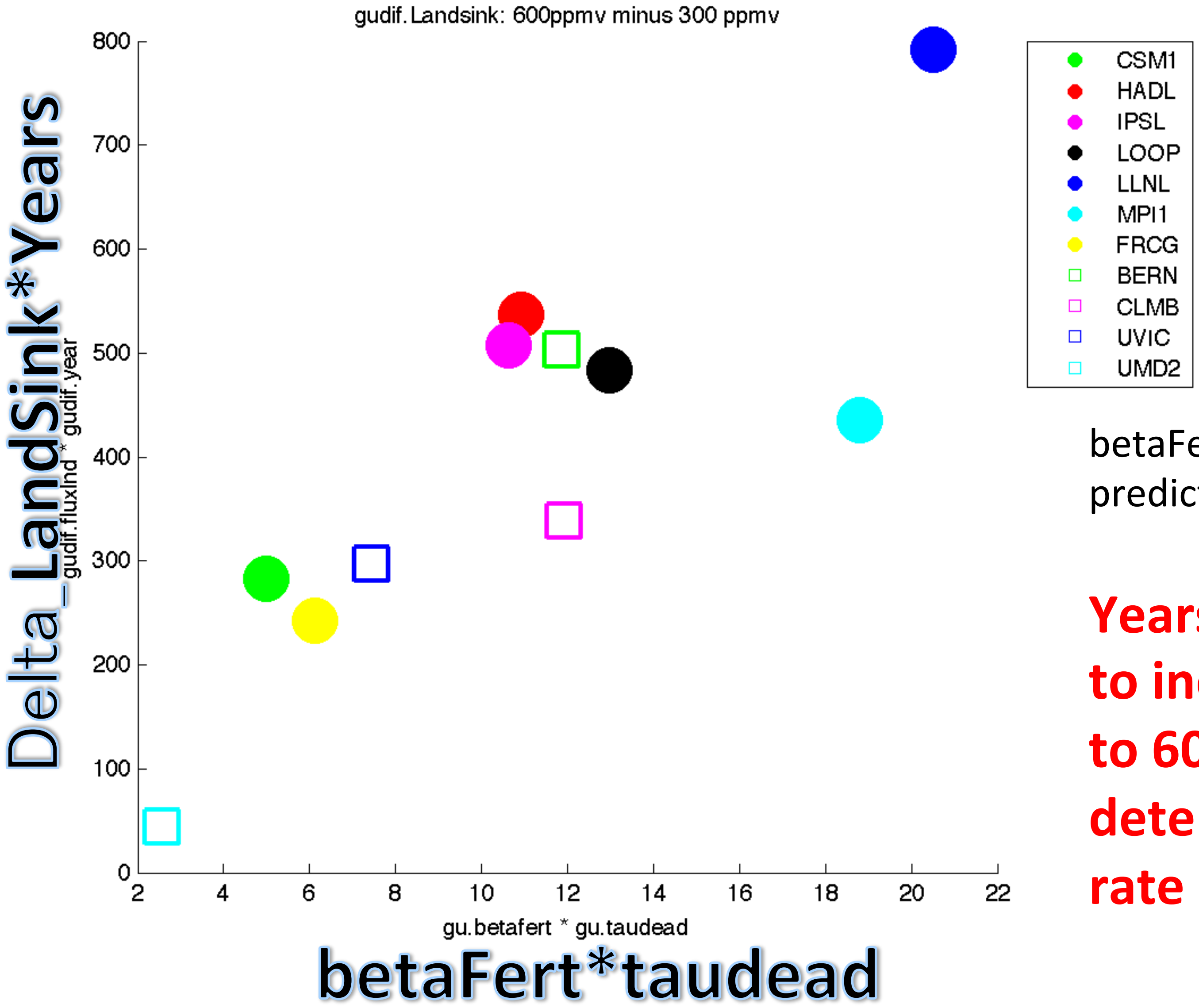
$$\tau\_dead = \frac{M_{soil}(300)}{Resp_{300}} = \frac{M_{soil}(300)}{NPP_{300}}$$

Control Climate: Land Uptake (300-500 ppmv) as a function of land parameters



- A lot of variety in Land carbon modules
- CO2 fertilization most likely too strong (no nutrient limitation in these models)

