

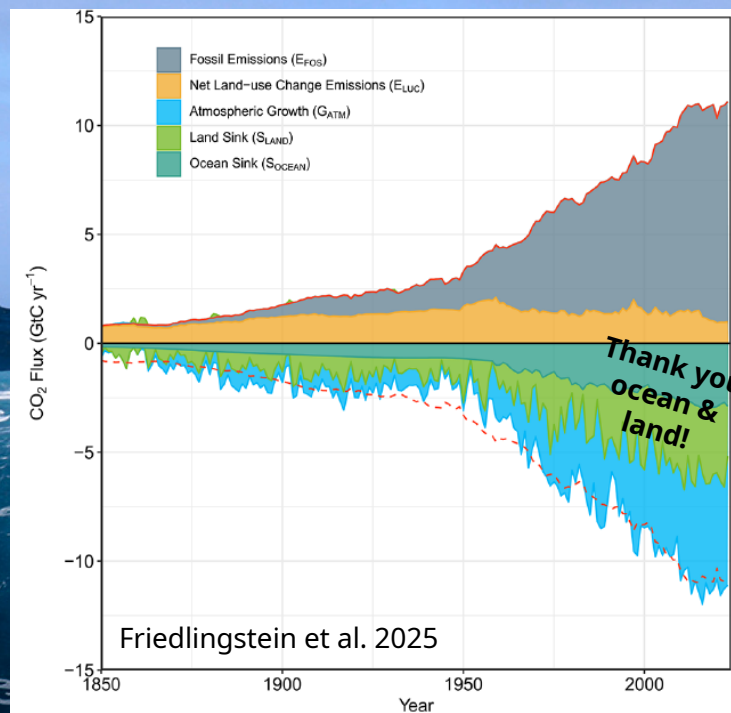
Weaker than expected future ocean carbon uptake due to carbon-climate feedbacks

Chris Danek, Özgür Gürses, Judith Hauck

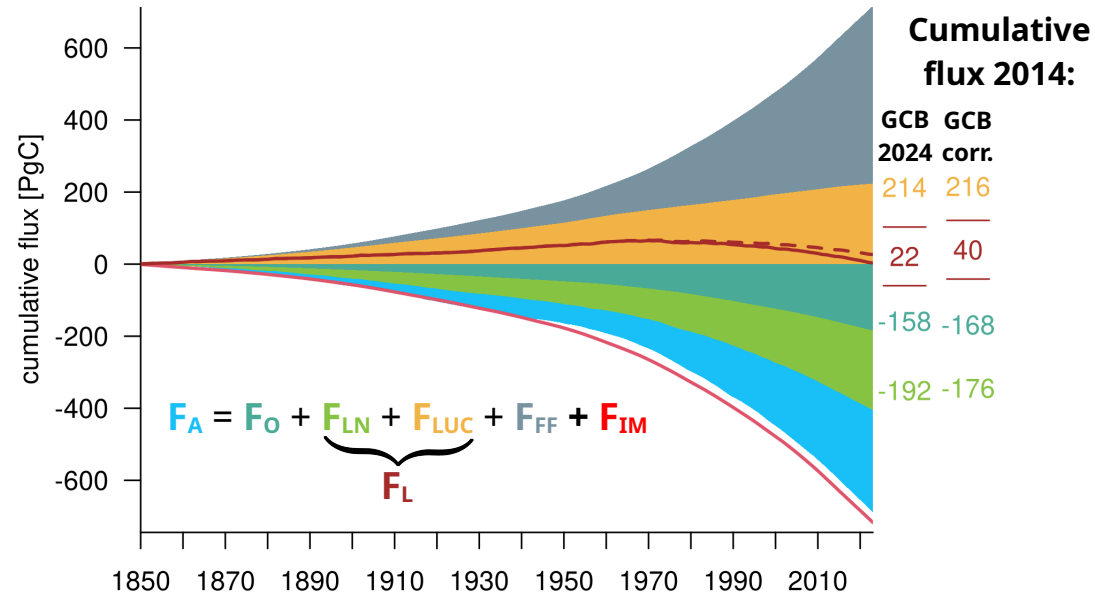


Weaker than expected future ocean carbon uptake due to carbon-climate feedbacks

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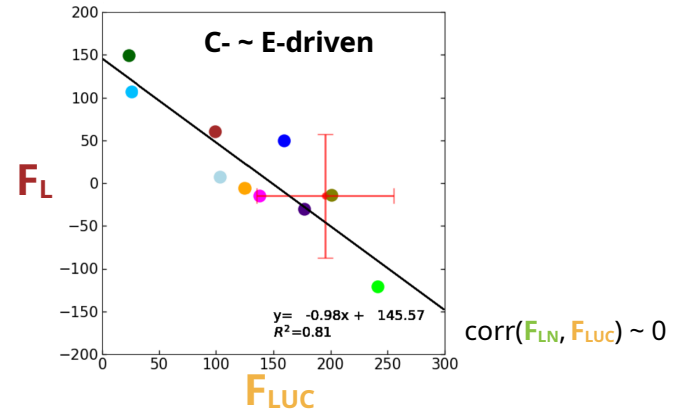
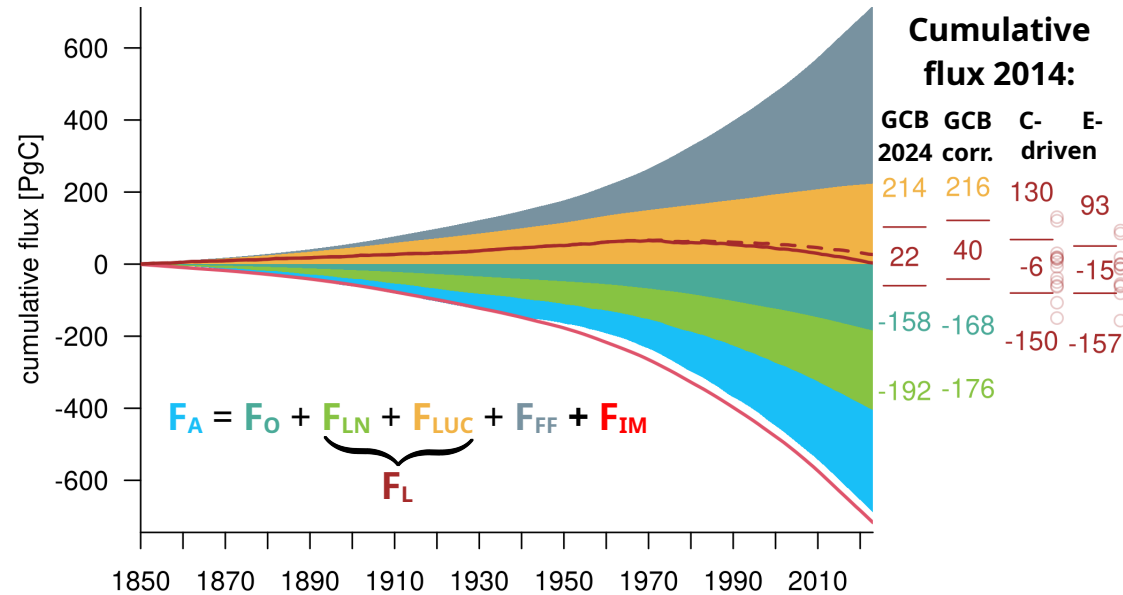
Carbon cycle uncertainties from Earth System Models



