Response to Reviewers' Comments

Reviewer #3:

'Comment on egusphere-2026-1091'.

General Comments

The manuscript led by Hui Xu and Jianping Guo presents a national-scale characterization of cloud vertical structure across China using a ground-based millimeter cloud radar network. The topic is important, and the dataset has potential value for understanding regional cloud climatology. The authors state that, to their knowledge, this is the first national-scale, high-frequency characterization of cloud vertical structure across China using a coordinated ground-based radar network, and that the study systematically quantifies thermodynamic, dynamical, and land-surface controls.

I have several major concerns and questions that need to be addressed before publication. In particular, the manuscript would benefit from a more explicit discussion of how these radar-derived statistics could be used (e.g., the connection between the observational findings and their implications for model evaluation or improvement, especially from only one year of data). I also think the authors need to be cautious about the interpretation of single-layer clouds and land-surface coupling.

Response: We thank the reviewer for his/her comprehensive evaluation and thoughtful comments, which help tremendously to improve the quality of our work. We have tried our best to address the reviewer's concerns one by one.

Per your kind suggestions, substantial changes have been made, including: (1) adding a more explicit discussion on how the one-year radar-derived statistics can be used for model evaluation and improvement, and acknowledging the caveats of using only one year of data, (3) revising the interpretation of land-cover influences on cloud base height (CBH) to avoid overstating causality, particularly for single-layer clouds-clarifying throughout the manuscript that the observed land-cover contrasts represent statistical associations rather than pure surface-driven control.

For clarity purpose, here we have listed the reviewer's comments in **black**, followed by our responses in **blue**, and the modifications to the manuscript are in italics. We sincerely hope that the reply and the revisions can satisfy the reviewer's expectations.

Major comments:

1. I recommend adding a more explicit discussion of how these radar-derived statistics could be used. Please clarify how the findings in this study can help improve weather and climate predictions. At present, the manuscript describes the observational characteristics well, but the pathway from these findings to improved model prediction is not sufficiently clear.

Response: We thank the reviewer for this constructive suggestion. To address this gap, we have supplemented targeted elaborations in the Conclusions (Section 4) to clearly illustrate the complete pathway from our CVS statistics toward model optimization and enhanced prediction skill, as follows:

"Overall, this study provides a high-resolution, observationally constrained snapshot of cloud vertical structure across China and establishes a quantitative framework linking CVS metrics to thermodynamic, dynamical, and land-surface controls (Figure 15). *These statistically derived linkages can directly inform model improvement in two ways. First, the observed sensitivities of CBH and CTH to* LTS_{surf} *and* q_{2m} *offer quantitative benchmarks for calibrating boundary-layer and convective parameterizations—the dominant sources of cloud-related uncertainty in weather and climate models (Bony et al., 2015; Cesana and Waliser, 2016). Second, the land-cover contrasts in CBH provide constraints for evaluating surface–atmosphere coupling in land surface models. Although this one-year record does not support long-term trend analysis, it establishes a robust baseline against which model-simulated CVS can be evaluated across timescales, especially when combined with multi-year satellite or reanalysis products, thereby supporting iterative improvement of cloud schemes and enhancing prediction skill from weather to climate scales....* "

2. The use of only one year of data needs more justification. The results appear to be based primarily on one year of observations, 2024. The authors should clearly state this limitation and explain how representative 2024 is relative to longer-term climatology. One year of data can provide valuable high-frequency observational statistics, but it may not be sufficient to draw robust climatological conclusions or to claim direct implications for model improvement. The authors should consider discussing whether 2024 was meteorologically typical or anomalous, and whether interannual variability could affect the reported cloud vertical structure statistics.

Response: We sincerely thank the reviewer for raising this insightful and critical comment regarding the representativeness of our single-year dataset. We fully agree that a single year of observations cannot constitute long-term climatology, and we have addressed this concern from three perspectives: (i) justification for selecting

2024, (ii) a quantitative representativeness assessment using ERA5 reanalysis, and (iii) tempered language throughout the revised manuscript.

(1) Why 2024 was selected

Prior to 2024, fewer than 30 MMCRs were operational across China, which was insufficient for reliable national-scale analysis of cloud vertical structure (CVS). In 2024, the network underwent a major expansion to nearly 120 stations, of which 80 met our strict data-quality criterion (≥100 valid observation days per year, defined as calendar days with at least 8 hours of valid MMCR measurements). Thus, 2024 represents the first year in which a sufficiently dense observing network became available, making it the only feasible foundation for this pioneering investigation. This justification has been added to Section 2.1.1 of the revised manuscript, as follows:

"MMCR data have been widely used in cloud boundary detection (e.g., Zhang et al., 2017; Zhou et al., 2019; Fang et al., 2023) and exhibit strong consistency with radiosonde observations (Wang et al., 2016; Zhao et al., 2017; Chen et al., 2022). In this study, MMCR data for the year of 2024 were obtained from the China Meteorological Administration (CMA). Of the 120 MMCR stations operating across China in 2024, only those with at least 100 valid observation days annually (*defined as calendar days with at least 8 hours of valid MMCR measurements*) were retained to ensure data quality. This criterion resulted in the selection of 80 stations for subsequent analysis (Fig. 1). *Notably, we selected 2024 because it was the first year in which the MMCR network achieved sufficient density for national-scale analysis. Before 2024, fewer than 30 stations were operational nationwide, which was inadequate for a robust spatial characterization of CVS. The major expansion in 2024, with nearly 120 MMCRs deployed, made this pioneering investigation feasible. Even though this single-year dataset does not constitute a long-term climatology, it provides the first observationally dense and vertically resolved national snapshot of CVS across China.* "