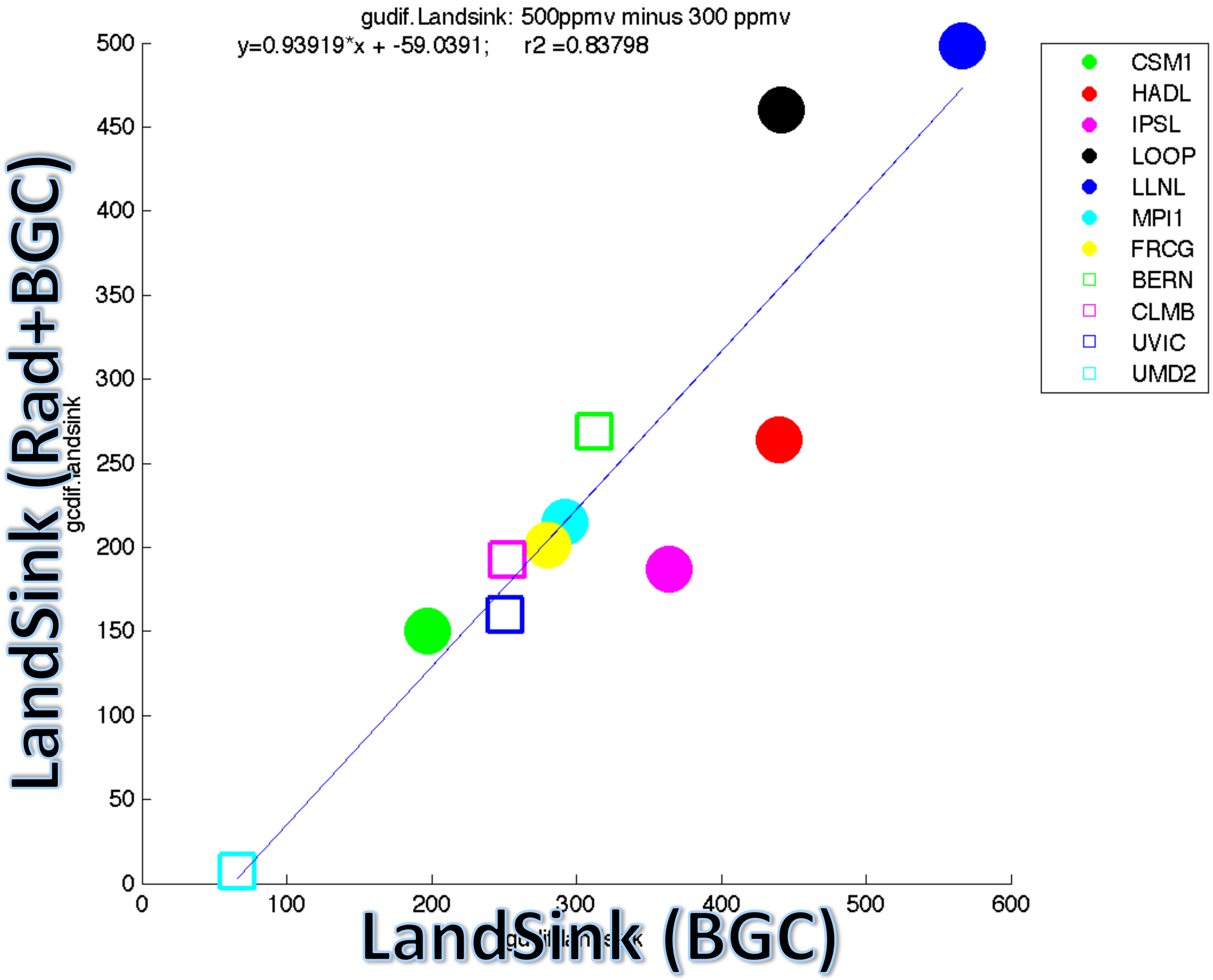
No Climate Feedback:
Land Sink(600ppm) – LandSink(300ppm)