- A:** Atmosphere
- O:** Ocean sink
- LN:** Natural land sink
- LUC:** Land use change emissions
- FF:** Fossil fuel emissions
- L:** Net land
- IM:** Imbalance

GCB2024: Friedlingstein et al., 2025
 GCB correction: Friedlingstein et al., 2026
 C- & E-driven CMIP6: Hajima et al., 2025

Carbon cycle uncertainties from Earth System Models

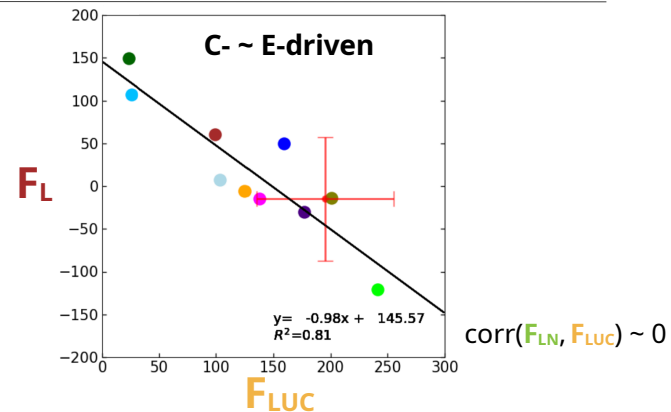
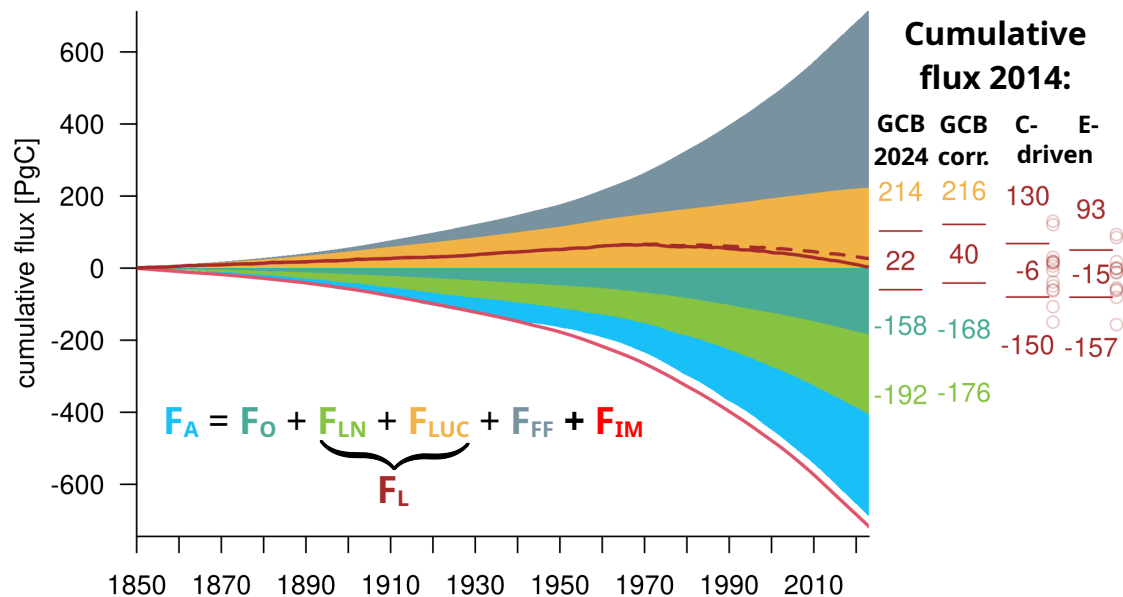


→ Net land CO₂ sink **F_L** highly uncertain and depending on **F_{LUC}** in GCB and CMIP6

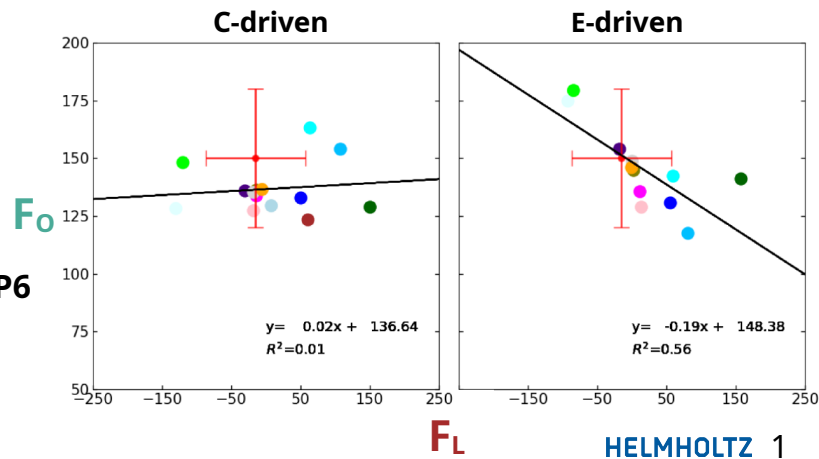
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Carbon cycle uncertainties from Earth System Models



