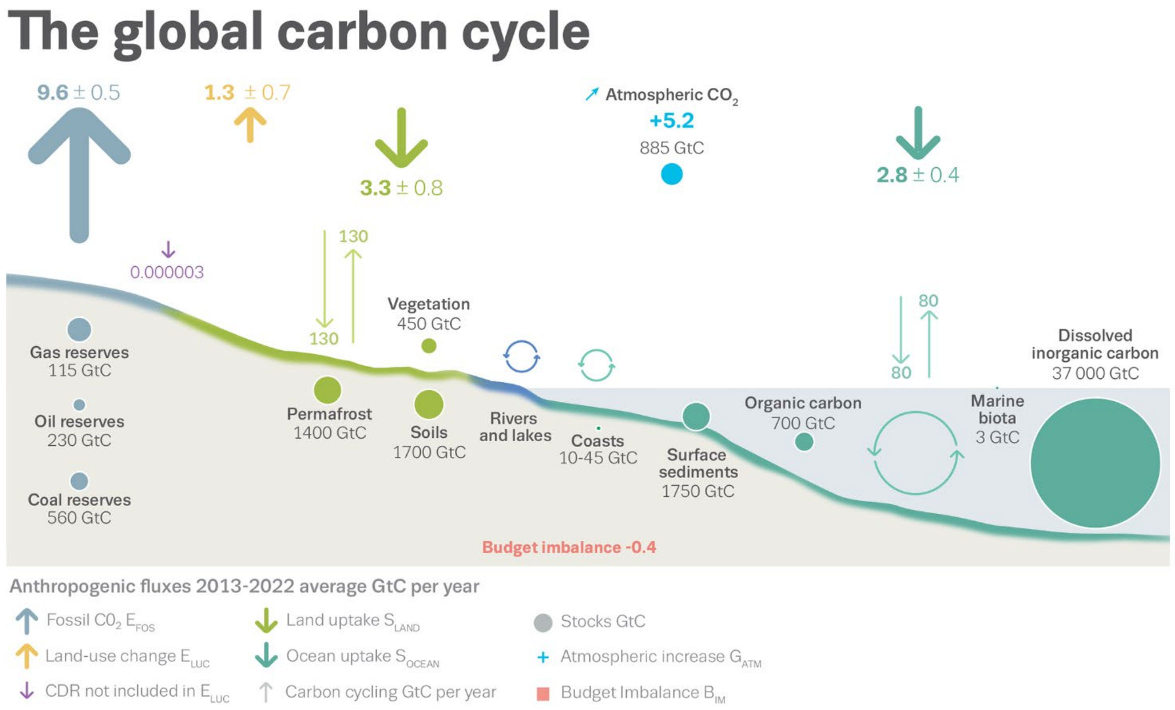
Characterizing Carbon Sink Responses to Decarbonization across Model Structures

Greta Shum[1], James Yoon[1], Olivia Truax[1,2], Claire Zarakas[1], Dargan Frierson[1], Charlie Koven[3], and Abby Swann[1,4]

[1] Atmospheric Sciences Department, University of Washington, Seattle, WA
[2] School of Earth and Environment, University of Canterbury, Christchurch, NZ
[3] Lawrence Berkeley National Lab, Berkely, CA
[4] Biology Department, University of Washington, Seattle, WA

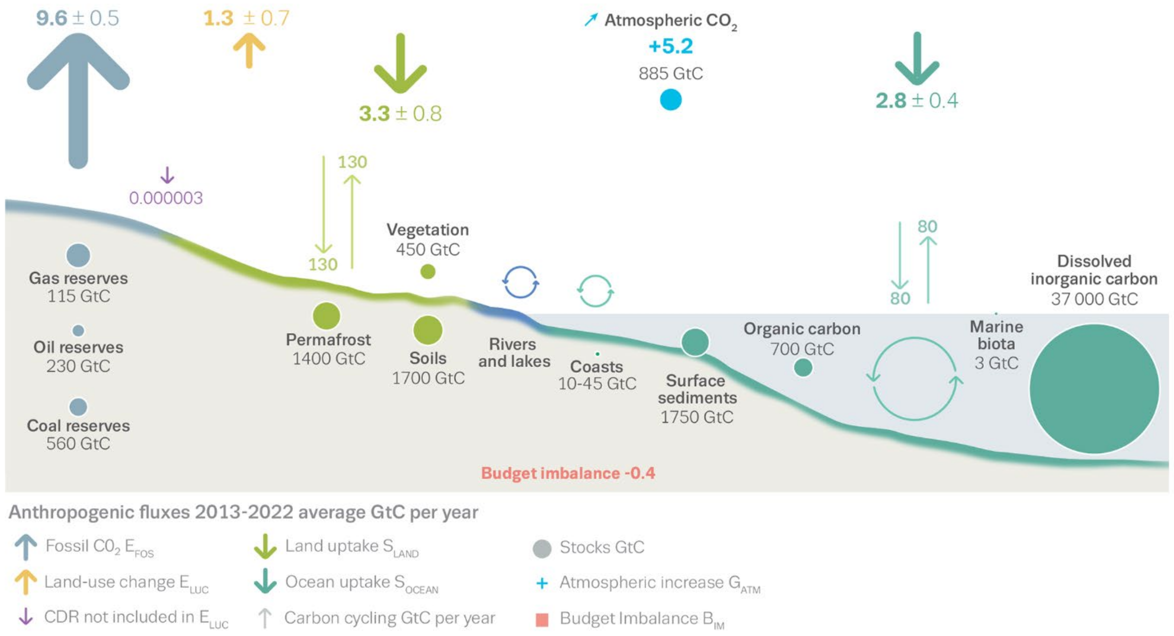
Biogeochemical feedbacks dictate the net land and ocean carbon sinks



Friedlingstein et al. 2022

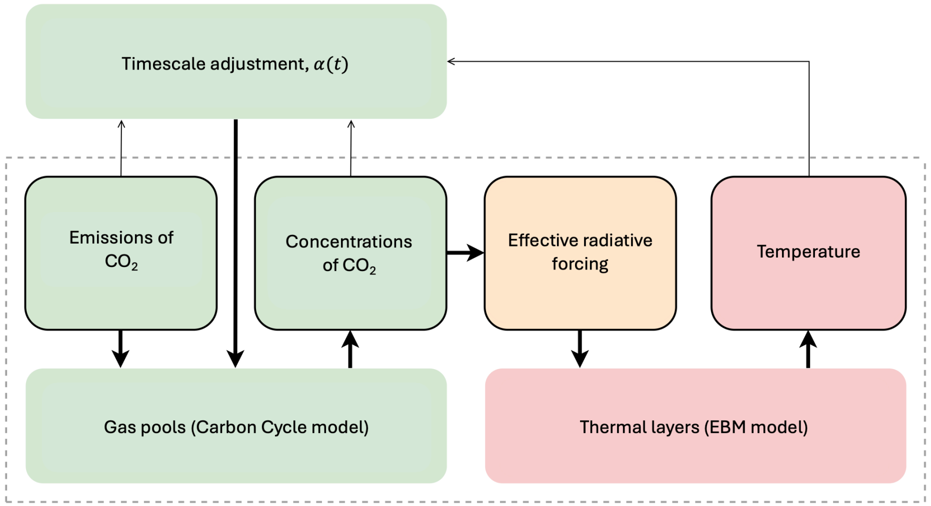
Biogeochemical feedbacks dictate the net land and ocean carbon sinks

The global carbon cycle



Friedlingstein et al. 2022

Structure of FaIR (Simple Climate Model)



Timescale adjustment, $\alpha(t)$

Emissions of CO$_2$

Concentrations of CO$_2$

Effective radiative forcing

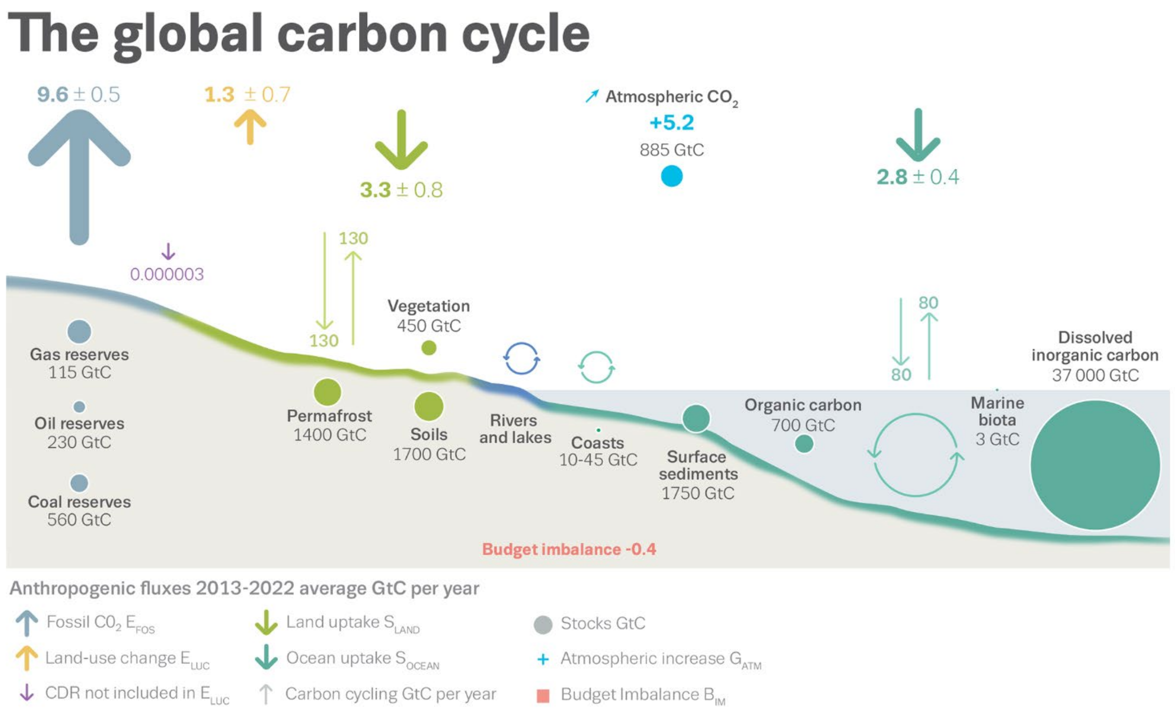
Temperature

Gas pools (Carbon Cycle model)

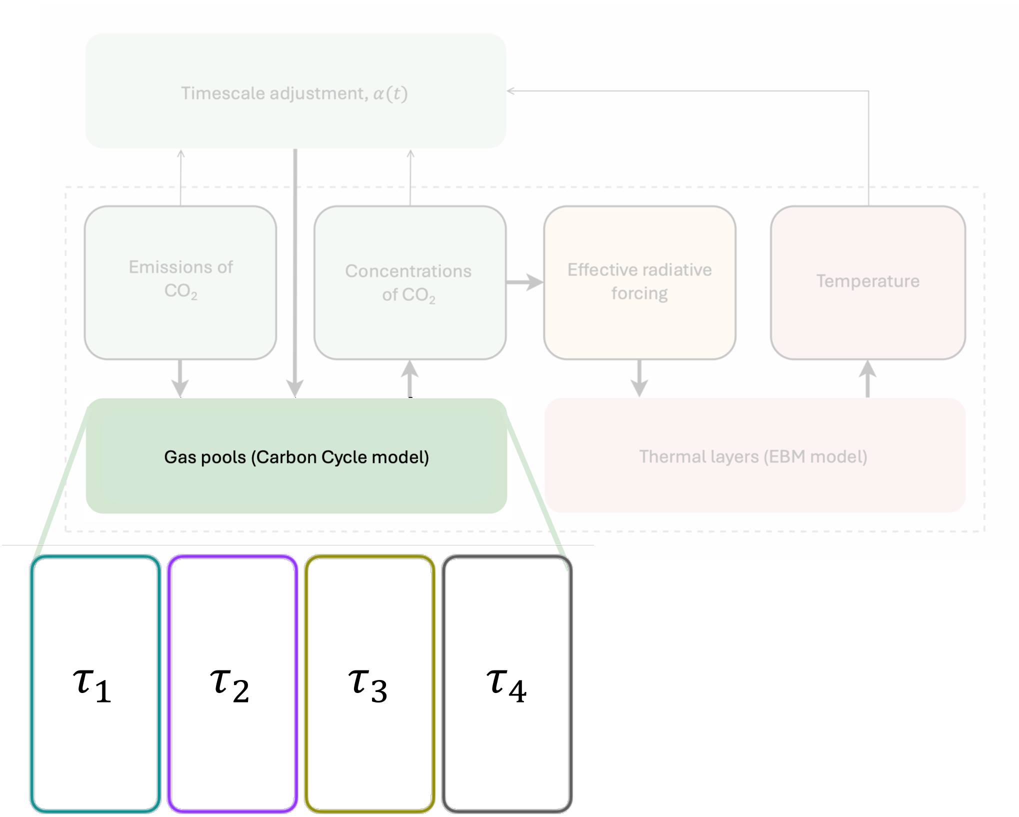
Thermal layers (EBM model)

Adapted from Leach et al. 2021

Biogeochemical feedbacks dictate the net land and ocean carbon sinks



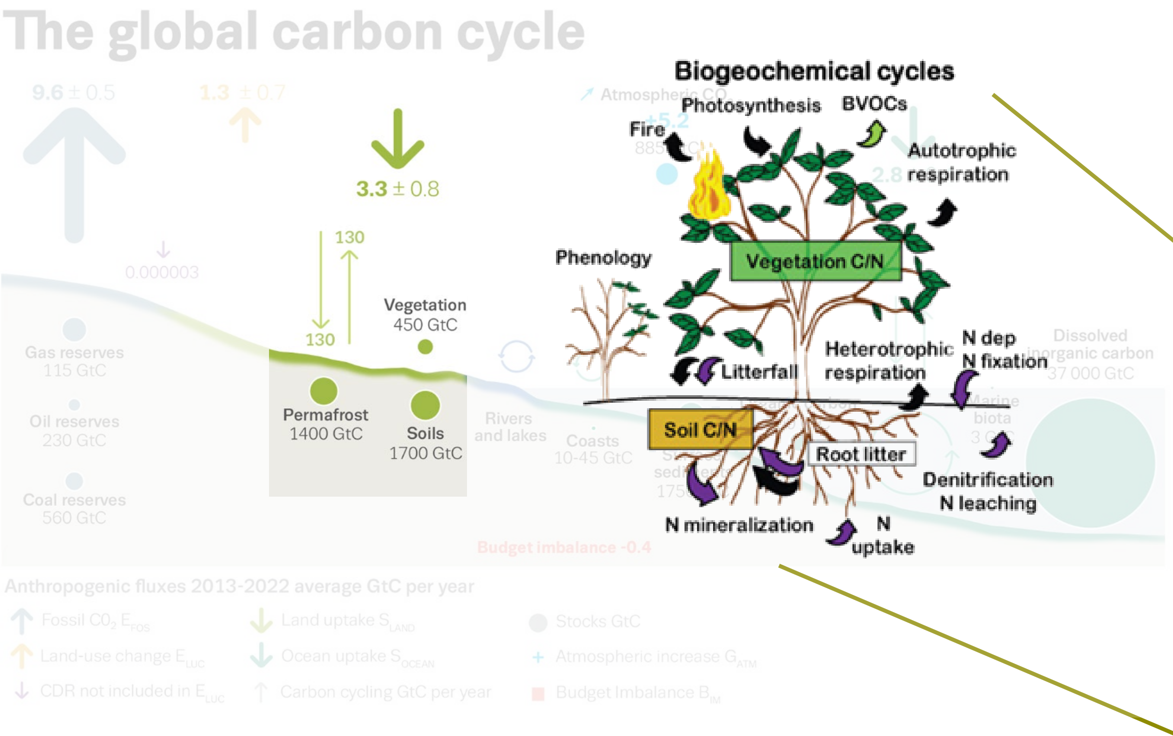
Structure of FaIR (Simple Climate Model)



Friedlingstein et al. 2022

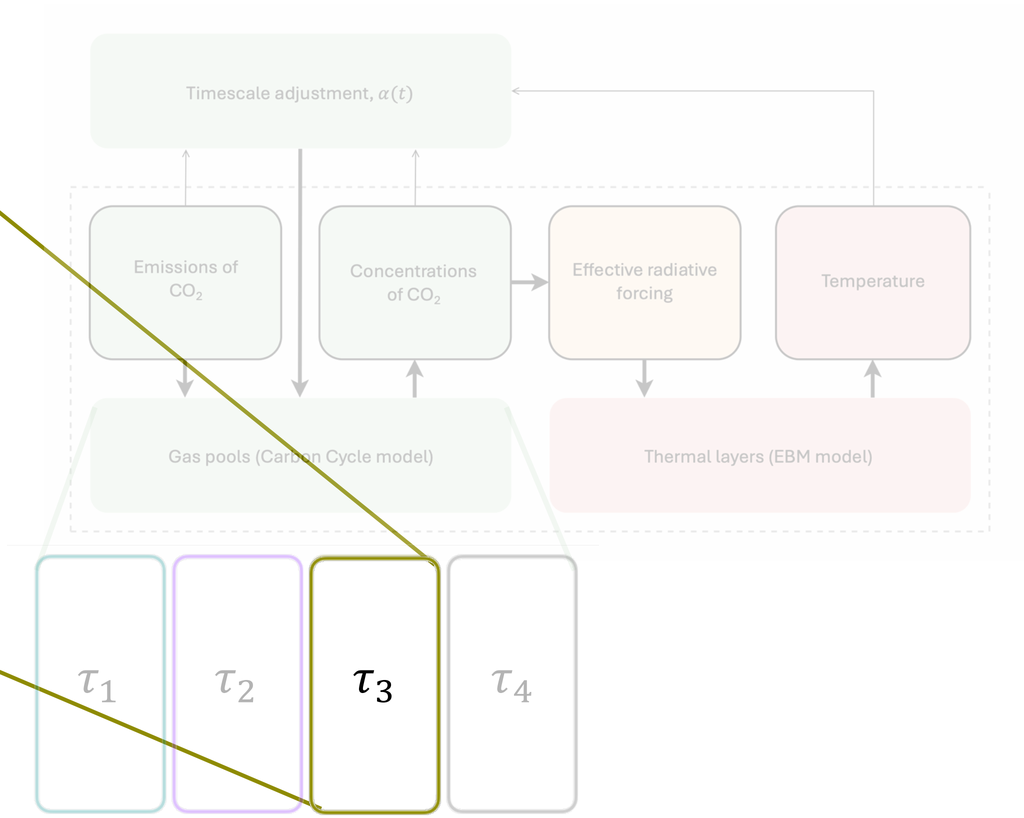
Adapted from Leach et al. 2021

Biogeochemical feedbacks dictate the net land and ocean carbon sinks



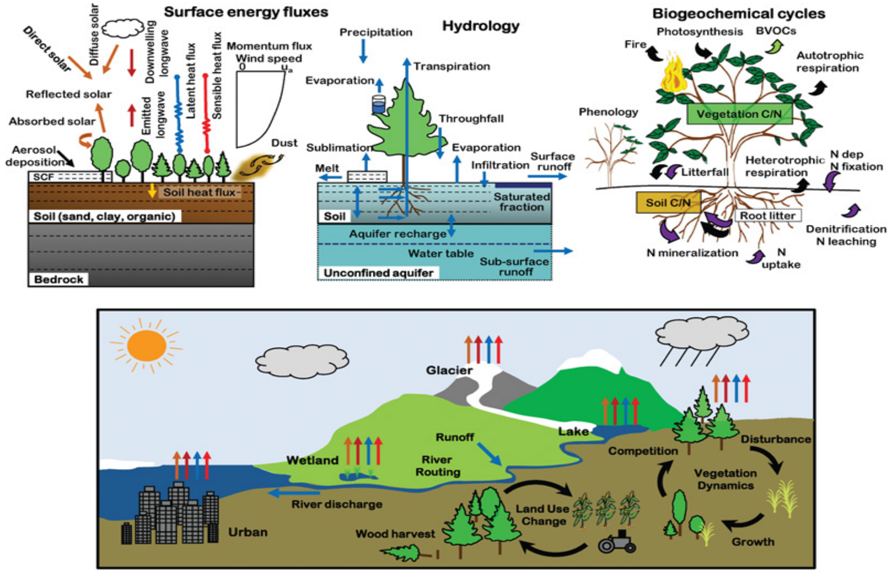
Friedlingstein et al. 2022

Structure of FaIR (Simple Climate Model)

