NEW MODELS, OLD MESSAGE: DEEP EMISSION CUTS IN THE NEXT DECADE ARE KEY

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Summary

A number of the latest generation climate models (CMIP6) project greater future warming than previously assessed, but drawing conclusions about the implications for emission reduction targets is premature.

The higher warming these new models project is due to higher climate sensitivity, which might be partly explained by how these models incorporate new knowledge about the interactions between clouds and the climate.

A growing number of studies suggest that CMIP6 model sensitivities might lead to overestimating future warming. More importantly however, the change in the quantity in CMIP6 models, which is relevant for calculating carbon budgets - the transient climate response to emissions (TCRE) - may be smaller than the potential increase in long-term equilibrium warming.

Preliminary results based on a limited set of models suggest that even TCRE estimates from more sensitive CMIP6 models, if proven correct, would only reduce the best estimate for the 1.5°C carbon budget by a few percent. These differences are very small compared with the uncertainties surrounding these carbon budget estimates, and do not allow for any robust conclusions. If anything they only re-emphasise the need for stringent near-term emission reductions to achieve the Paris Agreement goal.

The world is 1°C warmer than pre-industrial levels and continues to warm at about 0.2°C per decade. Slowing down warming over the next decades is crucial to limit warming to 1.5°C. Stringent emission reductions, as implied by Paris Agreement compatible pathways, can reduce near-term warming rates by up to 50%. Near-term emissions reductions are key to keep the Paris Agreement's long-term temperature goal in sight.

Note: This analysis is largely based on findings in scientific manuscripts that are currently under revision in an open review process ("discussion phase") and have not yet undergone peer review. These are also only based on a subset of CMIP6 models. Results are therefore only preliminary and may change once more models become available. At the same time, there are some minor inconsistencies between different studies that may also be reconciled during the revision.

The Intergovernmental Panel on Climate Change (IPCC), the United Nations body for assessing the latest climate change science, will release its 6th Assessment Report (AR6) in 2021. A great deal of the findings in AR6 will be based on the latest generation of climate models from the 6th phase of the Coupled Model Intercomparison Project (CMIP6). Therefore, it is crucial to assess whether these models provide a better representation of the climate system and offer more realistic projections of global warming than their predecessors.

Equilibrium vs. transient warming in CMIP6 models

Early results indicate that some CMIP6 models show a more pronounced warming for a given emissions pathway[1]. This is due to the fact that these models show a higher warming sensitivity to the same amount of greenhouse gas forcing than the previous generation of models (CMIP5), which was used in the last IPCC Assessment Report (AR5).

In particular, the **Equilibrium Climate Sensitivity (ECS),** quantifying the long-term global mean temperature change in response to a doubling of pre-industrial atmospheric CO_2 concentrations, appears to be substantially higher in some CMIP6 models than for the previous model generation (CMIP5). Preliminary results from Zelinka et al. (2019) provide an ECS for a (yet incomplete) CMIP6 model ensemble of 3.9 +/- 1.1 °C ensemble mean and standard deviation) compared to the full CMIP5 ensemble (3.3 +/- 0.7 °C). The central ECS estimate for this model ensemble is thereby about 20% higher than the best estimate for the CMIP5 model ensemble. Note, however, that these values may still change once more models become available and further constraining in relation to the high ECS outcomes is being conducted.

While the ECS aims to capture the warming after the earth system has reached an equilibrium state, there are other metrics, which focus on near-term warming that are more relevant to carbon budget estimation for warming limits, such as the **transient climate response**.

Currently, different research groups in Switzerland, UK, and Canada are arriving at similar conclusions independently: warming is overestimated by some CMIP6 models, which have high ECS values and are unconstrained (forthcoming). Constraining can be done for example by assessing model performance against the observational record (Gillett et al., 2013). Preliminary results show that observationally constrained ranges of future warming in CMIP6 models and TCR values are lower than those based on raw model responses.

Preliminary assessments of CMIP6 warming responses and carbon budgets

While high ECS outcomes need to be assessed carefully, they are not directly linked to the derivation of the (remaining) carbon budget. Carbon budgets are related to the **transient climate response to cumulative emissions of CO_2 (TCRE)**, which is closely linked to TCR, but includes the carbon cycle response. For a more comprehensive overview of carbon budgets, different climate response concepts and their linkages, see the 2019 CONSTRAIN report (Nauels et al., 2019).

