Decomposition of CO2 fertilization effect into contributions by land ecosystem processes: comparison among CMIP5 Earth system models

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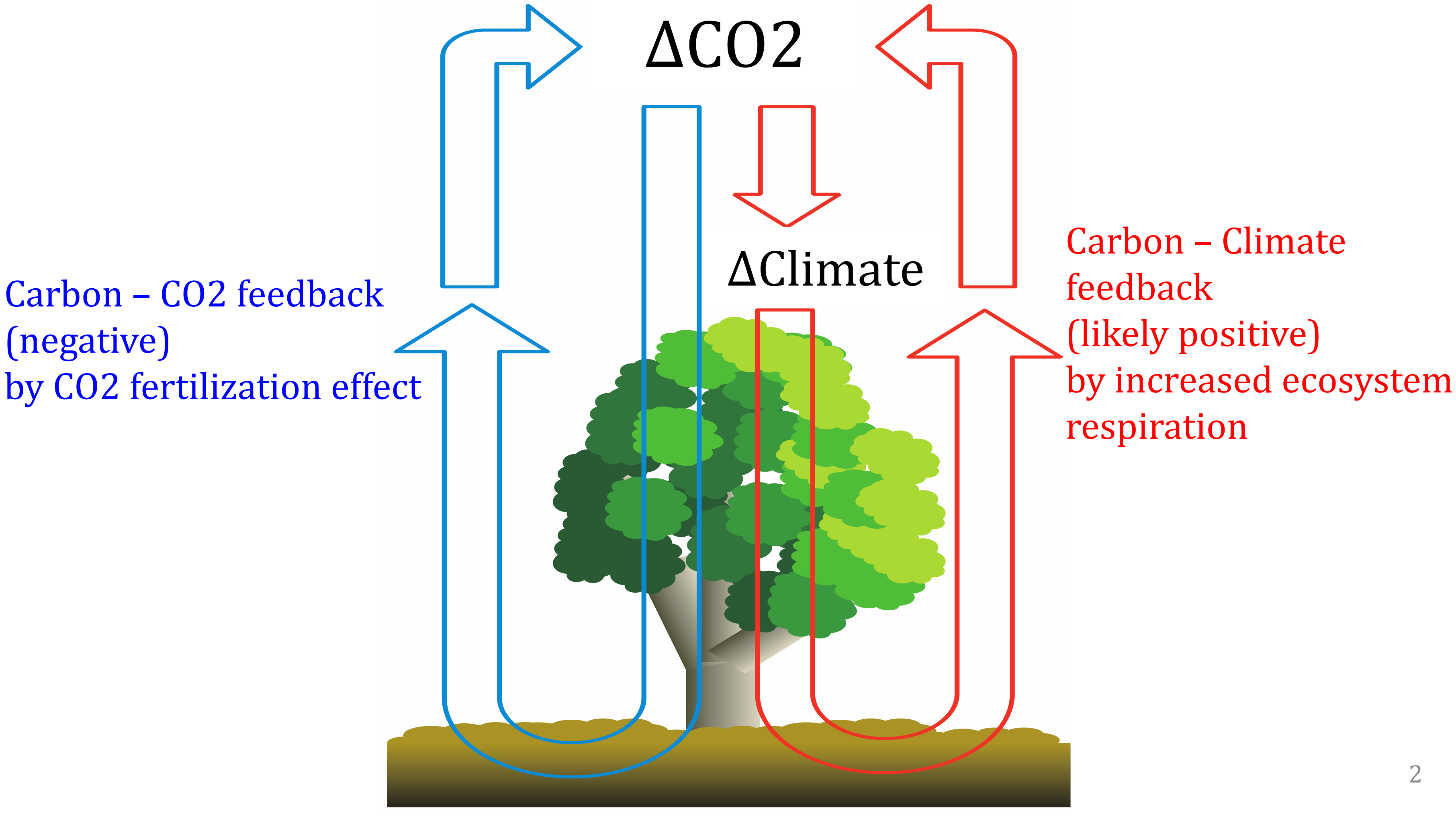
Hajima et al. 2014, J. Clim

