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INSTITUT POLYTECHNIQUE DE PARIS

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LSCE

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16/11/21

ORCHIDEE DEV – Impact of a parametrization on climate-carbon cycle feedbacks future evolution

Outline

I. Introduction

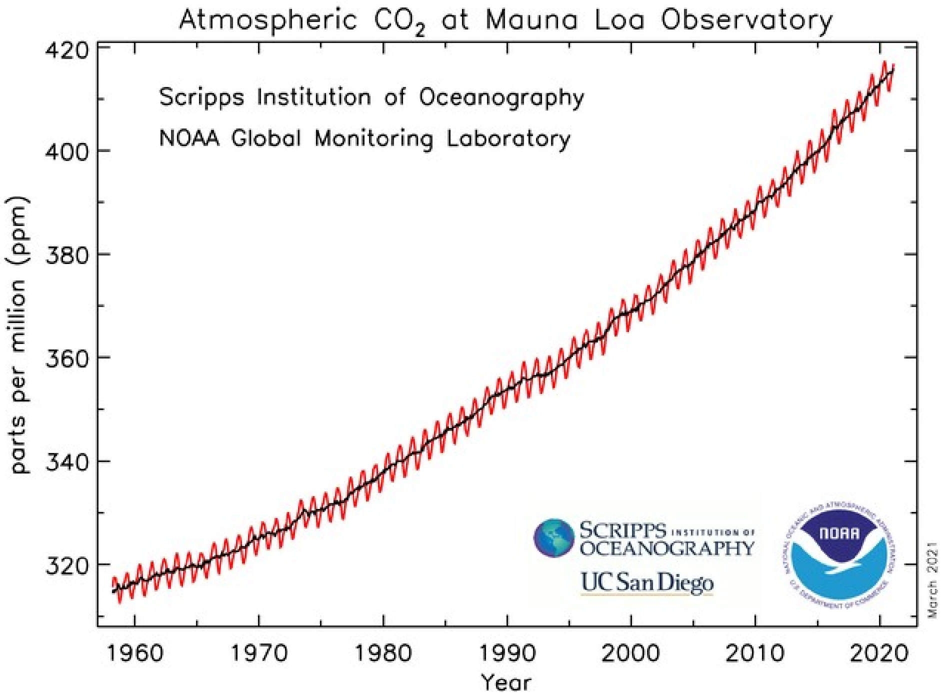
II. Climate-carbon feedbacks

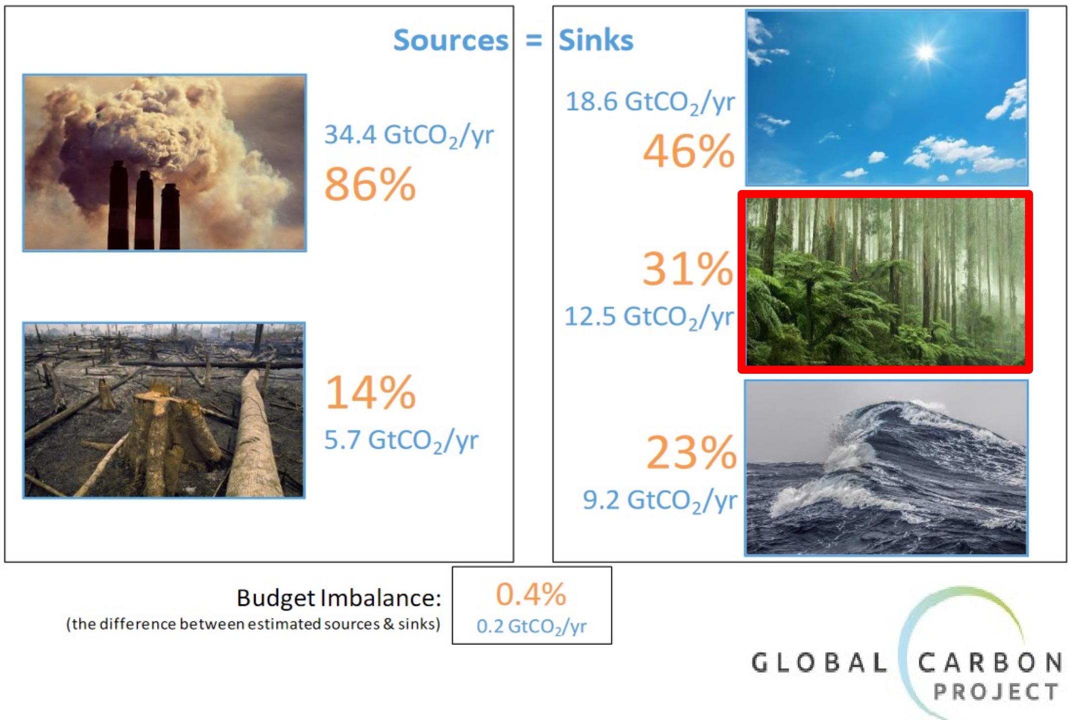
III. Idealized simulations : feedbacks determination

IV. Historical and future scenarios simulations

V. Conclusion

Introduction



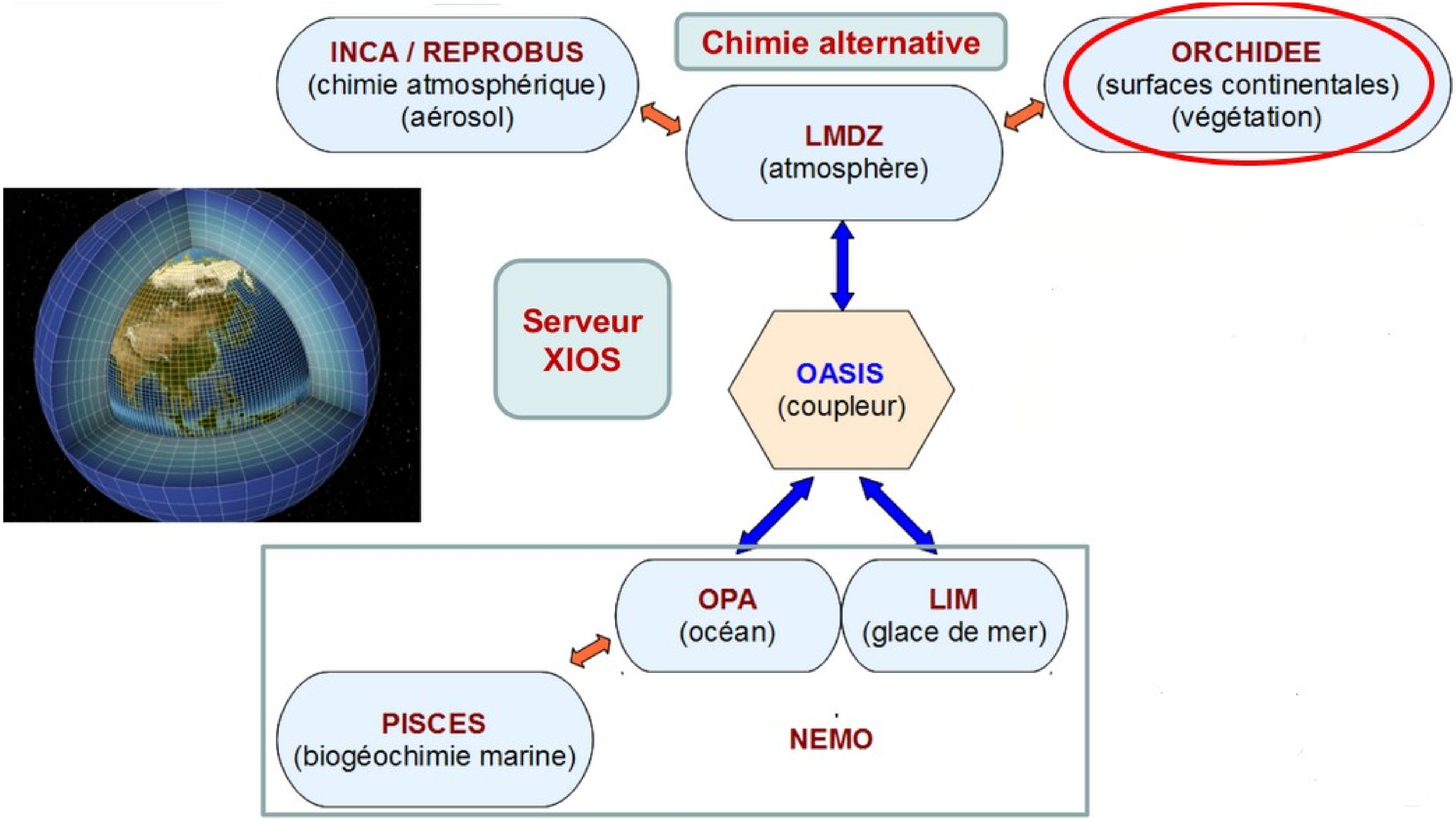


What does CO_2 become once in the atmosphere ?

Anthropogenic emissions are partly taken up by natural carbon sinks : **ocean** and **terrestrial biosphere**.

Land sink is much more variable.

Introduction – A main tool : IPSL coupled model



- Allows for the study of specific processes separately.
- Tool for future predictions.

Introduction – An international framework : C4MIP

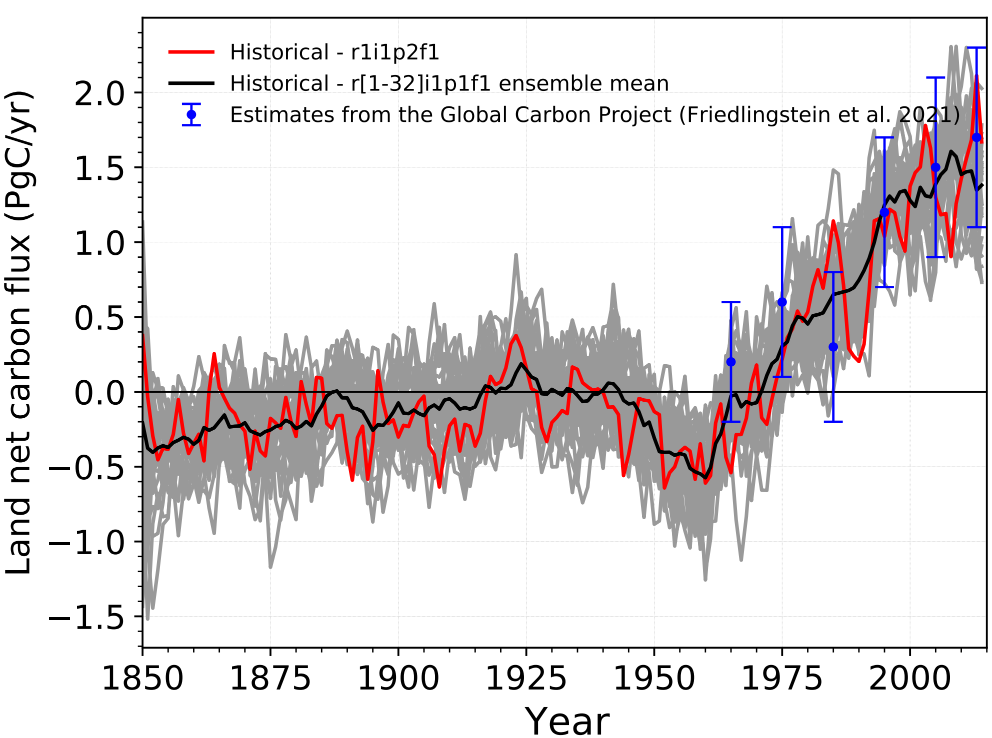
► International project (branch of CMIP) aiming to improve modelling and understanding of climate-carbon cycle interactions.

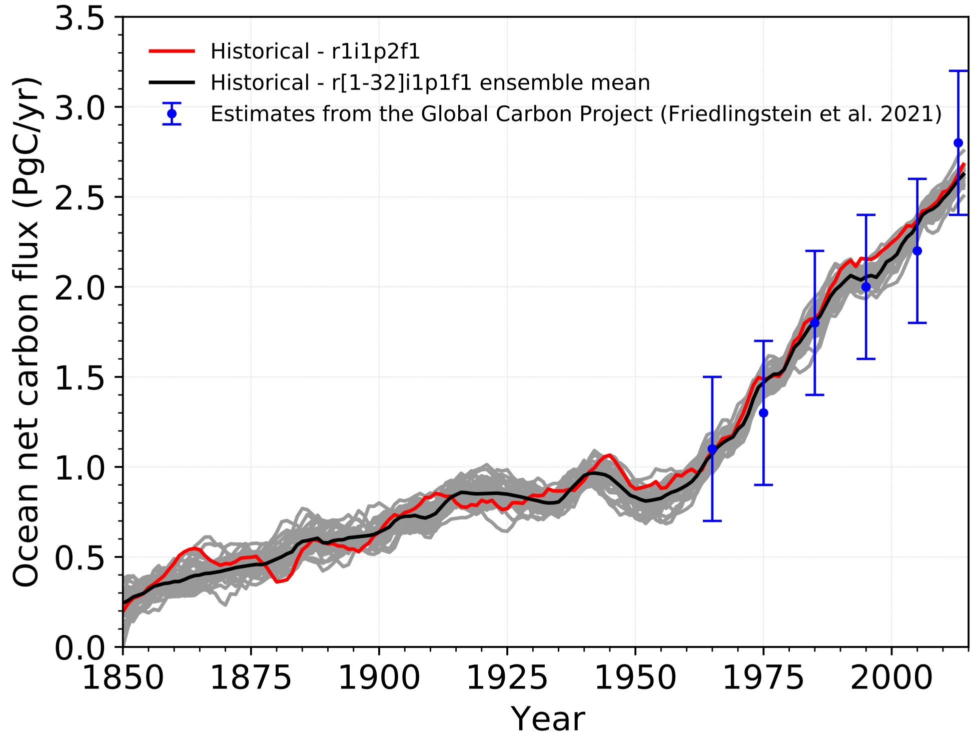
► Similar working frame and protocols to allow for comparison and statistical treatment.

► Reduce uncertainties on carbon-climate interactions and future carbon cycle projections.

► Last exercise : CMIP6 (2019-2020) gathering 86 models. 11 models for C4MIP among which IPSL-CM6A-LR.

