The influence of land carbon cycle representation on terrestrial sink sensitivity, total warming, and global carbon budgets

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27 February 2024

Uncertainty in land and ocean carbon sink behavior in the decarbonization regime.

Current emissions

Climate targets

Uncertainty in land and ocean carbon sink behavior in the decarbonization regime.

Uncertainty in land and ocean carbon sink behavior in the decarbonization regime.

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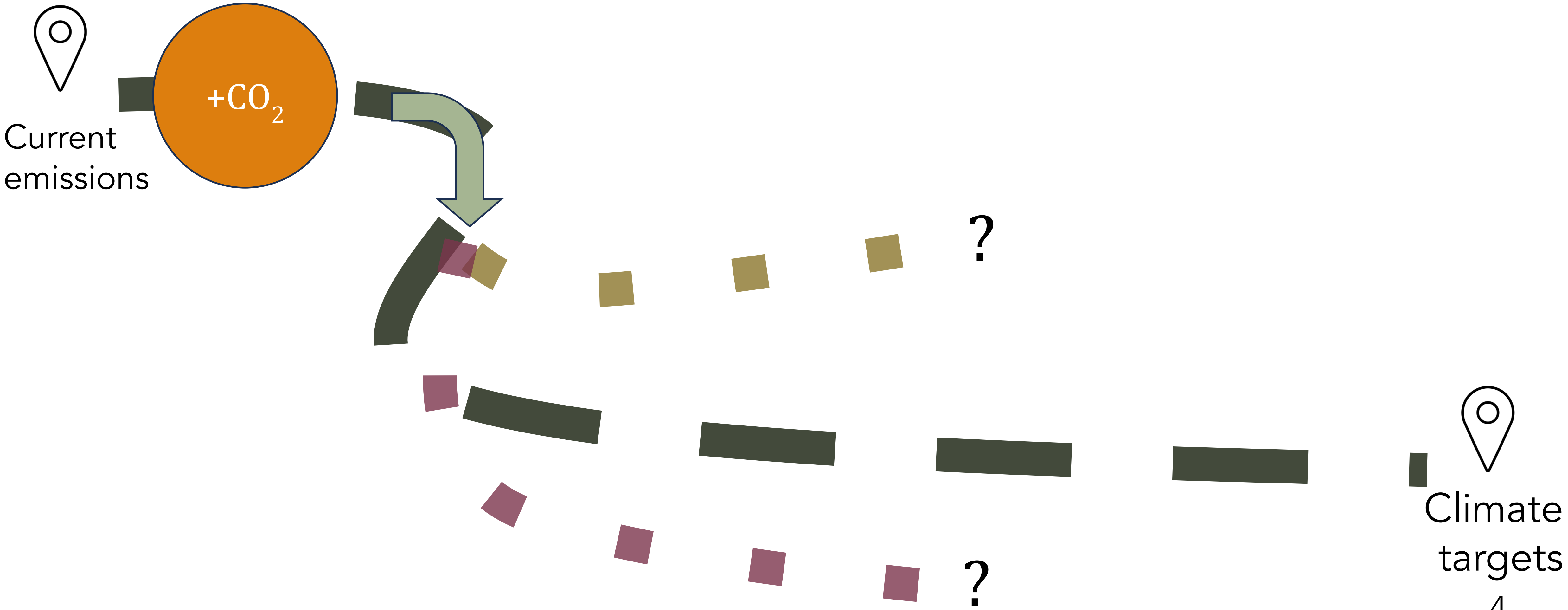
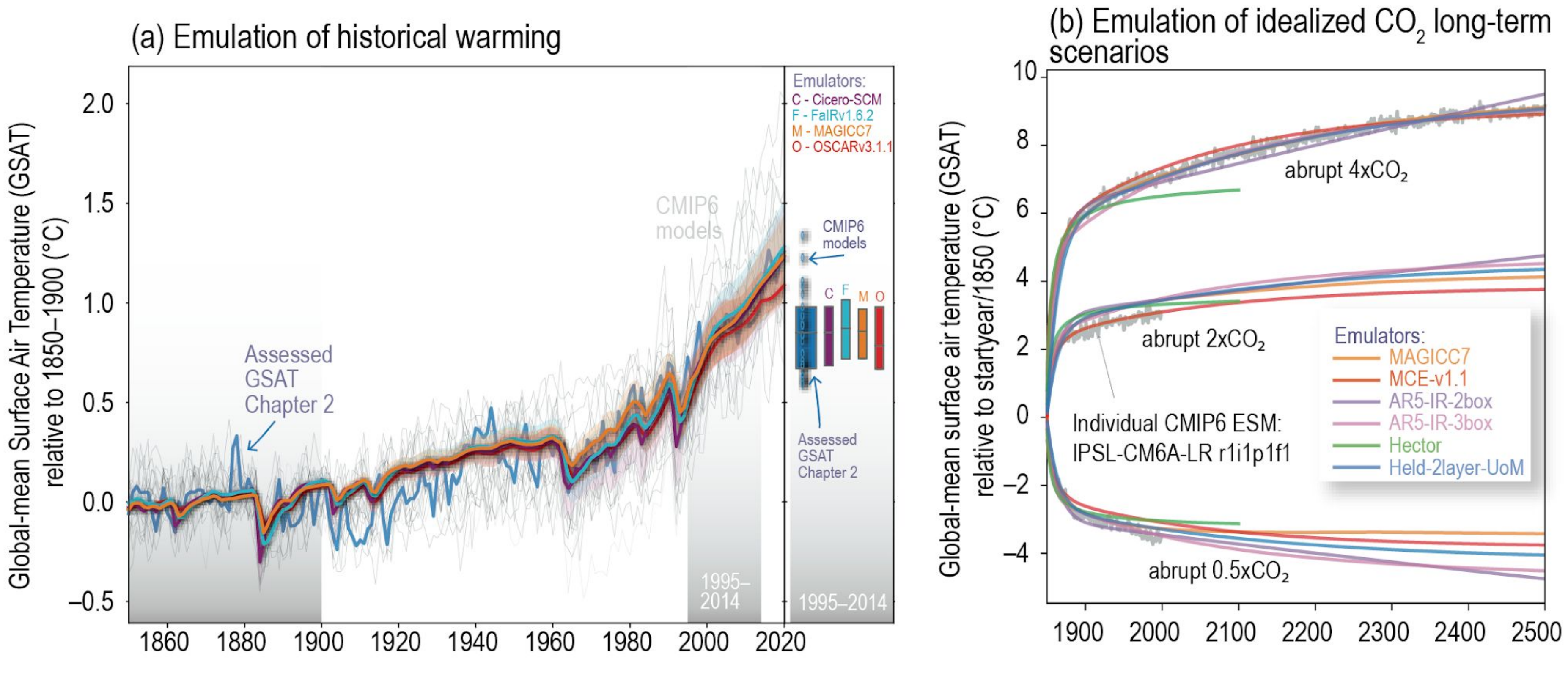
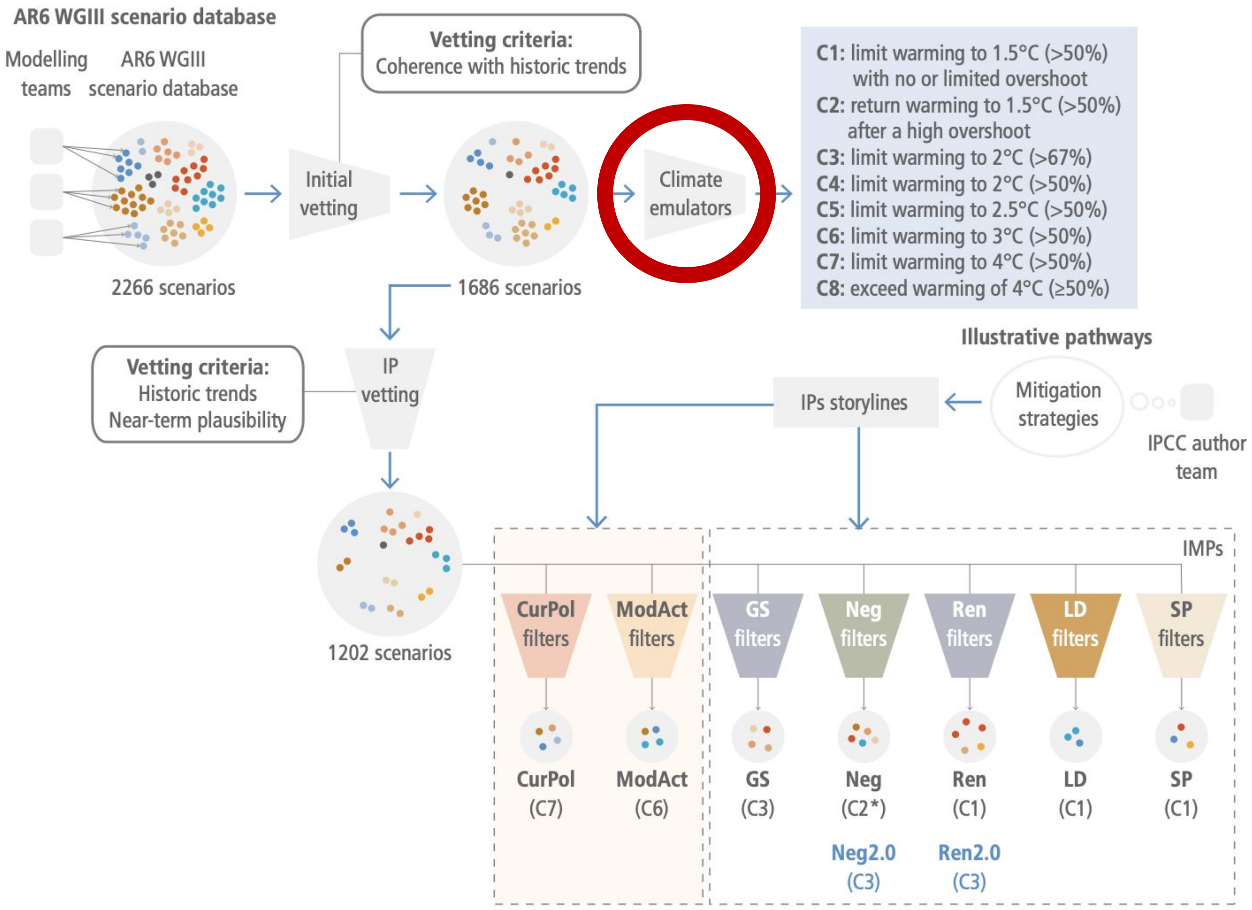


Emissions-driven climate model emulators can reproduce GCM dynamics, offer insight into dominant CC-climate processes.



