# Emissions driven puzzles from CMIP6 and needs for CMIP7

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Rosie Fisher, Stuart Jenkins, Glen Peters, Myles Allen

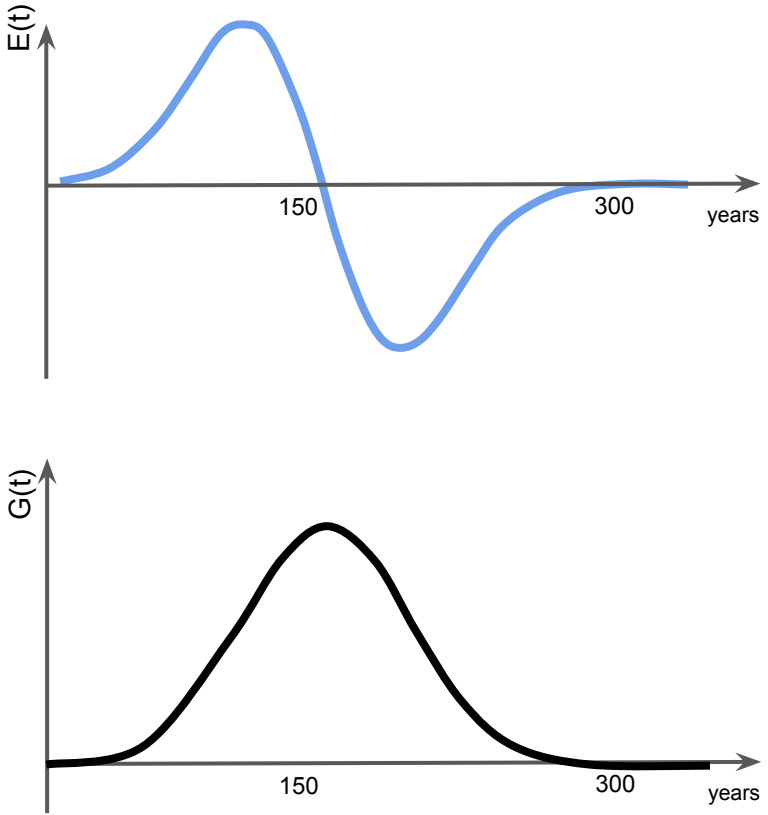
CESM BGCWG
Summer 2023

esm Earth System Models for the future 2025

CICERO Senter for klimaforskning

# What are the limits of TCRE?

- “Climate restoration” experiment
- Net zero at year 150
- Complete removal at year 300

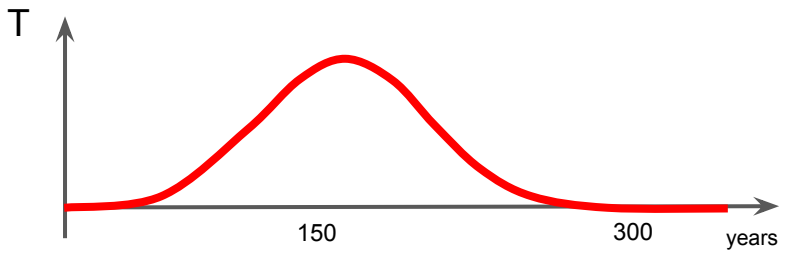



Koven, C. D., Sanderson, B. M., & Swann, A. L. (2023). Much of zero emissions commitment occurs before reaching net zero emissions. *Environmental Research Letters*, *18*(1), 014017.

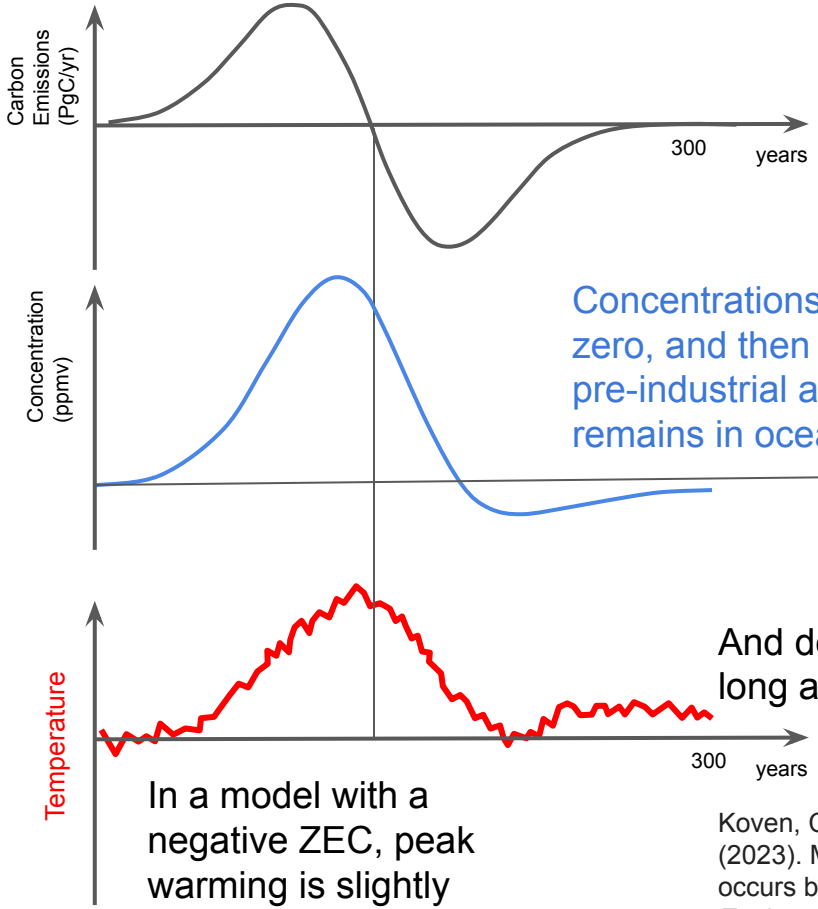
- TCRE response would be proportional to the cumulative emissions curve

$$\Delta T = \kappa_E(\Delta G)$$

TCRE-like response



# CESM2 results




Concentrations peak before net zero, and then go below pre-industrial as some carbon remains in oceans

And deep-ocean heat persists long after removal of all carbon

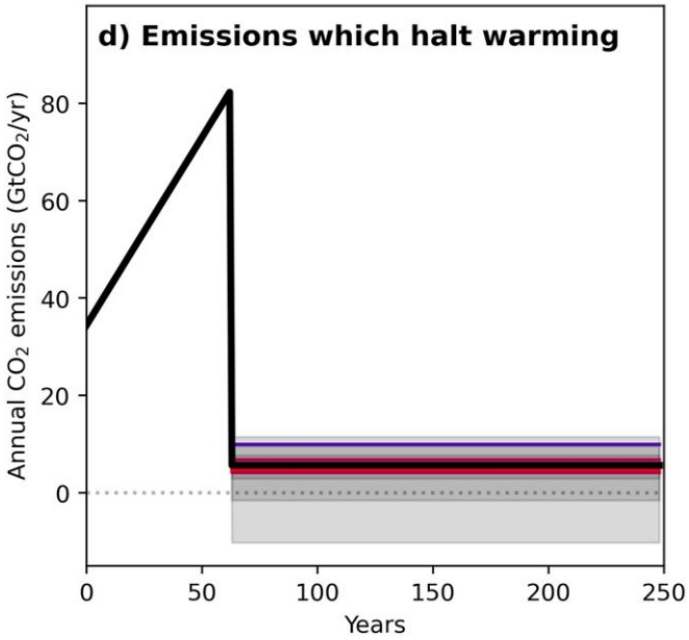
In a model with a negative ZEC, peak warming is slightly before net zero

Koven, C. D., Sanderson, B. M., & Swann, A. L. (2023). Much of zero emissions commitment occurs before reaching net zero emissions. *Environmental Research Letters*, *18*(1), 014017.

- Can we modify the TCRE framework to account for these factors?

$$G(t) = \int E(t)\mathrm{d}t$$

$$\Delta T = \kappa_E\left(\Delta G + o\overline{G}\Delta t\right)$$




"RAZE (Rate of adjustment to Zero Emissions)" describes the long term emissions compatible with halting warming

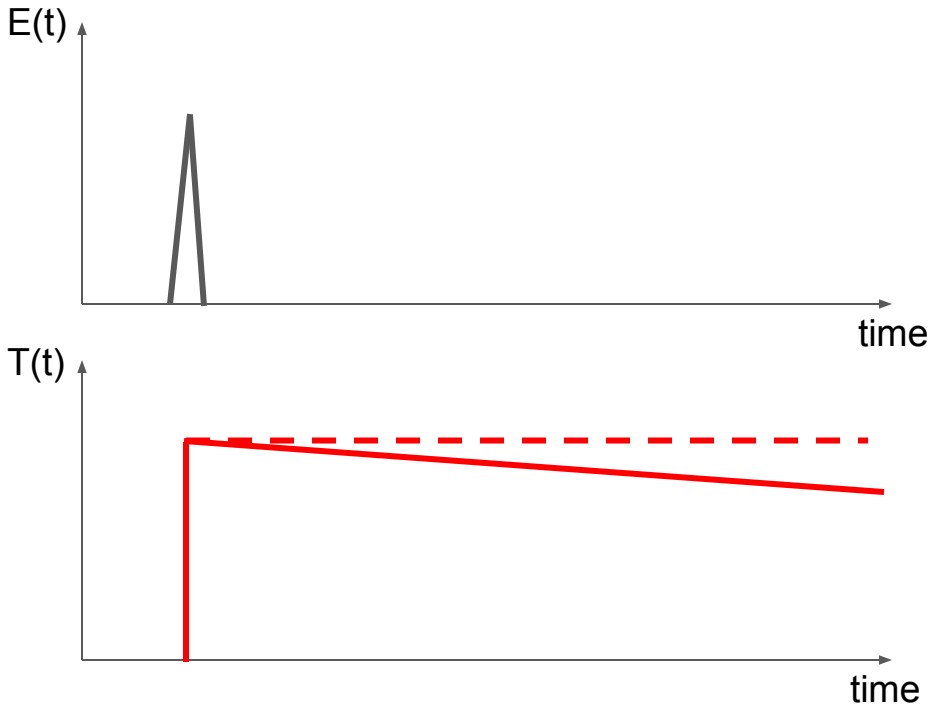
Jenkins, S., Sanderson, B., Peters, G., Frölicher, T.L., Friedlingstein, P. and Allen, M., 2022. The multi-decadal response to net zero CO2 emissions and implications for emissions policy. *Geophysical Research Letters*, p.e2022GL101047.

