

Introduction

The **quasi-biennial oscillation (QBO)** is a major mode of tropical stratospheric variability, characterised by alternating easterly and westerly winds with a period of ~28 months. The QBO influences the tropical troposphere, altering temperature, stability and humidity, with consequences for high clouds (Fig. 1.).

Observations show that the **QBO modulates high clouds**, with enhanced high-cloud cover during the easterly phase (Sweeney et al., 2023). However, the **meteorological controls underlying this response** and their representation in climate models remain uncertain. We investigate the QBO–cloud relationship using **satellite observations and climate models**, focusing on the key factors controlling high-cloud variability.

Fig. 1. QBO impacts on tropical upper atmosphere

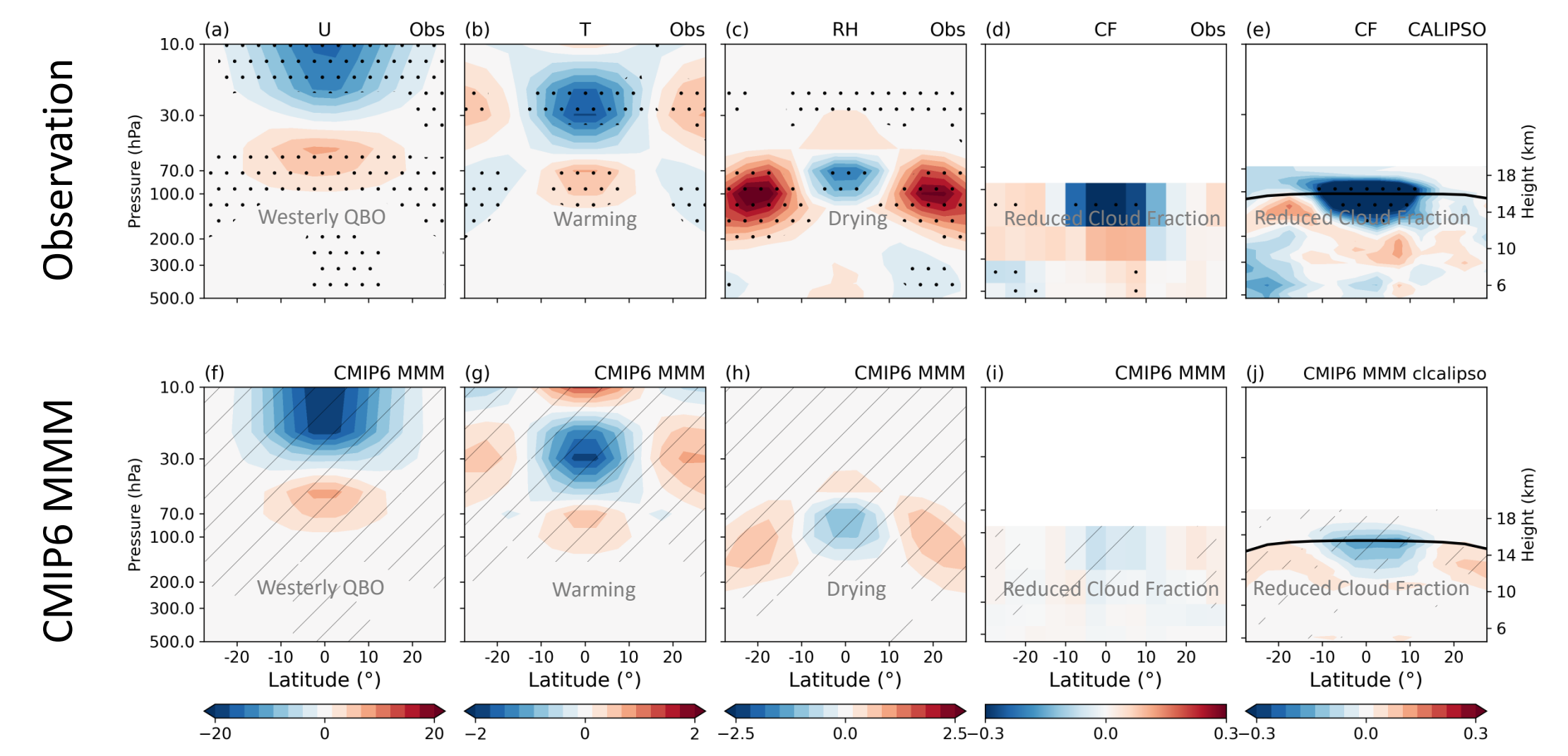


Figure 1: Latitude–height sections of QBO-regressed (a) zonal-mean zonal wind, (b) temperature, (c) relative humidity from ERA-5, (d) cloud fraction from MODIS and (e) CALIPSO between ±30° latitude. (f–j) Similarly for the CMIP6 multi-model mean