IPCC AR6 Report Cross-Chapter Box 7.1, Figure 1

SCMs are used to emulate the climate for economic models, scoping CMIP scenario development and decarbonization pathway assessment.



IPCC AR6 WG3 Figure 3.5a

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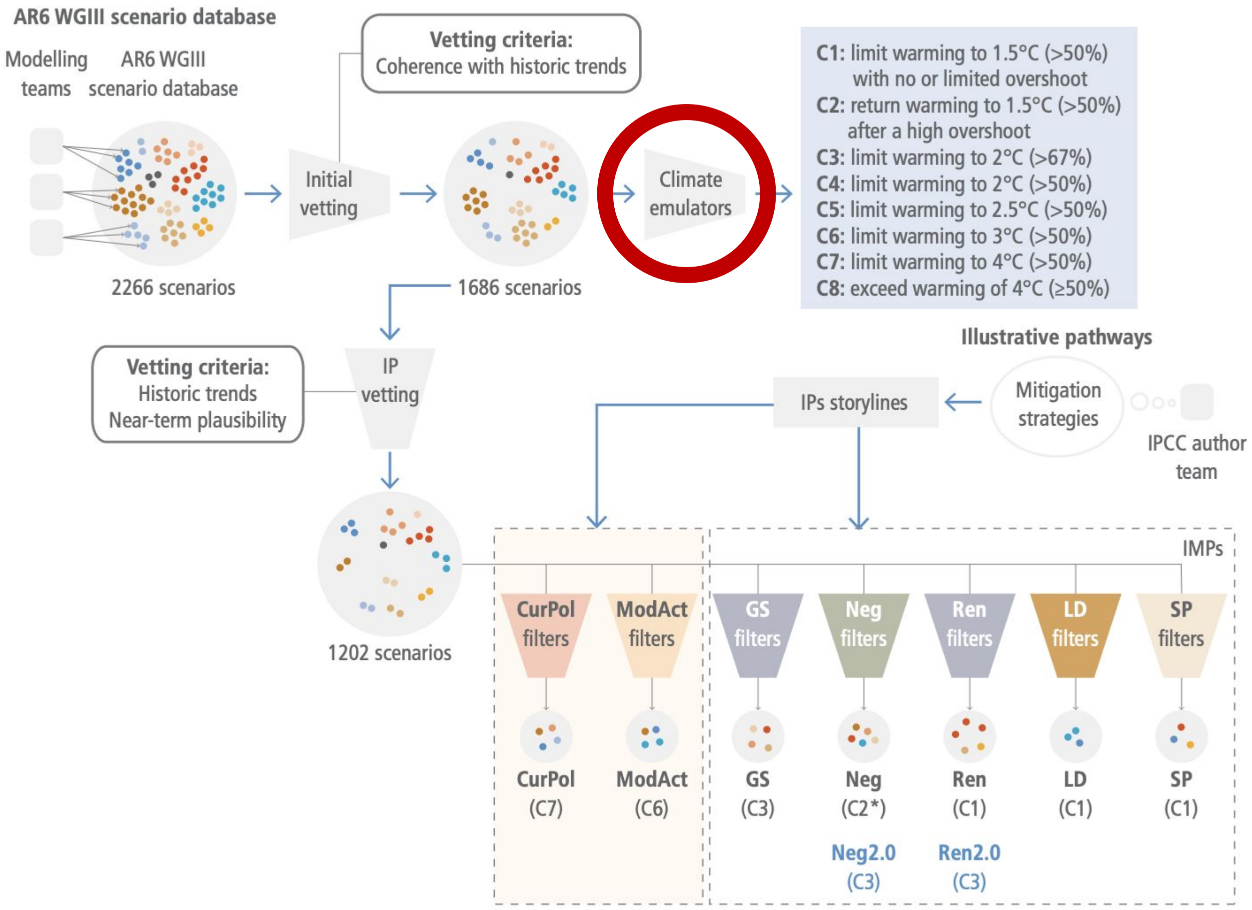
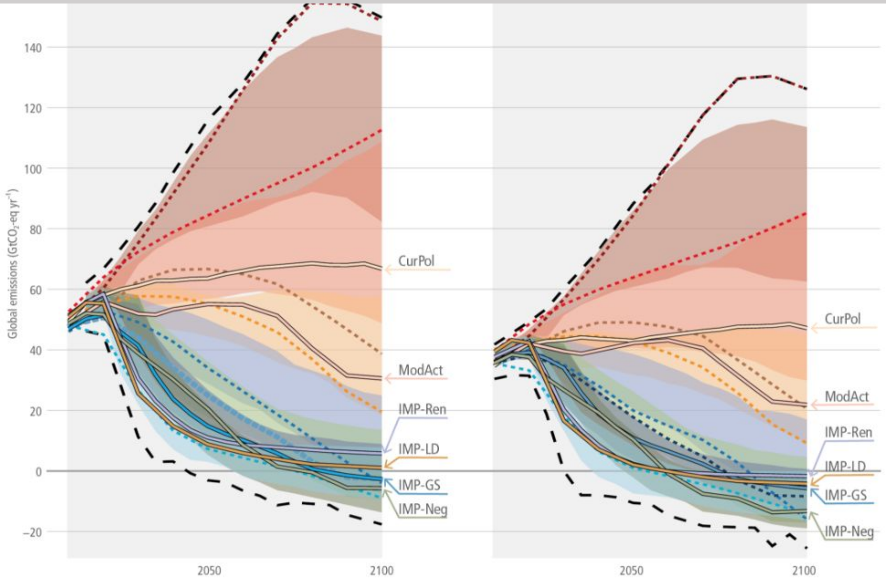
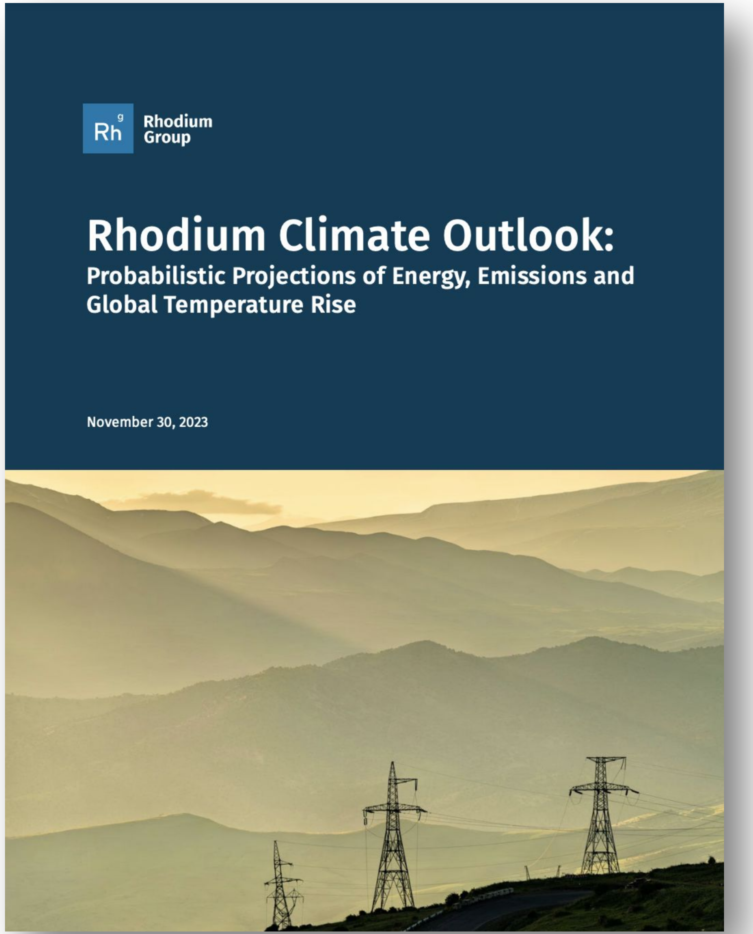


"Only the results of MAGICC are shown in this chapter as it adequately covers the range of outcomes. The emulators are calibrated against the behaviour of complex climate models and observation data, consistent with the outcomes of AR6 WGI" (WG3 Ch. 3.2)



IPCC AR6 WG3 Figure 3.5a

Smaller scale: SCMs are tools for policy analysts, the media, and government to scope mitigation scenarios.



