High-sensitivity Earth System Models Most Consistent with Observations

Menghan Yuan[1], Thomas Leirvik[2], Trude Storelvmo[3], Kari Alterskjær[2], Peter C.B. Phillips[4], and Christopher J. Smith[5]

[1]University of Oxford [2]Nord University [3]University of Oslo

[4]University of Auckland [5]University of Leeds

EGU22, Vienna, May 2022

Background and Research Question

Econometric estimates of Earth's transient climate response (TCR) based on observations and climate model simulations

- TCR measures the change of global temperature at the year in which atmospheric CO_2 concentrations have doubled given a 1% increase each year.
- The latest generation of Earth System Models (ESMs) in the CMIP6 ensemble produces a mean TCR of 2.0 ± 0.4℃ ($\pm 1\sigma$), whereas the Sixth Assessment Report (AR6) of IPCC reports the best estimate of TCR to be 1.8 ± 0.6℃ (66% confidence).
- Lower TCR estimates are suggested in AR6 and in other recent studies which applied observational constraints on global warming to CMIP6 (see e.g., Nijsse, Cox, and Williamson, 2020; Tokarska et al., 2020).
- These constraints focus on the historical warming over recent 3-4 decades during which aerosol effects are nearly constant. We incorporated aerosol cooling effects in our model and focused on a longer period starting from the early 1960s.

Background and Research Question

Econometric estimates of Earth's transient climate response (TCR) based on observations and climate model simulations

- TCR measures the change of global temperature at the year in which atmospheric CO_2 concentrations have doubled given a 1% increase each year.
- The latest generation of Earth System Models (ESMs) in the CMIP6 ensemble produces a mean TCR of 2.0 ± 0.4℃ ($\pm 1\sigma$), whereas the Sixth Assessment Report (AR6) of IPCC reports the best estimate of TCR to be 1.8 ± 0.6℃ (66% confidence).
- Lower TCR estimates are suggested in AR6 and in other recent studies which applied observational constraints on global warming to CMIP6 (see e.g., Nijsse, Cox, and Williamson, 2020; Tokarska et al., 2020).
- These constraints focus on the historical warming over recent 3-4 decades during which aerosol effects are nearly constant. We incorporated aerosol cooling effects in our model and focused on a longer period starting from the early 1960s.

Background and Research Question

What we did in the current study:

- We incorporate aerosol cooling effects in our econometric model and obtain an observational TCR estimate.
- We validate our empirical estimation method by retrieving inputs from 22 ESMs in CMIP6 and compare the TCR estimates to the reported TCR;
- We further inform the implications of the observational TCR on the remaining carbon budget.

Econometric Framework for TCR estimation

The original econometric model was proposed in Phillips, Leirvik, and Storelvmo (2020). Our empirical model explicitly incorporates aerosol forcing effects in addition to greenhouse gas warming effects.

The framework relates global mean temperature, surface solar radiation (SSR), and CO_2 equivalent emissions ($\bar{T}_t, \bar{R}_t, ln(CO_{2,t})$) in a dynamic cointegrated system given by

$$\bar{T}_{t+1} = \gamma_0 + \gamma_1 \bar{T}_t + \gamma_2 \bar{R}_t + \gamma_3 ln(CO_{2,t}) + \bar{u}_{t+1}$$

from which TCR is estimated as $TCR = \frac{\gamma_3}{1-\gamma_1} \times ln(2)$.

Conversion from land TCR (TCR_L) to global TCR (TCR_G)

$$TCR_G = TCR_L \cdot \frac{A_L \cdot w_L + A_o \cdot w_O}{w_L}$$

where A_L and A_O are land and ocean area fraction; w_L and w_O are warming over land and ocean.

