Much of Zero Emissions Commitment Occurs Before Reaching Net Zero Emissions

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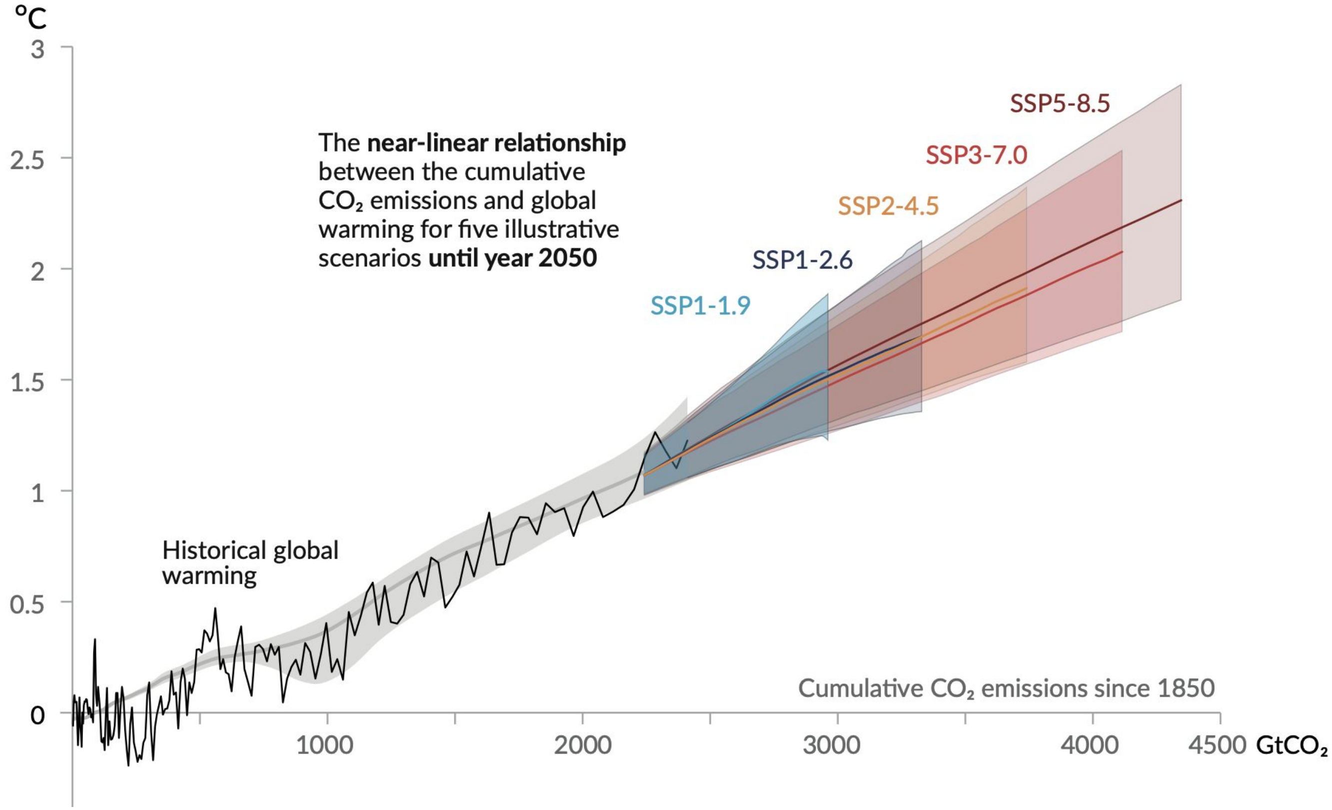
Every tonne of CO_2 emissions adds to global warming

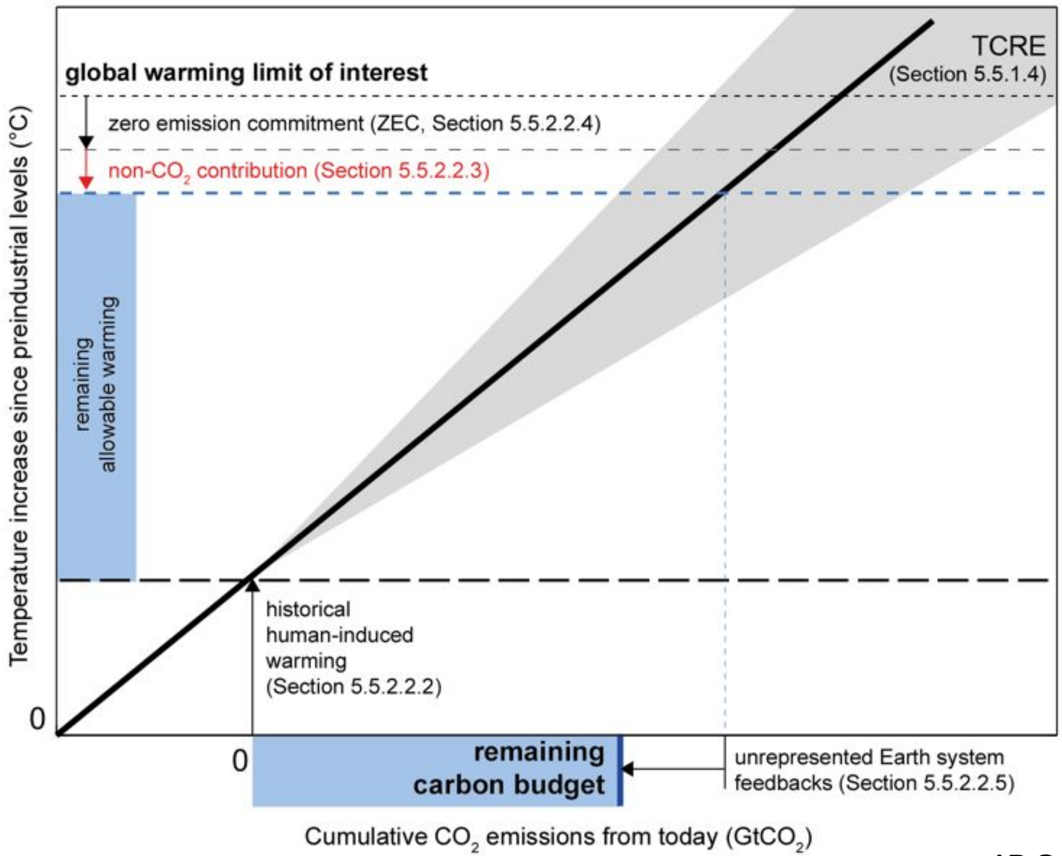
Global surface temperature increase since 1850–1900 (°C) as a function of cumulative CO_2 emissions ($GtCO_2$)



"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."

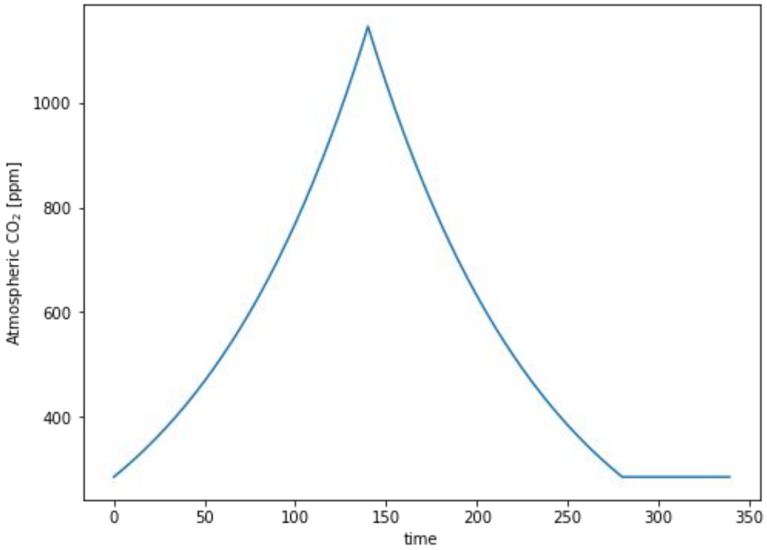
IPCC AR6 WG1 fig. SPM.10

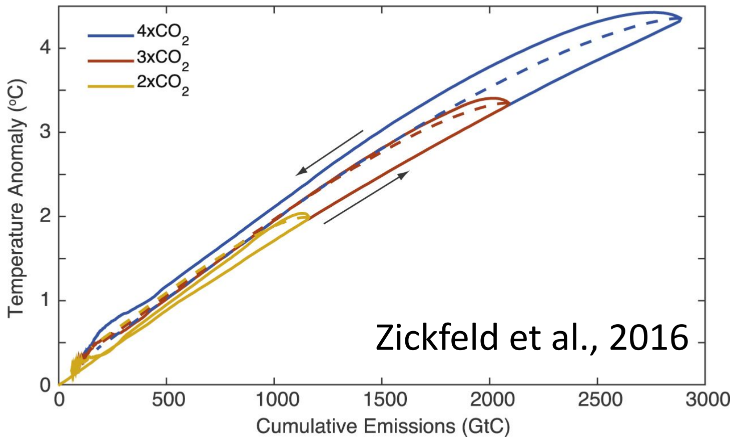
The existence of the two coupled carbon-climate metrics TCRE and ZEC, alongside other factors, allows for the creation of a remaining carbon budget for climate stabilization

