**Article:**

Forster, PM orcid.org/0000-0002-6078-0171, Maycock, AC orcid.org/0000-0002-6614-1127, McKenna, CM orcid.org/0000-0002-9677-4582 et al. (1 more author) (2020) Latest climate models confirm need for urgent mitigation. Nature Climate Change, 10 (1). pp. 7-10. ISSN 1758-678X

https://doi.org/10.1038/s41558-019-0660-0

# *Latest climate models confirm need for urgent mitigation*

Piers M. Forster, Amanda C. Maycock, Christine M. McKenna and Christopher J. Smith

Priestley International Centre for Climate, University of Leeds

*Corresponding Author: Piers M. Forster, p.m.forster@leeds.ac.uk*

**Many recently updated climate models show larger future warming than previously. Separate lines of evidence suggest their warming rates may be unrealistically high, but the risk of such eventualities only emphasizes the need for rapid and deep reductions in emissions.**

To date, one third of the latest-generation climate models from the Coupled Model Intercomparison Project phase 6 (CMIP6) exhibits a higher equilibrium climate sensitivity (ECS) compared to the previous generation (CMIP5). As a result, several CMIP6 models exhibit greater warming over the 21$^{st}$ century (https://phys.org/news/2019-09-earth-quickly-climate.html). This might suggest smaller remaining carbon budgets or a need to reach net-zero emissions sooner to limit warming to targets set forth in the Paris Agreement. However, carbon budgets and net-zero emission dates are also sensitive to other factors, including the transient climate response (TCR) and aerosol effects. Here, we argue that the highest-warming CMIP6 models are unlikely to be representative of the real world and that CMIP6 projections of global surface temperature should not be exclusively relied on for policy-relevant decisions. Nevertheless, the new generation of results still has scientific value and strengthens the case for urgent mitigation.

## High Equilibrium Climate Sensitivity

Equilibrium climate sensitivity (ECS) represents how much warming we can expect for a doubling of the atmospheric $CO_2$ concentration from its preindustrial state. It has remained a persistent uncertainty in climate science with a likely range (66% probability) of 1.5°C-4.5°C assessed in IPCC reports and elsewhere[1,2]. Recently, the preliminary ECS range in CMIP6 has skewed high relative to CMIP5, with multiple models lying above the upper end of the likely ECS range (Figure 1). This has raised questions in the climate modelling and research community around the plausibility of high ECS values and implications for the projected rates of surface warming over this century[3].

The climate models in CMIP archives are developed by institutes around the world, each with different research and operational foci. Modelling groups generally do not develop their models with a target ECS in mind. Rather, they are built from fundamental physical laws, and each model's ECS is something that emerges from simulations once its development has been finalised. Many of the new-generation models improve on their predecessors in a variety of ways: for example, by more faithfully reproducing observations or by adding missing Earth system process. Many of these improvements do not impact ECS, but some do. One example is the UKESM1-0-LL model, developed by the UK Earth System Modelling project, which shows an improved representation of mid-latitude mixed phase clouds (judged against present-day satellite data)[4,5]. This leads to a reduced damping effect on temperature from cloud-phase changes[4]. The result of this improvement in the simulation of present climate, all else being equal, is an increase in ECS. This does not mean the resulting higher ECS is more realistic, as other processes may be contributing a high bias.

Climate models have previously informed the likely range of ECS, but over the last decade, increasing evidence has emerged from the paleoclimate record, from historic observations, and from advances in understanding of cloud processes that can be used to constrain ranges of ECS, more or less independently of climate models[2]. Since the CMIP archives are not explicitly designed to sample known uncertainties in ECS, there's no requirement for any one model's value to fall within the canonical range. Nevertheless, they have largely done so, until now (Figure 1).  We think that the diversity of ECS across CMIP6 should be celebrated; it means that groups are daring their models to be imperfect, and this will ultimately aid understanding and drive progress. The IPCC “likely” range implies a 33% probability that ECS would be outside a 1.5-4.5 $^{o}$C window, so a higher ECS value is not unexpected. However, the higher values seen in CMIP6 are not supported by other lines of evidence[2] and may eventually be proven wrong.