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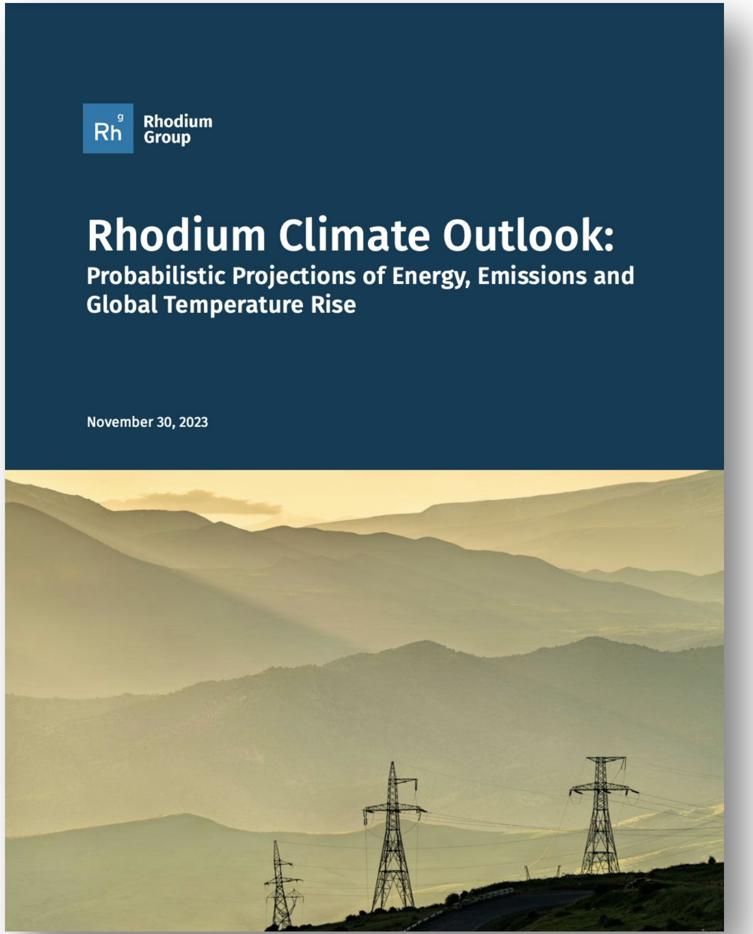
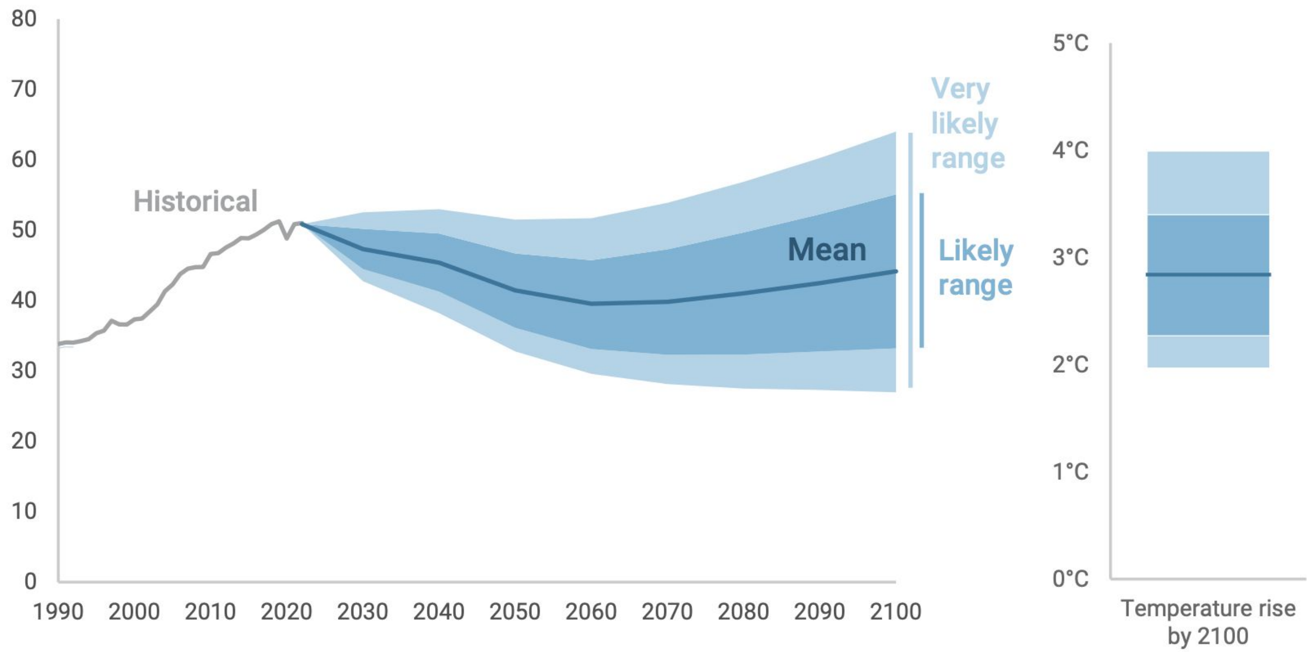


Global greenhouse gas emissions and temperature rise

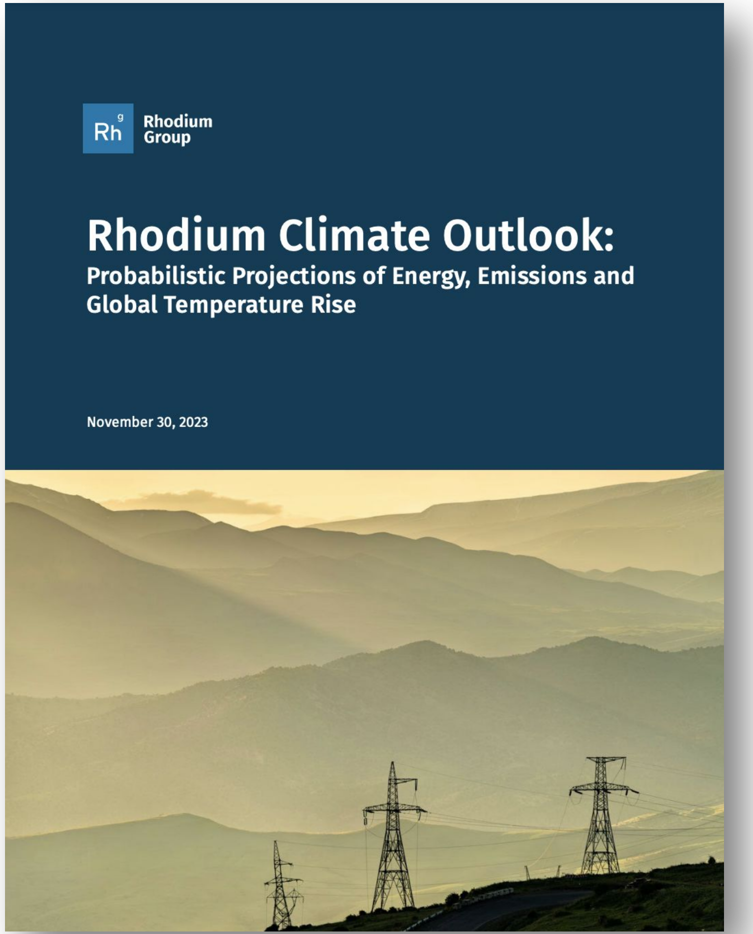
Net emissions including removals (billion metric tons of CO_2-equivalent)

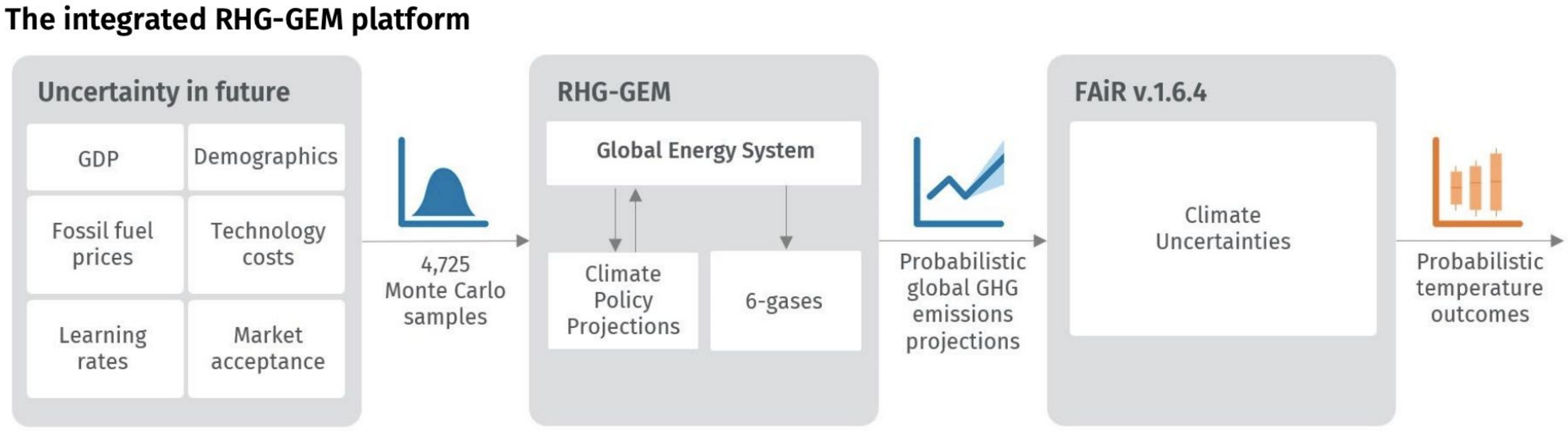


Source: Rhodium Climate Outlook, AR5 100-year GWP values. Following IPCC conventions, this report uses *very likely* to indicate a 90% probability of occurring and *likely* to indicate a 67% probability.

1. The world is very likely on track to exceed 2°C above pre-industrial levels, but we've avoided the most catastrophic projections.

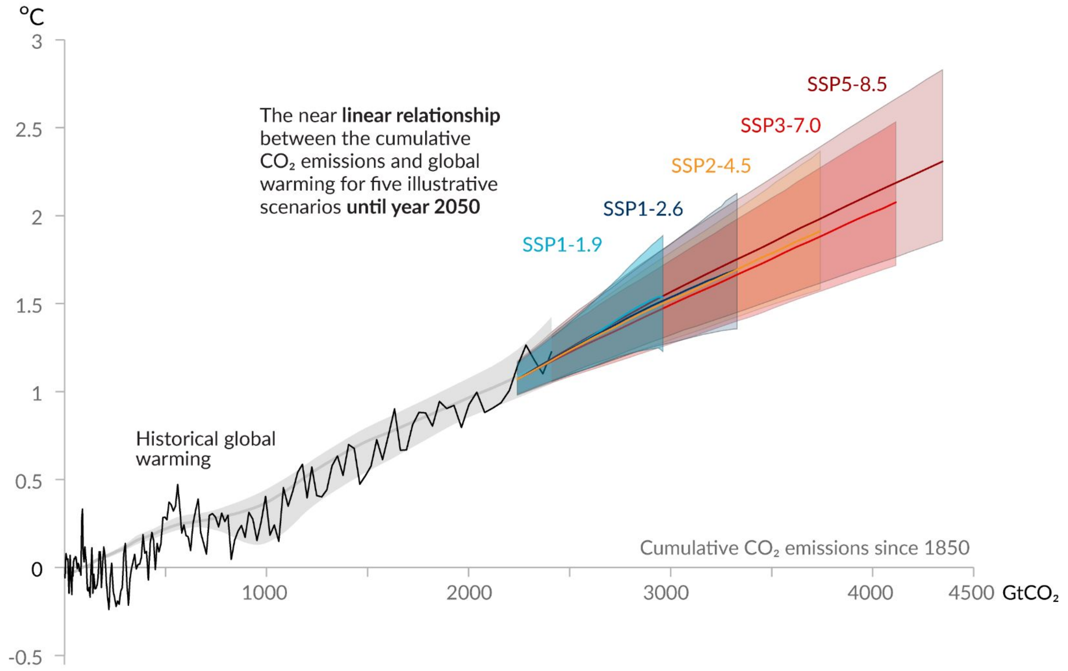
Smaller scale: SCMs are tools for policy analysts, the media, and government to scope mitigation scenarios.





