



Supplement of

The role of the QBO for tropical high-cloud variability in CMIP6 models and observations

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Sect. S1: TTL cloud sensitivity to T_{UT}

Figure S1a, b shows the TTL cloud sensitivity to T_{UT} for a sample grid box in observations and the CMIP6 MMM. In observations, T_{UT} exhibits negative sensitivities in the deep tropics and positive sensitivities at subtropical latitudes. Spatially aggregating these opposing sensitivities results in the patchy sensitivity structure seen in Fig. S11. This spatial structure in sensitivity could be a result of the meridional structure of the temperature field. For example, the QBO-related T_{UT} anomalies are warmer in the deep tropics while relatively colder outside, a meridional structure that can be expected from QBO-induced meridional circulation. Observed T_{UT} sensitivities in the equatorial Indian Ocean (Fig. S1a) indicate that the warmer temperature in the deep tropics and colder temperature outside the deep tropics will lead to a reduction in the cloud fraction in the equatorial grid box shown.

In contrast, the CMIP6 MMM (Fig. S1b) exhibits positive T_{UT} sensitivities in the deep tropics, indicating an increase in cloud fraction with warming. Thus, the discrepancy between observations and the MMM, as expected from Fig. 3p, primarily stems from the biased sensitivity values in the models.

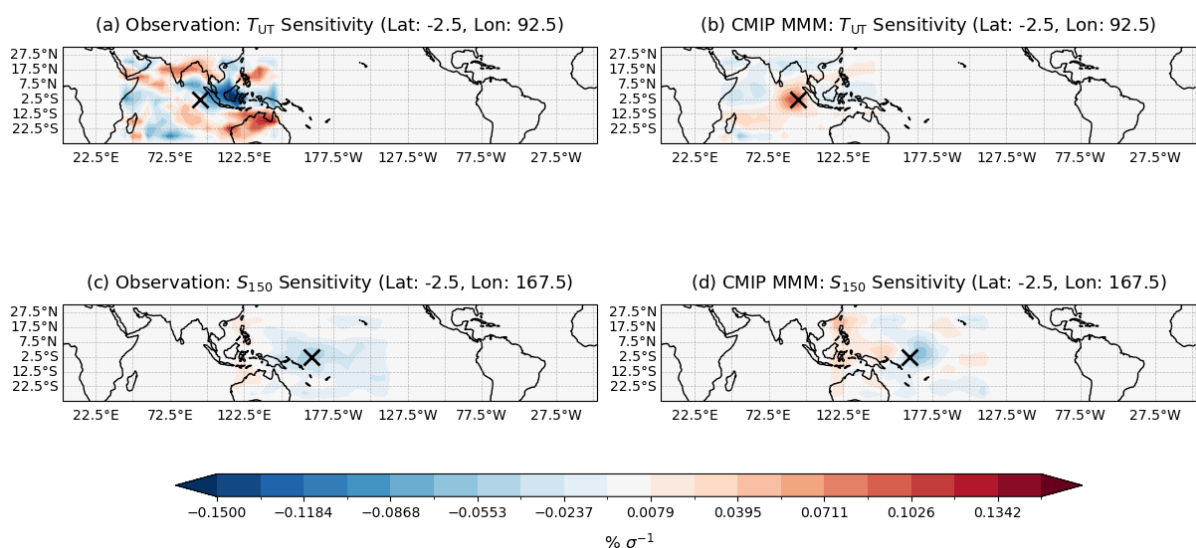


Figure S1: Historically-derived sensitivities of the TTL cloud fraction to upper tropospheric temperature (T_{UT}) and static stability at 150 hPa (S_{150}) in CALIPSO observations (a, c) and the CMIP6 MMM (b, d) for a sample grid box.

Sect. S2: Seasonality of the QBO-TTL cloud relationship

Similar to Sweeney et al. (2023), the seasonality of QBO influence on high clouds is explored (Fig. S2). As in the annual-mean response, the seasonal signals are also dominated by the Indian Ocean and western Pacific regions. Consistent with their findings, CALIPSO observations show that the TTL clouds (around 14-17 km) decrease most in the Indian Ocean region in boreal spring in response to QBO changes, whereas stronger responses are found over the western Pacific during boreal winter (see Fig. S2 and Sweeney et al. (2023) figure 4). The MMM captures some aspects of these observed patterns, but exhibits substantial inter-model differences, and the regression coefficients are approximately an order of magnitude weaker than observed. A notable bias is that the MMM captures a strong response over the Indian Ocean during boreal summer, but fails to reproduce the strong spring response. While the seasonal dependence of the QBO–cloud relationship warrants further investigation, we focus here on the total response.

