Response to Reviewers' Comments

Reviewer #1:

'Comment on egusphere-2026-1091'.

General Comments

This manuscript presents a comprehensive analysis of cloud vertical structure (CVS) across China using a national network of 80 MMCRs for the year 2024. The authors develop an improved CVS retrieval algorithm that incorporates height-dependent radar sensitivity and variance-based clutter suppression. They systematically characterize the spatial, seasonal, and diurnal variations of CVS metrics (cloud base height, cloud top height, cloud thickness, and cloud layer number) and quantify the regulatory effects of thermodynamic (lower-tropospheric stability, specific humidity at 850 hPa), dynamical (wind shear at 700 hPa), and land-surface factors. The findings provide valuable observational benchmarks for evaluating and improving cloud parameterization schemes in weather and climate models. Overall, the manuscript is well written and the concepts are clearly presented. However, several major and minor issues require further improvement. Therefore, I recommend that the authors revise their manuscript to address the following comments.

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, a series of revisions have been implemented, including streamlining the discussion of cloud thickness to eliminate redundancy, adding concise descriptions of supplementary Figures S3 and S4, and improving figure consistency to enhance the overall quality of the manuscript. We have also revised several potentially absolute statements to more rigorous wording and clarified the spatial scale mismatch between ERA5 reanalysis and MMCR point-based observations as a potential limitation. For more details, please refer to the revision manuscript.

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. The discussion of cloud thickness (CT) appears in Sections 3.5.3 (single-factor correlations) and 3.6.3 (bivariate analysis). While both add value, some redundancy exists. Consider streamlining the single-factor section to focus on broad patterns and reserving detailed interaction effects for the bivariate section.

Response: We agree with the reviewer that there was some overlap between the single-factor and bivariate discussions of cloud thickness (CT). In the revised manuscript, we have carefully streamlined the single-factor section (now Section 3.5.3) to focus on the dominant annual correlation patterns and their spatial characteristics. All detailed interaction effects, conditional responses, and combined constraints are now exclusively presented and discussed in the bivariate analysis (joint dependence on paired variables, Fig. 13).

Specifically, in the single-factor section, we have removed extended physical interpretation that duplicated the bivariate discussion, condensed the description of seasonal modulation to a single sentence per variable, keeping only the range of seasonal station percentages as supporting evidence, and shifted the mechanistic explanation of conditional behavior (e.g., why moisture alone is insufficient to guarantee thick clouds) entirely to the bivariate section.

As a result, the single-factor section now concentrates on what the broad patterns are, while the bivariate section addresses how the factors jointly constrain CT. We believe this revision eliminates redundancy and makes the logical flow clearer. The text about cloud thickness was revised in the revised manuscript, as follows (Lines 688–743):

"3.5.3 Impact of atmospheric thermal and dynamical factors on CT

Cloud thickness exhibits distinct correlation patterns that differ from those of CBH and CTH (Fig. 12). For q_{2m} *(Fig. 12a), positive correlations dominate across 71.3% of stations, indicating that abundant low-level moisture favors vertically extended clouds. This relationship is pronounced over southern China and the eastern Tibetan Plateau margins, where active moist convection prevails. Higher specific humidity sustains positive buoyancy over deeper layers, promoting thicker clouds (Johnson et al., 1999; Holloway and Neelin, 2009). Negative correlations (28.7% of stations), scattered over arid northwestern China and parts of Inner Mongolia, may reflect environments where moisture is insufficient to support deep convective development. Seasonal composite analyses (Fig. S8 a-d) show that this positive coupling is most widespread in summer (71.3%) and weakest in autumn (40.0%), confirming the strong but seasonally modulated link between moisture and cloud vertical extent.*