Introduction – Comparison to estimates

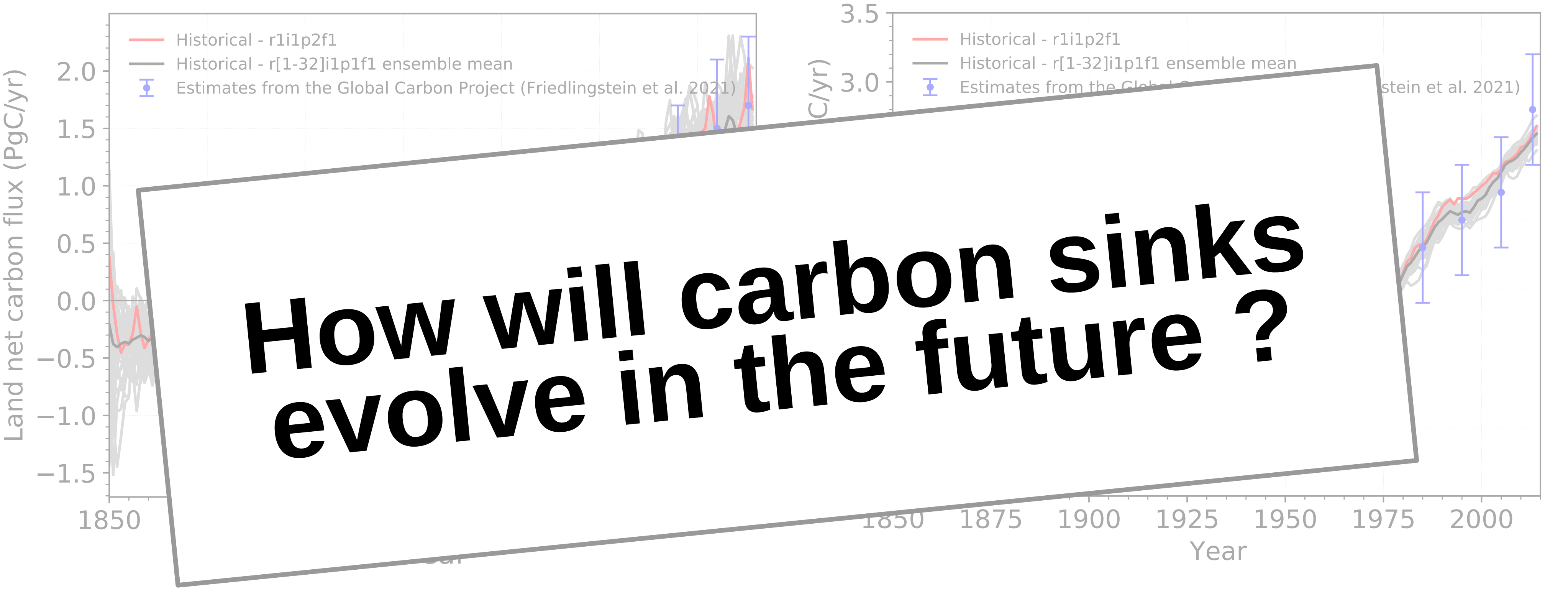




► Net carbon flux (NBP) is consistent with data-driven estimates both for land and ocean.

► NBP increases : sinks carbon uptake increases.

Introduction – Comparison to estimates



How will carbon sinks evolve in the future ?

► Net carbon flux (NBP) is consistent with data-driven estimates both for land and ocean.

► NBP increases : sinks carbon uptake increases.

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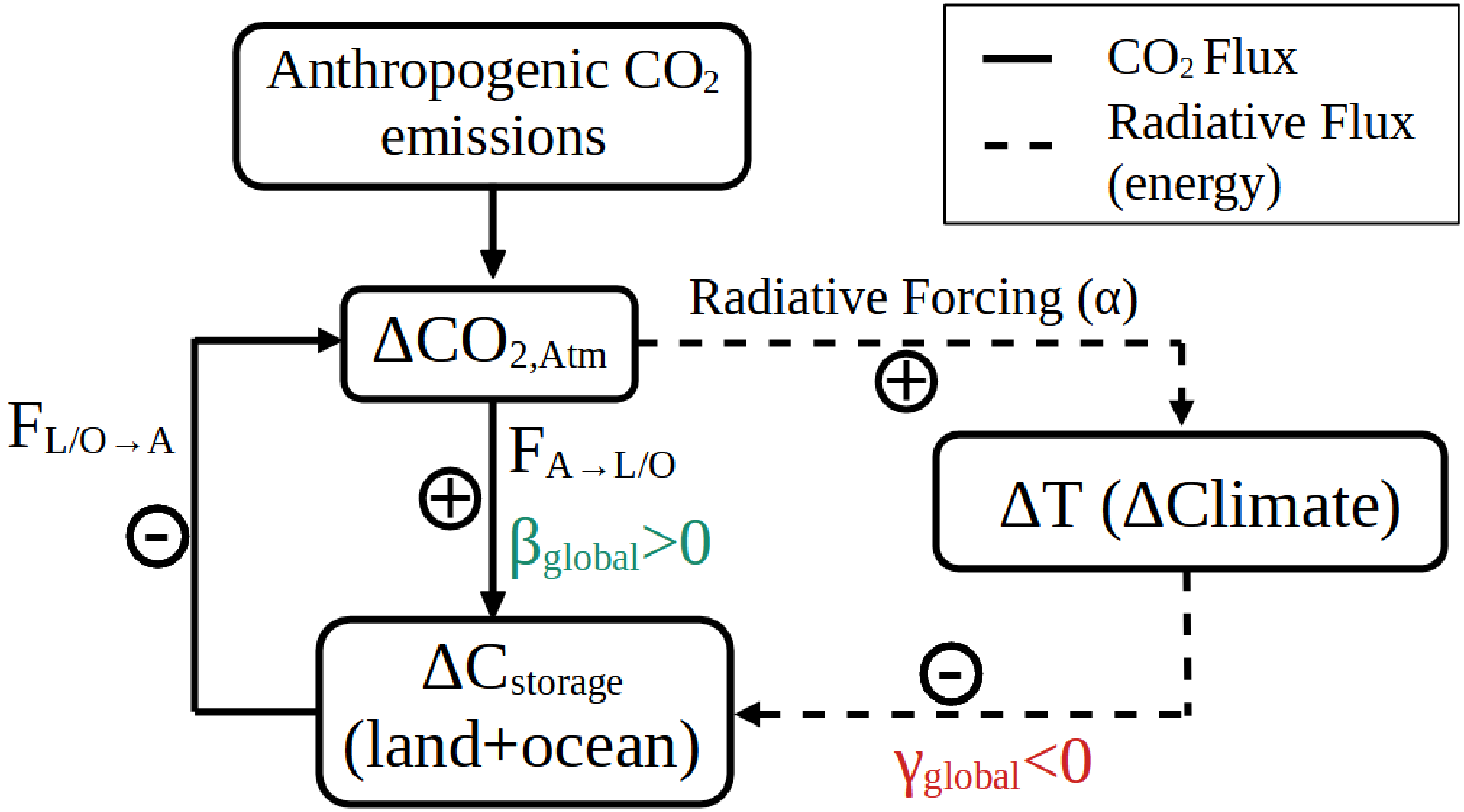
Climate-Carbon feedbacks – C^4MIP simulations

- Biogeochemical feedback (β, $PgC.ppm^{-1}$) enhances terrestrial sink of carbon.
- Climate feedback (γ, $PgC.K^{-1}$) weakens terrestrial sink of carbon.

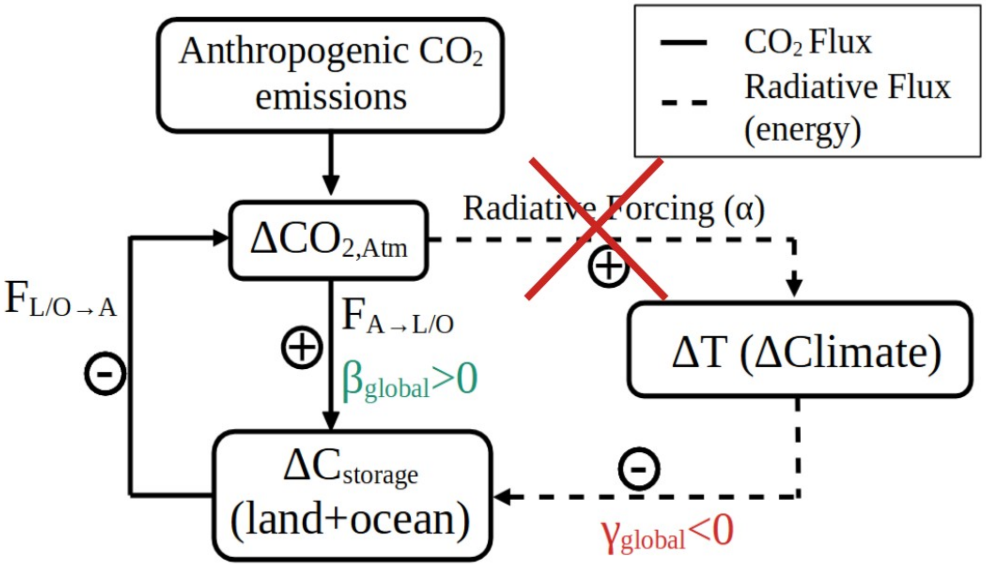


Δ = actual - 1850

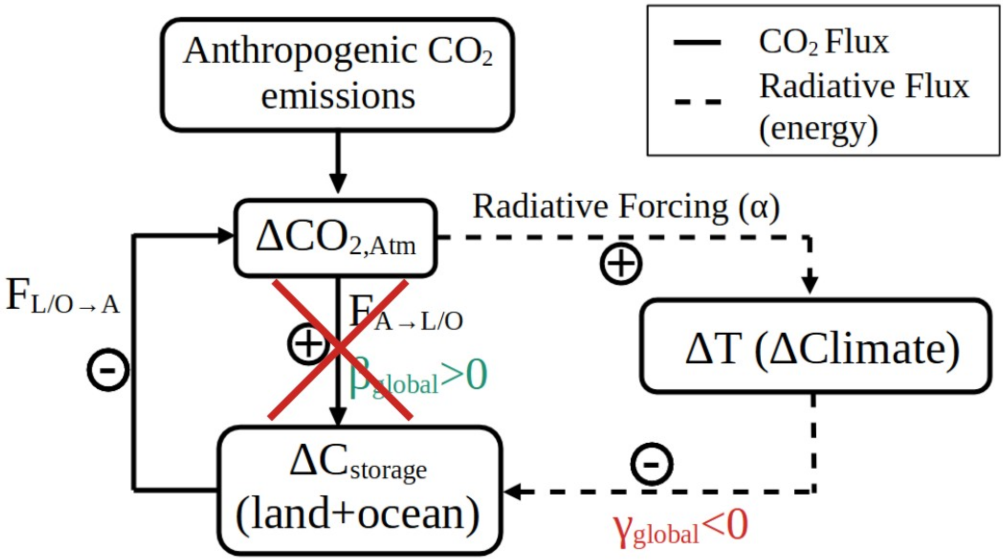
Climate-Carbon feedbacks – C[4]MIP simulations

► 2 additional simulations on the top of the fully coupled (COU) simulation

BGC



RAD

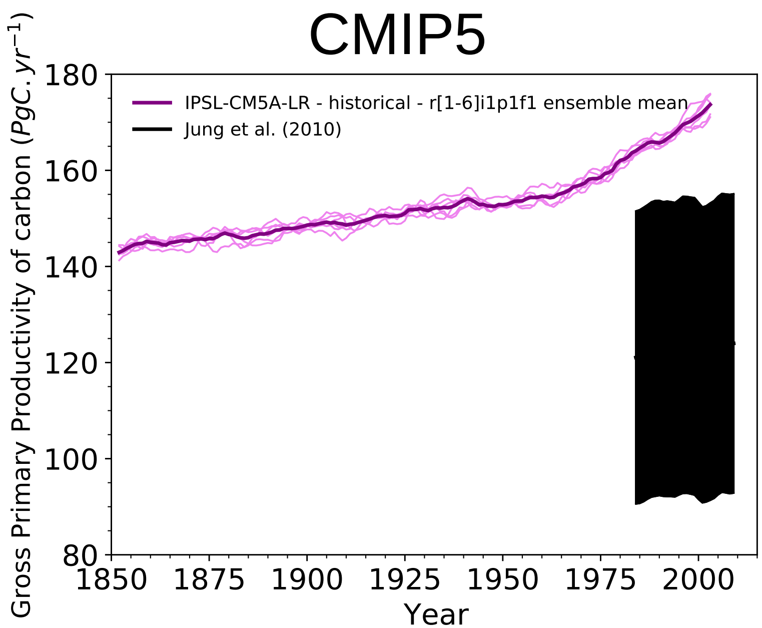


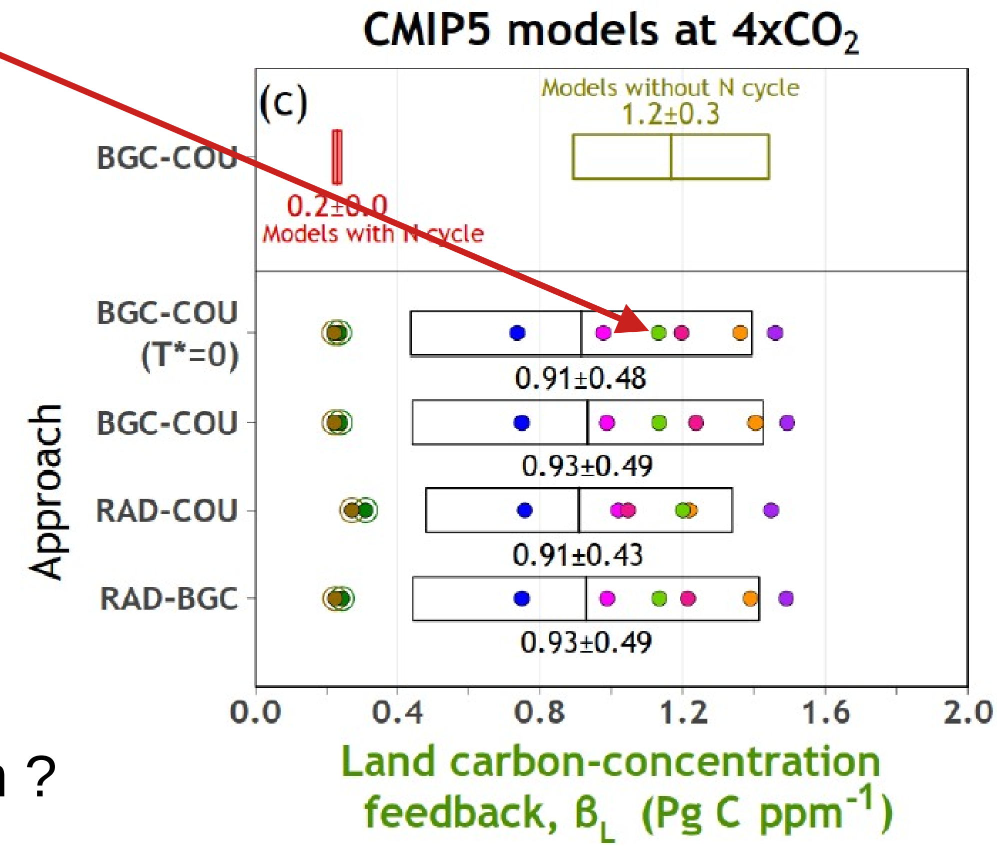
► Biogeochemically-coupled (BGC) simulation to study the fertilization effect.

► Radiatively-coupled (RAD) simulation to study the climate effect.

Climate-Carbon feedbacks – CMIP5

► **CMIP5** (2013) : high biogeochemical effect (β_L) in IPSL model…





[Aroral et al. (2020)]

...due to lack of nutrients representation ?

► At high CO_2 concentrations, the limiting factor for vegetation growth is nutrients availability

⇒ **nutrients limitation effect**.

Solution : explicitly introduce nutrients cycles into the model.

Climate-Carbon feedbacks – CMIP6

► **CMIP6** (2019) : explicit N cycle not ready in IPSL model
⇒ **Vcmax** parametrization [*Sellers et al. (1996)*] to mimic nutrient limitation and artificially decrease β at high CO_2.

► Vcmax is a key parameter for GPP/photosynthesis (Vcmax ↗ ⇒ GPP ↗)
⇒ Vcmax controls photosynthesis and land carbon capture.

