Large uncertainty in future warming due to aerosol forcing

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Abstract. Despite a concerted research effort and extensive observational record, uncertainty in climate sensitivity and aerosol forcing, the two largest contributions to future warming uncertainty, remains large. Here we highlight the stark disparity that different aerosol forcing can imply for future warming projections: Paris Agreement compatible scenarios can either easily meet the specified warming limits, or risk missing them completely using plausible samples from the IPCC AR6 assessed uncertainty ranges.

Reducing uncertainty in the response of the climate system could result in trillions of dollars of economic benefits[1] and lead to better mitigation and adaptation planning[2]. However, despite huge amounts of progress in recent years[3,4], the equilibrium climate sensitivity (ECS; the long-term warming expected in response to a doubling of atmospheric CO_2 concentrations) and the present-day aerosol effective radiative forcing (ERF_{aer}) still exhibit large uncertainty[5], being recently assessed as very likely (90% probability ranges) to be 2–5°C and –2.0 to –0.6 W m^{-2} (2005–2014 relative to 1750) respectively. ECS and ERF_{aer} are the two factors contributing most to the uncertainty in future warming[6] and while physical mechanisms have been proposed that could link them[7,8] they are often assumed to be independent. Nevertheless, because they have both affected historical temperatures[9], conditioning on observed temperatures necessarily introduces a correlation between them. Therefore, reducing the uncertainty in either ECS or ERF_{aer} would allow us to produce more precise projections of future climate for a given emissions scenario.

ECS is not an observable quantity. Despite recent improvements in estimates of ECS[3] (which are accounted for here) from emergent constraints, palaeo records, the instrumental record, and process understanding, different lines of evidence for ECS do not show a high level of agreement[5]. ERF_{aer} on the other hand can be inferred from the large regional emissions changes over the last few decades[10]; and approaches for reducing uncertainty in model estimates are starting to bear fruit[11,12]. We therefore focus on the implications of potential reductions in ERF_{aer} uncertainty and show that doing so would be at least as effective as reducing uncertainty in ECS for improving confidence in future climate change projections over the near-term.

The possibility of a strong ERF_{aer} masking a high climate sensitivity has long been known[15], but since aerosols contribute a diminishing proportion of anthropogenic forcing under high greenhouse gas scenarios they are sometimes viewed as being irrelevant for determining future warming[13]. Under more ambitious mitigation scenarios however, large ERF_{aer} reductions can contribute a significant fraction of warming[14] and air quality policies will play an important role in meeting the Paris agreement. The contribution of ERF_{aer} uncertainty to uncertainty in the year of crossing 1.5°C of warming has recently been demonstrated to be significant[16], but this work relied on a single climate model, only used a very simple approximation of the relationship between ECS and ERF_{aer} and was unable to explore the high-ambition scenarios that are increasingly relevant for policy discussions. The role of aerosol forcing uncertainty on future warming uncertainty, particularly given our improved process understanding and the longer temperature records that are now available[4], has not been robustly quantified.

Here we determine the consequences for future warming in two climate mitigation scenarios (SSP1-1.9 and SSP1-2.6, designed to be 1.5°C and 2°C consistent scenarios, respectively[17]) if the uncertainty in ERF_{aer} were to be substantially reduced. Starting with an ensemble of constrained climate projections used in the IPCC's Sixth Assessment Report[5], we sub-sample regions of the ensemble that fall into strong (-1.5 ± 0.1 W m^{-2}), moderate (-1.0 ± 0.1 W m^{-2}) and weak (-0.5 ± 0.1 W m^{-2}) ERF_{aer} (all ranges expressed as 1-σ and forcing quantities defined for 2005–2014 relative to 1750). We therefore explore the implications of using some of the approaches outlined above to achieve an ambitious increase in the 1-σ precision of ERF_{aer} from ±0.3 to ±0.1 W m^{-2}. Secondarily, we also investigate the same projections but subsampling for ECS ranges that are approximately from the lower (10th percentile), central (50th percentile), and upper (90th percentile) of the ECS distribution from the original constrained ensemble (2.2°C, 2.95°C and 4.4°C, each with a ±10% 1-σ range).