(2) Representativeness of 2024 relative to the past decade

Following the reviewer's suggestion, we evaluated the representativeness evaluation of 2024 using ERA5 reanalysis data for 2014 to 2023 as the climatological baseline. We calculated standardized anomalies (Z-scores) of annual mean total cloud cover, precipitation, and 2m specific humidity (q_{2m}) in 2024. A Z-score within ±2 is generally considered to reflect typical interannual variability. The key results are summarized in Figure R1 (provided below for the reviewer's reference only), as follows,

Total cloud cover: The ERA5-derived annual mean cloud cover for 2024 is 54.54%, nearly identical to the 2014–2023 climatological mean of 54.05% (relative deviation

0.9%, Z-score well below 1.0). This indicates that the overall cloud amount in 2024 falls well within the range of natural interannual variability, and that our MMCR-derived cloud occurrence statistics are not unduly influenced by anomalous cloud cover. This supports the reliability of the CVS metrics (CBH, CTH, CT) derived from the 2024 observations.

Precipitation: The Z-score for annual mean precipitation in 2024 is 1.8, indicating a notably wetter-than-normal year.

Low-level moisture: 2024 shows a pronounced positive anomaly in q_{2m}, with a Z-score of 3.5, representing an exceptionally high value relative to the past decade.

Rather than undermining our conclusions, these anomalous moisture and precipitation conditions provide a valuable "natural experiment" that reinforces the physical mechanisms proposed in our study. As we demonstrate in Section 3.5, enhanced low-level moisture promotes deeper vertical cloud development. The anomalously high precipitation in 2024 is consistent with this enhanced moisture-driven convection, and it aligns with our observed elevated cloud top heights and cloud thickness under humid conditions. In other words, 2024 exhibited near-normal cloud frequency but extreme low-level moisture—exactly the combination that our core argument predicts: moisture availability primarily controls the vertical extent of clouds once they form, rather than their occurrence frequency. Therefore, the CVS–thermodynamic relationships we derive are not artifacts of an anomalous year; rather, they are physically consistent and likely conservative relative to drier years.

We acknowledge that the single-year nature of the dataset precludes definitive multi-year climatological conclusions. We have therefore adopted a cautious tone throughout the manuscript, replacing absolute statements with precise wording such as "first observational assessment for 2024" and "an unprecedented snapshot." In the Abstract and Conclusions, we explicitly state that this record provides a baseline for future multi-year evaluations rather than long-term climatology.

(3) Specific textual revisions

We have revised the Abstract as follows:

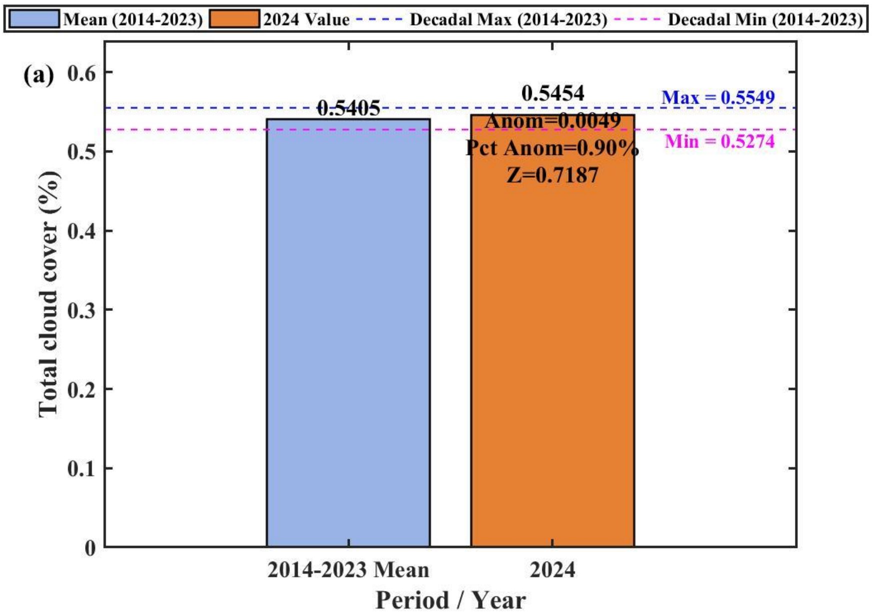
"Using a newly established national network of 80 Ka-band millimeter-wave cloud radars (MMCRs), *here we present a high-spatiotemporal-resolution (vertical resolution of 30 m, temporal resolution of 1 min) characterization of CVS across China based on one year (2024) of observations*, and quantify its thermodynamic, dynamical, and land-surface controls. "

In the Summary and Conclusions, we now state:

"This study presents the first national-scale, high-spatiotemporal-resolution *analysis* of CVS across China based on observations from a coordinated network of 80 Ka-band cloud radars *during 2024, providing an unprecedentedly detailed* *snapshot (30 m vertical, 1 min temporal resolution) of cloud vertical structures and their governing factors*."

"Overall, this study provides a high-resolution, observationally constrained snapshot of cloud vertical structure across China and establishes a quantitative framework linking CVS metrics to thermodynamic, dynamical, and land-surface controls (Figure 15). ... *Although this one-year record does not support long-term trend analysis, it establishes a robust baseline against which model-simulated CVS can be evaluated across timescales, especially when combined with multi-year satellite or reanalysis products, thereby supporting iterative improvement of cloud schemes and enhancing prediction skill from weather to climate scales. Future work should extend this analysis to multi-year datasets to assess interannual variability and explore the role of CVS in extreme weather events and regional climate feedbacks....* "

We believe these revisions and the accompanying analysis adequately address the Reviewer's concern. We are grateful for the suggestion, which has significantly strengthened the manuscript.