Does our structural representation of the carbon cycle influence what we think the sink rate is?

How does that affect what we predict for the amount and timing of warming?



Global Carbon Project 2022

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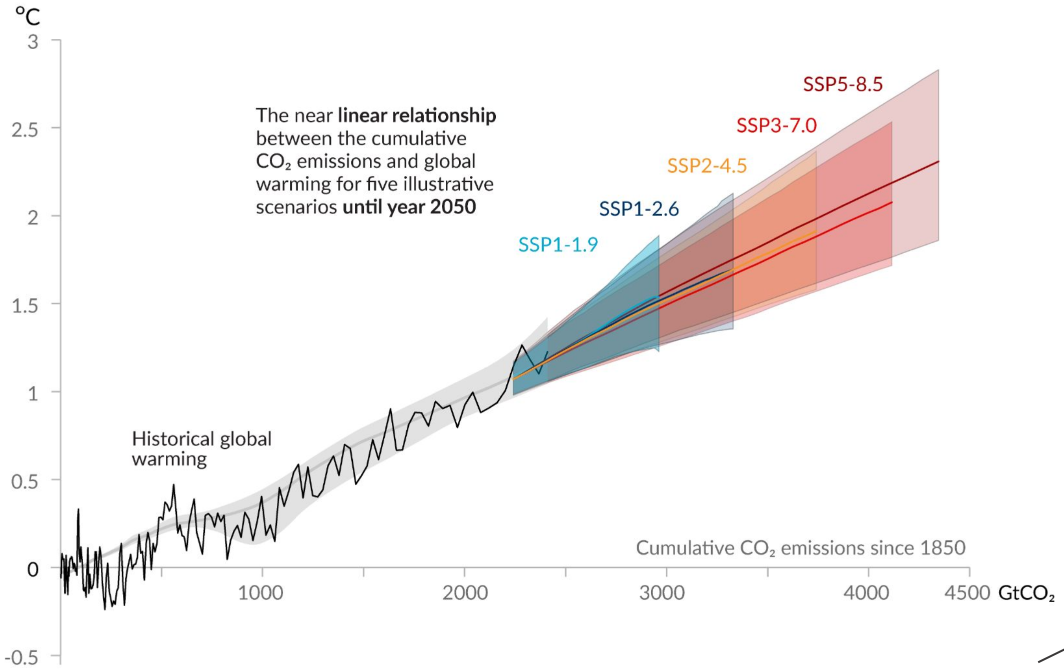
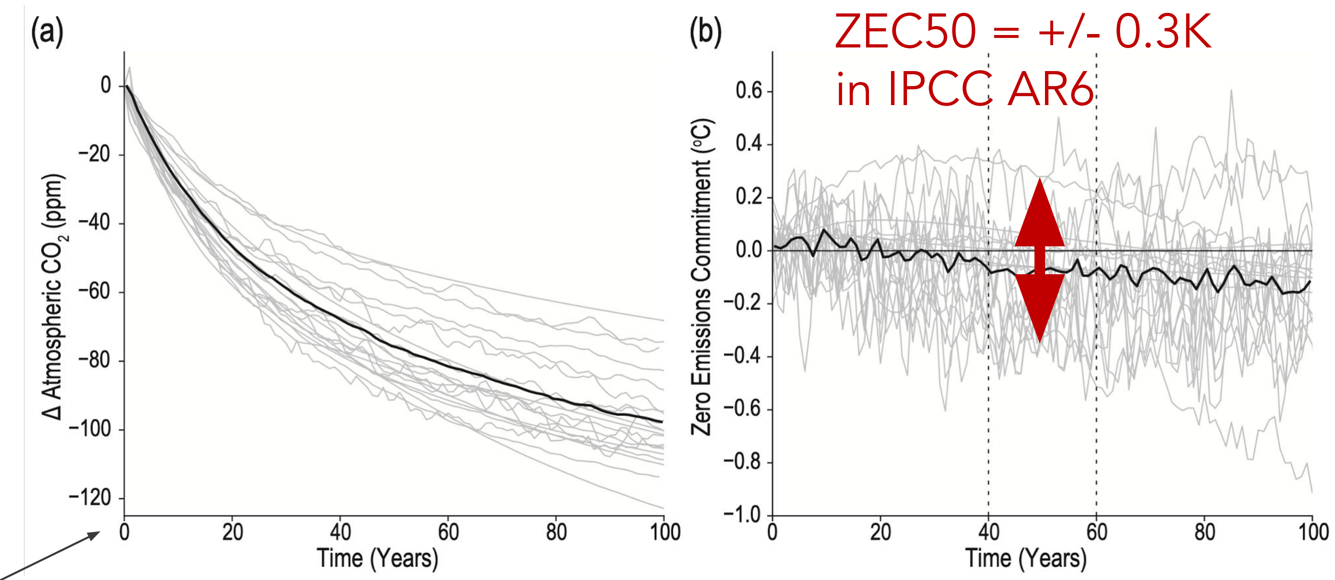
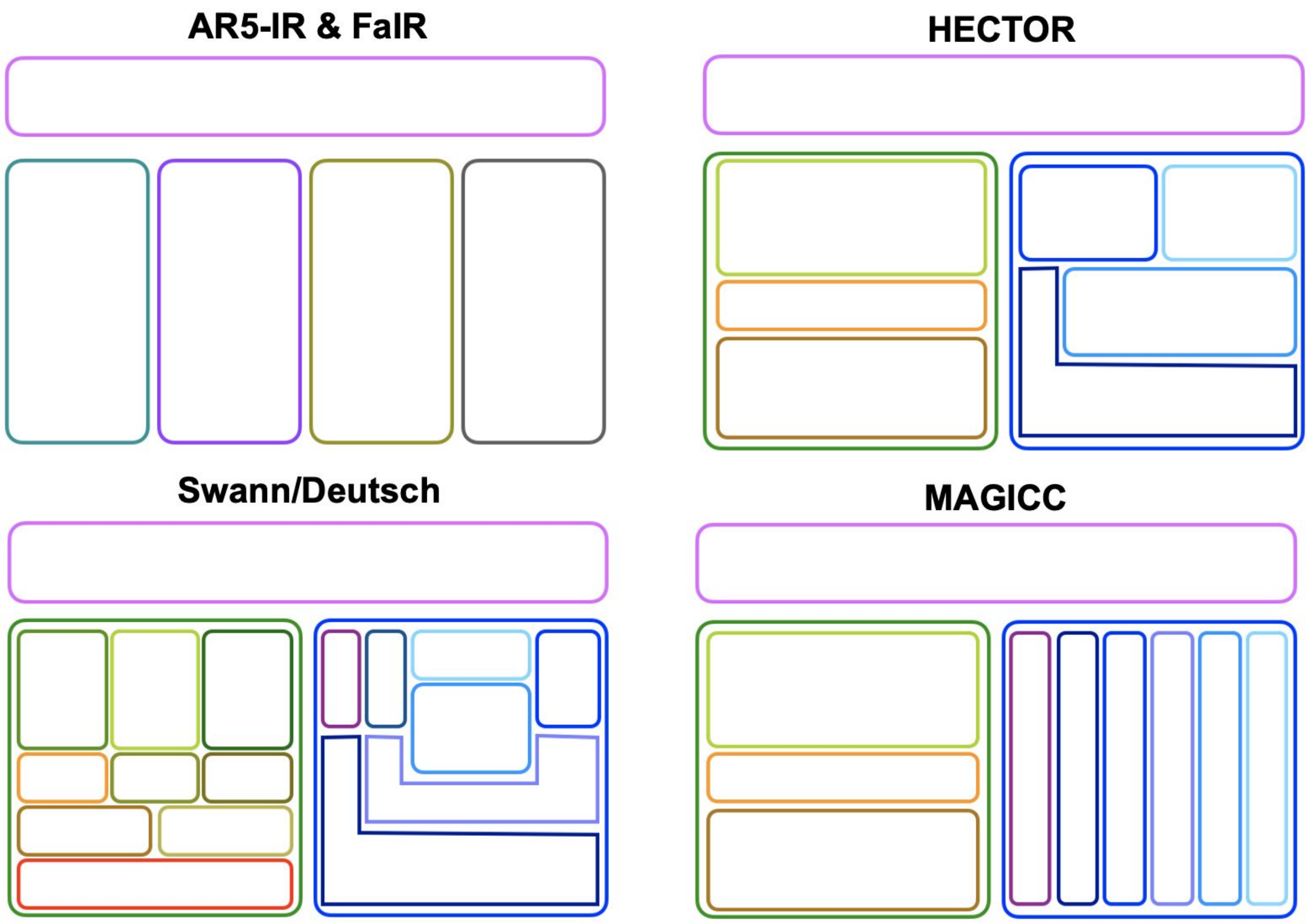




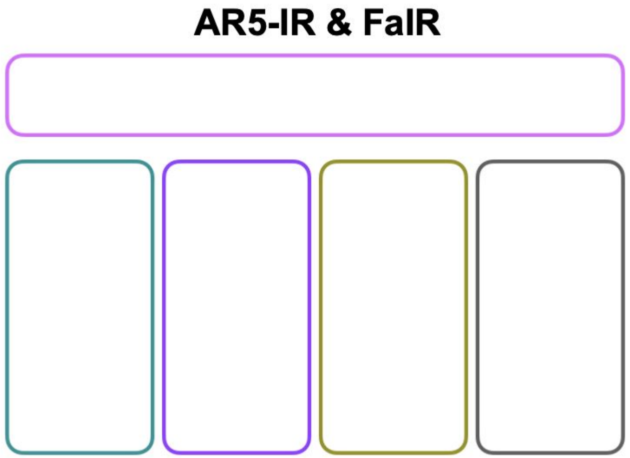
Emissions = 0

Global Carbon Project 2022, IPCC AR6 WGI Fig. 4.39

Simple models for Understanding in the Carbon Cycle and SINKs for Tomorrow (SUCCINKT) MIP



Compare climate model emulators with varying structures in representing the global carbon cycle.



