Response to the Editor and Reviewers

Ruixue Li et al. (Authors)

We sincerely thank the Editor and both reviewers for their careful evaluation of our revised manuscript. Following the Editor's additional comments, we have further revised the regression methodology, repeated the cloud-controlling-factor analysis after detrending, clarified the interpretation of the regional vertical-velocity changes over the tropical Pacific, and addressed all technical corrections raised by Reviewer #1.

Please see our point-by-point reply to comments. All revisions are shown in the revised manuscript by using track changes. The line numbers involved in the response correspond to the clear version of the manuscript.

Response to the Editor

1. **Comment:** In the construction of the regression model (Equation 17), both the cloud fraction and meteorological variables are deseasonalized, but are their trends also removed? If not, the authors should discuss the sensitivity of their results to this methodological choice, as trends could factor into the calculation of the regression coefficients and bias their amplitude.

   Response: We sincerely thank the Editor for raising this important and constructive methodological concern. In the previous version of the manuscript, cloud fraction (CF) and the meteorological predictors were deseasonalized but were not linearly detrended before estimating the regression coefficients. We agree that common trends between otherwise weakly related variables could introduce spurious associations and bias the magnitude of the regression coefficients. We have therefore revised the analysis by removing linear trends from both the deseasonalized CF anomalies and all candidate meteorological predictors before performing the stepwise multiple linear regression.

   The results obtained using the detrended regression are broadly consistent with those from the original analysis. The principal contributing factors and the main meridional and cloud-type patterns identified in the manuscript remain unchanged and continue to support the corresponding Results and Discussion.

To ensure methodological consistency throughout the manuscript, we have adopted the detrended regression as the primary analysis and replaced all affected figures with results obtained using the revised method. These include Fig. 6 in the main manuscript and Figs. S5–S8 in the Supplement. For transparency, comparisons between the original and detrended results are provided below in Figs. R1–R5.

In addition, we have explicitly stated in the Methods section that the results presented are based on detrended data:

Revised manuscript text (L270-295):

For each grid cell and cloud type, we first remove the seasonal cycles from CF and the meteorological predictors. To prevent common long-term trends from biasing the regression coefficients, linear trends are then removed from both the deseasonalized CF and predictor anomalies. The detrended predictor anomalies are standardized, whereas the detrended CF anomalies remain unstandardized. A stepwise multiple linear regression is then fitted as:

$$\Delta CF_c^{DT}(x,t) = \beta_0(x) + \sum_{k=1}^{K} \beta_k(x) \cdot \Delta V_k^{DT}(x,t) \quad (17)$$

where ΔCF_c^{DT} is the detrended CF anomaly for cloud type c at location x and time t, ΔV_k^{DT} is the detrended and standardized anomaly of the k-th meteorological variable, β_k are the regression coefficients, and β_0 is the intercept. The stepwise procedure is implemented with an entry significance level of $p < 0.05$ and a removal significance level of $p < 0.10$, ensuring that only variables with statistically meaningful explanatory power are retained. Because only the predictors are standardized, the resulting coefficients β_k represent the change in CF per unit standard deviation (STD) change in each predictor.

To estimate each factor's contribution to the observed CF trend, we apply the regression coefficient to the deseasonalized predictor anomaly before detrending, thereby retaining its observed long-term trend:

$$Contrib_k(x,t) = \beta_k(x) \cdot \Delta V_k^{OBS}(x,t) \tag{18}$$

where ΔV_k^{OBS} denotes the deseasonalized predictor anomaly retaining its linear trend and scaled using the same standard deviation as in Eq. (17). For each of the six latitude zones, cloud type, and meteorological variable, we compute the area-weighted zonal mean contribution at each month. For each resulting zonal-mean time series, we then estimate the linear trend (% decade^{-1}) using ordinary least squares, representing the contribution of each meteorological factor to the long-term CF trend in that latitude zone.