Scientific Questions

- How does the QBO influence high clouds, particularly tropical tropopause layer (TTL) clouds, in observations and CMIP6 models?
- Can the modulation of TTL clouds by the QBO be explained through cloud controlling factor (CCF) analysis?

Methodology

- 8 CMIP6 historical experiments (1850–2014), CALIPSO (2002–2024) and ERA5 (1979–2024).
- CCF analysis:** $\frac{dAMT(r)}{dQBO} = \sum_{i=1}^M \frac{\partial AMT(r)}{\partial X_i(r)} * \frac{dX_i(r)}{dQBO} = \sum_{i=1}^M \theta_i * \frac{dX_i(r)}{dQBO}$ Eq.(1)
- θ_i represents the sensitivity of high cloud fraction ($AMT(r)$) to the i -th cloud controlling factor (X_i), calculated using ridge regression.
- CCFs (X_i): upper tropospheric temperature (T_{UT}), static stability at 150 hPa (S_{150}), relative humidity at 700hPa (RH_{700}), vertical velocity at 300hPa (ω_{300}), upper tropospheric wind shear (ΔU_{300}), and upper tropospheric relative humidity (RH_{UT}) (Wilson Kemsley et al., 2025)

Results

1.: Figure 2: A decrease in TTL cloud amount during QBO westerly anomalies is evident in both observations and CMIP6 models but is much weaker in the latter. The QBO–TTL cloud relationship is successfully reconstructed using CCF analysis.

2.: Figure 3: T_{UT} , S_{150} and RH_{UT} play major roles in modulating the QBO–cloud relationship across all models. The inter-model spread in the QBO–cloud relationship is primarily driven by differences in TTL cloud sensitivities to T_{UT} and S_{150} .

3.: Figure 4: Biases in cloud sensitivities to CCFs are a primary reason why models fail to capture the observed QBO–cloud relationship. The QBO modulation of CCFs is also underestimated, particularly for static stability.