The proportionality between warming and cumulative emissions is a central finding of climate science (IPCC, 2013). The slope of this proportionality is captured by the TCRE and therefore carbon budgets can be directly derived from the TCRE estimate (Rogelj et al., 2019). There are different preliminary estimates of the TCRE of the CMIP6 model ensemble, also based on slightly different subsets of models (Arora et al., 2020; MacDougall et al., 2020). We provide an overview of these estimates in Table 1.

[1] CRESCENDO: **Climate Sensitivity in CMIP6: Causes, consequences and uses**, 2020

Table 1: Overview of TCRE estimates from different sources. Mean values and one standard deviation uncertainty range is provided. Note that the IPCC AR5 does not provide a central estimate, but only a range (0.7-2.6) that is taken here as the one standard deviation range for a normal distribution.

TCRE Estimate	**TCRE (°C per 1000 Gt C)**	**Reference**
IPCC AR5 *(multiple lines of evidence)*	1.65 +/- 0.9	IPCC AR5
CMIP5	1.65 +/ 0.5	Gillett et al. (2013)
CMIP6 Arora	1.8 +/- 0.4	Arora et al. (2020)
CMIP6 MacDougall	1.7 +/- 0.4	MacDougall et al. (2020)

While available TCRE estimates for CMIP6 are higher than the central estimates based on CMIP5 (or those derived based on AR5), the differences are much smaller compared with those estimated for the ECS - only about 8% for Arora and 3% for MacDougall. The resulting normal distributions for the TCRE central estimates are shown in the following Figure 1. These differences are very small compared to the uncertainty associated with each of the estimates.

Based on these CMIP6 TCRE estimates, we derive the remaining carbon budget from 2020 onwards following the methodology established in the CONSTRAIN report series (Nauels et al., 2019). Here, we only provide budgets for staying below 1.5°C with a 50% likelihood (Table 2). Budgets for higher probabilities are dependent on the uncertainty range that is not sufficiently captured by modelled estimates alone (note that the AR5 standard deviation is about twice the range based on CMIP5/6 estimates, also see Figure 2).

For the higher CMIP6 estimate (Arora), the remaining 1.5°C budget is about 30 Gt CO_2 (about 8%) smaller than the best estimate based on the full AR5 TCRE (3% for the MacDougall estimate). This difference is very small compared to the uncertainties surrounding carbon budget estimates in the order of up to several 100 Gt CO_2 (Rogelj et al., 2018). Such preliminary estimates based on CMIP6 output therefore do not fundamentally change the assessment of the challenge of limiting warming to 1.5°C. If anything, these estimates reemphasize the need for stringent emissions reductions (Forster et al., 2020).

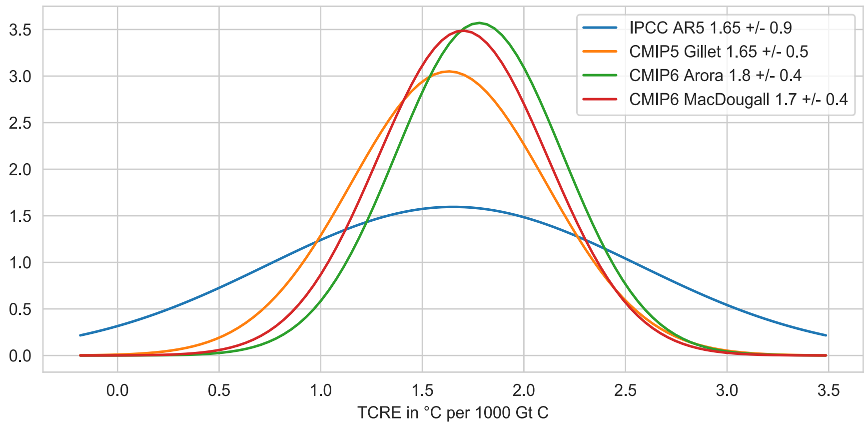

Figure 1: TCRE distributions following different best estimates for TCRE from the literature (compare Table 1) assuming normally distributed TCRE.