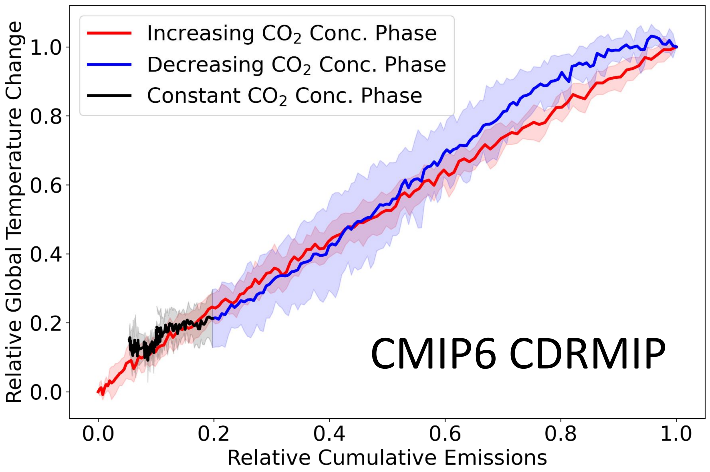


IPCC AR6 WG1 fig. 5.31

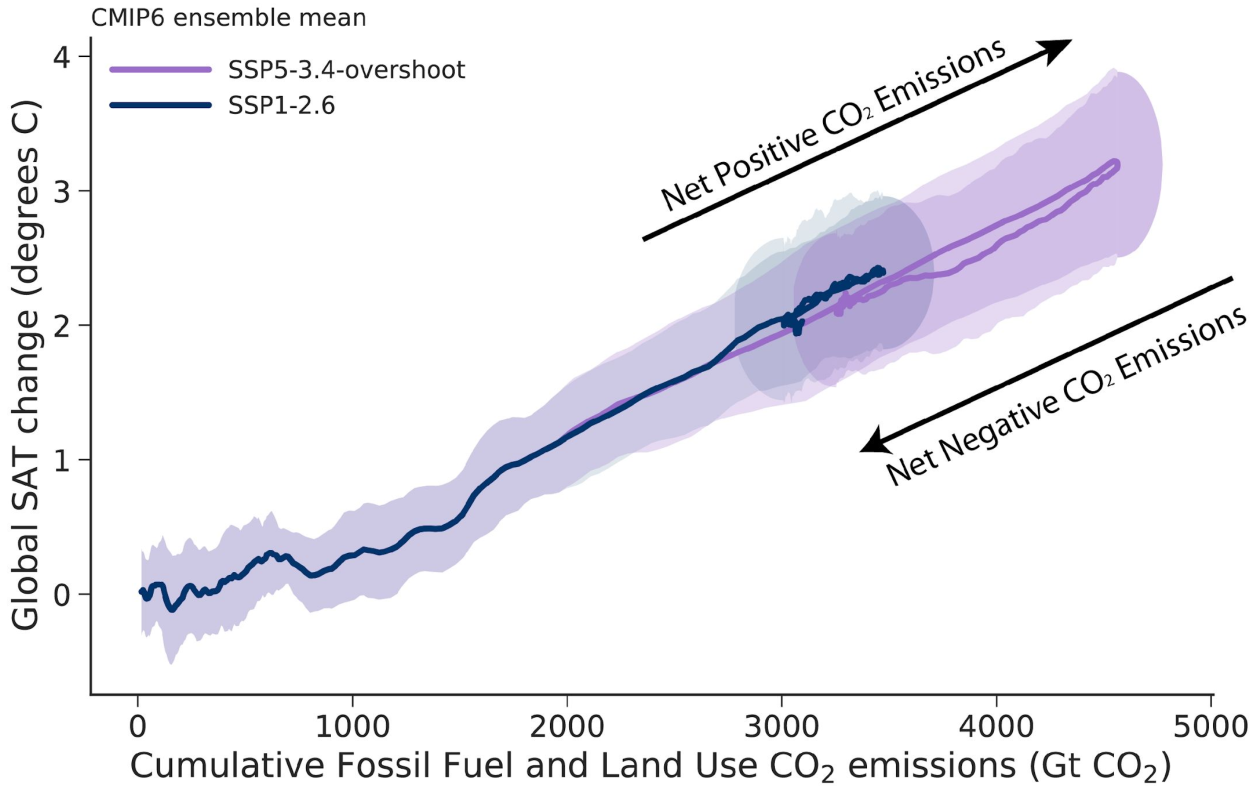
Does the TCRE relationship hold under net-negative CO_2 emissions? Idealized 1% CO_2 concentration reversal experiments say that no, there is a consistent positive asymmetry…





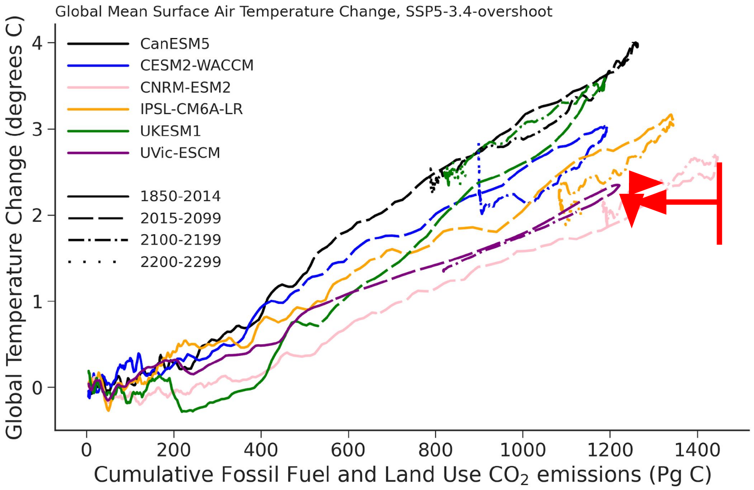


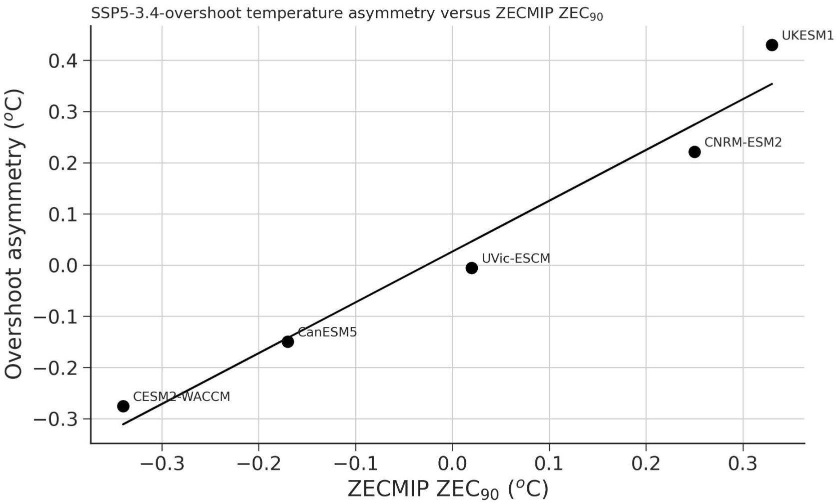
Whereas non-idealized experiments say that yes, the TCRE relationship actually does still basically hold.