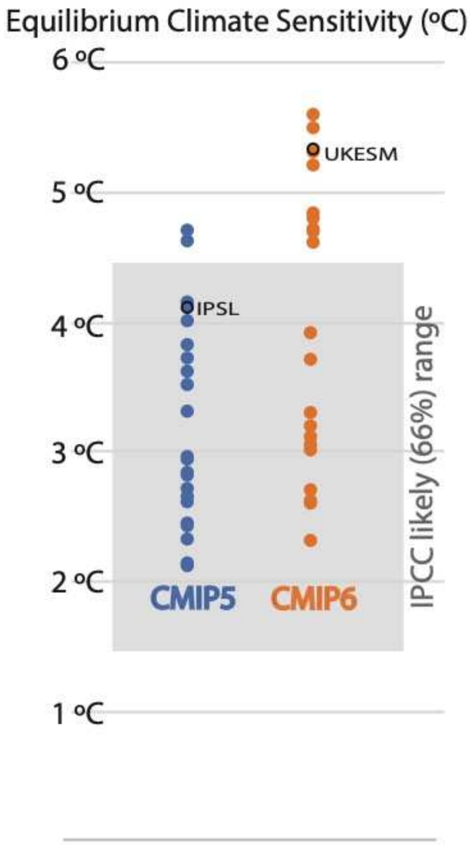


*Figure 1.* ***The Equilibrium Climate Sensitivity (ECS) from CMIP5 and 21 currently available CMIP6 climate models.*** *Data as of 05.11.2019 from the ESMValTool team as part of the European Union's Horizon 2020 CRESCENDO project[6]. The ECS from the IPSL-CM5A-MR model (IPSL) and UKESM1-0-LL (UKESM) models are used in later figures as they lie around the 95$^{th}$* percentile of the CMIP5 and CMIP6 ECS distributions, respectively.

## Global warming projections

Projections of possible climate futures from complex climate models are strongly affected by their ECS. Complementary simple physical climate modelling approaches that make assumptions on ranges of ECS and radiative forcing can also be used to make projections for a smaller range of physical quantities. For example, the IPCC AR5 Working Group III report employed the MAGICC simple climate model[7] to make temperature projections for many different scenarios. The IPCC Special Report on 1.5°C (IPCC SR1.5) used both MAGICC and FaIR[8], another simple climate model, for its projections. These models make gross assumptions but can explore a much broader sampling of uncertainty compared to any complex model. Here we use the FaIR model in its calibration based on IPCC-assessed ranges of input parameters to examine the plausibility of CMIP6 warming trajectories.

ECS explicitly describes the long-term global surface temperature response to a doubling of atmospheric $CO_2$ concentration, but it is still a useful measure to interpret temperature projections over the next several decades. The transient climate response (TCR) is also an important measure for projections[9], as it quantifies the surface temperature response to a 1% per year steadily increasing level of $CO_2$ to the time of doubling. The difference between ECS and TCR relates to the warming of the deep ocean that takes longer to emerge, thus ECS is larger than TCR. Models like MAGICC and FaIR can be used to investigate the effect of ECS and TCR on projections.

Figure 2 shows that some CMIP6 models exhibit more mid- and late-century warming compared to their CMIP5 counterparts. This is true for both the strong mitigation (Figure 2, left) and high-emissions scenarios (Figure 2, right). The higher warming models in both cases tend to be the ones with high ECS. Similar to Figure 1 for ECS, several CMIP6 models have temperature projections outside the likely range produced by the uncertainty analysis from FaIR as employed in IPCC SR1.5. This is illustrated by the shading in Figure 2 based on assessed ranges of ECS, TCR and radiative forcing. However, the CMIP6 models still fall within the broader 99% range plume from the FaIR analysis. This indicates that these high-end CMIP6 projections are not outside the assessed range of possible futures, but they are unlikely futures. These larger warming models also overestimate the current warming trend, again suggesting that their future warming could be too strong. Even if this is the case, such models are still useful for understanding the very low-probability, high-risk outcomes, which has been a gap in previous IPCC assessments[10].