► Parametrization calibrated with FACE experiments [*Norby et al. (2010)*]
⇒ **until 600ppm CO_2.**

P1 :

$$Vcmax = Vcmax25 \cdot \left[1 - \text{coef\_down\_reg} \cdot \log\left(\frac{CO_2}{380}\right)\right]$$

⇒ too strong Vcmax decrease at high CO_2

P2 :

$$Vcmax = Vcmax25 \cdot \left[1 - \text{coef\_down\_reg} \cdot \left(\frac{CO_2 - 380}{CO_2 + \text{coef\_curve}}\right)\right]$$

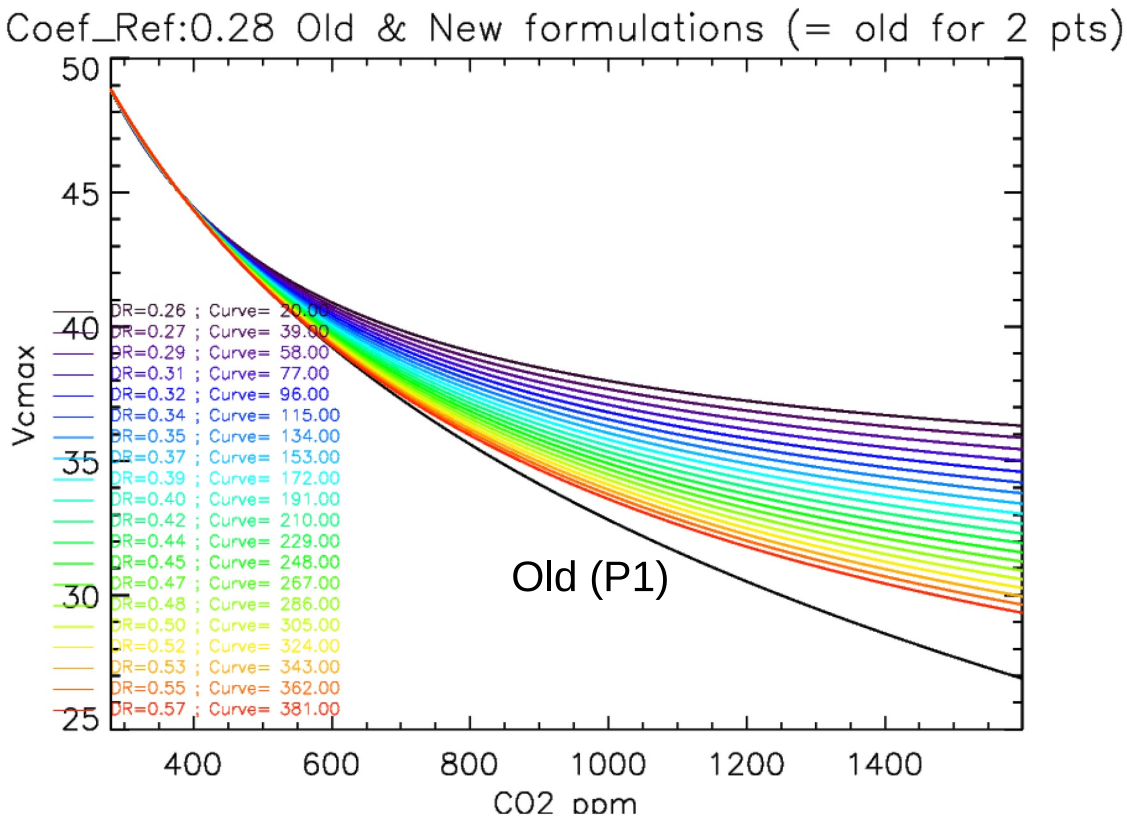
Climate-Carbon feedbacks – Vcmax calibration

Calibration of the parameters “coef_down_reg” & “coef_curve” to have :

► The same Vcmax as P1 over the historical period (280 and 380 ppm)

► A smaller reduction of Vcmax with high CO2 concentration (above 800 ppm)

► Vcmax is PFT dependent



P2 :

$$Vcmax = Vcmax25 \cdot \left[1 - \text{coef\_down\_reg} \cdot \left(\frac{CO_2 - 380}{CO_2 + \text{coef\_curve}} \right) \right]$$

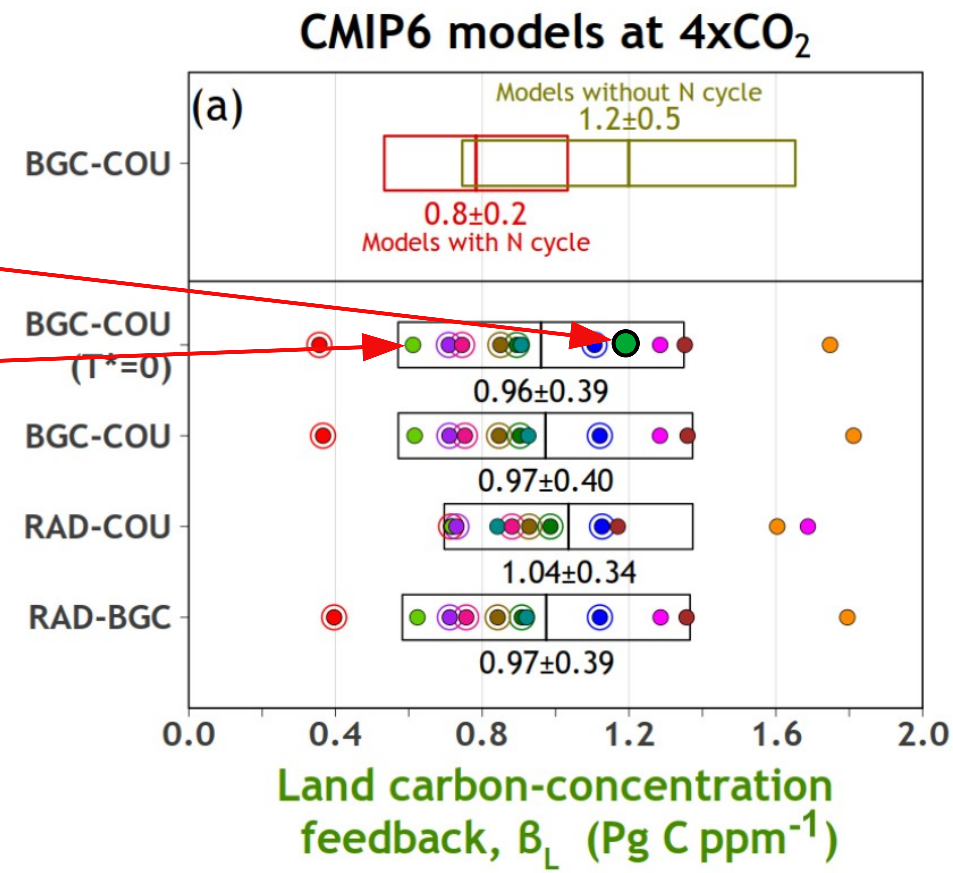
Idealized simulations – Comparison to C⁴MIP models

► Overall reduction of global β compared to CMIP5.

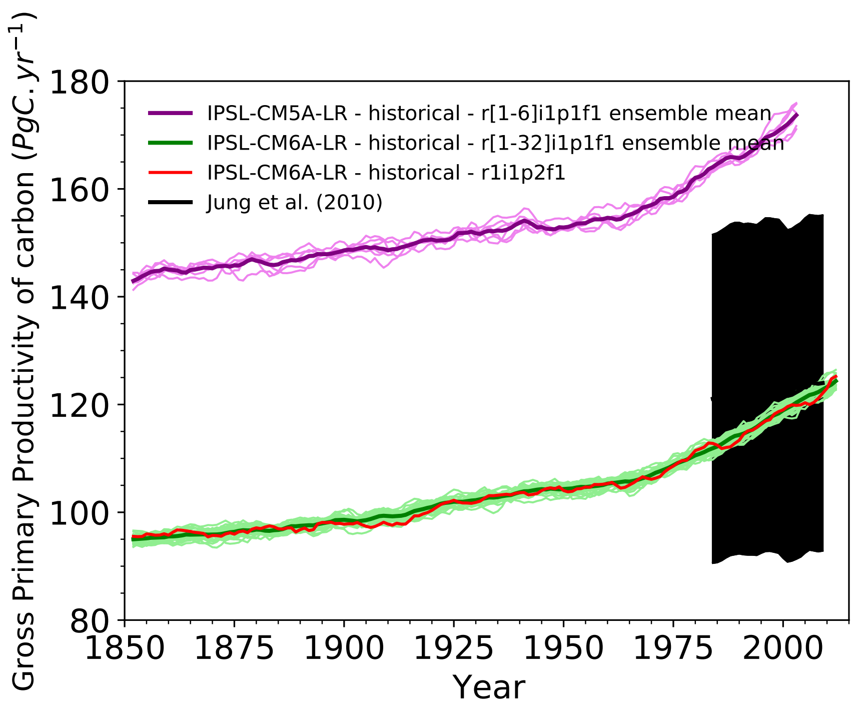
From here (CMIP5)…

… to there (CMIP6 with P1).

► Global β in the range if models with explicit N cycle.



[Aroral et al. (2020)]



► GPP has been reduced in CMIP6 to get closer to data-driven estimates.

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Idealized simulations – Effect of parametrization on GPP

► **CMIP5** : no parametrization
⇒ highest GPP sensitivity to CO_2 increase.

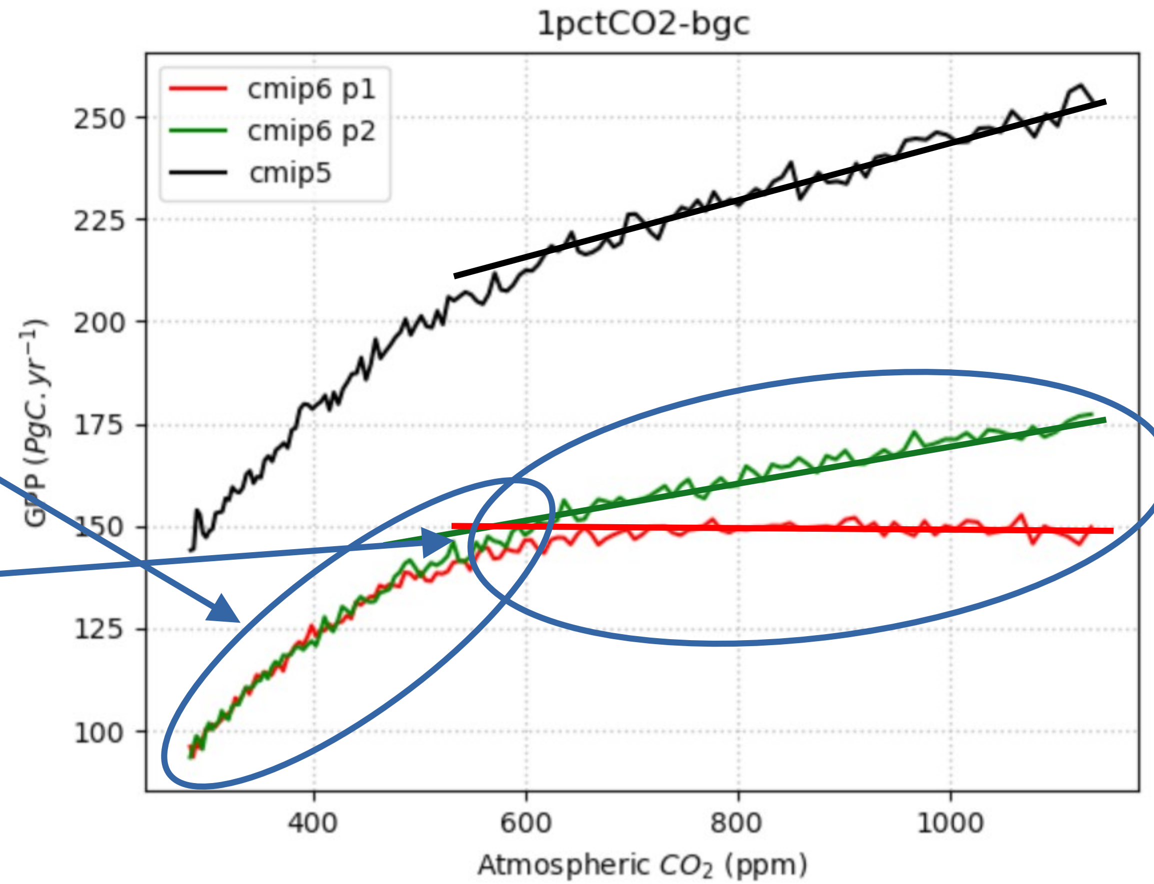
► **CMIP6** :

- before 600ppm : no difference

- after 600 ppm : influence of parametrization

- GPP sensitivity to CO_2 increase is higher for P2 than P1 (but lower than CMIP5).

► Vcmax parametrization has a direct consequence on GPP, i.e. on land ability to take up carbon.



Idealized simulations – Effect of parametrization on β

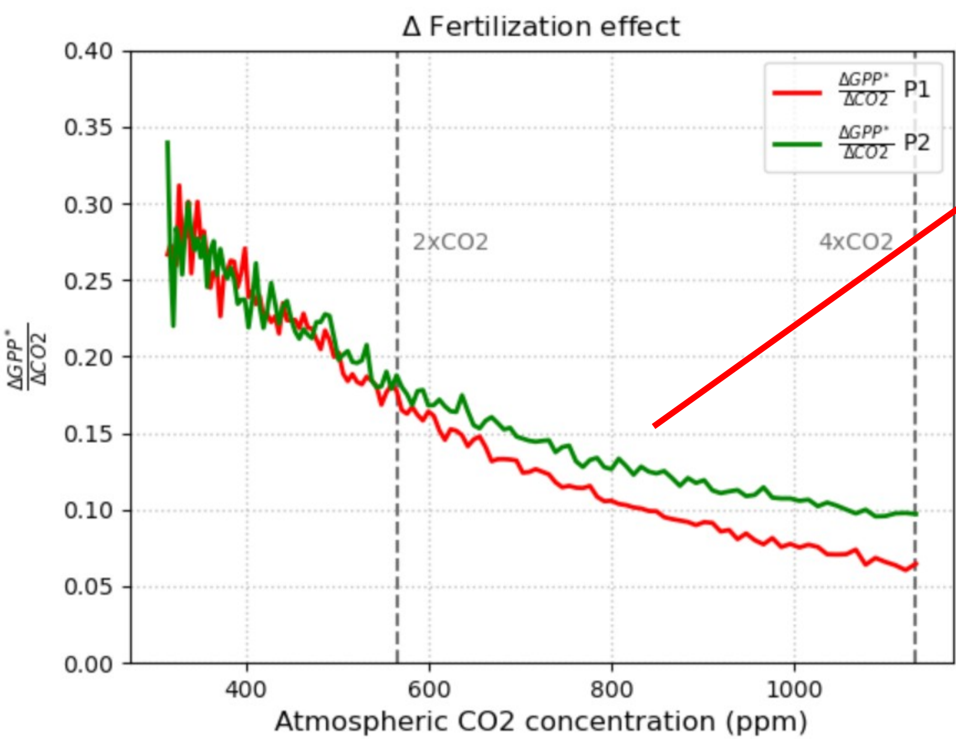
- Global fertilization effect $\frac{\Delta GPP}{\Delta CO_2}$:

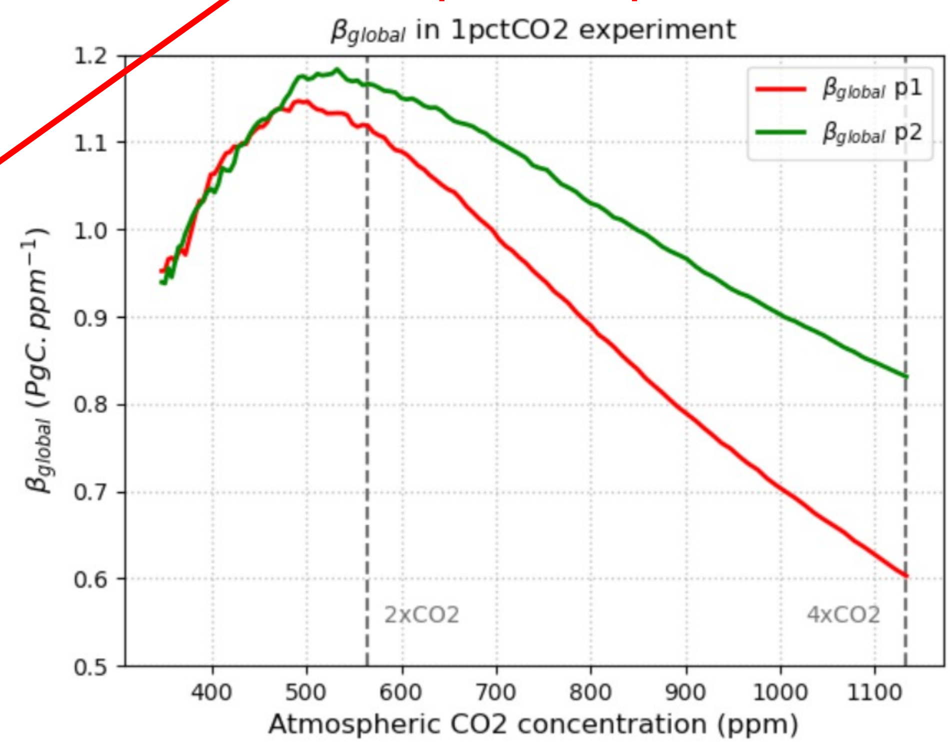
- higher for P2 than P1.

