

# Refining the budget: limits of the cumulative emissions framework and implications for policy

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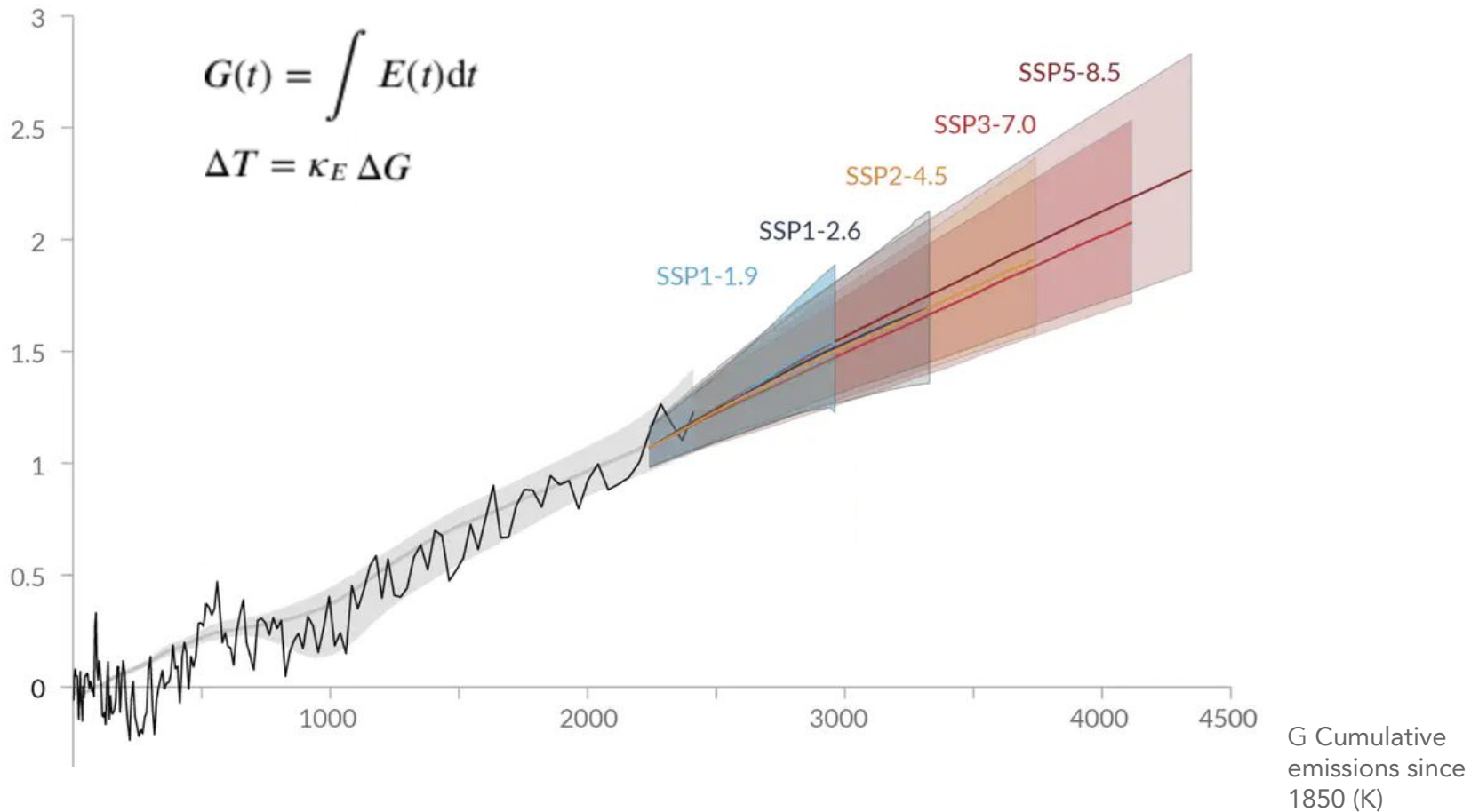
**°CICERO**

Senter for klimaforskning

Warming since  
1850 (K)

