Coupled climate models systematically underestimate radiation response to surface warming

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Take home messages

1| Although we know that uncoupled models realistically simulate TOA radiation trends, it remains unknown whether fully coupled climate models (GCMs) realistically simulate the coupling between surface warming and TOA radiation.

2| We show that GCMs systematically underestimate the observed global mean 2001-2020 TOA radiation trend.

3| This underestimation is caused by a too weak local coupling between surface warming and TOA radiation.

4| Coupled models with a less severe underestimation of the TOA radiation response to surface warming have a low equilibrium climate sensitivity (ECS).

5| This common model bias represents a so far unknown uncertainty in climate projections.

Underestimated TOA radiation trend

- A realistic representation of TOA radiation by coupled climate models (GCMs) is key for trust in climate projections, yet, whether TOA radiation is realistically simulated by GCMs is unclear.

- We find that although some ensemble members represent the observed interannual variability (Fig. 1a-h), **99% of 432 ensemble members underestimate the observed 2001-2020 TOA radiation trend** (Fig 1i).

- We further find that GCMs better represent the observed 2001-2020 surface temperature trend (Fig 1j), suggesting that **biases of surface warming alone cannot explain the systematic underestimation of the TOA radiation trend**.

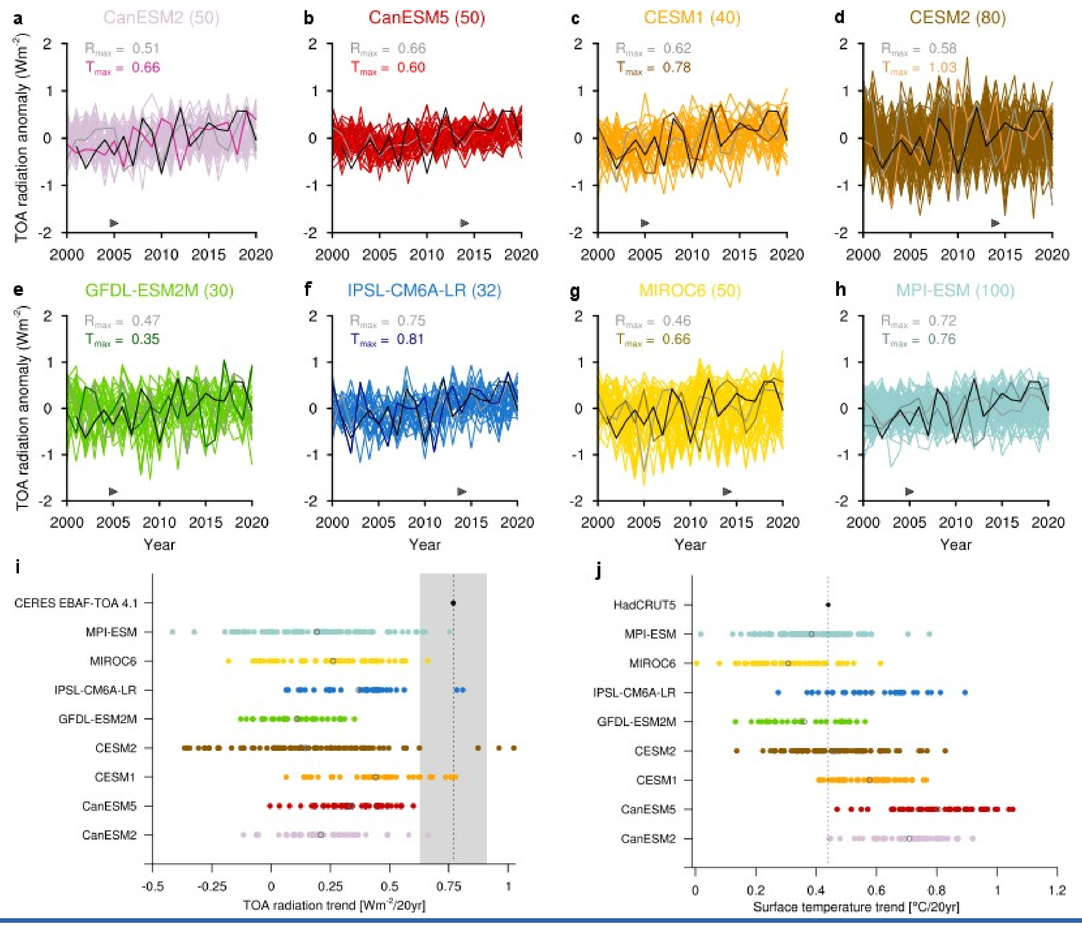
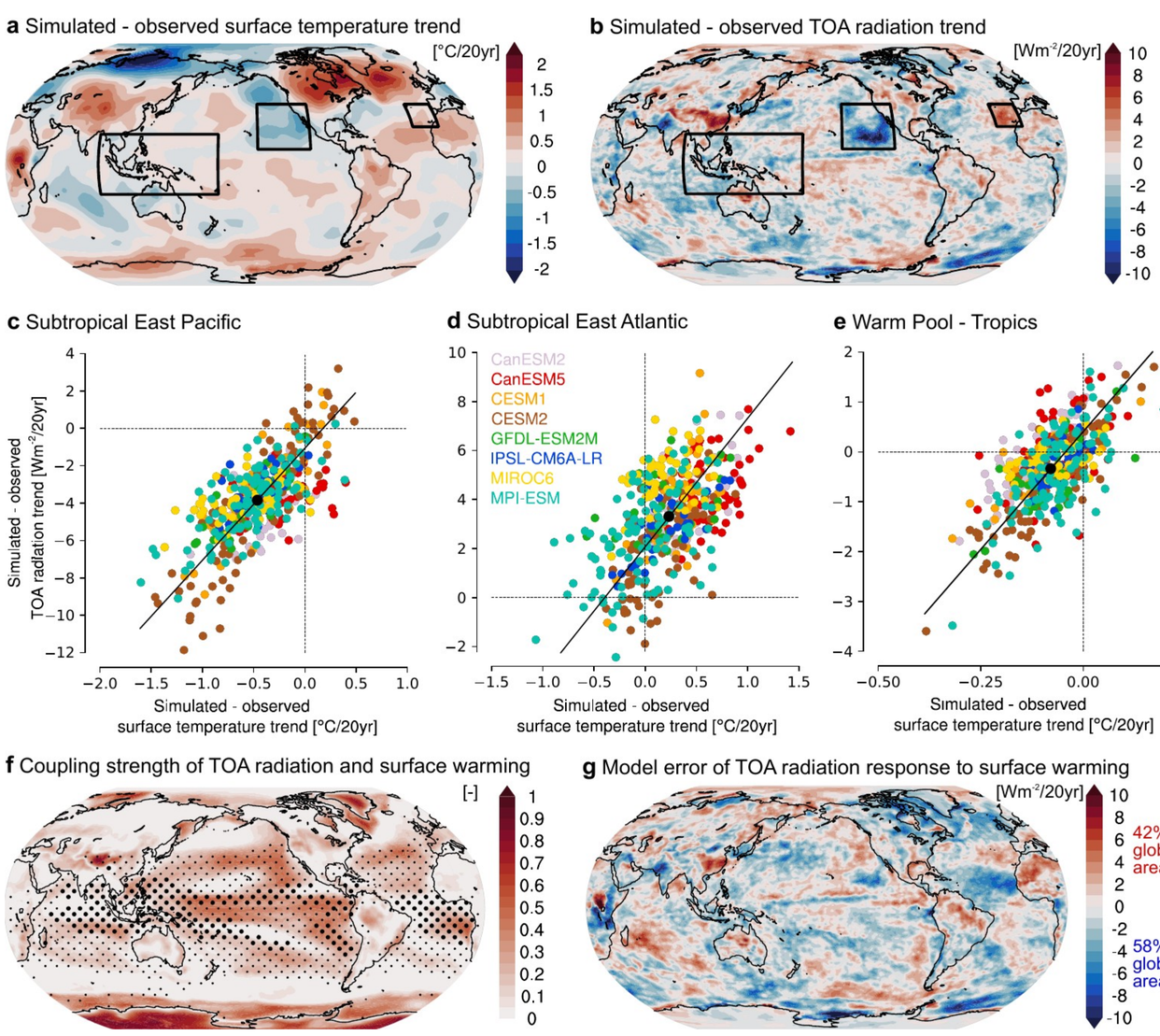


