Evaluating the representation of tropical stratocumulus and shallow cumulus clouds as well as their radiative effects in CMIP6 models using satellite observations

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Abstract

Figure : A complex stratocumulus—shallow cumulus scenario occurring in a real world.

Low clouds over tropical oceans reflect a great amount of solar radiation back to space and thereby cool the Earth, yet this phenomenon was poorly simulated in several generations of climate models. The principal aim of the present work is to employ satellite observations to evaluate the representation of marine tropical low clouds and their radiative effect at the top of the atmosphere in latest climate models participating in CMIP6. We strive for regime-oriented model validation and hence introduce a proficient method to discriminate stratocumulus (Sc) from shallow cumulus (Cu), because CMIP diagnostics do not distinguish between stratiform and convective clouds. We find that CMIP6 models still underestimate low-cloud cover in both Sc- and Cu-regions of tropical oceans. We further demonstrate that tropical low cloudiness in CMIP6 models remains too bright. A more detailed investigation of cloud biases reveals that in most climate models Cu occurs too frequently relative to Sc. The regime-oriented validation represents the basis for improving parameterizations of physical processes that determine the cloud cover and radiative impact of Sc and Cu, which are still misrepresented in current climate models.

Scientific Background

- Previous generations of climate models commonly underestimated the amount of tropical low-level clouds and overestimated their reflectivity, which is known as the **'too-few, too bright' tropical low-cloud problem** (Nam et al., 2012).
- Research objective: We aim to evaluate the representation of marine tropical low clouds and their radiative effects in newest climate models. We thereby strive to differentiate between individual low-cloud regimes (**Sc**, **Cu**), which provides a proper guidance for climate model development.

Data and Methods

Satellite observations and climate models:

- Cumulus And Stratocumulus CloudSat-CALIPSO Dataset (CASCCAD; Cesana et al., 2019),
- CALIPSO-GOCCP observations of low-cloud cover (LCC),
- CERES observations of SW cloud-radiative effect (CRE),
- Twelve CMIP6 climate models from various modeling centres (AMIP experiments),
- We analyze 8 years of monthly data (Jan 2007—Dec 2014), where CMIP6 simulations overlap with CASCCAD time range.

Methodology to establish low-cloud regimes:

- We restrict our analysis on subsidence regimes over tropical oceans (between 35°S and 35°N), where low clouds are not obscured by mid- and high-level clouds.
- A traditional approach to define low-cloud regimes relies on a fixed threshold of estimated inversion strength (EIS) and generally has limitations when applied to climate models.
- We therefore introduce a novel method to discriminate Sc from Cu utilizing a dynamic LCC threshold (averaged LCC in tropical subsidence oceanic regions in each month).
- Both approaches work well when applied to observational LCC dataset, evaluated against benchmark Sc and Cu components derived from CASCCAD.

