The Zero Emission Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: Quantifying committed climate changes following zero carbon emissions

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Abstract.

The amount of additional future temperature change following a complete cessation of CO_2 emissions is a measure of the unrealized warming to which we are committed due to CO_2 already emitted to the atmosphere. This "Zero Emissions Commitment" (ZEC) is also an important quantity when estimating the remaining carbon budget – a limit on the total amount of CO_2 emissions consistent with limiting global mean temperature at a particular level. In the recent IPCC Special Report on Global Warming of 1.5°C, the carbon budget framework used to calculate the remaining carbon budget for 1.5°C included the assumption that the ZEC due to CO_2 emissions is negligible and close to zero. Previous research has shown significant uncertainty even in the sign of the ZEC. To close this knowledge gap, we propose the Zero Emissions Commitment Model Intercomparison Project (ZECMIP), which will quantify the amount of unrealized temperature change that occurs after CO_2 emissions cease and investigate the geophysical drivers behind this climate response. Quantitative information on ZEC is a key gap in our knowledge, and one that will not be addressed by currently planned CMIP6 simulations, yet it is crucial for verifying whether carbon budgets need to be adjusted to account for any unrealized temperature change resulting from past CO_2 emissions. We request only one top priority simulation from comprehensive general circulation Earth System Models (ESMs) and Earth System Models of Intermediate Complexity (EMICs) – a branch from the 1% CO_2 run with CO_2 emissions set to zero at the point of 1000 PgC of total CO_2 emissions in the simulation – with the possibility for additional simulations, if resources allow. ZECMIP is part of CMIP6, under joint sponsorship by C4MIP and CDRMIP, with associated experiment names to enable data submissions to Earth System Grid Federation. All data will be published and made freely available.

1. Introduction

The Zero Emissions Commitment (ZEC), or the amount of global mean temperature change that is still expected to occur after a complete cessation of CO_2 emissions, is a key component of estimating the remaining carbon budget to stay within global warming targets as well as an important metric to understand impacts and reversibility of climate change (Matthews and Solomon, 2013). Much effort is put into measuring and constraining the TCRE - the Transient Climate Response to cumulative CO_2 Emissions (Allen et al., 2009; Matthews et al., 2009; Zickfeld et al., 2009; Raupach et al., 2011; Gillett et al., 2013; Tachiiri et al., 2015; Goodwin et al., 2015; Steinacher and Joos, 2016; MacDougall, 2016; Ehlert et al., 2017; Millar and Friedlingstein, 2018). The TCRE describes the ratio between CO_2-induced warming and cumulative CO_2 emissions up to the same point in time, but it does not capture any delayed warming response to CO_2 emissions beyond the point that emissions reach zero. When using the TCRE to derive the carbon budget consistent with a specific temperature limit, the ZEC is often assumed to be negligible and close to zero (Matthews et al., 2017; Rogelj et al., 2011, 2018). Constraints on ZEC have not been systematically researched so far, although both TCRE and ZEC are required to relate carbon emissions to the eventual equilibrium warming (Rogelj et al., 2018).

It has been shown that continued CO_2 removal by natural sinks following cessation of emissions offsets the continued warming that would result from stabilised CO_2 concentration (Matthews and Caldeira, 2008; Solomon et al., 2009; Frölicher and Joos, 2010; Matthews and Weaver, 2010; Joos et al., 2013). This is partly due to the ocean uptake of both heat and carbon sharing some similar processes and timescales and it is therefore expected to lead to ZEC being small (Allen et al., 2018; Ehlert and Zickfeld, 2017; Gillett et al., 2011; Matthews and Zickfeld, 2012). This has been shown to be a general result across a range of models (Gillett et al., 2011; Lowe et al., 2009; Matthews and Zickfeld, 2012; Zickfeld et al., 2013). Most such literature focused on long timescales (up to and beyond a century). This led IPCC SR15 (Rogelj et al., 2018) to make the assumption for the estimation of carbon budgets that for timescales up to a century ZEC was uncertain, yet centred around zero. More detailed studies, however, have shown that ZEC can be (a) non-zero, possibly of either positive or negative sign that may change in time during the period following emissions ceasing (Frölicher et al., 2014; Frölicher and Paynter, 2015); and (b) it is both state and rate dependent - i.e. it varies depending on the amount of carbon emitted and taken up by the natural carbon sinks, and the CO_2 emissions pathway of its emissions prior to cessation (Ehlert and Zickfeld, 2017; Krasting et al., 2014; MacDougall, 2019).

When we consider stringent climate targets, such as limiting global mean warming to 1.5 or 2°C, and in light of approximately 1°C warming to date and potential future warming from non-CO_2 greenhouse gases, an uncertainty in ZEC of 0±0.1ºC already leads to a substantial uncertainty in the remaining carbon budget. Given the current central estimate of the TCRE of 1.6°C per 1000 PgC (Collins et al., 2013), each 0.1ºC of warming equates to approximately 60 PgC of CO_2 emissions, or approximately 6 years of current fossil fuel emission rates (Le Quéré et al., 2018). It has therefore emerged that quantitative information on

ZEC is a key gap in our knowledge, and one that is not filled by currently planned simulations for the Sixth phase of the Coupled Model Intercomparison Project (CMIP6).

ZECMIP aims to fill this gap as efficiently as possible. Thereby, ZECMIP will support the assessment of remaining carbon budgets based on the CMIP6 simulations and supersede the current practice of applying a single model estimate of ZEC or an estimate from a limited number of studies from the literature. Much more preferable is to coordinate parallel studies, with Earth System General Circulation Models (ESMs) and Earth System Models of Intermediate Complexity (EMICs), to measure both TCRE and ZEC in a common scenario. Hence, we proposed using the 1% per annum increase in CO_2 concentration experiment (1pctCO2) from the CMIP6 Diagnostic Evaluation and Characterisation of Klima (DECK) simulations (Eyring et al., 2016) as a common baseline simulation for estimating both the TCRE and the ZEC.

