



A Comparison of Regional Climate Changes Under Idealized Zero-Emissions and Exceedance-and-Return Experiments

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Abstract. We examine the behavior of ten Earth system models under a set of idealized CO₂ emissions-driven simulations to look at regional temperature and precipitation changes in response to either an abrupt cessation of emissions or an idealized exceedance-and-return pathway, in which emissions linearly ramp down from positive to negative emissions. This allows a comparison of the regional climate at three different time points, all of which have the same level of cumulative CO₂ emissions and therefore the same expected global warming amount. I.e., this lets us ask how regional climates would differ if we first emit, and then remove, a given amount of CO₂, as compared to a case where the CO₂ past a certain amount hadn't been emitted, and the coupled carbon-climate system had been left to freely evolve over the same length of time. We find consistently higher global precipitation for a given global temperature after zero emissions in both pathways, with a larger increase under the exceedance-and-return pathway than the zero-emissions pathway. Averaging over land and ocean domains, we find cooling over land relative to ocean, which is also stronger under exceedance-and-return than zero-emissions, and for about half of the models a difference in the relationship between land-ocean temperature contrast and global mean temperature change than occurs under positive emissions. We find low agreement across different models in the



regional patterns of both temperature and precipitation change in all scenarios. For most of the models, there is a strong gridcell-level correlation between the temperature changes in the exceedance-and-return and zero-emissions responses, such that roughly half of the regional variance in temperature change at a given location that occurs under the exceedance-and-return pathway also occurs under zero emissions. Because only a single realisation of each experiment is available, this shared fraction is a lower bound on the common forced response: internal variability, which is uncorrelated between the two experiments, acts to reduce the apparent correspondence rather than inflate it. However, for some models there is low or negative correlation between the regional climate changes in the two cases, indicating a potential for fundamentally different regional climate change under exceedance-and-return than under zero emissions. Regional precipitation changes are more different between the exceedance-and-return and zero-emissions responses for all models.

1 Introduction:

The world is in the midst of breaching the warming level of 1.5 °C, set in the Paris agreement as a key level that nations would pursue efforts to limit warming to (Bevacqua et al. 2025). Stabilizing global temperatures will require reaching net zero emissions, and warming will continue until net zero is reached, meaning that unless CO₂ emissions drop rapidly in the near future, the climate system will continue to breach higher warming levels (IPCC 2021). Even after a given warming level has been crossed, a set of questions around mitigating climate at that warming level remain: 1) whether, and how, the world might return to that warming level after it has been exceeded, 2) how the climate system might differ as a result of first exceeding and then returning to that warming level, and 3) what a broader set of impacts might be as a result of exceeding and returning to that warming level (Schleussner et al. 2024).

The theory that global warming is nearly proportional to cumulative CO₂ emissions (Matthews et al. 2009; Allen et al. 2009) underlies both the hypotheses that net zero emissions roughly equate to climate stabilization (MacDougall et al. 2020; Allen et al. 2022; Matthews and Caldeira 2008; Solomon et al. 2009), and that net-negative emissions may be roughly as effective in cooling the climate as positive emissions are at warming the climate (Sanderson et al. 2025; Koven et al. 2023; Zickfeld et al. 2016; Brovkin et al. 2025). This theory applies only to global mean temperatures. Therefore, even under net zero emissions, continued regional climate changes (MacDougall et al. 2022; Cassidy et al. 2024; Bossert et al. 2026), as well as continued and worsening climate impacts, would still be expected. This is also true for exceedance-and-return pathways (also frequently called “overshoot pathways”, though we avoid that term here due to ambiguities in its meaning and usage (Rogelj et al. 2026)), where regional climate impacts are irreversible even if global mean climate is reversible (Pfleiderer et al. 2024; Walton and Huntingford 2024; Steinert et al. 2025; Roldán-Gómez et al. 2025; Douglas et al. 2025; Kim et al. 2022; Koven et al. 2022).

Since ongoing changes to the climate system beyond global mean temperatures are expected to occur even under net-zero, the most relevant baseline against which to assess the climatic consequences of exceeding and returning to a given temperature is not the climate at that temperature before reaching net zero, but one that stabilized at



that temperature under a net-zero pathway for an equivalent amount of time, instead of following the exceedance-and-return pathway. However, while previous experimental protocols allowed investigating the regional climate response to both net-zero and exceedance-and-return pathways, they precluded a clean comparison between the two. The goal of this analysis is to compare two sets of changes to the climate system beyond global mean surface temperature: those that would occur under approximate climate stabilization at a given global warming level due to zero emissions, and those that would occur if that warming level is first crossed due to positive emissions, and then returned approximately back to the original level through net negative emissions that achieve the same cumulative CO₂ emissions.

2 Methods:

We use an idealized set of experiments from flat10MIP (Sanderson et al. 2025), in which Earth system models (ESMs) are run in a simplified emissions-driven framework. The set of experiments comprise three separate ESM runs: 1) *esm-flat10*, in which emissions are set at a constant 10 Pg C / yr for at least 150 years, 2) *esm-flat10-zec*, which branches from year 100 of *esm-flat10*, after which CO₂ emissions are abruptly set to zero and held there subsequently, and 3) *esm-flat10-cdr*, which also branches from year 100 of *esm-flat10* but in which the rate of CO₂ emissions linearly ramps down from 10 Pg C/yr to -10 Pg C/yr over the interval from years 100 to 200, and then remains constant after year 200. Cumulative CO₂ emissions of the three experiments, and thus also the expected global mean surface temperature anomalies, are shown in Fig. 1. The cumulative emissions for the *esm-flat10-zec* and *esm-flat10-cdr* experiments diverge from the same level (1000 Pg C) in year 100, at which level *esm-flat10-zec* remains subsequently, while *esm-flat10-cdr* exceeds and then returns to that same level of cumulative emissions in year 200.

The flat10MIP experimental design allows for a separation of two distinct effects (Fig. 1). The first is the “zero emissions response” (which for the global mean surface temperature is the zero emission commitment, or ZEC), which is governed by the unforced slow adjustment of the Earth system to prior emissions. Under long-term zero emissions, atmospheric CO₂ is continued to be taken up by the land and ocean, which tends to cool the climate, but this is counteracted by continued but weakening ocean heat uptake, which tends to warm the climate (Palazzo Corner et al. 2023). The drivers of the ZEC, and in particular the near-cancellation between deep ocean warming and post-cessation carbon drawdown, are analysed in a companion study using a coupled impulse-response framework fitted to the same flat10MIP ensemble (Sanderson et al. 2026), which also shows that the linear carbon-climate feedback diagnosed from *esm-flat10* and *esm-flat10-zec* does not generalise to *esm-flat10-cdr*. The second is the “exceedance-and-return response” which is due to addition and subsequent removal of carbon dioxide from the atmosphere, which leads first to forced warming and then to forced cooling. Crucially, comparing the climate before and after an addition and subsequent removal of CO₂ mixes the time-evolving response with the response to exceedance and return. Thus it is possible that some of the projected changes over the time interval would have occurred in the absence of any CO₂ emissions, and we can measure this difference using the *esm-flat10-zec* experiment.

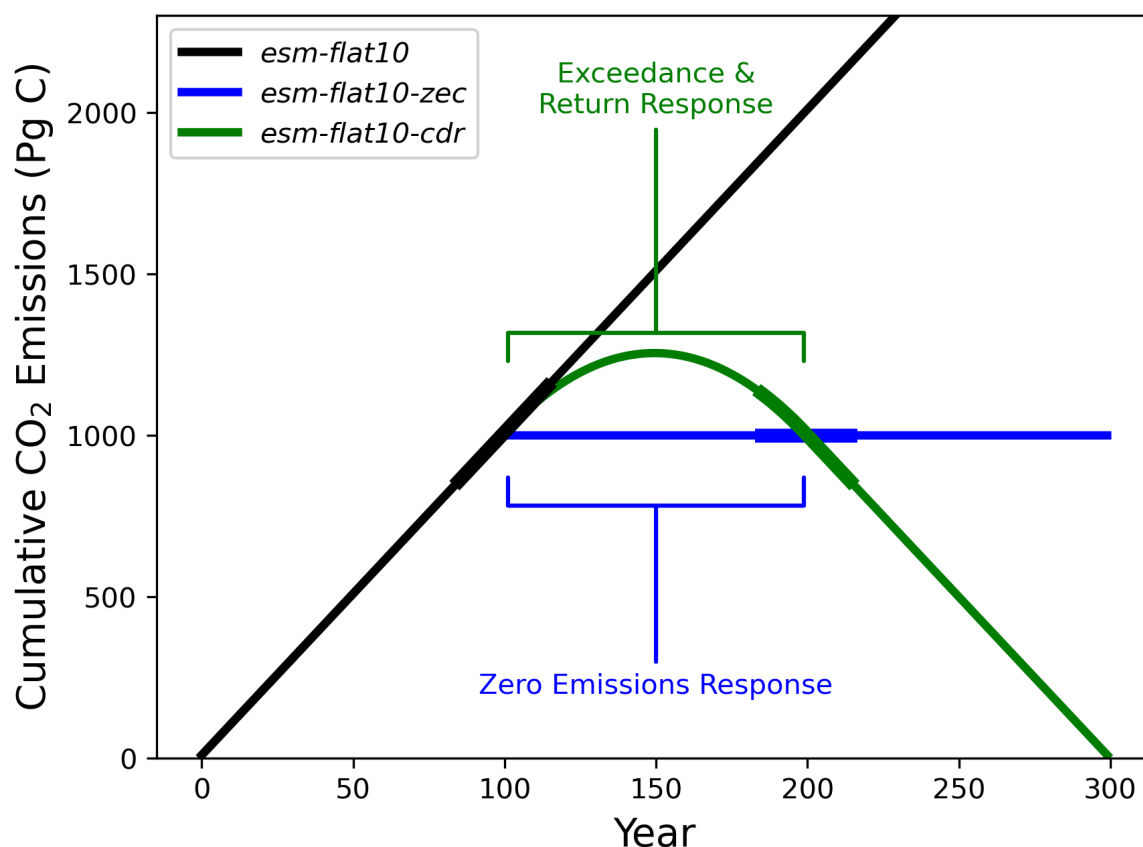


Figure 1: Diagram of experimental design and analysis. The ‘Zero Emissions Response’ is the difference between a given variable at year 200 of the *esm-flat10-zec* experiment relative to year 100 of the *esm-flat10* experiment. The ‘Exceedance and Return Response’ is the difference between a given variable at year 200 of the *esm-flat10-cdr* experiment, also relative to year 100 of the *esm-flat10* experiment. All three points have the same cumulative emissions (1000 Pg C). For all analyses, 30-year periods (thick lines) centered on each of these three points are used.

Here, we analyze results from ten Earth system models that participated in flat10MIP (table 1). In addition to the ten ESMs, three simple climate models (SCMs) and one Earth system model of intermediate complexity (EMIC) also participated in flat10MIP, however we do not analyze these models as they either do not predict regional climate dynamics or do so using fundamentally different approaches from the ESMs. Details of the experimental protocol, as well as key coupled global-scale metrics for each model, are described in (Sanderson et al. 2025). For each model, we analyze 30-year mean temperature and precipitation patterns at periods centered on the three key time points: year 100 of the *esm-flat10* experiment, year 200 of the *esm-flat10-zec* experiment, and year 200 of the *esm-flat10-cdr* experiment. We calculate the “zero emissions response” as the difference of a given variable between the period centered at year 200 of *esm-flat10-zec* and year 100 of *esm-flat10*, and the



"exceedance-and-return response" as that between year 200 of *esm-flat10-cdr* and year 100 of *esm-flat10*. These regional responses correspond to two of the metrics defined in (Sanderson et al. 2025) for the global mean surface air temperature: ZEC100 (the zero emissions commitment 100 years after abrupt emissions cessation) and TR1000 (the temperature difference after returning to 1000 Pg C cumulative emissions). The inter-model variance of these two global-mean temperature metrics have a high correlation, and thus the key question here is whether that extends to regional variation of temperature and precipitation as well.

We assess statistical significance to the results within any given model by comparing to the emissions-driven control runs, *esm-piControl*, for each model. We calculate differences in the climate between 1000 pairs of random, non-overlapping 30-year periods for each model, and assess significance if the gridcell-level changes are less than the 5th percentile or greater than the 95th percentile of the control run changes. For inter-model consistency, we assess that changes are consistent if >90% of the models (i.e. nine or ten, out of ten) agree in the sign of the response.