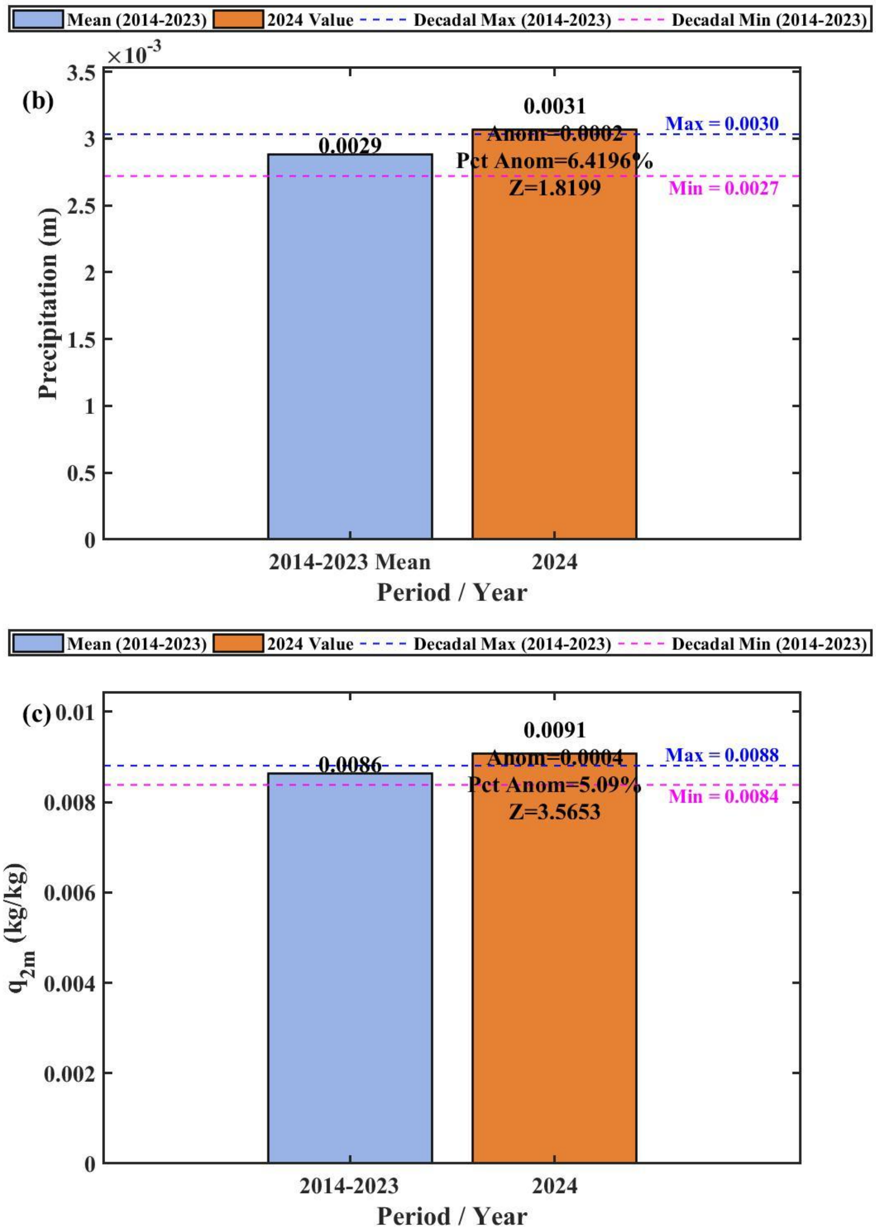


Figure R1. Comparison of the annual mean (a) total cloud cover (%), (b) precipitation (m), and (c) 2-m specific humidity (kg kg^{-1}; q_{2m}) over China between the 2014–2023 decadal mean (blue bars) and the year 2024 (orange bars). In each subfigure, the dashed horizontal lines represent the decadal maximum (blue) and minimum (magenta) over the 2014–2023 period. Numerical values are displayed on or with the bars; for 2024, the label additionally includes the absolute anomaly (2024 minus decadal mean), the percentage anomaly relative to the decadal mean, and the standardized anomaly (Z-score, normalized by the decadal standard deviation). The legend shown at the top applies to all three panels.

3. Interpretation of single-layer clouds and land-surface coupling. Please clarify whether the single-layer cloud category includes high-level clouds. If so, the discussion in Section 3.7 may need to be reconsidered. High-level single-layer clouds

are not necessarily strongly coupled to land-surface processes, whereas low-level clouds are more directly influenced by boundary-layer thermodynamics and land-atmosphere interactions. One suggestion could be: separating single-layer clouds by cloud-base or cloud-top height before discussing land-surface controls. Otherwise, the relationship between single-layer cloud occurrence and land-surface properties may be difficult to interpret physically.

Response: We sincerely thank the reviewer for this insightful comment, which has substantially improved the physical interpretation of land–atmosphere coupling in our study. Following the reviewer's suggestion, we have reanalyzed the land surface modulation of cloud vertical structure by focusing on low clouds (CTH < 3 km) and separating them into all-hour low clouds and afternoon (1400–1800 LT) single-layer low clouds. Key results based on median CBH are summarized below:

Diurnal uplift: Afternoon median CBH is systematically higher (e.g., barren: 1.32 → 1.44 km; grasslands: 0.99 → 1.26 km; cropland/natural vegetation mosaics: 0.48 → 0.57 km), consistent with daytime boundary-layer deepening.

Amplified land-cover contrasts: The diurnal increase is most pronounced over moist, vegetated surfaces (e.g., evergreen broadleaf +41.7%, croplands +33.3%) and smallest over dry surfaces (barren +9.1%) or water (+3.9%), reflecting the balance between sensible heating and evapotranspiration.

The systematically higher afternoon CBH is jointly driven by the restriction to single-layer clouds and the afternoon deepening of the boundary layer, while land-cover heterogeneity further modulates local cloud-base height through differential surface fluxes.