AR5-IR:

$$C(t)/C_0 = a_0 + \sum_{i=1}^{3} a_i \, e^{-t/\tau_i}$$

Box	0	1	2	3
Fraction a	0.22	0.22	0.28	0.28
Timescale τ	1,000,000	390	37	4.3
Interpretation	Chemical weathering on land	Deep ocean carbon uptake	Land carbon uptake	Surface ocean carbon uptake

Joos et al., (2013)

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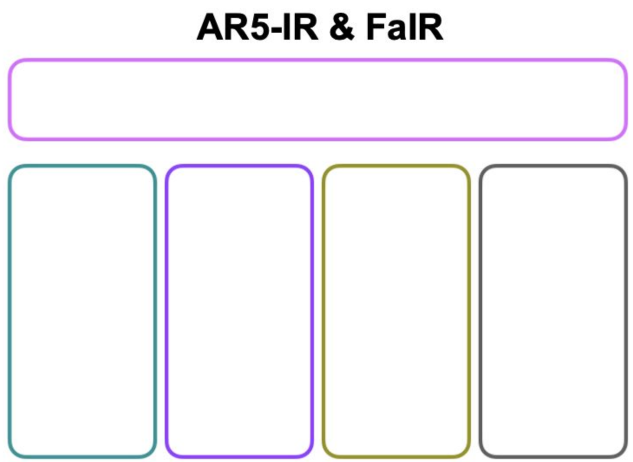

AR5-IR:

$$C(t)/C_0 = a_0 + \sum_{i=1}^{3} a_i \, e^{-t/\tau_i}$$

FaIR:

$$C(t)/C_0 = a_0 + \sum_{i=1}^{3} a_i \, e^{\frac{-t}{\alpha \tau_i}}$$

$$iIRF_{100} = r_0 + r_C C_{acc} + r_T T$$

Box	0	1	2	3
Fraction a	0.22	0.22	0.28	0.28
Timescale τ	1,000,000	390	37	4.3
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Joos et al., (2013), Millar et al., (2017), Smith et al., (2018), Dvorak et al., (2022)

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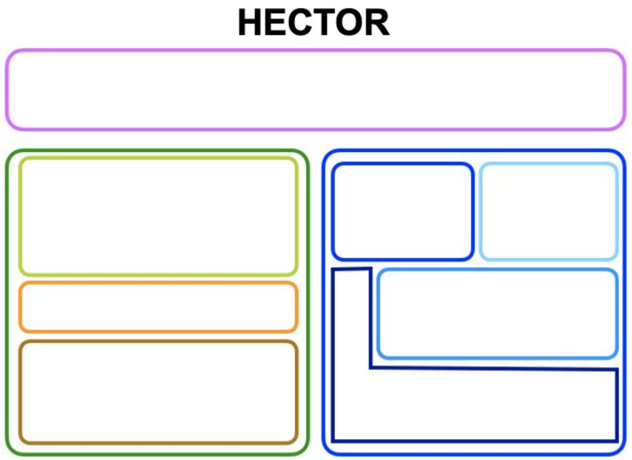


$$\frac{dC_{atm}}{dt} = F_A(t) + F_{LC}(t) - F_O(t) - F_L(t)$$

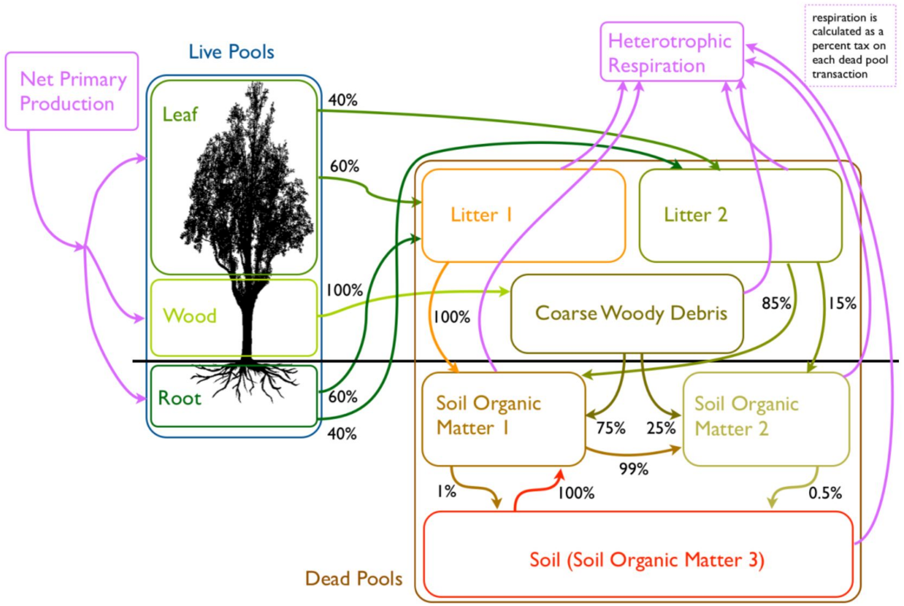
Emissions

Land model:
1 global biome, 3 carbon pools with photosynthesis (modified by CO_2 fertilization) and respiration (modified by Q_{10})

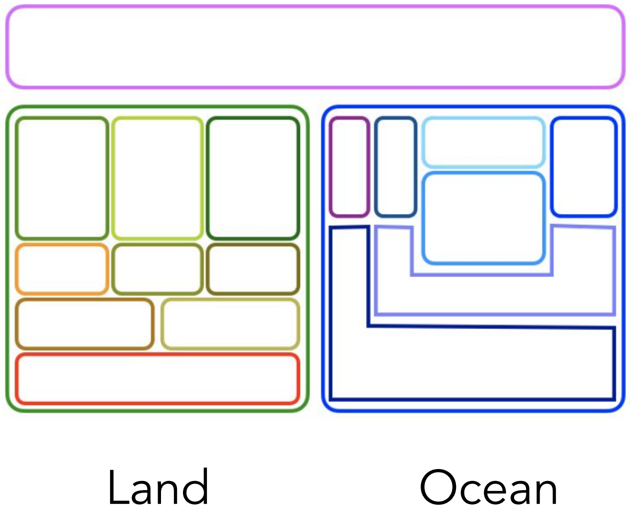
Ocean model:
4 boxes with prescribed circulation (thermohaline circulation), chemistry of inorganic carbon (modified by temperature, pH)

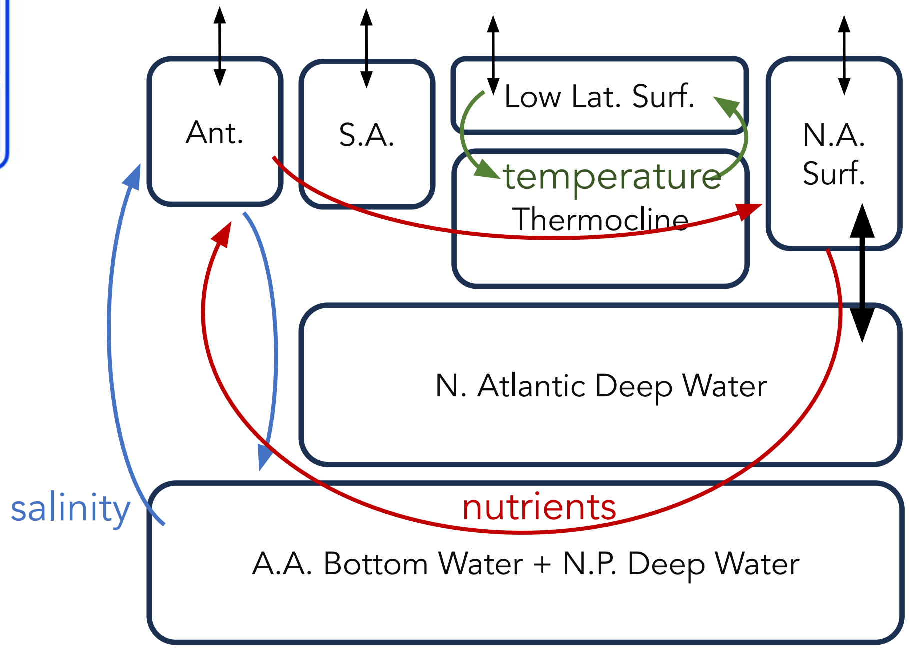
Hartin et al., (2015)

Compare climate model emulators with varying structures in representing the global carbon cycle.



Swann/Deutsch





Swann (2010), Sarmiento & Toggweiler (1984), Toggweiler (1999)