Adapted from Koven et al., 2022

Looking at individual models in a non-idealized overshoot scenario, any overshoot asymmetry is well predicted by ZEC

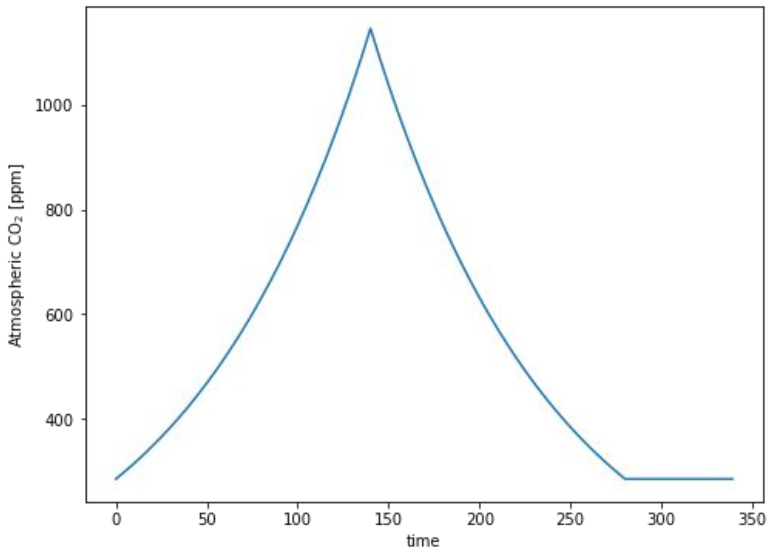




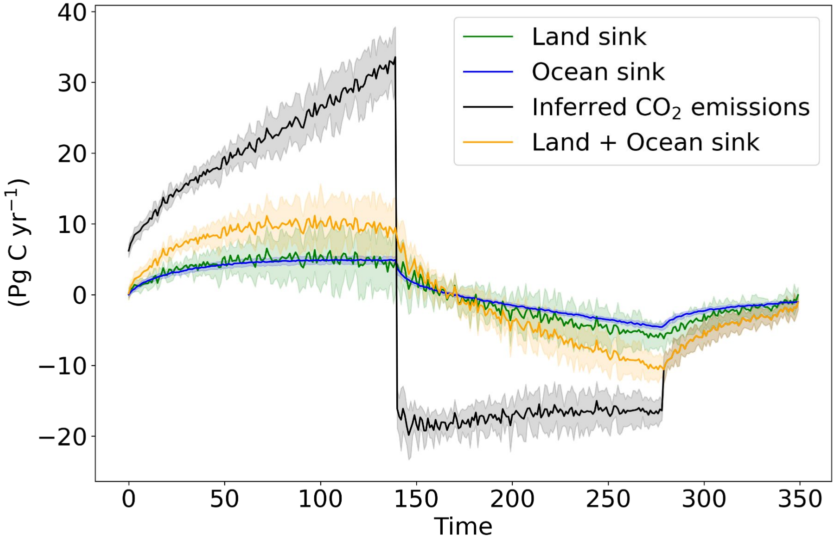
Koven et al., ESD, 2022

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?

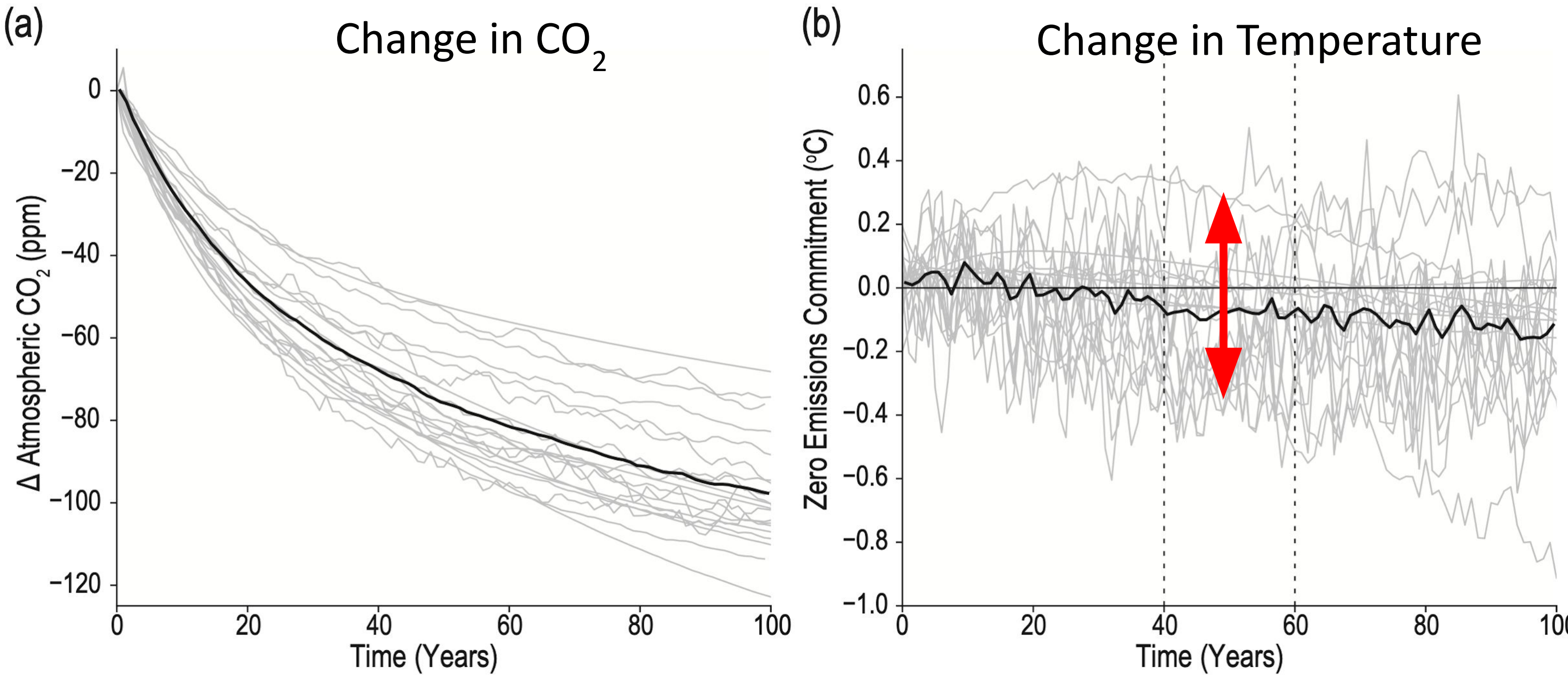


CMIP6 CDRMIP



The zero emissions commitment (ZEC) and origin of the *path-independence* of TCRE relationship

ZEC quantified using an *emissions-forced* climate model that goes abruptly to zero emissions from a 1%/yr increasing CO_2 *concentration-forced* run



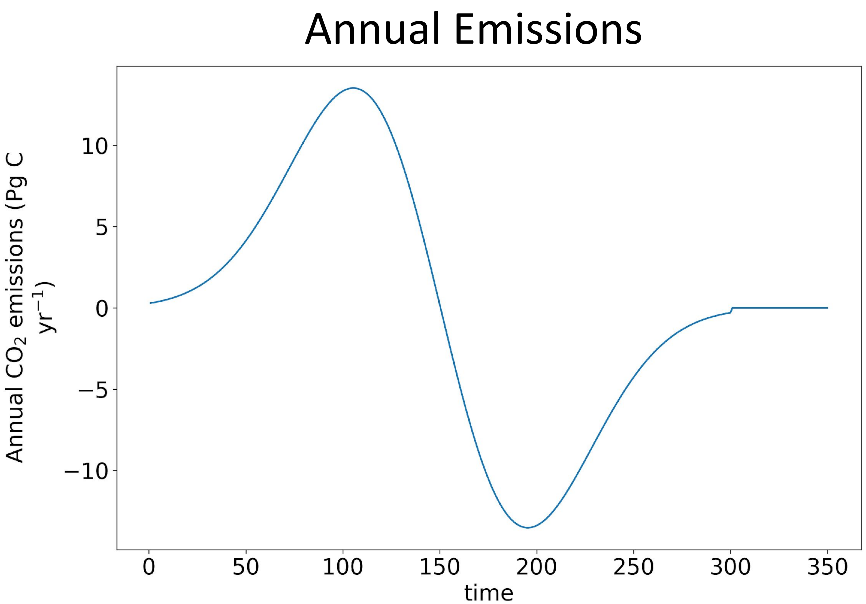
IPCC AR6 assessed *likely* range: +/- 0.3C at 50 years

