Review of: Carbon Budget Concept, its Deviations and the Equation: Climate Economics Perspective

Overall Assessment:

The paper examines the deviations from linearity and path-dependence in the cumulative emissions of CO_2 – global temperature relationship, using Fair and an analytical approximation of Fair. The goal of the paper is to find a way incorporate these effects into the simple models of carbon budget used in economic analysis. While the paper is mathematically sound, there are substantial conceptual and scientific problems, which prevent publication in its present form. I suggest that the paper be rejected with an invitation to re-submit.

General Comments:

(1) The key conclusion of the paper is that the common approximation of the cumulative emissions of CO_2 – global temperature relationship should be modified in order to account for the reduction in TCRE at higher cumulative emissions. While this conclusion was reached earnestly, it is an error originating from the use of Fair. Simple and intermediate complexity climate models show a clear diminishing TCRE at higher cumulative emissions, full complexity Earth system model do not. This was clearly shown in Tokarska et al. 2016, and has not been contradicted by CMIP6 results. Full complexity Earth system model show the linear relationship holds to 5000 PgC, well beyond what is needed for economic models. Figure 3 from Tokarska et al. 2016 is copied below:

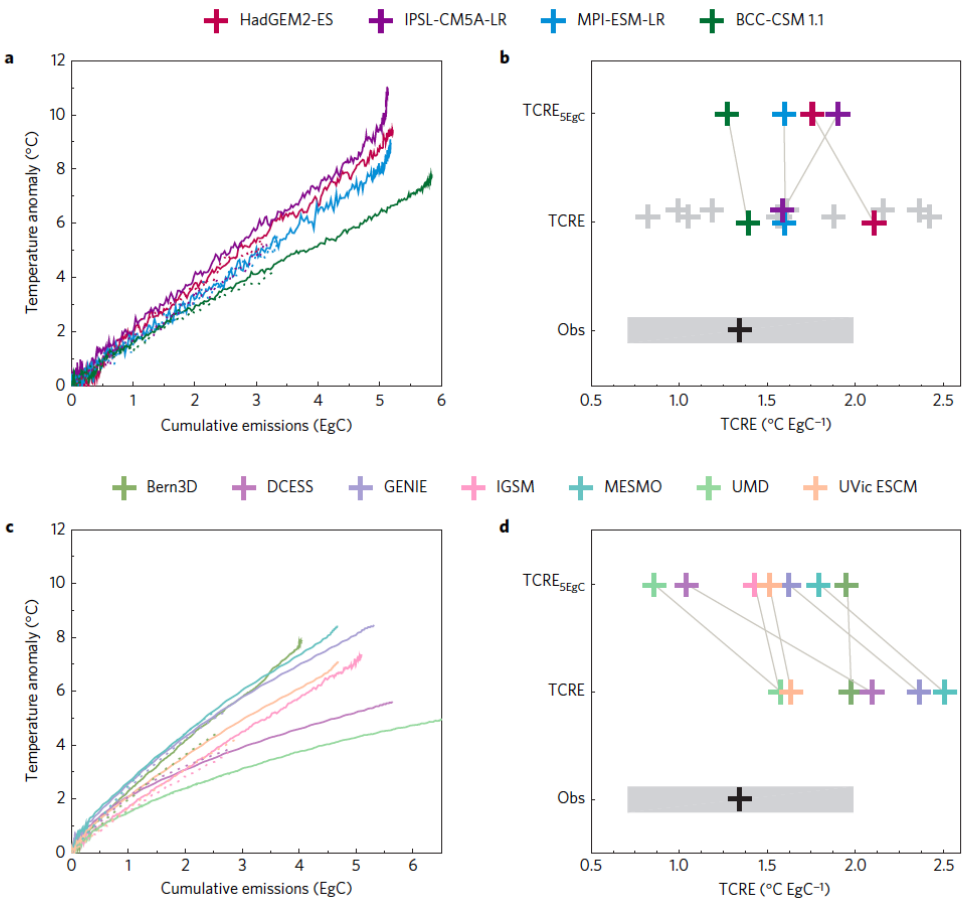

Figure 3 | CO_2-attributable warming as a function of cumulative CO_2 emissions, and the resulting ratio of warming to emissions for CMIP5 ESMs and EMICs. a, Simulated CO_2-attributable warming as a function of cumulative CO_2 emissions based on historical and RCP 8.5-Ext (solid) and 1PCTCO_2 simulations (dotted) from four CMIP5 models. **b**, The ratio of CO_2-attributable warming to cumulative emissions at 5 EgC emissions ($TCRE_{5EgC}$, top row) for these CMIP5 models, compared with TCRE for these models and other CMIP5 models (grey crosses, middle row)[10], and an observationally constrained estimate of TCRE (bottom row)[10]. **c**,**d**, The same as in **a**,**b** but for seven EMICs.