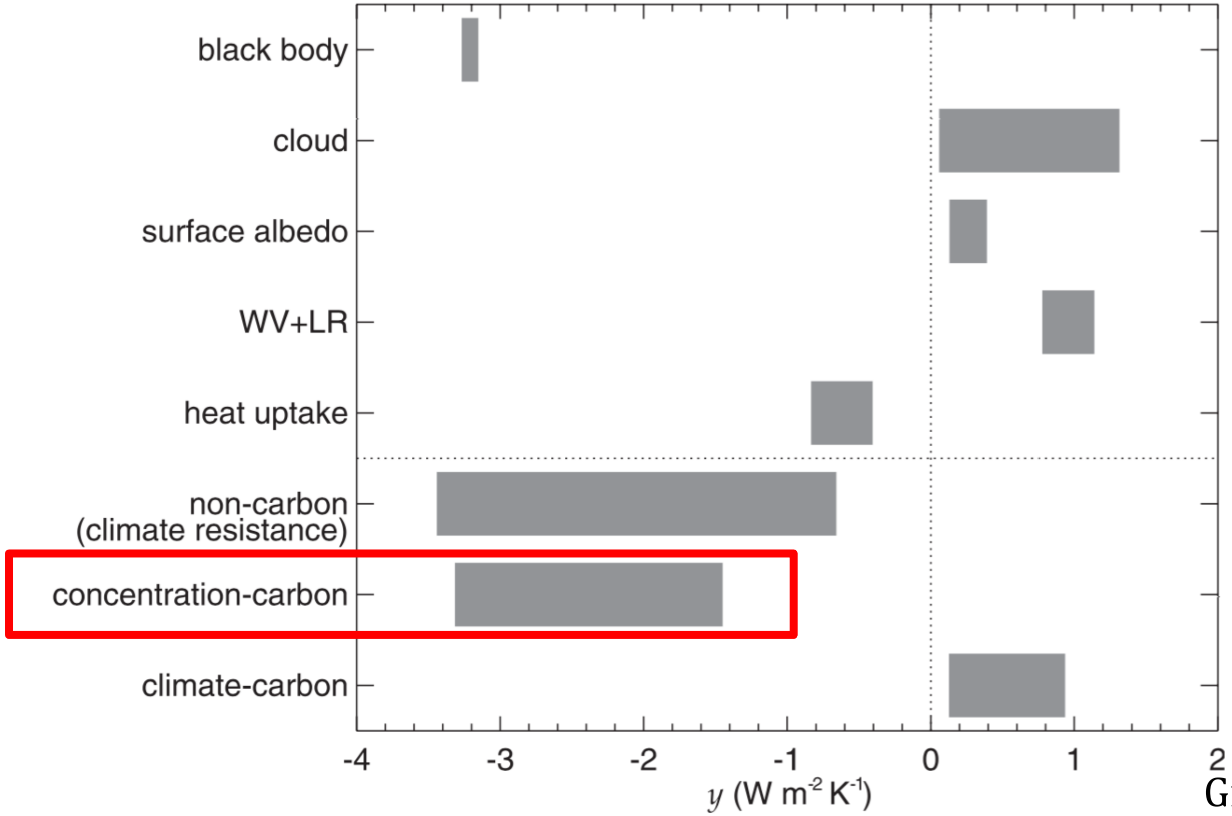
CO2 fertilization

- CO_2 increase in the atmosphere stimulates photosynthesis, and hence promotes net carbon uptake by land ecosystems.
- This effect forms a negative feedback loop: “CO_2-carbon feedback”
- Another important feedback process: “climate-carbon feedback”



Why CO2 fertilization effect ?

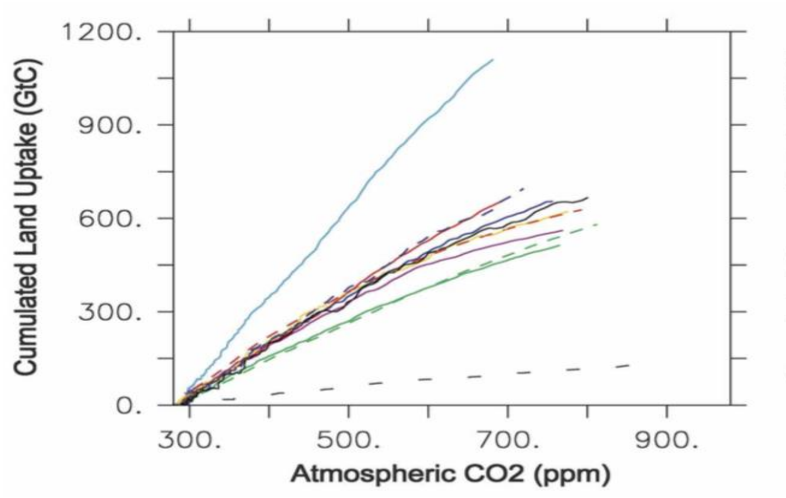
CO2 fertilization effect forms one of the strongest feedbacks in the Earth system, and has large uncertainty