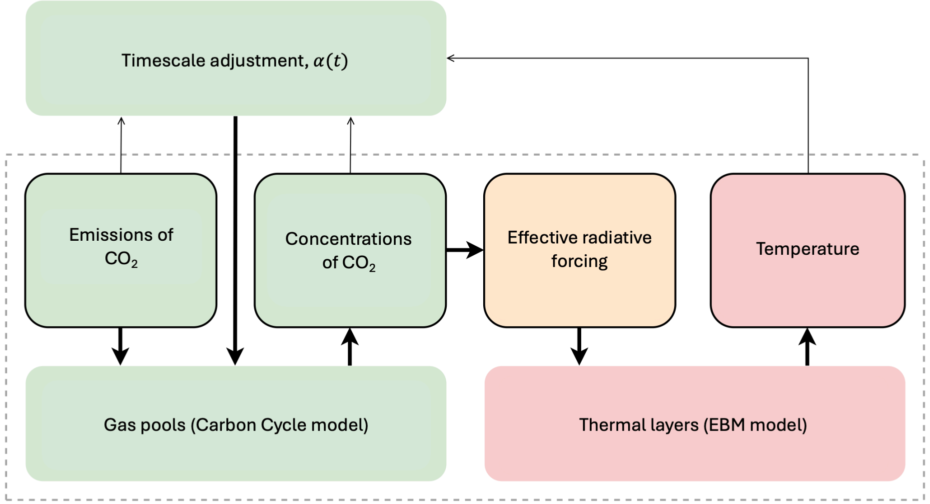


Adapted from Leach et al. 2021

SCMs are tuned to observations and ESMs, only ESMs in the future



ESM process representation



Timescale adjustment, $\alpha(t)$

Emissions of CO_2

Concentrations of CO_2

Effective radiative forcing

Temperature

Gas pools (Carbon Cycle model)

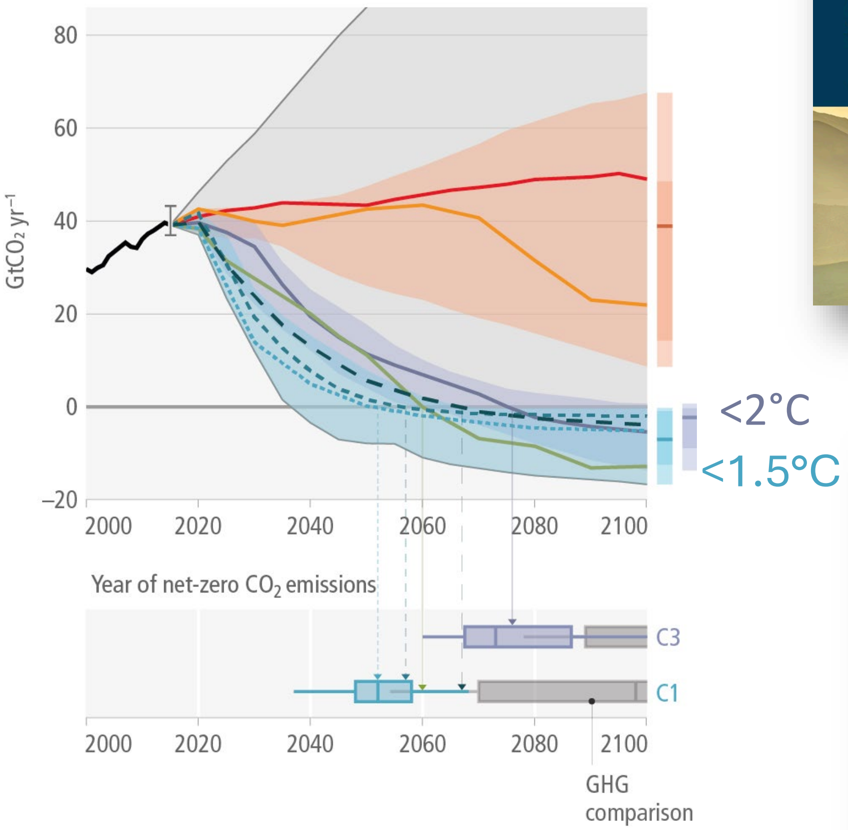
Thermal layers (EBM model)

SCMS parameters are tuned to reproduce the ESM output (using CMIP scenarios for future)

SCMs increasingly used to assess and interpret climate mitigation

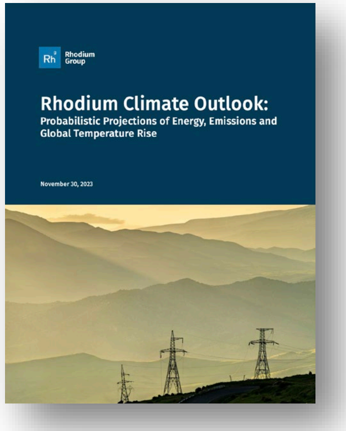
MAGICC

\+ FaIR + Cicero_scm



IPCC AR6 WGIII Figure 3.6

FaIR



Rhodium Climate Outlook:
Probabilistic Projections of Energy, Emissions and Global Temperature Rise

November 30, 2023

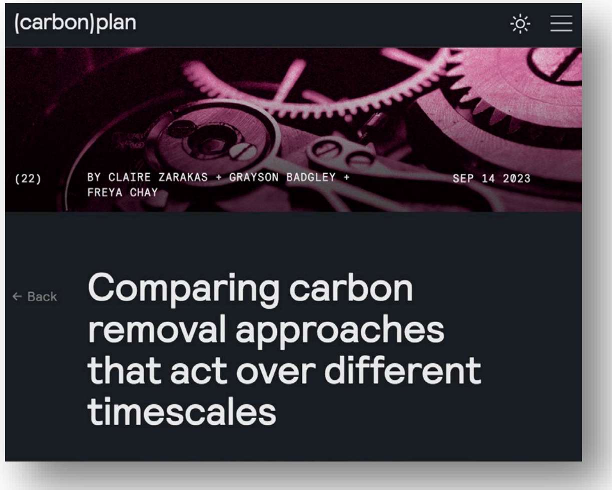
FaIR

BY GRAYSON BADGLEY + FREYA CHAY + JEREMY FREEMAN + KATA MARTIN

MAY 03 2023

Problems with Quebec's new reforestation offsets protocol

HECTOR



BY CLAIRE ZARAKAS + GRAYSON BADGLEY + FREYA CHAY

SEP 14 2023

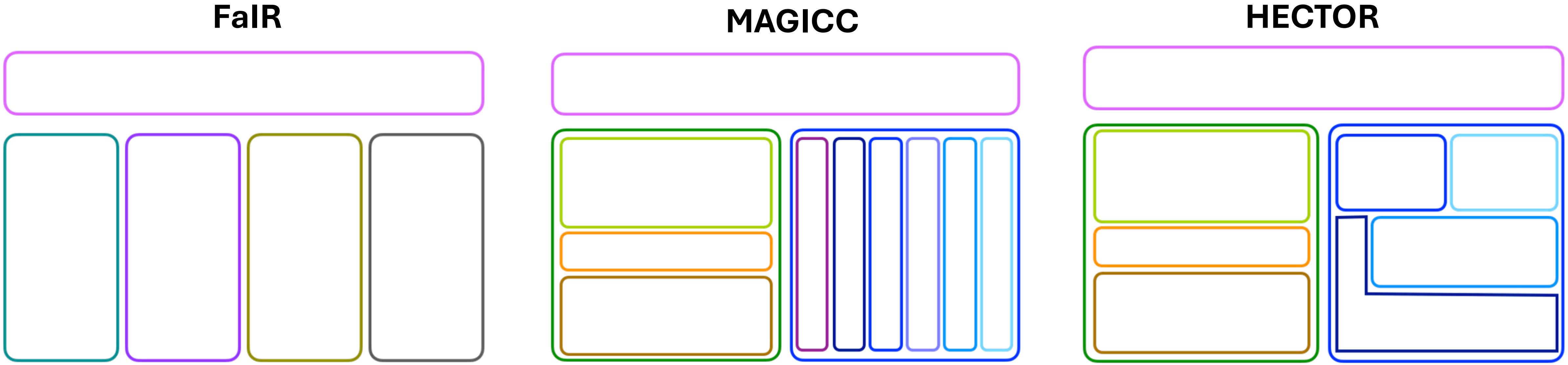
Comparing carbon removal approaches that act over different timescales

MAGICC

Global Energy Perspective 2023: CO_2 emissions outlook

January 24, 2024 | Article

Structure of the carbon cycle inside these SCMs varies a lot



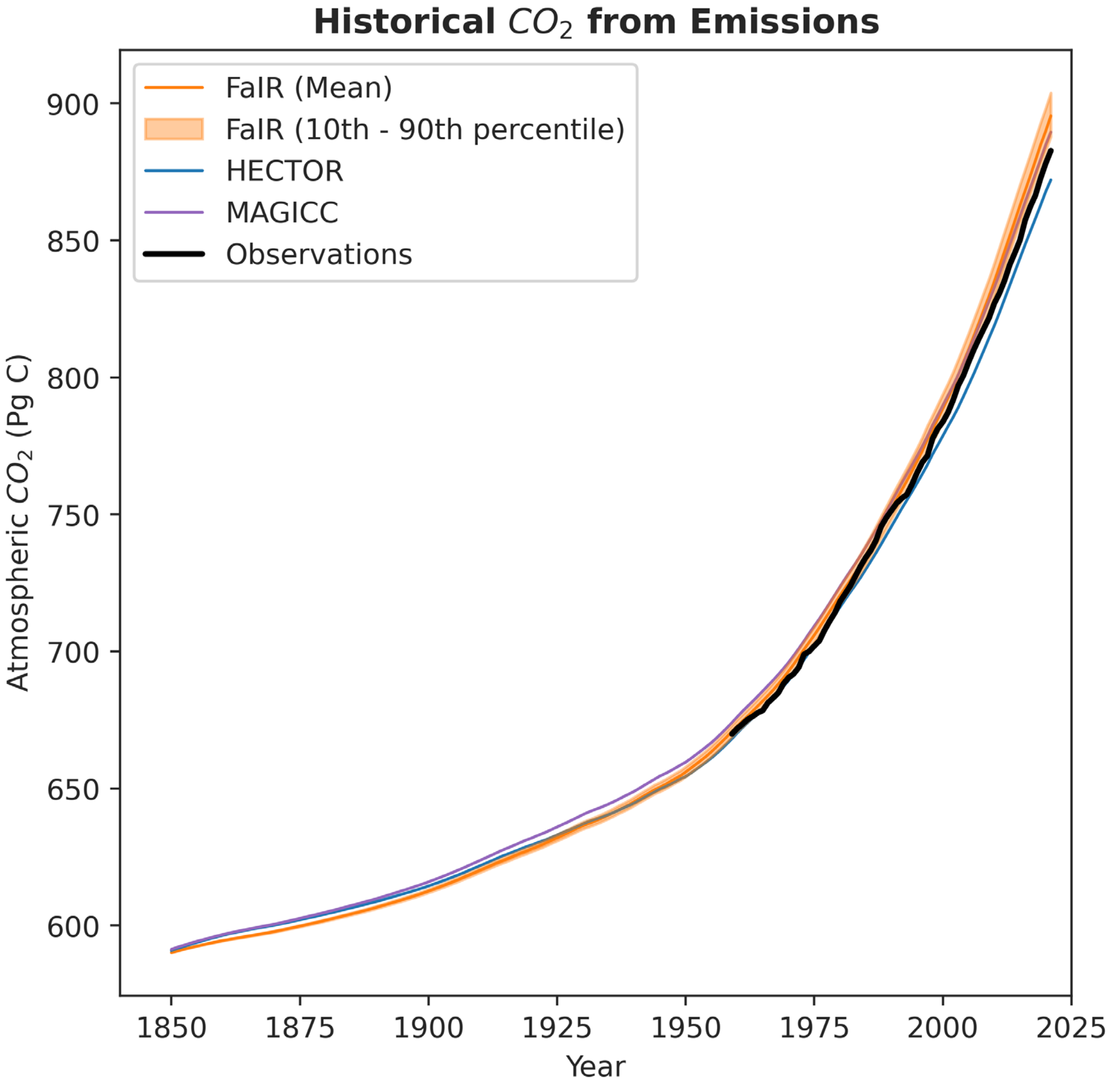
FaIR

MAGICC

HECTOR

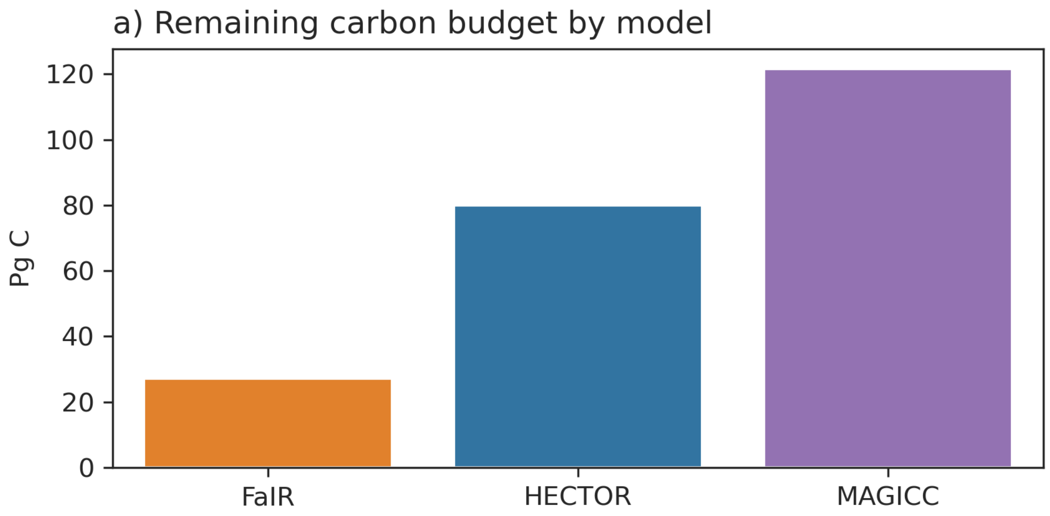
Models reproduce historical emissions to concentration

- Out of the box, models can reproduce observed record of CO_2 concentrations since pre-industrial
  - FF and LUC emissions data from Global Carbon Budget 2021 (Friedlingstein et al., 2022)
- Demonstrates their ability to capture carbon cycle in an emissions regime.



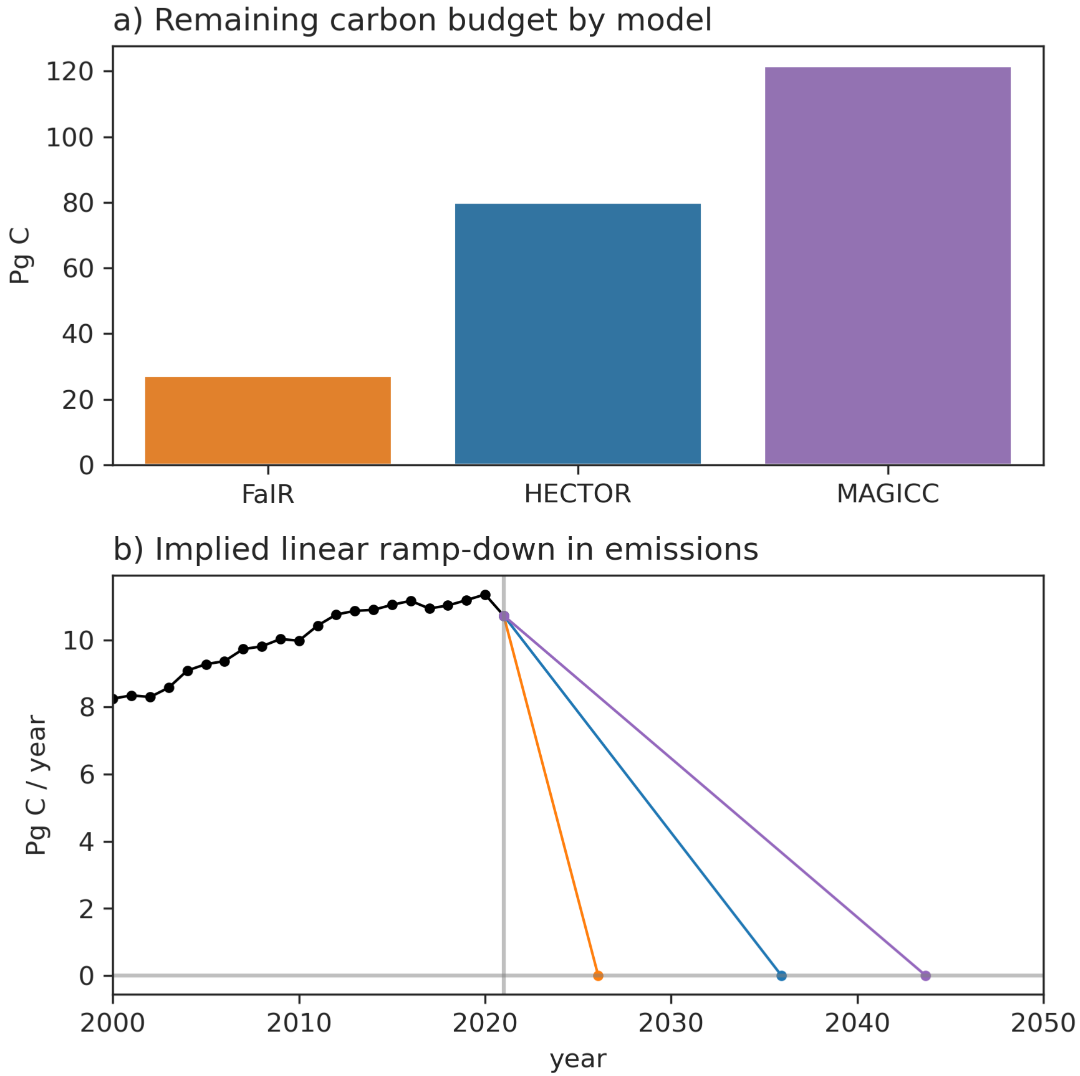
SCMs vary by ~100 Pg C in remaining carbon budget

- Using each model’s TCRE and ZEC, we can compute remaining carbon budgets for a temperature change limit of 1.5°C.