Earth System Model	Primary Reference
ACCESS-ESM1-5	(Ziehn et al. 2020)
CESM2	(Danabasoglu et al. 2020)
GFDL-ESM4	(Dunne et al. 2020)
GISS-E2.1	(Kelley et al. 2020)
NorESM2-LM	(Seland et al. 2020)
MPI-ESM1-2-LR	(Mauritsen et al. 2019)
CNRM-ESM2-1	(Séférián et al. 2019)
UKESM1.2	(Mulcahy et al. 2023)
HadCM3LC-Bris	(Valdes et al. 2017)
MIROC-ES2L	(Hajima et al. 2020)

Table 1: List of models and their primary references used in this study.



3 Results

3.1 Global Mean Responses

Global mean temperature responses (Fig. 2, top panels) follow the expected proportionality between temperature and cumulative emissions for all experiments, as described in greater detail in (Sanderson et al. 2025). Globally-integrated precipitation changes (Fig. 2, bottom panels) also follow the temperature changes, with models that warm the most during the *esm-flat10* experiment also showing a higher fractional increase in global precipitation. A key difference in the timeseries of precipitation and temperature can be seen after net zero (starting at year 100) in the *esm-flat10-zec* experiment, in which precipitation continues to increase in most models, despite approximate temperature stabilization across the ensemble. This is similar to the results described in (Borowiak et al. 2024), also under zero emissions, who note a suggestion that precipitation tends to increase but that the changes are not consistently outside the range of interannual variability across models. Likewise, in the *esm-flat10-cdr*, precipitation decreases lag temperature decreases across the ensemble.

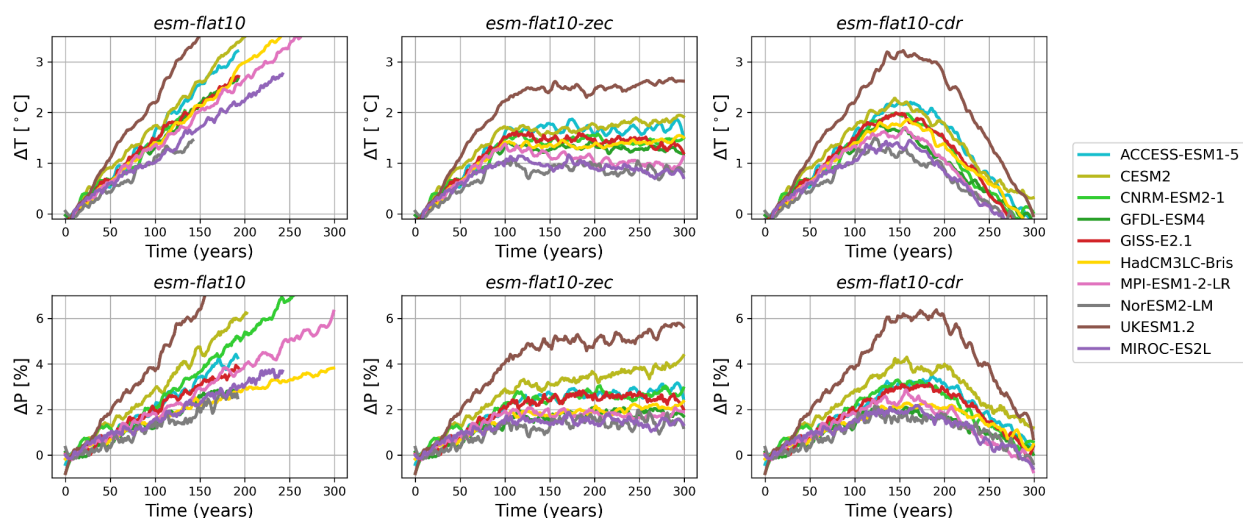


Figure 2. Timeseries of global mean temperature and precipitation changes relative to the first two decades of the *esm-flat10* simulation under each of the experiments in flat10MIP. All temperature and precipitation timeseries are shown as smoothed using a 15-year Savitzky-Golay filter.

Since atmospheric CO₂ is prognostic in these experiments, we show the time-evolving change in atmospheric CO₂ concentrations relative to their value for each model at year 100 of *esm-flat10* in Fig. 3a. By year 200 of *esm-flat10-zec*, CO₂ concentrations decrease by 67 ± 9 ppm, whereas they decrease by 92 ± 13 ppm in *esm-flat10-cdr*. Thus, for any individual ESM, CO₂ decreases more at year 200 in *esm-flat10-cdr* than in *esm-flat10-zec* by 25 ± 5 ppm, even though cumulative CO₂ emissions are the same at this point in both experiments. The reason for the larger decrease in atmospheric CO₂ in the exceedance-and-return experiment is that additional positive CO₂ emissions (years 100-150) happen before the negative emissions (years 150-200), and thus the positive emissions have a longer time to propagate away from the atmosphere and into the deep



ocean and long-lived land reservoirs than the negative emissions (Koven et al. 2023). Thus the atmospheric CO₂ anomalies from the positive emissions are more attenuated than those from the negative emissions, leading to a negative atmospheric CO₂ anomaly at year 200 as compared to the zero-emissions case. There may also be some contribution to the asymmetric CO₂ concentration response to emissions due to fundamental process asymmetry or climate feedbacks, as in (Chimuka and Zickfeld 2026; Asaadi et al. 2024), but these cannot be separated here without partially-coupled flat10MIP variants, which are proposed for the Coupled Model Intercomparison Project phase 7 (CMIP7) Coupled Carbon-Cycle Climate Model Intercomparison Project (C⁴MIP) in Arora et al., (*in prep*). Under *esm-flat10-zec*, the ensemble-mean CO₂ concentrations are still larger than year-200 *esm-flat10-cdr* at the end of the experiment at year 300 (at which point the decrease in CO₂ for *esm-flat10-zec* is 86 ± 13 ppm), even though the cumulative emissions for *esm-flat10-zec* are the same as year-200 of *esm-flat10-cdr* throughout.

Notably, the pattern for temperature is different, with the ensemble-averaged global mean surface temperatures close at year 200 both to each other and to the global mean temperature at year 100 (Fig. 3b; mean $\pm$ 1 standard deviation temperature difference for *esm-flat10-zec* is -0.02 ± 0.12 and for *esm-flat10-cdr* is -0.02 ± 0.24). This is expected given the TCRE proportionality, but we also note that there is wider ensemble spread relative to the year-100 values in *esm-flat10-cdr* than in *esm-flat10-zec*.

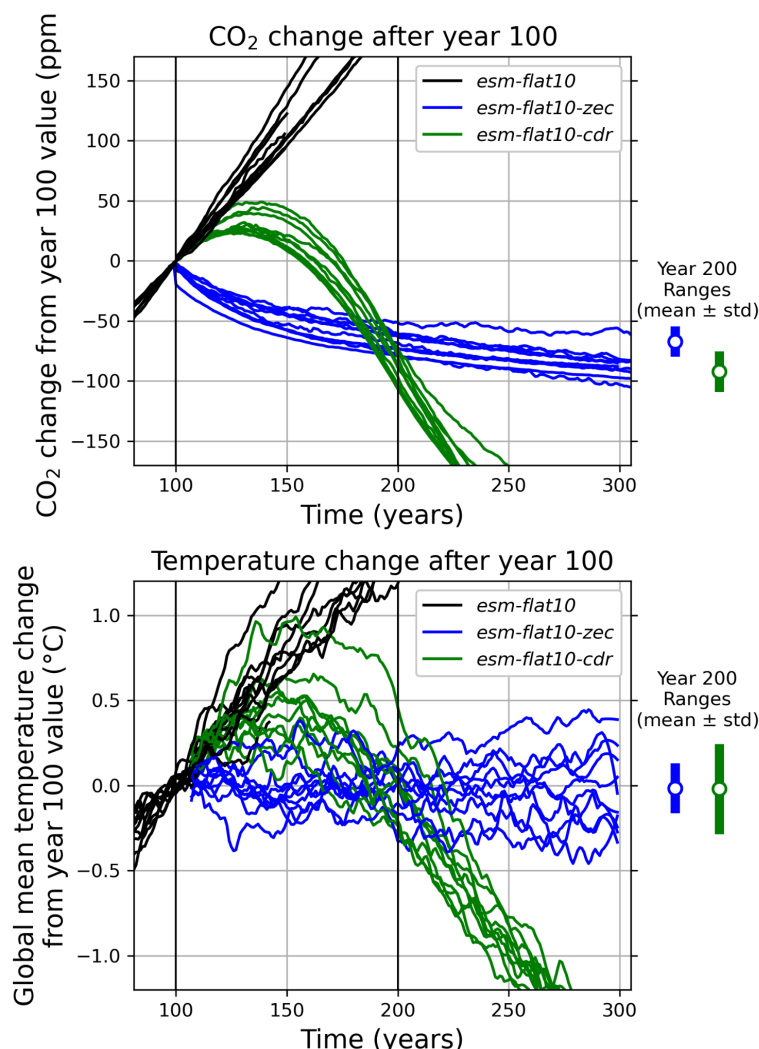


Figure 3 (a) Timeseries of CO₂ for all ESMs in the three experiments *esm-flat10* (black), *esm-flat10-zec* (blue) and *esm-flat10-cdr* (green), relative to the CO₂ concentrations for each ESM at year 100 of *esm-flat10*, when the three experiments diverge. **(b)** Corresponding timeseries of global mean surface air temperature anomalies with respect to the year-100 values. Bars to right of each panel show ensemble means and standard deviations of year-200 values for the *esm-flat10-zec* (blue) and *esm-flat10-cdr* (green) experiments.

The lower year-200 CO₂ concentration under *esm-flat10-cdr* relative to *esm-flat10-zec*, despite having the same cumulative emissions and similar temperatures, points to a general mechanism that might be expected to differentiate the climate responses between these two scenarios (fig. 4). The fundamental tradeoff that gives rise to a near-zero ZEC—and near-zero path-dependency to the temperature cumulative emissions relationship more generally—is between declining CO₂ concentrations and declining ocean heat uptake (Palazzo Corner et al.



2023). That tradeoff is stronger for *esm-flat10-cdr* in year 200 than for *esm-flat10-zec*: CO₂ concentrations are lower in *esm-flat10-cdr* and temperatures are similar, implying a greater decline in ocean heat uptake as the ocean transitions from a heat sink to a heat source to the atmosphere during the cooling period. This transition of ocean heat uptake in *esm-flat10-cdr* was shown for one model in (Brovkin et al. 2025), and explored further in Romanou et al., (in prep). However, that tradeoff does not apply to all aspects of the climate system or equally in all locations – e.g., land might respond more rapidly than ocean to declining CO₂ due to both differing thermal inertia and plant biophysical effects, or precipitation might respond differently than temperature. As a result, temperature and precipitation changes driven by this tradeoff might be hypothesized to show an amplified pattern in their exceedance-and-return response relative to those that appear in the zero-emissions response.

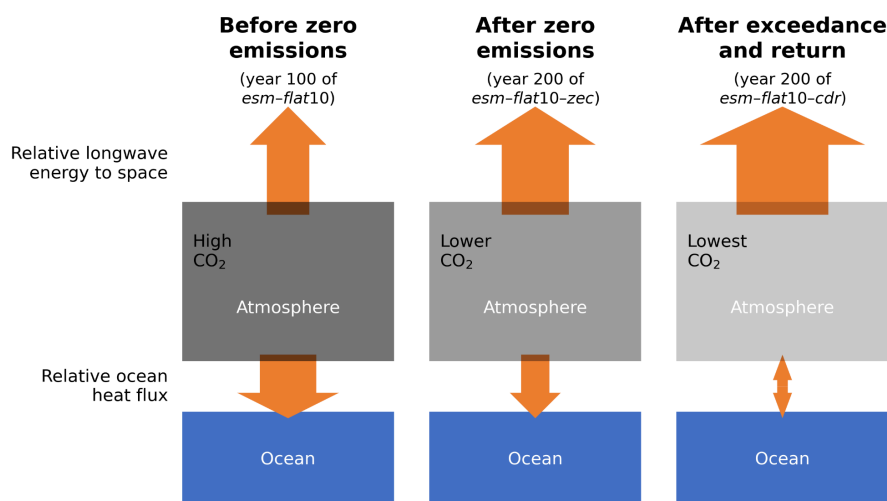


Figure 4 Schematic of relative differences in the energetic balance for the three time points considered here (year 100 of *esm-flat10*, year 200 of *esm-flat10-zec*, and year 200 of *esm-flat10-cdr*). All three time points have the same level of cumulative CO₂ emissions, and similar global mean surface air temperature, which reflects different energetic balance due to the differing atmospheric CO₂ concentrations and ocean heat uptake between the three points. Prior to net zero (left), concentrations are highest, inhibiting radiative loss to space and leading to ocean heat uptake and warming. After zero emissions (center), CO₂ concentrations decline, allowing greater radiative heat loss, which is roughly balanced by the decline in ocean heat uptake to give a similar global temperature. After exceedance and return (right), concentrations are lower still, allowing further radiative energy loss, while ocean heat uptake declines further and reverses sign to become a small net ocean heat source to the atmosphere either before or after the time point of interest, depending on models (Romanou et al., in prep), again leading to similar global temperature.