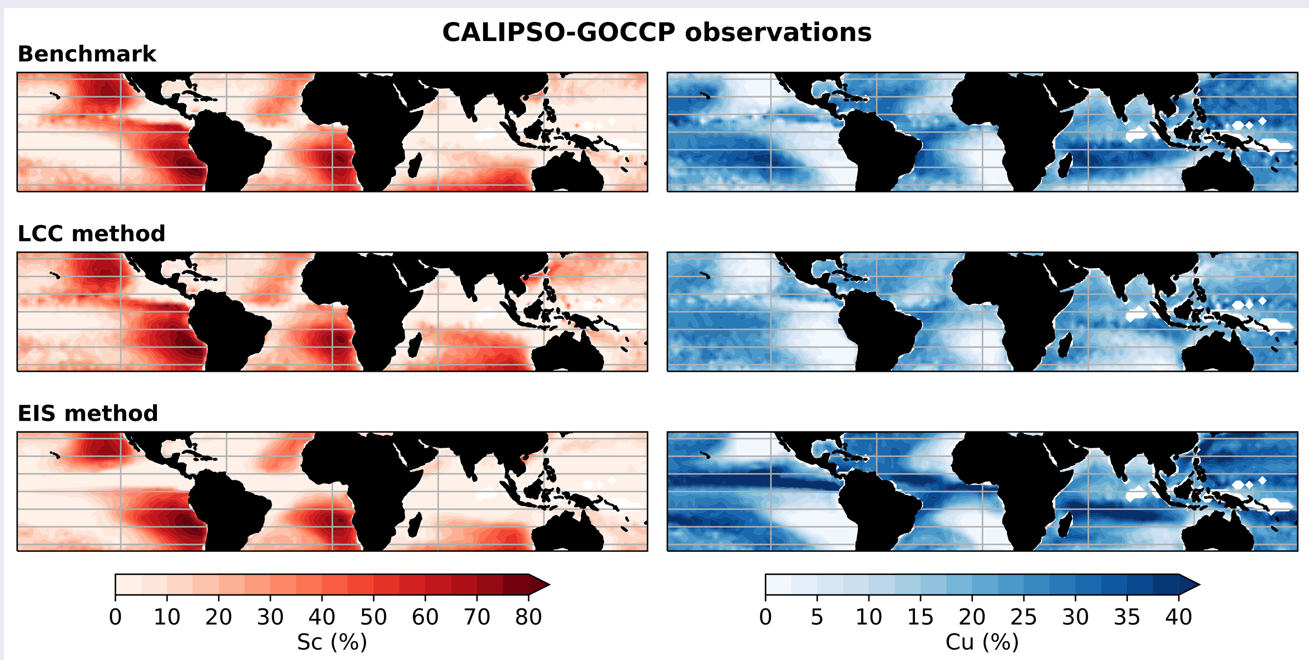

Figure : Evaluation of the two methods using either dynamic LCC or fixed EIS threshold to define low-cloud regimes in observations.

Key Results

- The 'too-few, too bright' tropical low-cloud problem persists in CMIP6 models within Sc and Cu regimes

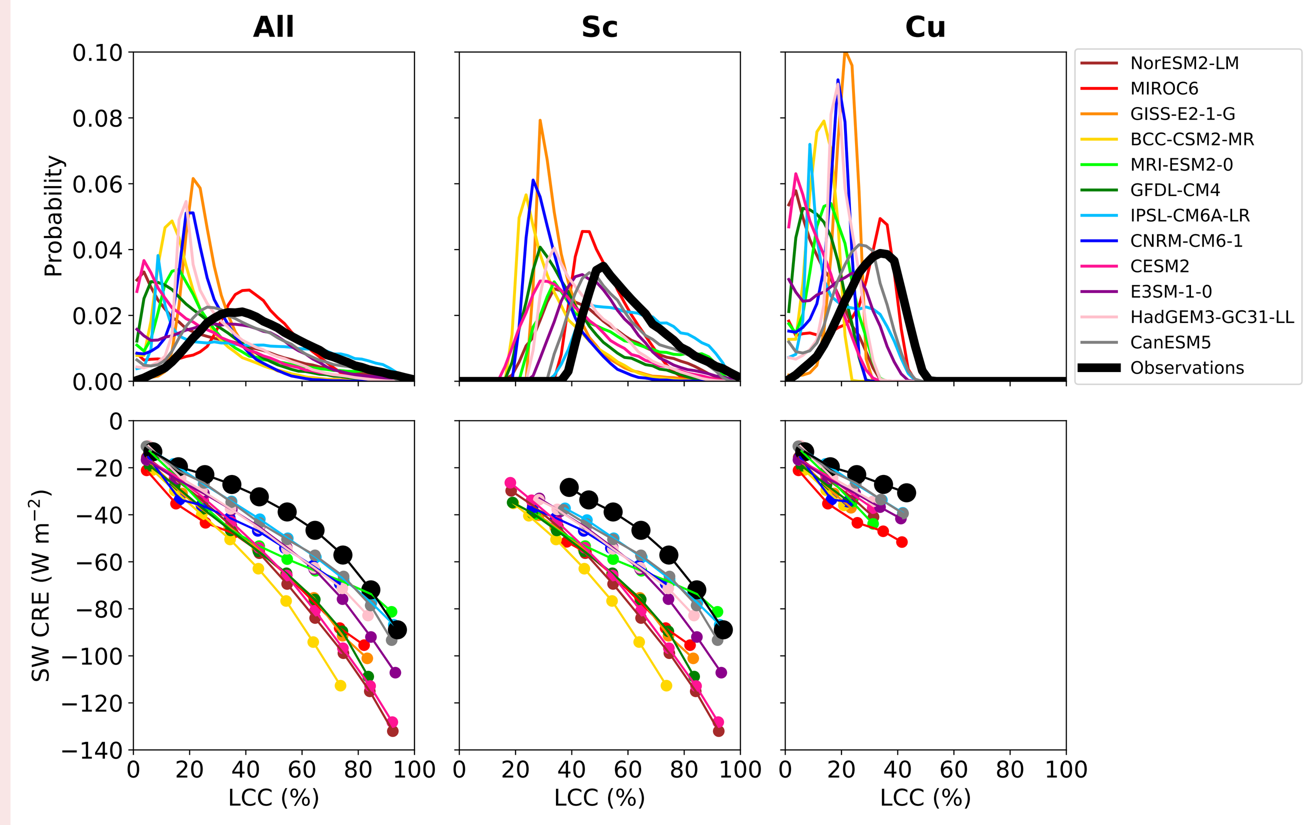

Figure : Probability density of LCC (top) and the relationship between LCC and SW CRE (bottom). Subsidence areas of tropical oceans are decomposed into Sc and Cu regimes using the novel method based on dynamic LCC threshold.