$$G(t) = \int E(t)\mathrm{d}t$$

$$\Delta T = \kappa_E\left(\Delta G + o\overline{G}\Delta t\right)$$

TCRE-like response

Long term adjustment (RAZE)



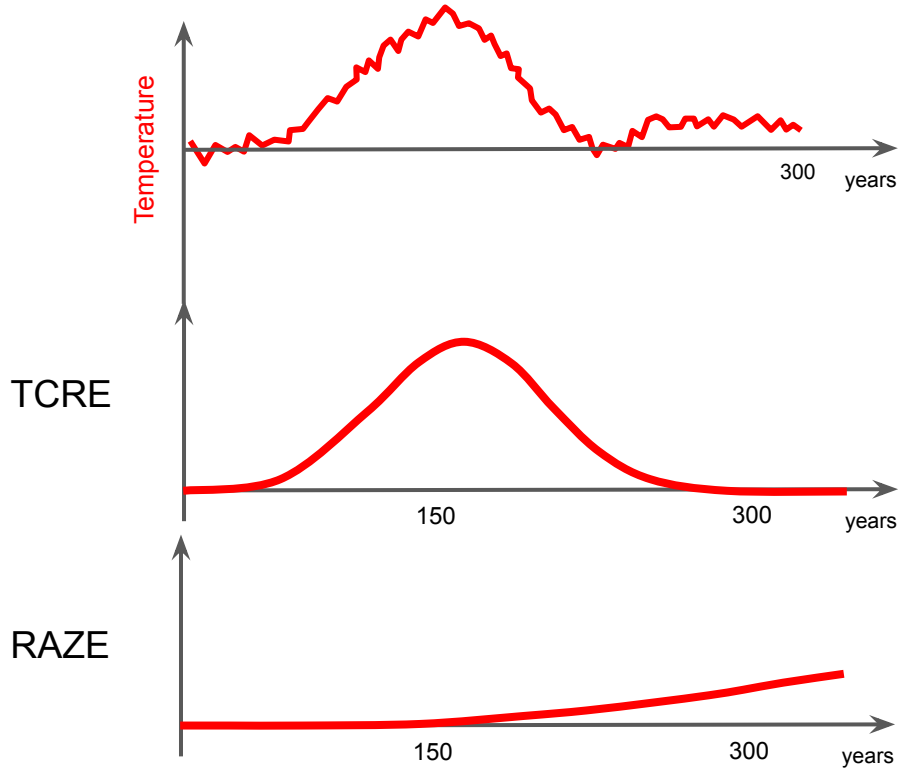

ZEC+RAZE adds a long term linear trend to the Impulse Response Function

- TCRE+RAZE can represent long term warming, but not ‘dip’ or early peak warming

$$\Delta T = \kappa_E (\Delta G + o\bar{G}\Delta t)$$

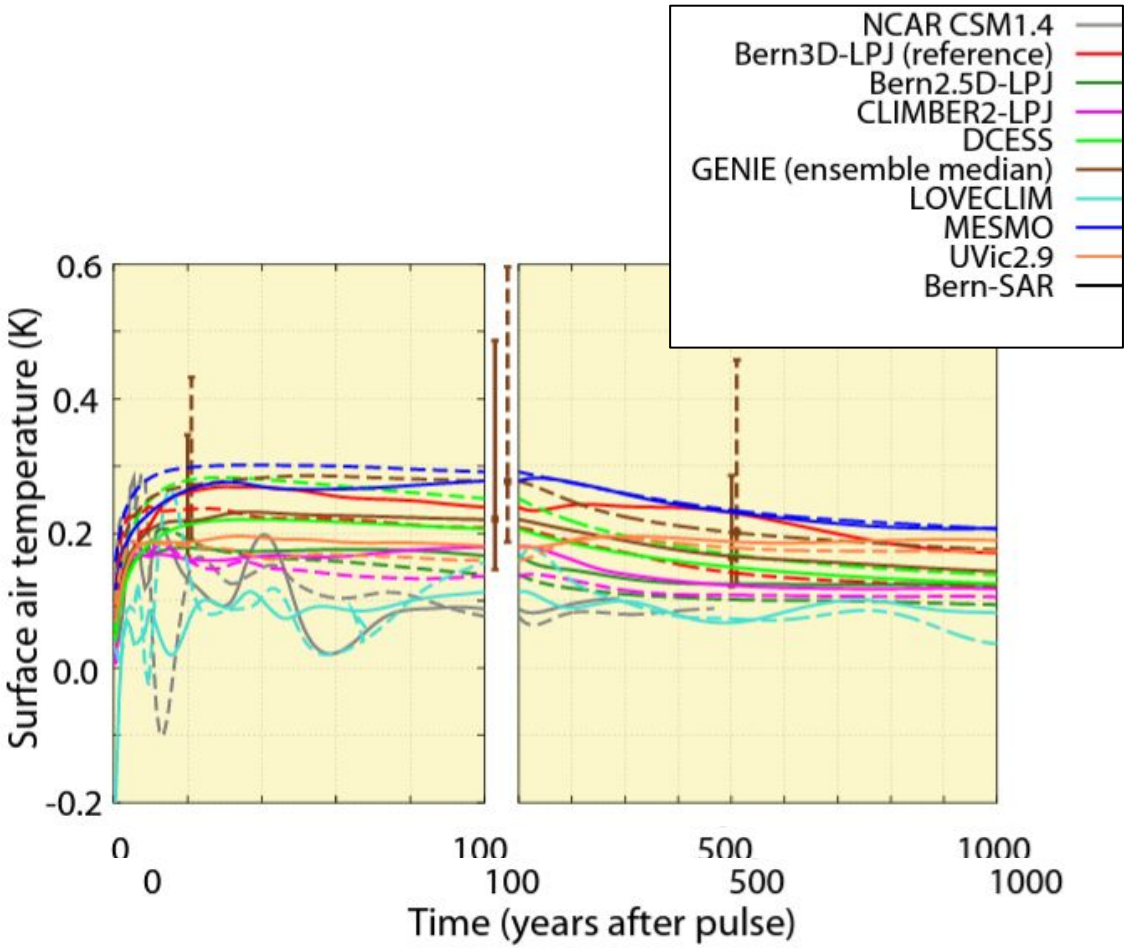
TCRE-like response

Long term adjustment (RAZE)



# So what are we missing?

- Most models also exhibit transient effects in the immediate aftermath of the pulse (AGTP)
- They can be +ve or -ve corrections to the multi+decadal response




Joos, Fortunat, Raphael Roth, Jan S. Fuglestvedt, Glen P. Peters, Ian G. Enting, Werner Von Bloh, Victor Brovkin et al. "Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis." *Atmospheric Chemistry and Physics* 13, no. 5 (2013): 2793-2825.

Cumulative emissions

$$\Delta G(t) = \int_{t_0}^{t} E(t)\mathrm{d}t$$

Recent emissions

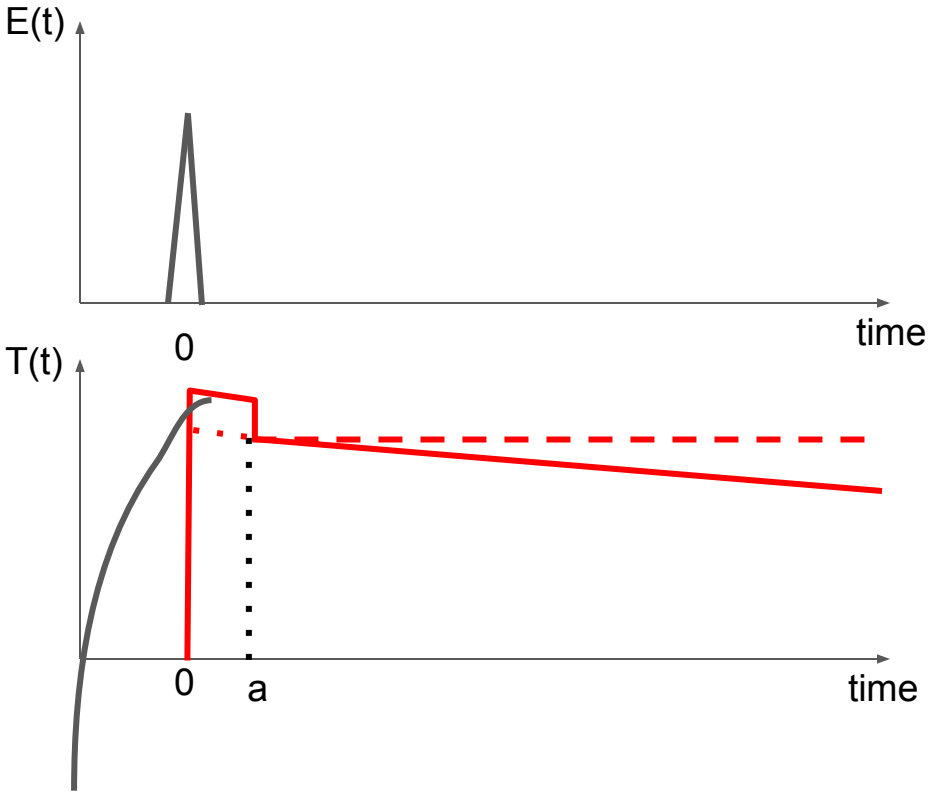
$$R(t) = \int_{t-a}^{t} E(t)\mathrm{d}t$$

$$\Delta T = \kappa_E(\Delta G + o\bar{G}\Delta t + \rho R)$$

TCRE-like response

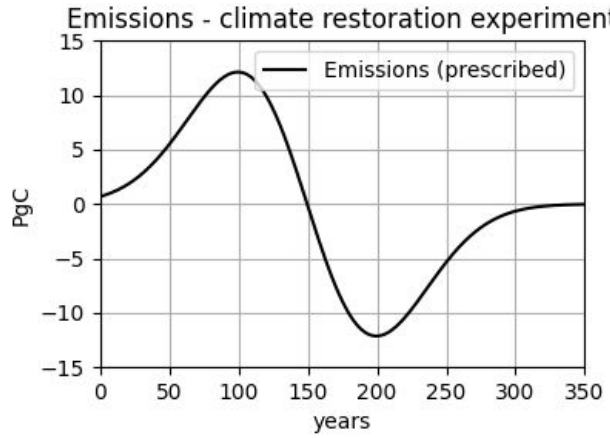
Long term adjustment (RAZE)

