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Carbon cycle response to temperature overshoot beyond 2 °C – an analysis of CMIP6 models

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Melnikova et al. (*Earth's Future*, 2021)
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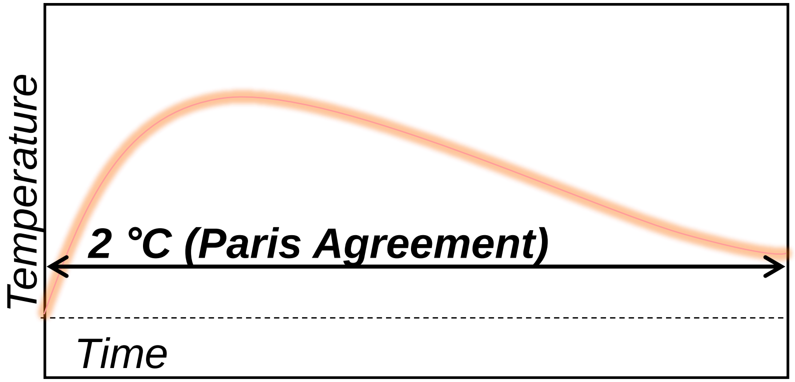
Motivations for Achieving the Paris Agreement Temperature Targets after Overshoot (PRATO) project



Gap

2030

- **Science (IPCC SR15):** *Net anthropogenic CO_2 emissions need to decline by 2030 up to 45% (25%) from 2010 levels for 1.5 °C (2 °C) target*
- **National policies:** *NDCs indicate a slight increase in CO_2 emissions from 2020 levels (emission pledges need to be more than halved (Höhne et al., 2020))*

Converging?

2050

- **Science (IPCC SR15):** Net zero CO_2 emissions required to be on track for 1.5 °C (or by 2070 for 2 °C)
- **National policies:** Major economy countries adopted "net zero" targets by 2050-2060 (December 2020, Climate Action Tracker)
- **Hausfather & Peters, 2020 :** global warming is on course to 3 °C by the end of this century.

End of the 21st century

- **Paris Agreement**
  - To limit warming below 2 °C (1.5 °C)

Overshooting the temperature target is becoming more likely

Background studies

Study	Model	Design	Results
Boucher *et al.*, 2012, Zickfield *et al.*, 2016	HadGEM2-ES, Uvic ESCM	572-1144 ppm CO_2, 2.0 to 5.5 °C warming (idealized)	**Ocean becomes a source** in a few decades, **land is sink** for long time
Tokarska *et al.*, 2019	UVic ESCM	480-620 ppm CO_2, 1.5 to 2.5 °C warming (idealized)	**Ocean and land** are **decreasing sinks** after ramp-down, more carbon is stored in the ocean
Palter *et al.*, 2018	GFDL-ESM2M	>580 ppm, ≈2 °C warming	**Land and ocean** become a **carbon source** nearly two to three decades after the peaks of CO_2 concentration and temperature
Schwinger & Tjiputra, 2018	NorESM	>800 ppm, ≈4 °C warming (idealized)	**Carbon source only after a strong reduction** in atmospheric CO_2