- Net land CO₂ sink F_L highly uncertain and depending on F_{LUC} in GCB and CMIP6
- E-driven ocean sink F_O depends on F_L



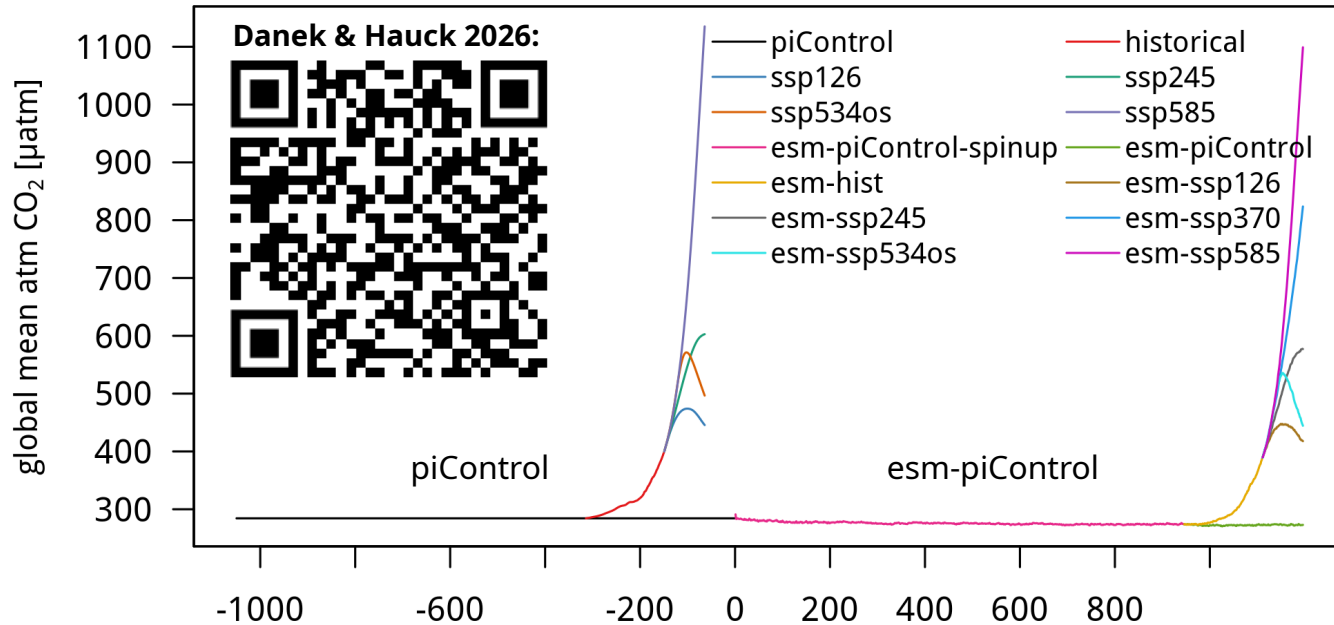
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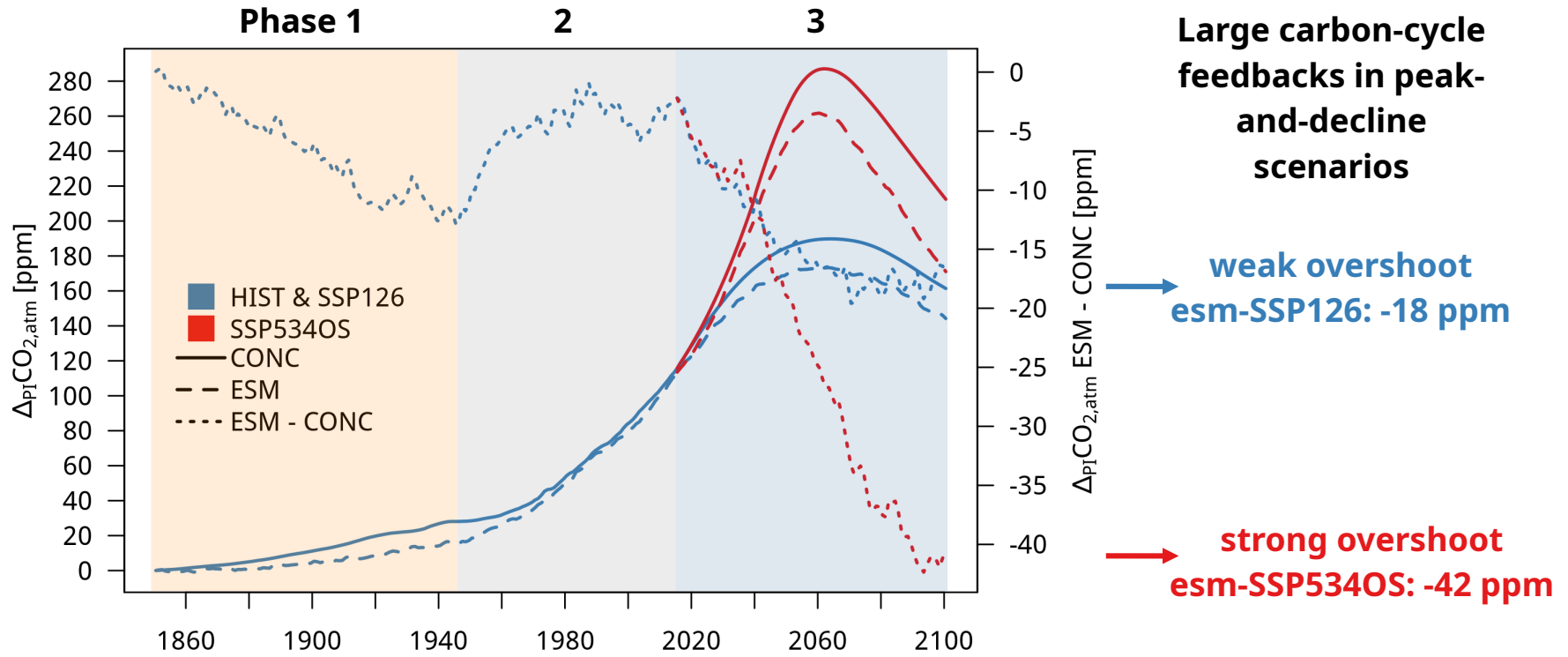
- C- and E-driven CMIP6 Earth System Model **AWI-ESM-1-REcoM**
- Ocean physics + biogeochemistry: **FESOM1 + REcoM2**
- Atmosphere + land: ECHAM6 + JSBACH3 with dynamic vegetation & disturbances
- **~2k yrs spinup**: 1051 yrs C-driven piControl + 945 yrs E-driven esm-piControl