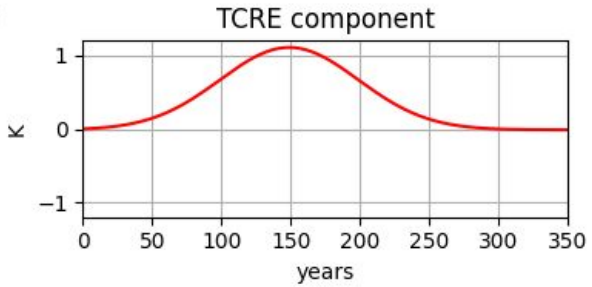
Short term adjustment (DARE)

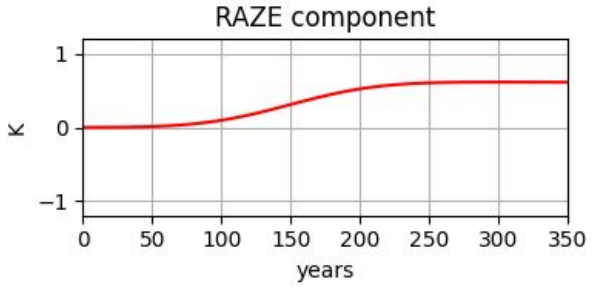


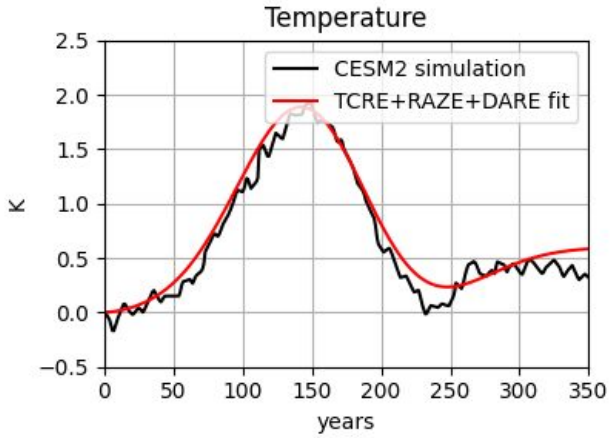

DARE = “Delayed Adjustment to Recent Emissions”

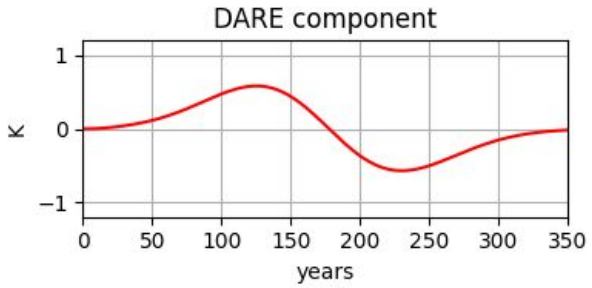
This model empirically accounts for the warming trajectory in the idealised overshoot (with some error)