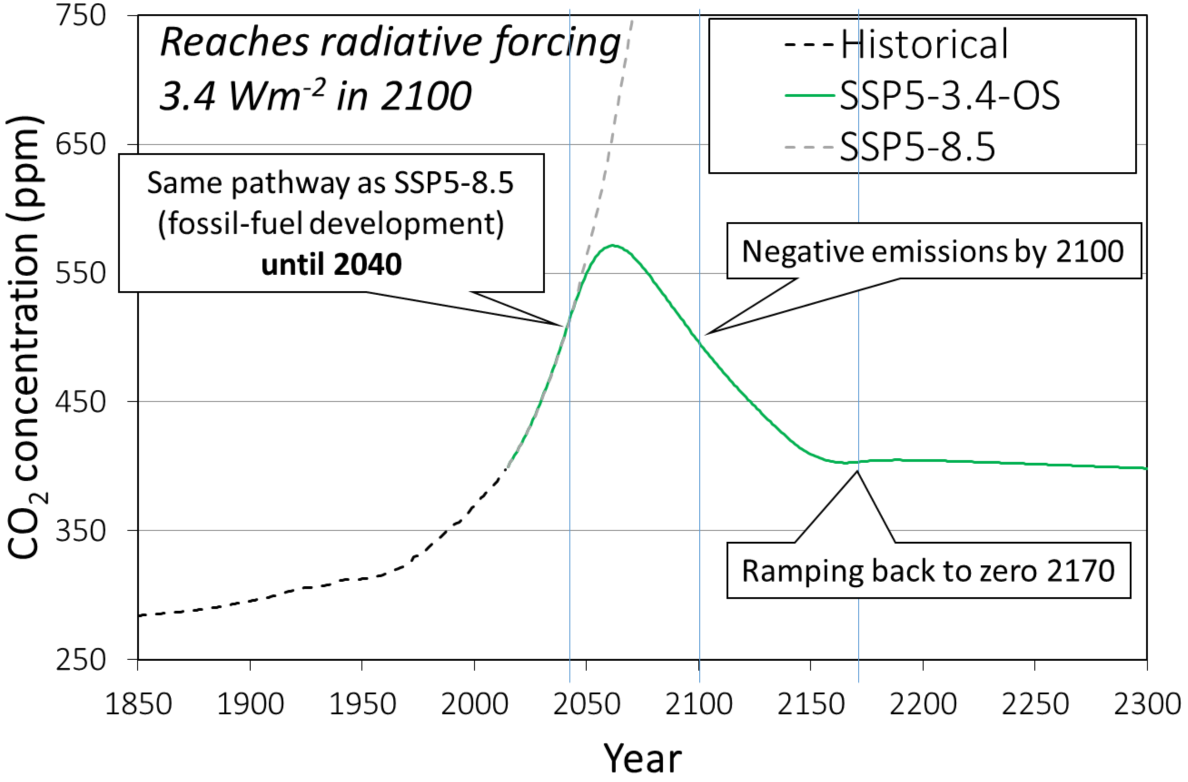
- Different, highly idealized scenarios
- Limited number of models, sometimes of intermediate complexity

What controls the response of the carbon cycle to the CO_2 and temperature overshoots is not well-known

Study purpose

To explore the carbon cycle feedbacks over land and ocean under overshoot scenario

SSP5-3.4 OS



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CMIP6 ESMs

1) IPSL-CM6A-LR
2) CNRM-ESM2-1
3) CanESM5
4) UKESM1-0-LL
5) MIROC-ES2L
6) CESM2-WACCM

Methods

- We investigate the temporal changes in carbon fluxes by six CMIP6 ESMs.
- We apply **the carbon cycle feedback framework** to quantify the carbon cycle feedbacks of the CMIP6 ESMs under the SSP5-3.4-OS pathway.

Carbon cycle feedback framework

$$\Delta C = \boldsymbol{\beta \Delta CO_2} + \boldsymbol{\gamma \Delta T}$$

Beta, β: carbon-concentration feedback ($\Delta C\ ppm^{-1}$)

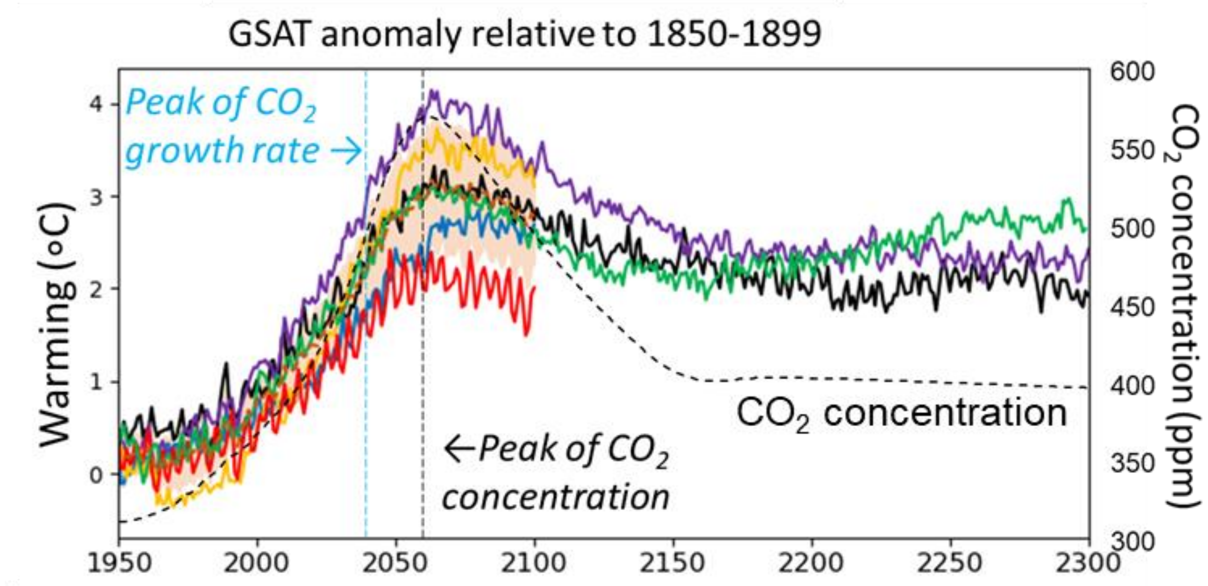
Gamma, γ: carbon-climate feedback: ($\Delta C\ °C^{-1}$)