Table 2: Remaining carbon budgets for limiting warming to 1.5°C with 50% probability and different TCRE estimates.

TCRE Estimate	Remaining Carbon Budget (2020)
CONSTRAIN report (AR5)	395 Gt CO_2
CMIP6 Arora	365 Gt CO_2
CMIP6 MacDougall	385 Gt CO_2

Focusing on CO_2 alone, carbon budgets present an incomplete picture of the implications of CMIP6 models for achieving the Long-Term Temperature Goal (LTTG) of the Paris Agreement. A more comprehensive assessment needs to also include non-CO_2 greenhouse gases, like methane, as well as other climate forcers such as aerosols. Of fundamental importance for the achievement of the 1.5°C limit are the near-term warming rates for different scenarios.

These have been assessed in the CONSTRAIN report series for an ensemble of CMIP6 models as well as the simple climate model FaIR (Smith et al., 2018). These projections indicate that warming rates over the next decades could be reduced by up to half under stringent emission reduction efforts (Figure 2), outlining the importance of stringent emissions reductions for achieving the Paris Agreement goal.

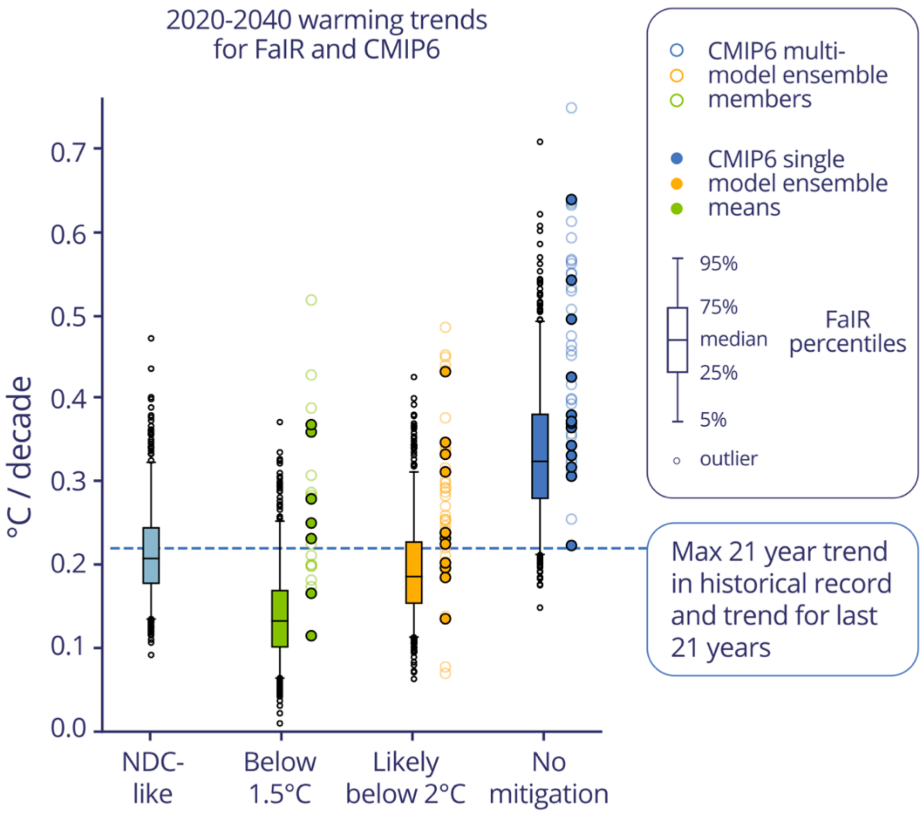

Figure 2: Global surface air temperature change per decade for 2020-2040 from the constrained simple climate model FaIR and the 6th phase of the Coupled Model Intercomparison Project (CMIP6). For more details see CONSTRAIN report. Figure credit: CONSTRAIN Project

Background

Climate Sensitivity in CMIP6

Climate sensitivity can be assessed by quantifying the global mean temperature change in response to a doubling of pre-industrial atmospheric CO_2 concentrations. There are several metrics corresponding to climate sensitivity. Equilibrium Climate Sensitivity (ECS) is defined as the global mean warming from a sustained doubling of CO_2 concentration, after the Earth System has reached a steady state. This includes processes such as ocean heat uptake, which can modify global mean temperatures for centuries after the atmospheric concentration has doubled.