Consistent with the findings of Sweeney et al. (2023), our analysis also indicated a strong QBO-TTL cloud relation during boreal spring over the Indian Ocean. However, the CMIP6 MMM suggests that models do not accurately capture the seasonal relationship and the QBO-TTL cloud relationship is strong over the Indian Ocean during boreal summer in the models.

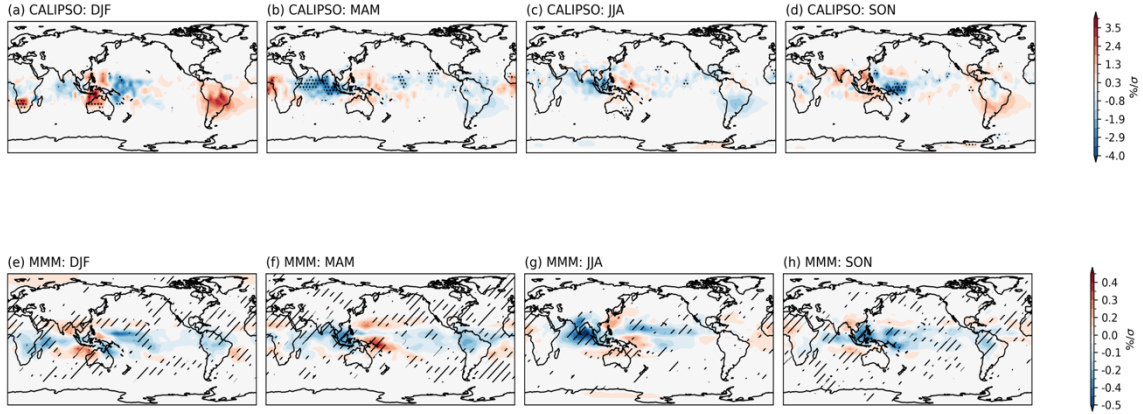


Figure S2: QBO regressed TTL cloud fraction from CALIPSO (a-d) and MMM (e-h) for DJF, MAM, JJA and SON respectively. Stippling in (a-d) denotes 90% confidence, and hatching in (e-h) denotes 6 out of 7 models having the same sign.

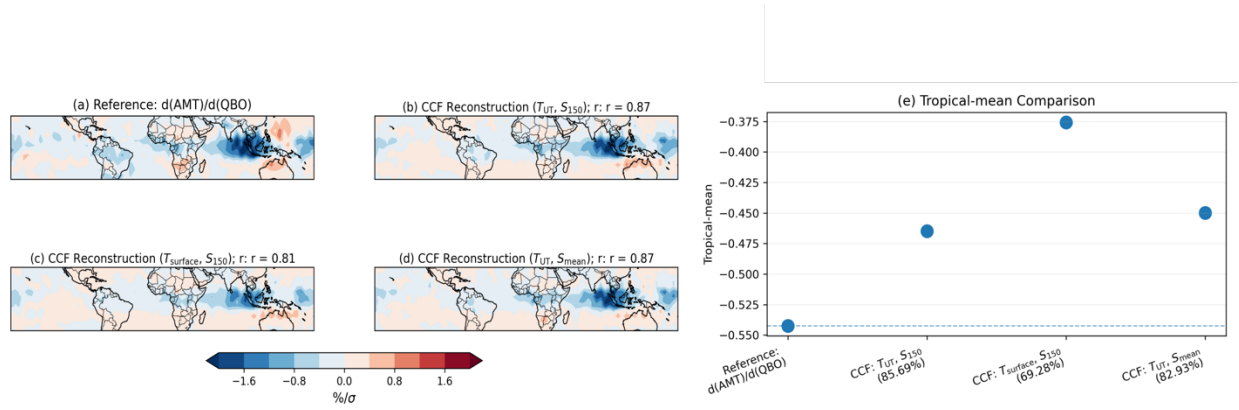


Figure S3: (a; same as Fig. 2c) QBO-regressed TTL cloud fraction and (b; same as Fig. 3a) its reconstruction using the CCF set described in the study, (c) the CCF set used in the study but with T_{UT} replaced by $T_{surface}$, and (d) the CCF set used in the study but with S_{150} replaced by S_{mean} . (e) Tropical-mean QBO-regressed TTL cloud fraction and its reconstructions. The values (%) in parentheses next to the reconstruction labels indicate the relative amplitudes of the tropical mean reconstruction compared to reference.