As a late addition to CMIP6, ZECMIP has been designed to address this important question with only one high priority simulation – **A1: "a zero-emission experiment following 1000 PgC emissions,"** implemented as a branch off the 1pctCO2 simulation from the point at which 1000 PgC in diagnosed cumulative emissions is reached. Additional simulations of lower priority are also suggested which will aid further analysis. Branching from this idealised simulation avoids complications of non-CO_2 forcing and land-use or nitrogen deposition impacts on the carbon cycle, and also makes the ZEC quantified consistent with the TCRE values also derived from this simulation.

This paper documents the ZECMIP simulations, with a focus on the details needed for ESMs and EMICs to contribute the top priority simulation of a ZEC run from the point of 1000 PgC emissions following 1% per year growth in CO_2.

ZECMIP analysis will draw on carbon cycle feedbacks and process understanding from C4MIP (Coupled Climate Carbon Cycle Model Intercomparison Project; Jones et al., 2016) and aims to complement analysis on reversibility and CO_2 removal under CDRMIP (Carbon Dioxide Removal Model Intercomparison Project; Keller et al., 2018). Both C4MIP and CDRMIP encourage participation in the ZECMIP top priority simulation. For simplicity the data request is a replica of that for the CMIP6 emission-driven historical simulation (esm-hist). No new variables have been added. For EMICs the request is to output the same model variables as from the 1% run which forms the basis of ZECMIP, with the one addition of also providing atmospheric CO_2 concentration. Data can be published via the Earth System Grid Federation (ESGF) (for ESMs contributing to CMIP6). An equivalent data repository will be available for EMICs and likely based at University of Victoria – details will be communicated during summer 2019 via C4MIP and CDRMIP websites.

2. Simulation Protocol

Due to time pressures and limit in computational resources on modelling groups ZECMIP has just one high priority simulation, with a lower priority second simulation suggested (See Table 1). Other lower priority simulations are also detailed and welcomed. For EMIC model groups there is an extended protocol with longer and additional experiments. We welcome ESM groups to also perform these additional simulations, but this is not required. Given that the overall CMIP6 protocol (Eyring et al., 2016) has been years in development, it is not possible to initiate a new MIP, nor allocate new CMIP tier-1 simulations during 2019. Instead, ZECMIP simulations are being included under C4MIP and CDRMIP and included in CMIP as tier-2 and tier-3 simulations so that they do not become mandatory "entry card" requirements for C4MIP or CDRMIP. Hence, our top priority simulation, A1, is classed as CMIP tier-2 simulation; all others are classified as tier-3 simulations. However, Table 1 lists the simulations prioritised by ZECMIP to guide groups who have limited resources to perform the simulations. We hope as many groups as possible perform as many of the simulations as possible, and participating model groups will be offered co-authorship on the manuscript containing the analysis to be submitted this year (by December 2019).

2.1. Simulation set – A: Abrupt-zero emissions

All ZECMIP simulations are required to be in "emissions-driven mode". Experiments under set "A" require branching off from a simulation where CO_2 concentration follows a 1% per annum increase from pre-industrial levels. This presents model groups with a choice of how to initialise experiments A1 to A3. Some models may have the capability to switch from concentration-driven to emissions-driven configuration, but some models may not, or model groups may not have confidence that they can do so without a shock to the model system. In the case of the former, the concentration-driven DECK 1pctCO2 simulation can be used to initiate experiments A1 to A3. Otherwise, models should perform simulation A0 to generate initial conditions for A1 to A3.

We do not specify a precise definition of how to make this choice but suggest that when an emissions-driven control run is initiated from a concentration driven control run, any subsequent change in atmospheric CO_2, major carbon stores, or global temperature should all be approximately within the expected inter-annual variability of the control run. We note that if simulation A0 is required to initialise the A1 simulation then it should be treated as equal priority to A1 and data submission to the ESGF is required.

A0. "esm-1pctCO2". Run an emissions-driven version of 1pctCO2 to get to the branch-off point for A1 to A3. The requirement to run this is a model-by-model decision. The compatible emissions timeseries for this simulation should be calculated from the 1pctCO2 and used to branch esm-1pctCO2 from esm-piControl to replicate the 1% profile as closely as possible up to the desired cumulative emission before setting emissions to zero from this point.

The compatible emission rate E (PgC yr^{-1}) can be calculated from the 1pctCO2 concentration-driven simulation, as described in Jones et al. (2013): see their section 2b. In summary, changes in atmospheric CO_2 concentration (C_A) are balanced by anthropogenic emissions, E, and changes in the natural land and ocean carbon reservoirs (C_L and C_O respectively). Therefore, the compatible emissions can be calculated simply as:

$$E = \frac{d}{dt}(C_{Tot}) = \frac{d}{dt}(C_A) + \frac{d}{dt}(C_L + C_O)$$

Where units of all quantities are in PgC. Changes in atmospheric CO_2 can be converted from concentration (ppm) to mass (PgC) by a simple scaling of 2.12. Typically, the time derivative *d/dt*, is taken to imply changes per year – i.e. annual changes in the carbon stores are used in order to calculate annual emission, E. The calculation is done using global total amounts. Emissions should be prescribed as globally uniform at the surface. Models that have run multiple ensemble members for the concentration-driven 1pctCO2 experiment should use ensemble-mean values of C_L and C_O from those runs to derive the emissions for forcing the esm-1pctCO2 simulation. This will minimize the effect of interannual variability of carbon sinks on the diagnosed compatible emissions. If desired, numerical smoothing of the global mean timeseries of emissions may also be applied as long as the cumulative total is not affected.

ZECMIP simulation set A is based on CO_2-only, 1% run (either concentration driven DECK: "1pctCO2", or the above described A.0 "esm-1pctCO2"), with all the other external forcing held at pre-industrial conditions (i.e., non-CO_2 greenhouse gases, aerosols, volcanoes, land-use changes, solar irradiance). After following the CO_2 concentration up to the level described below, branch off with prognostic CO_2 (a.k.a. "Emissions driven") but with carbon emissions set to zero (E=0). Simulate the subsequent reduction in atmospheric CO_2 and change in climate for at least 100 years.