Fig 2. QBO impact on TTL cloud fraction

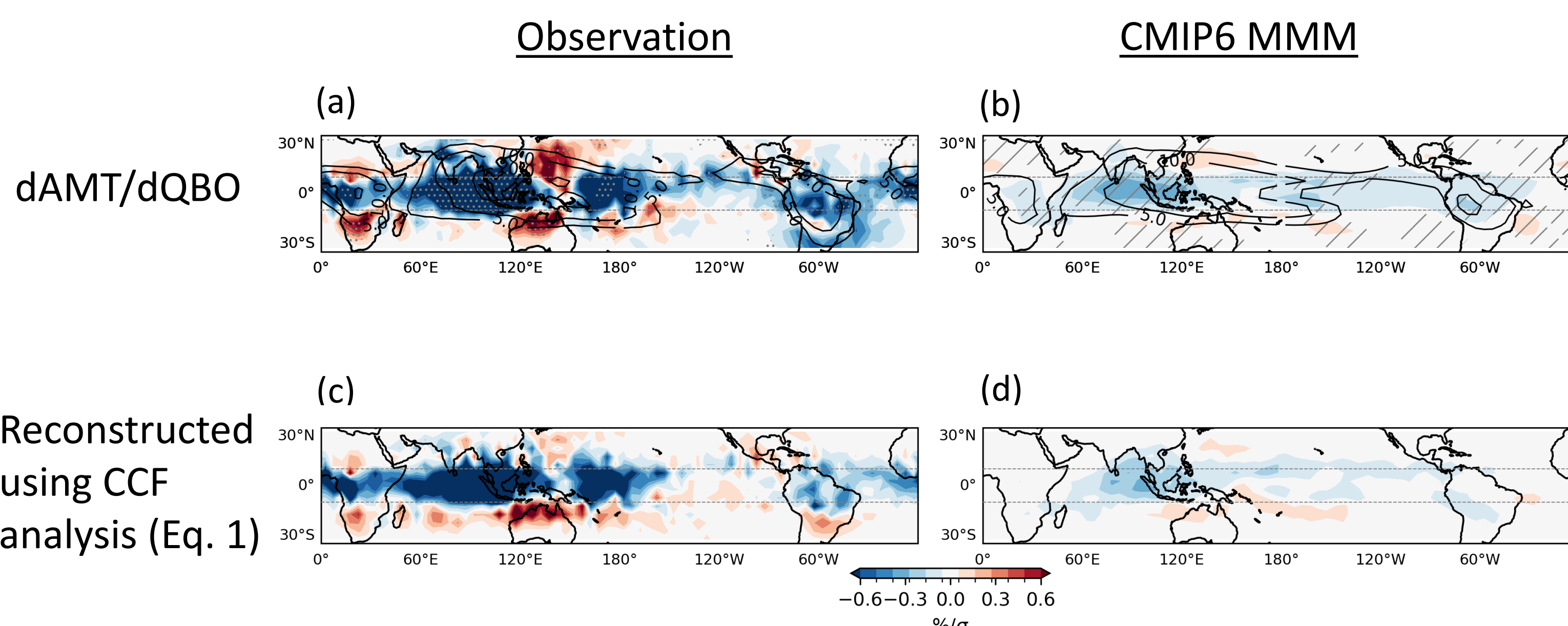


Fig 3. Contribution of each CCF to QBO-TTL cloud relationship.