The 3.6 Land surface modulation of cloud vertical structure Section is revised as follows,

"***3.6 Land surface modulation of cloud vertical structure***

Beyond atmospheric thermal and dynamical factors, land-surface characteristics also influence cloud vertical structure through their effects on PBL moisture, surface energy partitioning, and turbulence (e.g., Bonan, 2008; Fu et al., 2020; Wang et al., 2021). Since CBH is tightly coupled to PBL thermodynamics, it serves as a useful metric for assessing surface–cloud coupling. This coupling is only meaningful for boundary-layer clouds; high-level single-layer clouds are dominated by large-scale upper-tropospheric processes and, as confirmed in our analysis, are insensitive to surface type. We therefore focus on single-layer low clouds (CTH < 3 km), which are largely confined within the boundary layer. To quantify the land-surface influence, we compare CBH across land-cover types for (i) all-hour low clouds and (ii) afternoon (1400–1800 LT) single-layer low clouds (Fig. 14). The afternoon subset captures the period of strongest coupling, when the boundary layer is fully developed and *land-atmosphere fluxes are maximized. .*

3.6.1 All-hour low clouds

Under all-hour conditions, low clouds (CTH <3 km) exhibit a systematic dependence of CBH on underlying land cover type (Fig. 14, left panels). Barren land (type 10) shows the highest median CBH (1.32 km), consistent with limited surface moisture availability and elevated LCLs. Densely vegetated surfaces yield markedly lower medians: cropland/natural vegetation mosaics (type 9) record the lowest value (0.48 km), followed by evergreen broadleaf forests (type 2, 0.72 km), deciduous broadleaf forests (type3, 0.72 km), and croplands (type 7, 0.72 km). Water bodies (type 1, 1.02 km) and urban and built-up lands (type 8, 0.90 km) fall in the intermediate range.

These contrasts can be explained by the biophysical properties of the land cover. Forests sustain high evapotranspiration, which moistens the boundary layer and lowers the lifting condensation level, favouring lower cloud bases (Spracklen et al., 2012; Zhang et al., 2024). In addition, the greater surface roughness and lower albedo of forests enhance turbulent exchange and boundary-layer growth, promoting cloud formation, although the net effect of deeper mixing may partially offset the moisture-driven lowering. Overall, the moisture supply over vegetated surfaces appears to dominate, yielding lower CBH relative to barren land. This interpretation aligns with studies showing that land-use and land-cover change can modify CBH by altering surface energy partitioning and boundary-layer thermodynamics (Syktus and McAlpine, 2016; Xu et al., 2022; Duveiller et al., 2023).

3.6.2 Afternoon single-layer low clouds

Land cover type exerts a stronger modulating effect on the CBH of afternoon single-layer low clouds (Fig. 14, right panels). The overall ranking of median CBH is consistent with the all-hour pattern: barren land remains highest (1.44 km), while cropland/natural vegetation mosaics remain lowest (0.57 km). Notably, afternoon CBH is systematically higher than the all-hour climatology across all land-cover types, with a mean increase of approximately 21.7%. The diurnal increase is most pronounced over densely vegetated surfaces—evergreen broadleaf forests (+41.7%), croplands (+33.3%), and woody savannas (+32.1%)—and smallest over barren land (+9.1%) and water bodies (+3.9%).

The systematically higher afternoon CBH primarily reflects the deepening of the boundary layer and the associated rise in the LCL due to strong surface heating. Additionally, restricting the sample to single-layer clouds may exclude very low cloud bases typical of multi-layer or decoupled stratiform decks, further contributing to the elevated median values. The amplified land-cover contrasts during afternoon indicate that boundary-layer evolution under strong insolation is highly sensitive to surface *heterogeneity. Heterogeneous landscapes can generate mesoscale circulations and spatial gradients in moisture and heat fluxes that modulate cloud initiation and CBH (Rieck et al., 2014).*

The small increase over barren land is expected, as its cloud base is already elevated under all-hour conditions due to persistent moisture limitation. The modest rise over cropland/natural vegetation mosaics (+18.8%)—despite having the lowest absolute CBH—is consistent with strong evapotranspiration partially counteracting the boundary-layer deepening. Water bodies show minimal diurnal change (+4.4%), reflecting the large thermal inertia that suppresses the amplitude of boundary-layer development.

Overall, Fig. 14 demonstrates a measurable influence on CBH, with the strongest contrasts emerging for afternoon single-layer low clouds. These results highlight the importance of surface-driven moisture supply, energy partitioning, and boundary-layer dynamics in shaping cloud-base variability. Similar forest–open land contrasts in CBH have been reported in other regions (e.g., tropical montane environments; Trivedi et al., 2025), suggesting that land-surface modulation of low cloud vertical structure is a robust feature across diverse geographic settings.