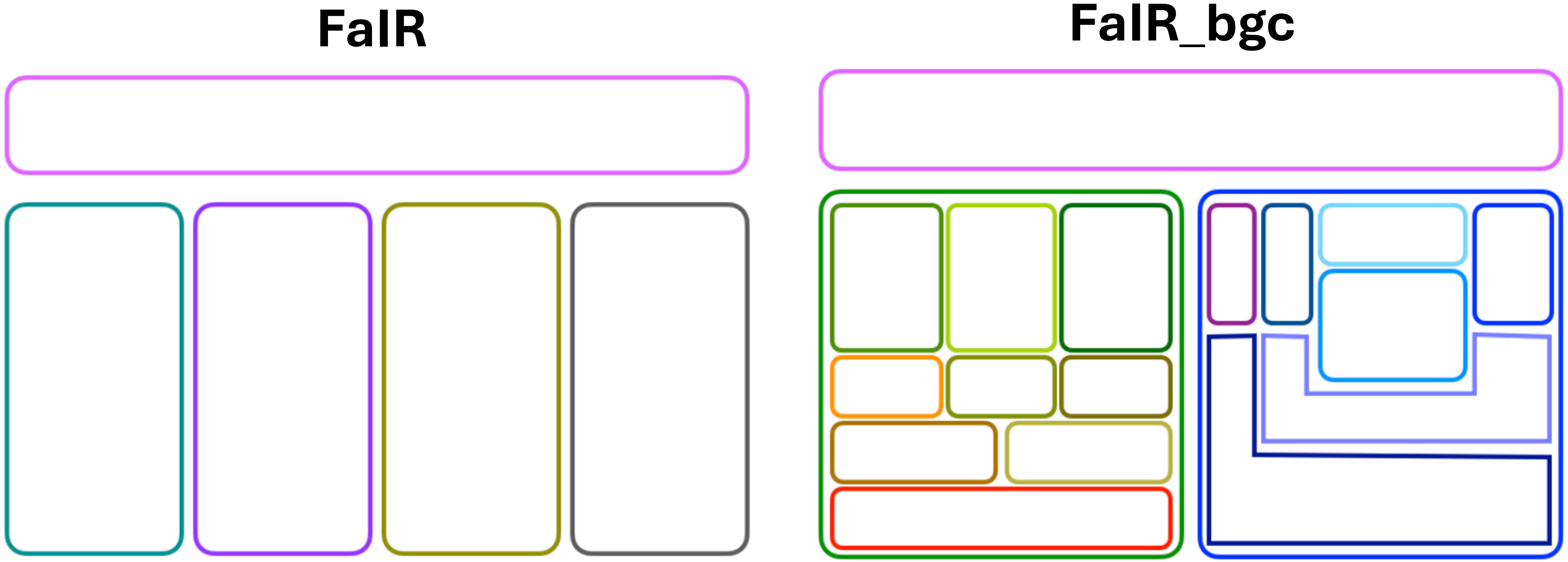


SCMs show spread in remaining carbon budget and net-zero date

- Using each model’s TCRE and ZEC, we can compute remaining carbon budgets for a temperature change limit of 1.5°C.
- From these budgets, we can project simplified linear ramp-down trajectories to estimate time-to-net-zero emissions.
- RCBs vary by ~100 Pg C and 20 years in net-zero date.



Replaced timescales in FaIR with a 9-box land and 7-box ocean model

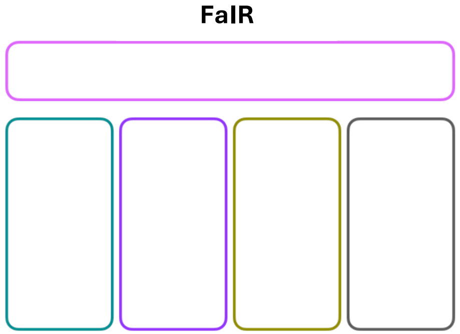


Parton et al. 1987, 1988 (CENTURY), Potter et al. 1993 (CASA), Swann 2010, Toggweiler 1999

Sampled biogeochemical feedbacks by perturbing parameters

FaIR:

- **3 parameters that influence the carbon cycle**
- 11 parameters → energy balance model
- Concentrations of CH_4 and N_2O are held constant



r_0, preindustrial uptake from atmos.

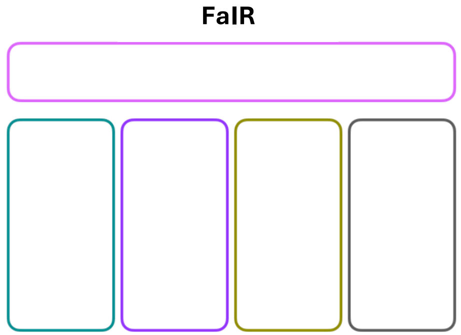
r_U, lifetime adjustment to cumulative uptake

r_T, lifetime adjustment to atmos. temperature

Sampled biogeochemical feedbacks by perturbing parameters

FaIR:

- **3 parameters that influence the carbon cycle**
- 11 parameters → energy balance model
- Concentrations of CH_4 and N_2O are held constant



r_0, preindustrial uptake from atmos.

r_U, lifetime adjustment to cumulative uptake

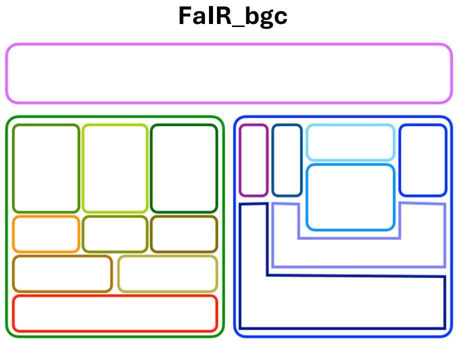
r_T, lifetime adjustment to atmos. temperature

FaIR_bgc:

- **5 parameters that influence the carbon cycle**
- 11 parameters → energy balance model
- Concentrations of CH_4 and N_2O are held constant

β, fertilization factor

Q_{10}, respiration rate ratio



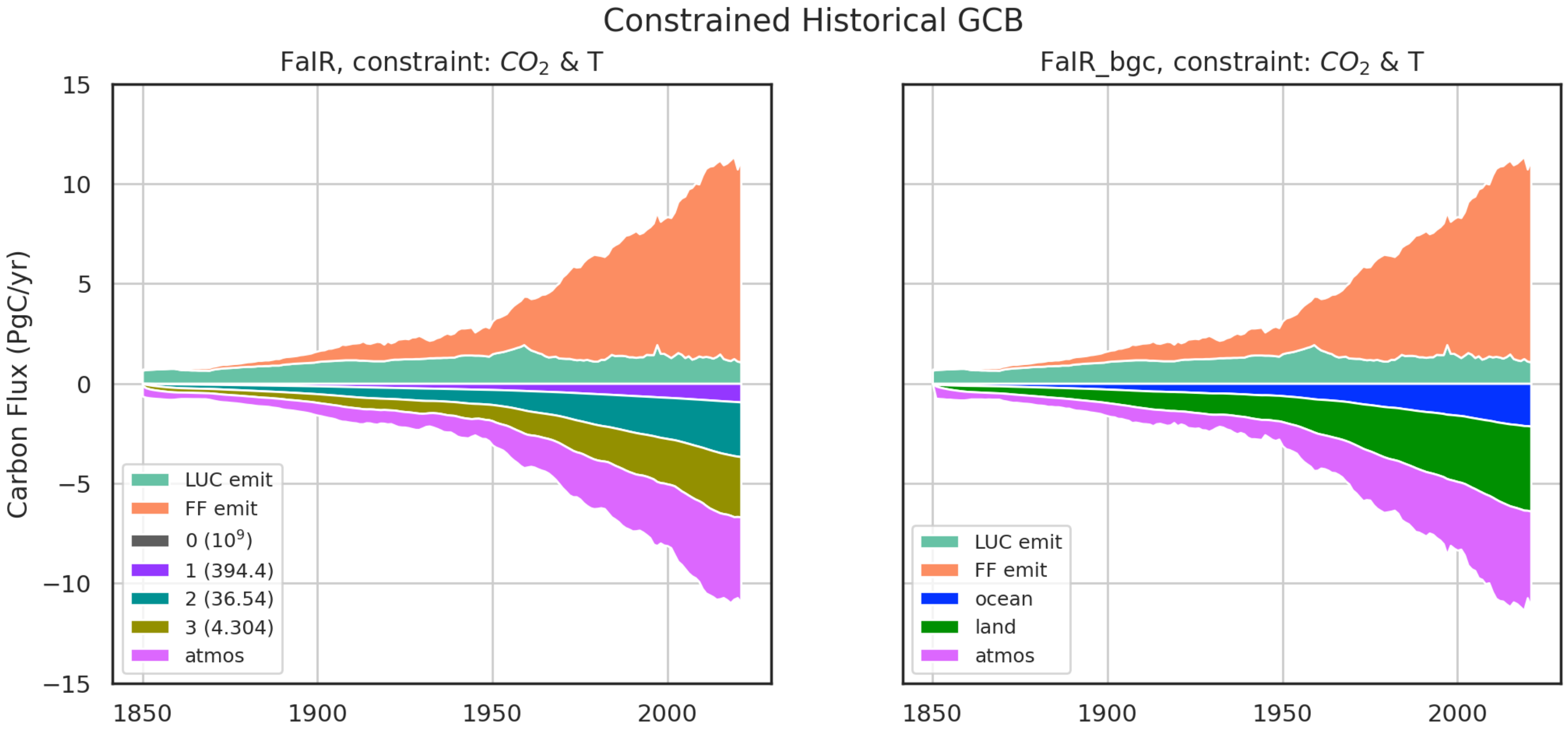
S_{kw}, gas exchange scaling

S_{Ψ}, circulation scaling

$S_{\frac{d\Psi}{db}}$, circ. response to climate

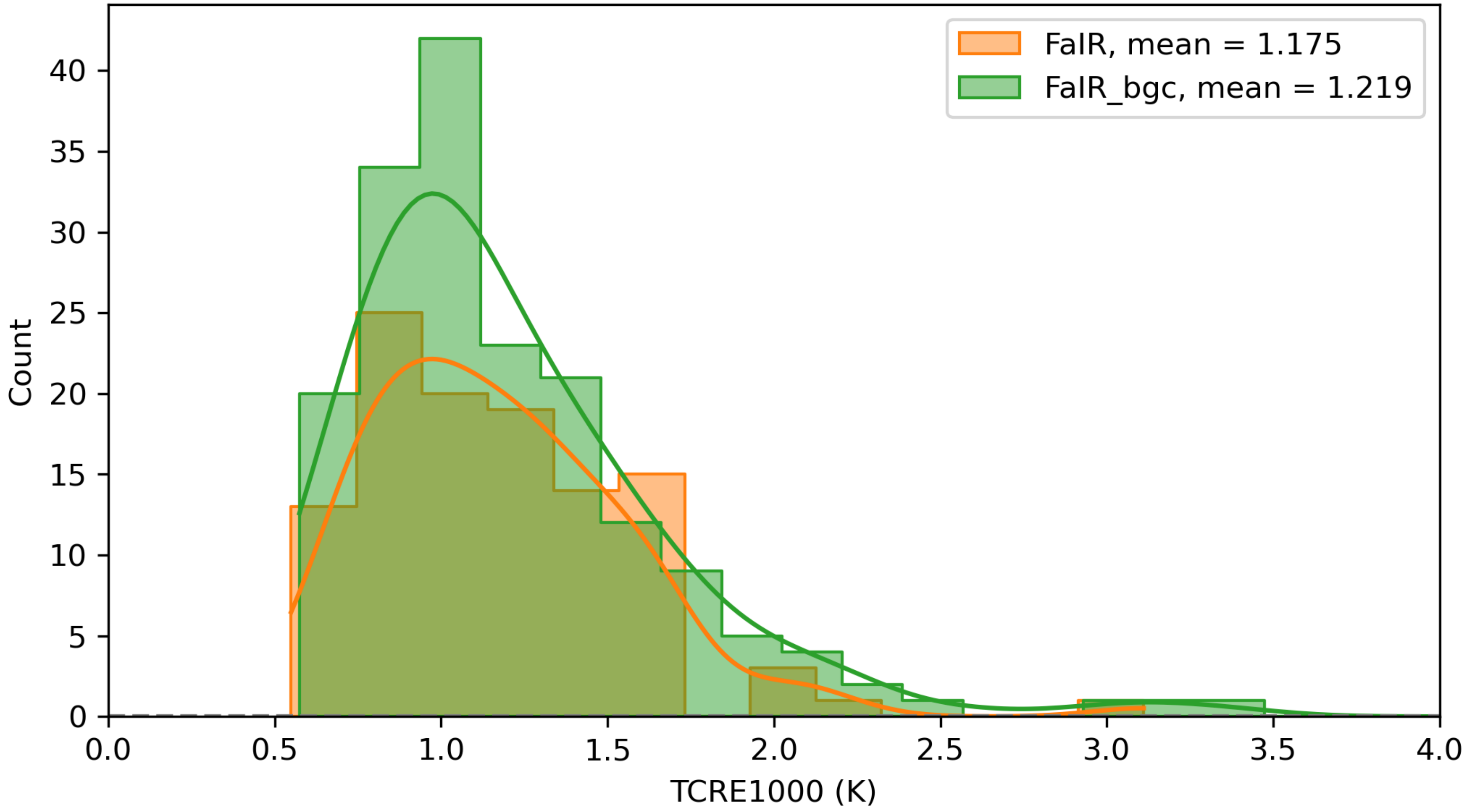
Parton et al. 1987, 1988 (CENTURY), Potter et al. 1993 (CASA), Swann 2010, Toggweiler 1999