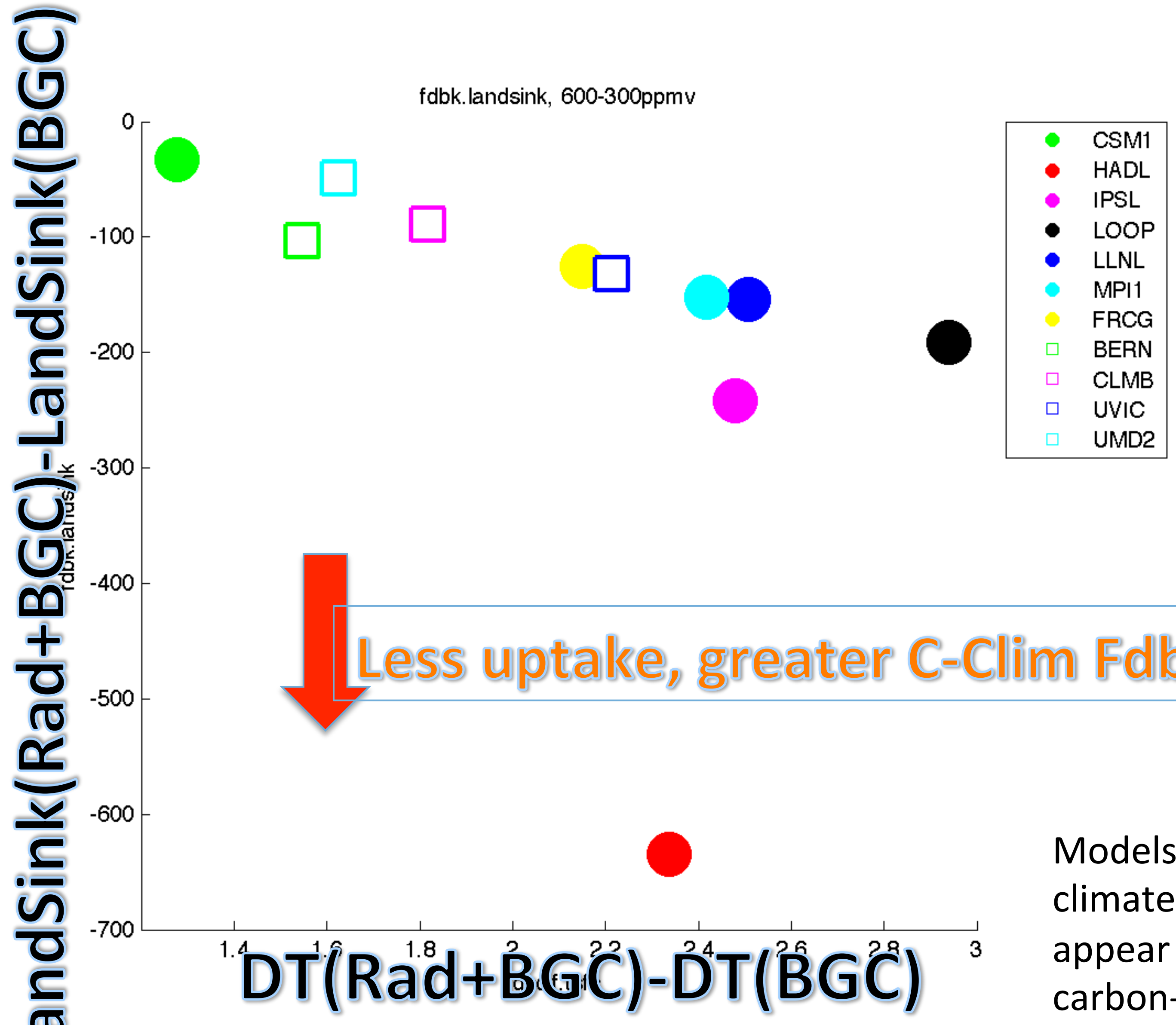
betaFert, taudead not too predictors of land sink

Years: Time for CO2 to increase from 300 to 600ppm is determined by the rate of ocean uptake

Fdbk.landsink - correlates with uncoupled landsink. Very good news. Whew!



With Climate Feedback: 600-300ppm



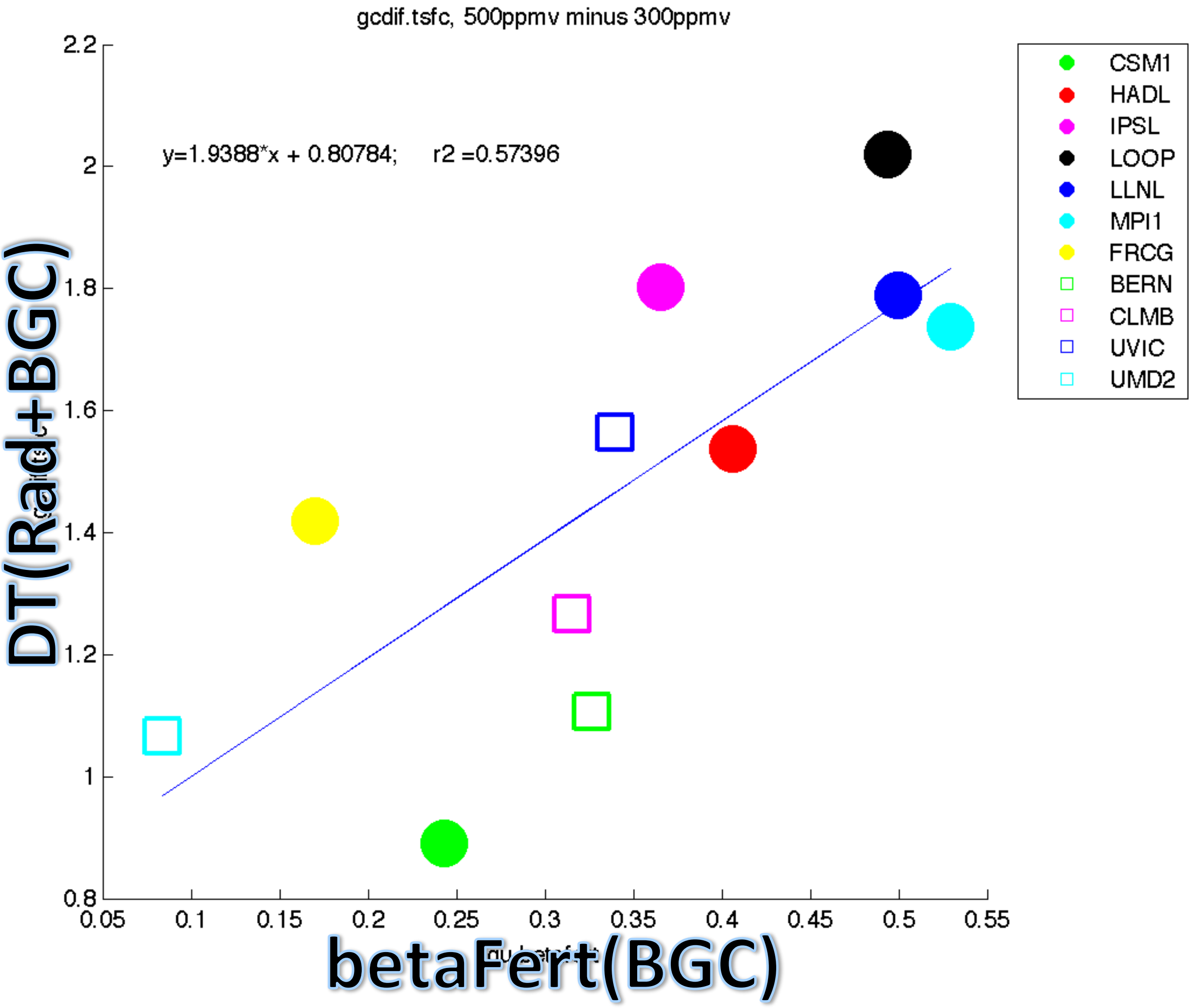
LandSink(Rad+BGC)-LandSink(BGC)