Figure 1a makes the role of ERF_{aer} uncertainty in future warming uncertainty explicit and clearly shows the improvements that could be achieved through better knowledge of ERF_{aer}, particularly for lower ERF_{aer} as discussed below. Figure 1b shows the average ERF_{aer} across the ensemble binned into their temperature response in each year, as well as sub-samples based on reduced uncertainty as indicated by squares in Figure 1a. The members exhibiting a strong ERF_{aer} show a stronger than average cooling before 2000 and stronger than average warming after 2020, and vice versa. (This highlights the value of using estimates of the 2000-2020 trend in ERF_{aer} to constrain future warming[18].) The subset of strong ERF_{aer} members results in SSP1-2.6 temperatures just remaining under 2°C with 50% probability (it would be a "Higher 2°C" scenario in the IPCC's Special Report[19]), whereas the weak ERF_{aer} results in the same socio-economic scenario remaining under 1.5°C with >50% probability (a "Below 1.5°C" scenario). Such large differences undermine adaptation and mitigation efforts: there is a substantial disparity in the climate impacts of 1.5°C and 2°C of warming on heat extremes, tropical coral reefs, water availability and agricultural yield[20]. Similarly large differences are found for SSP1-1.9 with a 50% chance of returning below 1.0°C by the end of the century under a weak ERF_{aer}, and >50 % chance of exceeding 1.5°C assuming a strong ERF_{aer} (see Fig. S1).

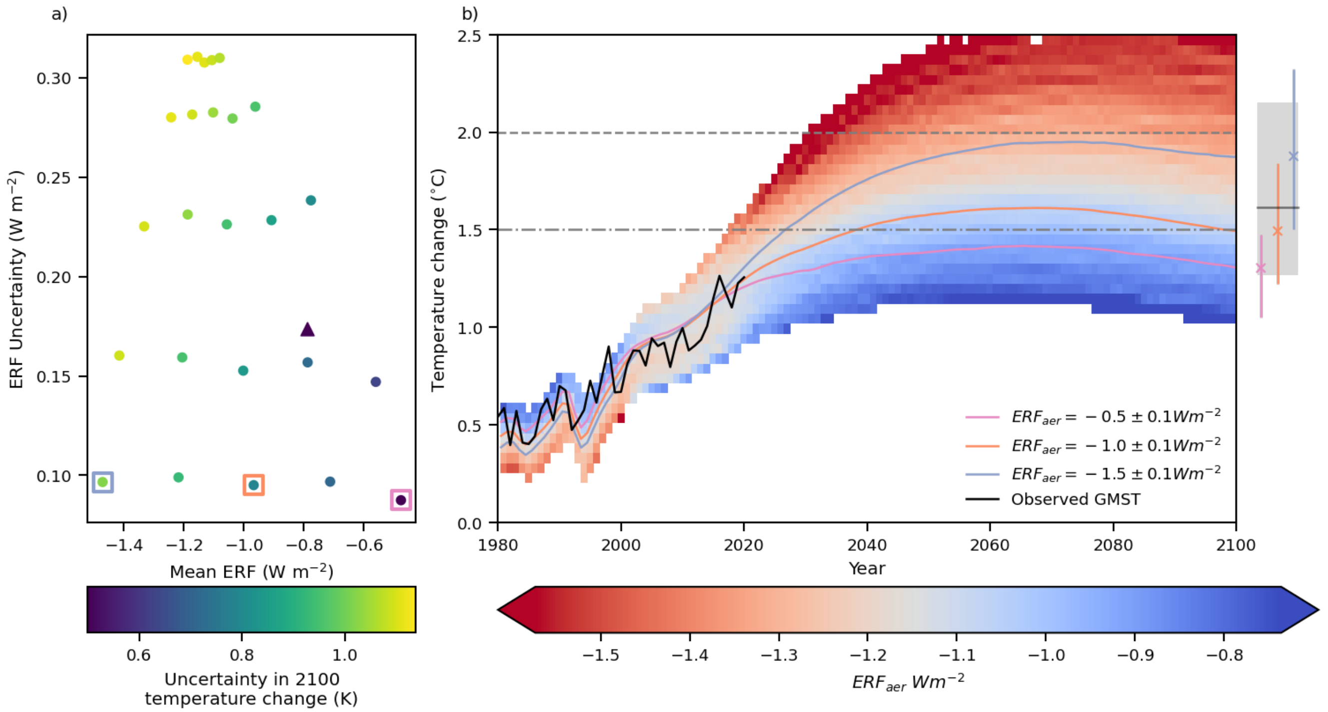

Figure 1 - The effect of aerosol forcing uncertainty on future temperature projections: a) The 90% confidence range in global mean surface temperature change depicted in (b) as a function of ERF_{aer} uncertainty and mean ERF_{aer} sampled as described in the methods. Using a lower bound on ERF_{aer} of 1 W m^{-2} is denoted with a triangle. b) The surface mean temperature change under SSP1-2.6 assuming three different reduced ERF_{aer} uncertainty estimates. The 90% confidence range for each subset at the end of the century is indicated to the right of the axis. Observed surface temperatures averaged across four available datasets are shown in black. The heatmap shows the mean ERF_{aer} of the ensemble members for a given temperature change.