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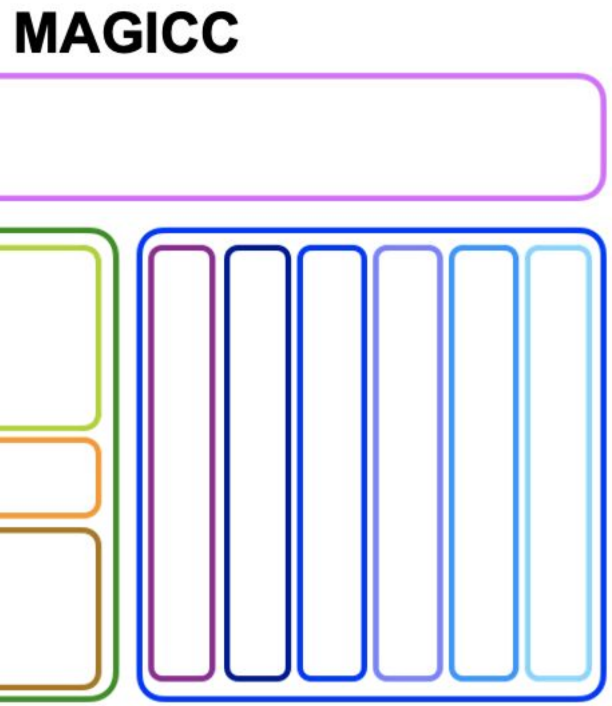
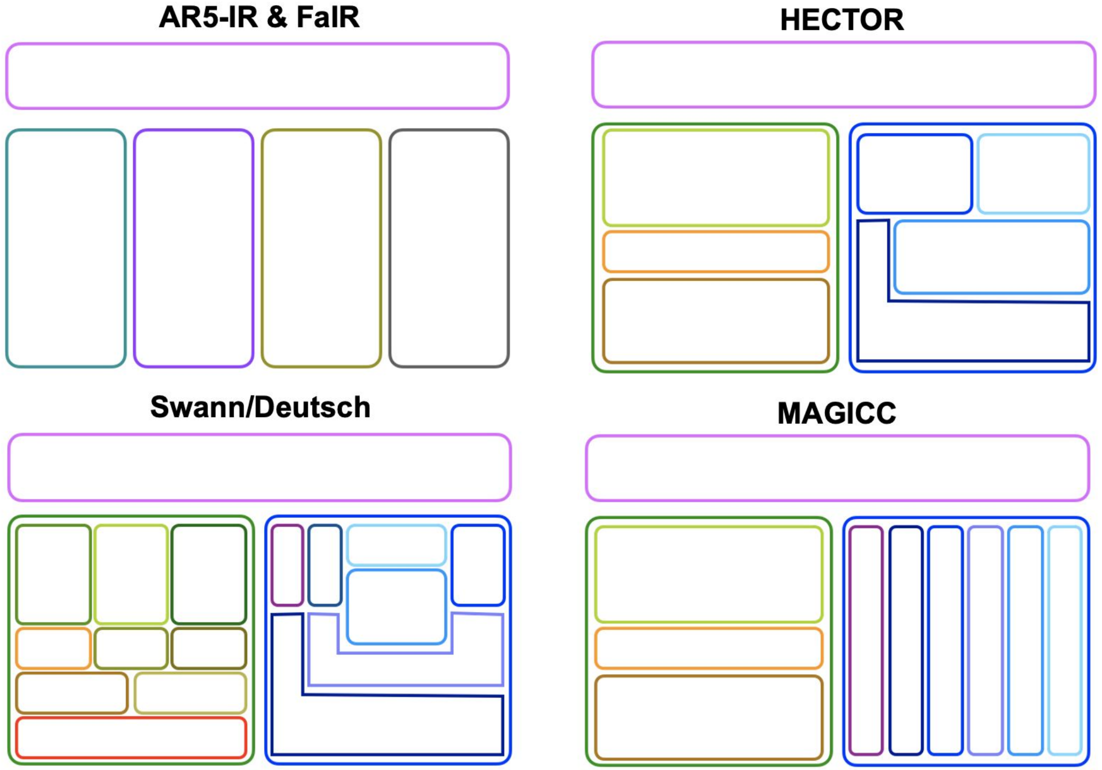


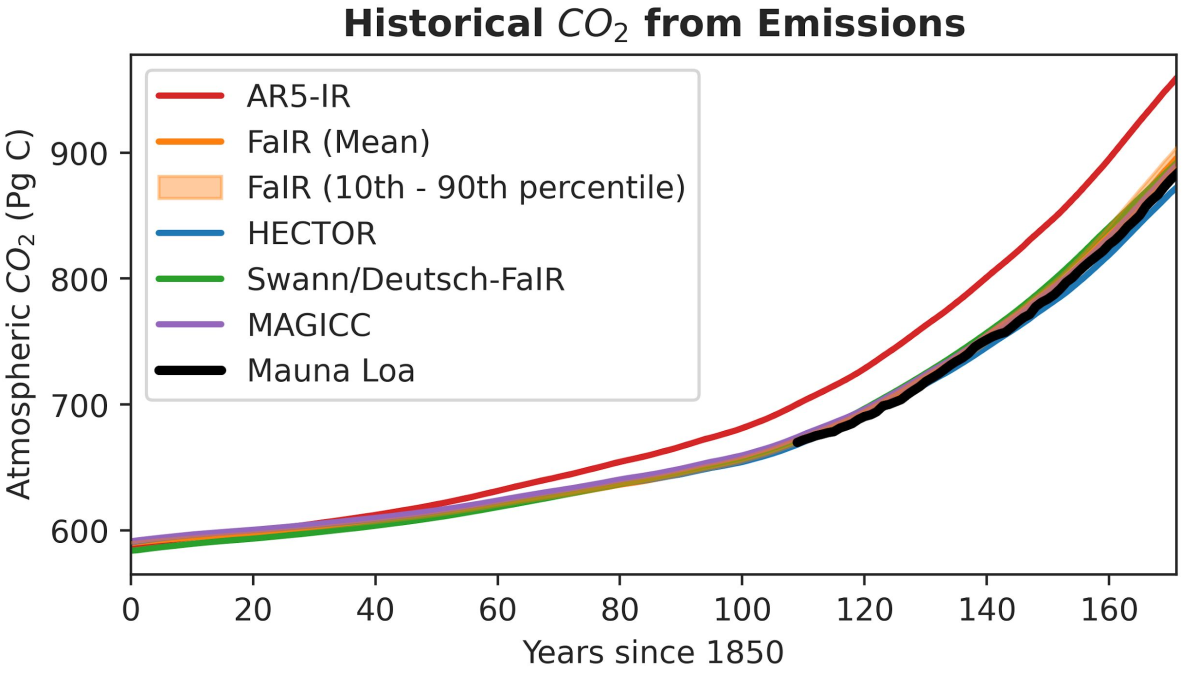
Land model:
1 global biome, 3 carbon pools
(live, detritus and soil)

Ocean model:
6-timescale impulse response function
(more complex energy components)

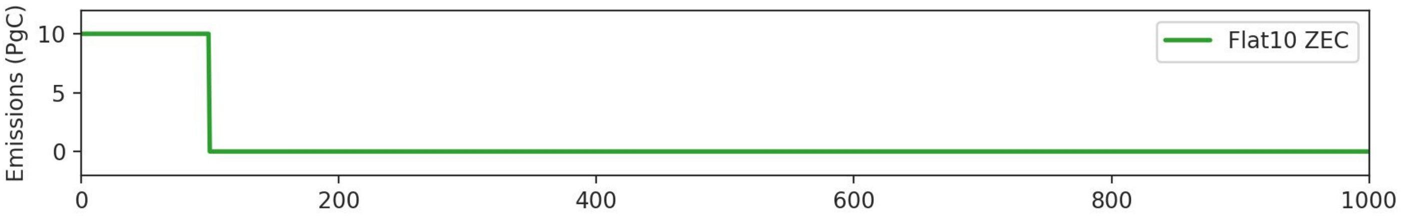
Wigley and Raper (1987, 1992), Meinshausen et al., (2011a)

Very little difference in historical atmospheric CO_2 across model structure (when increasing emissions).