Less uptake, greater C-Clim Fdback

DT(Rad+BGC)-DT(BGC)

Models with greater climate sensitivity appear to have stronger carbon-climate fdbk for land

Should not have a line. But note that models with high climate sensitivity happen to be models with high betafert



C4MIP vs CMIP5

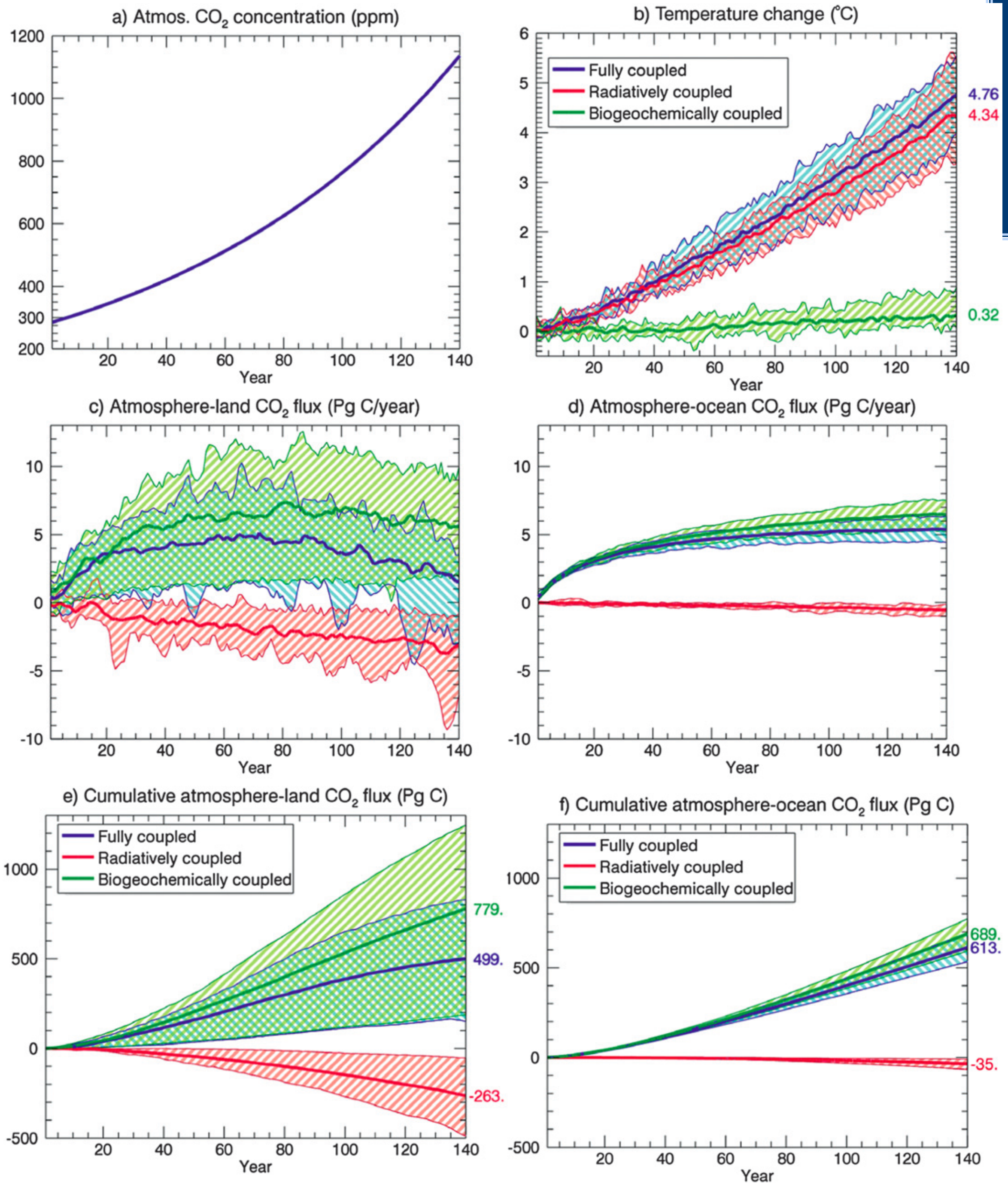
C4MIP

- Specify Emission
- Calculate dCO2/dt