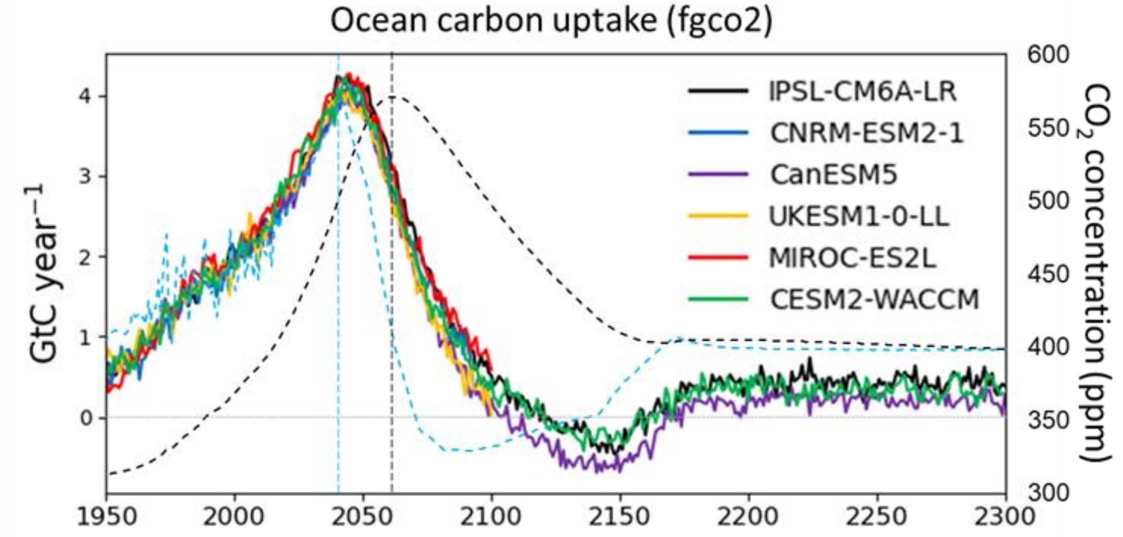
ΔC , $\boldsymbol{\Delta CO_2}$, $\boldsymbol{\Delta T}$ are the changes of carbon mass (GtC), CO_2 concentration (ppm) and air temperature (°C) relative to their unperturbed preindustrial states