The changing relationship between global temperature and precipitation after net zero can be seen more clearly in Fig. 5, which shows the changes in temperature and precipitation relative to the first two decades of the *esm-flat10* simulation plotted against each other. As expected based on energetic constraints to precipitation changes (Held and Soden 2006), under the positive emissions of the *esm-flat10* experiment, precipitation increases by 1-2 %/°C (median 1.4%/°C) across the ensemble. Under zero emissions, the precipitation relationship to global temperature has a steeper slope (median 2.2%/°C) in all but one ESM, where the one exception (MIP-ESM) has a strongly negative ZEC. Under negative emissions (*esm-flat10-cdr*, after year 150) the precipitation response returns to a similar slope as under positive emissions (median 1.3%/°C), but with a substantial offset (median 0.8% increase in precipitation) that is consistent with the time-integrated change under zero emissions. For all regressions shown in Fig. 5, slopes are significantly different from zero, and all regressions for *esm-flat10-zec* and *esm-flat10-cdr* have slopes and/or intercepts that are significantly different from those of the corresponding *esm-flat10* regressions based on a Chow test at 0.05 significance level. The change in slope under zero emissions, and consistent positive offset under negative emissions, shows a consistency towards greater total precipitation at a given global temperature under both zero emissions and net-negative emissions, even if global temperatures decrease. This also explains the lack of a consistent increase in precipitation under zero emissions reported in (Borowiak et al. 2024), where the one model that showed a global precipitation decrease (also MPI-ESM) also showed a strongly negative ZEC. Thus, at the global level, a substantial change in the relationship between temperature and precipitation change is expected to occur after net zero, towards higher global precipitation rates at a given global temperature, across pathways. We discuss this further in the discussion section.

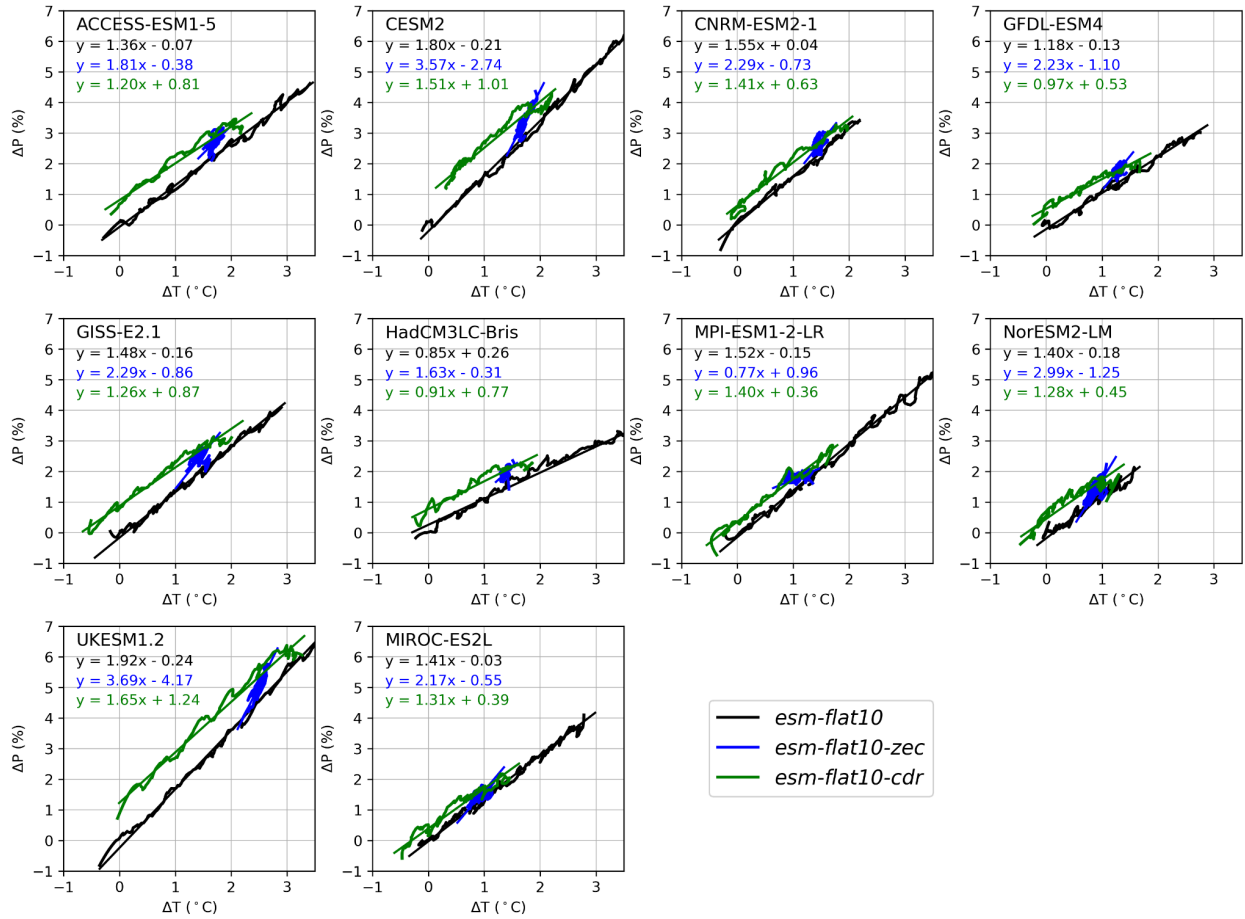


Figure 5: Temperature change versus precipitation change, both relative to the first two decades of the *esm-flat10* simulation, across all experiments and models. Regression equations apply to the *esm-flat10* data (black), *esm-flat10-zec* data (blue), and the post-net-zero period of the *esm-flat10-cdr* data (green). Individual-year data for each model was smoothed using a 15-year Savitzky-Golay filter for each curve, and unsmoothed data was used for regressions.

3.2 Regional Temperature Responses

Maps of the zero emissions response, the exceedance-and-return response, and the difference between the two responses, are shown for each ESM in Fig. 6. Stippling covers areas where the response for a given model lies between the 5th and 95th percentiles of pairs of randomly-chosen period differences from the control run. Most models show a similar spatial pattern between the zero emissions response and exceedance-and-return response. However, in some cases the pattern differs strongly between the zero emissions response and the exceedance-and-return response, either by being amplified (ACCESS-ESM1.5, UKESM1.2, MIROC-ES2L), weakened (NorESM2-LM), or just entirely different (GFDL-ESM4). Further, the consistency in spatial



temperature change patterns across models is weak, with no regions showing significant and consistent change across all the models for any of the responses.

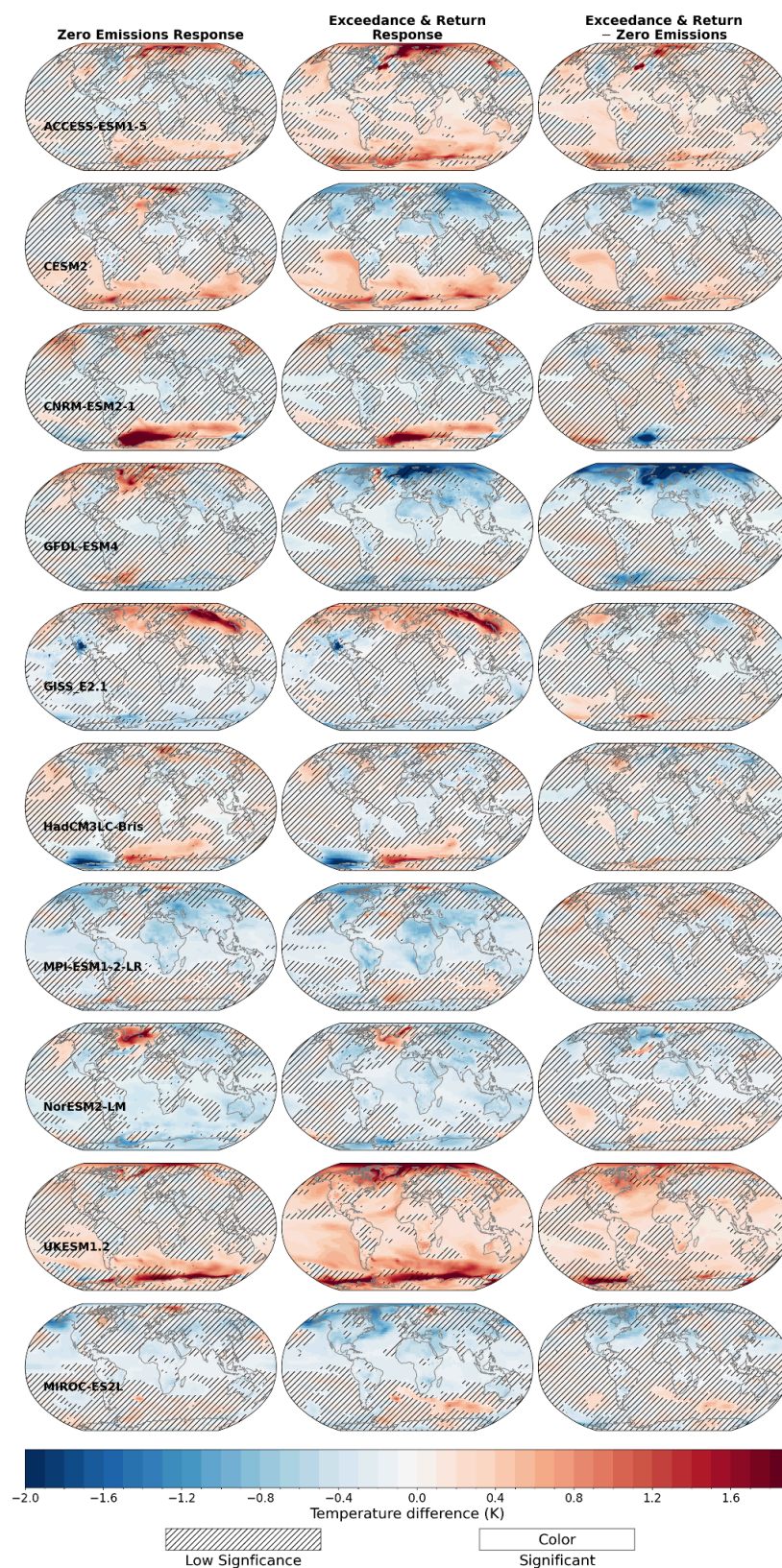




Figure 6. Maps of mean surface air temperature changes under zero emissions (left column) exceedance-and-return (middle column), and the difference between exceedance-and-return and zero emissions (right column). The zero emissions response is defined as year 200 of *esm-flat10-zec* minus year 100 of *esm-flat10*, and the exceedance-and-return response is defined as year 200 of *esm-flat10-cdr* minus year 100 of *esm-flat10*. Hatching indicates that the response is between the 5th and 95th percentiles of differences between pairs of random 30-year periods in the control simulation for each model and gridcell.

This lack of inter-model spatial pattern coherence can be further seen in Fig. 7, which shows the ensemble mean response, with stippling covering areas with less than 90% agreement in the sign of the response between models. For the zero emissions response, robust changes include cooling over some continental regions including Central Asia, Southern Africa, and the southern US, and warming over some ocean regions including the North Atlantic and parts of the Southern Ocean. For the exceedance-and-return response, again a large majority of the planet does not show a robust agreement in the sign of the response, but some further areas of common responses include cooling over land regions that include Central Asia, and parts of the Amazon and the US, and warming over parts of the Southern Ocean. For the difference between the exceedance-and-return and zero emissions responses, essentially no land regions show robust changes, while there is agreement for weak cooling in part of the Western Equatorial Pacific and warming in parts of the Southern Ocean. Taken together, these results mean that, under both zero emissions and exceedance-and-return pathways, there is model agreement that many land regions will cool relative to the climate just before zero emissions, however, there is not a robust signal in the sign of the difference between these pathways at these points.

