Much of the zero emissions commitment occurs before reaching net zero emissions

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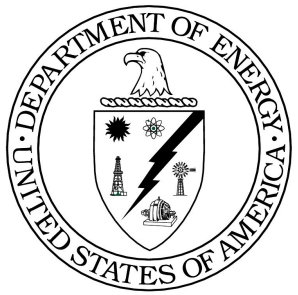

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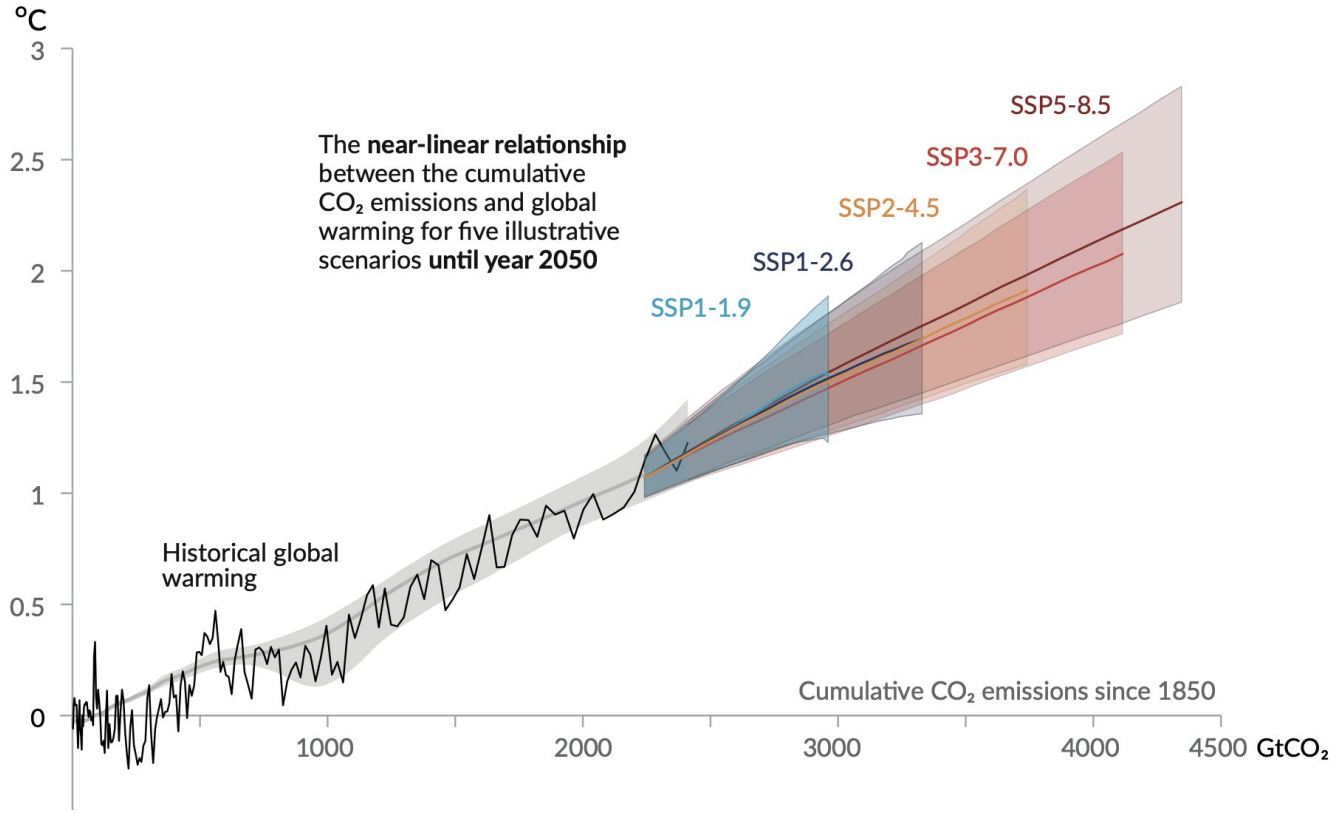
Every tonne of CO_2 emissions adds to global warming

Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)

