Check for updates

High climate sensitivity in CMIP6 model not supported by paleoclimate

To the Editor — Equilibrium climate sensitivity (ECS) is the long-term response of global mean surface temperature (GMST) to a doubling of atmospheric CO_2 concentrations. It is poorly constrained with a 'likely' range of 1.5–4.5 °C, which has remained nearly unchanged since the Charney report 40 years ago[1]. Ten in twenty-seven of the available climate models participating in the Coupled Model Intercomparison Project phase 6 (CMIP6) have an ECS higher than the upper end of this range, in contrast to two in twenty-eight CMIP5 models[2,3]. For example, the ECS in the Community Earth System Model version 2 (CESM2)[4] — a CMIP6 model — is 5.3 °C (ref. [5]). Determining whether this high ECS is realistic is paramount for estimating future climate and crafting effective policies and adaptation plans. Without a historical benchmark to test the ECS of CMIP6 models against, they can be evaluated against past warm periods, such as the Early Eocene Climate Optimum (EECO), a period of sustained high GMST ~53–50 mya[6,7].

Here, we report EECO simulations using CESM2 and find that its high ECS is not supported by geological evidence. Our simulations incorporate the latest reconstructions of EECO boundary conditions, including paleogeography, vegetation cover and land surface properties[6]. Reconstructions of atmospheric CO_2 for past times that predate ice-core records rely on geochemical and paleobotanical proxies and have large uncertainties; EECO values are estimated to have been ≥ 1,000 ppm (95% confidence level), with a best estimate of 1,625 ± 760 ppm (95% confidence interval)[6,8], ~3–9× the pre-industrial CO_2 ($piCO_2$) value of 285 ppm. We conduct EECO simulations with 1×, 2× and 3× $piCO_2$ levels and compare the modelled GMST and meridional sea surface temperature gradient (MTG; in per cent of the pre-industrial value) in these runs with the latest proxy estimates (29 ± 3 °C and 69 ± 13%, respectively; 95% confidence interval)[7,9]. With 3× $piCO_2$, at the low end of the proxy CO_2 range, modelled GMST is 37.5 °C, 5.5 °C greater than the upper end of proxy temperature estimates (Fig. 1a). Moreover, modelled tropical land temperature exceeds 55 °C, which is much higher than the temperature tolerance of plant photosynthesis[10] and is inconsistent with fossil evidence of an Eocene Neotropical rainforest[11]. CESM2 simulates an EECO GMST of 29.9 °C and a MTG of 86% with 2× $piCO_2$, a level well below the proxy range and a MTG that is too steep (Fig. 1b).

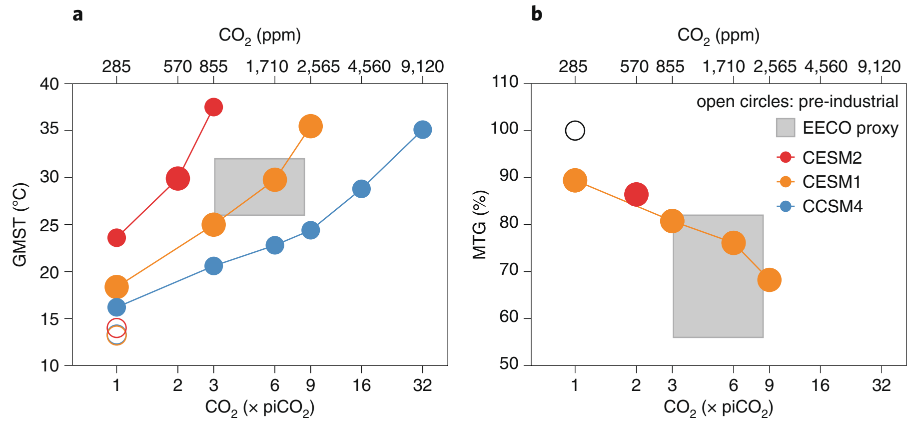

Fig. 1 | Model-data comparison of GMST and MTG. a, EECO GMST as a function of atmospheric CO_2 based on proxy estimates (grey box) and model simulations (dots) using CESM2 (red), CESM1 (orange) and CCSM4 (blue). **b**, The same as **a**, but for MTG in per cent of the corresponding pre-industrial values. For reference, pre-industrial GMST and MTG are marked as open circles in **a**,**b**. Note the logarithmic scale of *x* axes and $piCO_2$ = 285 ppm. Details of the CCSM4 and CESM1 simulations and methods for compiling proxy records are documented in ref. [9]. CESM2 simulations conducted here use the same Eocene boundary conditions as in ref. [9] but a higher resolution for the atmosphere and land (~1° versus ~2°). The fully coupled CESM2 simulation with 2× $piCO_2$ is initialized from CESM1 simulation with 6× $piCO_2$, of which explorations using slab ocean model (SOM) simulations estimate to have a similar GMST. This is confirmed, as CESM2 2× $piCO_2$ has reached quasi-equilibrium in surface climate after 500 model years with a similar GMST and top-of-atmosphere energy imbalance as CESM1 6× $piCO_2$ after 2,000 years. CESM2 with 1× and 3× $piCO_2$ and CCSM4 simulations are conducted using a SOM without active ocean dynamics (smaller dots in **a**), as fully coupled simulations are computationally demanding. Ocean mixed layer depth and heat transport convergence in SOM simulations are from the corresponding fully coupled CESM1 simulations with the same CO_2. Using the same boundary conditions, SOM simulations reproduce GMST in fully coupled simulations with a difference of < 1 °C (refs. [9,16]), but MTG depends on the prescribed ocean mixed layer depth and heat transport convergence and is omitted in **b**.