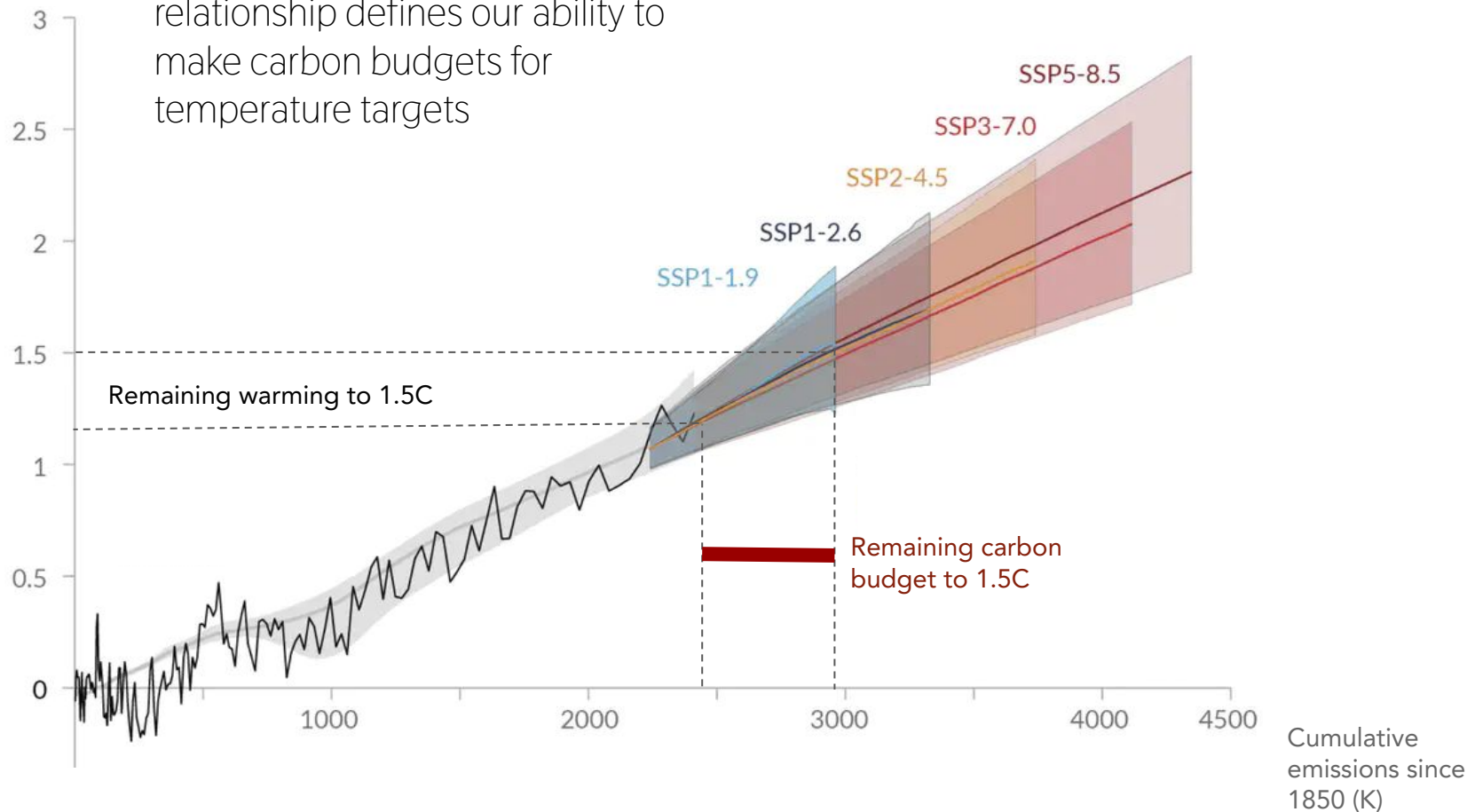
$$G(t) = \int E(t)dt$$

$$\Delta T = \kappa_E \Delta G$$



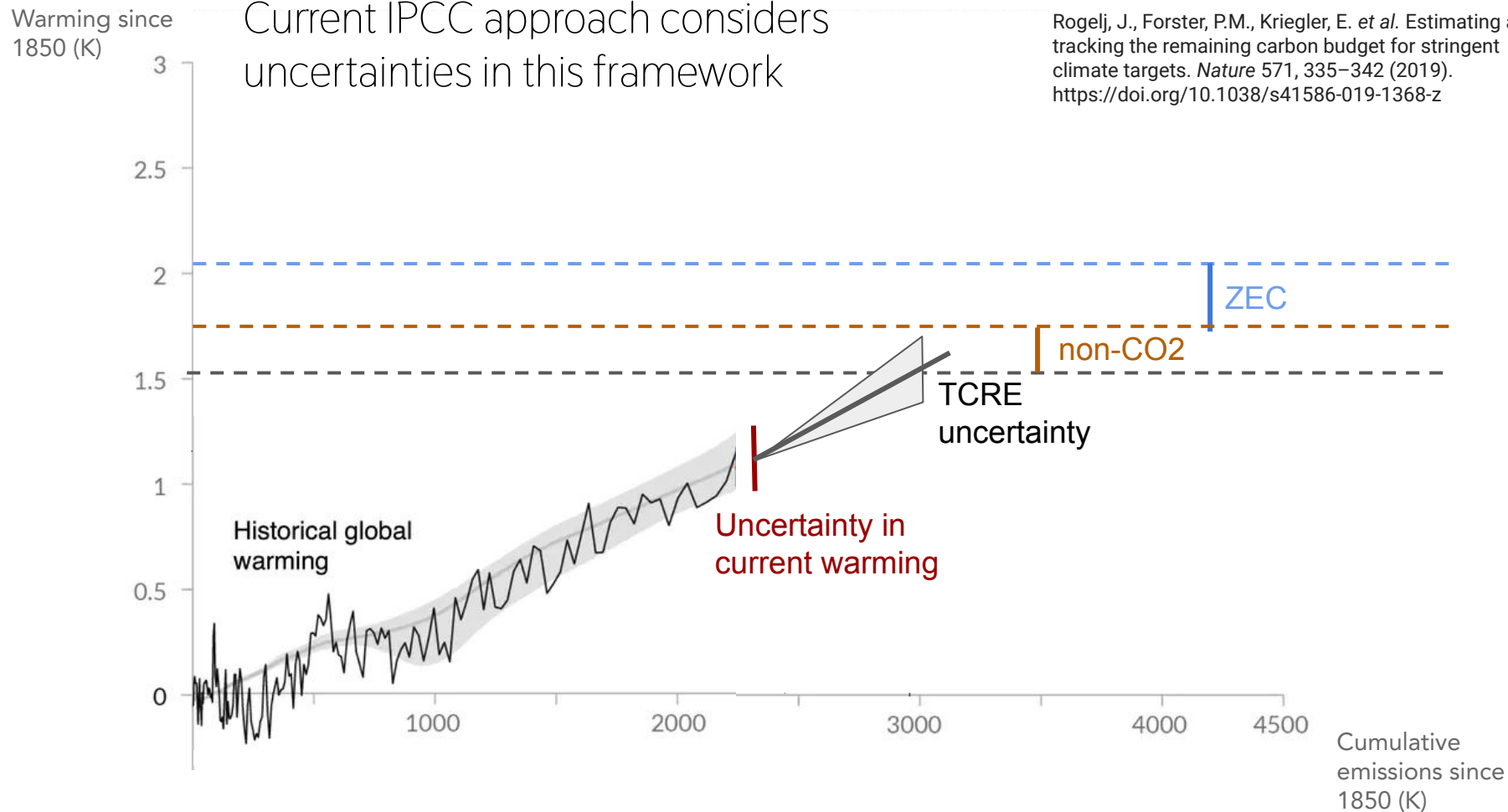
Warming since 1850 (K)

The cumulative emissions relationship defines our ability to make carbon budgets for temperature targets



Current IPCC approach considers uncertainties in this framework

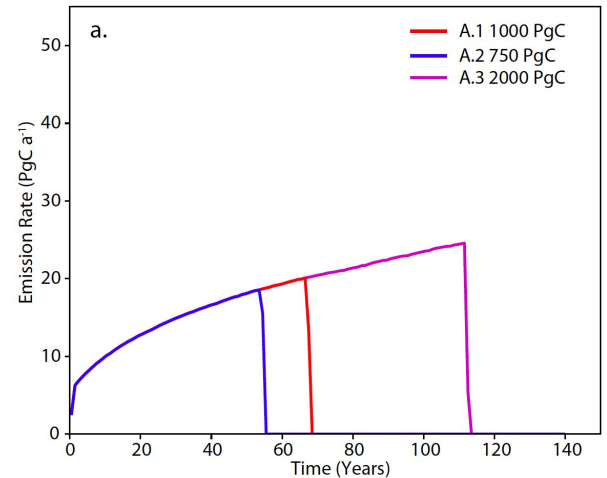
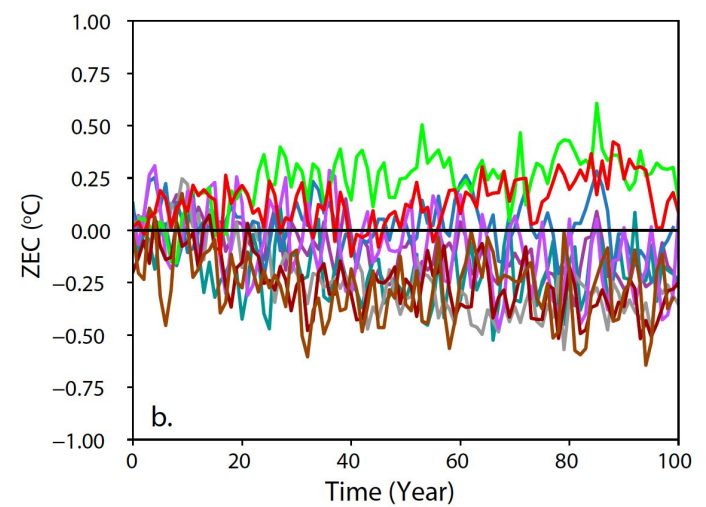
Rogelj, J., Forster, P.M., Kriegler, E. *et al.* Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* 571, 335–342 (2019). <https://doi.org/10.1038/s41586-019-1368-z>



## Zero Emissions Commitment

- The response of the system  $n$  years after net-zero has been achieved in an idealised emissions pathway
- How does this relate to real-world mitigation?

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., ... & Ziehn, T. (2020). Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO<sub>2</sub>. *Biogeosciences*, 17(11), 2987-3016.



$$G(t) = \int E(t) dt$$

$$\Delta T = \kappa_E \Delta G$$

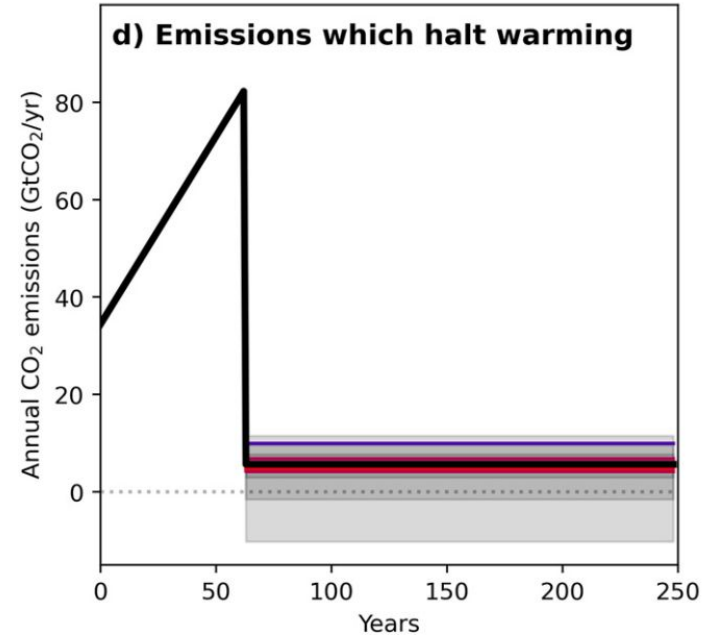
A temperature Impulse Response function for a model with no ZEC would be a step function



$$G(t) = \int E(t)dt$$

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

“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 CO<sub>2</sub> emissions and implications for emissions policy. *Geophysical Research Letters*, p.e2022GL101047.