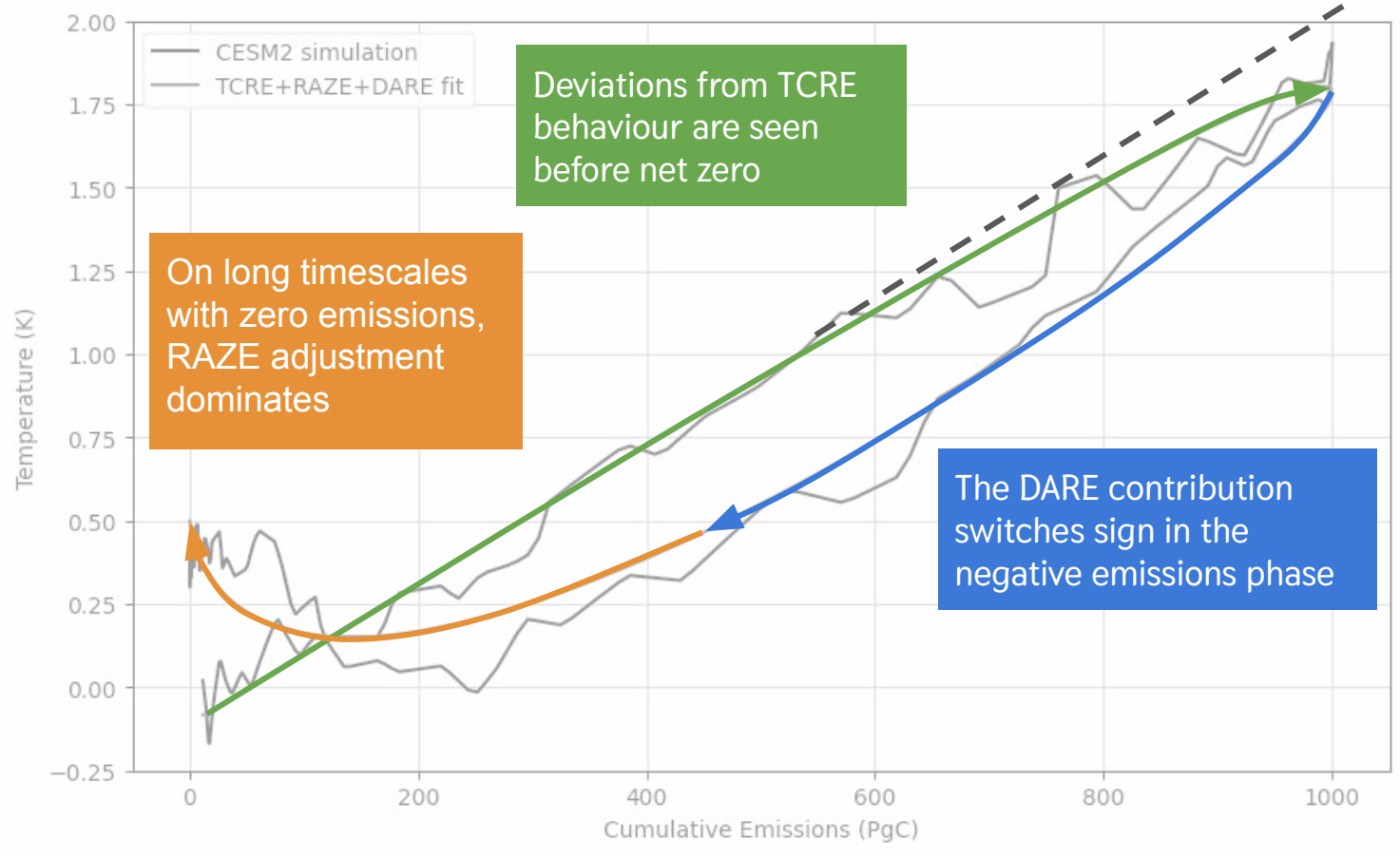


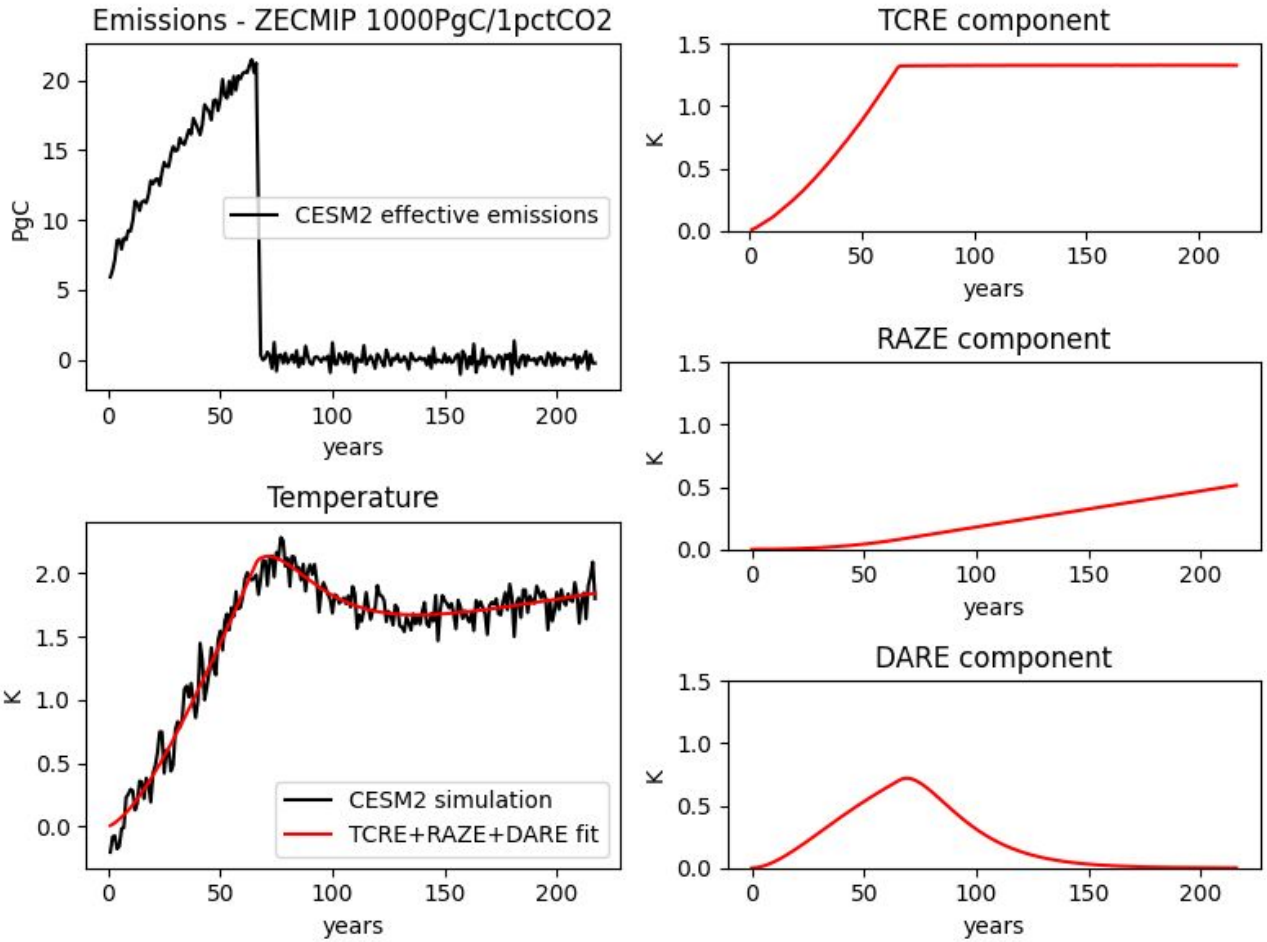



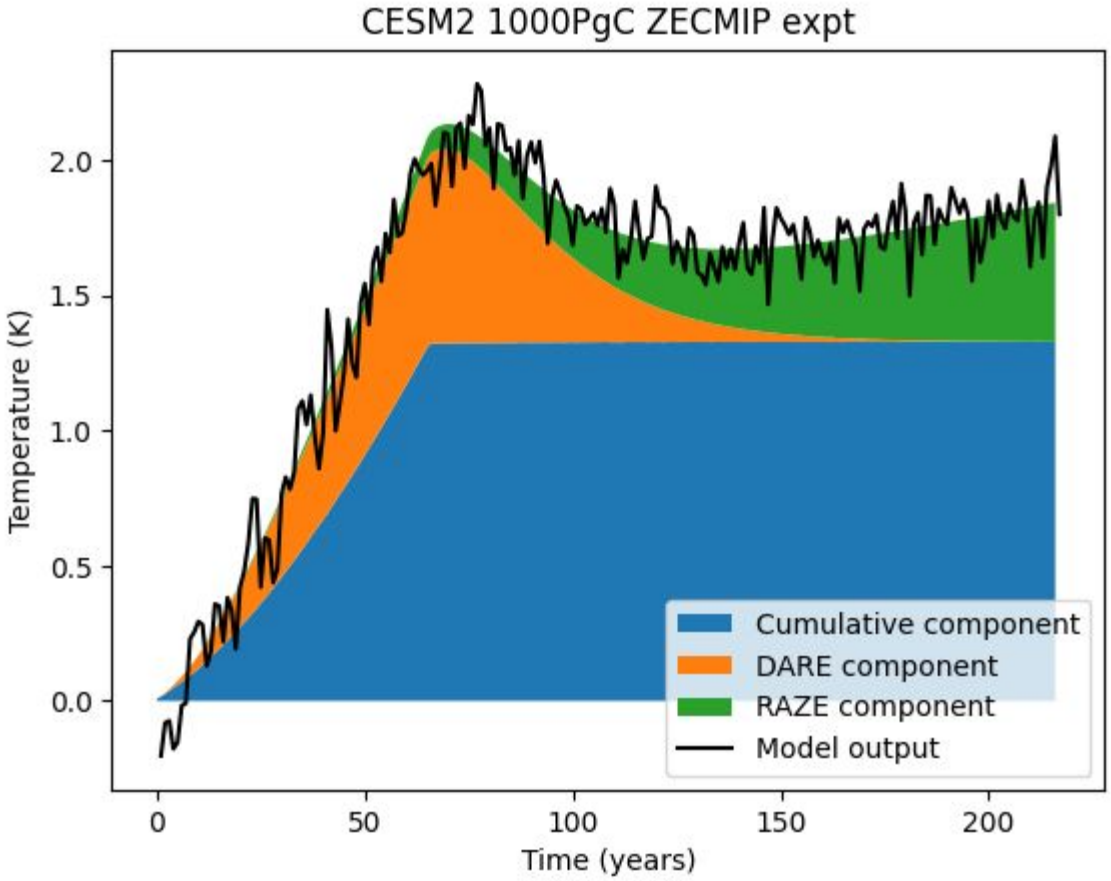




CESM2 simulation
TCRE+RAZE+DARE fit
Deviations from TCRE behaviour are seen before net zero
On long timescales with zero emissions, RAZE adjustment dominates
The DARE contribution switches sign in the negative emissions phase
Temperature (K)
Cumulative Emissions (PgC)
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
−0.25
0
200
400
600
800
1000

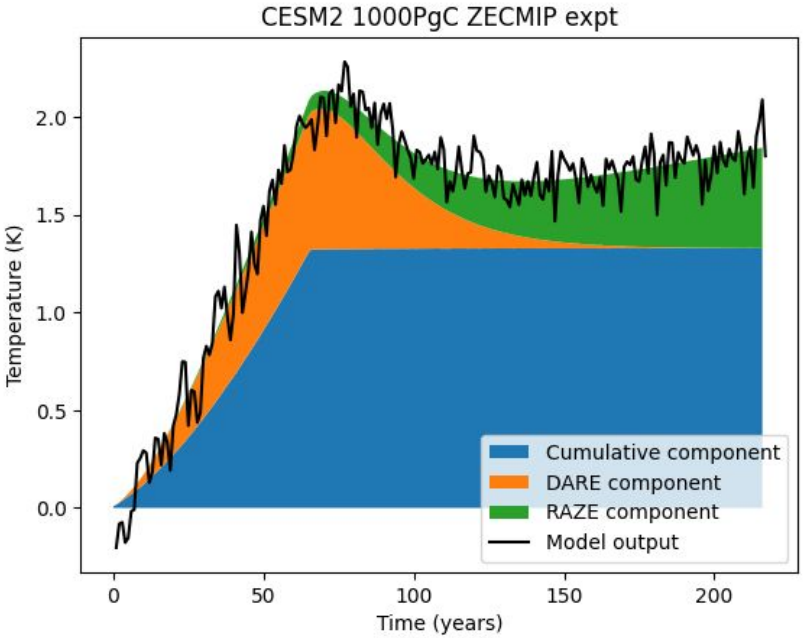
TCRE, DARE & RAZE can be fitted from existing ZECMIP experiments



But what we currently call TCRE can be a mixture of transient and permanent effects

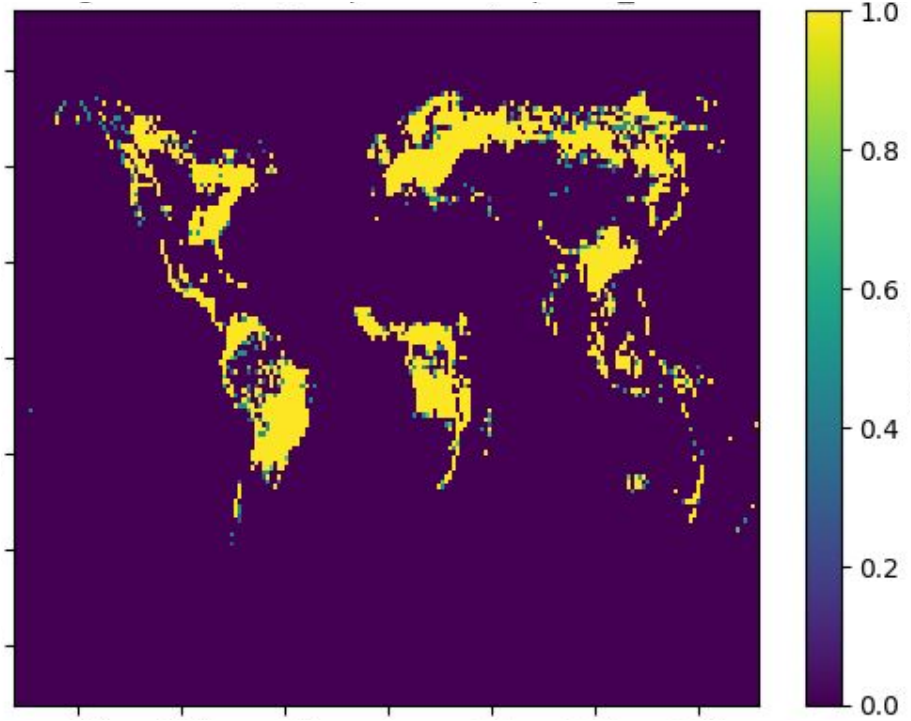


# Conclusions (Part 1)

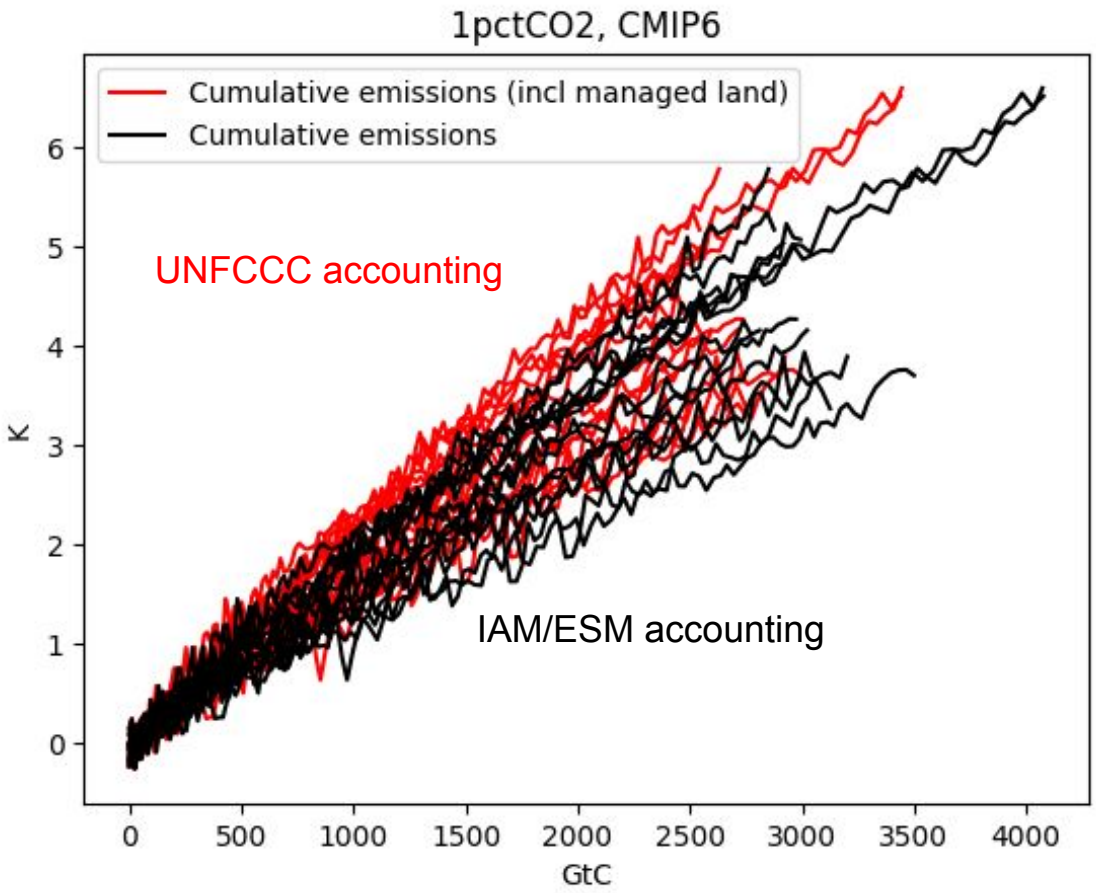



- “ZEC” can be represented as a combination of short term adjustments to recent emissions (DARE) and long term adjustments (RAZE)
- DARE has implications for the level and timing of peak warming
- “TCRE” can be a mix of permanent and transient effects