- We find further contrasting results for Sc and Cu regimes when evaluating spatial patterns of LCC and SW CRE

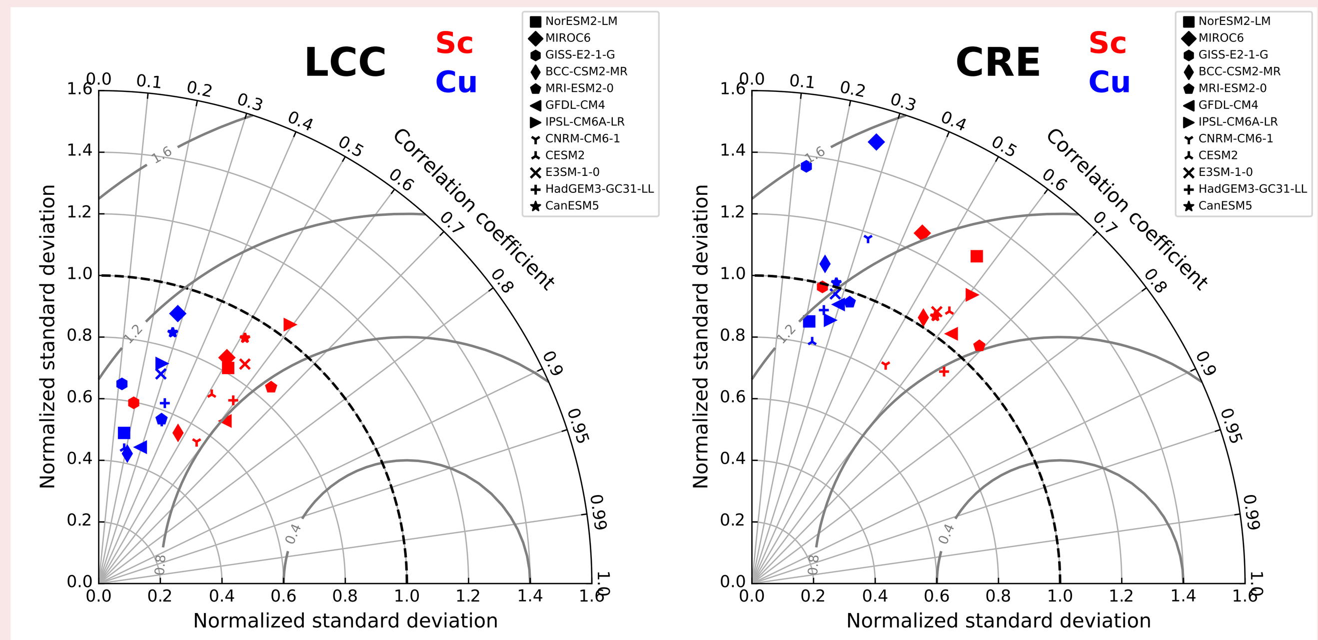

Figure : Taylor diagrams evaluating Sc and Cu components of simulated LCC and SW CRE.

- Climate models mostly underestimate $\overline{LCC}$; and underestimate RFO of Sc, whereas they overestimate RFO of Cu