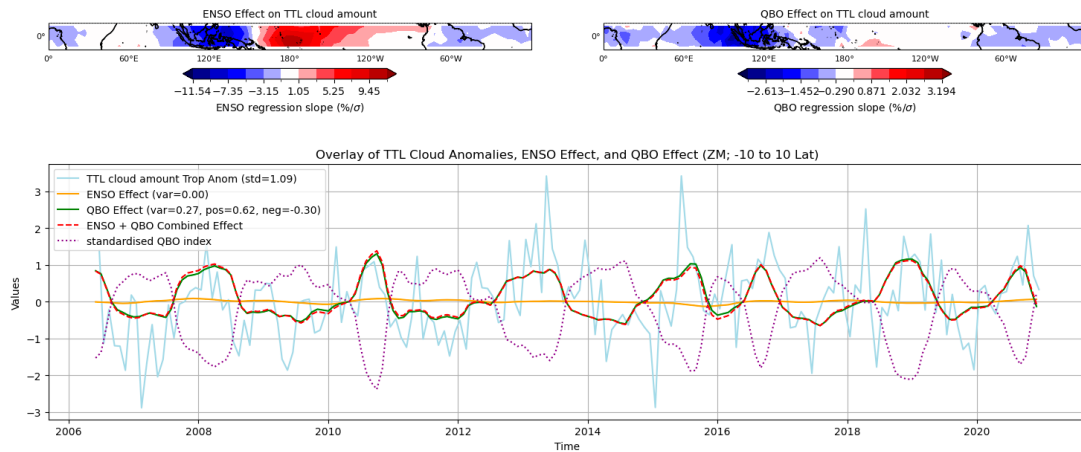


Figure S4: Tropical TTL cloud amount anomalies over time. ENSO and QBO contributions are shown as yellow and green lines respectively.

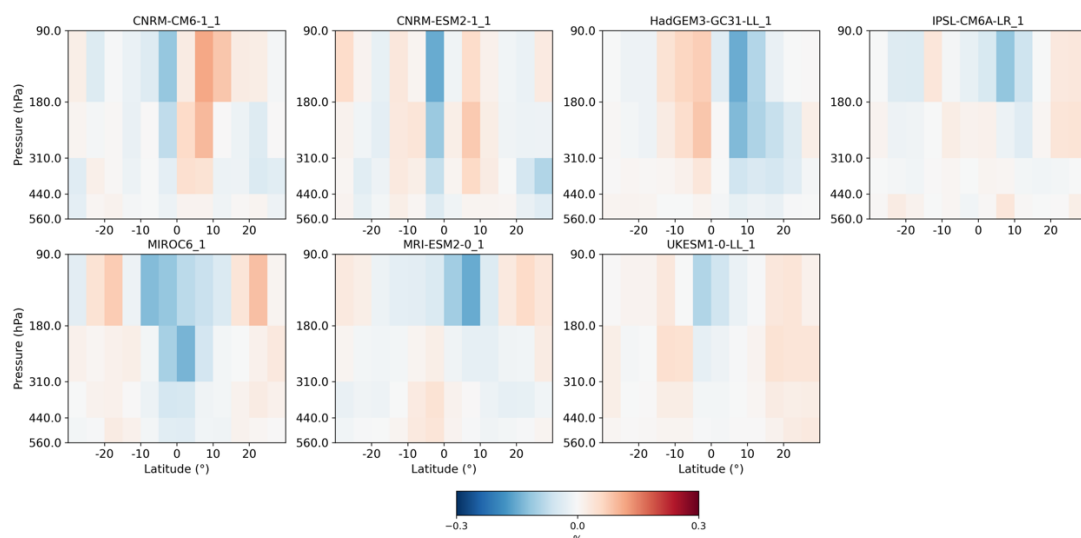


Figure S5: Same as figure 1i but for individual models.

