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Earth System Dynamics
Discussions

Interactive comment on "Constraints on long term warming in a climate mitigation scenario" *by* Benjamin Sanderson

Anonymous Referee #1

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The author makes use of a simple climate model emulator that accounts for the long-term effects of changing climate feedbacks. Such model output is constrained by different observed quantities to obtain constrained warming projections under RCP 8.5 and RCP 2.6 scenarios. The sensitivity to different priors and assumptions is also explored. Based on this work, the author makes conclusions regarding near-term carbon budgets, TCRE behaviour under net-zero and negative emissions, and policy implications of those findings.

This paper introduces an interesting concept of how to account for the long-term effects (such as changing climate feedback parameter) in the carbon budgets framework. However, I found it challenging to understand this study in the context of applications to carbon budgets, and how these findings should be interpreted. I would recommend re-

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vising the framing of this paper to make it more relevant and easier to follow for readers familiar with the carbon budgets literature. The paper could also benefit from clarifications, and consistency with the most recent literature on carbon budgets and TCRE. In particular, the role of non-CO2 forcing on hysteresis of the effective TCRE curves discussed in the paper should be clearly separated from making claims on hysteresis in TCRE alone (which applies to CO2-induced warming only). I included several suggestions that potentially could help to clarify the points of confusion.

Furthermore, I would suggest discussing the uncertainties in the observational datasets explicitly in the main text, and how they affect the results of constraining the simple model. Also, I would suggest putting the findings of this paper in the context of the overall uncertainties in carbon budgets (see IPCC Special Report, Table 2.2, Chapter 2, for a summary of different uncertainties), which I suppose are much larger than the uncertainties in carbon budgets due to changing climate feedbacks.

Major points and suggestions:

1. Model description

It is unclear what model is used in this study -is it a version of the FaIR model with additional components that would account for changing long-term feedbacks, or is it a simpler impulse-response model that contains less processes than FaIR? (the references are a bit vague). I would suggest to include basic description of the model in the main text (e.g. on lines 70-75) in the context of recent climate model emulators (or how it differs component-wise from FaIR) for the readers to have a brief idea of how the climate response is determined without the need of referring to the appendix.

Lines 180-185: It is unclear how the emulator used here differs from the FaIR emulator? Is this an extension of FaIR that accounts for the possibility of changing feedbacks, or is it a simplified version of it.

2. Observational constraints from the historical period

It is unclear how the observational uncertainty both in the observed warming and in the estimates of cumulative CO2 emissions from the global carbon project affects the results. I would suggest either illustrating it on Figure 1 or at least discussing the following points in the main text:

Figure 1: 'observed' cumulative CO2 emissions – Please include references to the observational datasets in the perhaps in the figure caption, and specify if they include the total CO2 emissions (from fossil fuels and land use change?) If so, the uncertainty on estimated CO2 land use change emissions in the historical period is quite large (even up to +/-50 percent for the annual E luc emissions), and it should be indicated on the figure or at least mentioned in the text and the figure caption. (e.g. see Table 5 from the recent Global Carbon Project 2019).

Figure 1: observed warming from HadCRUT4 – is it adjusted for the blending-masking effects? If not, it is not like-for-like comparison with the global (and complete coverage) climate models' output. In such case, at least a caveat in the figure caption and a short mention of this point would be useful. (e.g. see Cowtan et al. 2015; Richardson et al. 2016, 2018).

Uncertainties in the other observation-based quantities (heat content, paleo and RWF) should be discussed, as some of those inputs/constraints have narrower uncertainties, while others are a lot larger.

Lines 70-75: Please discuss the uncertainty in the observational parameters that are used to constrain the model output. Also, perhaps include a figure showing the observation-based priors used. Do historical emissions include emissions from land use change? If so, the uncertainty on cumulative emissions is much larger than the uncertainty resulting from observed temperature.

Also, the discussion regarding constraints from the historical record could use the following reference and a short discussion: Millar, R. J. Friedlingstein, P. The utility of the historical record for assessing the transient climate response to cumulative emissions.

Phil. Trans. R. Soc. A 376, 20160449 (2018).

References:

Cowtan, K. et al. Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. Geophysical Research Letters 42, 6526–6534 (2015).

Richardson, M., Cowtan, K., Hawkins, E. Stolpe, M. B. Reconciled climate response estimates from climate models and the energy budget of Earth. Nature Climate Change 6, 931 (2016).