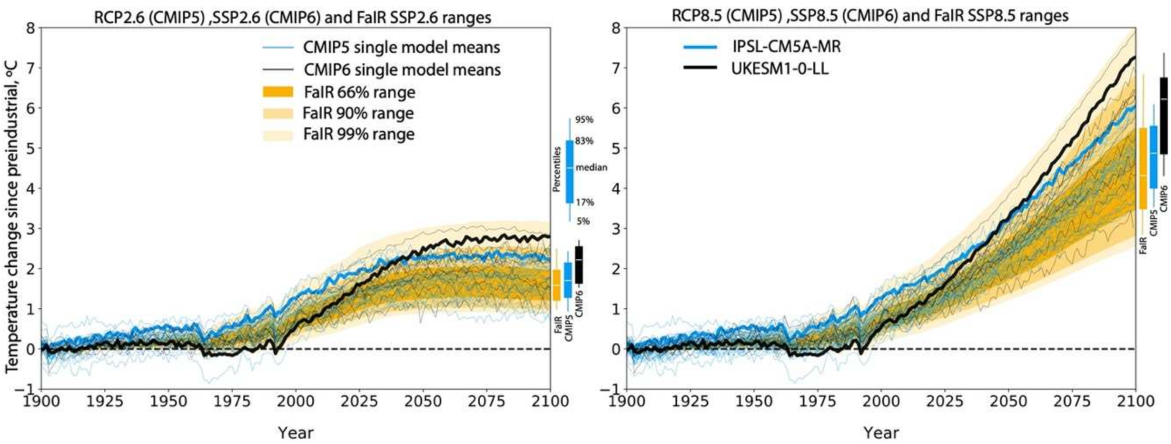


*Figure 2.* ***Temperature response to low- and high-end emissions scenarios.*** *Modelled global average surface air temperature change over 1900-2100 is shown in a strong mitigation scenario (left) and a high emissions scenario (right). CMIP5 and CMIP6 model projections are shown as individual curves superimposed on FaIR simple model projections (shading) from a broader uncertainty analysis of possible futures, based on lines of evidence for ECS, TCR, and radiative forcing updated from those used in similar analysis for IPCC SR1.5. Note that CMIP5 and CMIP6 employed slightly different emission scenarios but FaIR simulations available from the GitHub repository below suggest this has a minimal effect on the projected CMIP6 and CMIP5 differences. UKESM1-0-LL and IPSL-CM5A-MR projections are highlighted in the figures. The CMIP5 and CMIP6 percentile ranges for 2100 are shown on the figure to aid the reader in identifying the differences of the CMIP models compared with the FaIR ranges. However, as stated in the main text, the CMIP ensemble*

*does not represent a broad statistical sample, so differences in percentiles are not necessarily meaningful. Data and additional figures comparing SSPs and RCPs are available from https://github.com/Priestley-Centre/CMIP5_CMIP6_FaIR_gsat_data.*

## Implications for net-zero dates

Targets for mitigation action are often framed around the remaining carbon budget and/or dates to reach net-zero greenhouse gas emissions. Higher ECS models might be expected to mean smaller remaining carbon budgets and earlier net-zero dates. However, the relationship between ECS and the remaining carbon budget is not straightforward[11]. Net-zero dates and carbon budgets are in fact more sensitive to the TCR and to changes in the natural sink of $CO_2$, as well as non-$CO_2$ forcing agents such as aerosols[12].

Figure 3 compares the response to idealised net-zero greenhouse emission dates emulated with FaIR using inputs for ECS, TCR, and effective radiative forcing that come from either assessed ranges (Figure 3b) or are chosen to match the IPSL-CM5A-MR and UKESM1-0-LL models (Figures 3c and 3d). These bottom panels show how the response might differ if the Earth behaved like the models sitting around the 95$^{th}$ percentile of the ECS distribution from CMIP5 and CMIP6, respectively.

IPCC SR1.5 concluded that net-zero greenhouse gas emission dates around 2070 or earlier are needed for a 50% chance to limit global warming in 2100 to 1.5 $^{o}$C. Probabilistic chances of meeting the target are made as the physical climate response remains uncertain. The median FaIR analysis and the IPSL-CM5A-MR model, even with its relatively high ECS, both manage to stay close to 1.5 $^{o}$C with a 2070 net-zero date, supporting the IPCC SR1.5 assessment. The IPSL-CM5A-MR model has a relatively modest TCR and aerosol cooling, which limits the amount of near-term warming in rapid mitigation pathways. In contrast, the UKESM1-0-LL model has a high ECS accompanied by a high TCR and strong aerosol cooling. This would lead to an unavoidable additional 0.5 °C of rapid warming from the mitigation scenarios, which would make staying below even 2 °C challenging.

But does the real world behave the same way as UKESM1-0-LL? The answer is probably not. The simulations of the UKESM model shown in Figure 2 indicate that current warming rates are biased high. This, coupled with an overestimated ECS when considering other lines of evidence[2], would suggest the model results should be downplayed.

IPCC has tended to rely on ensembles of available complex models for surface temperature projections and give each model equal weight in its analysis. This has long been known to be imperfect but it has been difficult to reach a community consensus on alternative choices[13]. As we have shown that raw projections of surface temperature from CMIP6 should not be used directly in creating policy involving temperature targets, a way of translating the model results to improve their policy relevance is needed. Well-tested and calibrated simple models can be used both to translate evidence from the more complex models and to make more policy relevant projections of global surface temperature that draw on multiple lines of evidence, including process evidence from the complex models. We recommend that such simple modelling approaches become central tools in future assessments.