- decreases with increasing CO_2.

- $$\beta = \frac{\Delta C_L}{\Delta CO_2} = \frac{\Delta C_{Veg}}{\Delta CO_2} + \frac{\Delta C_{Soil+Litter}}{\Delta CO_2}$$
$$= \Delta\tau_{Veg} \Delta CUE \frac{\Delta GPP}{\Delta CO_2} + \Delta\tau_{Soil+Litter} \frac{\Delta RH}{\Delta LF} \frac{\Delta LF}{\Delta CO_2}$$

Impact of parametrization





- Same shape for both parametrizations : maximum β around 500ppm.

- At low CO_2 : same β for both parametrizations.
At high CO_2 : β is higher for P2.

Idealized simulations – Comparison to C[4]MIP models

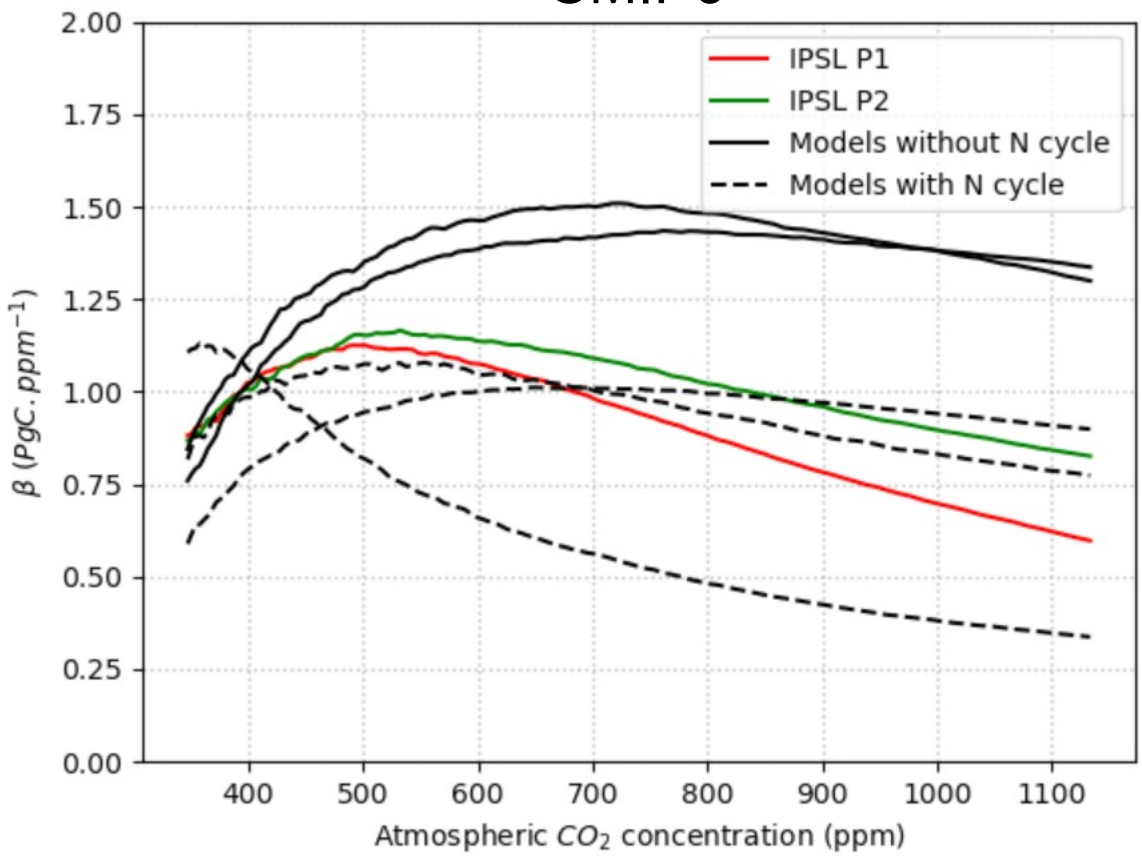
► Models with explicit N cycle have lower β due to N limitation effect at high CO_2 concentrations.

► IPSL model is close to models with explicit N cycle :

⇒ the global biogeochemical response is consistent with more advanced models.

⇒ Vcmax parametrization is efficient to get a correct global β effect.

CMIP6

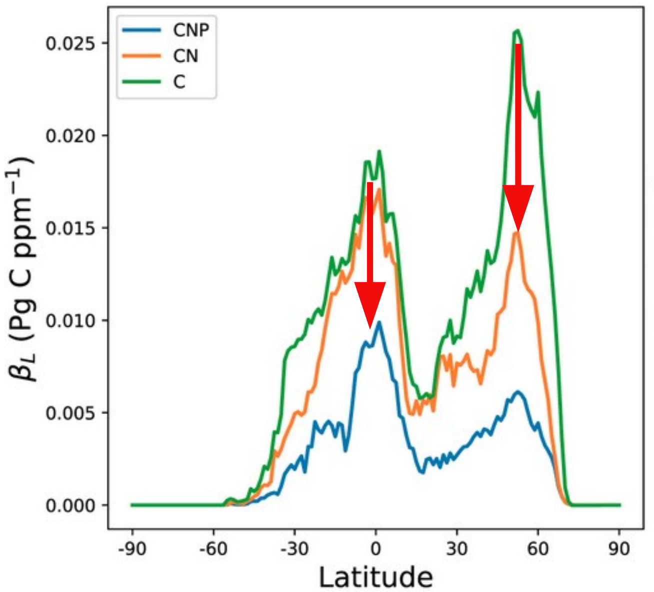


Idealized simulations – Comparison to C4MIP models

► Models with explicit N cycle have lower β at all latitudes.

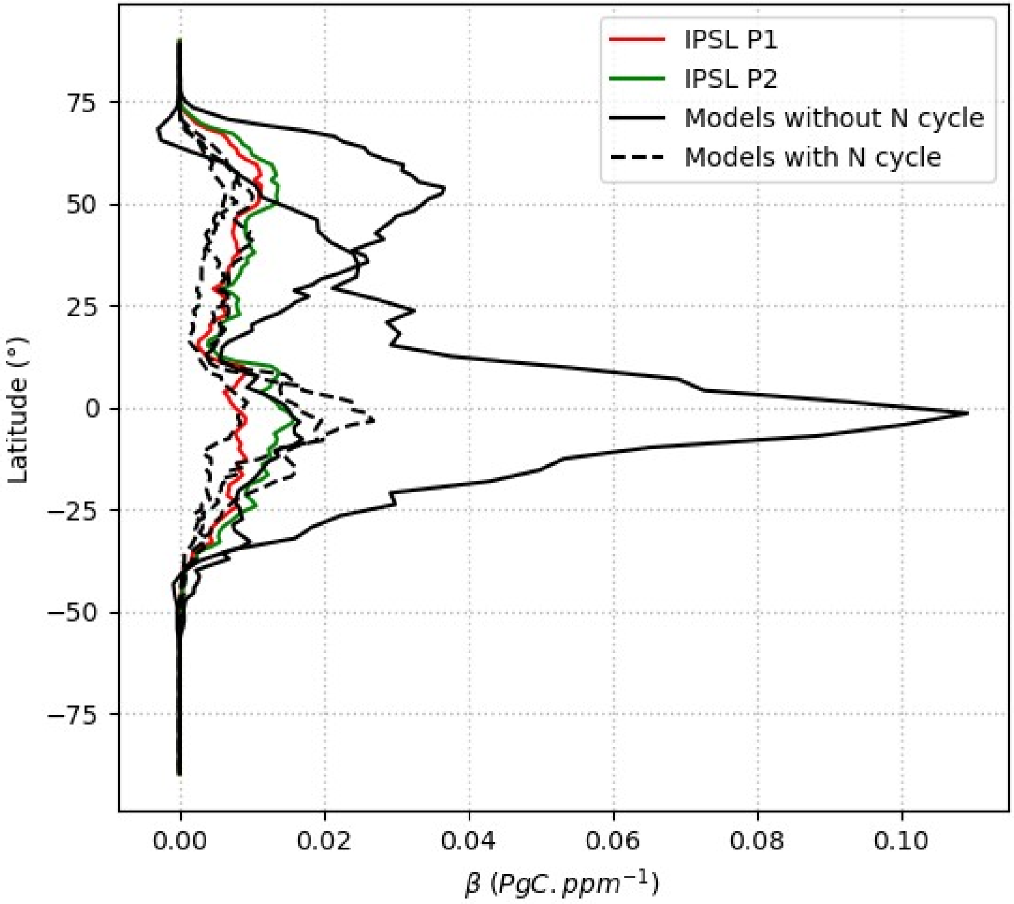
► IPSL model is still in the range of models with explicit N cycle with a slight β overestimation at mid to high latitudes.

► Difference between P1 and P2 in equatorial and tropical regions…



[Ziehn et al. (2021)]

CMIP6 at 4xCO2



…not consistent with N limitation.

► N limitation in mid-to-high latitudes
► But P limitation in tropical and equatorial regions.

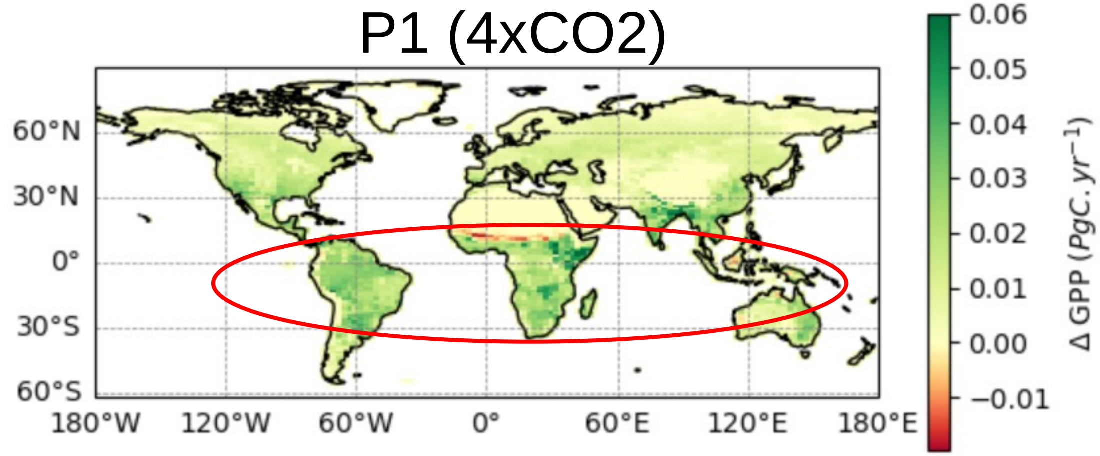
Idealized simulations – Regional differences

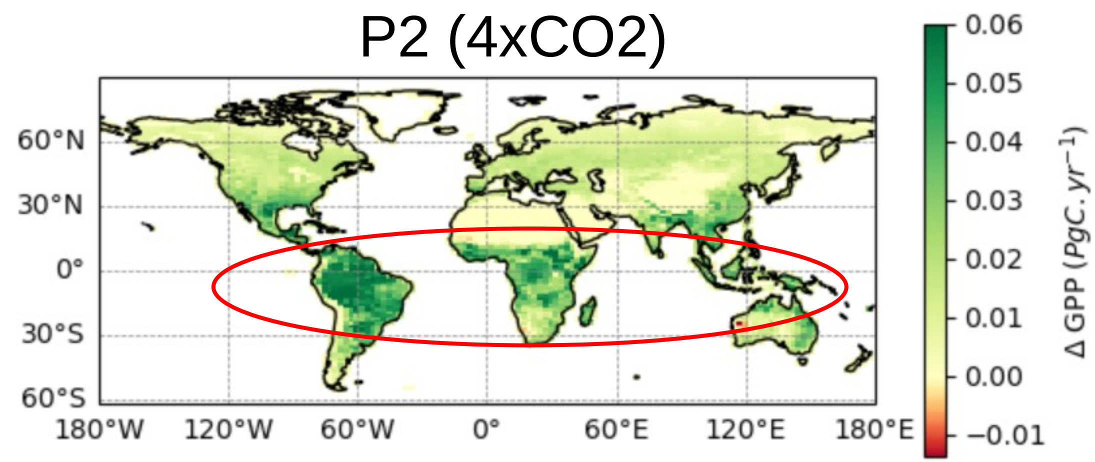
► ΔGPP>0 in almost all regions : fertilization effect.

► Highest GPP increase in **tropical and equatorial regions**.

► Higher GPP increase for P2 than for P1 ⇒ higher fertilization effect for P2.

► GPP difference P2-P1 is also higher in **equatorial and tropical regions** ⇒ parametrization acts mainly through these regions.