Compare atmospheric CO_2 and carbon sinks to observations

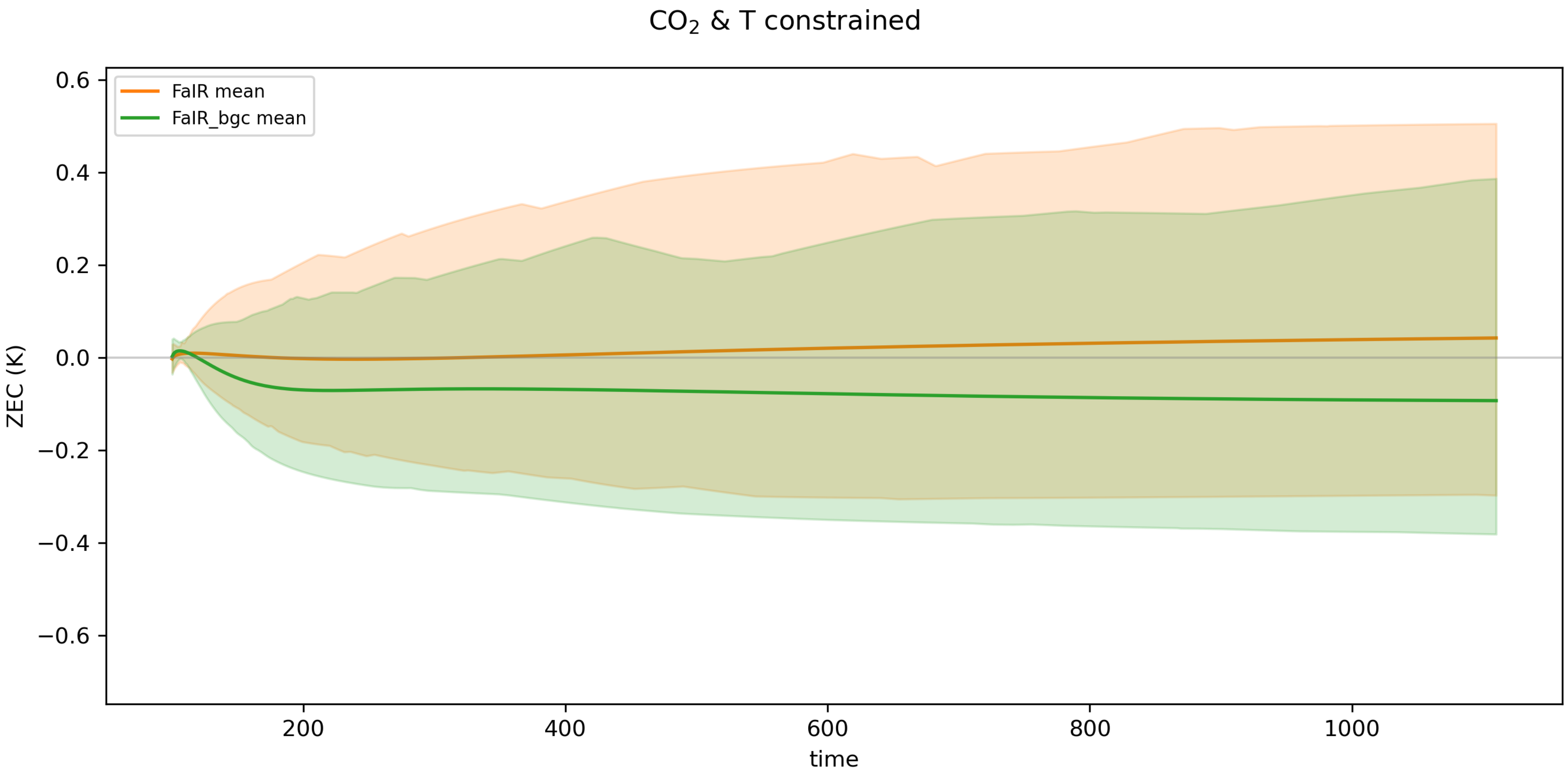


Friedlingstein et al. 2022

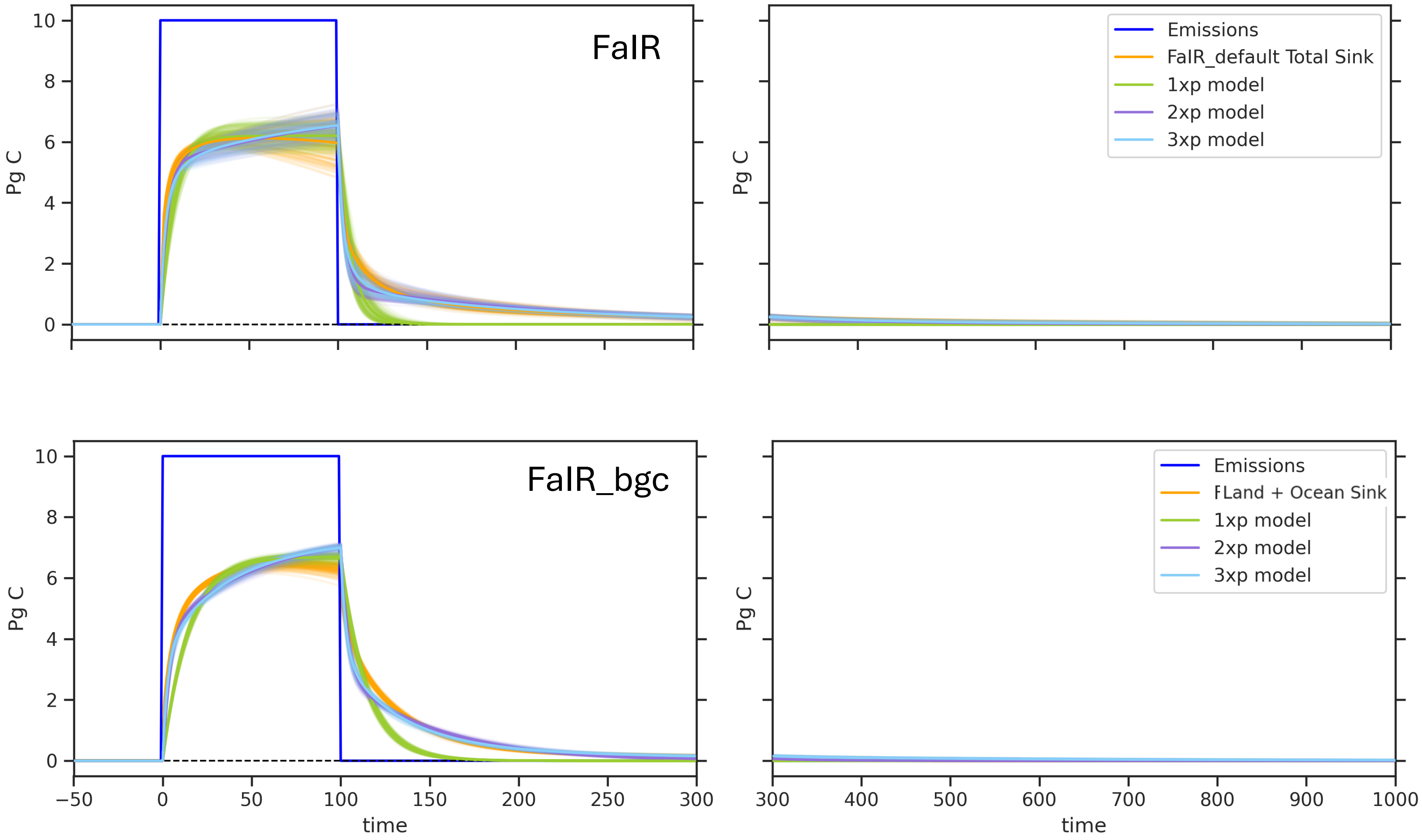
We see minimal changes to TCRE (calculated using the esm-flat10-zec emissions trajectory)



Small shift in ZEC with different carbon cycle structures

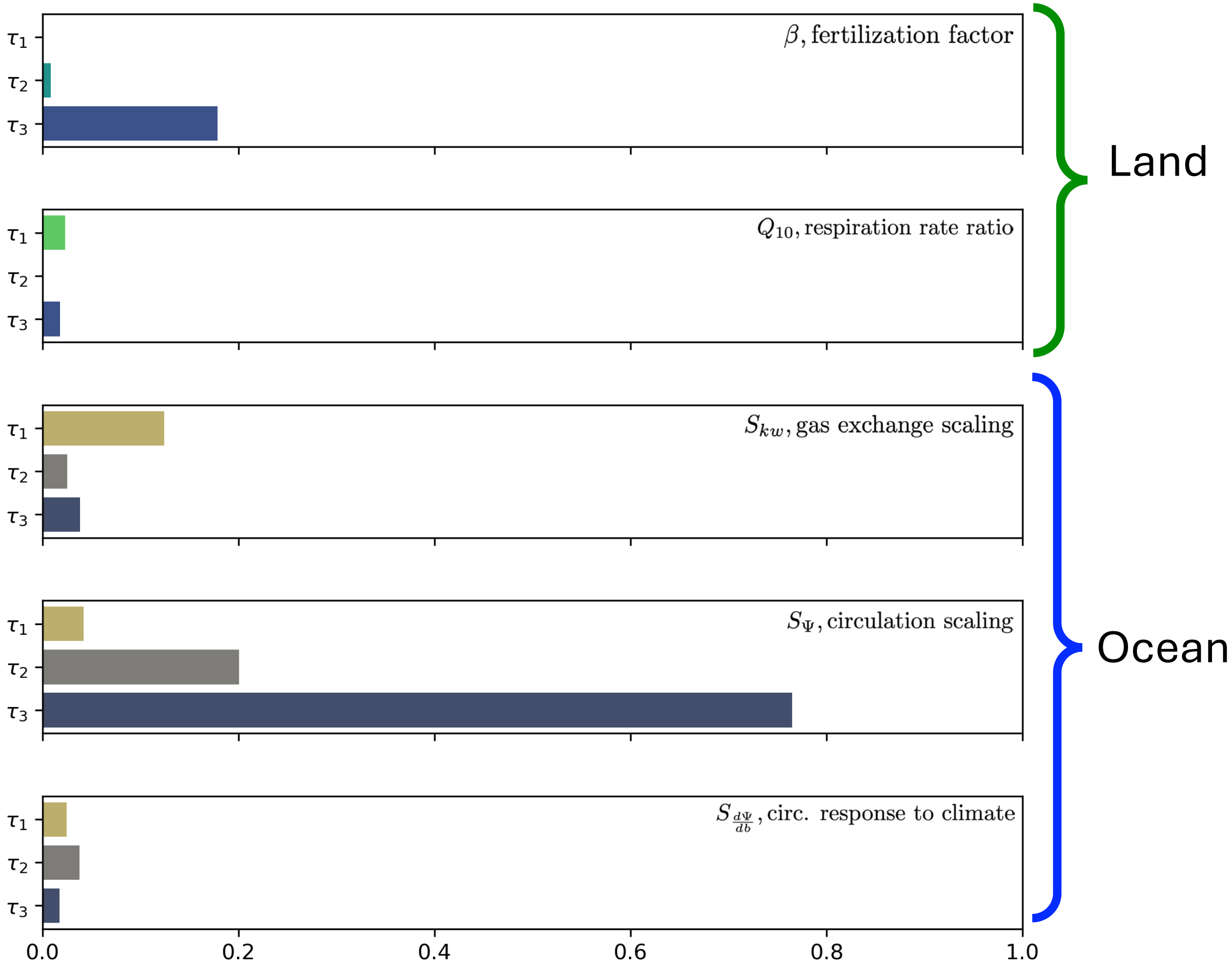


Use 3xp to diagnose emergent timescales of carbon removal

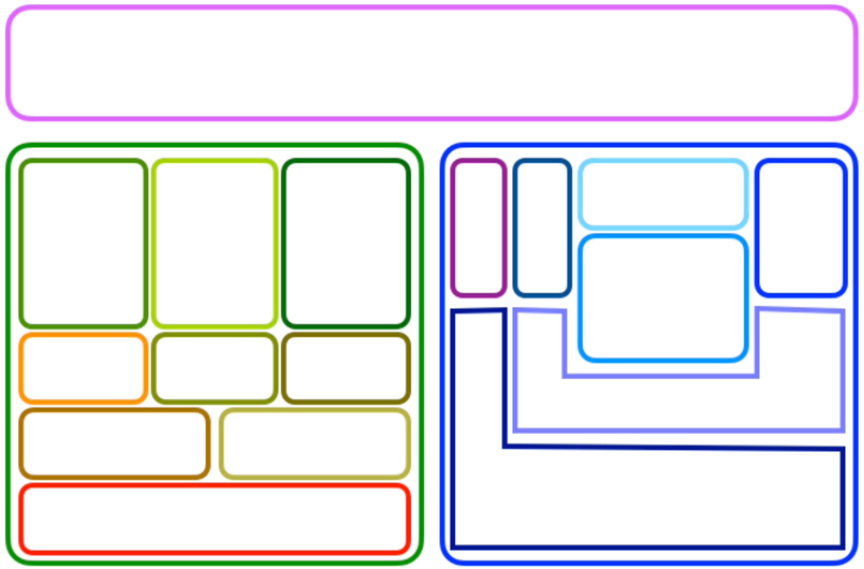


FaIR_bgc carbon cycle parameters connect timescales with processes

Variance explained (R^2) by FaIR_bgc parameter

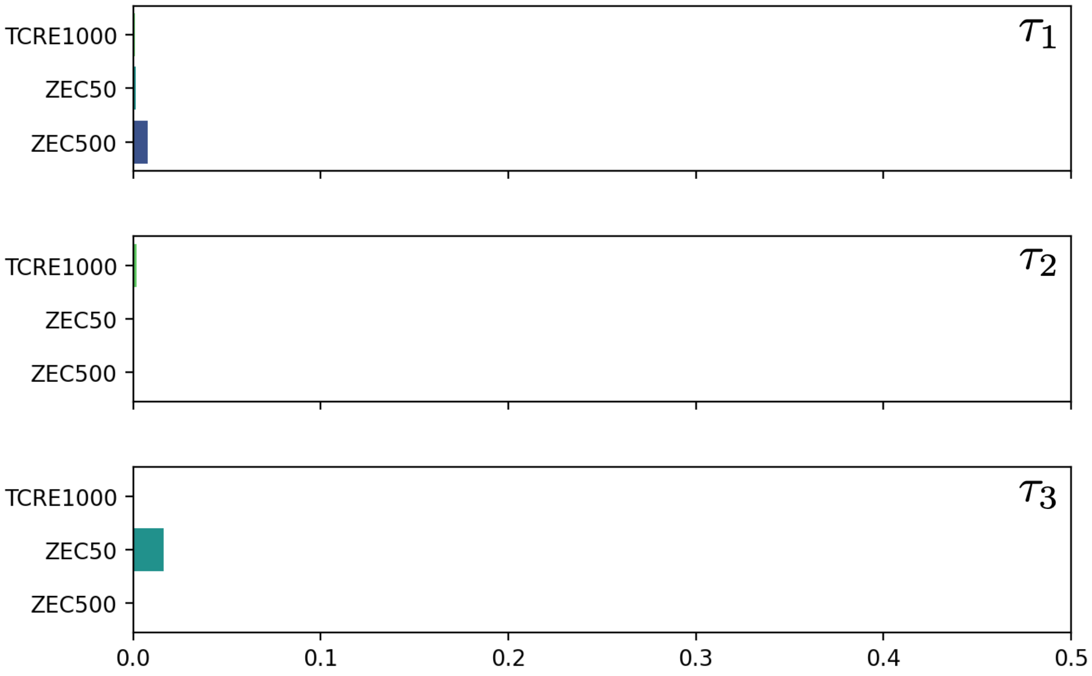


FaIR_bgc



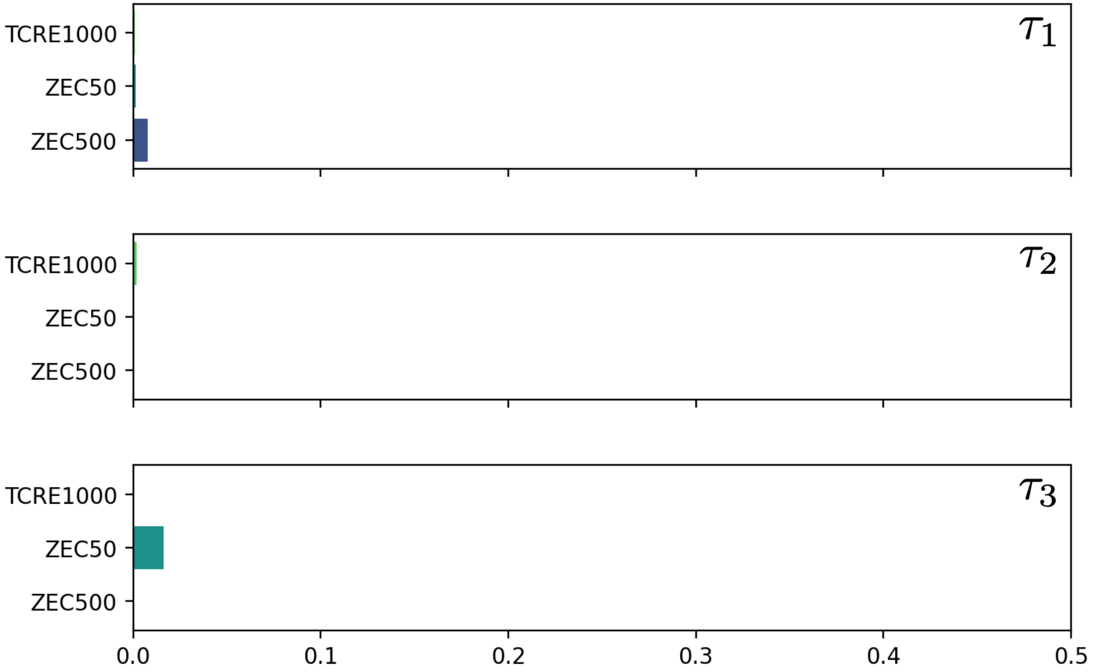
FaIR_bgc timescales cannot explain variance in temperature response

Variance explained (R^2) by FaIR_bgc timescales



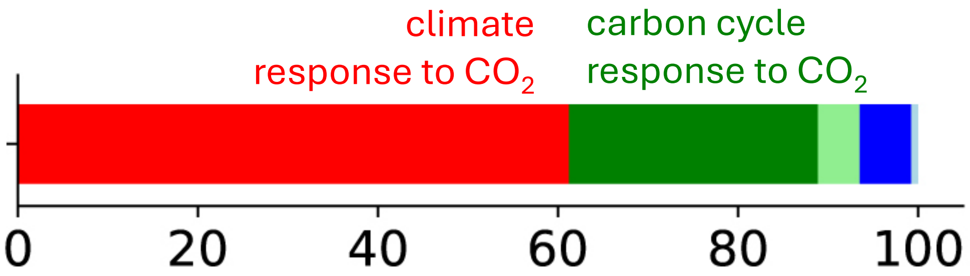
FaIR_bgc timescales cannot explain variance in temperature response

Variance explained (R^2) by FaIR_bgc timescales



For comparison:

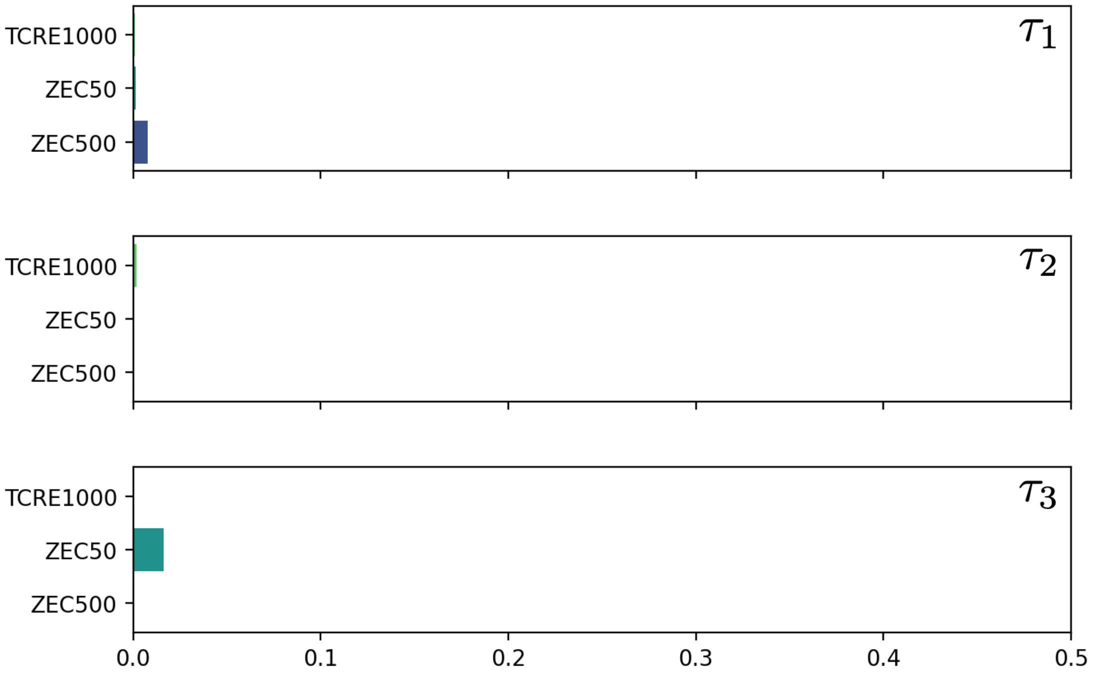
Contributions to TCRE in C4MIP ESMs:



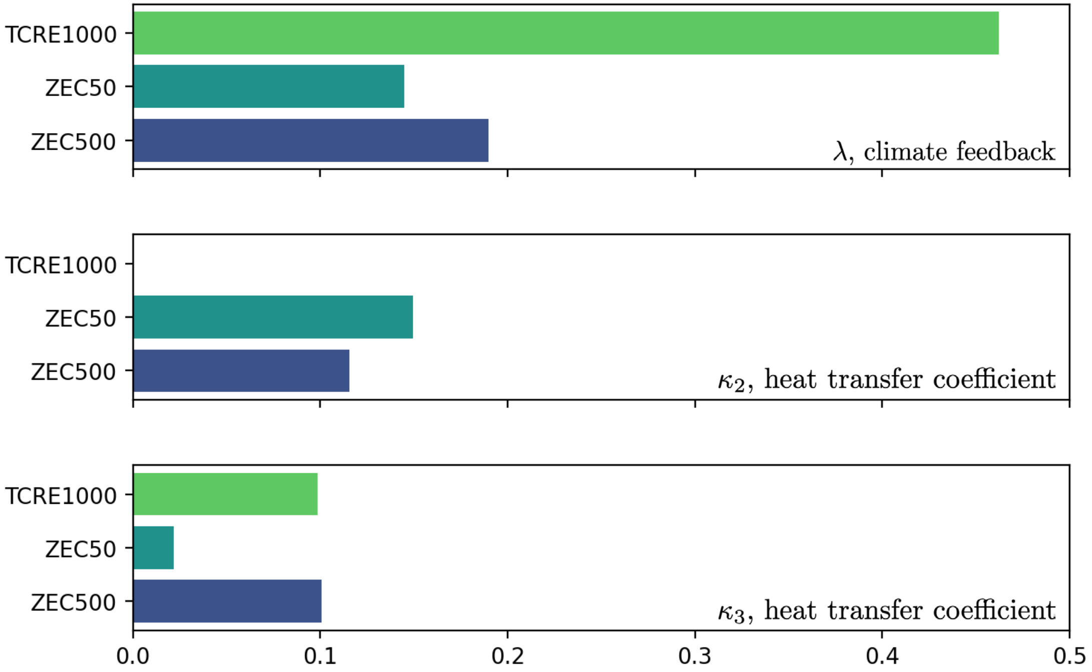
Jones and Frieldingstein 2020

FaIR_bgc energy balance model parameters explain variance in temperature response