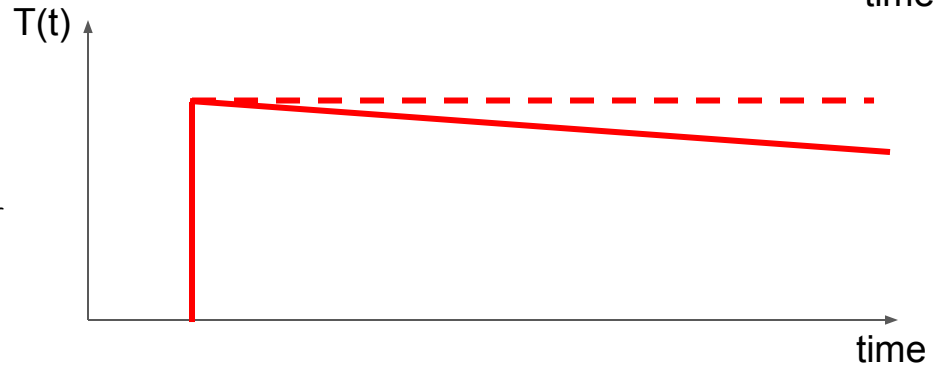
$$G(t) = \int E(t)dt$$

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

TCRE-like  
response

Long term  
adjustment  
(RAZE)

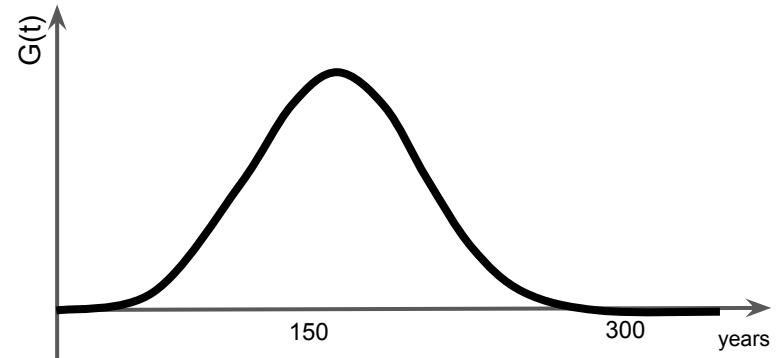
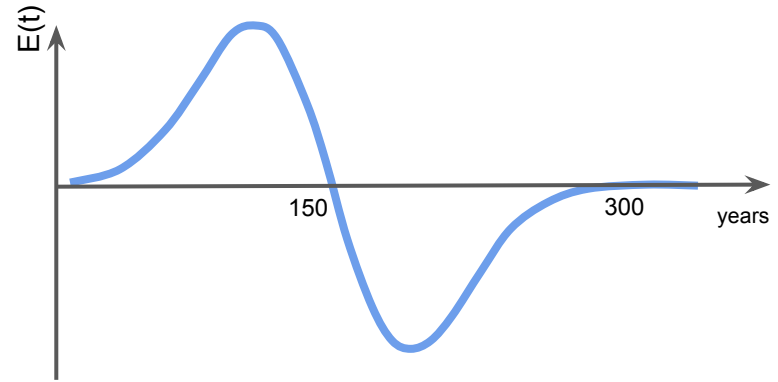
ZEC+RAZE adds a long term linear  
trend to the Impulse Response  
Function





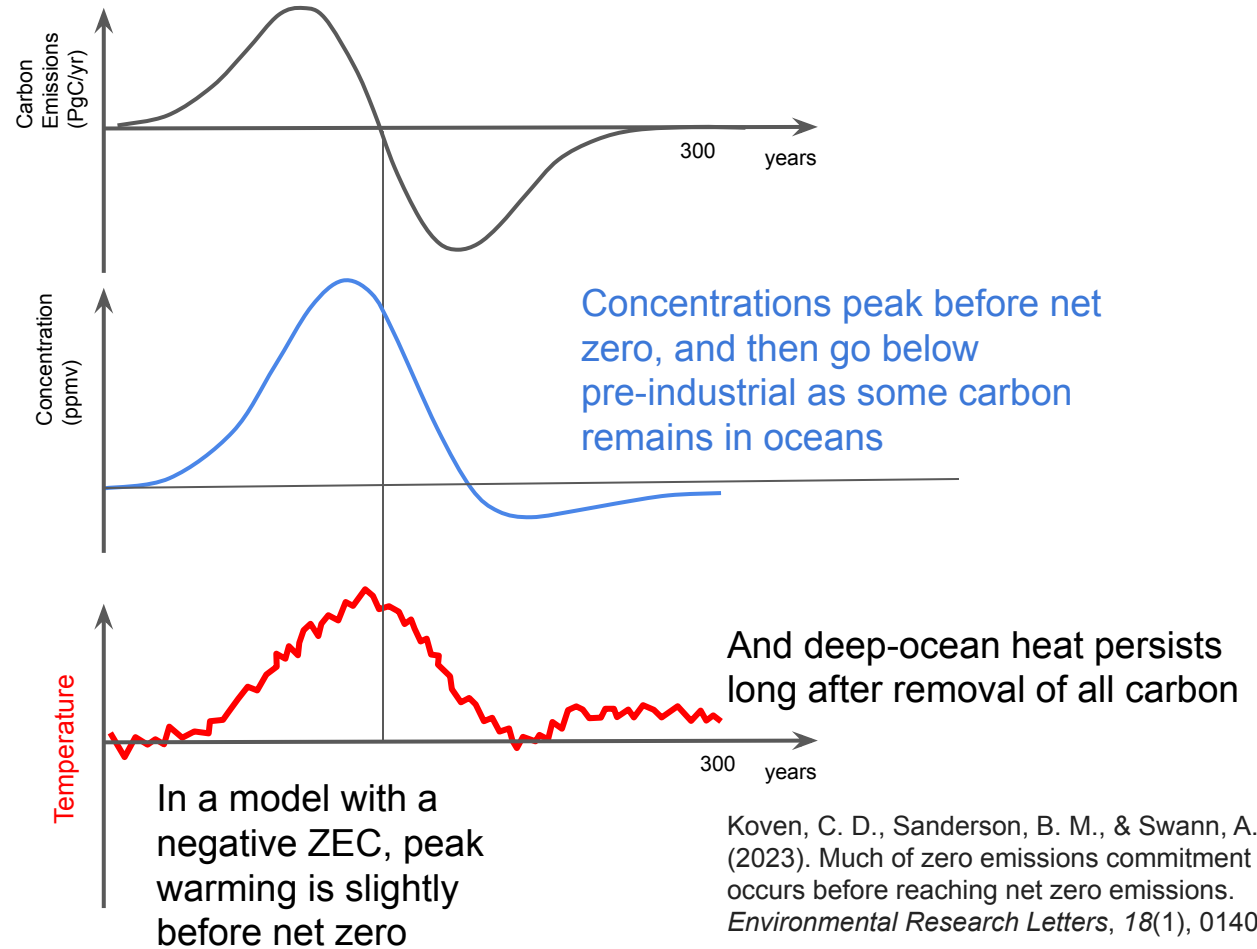
## Does this help explain an idealised emissions overshoot?

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



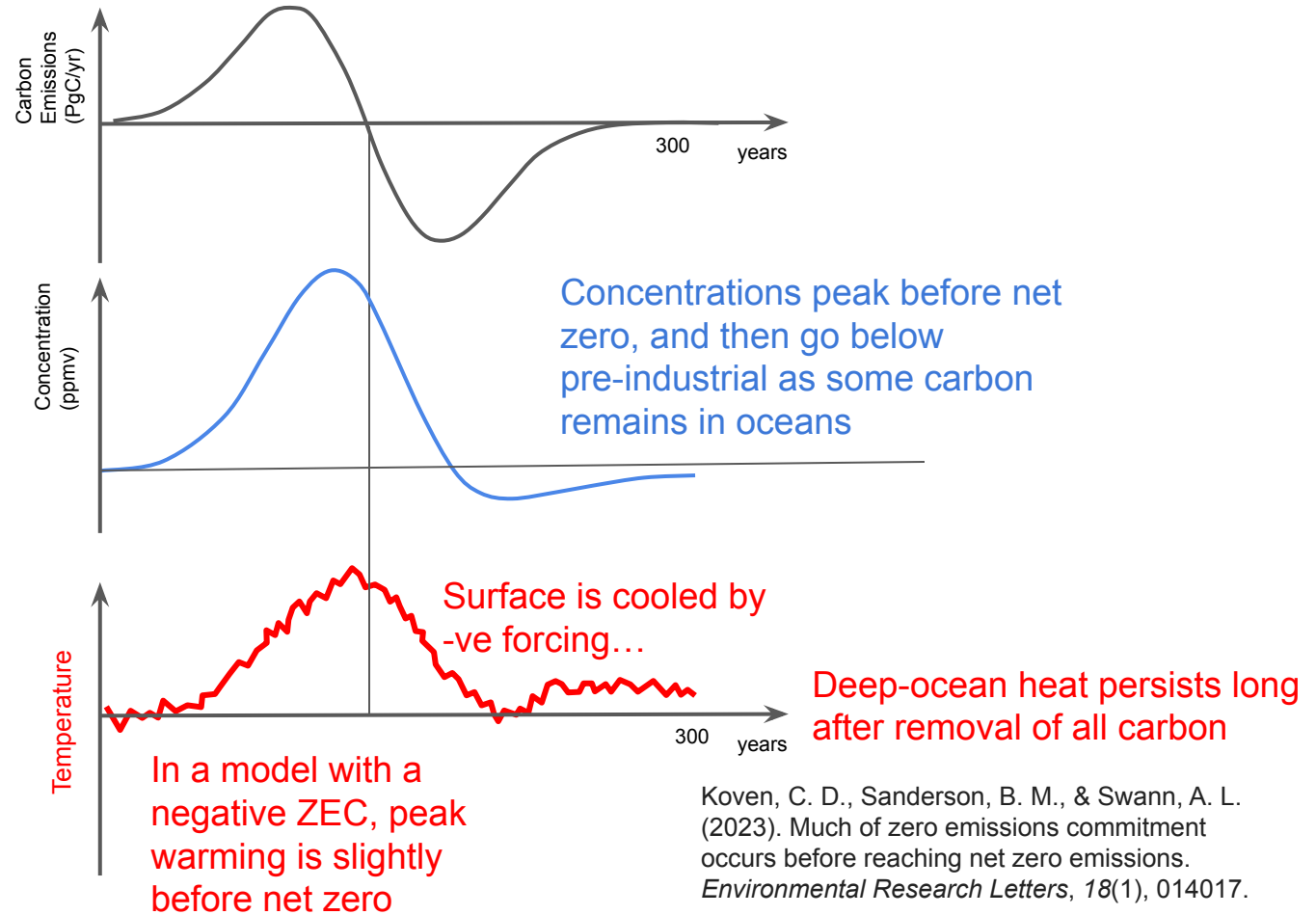
Koven, C. D., Sanderson, B. M., & Swann, A. L. (2023). Much of zero emissions commitment occurs before reaching net zero emissions. *Environmental Research Letters*, 18(1), 014017.