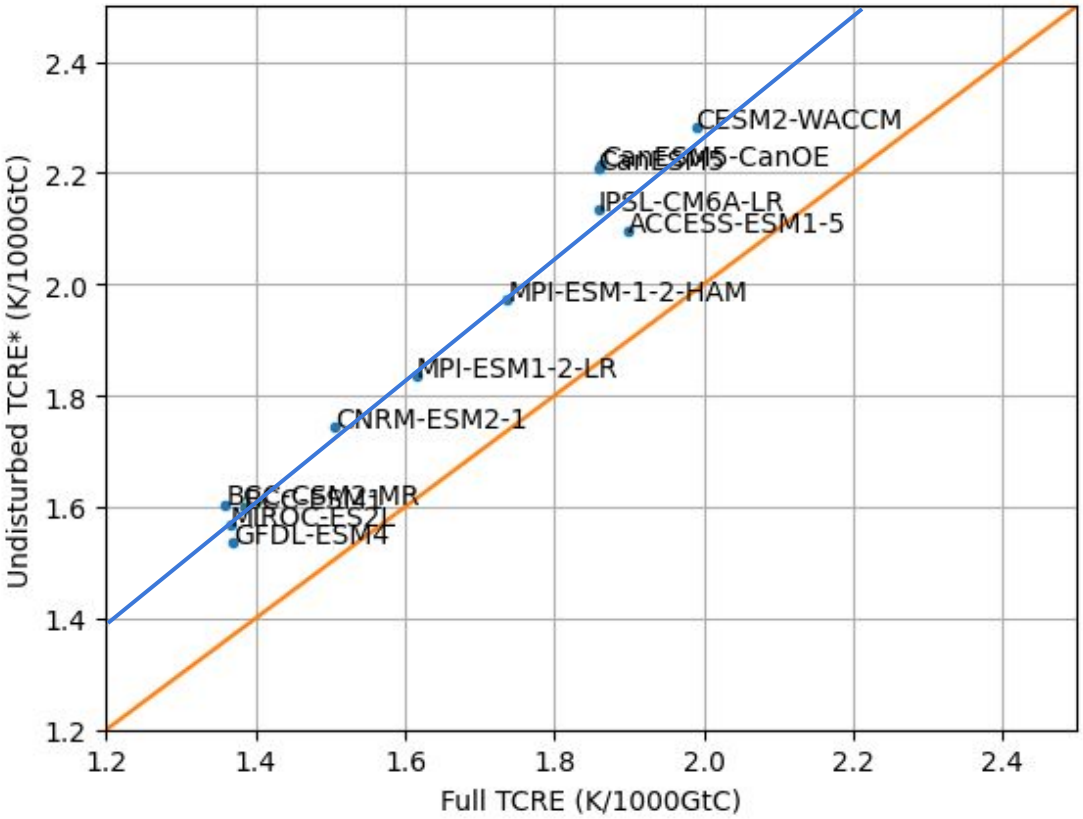
# Part 2 - The Grassi correction (from an ESM perspective)




- We can use the pristine land product used in Grassi et al to partition Land sink into managed and non-managed components

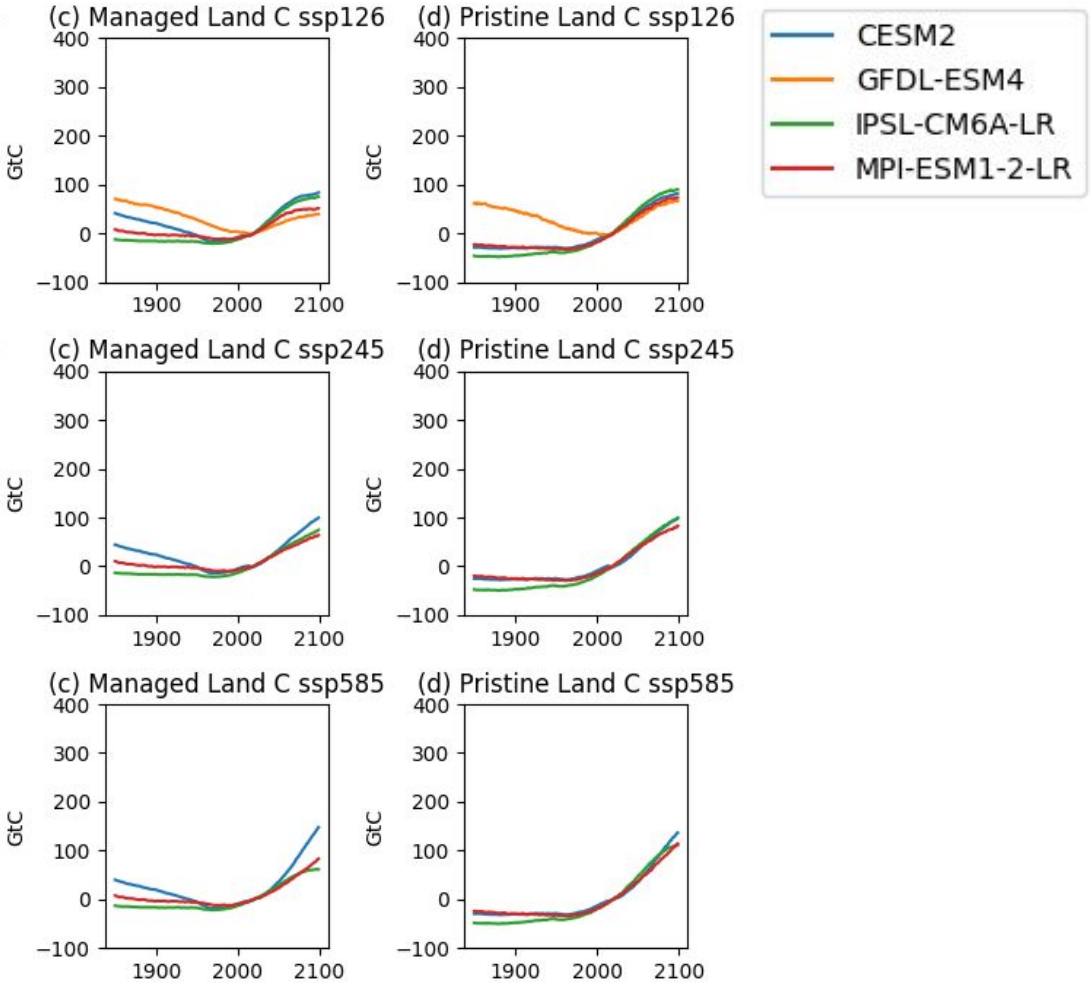



- This allows us to calculate cumulative emissions including and excluding managed land

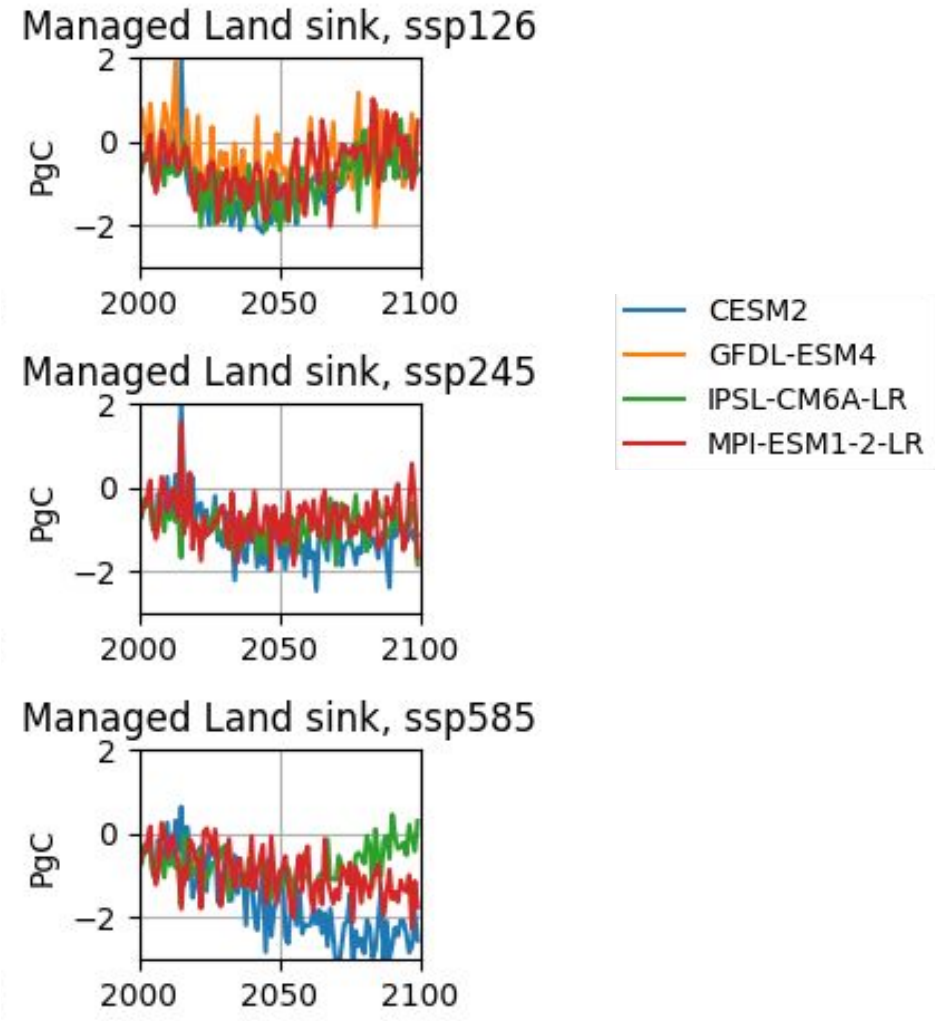



- Cumulative emissions (incl managed land) can be reconciled with expected warming levels by using an ‘undisturbed’ TCRE* which excludes those Earth System feedbacks associated with managed land
- TCRE* gives a higher warming per unit emissions due to exclusion of managed land sink, with a near-constant offset