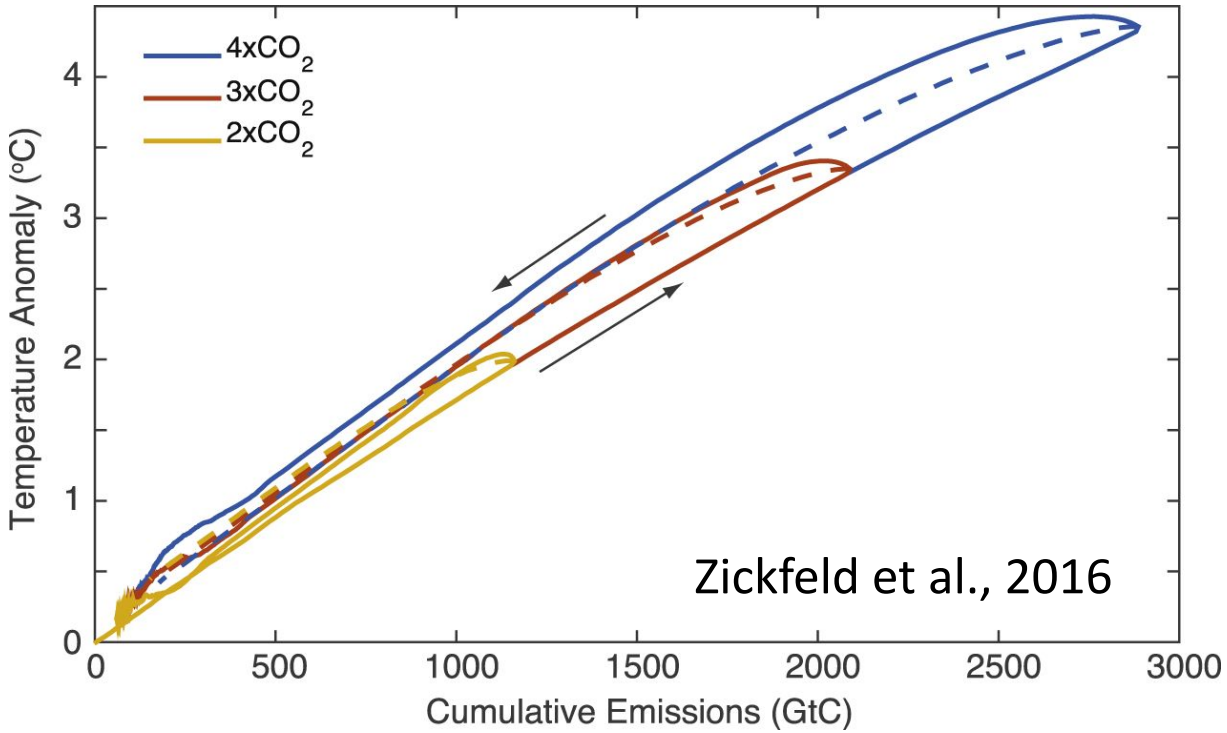


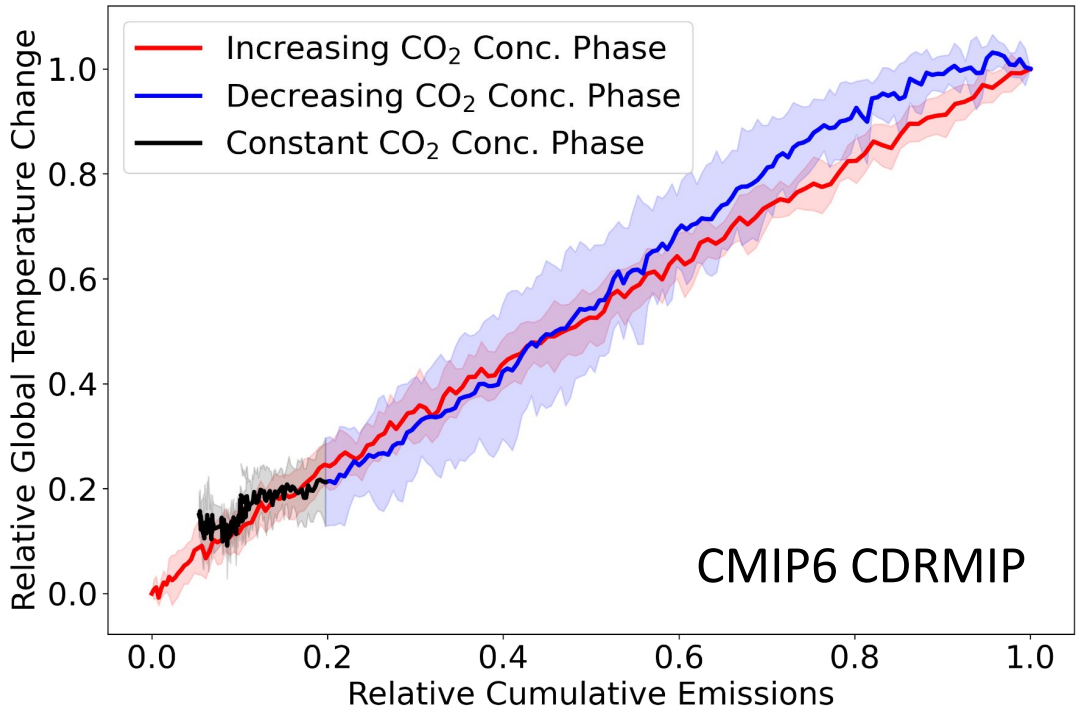
"The relationship is illustrated over the domain of cumulative CO_2 emissions for which there is *high confidence* that the transient climate response to cumulative CO_2 emissions (TCRE) remains constant, and for the time period from 1850 to 2050 over which global CO_2 emissions remain net positive under all illustrative scenarios as there is *limited evidence* supporting the quantitative application of TCRE to estimate temperature evolution under net negative CO_2 emissions."

IPCC AR6 WG1 fig. SPM.10

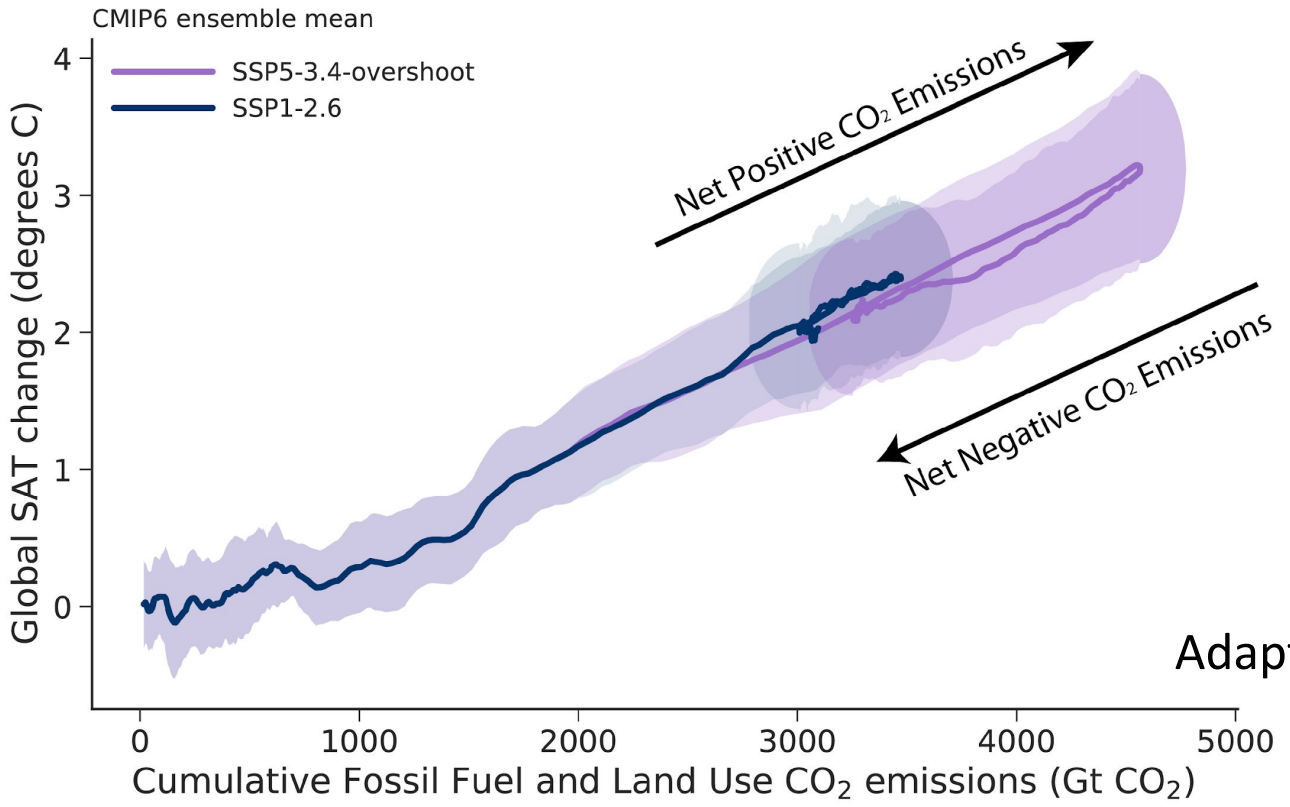
Does the TCRE relationship hold under net-negative CO_2 emissions?