- Analyze cumulative changes from 1800 to 2100
- Alpha, beta, gamma for cumulative fluxes

C5MIP

- Specify dCO2/dt = 1%/yr
- Diagnose implied Emission
- Analyze year-to-year changes
- ALPHA, BETA, GAMMA for annual fluxes

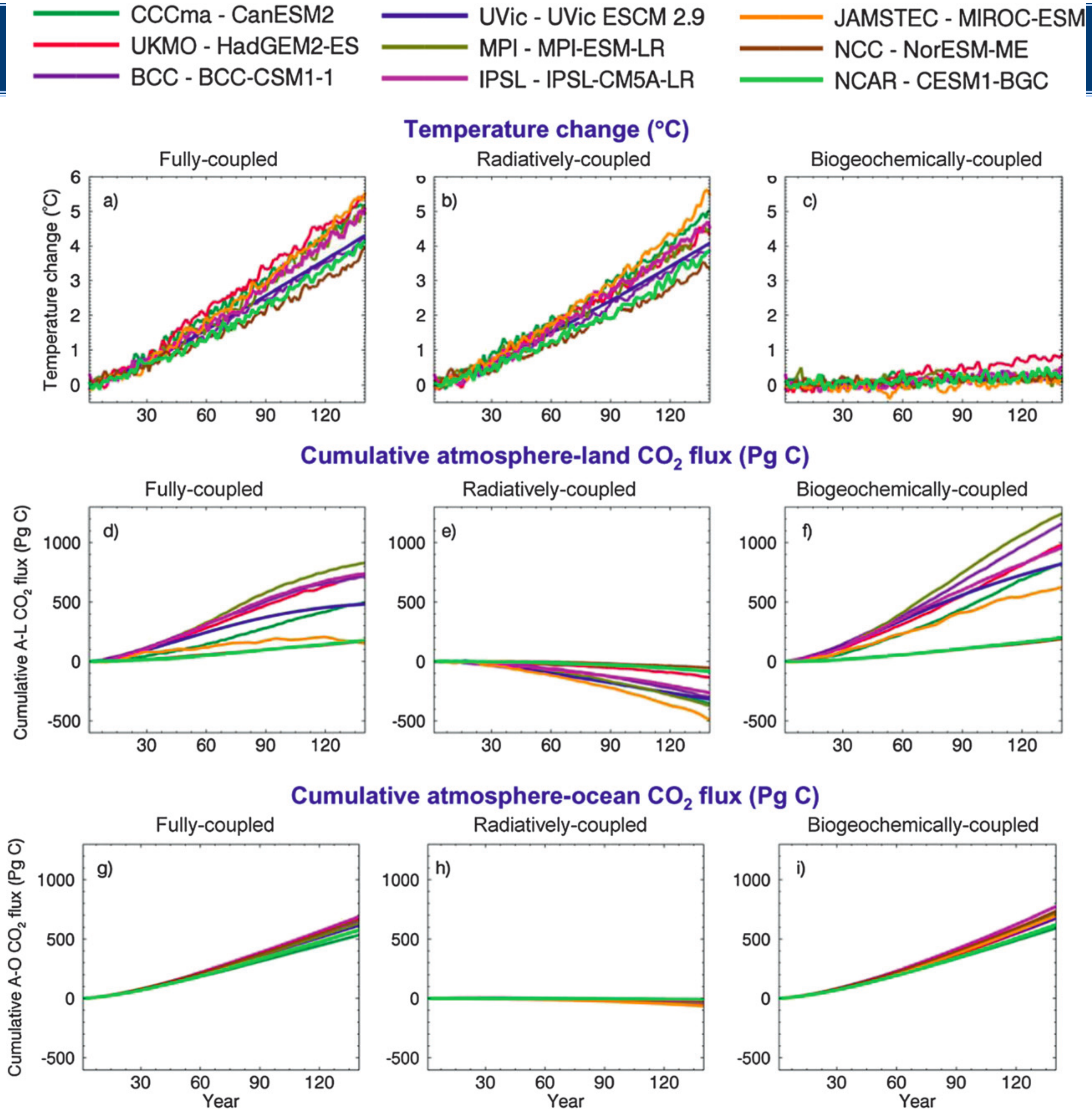
C5MIP
$dCO2/dt=1\%/yr$



- No collapse of rainforest
- LandSink ~ Ocean Sink
- Coupling→ small diff in DT (CO2 specified)