The Transient Climate Response (TCR), on the other hand, is defined as the change in global mean temperature that occurs around the time of doubling atmospheric CO_2 concentrations, after gradually increasing it for 70 years. Therefore, TCR is a more appropriate measure of near-term warming than ECS. TCRE, the transient climate response to cumulative emissions of CO_2, is the amount of warming for a unit of cumulative CO_2 emissions, usually given in °C/1000 PgC. TCRE is crucial for the calculation of remaining carbon budgets. Generally, we can say that the higher the sensitivity, the higher the projections of global mean warming (Nauels et al., 2019).

Climate sensitivity estimates have been persistently uncertain with the IPCC Fifth Assessment Report (AR5) providing a likely ECS range of 1.5 – 4.5 °C (Figure 3), a TCR range of 1 – 2.5 °C and a TCRE range of 0.8 – 2.5 °C per 1000 PgC, based on combining different lines of evidence including climate models and paleoclimate data (IPCC, 2013).
The largest part of this uncertainty stems from complex feedback mechanisms in the climate system and an incomplete understanding of how these will change in the future. For CMIP6, early results indicate that the ECS range across models has widened to 1.8 – 5.6 °C, with nine models exceeding 4.5 °C and the ECS multi-model mean increasing from 3.3 °C in CMIP5 to 3.9 °C in CMIP6 (Zelinka et al. 2019).

Estimates of TCR are narrower as they are derived over a shorter time horizon and less affected by uncertainties related to carbon cycle processes or ocean uptake. The absolute TCR range has shifted upwards to 1.5 – 3 °C with a quarter of models exceeding 2.5 °C in CMIP6. The TCR multi-model mean has increased from 1.8 °C in CMIP5 to 2.1 °C for the models analysed in Nijsse et al. (2020). Estimates for TCRE have shifted upwards as well with different preliminary estimates indicating a mean of 1.7 – 1.8 °C per 1000 PgC (see also Table 1) and a range of 1.3°C – 2.6°C in CMIP6 (MacDougall, et al. 2020), compared to 1.65 °C per 1000 PgC in the AR5.

First analysis suggests that the main reason for this increase in climate sensitivity might be linked to a revised physical representation of clouds in the latest model generation (Zelinka et al., 2019). Global

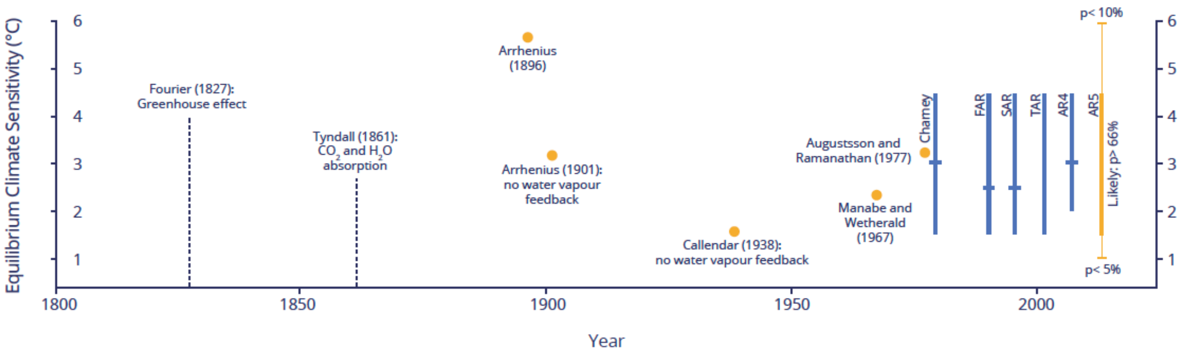

Figure 3: Overview of historical ECS estimates. Figure credit: Thorsten Mauritsen/CONSTRAIN

warming leads to a decrease in extratropical low-cloud water content and coverage and thereby to a decrease in reflectiveness. This enhances the absorption of radiation from the sun, which again leads to further warming – a reinforcing feedback. In CMIP6 models, the mean and variance of non-cloud feedbacks remain on average unchanged compared to CMIP5 (Zelinka et al., 2019). It can be assumed that the stronger extratropical low-cloud feedback, better represented in CMIP6 models, is the key factor behind the higher sensitivity values.