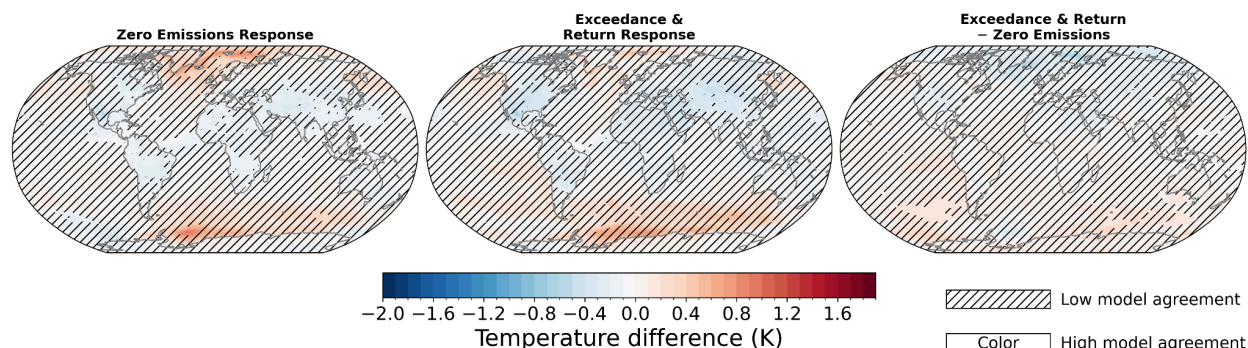


Figure 7. Multi-model mean regional temperature responses. Hatching indicates less than 90% agreement in the sign of the response between the models.

Separating gridcells based only on whether they are land or ocean (using a 10% land fraction as the masking condition), and looking at aggregate changes to the histograms of area-weighted gridcell-level temperature in each response (Fig. 8) shows a more consistent response. On land (Fig. 8, upper panels), the ensemble mean response is one of widespread cooling for both the zero-emissions and exceedance-and-return responses (medians -0.12 and -0.15 °C). The difference between the two responses over land is also broadly negative (median -0.04), showing that the exceedance-and-return response is a stronger cooling than the zero-emissions response, and supporting the hypothesis that the exceedance-and-return response should be amplified relative to the



zero-emissions response. Over the oceans (Fig. 8, lower panels), the histograms for both responses show a peak just below zero (medians -0.04 and -0.02 °C), but offset by tails extending farther into positive temperatures, and no clear pattern in the difference between the two responses (median 0.01 °C). In all cases, median values lie outside the 5th-95th percentiles of equivalent differences in the ensemble means of paired 30-year periods from PI control runs (± 0.005 °C land and ± 0.003 °C ocean). However, none of the ensemble mean values of mean land or ocean temperature changes in any of the three responses are more than one ensemble standard deviation of the mean land or ocean response away from zero, indicating that the structural uncertainty remains dominant even at this aggregated level.

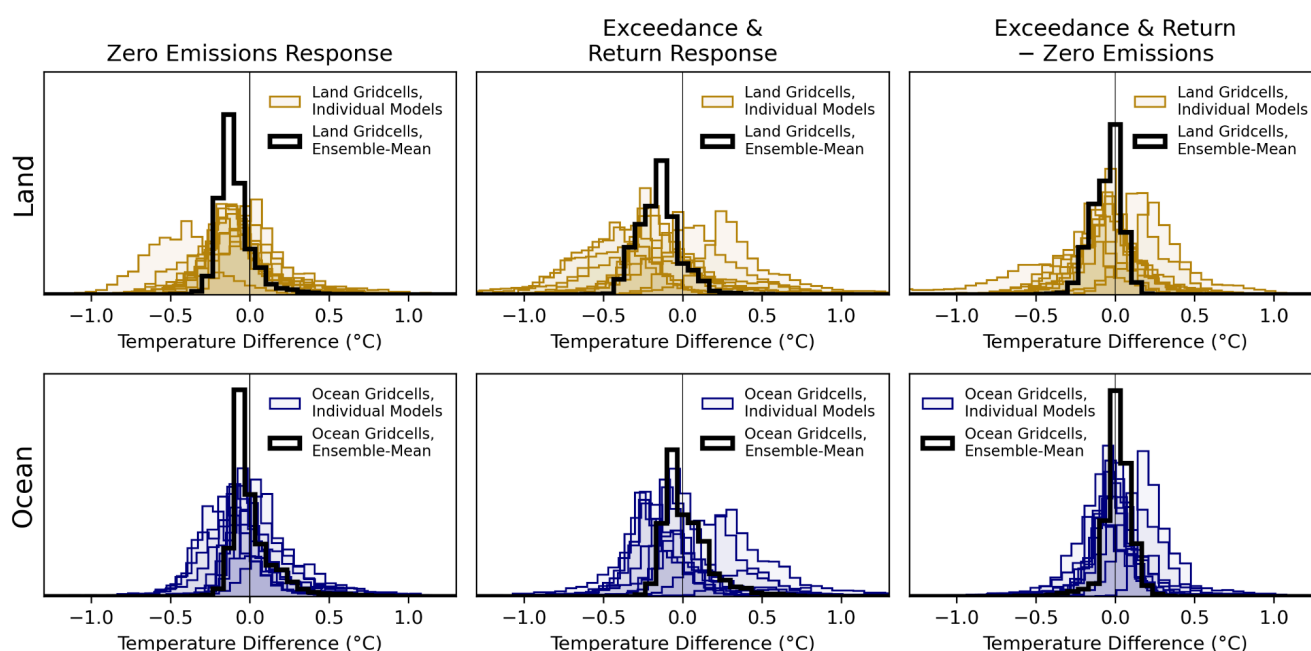


Figure 8. Land-ocean Differences in temperature responses. Histograms of area-weighted gridcell-level temperature responses on land (top row) and over the ocean (bottom row). Zero-emissions response (left column), Exceedance-and-return response (center column) and the difference between the exceedance-and-return and zero-emissions responses (right column). Thick black lines show histograms of the multi-model ensemble mean temperature response, colored lines show the individual-model histograms on land (brown) and ocean (blue).

To more clearly investigate whether the differential land-ocean temperature responses are driven by changes in the global mean temperature, figure 9 shows, for each model, the average land minus average ocean surface air temperatures as a function of global mean surface air temperature. For the *esm-flat10* experiment in all models, there is a proportional relationship between the two quantities, as seen in previous global warming experiments and expected from theory (Joshi et al. 2008; Byrne and O’Gorman 2013). After net zero, however, about half of the models show a different response, with cooler land for a given temperature than under warming; the other half



of the models follow the same rough relationship, although only the NorESM regression for *esm-flat10-zec* is statistically indistinguishable from its *esm-flat10* regression, with all other models showing statistically significant differences in regression slopes and/or intercepts in *esm-flat10-zec* and *esm-flat10-cdr* than for *esm-flat10* based on a Chow test at 0.05 level. There is thus not a uniform response across models in the relative amplification of total global warming over land relative to the ocean after net zero, with either no clear change or a tendency towards a decrease in the land-ocean temperature gradient at a given global mean surface temperature after net zero. We discuss this further in the discussion section.

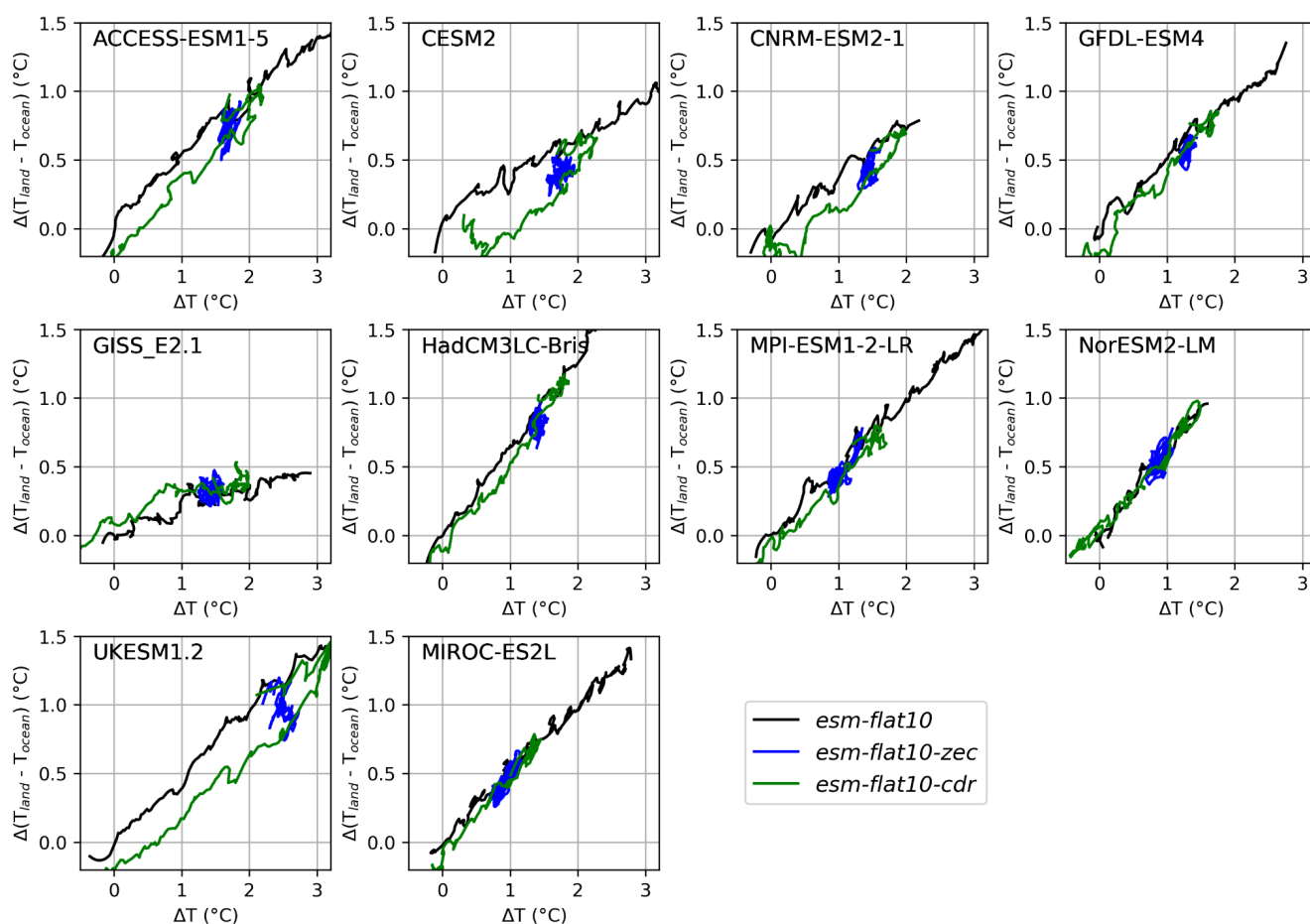


Figure 9. Changes in the global mean surface air temperature versus changes in the difference between the surface air temperature averaged over all global land areas minus the surface air temperature averaged over all global ocean areas.

To better quantify the degree of similarity between the regional zero emissions and exceedance-and-return temperature responses, Fig. 10 shows, for each model, the gridcell-level relationships between the two responses. For all but one model, there is a clear positive relationship between the two, with regression slopes ranging from



0.58 to 1.25 (median 0.87), and regression r^2 values ranging from 0.4 to 0.77 (median 0.63). The cooler land than ocean responses can be seen in the relative separation of the land and ocean gridcells in this space. The one outlier model, GFDL-ESM4, shows a dramatically different pattern of temperature change in the exceedance-and-return and zero emissions responses, with substantial cooling over the North Atlantic in the exceedance-and-return response but warming there in the zero emissions response.

Given that the regression slopes between the zero emissions and exceedance-and-return responses are, aside from the one exception, all positive, and many cluster around a value of one, we also compute the r^2 values for the 1:1 line between the two responses. Again, for most models the zero emissions response directly predicts a substantial fraction of the regional variance in the exceedance-and-return response, with R^2 values of the 1:1 line ranging from -0.9 to 0.75, and a median value of 0.54. Thus, roughly half of the regional variance in exceedance-and-return responses is directly predicted by the zero emissions responses. Though we note the bimodality, whereby one model (GFDL-ESM4) is behaving opposite the others in its relationship between the two responses.

