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Emission budgets and pathways consistent with limiting warming to 1.5 °C

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Abstract

The Paris Agreement has opened debate on whether limiting warming to 1.5 °C is compatible with current emission pledges and warming of about 0.9 °C from the mid-nineteenth century to the present decade. We show that limiting cumulative post-2015 CO_2 emissions to about 200 GtC would limit post-2015 warming to less than 0.6 °C in 66% of Earth system model members of the CMIP5 ensemble with no mitigation of other climate drivers, increasing to 240 GtC with ambitious non-CO_2 mitigation. We combine a simple climate–carbon-cycle model with estimated ranges for key climate system properties from the IPCC Fifth Assessment Report. Assuming emissions peak and decline to below current levels by 2030, and continue thereafter on a much steeper decline, which would be historically unprecedented but consistent with a standard ambitious mitigation scenario (RCP2.6), results in a likely range of peak warming of 1.2–2.0 °C above the mid-nineteenth century. If CO_2 emissions are continuously adjusted over time to limit 2100 warming to 1.5 °C, with ambitious non-CO_2 mitigation, net future cumulative CO_2 emissions are unlikely to prove less than 250 GtC and unlikely greater than 540 GtC. Hence, limiting warming to 1.5 °C is not yet a geophysical impossibility, but is likely to require delivery on strengthened pledges for 2030 followed by challengingly deep and rapid mitigation. Strengthening near-term emissions reductions would hedge against a high climate response or subsequent reduction rates proving economically, technically or politically unfeasible.

Subject terms: Climate and Earth system modelling Climate-change mitigation

References

1. *Adoption of the Paris Agreement* FCCC/CP/2015/L.9/Rev. 1 (UNFCCC, 2015); http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf
2. Otto, F. E. L., Frame, D. J., Otto, A. & Allen, M. R. Embracing uncertainty in climate change policy. *Nat. Clim. Change* **5**, 917–920 (2015).
3. Morice, C. P., Kennedy, J. J., Rayner, N. A. & Jones, P. D. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: the HadCRUT4 data set. *J. Geophys. Res.* **117**, D08101 (2012).
4. Rogelj, J. *et al*. Energy system transformations for limiting end-of-century warming to below 1.5 °C. *Nat. Clim. Change* **5**, 519–527 (2015).
5. Sanderson, B. M., O'Neill, B. C. & Tebaldi, C. What would it take to achieve the Paris temperature targets? *Geophys. Res. Lett.* **43**, 7133–7142 (2016).
6. Fawcett, A. A. *et al*. Can Paris pledges avert severe climate change? *Science* **350**, 1168–1169 (2015).
7. Matthews, H. D. & Caldeira, K. Stabilizing climate requires near-zero emissions. *Geophys. Res. Lett.* **35**, L04705 (2008).
8. Allen, M. R. *et al*. Warming caused by cumulative carbon emissions towards the trillionth tonne. *Nature* **458**, 1163–1166 (2009).
9. Meinshausen, M. *et al*. Greenhouse-gas emission targets for limiting global warming to 2 °C. *Nature* **458**, 1158–1162 (2009).
10. Zickfeld, K., Eby, M., Matthews, H. D. & Weaver, A. J. Setting cumulative emissions targets to reduce the risk of dangerous climate change. *Proc. Natl Acad. Sci. USA* **106**, 16129–16134 (2009).
11. IPCC *Climate Change 2014: Synthesis Report* (eds Pachauri, R. K. & Meyer, L. A.) (Cambridge Univ. Press, 2014).
12. Le Quéré, C. *et al*. Global carbon budget 2015. *Earth Syst. Sci. Data* **7**, 349–396 (2015).
13. Rogelj, J. *et al*. Paris Agreement climate proposals need boost to keep warming well below 2 °C. *Nature* **534**, 631–639 (2016).
14. Collins, M. *et al*. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) 1029–1136 (IPCC, Cambridge Univ. Press, 2013).
15. Rogelj, J. *et al*. Differences between carbon budget estimates unravelled. *Nat. Clim. Change* **6**, 245–252 (2016).
16. IPCC *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) (Cambridge Univ. Press, 2013).
17. Richardson, M., Cowtan, K., Hawkins, E. & Stolpe, M. B. Reconciled climate response estimates from climate models and the energy budget of Earth. *Nat. Clim. Change* **6**, 931–935 (2016).
18. Hawkins, E. *et al*. Estimating changes in global temperature since the pre-industrial period. *Bull. Am. Meteorol. Soc.* http://dx.doi.org/10.1175/BAMS-D-16-0007.1 (2017).
19. MacDougall, A. H., Zickfeld, K., Knutti, R. & Matthews, H. D. Sensitivity of carbon budgets to permafrost carbon feedbacks and non-CO_2 forcings. *Environ. Res. Lett.* **10**, 125003 (2015).
20. Myhre, G. *et al*. Multi-model simulations of aerosol and ozone radiative forcing due to anthropogenic emission changes during the period 1990–2015. *Atmos. Chem. Phys.* **17**, 2709–2720 (2017).
21. van Vuuren, D. *et al*. RCP 2.6: exploring the possibility to keep global mean temperature increase below 2 °C. *Climatic Change* **109**, 95–116 (2011).
22. Riahi, K. *et al*. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. *Climatic Change* **109**, 33–57 (2011).