CESM2 GMSTs are substantially higher than results using its predecessors, CESM1 (ref. [12]) and the Community Climate System Model version 4 (CCSM4)[13]. In a CESM1 EECO simulation with 6× $piCO_2$, GMST is 29.8 °C and the MTG is 76%, agreeing well with proxy evidence[9]. In CCSM4, CO_2 levels of 16× $piCO_2$ are necessary to attain an EECO GMST, values that are much higher than proxy estimates. Sensitivity to the non-CO_2 EECO climate forcings — paleogeography, vegetation, and the removal of anthropogenic aerosols and land ice sheets — are estimated to be 9.4 °C, 5.1 °C and 2.9 °C in CESM2, CESM1 and CCSM4, respectively, showing a monotonic but nonlinear dependence between model sensitivity and its pre-industrial ECSs, which are 5.3 °C, 4.2 °C and 3.2 °C (refs. [5,14]), respectively. The nonlinear relationship results from the increase of ECS with GMST[9] and potential increases in the effectiveness of non-CO_2 climate forcings between model versions, for which the underlying mechanisms merit further research. The dependence of ECS on model versions and GMST has been attributed to the cloud feedback — that is, the amplification of surface warming through changes in clouds[5,9].

CESM2 produces a better representation of the current climate than CESM1 (ref. [5]) and is among the best-performing CMIP6 models based on mean pattern correlations of a variety of climate fields[15]. Nonetheless, the high ECS in CESM2 is incompatible with known Eocene greenhouse climate. Though this analysis is limited to CESM2, we expect that other models with similarly high ECS may also be biased too warm when driven by high levels of atmospheric CO_2. Our study illustrates that the development and tuning of models to reproduce the instrumental record does not ensure that they will perform realistically at high CO_2. In this regard, paleoclimate constraints are especially important to guide model development and choices of physical parameterizations, because they represent the only real-world estimates of equilibrium surface temperature under atmospheric CO_2 concentrations outside the range of instrumental records. For this reason, we recommend that paleoclimate constraints, from both past warm and cold climates, be used to benchmark the performance of other CMIP6 models and future generations.

Data availability

CESM1 simulation data are available in the Zenodo repository at https://zenodo.org/record/2642536#.Xo7xa5NKjyI. CESM2 data can be requested from J.Z.

Code availability

CESM2 model code is available at https://github.com/ESCOMP/CESM/releases/tag/release-cesm2.1.1. CESM1 and CCSM4 model code is available at https://svn-ccsm-models.cgd.ucar.edu/cesm1/release_tags/cesm1_2_2_1/. ❐

Jiang Zhu[1✉], Christopher J. Poulsen[1] and Bette L. Otto-Bliesner[2]
[1]*Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI, USA.*
[2]*Climate and Global Dynamics Laboratory, National Center for Atmospheric Research, Boulder, CO, USA.*
✉*e-mail: jiazhu@umich.edu*

Published online: 30 April 2020
https://doi.org/10.1038/s41558-020-0764-6

References

1. Charney, J. G. et al. *Carbon Dioxide and Climate: a Scientific Assessment* (National Academy of Sciences, 1979).
2. *Nat. Clim. Change* **9**, 727 (2019).
3. Zelinka, M. D. et al. *Geophys. Res. Lett.* **47**, e2019GL085782 (2020).
4. Danabasoglu, G. et al. *J. Adv. Model. Earth Sy.* **12**, e2019MS001916 (2020).
5. Gettelman, A. et al. *Geophys. Res. Lett.* **46**, 8329–8337 (2019).
6. Lunt, D. J. et al. *Geosci. Model Dev.* **10**, 889–901 (2017).
7. Hollis, C. J. et al. *Geosci. Model Dev.* **12**, 3149–3206 (2019).
8. Anagnostou, E. et al. *Nature* **533**, 380–380 (2016).
9. Zhu, J., Poulsen, C. J. & Tierney, J. E. *Sci. Adv.* **5**, eaax1874 (2019).
10. Berry, J. & Bjorkman, O. *Annu. Rev. Plant Physio.* **31**, 491–543 (1980).
11. Wing, S. L. et al. *Proc. Natl Acad. Sci. USA* **106**, 18627 (2009).
12. Hurrell, J. W. et al. *B. Am. Meteorol. Soc.* **94**, 1339–1360 (2013).
13. Gent, P. R. et al. *J. Climate* **24**, 4973–4991 (2011).
14. Gettelman, A., Kay, J. E. & Shell, K. M. *J. Climate* **25**, 1453–1469 (2012).
15. Fasullo, J. T. *Climate Model Assessment Tool CMIP6 Analysis (CMAT-CMIP6)* (2020); http://webext.cgd.ucar.edu/Multi-Case/CMAT/CMATv1_CMIP6/index.html
16. Caballero, R. & Huber, M. *Proc. Natl Acad. Sci. USA* **110**, 14162–14167 (2013).

Acknowledgements

This work was supported by Heising-Simons Foundation (grant nos. 2016-05 and 2016-12) and National Science Foundation (NSF; grant no. 2002397) to C.J.P. We acknowledge the computational resources provided by the CESM Paleoclimate Working Group for high-performance computing support from Cheyenne (https://www2.cisl.ucar.edu/user-support/acknowledging-ncarcisl) provided by the National Center for Atmospheric Research's CISL, sponsored by NSF. The CESM project is supported primarily by the NSF. This material is based upon work supported by the National Center for Atmospheric Research, which is a major facility sponsored by the NSF under Cooperative Agreement no. 1852977.