Branch off at given cumulative emissions of:

- **A1. "esm-1pct-brch-1000PgC".** 1000 PgC. ZECMIP top priority simulation. This corresponds to approximately 2ºC CO_2-induced warming above pre-industrial (with the year 1850 here taken as proxy for pre-industrial). This is the top priority ZECMIP simulation. Figure 1 shows example results from two models.
- **A2. "esm-1pct-brch-750PgC".** 750 PgC. This is a simulation corresponding to approximately 1.5ºC CO_2-induced warming above 1850. Optional.
- **A3. "esm-1pct-brch-2000PgC".** 2000 PgC). This simulation will give insights in ZEC for a possible higher CO_2-induced warming. Optional.

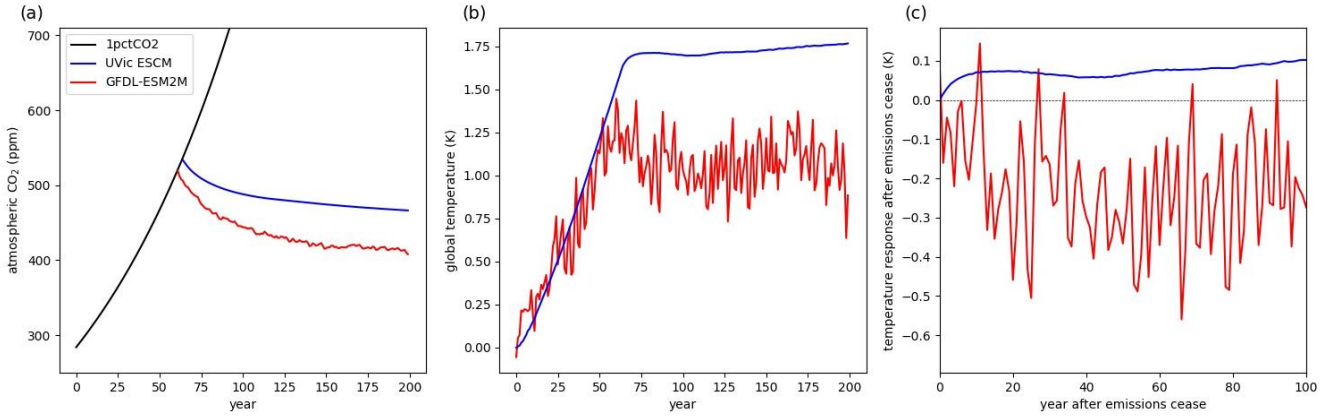

Figure 1. Example results from simulation A1 from the UVIC ESCM (Weaver et al., 2001; MacDougall and Knutti, 2016; blue) and GFDL-ESM2M (Dunne et al., 2012, 2013; red) models. (a) CO_2 concentration prescribed (black line) in the 1pctCO2 simulation and simulated (red, blue lines) by the two models; (b) simulated global mean surface air temperature for the same period; (c) global mean temperature response from the branch point off the 1% simulation with zero subsequent emissions.

The experimental design is for all models to branch off at a common cumulative carbon emission level, acknowledging that this will mean a different year for ceasing emissions and thus a slightly different atmospheric CO_2 concentration and departure of global mean temperature from 1850 for each model at the beginning of the ZECMIP simulations. EMICs should run the simulations for at least 1000 years. We anticipate that the small signal-to-noise ratio of the ZEC versus the internal climate variability may require ensemble of simulations. However, acknowledging ESM time pressure and limits in computational resources only one ensemble member is required.

Experiment A1 aims to quantify ZEC at 1000 PgC (cumulative emissions), at which point TCRE will be calculated. A2 and A3 explore the ***state*** dependence of ZEC at approximately 1.5ºC CO_2-induced warming above 1850 and at significantly higher cumulative emissions respectively.

2.2. Simulation set – B: Bell-shape zero emissions

This second set of experiments, B1 to B3, aims to explore the dependence of ZEC on CO_2 emissions ***rate*** by following a pathway emitting the same cumulative emissions as A1 to A3 but with a smooth transition to zero emissions, followed by 100 years of E=0 (EMICs for at least 1000 years). The main purpose of this experiment is to quantify the dependency of ZEC on emission pathways and the emission rate prior to the point when TCRE is evaluated, as the Earth system is subject to comparatively low emissions, occurring just before the TCRE evaluation point of zero emission after 100 years of simulation – compared to the sudden cessation of high emissions in experiment A.1, A.2 and A.3.

The conventional way of estimating TCRE is using 1% CO2 model simulations. The tier-1 A1 simulation thus provides the most complementary and internally consistent quantification of the ZEC which is why we consider this to be the top priority. However, additional ZECMIP experiments with more gradually phased out emissions enable us to determine how the ZEC is expected to materialize over the timescales of more societally relevant CO2 emissions reduction rates. Analysis of pairs of "A" and "B" experiments will allow us to generalize the findings for other emission reduction pathways, allowing us to answer the question if temperature will continue to increase following a more realistic cessation of CO2 emissions.

These B-experiments are run in emissions-driven configuration (CO_2-only: following 1pctCO2 and piControl, all other external forcing is fixed at pre-industrial), assuming a "bell shaped" emissions profile (Figure 2), for which we have chosen an arbitrary Gaussian distribution (see Appendix A). At end of 100 years emissions profile, simulations should continue with zero emissions for at least 100 years (for ESMs) and 1000 years (EMICs).