23. IPCC *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al*.) (Cambridge Univ. Press, 2014).
24. Clarke, L. E. *et al*. in *Climate Change 2014: Mitigation of Climate Change* (eds Edenhofer, O. *et al*.) 413–510 (IPCC, Cambridge Univ. Press, 2014).
25. Shindell, D. T. Inhomogeneous forcing and transient climate sensitivity. *Nat. Clim. Change* **4**, 18–21 (2014).
26. Kummer, J. R. R. & Dessler, A. E. E. The impact of forcing efficacy on the equilibrium climate sensitivity. *Geophys. Res. Lett.* **41**, 3565–3568 (2014).
27. Andrews, T., Gregory, J. M., Webb, M. J. & Taylor, K. E. Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere–ocean climate models. *Geophys. Res. Lett.* **39**, L09712 (2012).
28. Myhre, G. *et al*. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) 659–740 (IPCC, Cambirdge Univ. Press, 2013).
29. Millar, R. J., Nicholls, Z. R., Friedlingstein, P. & Allen, M. R. A modified impulse-response representation of the global near-surface air temperature and atmospheric concentration response to carbon dioxide emissions. *Atmos. Chem. Phys.* **17**, 7213–7228 (2017).
30. Weaver, A. J. *et al*. The UVic Earth System Climate Model: model description, climatology, and applications to past, present and future climates. *Atmos.-Ocean* **39**, 361–428 (2001).
31. Eby, M. *et al*. Historical and idealized climate model experiments: an intercomparison of Earth system models of intermediate complexity. *Clim. Past* **9**, 1111–1140 (2013).
32. Zickfeld, K. *et al*. Long-term climate change commitment and reversibility: an EMIC intercomparison. *J. Clim.* **26**, 5782–5809 (2013).
33. Millar, R., Allen, M., Rogelj, J. & Friedlingstein, P. The cumulative carbon budget and its implications. *Oxford Rev. Econ. Policy* **32**, 323–342 (2016).
34. Jarvis, A. J., Leedal, D. T. & Hewitt, C. N. Climate-society feedbacks and the avoidance of dangerous climate change. *Nat. Clim. Change* **2**, 668–671 (2012).
35. Stevens, B. Rethinking the lower bound on aerosol radiative forcing. *J. Clim.* **28**, 4794–4819 (2015).
36. Etminan, M., Myhre, G., Highwood, E. J. & Shine, K. P. Radiative forcing of carbon dioxide, methane, and nitrous oxide: a significant revision of the methane radiative forcing. *Geophys. Res. Lett.* **43**, 12614–12623 (2016).
37. *Emission Gap Report 2015* (UNEP, 2015).
38. Rogelj, J. *et al*. Understanding the origin of Paris Agreement emission uncertainties. *Nat. Commun.* **8**, 15748 (2017).
39. Fuglestvedt, J. S., Berntsen, T. K., Godal, O. & Skodvin, T. Climate implications of GWP-based reductions in greenhouse gas emissions. *Geophys. Res. Lett.* **27**, 409–412 (2000).
40. Pierrehumbert, R. T. Short-lived climate pollution. *Annu. Rev. Earth Planet. Sci.* **42**, 341–379 (2014).
41. Allen, M. R. *et al*. New use of global warming potentials to compare cumulative and short-lived climate pollutants. *Nat. Clim. Change* **6**, 773–776 (2016).
42. Bowerman, N. H. A. *et al*. The role of short-lived climate pollutants in meeting temperature goals. *Nat. Clim. Change* **3**, 8–11 (2013).
43. Pfeiffer, A., Millar, R., Hepburn, C. & Beinhocker, E. The '2 °C capital stock' for electricity generation: committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. *Appl. Energy* **179**, 1395–1408 (2016).
44. Riahi, K. *et al*. Locked into Copenhagen pledges—implications of short-term emission targets for the cost and feasibility of long-term climate goals. *Technol. Forecast. Soc. Change* **90**, 8–23 (2015).
45. Smith, P. *et al*. Biophysical and economic limits to negative CO_2 emissions. *Nat. Clim. Change* **6**, 4–50 (2015).
46. Jackson, R. B. *et al*. Reaching peak emissions. *Nat. Clim. Change* **6**, 7–10 (2015).
47. Grubb, M. *et al*. A review of Chinese CO_2 emission projections to 2030: the role of economic structure and policy. *Clim. Policy* **15**, S7–S39 (2015).
48. Green, F. & Stern, N. China's changing economy: implications for its carbon dioxide emissions. *Clim. Policy* **17**, 423–442 (2017).

49. Kirtman, B. *et al*. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) 95–1028 (IPCC, Cambridge Univ. Press, 2013).

50. Pueyo, S. Solution to the paradox of climate sensitivity. *Climatic Change* **113**, 163–179 (2012).

51. Armour, K. C. Energy budget constraints on climate sensitivity in light of inconstant climate feedbacks. *Nat. Clim. Change* **7**, 331–335 (2017).

52. Millar, R. J. *et al*. Model structure in observational constraints on transient climate response. *Climatic Change* **131**, 199–211 (2015).

53. 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).

54. Stocker, T. F. *et al*. in *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. F. *et al*.) 33–115 (IPCC, Cambirdge Univ. Press, 2013).

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Contributions

R.J.M. conducted the analysis and produced Figs 2 and 3. J.R. conducted the CMIP5 analysis and produced Fig. 1. H.D.M. conducted the integrations with the UVic ESCM. R.J.M. produced an initial draft of the manuscript along with J.S.F., M.G., P.F. and M.R.A. All authors contributed to the experimental design, interpretation and revisions of the manuscript.

Competing financial interests

The authors declare no competing financial interests.

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Supplementary information

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