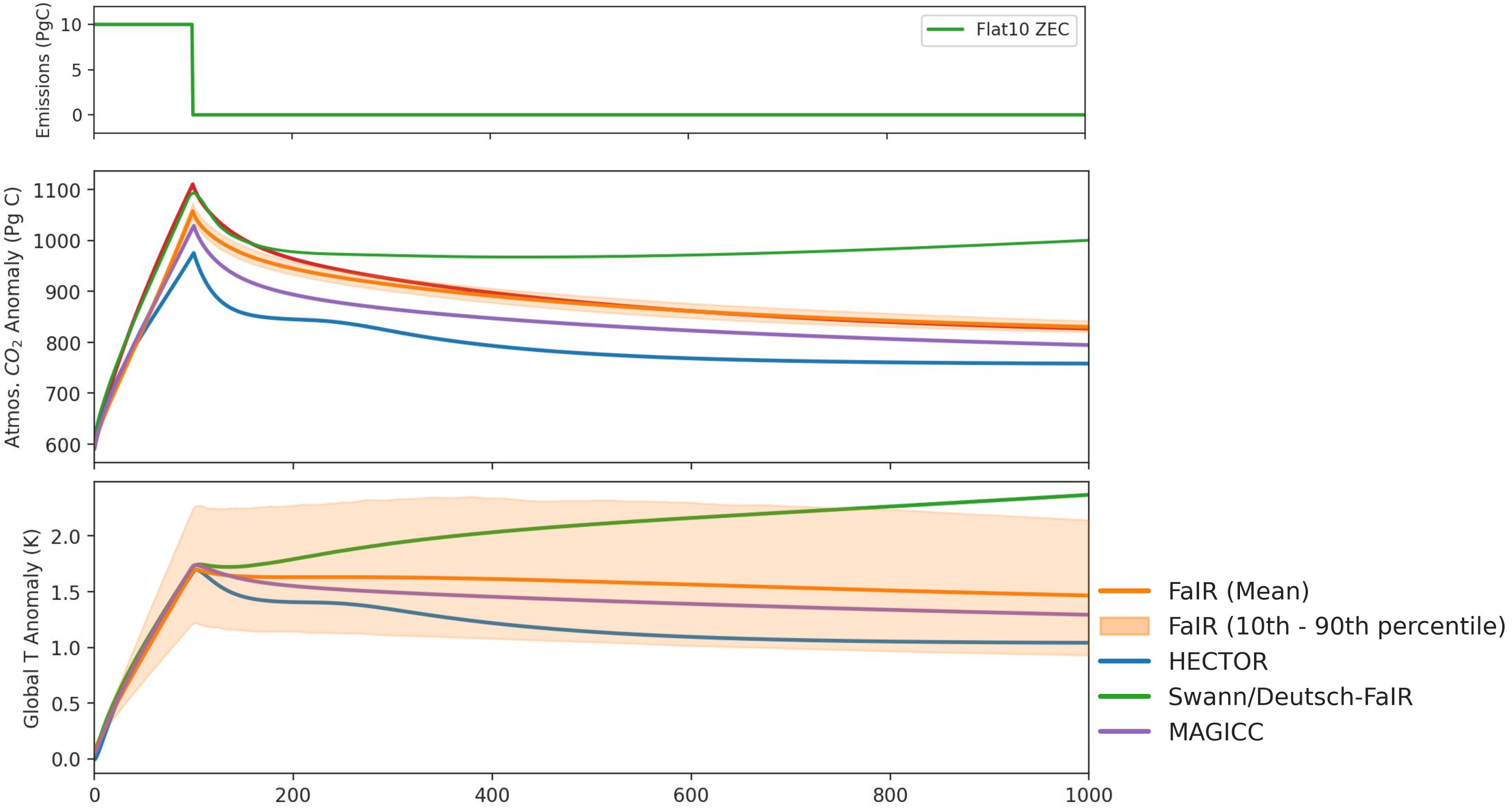




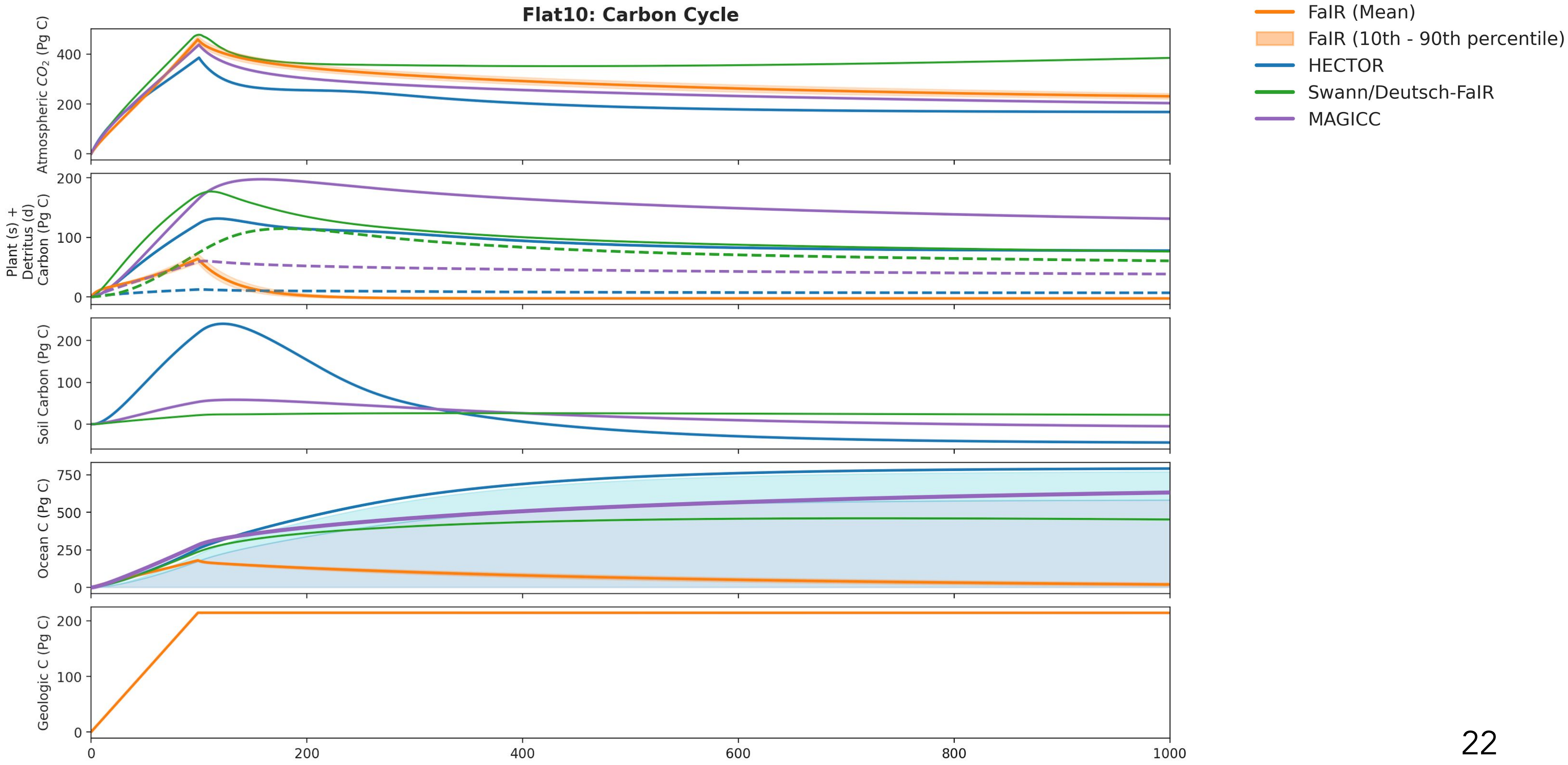
Idealized emissions trajectory: Flat10 ZEC



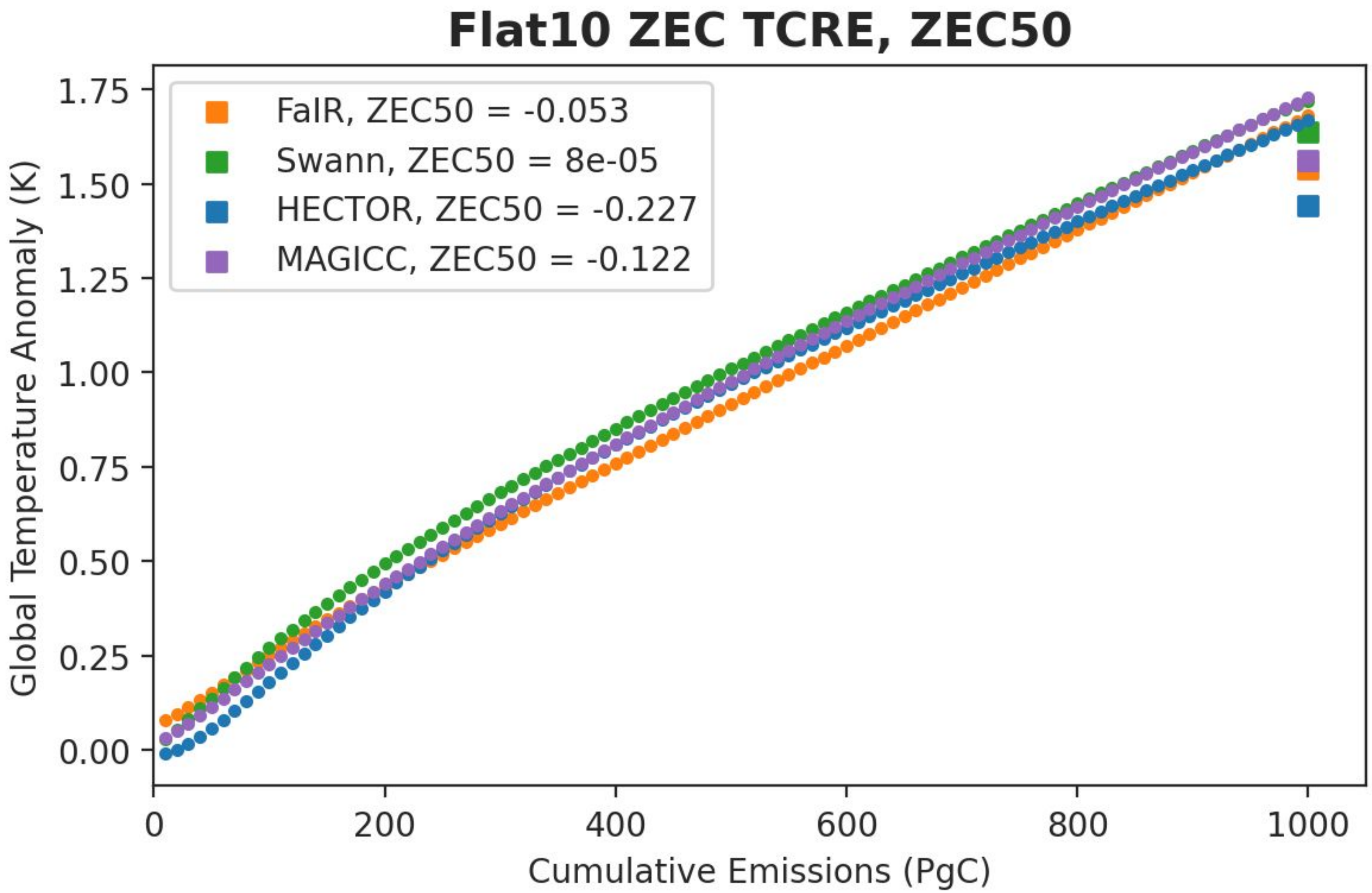
Spread in climate response to idealized emissions across model structures.



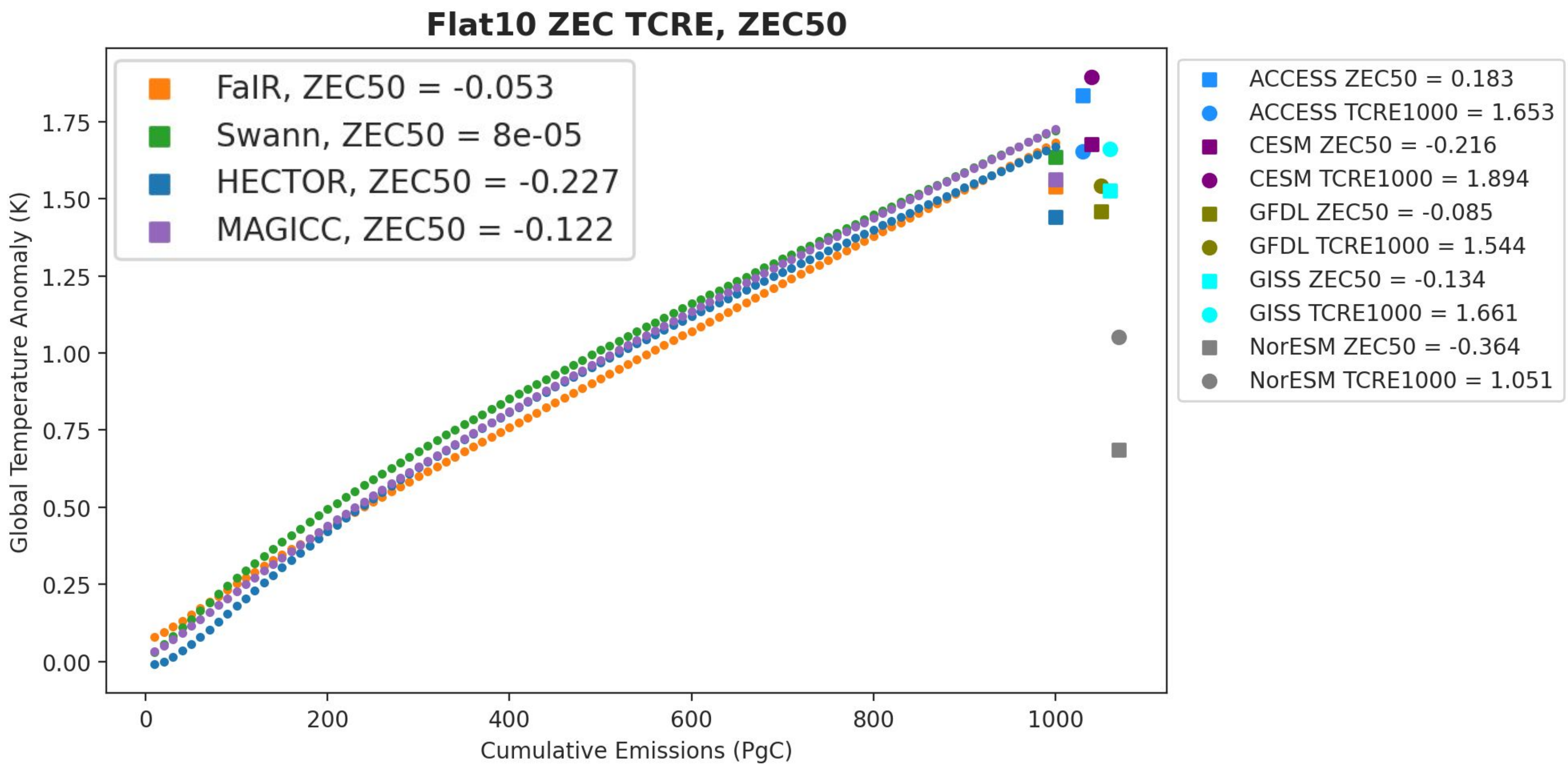
Carbon cycle responses to emissions varies by model.