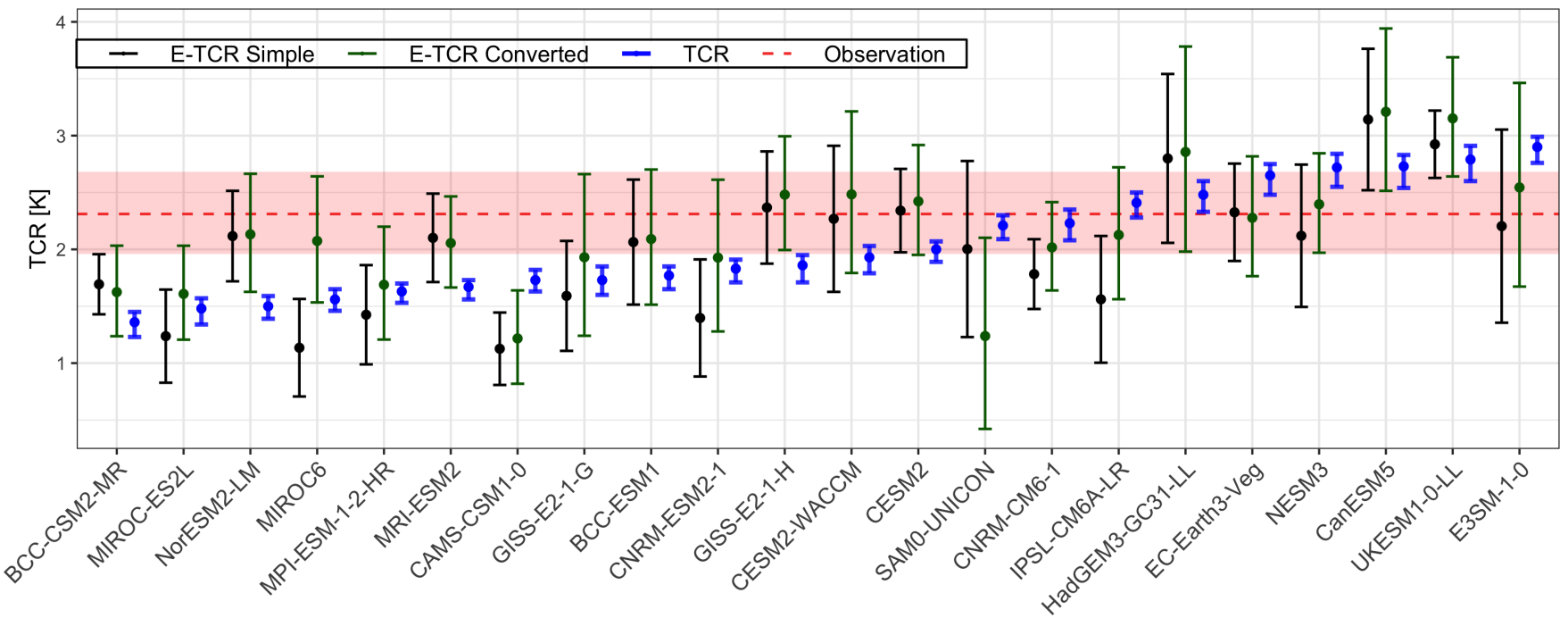
Datasets

- **Temperature and SSR**:
  - **Simulations**
    This study uses data from 22 Earth System Models in CMIP6 available at the time we conducted the analysis. The first realization of each model is downloaded from the ESGF.
  - **Observations**
    Observational temperature data is from CRU (Climatic Research Unit); surface solar radiation data is from an imputed dataset constructed based on GEBA (Global Energy Balance Archive) by Yuan, Leirvik, and Wild (2021).
- CO_2 **equivalent concentrations**:
  We use the NOAA Annual Greenhouse Gas Index (AGGI).

