Proposal for *esm-flat10* - a potential emissions-driven diagnostic experiment for the CMIP7 DECK

Ben Sanderson[1], Isla Simpson[2], Charles Koven[3] and John Dunne[4]

1- CICERO Centre for International Climate and Environmental Research, Oslo, Norway
2 - National Center for Atmospheric Research, Boulder CO, USA

The CMIP DECK (Diagnostic, Evaluation, and Characterization of Klima) Experiments are a standardized set of experiments and simulations that were conducted as part of the Coupled Model Intercomparison Project Phase 6 (CMIP6). The DECK consists of a series of simulations that are designed to assess model performance and a minimal set of critical metrics of response of the Earth climate system to climate forcers. Early framing discussions for CMIP7 have recognised the need to accommodate a greater variety of models in the next phase - including computationally intensive high resolution configurations and a greater focus on emissions-driven simulations. Here we outline a candidate for an efficient ESM diagnostic experiment for the CMIP7 DECK to compute TCRE, ZEC and climate reversibility metrics in an efficient emissions-driven framework.

Description of novel experiments

We outline the novel experiments in Table 1 and the text below. Tier 1 experiments assess TCRE and ZEC, while tier 2 experiments measure idealized climate reversibility. We also illustrate the experiments using a 200 member perturbed ensemble of the FaIR simple climate model (Smith et al. 2018), using the methodology outlined in (Koven, Sanderson, and Swann 2023).

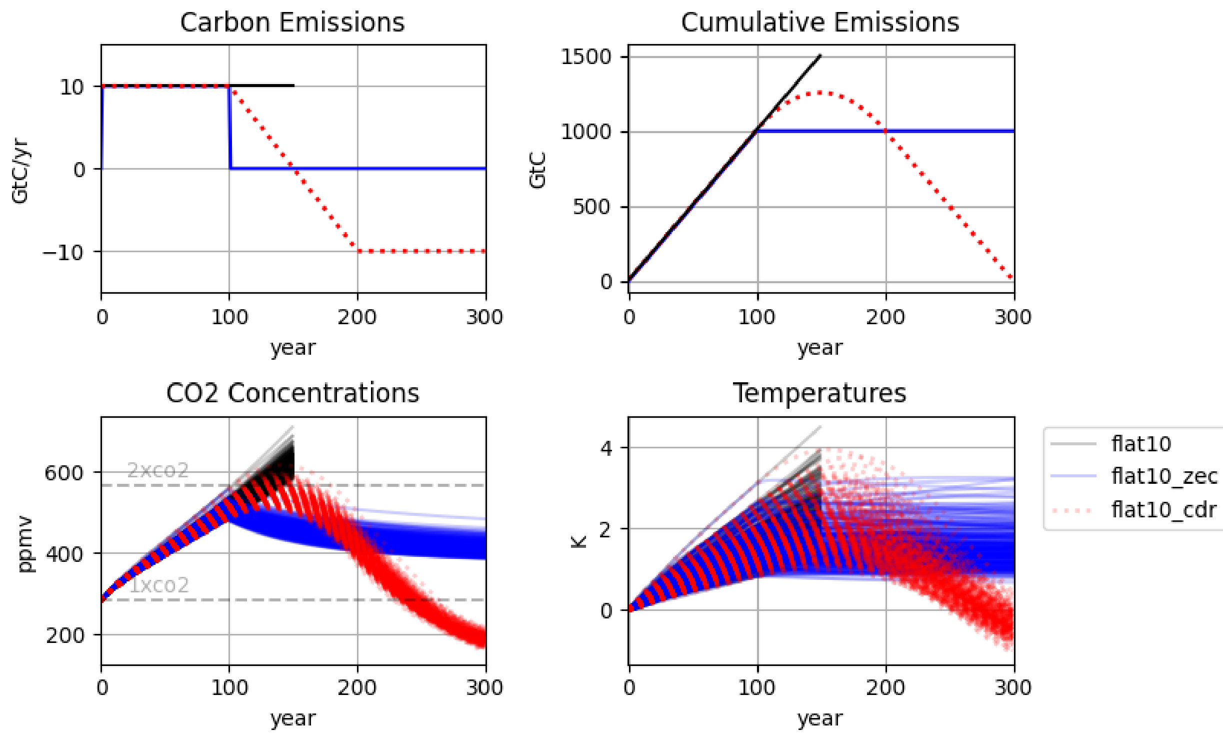

Figure 1: emissions, cumulative emissions, CO2 concentrations and Global Mean temperatures in the 4 proposed experiments (flat10, flat10_zec and flat10_cdr) as simulated in a perturbed ensemble of the simple climate model FaIR (Smith et al. 2018). Tier 1 experiments have solid lines, while tier 2 experiments are dotted.

