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Climate-Carbon Interactions in the Current Century

Draft report on TCRE assessment including non-CO2 emissions and observational constraints

Deliverable 3.3

Authors: Myles Allen, Veronika Eyring, Pierre Friedlingstein, Thomas Froelicher & Stuart Jenkins

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Table of Contents

About 4C

Climate-Carbon Interactions in the Coming Century (4C) is an EU-funded H2020 project that addresses the crucial knowledge gap in the climate sensitivity to carbon dioxide emissions, by reducing the uncertainty in our quantitative understanding of carbon-climate interactions and feedbacks. This will be achieved through innovative integration of models and observations, providing new constraints on modelled carbon-climate interactions and climate projections, and supporting Intergovernmental Panel on Climate Change (IPCC) assessments and policy objectives.

1 Executive Summary

Work under this deliverable has focused in three areas: (1) First, we have updated observational constraints on the Transient Climate Response to Emissions, TCRE, using up-to-date estimates of observations and forcings consistent with the IPCC Special Report on 1.5°C (IPCC, 2018) and using a novel approach quantifying TCRE using CO_2-forcing-equivalent emissions (Jenkins et al, 2018; Jenkins et al, 2020) with particular attention given to the implications of the distinction between global mean, spatially-incomplete merged land-surface-air and sea-surface-water temperature, GMST, and global mean surface air temperatures, or GSAT. This work provides an estimate of 0.35 °C/TtCO2, with a 90% confidence interval of 0.23-0.68 °C/TtCO2 (1.3°C/TtC with a range of 0.8-2.5°C for a TCRE based on GMST. This is an identical range to AR5 but indicating a log-normal distribution within that range and encompasses the range of TCREs from CMIP6 models. TCREs based on globally complete GSAT observations would be approximately 10% higher, with important implications for the classification of emissions scenarios with respect to temperature goals. (2) Second, in a new study (MacDougall et al., 2020), we investigated how much warming is still in the pipeline once carbon emission are stopped. This Zero Emissions Commitment (ZEC) is often assumed zero or negligible (i.e. IPCC SR15 report). A positive ZEC would reduce the remaining carbon budget to account for unrealized warming after CO2 emissions are halted. Similarly, a negative ZEC would increase the remaining budget, but only if its timescale is shorter than the pace of emissions reductions to net-zero CO2. Using 18 Earth system models (including nine CMIP6 models) following the ZECMIP protocol (Jones et al., 2019) we show that 50 years after stopping CO2 emissions, the median temperature change is -0.05°C with a standard deviation of 0.19°C (Figure 1). Climate models show a range of behaviors after emissions ceases: some continue to warm slowly for decades to millennia and others cool substantially. Both carbon uptake by the ocean and the terrestrial biosphere are important for counteracting the warming resulting from a reduction in ocean heat uptake in the decades after emissions cease. The warming effect is difficult to constrain because of the high uncertainty in the efficacy of ocean heat uptake. Overall, the most likely value of ZEC on multi-decadal timescales is close to zero, consistent with previous model experiments and simple theory. (3) Third, noting the uncertainty in TCRE remains a key impediment to its use in carbon budget calculations, another new study (Jones and Friedlingstein, 2020) explored the key sources of uncertainty which propagate through to TCRE. This analysis brings new insights which will allow us to determine how we can better direct our research priorities in order to reduce this uncertainty, emphasises that uses of carbon budget estimates must bear in mind the uncertainty stemming from the biogeophysical Earth system, and recommends specific areas where the carbon cycle research community needs to re-focus activity in order to try to reduce this uncertainty. This paper conclude that we should revise focus from the climate feedback on the carbon cycle to place more emphasis on CO2 as the main driver of carbon sinks and their long-term behaviour. Our proposed framework will enable multiple constraints on components of the carbon cycle to propagate to constraints on remaining carbon budgets.