REcoM

Regulated
Ecosystem Model



C- vs E-driven carbon cycle in AWI-ESM-1-REcoM

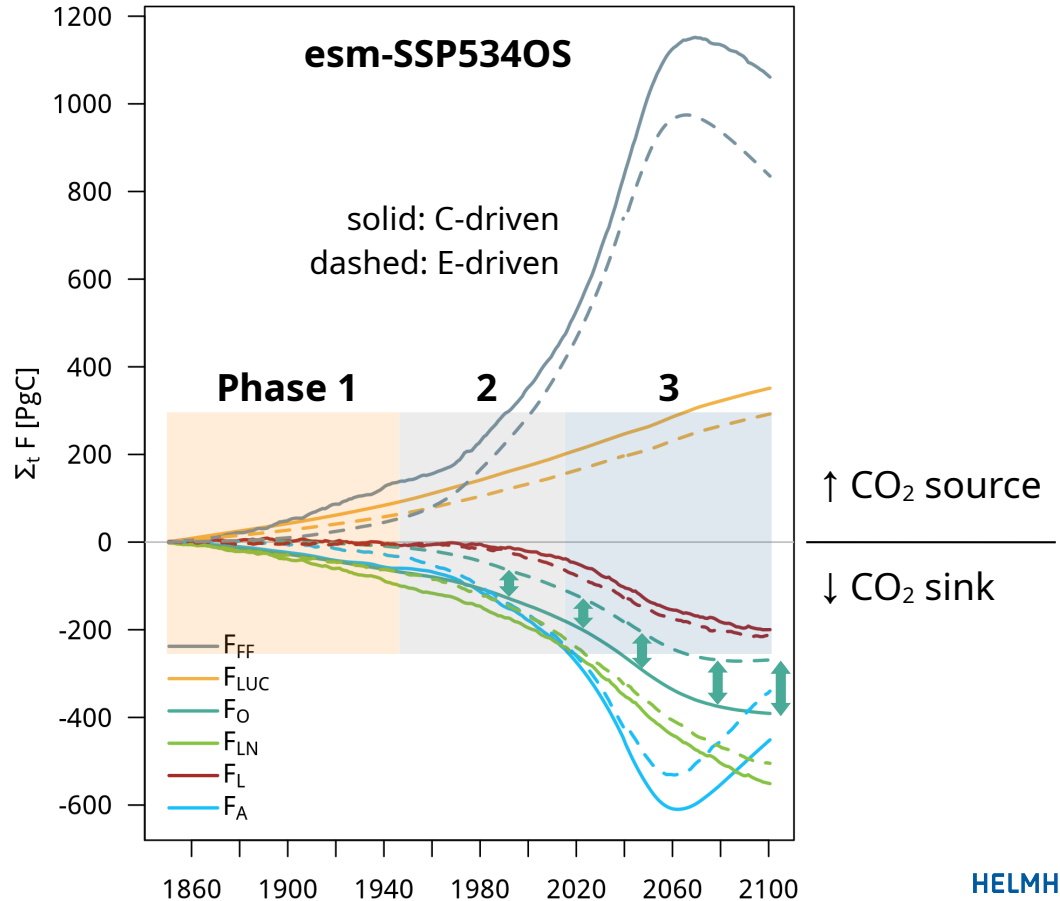


C- vs E-driven carbon cycle in AWI-ESM-1-REcoM

- carbon budget:

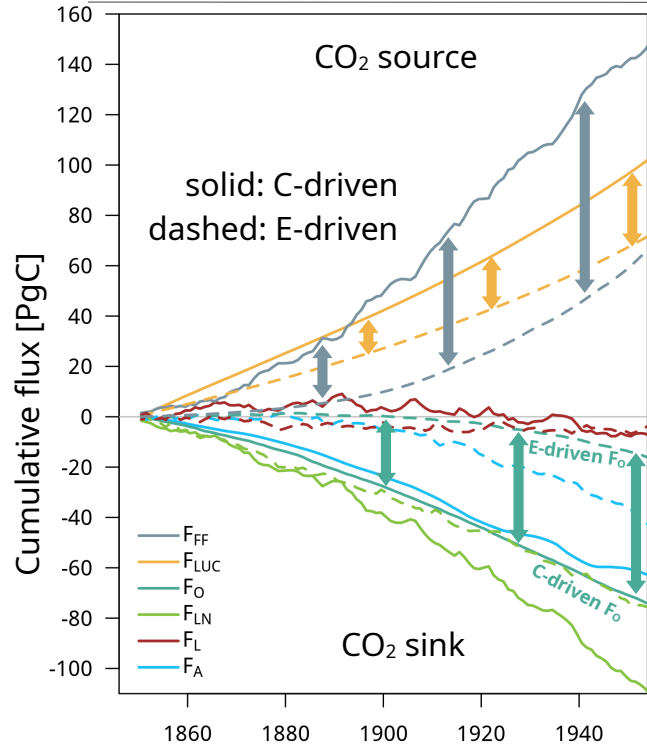
$$F_A = F_O + \underbrace{F_{LN} + F_{LUC}}_{F_L} + F_{FF}$$