Comparisons between the original and detrended results:

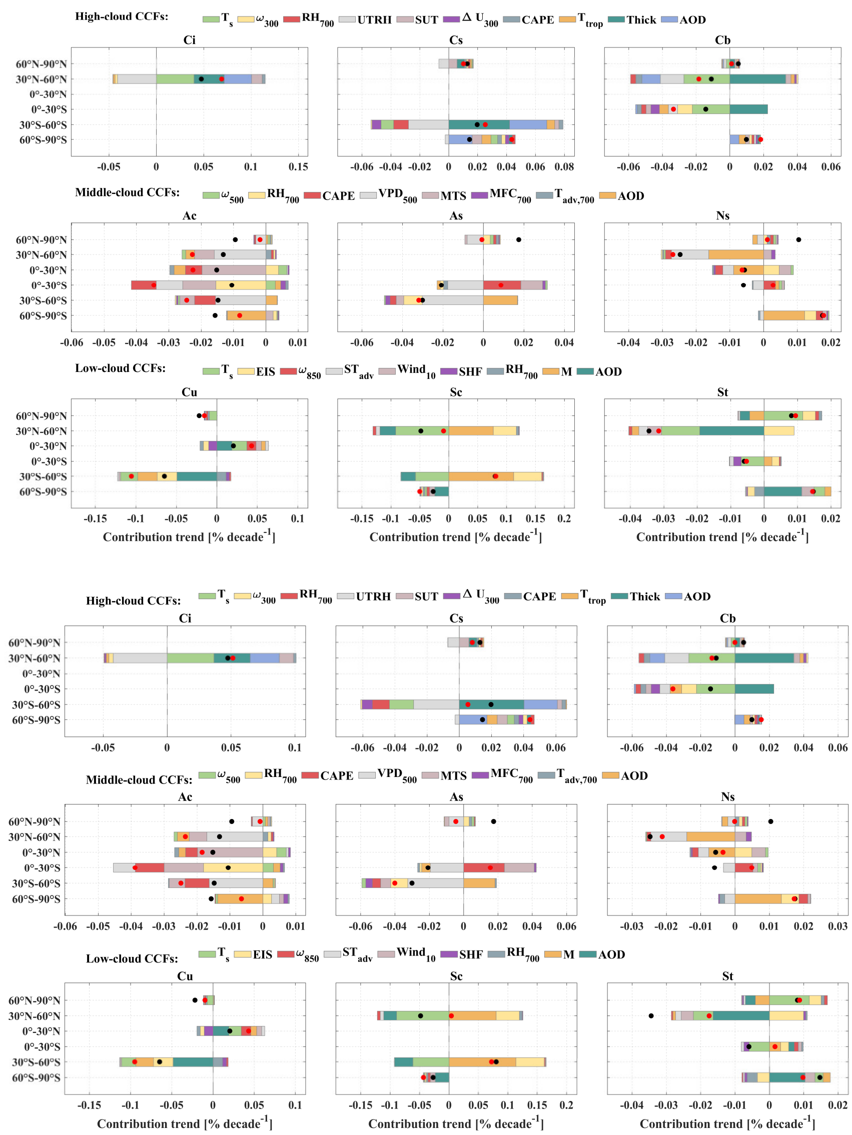

Figure R1. Comparison of the contributions of meteorological factors to CF trends before detrending (upper panel) and after detrending (lower panel). **The lower panel corresponds to the revised Fig. 6.**