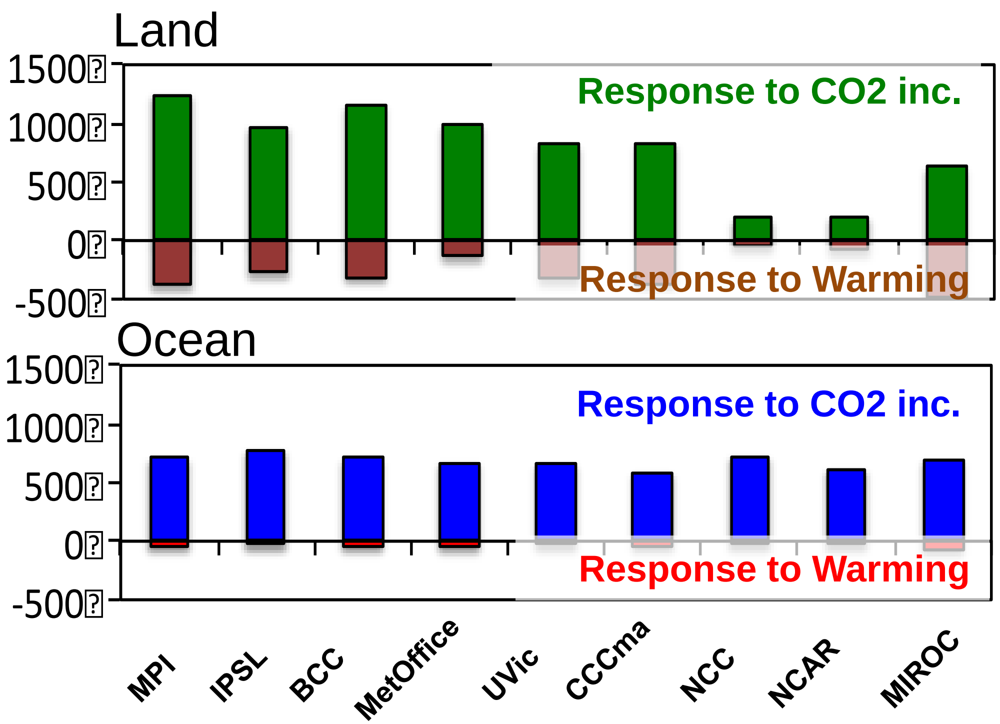


Gregory et al. (2009) J. Clim

A comparison of components of feedback, based on CMIP3 AOGCMs and C4MIP (Friedlingstein et al. (2006)); grey bars indicate 1.65 S.D.;

CO2 fertilization effect on terrestrial carbon change in ESMs





First investigation on CO2 fertilization effect using multiple climate-carbon cycle models was carried out by Friedlingstein et al. (2006) (but more attentions were paid to climate-carbon feedback).

In CMIP5, Arora et al. (2013) evaluated the two types of feedback by using total carbon change, and found large spread among models in the land response to CO2 increase.

These and other existing studies mainly analyzed the change in global terrestrial carbon storage, with limited focus on the mechanism of that.

Purpose

- Identify the cause of large spread found in CMIP5-ESM on land carbon response to CO2 increase, by evaluating the detailed process of land carbon cycle processes

Method: decomposition of CO2 fertilization effect

$$\frac{\Delta C_{LAND}}{\Delta CO_2} = \frac{\Delta gpp}{\Delta CO_2} \times \frac{\Delta GPP}{\Delta gpp} \times \frac{\Delta NPP}{\Delta GPP} \times \frac{\Delta C_{VEG}}{\Delta NPP} \times \frac{\Delta C_{SOIL}}{\Delta C_{VEG}} \times \frac{\Delta HR}{\Delta C_{SOIL}} \times \frac{\Delta C_{LAND}}{\Delta HR}$$

- $\frac{\Delta C_{LAND}}{\Delta CO_2}$: Land carbon change by CO2 increase
- $\frac{\Delta gpp}{\Delta CO_2}$: Inc. in photosynthesis by CO2
- $\frac{\Delta GPP}{\Delta gpp}$: Change in LAI (gpp :=GPP / LAI)
- $\frac{\Delta NPP}{\Delta GPP}$: Change in Carbon use efficiency
- $\frac{\Delta C_{VEG}}{\Delta NPP}$: Change in residence time of veg. C
- $\frac{\Delta C_{SOIL}}{\Delta C_{VEG}}$: Change in carbon allocation between veg-soil
- $\frac{\Delta HR}{\Delta C_{SOIL}}$: Changes in turnover rate of soil C
- $\frac{\Delta C_{LAND}}{\Delta HR}$: Change in residence time of eco. C

<u>Similar to that used for "plant growth analysis" in ecophysiology:</u>

$$\frac{1}{M}\frac{dM}{dt} = \frac{1}{LAI}\frac{dM}{dt} \times \frac{LAI}{LM} \times \frac{LM}{M}$$