For LTS_{surf} *(Fig. 12b), cloud thickness shows a nearly equal split between positive and negative correlations (50% of each), with a spatially heterogeneous,* intermingled pattern across China rather than any dominant geographic signature. This mixed pattern reflects the dual role of thermodynamic stability in cloud development. On one hand, enhanced stability (e.g., strong temperature inversions) typically suppresses convective development, leading to negative correlations. On the other hand, stable stratification can favor the maintenance and thickening of stratiform clouds trapped beneath the inversion layer, especially under sustained moisture supply, thereby yielding positive correlations (Klein and Hartmann, 1993; Wood and Bretherton, 2006). Critically, seasonal composite analyses (Fig. S8 e-h) reveal that positive correlations dominate in summer (76.3%), when extensive stratiform cloud decks associated with the East Asian summer monsoon are prevalent, while the other seasons remain near parity. This seasonal contrast directly supports the interpretation that the sign of the CT – relationship is governed by the prevailing cloud type and moisture regime, rather than by stability alone.

Cloud thickness shows a predominantly negative correlation with VWS (73.9% of stations; Fig. 12c), indicating that stronger vertical wind shear generally suppresses vertical cloud development. Negative correlations are widespread across southern China, the Tibetan Plateau margins, northeastern China, and the North China Plain. Positive correlations (26.1% of stations), scattered across limited areas of northwestern China, may reflect environments where moderate shear organizes convection into longer-lived systems capable of greater vertical development consistent with the "optimal shear" concept (Weisman and Rotunno, 2000). Seasonally (Fig. S8 i-l), negative correlations are most widespread in winter (65.0%) and spring (61.4%), and least so in summer (41.3%), suggesting that the suppressing effect of shear on cloud thickness is more pronounced when deep convection is less frequent, while in summer, organized convective regimes may partially offset this suppression (Weisman and Rotunno, 2000; Houze, 2018).

CT exhibits distinct joint-dependence characteristics that integrate the controls on both cloud-base and cloud-top environmental processes. For the q_{2m}-LTS_{surf} combination (Fig. 13a), the thickest clouds occur under high specific humidity combined with high lower-tropospheric stability. This indicates that under high-humidity conditions, stronger stable stratification does not necessarily suppress cloud thickness; rather, it can support the accumulation of thick stratiform cloud layers beneath the inversion by trapping moisture within a confined boundary layer, thereby yielding considerable geometric thickness (Klein and Hartmann, 1993; Wood and Bretherton, 2006).

For the LTS_{surf}-VWS combination (Fig. 13b), the maximum CT occurs under moderate LTS_{surf} and moderate vertical wind shear. Both excessively high LTS_{surf} and intense shear markedly reduce cloud thickness. High LTS_{surf} strongly *suppresses deep convection, whereas intense shear enhances turbulent entrainment at the cloud top and disrupts organized updraft structures, thereby limiting vertical growth. In contrast, the combination of moderate stability and moderate shear provides conditions that are favorable for organizing cloud systems and allowing greater vertical development, without being overly constrained by either extreme stability or excessive turbulence (Weisman and Rotunno, 2000).*

For the q_{2m}*-VWS combination (Fig. 13c), CT increases primarily with humidity. Under low-humidity conditions, CT remains uniformly small regardless of shear intensity. Under high-humidity conditions, however, CT tends to increase with wind shear up to moderate–strong values. This indicates that moisture availability is the fundamental precondition for thick clouds, while moderate to strong shear can further enhances the vertical extent of moisture-rich air masses by modulating cloud organization and dynamic mixing. Collectively, these joint results confirm that moisture acts as the dominant driver for deep cloud systems, while stability and shear functions as strong regulators that either suppress or facilitate vertical development depending on their specific magnitudes.*