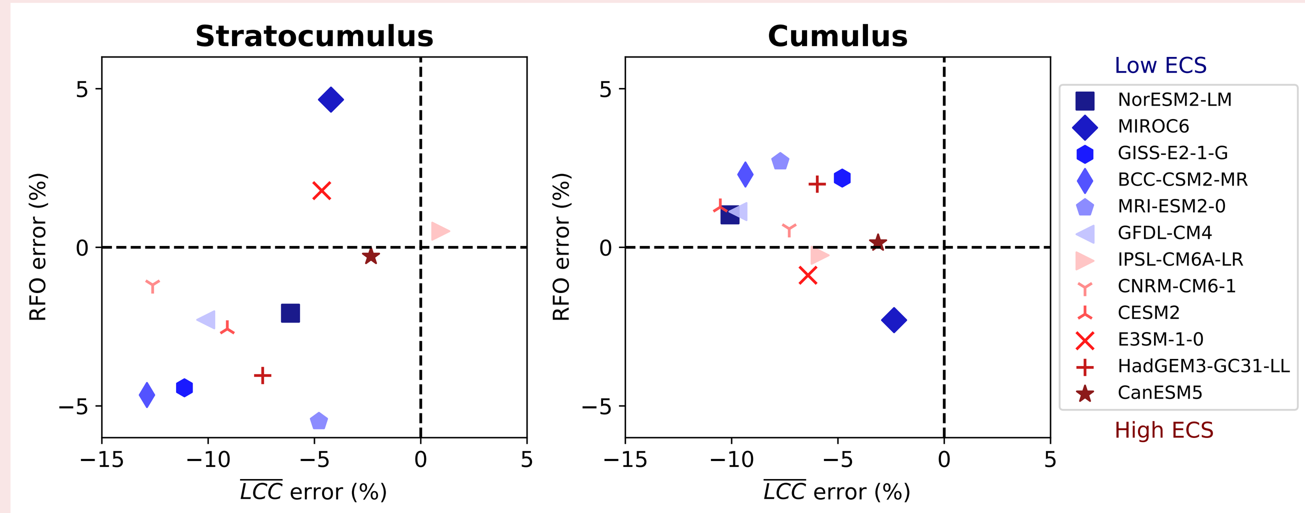

Figure : Classic error decomposition into mean LCC ($\overline{LCC}$) error versus relative frequency of occurrence (RFO) error within Sc and Cu regime. The small error covariance term is not displayed.

Comparison with traditional Sc-Cu discrimination

- The two methods to discriminate Sc from Cu based on LCC and EIS generally yield different results in climate models

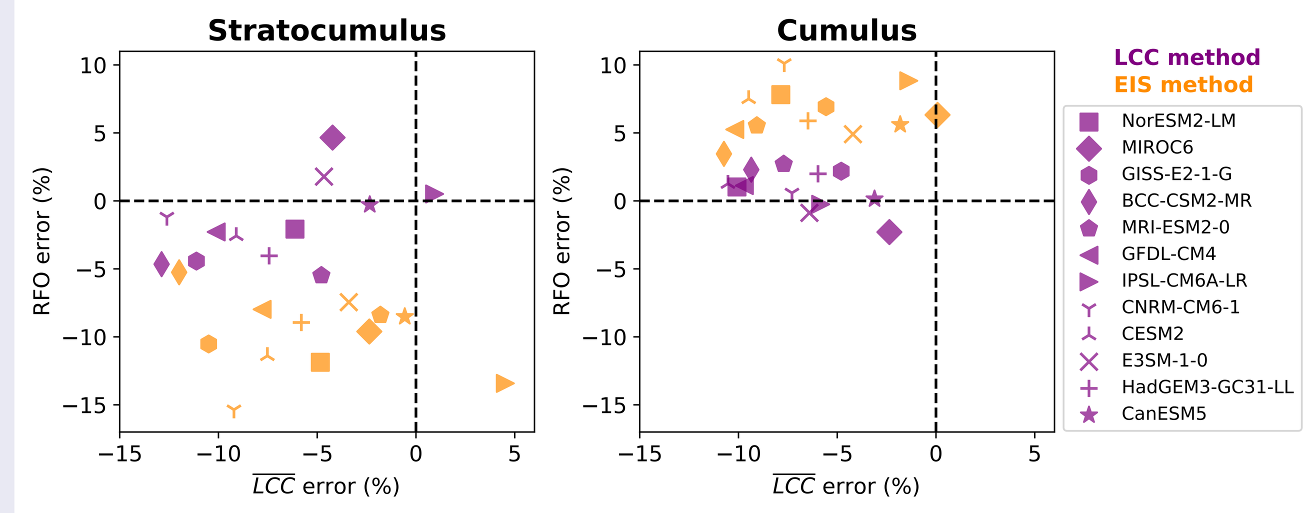

Figure : Classic error decomposition into $\overline{LCC}$ error versus RFO error. The two approaches using either dynamic LCC or fixed EIS threshold to establish Sc and Cu regimes are compared.

