https://doi.org/10.5194/egusphere-2025-903
Preprint. Discussion started: 17 March 2025

ESD Ideas: Extended net zero simulations are critical for informed decision making

Andrew D. King[1,2], Nerilie J. Abram[1,3], Eduardo Alastrué de Asenjo[4,5], Tilo Ziehn[6]

[1]ARC Centre of Excellence for the Weather of the 21st Century
[2]School of Geography, Earth and Atmospheric Sciences, University of Melbourne, Melbourne, Kulin nations, Australia
[3]Research School of Earth Sciences, The Australian National University, Ngunnawal country, Canberra ACT 2601, Australia
[4]Max Planck Institute for Meteorology, Hamburg, Germany
[5]Institute of Oceanography, Center for Earth System Research and Sustainability (CEN), University of Hamburg, Hamburg, Germany
[6]CSIRO Environment, Aspendale, Kulin nations, Australia

Correspondence to: Andrew D. King (andrew.king@unimelb.edu.au)

Abstract. Climate changes under net zero emissions will take many centuries to play out, particularly in the Southern Hemisphere and in the ocean and cryosphere. New millennial-length Earth System Model simulations are required to better understand these committed changes and their dependence on delays in reaching net zero emissions.

Main text. Earth's climate is rapidly changing in response to anthropogenic greenhouse gas emissions. Humanity must achieve net zero emissions to slow down climate change and to have any hope of meeting the Paris Agreement goals of limiting global warming to well below 2°C. However, some aspects of the climate are changing faster than others; notably, there is a high degree of inertia in the ocean and cryosphere and changes in these systems will continue long after net zero emissions are achieved. As a result, regional and local climates will continue to evolve for many centuries. There is surprisingly little known about these longer timescale climate changes despite their policy relevance, mainly due to a lack of suitable model experiments.

Prior to the Paris Agreement and nations setting net zero goals, climate projections were primarily based on scenarios of increasing atmospheric carbon dioxide concentrations over the 21st century to determine associated global warming and other climate impacts. In recent years, new multi-model experiments, including new model intercomparison projects (MIPs), have been designed to better address the needs of policymakers to understand the implications of net zero emissions.

Multi-model experiments, especially from the Zero Emissions Commitment Model Intercomparison Project (ZECMIP; Jones et al., 2019), have been used to reach conclusions about global-average temperature and carbon cycle changes under net zero (Borowiak et al., 2024; MacDougall et al., 2020) as well as some limited regional analysis (Cassidy et al., 2023; MacDougall et al., 2022). Those studies have, by necessity, focussed on relatively short timescale changes given the limited length of

https://doi.org/10.5194/egusphere-2025-903
Preprint. Discussion started: 17 March 2025

these simulations. Existing net zero emissions simulations in ZECMIP and those planned in new protocols - flat10MIP (Sanderson et al., 2024a) and TipMIP (Finalized TIPMIP Tier 1 ESM protocol, 2025) – suggest simulations of 300 years in length should be run.

A significant knowledge gap exists around long-term changes in the climate under net zero and the long-lasting effects of a potential delay in emissions cessation. The large uncertainty in long-term climate changes under net zero was highlighted in a recent review by Palazzo Corner et al., (2023) which included an expert assessment of Earth system changes under net zero of which most were deemed to be "speculative" or "low confidence", particularly on timescales beyond a century.

Despite the current lack of multi-model net zero experiments, there is some understanding from other work that we should expect to see some climate changes continue for centuries even if emissions were to cease. Model experiments under fixed atmospheric carbon dioxide concentrations point to long-lasting changes in the climate system, particularly due to inertia in the ocean and cryosphere. These long-term commitments include increases in sea level (Mengel et al., 2018), warming of the Southern Ocean (Armour et al., 2016) and possible shifts in precipitation patterns (Grose and King, 2023).

However, fixed concentration simulations overstate committed warming and are insufficient to understand changes under policy-relevant net-zero emissions targets (Matthews and Weaver, 2010; Sanderson et al., 2024b). A limited set of single model experiments under net zero emissions run over multi-century to millennial windows suggest significant changes in some aspects of the climate system. For example, Sigmond et al., (2020) ran simulations of CanESM2 under net zero emissions for 500-600 years and found that global-mean sea level continues to rise and that the Atlantic Meridional Overturning Circulation (AMOC) starts to recover from its decline under rapid emissions.