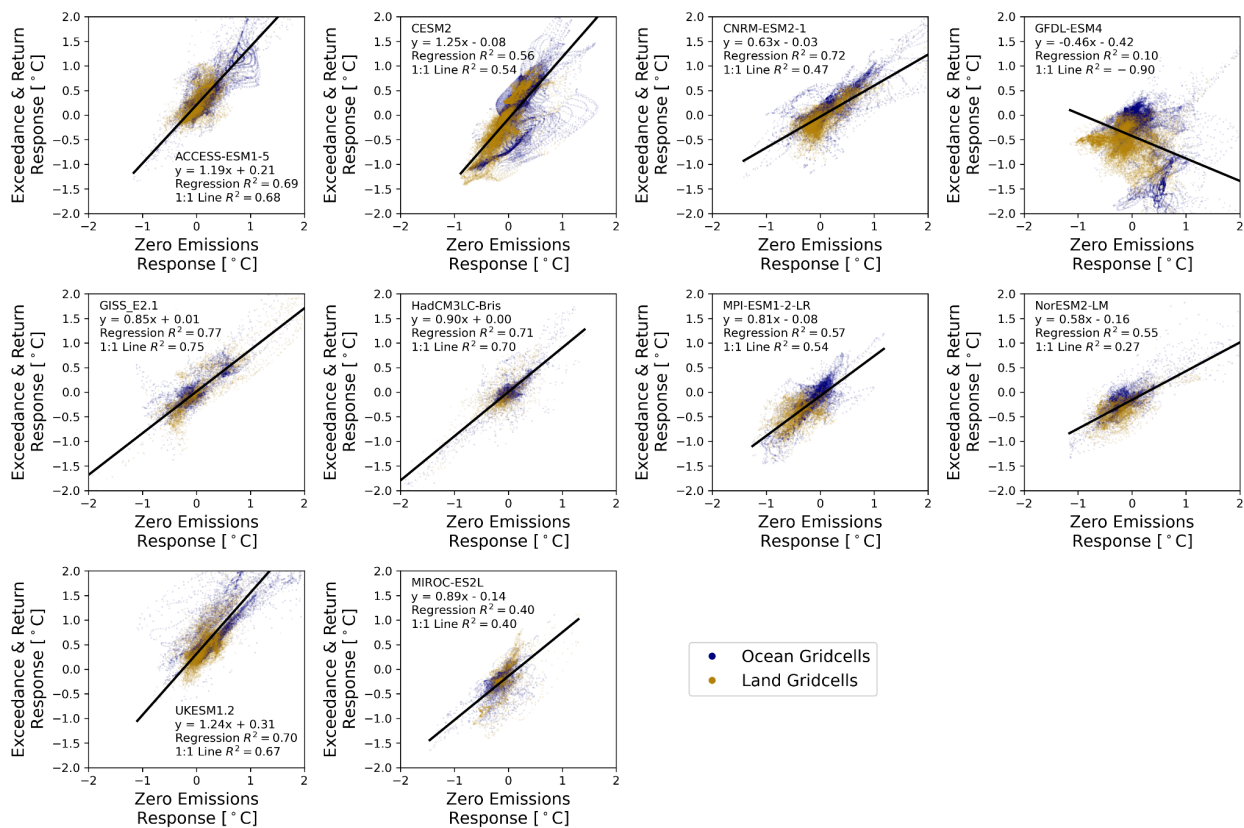


Figure 10: Regional exceedance-and-return responses for surface air temperature (difference of period centered on year 200 of *esm-flat10-cdr* experiment relative to the period centered on year 100 of *esm-flat10*)



experiment) as compared to zero emissions responses (difference of period centered on year 200 of *esm-flat10-zec* experiment relative to the period centered on year 100 of *esm-flat10* experiment).

3.3 Regional Precipitation Responses

Regional patterns of precipitation changes for the zero emissions response, exceedance-and-return response, and exceedance-and-return minus zero emissions response are shown in Fig. 11. As with the temperature maps shown in Fig. 6, stippling covers areas where the response for a given model lies between the 5th and 95th percentiles of pairs of randomly-chosen period differences from the control run. There is substantial disagreement between models in each of the patterns, and much less of a response in all models that is significantly outside the range of unforced variability. Further, the correspondence between the exceedance-and-return response and zero emissions response for any given model is substantially weaker for precipitation than for temperature. Several of the models show asymmetric responses between the ITCZ precipitation in each hemisphere, which in some cases (e.g., ACCES-ESM1.5, GFDL-ESM4) have a consistent sign in the zero emissions and exceedance-and-return responses, while in other cases (e.g. CESM2, HadCM3LC-Bris) the two responses differ in the sign of their hemispheric asymmetry.

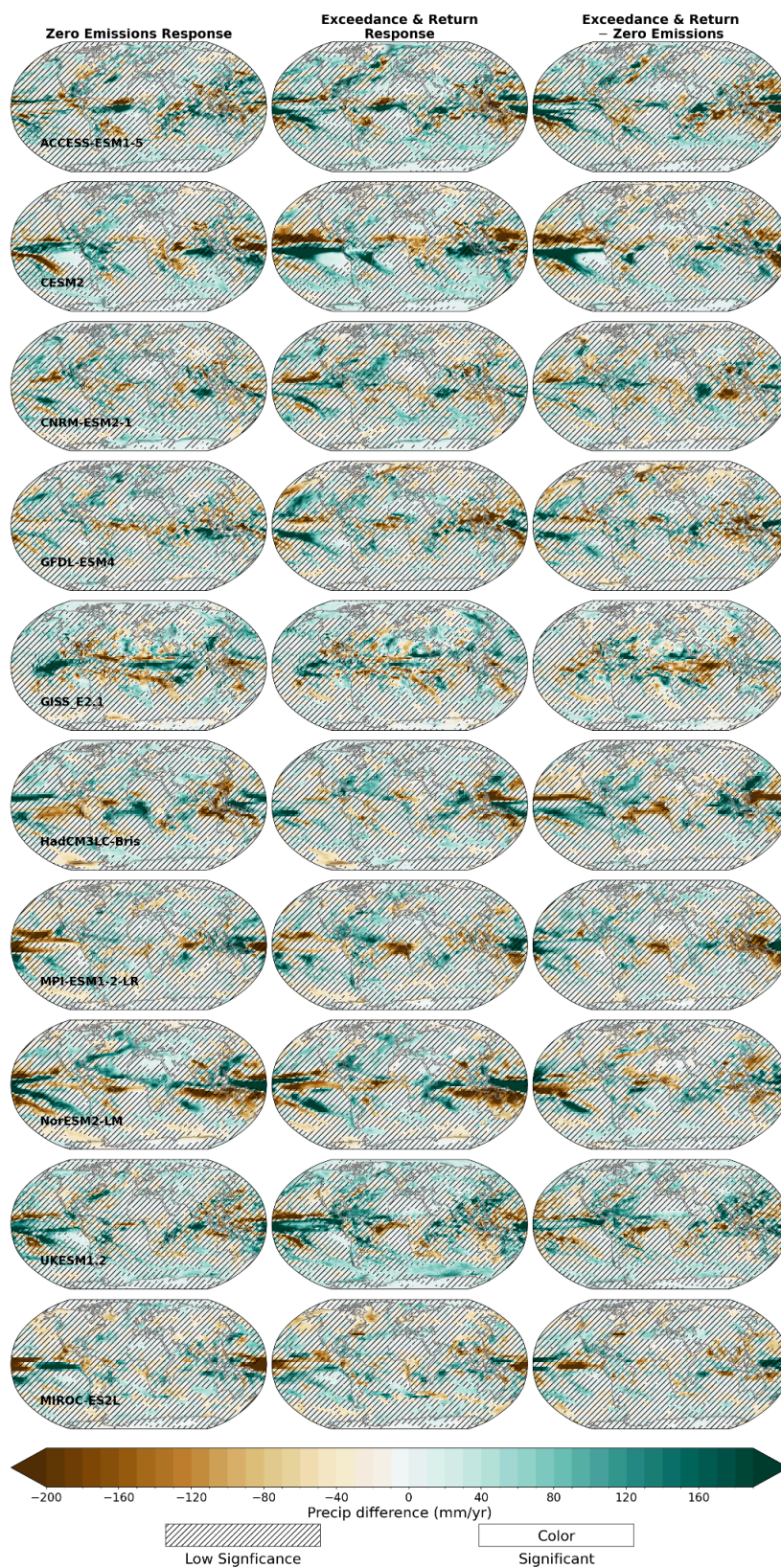




Figure 11: Maps of mean precipitation changes under zero emissions (left column) net-negative emissions (middle column), and the difference between net-negative and zero emission (right column). Hatching indicates that the response is between the 5th and 95th percentiles of differences between pairs of random 30 year periods in the esm-piControl simulation for that model and gridcell.

Ensemble-mean precipitation response maps (Fig. 12) show very little agreement between the predicted sign of the response across models, particularly for the zero emissions response where only small patches of ocean, and almost no land, show a consistent response. One consistent pattern is an increase in precipitation in the North Atlantic, which may be driven by the consistent increase in temperature in that region shown in figure 7. There is somewhat greater agreement in the exceedance-and-return response for an increase in precipitation in the southern tropical Pacific, which is consistent with previous research using a different idealized negative emission scenario (Kug et al. 2022). In addition, there is a robust prediction of increased precipitation in the subtropical Atlantic, as well as a reduction in precipitation over tropical Africa across the ensemble in the exceedance-and-return response.

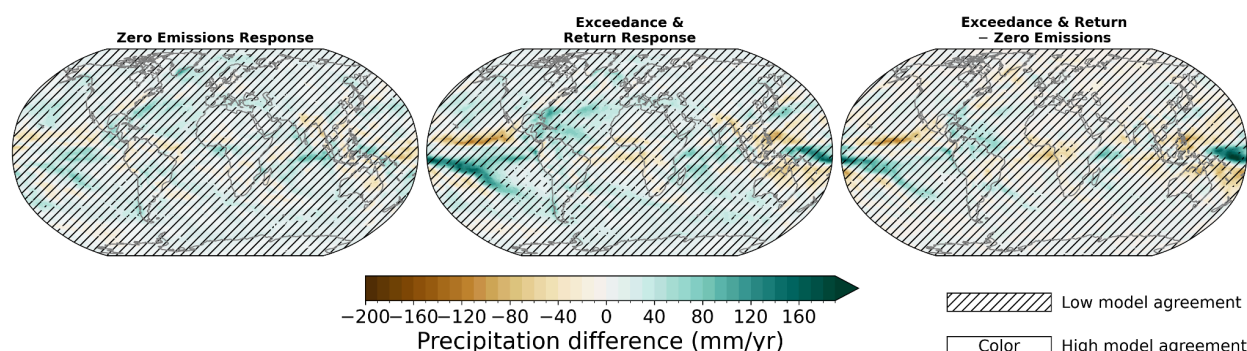


Figure 12: Multi-model mean regional precipitation responses. Hatching indicates less than 90% agreement in the sign of the response between the models.

Aggregating again across land and ocean regions to highlight the overall differences in the responses between the two domains, Fig. 13 shows histograms of each of the precipitation responses. As with Fig. 8, clear differences in the patterns can be seen over land and ocean. Over land, the ensemble mean histograms in both responses broadly show a tendency towards increased precipitation (median values 2.2 and 3.1 mm/yr). The difference between the two over land is more symmetric around zero (median value 0.55), so showing only weak evidence for an amplified exceedance-and-return relative to a zero-emissions response. Over the oceans, the histograms are more shifted than over land towards positive precipitation responses (median values 6.5 and 9.2 mm/yr), and with a clearer difference (median value 2.4 mm/yr) showing an amplified exceedance-and-return response than the zero-emissions response. As with temperature, in all cases, median values lie outside the 5th-95th percentiles of equivalent differences in the ensemble means of paired 30-year periods from PI control runs (± 0.15 mm/yr land and ± 0.13 mm/yr ocean), but none of the ensemble mean values of mean land or ocean precipitation changes are more than one ensemble standard deviation away from zero.