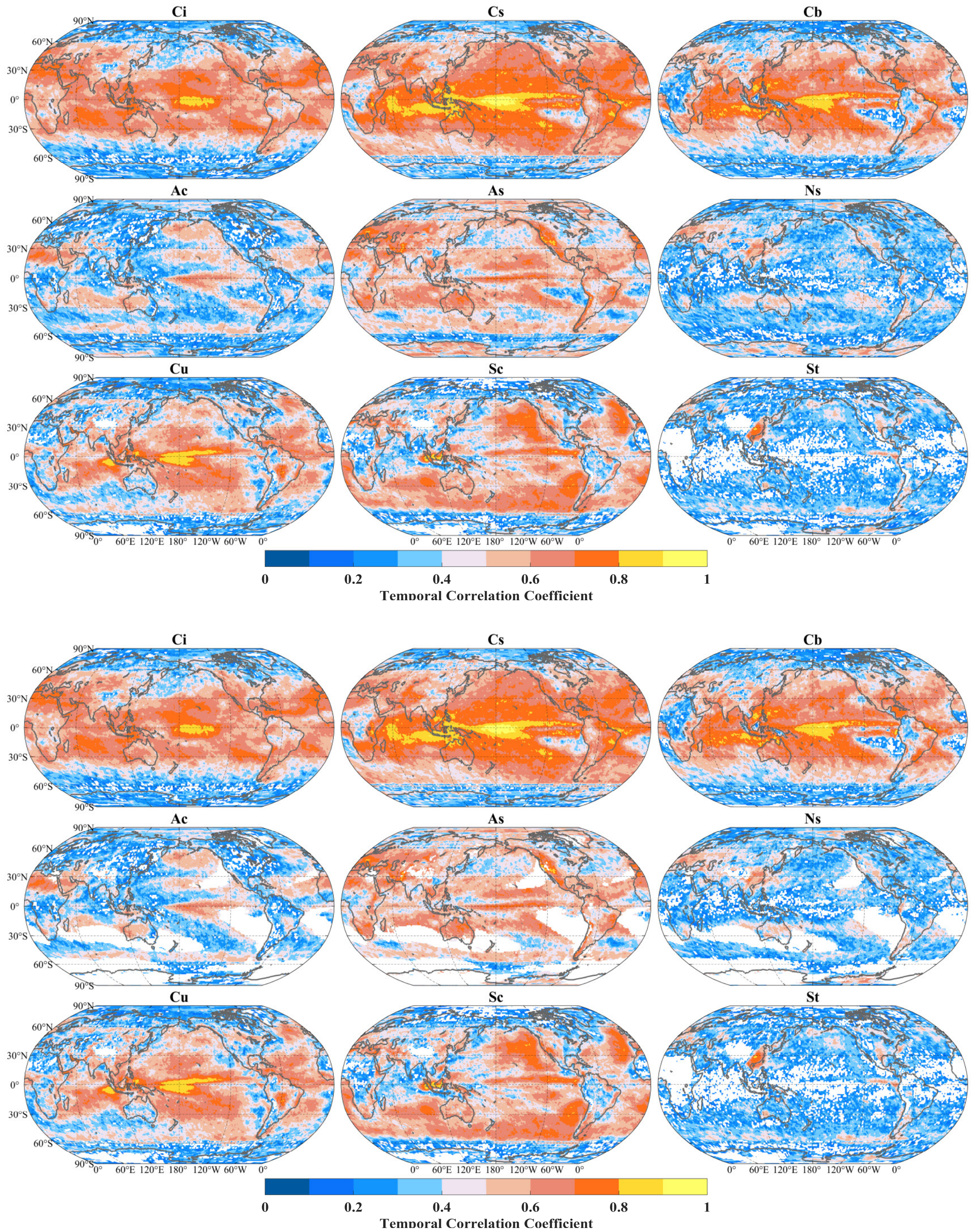

Figure R2. Comparison of the spatial distributions of the temporal correlations between observed and regressed CF anomalies before detrending (upper panel) and after detrending (lower panel). **The lower panel corresponds to the revised Fig. S5.**