# CESM2 results



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.

# CESM2 results

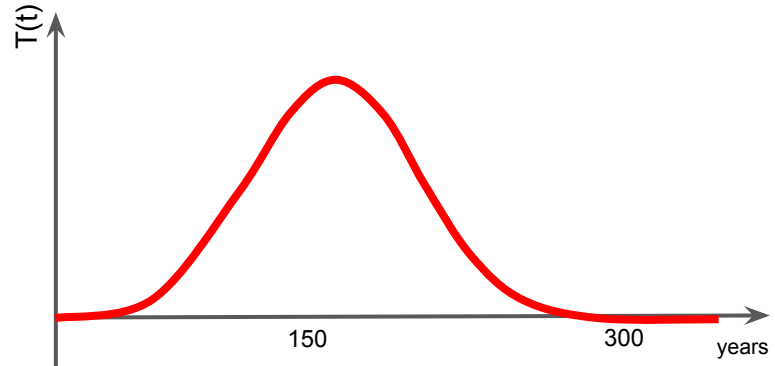
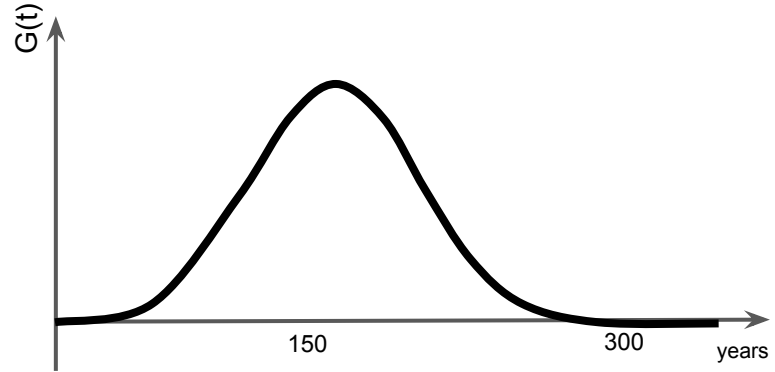