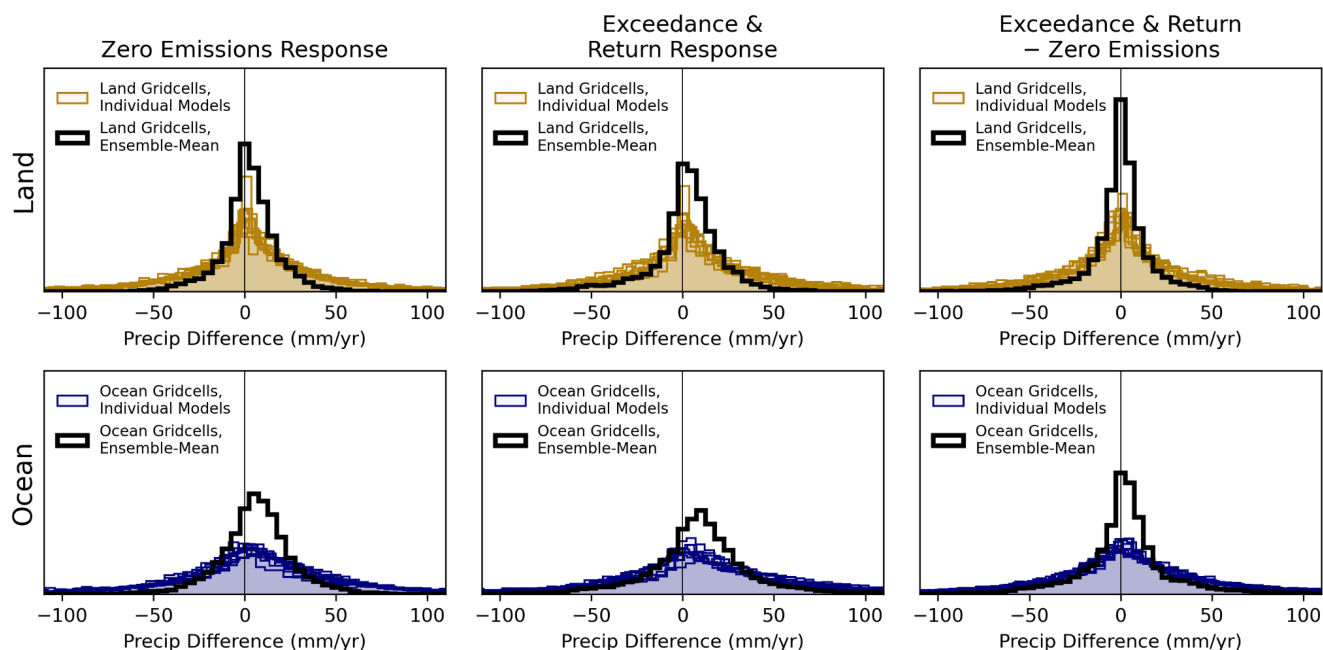


Figure 13: Land-ocean Differences in precipitation responses. Histograms of gridcell-level precipitation responses on land (top row) and over the ocean (bottom row). Zero-emissions response (left column), Exceedance-and-return response (center column) and the difference between the exceedance-and-return and zero-emissions responses (right column). Thick black lines show histograms of the multi-model ensemble mean response, colored lines show the individual-model histograms on land (brown) and ocean (blue).

Scatterplots of the zero emissions and exceedance-and-return responses for each model (Fig. 14) support the much poorer correspondence for precipitation than for temperature. Regression lines are all less than one (0.41-0.79, median value 0.54), and the regression R^2 values are much lower (.15-.57, median value 0.25) than for temperature. Interestingly, the one model that has very low correlation between the zero emissions and exceedance-and-return responses for temperature, GFDL-ESM4, has one of the highest correlations for precipitation. The direct prediction of exceedance-and-return responses by zero emissions responses, as measured by the R^2 of the 1:1 lines in these plots, is much weaker, with values ranging from -.23 to .53 (median .08). Thus, little of the regional variance in precipitation response under exceedance-and-decline would also occur under zero emissions, unlike the case for temperature.

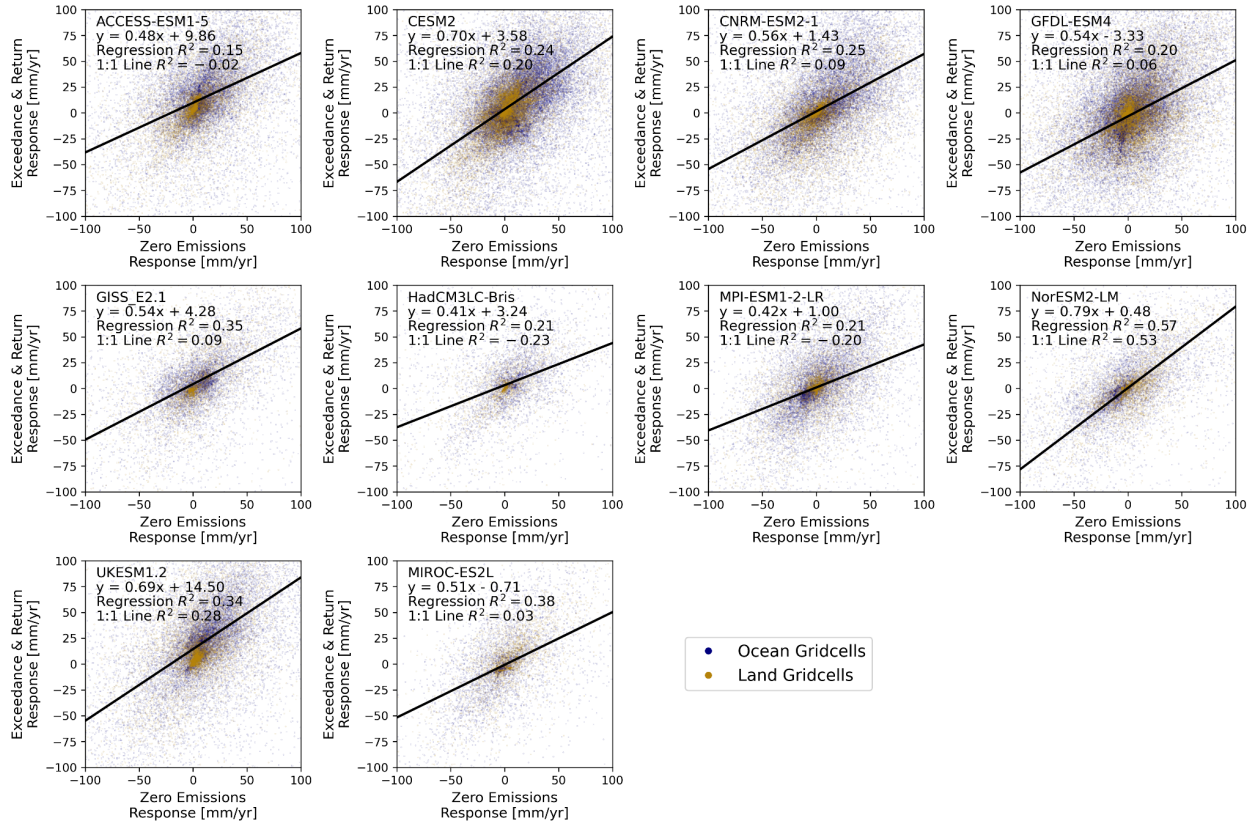


Figure 14: Regional exceedance-and-return responses for precipitation (difference of year 200 of *esm-flat10-cdr* experiment relative to year 100 of *esm-flat10* experiment) as compared to zero emissions responses (difference of year 200 of *esm-flat10-zec* experiment relative to year 100 of *esm-flat10* experiment).

4 Discussion

At the global scale, the ESMs all show a consistent pattern of increasing global precipitation at a given global temperature for both the *esm-flat10-zec* and *esm-flat10-cdr* experiments (Fig. 5). This response is consistent with that previously observed for CO₂ concentration stabilization and reversal experiments (Wu et al. 2010), as well as zero emissions experiments (Borowiak et al. 2024) and are explained by (Cao et al. 2011) as the differing response of precipitation to CO₂ on long and short timescales, as the reverse of what is seen under increasing CO₂ concentrations (Andrews et al. 2009). Because the energy released in the atmosphere through precipitation must be balanced by radiative energy loss, the addition of CO₂ on short timescales leads to a precipitation adjustment, whereby the increased CO₂ concentration decreases the longwave radiative loss to space and precipitation must decrease in response (Allen and Ingram 2002). Over longer timescales, this is offset by the hydrological sensitivity, whereby warming increases both ocean evaporation and radiative energy losses to space and, as a result, precipitation. The set of processes that gives rise to a near-zero ZEC also involve a tradeoff between these



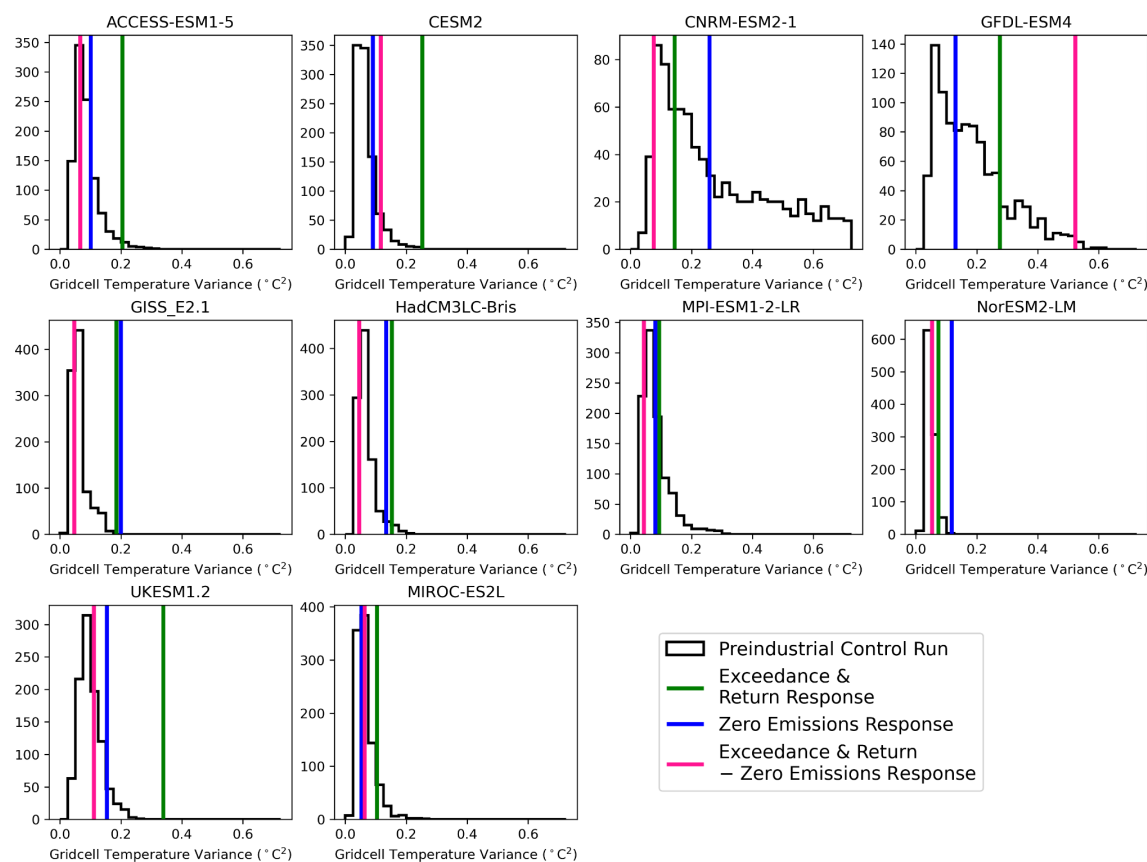
two timescales of atmospheric energetic balance responses to CO₂, as a near-zero ZEC is characterised by a decrease in atmospheric CO₂ concentrations due to continued but weakening carbon sinks in the land and ocean, which is offset by continued but declining ocean heat uptake (Palazzo Corner et al. 2023; Sanderson et al. 2026). At the same time as the ocean heat uptake weakens, CO₂ concentrations also drop and, as a result, the radiative loss of energy to space increases. The synchronized balance between these two shifts is what allows for global temperature stabilization under zero emissions, which here acts analogously to the fixed-SST experiments that are frequently used to quantify precipitation adjustment (Richardson et al. 2016). This response is stronger in *esm-flat10-cdr* than in *esm-flat10-zec* (fig. 4). From an atmospheric energetic perspective, this shift of energy from ocean heat sinks to radiative losses to space, all at a roughly constant temperature, means that precipitation should also increase to balance the increased radiative energy loss. This is roughly what is seen in all ESMs (Fig. 5) for the *esm-flat10-zec* experiment, and the offset in the *esm-flat10-zec* response is also observed in the increase in intercepts of the regression lines for the *esm-flat10-cdr* experiments. Further, in the ensemble mean, the precipitation increase is larger in the exceedance-and-return response than the zero-emissions response (fig. 8). Thus the increased precipitation at a given temperature reflects a common set of processes that occur after net zero, and which will be relatively stronger after negative emissions than under net zero at a given cumulative emissions level due to the lower CO₂ concentrations under such pathways.

