Coupled climate models systematically underestimate radiation response to surface warming

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Take home messages

1I GCMs systematically underestimate the observed global mean TOA radiation trend during 2001-2022.

2I Locally, even if a simulation reproduces observed surface warming, TOA radiation trends are more likely under- than overestimated.

3I Surface warming patterns and atmospheric physics matter for the observation-model discrepancy.

4I Models with a small bias in the coupling between surface warming and TOA radiation trends have a relatively low EffCS.

1. GCMs underestimate the observed TOA radiation trend

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

Although some realizations represent the observed interannual variability (**Fig. 1a-k**), all of **552 realizations** from 11 GCMs **underestimate the observed** 2001-2022 global mean **TOA radiation trend** (**Fig. 1l**).

GCMs better represent the observed surface warming (**Fig. 1m**) than TOA radiation trends, suggesting that **biases of surface warming alone cannot explain the systematic underestimation of the TOA radiation trend**.

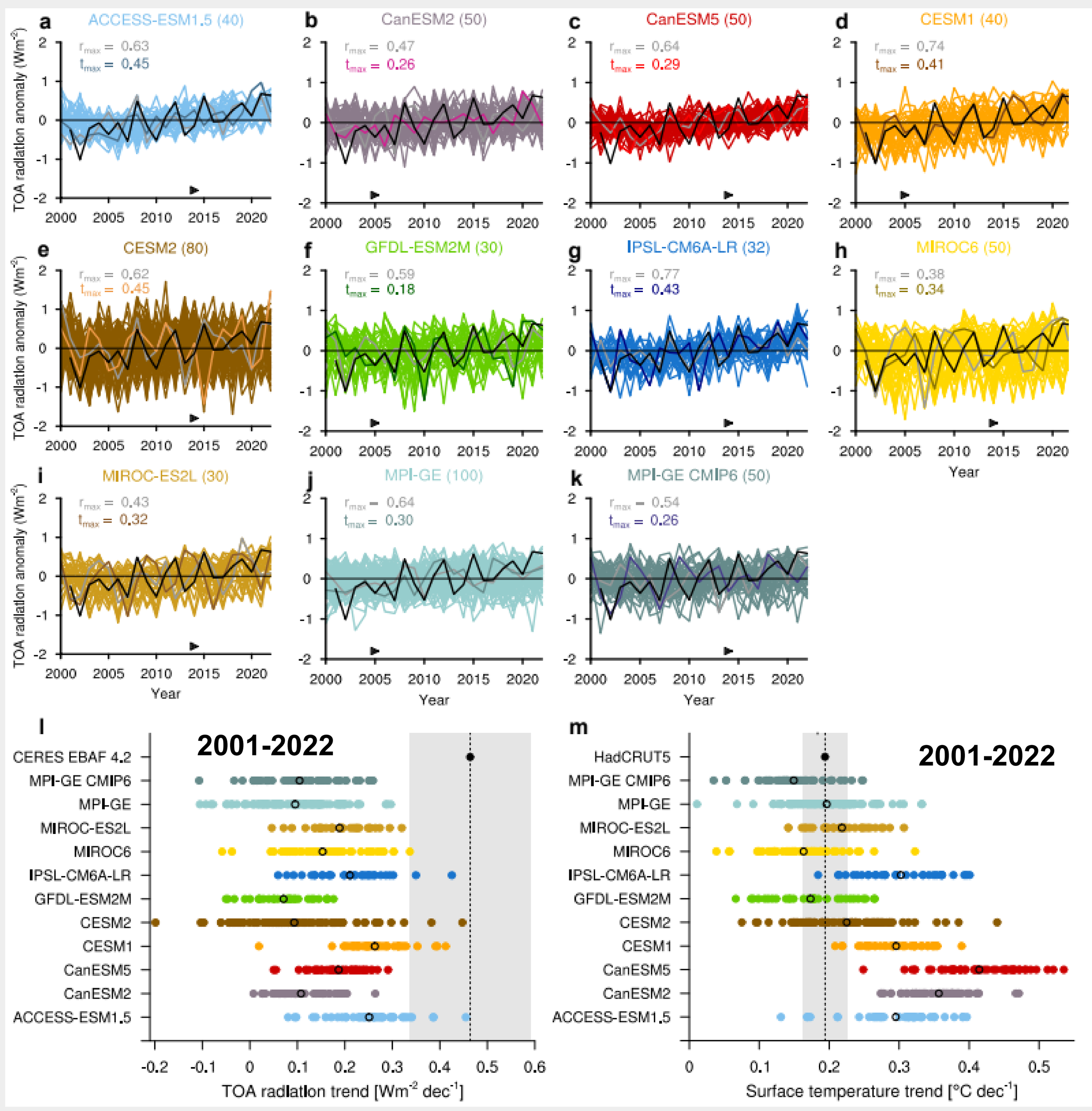


Fig. 1: Observed and simulated global-mean radiation anomaly at TOA. **a-k** CERES observations are shown in black and model simulations in color. Ensemble members with the maximum correlation coefficient to the observations (r_{max}) are gray, and the ones with the maximum 22-year trend (t_{max}) highlighted in color. The mean of the entire period is subtracted for observations and GCMs. **l-m** Observed (black) and simulated (colored) 2001-2022 trends in **i** global mean TOA radiation and **j** global mean surface temperature. Each filled dot represents one ensemble member; gray circles represent the ensemble mean. The vertical dashed line and gray shading shows the observed trend ±2 standard errors of the linear regression.