Conclusion : the global land sensitivity to elevated CO_2 concentration comes from equatorial and tropical regions where ecosystems are more sensitive to the parametrization.
⇒ **not consistent with other models having explicit N cycle.**

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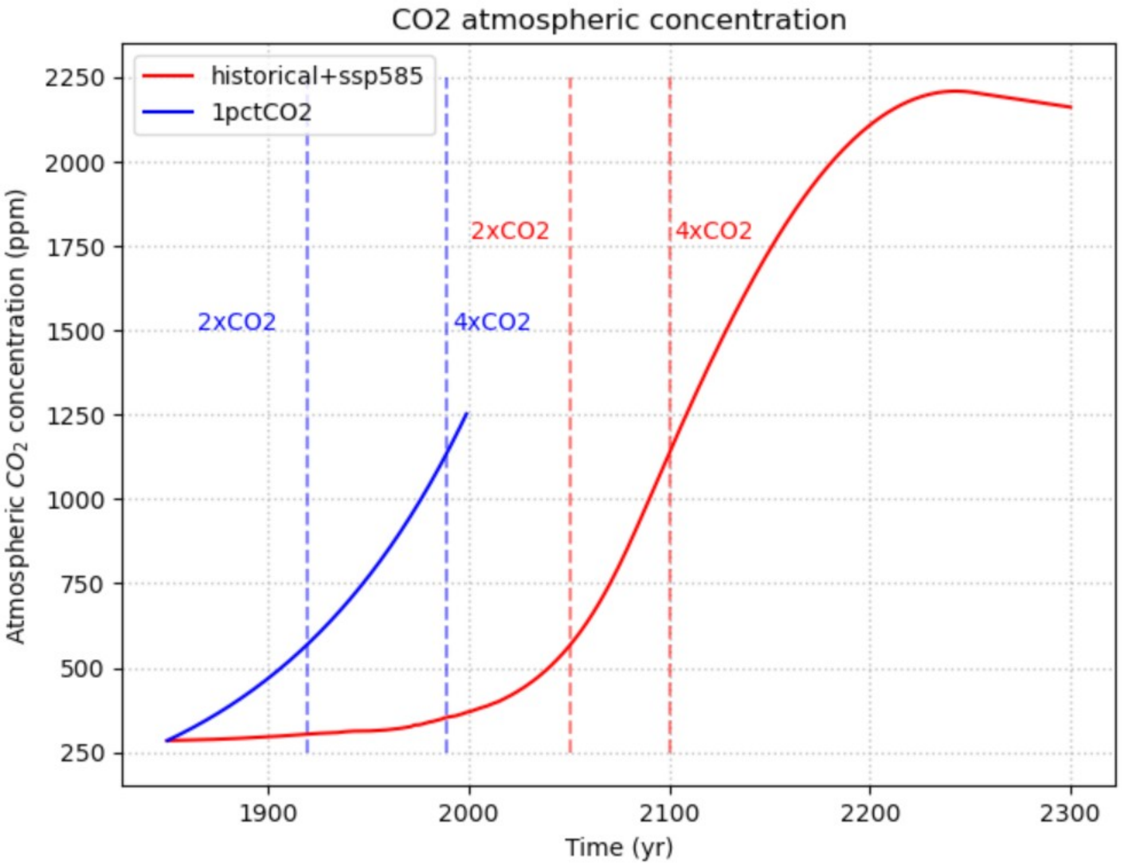
Historical and scenarios simulations – Presentation

► Historical data combined to SSP-585 (high-emission) scenario.

► Atmospheric CO_2 :
- 2050 ⇒ 2xCO2
- 2100 ⇒ 4xCO2

► All forcings : CO_2, other greenhouse gas, aerosols, land-use change.

► 2 simulations : with or without land-use change.



Historical and scenarios simulations – Comparison to idealized simulations

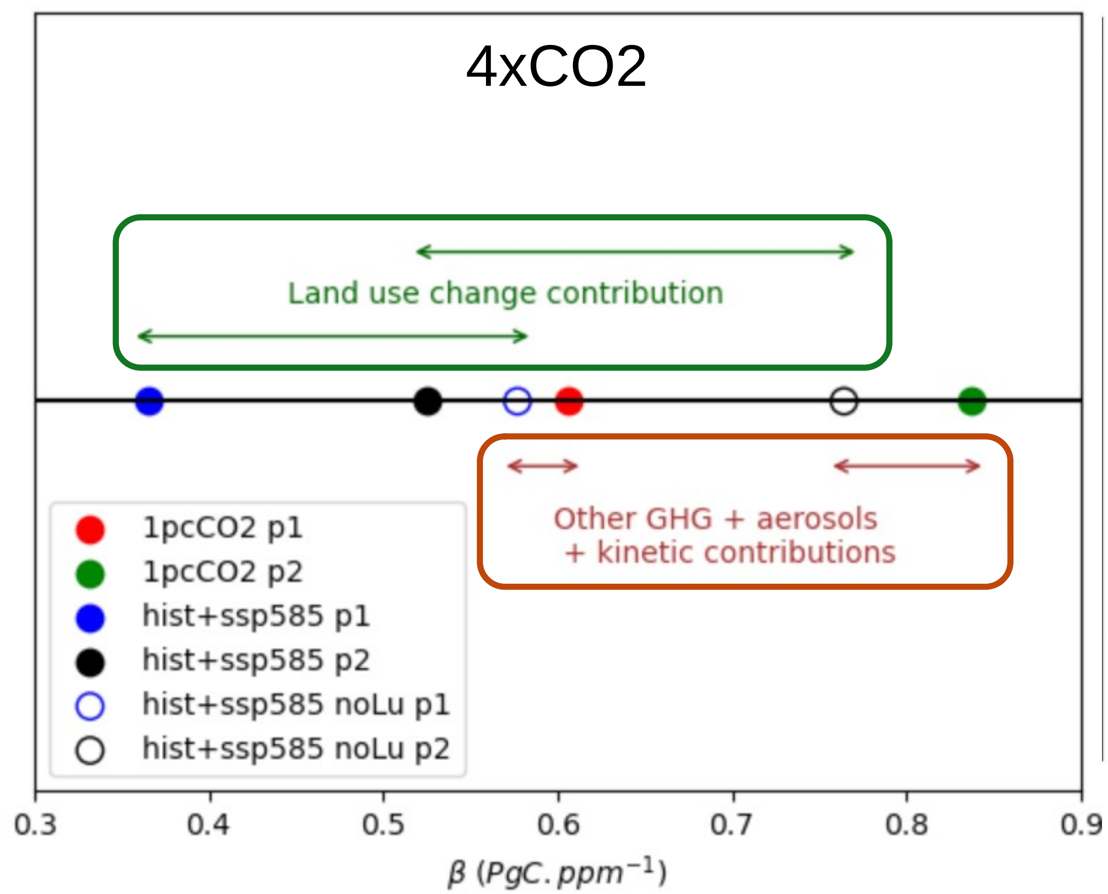
► Smaller β for P1 than P2 in each simulation (other forcings do not change the order in SSP-585).

► Higher β for idealized simulations (higher fertilization effect) than SSP-585 :

- influence of other GHG and aerosols (not spatially uniform).

- difference in “speed of increase” of CO_2 concentration (kinetic effect).

- land-use change (deforestation) decreases land carbon stocks.



► Land-use change causes the biggest β decrease (25% to 40% of its value) due to loss in terrestrial carbon stocks.

► Other GHG, aerosols and kinetic effect are responsible for a smaller β decrease than cannot be easily interpreted.

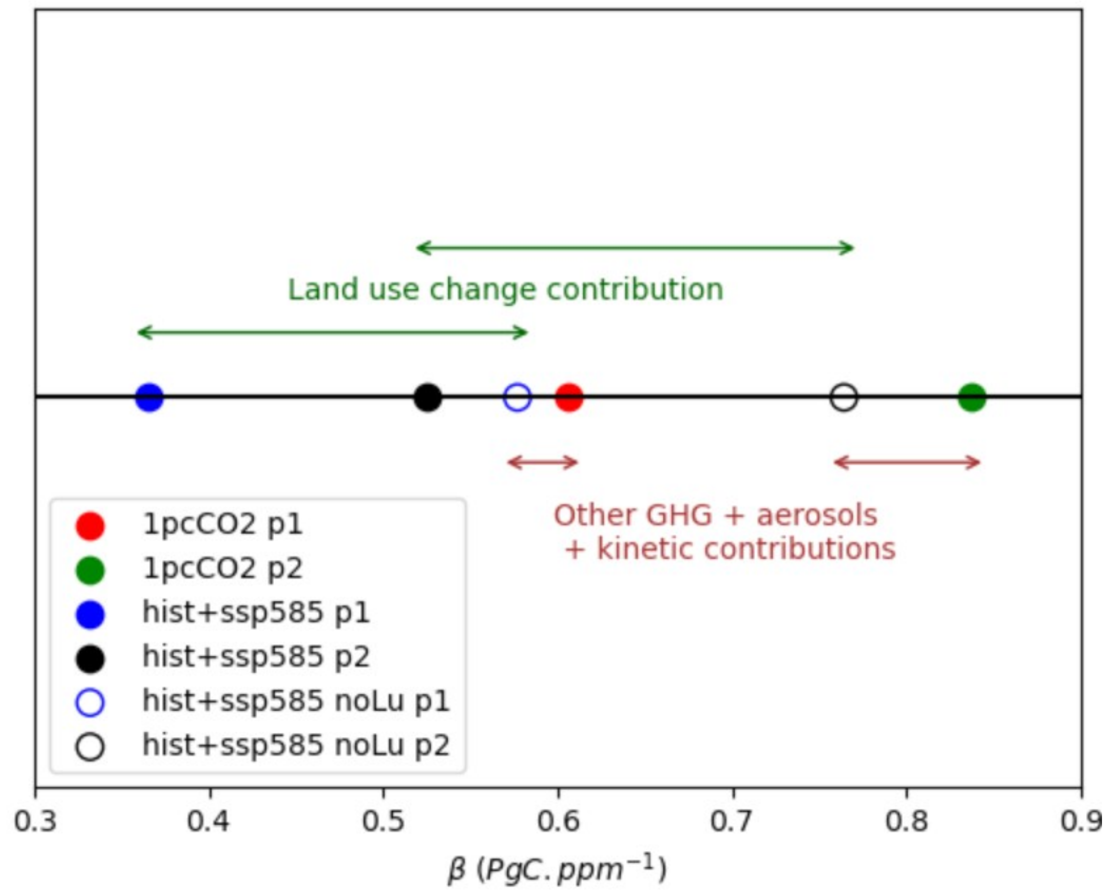
Historical and scenarios simulations – What's next ?

► Design of new simulations to disentangle contributions to β :

- CO_2 forcing alone with future scenario concentrations.
- Land-use change forcing alone.
- Other GHG+aerosols forcing alone.

► Better understanding and quantification of different forcings contributions for future land carbon uptake.

► Identification of main causes to β decrease will allow taking relevant decisions
⇒ societal and political impact.



► Importance of parametrization only for high-emission scenarios.

Historical and scenarios simulations – Compatible emissions

► At 2xCO2 :

- CO_2 concentration is lower than 600ppm : no significant difference between P1 and P2.

- ~30% of CO_2 emissions are captured by carbon sinks.

- surprisingly γ>0.

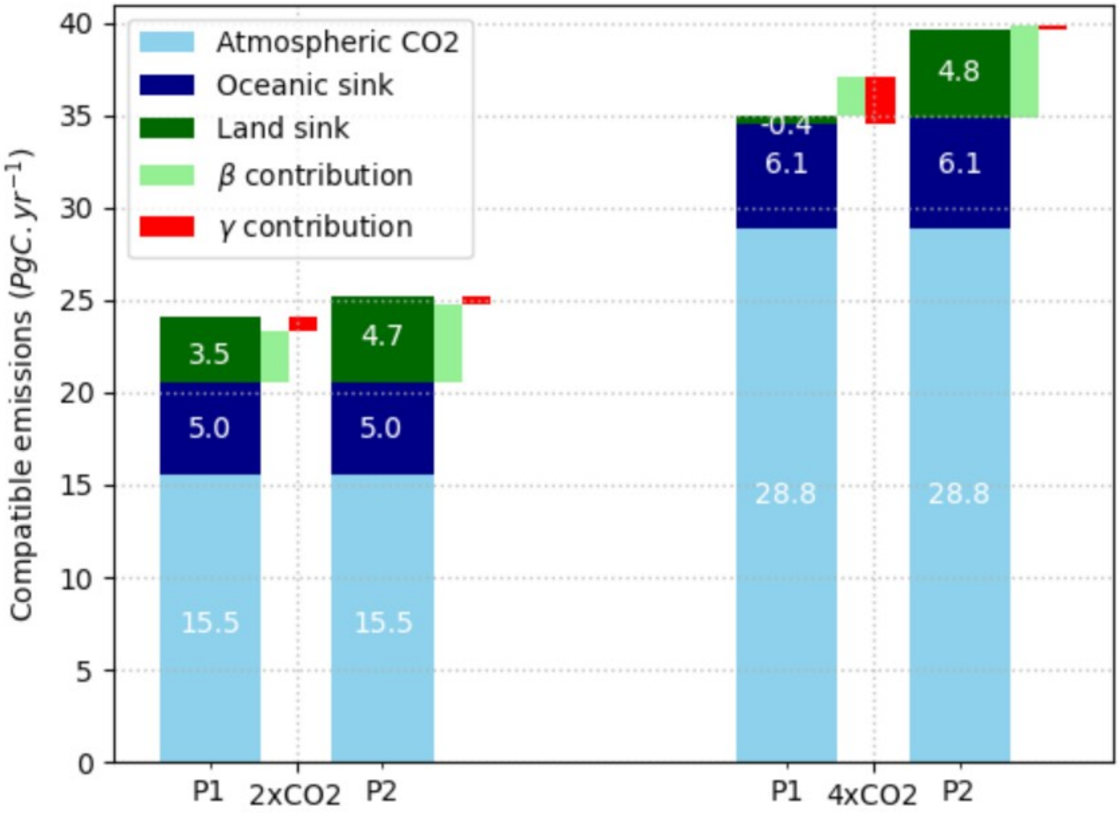
► At 4xCO2 :

- land sink remained stable for P2

- land becomes a carbon source for P1 : negative climate contribution dominates the fertilization effect.

- ~15% to 20% of CO_2 emissions are taken up by carbon sinks.

SSP-585



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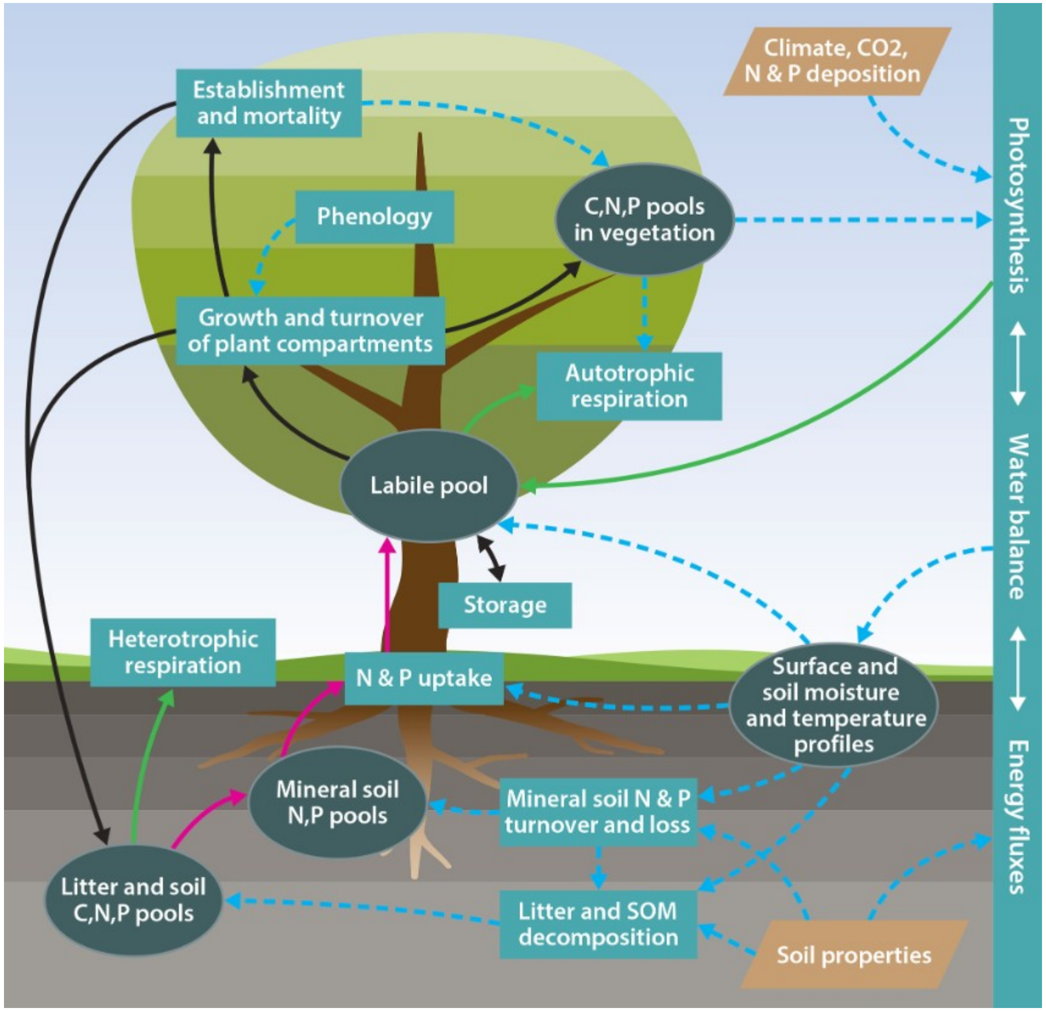
Conclusion – Limits of Vcmax parametrization

► GPP evolution for models with N cycle is very different ⇒ other processes than nutrients limitation govern land response to CO_2 increase and are not represented by a simple parametrization :

- Heterotrophic respiration, water cycle (soil moisture), carbon allocation...are affected by N cycle.