Keywords: Transient Climate Response to Emissions, Zero Emissions Commitment, non-CO2 forcing

Brief summary of deliverable:

Draft report on TCR/TCRE assessment including non-CO2 emissions and observational constraints

1 Updating observational constraints on the TCRE

This deliverable component is submitted for publication as Jenkins et al (2020) submitted.

1.1 The need for a new approach to estimating TCRE accounting for non-CO2 forcing

Early estimates of TCRE (e.g. Gillett et al, 2013) relied on the use of detection and attribution methods to separate warming attributable to CO2 from total anthropogenic warming to date. CO2-induced warming was then compared with cumulative CO2 emissions to date to compute a TCRE. This TCRE was then to compute remaining carbon budgets, either by subtracting estimates of future warming due to non-CO2 forcing agents applied (e.g. in IPCC, 2018) or by making assumptions about the ratio of future non-CO2 to CO2-induced warming (e.g. Matthews et al, 2017; Leach et al, 2018; Millar and Friedlingstein, 2018). This approach becomes problematic in the assessment of ambitious mitigation scenarios, because the uncertainty arising from non-CO2 forcing becomes comparable to the remaining CO2 warming budget (see figure 1d, dotted lines). Furthermore, when comparing with the latest generation of CMIP models because many of these display very high non-CO2 forcing over recent decades, resulting in no consistent relationship between warming and cumulative CO2 emissions, undermining the utility of the concept of an “effective TCRE” (see figure 2).

The solution proposed in Jenkins et al (2020) was to compute and utilize a TCRE based on cumulative CO2-forcing-equivalent emissions, a concept dating back to Wigley (1998) and re-introduced by Jenkins et al (2018). CO2-forcing-equivalent emissions represent the quantity of CO2 emissions that would be required to reproduce the forcing history of any combination of anthropogenic forcing agents. They are obtained by expressing a time-series of Effective Radiative Forcing (ERF) as CO2-equivalent concentrations and then inverting a carbon-cycle model to calculate the CO2 emissions timeseries that would be required to reproduce this series of CO2-equivalent concentrations. CO2-forcing-equivalent emissions are a physically-determined quantity, and do not depend on the imposition of an arbitrary time-horizon, as is the case for traditional CO2-equivalent emissions calculated with metrics such as the Global Warming Potential. Figure 1d shows a much more linear relationship between cumulative CO2-forcing-equivalent emissions and total anthropogenic warming, indicating the utility of this concept in computing remaining budgets. In particular, the concept of a limited CO2-forcing-equivalent budget also extends to overshoot scenarios (lines that turn back on themselves, corresponding to periods of negative CO2-forcing-equivalent emissions and declining global temperatures).

1.2 Application of CO2-forcing-equivlent emissions to estimating TCRE from the historical record

Having demonstrated how the TCRE can be extended to multi-gas scenarios using CO2-fe emissions, we now consider how CO2-fe emissions can be used to investigate the TCRE itself by comparing total anthropogenic

warming with total cumulative CO2-fe emissions over the historical record. Previous TCRE estimates (Gillett et al, 2013) have compared cumulative pure-CO2 emissions with warming attributable to CO2, but the fractional uncertainty in the latter is higher than uncertainty in total anthropogenic warming, suggesting this is a potentially useful complementary approach. To estimate anthropogenic warming over the historical period, we use conventional "optimal fingerprinting" applied to GMST, using a two-timescale impulse response model (Millar et al, 2017) to estimate responses to anthropogenic and natural forcing given a 1000-member ensemble of representative ERF timeseries (Dessler and Forster, 2018). GMST observations (monthly mean of HadCRUT4, Cowtan-Way, NOAA and GISTEMP) are regressed onto each pair of natural and anthropogenic response timeseries with added CMIP5 control simulations to account for internal climate variability. Estimated anthropogenic warming in 2018 relative to 1850-1900 is 1.10°C (0.98°C-1.27°C) (5-95% confidence interval), slightly higher than (IPCC, 2018, SR1.5) due to updates in the datasets.