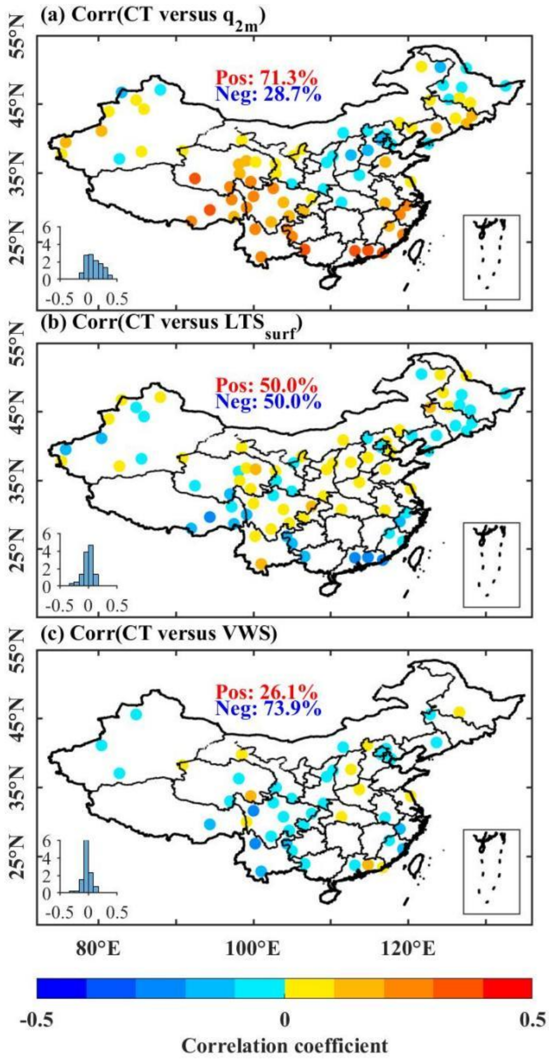

Figure 12. *Similar as Figure 8, but for CT*.

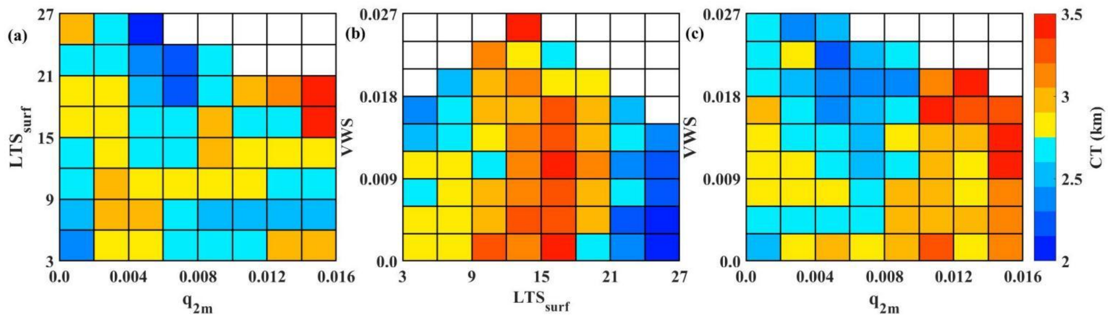

Figure 13. *Similar as Figure 9, but for CT*.