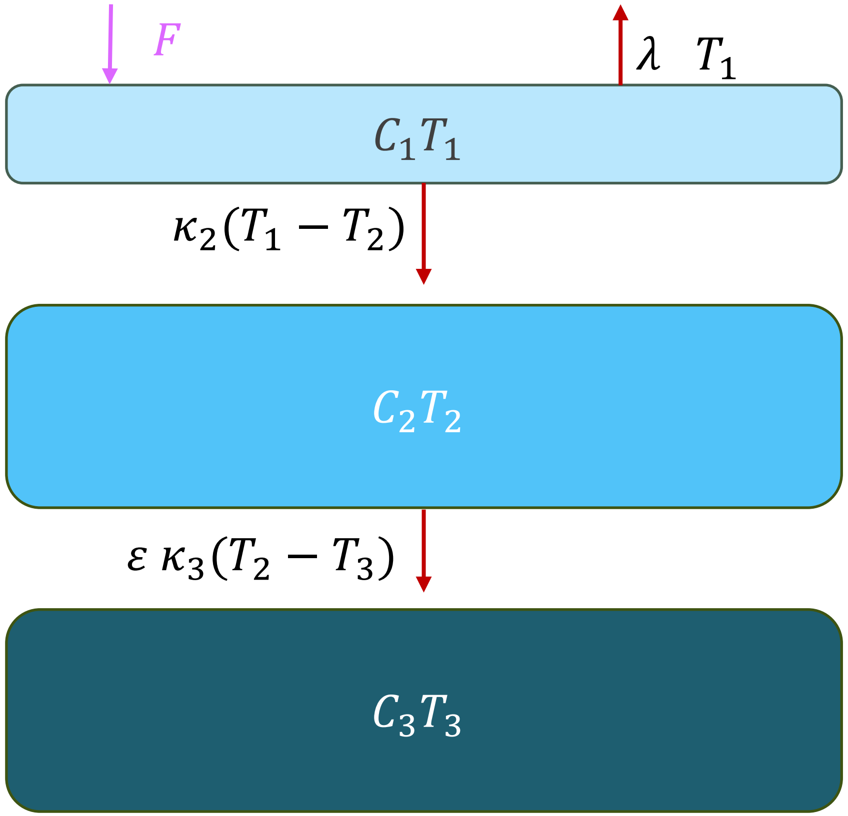
Variance explained (R^2) by FaIR_bgc timescales



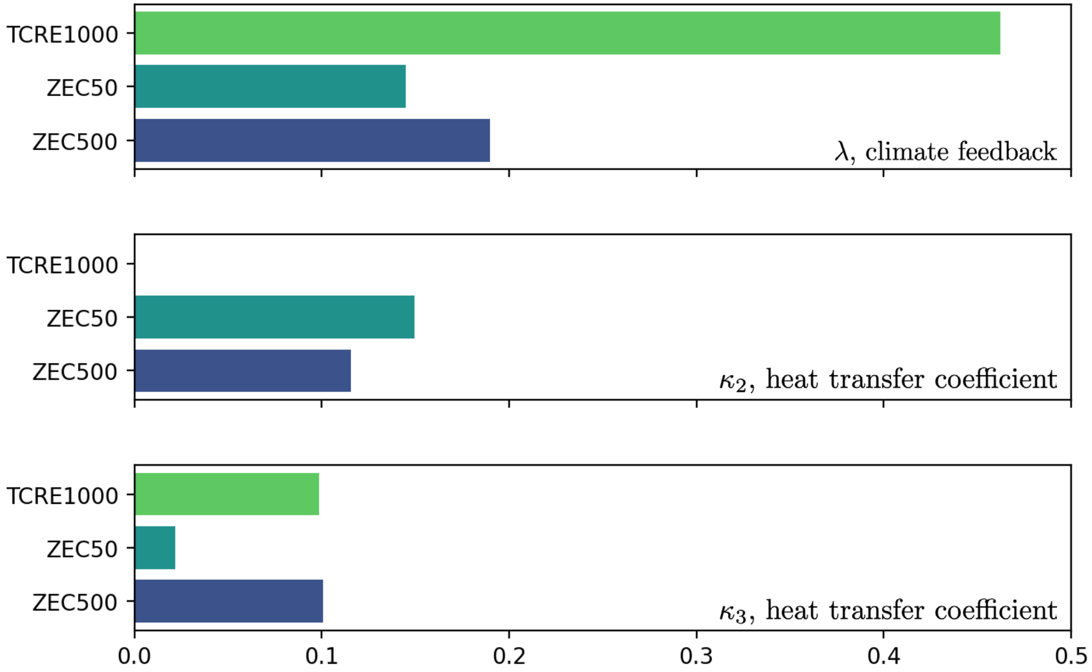
Variance explained (R^2) by EBM parameters



EBM parameters the control energy fluxes and evolution of temperature

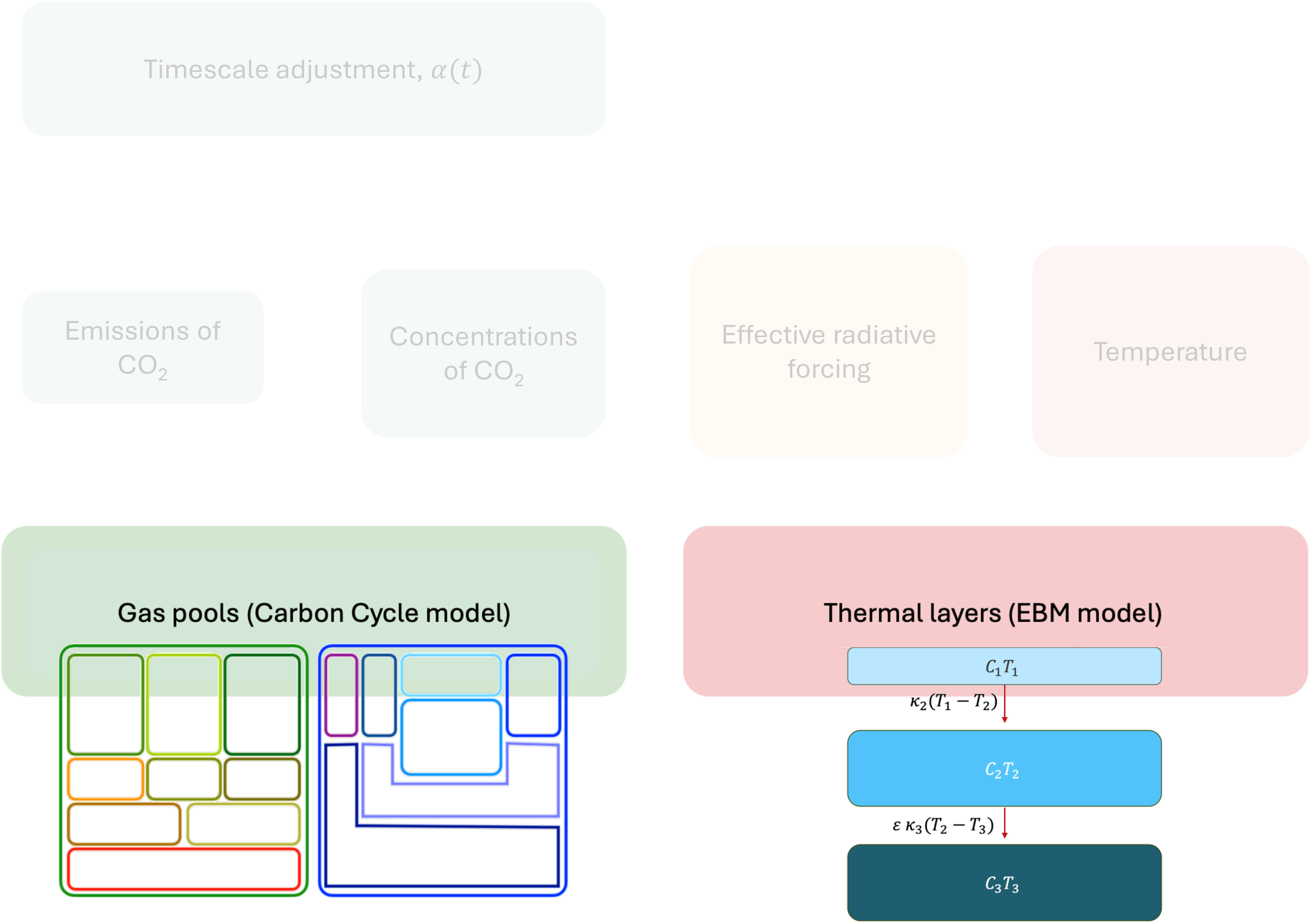


Variance explained (R^2) by EBM parameters



Cummins et al. 2020

Why do carbon sink timescales influence ZEC so little?



Timescale adjustment, $\alpha(t)$

Emissions of CO_2

Concentrations of CO_2

Effective radiative forcing

Temperature

Gas pools (Carbon Cycle model)

Thermal layers (EBM model)

Why do carbon sink timescales influence ZEC so little?

Timescale adjustment, $\alpha(t)$

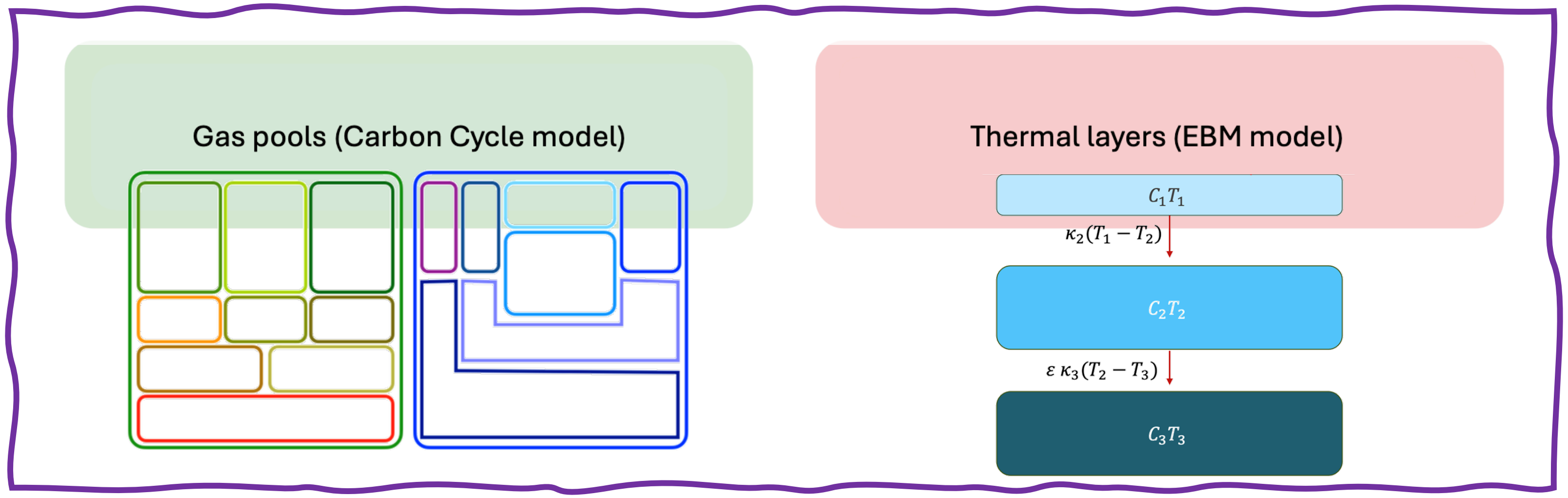
Emissions of CO_2

Concentrations of CO_2

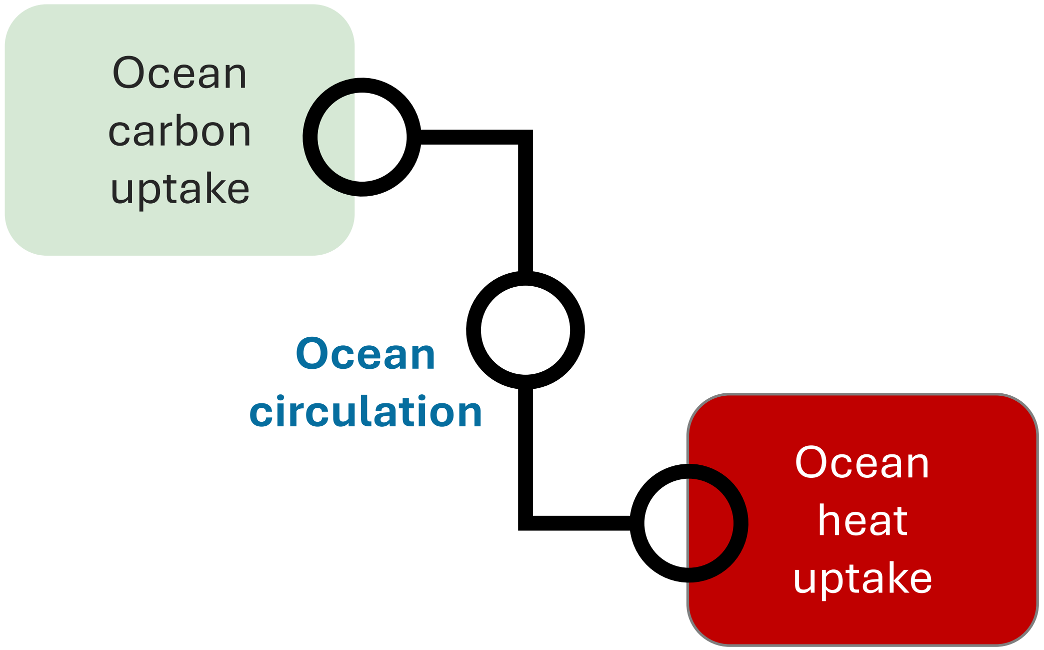
Effective radiative forcing

Temperature

No structural link between processes that govern carbon and energy fluxes!



Ocean carbon uptake and heat uptake are both impacted by circulation



Ocean carbon uptake

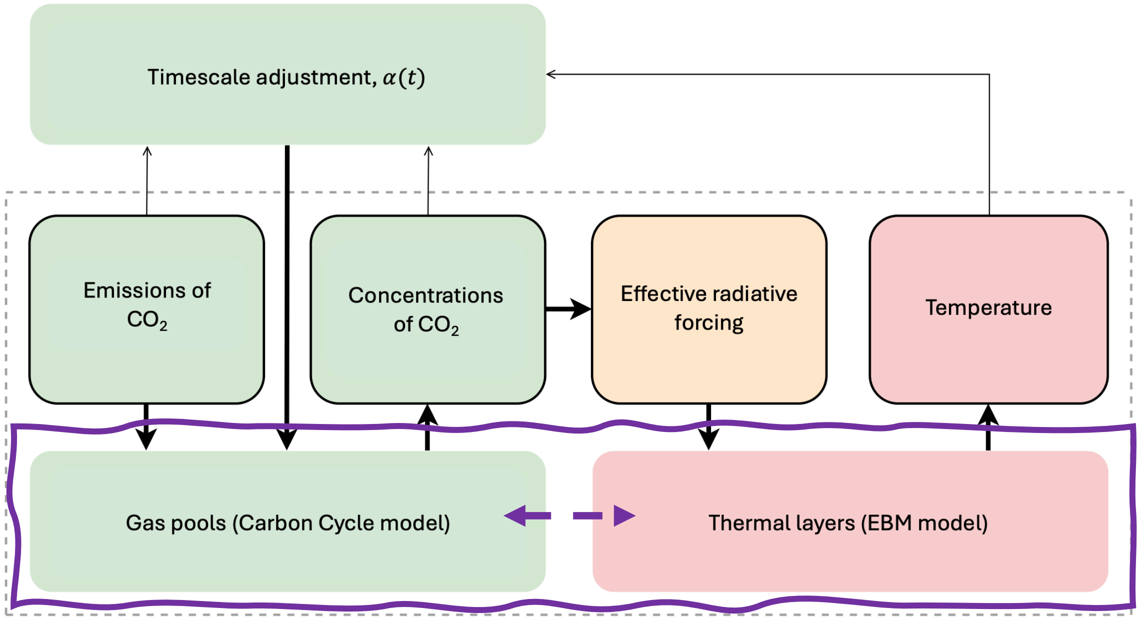
Ocean circulation

Ocean heat uptake

Hypothesis: if we correlate ocean circulation with ocean heat uptake, the influence of carbon uptake on ZEC may change

Does the influence of carbon cycle timescales increase when thermal boxes are connected through correlation to carbon cycle boxes?

- Created a new Latin Hypercube ensemble with **correlated parameter values** for S_ψ and heat transport, κ_3.