We express each anthropogenic ERF timeseries as a set of 1000 CO2-fe emissions pathways accounting for uncertainty in cumulative CO2 airborne fraction to date (0.4±0.0430) in carbon cycle parameters. Pink dots in figure 4, shows the resulting joint distribution of cumulative anthropogenic CO2-fe emissions 1875 to 2013 inclusive and human-induced warming to the decade 2009-2018 relative to 1850-1900. The cumulative anthropogenic CO2-fe emissions and human-induced warming estimate for each symbol correspond to the same ERF timeseries to account for any covariance, while CO2 airborne fraction and internal climate variability are sampled independently. Shading indicates isolines of TCRE, while different coloured scatter points show the decadal co-evolution of these quantities from 1960 to 2018, with ellipses encompassing the central 90% of the distribution, coloured by decade. The best-fit TCRE is estimated as 0.35 °C/TtCO2 (0.23-0.68 °C/TtCO2 90% confidence interval based on the most recent decade). These could be interpreted as median and 5-95% percentiles of a probability distribution if the input ERF pathways are assumed to be equiprobable, but more research characterising the distribution of uncertainty in radiative forcing to date is needed. For comparison a number of GMST-consistent TCREs derived from the CMIP6 1%/yr CO2 concentration increase experiment lie in the range 0.31-0.60 °C/TtCO2.

2 Updating observational constraints on the TCR

This deliverable component is submitted for publication as Leach et al (2020), submitted.

A number of recent studies, including a synthesis from multiple lines of evidence, have reassessed fundamental climate system responses including Equilibrium Climate Sensitivity (ECS) and Transient Climate Response (TCR). In this study, we used a Bayesian updating procedure to constrain ECS and TCR using updated estimates of attributable anthropogenic warming to date, accounting for uncertainty in anthropogenic forcing, and using a 3-time-constant representation of the thermal climate response that best replicates the response of more complex models. Results show that the observed climate record provides an effective constraint on TCR, with a central estimate of 1.77°C for a doubling of CO2, with a 90% confidence interval of 1.25-2.41°C.

3 Implications of updated models and scenarios for the Zero Emissions Commitment

This deliverable component has appeared as MacDougall et al (2020).

The Zero Emissions Commitment (ZEC) is the change in global mean temperature expected to occur following the cessation of net CO2 emissions and as such is a critical parameter for calculating the remaining carbon budget. The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) was established to gain a better understanding of the potential magnitude and sign of ZEC, in addition to the processes that underlie this metric. A total of 18 Earth system models of both full and intermediate complexity participated in ZECMIP. All models conducted an experiment where atmospheric CO2 concentration increases exponentially until 1000 PgC has been emitted. Thereafter emissions are set to zero and models are configured to allow free evolution of atmospheric CO2 concentration. Many models conducted additional second-priority simulations with different cumulative emission totals and an alternative idealized emissions pathway with a gradual transition to zero emissions. The inter-model range of ZEC 50 years after emissions cease for the 1000 PgC experiment is −0.36 to 0.29°C, with a model ensemble mean of −0.07°C, median of −0.05°C, and standard deviation of 0.19°C (figure 5). Models exhibit a wide variety of behaviours after emissions cease, with some models continuing to warm for decades to millennia and others cooling substantially. Analysis shows that both the carbon uptake by the ocean and the terrestrial biosphere are important for counteracting the warming effect from the reduction in ocean heat uptake in the decades after emissions cease. This warming effect is difficult to constrain due to high uncertainty in the efficacy of ocean heat uptake. Overall, the most likely value of ZEC on multi-decadal timescales is close to zero, consistent with previous model experiments and simple theory.

4 Key uncertainties and research priorities for constraining the TCRE

This deliverable component is based on Jones and Friedlingstein (2020).