(2) The Green function used to approximate Fair is a 3rd order approximation, so rigour is needed to establish weather it can accurately capture path-independence. The Green function is approximating Fair, which is approximating full complexity Earth system models, which approximate the natural Earth system. MacDougall 2017 showed that path-independence in the cumulative emissions of CO_2 – global temperature relationship originates from ocean carbonate chemistry. Fair does not explicitly represent ocean carbonate chemistry and it is unclear from Leach et al. 2021 if Fair can even capture path-independence (given the results of the paper likely can but this needs to be explicitly shown).

To address this point the author can conduct a simple series of idealized experiments with Fair using different rates of emission. An example of such a set is shown in MacDougall 2017 Figure 1 (copied below):

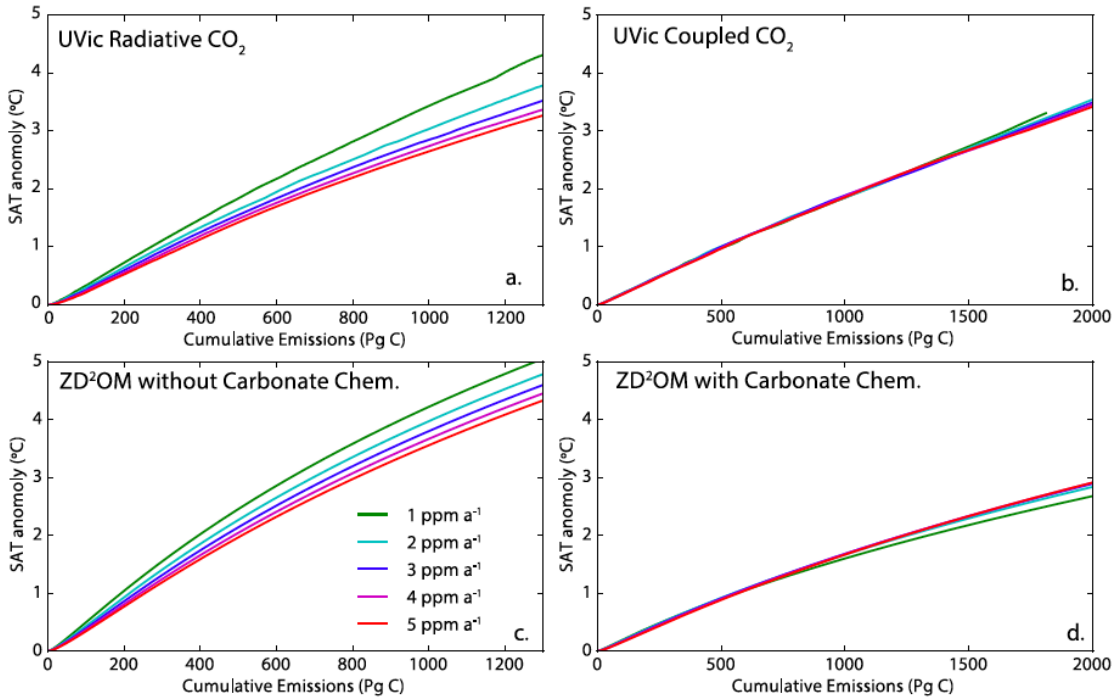

Figure 1. Surface air temperature (SAT) anomaly versus cumulative emissions of CO_2 curves for: (**a**) simulations with the UVic ESCM forced with CO_2 that is uncoupled from the model's biogeochemical components (radiatively coupled CO_2 – R-CO_2). (**b**) Simulations with the UVic ESCM forced with fully coupled CO_2. (**c**) Solutions for the ZD^{2}OM not accounting for ocean carbonate chemistry or land carbon uptake. (**d**) Solutions for the full ZD^{2}OM. All models are forced with scenarios where atmospheric CO_2 concentration changes at a constant rate. Note that the horizontal scale is different in the right and left columns as R-CO_2 emission have an airborne fraction of 1.