Esm-flat10 [tier 1/high priority]

This experiment would serve as an emissions-driven experiment to diagnose the Transient Climate Response to cumulative Emissions (TCRE), which is the warming from pre-industrial levels observed after the emission of 1000PgC in a transient scenarios. The *esm-flat10* experiment would branch from a stable esm-pictrl simulation, with a constant annual prescribed anthropogenic flux of carbon of 10PgC/year into the atmosphere, with globally homogenous emissions. 150 years of simulation requested. In *esm-flat10,* the 1000PgC threshold would occur in year 100 - such that TCRE could be estimated as the time average between global mean warming in years 90-110, sampling over internal variability in this period. 150 years of simulation are requested to allow the simulation to reach 2x pre-industrial CO2 concentrations in most cases, allowing an independent calculation of TCRE as the product of TCR and airborne fraction at the point of CO2 doubling (for direct comparison with TCRE calculated from 1pctCO2).

Esm-flat10-zec [tier 1/high priority]

This experiment would serve as an emissions-driven experiment to diagnose the Zero Emissions Commitment (ZEC), which is the additional warming seen a certain number of years after the cessation of emissions. The *esm-flat10-zec* experiment would branch from year 100 of the esm-flat10 experiment, with an immediate cessation of emissions, such that the system is left to evolve for 200 years. ZEC50 would thus be the average temperatures in a 20 year period, 50 years after the cessation of emissions (i.e. years 140-160). ZEC100 would similarly be calculated as years 190-210). An additional metric (ZEC190) would be the time average of years 280-300.

Esm-flat10-cdr [tier 2]

This experiment would serve as an emissions-driven experiment to diagnose the response of the climate system to reducing, and ultimately reaching net-negative emissions and will provide a measure of climate reversibility when all cumulative anthropogenic emissions are removed at the end of the experiment. The *esm-flat10-cdr* experiment would branch from year 100 of the esm-flat10 experiment, with a linear ramp down of emissions (from a starting point of10PgC/yr) of -2PgC/decade - such that net zero emissions are achieved in year 150 and a negative flux of -10PgC/yr is achieved in year 200. A negative emission flux of -10PgC/yr would be then held constant from years 200-300, such that in year 300 - cumulative emissions from the start of the simulation would be zero.

Experiment	Branches from	Years	emissions	Metrics
Tier 1 (high priority) experiments				
esm-flat10	esm-pictrl	150 years (From year 0 to year 150)	10GtC/year constant emissions, globally homogenous flux	TCRE
esm-flat10_zec	esm-flat10 (branch year 100)	200 years (From year 100 to year 300)	0 GtC/yr constant	ZEC50 ZEC100 ZEC190
Tier 2 (lower priority) experiments				
esm-flat10_cdr	esm-flat10 (branch year 100)	210 years (From year 100 to year 310)	- Linearly declining emissions by 2GtC/decade from 10GtC/yr (year 100) to -10GtC/Yr (year 200) - Constant -10GtC/yr	TNZ, TR1000,TR0 (see last section)

			(years 200-300) - Zero emissions for year 300+ (optional)	

Comparison of TCRE and ZEC derived using concentration-driven metrics

In the CMIP6 design(Eyring et al. 2016), TCRE was calculated from the *1pctCO2,* calculating the warming in the year in which cumulative compatible emissions exceed 1000PgC. In *1pctCO2 -* these compatible emissions vary by model, such that the 1000PgC threshold varies by of order 5 years (see Figure 2). The compatible emissions also vary in time during the evolution of the 1pctCO2 experiment, with emissions disproportionately represented in the latter years of the experiment in *1pctCO2* (see Figure 2)