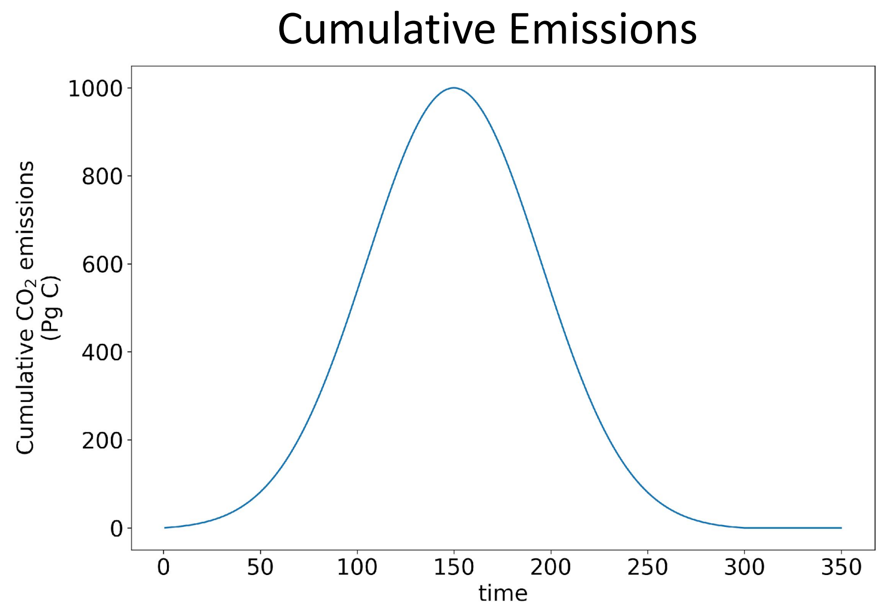
IPCC AR6 WG1 fig. 4.39

Near-zero ZEC arises from ***two opposing sets of processes***:

1. The land and ocean carbon sinks remain active, though steadily weakening over time. This causes atmospheric CO_2 concentrations to decrease over time.
2. The physical climate sensitivity shifts—and increases—from the transient climate response (TCR) value towards the equilibrium climate sensitivity (ECS) value, driven by continued ocean heat uptake.

An idealized climate restoration experiment: continuous, symmetric transition from positive to negative CO_2 emissions



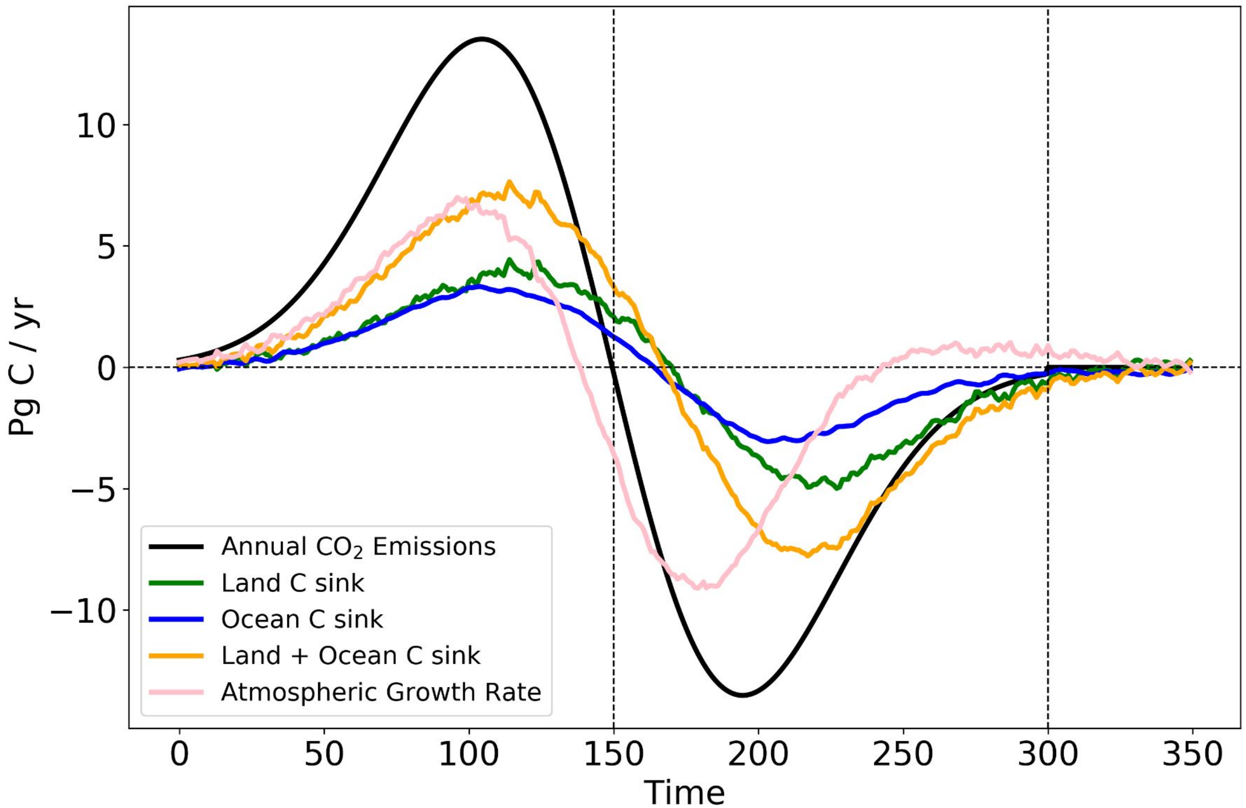


Run through emissions-driven ESM. **Hypothesis is that warming follows TCRE proportionality during the positive emissions phase, and follows the TCRE proportionality + ZEC during the negative emissions phase.**

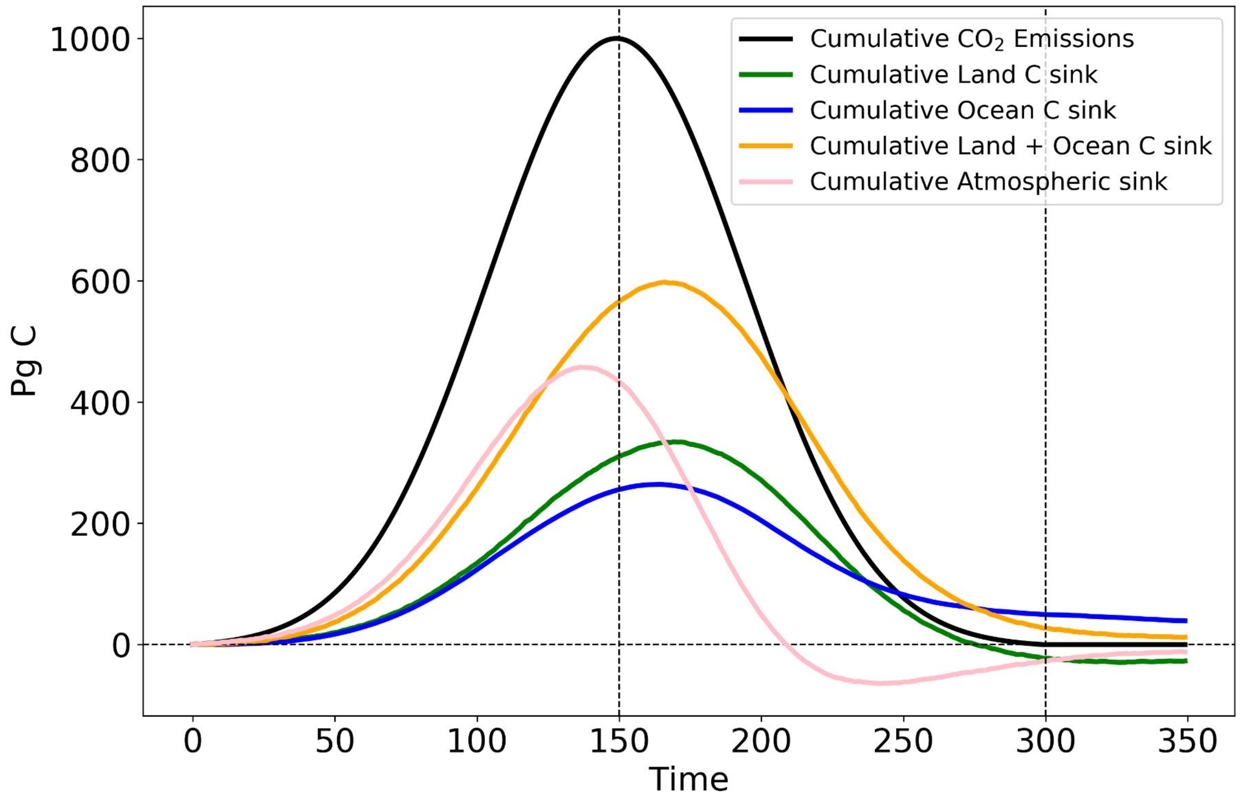
We first use CESM2 because we want an ESM with published TCRE and ZEC values, and a nonzero ZEC