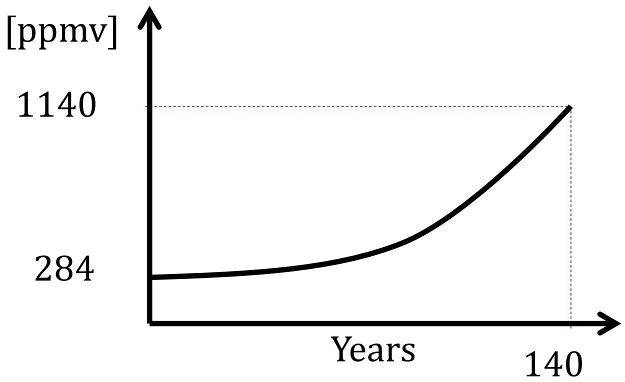
- $\frac{1}{M}\frac{dM}{dt}$: Relative Growth Rate
- $\frac{1}{LAI}\frac{dM}{dt}$: Net Assimilation Rate
- $\frac{LAI}{LM}$: Specific Leaf Area
- $\frac{LM}{M}$: Leaf Mass Ratio

t: time; M: Dry matter; LAI: Leaf Area; LM: Leaf mass

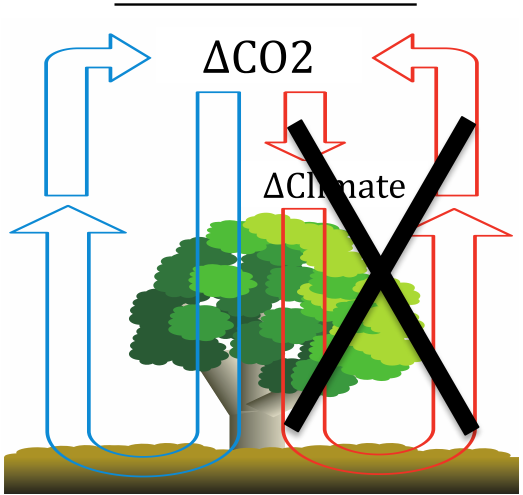
Models & simulations

- CO2 increase by 1.0[%/yr] during 140 years
- Only carbon cycle "sees" the CO2 increase: named in CMIP5 as "esmFixClim1" (sometimes called "biogeochemically coupled" experiment)
- Eight CMIP5-ESMs

CO2 conc.



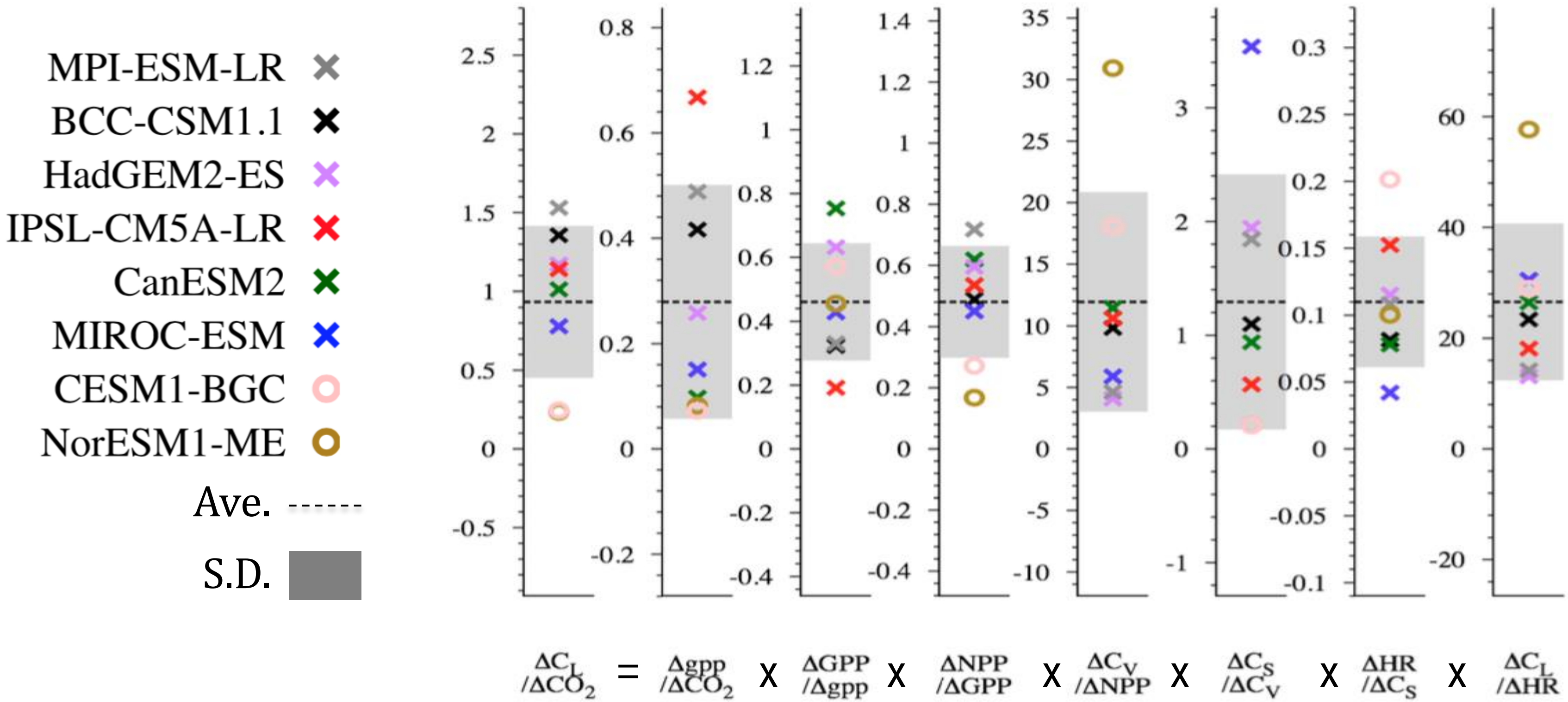
"esmFixClim1"