## Cumulative Land carbon sink

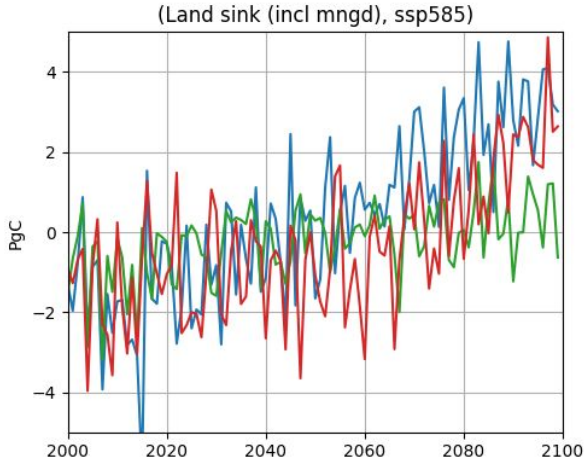


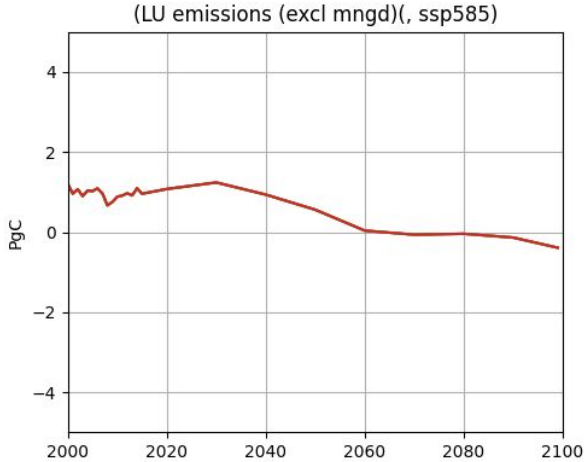

- In scenarios, there is more uncertainty associated with the managed land sink than the pristine land sink



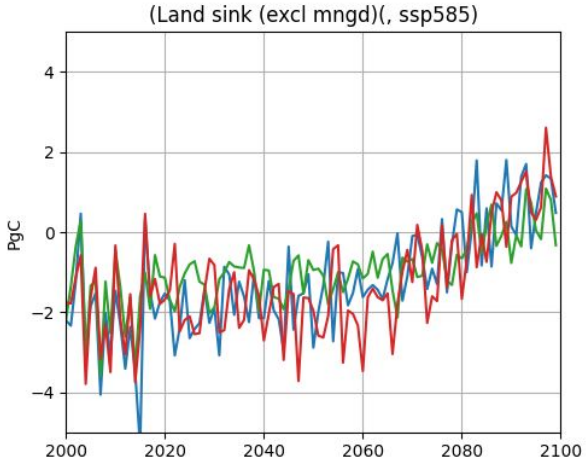

- Uncertainty in managed land sink is scenario-dependent:
  - Agreement on near-zero sink in SSP126
  - Agreement on constant sink in SSP245 (with spread)
  - Large disgreememnt in SSP585

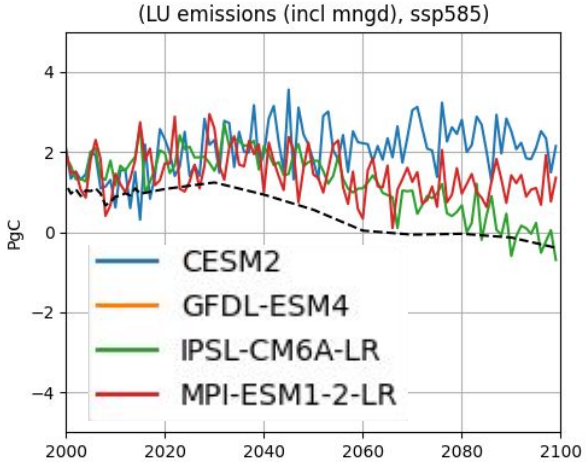
## IAM/ESM accounting



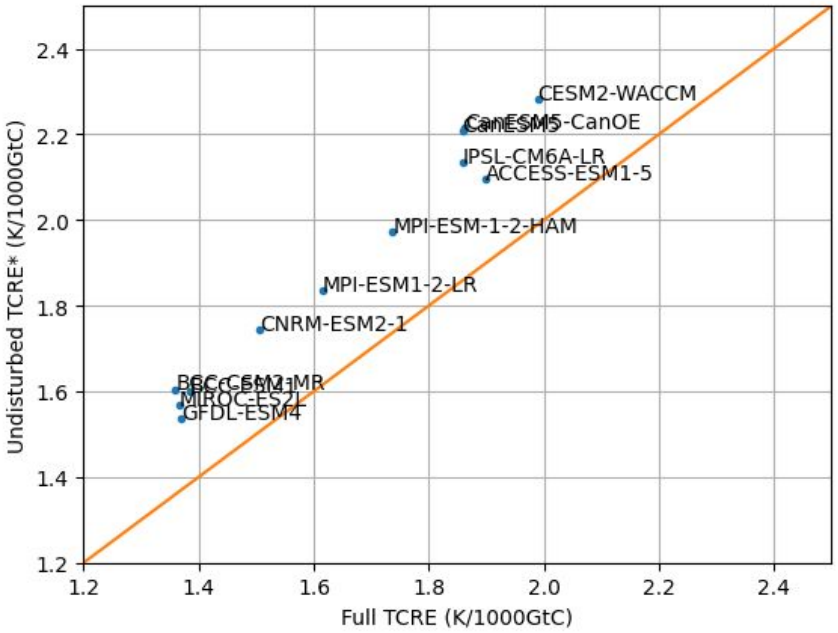

## UNFCCC accounting




- There is significantly more uncertainty associated with the net land sink if managed land is included
- This uncertainty is part of the land sink in IAM/ESM accounting, and part of emissions in UNFCCC accounting

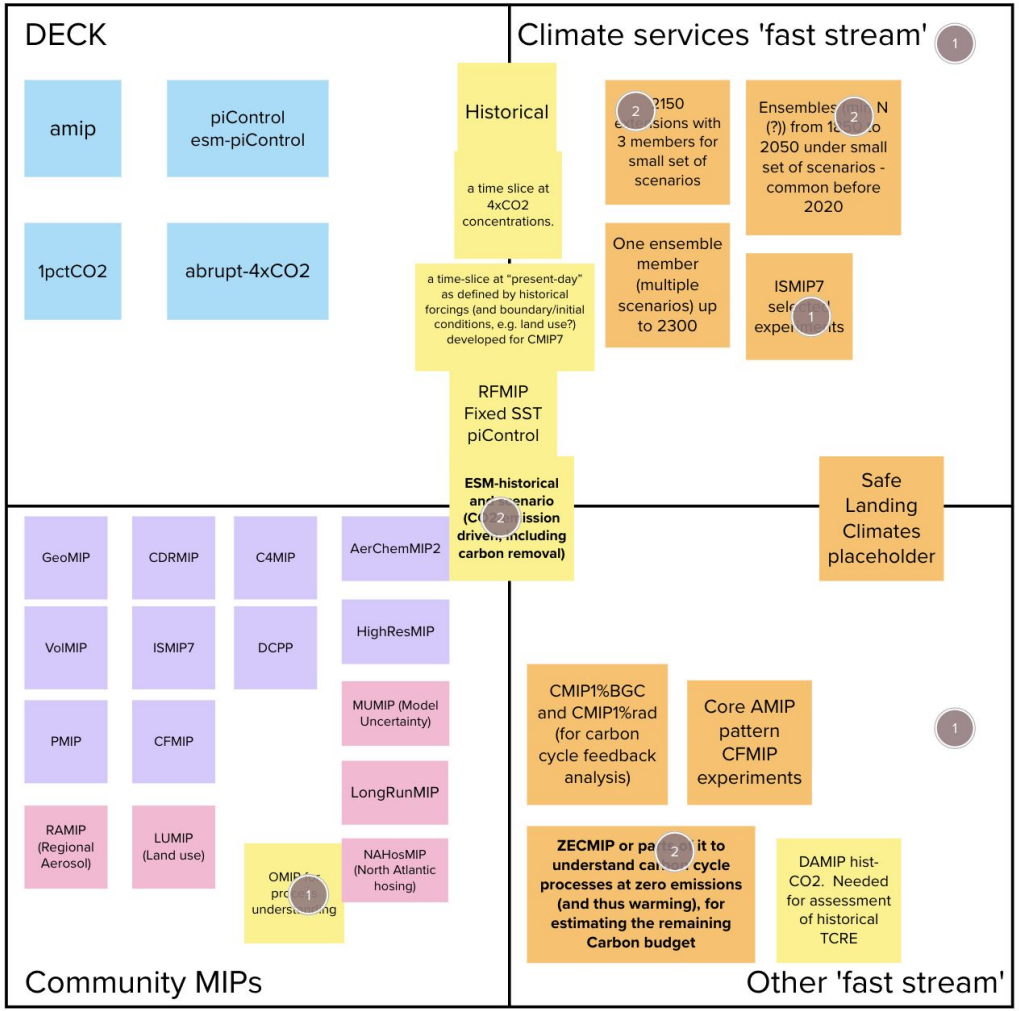
# Conclusions (Part 2)