While we use representative reductions in ERF_{aer} uncertainty to demonstrate the effect of reducing future temperature change uncertainties, it should be noted that a lower (most negative) bound on ERF_{aer} would also provide a valuable constraint. Indeed, the recently proposed[21] lower bound of –1.0 Wm^{-2} is included in Figure 1a and would reduce the upper (90% confidence) estimate or temperature change at the end of the century from 2.2°C to 1.7°C for SSP1-2.6 (although this bound is contested and relied on historical temperature trends which are already accounted for here).

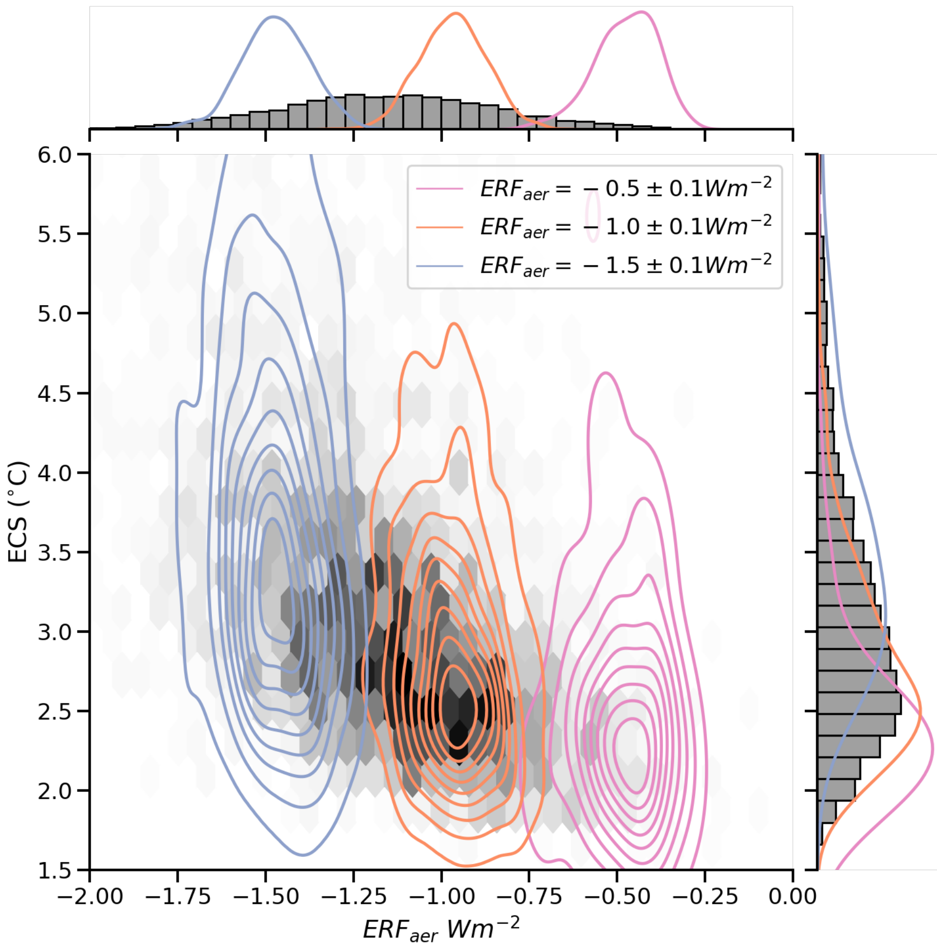

Figure 2 – the close relationship between ECS and ERF_{aer}: The joint and marginal densities of ECS and ERF_{aer} in the constrained ensemble (grey). Also shown are the joint and marginal densities of each subsampled ensemble of strong (red), medium (green) and weak ERF_{aer} (blue), each to within ±0.1 W m^{-2}.

The joint distribution between ECS and ERF_{aer} in the full ensemble and the three reduced uncertainty aerosol subsamples is shown in Fig. 2 and clearly shows the source of this behaviour. A stronger present-day ERF_{aer} is masking a more sensitive climate in the constrained ensemble, which would imply more warming in the future as clean air legislation continues to reduce aerosol burdens. The distribution is not symmetric though: by ruling out strong ERF_{aer} we would be able to rule out high values of ECS, while better quantifying a strong ERF_{aer} leaves weaker constraints on ECS and hence leads to larger temperature uncertainties. This is demonstrated by the larger uncertainties in temperature change of the strong aerosol distribution in SSP1-2.6 of Figure 1, and even more so for SSP1-1.9 (Fig. S1). The similarly ambitious reductions in uncertainty of ECS described above, although harder to achieve in practice, lead to very similar reductions in uncertainty in future projections (see Fig. S2).