Models

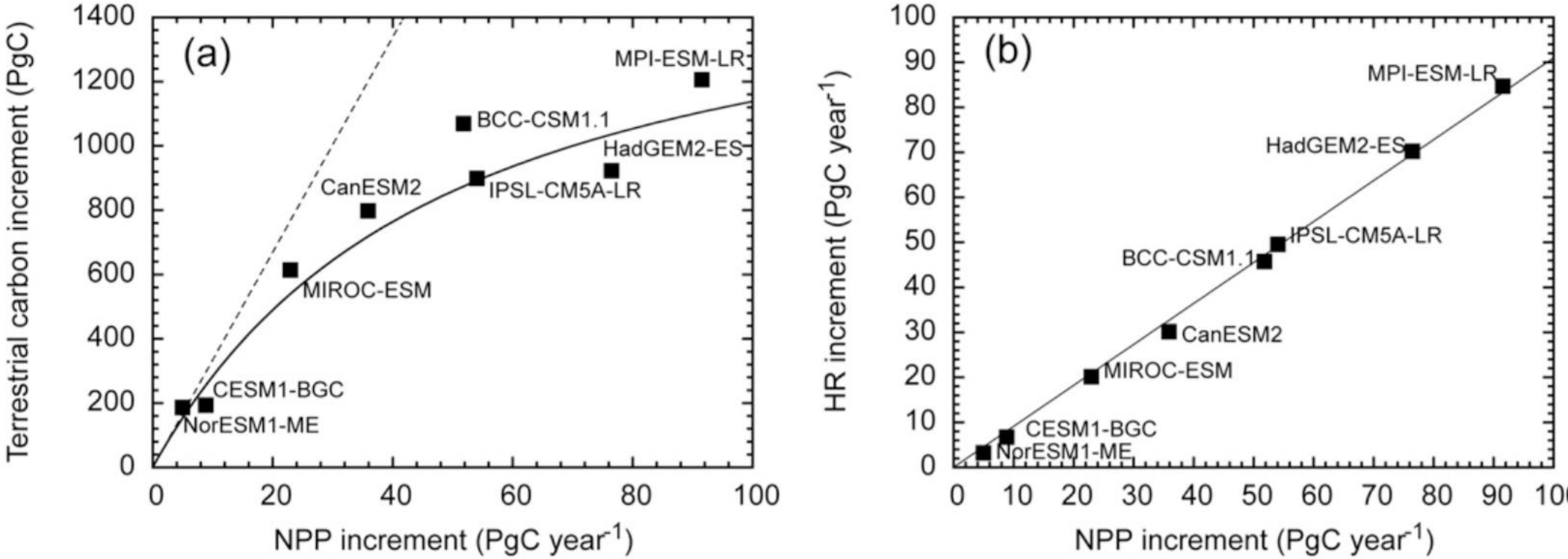
ESM	Component for Land eco.
BCC-CSM1.1	BCC-AVIM1.0
CanESM2	CTEM
CESM1-BGC	CLM4
HadGEM2-ES	TRIFFID
IPSL-CM5A-LR	ORCHIDEE
MIROC-ESM	SEIB-DGVM
MPI-ESM-LR	JSBACH
NorESM1-ME	CLM4

Result: Decomposition



- CO2 increase does not only affect photosynthesis processes (Δgpp/ΔCO2) but also stimulates the subsequent (“downstream”) carbon cycle processes.
- Models display different response pattern to the CO2 increase.
- This method can characterize the models’ response to ΔCO2 in detail:
  e.g. Hadley & IPSL models show similar magnitude for ΔCL/ΔCO2, but IPSL model has stronger response in Δgpp/ΔCO2 than Hadley and weaker in ΔGPP/Δgpp (=ΔLAI)

What controls CO2 fertilization effect in CMIP5 ESMs?