Figure 1: Observed and simulated global-mean radiation anomaly at TOA. a-h CERES observations are shown in black and model simulations in color. The ensemble member with the maximum correlation coefficient to the observations (R_{max}) is depicted in grey and the ensemble member with the maximum 20-year trend (T_{max}) is highlighted in color. The observed 20-year trend is 0.77±0.14 Wm^{-2}. The number of ensemble members is shown in the panel title. The triangle shows where the historical simulations are continued with the scenario simulations. The mean of the entire period is subtracted for observations and GCMs. **i-j** Observed (black) and simulated (colored) 2001-2020 trends in **i** global mean TOA radiation and **j** global mean surface temperature. Each filled dot represents one ensemble member; grey circles represent the ensemble mean. The vertical dashed line and grey shading shows the observed trend and measurement uncertainty.

Too weak TOA radiation response to surface warming



- From comparing Fig. 2a and b, we find that regions with too weakly (strongly) simulated surface temperature trends also underestimate (overestimate) TOA radiation trends, confirming a strong coupling between surface warming and TOA radiation primarily in the tropics and subtropics.

- From regressing the discrepancy in surface temperature trends and TOA radiation trends of all ensemble members averaged for regions of interest (Fig. 2c-e, compare with black boxes in panel a and b), we find that GCMs underestimate or overestimate the observed TOA radiation trend even if they reproduce the observed surface temperature trend (intercept at x=0). This implies a **consistently too weakly simulated response of TOA radiation to surface temperature trends**.

- From interpreting the R^2 and the regression coefficient, we find the strongest local coupling of TOA radiation to surface temperatures over tropical and subtropical oceans (Fig. 2f), suggesting that biases in coupling are most relevant in these regions.