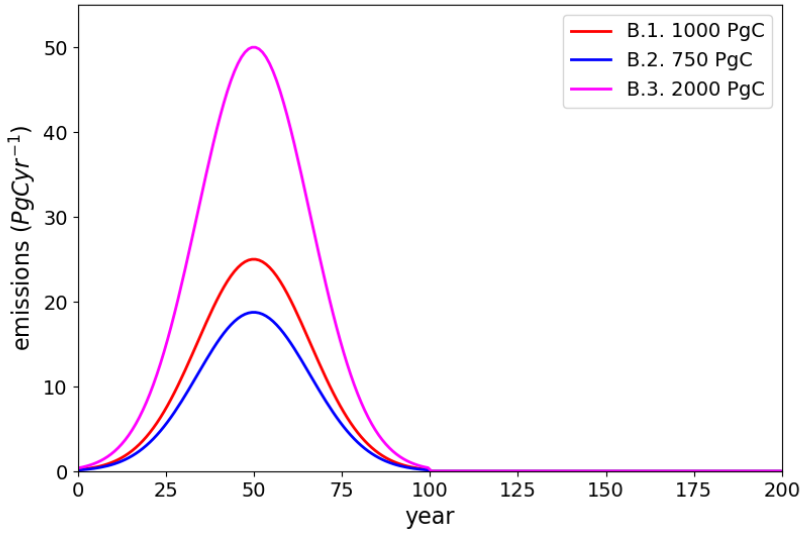

Figure 2. Time series of global CO_2 emissions for bell curve pathways B1 to B3. The numbers in the legend indicate the cumulative amount of CO_2 emissions for each simulation.

The bell-curve is designed to give cumulative emissions of:

- **B1. "esm-bell-1000PgC".** 1000 PgC. Figure 3 shows example results from two models.
- **B2. "esm-bell-750PgC".** 750 PgC.
- **B3. "esm-bell-2000PgC".** 2000 PgC.

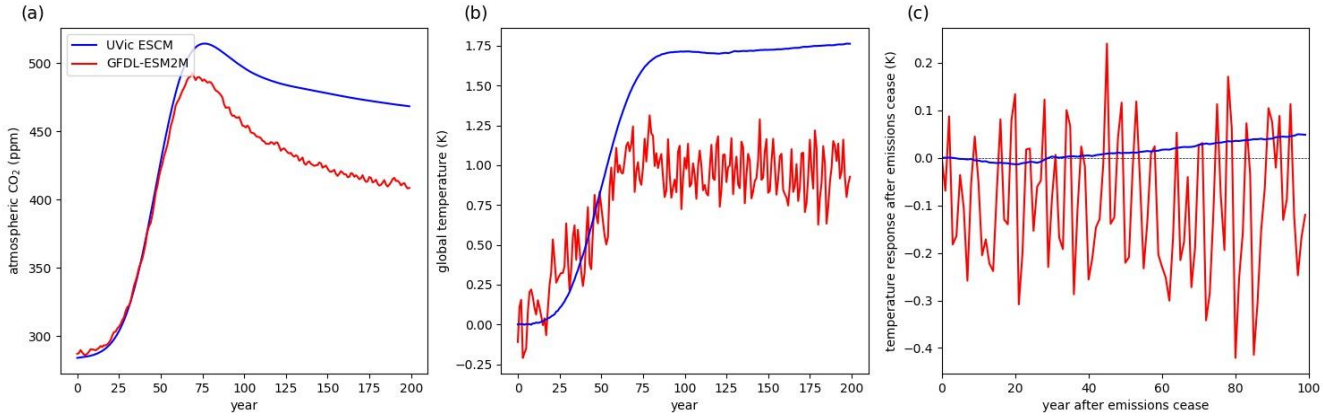

Figure 3. Example results from simulation B1 from the UVIC ESCM (Weaver et al., 2001; MacDougall and Knutti, 2016; blue) and GFDL-ESM2M (Dunne et al., 2012, 2013; red) models. (a) CO_2 concentration simulated by the two models; (b) simulated global mean surface air temperature for the same period; (c) global mean temperature response from year 100 onwards with zero subsequent emissions.

By design, this set of B-experiments utilise the same cumulative emissions as the respective simulations in set "A" experience up to their branch point. These emissions are applied over 100 years, followed by zero emissions for 100 years (ESMs) or 1000 years (EMICs). These additional simulations allow for a direct comparison of the two ZEC experiment sets, given the same amount of cumulative emissions. A model decision is required on the spatial pattern of emissions – we suggest globally uniform at surface. The timeseries of global CO_2 emissions for the above curves is listed in Appendix A and is hosted on the C4MIP (www.c4mip.net) and CDRMIP (https://www.kiel-earth-institute.de/CDR_Model_Intercomparison_Project.html) websites.

3. ZECMIP outlook and conclusions

The experiments outlined above will lay the foundation for coordinated multi-model analysis of the Zero Emissions Commitment. The absence of a dedicated experiment to quantify ZEC across CMIP models was identified and is addressed by our top priority experiment, A1. Investigations into the state, rate and pathway dependence of the ZEC are aided by further experiments with sudden and gradual cessation of emissions. ZECMIP was motivated to keep the experiment design both lightweight and simple to follow, but in future, further simulations could be defined to explore additional issues such as cessation of emissions of non-CO_2 greenhouse gases, aerosols, or from land-use activities. The complexity of defining such experiments precluded an exhaustive inclusion in this first generation of ZECMIP but we acknowledge the importance of rate- and pathway dependency, as well non-CO_2 aspects in determining ZEC and the remaining carbon budget overall (MacDougall et al., 2015; Rogelj et al., 2015; Mengis et al., 2018; Tokarska et al., 2018).

The requirement for specific information regarding ZEC to assess remaining carbon budgets was identified in the IPCC Special Report on Global Warming of 1.5°C (Rogelj et al., 2018). An initial paper exploring ZEC in this context, explicitly on timescales of relevance to 21st century carbon budgets, is planned on a timeline that could support an improved assessment of the ZEC and its influence on carbon budgets in the IPCC Sixth Assessment. All participating model groups who are able to complete and provide data for simulation A1 in time will be invited to join this analysis.

ZECMIP welcomes community engagement in the participation of simulations and their analysis, and input to future analysis and experimental design. We hope to bring together ESMs and EMICs to enable analysis across timescales from decadal to centennial to millennial.

Furthermore, as a set of numerical simulations, ZECMIP is intended to complement existing CMIP activity especially on carbon cycle feedbacks, CO_2 removal and reversibility of the climate system. C4MIP simulations aim to address model evaluation during the historical period from 1850 to present day, along with process-level feedback analysis. CDRMIP adds to this with exploration of the processes controlling the response of the climate and carbon cycle to negative emissions, and reversibility of components of the Earth System. ZECMIP will contribute additional simulations and analysis to aid understanding of the mechanisms of the climate response to CO_2 emissions and relationships between transient and equilibrium climate sensitivities. We hope that ZECMIP analysis will address the crucial knowledge gap surrounding committed warming following ceasing emissions and provide valuable support for assessment of carbon budgets to achieve climate targets.