- Although CO2 increase stimulates various carbon cycle processes, total carbon change by CO2 fertilization effect can be well explained by NPP increase in response to ΔCO2.
- Further evaluation of detailed processes (e.g. Δgpp/ΔCO2, ΔGPP/Δgpp, ΔNPP/ΔGPP in the previous slide) and its constrain by observation would be needed to reduce the uncertainty.
- What are influential to global NPP: photosynthetic rate for individual leave, plant community LAI, and plant respiration rate; length of the growing season, and areas of plant and plant species distribution; nitrogen cycle

Simplified model

The scenario dependence of the CO_2-carbon feedback is investigated, using a simplified model.

$$\frac{dC_V}{dt} = \mathrm{GPP} - (\mathrm{AR} + \mathrm{LF})$$

$$\mathrm{GPP} = \mathrm{GPP}_0 + \frac{k_{\mathrm{GPP1}} \Delta \mathrm{CO}_2}{k_{\mathrm{GPP2}} + \Delta \mathrm{CO}_2}$$

$$\mathrm{AR} = k_{\mathrm{AR}} C_V$$

$$\mathrm{LF} = k_{\mathrm{LF}} C_V$$

$$\frac{dC_S}{dt} = \mathrm{LF} - \mathrm{HR}$$

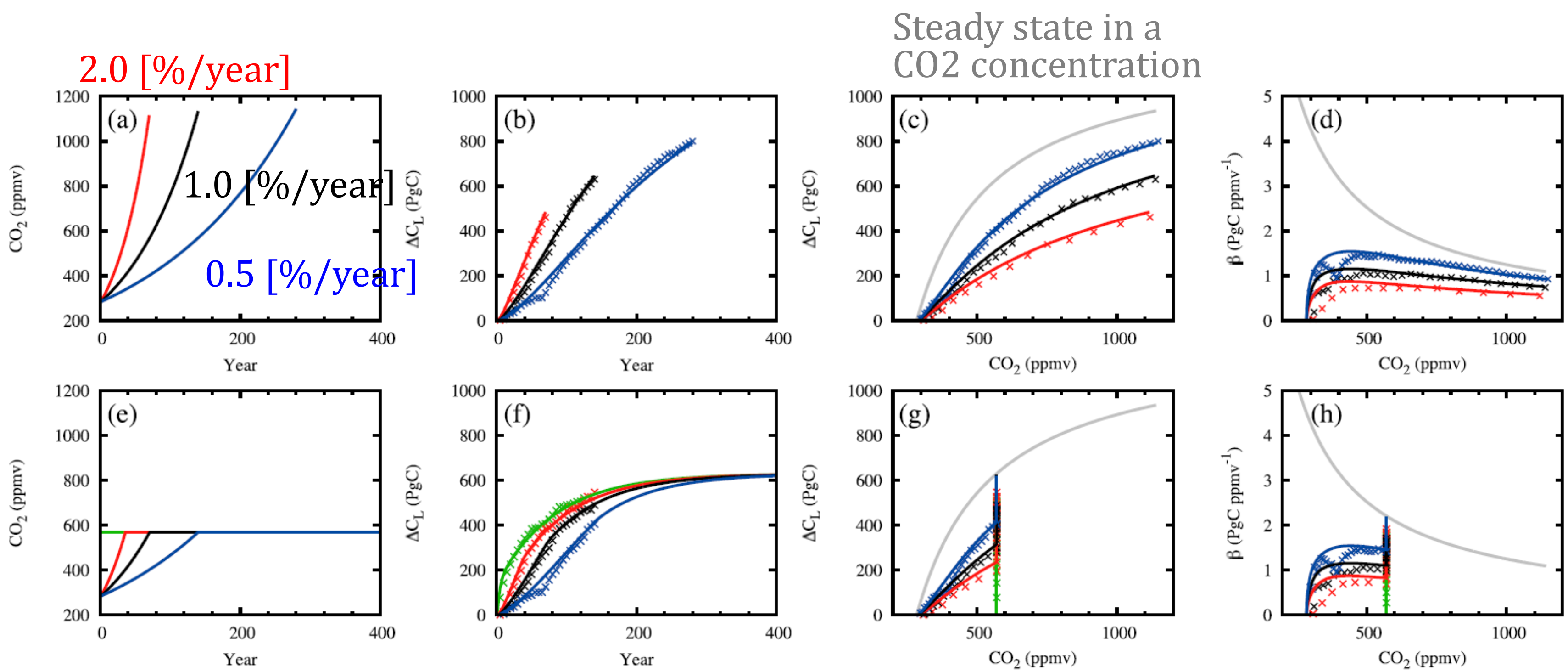
$$\mathrm{HR} = k_{\mathrm{HR}} C_S$$

Initial conditions

$$C_{V,0} = \frac{\mathrm{GPP}_0}{(k_{\mathrm{AR}} + k_{\mathrm{LF}})}$$

$$C_{S,0} = \frac{k_{\mathrm{LF}}}{k_{\mathrm{HR}}} \frac{\mathrm{GPP}_0}{(k_{\mathrm{AR}} + k_{\mathrm{LF}})}$$

