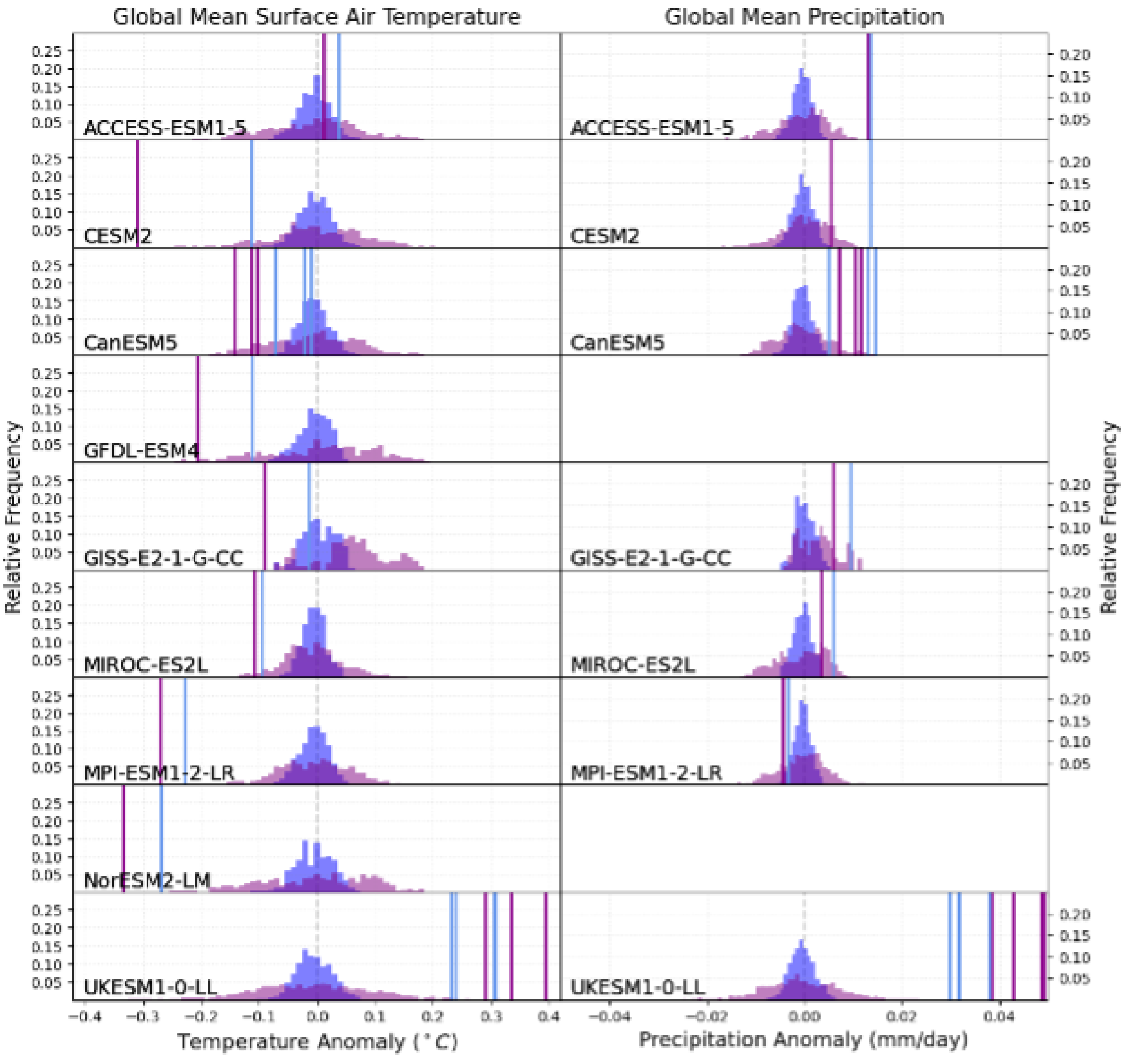
Figure 1.