# How does this relate to our empirical model?

- Pure TCRE response would also be a Gaussian curve

$$G(t) = \int E(t) dt$$

$$\Delta T = \kappa_E \Delta G$$

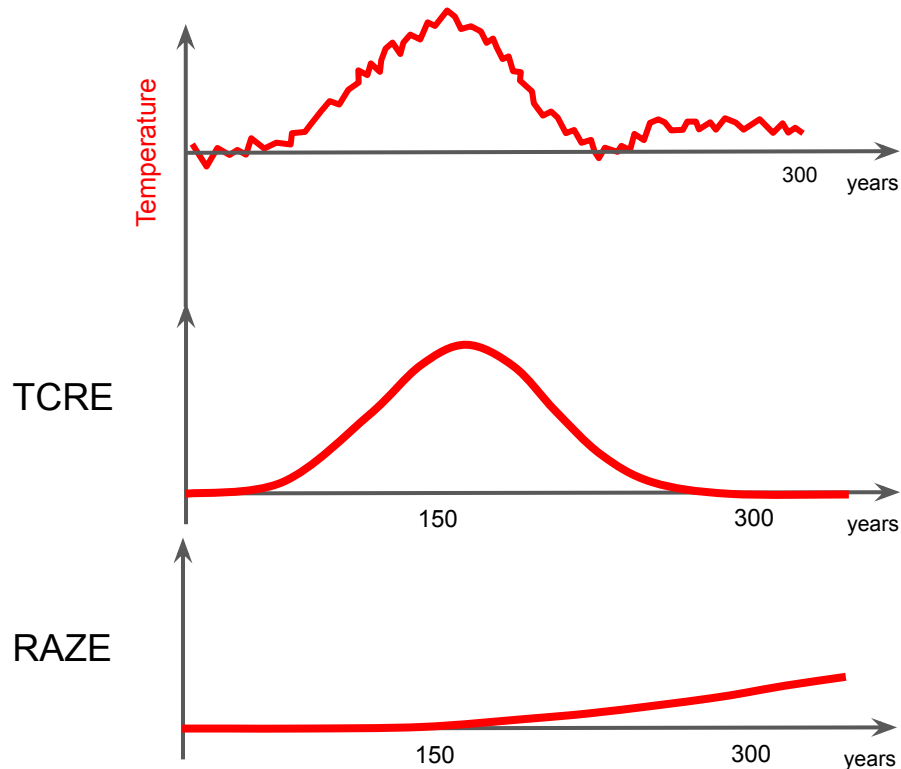


- TCRE+RAZE can represent long term warming, but not 'dip' or early peak warming

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

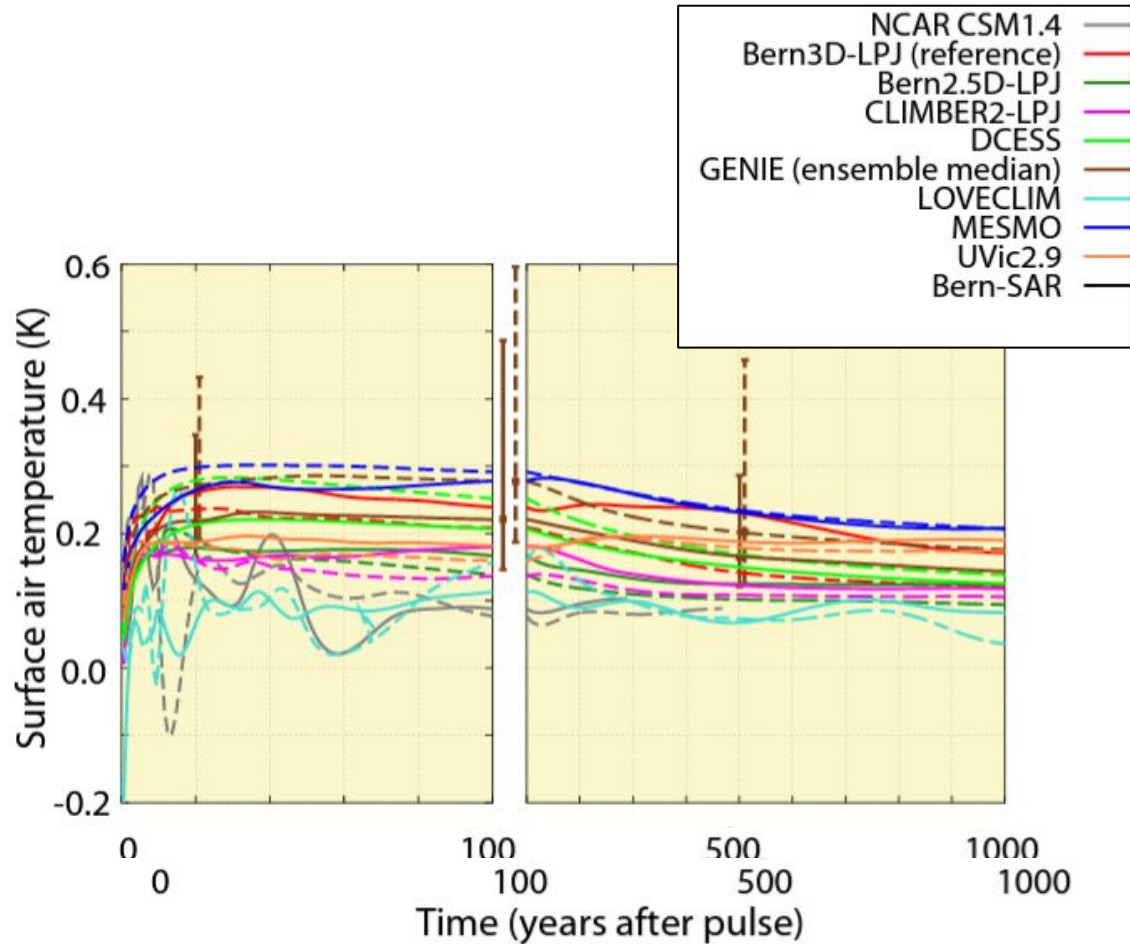
TCRE-like response

Long term adjustment (RAZE)



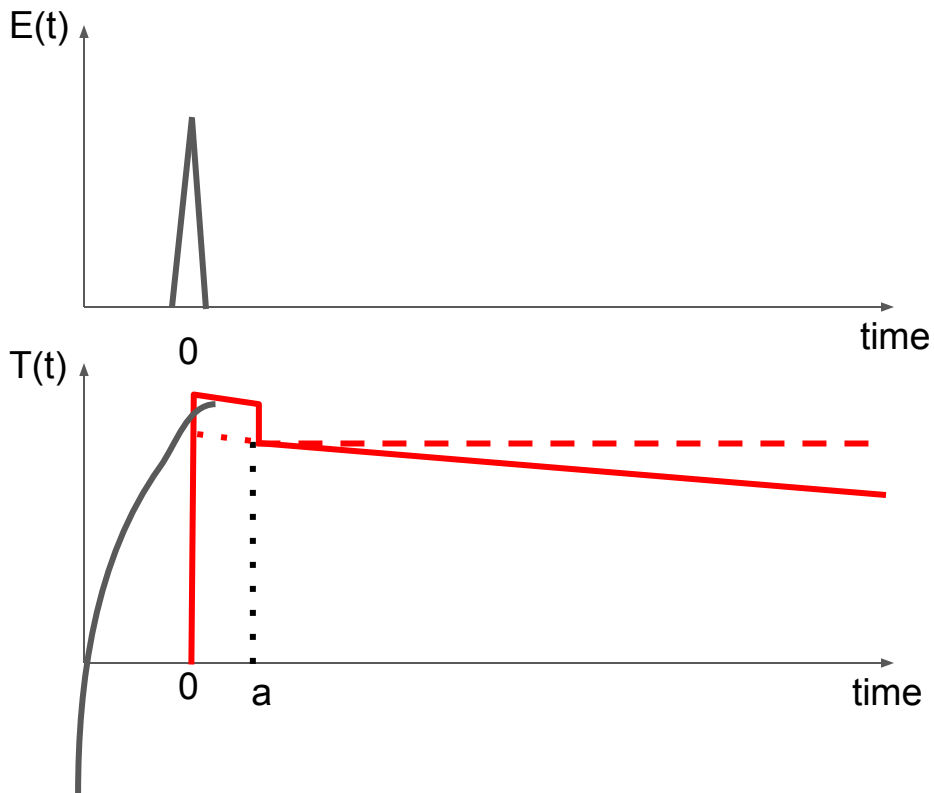
## So what are we missing?

- 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. Fuglestedt, 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.

We can parameterise these transients by allowing a correction for the temporary effect of recent emissions



**DARE = “Delayed Adjustment to Recent Emissions”**

Cumulative emissions

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

Recent emissions

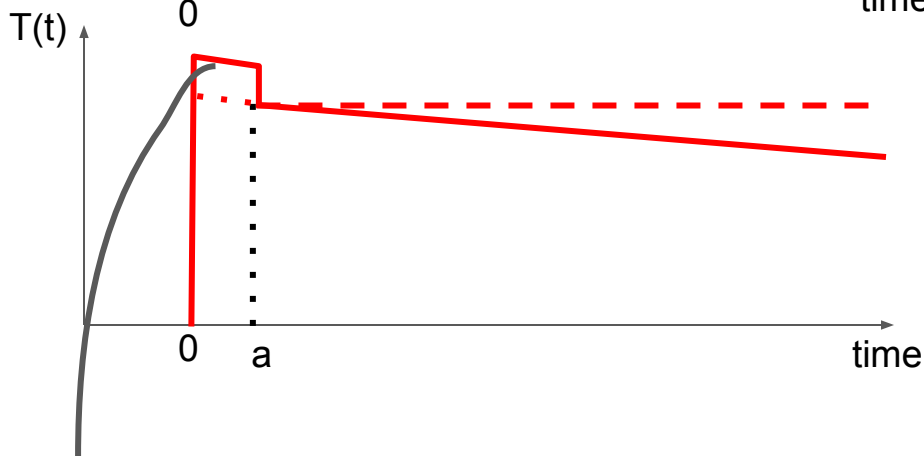
$$R(t) = \int_{t-a}^t E(t) dt$$

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

TCRE-like response

Short term adjustment (DARE)

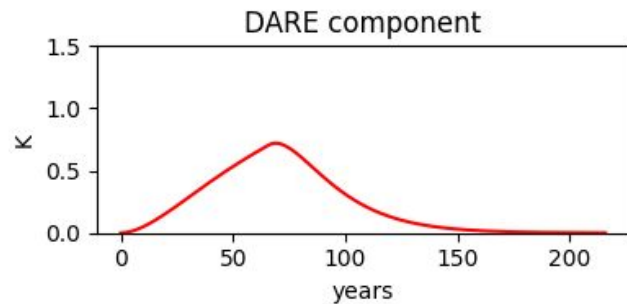
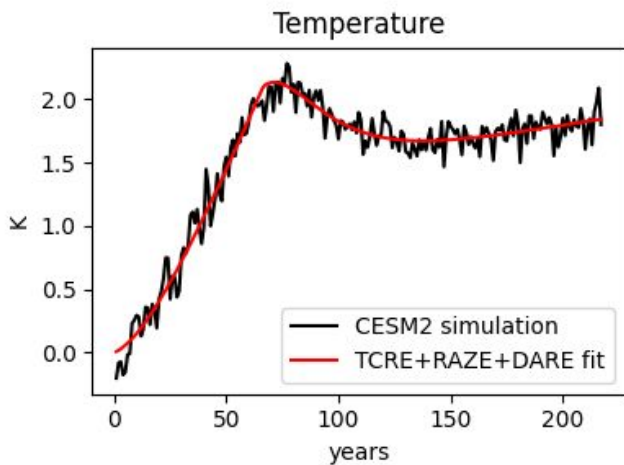
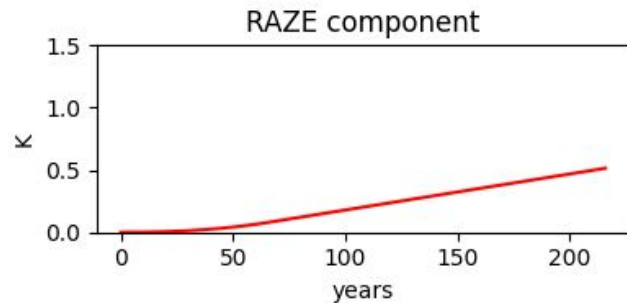
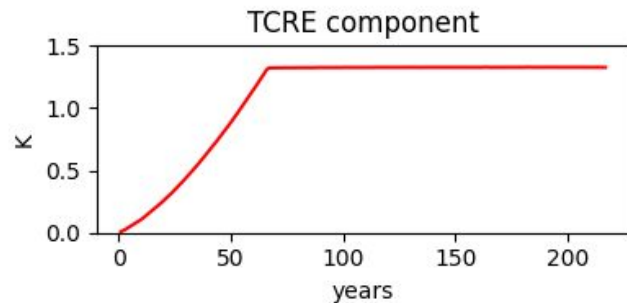
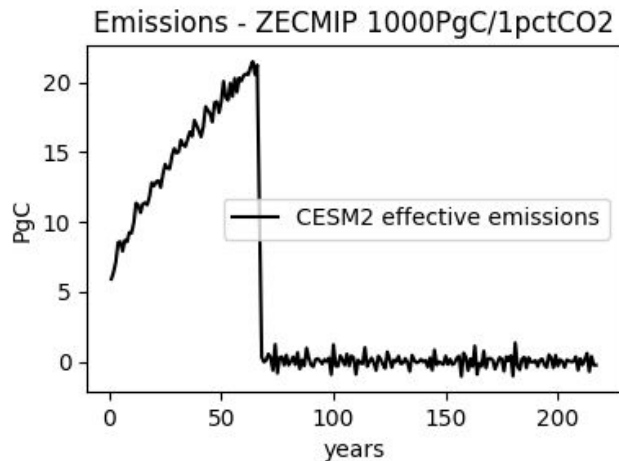
Long term adjustment (RAZE)