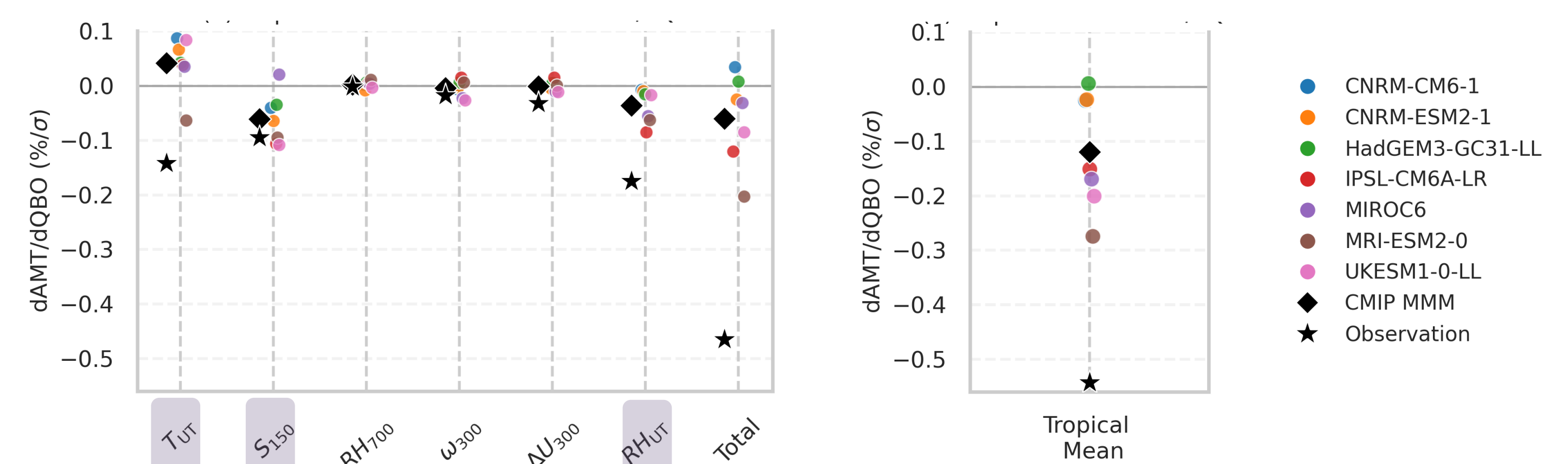
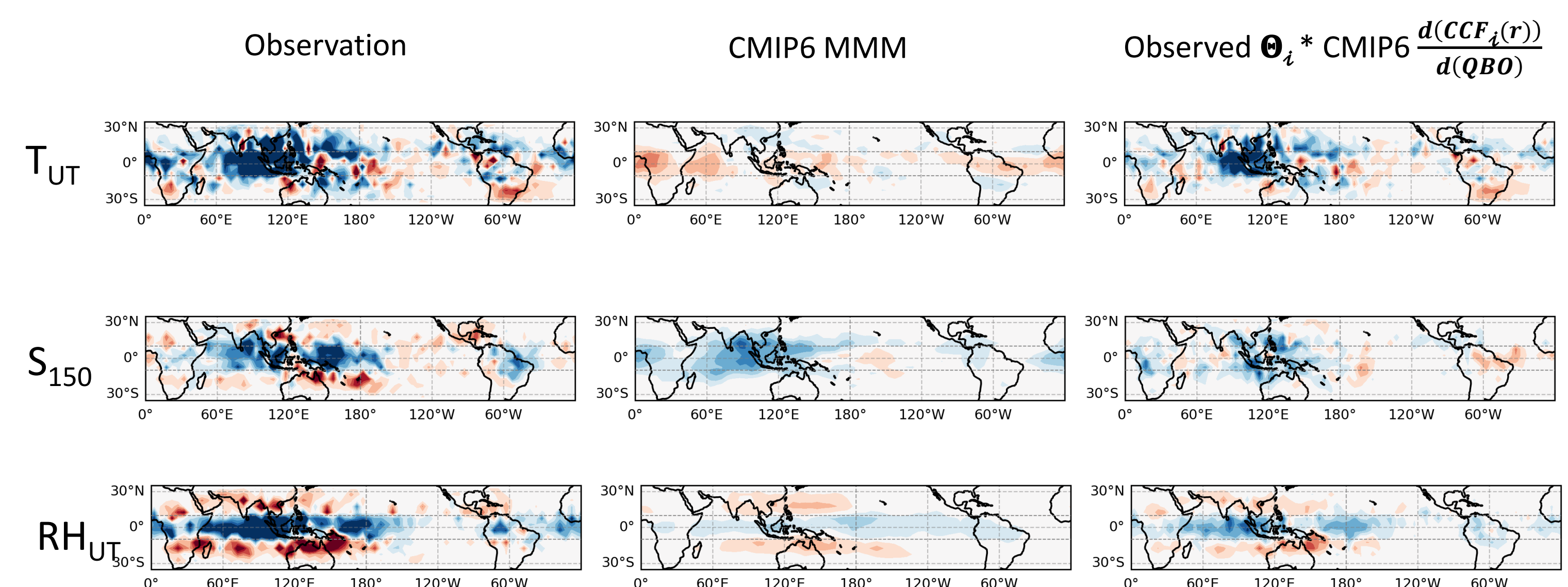


Fig. 4. Explaining Model Biases in QBO–TTL Cloud relationship



Improving TTL cloud sensitivity to meteorological fields improves the QBO–TTL cloud relationship in models.

Conclusions

- Observations show a clear QBO modulation of TTL high clouds.
- CMIP6 models show much weaker QBO–cloud relationship than observed.
- CCF analysis identifies the key meteorological variables driving the QBO–TTL cloud relationship.
- Improving cloud sensitivity to CCFs could reduce model biases in QBO–cloud relationship.
- This framework can help investigate the QBO–MJO relationship and cloud responses to future stratospheric changes.

Acknowledgements

AMJ was supported by Philip Leverhulme Prize funds awarded to PC. PC was supported by UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding Guarantee (grant EP/Y036123/1). PC was additionally supported through UK Natural Environment Research Council (NERC) grants NE/V012045/1 and NE/T006250/1.

References

- [1] Sweeney et al.; Seasonality of the QBO impact on equatorial clouds. Journal of Geophysical Research: Atmospheres, 2023
- [2] Wilson Kemsley et al., Climate models underestimate global decreases in high-cloud amount with warming, Geophysical Research Letters, 2025