Flux responses to emissions reversal

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

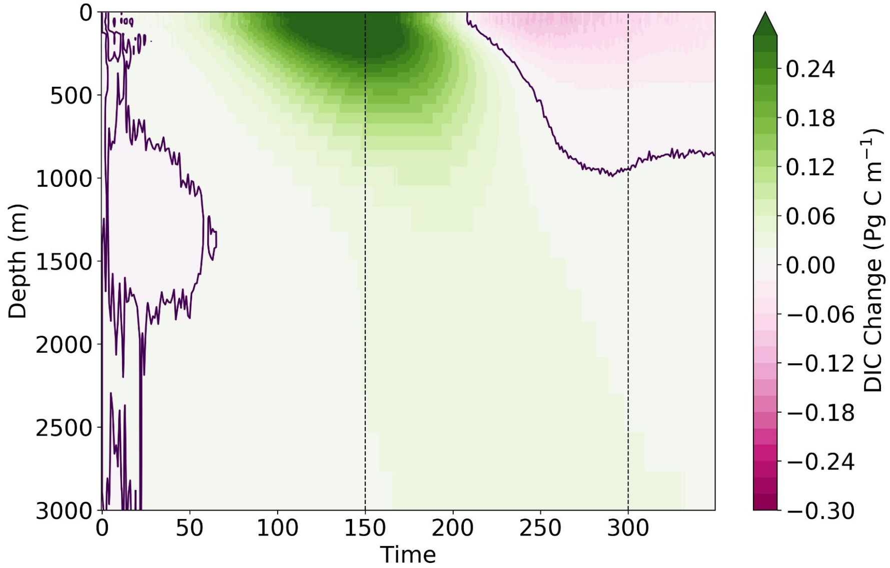


At the end of the scenario, some net anthropogenic carbon remains in the deep ocean, and thus land and atmosphere both have *less carbon than preindustrial*.

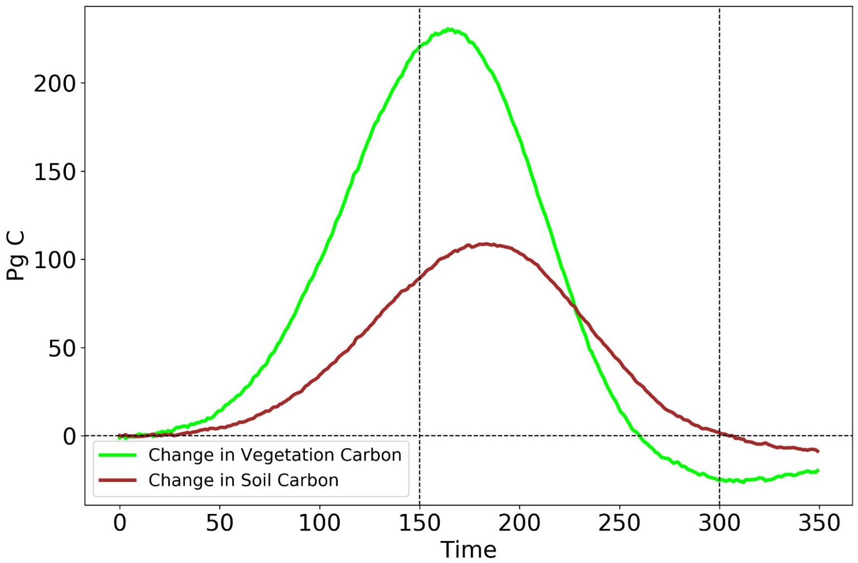


Where and when does the carbon go to (and then come from) ?

Ocean

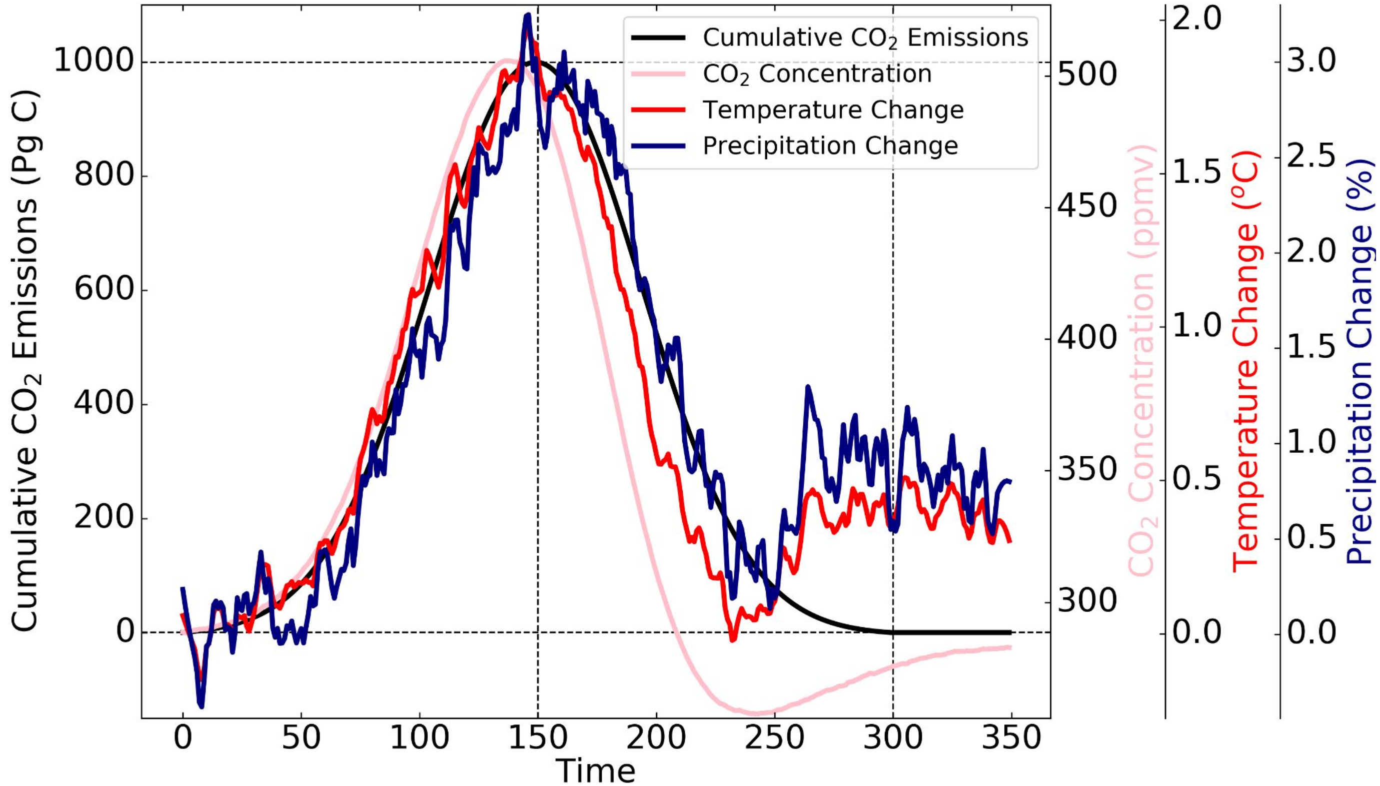


Land



Lag mainly a function of depth in the ocean, and a function of carbon pool type on land.