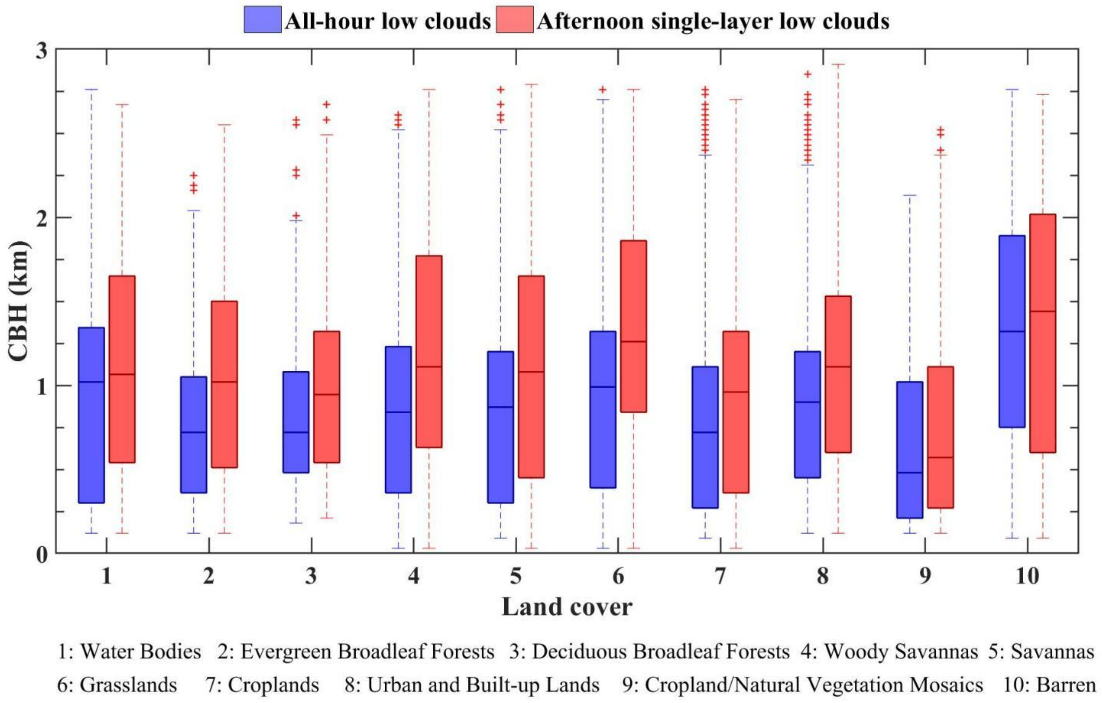


Figure 14. Land-surface influence on CBH across China in 2024, based on 80 MMCR stations. Blue bars indicate all hour low clouds, and red bars represent afternoon single-layer low clouds. Land cover types are derived from the MODIS Land Cover Type Yearly Climate Modeling Grid product (MCD12C1;

https://lsdsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MCD12C1).

4. Please explain the scientific motivation for separating two-layer clouds from multi-layer clouds.

Response: We thank the reviewer for this question. In Figure 3, we deliberately separate two-layer clouds from multi-layer clouds (defined as three or more cloud layers) because they exhibit distinct spatial characteristics and are governed by different formation mechanisms.

From an observational perspective, our prior near-global radiosonde study (Xu et al., 2023) demonstrated that two-layer configurations account for 62.2% of all broadly defined multi-layer cloud occurrences (clouds with ≥2 layers), and importantly, show no consistent regional preference. This characteristic spatial pattern is fully reproduced in the present MMCR radar dataset as shown in Section 3.1 and Figure 3c, two-layer cloud fractions show negligible east-west spatial divergence nationwide. By contrast, single-layer clouds occur much more frequently across arid northwest China (Fig. 3b), while multi-layer clouds (defined as systems with three or more layers in the present study) are concentrated over humid southeastern regions (Fig. 3d). The consistent spatial signatures retrieved from both radiosonde and radar observations verify that two-layer clouds constitute a unique transitional cloud regime. This spatial decoupling—where two-layer clouds behave as a transitional regime between the other two categories—would be completely obscured if we adopted a simple binary classification (single-layer vs. all clouds with ≥2 layers). Separating two-layer clouds thus preserves a distinct observational signature that is consistently captured by two independent observing systems.

Physically, two-layer and multi-layer clouds arise from different processes. Two-layer clouds frequently result from decoupling of the cloud-topped boundary layer, where the surface mixed layer separates from the overlying cloud deck, forming a stable interface between them (Bretherton and Wyant, 1997; Wyant et al., 1997). This allows the lower and upper layers to respond to different thermodynamic controls. In contrast, multi-layer clouds (≥3 layers) are more commonly associated with organized deep convection or frontal systems, where multiple cloud layers coexist within a single dynamically coupled structure. Merging these two categories would conflate clouds formed by boundary-layer decoupling with those embedded in deep convective or baroclinic systems, weakening the physical interpretability of our classification.

For these reasons, we retained the three-category classification in Figure 3 and clarified the scientific motivation at the end of Section 3.1, as follows:

“*We separate two-layer from multi-layer clouds (≥3 layers) because they exhibit distinct spatial patterns and formation mechanisms. Two-layer clouds lack a clear regional preference in both a previous global radiosonde study (Xu et al., 2023) and the present MMCR observations (Fig. 3c,d), confirming their transitional nature. Physically, two-layer clouds often result from boundary-layer decoupling (Bretherton and Wyant, 1997), whereas multi-layer clouds are more typical of organized deep convection or frontal systems. Merging these categories would conflate dynamically distinct cloud populations*.”

References:

Xu, H., Guo, J., Tong, B., Zhang, J., Chen, T., Guo, X., Zhang, J., and Chen, W.: Characterizing the near-global cloud vertical structures over land using high-resolution radiosonde measurements, *Atmos. Chem. Phys.*, 23, 15011–15038, https://doi.org/10.5194/acp-23-15011-2023, 2023.

Bretherton, C. S., and Wyant, M. C.: Moisture transport, lower-tropospheric stability, and decoupling of cloud-topped boundary layers, J. Atmos. Sci., 54, 148–167, https://doi.org/10.1175/1520-0469(1997)054<0148:MTLTSA>2.0.CO;2, 1997.

Specific comments:

1. Line 166: Please clarify what is meant by “valid observation days”. Does this refer to days with continuous/full-day radar observations, or days that meet a minimum data availability threshold? If a threshold was used, please specify it.

Response: In our data processing, a “valid observation day” is defined as a calendar day with at least 8 hours of valid MMCR measurements. This threshold ensures that the daily data are sufficiently representative of the diurnal cloud cycle while excluding days with major instrument maintenance, system malfunctions, or incomplete data records due to power outages or communication failures.