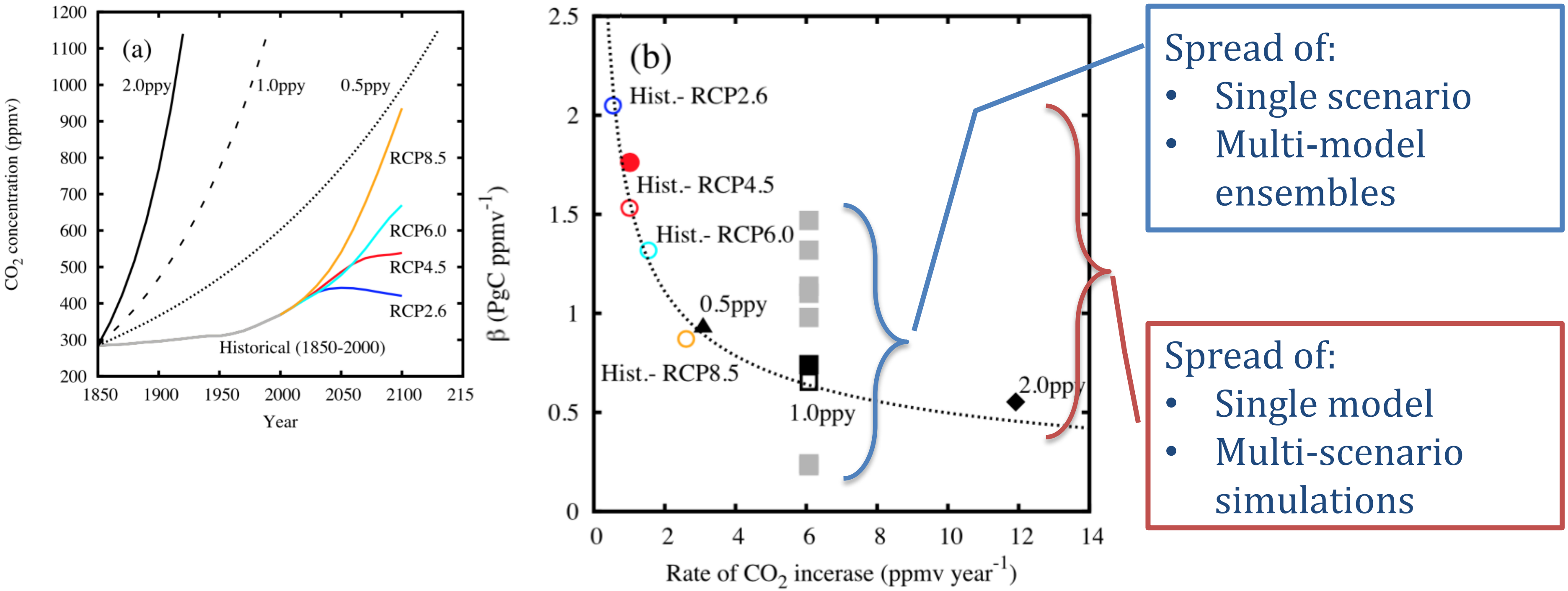
Carbon storage change in different scenarios



- At the carbon state in a same level of CO2 concentration, simulation with slower CO2 increase scenario locates nearby the new equilibrium state.

- Beta, the concentration–carbon feedback parameter, is also affected by that.