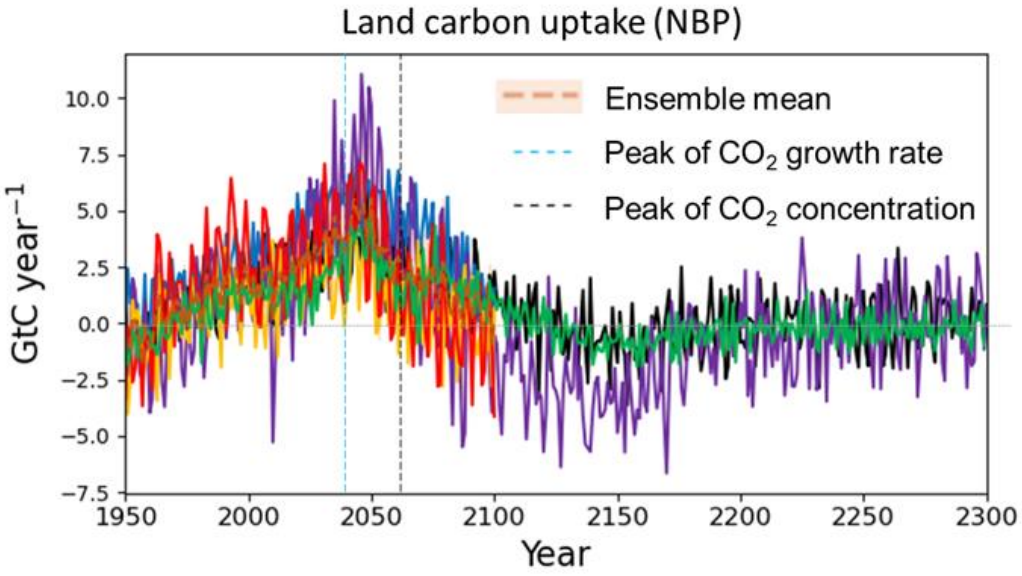
Gregory *et al.* 2009, Jones *et al.*, 2016

- Attribution of the changes in carbon fluxes before and after the peaks to the changes in CO_2 concentration and temperature (climate)
- Was never applied for both land and ocean in the overshoot study
- Require COU and BGC simulations

Land and ocean carbon uptakes



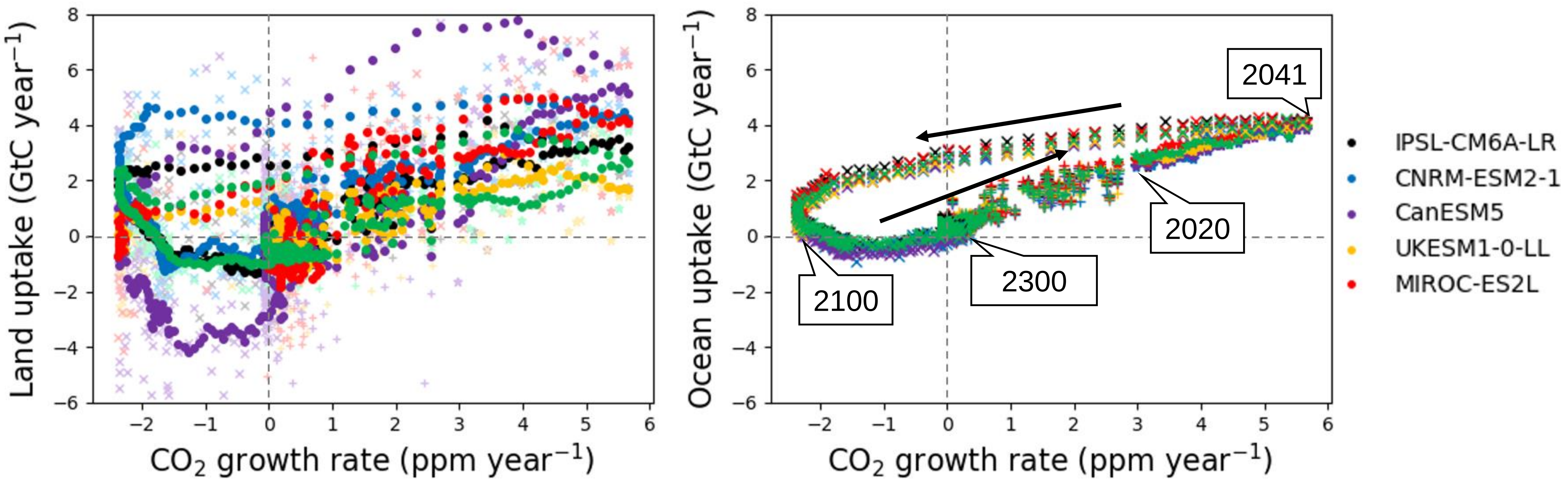




- CO_2 concentration peaks two decades after CO_2 growth rate
- ESMs differ in the response of temperature to the prescribed changes in CO_2 concentration, but all agree on a delayed response