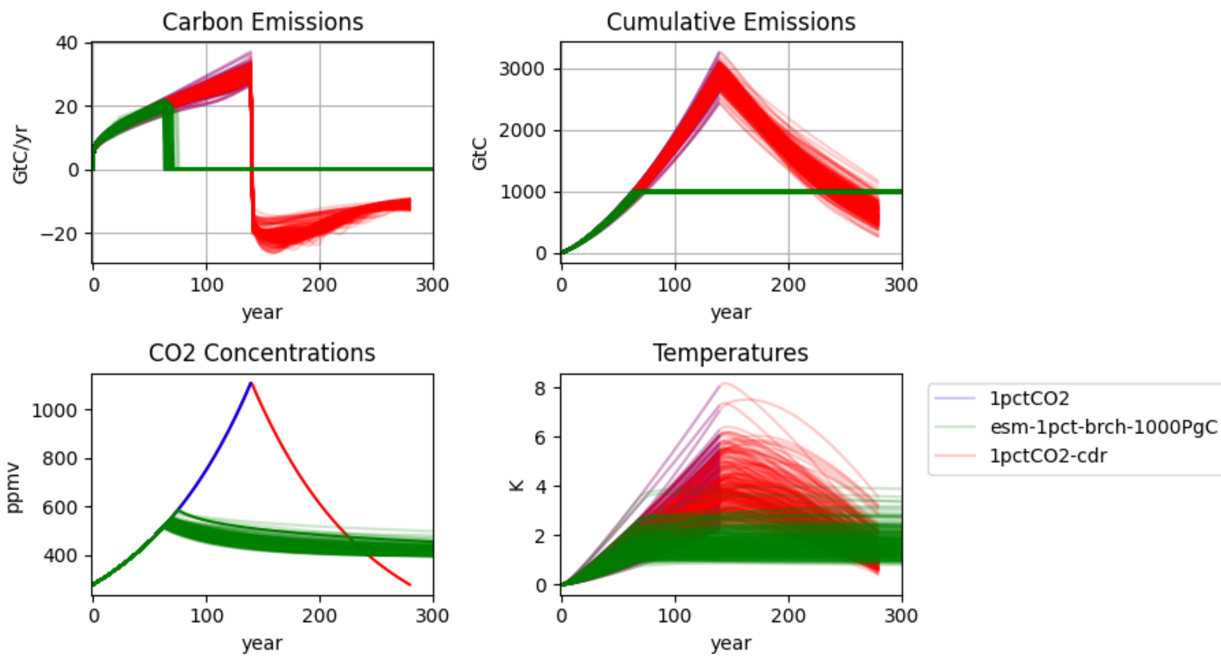

Figure 2: emissions, cumulative emissions, CO2 concentrations and Global Mean temperatures in existing CMIP6(Eyring et al. 2016), ZECMIP(Jones et al. 2019) and CDRMIP(Keller et al. 2019) experiment (1pctCO2, esm-1pct-brch-1000PgC and 1pctCO2-cdr) as simulated in a perturbed ensemble of the simple climate model FaIR (Smith et al. 2018)

Flat10 allows for a more automated assessment of TCRE for esm configurations - compatible emissions do not need to be computed and the TCRE can be easily calculated as a time average in the experiment. This difference in the timing of emissions in the simulation has a small effect on the derivation of TCRE in simple climate model experiments.

Figure 3a shows TCRE as estimated in the FaIR simple climate model ensemble using the 1pctCO2 and flat10 experiments - with TCRE generally slightly higher when calculated from *flat10_zec* than when calculated from *esm-1pct-brch-1000PgC*, and differences of less than 0.2K for all perturbed ensemble members, with models with the largest positive values of ZEC50 exhibiting the greatest difference in methodology. The differences in the overall histograms of ZEC50, ZEC100 and TCRE are, however, small between the two approaches (Figure 4).