Data availability

As with all CMIP6-endorsed MIPs, the model output from the ZECMIP simulations described in this paper will be distributed through the Earth System Grid Federation (ESGF) with version control and digital object identifiers (DOIs) assigned. No additional model forcings are required beyond those already used for piControl and 1pctCO2 simulations apart from the emission inputs for the proposed B experiments which are described in Appendix A to this paper and are hosted on the C4MIP and CDRMIP websites.

Author contributions

All authors partook in workshop discussions to identify research needs and design the experimental protocol described here to address them. All authors contributed to the development of the manuscript.

Competing interests.

The authors declare that they have no conflict of interest.

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References

Allen, M. R., Frame, D. J., Huntingford, C., Jones, C. D., Lowe, J. A., Meinshausen, M. and Meinshausen, N.: Warming caused by cumulative carbon emissions towards the trillionth tonne, Nature, 458(7242), 1163–1166, doi:10.1038/nature08019, 2009.

Allen, M. R., Dube, O. P., Solecki, W., Aragón–Durand, F., Cramer, W., Humphreys, S., Kainuma, M., Kala, J., Mahowald, N., Mulugetta, Y., Perez, R., Wairiu, M. and Zickfeld, K.: Chapter 1 Framing and Context., in Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change,., 2018.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shongwe, M., Tebaldi, C., Weaver, A. J. and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, in Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midgley, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 2013.

Dunne, J. P., John, J. G., Adcroft, A. J., Griffies, S. M., Hallberg, R. W., Shevliakova, E. N., Stouffer, R. J., Cooke, W., Dunne, K. A., Harrison, M. J., Krasting, J. P., Levy, H., Malyshev, S. L., Milly, P. C. D., Phillipps, P. J., Sentman, L. T., Samuels, B. L., Spelman, M. J., Winton, M., Wittenberg, A. T. and Zadeh, N.: GFDL's ESM2 global coupled climate-carbon Earth System Models Part I: Physical formulation and baseline simulation characteristics, J. Clim., doi:doi:10.1175/JCLI-D-11-00560.1., 2012.

Dunne, J. P., John, J. G., Shevliakova, E., Stouffer, R. J., Krasting, J. P., Malyshev, S. L., Milly, P. C. D., Sentman, L. T., Adcroft, A. J., Cooke, W., Dunne, K. A., Griffies, S. M., Hallberg, R. W., Harrison, M. J., Levy, H., Wittenberg, A. T., Phillips, P. J. and Zadeh, N.: GFDL's ESM2 Global Coupled Climate–Carbon Earth System Models. Part II: Carbon System Formulation and Baseline Simulation Characteristics, J. Clim., 26(7), 2247–2267, doi:10.1175/JCLI-D-12-00150.1, 2013.

Ehlert, D. and Zickfeld, K.: What determines the warming commitment after cessation of CO2 emissions?, Environ. Res. Lett., doi:10.1088/1748-9326/aa564a, 2017.

Ehlert, D., Zickfeld, K., Eby, M. and Gillett, N.: The sensitivity of the proportionality between temperature change and cumulative CO2 emissions to ocean mixing, J. Clim., doi:10.1175/JCLI-D-16-0247.1, 2017.

Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J. and Taylor, K. E.: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization, Geosci. Model Dev., 9(5), 1937–1958, doi:10.5194/gmd-9-1937-2016, 2016.

Frölicher, T. L., Winton, M. and Sarmiento, J. L.: Continued global warming after CO2 emissions stoppage, Nat. Clim. Chang., 4(1), 40–44, doi:10.1038/nclimate2060, 2014.

Frölicher, T. L. and Joos, F.: Reversible and irreversible impacts of greenhouse gas emissions in multi-century projections with the NCAR global coupled carbon cycle-climate model, Clim. Dyn., doi:10.1007/s00382-009-0727-0, 2010.

Frölicher, T. L. and Paynter, D. J.: Extending the relationship between global warming and cumulative carbon emissions to multi-millennial timescales, Environ. Res. Lett., 10(7), 075002, doi:10.1088/1748-9326/10/7/075002, 2015.

Gillett, N. P., Arora, V. K., Zickfeld, K., Marshall, S. J. and Merryfield, W. J.: Ongoing climate change following a complete cessation of carbon dioxide emissions, Nat. Geosci., doi:10.1038/ngeo1047, 2011.

Gillett, N. P., Arora, V. K., Matthews, D. and Allen, M. R.: Constraining the ratio of global warming to cumulative CO2emissions using CMIP5 simulations, J. Clim., doi:10.1175/JCLI-D-12-00476.1, 2013.

Goodwin, P., Williams, R. G. and Ridgwell, A.: Sensitivity of climate to cumulative carbon emissions due to compensation of ocean heat and carbon uptake, Nat. Geosci., doi:10.1038/ngeo2304, 2015.

Jones, C., Robertson, E., Arora, V., Friedlingstein, P., Shevliakova, E., Bopp, L., Brovkin, V., Hajima, T., Kato, E., Kawamiya, M., Liddicoat, S., Lindsay, K., Reick, C. H., Roelandt, C., Segschneider, J. and Tjiputra, J.: Twenty-First-Century Compatible CO2 Emissions and Airborne Fraction Simulated by CMIP5 Earth System Models under Four Representative Concentration Pathways, J. Clim., 26(13), 4398–4413, doi:10.1175/JCLI-D-12-00554.1, 2013.

Jones, C. D., Arora, V., Friedlingstein, P., Bopp, L., Brovkin, V., Dunne, J., Graven, H., Hoffman, F., Ilyina, T., John, J. G.,

Jung, M., Kawamiya, M., Koven, C., Pongratz, J., Raddatz, T., Randerson, J. T. and Zaehle, S.: C4MIP-The Coupled Climate-Carbon Cycle Model Intercomparison Project: experimental protocol for CMIP6, Geosci. Model Dev., 9(8), 2853–2880, doi:10.5194/gmd-9-2853-2016, 2016.