- Wrong regional representation : miss spatial distribution of N (agricultural areas...).

- Only partial response of C cycle to climate change : increase in N mineralization (boosting vegetation productivity) not represented.



⇒ Importance of integrating nutrients cycles to the IPSL model.

Conclusion – Is IPSL model with downregulation efficient to simulate N limitation ?

► **YES** if we aim to represent :

- the global β effect and thus the global biogeochemical feedback.

- historical evolution of global GPP and NBP.

► **NO** if we aim to represent :

- the regional β effect and local biogeochemical feedbacks (P1 is even better than P2 in this case).

- processes involving carbon-nitrogen interactions.

Conclusion – Limits of model validation

► Data-driven estimates of GPP used for validation.

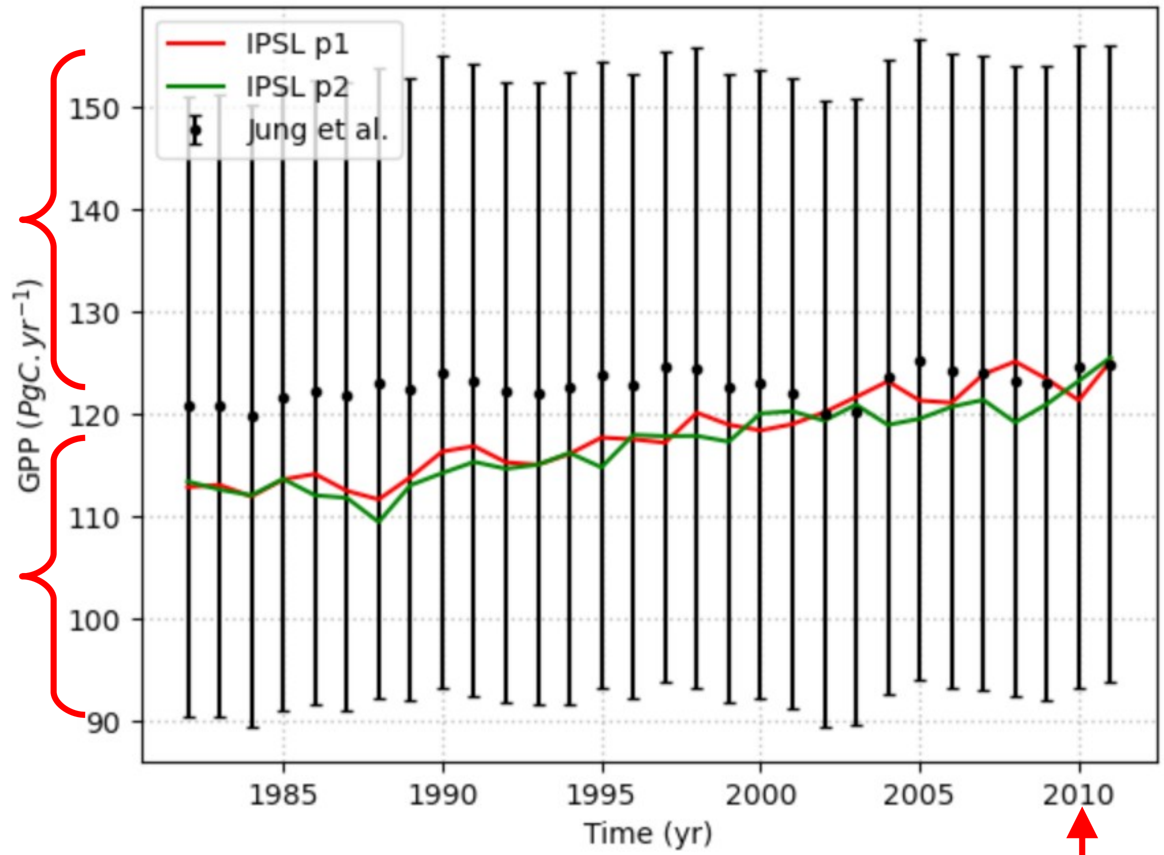
► GPP is similar for P1 and P2 (“low” CO_2 values) and consistent with observations.

► Limits :

- high uncertainty on measurements (~25% on each side).

- too low CO_2 values to separate P1 from P2.

- different climate in the model and the observations.



⇒ Important ways of improvement : reduce observation uncertainties and better constrain models.

Conclusion

► However, **the main lines of future climate and carbon cycle evolutions are known** and models uncertainties should not be used to delay political action.

►Regardless the precision of Earth System Models, **reducing anthropogenic carbon emissions is crucial and must be a priority**.

Thank you for your attention !

Backup slides

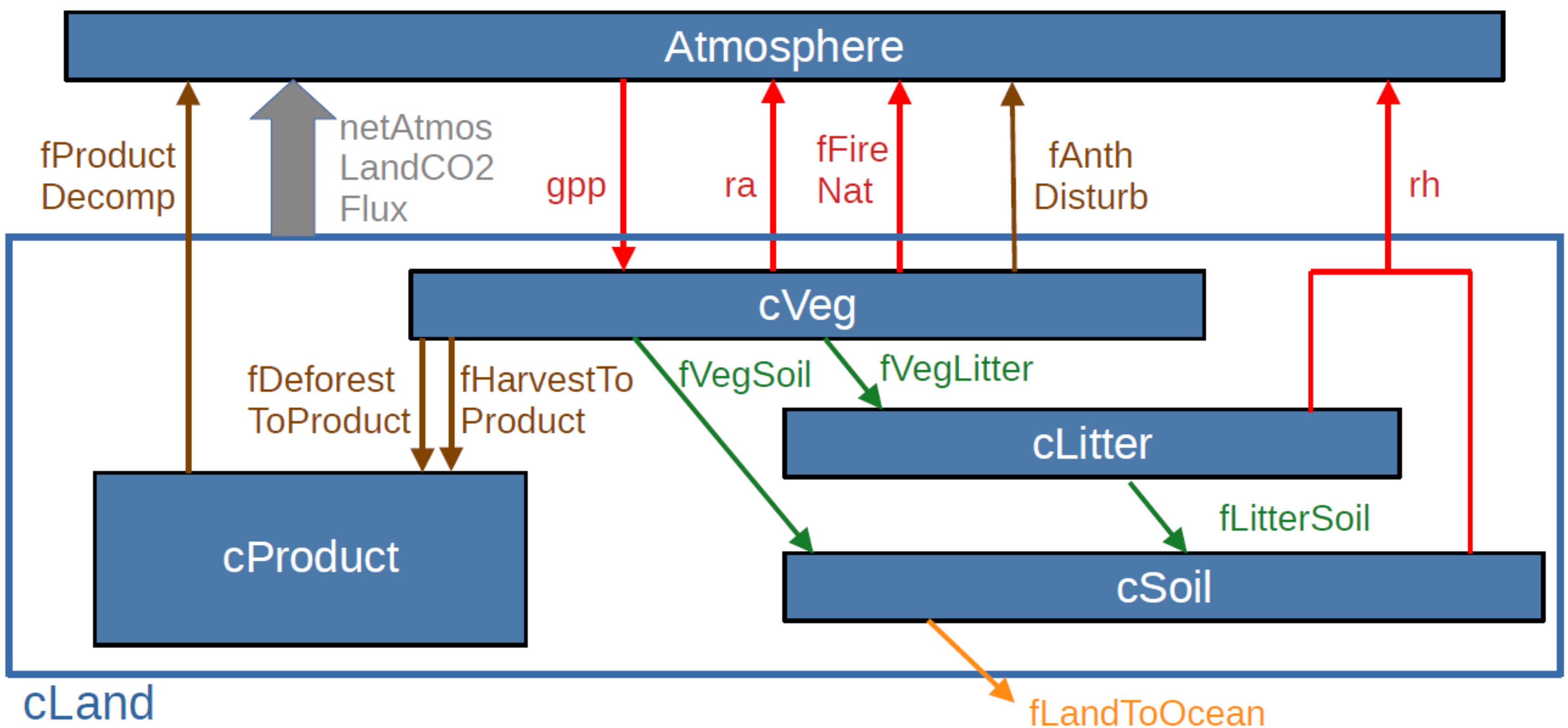
Model – Carbon pools and fluxes

- Carbon pools : where carbon is stored.
  Carbon fluxes : transfer between pools.

  } Common variables among C⁴MIP models

- Land carbon capture : GPP
  Land carbon release : RH, RA, fires, anthropogenic disturbance…

  Net carbon flux : NBP = GPP – RH – RA - disturbances



Climate-Carbon feedbacks – Framework

► Carbon source/sinks balance :

$$\underbrace{\frac{dCO_{2,Atm}}{dt}+\frac{dC_L}{dt}+\frac{dC_O}{dt}}_{\text{Sinks}}=\underbrace{E}_{\text{Source}}$$

► Coupled carbon cycle – climate feedback parameters :

COU $$\int \frac{dC_L'}{dt}=\overbrace{\underbrace{\gamma_L \Delta T'}_{\text{C-Climate}}+\underbrace{\beta_L \Delta CO_{2,Atm}'}_{\text{Biogeochemical}}}^{\text{Linearity assumption}}$$

RAD $$\int \frac{dC_L^+}{dt}=\gamma_L \Delta T^+$$

BGC $$\int \frac{dC_L^*}{dt}=\gamma_L \Delta T^*+\beta_L \Delta CO_{2,Atm}'$$

BGC-COU approach ⇒ $\Delta T^* \approx 0$

$$\gamma_L=\frac{\Delta C_L'-\Delta C_L^*}{\Delta T'}<0$$ (often)

$$\beta_L=\frac{\Delta C_L^*}{\Delta CO_{2,Atm}'}>0$$

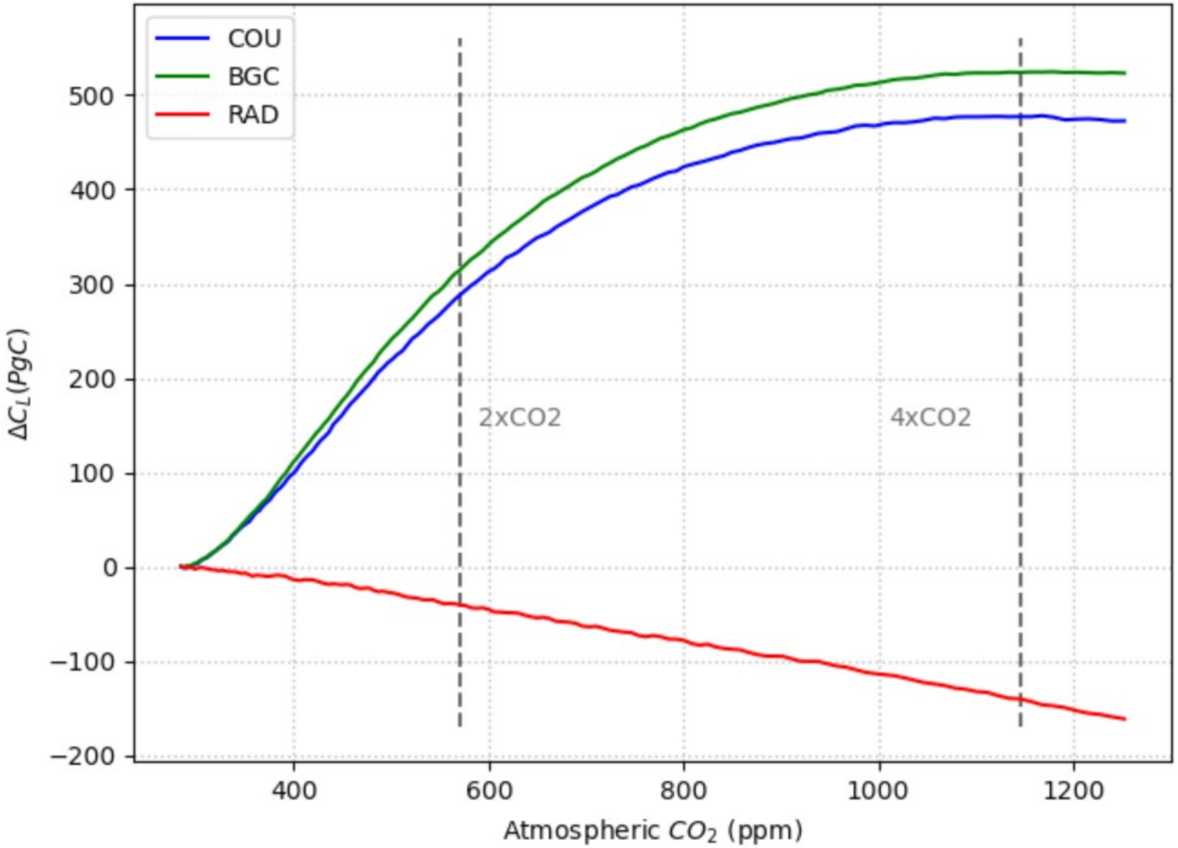
Climate-Carbon feedbacks – Carbon land capture

► Idealized 1%CO_2/yr increase simulations in COU, BGC and RAD modes.
⇒ Framework to calculate β and γ.

► BGC shows the **fertilization effect** by increasing CO_2 concentration : $\beta_L>0$.

► RAD shows the influence of **climate change** on land carbon capture : $\gamma_L<0$.

► COU shows the combination of fertilization and climate change effects.



COU differs from the sum of BGC and RAD : linear combination is a debatable assumption.