(MacDougall et al. 2022) show similar patterns in the regional temperature changes under the ZECMIP experiment to what is shown here in Fig. 6. Notably, (MacDougall et al. 2022) point out the high inter-model variation in the projected response after zero emissions, as well as some common features such as the cooling over land relative to the ocean, is also shown here in Figs. 7 and 8. However, we note that the cooling over land relative to the ocean is not common across all models, hence the widespread hatching over most of the land surface in Fig. 7 despite the clear signal in the ensemble mean, as well as the different responses in different models in the relationship between global mean temperature change and land-sea temperature differential seen in Fig. 9. Both aspects of the cooling over land seen in the zero emissions response—the clear pattern in the ensemble mean and lack of high model agreement in sign—are also seen in the exceedance-and-return response, again indicating that this is a common feature of post-net-zero trajectories, although likely amplified under exceedance-and-return pathways than zero-emissions ones. The driver for this land-ocean temperature difference is unclear, as there are at least two potential mechanisms that might cause it. The first is that the lower CO₂ concentrations after net zero may lead to radiative cooling over land that is less balanced by greater ocean heat content than over the ocean. The second is that lower CO₂ concentrations and their physiological impact on plant functioning, in combination with changes to precipitation, may lead to changes in evapotranspiration, latent cooling, and relative humidity over land, which in turn may govern land-sea temperature contrasts via differential lapse rates over land and ocean (Joshi et al. 2008; Byrne and O’Gorman 2013). Separating these responses will be enabled by partially-coupled experiments in the proposed CMIP7 C4MIP experimental protocol (Arora et al., *in prep*).

In the initial flat10MIP experiment, there is only a single ensemble member of each model for each experiment, thus it is difficult to quantify how much of the observed changes are due to internal rather than forced variability. However, the pattern that roughly 50% of the variance in the exceedance-and-return response of regional



temperature change is common to the zero emissions response (median 1:1 line $R^2 = 0.54$ in Fig. 8) suggests that the remaining 50% must be shared between pathway-dependent forced changes in the exceedance-and-return response, and internal variability. Internal variability contributes strongly to regional variance, however the size of this contribution varies greatly between the pairs of random periods in the control run (Fig. 15), which prevents further decomposition of variance into forced and unforced responses. However, the greater-than-zero unforced variance implies that the forced exceedance-and-return-specific response must be smaller than the zero emissions response that is common to both experiments, at least for the median model. Further, there are effectively no consistent spatial patterns in the residual exceedance-and-return minus zero emissions response for temperature, particularly over land. Thus, while we can say that the regional exceedance-and-return responses will differ from the zero emissions responses, it is not clear how they will differ at any location.



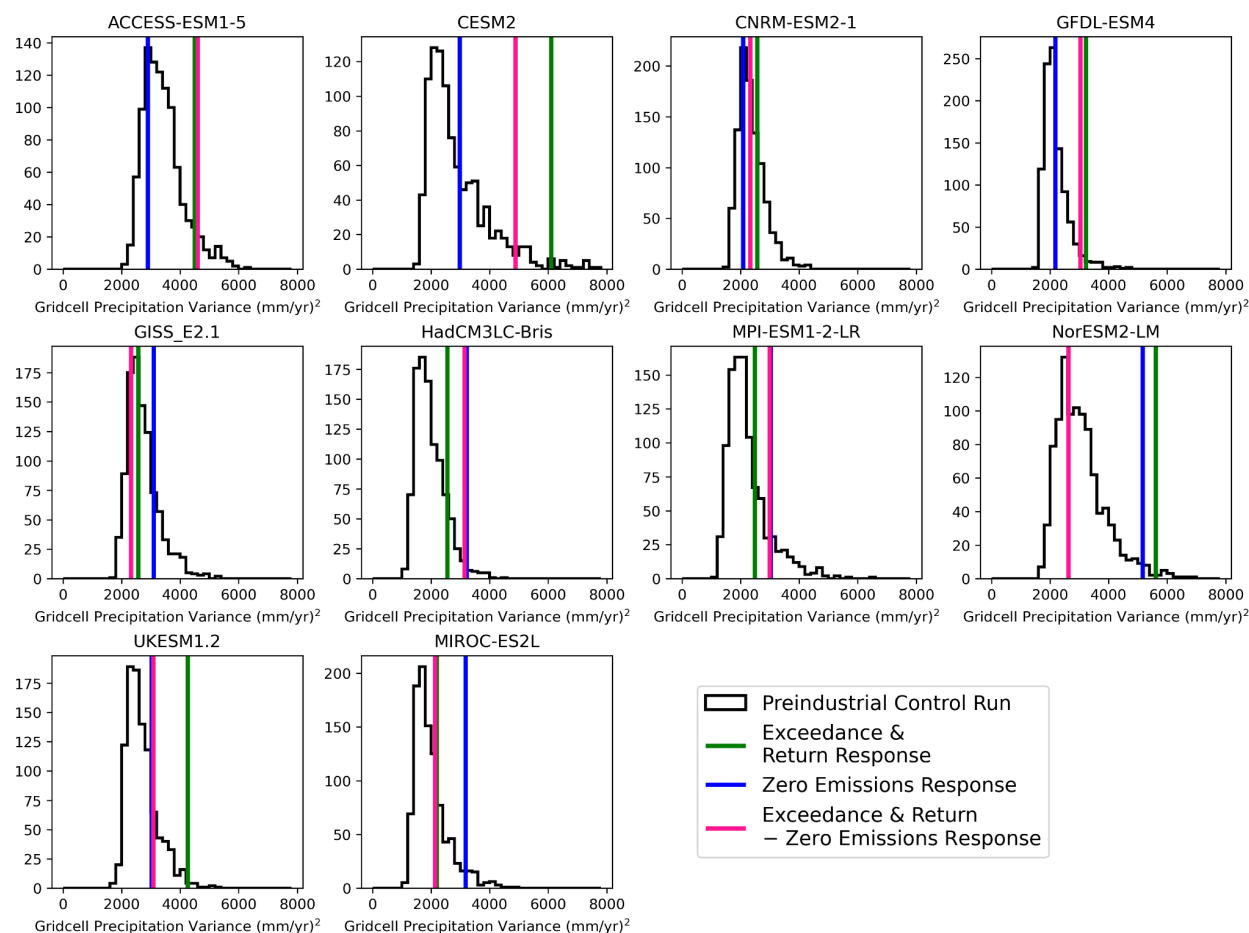


Figure 15. Histograms of global gridcell-level spatial variance in temperature and precipitation across the Zero Emissions and Exceedance and Return responses, as well as in a set of random differences between thirty-year periods in the preindustrial control runs.

However, the very different dynamics in some models, particularly GFDL-ESM4, which shows essentially no link in the temperature pattern between the two experiments, suggests the possibility for crossing thresholds in the *esm-flat10-cdr* experiment that lead to qualitatively different dynamics than expected under zero emissions. The specific pattern of temperature change in GFDL (cooling centered on the North Atlantic but extending throughout the northern hemisphere) suggests an AMOC-weakening origin. This is consistent with the idea that the additional emissions under the positive phase of the *esm-flat10-cdr* experiment might trigger a tipping dynamic that cannot be reversed under exceedance-and-return. (Schleussner et al. 2024), using a somewhat different experiential protocol, also point to AMOC as potentially governing a consistently different regional temperature response under overshoot than under zero emissions. Here, the North Atlantic-centered temperature



variability indicative of AMOC is not consistently different between the simulations, but rather as a possible difference, particularly where the overall regional variation in responses differ most strongly.

The dynamics of regional precipitation change are fundamentally different from those of regional temperature change. Despite the unambiguous global-mean increase in precipitation, there are even fewer areas of widespread model agreement in the sign of the response under either emissions pathway. One pattern that appears to be robust is the interhemispheric shift towards greater precipitation in the southern tropical Pacific under exceedance-and-return, which was also identified by (Kug et al. 2022; Steinert et al. 2025) under CO₂ concentration reversal experiments, and which is not observed consistently for the zero emissions experiment here. Further, a consistent pattern across models is that the zero emissions response in precipitation is less predictive of the exceedance-and-return response (median 1:1 line $R^2 = 0.09$) than it is for temperature. It is possible that the relative magnitude of internal variability to forced response is larger for precipitation than for temperature, but we do not separate these contributions here since we have only the single ensemble member. Nonetheless the results here point to a greater degree of pathway dependence in the regional variability of precipitation change than for temperature change.

The hypothesis that a given exceedance-and-return response should be amplified relative to the zero-emissions one, based on the lower CO₂ concentration at year 200 of *esm-flat10-cdr* relative to *esm-flat10-zec* despite the same level of cumulative emissions (schematic in Fig. 4), is partially supported by the aggregated temperature change histograms in Fig. 8 and more strongly for the aggregated precipitation change histograms in Fig. 13, but not clearly supported by the gridcell-level spatial patterns or correlations in the responses of the two experiments. Taken together, these point to a greater confidence that there will be a consistent set of changes to temperature (with cooler land than ocean) and that a greater amount of precipitation will occur, on a given timescale under pathways that exceed and then return to a given temperature than under ones that stabilize via zero emissions, but with little confidence in the spatial patterns associated with those changes.

Taken together, the results discussed above support a conclusion that, for regional temperature change, the hysteretic aspects under several decades-worth (here, 250 Pg C) of cumulative CO₂ emissions followed by removal are likely to be smaller than the time-dependent changes that would happen even without the additional emissions and removal. However, the risk of crossing some threshold that substantially changes the dynamics of the climate system increases as a result of the additional emissions and removal. And other aspects of the climate system, such as regional precipitation variability, may be more pathway-dependent and more prone to irreversible changes than regional temperature variation.



5 Conclusions

The idealized emissions-driven experimental design of flat10MIP allows a straightforward comparison of the differing response of the coupled carbon-climate system to either an abrupt zeroing of CO₂ emissions to one where emissions gradually decline to zero and then proceed on to net negative emissions, returning to the same level of cumulative emissions as in the net zero case after a period of time. This lets us separate the time-evolving response of the Earth system to the forced response of positive and then negative emissions. We note that although the three analysis points share the same cumulative emissions (1000 Pg C), they do not share the same atmospheric CO₂ concentration, due to their differing emissions pathways (Fig. 3). The airborne fraction depends on the rate and direction of emissions, so the year-200 *esm-flat10-zec* and year-200 *esm-flat10-cdr* states reach 1000 Pg C along different uptake histories that differ in concentration, and therefore in CO₂ radiative forcing, (fig. 4) at the comparison point. This distinction matters particularly for the precipitation analysis, where a residual difference in concentration drives a fast atmospheric energetic response that is separable from the slow temperature-mediated response.

Overall, we find several aspects of the climate system are consistent between these two emissions pathways. Approximately half of the regional variance in temperature change is common to both pathways, although the differences between models are large both in how much variance is shared, as well as the specific temperature patterns associated with either pathway. For precipitation, at the global scale, there is a shared dependency on time such that global precipitation increases for a given warming level under both the abrupt zero emissions and during the gradual transition from positive to negative emissions. Regionally, there is little consistent pattern across models for the response to zero emissions, but a more consistent increase in Southern Tropical Pacific under negative emissions. Less of the regional variance in precipitation is shared between the two scenarios than for temperature. At the same time, we show that key aggregated responses are amplified under exceedance-and return relative to the zero-emissions response, in particular a stronger land-ocean temperature contrast and precipitation increase in the ensemble mean, driven by roughly half the models..

These results inform the expected response of the climate system to mitigation in a few key ways. The observation that about half of the regional variation in temperature under negative emissions also occurs under positive emissions suggests that much of the regional changes are shared across a wide set of post-zero-emission pathways, and so will occur regardless of whether climate is stabilized at a given warming level or that warming level is first exceeded and then returned to. However, other aspects will differ strongly between these pathways,



in particular for regional changes to precipitation. This supports the idea that we must both not be overconfident that regional climate changes can be straightforwardly reversed through negative emissions, even if such an approach is effective in reversing global mean temperatures, and that we should focus efforts to better understand the expected ongoing changes to the climate system that will occur after we reach net zero, even as we pursue efforts to achieve that goal as rapidly as possible.

Code and data availability

All analysis code required to reproduce all figures is available at https://github.com/ckoven/flat10mip_regional_climatechange. The flat10MIP data is available at <https://archive.sigma2.no/dataset/flat10-mip>. No AI Tools were used in writing or editing of manuscript. An AI tool (Google search) was used for short (<10 lines) contributions to data analysis and visualization codes.