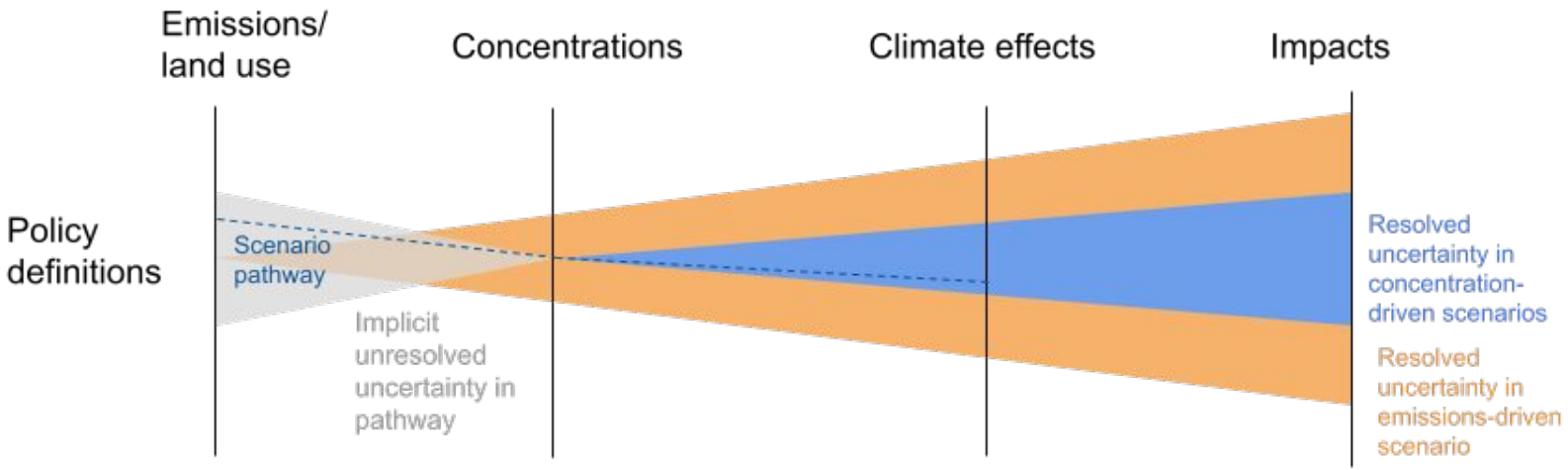

- UNFCCC carbon accounting can be simply related to temperature targets through an alternatively defined TCRE*
- Uncertainties in land sink are disproportionally larger in managed areas - hence multi-model agreement on  TCRE* is greater
- This uncertainty is transferred into the emissions space - with evidence of significant scenario dependency

# Prioritized emission-driven scenarios in CMIP7?

# CMIP7 structure (NOT FINAL)



Perspective: A higher emphasis on emissions-driven simulations for CMIP7? (contact me if you'd like to be involved)



# Draft proposal for emissions-driven runs in CMIP7

bit.ly/emiscmip7

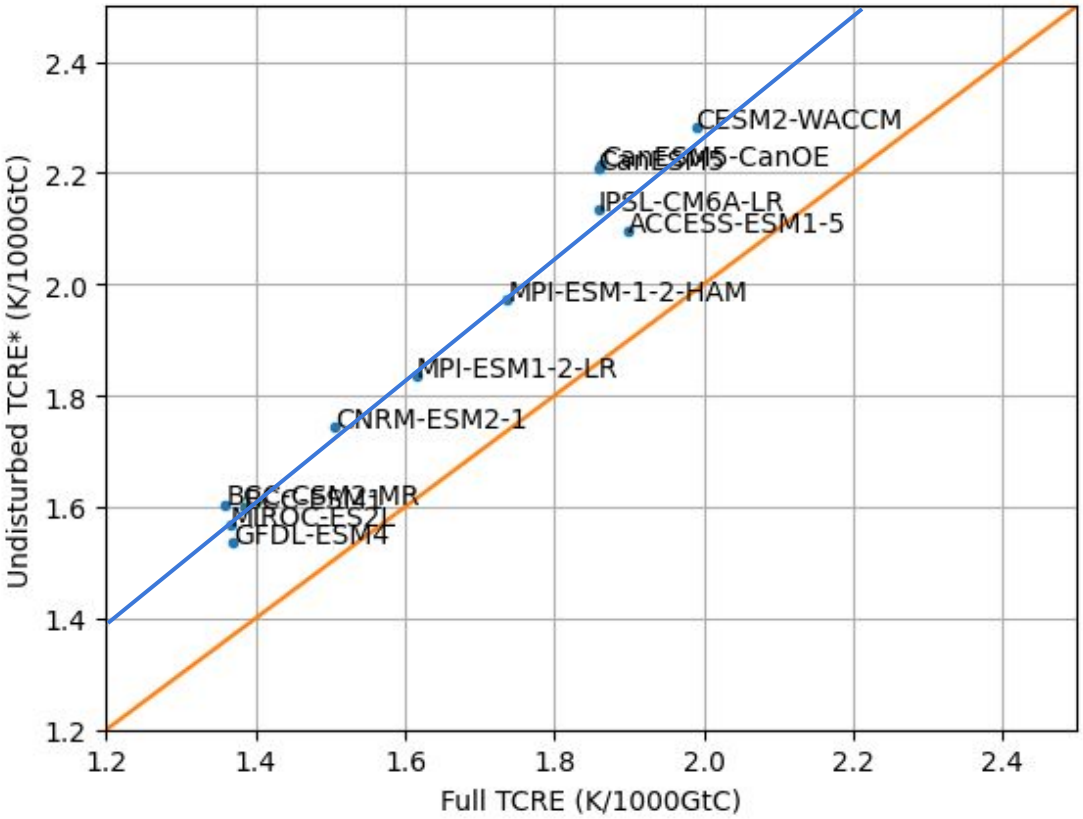
esm 2025
Earth System Models for the future

**UKESM, CNRM, NorESM**

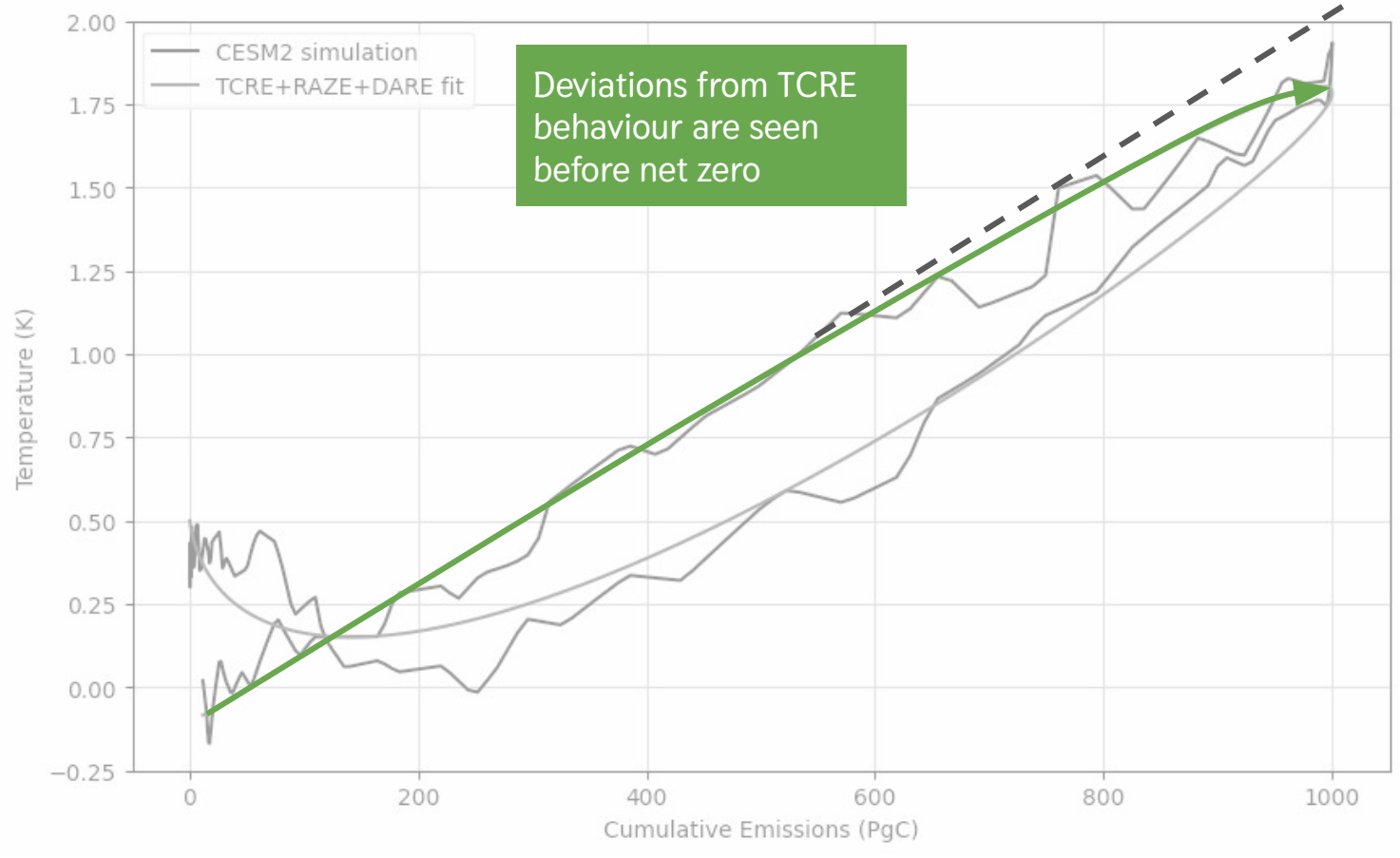
1. **Real/policy relevant runs**
   a. emission-driven piControl + e-HIST
   b. e-scenarios-overshoot: (i) A high (e.g. 3°C) and (ii) low (e.g. 2.25°C) overshoot of GWL=2°C, with a return and stabilization (zero-emission) at 2°C and possibly 1.5°C, with speed of return to these levels determined by what is feasible (runs likely extend beyond 2100)
   c. e-scenarios-non-overshoot : (i) current policies (e.g. NDCs), (ii) strong mitigation, and (iii) current policies/promises failing e.g. something like an RCP4.5 or 6.0 ? e.g. higher end.