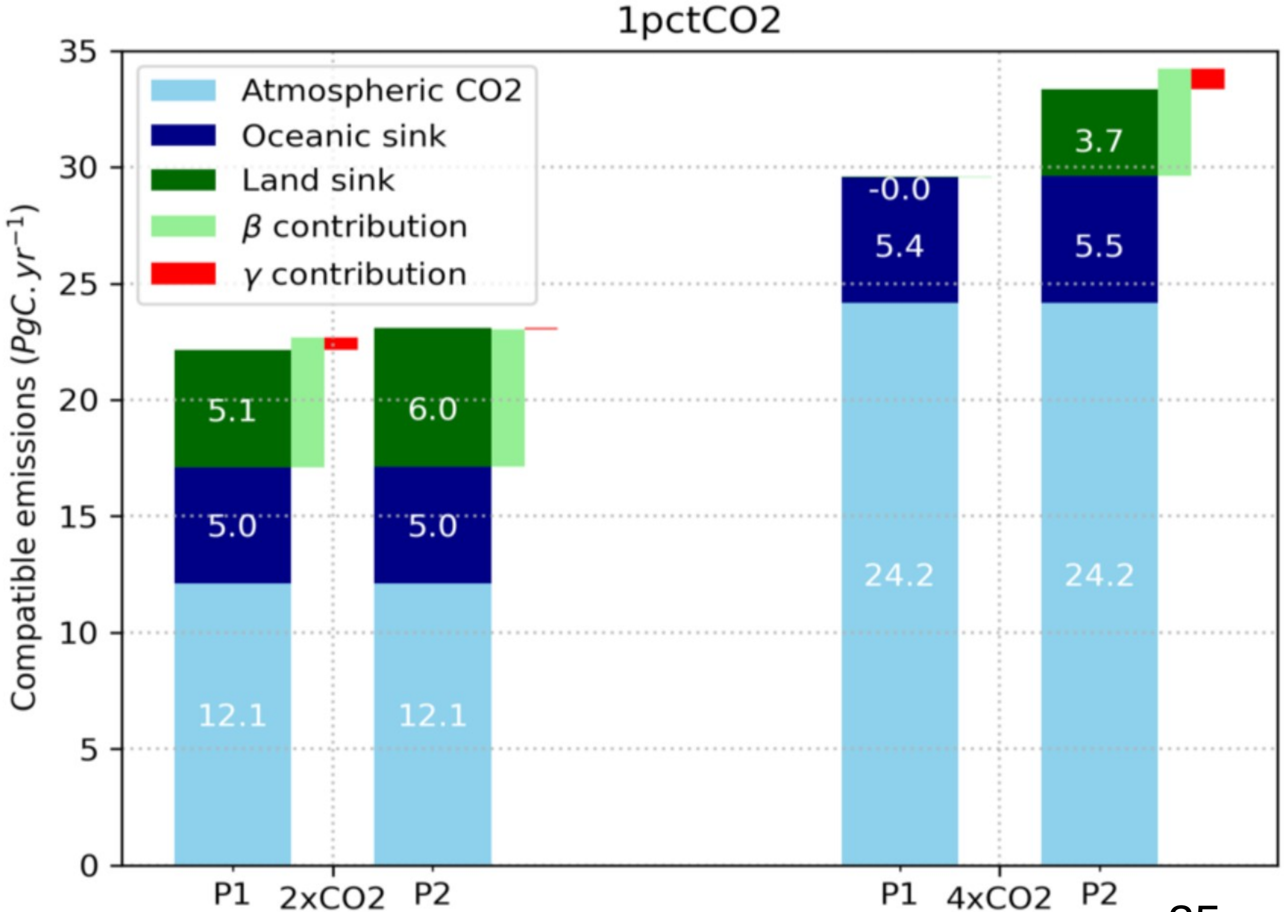
Results – Compatible emissions (CE)

- ► Compatible emissions = change in C pools : $\int_{1850}^{t} E\,dt = \Delta CO_2 + \Delta C_L + \Delta C_O$
- ► Prescribed atmospheric CO2 concentrations ⇒ same for P1 and P2.
- ► Oceanic sink almost independent from Vcmax parametrization.
- ► Land sink split into β and γ contributions.

► **2xCO2 :**

- only difference is internal model variability.

- half of the emissions are captured by carbon sinks.



Results – Compatible emissions (CE)

- ► Compatible emissions = change in C pools : $\int_{1850}^{t} E\,dt = \Delta CO_2 + \Delta C_L + \Delta C_O$
- ► Prescribed atmospheric CO2 concentrations ⇒ same for P1 and P2.
- ► Oceanic sink almost independent from Vcmax parametrization.
- ► Land sink split into β and γ contributions.

► **4xCO2 :**

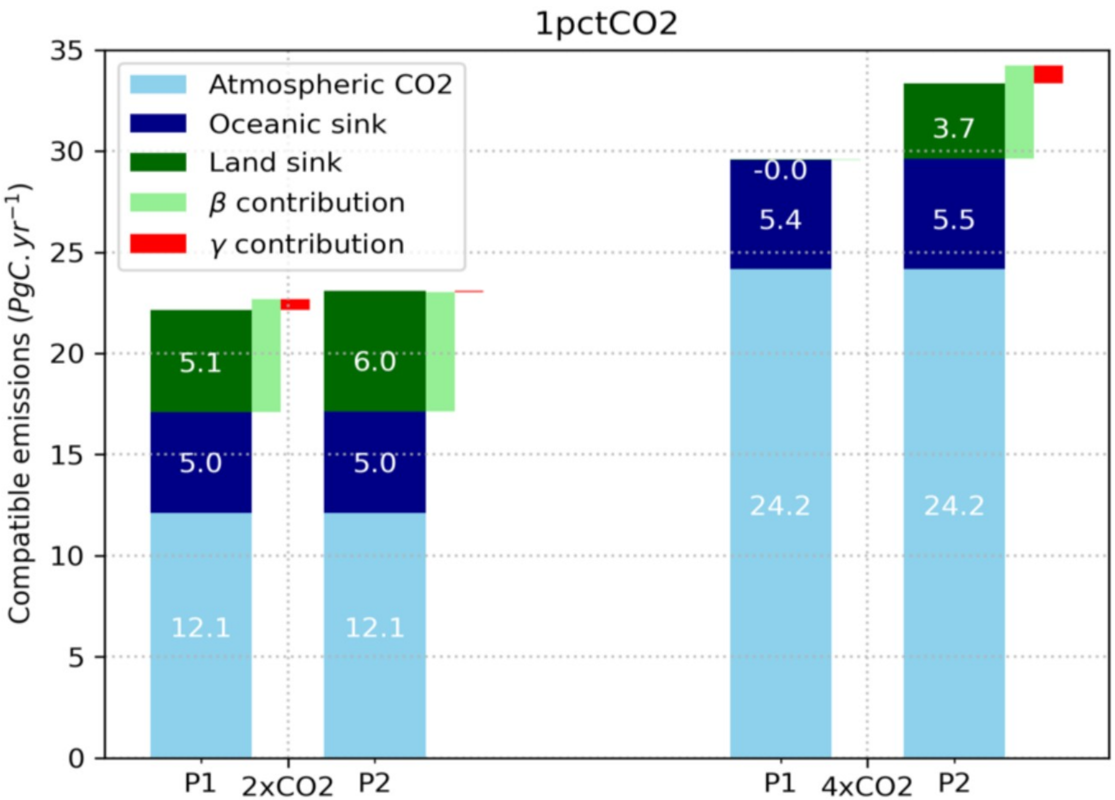
- CE higher than at 2xCO2

- Partition has changed : 70% of emissions remain in the atmosphere. Sinks efficiency ⇘.

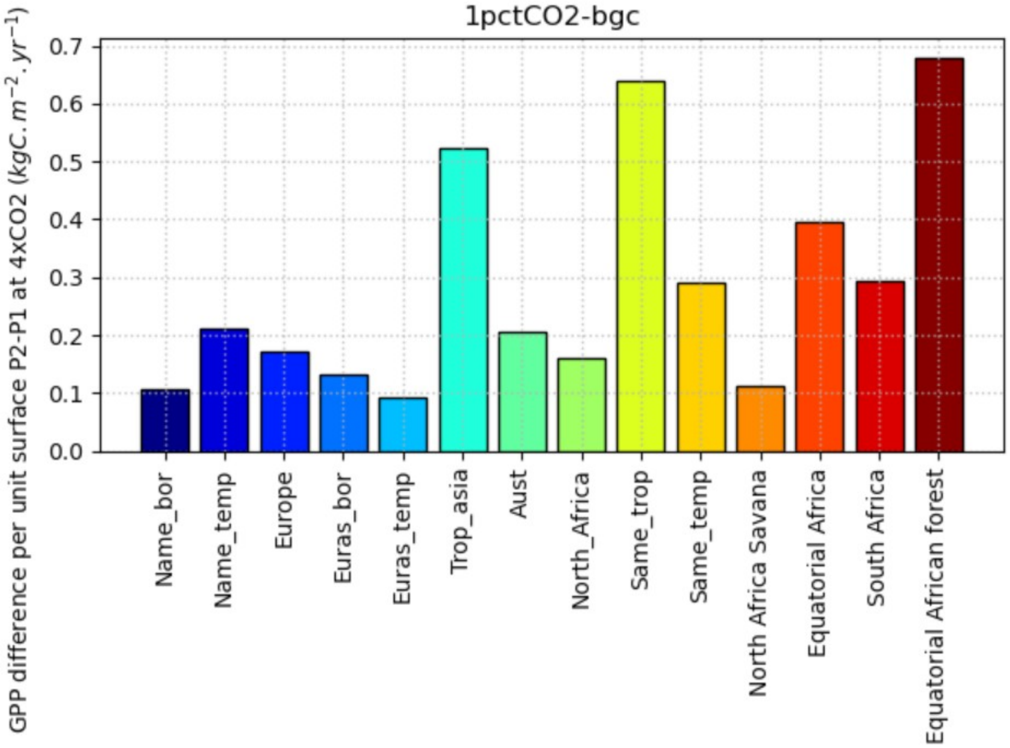
- For P1, land is not a sink anymore. For P2, the sink has decreased compared to 2xCO2.

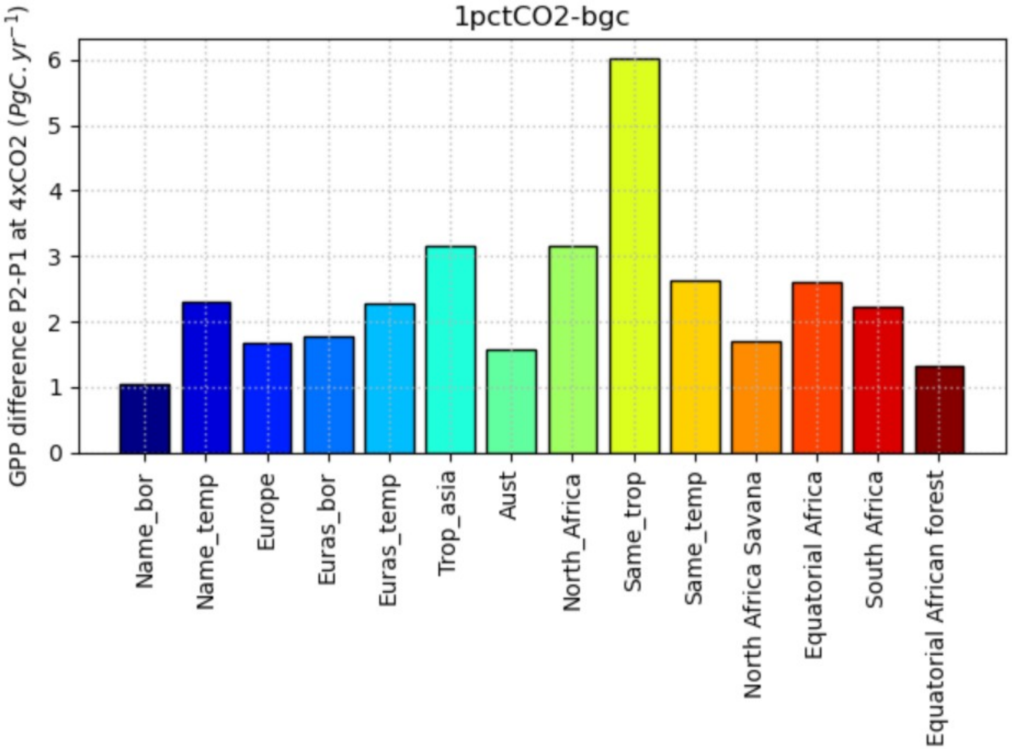
- **Change in C uptake dominated by β contribution.**

- Higher CE for P2 come from higher land sink (or higher β contribution).



Results – Regional GPP differences





► GPP difference per unit surface = change in GPP efficiency between P2 and P1.

► Higher for equatorial and tropical regions.

► GPP difference = change in GPP efficiency + size of the region (absolute change in GPP higher in large regions).

► Higher for equatorial and tropical regions, but less obvious than per unit surface.

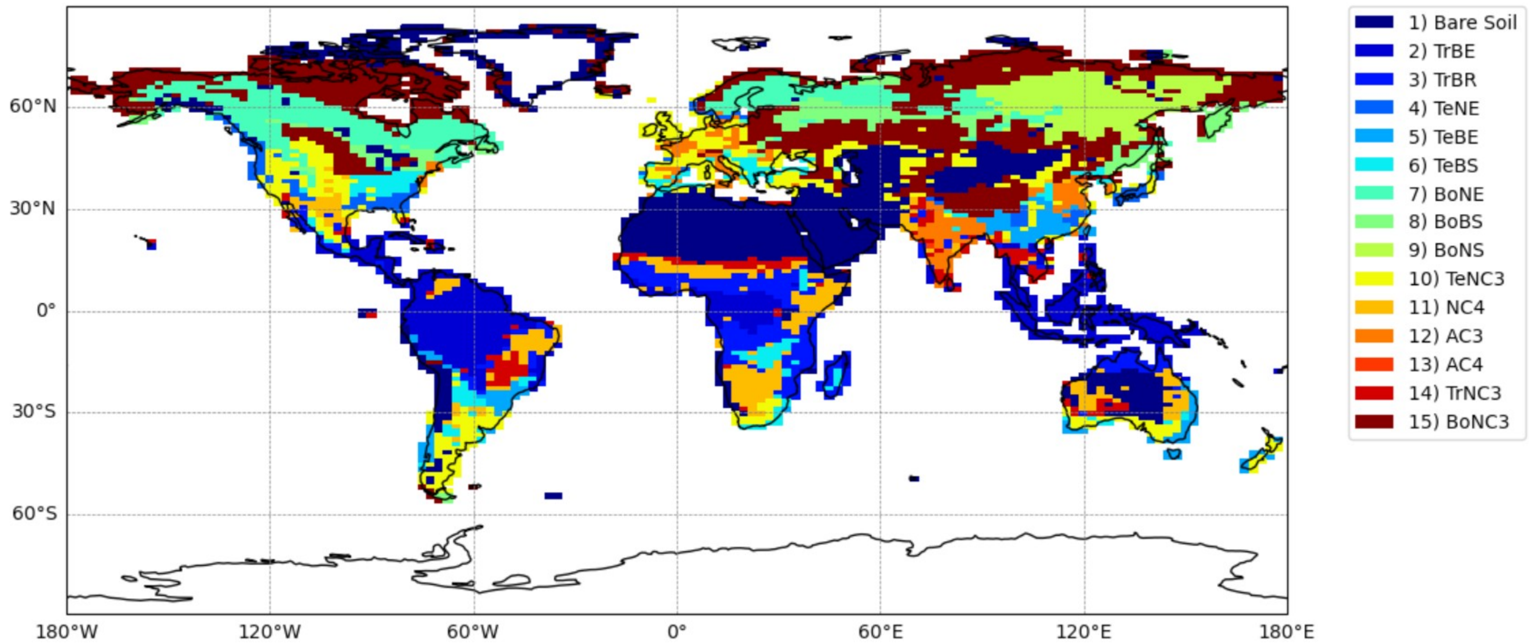
Results – Vegetation in ORCHIDEE : PFTs

► Vegetation described by 15 Plant Functional Types (PFTs) representing various ecosystems.

► GPP parametrization differs for each PFT ⇒ global GPP is a sum of all ecosystems GPP.

► PFT2 (Tropical Broadleaf Evergeen trees) dominates in equatorial and tropical regions.