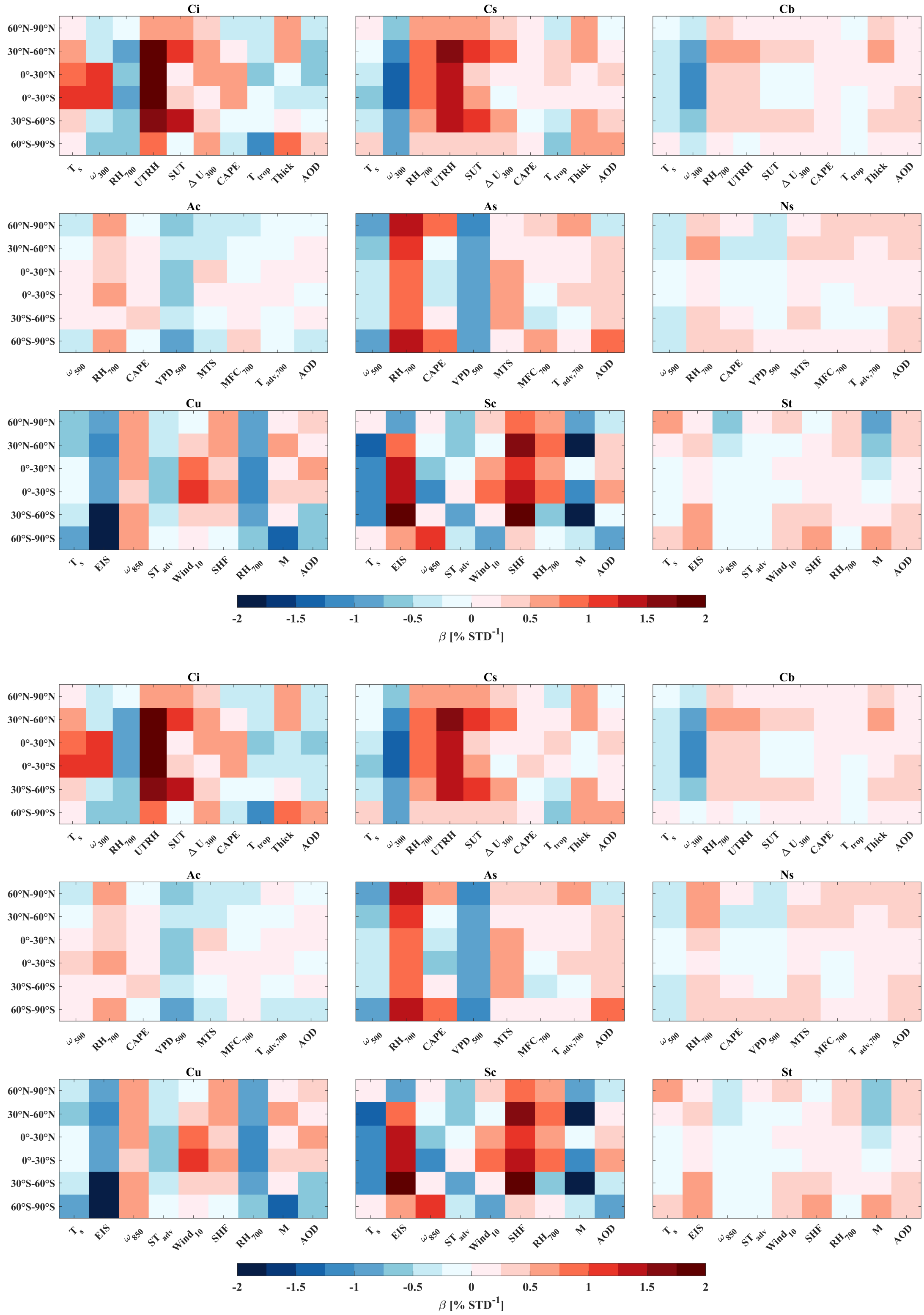

Figure R3. Comparison of the standardized regression coefficients before detrending (upper panel) and after detrending (lower panel). **The lower panel corresponds to the revised Fig. S6.**