Flat10_zec allows for computation of temperature changes after an immediate cessation of emissions, similar to the ZEC concept assessed in (Jones et al. 2019). However, although ZEC50 is highly correlated between the flat10 experiments and the ZECMIP protocol, we see values which are here we see more significant differences in the derived values due to the greater weighting of emissions towards the end of the experiment in *1pctCO2 -* with values of ZEC50 order 50% greater when calculated in *esm-1pct-brch-1000PgC (see Figure 3b).* Differences in ZEC100 are smaller (around 10%) between the two experiments.

We can understand these differences due to the partitioning of warming between TCRE and ZEC in the two experimental designs. This is evident in Figure 3d - where we show that TCRE+ZEC50 is near-identical for both methodologies. The tendency for emissions to be weighted towards the latter years of the simulation in *1pctCO2*, as well as the shorter total time period over which emissions occur in *1pctCO2* (~70 vs 100 years), means that models with a higher ZEC50 have a greater fraction of unrealised warming at the time the 1000PgC threshold is exceeded in the *1pctCO2* than in the *flat10* case, where emissions are evenly distributed through a longer experiment - such that more warming is realised in year 100 (corresponding to a cumulative emission of 1000PgC).

Given this, we argue that, although there are small differences in the assessment of ZEC50 in particular, esm-flat10-zec is a more intuitive assessment of ZEC than the 1pctCO2 branching used in CMIP6, which will convey a number of advantages:

- Emissions are constant for all models in the transient phase of the experiment, removing the model-specific time evolving compatible emissions seen in the 1pctCO2 experiment, which complicate interpretation of ZEC
- Experiments are easier to run - In the ZECMIP protocol, it is necessary to switch from a concentration-driven configuration to an emissions-driven configuration at the time of exceedance of 1000PgC. This presents technical challenges for some models, which have been required to repeat the 1pctCO2 simulation in emissions driven mode using compatible emissions derived from a concentration-driven experiment. Flat10-zec would be emissions driven throughout
- Experiments are easier to automate - because the 1000PgC threshold is exceeded in year 100 in all models, the experiment can be run automatically without the need to assess compatible emissions and isolate the model-specific branch year for each simulation
- The maximum rate of CO2 emissions in *flat10* (10 Pg C/yr, vs ~20 Pg C/yr for *1pctCO2*) is closer to that projected for ambitious policy scenarios, where emissions must peak and

decline from their present values of ~10 Pg C/yr within decades to achieve Paris Agreement-compatible warming targets.