- From plotting the intercept at x=0 (Fig. 2g), we find that the global mean underestimation of the TOA radiation trend is primarily caused by a too weak local coupling between surface warming and TOA radiation in all GCMs considered here, reflected by a **larger region (58% of global area) with an underestimated radiation response to surface warming than with an overestimation (42% of global area**).

- **We conclude that given a simulation replicates the observed surface warming, the observed TOA radiation trend is more often under- than overestimated.**

Figure 2: Relationship between trends in TOA radiation and surface temperature. a-b Discrepancy between each ensemble member and observed 2001-2020 trends in **a** surface temperatureand **b** TOA radiation averaged across all GCMs. The black boxes frame regions of interest used in panel c-e. **c-e** Orthogonal regression across all ensemble members between **a** and **b** averaged for the subtropical East Pacific (210◦W-250◦W, 10◦N-40◦N), the subtropical East Atlantic (330W◦-350◦W, 25◦N-40◦N) and the West-Pacific warm pool (90◦E-180◦W, 20◦N-20◦S) minus the entireTropics (30◦N-30◦S). The individual ensemble members are shown as dots colored for each GCM as shown in the label bar in panel **d**. The multi-model ensemble mean is shown as black filled dot. **f** Pattern of the coupling strength between **a** and **b** measured as the coefficient of determination, r2, of the regression across all ensemble members of the GCMs. Stippling highlights regions where the regression coefficient is >10Wm^{-2}/20yr (bold stippling) or >5Wm^{-2}/20yr (weak stippling). **g** Pattern of the model bias of TOA radiation trends to observed surface temperature trends measured as the y-intercept of the regression line at x = 0. The percentages indicate the global area for which the GCMs overestimate (red) or underestimate (blue) the observed radiation response to surface temperature trends.

Systematic model bias reflects in ECS

- We further find that the global mean underestimation of the TOA radiation response to surface warming (global mean of Fig. 2g) is correlated to the GCMs' effective climate sensitivity (ECS, Fig. 3a).

- This correlation represents a **new line of evidence that low-ECS GCMs more realistically reproduce climate change over the last 20 year** than high-ECS GCMs.

- **Because of the remote impact of surface temperature on the local TOA radiation, our results suggest that simulating the observed surface warming patterns is key for correctly simulating the local and global TOA radiation response to that surface warming.**

- **This systematic bias of GCMs represents a so far unknown uncertainty in short term climate projections**, but also provides a new pathway to deduce longterm global warming from the observed coupling between surface warming and its TOA radiation response.

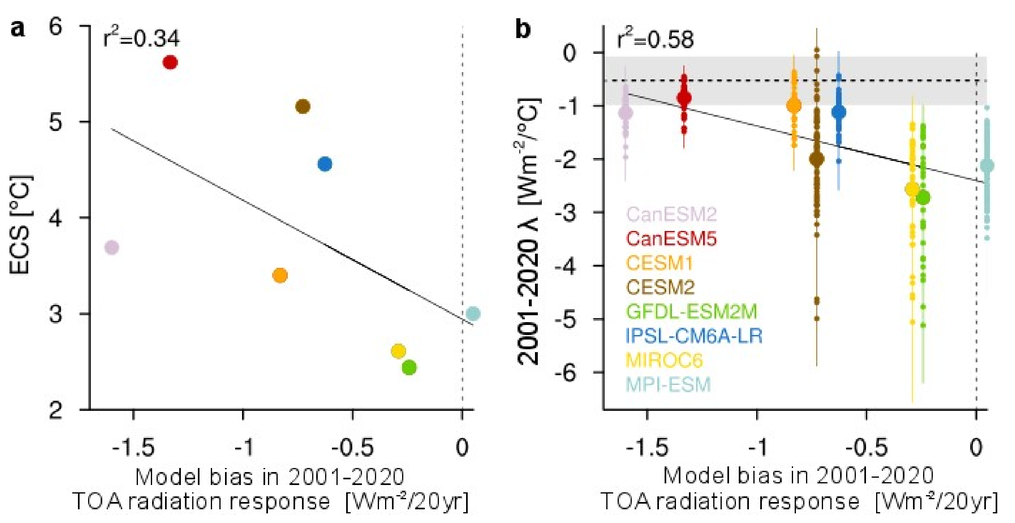


Figure 3: Relationship between the 2001-2020 model bias of the global mean TOA radiation response to observed surface warming and equilibrium climate sensitivity (ECS). a Relationship between the model bias of global mean TOA radiation response to surface warming and ECS. **b** Relationship between the model bias of global mean TOA radiation response to surface warming and the climate feedback parameter λ. Large filled dots represent the ensemble mean and small filled dots each ensemble member for $\lambda = (N-F)/\Delta T$ with F = 1 Wm^{-2}/20yr. The vertical colored lines show the range of λ from varying F between 0.8 and 1.2 Wm^{-2}/20yr. The horizontal dashed line represents the observed λ with F = 1 Wm^{-2}/20yr and the grey area the forcing uncertainty from varying F between 0.8 and 1.2Wm^{-2}/20yr. The vertical dashed lines in **a** and **b** indicate no model bias to the observed global mean TOA radiation response to surface warming.

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