Timescale adjustment, $\alpha(t)$

Emissions of CO_2

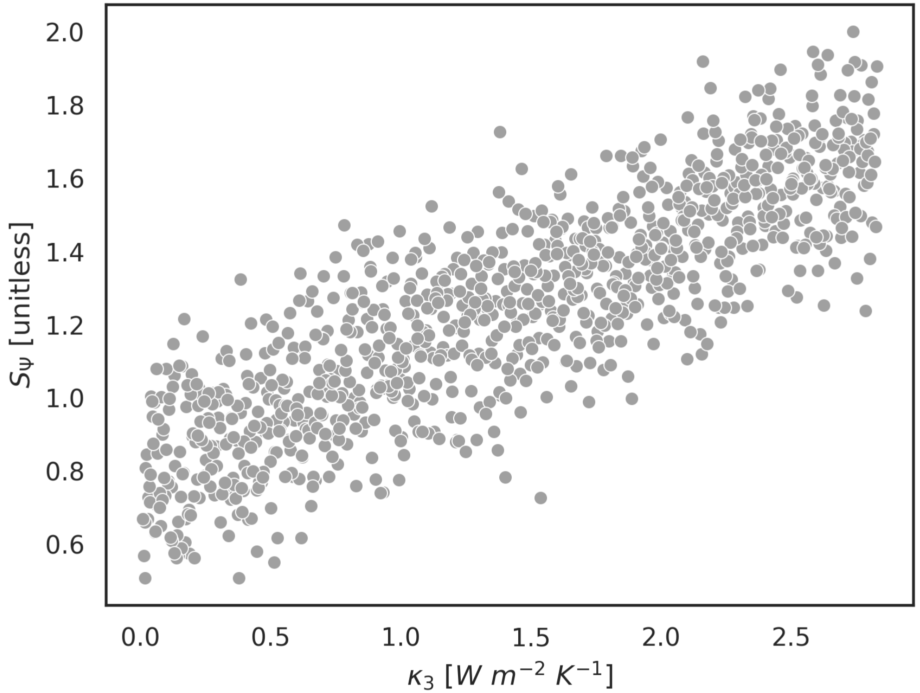
Concentrations of CO_2

Effective radiative forcing

Temperature

Gas pools (Carbon Cycle model)

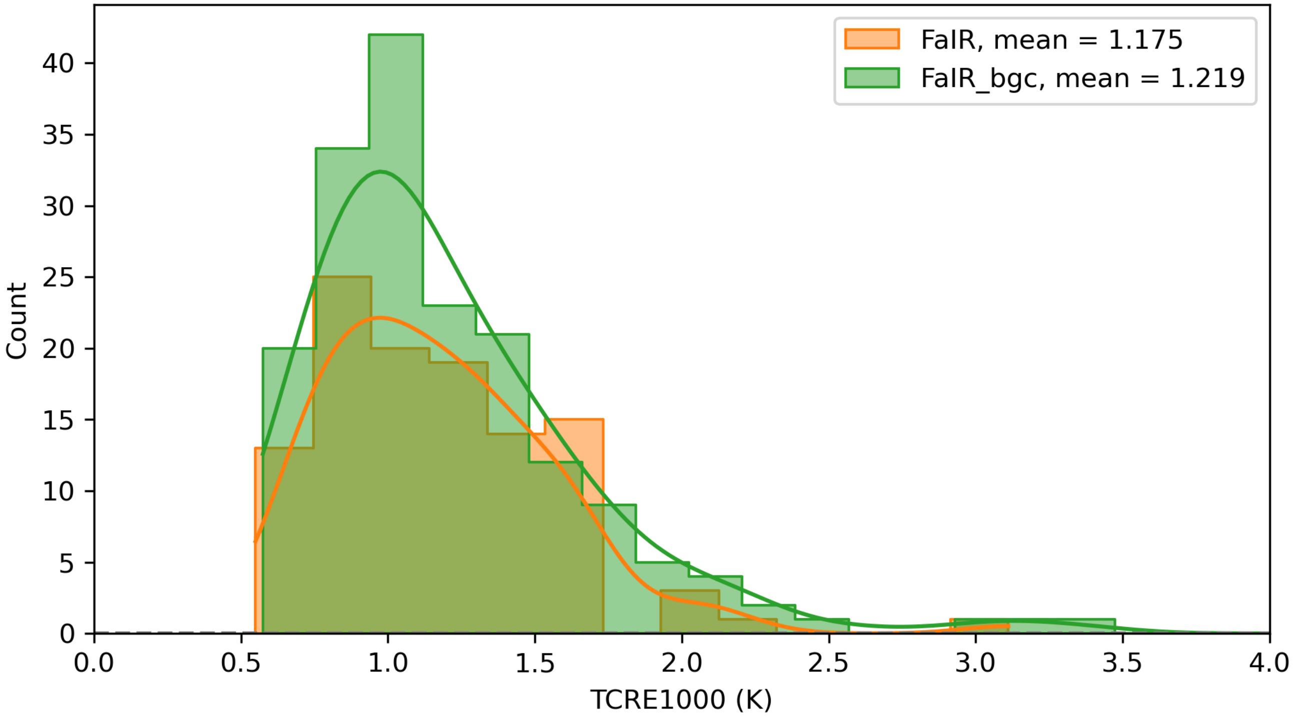
Thermal layers (EBM model)



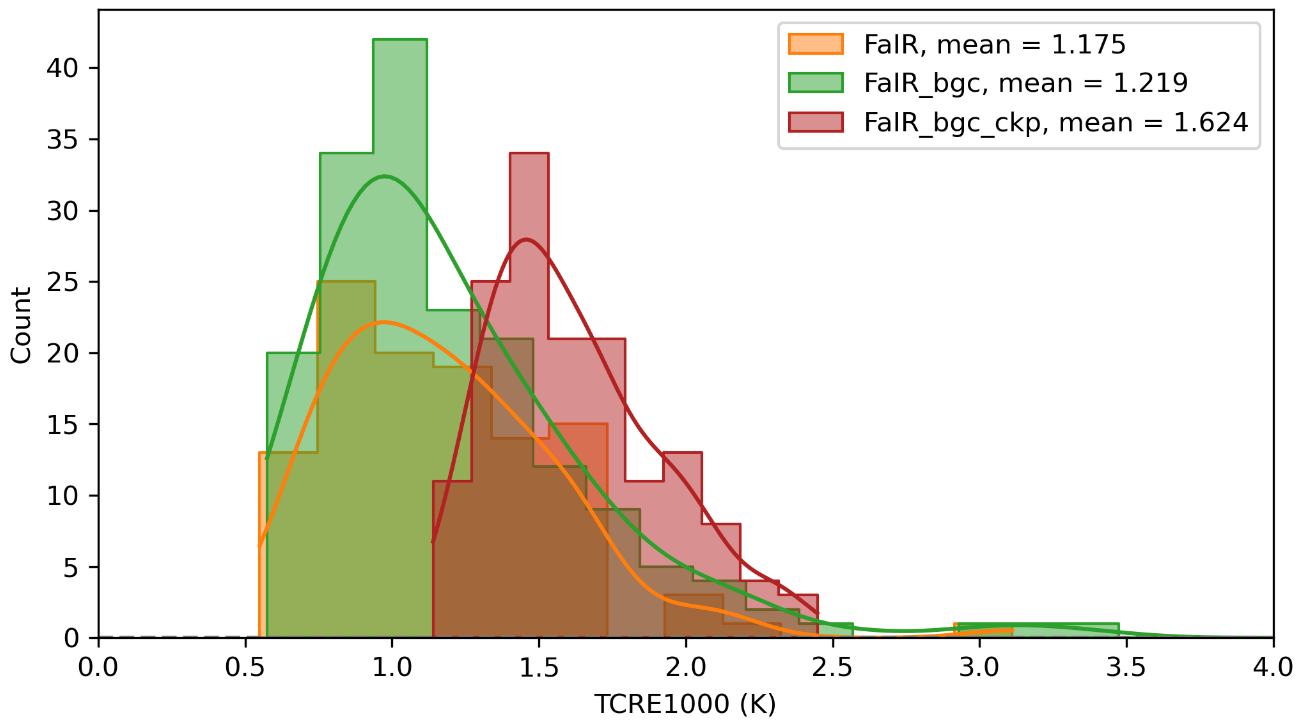
Ocean circulation scalar

Heat transport to deep ocean

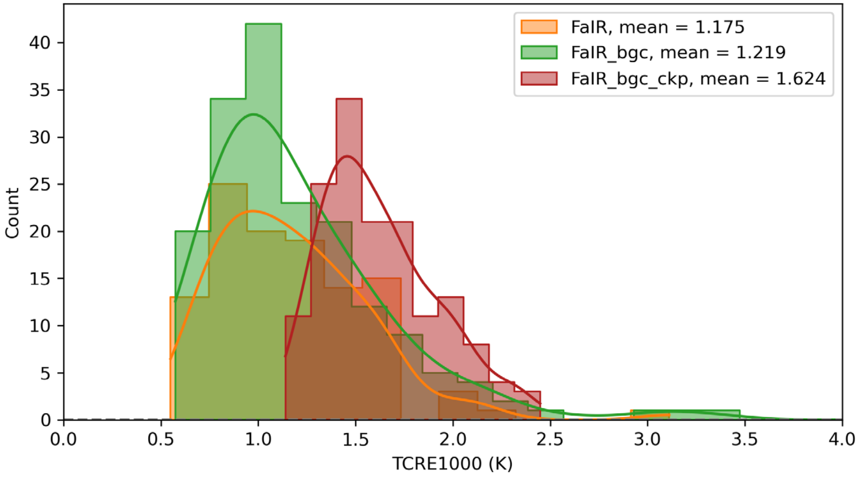
Can adding correlation between circulation rate and thermal transfer shift TCRE?

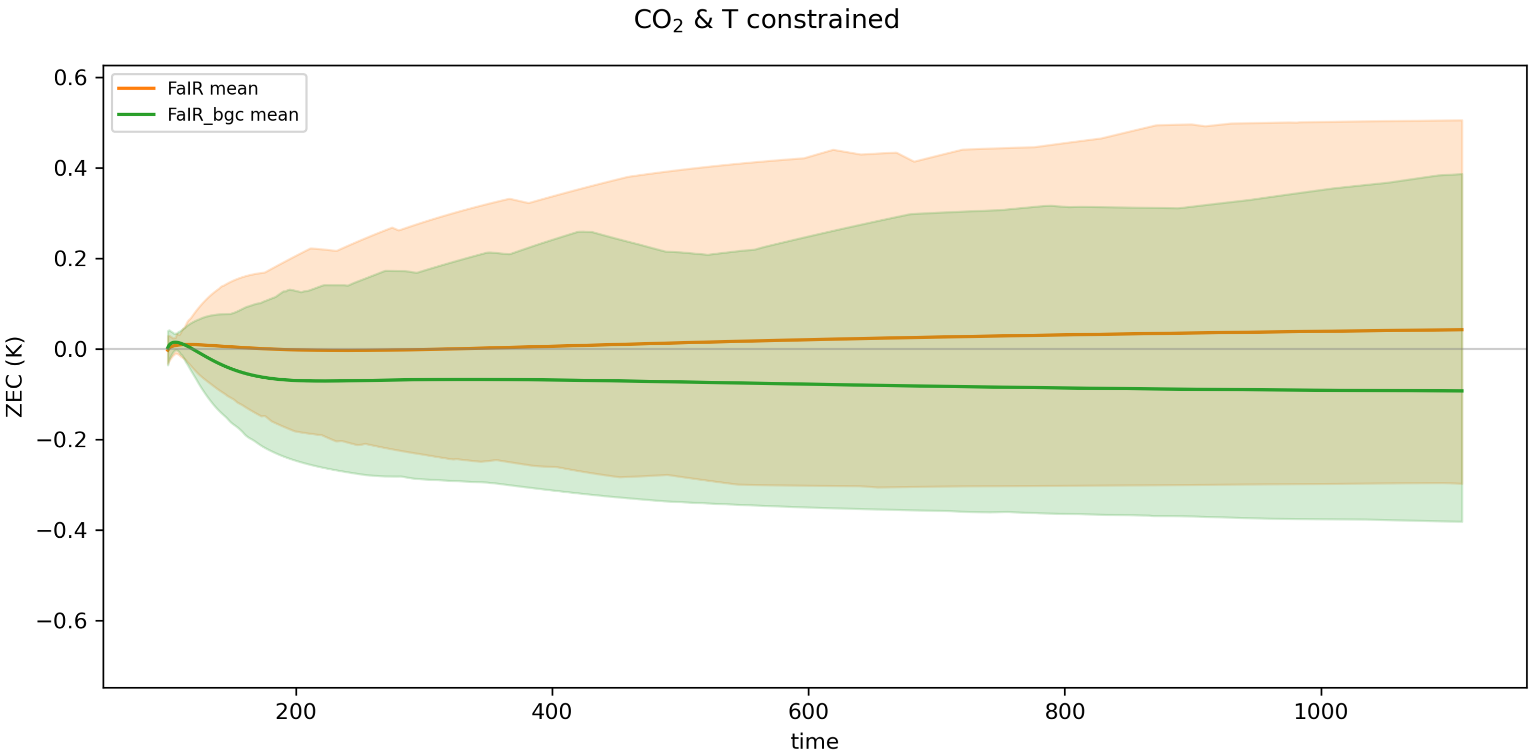


TCRE gets stronger!

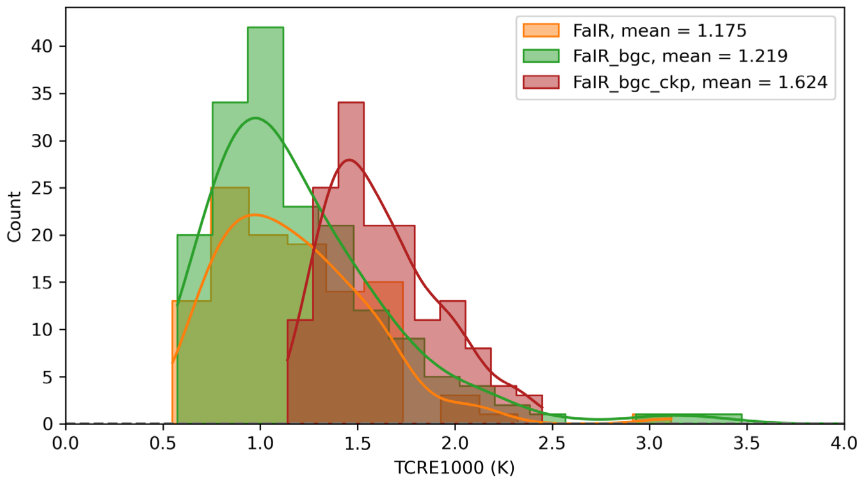


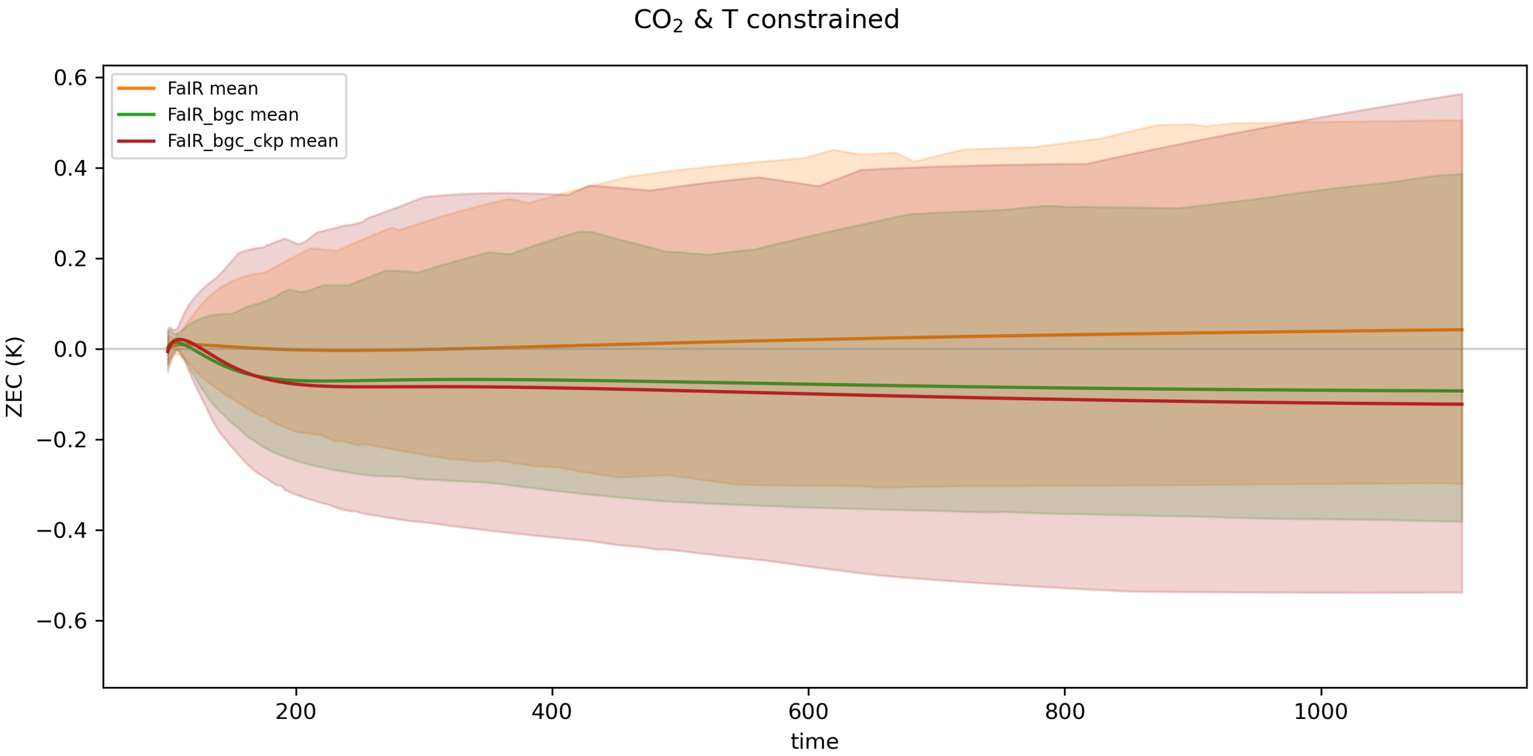
Can adding correlation between circulation rate and thermal transfer shift ZEC?