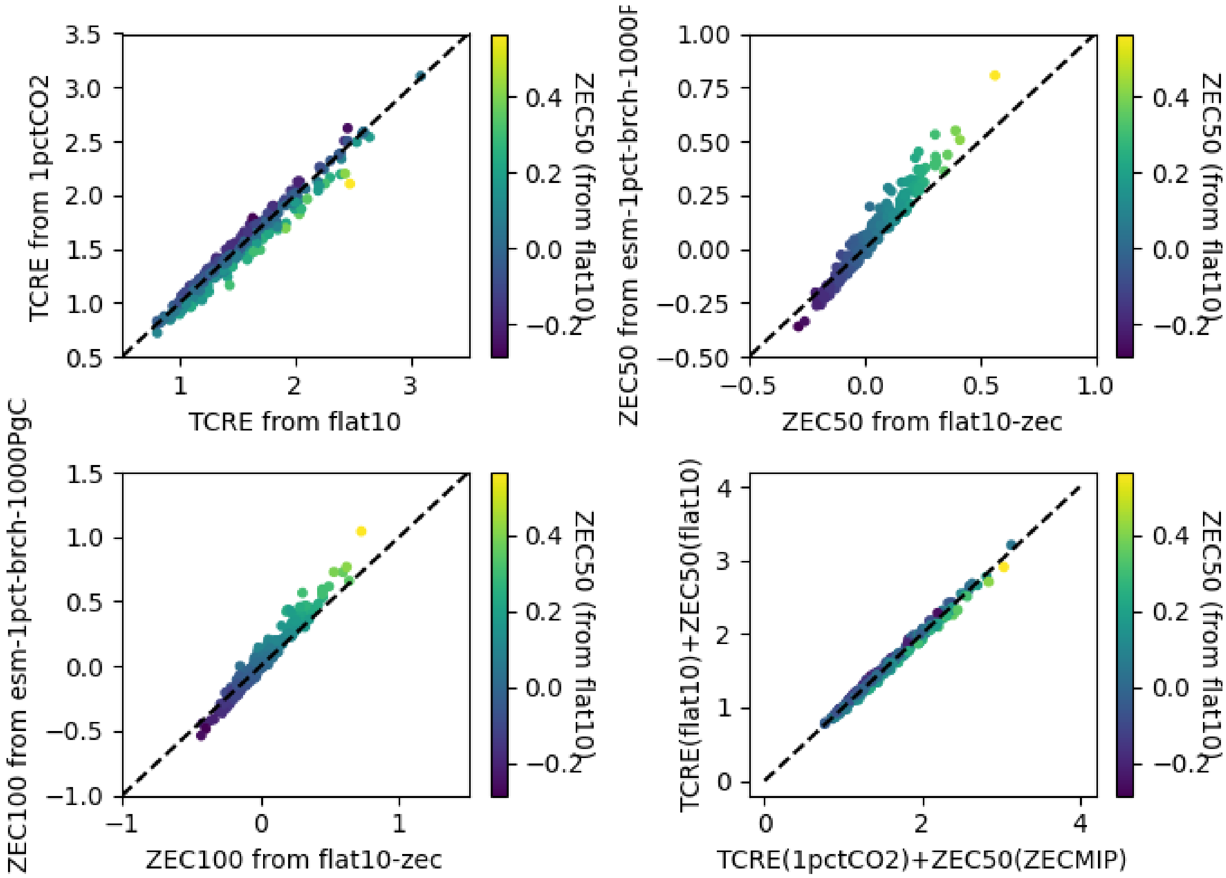

Figure 3: Comparative calculations of TCRE, ZEC50, ZEC100 and (TCRE+ZEC50) from flat10 experiments and the CMIP6 experiments 1pctCO2 and esm-1pct-brch-1000PgC Reversibility experiments (tier 2)