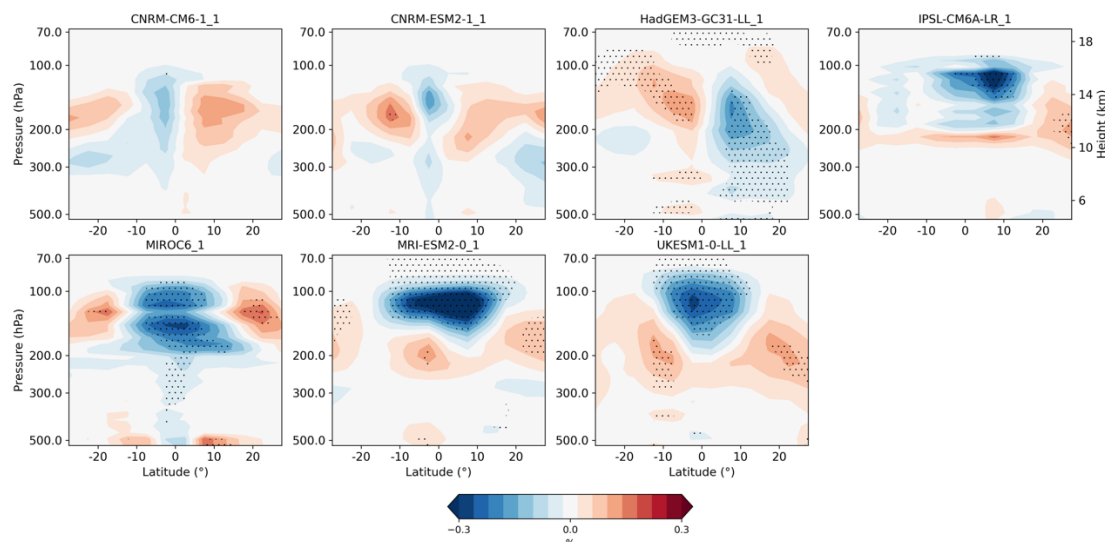


Figure S6: Same as figure 1j but for individual models. Stippling denotes statistically significant results (95% confidence).

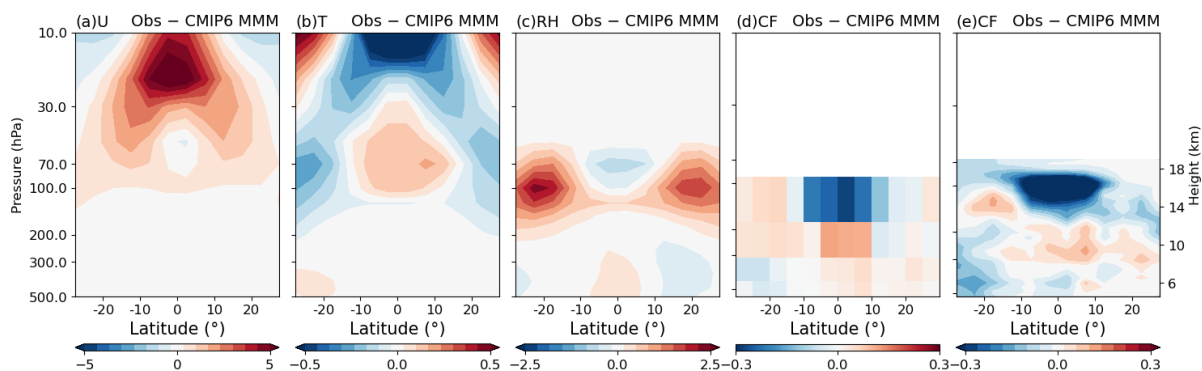


Fig. S7: Difference plot between observations and CMIP6 MMM for the variables shown in Fig. 1.

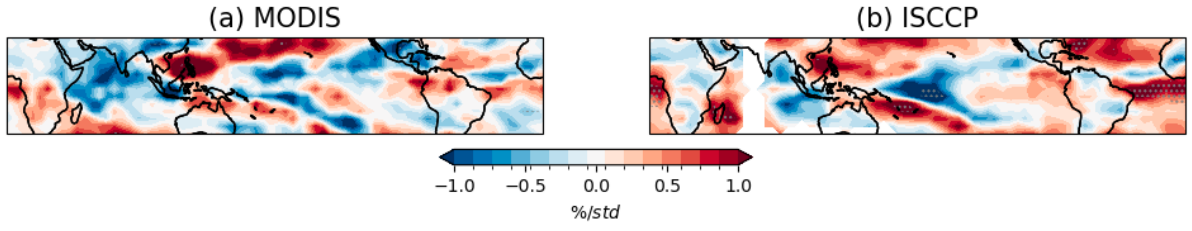


Figure S8: QBO regressed high-cloud fraction (<440hPa) from (a) MODIS and (b) ISCCP