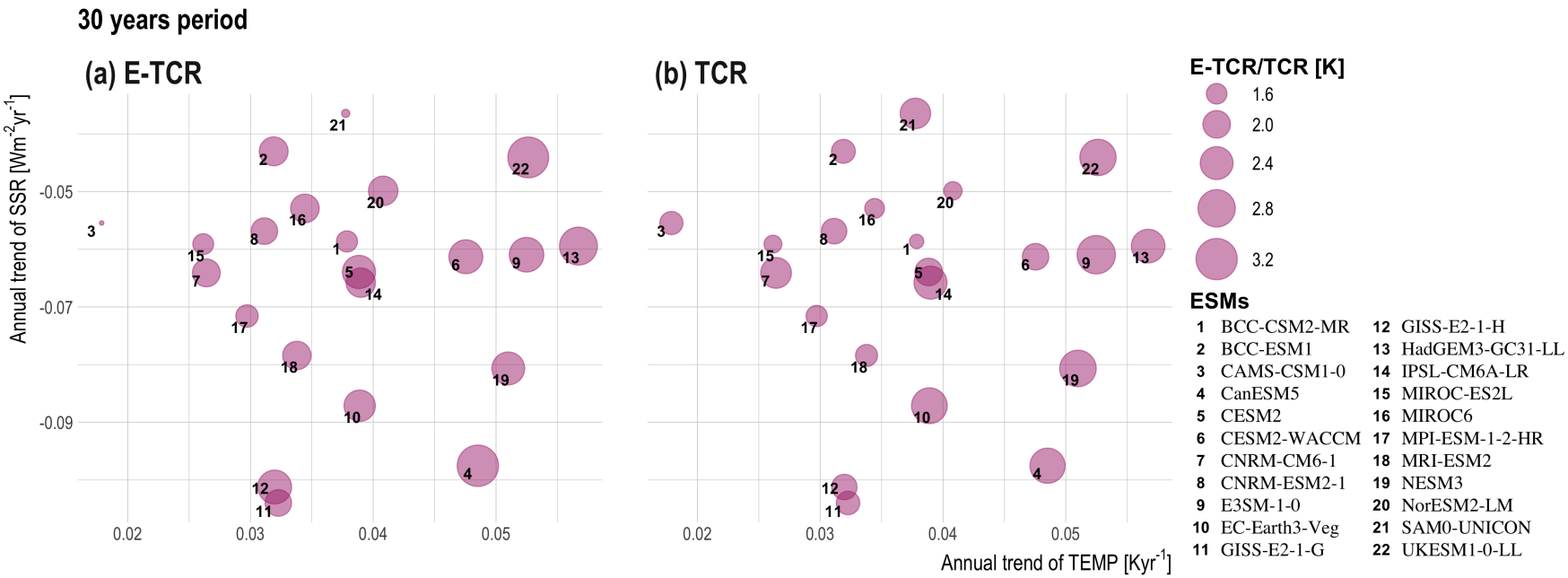
Time period: from 1964 to 2014.

Results–TCR Estimates

- Observational TCR estimate: 2.3±0.4℃ (red band, 95% confidence).
- ESM TCR estimates: i) using global datasets (black bars); ii) using land datasets then converted to global estimates (green bars); iii) reported TCR from ESMs (blue bars).