2. **Idealized**
   a. A linear increase of CO2 emissions from piControl with rates either (i) a fixed CO2 emission rate (e.g. 10GtC/yr) or (ii) a fixed warming rate (~0.2°C/decade), which equates to XGtC/yr for each model derived from their respective TCRE values. And then switch to zero emissions either at (iii) one or more GWL levels and/or (iv) a fixed cumulative emission e.g. 1000 GtC

3. **Solutions oriented experiments.**
   e.g. regional afforestation, other modes of climate restoration etc




- The near-constant 0.2K increase in TCRE to TCRE* implies the **relative** variance in TCRE* is smaller than in TCRE
- we are excluding the uncertain feedback associated with the land sink from TCRE*, so although its value grows, the signal:noise is increased


CESM2 simulation
TCRE+RAZE+DARE fit
Deviations from TCRE behaviour are seen before net zero
Temperature (K)
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1.75
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200
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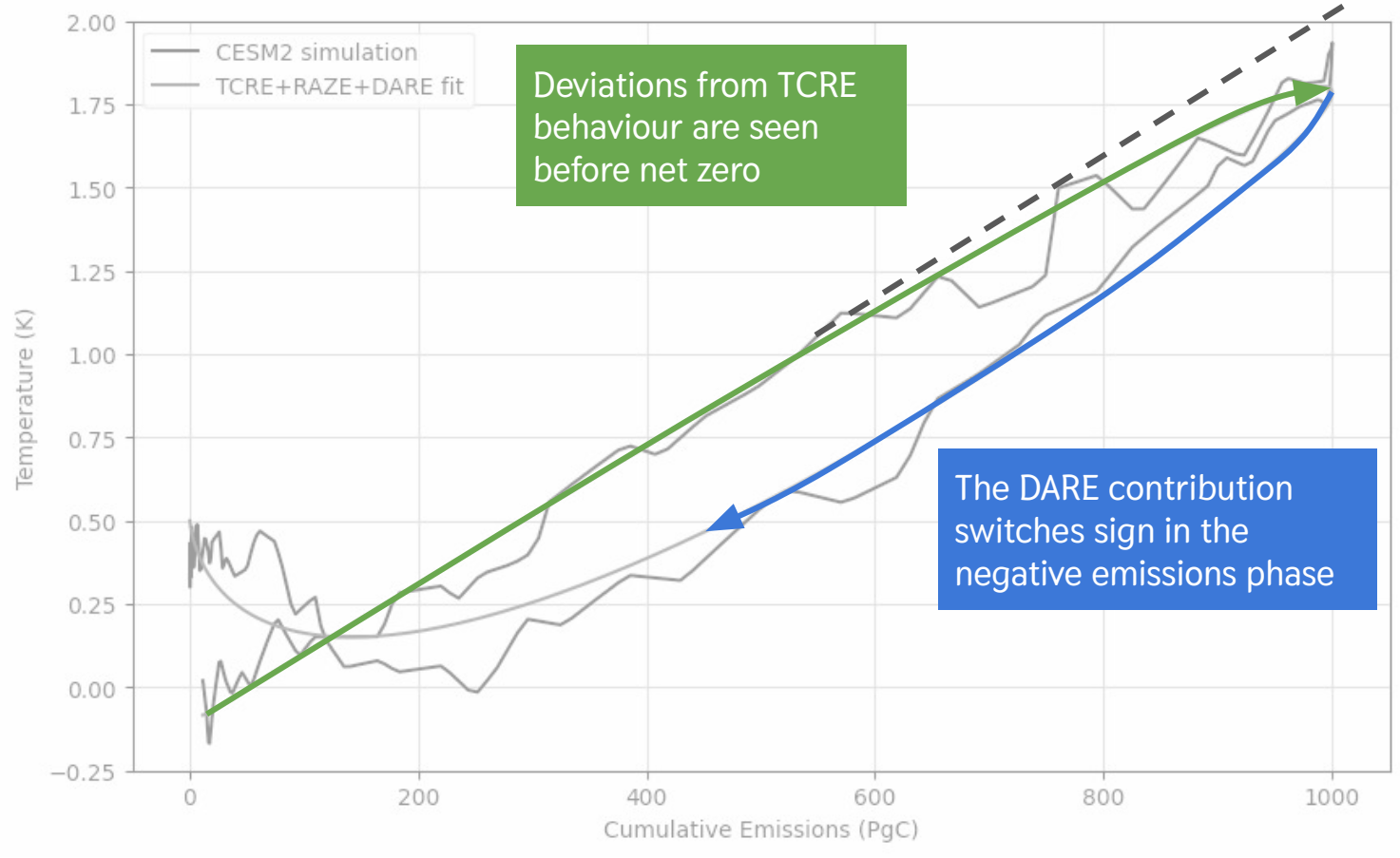
Cumulative Emissions (PgC)


CESM2 simulation
TCRE+RAZE+DARE fit
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The DARE contribution switches sign in the negative emissions phase
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−0.25
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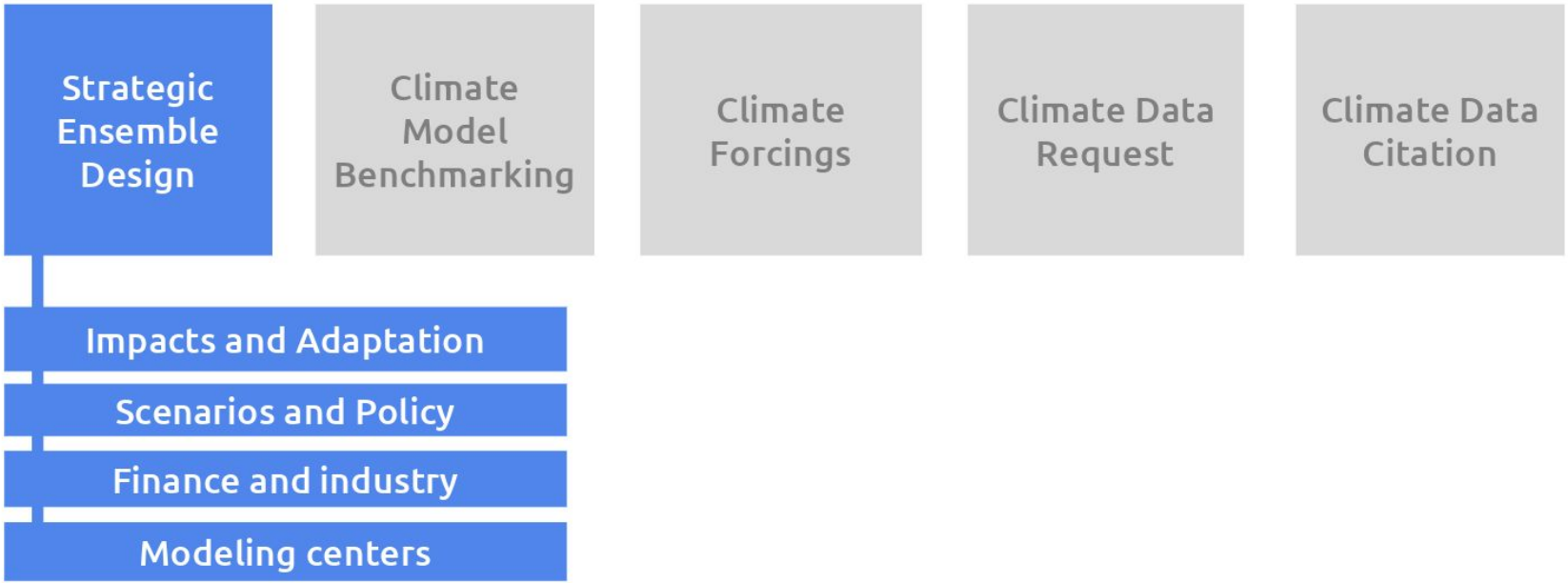
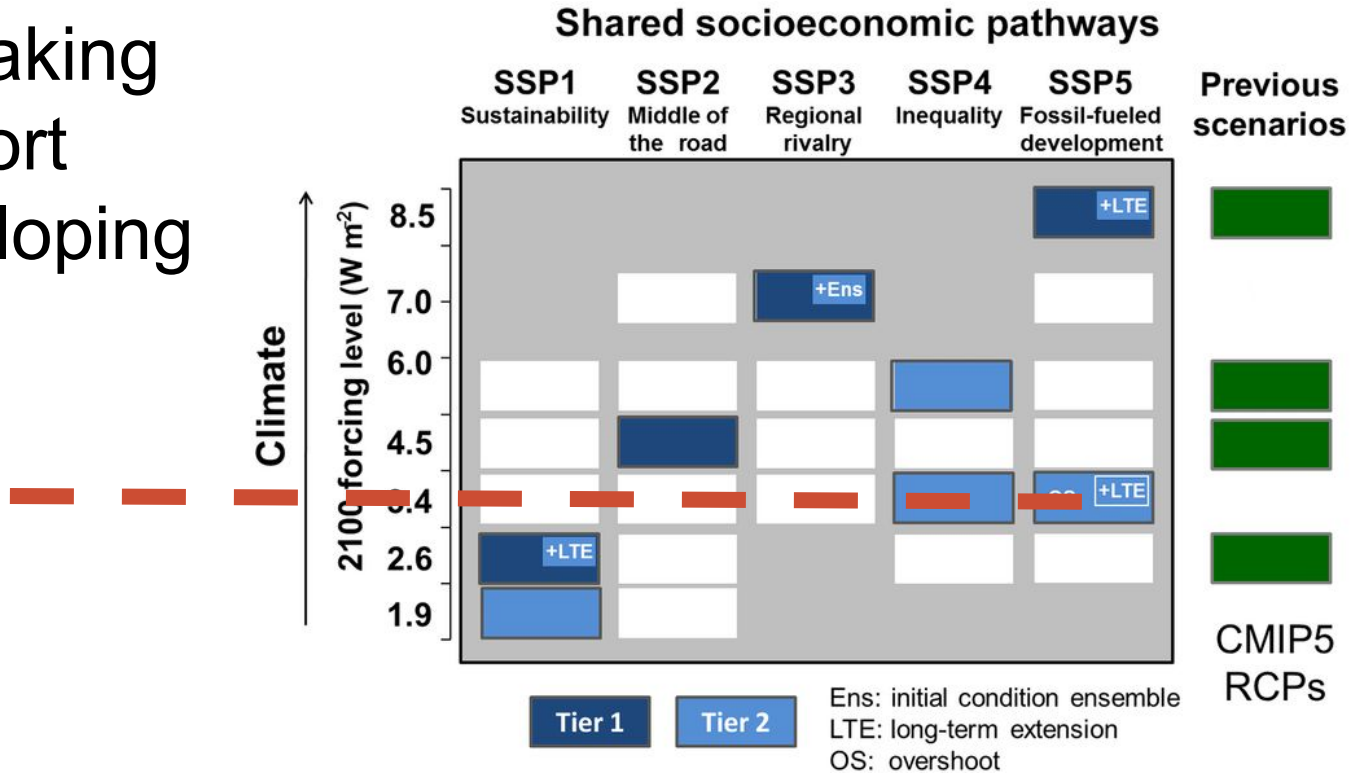
# CMIP7 Task Teams




Stakeholder groups

Is the SSP-RCP framework making use of the effort spent in developing ESMs?



# Different mitigation strategies, with different risks...