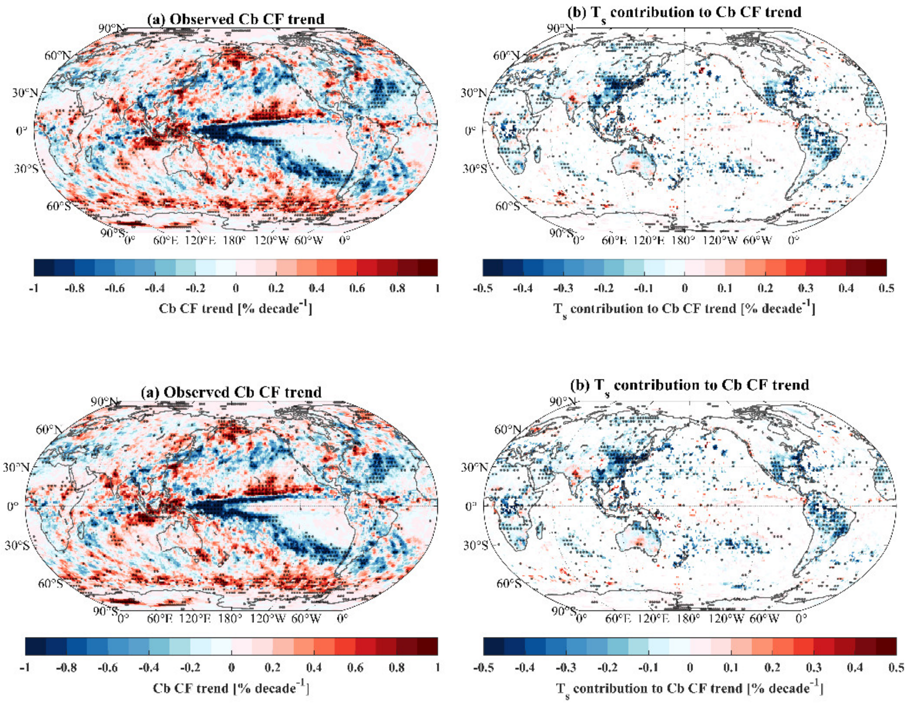

Figure R4. Comparison of the observed Cb cloud-fraction trend and the estimated Ts contribution before detrending (upper panel) and after detrending (lower panel). **The lower panel corresponds to the revised Fig. S7.**

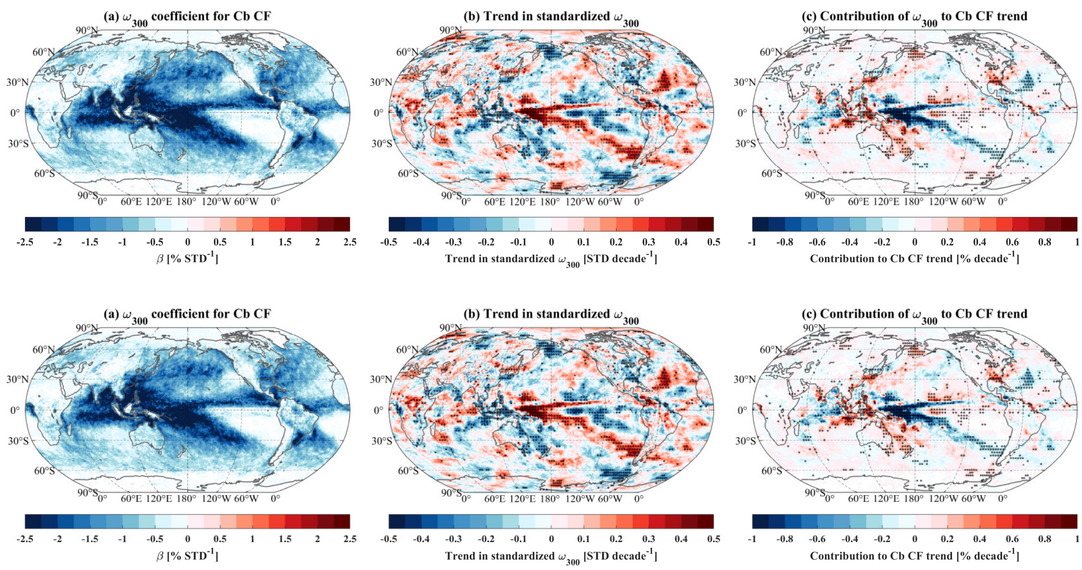

Figure R5. Comparison of the ω300–Cb coefficient, standardized ω300 trend, and resulting contribution to the Cb trend before detrending (upper panel) and after detrending (lower panel). **The lower panel corresponds to the revised Fig. S8.**

2. **Comment 2:** Line 563: The authors need to reconcile their statement here with the majority of recent literature that has emphasized strengthening trends in the Walker circulation in recent decades (e.g., Wills et al., 2022).

   Response: We thank the Editor for drawing attention to this inconsistency. We agree that our original statement interpreted a localized weakening of upper-tropospheric ascent over the western equatorial Pacific too broadly as a weakening of the Pacific Walker circulation. The spatial trend in ω_{300} represents a regional circulation feature and does not provide a basin-scale measure of Walker circulation strength. We have removed the claim that the observed regional feature represents an overall weakening of the Walker circulation. We now explicitly distinguish the local weakening of ascent from the strengthening of the Walker circulation reported in recent observational studies. We also clarify the interpretation of Wu et al. (2021), who found an observed strengthening during 1980–2015, despite projecting a likely weakening in subsequent decades.

   Revised manuscript text (L565-576): The spatial distributions in Fig. S8 show that the negative ω_{300}–Cb regression coefficients over the western equatorial Pacific coincide with significant positive local trends in ω_{300}, indicating weakened ascent. This spatial correspondence produces a negative contribution of ω_{300} to the Cb trend in this region (Fig. S8c), which dominates the negative zonal-mean contribution shown in Fig. 6. The local weakening of ascent over the western equatorial Pacific would tend to suppress convective development and vertical moisture transport, thereby limiting Cb formation. While recent studies have emphasized a strengthening trend in the Walker circulation over recent decades (Wu et al., 2021; Wills et al., 2022), our result should not be interpreted as a weakening of the Pacific Walker circulation as a whole. Instead, the local signal may reflect regional variability or a zonal reorganization within the broader Walker circulation.