Global Mean Surface Air Temperature
Global Mean Precipitation
Relative Frequency
ACCESS-ESM1-5
CESM2
CanESM5
GFDL-ESM4
GISS-E2-1-G-CC
MIROC-ES2L
MPI-ESM1-2-LR
NorESM2-LM
UKESM1-0-LL
Temperature Anomaly (°C)
Precipitation Anomaly (mm/day)

Projected Global Temperature Changes after Net Zero are Small but Significant

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Key Points

- Changes in global mean surface temperature after the abrupt cessation of emissions are significant compared to natural variability.
- Global mean precipitation changes after 50 years are only significant compared to natural variability in models that warm.
- The temperature changes post-net zero have uncertain implications for the remaining carbon budget.

Abstract

As more countries make net zero greenhouse gas emissions pledges, it is crucial to understand the effects on global climate after achieving net zero emissions. The climate has been found to continue to evolve even after the abrupt cessation of CO_2 emissions, with some models simulating a small warming and others simulating a small cooling. In this study, we analyse if the temperature and precipitation changes post abrupt cessation of CO_2 emissions are significant compared to natural climate variations. We find that the temperature changes are outside of natural variability for most models, whilst the precipitation changes are mostly non-significant. We also demonstrate that post-net zero temperature changes have implications for the remaining carbon budget. The possibility of further global warming post-net zero adds to the evidence supporting more rapid emissions reductions in the near-term.

Plain Language Summary

As more countries commit to achieving net-zero greenhouse gas emissions, it is essential to understand the impact this will have on the global climate beyond this point. It has been found that even after CO_2 emissions are abruptly halted, the climate continues to change, with various models predicting either a slight warming or cooling effect. In our study, we investigate whether the temperature and precipitation changes that occur after the sudden cessation of CO_2 emissions are noteworthy when compared to natural climate variations. Our analysis reveals that the temperature changes, in the majority of models, surpass what can be attributed to natural variability. However, the precipitation changes are generally not significant. Additionally, we

observe that the temperature changes post-net zero have implications for the remaining carbon budget.

Introduction

Global greenhouse gas emissions must be reduced to near zero to prevent continued global warming (MacDougall et al., 2020; Matthews & Zickfeld, 2012). This is required if the target of "[…] holding the increase in the global average temperature to well below 2˚C above preindustrial levels and pursuing efforts to limit the temperature increase to 1.5°C […]" (UNFCCC, 2015) outlined by the Paris Agreement is to be achieved. As such, many countries have made net zero pledges (*Energy & Climate Intelligence Unit | Net Zero Scorecard*, n.d.).

Several experiments have been run that aim to quantify the response of the global and local climate after the cessation of emissions (Dvorak et al., 2022; Jones et al., 2019; Sherwood et al., 2022). One such experiment, the Zero Emissions Commitment Model Intercomparison Project (ZECMIP)(Jones et al., 2019), aims to understand the evolution of the climate after the abrupt cessation of CO_2 emissions at around 1.5˚C. In this scenario, Earth System Models (ESMSs) and Earth System Models of Intermediate Complexity (EMICs) predict a post-net zero global average temperature change of -0.07˚C (-0.36˚C to 0.29˚C between models) 50 years after emission cease – this is the Zero Emissions Commitment (ZEC) (MacDougall et al., 2020). A warming may occur due to the thermal inertia of the oceans, causing further increases in the global average temperature. Cooling may occur due to carbon dioxide removal by the terrestrial biosphere and ocean. Ultimately, the trajectory of the climate after the cessation of emissions, and whether the climate will warm or cool, depends on the magnitude of these two effects (MacDougall et al., 2020, 2022).

As the ZEC is small, it is important to know if this is robustly distinct from the background climate variations. Previous studies have averaged ZEC across a multi-model ensemble but not assessed the internal variability of each model which is known to cause apparent trends on short timescales. Here, we analyse whether global temperature changes after the abrupt cessation of CO_2 emissions are significant for several ESMs compared to the natural variability of their climate. We also analyse if the global mean precipitation changes post-net zero are significant compared to their natural variability.