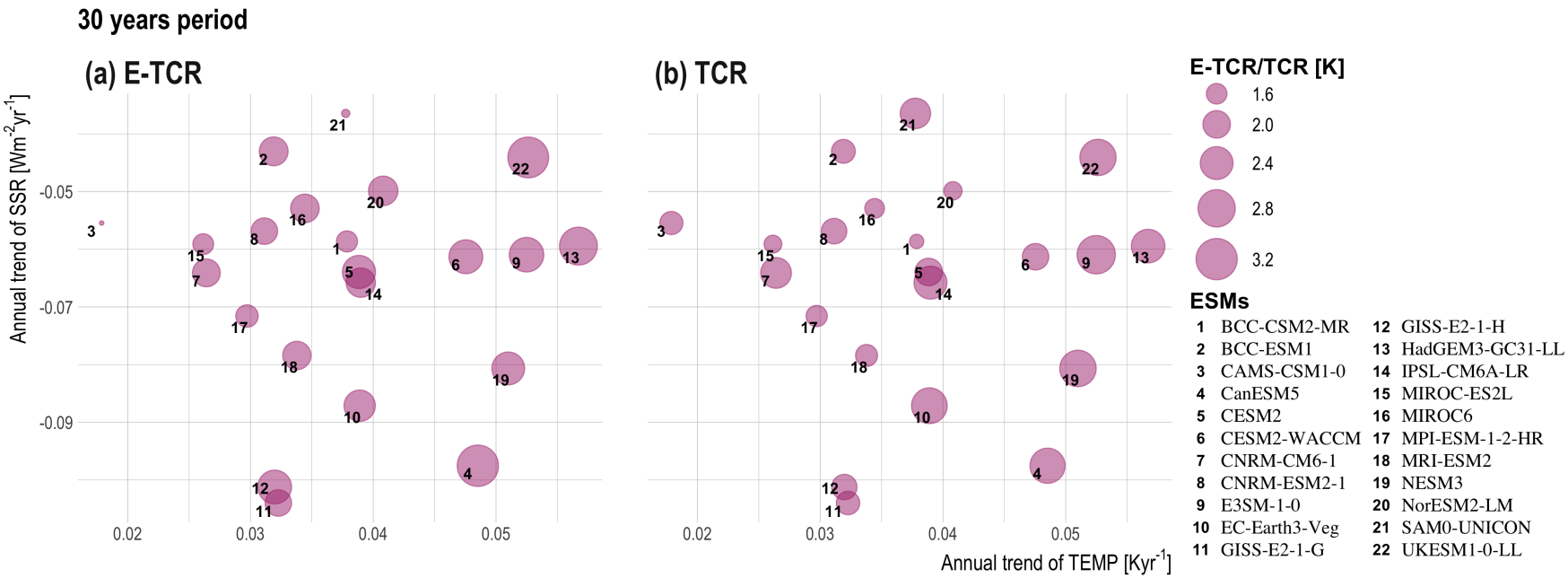


Results–TCR and Climate Trends over Land



- E-TCR and TCR are estimated and reported TCR, respectively.
- SSR trends are for the period 1964–1994; temperature trends are for 1984-2014. Observational trends: SSR $[-0.24 Wm^{-2} yr^{-1}]$, temperature $[0.03^{\circ} C\, yr^{-1}]$.

Results–TCR and Climate Trends over Land



- E-TCR and TCR are estimated and reported TCR, respectively.
- SSR trends are for the period 1964–1994; temperature trends are for 1984-2014. Observational trends: SSR $[-0.24 Wm^{-2} yr^{-1}]$, temperature $[0.03^{\circ} C\, yr^{-1}]$.

Results–Implications on remaining carbon budget

- We calculated the ***remaining carbon budget*** constrained by a 1.5℃ warming target aligned with the Paris agreement goals. Alternative scenarios for the TCR distribution:

Scenario	Distribution	Mean	St. Dev.
Observation	Normal	2.31	0.18
CMIP6 Models	Gamma	2.05	0.45
Sherwood et al. (2020)	Normal	1.85	0.35