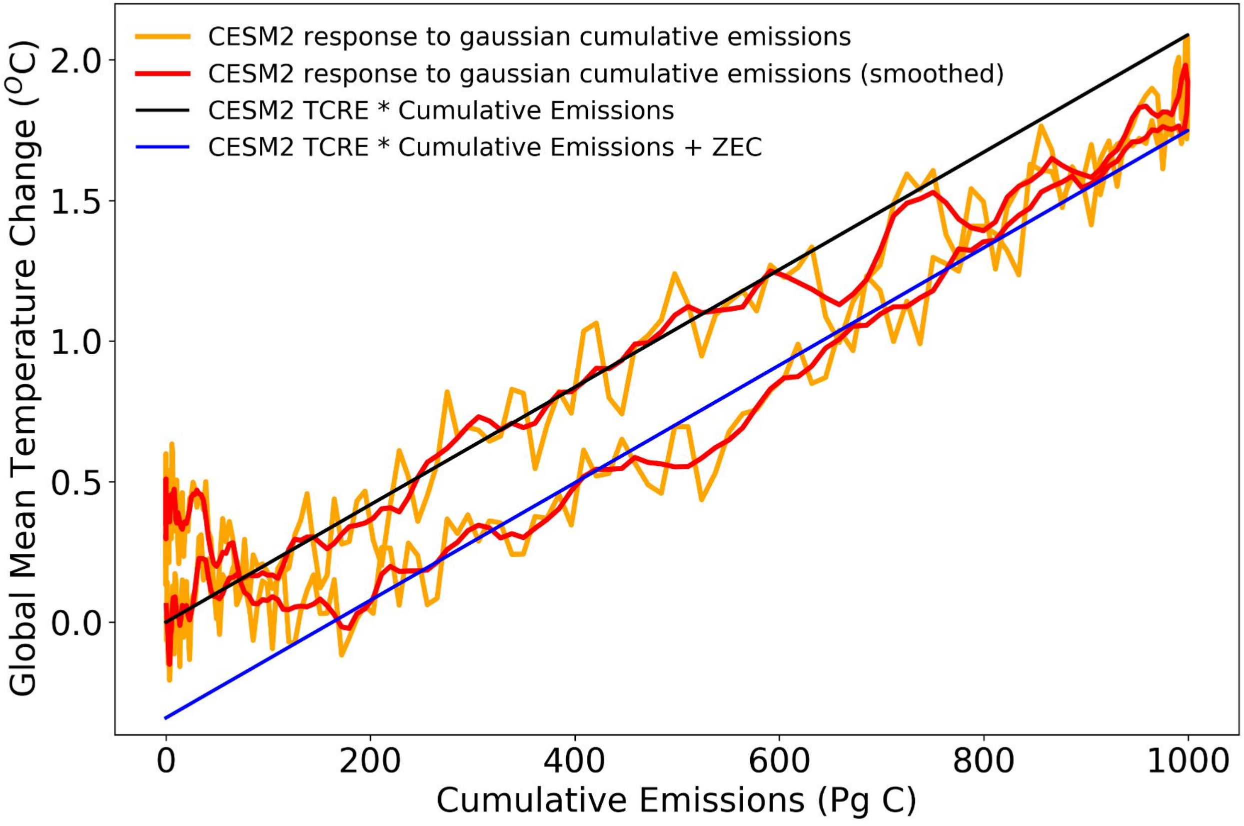
Climate responses to emissions reversal



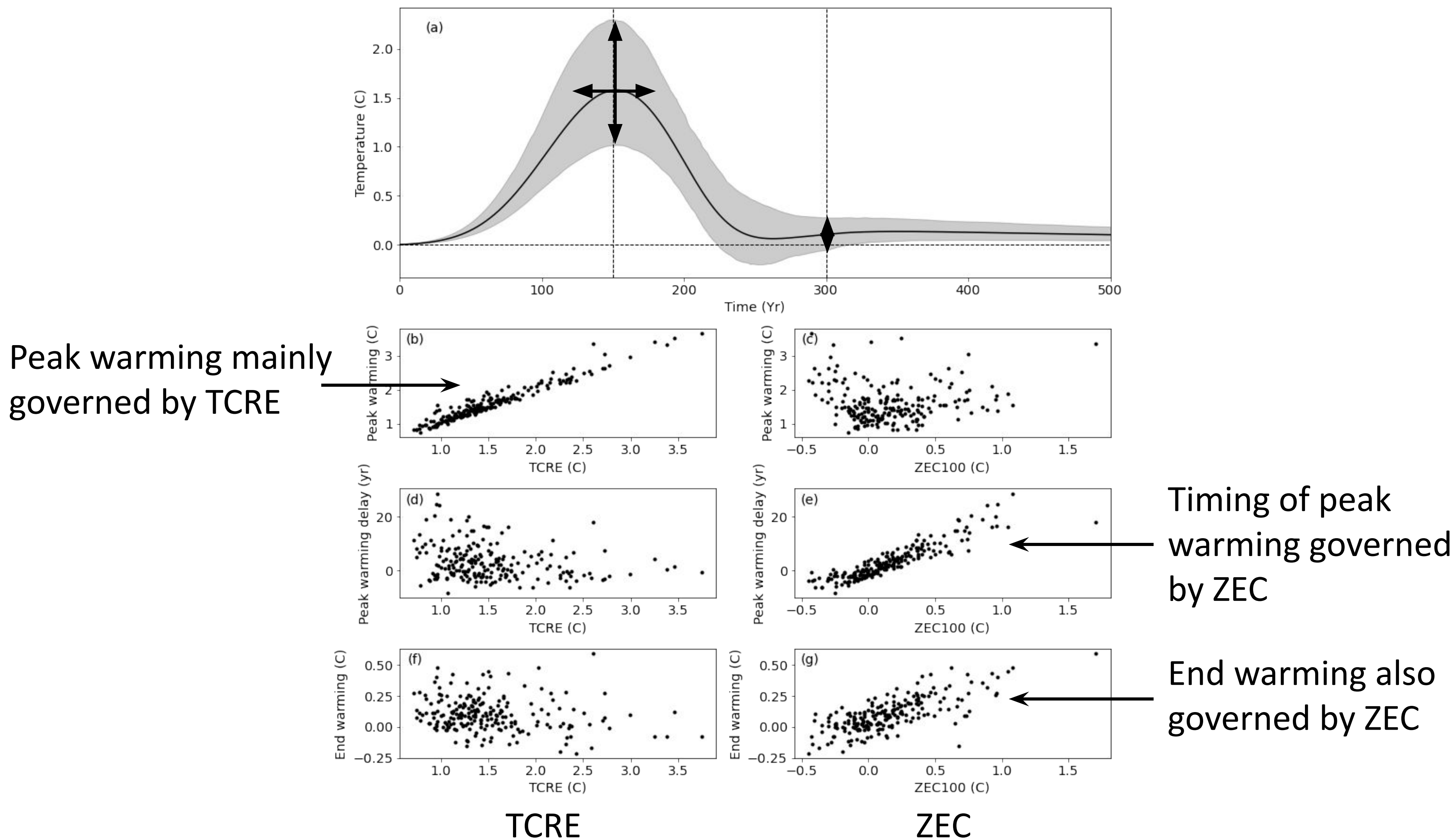
The key surprise here is that temperature *leads* cumulative emissions.

The hypothesis mostly holds.

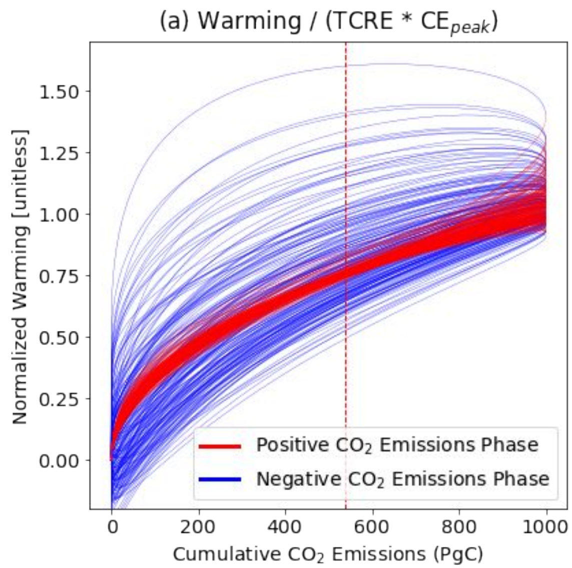
Warming roughly follows the TCRE proportionality on the upslope and the TCRE proportionality plus ZEC on the downslope. But it switches lines before peak cumulative emissions. Thus the ZEC appears *before net zero*.