- The approach based on EIS allocates an insufficient amount of LCC to Sc and an excessive amount of LCC to Cu in models

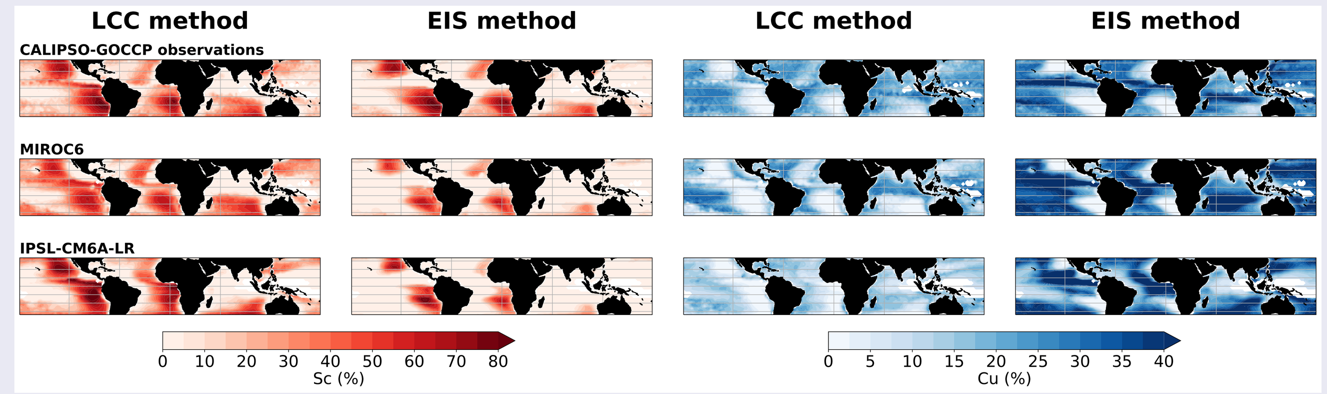

Figure : Highlighting the disparity between the outcome of the two Sc-Cu discrimination methods in problematic MIROC6 and IPSL-CM6A-LR models.

- Climate models underestimate EIS and generally do not match the relationship between EIS and LCC implied by obs/reanalysis

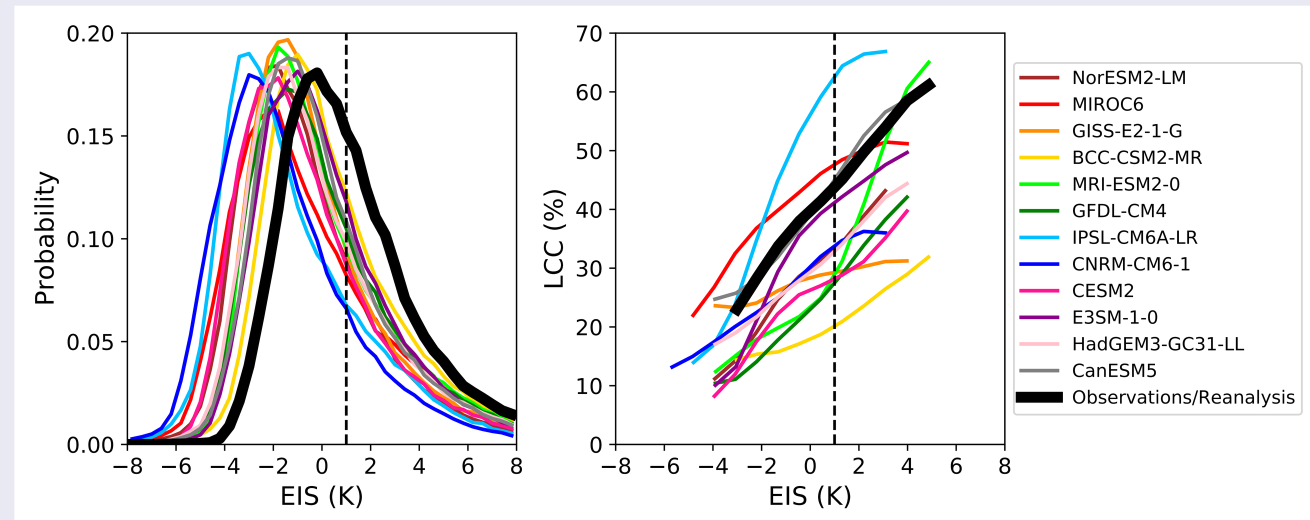

Figure : Probability density of EIS (left) and the relationship between EIS and LCC (right). The dashed line at EIS of 1 K marks a common threshold to discriminate Sc from Cu.

Conclusions

- The 'too-few, too bright' tropical low-cloud problem persists in twelve CMIP6 models within Sc and Cu regimes, which is in further support of a recent study by Konsta et al. (2022).
- The newly proposed method to discriminate Sc from Cu based on cloud properties is more reliable than the traditional approach based on environmental low-level inversion strength.
- We find no relationship between low-cloud biases in the present-day climate and equilibrium climate sensitivity (ECS).

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