Idealized 1% CO_2 abrupt concentration reversal experiments say that no, there is a consistent positive asymmetry…





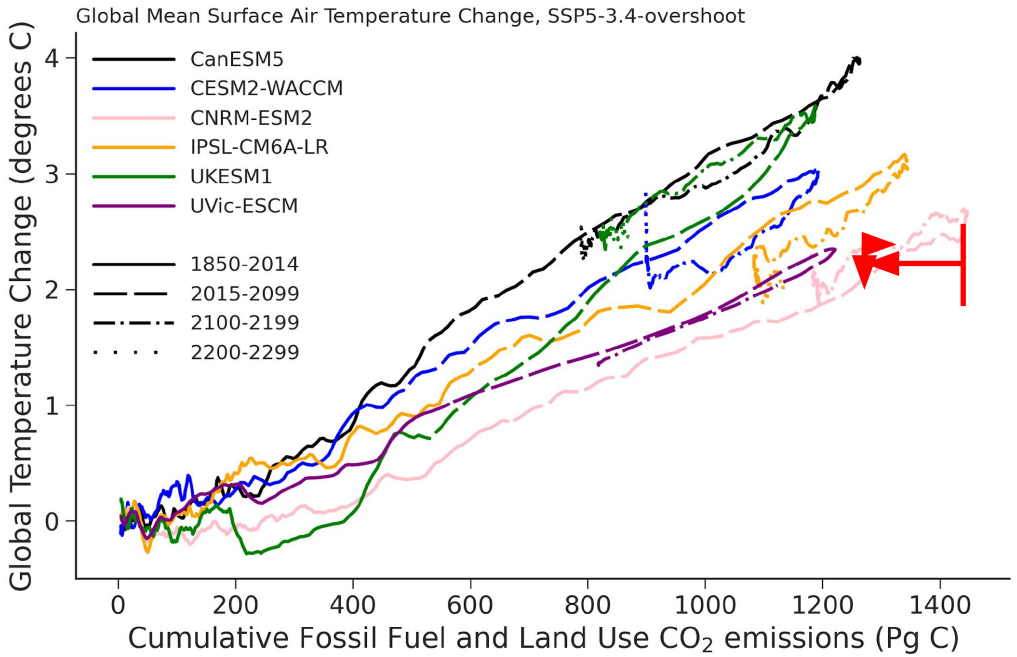
… Whereas non-idealized scenario experiments say that yes, the proportionality* actually does still hold…

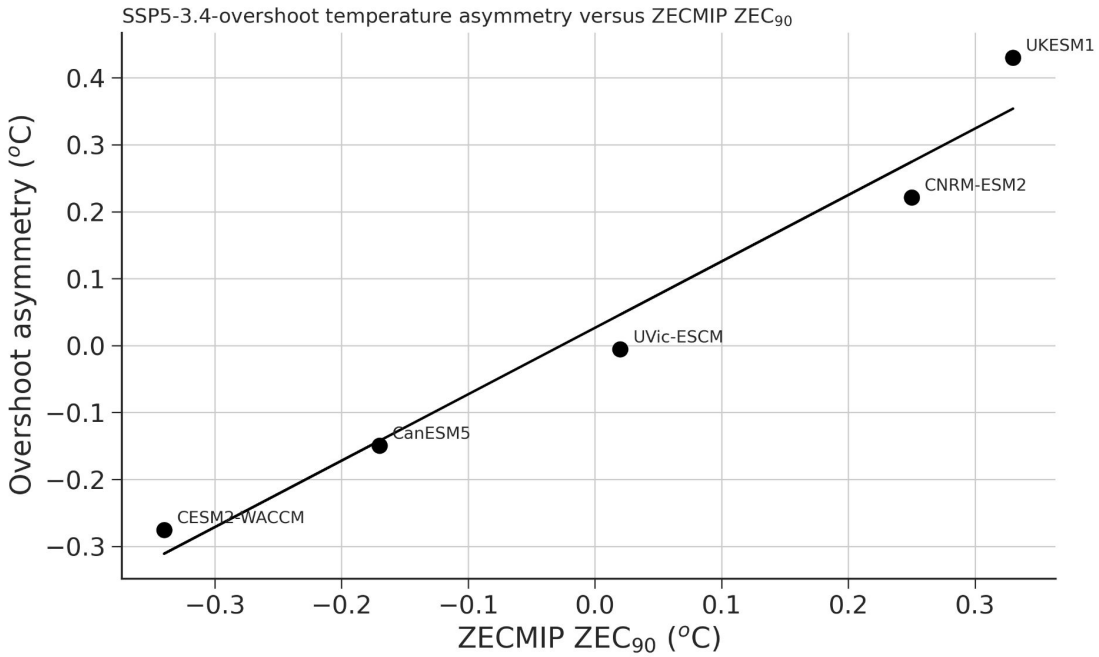


Adapted from Koven et al., 2022

* Not the TCRE proportionality though, because non-CO_2 GHGs are present, thus an Effective TCRE