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



Normalizing warming by different combinations of climate metrics allows seeing where they best predict across the ensemble.



What does all this mean?

- ZEC is a metric quantified as the response of the climate system to an instantaneous cessation of CO_2 emissions.
- ZEC is thus typically defined as the committed warming that will occur *after we reach net zero.*
- But ZEC shows up in the temperature to cumulative emissions relationship here *before reaching net zero.*
- A key point is that ZEC is quantified relative to the same experiment that is used to quantify TCRE (1%/yr)
- A better definition of ZEC is the long-term committed warming *relative to the expected TCRE relationship.*

What does all this mean? (2)

- In the "old" definition of ZEC, its value is very path-dependent.
- In the proposed "new" definition of ZEC, it becomes *a measure of the path-dependence* of the TCRE relationship under strong climate mitigation:
  - Amount of committed warming relative to TCRE proportionality after reaching net zero
  - Asymmetry of TCRE relationship under negative emissions
  - Relative timing between peak CO_2 -driven warming and peak cumulative CO_2 emissions
  - How much warming would remain *even if we took all the CO_2 that we had previously emitted out of the atmosphere*
- Importantly, this doesn't require any changes to how ZEC is used in the IPCC remaining carbon budget, because that already adds ZEC to the TCRE proportionality.

Summary

- Emissions-driven experiments are really useful!
- Idealized emissions reversal experiment allows exploring under what conditions the TCRE & ZEC metrics hold.
    - Avoids artifacts in CMIP6 CDRMIP abrupt concentration reversal.
    - Could serve a useful role in CMIP7.
- ZEC, if defined relative to the TCRE relationship, is roughly scenario-independent across a wide range of high-mitigation scenarios.
- If ZEC is negative, peak warming may occur *before* reaching net zero emissions.
- ZEC is important and we should try to better understand and quantify it.
- Large-scale net-negative CO_2 emissions, if both possible and desirable, would be equally effective at reducing global mean temperatures as net-positive CO_2 emissions are at increasing global mean temperatures.
- Even if possible and desirable, net-negative CO_2 emissions could not, over the next several centuries, fully restore the climate system to a preindustrial-like state, but they could restore the climate system to something closer to the preindustrial climate than the current climate is.

Thanks!

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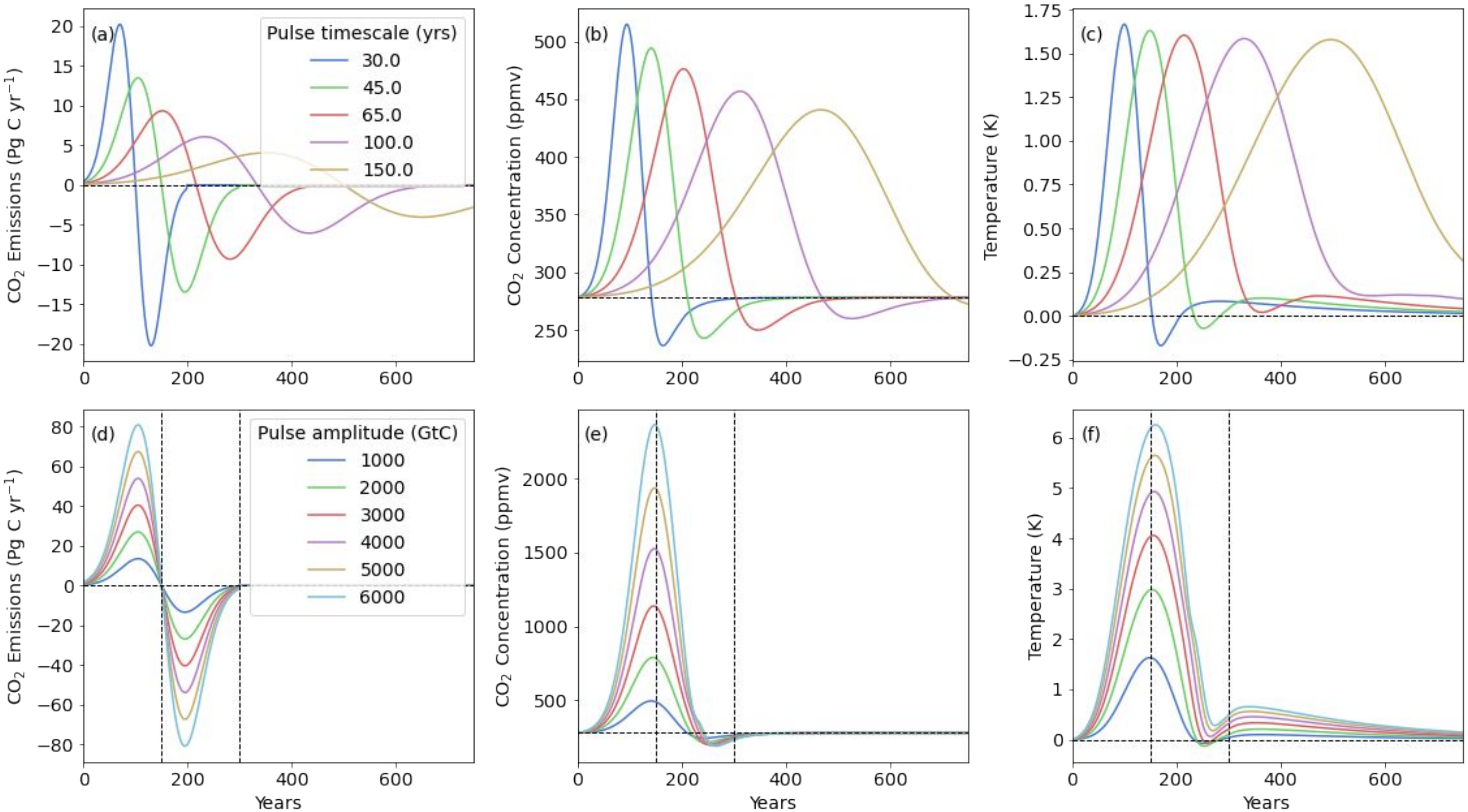
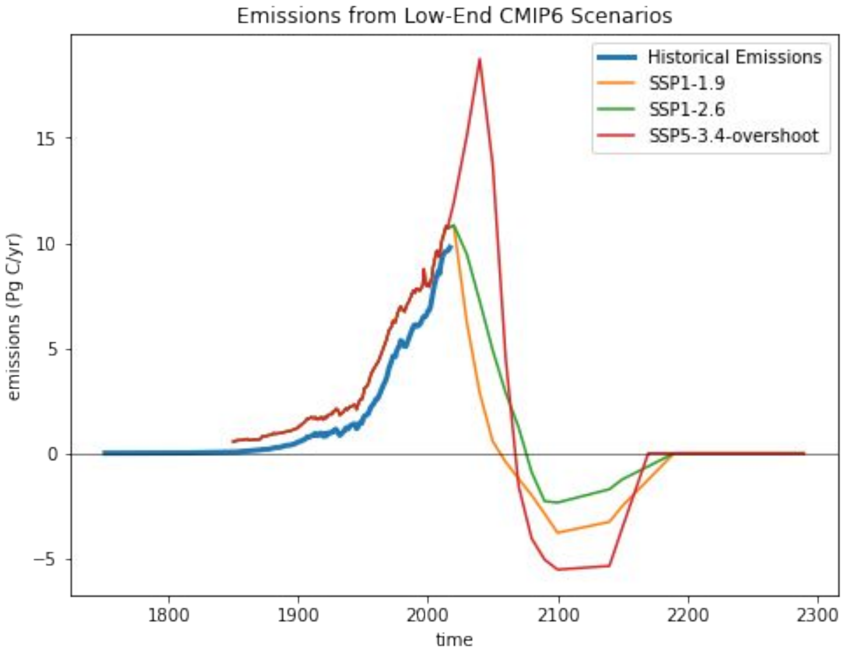
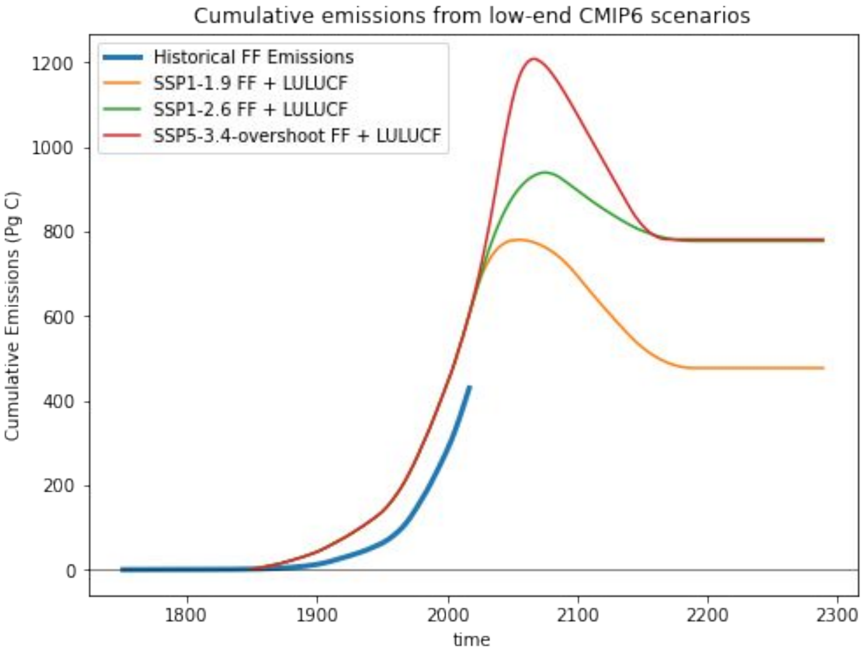
Extra slides / FAQs