Joos, F., Roth, R., Fuglestvedt, J. S., Peters, G. P., Enting, I. G., Von Bloh, W., Brovkin, V., Burke, E. J., Eby, M., Edwards, N. R., Friedrich, T., Frölicher, T. L., Halloran, P. R., Holden, P. B., Jones, C., Kleinen, T., Mackenzie, F. T., Matsumoto, K., Meinshausen, M., Plattner, G. K., Reisinger, A., Segschneider, J., Shaffer, G., Steinacher, M., Strassmann, K., Tanaka, K., Timmermann, A. and Weaver, A. J.: Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: A multi-model analysis, Atmos. Chem. Phys., doi:10.5194/acp-13-2793-2013, 2013.

Keller, D. P., Lenton, A., Scott, V., Vaughan, N. E., Bauer, N., Ji, D., Jones, C. D., Kravitz, B., Muri, H. and Zickfeld, K.: The Carbon Dioxide Removal Model Intercomparison Project (CDRMIP): rationale and experimental protocol for CMIP6, Geosci. Model Dev., 11(3), 1133–1160, doi:10.5194/gmd-11-1133-2018, 2018.

Krasting, J. P., Dunne, J. P., Shevliakova, E. and Stouffer, R. J.: Trajectory sensitivity of the transient climate response to cumulative carbon emissions, Geophys. Res. Lett., 41(7), 2520–2527, doi:10.1002/2013GL059141, 2014.

Le Quéré, C., Andrew, R., Friedlingstein, P., Sitch, S., Hauck, J., Pongratz, J., Pickers, P., Ivar Korsbakken, J., Peters, G., Canadell, J., Arneth, A., Arora, V., Barbero, L., Bastos, A., Bopp, L., Ciais, P., Chini, L., Ciais, P., Doney, S., Gkritzalis, T., Goll, D., Harris, I., Haverd, V., Hoffman, F., Hoppema, M., Houghton, R., Hurtt, G., Ilyina, T., Jain, A., Johannessen, T., Jones, C., Kato, E., Keeling, R., Klein Goldewijk, K., Landschützer, P., Lefèvre, N., Lienert, S., Liu, Z., Lombardozzi, D., Metzl, N., Munro, D., Nabel, J., Nakaoka, S. I., Neill, C., Olsen, A., Ono, T., Patra, P., Peregon, A., Peters, W., Peylin, P., Pfeil, B., Pierrot, D., Poulter, B., Rehder, G., Resplandy, L., Robertson, E., Rocher, M., Rödenbeck, C., Schuster, U., Skjelvan, I., Séférian, R., Skjelvan, I., Steinhoff, T., Sutton, A., Tans, P., Tian, H., Tilbrook, B., Tubiello, F., Van Der Laan-Luijkx, I., Van Der Werf, G., Viovy, N., Walker, A., Wiltshire, A., Wright, R., Zaehle, S. and Zheng, B.: Global Carbon Budget 2018, Earth Syst. Sci. Data, doi:10.5194/essd-10-2141-2018, 2018.

Lowe, J. A., Huntingford, C., Raper, S. C. B., Jones, C. D., Liddicoat, S. K. and Gohar, L. K.: How difficult is it to recover from dangerous levels of global warming?, Environ. Res. Lett., doi:10.1088/1748-9326/4/1/014012, 2009.

MacDougall, A. H.: The Transient Response to Cumulative CO2 Emissions: a Review, Curr. Clim. Chang. Reports, 2(1), 39–47, doi:10.1007/s40641-015-0030-6, 2016.

MacDougall, A. H.: Limitations of the 1% experiment as the benchmark idealized experiment for carbon cycle intercomparison in C4MIP, Geosci. Model Dev., 12(2), 597–611, doi:10.5194/gmd-12-597-2019, 2019.

MacDougall, A. H. and Knutti, R.: Projecting the release of carbon from permafrost soils using a perturbed parameter ensemble modelling approach, Biogeosciences, 13(7), 2123–2136, doi:10.5194/bg-13-2123-2016, 2016.

MacDougall, A. H., Zickfeld, K., Knutti, R. and Matthews, H. D.: Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO2 forcings, Environ. Res. Lett., doi:10.1088/1748-9326/10/12/125003, 2015.

Matthews, H. D. and Caldeira, K.: Stabilizing climate requires near-zero emissions, Geophys. Res. Lett., 35(4), L04705, doi:10.1029/2007GL032388, 2008.

Matthews, H. D. and Solomon, S.: Irreversible Does Not Mean Unavoidable, Science (80-.)., 340(6131), 438 LP – 439, doi:10.1126/science.1236372, 2013.

Matthews, H. D. and Weaver, A. J.: Committed climate warming, Nat. Geosci., 3, 142, https://doi.org/10.1038/ngeo813, 2010.

Matthews, H. D. and Zickfeld, K.: Climate response to zeroed emissions of greenhouse gases and aerosols, Nat. Clim. Chang., 2(5), 338–341, doi:10.1038/nclimate1424, 2012.

Matthews, H. D., Gillett, N. P., Stott, P. A. and Zickfeld, K.: The proportionality of global warming to cumulative carbon emissions, Nature, 459(7248), 829-U3, doi:10.1038/nature08047, 2009.

Matthews, H. D., Landry, J. S., Partanen, A. I., Allen, M., Eby, M., Forster, P. M., Friedlingstein, P. and Zickfeld, K.: Estimating Carbon Budgets for Ambitious Climate Targets, Curr. Clim. Chang. Reports, doi:10.1007/s40641-017-0055-0, 2017.

Mengis, N., Partanen, A.-I., Jalbert, J. and Matthews, H. D.: 1.5°C carbon budget dependent on carbon cycle uncertainty and future non-CO2 forcing, Sci. Rep., 8(1), 5831, doi:10.1038/s41598-018-24241-1, 2018.