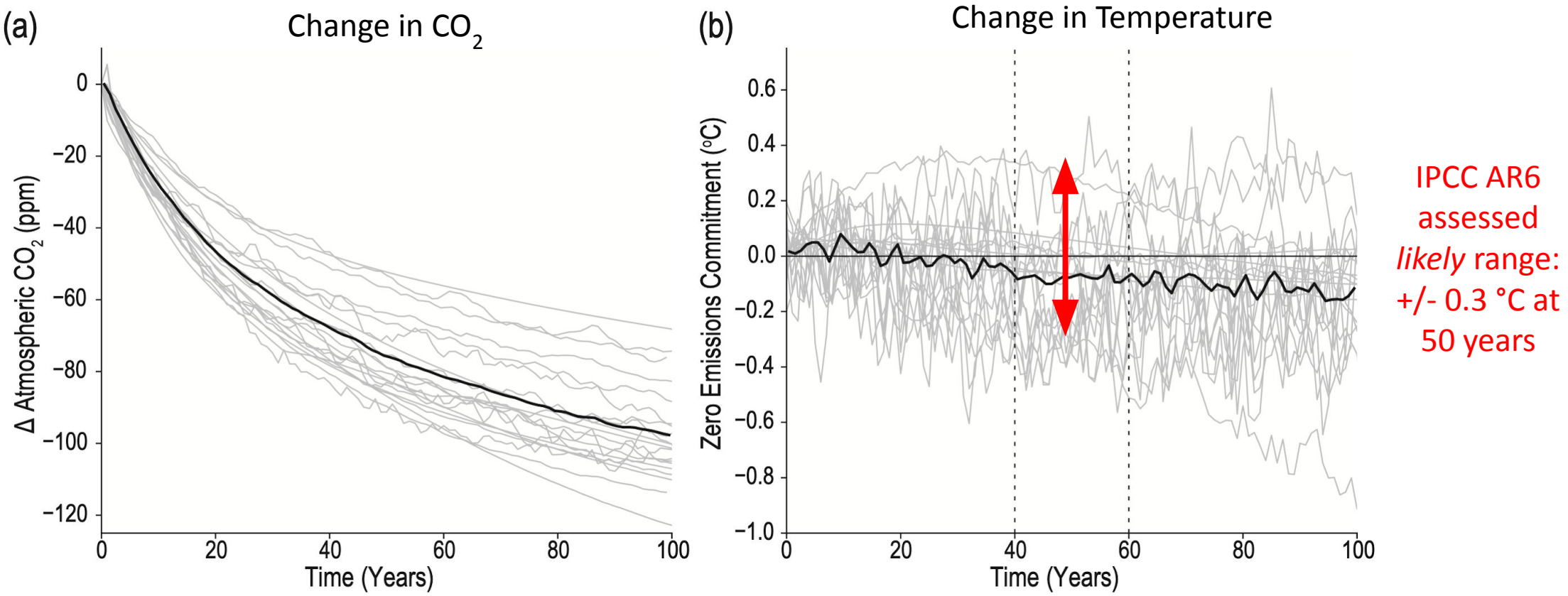
… and any deviation from proportionality is well explained by the Zero Emissions Commitment (ZEC) …





Koven et al., ESD, 2022

… where ZEC is a measure of how much warming would occur if CO_2 emissions were to abruptly stop.



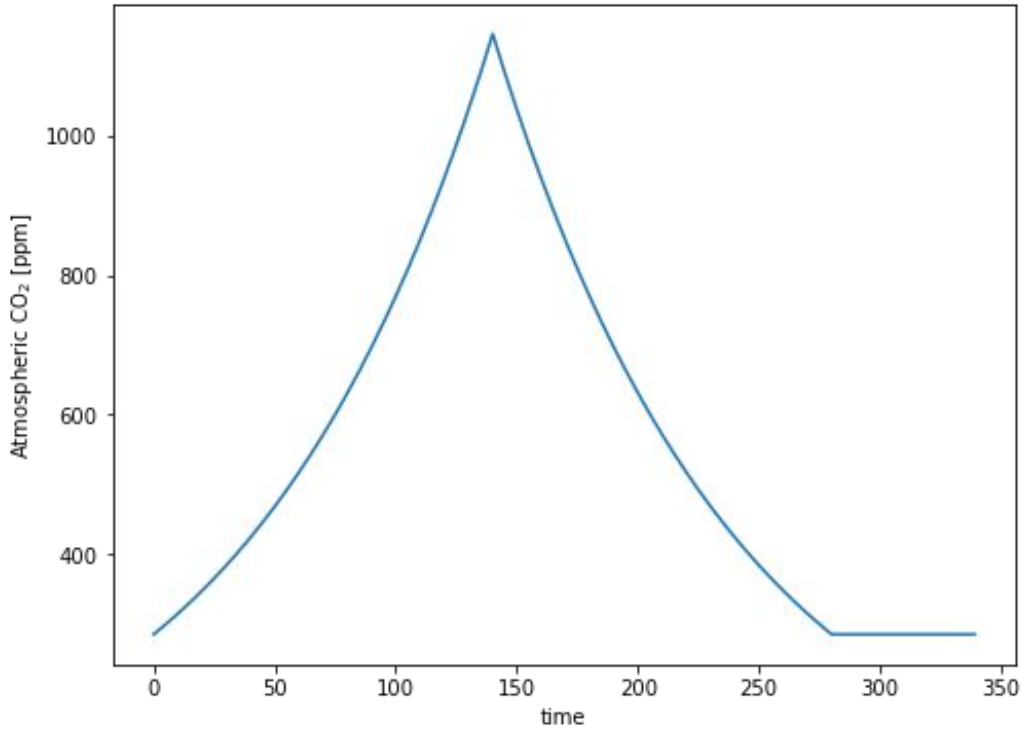
IPCC AR6 assessed *likely* range: +/- 0.3 °C at 50 years