A recent study using ACCESS-ESM-1.5 experiments run for 1000 years with net zero emissions commencing at different times in the 21st century found substantial warming of the oceans and decline of Antarctic sea ice extent over the course of the climate stabilisation simulations (King et al., 2024). Furthermore, these projections suggest that delays in achieving net zero emissions by even just a few decades can result in very different magnitudes of long-term commitments in the following centuries under net zero. Figure 1 summarises projected changes between 300 years (when most existing net zero experiments end) and 1000 years after net zero emissions are achieved. These differences suggest there are potential large-scale climate changes expected under net zero emissions beyond the timescale of existing experiments and that these may be highly dependent on the timing/global warming level that emissions cease.

https://doi.org/10.5194/egusphere-2025-903
Preprint. Discussion started: 17 March 2025

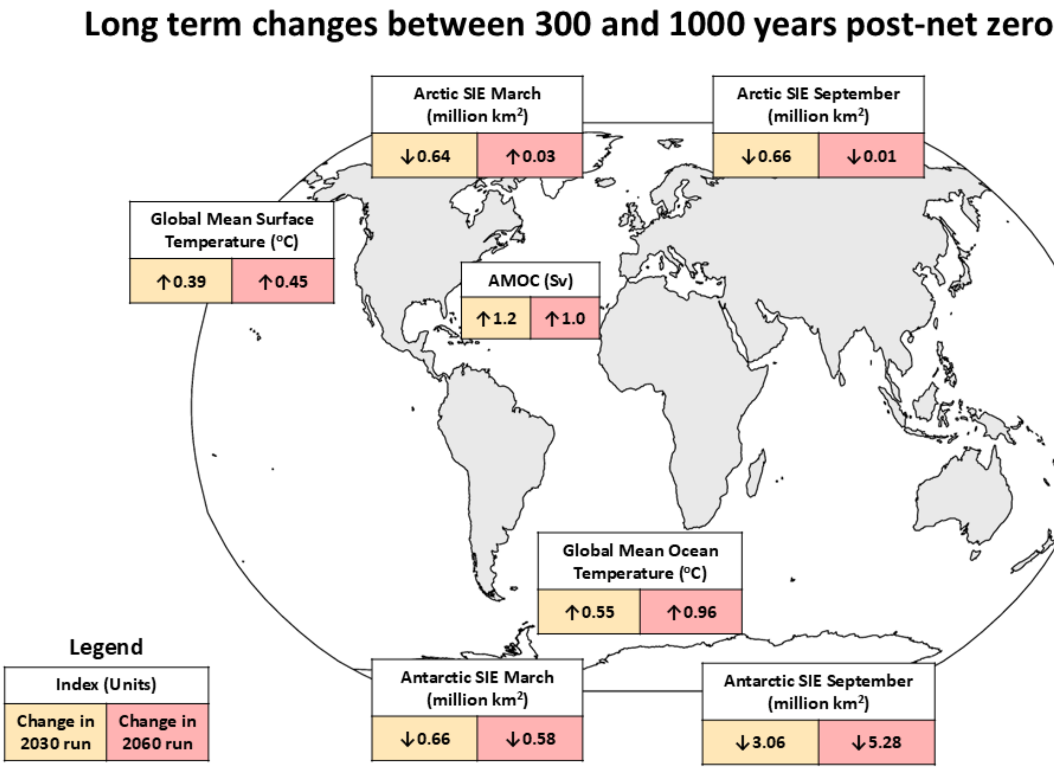

Figure 1: Summary of changes projected in the climate system between the third century (200-300 years) and the tenth century (900-1000 years) after net zero emissions is imposed in the ACCESS-ESM-1.5 experiments (King et al., 2024)**. The changes in orange cells are from a simulation with emissions cessation in 2030 and the changes in red cells are from a simulation where emissions cessation was delayed to 2060. SIE refers to Sea Ice Extent.**

Policymakers require more regional information for robust decision-making but are not well served by the lack of multi-model net zero experiments on long timescales. This is particularly problematic for understanding changes in interannual-to-multidecadal climate variability for which changes are only likely to be detectable over long periods. The same is true for multi-year extremes, such as multi-year droughts (Falster et al., 2024), for which limited information may be gained from shorter simulations.

The lack of extended net zero simulations risks understating the long-lasting impacts of increased global temperatures relative to pre-industrial levels. However, ESM simulations longer than a few hundred years are computationally expensive, so a compromise needs to be reached. We would suggest that modelling centres run two 1000-year-long simulations as extensions of existing plans. We recommend these could either be at the 1000PgC and 1500PgC cumulative emissions levels (in the flat10MIP framework; Sanderson et al., 2024a) or at the 2°C and 4°C global warming levels (in the TipMIP framework; Finalized TIPMIP Tier 1 ESM protocol, 2025). This would constitute extensions to existing simulations and would minimise additional computational expense.

https://doi.org/10.5194/egusphere-2025-903
Preprint. Discussion started: 17 March 2025