Millar, R. J. and Friedlingstein, P.: The utility of the historical record for assessing the transient climate response to cumulative emissions, Philos. Trans. R. Soc. A Math. Phys. Eng. Sci., doi:10.1098/rsta.2016.0449, 2018.

Raupach, M. R., Canadell, J. G., Ciais, P., Friedlingstein, P., Rayner, P. J. and Trudinger, C. M.: The relationship between peak warming and cumulative CO2 emissions, and its use to quantify vulnerabilities in the carbon-climate-human system, Tellus, Ser. B Chem. Phys. Meteorol., 63(2), 145–164, doi:10.1111/j.1600-0889.2010.00521.x, 2011.

Rogelj, J., Hare, W., Lowe, J., van Vuuren, D. P., Riahi, K., Matthews, B., Hanaoka, T., Jiang, K. and Meinshausen, M.: Emission pathways consistent with a 2°C global temperature limit, Nat. Clim. Chang., 1, 413–418, 2011.

Rogelj, J., Meinshausen, M., Schaeffer, M., Knutti, R. and Riahi, K.: Impact of short-lived non-CO2mitigation on carbon budgets for stabilizing global warming, Environ. Res. Lett., doi:10.1088/1748-9326/10/7/075001, 2015.

Rogelj, J., Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., Handa, C., Kheshgi, H., Kobayashi, S., Kriegler, E., Mundaca, L., Séférian, R. and Vilariño, M. V.: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development, in Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, edited by V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, 2018.

Solomon, S., Plattner, G.-K., Knutti, R. and Friedlingstein, P.: Irreversible climate change due to carbon dioxide emissions, Proc. Natl. Acad. Sci., 106(6), 1704–1709, doi:10.1073/pnas.0812721106, 2009.

Steinacher, M. and Joos, F.: Transient Earth system responses to cumulative carbon dioxide emissions: Linearities, uncertainties, and probabilities in an observation-constrained model ensemble, Biogeosciences, doi:10.5194/bg-13-1071-2016, 2016.

Tachiiri, K., Hajima, T. and Kawamiya, M.: Increase of uncertainty in transient climate response to cumulative carbon emissions after stabilization of atmospheric CO2 concentration, Environ. Res. Lett., doi:10.1088/1748-9326/10/12/125018, 2015.

Tokarska, K. B., Gillett, N. P., Arora, V. K., Lee, W. G. and Zickfeld, K.: The influence of non-CO 2 forcings on cumulative carbon emissions budgets, Environ. Res. Lett., doi:10.1088/1748-9326/aaafdd, 2018.

Weaver, A. J., Eby, M., Wiebe, E. C., Bitz, C. M., Duffy, P. B., Ewen, T. L., Fanning, A. F., Holland, M. M., MacFadyen, A., Matthews, H. D., Meissner, K. J., Saenko, O., Schmittner, A., Wang, H. X. and Yoshimori, M.: The UVic Earth System Climate Model: Model description, climatology, and applications to past, present and future climates, Atmosphere-Ocean, 39(4), 361–428, 2001.

Zickfeld, K., Eby, M., Matthews, H. D. and Weaver, A. J.: Setting cumulative emissions targets to reduce the risk of dangerous climate change., Proc. Natl. Acad. Sci. U. S. A., 106(38), 16129–34, doi:10.1073/pnas.0805800106, 2009.

Zickfeld, K., Eby, M., Weaver, A. J., Alexander, K., Crespin, E., Edwards, N. R., Eliseev, A. V., Feulner, G., Fichefet, T., Forest, C. E., Friedlingstein, P., Goosse, H., Holden, P. B., Joos, F., Kawamiya, M., Kicklighter, D., Kienert, H., Matsumoto, K., Mokhov, I. I., Monier, E., Olsen, S. M., Pedersen, J. O. P., Perrette, M., Philippon-Berthier, G., Ridgwell, A., Schlosser, A., Von Deimling, T. S., Shaffer, G., Sokolov, A., Spahni, R., Steinacher, M., Tachiiri, K., Tokos, K. S., Yoshimori, M., Zeng, N. and Zhao, F.: Long-Term climate change commitment and reversibility: An EMIC intercomparison, J. Clim., doi:10.1175/JCLI-D-12-00584.1, 2013.

Table 1. ZECMIP simulations and priorities for ESMs and EMICs.

ZECMIP experiment	CMIP6 experiment ID	Description	ESM priority (at least 100 years)	EMIC priority (1000 years)
A0	*esm-1pctCO2*	An emissions-driven simulation (fully interactive CO_2), initiated from the esm-piControl using CO_2 emissions diagnosed from the 1pctCO2 experiment so that the emissions-driven run replicates as closely as possible the 1pctCO2 concentration profile. Required to create start conditions for A1-3. Not required if model can use DECK 1pctCO2.	If required	If required
A1	*esm-1pct-brch-1000PgC*	A zero-emissions simulation (fully interactive CO_2), branched from the point in the 1pctCO2 experiment (or A0 above) when the cumulative carbon emissions reach 1000 PgC	1	1
A2	*esm-1pct-brch-750PgC*	A zero-emissions simulation (fully interactive CO_2), branched from the point in the 1pctCO2 experiment (or A0 above) when the cumulative carbon emissions reach 750 PgC	2	1
A3	*esm-1pct-brch-2000PgC*	A zero-emissions simulation (fully interactive CO_2), branched from the point in the 1pctCO2 experiment (or A0 above) when the cumulative carbon emissions reach 2000 PgC		2
B1	*esm-bell-1000PgC*	An emissions-driven simulation (fully interactive CO_2), initiated from esm-piControl using CO_2 emissions, amounting to 1000 PgC, following a bell-shape curve for 100 years followed by zero-emissions for at least 100 years		1
B2	*esm-bell-750PgC*	An emissions-driven simulation (fully interactive CO_2), initiated from esm-piControl using CO_2 emissions, amounting to 750 PgC, following a bell-shape curve for 100 years followed by zero-emissions for at least 100 years		2
B3	*esm-bell-2000PgC*	An emissions-driven simulation (fully interactive CO_2), initiated from esm-piControl using CO_2 emissions, amounting to 2000 PgC, following a bell-shape curve for 100 years followed by zero-emissions for at least 100 years		2

Appendix A. CO_2 Emissions for Bell-curve simulations B1-3.