What if we change the size or timescale of the CO_2 pulse?

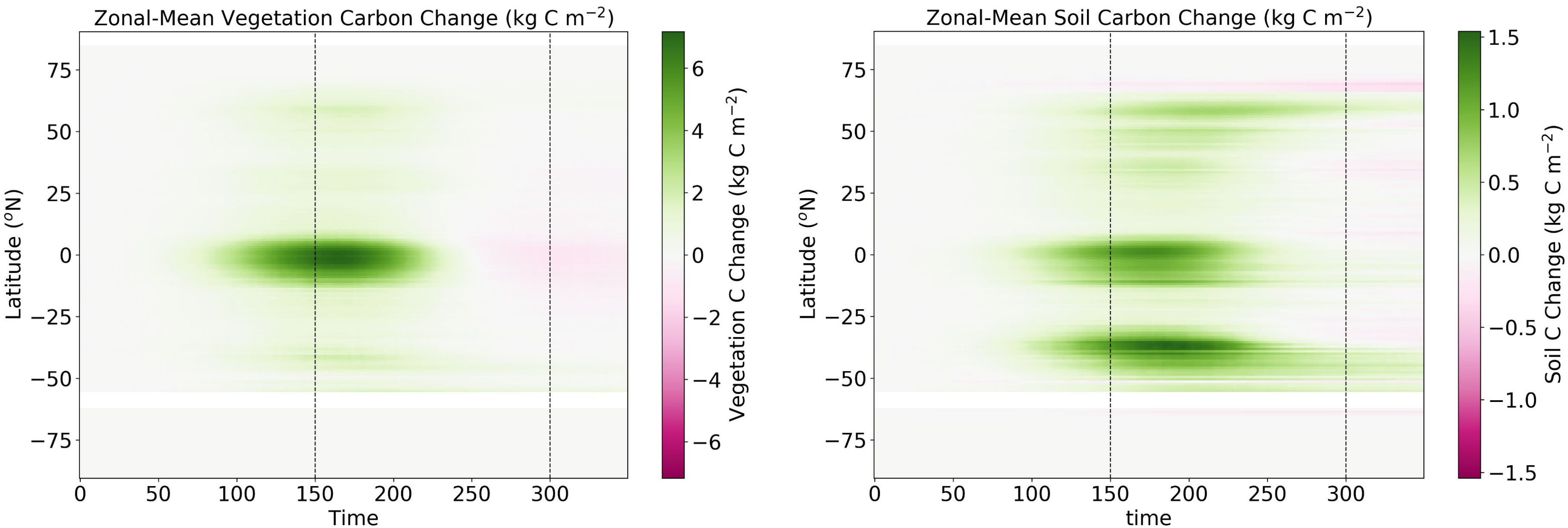


What shape do emissions take in SSP overshoot and stabilization scenarios?

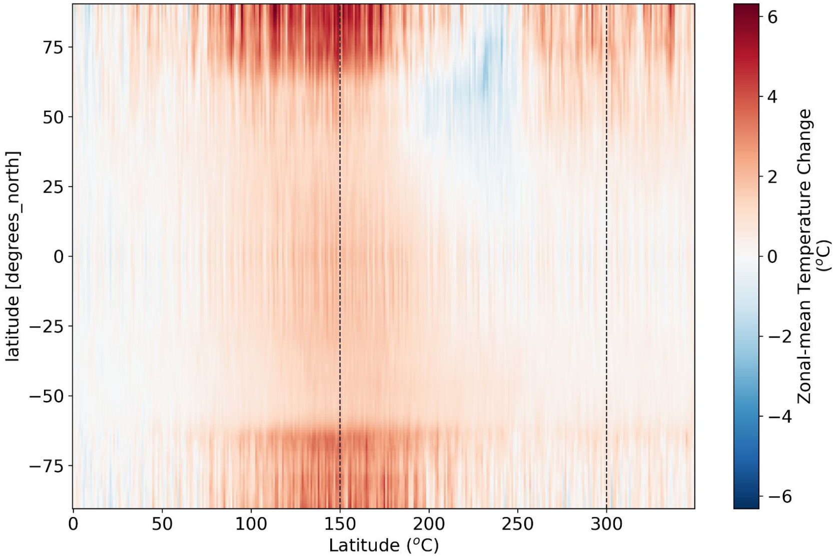


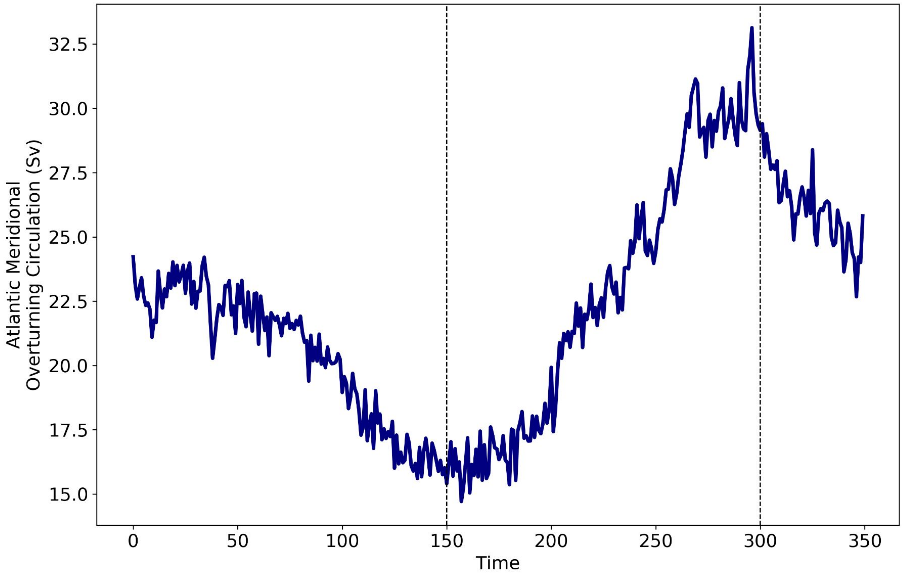


What are the zonal-mean patterns of land carbon stocks?



What is going on with CESM2 at the end of the scenario?





Why is the lag of sinks to emissions roughly the lead of the atmospheric growth rate to emissions?

Consider an even simpler model: sinusoidal emissions where sinks are equal to half of emissions with a lag. With small-angle approximations, lead of atm growth rate ≈ lag of sinks