2. Underestimation caused by too weak local surface-TOA coupling

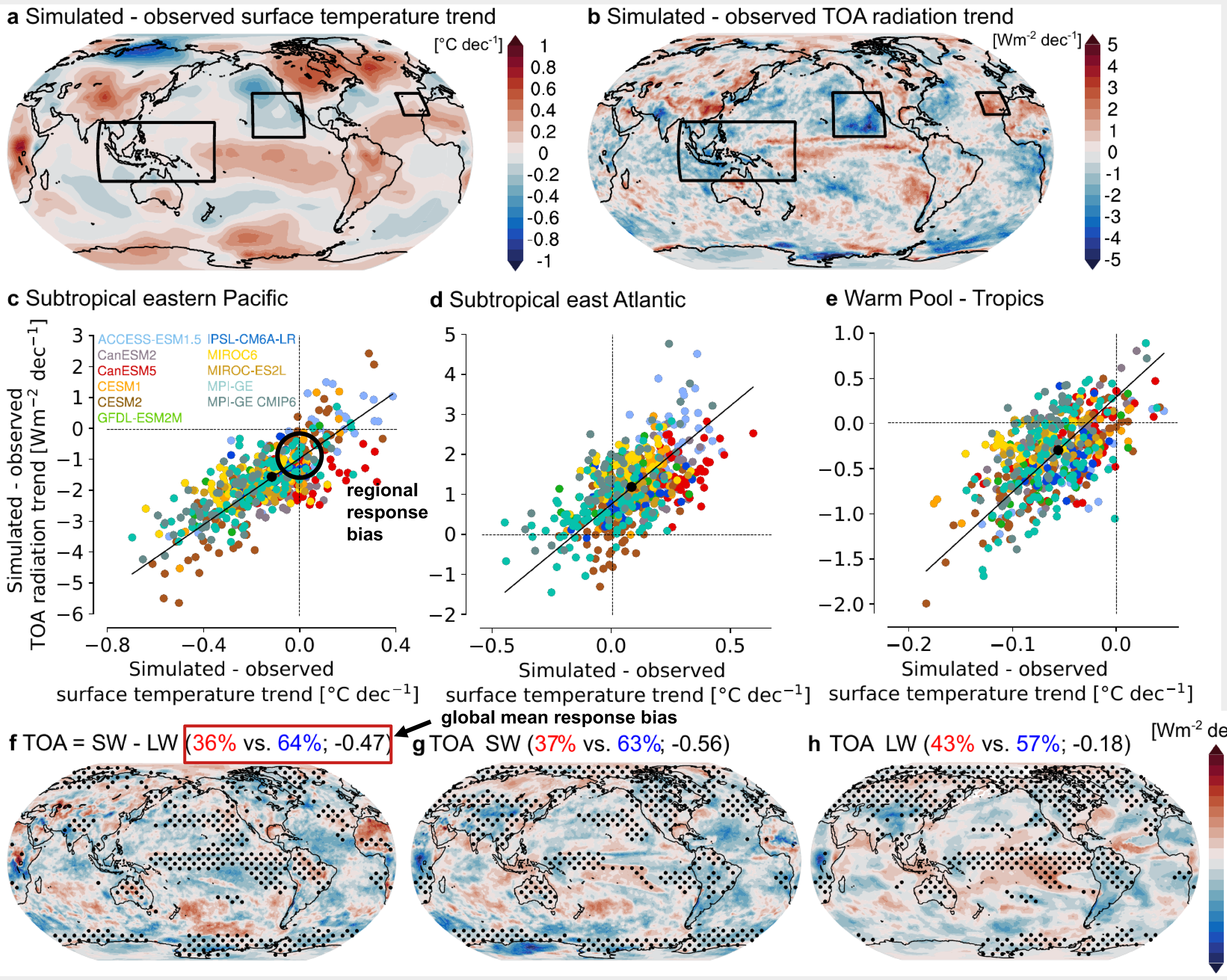


Fig. 2: Relationship between trends in TOA radiation and surface temperature. **a-b** Discrepancy between each ensemble member and observed 2001-2022 trends in **a** surface temperature and **b** TOA radiation averaged across all GCMs. Black boxes frame regions of interest used in panel c-e. **c-e** Orthogonal regression across all ensemble members between **a** and **b** averaged for the named regions. Pattern of the response bias of TOA radiation trends to observed surface temperature trends measured as the y-intercept of the regression line at x = 0 (compare c-e) for TOA **f** net, **g** shortwave and **h** longwave radiation. Stippling highlights regions where r^2 of the regression is >0.25 and the regression coefficient is >1Wm^{-2}/°C. The percentages indicate the global area for which the models over- (red) or underestimate (blue) the observed TOA radiation response, and the number in black shows the magnitude of the global mean response bias.