IPCC AR6 WG1 fig. 4.39

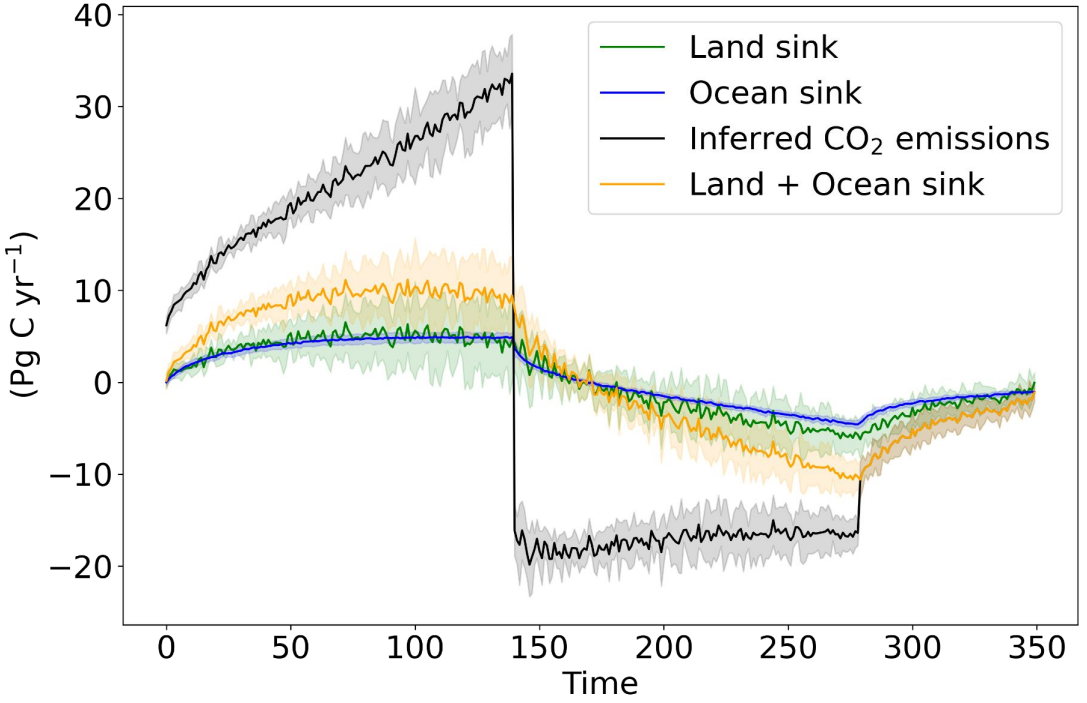
Note: TCRE and ZEC are the two carbon-climate sensitivity metrics used in calculating the IPCC remaining carbon budget for climate stabilization

A hypothesis for what causes the asymmetry in 1% concentration reversal experiments:
~50 Pg C / yr abrupt change in emissions.
Is that too much to ask of path-independence?

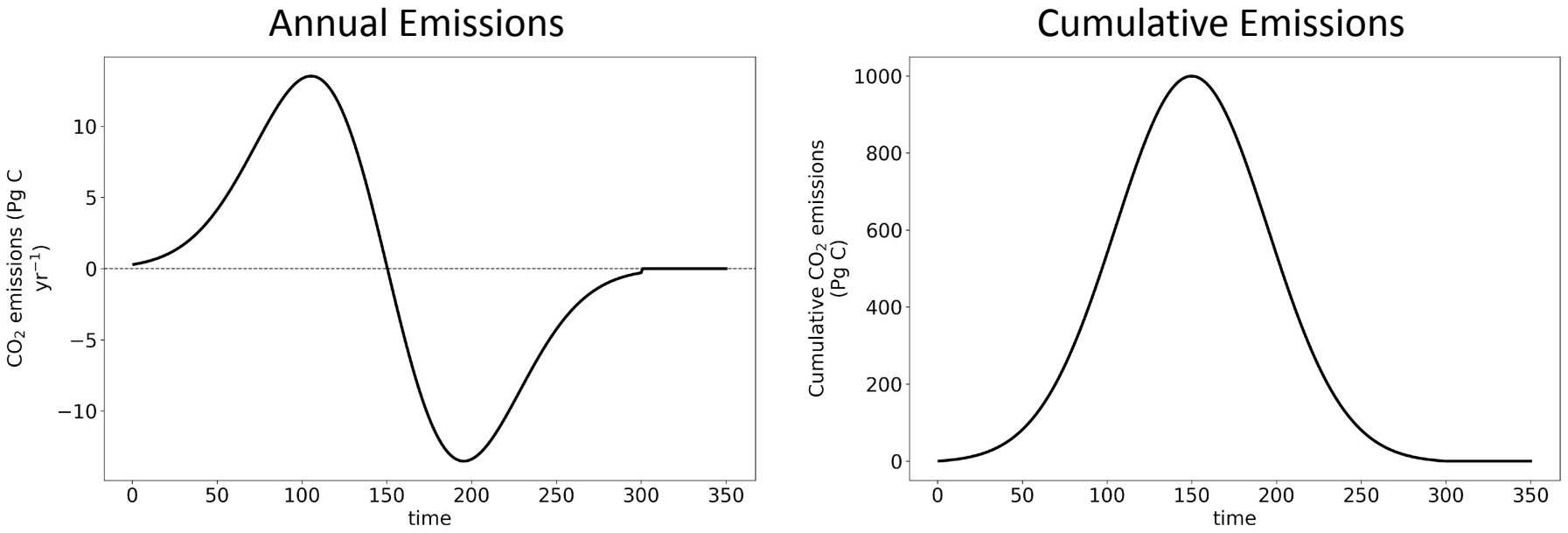
CDRMIP 1%/yr CO_2 concentrations



CMIP6 CDRMIP implied fluxes and emissions



An idealized climate restoration experiment: continuous, symmetric transition from positive to negative CO_2 emissions. Allows asking whether TCRE proportionality holds under idealized non-abrupt transition to net-negative emissions, and if so, whether there are limits to the proportionality.