Author contributions

CDK: Conceptualization, Formal analysis, Methodology, Visualization, Writing (original draft preparation).
CDK, VB, JD, RAF, TH, CDJ, SL, AR, ALSS, BMS, NJS, RS, JT, TZ: Writing (review and editing). All authors: Data curation, Software, Resources, Investigation.

Competing interests

The authors declare that they have no conflict of interest.

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References

- Allen, Myles R., David J. Frame, Chris Huntingford, et al. 2009. "Warming Caused by Cumulative Carbon Emissions towards the Trillionth Tonne." *Nature* 458 (7242): 1163–1166.
- Allen, Myles R., Pierre Friedlingstein, Cécile A. J. Girardin, et al. 2022. "Net Zero: Science, Origins, and Implications." *Annual Review of Environment and Resources* 47 (1): 849–887.
- Allen, Myles R., and William J. Ingram. 2002. "Constraints on Future Changes in Climate and the Hydrologic Cycle." *Nature* 419 (6903): 224–232.
- Andrews, Timothy, Piers M. Forster, and Jonathan M. Gregory. 2009. "A Surface Energy Perspective on Climate Change." *Journal of Climate* 22 (10): 2557–2570.
- Asaadi, Ali, Jörg Schwinger, Hanna Lee, et al. 2024. "Carbon Cycle Feedbacks in an Idealized Simulation and a Scenario Simulation of Negative Emissions in CMIP6 Earth System Models." *Biogeosciences* 21 (2): 411–435.
- Bevacqua, Emanuele, Carl-Friedrich Schleussner, and Jakob Zscheischler. 2025. "A Year above 1.5 °C Signals That Earth Is Most Probably within the 20-Year Period That Will Reach the Paris Agreement Limit." *Nature Climate Change* 15 (3): 262–265.
- Borowiak, Alex, Andrew D. King, Josephine R. Brown, et al. 2024. "Projected Global Temperature Changes after Net Zero Are Small but Significant." *Geophysical Research Letters* 51 (8). <https://doi.org/10.1029/2024gl108654>.
- Bossert, Isaline, Roland Séférian, Yeray Santana-Falcón, and Thibault Guinaldo. 2026. "Ocean and Marine Heatwaves Responses to Multiple Net-Zero Worlds." *EGUsphere*, March 17, 1–32.
- Brovkin, Victor, Benjamin M. Sanderson, Noel G. Brizuela, et al. 2025. "On a Simplified Solution of Climate-Carbon Dynamics in Idealized flat10MIP Simulations." *Earth System Dynamics* 16 (6): 2021–2034.
- Byrne, Michael P., and Paul A. O’Gorman. 2013. "Land–ocean Warming Contrast over a Wide Range of Climates: Convective Quasi-Equilibrium Theory and Idealized Simulations." *Journal of Climate* 26 (12): 4000–4016.
- Cao, Long, Govindasamy Bala, and Ken Caldeira. 2011. "Why Is There a Short-Term Increase in Global Precipitation in Response to Diminished CO₂ forcing?" *Geophysical Research Letters* 38 (6). <https://doi.org/10.1029/2011gl046713>.
- Cassidy, Liam J., Andrew D. King, Josephine R. Brown, et al. 2024. "Regional Temperature Extremes and Vulnerability under Net Zero CO₂ Emissions." *Environmental Research Letters* 19 (1): 014051.
- Chimuka, V. Rachel, and Kirsten Zickfeld. 2026. "Asymmetry in Carbon Cycle Feedbacks and Transient Climate Response under Positive and Negative CO₂ Emissions." *EGUsphere*, January 12, 1–27.



- Danabasoglu, G., J. -F Lamarque, J. Bacmeister, et al. 2020. “The Community Earth System Model Version 2 (CESM2).” *Journal of Advances in Modeling Earth Systems* 12 (2): 106.
- Douglas, Hunter C., Laura E. Revell, Andrew King, Luke J. Harrington, and David J. Frame. 2025. “Effects of Temperature Overshoot Amplitude on Regional Climate.” *Environmental Research Letters* 20 (11): 114043.
- Dunne, J. P., L. W. Horowitz, A. J. Adcroft, et al. 2020. “The GFDL Earth System Model Version 4.1 (GFDL-ESM 4.1): Overall Coupled Model Description and Simulation Characteristics.” *Journal of Advances in Modeling Earth Systems* 12 (11). <https://doi.org/10.1029/2019ms002015>.
- Hajima, Tomohiro, Michio Watanabe, Akitomo Yamamoto, et al. 2020. “Development of the MIROC-ES2L Earth System Model and the Evaluation of Biogeochemical Processes and Feedbacks.” *Geoscientific Model Development* 13 (5): 2197–2244.
- Held, Isaac M., and Brian J. Soden. 2006. “Robust Responses of the Hydrological Cycle to Global Warming.” *Journal of Climate* 19 (21): 5686–5699.
- IPCC. 2021. “Summary For Policymakers.” In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by V. Masson-Delmotte, P. Zhai, A. Pirani, et al.
- Joshi, Manoj M., Jonathan M. Gregory, Mark J. Webb, David M. H. Sexton, and Tim C. Johns. 2008. “Mechanisms for the Land/sea Warming Contrast Exhibited by Simulations of Climate Change.” *Climate Dynamics* 30 (5): 455–465.
- Kelley, Maxwell, Gavin A. Schmidt, Larissa S. Nazarenko, et al. 2020. “GISS-E2.1: Configurations and Climatology.” *Journal of Advances in Modeling Earth Systems* 12 (8): e2019MS002025.
- Kim, Soong-Ki, Jongsoo Shin, Soon-Il An, et al. 2022. “Widespread Irreversible Changes in Surface Temperature and Precipitation in Response to CO₂ Forcing.” *Nature Climate Change* 12 (9): 834–840.
- Koven, Charles D., Vivek K. Arora, Patricia Cadule, et al. 2022. “Multi-Century Dynamics of the Climate and Carbon Cycle under Both High and Net Negative Emissions Scenarios.” *Earth System Dynamics* 13 (2): 885–909.
- Koven, Charles D., Benjamin M. Sanderson, and Abigail L. S. Swann. 2023. “Much of Zero Emissions Commitment Occurs before Reaching Net Zero Emissions.” *Environmental Research Letters* 18 (1): 014017.
- Kug, Jong-Seong, Ji-Hoon Oh, Soon-Il An, et al. 2022. “Hysteresis of the Intertropical Convergence Zone to CO₂ Forcing.” *Nature Climate Change* 12 (1): 47–53.
- MacDougall, Andrew H., Thomas L. Frölicher, Chris D. Jones, et al. 2020. “Is There Warming in the Pipeline? A Multi-Model Analysis of the Zero Emissions Commitment from CO₂.” *Biogeosciences* 17 (11): 2987–3016.



- MacDougall, Andrew H., Josie Mallett, David Hohn, and Nadine Mengis. 2022. "Substantial Regional Climate Change Expected Following Cessation of CO₂ Emissions." *Environmental Research Letters*, ahead of print, November 2. <https://doi.org/10.1088/1748-9326/ac9f59>.
- Matthews, H. Damon, and Ken Caldeira. 2008. "Stabilizing Climate Requires Near-zero Emissions." *Geophysical Research Letters* 35 (4). <https://doi.org/10.1029/2007gl032388>.
- Matthews, H. Damon, Nathan P. Gillett, Peter A. Stott, and Kirsten Zickfeld. 2009. "The Proportionality of Global Warming to Cumulative Carbon Emissions." *Nature* 459 (7248): 829–832.
- Mauritsen, Thorsten, Jürgen Bader, Tobias Becker, et al. 2019. "Developments in the MPI-M Earth System Model Version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO₂." *Journal of Advances in Modeling Earth Systems* 11 (4): 998–1038.
- Mulcahy, Jane P., Colin G. Jones, Steven T. Rumbold, et al. 2023. "UKESM1.1: Development and Evaluation of an Updated Configuration of the UK Earth System Model." *Geoscientific Model Development* 16 (6): 1569–1600.
- Palazzo Corner, Sofia, Martin Siegert, Paulo Ceppi, et al. 2023. "The Zero Emissions Commitment and Climate Stabilization." *Frontiers in Science* 1 (November). <https://doi.org/10.3389/fsci.2023.1170744>.
- Pfleiderer, Peter, Carl-Friedrich Schleussner, and Jana Sillmann. 2024. "Limited Reversal of Regional Climate Signals in Overshoot Scenarios." *Environmental Research: Climate* 3 (1): 015005.
- Richardson, T. B., B. H. Samset, T. Andrews, G. Myhre, and P. M. Forster. 2016. "An Assessment of Precipitation Adjustment and Feedback Computation Methods." *Journal of Geophysical Research: Atmospheres* 121 (19): 11,608–11,619.
- Rogelj, Joeri, Anna Pirani, Andy Reisinger, and Carl-Friedrich Schleussner. 2026. "Practical Guidance towards Consistent Use of Overshoot Terminology." *Environmental Research Letters* 21 (11): 110201.
- Roldán-Gómez, Pedro José, Paolo De Luca, Raffaele Bernardello, and Markus G. Donat. 2025. "Regional Irreversibility of Mean and Extreme Surface Air Temperature and Precipitation in CMIP6 Overshoot Scenarios Associated with Interhemispheric Temperature Asymmetries." *Earth System Dynamics* 16 (1): 1–27.
- Sanderson, Benjamin M., Victor Brovkin, Rosie A. Fisher, et al. 2025. "flat10MIP: An Emissions-Driven Experiment to Diagnose the Climate Response to Positive, Zero and Negative CO₂ Emissions." *Geoscientific Model Development* 18 (17): 5699–5724.
- Sanderson, Benjamin M., Marit Sandstad, Alejandro Romero-Prieto, et al. 2026. "Decomposition of the Zero Emissions Commitment into Thermal Warming Pipeline and Carbon Buffering Components." May 19. <https://doi.org/10.5194/egusphere-2026-1875>.



- Schleussner, Carl-Friedrich, Gaurav Ganti, Quentin Lejeune, et al. 2024. “Overconfidence in Climate Overshoot.” *Nature* 634 (8033): 366–373.
- Séférian, Roland, Pierre Nabat, Martine Michou, et al. 2019. “Evaluation of CNRM Earth System Model, CNRM-ESM2-1: Role of Earth System Processes in Present-day and Future Climate.” *Journal of Advances in Modeling Earth Systems* 11 (12): 4182–4227.
- Seland, Øyvind, Mats Bentsen, Dirk Olivié, et al. 2020. “Overview of the Norwegian Earth System Model (NorESM2) and Key Climate Response of CMIP6 DECK, Historical, and Scenario Simulations.” *Geoscientific Model Development* 13 (12): 6165–6200.
- Solomon, Susan, Gian-Kasper Plattner, Reto Knutti, and Pierre Friedlingstein. 2009. “Irreversible Climate Change due to Carbon Dioxide Emissions.” *Proceedings of the National Academy of Sciences of the United States of America* 106 (6): 1704–1709.
- Steinert, Norman Julius, Jörg Schwinger, Robin Chadwick, Jong-Seong Kug, and Hanna Lee. 2025. “Irreversible Land Water Availability Changes from a Potential ITCZ Shift during Temperature Overshoot.” *Earth’s Future* 13 (5). <https://doi.org/10.1029/2024ef005787>.
- Valdes, Paul J., Edward Armstrong, Marcus P. S. Badger, et al. 2017. “The BRIDGE HadCM3 Family of Climate Models: HadCM3@Bristol v1.0.” *Geoscientific Model Development* 10 (10): 3715–3743.
- Walton, Jeremy, and Chris Huntingford. 2024. “Little Evidence of Hysteresis in Regional Precipitation, When Indexed by Global Temperature Rise and Fall in an Overshoot Climate Simulation.” *Environmental Research Letters* 19 (8): 084028.
- Wu, Peili, Richard Wood, Jeff Ridley, and Jason Lowe. 2010. “Temporary Acceleration of the Hydrological Cycle in Response to a CO₂ Rampdown.” *Geophysical Research Letters* 37 (12). <https://doi.org/10.1029/2010gl043730>.
- Zickfeld, Kirsten, Andrew H. MacDougall, and H. Damon Matthews. 2016. “On the Proportionality between Global Temperature Change and Cumulative CO₂ Emissions during Periods of Net Negative CO₂ Emissions.” *Environmental Research Letters: ERL [Web Site]* 11 (5): 055006.
- Ziehn, Tilo, Matthew A. Chamberlain, Rachel M. Law, et al. 2020. “The Australian Earth System Model: ACCESS-ESM1.5.” *Journal of Southern Hemisphere Earth System Science* 70 (1): 193–214.