The congruity of large-scale regions with negative or positive discrepancy in both simulated surface temperature and TOA radiation trends primarily over tropical and mid-latitude oceans suggests a connection between the two (= **local surface-TOA coupling**, **Fig. 2a,b**).

Regressing the discrepancy in surface temperature and TOA radiation trends of all ensemble members averaged for regions of interest [1-4] (**Fig. 2c-e**), shows that GCMs underestimate (**Fig. 2c**) or overestimate (**Fig. 2d**) the observed sensitivity of the local TOA radiation to surface warming (intercept at x=0). The observed trend in TOA radiation is more often under- than overestimated, both in larger areas (64% versus 36% of the global area, **Fig. 2f**) and with stronger magnitude (-0.47 Wm^{-2}/dec^{-1} in the global mean) **= response bias**.

Net, SW, and LW fluxes all show larger areas of negative than positive discrepancy of the simulated TOA radiation for a correct surface warming but with twice as large magnitude in the SW radiation than the LW radiation trends (**Fig. 2g-h**).

3. Causes for the response bias

Possible causes for the too weak local surface-TOA coupling are:

1) the discrepancies in observed and simulated **surface warming patterns** [3-7]

2) **errors in atmospheric physics** that render the TOA response to a correct surface warming wrong [1,8-9]

To separate both effects, we compare the GCM simulations to AMIP simulations (Fig. 3), being limited to the use of five models and the period 2001-2014.

Three out of five AMIP ensembles also underestimate the observed TOA radiation trend, but at a lower magnitude and within observational uncertainty (black dots).

In the model mean, **about one third of the models' error in surface-TOA coupling stems from atmospheric processes alone**. However, we find substantial inter-model differences.

This is in line with recent research showing that radiative feedbacks in AMIP simulations do not match observations substantially better than the ones in GCMs [10,11].

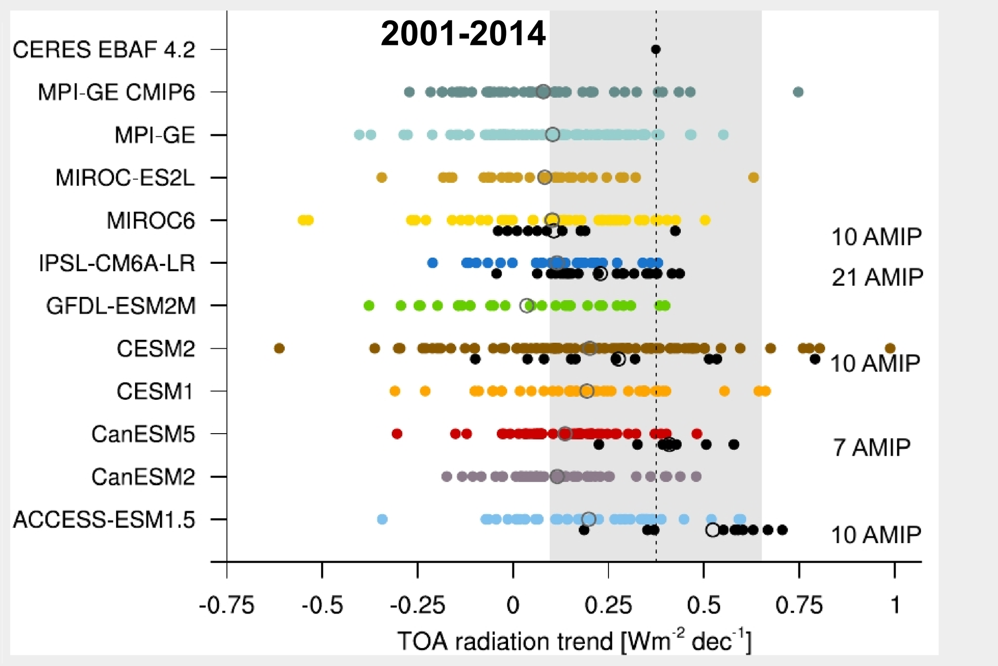


Fig. 3: Comparison of 2001-2014 trends in GCMs and AMIP simulations. Same as Fig. 1l, but for the period 2001-2014, averaged across 60°N-60°S and for additional AMIP simulations from five GCMs. The vertical dashed line and grey shading shows the observed trend ±2 standard errors of the 14-year linear regression.