In 140 years

- Coupling → Very large difference in CumLandSink


CCCma - CanESM2
UKMO - HadGEM2-ES
BCC - BCC-CSM1-1
UVic - UVic ESCM 2.9
MPI - MPI-ESM-LR
IPSL - IPSL-CM5A-LR
JAMSTEC - MIROC-ESM
NCC - NorESM-ME
NCAR - CESM1-BGC
Temperature change (°C)
Fully-coupled
Radiatively-coupled
Biogeochemically-coupled
a)
b)
c)
Temperature change (°C)
0
1
2
3
4
5
6
30
60
90
120
Cumulative atmosphere-land CO2 flux (Pg C)
Fully-coupled
Radiatively-coupled
Biogeochemically-coupled
d)
e)
f)
Cumulative A-L CO2 flux (Pg C)
1000
500
0
-500
30
60
90
120
Cumulative atmosphere-ocean CO2 flux (Pg C)
Fully-coupled
Radiatively-coupled
Biogeochemically-coupled
g)
h)
i)
Cumulative A-O CO2 flux (Pg C)
1000
500
0
-500
30
60
90
120
Year

Transient Carbon Climate Feedback

$$\Delta T^{Rad+BGC}(t) = \alpha \bullet m \bullet \Delta CO_2^{specified}(t)$$

$$\Delta C_L^{BGC}(t) = B_L \bullet m \bullet \Delta CO_2^{specified}(t)$$

$$\Delta C_O^{BGC}(t) = B_O \bullet m \bullet \Delta CO_2^{specified}(t)$$

$$\Delta C_L^{Rad+BGC}(t) = B_L \bullet m \bullet \Delta CO_2^{specified}(t) + G_L \bullet \Delta T^{Rad+BGC}(t)$$

$$\Delta C_O^{Rad+BGC}(t) = B_O \bullet m \bullet \Delta CO_2^{specified}(t) + G_O \bullet \Delta T^{Rad+BGC}(t)$$