Dominant PFT at each grid cell

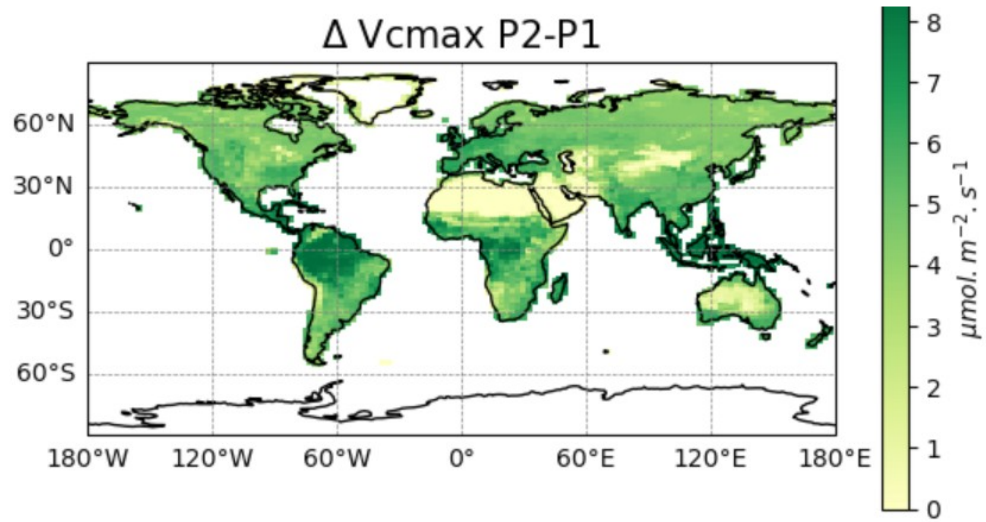


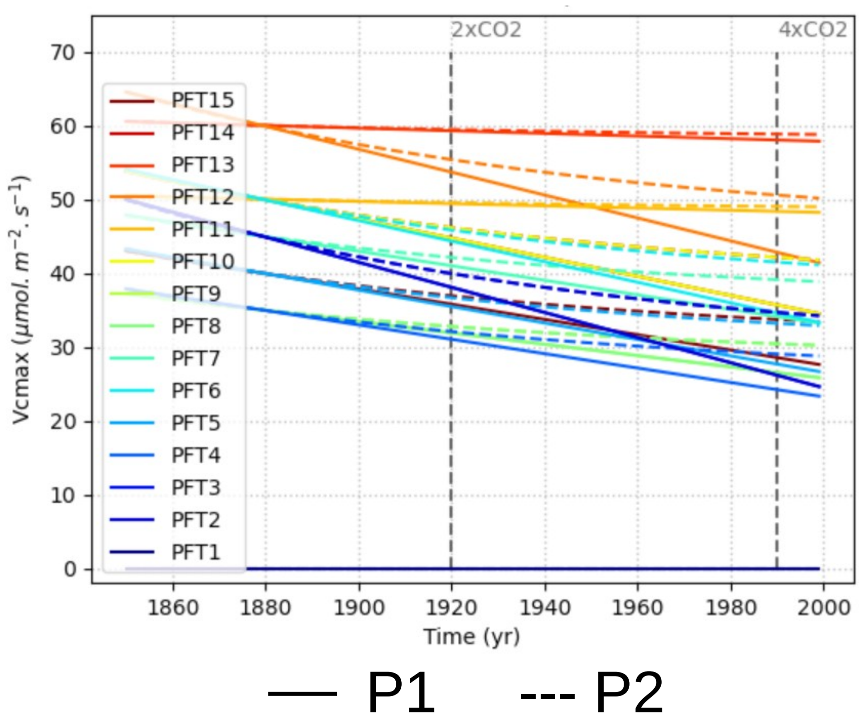
Results – Vcmax evolution

► Vcmax is consistently higher for P2 than P1. The biggest difference occurs in the equatorial and tropical areas.

► Difference in Vcmax between P2 and P1 is the highest for PFT2
⇒ high parametrization effect on GPP in the equatorial and tropical regions is due to PFT2 being both dominant and more sensitive to changes in parametrization.

► **Conclusion :** the global lower land uptake for P1 (lower compatible emissions) mainly results from a response of equatorial and tropical areas, dominated by PFT2 which is the most sensitive to Vcmax parametrization.





Idealized simulations – Comparison to C^4MIP models

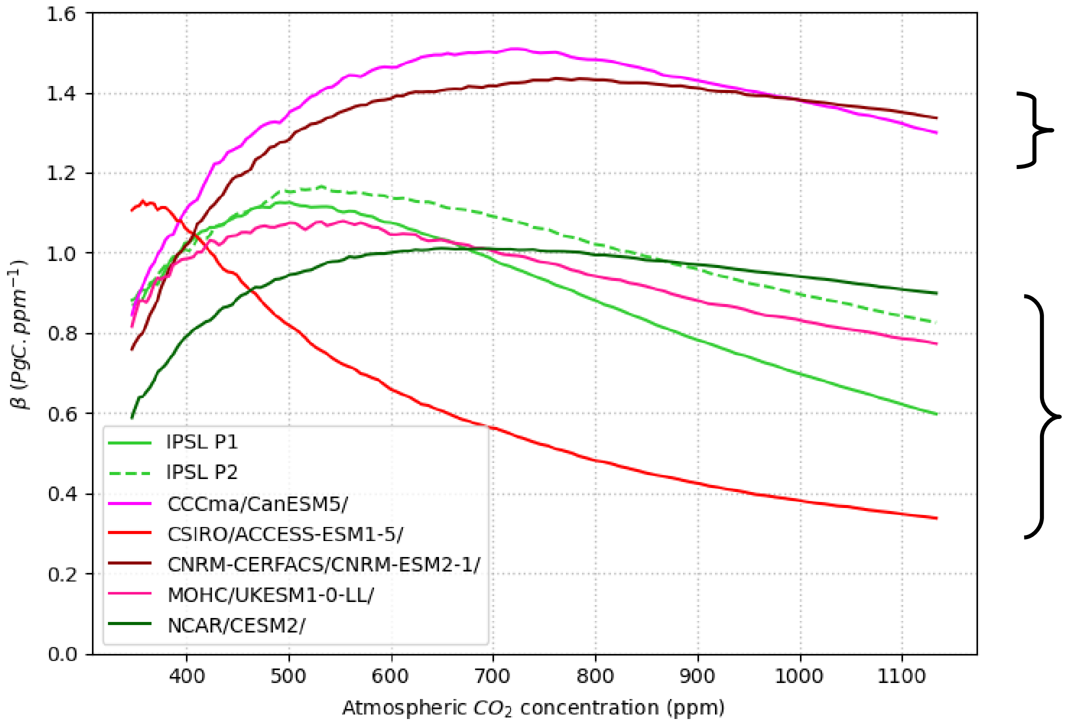
► Models with explicit N cycle have lower β due to N limitation effect at high CO_2 concentrations.

► IPSL model is close to models with explicit N cycle :

⇒ the global biogeochemical response is consistent with more advanced models.

⇒ Vcmax parametrization is efficient to get a correct global β effect.

CMIP6

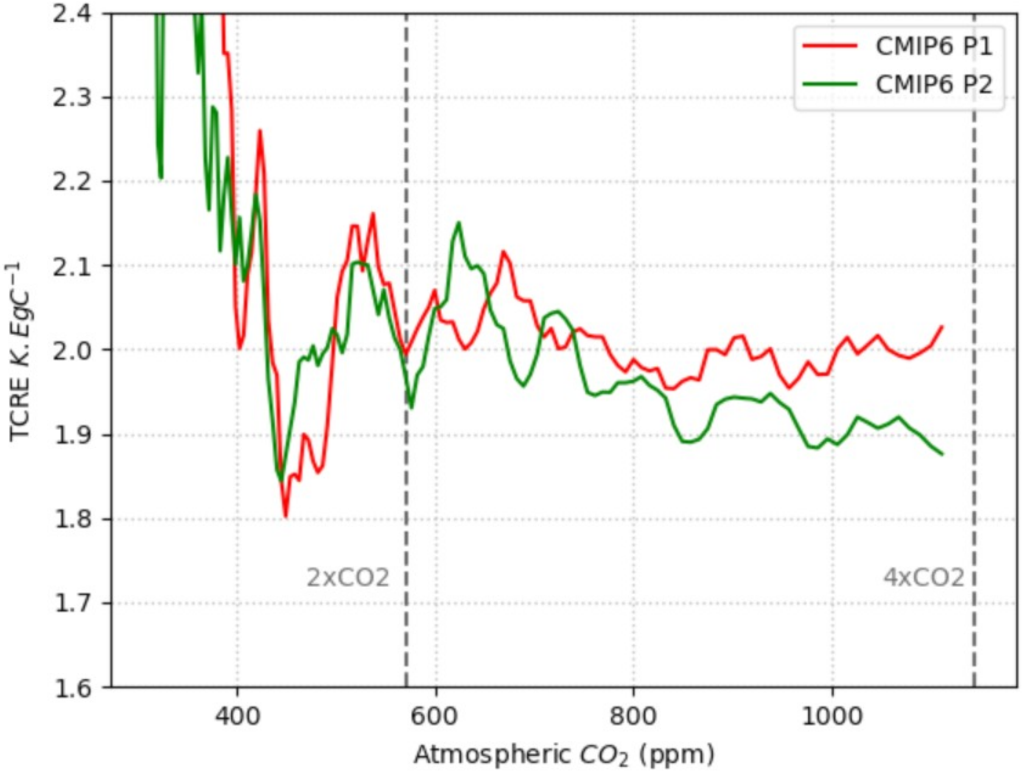


Models without an explicit N cycle representation

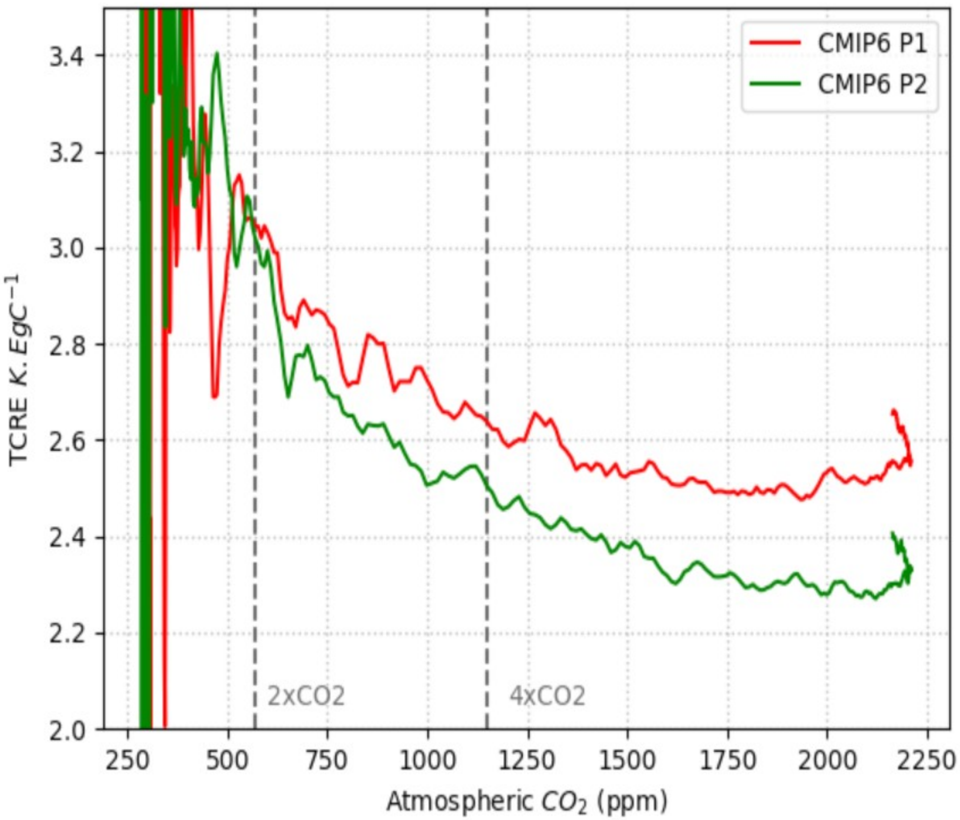
Models with an explicit N cycle representation

Results – TCRE

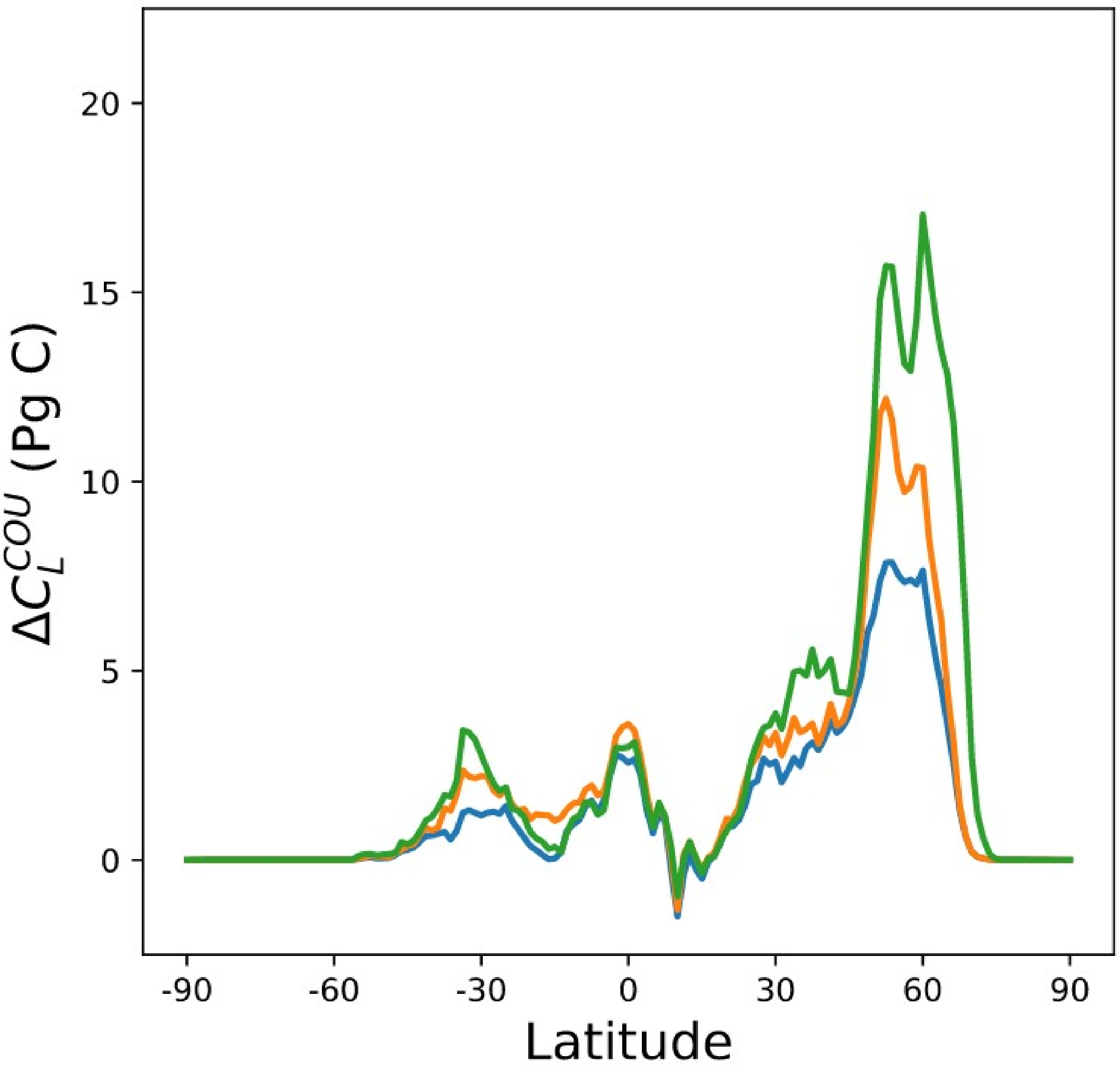
1pctCO2



SSP-585



Change in land carbon stock – ACCESS with N and P cycles



[Ziehn et al. (2021)]