To avoid ambiguity, we have added a clear definition of “valid observation days” in the revised manuscript in Section 2.2.1 as follows:

“Of the 120 MMCR stations operating across China in 2024, only those with at least 100 valid observation days annually (*defined as calendar days with at least 8 hours of valid MMCR measurements*) were retained to ensure data quality. This criterion resulted in the selection of 80 stations for subsequent analysis (Fig. 1).”

2. Please clarify whether radar wind profiler data were used during precipitation periods. If so, how were precipitation-contaminated periods handled? The reliability of RWP retrievals can vary substantially under clear-sky, cloudy, and precipitation conditions. Please discuss how the authors assessed the trustworthiness of RWP

observations under these different conditions, and whether any filtering or quality flags were applied before using the data in the analysis.

Response: We thank the reviewer for this important technical question. In our analysis, RWP data during precipitation periods were excluded to avoid contamination of the wind shear calculation.

The quality control of RWP data used in this study includes the following procedures: (1) within each profile over the 0.5-5.0 km height range, missing values and significant outliers exceeding 2.5 standard deviations from the mean were removed; (2) if more than 40% of the data points within this height range were outliers or missing, the entire profile was discarded; (3) discontinuous or missing data points were estimated using linear interpolation; and (4) observations were restricted to the 0.5 – 5.0 km height range to avoid near-surface clutter and beam attenuation, ensuring the accuracy of VWS calculations.

We have added a brief clarification in Section 2.2.2 of the revised manuscript. The added text reads as follows:

"*Before deriving VWS from the RWP measurements, we applied a multi-step quality control procedure following Wei et al. (2014) and Miao et al. (2018). First, data during precipitation periods were excluded to avoid contamination from precipitation particles, which can introduce significant errors in Doppler-based wind retrieval. Second, within each profile over the 0.5-5.0 km height range, missing values and outliers exceeding 2.5 standard deviations from the mean were removed. Third, if more than 40% of the data points within this height range are outliers or missing, the entire profile was discarded. Fourth, discontinuous or missing data points were estimated using linear interpolation. Fifth, only observations within the 0.5-5.0 km height range were retained to avoid near-surface clutter and beam attenuation. The resulting quality-controlled RWP data were then used to calculate VWS according to Eq. (1) at the appropriate pressure level (700 hPa for stations with elevation < 3 km, and 500 hPa for stations with elevation ≥ 3 km).* "

References:

Miao, Y., Guo, J., Liu, S., Wei, W., Zhang, G., Lin, Y., and Zhai, P.: The Climatology of Low-Level Jet in Beijing and Guangzhou, China, *J. Geophys. Res.-Atmos.*, 123(5), 2816–2830, https://doi.org/10.1002/2017jd027321, 2018.

Wei, W., Zhang, H. S., and Ye, X. X.: Comparison of low-level jets along the north coast of China in summer, *J. Geophys. Res.-Atmos.*, 119(16), 9692–9706, https://doi.org/10.1002/2014jd021476, 2014.

3. Line 187: The manuscript should provide more details on the quality control procedures applied to the observations. For example, what types of artifacts were removed? Were thresholds applied to signal-to-noise ratio, reflectivity, velocity, or

other radar moments? Were insects, precipitation, ground clutter, or non-meteorological echoes filtered? Were quality flags provided by the instrument data stream used? Because cloud vertical structure statistics can be sensitive to radar sensitivity and QC choices, a more detailed description is needed to make the results reproducible and interpretable.

Response: We thank the reviewer for this detailed and constructive comment regarding the quality control procedures applied to the observations. We agree that the original manuscript lacked sufficient details on the QC procedures for the RWP data. To address this, we have made the following revisions:

First, we have expanded the description of RWP quality control in Section 2.2.2. as in the previous Response,

"*Before deriving VWS from the RWP measurements, we applied a multi-step quality control procedure following Wei et al. (2014) and Miao et al. (2018). First, data during precipitation periods were excluded to avoid contamination from precipitation particles, which can introduce significant errors in Doppler-based wind retrieval. Second, within each profile over the 0.5-5.0 km height range, missing values and outliers exceeding 2.5 standard deviations from the mean were removed. Third, if more than 40% of the data points within this height range are outliers or missing, the entire profile was discarded. Fourth, discontinuous or missing data points were estimated using linear interpolation. Fifth, only observations within the 0.5-5.0 km height range were retained to avoid near-surface clutter and beam attenuation. The resulting quality-controlled RWP data were then used to calculate VWS according to Eq. (1) at the appropriate pressure level (700 hPa for stations with elevation < 3 km, and 500 hPa for stations with elevation ≥ 3 km).* "

Second, regarding the MMCR data, we note that the QC procedures are already detailed in Section 2.3 of the revised manuscript. These include: (1) the height-dependent NER threshold (Eq. 4) to remove random instrumental noise; (2) the variance-based clutter suppression method (Kalapureddy et al., 2018) using $\mu<2.0$ dBZ and $\sigma<1.0$ dBZ to distinguish cloud signals from non-meteorological clutter (including ground clutter, insects, and turbulence-induced echoes); (3) the −20 dBZ reflectivity filter to exclude residual noise or sub-detection-limit echoes; and (4) thin-layer merging/removal rules (210 m thickness threshold and 720 m separation threshold) to reduce artificial layer fragmentation. These thresholds are consistent with established practices in Ka-band cloud radar studies (Clothiaux et al., 1999; Kalapureddy et al., 2018; Zhang et al., 2019).

4. ERA5 data have an hourly temporal resolution. Did the authors average or aggregate the MMCR observations to hourly resolution before matching them with ERA5? Please describe the temporal matching procedure clearly.