→ substantially weaker ocean carbon sink F_O in E-driven setup



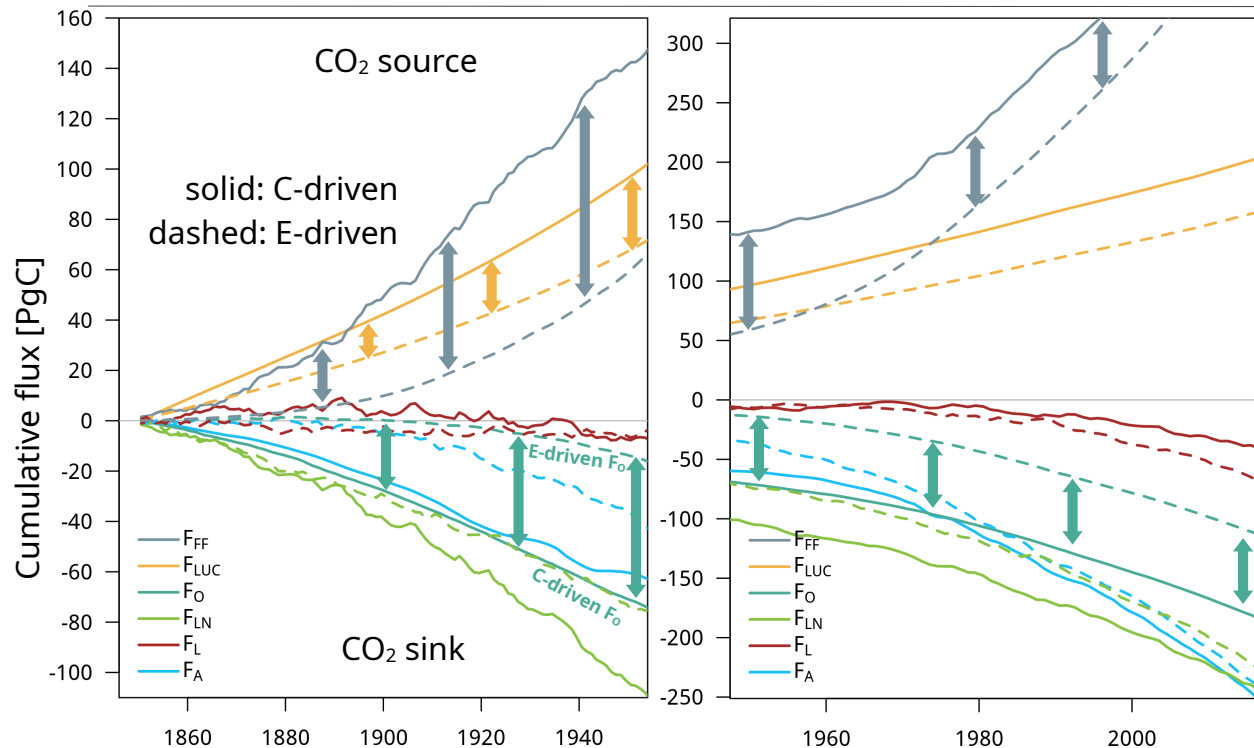
A: Atmosphere
O: Ocean sink
LN: Natural land sink
LUC: Land use change emissions
FF: (Compatible) Fossil fuel emissions
L: Net land

C- vs E-driven carbon cycle in AWI-ESM-1-REcoM



- Larger increase of C-driven F_{LUC} (initial cond.)
- Larger increase of C-driven compatible F_{FF}
- and C-driven F_L source and not sink
- Larger growth of C-driven F_O

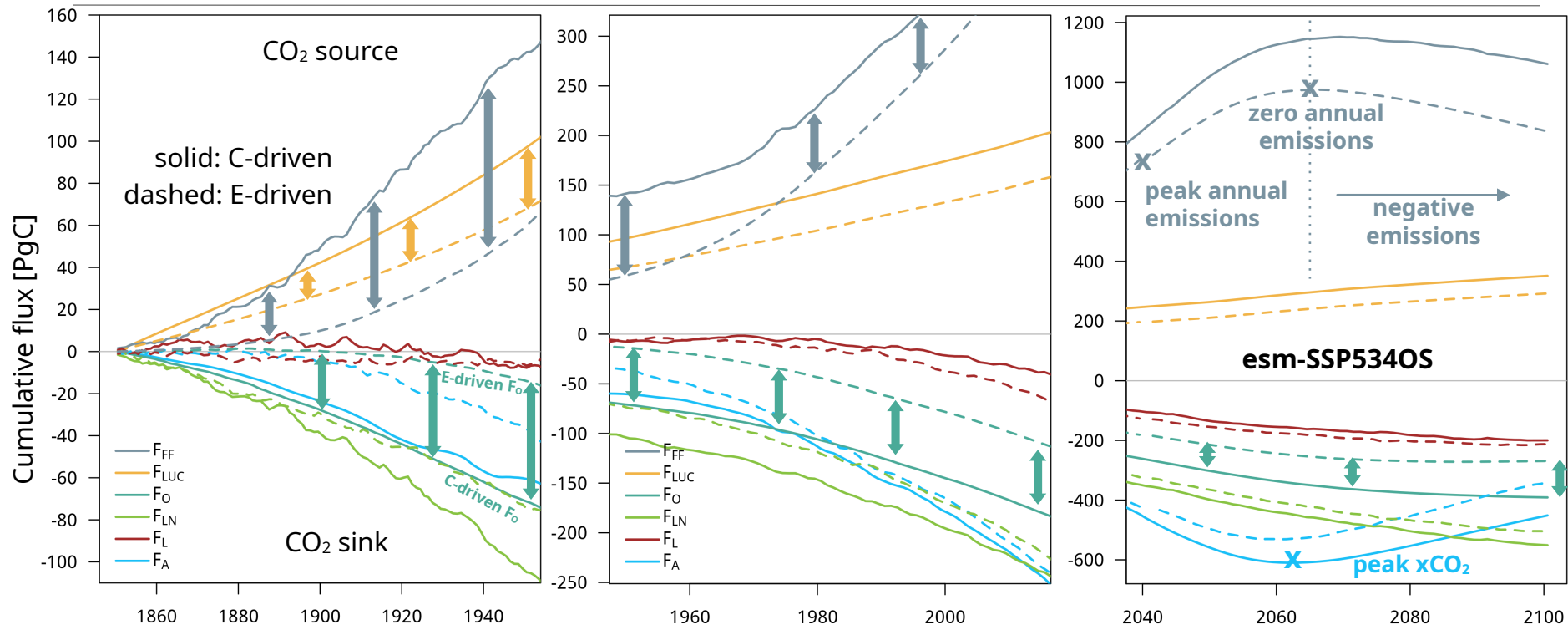
C- vs E-driven carbon cycle in AWI-ESM-1-REcoM