In spite of the issues discussed in this commentary, the high-end warming outcomes seen in some CMIP6 models cannot be ruled out at the 1% level. The best way to avoid the potentially devastating impacts of a high ECS (even if low probability) is to mitigate towards net-zero emissions as urgently as possible. As such, CMIP6 model results reinforce the IPCC SR1.5 conclusion that urgent mitigation towards net-zero emissions is needed to limit future climate change risk. They also reinforce that we need to develop adaptation strategies to cope with global temperatures in excess of 2°C above pre-industrial levels. To echo the words from the IPCC SR1.5 press conference in October 2018, “Every bit of warming matters, every year matters, every choice matters”.

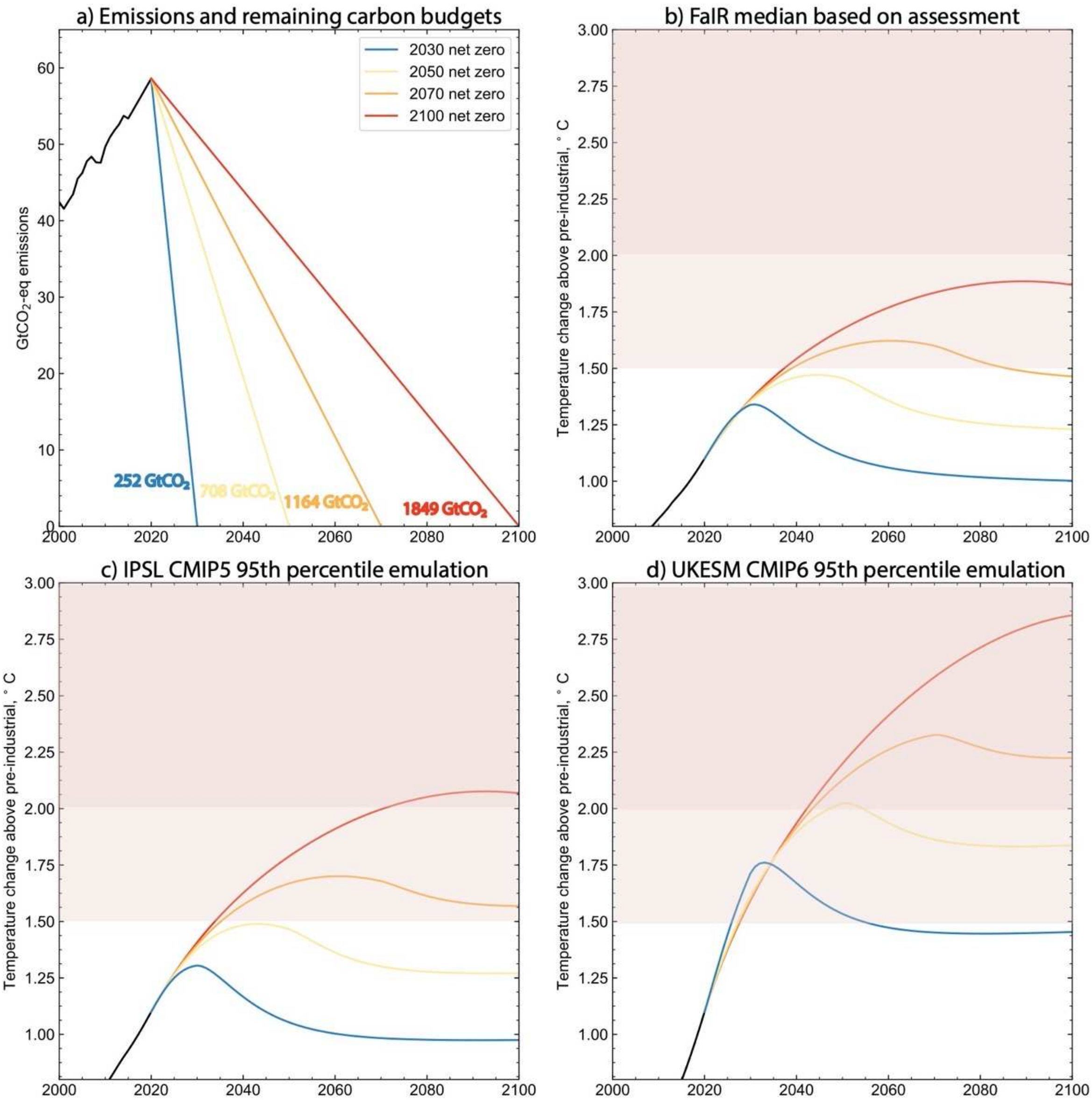


*Figure 3.* ***Idealised emissions scenarios with different net-zero dates and associated surface temperature change.*** *These simple scenarios assume that $CO_2$ and non-$CO_2$ emissions (including aerosol precursor emissions) are phased out at the same rate to zero*