Jones and Friedlingstein (2020) explore multi-model carbon cycle simulations across three generations of Earth system models to quantitatively assess the sources of uncertainty which propagate through to TCRE. Our analysis brings new insights which will allow us to determine how we can better direct our research priorities in order to reduce this uncertainty. We emphasise that uses of carbon budget estimates must bear in mind the uncertainty stemming from the biogeophysical Earth system, and we recommend specific areas where the carbon cycle research community needs to re-focus activity in order to try to reduce this uncertainty. We conclude that we should revise focus from the climate feedback on the carbon cycle to place more emphasis on CO2 as the main driver of carbon sinks and their long-term behaviour. Our proposed framework will enable

multiple constraints on components of the carbon cycle to propagate to constraints on remaining carbon budgets.

The underlying conceptual framework for understanding sources of uncertainty in the TCRE is summed up in the following equation:

$$\mathrm{TCRE} = \frac{\alpha}{k + \beta_{\mathrm{land}} + \beta_{\mathrm{ocean}} + \alpha(\gamma_{\mathrm{land}} + \gamma_{\mathrm{ocean}})}$$

In this equation, α is the change in GMST per unit change in atmospheric CO2 concentration, which is directly proportional to the TCR. k is a constant of conversion from emissions to atmospheric CO2 concentration, β_{land} and is the increase in β_{ocean} are the increase in land and ocean carbon stocks per unit increase of atmospheric CO2 concentration assuming no increase in surface temperature, while γ_{land} and γ_{ocean} are the increase in land and ocean carbon stocks per unit increase of surface temperature assuming no increase in atmospheric CO2 concentration (hence assuming the increase in land and ocean carbon stocks can be represented as a linear superposition of the response to rising atmospheric concentrations and rising temperatures).

This conceptual framework allows contributions to uncertainty in TCRE to be broken down, as summarized in figure 6, which shows that, consistent across a range of model intercomparison projects, uncertainty in TCR continues to contribute the largest single uncertainty to TCRE, followed by uncertainty in the response of the land carbon stock to an increase in atmospheric CO2 concentration.

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Figures:

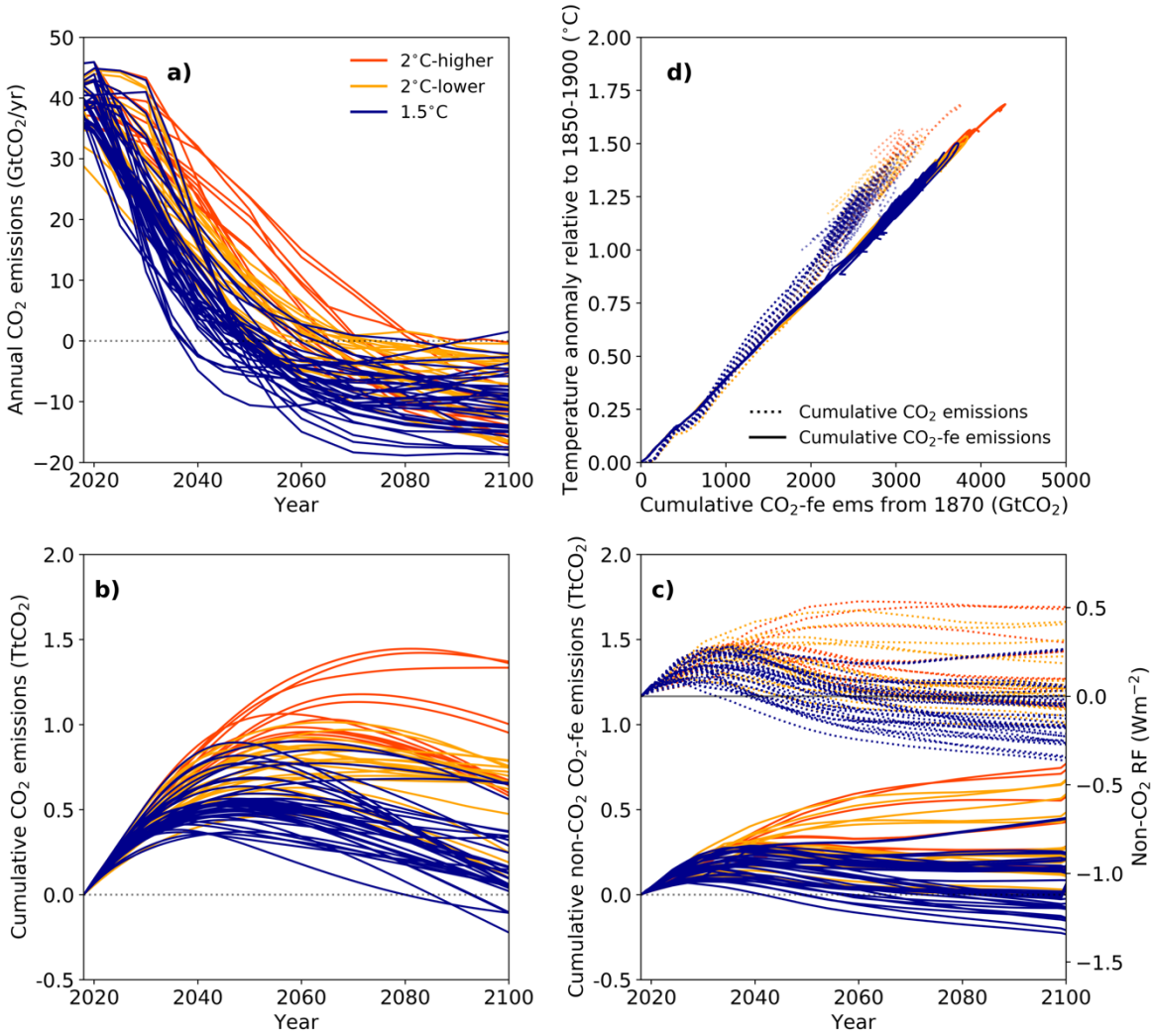

Figure 1: IIASA IAMC database of scenarios in the IPCC Special Report on the Global Warming of 1.5°C. Panel a plots the annual CO_2 emissions. Panel b (below a) shows the running sum (or cumulative) CO_2 emissions from 2018. Panel c (bottom right) shows the non-CO_2 radiative forcing for each scenario (dotted lines, right hand axis). Also on panel c are the cumulative non-CO_2 CO_2-fe emissions from 2018 corresponding to each non-CO_2 RF line (solid lines, left hand axis). The axes of panels b and c are scaled so the cumulative emissions from CO_2 and non-CO_2 are directly comparable. Panel d plots the FaIRv1.3-derived temperature response against the diagnosed cumulative CO_2-fe emissions (solid lines) and against the cumulative CO_2-only emissions (dotted lines). For FaIR temperature response TCR=1.6°C, ECS=2.75°C. Scenarios are coloured by category in the IAMC database: red for 2°C-higher, orange for 2°C-lower and blue for 1.5°C-compatible.