Richardson, M., Cowtan, K. Millar, R. J. Global temperature definition affects achievement of long-term climate goals. Environ. Res. Lett. 13, 054004 (2018).

3. TCRE definition, non-CO2 forcing and the effective TCRE hysteresis

Please note that the definition of TCRE should be applied to CO2-induced warming alone. If calculating carbon budgets directly from RCP scenarios that are subject to CO2 and non-CO2 forcing, please refer to the Effective TCRE (Matthews et al. 2016). The current version of the manuscript confuses these two concepts, referring to TCRE even if non-CO2 forcing is present, making the arguments difficult to follow, since the effective TCRE, per definition, is not necessarily linear, due to the non-linearities arising from non-CO2 forcing. This should be clarified throughout the text.

Based on earlier studies (e.g. MacDougall et al. 2015; Tokarska et al. 2019), I would expect that the apparent hysteresis behaviour depends on non-CO2 forcing scenario, and I am not convinced that observational constraints address this non-linearity.

Furthermore, if considering TCRE to CO2-emissions alone (with no non-CO2 influence), TCRE would likely be fully reversible (no hysteresis)- e.g. see Figure 2a in MacDougall et al. 2015.

Thus, regarding Figure 1, I would suggest discussing the effect on CO2-only response

separately, as I suppose most of these non-linearities arises due to the specific non-CO2 emission scenarios, and is not necessarily an inherent property of TCRE alone.

One way to address this issue would be to repeat the analysis using CO2-only simulations (according to RCP 2.6 scenarios), to illustrate if such hysteresis also arises in the absence of non-CO2 forcing.

References:

MacDougall, A. H., Zickfeld, K., Knutti, R. Matthews, H. D. Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO2 forcings. Environ. Res. Lett. 10, 125003 (2015).

Tokarska, K. B., Zickfeld, K. Rogelj, J. Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot. Earth's Future (2019).

Specific comments:

Lines 15-25: Please note that TCRE refers to CO2-only induced warming (originally defined in simulations where atmospheric CO2 concentrations increase at a rate of 1

Lines 20-25: I found this sentence confusing and inaccurate: 'the range of TCRE values observed in Earth System Models (ESMs) can be used to infer model-based carbon budgets which are compatible with 1.5 and 2 degree Celsius targets of the Paris Agreement. . .' Is this referring to model-based TCRE that is used then in conjunction with other quantities (such as estimates of observed warming and future warming from non-CO2 forcing, as in Rogelj et al. 2019a framework) to infer remaining carbon budgets? Or is this sentence referring to carbon budgets at 1.5 C and 2.0C directly inferred from ESM output, as in AR5, for example? (in that case, those budgets already account for CO2 and non-CO2 warming in RCP scenarios, for example), but those budgets are not calculated directly from TCRE.

Lines 115-125: Since CO2 emissions follow different trajectories, but non-CO2 forcing

follows the RCP 2.6 trajectory for each section, it is unclear how is the role of non-CO2 forcing distinct from CO2-induced changes? TCRE is pathway independent for CO2 emissions (both positive and negative), but if non-CO2 emissions are evolving in time (according to the RCP 2.6 scenario), the effective TCRE (to CO2 and non-CO2 forcing) is scenario-dependent, and heavily depends on the chosen non-CO2 scenario.

e.g. Reference: Mengis, N., Partanen, A.-I., Jalbert, J. Matthews, H. D. 1.5 °C carbon budget dependent on carbon cycle uncertainty and future non-CO2 forcing. Sci Rep 8, 5831 (2018).

4. Robustness of TCRE under negative emissions

Please note that there are several recent studies using climate models of different complexity, including comprehensive ESMs and EMICs, that should be cited on lines 30-40. Currently, the paper gives an impression that this topic has not been studied in-depth, while quite the opposite is true. Some discussion of these more recent studies would also be helpful on lines 25-40.

Regarding Earth system response to negative emissions in ESMs and EMICs:

Ehlert, D. Zickfeld, K. Irreversible ocean thermal expansion under carbon dioxide removal. Earth System Dynamics 9, 197–210 (2018).

Jones, C. D. et al. Simulating the Earth system response to negative emissions. Environmental Research Letters 11, 095012 (2016).

Tokarska, K. B. Zickfeld, K. The effectiveness of net negative carbon dioxide emissions in reversing anthropogenic climate change. Environ. Res. Lett. 10, 094013 (2015).