The TCRE is consistent across emulators, negative ZEC.



Inside envelope of ESM response, perhaps under-sampling range of near-term ZEC.



Thanks to Ben Sanderson, Charlie Koven & Abby Swann for ESM data

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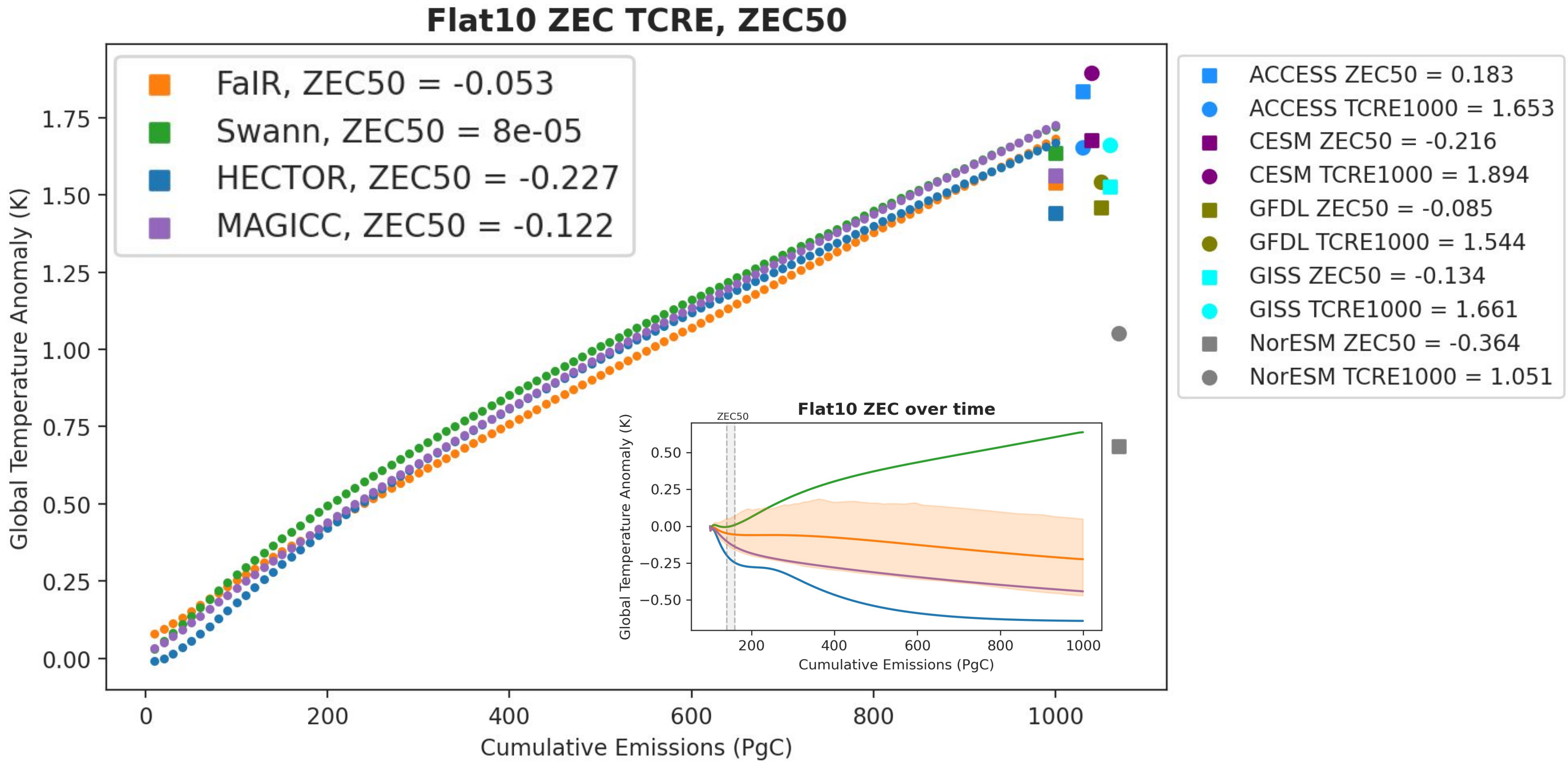

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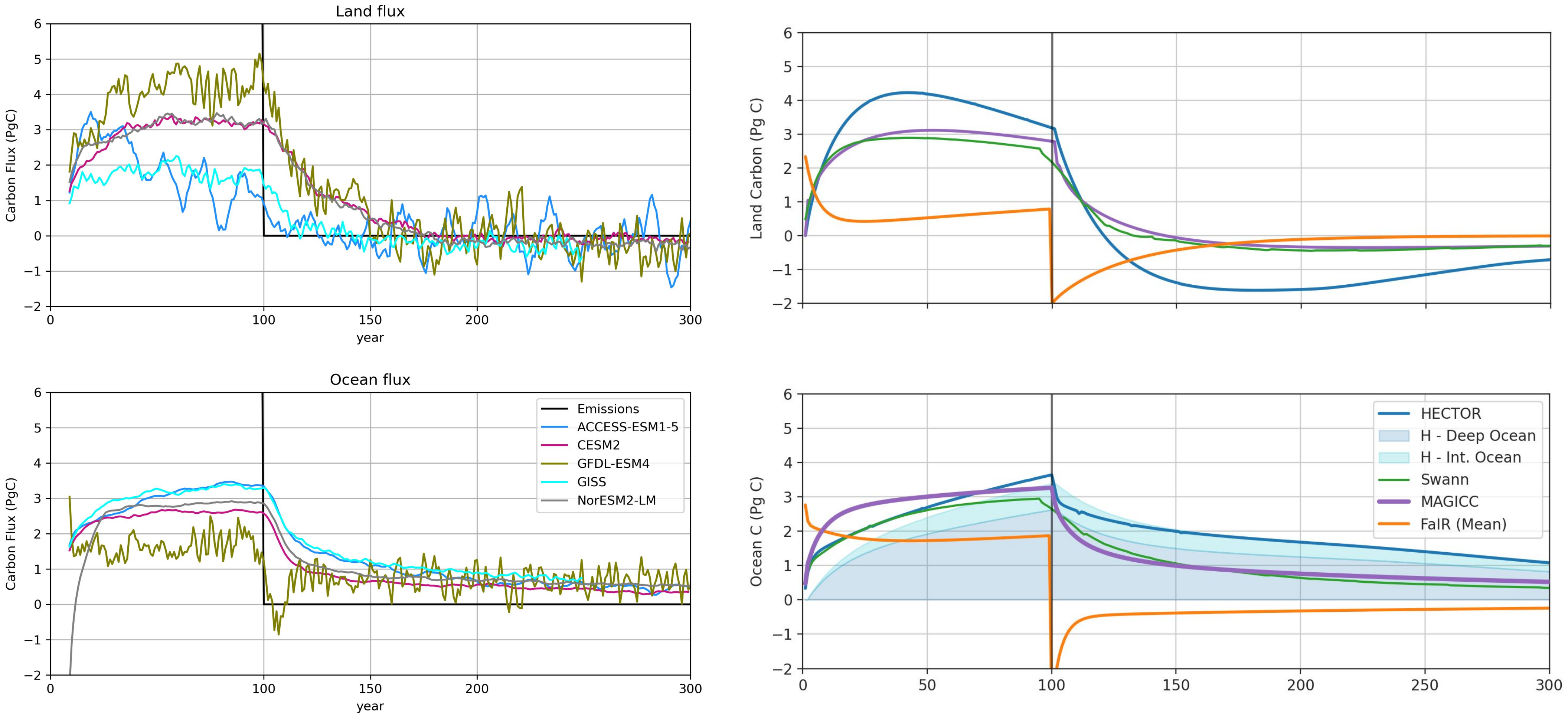
Carbon fluxes between atmosphere and each sink in SCMs span a similar range as ESM spread.



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Conclusions & Implications

- Comparing across reduced complexity climate models allows us to quantify structural uncertainty in the climate system.
  - Structural uncertainty emerges in decarbonization. As emissions dip toward zero in emulators, the spread between models increases.
  - Spread in expected emissions-driven warming grows after reaching net-zero.
- □ Need for emissions-forced ESM decarbonization runs to train emulators (building reliability and insight).
- □ Danger in using one model to project carbon cycle for any generalized use case (including remaining carbon budget, potential carbon removal assessment).

- *Next*: Carbon cycle parameter sensitivity tests to compare parametric uncertainty (within models) to structural uncertainty (across models)