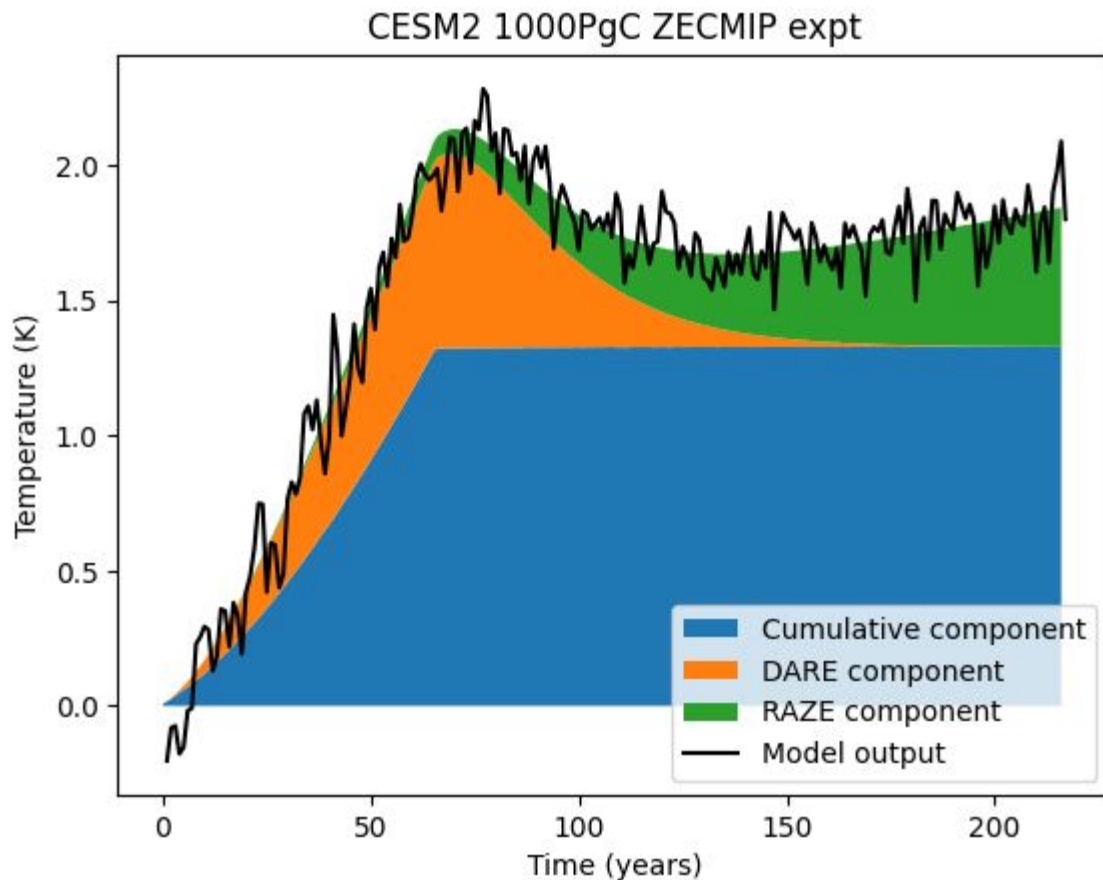
DARE = "Delayed Adjustment to Recent Emissions"



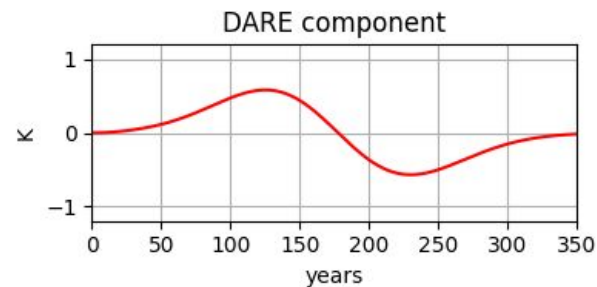
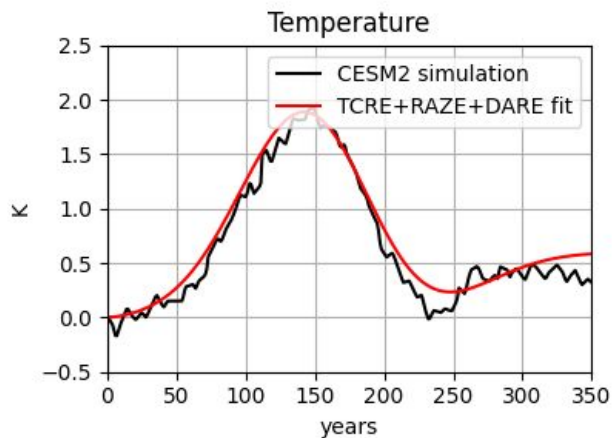
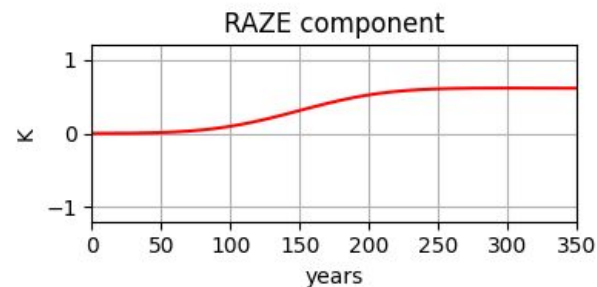
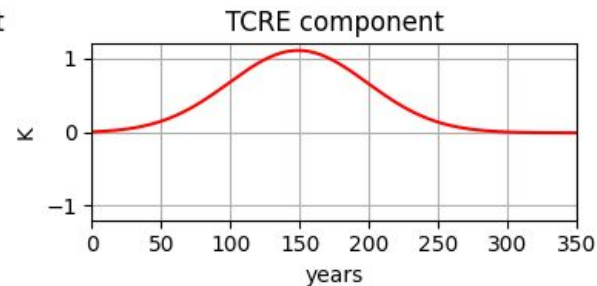
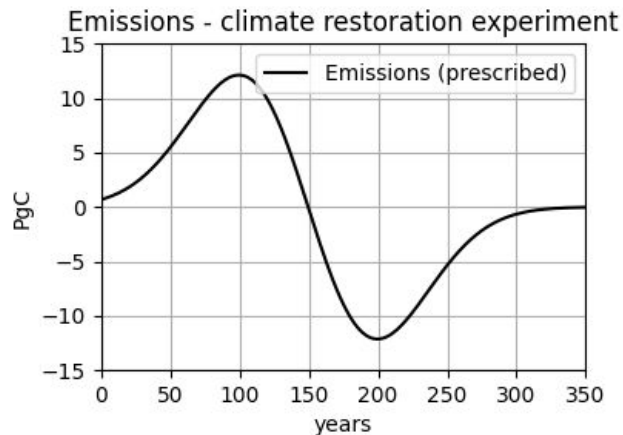
TCRE, DARE & RAZE  
can be fitted from  
existing ZECMIP  
experiments