Regarding TCRE behaviour under negative emissions:

Zickfeld, K., MacDougall, A. H. Matthews, H. D. On the proportionality between global temperature change and cumulative CO2 emissions during periods of net negative CO 2 emissions. Environ. Res. Lett. 11, 055006 (2016).

Tokarska, K. B., Zickfeld, K. Rogelj, J. Path independence of carbon budgets when meeting a stringent global mean temperature target after an overshoot. Earth's Future (2019).

MacDougall, A. H., Zickfeld, K., Knutti, R. Matthews, H. D. Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO2 forcings. Environ. Res. Lett. 10, 125003 (2015).

Lines 30-35: '[TCRE] robustness in complex models under large negative emissions is relatively unexplored' – There are at least several recent studies that look at ESM model responses under different amounts of negative emission scenarios, and reversibility of TCRE after an overshoot (see several examples above).

Lines 80-85 claim that the TCRE relationship is not robust under negative emissions. However, it is unclear what fraction of this hysteresis behaviour is due to non-CO2 forcing. In intermediate-complexity model (UVic ESM) TCRE is reversible under negative CO2 emissions. At least a discussion of this claim in the context of these two following studies would be helpful here.

Lines 105-110: Figure 1b is not discussed in the previous section. I find it unconvincing why the TCRE framework would not hold under negative emissions even if model output is constrained by temperature and cumulative CO2 emissions (see major point above regarding reversibility). Please explain more your claim, possibly process-wise). Also, this hysteresis in the effective TCRE shown here may arise due to time-dependent non-CO2 forcing. Please see my comments below and in the above section 3 regarding the separation of CO2 and non-CO2 effects on the reversibility of TCRE.

Line 80: This paragraph suggests that TCRE relationship is not robust under negative emissions. However, TCRE (due to CO2 emissions alone, as originally defined) has shown to be reversible in overshoot scenarios with negative emissions, including RCP scenarios (see major point 3 above). The non-linearity probably arises due to time-varying non-CO2 forcing. This should be clarified here, and please refer to effec-

tive TCRE, if non-CO2 forcing is included. Also, this behaviour depends on non-CO2 forcing scenario, and I am not convinced that observational constraints address this non-linearity.

Lines 85 to 90: I would suggest discussing the effect on CO2-only response separately, as I suppose most of these non-linearities arises due to the specific non-CO2 emission scenarios, and is not necessarily an inherent property of TCRE alone.

Line 107: 'cumulative emissions framework is not guaranteed to hold under negative emissions' – This is a strong statement, which I am not convinced about. I would expect non-CO2 forcing in RCP 2.6 to be responsible for this hysteresis, and if considering RCP 2.6 CO2-only simulation, this hysteresis effect would be a lot smaller, if at all present?

5. Committed warming (after emissions reach net-zero):

The paper refers to peak warming occurring after the emissions reach net-zero. However, there is no discussion with the literature on the committed warming occurring after emissions are stopped, which is directly relevant to the carbon budgets framework. For example, a short mention in the introduction (e.g. lines 25-40) and a discussion of how this paper fits within earlier studies would be valuable.

Ehlert, D. Zickfeld, K. What determines the warming commitment after cessation of CO 2 emissions? Environ. Res. Lett. 12, 015002 (2017).

MacDougall, A. H. et al. Z. M. MacDougall, A.H, Frölicher, T.L., Jones, C.D., Rogelj,J., Matthews, H.D., Zickfeld K., Arora, V.K., Barrett, N.J., Brovkin, V., Burger, F.A., Eby, M., Eliseev, A.V., Mokhov, I.I., Hajima, T., Holden, P.B., Jeltsch-Thömmes,A., Séférian, R., Michou, M., Shaffer, G., Sokolov, A., Wiltshire, A., Ziehnand, T., Menviel, L. How much warming remains in the pipeline? A multi-model analysis of the CO2 zero emission commitment. (discussion paper/ in review). https://www.biogeosciences-discuss.net/bg-2019-492/

Also, regarding the parameter choices and how they influence TCRE – perhaps it would be valuable to discuss the results of this study in the context of earlier studies, for example:

MacDougall, A. H., Swart, N. C. Knutti, R. The Uncertainty in the Transient Climate Response to Cumulative CO2 Emissions Arising from the Uncertainty in Physical Climate Parameters. J. Climate 30, 813–827 (2016).