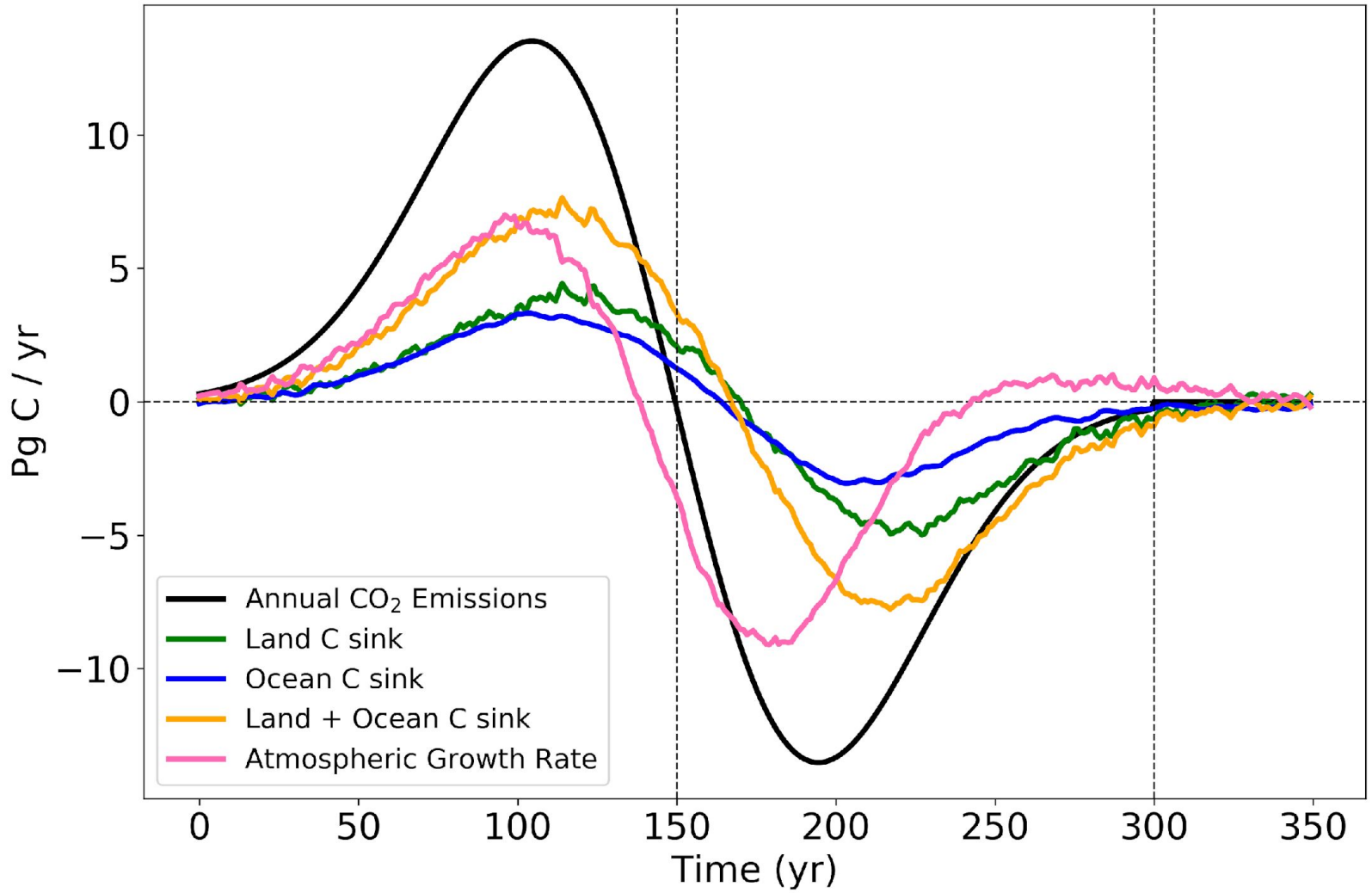


Run through emissions-driven ESM. **Hypothesis is that warming follows TCRE proportionality during the positive emissions phase, and follows the TCRE proportionality + ZEC during the negative emissions phase.**

CESM2 is ideal for this because it has a very negative ZEC (-0.3 ^{o}C).