Larger increase of C-driven F_{LUC} (initial cond.)
 → Larger increase of C-driven compatible F_{FF}
 and C-driven F_L source and not sink
 → Larger growth of C-driven F_O

Acceleration of E-driven F_{FF}
 → Similar increase of E- and C-
 driven F_O

C- vs E-driven carbon cycle in AWI-ESM-1-REcoM



Larger increase of C-driven F_{FLUC} (initial cond.)
 → Larger increase of C-driven compatible F_{FF}
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Acceleration of E-driven F_{FF}
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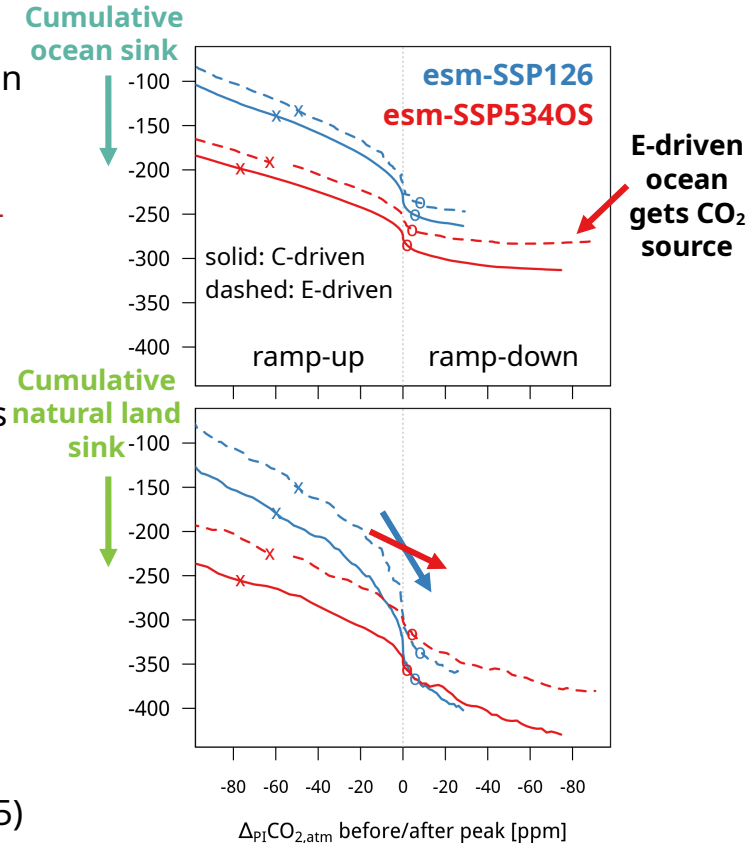
Quicker reduction of E-driven F_O after
 zero emissions → E-driven ocean
 becomes CO₂ source

- 1) Carbon-climate feedbacks reduce atm. CO₂ accumulation and ocean sink in AWI-ESM-1-REcoM
 - E-driven ocean sink F_o strongly depends on net land uptake F_L
 - Large uncertainty in net land uptake F_L due to F_{LUC}
 - E-driven standard in CMIP7 (Sanderson et al. 2024)

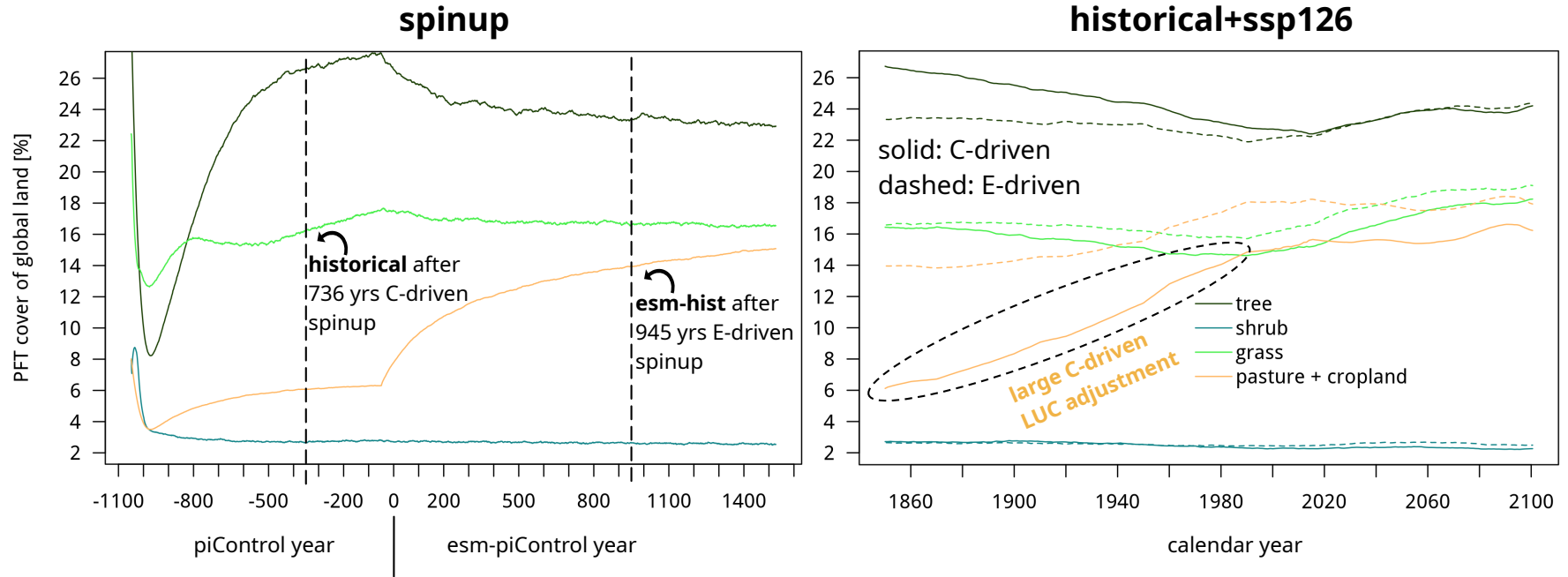
- 2) Early historical carbon cycle depends on piControl initial conditions
 - Vegetation distribution → F_{LUC} , and CO_{2,atm}
 - Comparison of C- and E-driven changes, not absolute values