We believe such simulations will play a critical role in improving understanding of long-term changes under net zero emissions, including for:

- Quantifying the long-term effect of delay in achieving net zero emissions. The ACCESS-ESM-1.5 analysis suggests changes under net zero emissions will greatly depend on whether emissions cessation is delayed (King et al., 2024). A multi-model analysis of the effects of delay in achieving net zero for the climate over the coming centuries is vital.
- Identification and constraint of differences in model responses for uncertain changes. Analysis of ZECMIP suggests that local and even global changes under net zero emissions are highly uncertain (Borowiak et al., 2024; Cassidy et al., 2023; MacDougall et al., 2022). At present, uncertainties in long-term changes are unknown.
- Robust quantification of mean and extreme climate changes under net zero emissions. Longer simulations should aid in better estimation of local changes and changes in high-impact extremes, such as drought.
- Identification of potential for tipping points in the climate under different cumulative emissions/global warming levels under net zero emissions. Analysis of the ACCESS-ESM-1.5 millennial length simulations suggests Antarctic sea ice extent will shrink for many centuries (King et al., 2024). Analysis of changes in Antarctica and other highly vulnerable aspects of the Earth system using multiple models would help constrain these projected changes.
- Analysis of changes in climate variability. Subtle changes in ENSO and some recovery in AMOC have been identified in existing analyses (King et al., 2024; MacDougall et al., 2022), but these are likely to be model-dependent results. Changes in ENSO and AMOC, among other climate modes, must be better quantified for understanding long-term regional climate changes through their teleconnections.

In our view, the set-up and analysis of such extended net zero simulations ahead of the Seventh Assessment Report of the Intergovernmental Panel on Climate Change is necessary and we hope that this suggestion is given due consideration.

Data Availability

The data used in this analysis is available here: 10.5281/zenodo.13168507.

Author contributions

A.D.K. conceived the paper and led the writing. All authors contributed to the writing of the manuscript.

Competing interests

The authors declare no competing interests.

https://doi.org/10.5194/egusphere-2025-903
Preprint. Discussion started: 17 March 2025

Acknowledgements

A.D.K. and N.J.A. acknowledge support from the Australian Research Council through the Centre of Excellence for the Weather of the 21st Century (CE230100012; A.D.K. and N.J.A.) and the Special Research Initiative Australian Centre for Excellence in Antarctic Sciences (SR200100008; N.J.A.). A.D.K. and T. Z. acknowledge the Australian Government National Environmental Science Program. E.A.dA. acknowledges funding by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy – EXC 2037 'CLICCS- Climate, Climatic Change, and Society' – Project Number: 390683824

References

Finalized TIPMIP Tier 1 ESM protocol: https://tipmip.pik-potsdam.de/news/tipmip_esm_protocol/, last access: 22 February 2025.

Armour, K. C., Marshall, J., Scott, J. R., Donohoe, A., and Newsom, E. R.: Southern Ocean warming delayed by circumpolar upwelling and equatorward transport, Nature Geoscience 2016 9:7, 9, 549–554, https://doi.org/10.1038/ngeo2731, 2016.

Borowiak, A., King, A. D., Brown, J. R., Jones, C. D., Ziehn, T., Meinshausen, M., and Cassidy, L.: Projected Global Temperature Changes After Net Zero Are Small But Significant, Geophys Res Lett, 51, e2024GL108654, https://doi.org/10.1029/2024GL108654, 2024.

Cassidy, L. J., King, A. D., Brown, J., MacDougall, A. H., Ziehn, T., Min, S.-K., and Jones, C. D.: Regional temperature extremes and vulnerability under net zero CO2 emissions, Environmental Research Letters, https://doi.org/10.1088/1748-9326/AD114A, 2023.

Falster, G. M., Wright, N. M., Abram, N. J., Ukkola, A. M., and Henley, B. J.: Potential for historically unprecedented Australian droughts from natural variability and climate change, Hydrol Earth Syst Sci, 28, 1383–1401, https://doi.org/10.5194/HESS-28-1383-2024, 2024.

Grose, M. R. and King, A. D.: The circulation and rainfall response in the southern hemisphere extra-tropics to climate stabilisation, Weather Clim Extrem, 100577, https://doi.org/10.1016/J.WACE.2023.100577, 2023.

Jones, C. D., Frölicher, T. L., Koven, C., MacDougall, A. H., Matthews, H. D., Zickfeld, K., Rogelj, J., Tokarska, K. B., Gillett, N. P., Ilyina, T., Meinshausen, M., Mengis, N., Séférian, R., Eby, M., and Burger, F. A.: The Zero Emissions Commitment Model Intercomparison Project (ZECMIP) contribution to C4MIP: quantifying committed climate changes following zero carbon emissions, Geosci Model Dev, 12, 4375–4385, https://doi.org/10.5194/gmd-12-4375-2019, 2019.