*by a specified year. The remaining carbon budget associated with each pathway is displayed. Using these scenarios, temperature changes are emulated with the FaIR simple model, using inputs based assessed ranges and on CMIP: (a) shows global emissions and carbon budgets; (b) shows the expected response computed with the FaIR median; (c) and (d) show how the response if the Earth behaved similarly to the CMIP5 IPSL-CM5A-MR model and CMIP6 UKESM1-0-LL model respectively. Note that unlike in Figure 2, the warming in both models has been scaled to match 1.1°C in 2020.*


## Acknowledgements

Colin Jones, Katarzyna Tokarska, Thorsten Mauritsen, Albert Klein Tank, Andrew Gettelman, Veronika Eyring, Carl Schleussner, Joeri Rogelj and Jochem Marotzke are thanked for useful discussions. Funding was provided by European Union's Horizon 2020 Research and Innovation Programme under grant agreement number 820829 (CONSTRAIN) and UKRI NERC grant NE/N006038/1 (SMURPHS). We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. Manuel Schlund is thanked for providing CMIP ECS data.


## Author Contributions

PMF conceived of the work and wrote the comment, with extensive contributions to both writing and ideas from ACM. CMM provided the analysis of CMIP6 projections, made Figure 2 and commented on the paper. CJS provided the FaIR analysis and made Figure 3.

## Competing Interests

The authors declare no competing interests

## References


1. Collins, M. *et al.* 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* (eds. Stocker, T. F. et al.) 1029–1136 (Cambridge University Press, 2013). doi:10.1017/CBO9781107415324.024
2. Knutti, R., Rugenstein, M. A. A. & Hegerl, G. C. Beyond equilibrium climate sensitivity. *Nat. Geosci.* **10**, 727–736 (2017).
3. Four news and blog discussions can be found here: http://www.realclimate.org/index.php/archives/2019/11/sensitive-but-unclassified/ https://www.sciencemag.org/news/2019/04/new-climate-models-predict-warming-surge https://www.carbonbrief.org/guest-post-why-results-from-the-next-generation-of-climate-models-matter https://phys.org/news/2019-09-earth-quickly-climate.html
4. Bodas-Salcedo, A., Mulcahy, J. P., Andrews, T., Williams, K. D., Ringer, M. A., Field, P. R., & Elsaesser, G. S. (2019). Strong dependence of atmospheric feedbacks on mixed-phase microphysics and aerosol-cloud interactions in HadGEM3. Journal of Advances in Modeling Earth Systems, 11, 1735– 1758. https://doi.org/10.1029/2019MS001688
5. Sellar, A. A., Jones, C. G., Mulcahy, J., Tang, Y., Yool, A., Wiltshire, A., et al (2019). UKESM1: Description and evaluation of the UK Earth System Model. *Journal of Advances in Modeling Earth Systems*, 11. https://doi.org/10.1029/2019MS001739

6. Eyring, V. *et al.* ESMValTool (v1.0)-a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP. *Geosci. Model Dev.* **9**, 1747–1802 (2016).

7. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11**, 1417–1456 (2011).

8. Smith, C. J. *et al.* FAIR v1.3: A simple emissions-based impulse response and carbon cycle model. *Geosci. Model Dev.* (2018). doi:10.5194/gmd-11-2273-2018

9. Grose, M. R., Gregory, J., Colman, R., & Andrews, T. (2018). What climate sensitivity index is most useful for projections? Geophysical Research Letters, 45, 1559– 1566. https://doi.org/10.1002/2017GL075742

10. Sutton, R. T. Climate Science Needs to Take Risk Assessment Much More Seriously. *Bull. Am. Meteorol. Soc.* **100**, 1637–1642 (2019).

11. Swart, N. C. *et al.* The Canadian Earth System Model version 5 (CanESM5.0.3). *Geosci. Model Dev. Discuss.* 1–68 (2019). doi:10.5194/gmd-2019-177

12. Rogelj, J., Forster, P. M., Kriegler, E., Smith, C. J. & Séférian, R. Estimating and tracking the remaining carbon budget for stringent climate targets. *Nature* **571**, 335–342 (2019).

13. Herger, N., Abramowitz, G., Knutti, R., Angélil, O., Lehmann, K., and Sanderson, B. M.: Selecting a climate model subset to optimise key ensemble properties, Earth Syst. Dynam., 9, 135–151, https://doi.org/10.5194/esd-9-135-2018, 2018