$$m = PgC / ppm$$

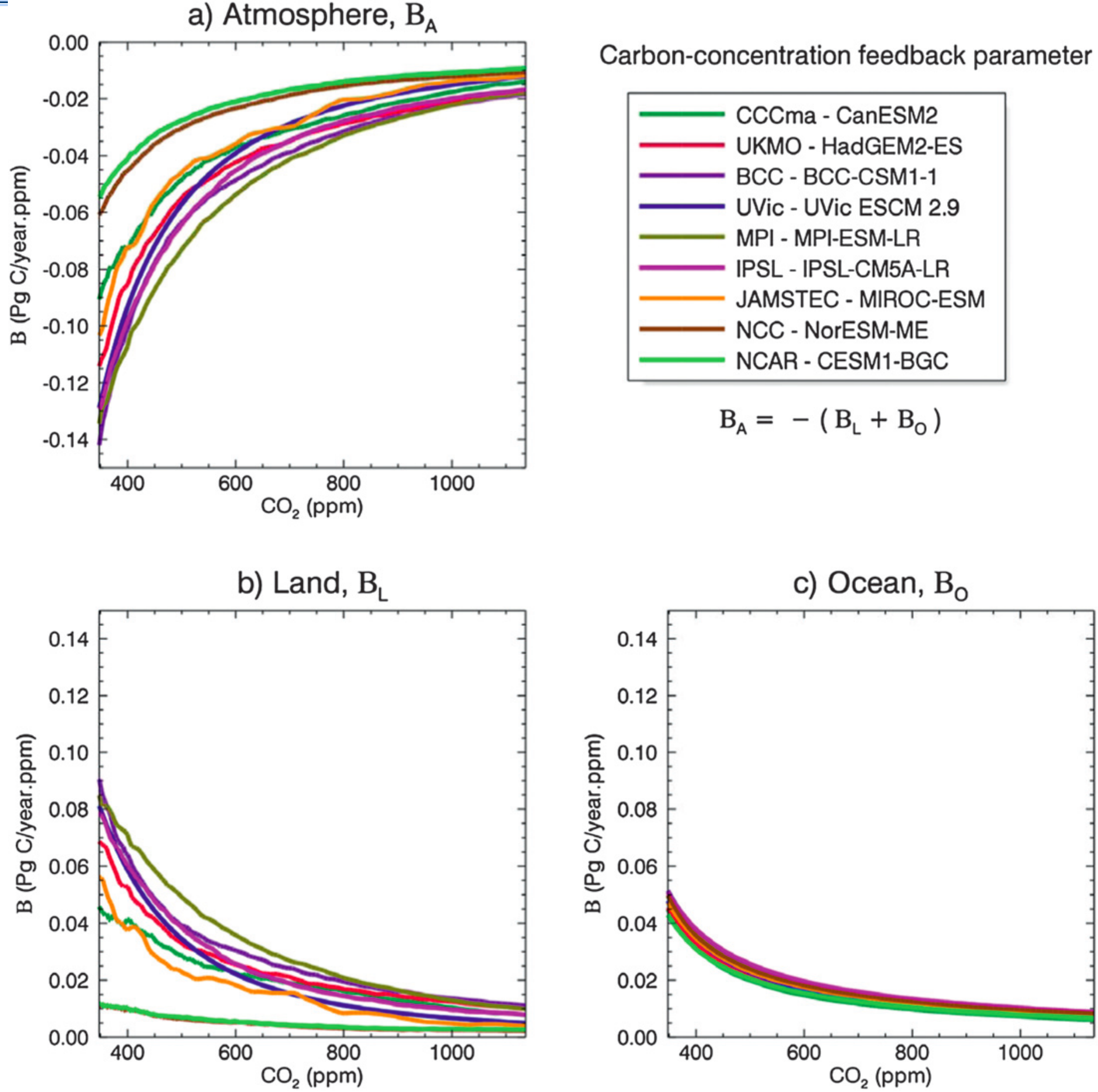
$$\alpha = K / ppm$$

$$B = PgC / ppm$$

$$G = PgC / K$$

Arora et al. J Climate 2013

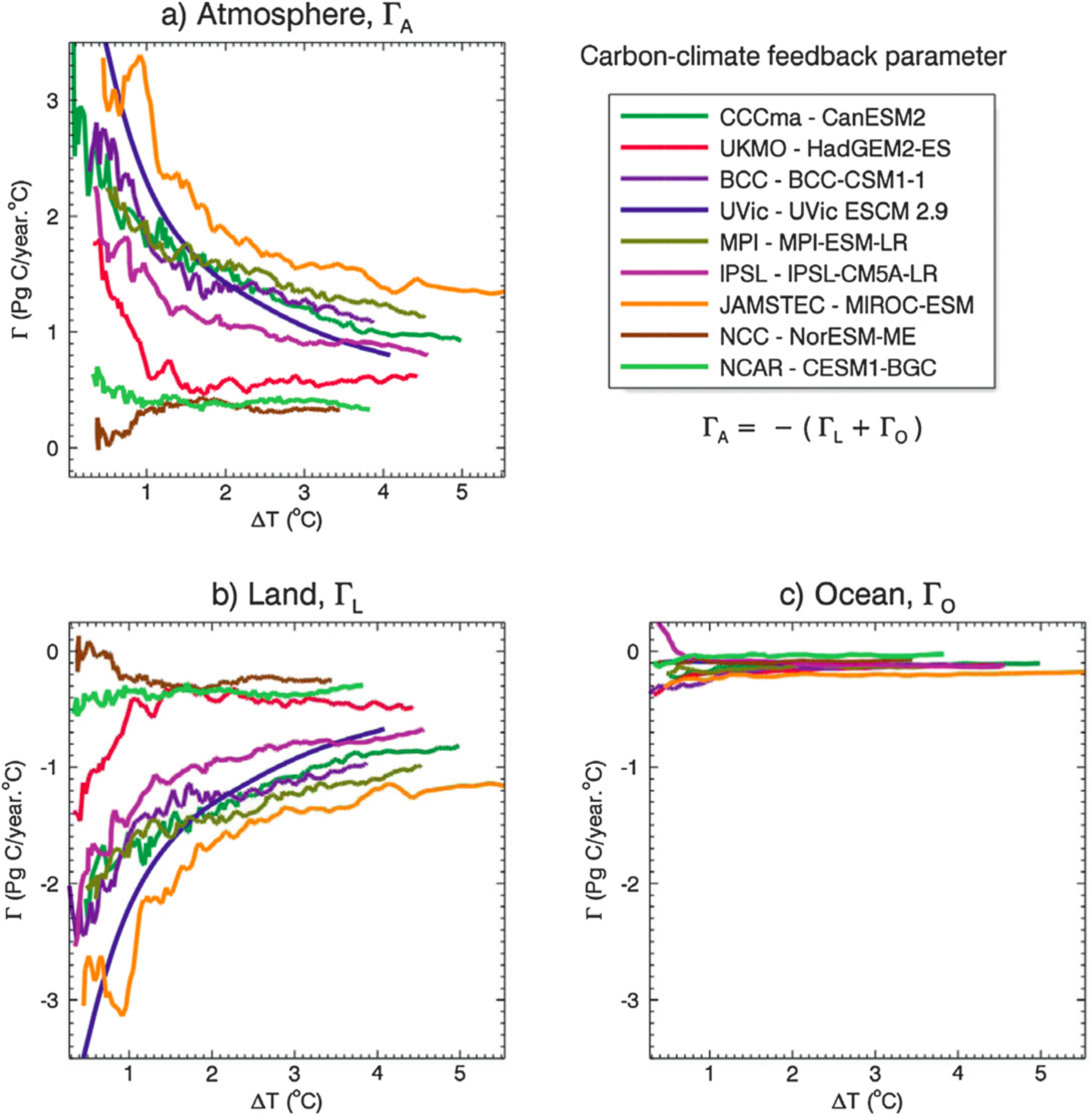
BETA: PgC/(yr.ppm)



$$B_A = -(B_L + B_O)$$

Saturation of feedback with increasing CO2

GAMMA: PgC/(yr.K)