Other important issues: delayed response of carbon pools

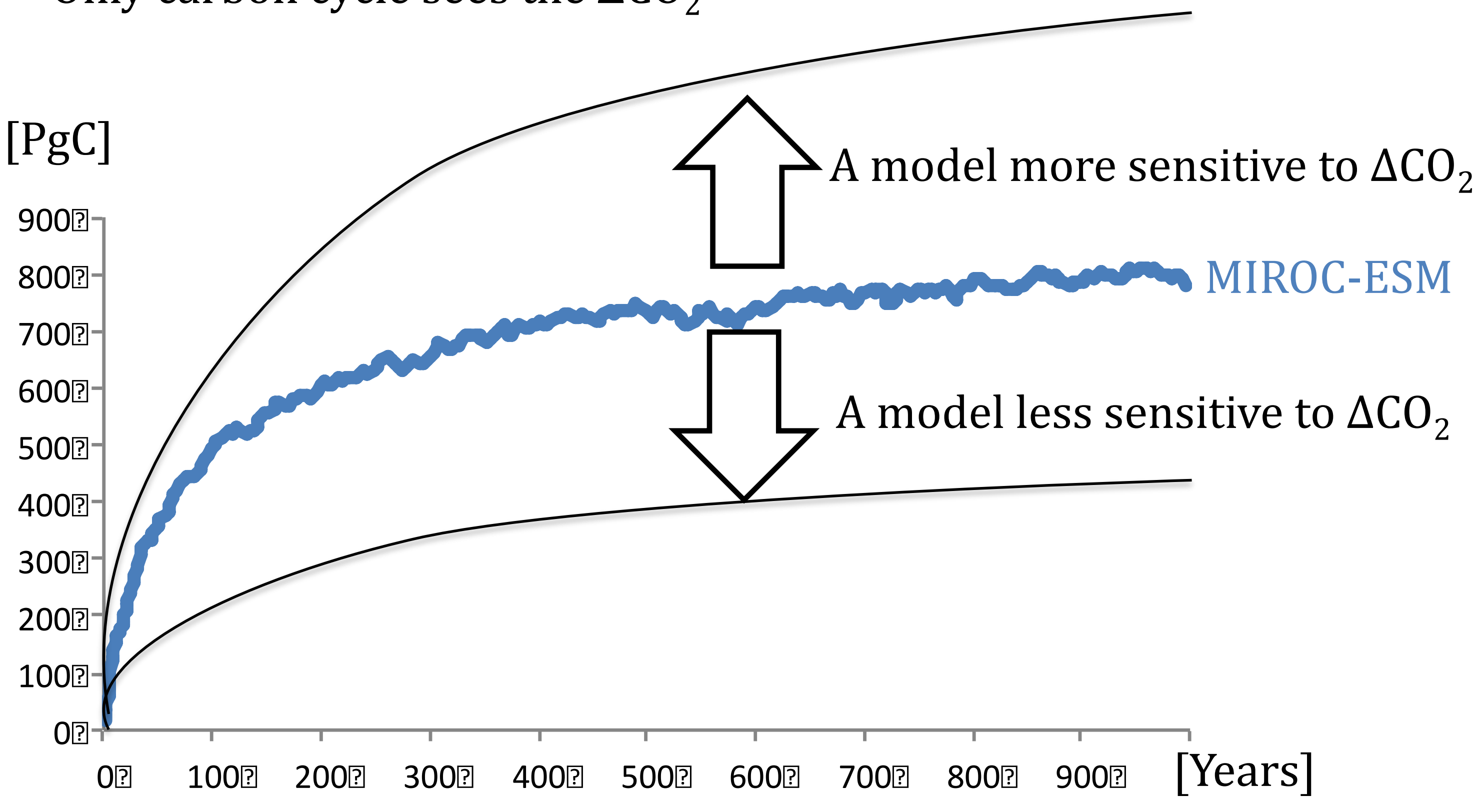


Open marks: simplified model; closed: ESMs

- Terrestrial carbon changes induced by CO2 fertilization effect strongly dependent on CO2 scenarios
- This is because carbon pools have time-lag for the CO2 forcing, which create different carbon states among different scenarios, even in a same CO2 concentration.

Equilibrium carbon state in doubled CO_2 concentration

- CO2 conc. is abruptly doubled from P.I. state and fixed during 1000 years
- Only carbon cycle sees the ΔCO_2



- Transient simulations inevitably include the influence of 1) changes in CO_2 forcing and 2) the lags of carbon pools behind the forcing change.
- To assess the models' sensitivity to ΔCO_2 accurately, an experiment with abrupt CO_2 doubling/quadrupling might be better, because by using that we can remove the effect of the changing forcing.
- It may be meaningful to define equilibrium land carbon increase for 2xCO_2.

Summary

- We attempted to decompose the concentration–carbon feedback in the terrestrial carbon cycle into contributions by land ecosystem processes using outcomes of CMIP5 ESMs simulations.
- The large spread of ΔC_L was well explained by the degree of NPP response to ΔCO_2 increase in each model, but models increase their NPP by different manner.
- In order to constrain the response to CO_2 increase, the decomposition used in this study and comparing the each term with observation data will be useful.
- There is a strong scenario dependence in the magnitude of CO_2 fertilization for a certain concentration level . Using a stabilized concentration scenario makes the analysis simpler.
- Similar to equilibrium climate sensitivity, it may be useful to define the equilibrium land carbon increase for the $2xCO_2$ level.