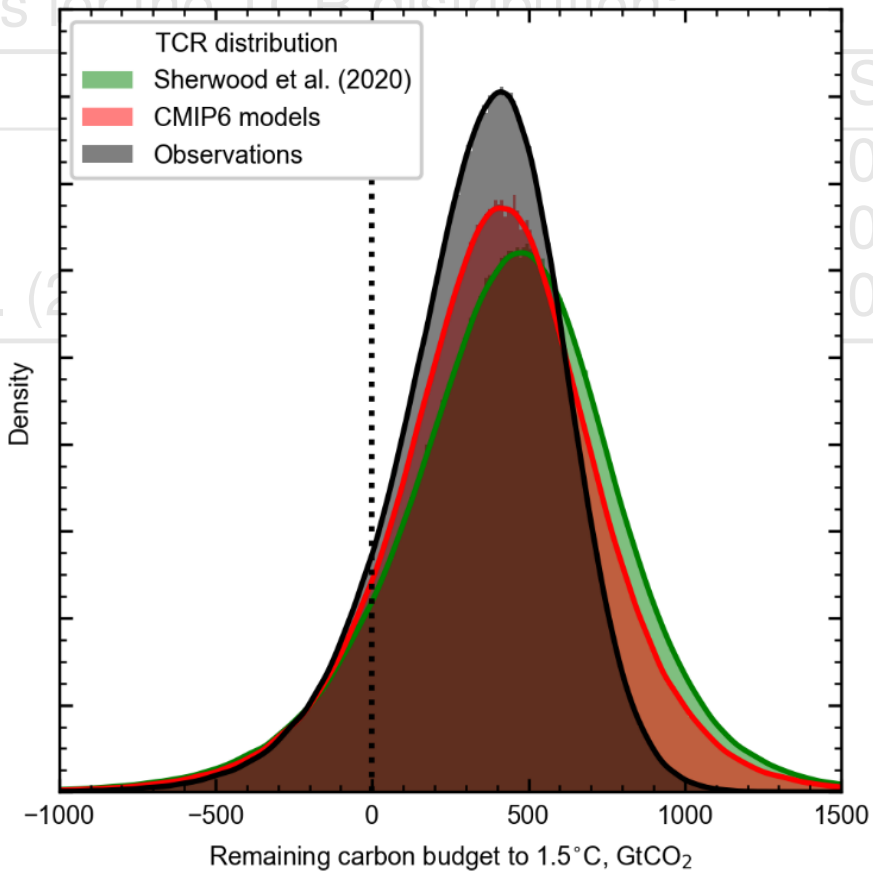
- Remaining carbon budget distribution

Results–Implications on remaining carbon budget

- We calculated the ***remaining carbon budget*** constrained by a 1.5℃ warming target aligned with the Paris agreement goals. Alternative scenarios for the TCR distribution:

Scenario	St. Dev.
Observation	0.18
CMIP6 Models	0.45
Sherwood et al. (2	0.35

- Remaining carbon budget distribution



References I

Nijsse, F. J., Cox, P. M., & Williamson, M. S. (2020). Emergent constraints on transient climate response (TCR) and equilibrium climate sensitivity (ECS) from historical warming in CMIP5 and CMIP6 models. *Earth System Dynamics*, *11*(3), 737–750. https://doi.org/10.5194/ESD-11-737-2020

Phillips, P. C., Leirvik, T., & Storelvmo, T. (2020). Econometric estimates of Earth's transient climate sensitivity. *Journal of Econometrics*, *214*(1), 6–32. https://doi.org/10.1016/j.jeconom.2019.05.002

Sherwood, S. C., Webb, M. J., Annan, J. D., Armour, K. C., Forster, P. M., Hargreaves, J. C., Hegerl, G., Klein, S. A., Marvel, K. D., Rohling, E. J., Watanabe, M., Andrews, T., Braconnot, P., Bretherton, C. S., Foster, G. L., Hausfather, Z., Heydt, A. S., Knutti, R., Mauritsen, T., ... Zelinka, M. D. (2020). An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*, *58*(4), e2019RG000678. https://doi.org/10.1029/2019RG000678

Tokarska, K. B., Stolpe, M. B., Sippel, S., Fischer, E. M., Smith, C. J., Lehner, F., & Knutti, R. (2020). Past warming trend constrains future warming in CMIP6 models. *Science Advances*, *6*(12). https://doi.org/10.1126/sciadv.aaz9549

Yuan, M., Leirvik, T., & Wild, M. (2021). Global trends in downward surface solar radiation from spatial interpolated ground observations during 1961-2019. *Journal of Climate*, *-1*, 1–56. https://doi.org/10.1175/JCLI-D-21-0165.1