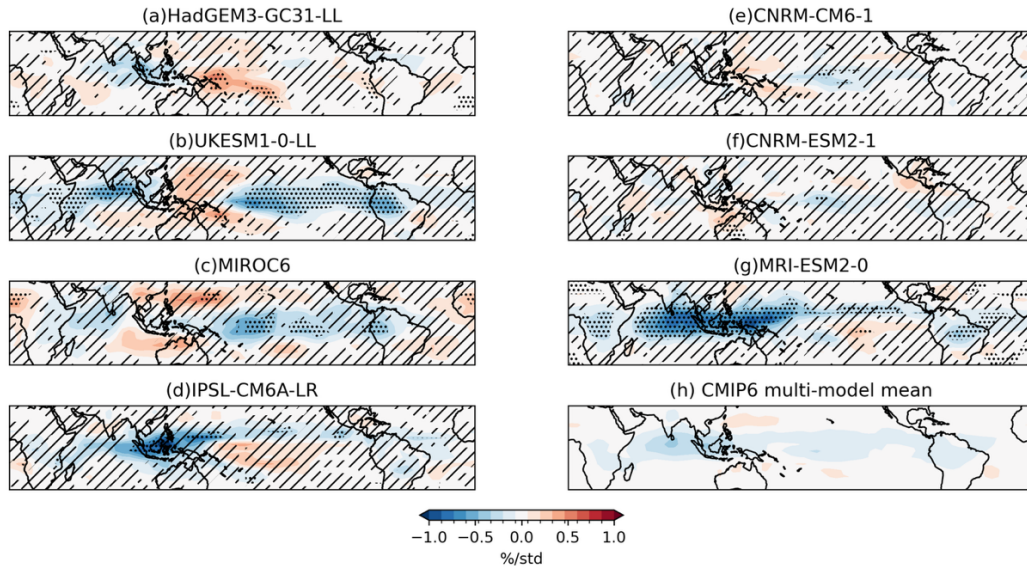


Figure S9: Same as Fig. 2d but for individual models. Hatching denotes regions where QBO regressions over eight consecutive 20-year segments did not agree in sign in 6 out of 8 (75%) segments.

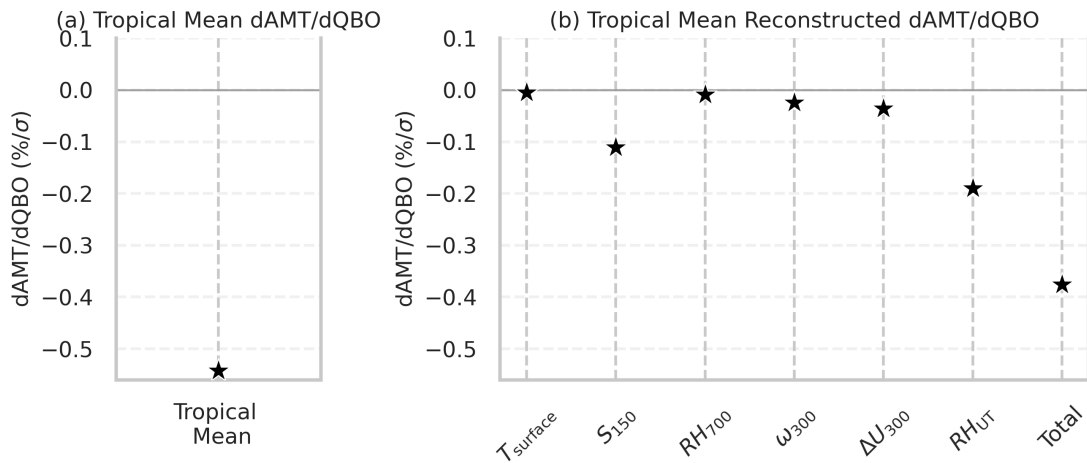


Figure S10: (a) Tropical mean (10S–10N) QBO-regressed TTL cloud fraction anomaly in observations. (b) Individual CCF contributions to the observed tropical-mean QBO-induced TTL cloud response and the total.