Conclusion

- 1) Carbon-climate feedbacks reduce atm. CO₂ accumulation and ocean sink in AWI-ESM-1-REcoM
 - E-driven ocean sink F_o strongly depends on net land uptake F_L
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- 2) Early historical carbon cycle depends on piControl initial conditions
 - Vegetation distribution → F_{LUC} , and CO_{2,atm}
 - Comparison of C- and E-driven changes, not absolute values
- 3) Stronger sensitivity of ocean and land CO₂ sinks in both E-driven setup AND weak overshoot scenario
 - E-driven ocean gets CO₂ source in strong overshoot scenario
 - Hysteresis behavior of carbon cycle (e.g. Melnikova et al. 2025)

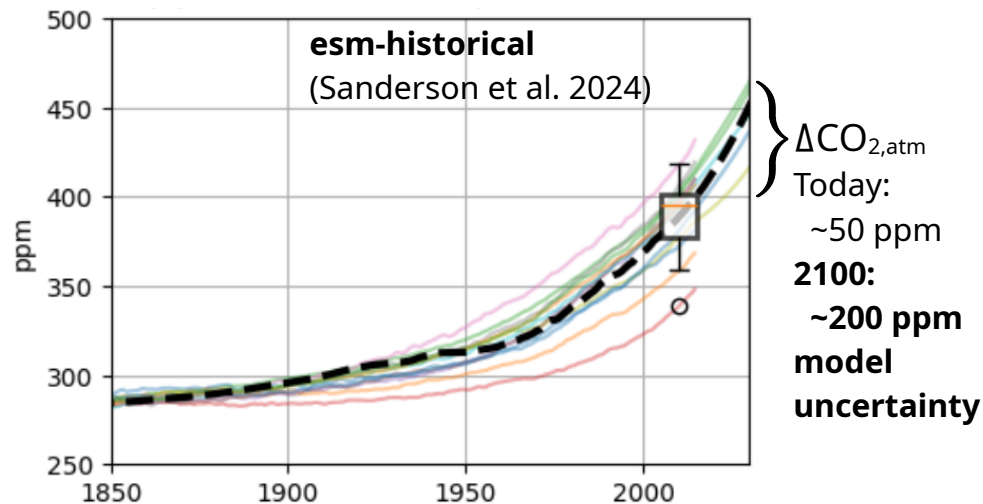


C-driven vs E-driven carbon budget from AWI-ESM-1-REcoM

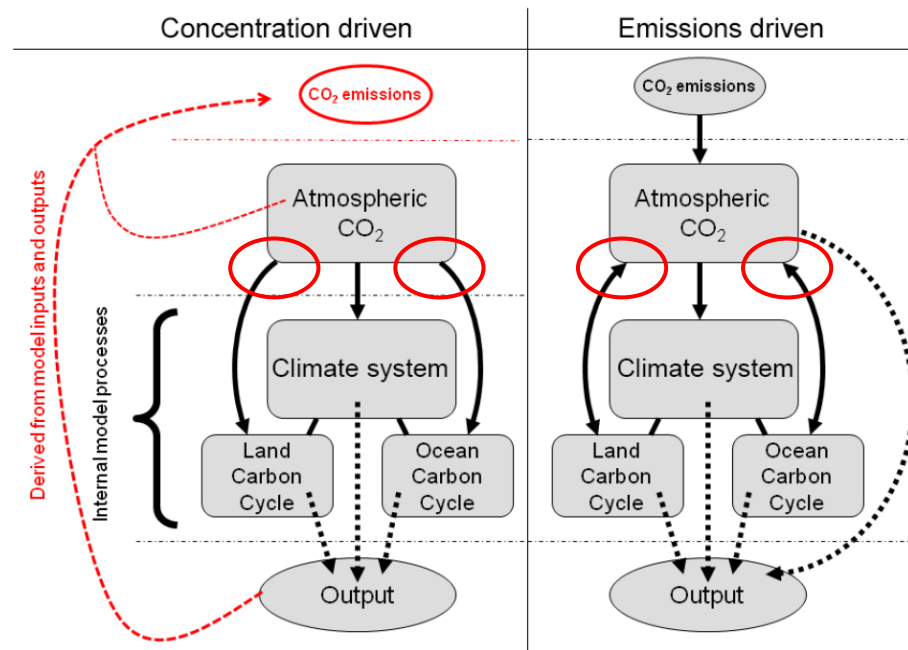


Concentration- versus Emissions-driven ESM setup

- carbon-concentration and carbon-climate **feedbacks missing** in **C-driven** ESMs
- E-driven** setup to represent full uncertainty range of coupled carbon-climate system



