Investigating Systematic Errors in Low Cloud Trends in ERA5

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- **ERA5 does not capture the observed increasing global trend in Earth's Energy Imbalance**
- **This is mostly due to low marine clouds**

•CERES Imbalance (EEI) has more than doubled decade-on-satellite data shows Earth's Energy decade in the 21st century (Loeb et al 2024).
•ERA5 largely replicates internal variability but does not capture this trend (Allan and Merchant 2025 , Fig 1a).
•The spatial pattern of the discrepancy in EEI follows errors in ASR over the oceans, while it is absent in the outgoing longwave and in clear sky conditions (Allan and Merchant 2025, Fig 1b-e).
•This is suggestive of a bias in low cloud properties in ERA5.

Aim: identify forcing or model related errors to provide a deeper, mechanistic explanation

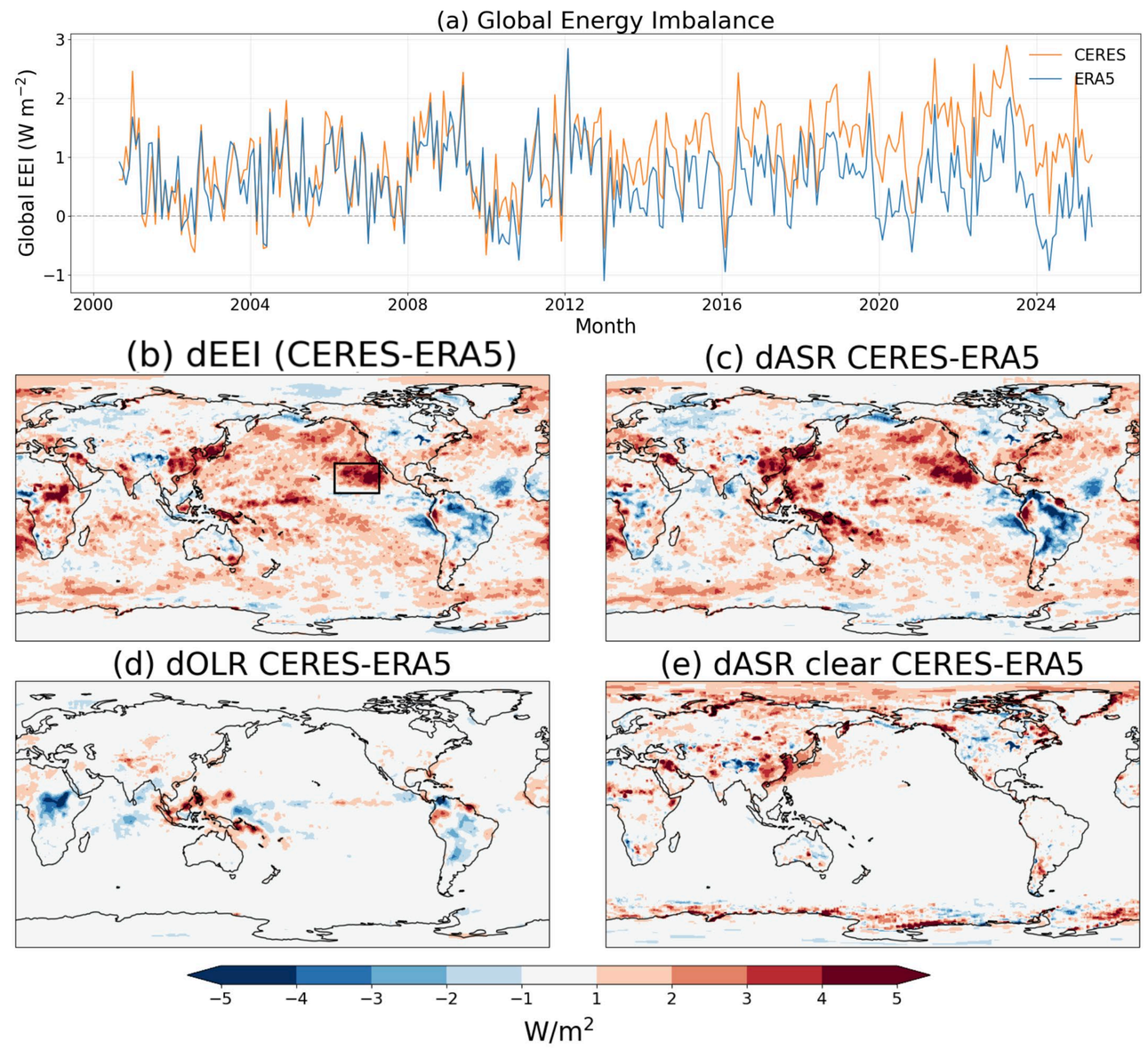

Fig 1 TOA flux trends in CERES and ERA5 respectively. (a) is a time series of globally averaged EEI with seasonal cycle removed. (b – e) show the average of CERES-ERA5 in 2014-2025 minus the average for 2004-2014 for (b) total EEI, (c) ASR, (d), OLR, and (e) ASR assuming clear sky conditions. Figures are reproductions of Figures 1a and 2c-f from Allan and Merchant 2025.