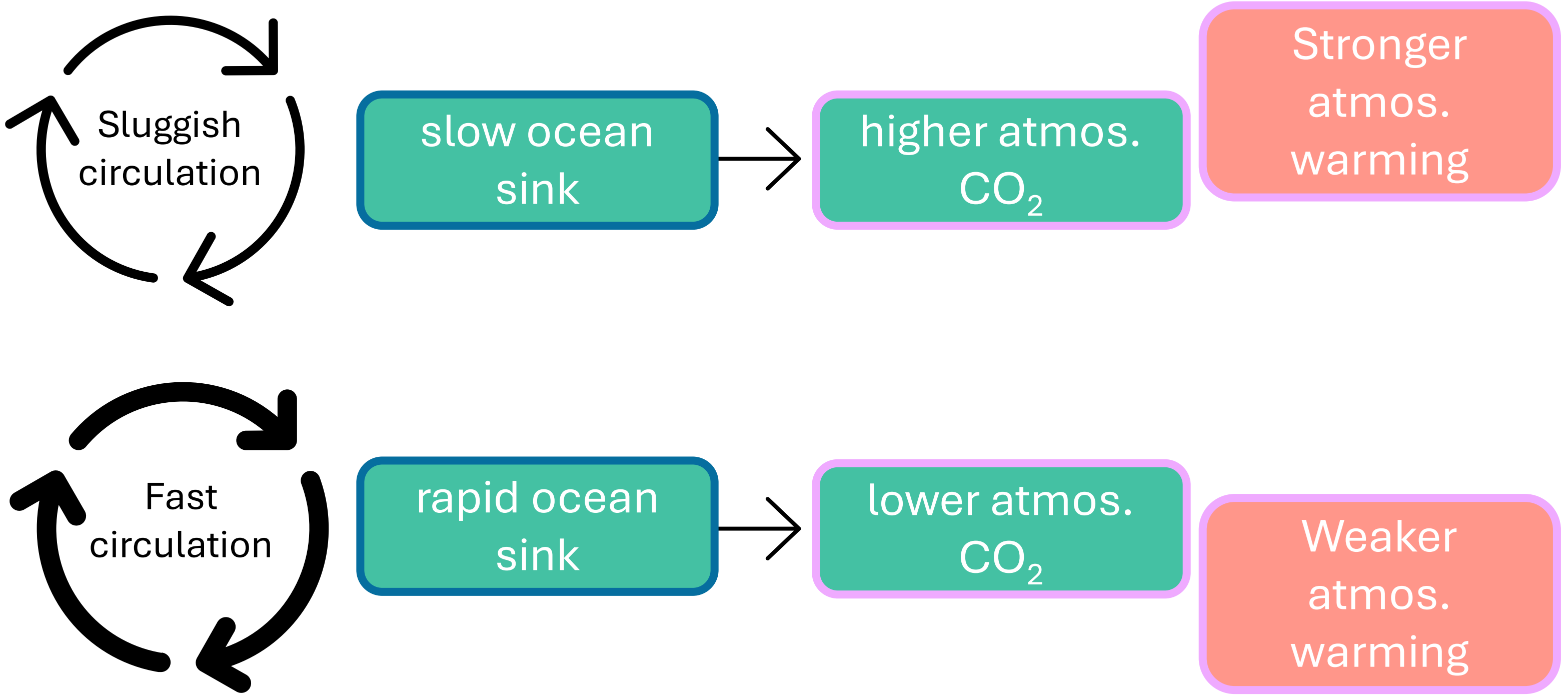
ZEC gets weakly more negative





Uncorrelated: circulation affects CO_2 and climate through atmos. CO_2

Historical
emission of
CO_2 →



Sluggish circulation

slow ocean sink → higher atmos. CO_2

Stronger atmos. warming

Fast circulation

rapid ocean sink → lower atmos. CO_2

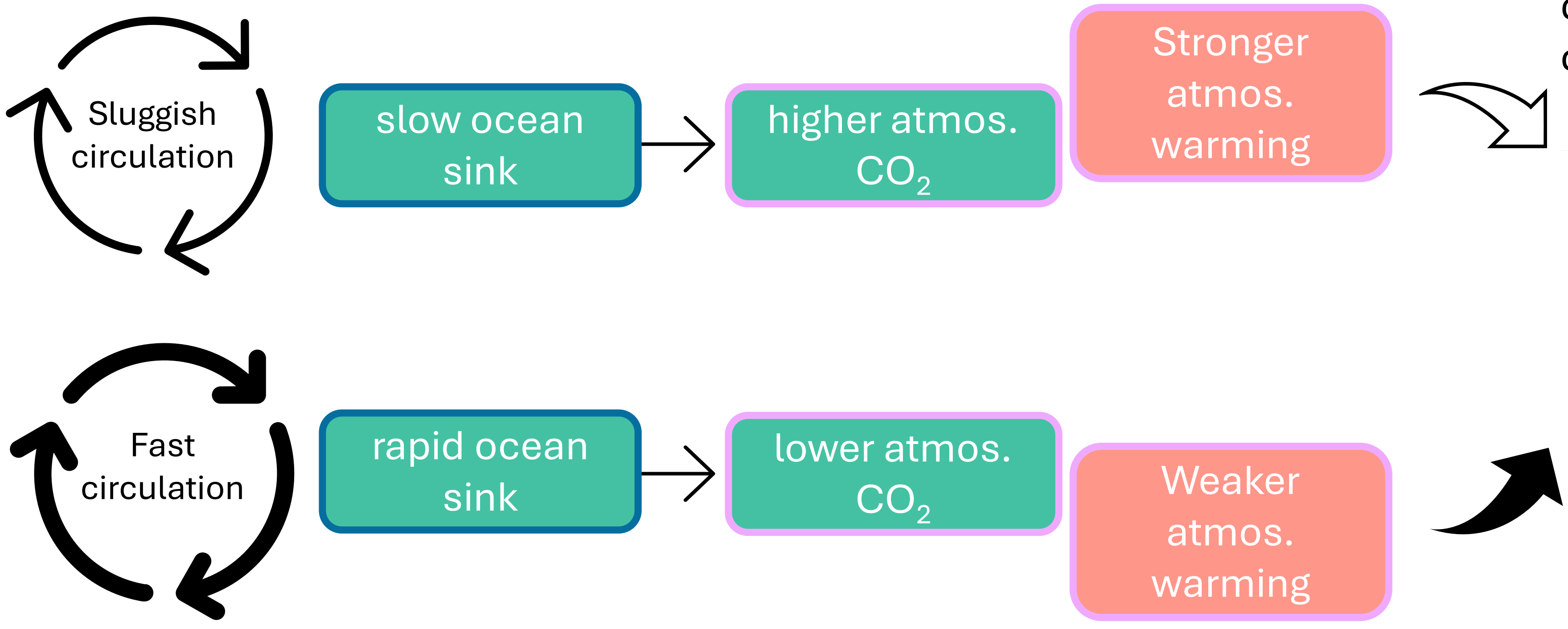
Weaker atmos. warming

In constraining to observed CO_2 and ΔT

We select other parameters that compensate for these circulation-driven outcomes.

Uncorrelated: circulation affects CO_2 and climate through atmos. CO_2

Historical
emission of
CO_2 →



Sluggish circulation

slow ocean sink

higher atmos. CO_2

Stronger atmos. warming

Fast circulation

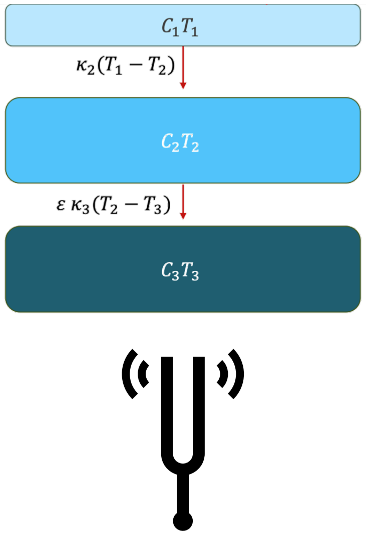
rapid ocean sink

lower atmos. CO_2

Weaker atmos. warming

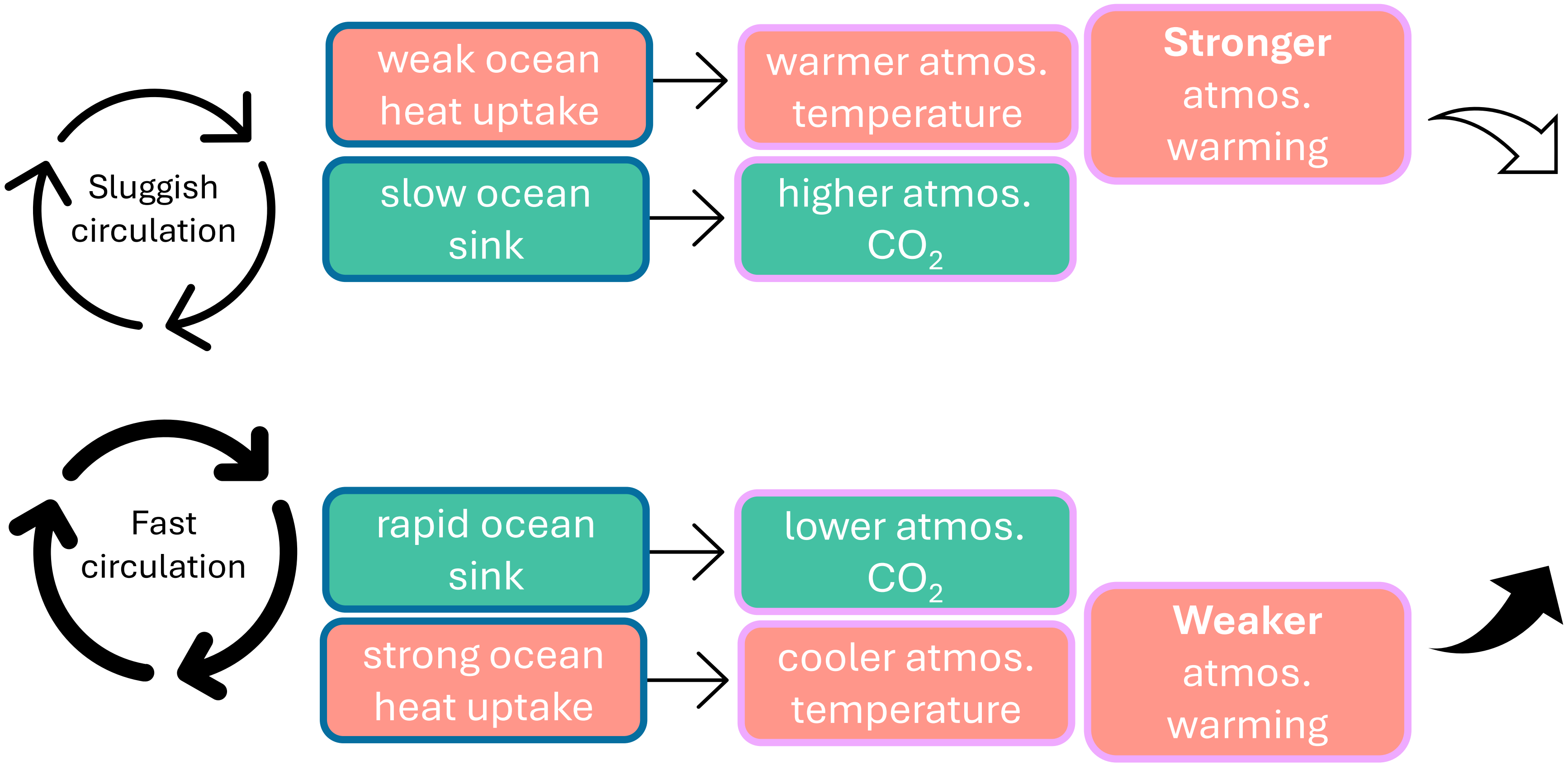
In constraining to observed CO_2 and ΔT

We select other parameters that compensate for these circulation-driven outcomes.



Correlated: circulation affects climate through atmospheric CO_2 and through heat uptake

Historical
emission of
CO_2 →



Sluggish circulation

weak ocean heat uptake → warmer atmos. temperature

slow ocean sink → higher atmos. CO_2

Stronger atmos. warming

Fast circulation

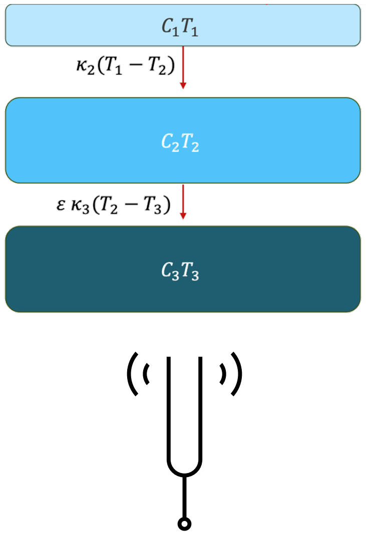
rapid ocean sink → lower atmos. CO_2

strong ocean heat uptake → cooler atmos. temperature

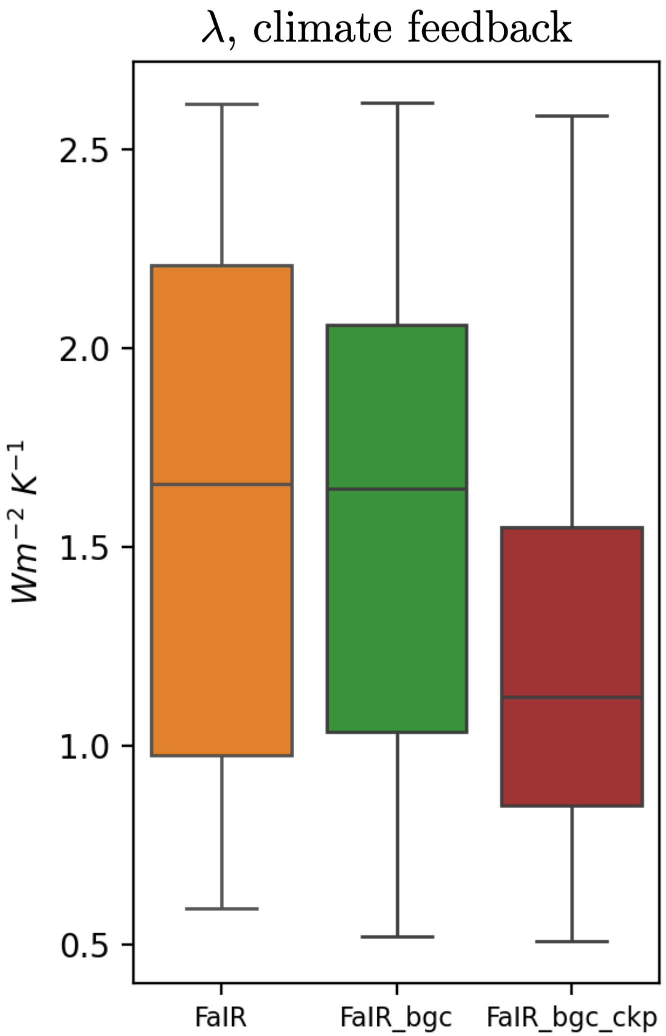
Weaker atmos. warming

In constraining to observed CO_2 and ΔT

We select other parameters that compensate for these circulation-driven outcomes.

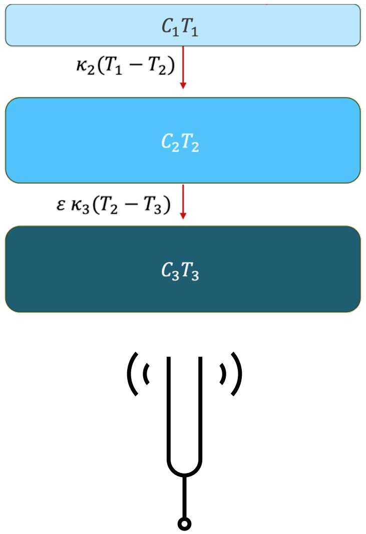


Compensating shift in EBM parameters when constrained to CO_2 & T

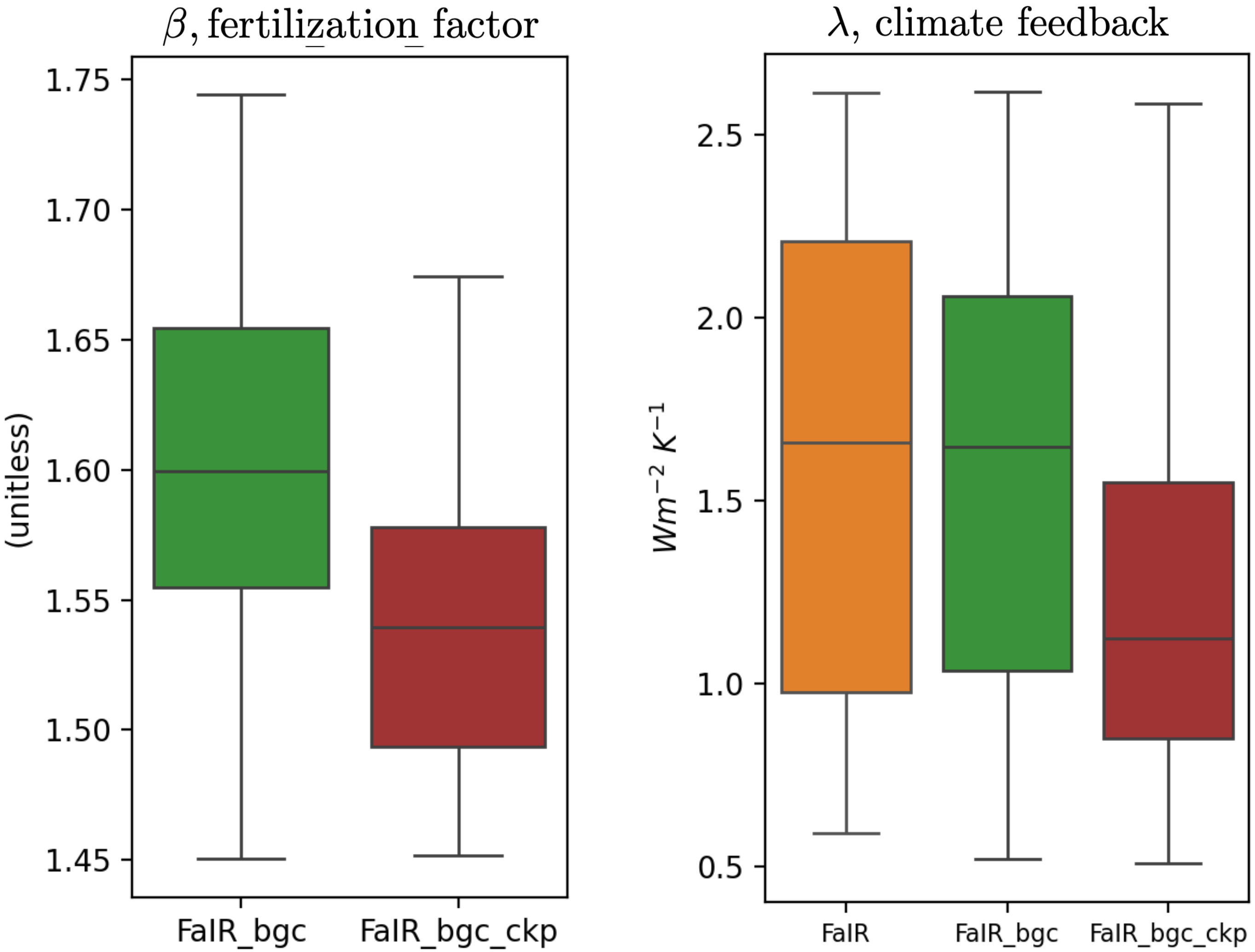


In constraining to observed CO_2 and ΔT

We select other parameters that compensate for these circulation-driven outcomes.