References:

Wills, R. C. J., Dong, Y., Proistosescu, C., Armour, K. C., and Battisti, D. S.: Systematic climate model biases in the large-scale patterns of recent sea-surface temperature and sea-level pressure change, Geophys. Res. Lett., 49, e2022GL100011, https://doi.org/10.1029/2022GL100011, 2022.

Wu, M., Zhou, T., Li, C., Li, H., Chen, X., Wu, B., Zhang, W., and Zhang, L.: A very likely weakening of Pacific Walker Circulation in constrained near-future projections, Nat. Commun., 12, 6502, https://doi.org/10.1038/s41467-021-26693-y, 2021.

Response to Reviewer #1

We sincerely thank the reviewer for the positive assessment of the revised manuscript and for identifying the remaining technical and linguistic issues. We have addressed each point as detailed below.

1. **Comment:** The term "zonal pattern" (of e.g. warming, cloud changes, etc.) appears throughout the manuscript. I believe that it is more correct to refer to a meridional pattern, since the manuscript is presenting zonal means and the meridional variation thereof. These occur in e.g. lines 13, 27, 371, 374, 384. Please go through the manuscript and ensure that the correct directions of variations are being referred to (i.e., meridional variations of zonal means).

   Response: We greatly appreciate the reviewer's careful reading and valuable comment. Our results describe differences among latitude zones, namely the meridional variation of zonal-mean quantities, rather than variations along the zonal direction. We have reviewed the manuscript and replaced "zonal pattern," "zonal warming pattern," and "zonally contrasting" with "meridional pattern of zonal-mean warming," "meridional warming pattern," or "contrasts across latitude zones," as appropriate.

   Representative revised manuscript text (Abstract):

   Cloud changes exert a weak net effect on global mean warming due to near-cancellation between shortwave warming and longwave cooling, but strongly modulate the meridional pattern of zonal-mean warming.

Our results establish a direct observational link between cloud-type changes, planetary albedo decline, and contrasting warming across latitude zones, characterizing the cloud-radiative changes in recent climate change.

Representative revised manuscript text (L376-380):

However, the near-cancellation at the global scale belies the critical role of clouds in affecting the meridional variation of zonal-mean warming. The individual shortwave and longwave cloud effects represent large, opposing radiative perturbations, quantifying them separately is therefore essential for characterizing their contributions to the observed meridional warming pattern.

2. **Comment:** L276: "p<0.05" and "p<0.10" are not in math mode.

   Response: Thank you for noting this typesetting issue. We have placed p and the corresponding thresholds in math mode: "$p < 0.05$", "$p < 0.10$".

3. **Comment:** L384: "Powerful" is hard to substantiate, and it is not necessary to include since the authors have presented the quantities.

   Response: We agree and have removed "powerful." We have also revised the sentence to describe the quantified meridional contrast directly.

   Revised manuscript text (L389-391): Therefore, while the global net cloud impact on the T_s trend is small, clouds exert a meridionally contrasting influence that is fundamental to understanding the observed pattern of climate change.

4. **Comment:** L404: "dominated by" may not be the most suitable word here; perhaps "accompanied by" or "related to" would work.

   Response: We agree that "dominated by" was unnecessarily strong in this context. We have replaced it with "related to".

   Revised manuscript text (L410-412): This is because a decrease in RSR_{cloud} related to reduced CR contributes to an increase in solar radiation reaching the surface, which offsets the concurrent reduction in clear-sky surface downwelling solar radiation (Fig. S3b).

5. **Comment:** L815–816: The statement "All data are available in the main text or the supplementary materials" is redundant and not accurate.

   Response: We agree and have removed this sentence.

Response to Reviewer #2

Comment: The authors have addressed my comments well, and I appreciate their efforts. The paper might be accepted for publication.

Response: We sincerely thank the reviewer for the positive assessment of our revision and for the constructive comments provided during the previous review round.