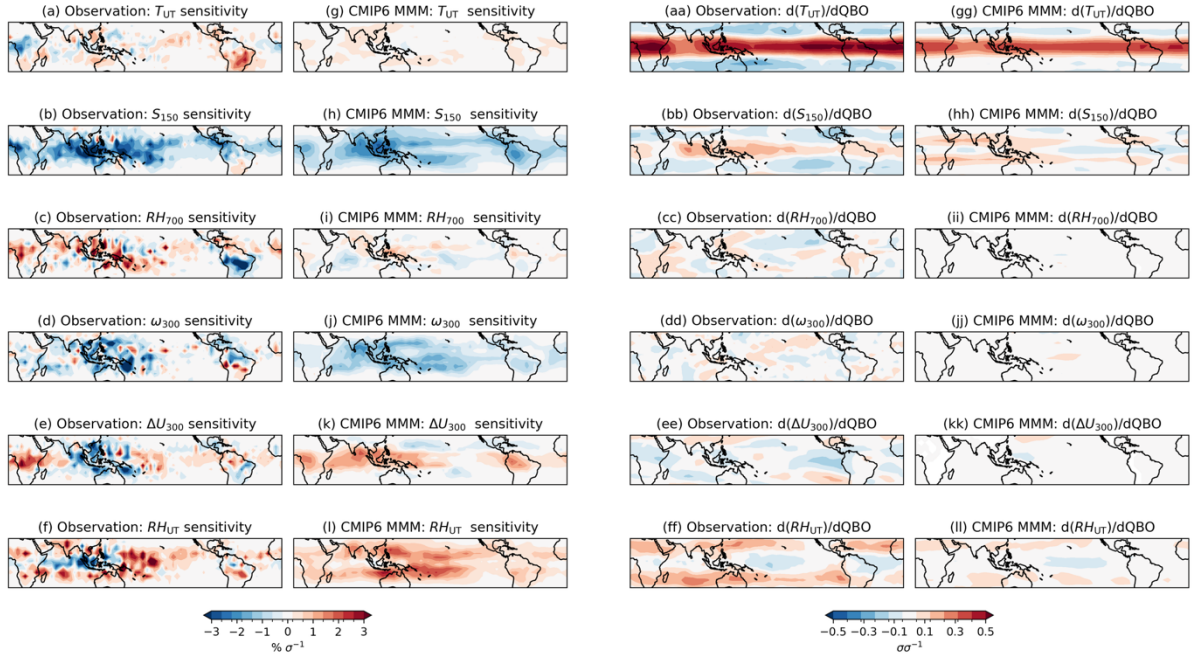


Figure S11: Similar to Fig. 4, but for all CCFs. Historically-derived sensitivities of the TTL cloud fraction to CCFs in observations (a-f) and CMIP6 MMM (g-l). QBO-regressed CCFs, in units of standard deviation of CCF per standard deviation of QBO, in observations (aa-ff) and CMIP6 MMM (gg-ll).

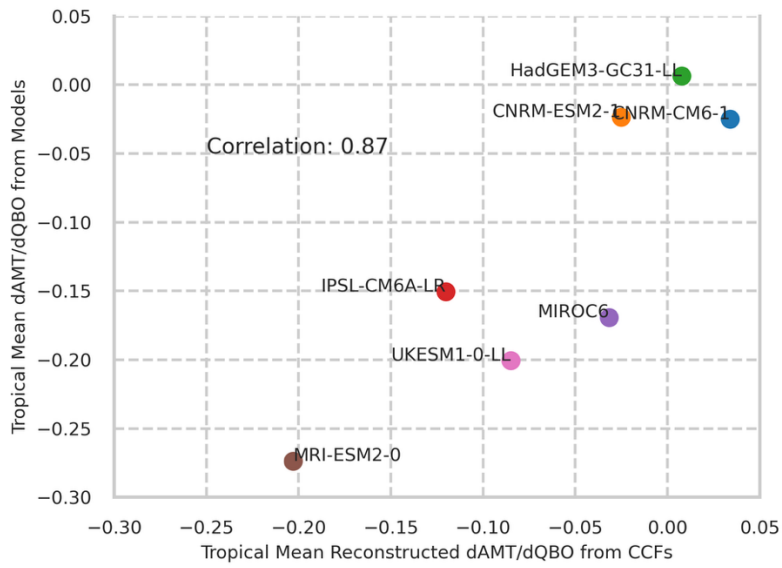


Figure S12: correlation between QBO-regressed TTL cloud fraction and its corresponding CCF-based reconstruction across CMIP6 models.