Paleoclimate records and historical observations are used to assess climate sensitivity in addition to climate model output. These efforts have resulted in a constrained ECS range between 1.5 and 4.5°C (Knutti et al., 2017). The ECS estimates from CMIP5 generally fall into that range. The CMIP6 models with higher ECS values, however, appear to be overly sensitive. And there are more indicators pointing to skewed sensitivity estimates in CMIP6: Most of the high warming CMIP6 models overestimate currently observed warming (Nijsse et al., 2020). However, CMIP6 models with an ECS that matches the constrained ECS range replicate the observed trend rather well. Importantly, when constrained by historical warming, CMIP6 models fall more or less within the CMIP5 ECS range. This makes ECS values larger than 4.5°C more unlikely. However, these are preliminary conclusions, largely based on literature which is not yet published. Forthcoming analysis conducted in time for the IPCC's Working Group I Sixth Assessment Report will likely shed further light on this issue.

References

Arora, V., Katavouta, A., Williams, R., Jones, C., Brovkin, V., Friedlingstein, P., et al. (2020). Carbon-concentration and carbon-climate feedbacks in CMIP6 models, and their comparison to CMIP5 models. *Biogeosciences Discussions*, (December), 1–124. https://doi.org/10.5194/bg-2019-473

Forster, P. M., Maycock, A. C., McKenna, C. M., & Smith, C. J. (2020). Latest climate models confirm need for urgent mitigation. *Nature Climate Change*, *10*(1), 7–10. https://doi.org/10.1038/s41558-019-0660-0

Gillett, N. P., Arora, V. K., Matthews, D., & Allen, M. R. (2013). Constraining the Ratio of Global Warming to Cumulative CO2 Emissions Using CMIP5 Simulations*. *Journal of Climate*, *26*(18), 6844–6858. https://doi.org/10.1175/JCLI-D-12-00476.1

IPCC. (2013). Summary for Policymakers. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, et al. (Eds.), *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Knutti, R., Rugenstein, M. A. A., & Hegerl, G. C. (2017). Beyond equilibrium climate sensitivity. *Nature Geoscience*, (September). https://doi.org/10.1038/ngeo3017

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., Matthews, H. D., Zickfeld, K., et al. (2020). Is there warming in the pipeline? A multi-model analysis of the zero emission commitment from CO$_2$. *Biogeosciences Discussions*, 1–45. https://doi.org/10.5194/bg-2019-492

Nauels, A., Rosen, D., Mauritsen, T., Maycock, A. C., Mckenna, C. M., Rogelj, J., et al. (2019). *ZERO IN ON the remaining carbon budget and decadal warming rates. The CONSTRAIN Project Annual Report 2019*. https://doi.org/10.5518/100/20

Nijsse, F. J. M. M., Cox, P. M., & Williamson, M. S. (2020). An emergent constraint on Transient Climate Response from simulated historical warming in CMIP6 models. *Earth System Dynamics Discussions*, (January), 1–14. https://doi.org/10.5194/esd-2019-86

Rogelj, J, Shindell, D., Jiang, K., Fifita, S., Forster, P., Ginzburg, V., et al. (2018). 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,*.

Rogelj, Joeri, Forster, P. M., Kriegler, E., Smith, C. J., & Séférian, R. (2019). Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature*, *571*(7765), 335–342. https://doi.org/10.1038/s41586-019-1368-z

Smith, C. J., Forster, P. M., Allen, M., Leach, N., Millar, R. J., Passerello, G. A., & Regayre, L. A. (2018). FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geoscientific Model Development*, *11*(6), 2273–2297. https://doi.org/10.5194/gmd-11-2273-2018

Zelinka, M. D., Myers, T. A., Mccoy, D. T., Po-chedley, S., Caldwell, P. M., Ceppi, P., et al. (2019). Causes of Higher Climate Sensitivity in CMIP6 Models, *12*(2), 1–12. https://doi.org/10.1029/2019GL085782