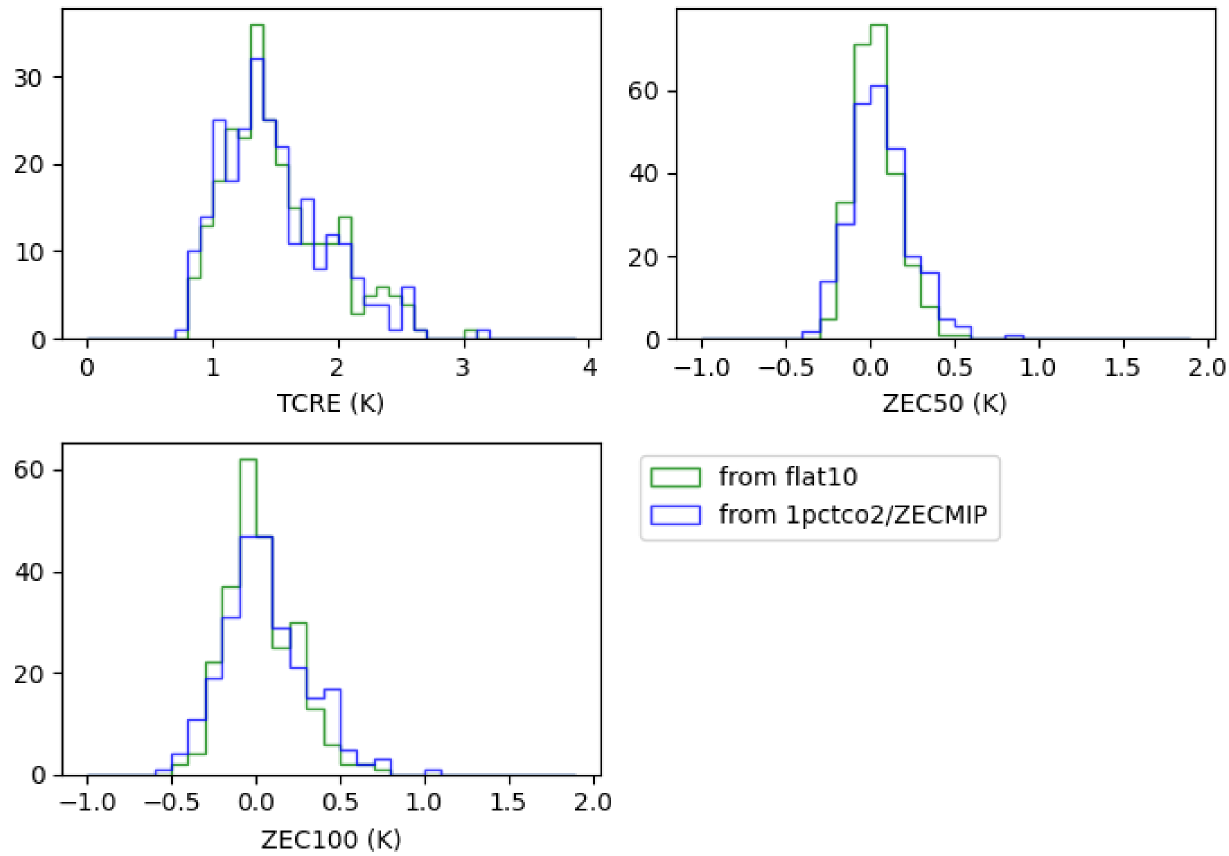

Figure 4: Comparative histograms of the distribution of TCRE, ZEC50 and ZEC100 assessed using the flat10 methodology and the 1pctCO2/ZECMIP methodology.

The esm-flat10-cdr experiment would serve as an emissions-driven idealized experiment to assess the dynamics of climate reversibility under reducing emissions and net-negative emissions. The experiment would allow for a number of simple idealized diagnostics which would be relevant to the net zero transition and the response of the system to net negative emissions.

- **TNZ can be calculated as a 20 year average around year 150 in esm-flat10-cdr minus a 20 year average around year 125 in esm-flat10.** TNZ would be the temperature simulated at net zero minus the expected temperature at net zero using cumulative emissions proportionality. This could be easily calculated using a combination of the flat10 and flat10-cdr experiments for a cumulative carbon emissions total of 1250GtC. *esm-flat10-cdr* reaches net zero emissions in year 150, with a cumulative emissions of 1250GtC (calculated from year 0, see Figure 1). *Esm-flat10* itself reaches 1250GtC in year 125.
- **TR1000 can be calculated as a 20 year average around year 200 in esm-flat10-cdr minus a 20 year average around year 100 in esm-flat10.** TR1000 would be a measure of hysteresis in global mean temperature when cumulative emissions return to 1000PgC on the downward branch minus the expectation from TCRE. This could be calculated using a combination of the flat10 and flat10-cdr experiments for a cumulative carbon emissions total of 1000GtC.

esm-flat10-cdr reaches 1000PgC cumulative emissions in year 200 on the downward branch (see Figure 1). *Esm-flat10* itself reaches 1000GtC in year 100.

- **TR0 can be calculated as a 20 year average around year 300 in esm-flat10-cdr minus mean global temperatures in esm-pictrl.** TR0 would be a measure of hysteresis in global mean temperature when cumulative emissions return to zero after a period of negative emissions. This could be calculated using a combination of the esm-pictrl and flat10-cdr experiments. *esm-flat10-cdr* reaches zero cumulative emissions in year 300 on the downward branch (see Figure 1).
- **Time to Peak Warming (tPW)** can be calculated as the time difference between the peak value of 20-year smoothed global mean temperatures and the point that net zero is achieved in *esm-flat10-cdr* (year 150). This metric has a clear policy-relevant translation as the expected time it will take for the climate system to achieve maximum CO2-driven global warming after (or before) reaching net zero emissions under a smooth positive-to-negative emissions transition.

In the FaIR SCM ensemble, we see some strong emergent relationships between these reversibility metrics and ZEC metrics (Figure 5) - but noting the structural assumptions in FaIR do not allow for threshold behavior which may be present in ESMs. As such, *esm-flat10-cdr* would provide an assessment - beyond ZEC, of underlying nonlinearities and irreversibilities in Earth System Models.