Two extensive assessments of ECS[3] and ERF_{aer}[4] were recently published which reviewed the available lines of evidence supporting the various ranges of each quantity independently. Given the close relationship which emerges between the two when applying the best constraint we currently have (the observed temperature record), we would urge closer coordination between the two communities to reduce the joint uncertainty in these quantities which is so important for increasing confidence in future temperature projections. To make the required progress these top-down constraints must be complemented by bottom-up process-based constraints, which have recently been demonstrated in individual models, and novel approaches of combining the two should be explored as a matter of urgency.

As has been recently highlighted[22], separate reporting of emissions of Short-Lived Climate Forcers (SLCFs; such as methane) from long-lived climate forcers (LLCFs; such as nitrous oxide) is key for unambiguous global temperature outcomes. Given the very short lifetime of both black carbon and sulphate aerosol, their non-linear forcing response and importance for future warming we would encourage emissions of these aerosol species to also be reported separately.

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Data availability: The full ensemble and constrained subsets will be made publicly available upon acceptance of the manuscript.

Code availability: The notebooks used to perform analysis and generate all plots in this manuscript will be made publicly available upon acceptance of the manuscript.

References

1. Hope, C. The 10 trillion value of better information about the transient climate response. *Philosophical Transactions Royal Soc Math Phys Eng Sci* 373, 20140429 (2015).

2. IPCC. *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, sustainable development, and efforts to eradicate poverty*. (2018).

3. Sherwood, S. C. *et al.* An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Rev Geophys* 58, e2019RG000678 (2020).

4. Bellouin, N. *et al.* Bounding Global Aerosol Radiative Forcing of Climate Change. *Rev Geophys Wash D C 1985* 58, e2019RG000660 (2020).

5. Forster, P. *et al. The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity*. (2021).

6. Smith, C. J. *et al.* Current fossil fuel infrastructure does not yet commit us to 1.5 °C warming. *Nat Commun* 10, 101 (2019).

7. Mülmenstädt, J. *et al.* An underestimated negative cloud feedback from cloud lifetime changes. *Nat Clim Change* 11, 508–513 (2021).

8. Gettelman, A., Lin, L., Medeiros, B. & Olson, J. Climate Feedback Variance and the Interaction of Aerosol Forcing and Feedbacks. *J Climate* 29, 6659–6675 (2016).

9. Kiehl, J. T. Twentieth century climate model response and climate sensitivity. *Geophys Res Lett* 34, (2007).

10. Kramer, R. J. *et al.* Observational evidence of increasing global radiative forcing. *Geophys Res Lett* (2021) doi:10.1029/2020gl091585.

11. McCoy, I. L. *et al.* The hemispheric contrast in cloud microphysical properties constrains aerosol forcing. *P Natl Acad Sci Usa* 117, 18998–19006 (2020).

12. Watson-Parris, D. *et al.* Constraining Uncertainty in Aerosol Direct Forcing. *Geophys Res Lett* 47, (2020).

13. Stevens, B. Uncertain then, irrelevant now. *Nature* 503, 47–48 (2013).

14. Jenkins, S. *et al.* Quantifying non-CO2 contributions to remaining carbon budgets. *Npj Clim Atmospheric Sci* 4, 47 (2021).

15. Andreae, M. O., Jones, C. D. & Cox, P. M. Strong present-day aerosol cooling implies a hot future. *Nature* 435, 1187–1190 (2005).

16. Peace, A. H. *et al.* Effect of aerosol radiative forcing uncertainty on projected exceedance year of a 1.5 C global temperature rise. *Environ Res Lett* 15, 0940a6 (2020).

17. O'Neill, B. C. *et al.* The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci Model Dev* 9, 3461–3482 (2016).

18. Smith, C. J. *et al.* Energy Budget Constraints on the Time History of Aerosol Forcing and Climate Sensitivity. *J Geophys Res Atmospheres* 126, (2021).

19. Rogelj, J. *et al. Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*. (2018).

20. Schleussner, C.-F. *et al.* Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 ∘C and 2 ∘C. *Earth Syst Dynam* 7, 327–351 (2016).

21. Stevens, B. Rethinking the Lower Bound on Aerosol Radiative Forcing. *J Climate* 28, 4794–4819 (2015).

22. Allen, M. R. *et al.* Indicate separate contributions of long-lived and short-lived greenhouse gases in emission targets. *Npj Clim Atmospheric Sci* 5, 5 (2022).