4. Response bias reflects in EffCS

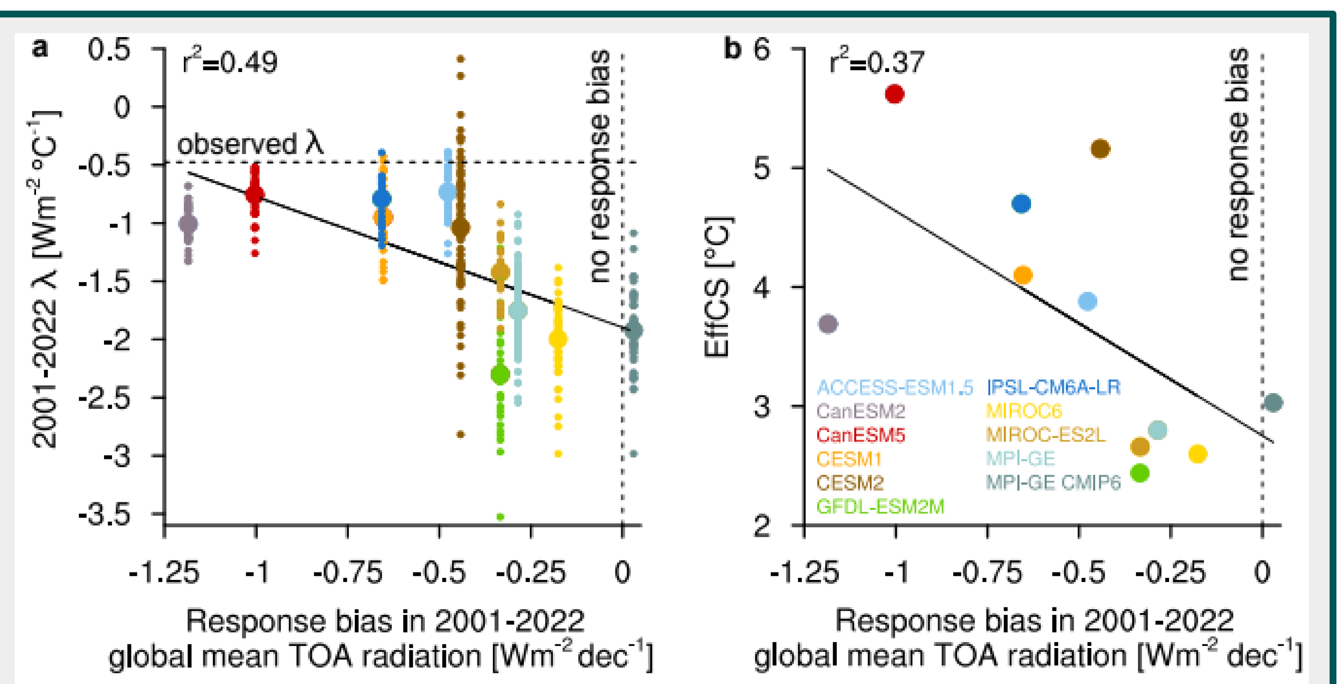
GCMs with a **smaller response bias** (global mean of Fig. 2f) have a **more negative 2001-2022 λ_{eff} (Fig. 4a)** and a **lower EffCS (Fig. 4b)**.

Importantly, ensemble members which reproduce the observed feedback do so combining a wrong TOA radiation trend with a wrong surface warming (compare Fig. 1i,j with Fig. 4a).

The response bias metric is a **new line of evidence that low-EffCS models more realistically reproduce climate change over the last 22 years** than high-EffCS models [12,13].

GCMs with a stronger response bias accumulate too much energy in the atmosphere which reflects in a higher EffCS. These models might have a less realistic pattern of warming leading to wrong magnitudes of ocean heat uptake and radiative feedbacks and/or larger errors in their atmospheric physics reflecting in wrong radiative feedbacks and forcing.

Fig. 4: Relationship between response bias, λ_{eff} and EffCS. **a** Relationship between the 2001-2022 response bias of global mean TOA radiation to surface warming and the simulated ensemble mean and spread of λ_{eff} compared to the observational estimate. λ_{eff} is calculated as anomalies in $\Delta N - \Delta F$ regressed against ΔT for both simulations and observations. **b** Relationship between the 2001-2022 response bias of global mean TOA radiation to surface warming and EffCS. The vertical dashed lines indicate no response bias of the observed global mean TOA radiation to surface warming.



For details see: Olonscheck & Rugenstein (2024), Geophysical Research Letters, in press, doi: 10.1029/2023GL106909

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