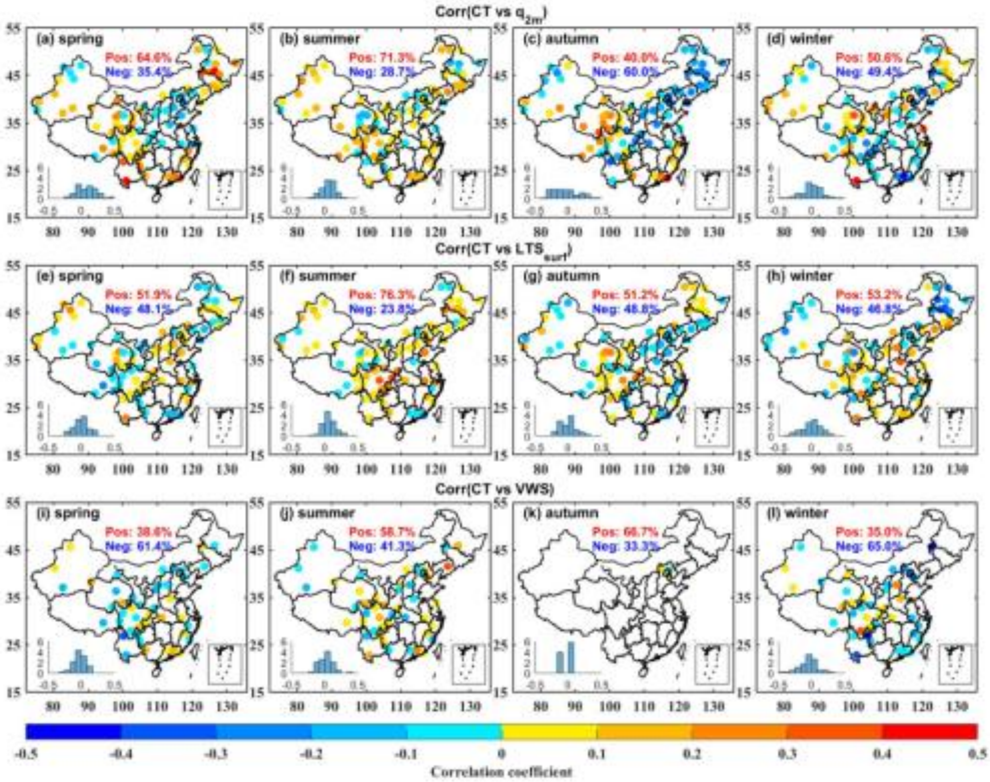

***Figure S8**. Similar as Figure S6, but for CT.* ”

Similar revision also has been done for CBH and CTH. Please see the details in the revised manuscript.

2. Supplementary figures (S2, S3) are mentioned but not described in the main text. Please add a brief summary of their key patterns (e.g., seasonal CTH and CT distributions) to make the main text more self-contained.

Response: We have added concise descriptions of the key spatial patterns shown in Figures S3 (seasonal CTH distribution) and S4 (seasonal CT distribution) in the revised version within Section 3.2. The revised text is provided below.

"CTH exhibits similar seasonal variability (Fig. S3), with mean values of 7.51 ± 1.00 km in summer, 6.37 ± 0.93 km in spring, 5.70 ± 0.71 km in autumn, and 4.70 ± 1.33 km in winter. *As shown in Fig. S3, summer CTH exceeds 8 km over much of eastern China (especially in the south) but remains below 6 km over the Tibetan Plateau. However, this east–west contrast diminishes in winter, when CTH is low (generally 3–5 km) across most of the country*. The higher summer CTH reflects enhanced convective instability and stronger vertical development, whereas wintertime stability limits cloud growth largely to the lower troposphere. Regionally, CTH over the Tibetan Plateau is systematically lower than over eastern China. This finding is consistent with Chen et al. (2017), who reported that deep convective clouds over the Plateau are approximately 20 – 30% thinner than those over eastern China, and with Luo et al. (2011), who noted that convection over the Plateau is generally shallower and less frequent. The reduced vertical extent may be related to weaker large-scale dynamical forcing and frequent weak upward motion over the Plateau (Chen et al., 2017)."

"CT follows a seasonal cycle similar to that of CTH, with mean values of 3.56 ± 0.72 km in summer, 3.13 ± 0.49 km in spring, 2.93 ± 0.47 km in autumn, and 2.56 ± 0.72 km in winter (Fig. S4). *In summer, the thickest clouds (~4 km) occur over southern China and the eastern Tibetan Plateau margins, whereas winter clouds are uniformly thin (~2 km) across the country. The spatial pattern of CT largely follows that of CTH, indicating that thicker clouds are primarily associated with higher cloud tops rather than lower bases.* The larger CT during summer reflects the combined effects of enhanced instability, deeper convective development, and increased moisture availability, while the thinner winter clouds are consistent with suppressed vertical growth under stable atmospheric stratification."