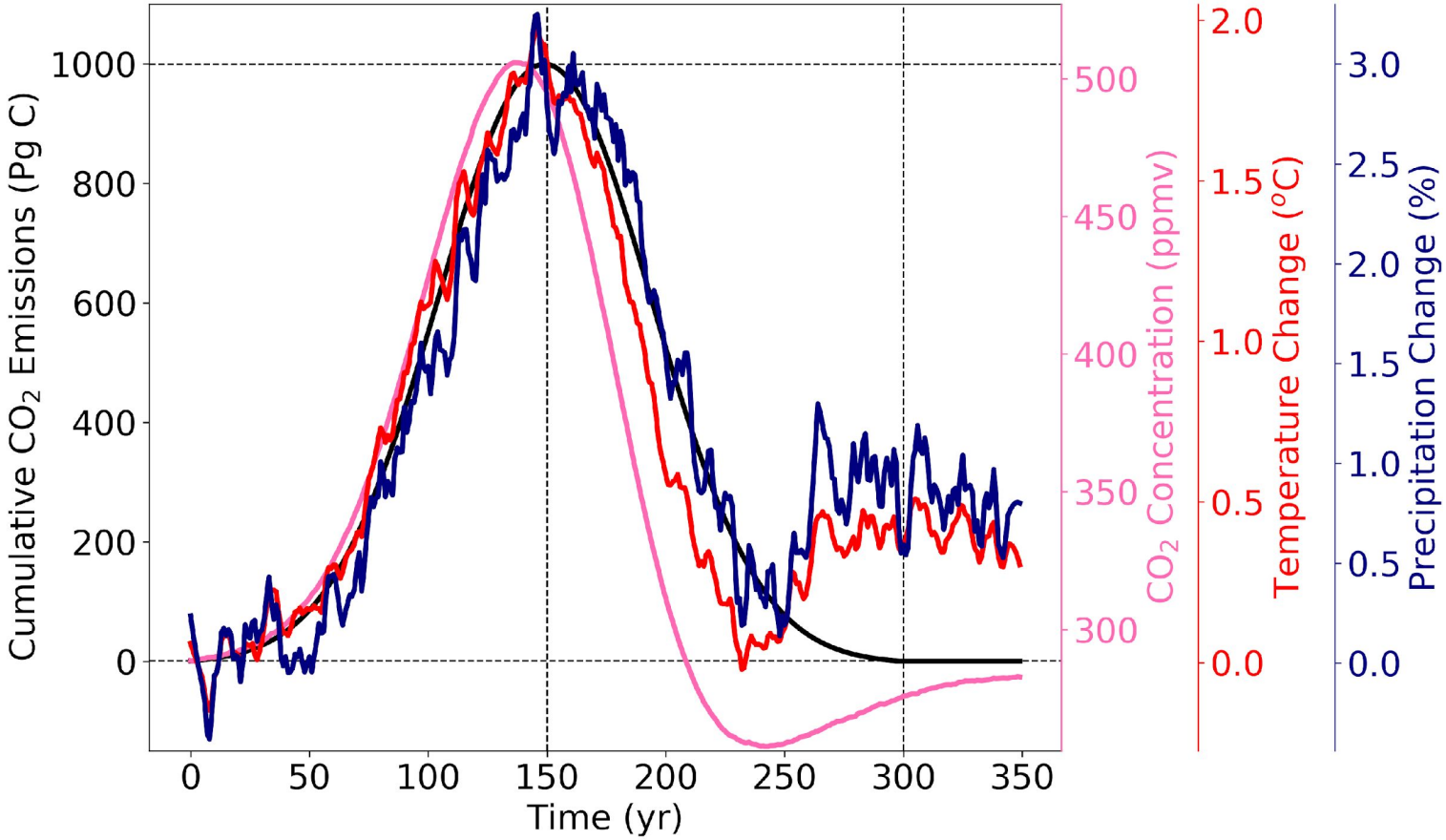
CESM2 CO_2 Flux responses to emissions reversal

Sinks follow emissions, with a lag. Atmospheric growth rate leads emissions *because* sinks lag emissions.



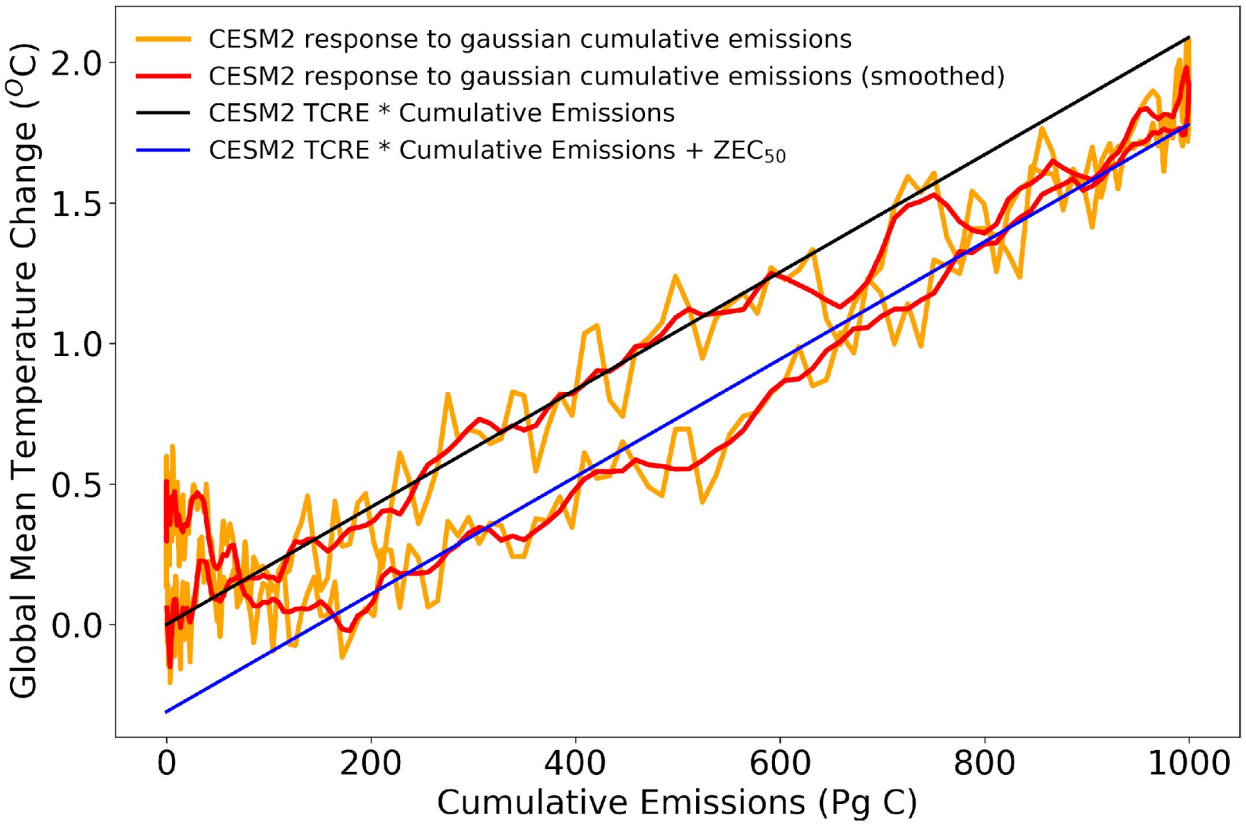
CESM2 Climate responses to CO_2 emissions reversal

- CO_2 concentration leads cumulative emissions, and drops below PI at end.
- Temperature *also leads* cumulative emissions for most of scenario (and then warms again at end).