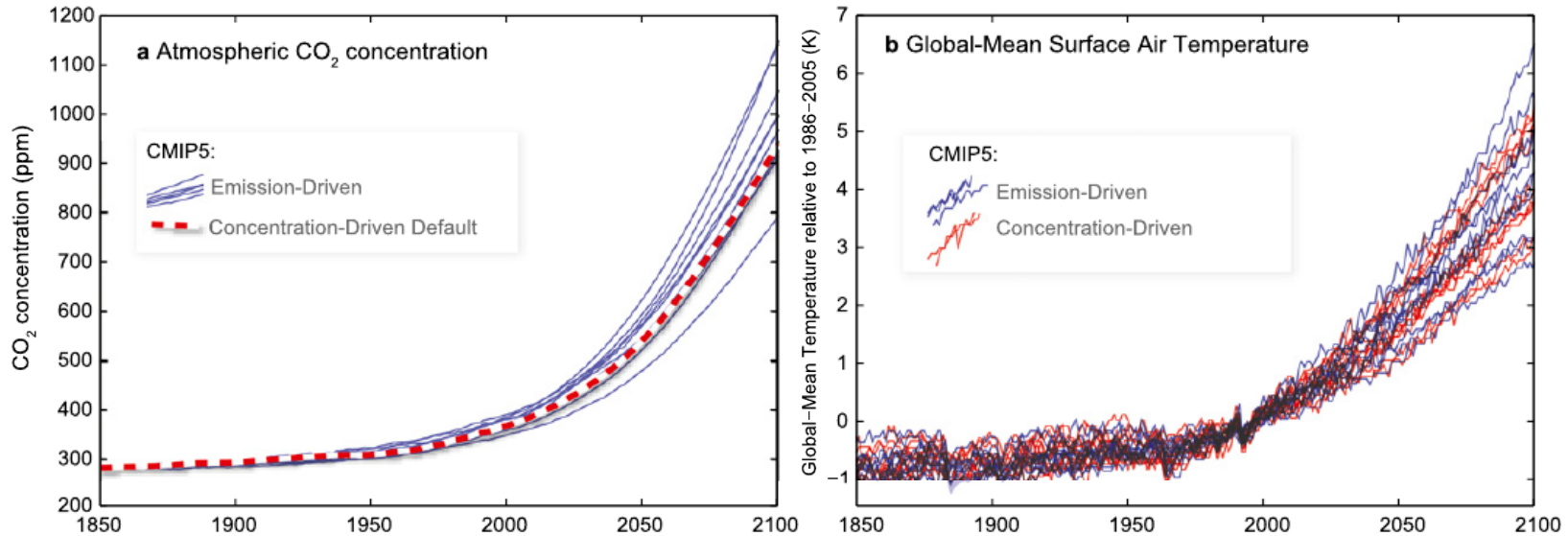
Friedlingstein et al. 2014
Lee et al. 2021



C⁴MIP: Jones et al. 2016

Model uncertainty in future carbon sink estimates

- considerable uncertainty in model estimates of future carbon-cycle and feedbacks with physical climate



Friedlingstein et al. 2014

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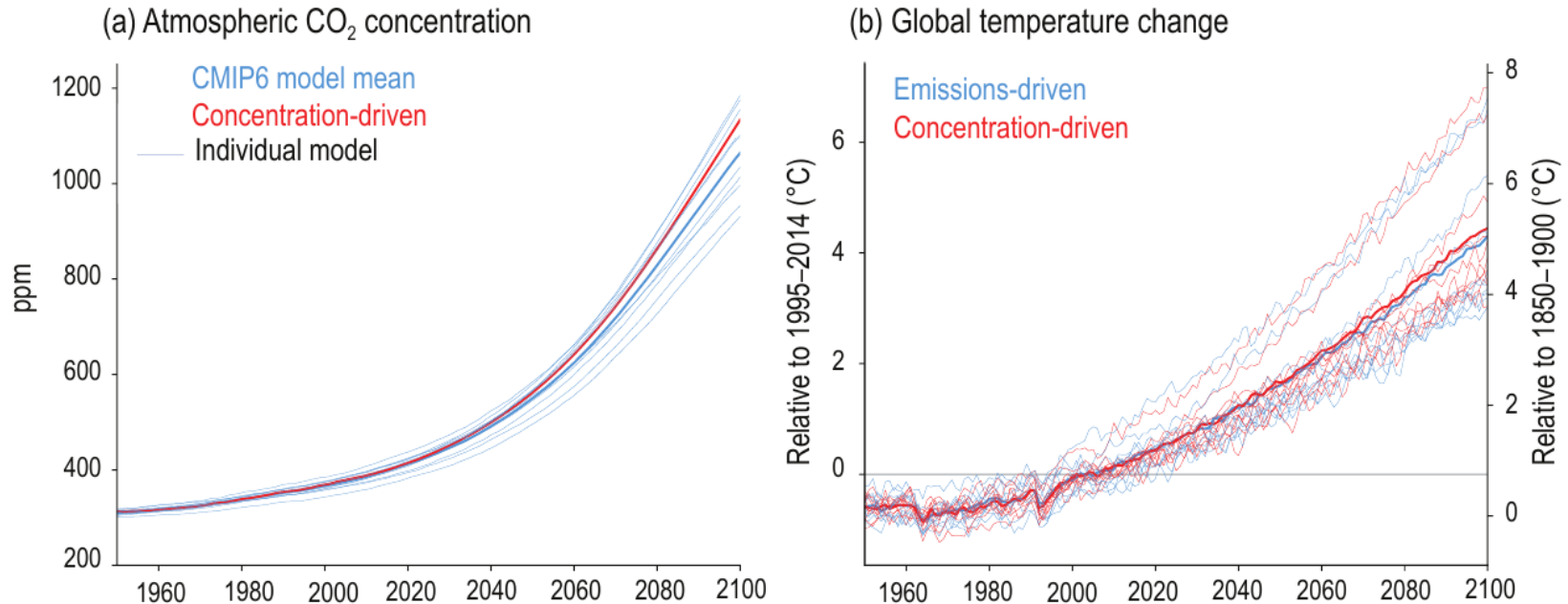


Fig. 4.3 of Lee et al. 2021
(AR6 Chapter 4)