3. ERA5 represents large-scale atmospheric conditions at 0.25° resolution (~31 km), whereas MMCR observations are point-based. The mismatch in spatial scales may introduce uncertainties, particularly in regions with complex terrain or strong local gradients. Please add a brief discussion of this limitation.

Response: We thank the Reviewer for this suggestion. We fully agree that the spatial scale mismatch between ERA5 (~31 km) and point-based MMCR observations may introduce uncertainties, particularly over complex terrain. In the revised manuscript (Section 2.2.3), we have added a discussion acknowledging this limitation. We also performed a sensitivity test using the higher-resolution ERA5-Land (0.1°), which confirmed that the key correlation patterns are robust to grid resolution (Supplementary Figs. S5). The added text reads (Lines 241-252):

"*A spatial scale mismatch inevitably exists between the gridded ERA5 fields (~31 km) and the point-based MMCR observations, which may introduce uncertainties over complex terrain and regions with strong surface heterogeneity. To evaluate the sensitivity of our results to this mismatch, we repeated the key correlation analyses using ERA5-Land (0.1°× 0.1°, ~9 km), which better resolves near-surface variability. The comparison (Figs. S5) shows that the correlation signs, spatial patterns, and magnitudes are highly consistent between the two products, confirming that our conclusions are not sensitive to the specific grid resolution. While some local-scale uncertainty is inherent in any point-to-grid comparison, the consistent spatial patterns across diverse climatic and topographic settings indicate that the identified relationships reflect robust large-scale physical mechanisms. The procedure for* *temporally aggregating the MMCR observations and matching them with ERA5 is described in Section 2.3.*”

Minor Comments

4. Lines 117-120: Introduction. The statement “no previous study has ever provided a national-scale, high-frequency characterization of CVS across China using a coordinated ground-based radar network” may be overly absolute. Please revise it.

Response: We have revised the description to a more rigorous and objective version, as follows (Lines 115-118):

“Despite these advances, most studies have focused on isolated factors or localized regions. *To our knowledge, a national-scale, high-frequency characterization of CVS across China based on a coordinated ground-based radar network remains lacking, and the combined thermodynamic, dynamical, and land-surface controls have yet to be systematically quantified.*”

5. Line 348, Section 3.2 paragraph 2: "favouring higher cloud bases." → "favoring" (consistent with American English spelling used throughout the manuscript).

Response: Done as suggested.

6. Reference list: Slingo, J. M. (2007) → The year in the text (Slingo, 1987) does not match the reference year; please correct the reference or the in-text citation.

Response: We thank the reviewer for pointing out this inconsistency. Upon checking, the correct publication year of Slingo’s classic paper on the cloud prediction scheme for the ECMWF model is indeed 1987, not 2007. Therefore, we have corrected the reference list entry from “2007” to “1987” to match the in-text citation. The correction has been made in the corresponding location in the main text as follows:

Slingo, J. M.: The development and verification of a cloud prediction scheme for the ECMWF model, *Quart. J. Roy. Meteor. Soc.*, 113, 899–927, https://doi.org/10.1002/qj.49711347710, 1987.

7. The term “lifting condensation level (LCL)” is used multiple times in the text. After its first definition, please use only “LCL” thereafter to avoid repetition.

Response: Done as suggested.