C5MIP

- BETA _L ~0.05 PgC/(yr.ppm)
- BETA _O ~0.02 PgC/(yr.ppm)
- GAMMA_L ~ -2 PgC/(yr.K)
- GAMMA_O ~ -0.01 PgG/(yr.K)

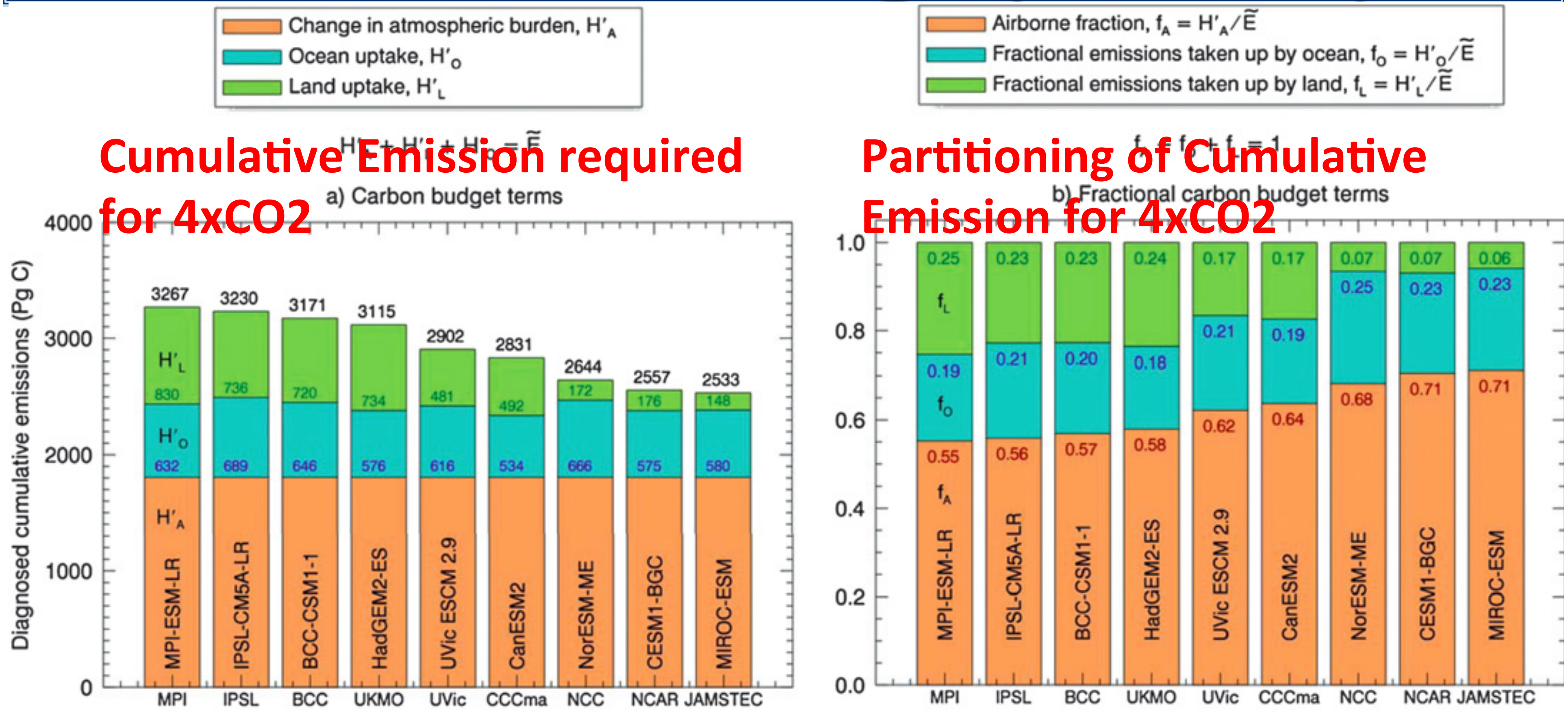
- DCO2 ~ 300 ppm
- DT ~ 2K

Carbon-Concentration feedback ~
4.5 X Carbon-Climate feedback

CMIP5: Carbon Budget (Rad+BGC)

Cumulative Emission required for 4xCO2

Partitioning of Cumulative Emission for 4xCO2



Very large difference in implied emission:
3267-2533=734 PgC