This table lists the global CO_2 emissions, in PgC yr^{-1}, to be applied for the first 100 years of simulations B1-3. This period should be followed by at least 100 years of zero emissions for ESMs and 1000 years for EMICs (see Figure 2). These emissions should be prescribed as globally uniform at the surface.

The data was calculated from a Gaussian curve according to:

$$E = k * \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Where emissions, E, are scaled by a constant, k, in order that the cumulative total matches the required amount for each scenario (1000 PgC for B1, 750 PgC for B2, 2000 PgC for B3). The parameters were set as μ=50 as the centre of the 100 year period, and σ=100/6 so that the distribution spans 3 standard deviations about the centre.

This data in .csv format is available from the C4MIP (www.c4mip.net) and CDRMIP (https://www.kiel-earth-institute.de/CDR_Model_Intercomparison_Project.html) websites.

year	B1. 1000 PgC	B2. 750 PgC	B3 2000 PgC
1	0.20873014	0.1565476	0.41746028
2	0.25276203	0.18957153	0.50552407
3	0.30488921	0.22866691	0.60977842
4	0.3663328	0.2747496	0.73266561
5	0.43844296	0.32883222	0.87688592
6	0.52270172	0.39202629	1.04540343
7	0.62072365	0.46554273	1.24144729
8	0.73425378	0.55069034	1.46850756
9	0.86516239	0.64887179	1.73032477
10	1.01543611	0.76157709	2.03087223
11	1.18716509	0.89037382	2.37433018
12	1.38252556	1.03689417	2.76505111
13	1.6037577	1.20281828	3.2075154
14	1.8531385	1.38985388	3.706277
15	2.13294934	1.59971201	4.26589868
16	2.44543847	1.83407885	4.89087694
17	2.79277839	2.09458379	5.58555678

18	3.17701853	2.3827639	6.35403707
19	3.60003364	2.70002523	7.20006728
20	4.06346858	3.04760144	8.12693716
21	4.56868053	3.4265104	9.13736106
22	5.11667948	3.83750961	10.233359
23	5.70806844	4.28105133	11.4161369
24	6.34298476	4.75723857	12.6859695
25	7.0210441	5.26578308	14.0420882
26	7.74128883	5.80596662	15.4825777
27	8.50214249	6.37660687	17.004285
28	9.30137222	6.97602916	18.6027444
29	10.1360608	7.60204558	20.2721216
30	11.0025899	8.25194241	22.0051798
31	11.8966362	8.92247716	23.7932724
32	12.8131814	9.60988606	25.6263628
33	13.746537	10.3099028	27.493074
34	14.6903849	11.0177887	29.3807697
35	15.6378333	11.728375	31.2756666
36	16.5814888	12.4361166	33.1629776
37	17.5135425	13.1351569	35.027085
38	18.4258706	13.819403	36.8517412
39	19.3101466	14.48261	38.6202932
40	20.1579639	15.1184729	40.3159277
41	20.9609659	15.7207244	41.9219317
42	21.7109814	16.2832361	43.4219629
43	22.400162	16.8001215	44.8003239
44	23.0211173	17.265838	46.0422347
45	23.5670474	17.6752855	47.1340948
46	24.0318658	18.0238993	48.0637315
47	24.4103126	18.3077344	48.8206251
48	24.6980536	18.5235402	49.3961072
49	24.8917628	18.6688221	49.7835257

50	24.9891865	18.7418898	49.9783729
51	24.9891865	18.7418898	49.9783729
52	24.8917628	18.6688221	49.7835257
53	24.6980536	18.5235402	49.3961072
54	24.4103126	18.3077344	48.8206251
55	24.0318658	18.0238993	48.0637315
56	23.5670474	17.6752855	47.1340948
57	23.0211173	17.265838	46.0422347
58	22.400162	16.8001215	44.8003239
59	21.7109814	16.2832361	43.4219629
60	20.9609659	15.7207244	41.9219317
61	20.1579639	15.1184729	40.3159277
62	19.3101466	14.48261	38.6202932
63	18.4258706	13.819403	36.8517412
64	17.5135425	13.1351569	35.027085
65	16.5814888	12.4361166	33.1629776
66	15.6378333	11.728375	31.2756666
67	14.6903849	11.0177887	29.3807697
68	13.746537	10.3099028	27.493074
69	12.8131814	9.60988606	25.6263628
70	11.8966362	8.92247716	23.7932724
71	11.0025899	8.25194241	22.0051798
72	10.1360608	7.60204558	20.2721216
73	9.30137222	6.97602916	18.6027444
74	8.50214249	6.37660687	17.004285
75	7.74128883	5.80596662	15.4825777
76	7.0210441	5.26578308	14.0420882
77	6.34298476	4.75723857	12.6859695
78	5.70806844	4.28105133	11.4161369
79	5.11667948	3.83750961	10.233359
80	4.56868053	3.4265104	9.13736106
81	4.06346858	3.04760144	8.12693716

82	3.60003364	2.70002523	7.20006728
83	3.17701853	2.3827639	6.35403707
84	2.79277839	2.09458379	5.58555678
85	2.44543847	1.83407885	4.89087694
86	2.13294934	1.59971201	4.26589868
87	1.8531385	1.38985388	3.706277
88	1.6037577	1.20281828	3.2075154
89	1.38252556	1.03689417	2.76505111
90	1.18716509	0.89037382	2.37433018
91	1.01543611	0.76157709	2.03087223
92	0.86516239	0.64887179	1.73032477
93	0.73425378	0.55069034	1.46850756
94	0.62072365	0.46554273	1.24144729
95	0.52270172	0.39202629	1.04540343
96	0.43844296	0.32883222	0.87688592
97	0.3663328	0.2747496	0.73266561
98	0.30488921	0.22866691	0.60977842
99	0.25276203	0.18957153	0.50552407
100	0.20873014	0.1565476	0.41746028