8. Figure 3. Please unify the longitude range in Figure 3 with that in the other figures.

Response: Corrected as suggested. The corrected figure is as follows,

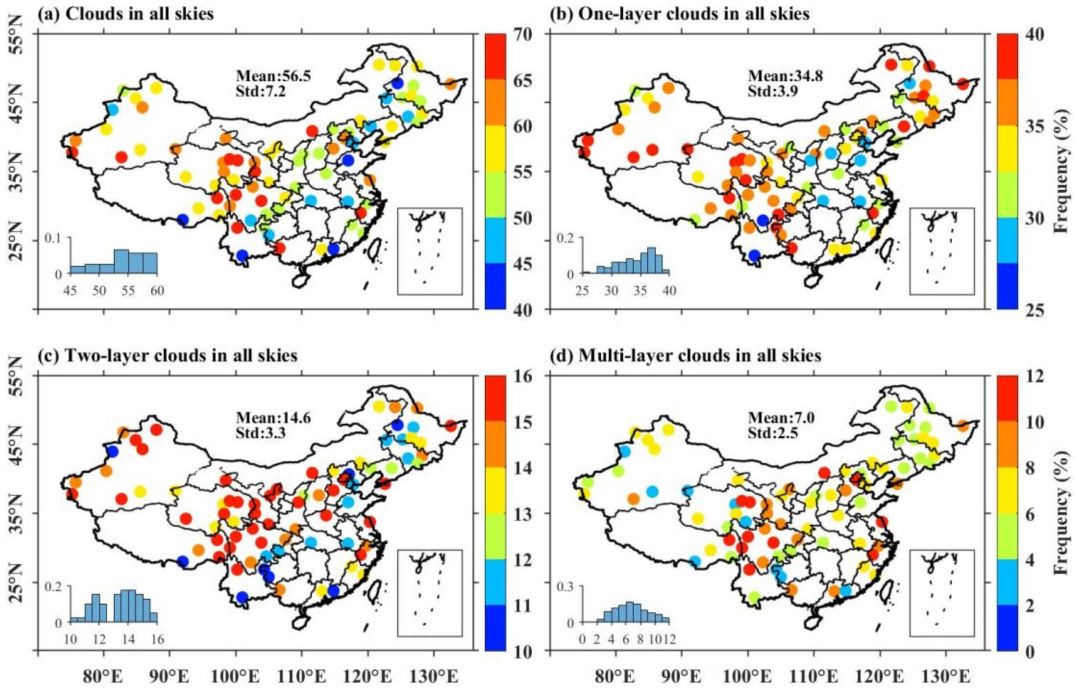

Figure 3. Spatial distribution of annual mean cloud occurrence frequency for different cloud layering classifications: (a) all clouds, (b) single-layer clouds, (c) two-layer clouds, and (d) multi-layer clouds (three-, four-, and five-layer clouds) under all-sky conditions in 2024. The data is derived from the 80 MMCR stations presented in Figure 1. Notably, the color bars are scaled independently across panels to improve visual clarity. In addition, each panel shows the histograms depicting the probability distributions of cloud occurrence frequencies, with the corresponding mean values and standard deviations also presented for each distribution.

9. Figure 15. The MMCR has been defined in Figure 1 already. Therefore, you don not need to define it here.

Response: The caption was corrected as follows (Lines 1350 to 1355),

"Figure 15. Schematic diagram showing (a) the national *MMCR* network across China in 2024, (b) the vertical distribution of cloud occurrence frequency in summer (red) and winter (blue), and (c) the key controlling factors (thermodynamic, dynamical, and land-surface) of the CVS. Upward and downward arrows indicate increases and decreases, respectively, in panel (c)."

10. In Section 3.7, "afternoon single-layer clouds" are defined as those occurring during peak daytime heating, but the exact time window is not specified. Please define "afternoon" (e.g., 1400–1800 LT) explicitly to ensure reproducibility.

Response: In the revised manuscript, we have explicitly defined the time window for "afternoon single-layer clouds" as 1400–1800 LT. Accordingly, we revised this sentence as follows:

“To quantify land-surface influences, we compare CBH across land cover types under two conditions: (i) *all-hour low clouds* and (ii) *afternoon (1400-1800 LT) single-layer low clouds* (Fig. 14). ”

11. Line 651-668: There is a numbering error: “3.7.1 All-cloud conditions” is followed by “3.7.1 Afternoon single-layer clouds.” The second subsection should be numbered “3.7.2.” Please correct.

Response: Corrected as suggested.