Response: We thank the Reviewer for this question. Prior to correlation analysis, we aggregated the original 1-minute MMCR observations to an hourly resolution and spatially matched them to the nearest ERA5 grid cell.

Specifically, for each station and each UTC hour, we calculated the hourly mean CBH, CTH, and cloud thickness (CT) from all valid 1-minute samples within that hour. The corresponding ERA5 variables (2 m specific humidity and lower-tropospheric stability) were extracted at the same UTC hour from the closest ERA5 grid point to the station. All subsequent correlation and joint-dependence analyses were performed on these fully synchronized, spatiotemporally matched hourly pairs.

We have added a full description of this procedure in Section 2.3 as follows:

"*With validated cloud boundaries in hand, we then prepared the data for correlation analysis. To ensure spatiotemporal consistency between the MMCR retrievals and ERA5 reanalysis, the 1-minute MMCR observations were first aggregated into hourly means of CBH, CTH, and CT. For each station, ERA5 meteorological variables were extracted at the corresponding UTC hour from the nearest grid point. All correlation and joint dependence analyses were subsequently conducted on these fully synchronized, spatiotemporally matched hourly paired datasets.*"

5. Line 223: The authors compare the detection limit of the China Ka-band cloud radars with ARM Ka-band radar observations. However, radar sensitivity depends strongly on hardware settings, calibration, operating mode, antenna configuration, pulse length, integration time, and processing algorithms. Please clarify how the authors confirmed that the detection limits are comparable between the ARM Ka-band radar and the China radar network. Were instrument specifications, calibration documents, or sensitivity estimates used? If not, the authors should be more cautious in making this comparison.

Response: We thank the reviewer for this careful observation. We apologize that our original wording may have inadvertently implied a direct comparison between of detection limits between the ARM MMCR and the China MMCR network. This was not our intention.

We referenced Clothiaux et al. (1999) solely to introduce the reflectivity threshold method and to explain why subsequent studies (e.g., Zhang et al., 2019; Chen et al., 2022; Fang et al., 2023) commonly adopt a threshold near −40 dBZ. It is a foundational paper documenting the typical reflectivity range of various cloud types observed by Ka-band cloud radars, not a comparison of instrument sensitivity between systems.

To remove any ambiguity, we have revised the relevant sentence in the manuscript as follows (Section 2.3):

"*In the literature, the reflectivity threshold method is a widely used approach for distinguishing cloud signals from background noise and clutter using a fixed reflectivity cutoff. Based on the operational characteristics of MMCR*, Clothiaux et al. (1999) reported that radar reflectivity (Z) for cirrus, stratus, and precipitating clouds typically ranges from –50 dBZ to 20 dBZ. Consequently, many previous studies have adopted a constant minimum threshold of approximately –40 dBZ for cloud detection (e.g., Zhang et al., 2019; Chen et al., 2022; Fang et al., 2023)."

This revision clarifies that Clothiaux et al. (1999) serves as a general literature reference for the reflectivity range of cloud targets, rather than as a specific instrument comparison. We appreciate the reviewer's suggestion, which has helped us improve the precision of our manuscript.

6. Line 295:I do not fully agree with the interpretation that the lower radar-derived cloud fraction relative to the MODIS long-term mean necessarily reflects a declining trend in total cloud fraction over East Asia. This difference could also be related to fundamental differences between observing systems.

Response: We thank the Reviewer for this important comment. We agree that our original interpretation placed undue emphasis on the long-term declining trend in cloud fraction over East Asia, without adequately acknowledging the fundamental differences between the two observing systems.

In the revised manuscript (Section 3.1), we have adopted a more balanced perspective that clearly delineates both contributing factors, as follows:

"This value is slightly lower than the long-term mean cloud fraction of approximately 61% derived from MODIS observations during 2003–2018 (Zhao et al., 2019). *Two factors may contribute to this disparity. First, the two quantities are not directly equivalent: MMCRs measure point-scale temporal cloud occurrence, whereas MODIS reports grid-averaged areal cloud fraction, and this fundamental difference warrants caution in quantitative comparisons. Second, the documented declining trend in cloud cover over East Asia (Zhou et al., 2022) may account for part of the offset, given that our 2024 observations represent a more recent period than the MODIS climatology. The relative contribution of this trend, however, cannot be isolated from the inherent observational differences.*"

7. Line 318: The authors correctly state that satellite products represent areal cloud fraction over large grid cells, whereas MMCR measurements capture local, vertically

resolved cloud occurrence. This is an important point. However, this also means that the manuscript should be very cautious when comparing satellite cloud fraction with MMCR-derived temporal cloud fraction. These two quantities are not directly equivalent. I suggest revising the relevant discussions.

Response: We thank the reviewer for this thoughtful and constructive comment. We fully agree that satellite-derived areal cloud fraction and MMCR-based temporal cloud occurrence are not directly equivalent quantities, and that any cross-platform comparison must be made with explicit caution.

In the revised manuscript, we have carefully revisited all such comparisons and added clarifying statements, as follows:

For the comparison of national mean values (Section 3.1): We have replaced the original one-sided attribution to a long-term trend with a balanced discussion that explicitly acknowledges the fundamental differences between the two data types. The revised text now reads:

"*Two factors may contribute to this disparity. First, the two quantities are not directly equivalent: MMCRs measure point-scale temporal cloud occurrence, whereas MODIS reports grid-averaged areal cloud fraction, and this fundamental difference warrants caution in quantitative comparisons. Second, the documented declining trend in cloud cover over East Asia (Zhou et al., 2022) may account for part of the offset, given that our 2024 observations represent a more recent period than the MODIS climatology. The relative contribution of this trend, however, cannot be isolated from the inherent observational differences.*"

8. Line 326:The discussion in this section relies mostly on citing previous studies. I suggest adding more analysis.

Response: We thank the reviewer for this constructive suggestion. To strengthen the analysis in Section 3.1, we have added additional quantitative analysis, as follows:

"*Single-layer clouds occur more frequently in northwestern China relative to southeastern regions (Fig. 3b), with the most substantial regional disparities in single-layer cloud frequency concentrated over arid inland basins and the Inner Mongolian Plateau. Multi-layer clouds show an opposite spatial tendency: their occurrence is consistently more prevalent throughout southeastern China than across inland northwestern areas (Fig. 3d). This regional divergence likely reflects differences in moisture availability and atmospheric instability. Southeastern China, influenced by abundant water vapor transport and intense solar heating, both of which favor deep convection and the development of vertically complex, multi-layered cloud system (Chi et al., 2022). By comparison, dry, stable boundary-layer conditions in northwestern China suppress vertical motion and cloud development, leading to single-layer clouds dominant (Chen et al., 2019).*

Two-layer cloud occurrence lacks a clear east-west or north-south spatial gradient nationwide (Fig. 3c), with only mild regional disparities in average occurrence separating southeastern and northwestern monitoring domains. This uniform distribution indicates two-layer clouds act as an intermediate transitional state between two dominant cloud regimes, and indicating that the transition from single-layer to multi-layer cloud systems cannot be described by a simple additive relationship. We separate two-layer from multi-layer clouds (⩾3 layers) because they exhibit distinct spatial patterns and formation mechanisms. Two-layer clouds lack a clear regional preference in both a previous global radiosonde study (Xu et al., 2023) and the present MMCR observations (Fig. 3c,d), confirming their transitional nature. Physically, two-layer clouds often result from boundary-layer decoupling (Bretherton and Wyant, 1997), whereas multi-layer clouds are more typical of organized deep convection or frontal systems. Merging these categories would conflate dynamically distinct cloud populations. ”

9. The authors state that cloud-base height is important for regional weather forecasting and climate change assessment, but this point needs clearer explanation. Please describe more specifically why CBH matters.

Response: We thank the Reviewer for this suggestion. In the revised manuscript, we have expanded the explanation of why CBH matters, grounding it in specific physical mechanisms and quantitative radiative sensitivities.

The revised text in Section 3.2 now reads:

“CBH, CTH, and CT are fundamental descriptors of cloud vertical structure. *Among these, CBH is particularly critical because of its role in modulating surface radiation and turbulent energy exchange, and because it serves as a key link between surface–atmosphere interactions and cloud formation. Dynamically, it influences the initiation and evolution of convective precipitation in numerical weather prediction models (Haliczer et al., 2025). Radiatively, it serves as a key variable for surface energy budget assessment: the cloud radiative effect at the surface decreases with increasing CBH at a rate of approximately 4–5 W m^{-2} per km at mid-latitude sites (Viúdez-Mora et al., 2015). Even modest uncertainties in CBH can produce substantial radiative biases—an uncertainty of 100 hPa in mid-level cloud base pressure can cause errors of at least 10 W m^{-2} in surface net longwave radiation (Fung et al., 1984), and smaller variations at lower levels can yield even larger uncertainties. Accurate CBH observations are therefore essential for quantifying cloud feedbacks in a changing climate (Zelinka and Hartmann, 2010; Costa-Surós et al., 2013).*”

References:

Costa-Surós, M., Calbó, J., González, J.A., and Martin-Vide, J.: Behavior of cloud base height from ceilometer measurements, *Atmos. Res.*, 127, 64−76, https://doi.org/10.1016/j.atmosres.2013.02.005, 2013.

Fung, I.Y., Harrison, D.E., and Lacis, A.A.: On the variability of the net longwave radiation at the ocean surface, Rev. Geophys., 22, 177–193, https://doi.org/10.1029/RG022i002p00177, 1984.

Haliczer, D.T., Mecikalski, J.R., and Kollias, P.: Use of satellite, surface observations and numerical weather prediction model data to improve cloud base height and cloud base vertical velocity estimation, *J. Geophys. Res.-Atmos*, 130, e2024JD041853, https://doi.org/10.1029/2024JD041853, 2025.

Valdez-Mora, A., Costa-Surós, M., Calbó, J., and González, J.A.: Modeling atmospheric longwave radiation at the surface during overcast skies: The role of cloud base height, J. Geophys. Res.-Atmos., 120, 199–214, https://doi.org/10.1002/2014JD022310, 2015.

Zelinka, M.D., and Hartmann, D.L.: Why is longwave cloud feedback positive? *J. Geophys. Res.*, 115, 1−16, https://doi.org/10.1029/2010JD013817, 2010.

10.Line 390: Please check the citation of Shupe et al. 2011. I guess that Shupe et al. focused primarily on Arctic (or high-latitude) cloud observations. If so, the citation may not be directly applicable to mid-latitude or China-region cloud regimes.

Response: We thank the Reviewer for this careful check. The Reviewer is correct that Shupe et al. (2011) focused on Arctic clouds. We agree that citing an Arctic-specific study to support a mid-latitude finding over China is inappropriate. We have therefore replaced the citation with studies directly relevant to the China region.

The sentence was revised as follows:

"This seasonal progression is consistent with previous studies (e.g., *Zhang et al., 2018*; Chi et al., 2022; Xu et al., 2023) and reflects the strong modulation of cloud formation by radiative forcing and boundary-layer dynamics."

Reference:

Zhang, Y., Zhang, L. J., Guo, J. P., Feng, J. M., Cao, L. J., Wang, Y., Zhou, Q., Li, L. X., Li, B., Xu, H., Liu, L., An, N., and Liu. H.: Climatology of cloud-base height from long-term radiosonde measurements in China, *Adv. Atmos. Sci.*, 35, 158−168, https://doi.org/10.1007/s00376-017-7096-0, 2018.