Any post-net zero changes will have implications on the remaining carbon budget (RCB). The RCB is the cumulative CO_2 that can be emitted while keeping the peak global average temperature rise below a global warming level (Dvorak et al., 2022). The RCB allows emissions reduction targets to be aligned with global warming levels. If annual emissions remain at 2022 levels (40.2 $GtCO_2$), nine years (380 $GtCO_2$) remain in the carbon budget from the beginning of 2023 for a 50% chance of avoiding exceeding 1.5˚C (*Global Carbon Project (GCP)*, n.d.). In previous work that used the ZEC when quantifying the RCB, the ZEC value is either ignored (Matthews et al., 2020), considered zero[11] or has an uncertainty distributed around zero (Matthews et al., 2021; IPCC, 2021). Here we calculate the impact of the ZEC on the RCB.

Model Data

ZECMIP Simulations

To analyse the temperature changes post-net zero, we used the Zero Emission Commitment Model Intercomparison Project (ZECMIP) A1 experiment (Jones et al., 2019) – the highest-priority experiment with more models available. Emissions in this experiment increase by 1% per year until 1000 PgC has been released, at which point CO_2 emissions are abruptly ceased. Nine Earth System Models have run the ZECMIP A1 experiment: NorESM2-LM (Tjiputra et al., 2020), MIROC-ES2L (Hajima et al., 2020), MPI-ESM1-2-LR (Mauritsen et al., 2019), GISS-E2-1-G-CC (Kelley et al., 2020), GFDL-ESM4 (Dunne et al., 2020), ACCESS-ESM1-5 (Law et al., 2017; Ziehn et al., 2020), CESM2 (Danabasoglu et al., 2020; Lawrence et al., 2019), UKESM1-0-LL (Sellar et al., 2019) and CanESM5 (Swart et al., 2019). All models are run as part of the Community Model Intercomparison Project Phase 6, and each contains an interactive carbon cycle. For a full summary of model features, see MacDougall et al., (2020). The global mean temperature anomalies and global mean precipitation anomalies after the cessation of emissions for each model can be seen in Supplementary figures 1 and 2. We do not include EMICs in this analysis as they do not have a realistic representation of interannual climate variability. Precipitation is not available for GFDL and NorESM2 models.

Pre-Industrial Control Simulations

Pre-industrial control simulations are initialised with greenhouse gas levels from the reference year 1850[7]. This year is selected as it precedes the commencement of large-scale industrialisation. Pre-industrial control simulations illustrate the climate's natural variability without human interference. The global mean temperature and global mean precipitation for all pre-industrial control simulations can be seen in Supplementary figures 3 and 4.

Methods

ZEC Calculation

The temperature and precipitation changes after the cessation of emissions are compared with the twenty-year average of the point at which the A1 experiment branches from the 1% CO_2 run. The ZEC_{25} and ZEC_{50} values are then calculated as the 20-year average centred on the years 25 and 50, respectively. To compare these values with the range in the pre-industrial control, we calculate the difference between two twenty-year average periods separated by five years corresponding to ZEC_{25}, and 30 years corresponding to ZEC_{50}. These values can then be used to create a distribution, as shown in figure 1. Values are considered outside the range of natural variability if they are below the 1st percentile or above the 99th percentile of the pre-industrial control anomalies.