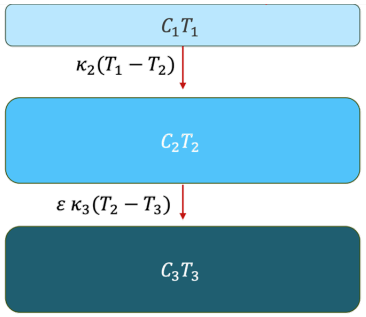


Compensating shift in CC parameters when constrained to CO_2 & T

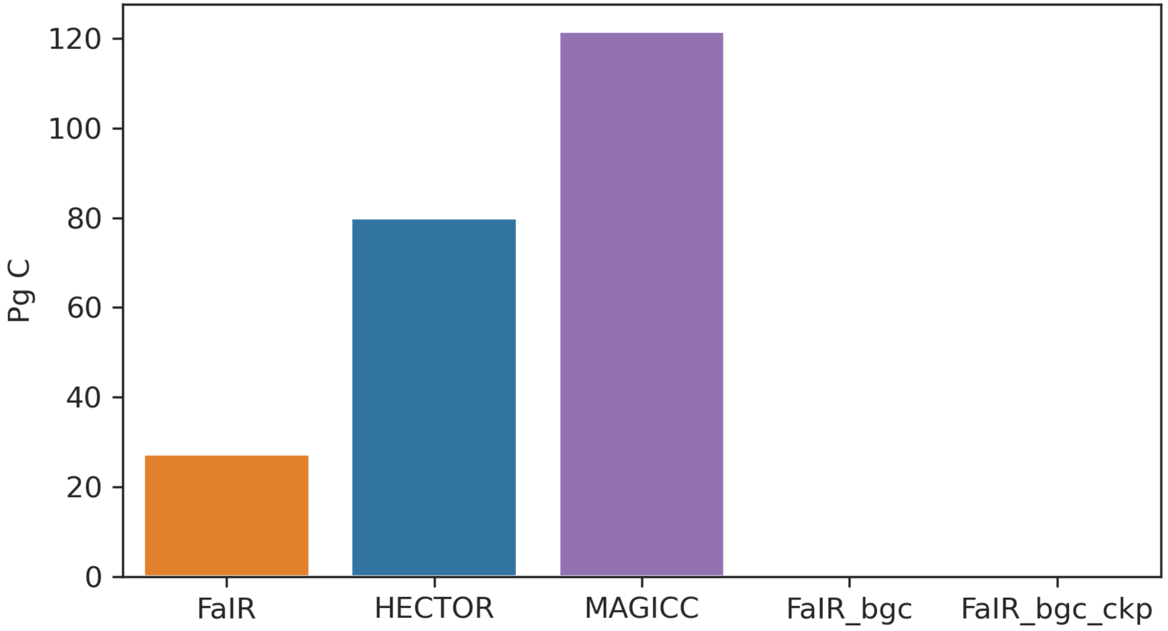


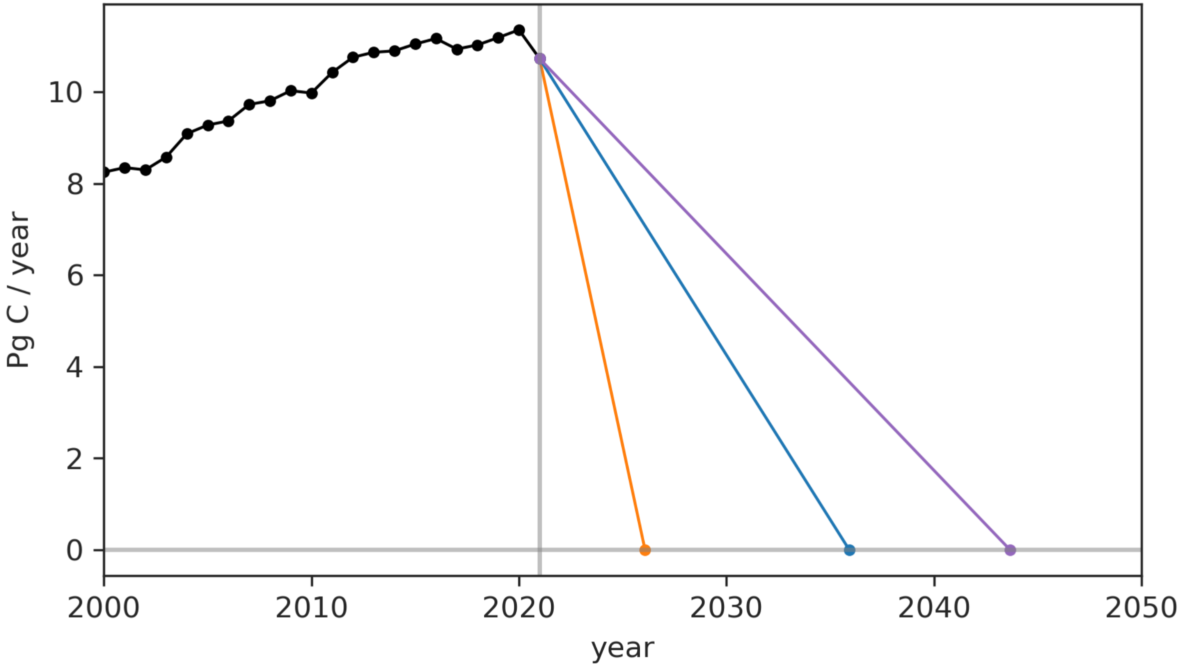
In constraining to observed CO_2 and ΔT

We select other parameters that compensate for these circulation-driven outcomes.

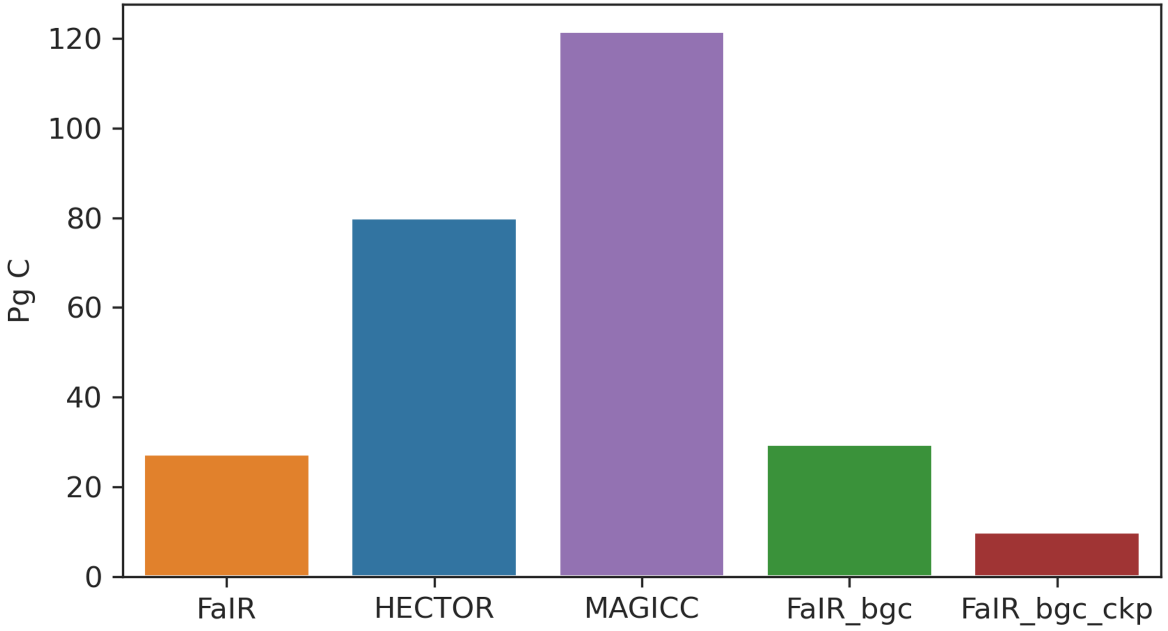


Implications for remaining carbon budget?

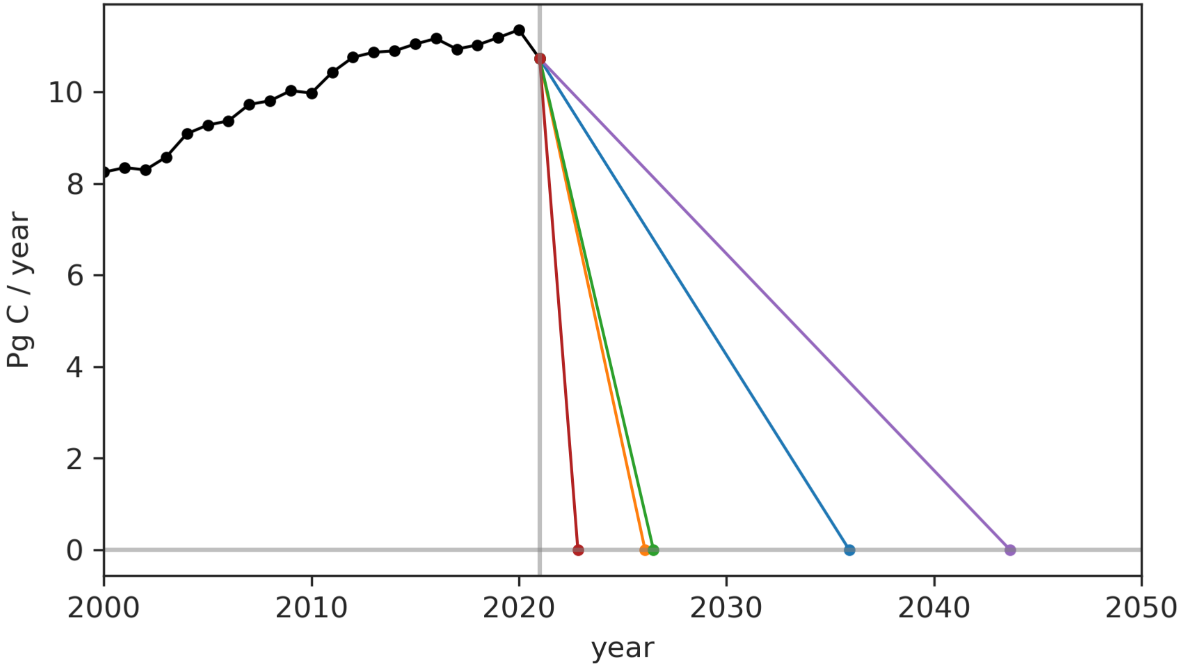

a) Remaining carbon budget by model


b) Implied linear ramp-down in emissions

Drop in RCB in correlated ensemble → different emissions necessary to meet mitigation goals.

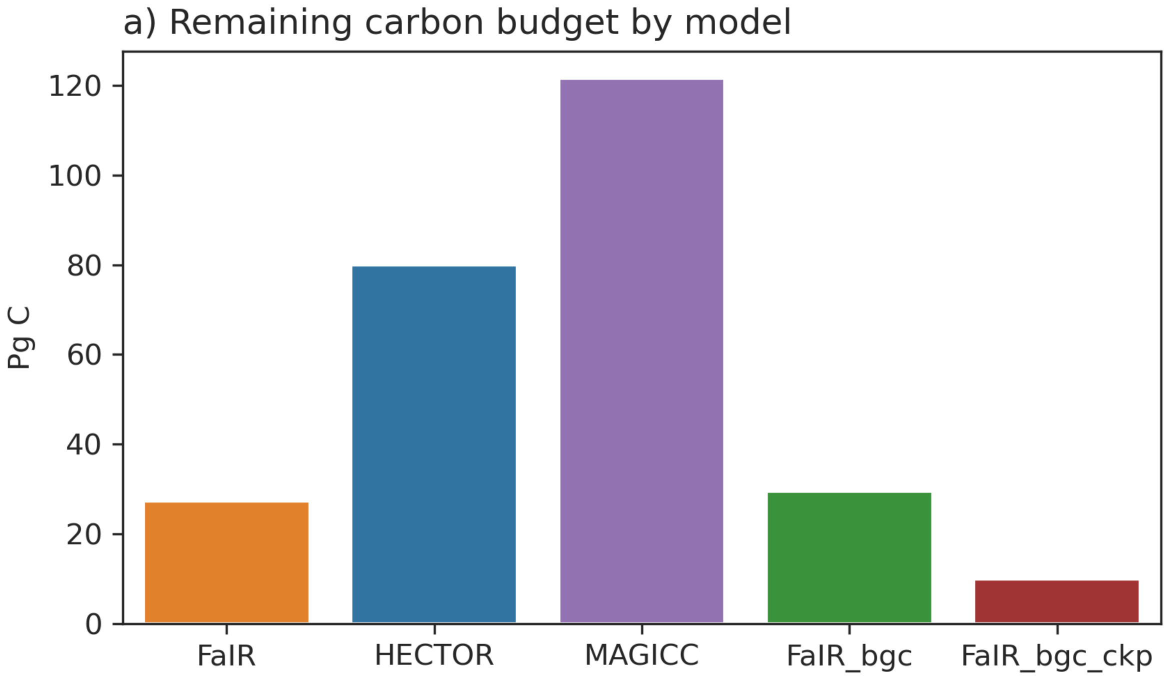


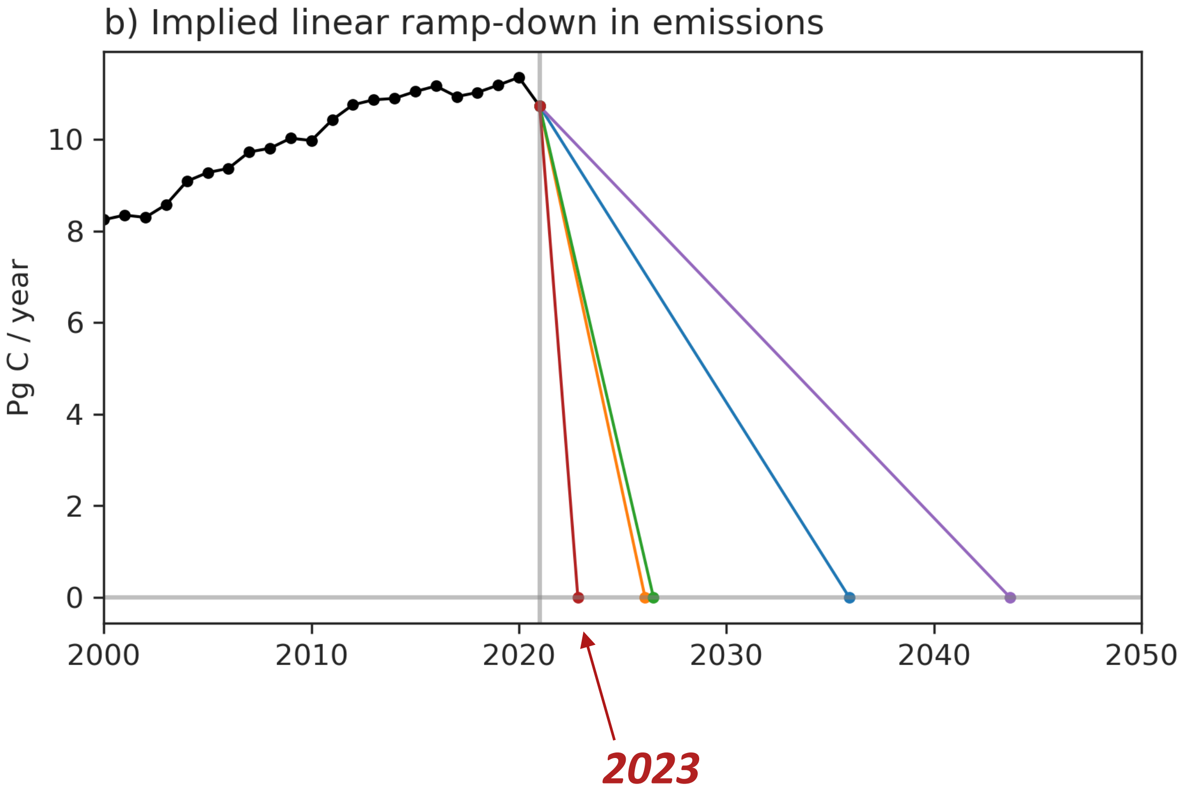
a) Remaining carbon budget by model



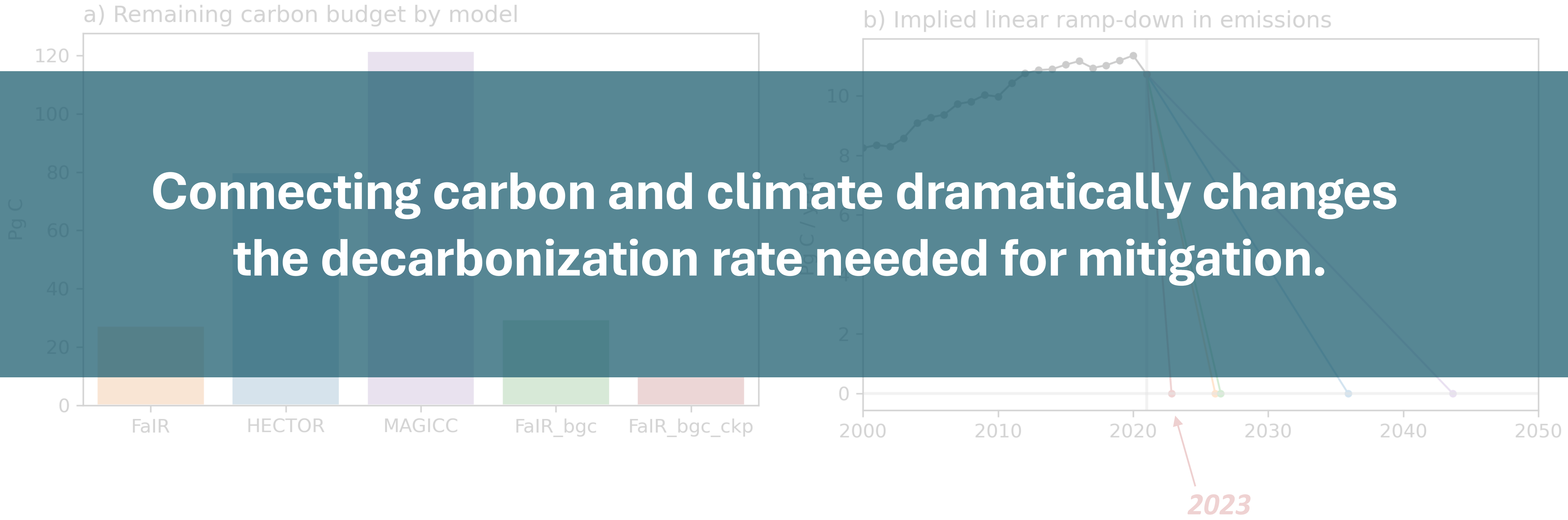
b) Implied linear ramp-down in emissions

Drop in RCB in correlated ensemble → different emissions necessary to meet mitigation goals.


a) Remaining carbon budget by model


b) Implied linear ramp-down in emissions

Drop in RCB in correlated ensemble → different emissions necessary to meet mitigation goals.



Connecting carbon and climate dramatically changes the decarbonization rate needed for mitigation.

Implications for CESM Community

Need for ESM-driven constraints on connections between processes that influence carbon and climate :

⟶ e.g. ESM carbon fluxes and heat fluxes as outputs from emissions-driven runs

⟶ Carbon cycle PPEs would allow us to sample across realizations of the carbon-climate system