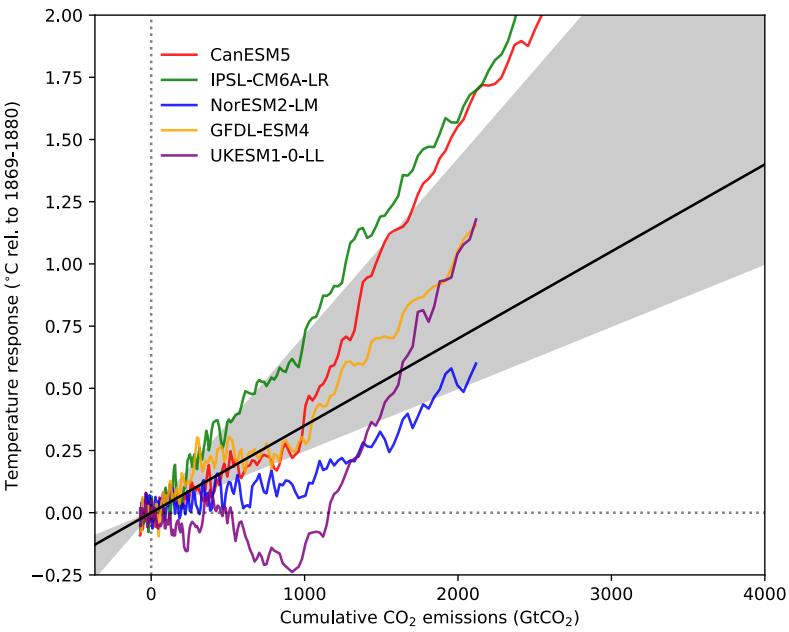

Figure 2: Temperature response of selected CMIP6 models plotted against best estimate historical CO2 emissions (from GCP7) and SSP2-45 CO2 emissions (from SSP database), showing the lack of a consistent "effective TCRE" in either historical or projected periods due to large variations in non-CO2 forcing. Grey shaded region shows observationally-constrained TCRE.

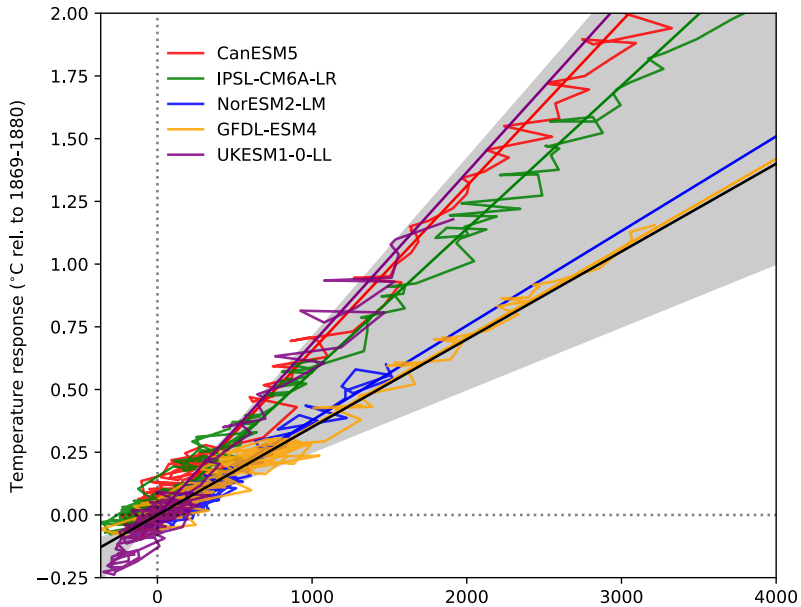

Figure 3: TCREs calculated for a range of CMIP6 models using CO2-forcing-equivalent emissions. FaIRv2.0 simple climate model used to emulate the carbon cycle and thermal responses of each GCM forced with ERF timeseries diagnosed from ERF experiments completed as part of RFMIP.