- After the peak of CO_2 growth rate, land and ocean take up carbon for at least 50 years but at a declining rate
- In the 22nd and 23rd centuries, ocean is a weak carbon sink, the response of land has a larger range of uncertainties
- Land and ocean carbon uptakes peak before the CO_2 concentration peak

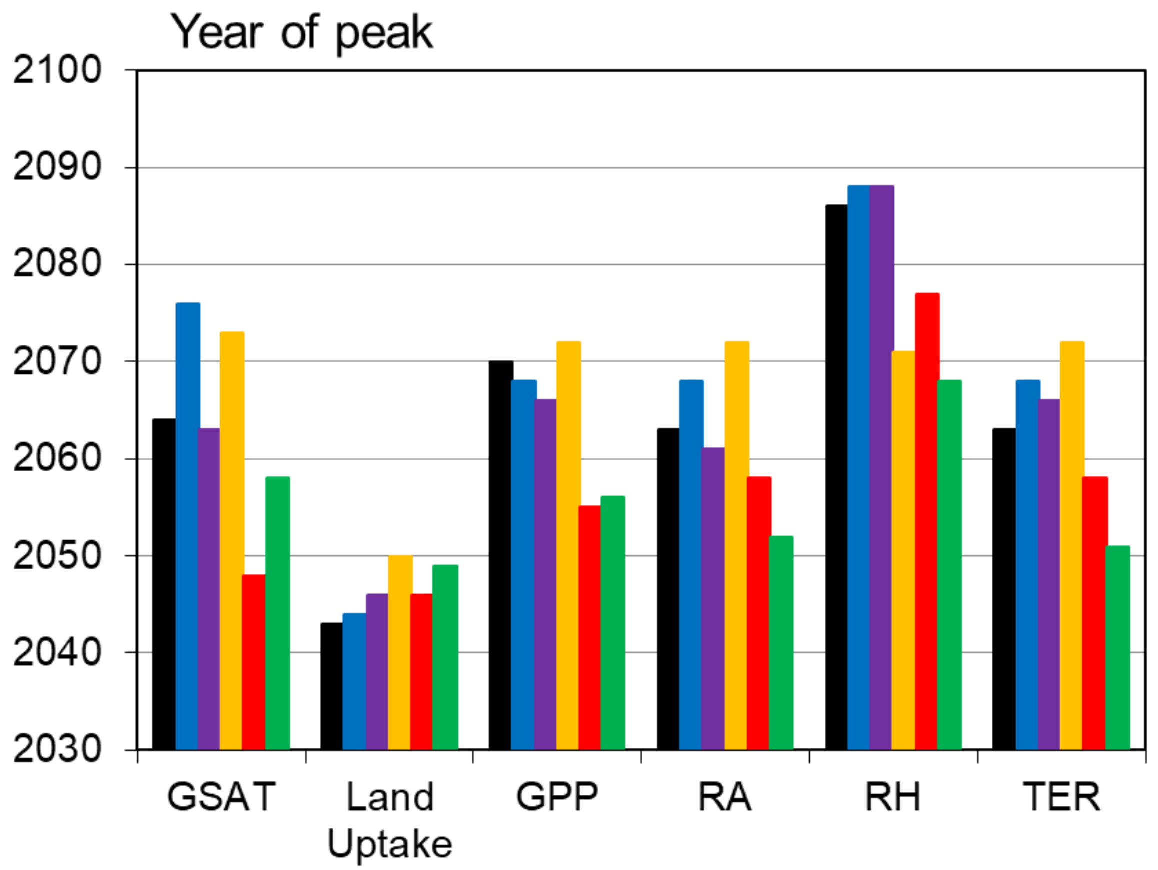
Peak of ocean carbon uptake

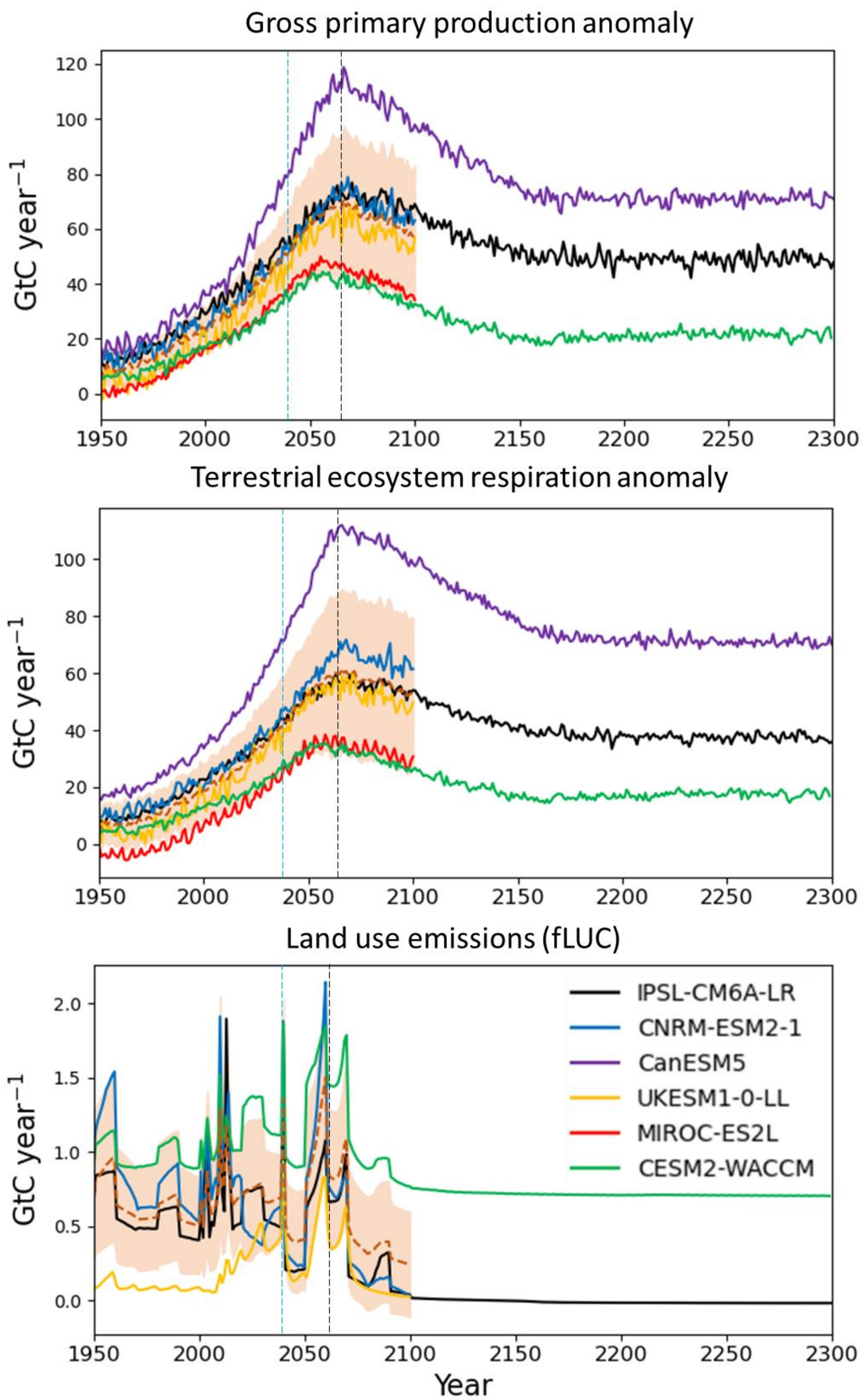


Global land and ocean carbon uptake has a nearly linear dependency on the atmospheric CO_2 growth rate with a hysteresis after the CO_2 growth rate peak

- In the short time scales, the changes are related the state disequilibrium. The greater the disequilibrium is (i.e., the larger the CO_2 growth rate is), the larger the responses of the land and ocean carbon uptakes are
- In the long time scales, the changes are more related to the state of the system itself