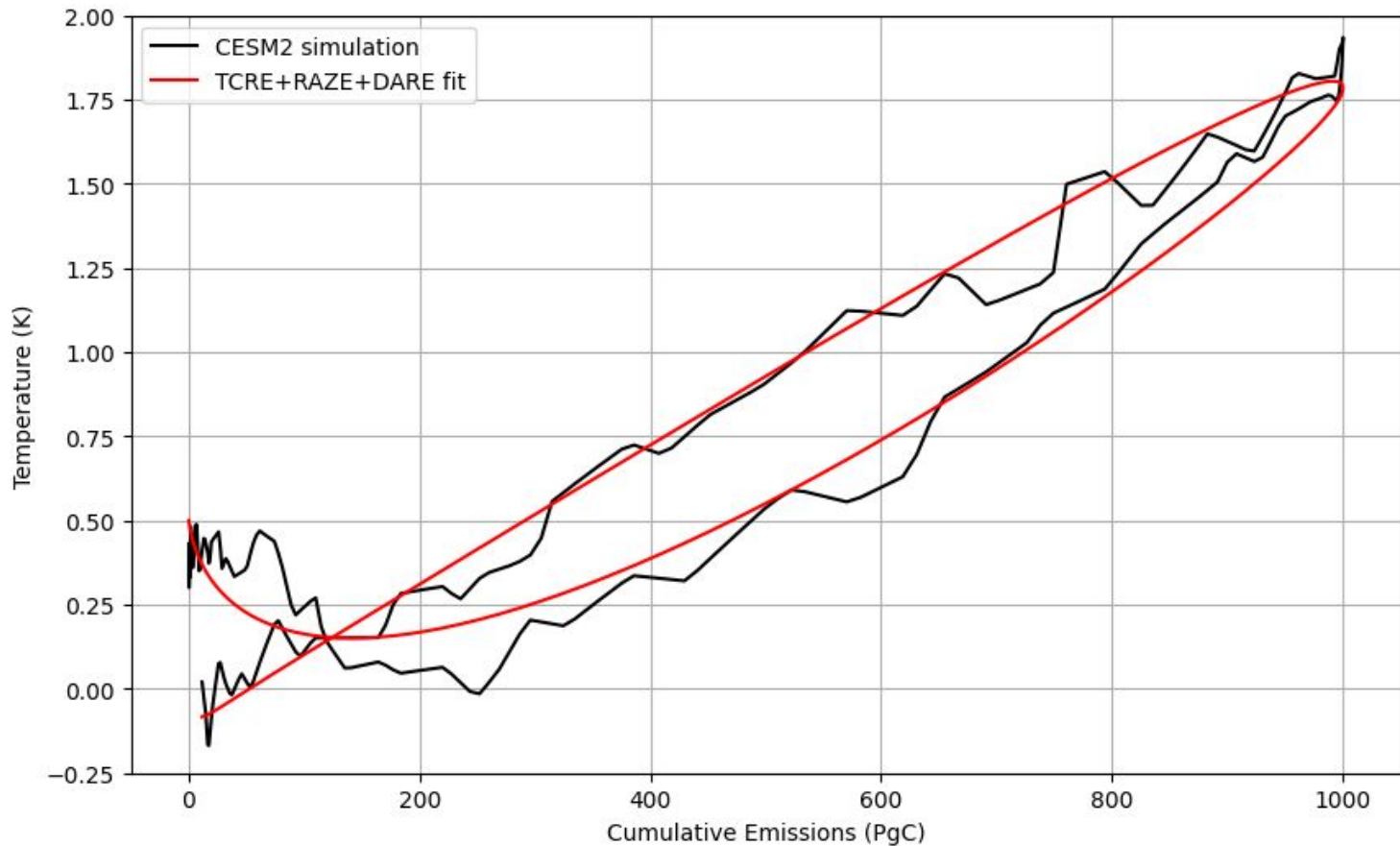


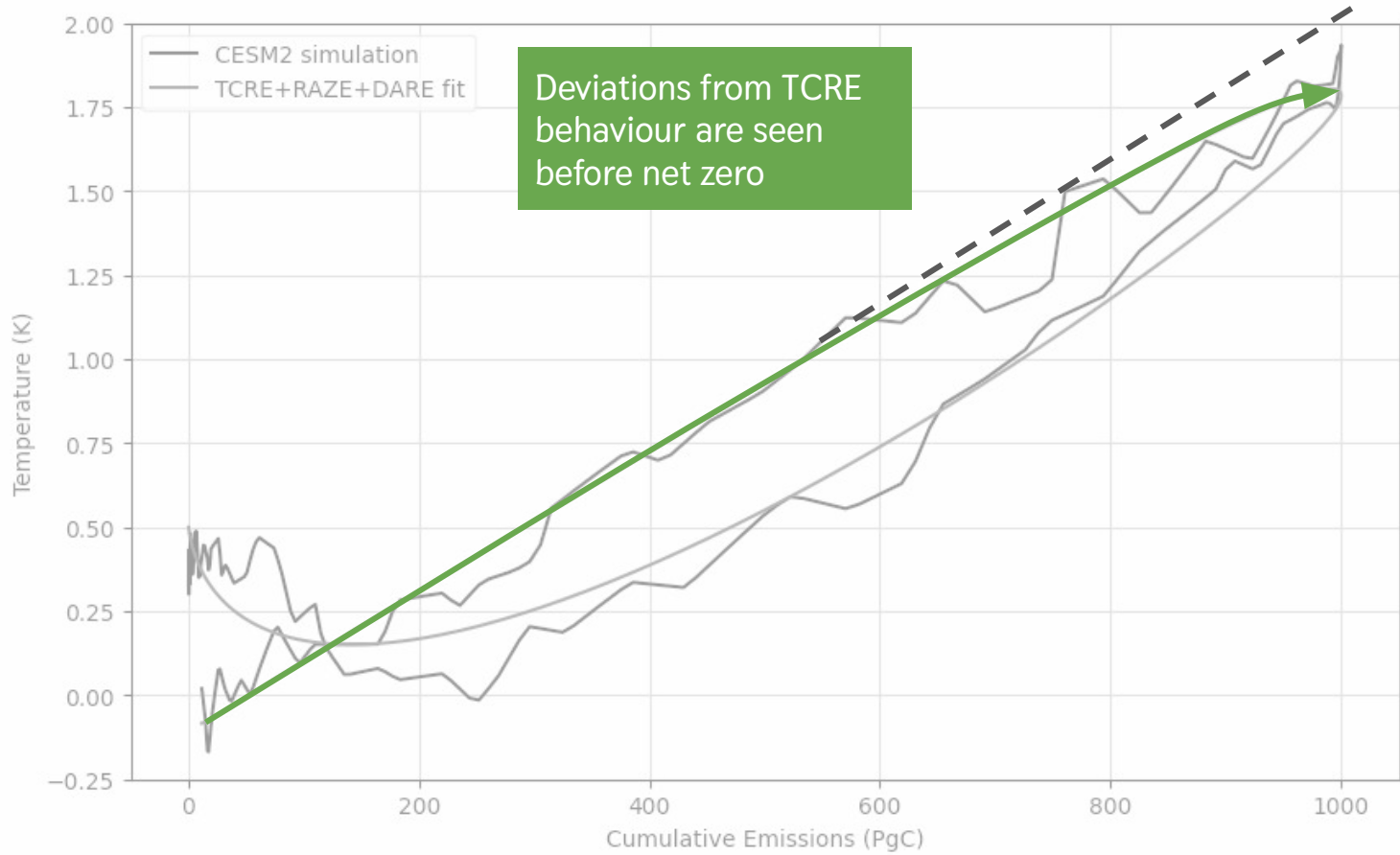
But what we currently call TCRE can be a mixture of transient and permanent effects