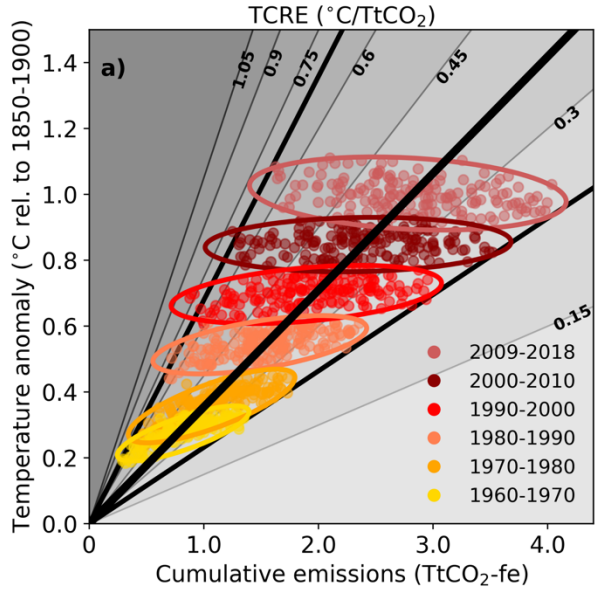

Figure 4: Observational constraints on the TCRE. Attributed human-induced warming against cumulative emissions of CO2-forcing-equivalent emissions. The space is shaded by the value of the TCRE and the points are coloured by decade in which the temperature (relative to 1850-1900 baseline) and cumulative CO2-fe emissions (relative to 1875) are diagnosed. An ellipse is drawn around central 90% of points. Black lines in panel a depict the 5th, 50th and 95th percentile of the overall observationally-constrained TCRE distribution based on the 2009-2018 decade.

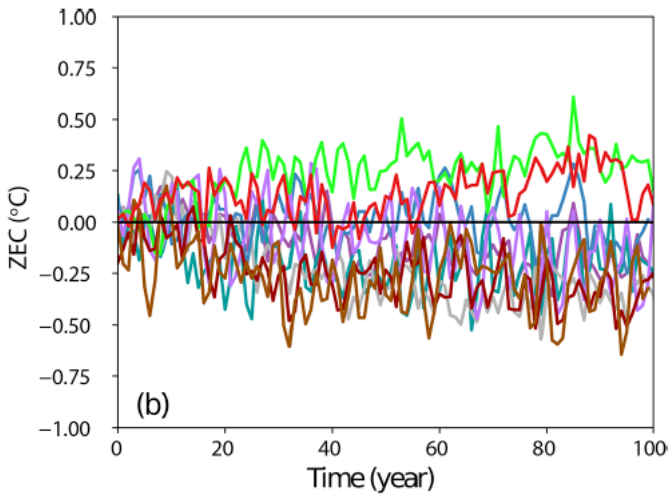

Figure 5: Simulated zero emission commitment (ZEC) following the cessation of carbon emissions during the experiment wherein 1000PgC was emitted following a 1% experiment. ZEC is the temperature anomaly relative to the estimated temperature at the year of cessation. The results are shown for CMIP6-type fully coupled Earth system models

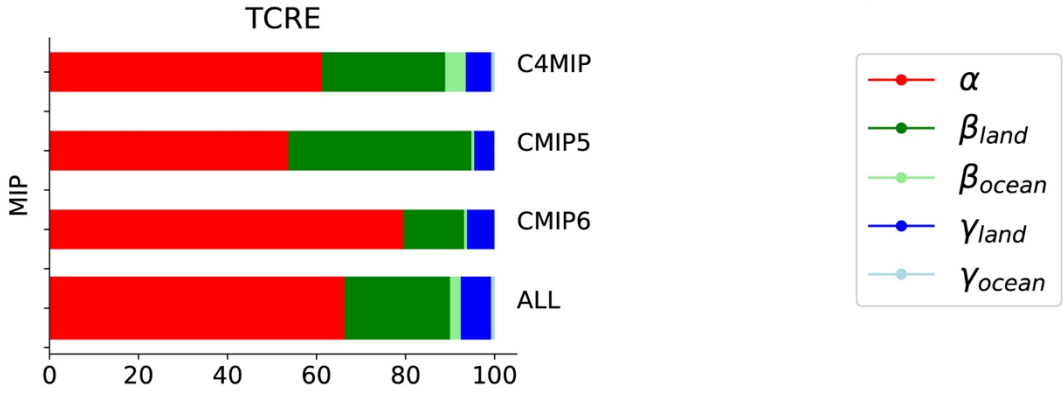

Figure 6: Contributions to uncertainty (variance) in TCRE in three recent model intercomparison projects, and combined. Red indicates contribution from thermal response (TCR) uncertainty, dark green (blue) the response of the land carbon sink to increasing atmospheric concentrations (temperatures), light green (blue) the response of the corresponding ocean sink.