Lines 170-175: I would suggest also discussing the zero-emission commitment (see examples above), which suggests, that on average, ZEC is close to zero for CO2-emission pathways (in ESMs). Also, part of the difference between the threshold exceedance and avoidance budgets may be non-CO2 forcing, which is not part of the TCRE relationship (it would be part of the effective TCRE, which, however, is not expected to be linear due to non-CO2 influence). Please see above major comments regarding framing.

Line 60: Please note that recent studies suggest that the peak warming after emissions are zeroed is likely to be close to zero (see examples above)

6. Long-term uncertainties in the context of overall carbon budget uncertainties

Lines 215-220: It would be good to put it in the context of other uncertainties on carbon budgets (see IPCC SR Ch2, Table 2.2). I would expect that other uncertainties such as permafrost carbon cycle feedbacks, model response to non-CO2 forcings, and non-CO2 forcing scenario uncertainty are still the dominant sources of uncertainness in the remaining carbon budgets.

Minor suggestions:

Title: I would suggest for the title to reflect more that the scope of this paper is also focusing on carbon budgets and TCRE framework

Abstract: The abstract gives the impression that the main source of uncertainties for near-term policy decision is future negative emissions capacity and the long-term re-

sponse to climate forcers as the main sources of uncertainty in for the near-term policy decisions. However, carbon budgets and related net-zero emissions targets are subject to much larger transient uncertainty from the future non-CO2 forcing (at the time of 1.5C or target warming level), and climate models' response to non-CO2 forcing, which varies largely among models, contributing to a large spread in the remaining carbon budgets. (See IPCC Special Report, Chapter 2, Table 2.2. therein for quantification of different sources of uncertainties). While non-CO2 forcing is not the main scope of this paper, I would suggest revising this framing to avoid the misconception about the key sources of uncertainties in the remaining carbon budgets and near-term emission targets.

Abstract: 'definite cumulative emissions budget' -I would suggest following terminology from Rogelj et al. 2019a framework, for consistency with other studies. Please specify if that is referring to the total or remaining budget?

Lines 90-100: While it is an interesting discussion, it is unclear how it relates to the transient timescales shown on Figure 1. (For example, it would be interesting to see the emulator behaviour until year 3000, for example, to assess the effect of non-linearities discussed in this study).

Figure 2 c. I found this plot confusing, and it is unclear what the baselines are. Following the SR1.5 and Rogelj et al 2019b recommendations, I would suggest plotting only the warming since 2006-2016, and offset it (as in SR 1.5 Table 2.2), so that the 1.5C and 2.0C target levels are clearly readable, Are cumulative emissions since 2010 or since 2020? (the figure caption and x-axis labels are inconsistent or confusing). Similarly, I suggest using the present-day warming baseline (as in SR 1.5), for consistency, in the whisker plots. Perhaps, to clarify the point of this figure, it would be also useful to show whisker plots for the remaining carbon budgets at the time when 1.5C and 2.0C target is reached for the first time (before the overshoot), which would help to illustrate the difference in the transient and long-term budgets. However, they are not expected to be the same due to the ongoing non-CO2 forcing contribution. This point would need

to be clarified as well.

Lines 130-135: I found this paragraph unclear and confusing. It seems to be comparing carbon budgets calculated from scenarios that non-CO2 forcing is constantly evolving over time, with carbon budget estimates directly inferred from TCRE, but how that latter estimate accounts for the future contribution from non-CO2 forcing?

Lines 135-155 and Figure 3: It is unclear how the budgets can be compared for the different time periods, given that they entail different levels of non-CO2 forcing that is evolving in time in the simulations considered in this study. (i.e. since those budgets depend on the future non-CO2 forcing levels that differ, how can they be compared in a like-for-like manner?)

Lines 200-205: Perhaps a brief discussion in the context of more recent literature would be interesting (e.g. see Rogelj et al. 2019)

Rogelj, J. et al. A new scenario logic for the Paris Agreement long-term temperature goal. Nature 573, 357–363 (2019).

Lines 205-215: Please note that carbon budgets should be calculated from anthropogenic warming estimate (Rogelj et al. 2019b. Haustein et al. 2017), which is not subject to internal variability. Reference: Haustein, K. et al. A real-time Global Warming Index. Scientific Reports 7, 15417 (2017).

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