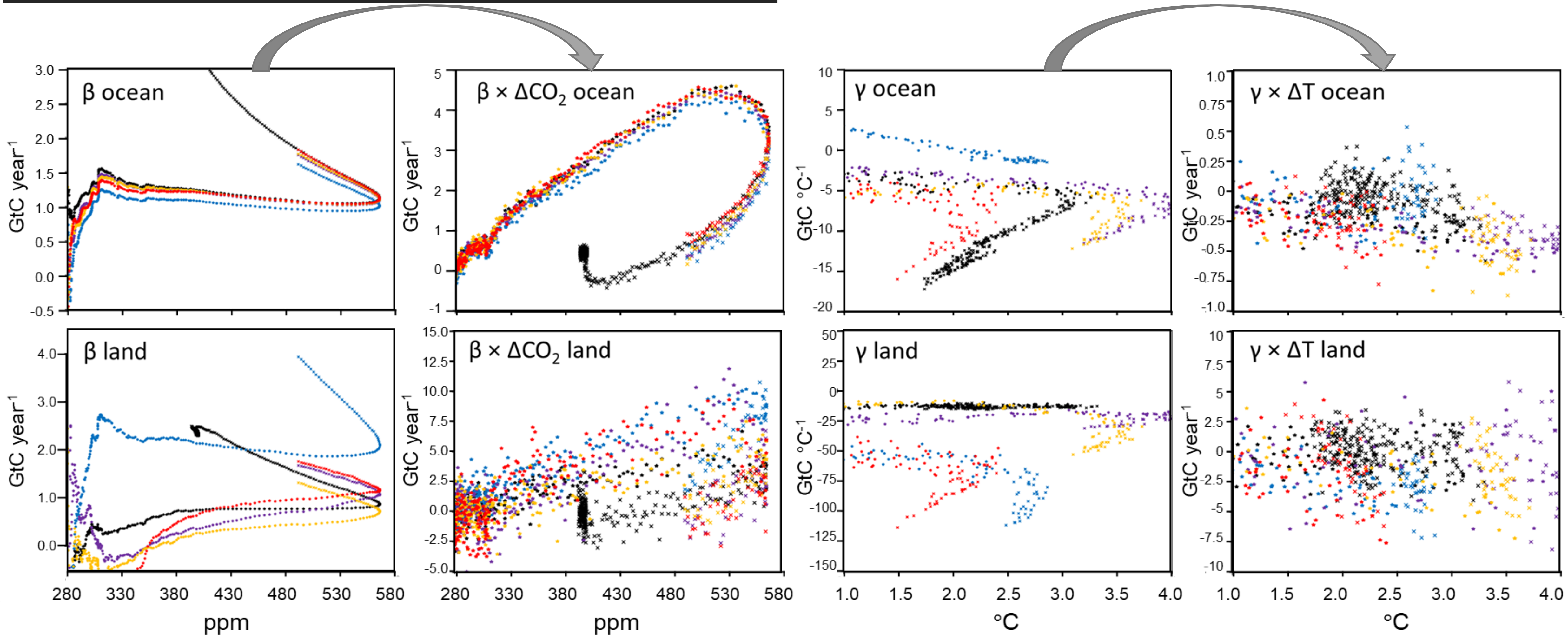
Peak of land carbon uptake





The land sink decrease is due to the **larger growth of respiration than photosynthetic production** and **concurrent land-use change emissions**

Carbon cycle feedbacks



- Under declining emissions, both land and ocean continue to take up carbon at an asymmetrically larger rate
- The total γ-driven loss of carbon is smaller than β gain at least till the end of the 21st century. The changes in the carbon cycle are dominated by β rather than γ

Conclusions

- In SSP5-3.4-OS, the land and ocean continue to remove carbon from the atmosphere at least for 50 years after the peak of the CO_2 growth rate. Land and ocean turn to a source afterward in the first half of the 22nd century for a short period and become a weak sink later, i.e., reach a new steady-state

- The ocean uptake decreases due to its dependency on the CO_2 growth rate

- The land uptake decreases due to a larger growth of respiration than GPP and concurrent LUC emissions

- The hysteresis in β and γ after their peaks causes amplification of carbon cycle feedback parameters.

- In SSP5-3.4-OS, the total β carbon gain $\beta\times\Delta CO_2$ is larger than γ loss $\gamma\times\Delta T$, and, thus, land and ocean continue to uptake carbon during the CO2 and temperature ramp-down periods.