- As a first-step, we investigate the relationship of global stratocumulus clouds to their large-scale meteorological cloud controlling factors as a proxy for process-related model errors.
- We implement the widely used framework on cloud controlling factors (CCF), which models changes in cloud properties such as SW cloud radiative effect (SW CRE) as a first-order Taylor expansion in their meteorological controlling factors, x_i (Eq. 1).

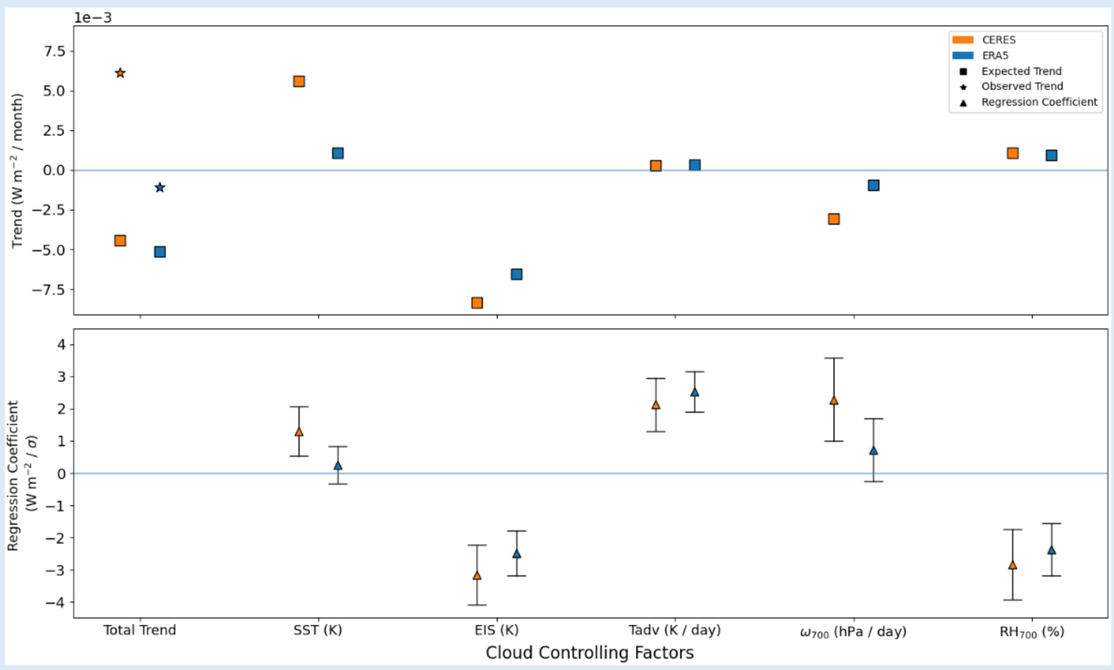

Figure 2 The relationship and trend of SW CRE to cloud controlling factors in global stratocumulus regions. the bottom panel shows the partial derivative in Eq1 estimated by multilinear regression coefficients. The top panel shows the expected trend. Error bars indicate the 95% confidence interval. The time-period is 2000-2025, and the domain is 60ºS to 60 ºN. The factors investigated are sea-surface temperature (SST), estimated inversion strength (EIS), temperature advection across the sea-surface temperature gradient (Tadv), vertical pressure velocity at 700 hPa (ω_{700}) and relative humidity at 700 hPa (RH_{700}).

- SW CRE-CCF relationship is largely well represented in ERA5, hence the correctly simulated internal variability (Fig 2, bottom panel)
- Errors are exacerbated due to changes in meteorology (particularly SST), but these in general compensate for each other (Fig 2, top panel)
- The total trend of SW CRE due to CCFs is largely consistent between CERES and ERA5, both of which are far from the observed SW CRE (orange star), suggesting feedback errors do not explain the trend.

- **Meteorological feedbacks do not explain the EEI trend error in stratocumulus regions**
- **Missing forcing or response to forcing could explain the trend**

Methods

$$\Delta C = \sum_i \frac{\partial C}{\partial x_i} \Delta x_i$$

Eq 1: The cloud-controlling factor framework.

- Multi-linear regression performed of SW CRE against cloud controlling factors to estimate the partial derivative
- Grid-points in dynamical stratocumulus regions were de-seasonalized, detrended and averaged prior to regression
- Change of x_i estimated using linear trend through time

Next Steps

- Aerosol forcing in ERA5 is outdated (it is based on CMIP5 and RCP 4.5)
- The aerosol indirect effect is not accounted for in the radiation scheme.
- Can we use analysis increments to further investigate this problem?

References

Loeb, Norman G., Seung-Hee Ham, Richard P. Allan, Tyler J. Thorsen, Benoit Meyssignac, Seiji Kato, Gregory C. Johnson, and John M. Lyman (Dec. 2024). "Observational Assessment of Changes in Earth's Energy Im-balance Since 2000". In: Surveys in Geophysics 45.6, pp. 1757–1783. ISSN: 0169-3298, 1573-0956. DOI:10.1007/s10712-024-09838-8.
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