Carbon Budget Calculation

The carbon budget is defined as the allowable remaining emissions for keeping the peak global average temperature below a certain global warming level. The allowable emission can be derived using a known linear relationship between warming and cumulative CO_2 emissions (Seshadri, 2017). This relationship is commonly estimated using the transient response to cumulative emissions (TCRE). TCRE change in the global mean temperature (ΔT) to increasing cumulative emissions (E).

$$TCRE = \frac{\Delta T}{E}$$

In this study, we have used a common method of estimating this parameter from the 1% CO_2 simulations by taking the 20-year average once 1000 PgC has been emitted. The 20-year average can then be converted to an anomaly by subtracting the average of the pre-industrial control simulation (all years for each model). This gives the sensitivity of the climate to increasing cumulative emissions (°C/GtCO_2), which can then be used to calculate the remaining emissions for a given peak global warming. In this study, we use this relationship to infer the associated emissions ($Budget_C$) with a given ZEC_{50}

$$Budget_C\ [GtCO_2] = ZEC_{50}\ [°C] * \frac{3670}{TCRE\ [°C/1000PgC]}$$

Results

The temperature changes after cessation of emissions are outside the range of natural variability in most models (figure 1 left column) (see Supplementary Table 1 for a summary of how the ZEC values compare with natural variability). Only ACCESS-ESM1-5 and two of the CanESM5 ensemble members show non-significant changes, with these models predicting little global average temperature change. Only two models simulate warming (ACCESS-ESM1-5 and UKESM1-0-LL); however, this warming is only significant compared to natural variability in the UKESM1-0-LL model. The remainder of the models cool, and the cooling, both after 25 and 50 years, is simulated to be lower than the range due to natural variability (except for GISS-E2-1-G-CC at 25 years, GFDL-ESM4 after 50 years and two of the ensemble members of CanESM5).

Thus, the response most commonly simulated after the cessation of emissions is a cooling that is significant compared to natural variability, based on the model simulations examined here.