King, A. D., Ziehn, T., Chamberlain, M., Borowiak, A. R., Brown, J. R., Cassidy, L., Dittus, A. J., Grose, M., Maher, N., Paik, S., Perkins-Kirkpatrick, S. E., and Sengupta, A.: Exploring climate stabilisation at different global warming levels in ACCESS-ESM-1.5, Earth System Dynamics, 15, 1353–1383, https://doi.org/10.5194/ESD-15-1353-2024, 2024.

https://doi.org/10.5194/egusphere-2025-903
Preprint. Discussion started: 17 March 2025

MacDougall, A. H., Frölicher, T. L., Jones, C. D., Rogelj, J., DamonMatthews, H., Zickfeld, K., Arora, V. K., Barrett, N. J., Brovkin, V., Burger, F. A., Eby, M., Eliseev, A. V., Hajima, T., Holden, P. B., Jeltsch-Thömmes, A., Koven, C., Mengis, N., Menviel, L., Michou, M., Mokhov, I. I., Oka, A., Schwinger, J., Séférian, R., Shaffer, G., Sokolov, A., Tachiiri, K., Tjiputra, J., Wiltshire, A., and Ziehn, T.: Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO2, Biogeosciences, 17, 2987–3016, https://doi.org/10.5194/BG-17-2987-2020, 2020.

MacDougall, A. H., Mallett, J., Hohn, D., and Mengis, N.: Substantial regional climate change expected following cessation of CO2 emissions, Environmental Research Letters, 17, 114046, https://doi.org/10.1088/1748-9326/AC9F59, 2022.

Matthews, H. D. and Weaver, A. J.: Committed climate warming, Nature Geoscience 2010 3:3, 3, 142–143, https://doi.org/10.1038/ngeo813, 2010.

Mengel, M., Nauels, A., Rogelj, J., and Schleussner, C.-F.: Committed sea-level rise under the Paris Agreement and the legacy of delayed mitigation action, Nat Commun, 9, 601, https://doi.org/10.1038/s41467-018-02985-8, 2018.

Palazzo Corner, S., Siegert, M., Ceppi, P., Fox-Kemper, B., Frölicher, T. L., Gallego-Sala, A., Haigh, J., Hegerl, G. C., Jones, C. D., Knutti, R., Koven, C. D., MacDougall, A. H., Meinshausen, M., Nicholls, Z., Sallée, J. B., Sanderson, B. M., Séférian, R., Turetsky, M., Williams, R. G., Zaehle, S., and Rogelj, J.: The Zero Emissions Commitment and climate stabilization, Frontiers in Science, 1, https://doi.org/10.3389/FSCI.2023.1170744/FULL, 2023.

Sanderson, B. M., Brovkin, V., Fisher, R., Hohn, D., Ilyina, T., Jones, C., Koenigk, T., Koven, C., Li, H., Lawrence, D., Lawrence, P., Liddicoat, S., Macdougall, A., Mengis, N., Nicholls, Z., O'Rourke, E., Romanou, A., Sandstad, M., Schwinger, J., Seferian, R., Sentman, L., Simpson, I., Smith, C., Steinert, N., Swann, A., Tjiputra, J., and Ziehn, T.: flat10MIP: An emissions-driven experiment to diagnose the climate response to positive, zero, and negative CO2 emissions, EGUsphere [preprint], https://doi.org/10.5194/EGUSPHERE-2024-3356, 2024a.

Sanderson, B. M., Booth, B. B. B., Dunne, J., Eyring, V., Fisher, R. A., Friedlingstein, P., Gidden, M. J., Hajima, T., Jones, C. D., Jones, C. G., King, A., Koven, C. D., Lawrence, D. M., Lowe, J., Mengis, N., Peters, G. P., Rogelj, J., Smith, C., Snyder, A. C., Simpson, I. R., Swann, A. L. S., Tebaldi, C., Ilyina, T., Schleussner, C.-F., Séférian, R., Samset, B. H., van Vuuren, D., and Zaehle, S.: The need for carbon-emissions-driven climate projections in CMIP7, Geosci Model Dev, 17, 8141–8172, https://doi.org/10.5194/GMD-17-8141-2024, 2024b.

Sigmond, M., Fyfe, J. C., Saenko, O. A., and Swart, N. C.: Ongoing AMOC and related sea-level and temperature changes after achieving the Paris targets, Nat Clim Chang, 10, 672–677, https://doi.org/10.1038/s41558-020-0786-0, 2020.