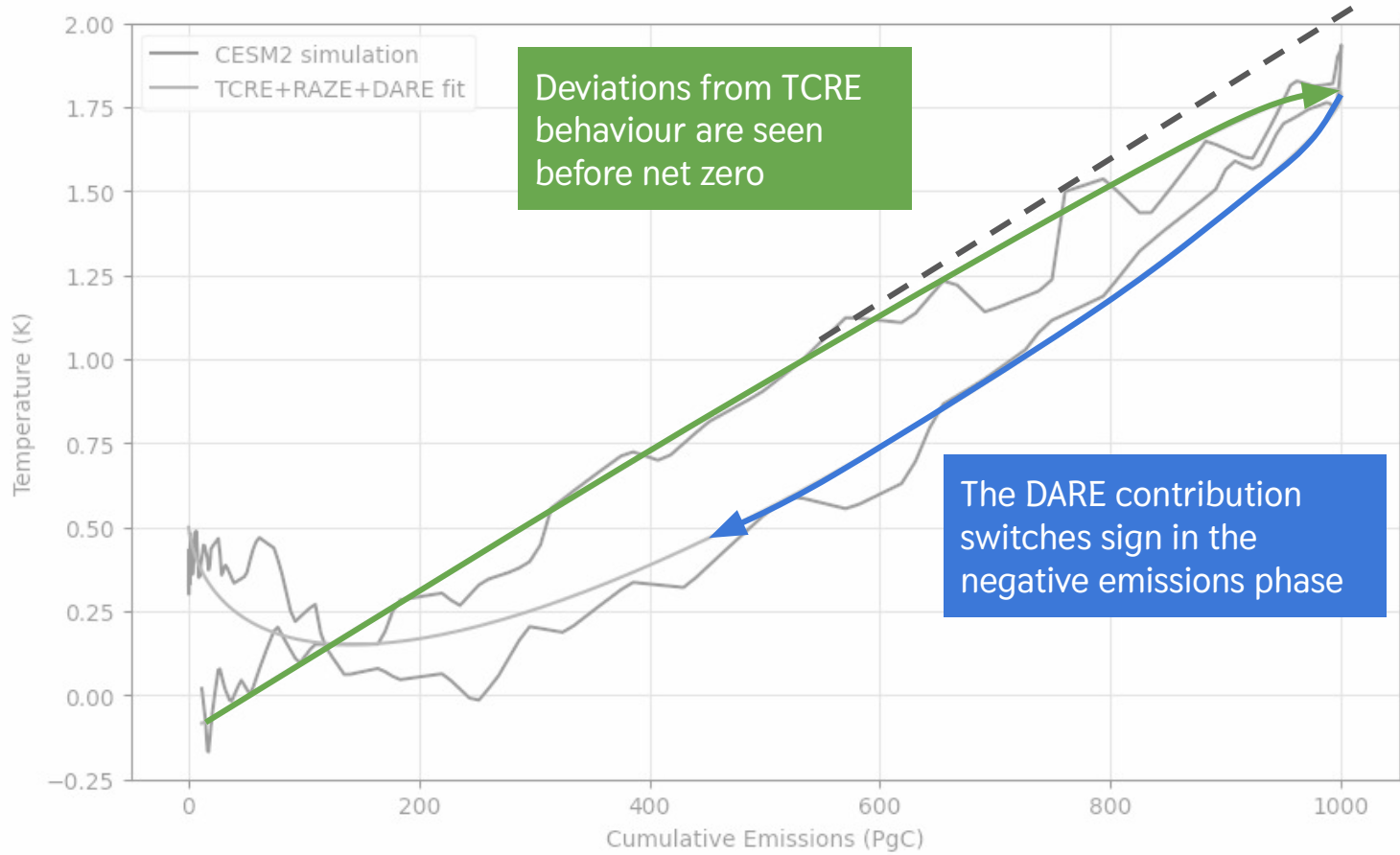
This model empirically accounts for the warming trajectory in the idealised overshoot (with some error)







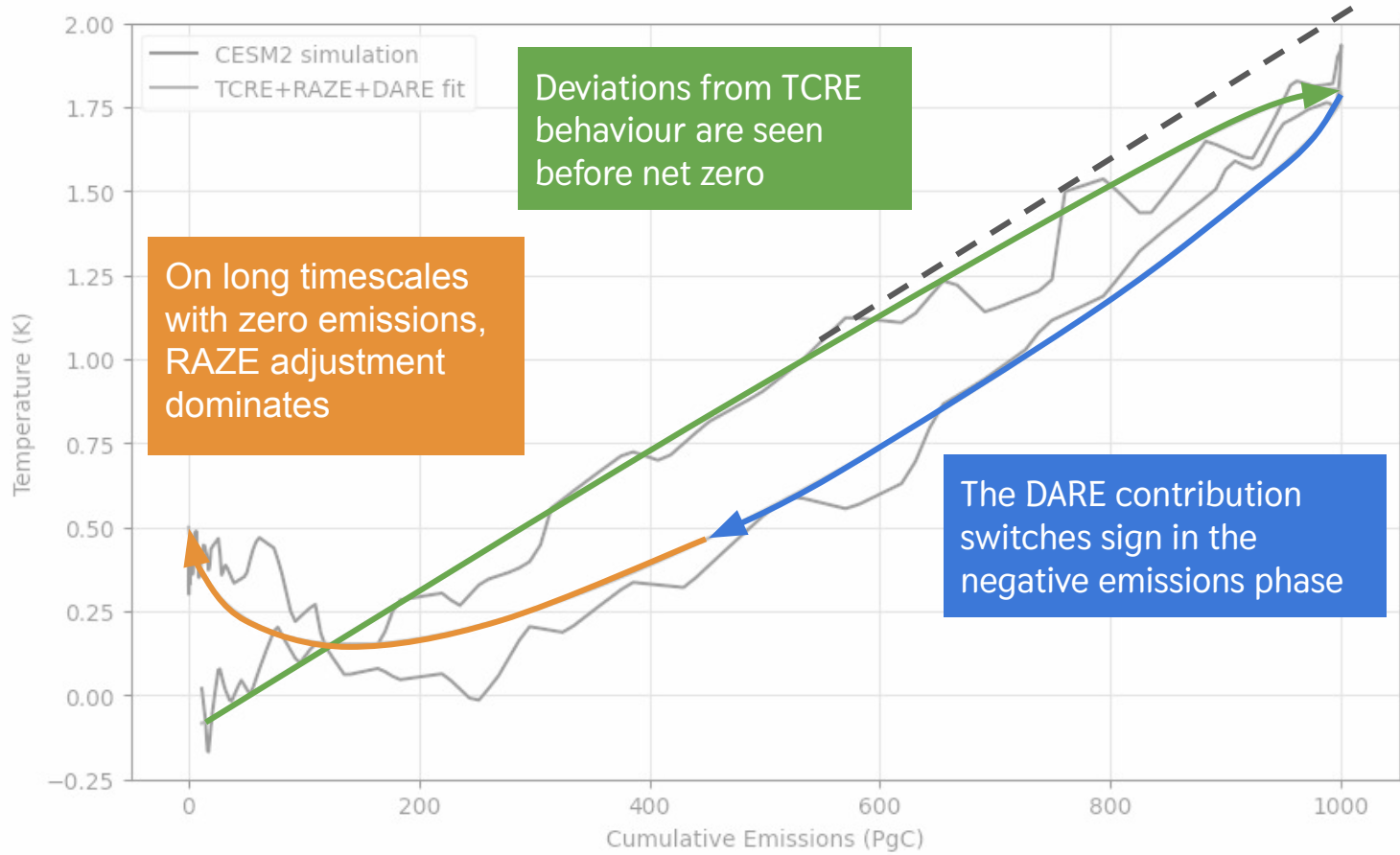
Deviations from TCRE behaviour are seen before net zero



— CESM2 simulation  
— TCRE+RAZE+DARE fit

Deviations from TCRE behaviour are seen before net zero

The DARE contribution switches sign in the negative emissions phase



— CESM2 simulation  
— TCRE+RAZE+DARE fit

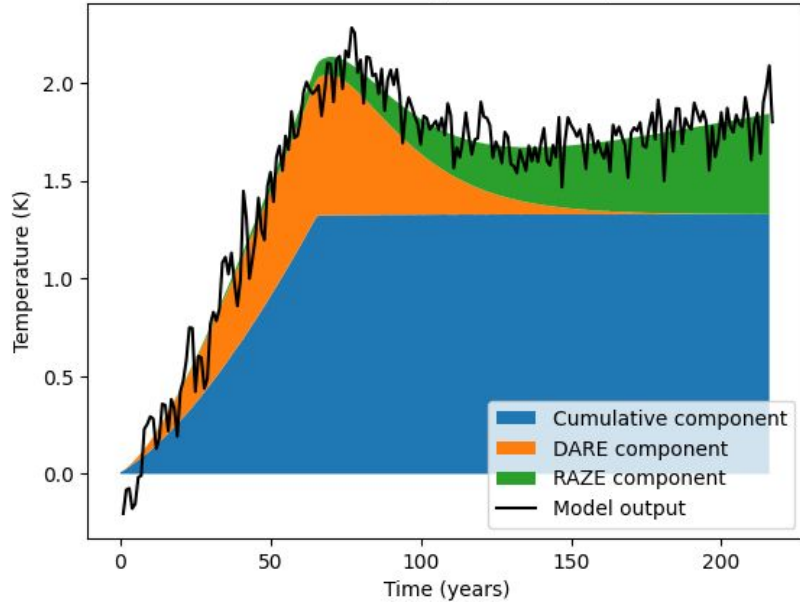
Deviations from TCRE behaviour are seen before net zero

On long timescales with zero emissions, RAZE adjustment dominates

The DARE contribution switches sign in the negative emissions phase

# Conclusions

CESM2 1000PgC ZECMIP expt



- “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