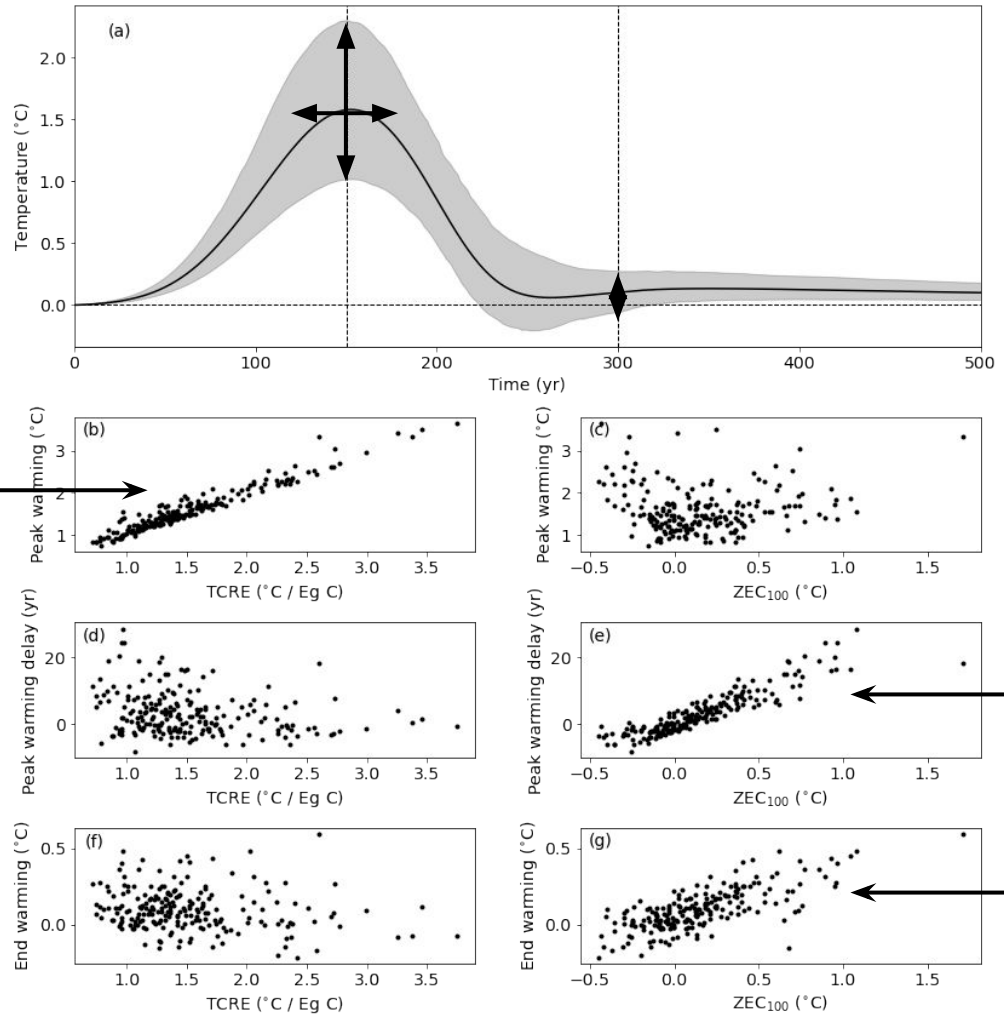


The hypothesis mostly holds.

CESM2 warming roughly follows the TCRE proportionality on the upslope and the TCRE proportionality plus ZEC on the downslope. But it switches lines before peak cumulative emissions. Thus the ZEC appears *before net zero*.



But that is just one ESM, what would a wider ensemble look like? We use a FaIR simple climate model PPE to look at responses as a function of TCRE and ZEC.



Peak warming mainly governed by TCRE (but TCRE + 0.5 * ZEC correlates even better)

Timing of peak warming governed by ZEC

End warming also governed by ZEC

TCRE

ZEC

Conclusions

- CO_2 sinks follow emissions, and reverse sign to become sources after emission reverse, with a decade-timescale lag.
- The lag between CO_2 fluxes and emissions causes atmospheric CO_2 concentrations to lead emissions.
- The TCRE proportionality holds under net-negative CO_2 emissions, subject to an asymmetry that is well quantified by ZEC.
- Much of the ZEC appears *before reaching net zero*, and thus ZEC also governs the timing of peak warming relative to net zero.
- Thus the ZEC actually works more robustly as a measure of the long-term path-dependence and deviation from the TCRE relationship under strong emissions, than it does as a measure of warming subsequent to reaching net zero.

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Some possible next steps...

- Why *does* CESM2 have such a negative ZEC?
- If CESM2 ZEC runs are extended longer, do they warm suddenly alongside AMOC restrengthening, as in SSP5-3.4-overshoot and this experiment?
- How does land use change fit into the TCRE/ZEC framework?
- What aspects of these dynamics are sensitive to parameter and structural differences, and how?
- Would this be a useful & practical CMIP7 experiment?
- **How else can we use emissions-driven CESM to explore climate mitigation scenarios?**

… and also a plug for a postdoc position at LBL: https://lbl.referrals.selectminds.com/jobs/amazon-vegetation-dynamics-postdoctoral-fellow-5550