(3) The translation of Fair to GAMS needs to be validated. In an appendix show Fair simulations from the Python and GAMS versions of the model to confirm there has been no coding errors.

(4) The author does not seem to be familiar with the concept of Zero Emissions Commitment (ZEC). In the climate sciences we now make a clear distinctions between TCRE and ZEC with TCRE describing the relationship between cumulative emissions of CO_2 and temperature while emissions continue, and ZEC quantifying the warming that occurs after emissions cease (See MacDougall et al. 2020 for recent model inter-comparison and background). In the present work the author is mixing up transient path-dependence and ZEC effects, which, in fairness, are related (Koven et al. 2023) but need to be distinguished to avoid confusion.

Specific Comments:

Line 24-25: 'inauguration' and 'skyrocketed' do not make sense in the context of these sentences. 'inclusion' and 'rose' would be more appropriate.

Line 28: Need working group for SPM

Equation 1: Lower-case lambda is a very poor choice of Greek letter. Little Lambda is always used for the climate feedback parameter in climate sciences. Capital Lambda has been used for TCRE in other papers, but you use that letter for another variable.

Line 46: TCRE is the Transient Climate Response to Cumulative CO_2 Emissions. The methanotropes get angry if 'carbon' is used instead of CO_2.

Line 46 to 50: Not quite right. The diminishing ocean heat uptake is also very important (see MacDougall & Friedlingstien 2015).

Line 52: This effect only exists in simple climate models and EMICs. Full complexity climate models remain linear to at least 5000 PgC.

Line 60: MacDougall 2017 suggested that the two effects might actually dependent, with models with low linearity having higher path-independence and vice versa.

Line 69 to 74: This is just wrong. If ZEC is 0 (the most likely value) the TCRE effect is essentially instantaneous. The lag from the carbon sinks (mostly the ocean) compensate exactly for the lag from ocean heat uptake. If ZEC is not 0 then small lags are expected.

Line 91: Calling Fair a 'full fledged' is bizarre. Fair is a simple climate model, barely above a climate emulator.

Line 111: 'prescribed' is a poor choice of words, since this term has a very precise meaning in climate sciences (basically a boundary condition).

Line 129: 'CO_2' not 'carbon'. Elemental carbon (graphite) is not very soluble, nor is methane.

Line 164: No rationale is given for using RCP6.0. Why not one of the SSPs? Especially since the CO_2 concentration for year 2020 is way off in RCP6.0. The observed value was 414 ppm, 12ppm above the prescribed value. Since non-CO2 forcing is not used why not just use the historical record?

Line 185: IPCC range is 1 to 2.3 with a best estimate of 1.65 K/EgC. See Table 5.7 AR6 WG1.

Section 3.1.3: This is just ZEC.

Section 3.1.4: Weird mix of idealized and historical scenarios. Why not just use an idealized experiment?

Figure 1: In the legend second red max should probably be a min?

Line 345 to 349: Should show these pathways in a figure so readers can see if they are physical.

Figure 2: Should the units for the shading be GtC yr^{-2}?

Line 360: Typo here

Figure 4: This should be figure 1 since it is mentioned in text first. Also SI prefixed exist for a reason, just give the units in mK and get rid of the hard-to-see $x10^{-3}$ in the corner.

Figure 5: Again SI prefixes are your friend.

References:

Koven, C. D., B. M. Sanderson, and A. L. Swann, 2023: Much of zero emissions commitment occurs before reaching net zero emissions. Environmental Research Letters, 18 (1), 014017.

MacDougall, A. H., 2017: The oceanic origin of path-independent carbon budgets. Scientific Reports, 7, 10 373, doi:10.1038/s41598-017-10557-x.

MacDougall, A. H. and P. Friedlingstein, 2015: The origin and limits of the near proportionality between climate warming and cumulative CO_2 emissions. Journal of Climate, 28, 4217–4230, doi:10.1175/JCLI-D-12-00751.1.

MacDougall, A. H., et al., 2020: Is there warming in the pipeline? a multi-model analysis of the zero emissions commitment from co_2. Biogeosciences, 17, 2987–3016.

Tokarska, K. B., N. P. Gillett, A. J.Weaver, V. K. Arora, and M. Eby, 2016: The climate response to five trillion tonnes of carbon. Nature Climate Change, doi:DOI: 10.1038/NCLIMATE3036.