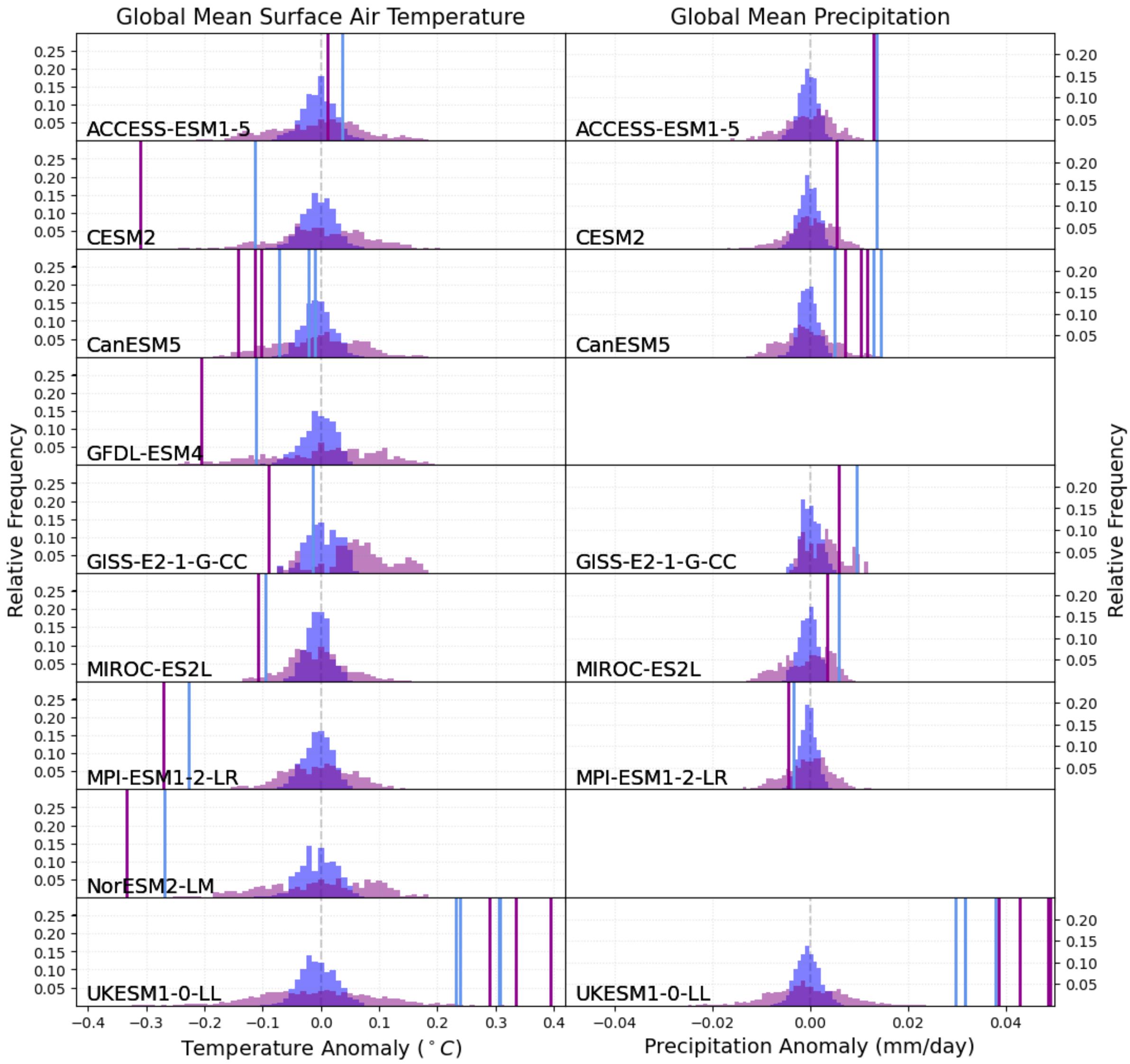

Figure 1: The distribution of differences in 20-year average global mean temperatures (left column) and global mean precipitation (right column) separated by 5 years (blue) and 30 years (purple) for each model (rows), compared with the ZEC_{25} (blue line(s)) and ZEC_{50} (purple lines(s)). Precipitation is not available for GFDL and NorESM2 models.

We next analyse the post-abrupt CO_2 emissions cessations effect on precipitation (figure 1 right column). The simulations show significant increases in precipitation in all models after 25 years, except MPI-ESM1-2-LR. By the year 50, precipitation changes are still positive for all models, excluding MPI-ESM1-2-LR; however, these changes are not significant for most models. As atmospheric CO_2 concentrations decline, the reverse of what is described in Andrews et al., (2009) may occur. The decreasing CO_2 will decrease the positive radiative component at the top of the atmosphere greater than the surface, increasing latent heat flux, resulting in increased evaporation, and more rainfall. This effect may counteract or add to the Clausius Clapeyron effect, which results in air temperature increases as surface temperatures increase. The only two models that see significant increases in precipitation after 50 years (ACCESS-ESM1-5 and UKESM1-0-LL), are both models that see increased global mean surface temperature (although ACCESS-ESM1-5 warming is non-significant). The decreased CO_2 and increased surface temperature, thus both act to increase precipitation. For all other models, the precipitation change is significant at year 25 compared to natural variability likely due to the inertia of global average precipitation that persists even after the global temperature is no longer increasing (Mitchell et al., 2016). However, by the year 50, as CO_2 concentrations are still decreasing in models, and surface temperature has decreased, these effects are likely to have counteract, resulting in non-significant precipitation changes. Additionally, the variability of precipitation is larger compared to temperature, and thus, the forced changes in precipitation must be greater in order to be significant relative to natural variability (Milinski et al., 2020). Our findings show that whilst the temperature changes after zero CO_2 emissions have a discernible influence on short-term precipitation patterns, longer-term changes in precipitation do not exceed the bounds of natural variability.