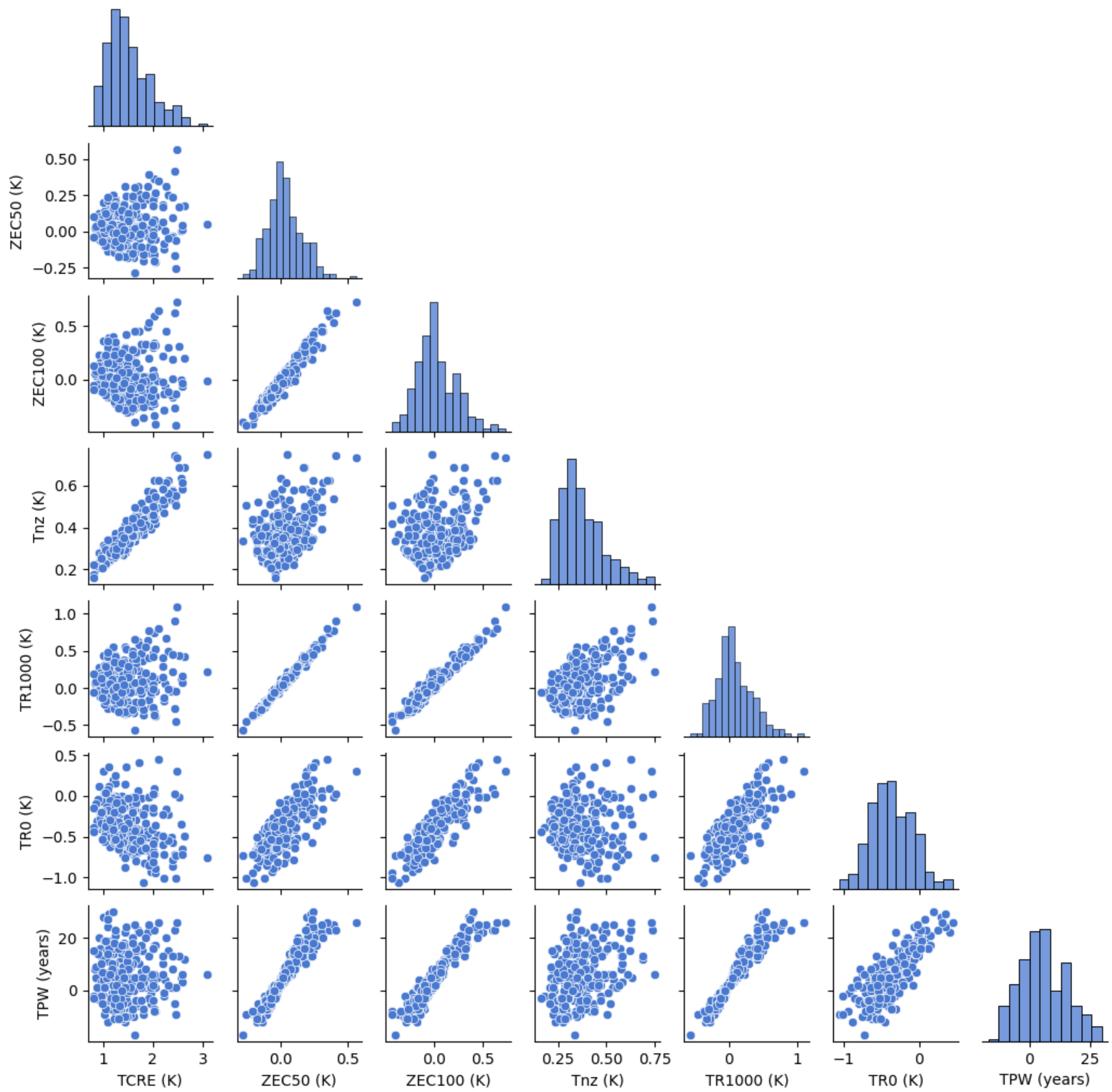

Figure 5: relationships between climate metrics assessed from the flat10 experiments - including the Transient Response to Cumulative Emissions (from flat10), ZEC50 and ZEC100 (from flat10-zec), Tnz, TR1000, TR0 and TPW (from flat10-cdr).

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