These post-net zero temperature changes may have implications for the RCB. The multi-model average RCB for 1.5˚C, based upon current warming of 1.2˚C (*Globalwarmingindex.Org -- Tracking Progress to a Safe Climate*, n.d.) is 535 $GtCO_2$ (see Supplementary Table 2 for details on each model). This value is larger than other reported values (Friedlingstein et al., 2022; Global Carbon Project (GCP), n.d.; IPCC, 2021; Matthews et al., 2021) however, is still within the range of possible values considering the large spread in the RCB and the limited number of models available for this analysis. Should the climate exhibit a significant warming post-cessation of emissions, a scenario identified here solely in the UKESM1-0-LL model, this results in a reduction of the carbon budget by 518 $GtCO_2$. Consequently, with the RCB estimate being 525 $GtCO_2$ from this subset of models, this suggests that even if CO_2 emissions ceased, the climate could still approach the 1.5˚C warming level. In models that predict a significant cooling after zero emissions, an average temperature reduction of 0.21˚C is simulated. This cooling could potentially increase the RCB for limiting global warming to 1.5˚C by an additional 475 $GtCO_2$, representing a substantial 75% boost to the available carbon budget. However, this extra carbon budget is only applicable under certain conditions. If CO_2 emissions were to be abruptly halted, the cooling effect would have no impact on the RCB. This is because the RCB is for the peak global mean temperature, and a negative ZEC would not reduce the peak temperature reached (see Supplementary figure 1). Rather, the negative ZEC will influence the climate evolution after the global mean temperature has peaked, returning the global mean temperature to stabilisation at a lower level. In reality, the reduction in emissions is likely to be a gradual and phased process. Some of the ZEC may be realised before reaching net-zero emissions (Koven et al., 2023), impacting the RCB. It is important to emphasise that the 475 $GtCO_2$ represents a maximum potential increase for the RCB for 1.5˚C, and the actual impact of ZEC on the RCB can vary depending on the emissions reduction trajectory and the cumulative emissions (Allen et al., 2022). There is currently a lack of available simulations to precisely determine how much of the ZEC effect will be realised with different pathways to net-zero emissions.

Discussion

Previous modelling studies have found that the changes in global average temperature after the immediate cessation of CO_2 emissions are small (global average range of -0.36˚C to 0.29˚C)(MacDougall et al., 2020), but it has not been investigated if this is only due to internal variability. The IPCC assessed that the changes after zero emissions are '[…] small compared with natural variability in GSAT [Global Surface Air Temperature]' (IPCC, 2021) but this was after averaging across the ensemble before making that comparison. Here, by comparing each model with its own natural variability we find that for most models in the ZECMIP A1 experimental ensemble, the changes in global average temperature are significant. The response is varied between models; however, the most commonly simulated response is a significant cooling compared to natural variability – seven out of nine models (only one of three simulations from CanESM5) cool significantly 50 years after the cessation of CO_2 emissions. However, the cooling after emissions are abruptly ceased does not affect the RCB for 1.5˚C, but may return global average temperatures to a lower global warming level, reducing impacts from climate change. Warming is less likely after the cessation of emissions, with only one model (UKESM1-0-LL) simulating significant warming compared to natural variability. This low-likelihood but high-impact outcome means we must still plan ambitious emissions reductions to avoid the possibility of exceeding the Paris Agreement warming levels following emissions cessation. Our study underlines the need for improved understanding and constraints on TCRE and ZEC, and we recommend larger ensembles of simulations are needed to enable more robust quantification of the magnitude of ZEC in the face of climate variability, as well as less idealised experiments to explore implications of net-zero.

The temperature and precipitation changes after net zero across climate models were found to be diverse, but the small ensemble of model simulations prevents robust probabilistic analysis of different outcomes under net-zero simulations. Given humanity's goal of reaching net zero emissions to prevent further global warming, it is imperative that the climate science community makes rapid advances in understanding the committed climate changes following net zero. Decision-makers need more information about the response of the climate to net zero emissions to plan accordingly. In the meantime, it may be prudent to account for the possibility of post-net zero emissions global warming and to take more rapid action to reduce greenhouse gas emissions as a result.

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Open Research

Data for the ZECMIP A1 experiment can be found at https://esgf.nci.org.au/projects/esgf-nci/. The final code used to conduct this analysis will be published after any revisions that need to be made.

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