



Supplement of

Cloud vertical structure across China from a national Ka-band cloud radar network: thermodynamic, dynamical, and land-surface controls

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1. Algorithm performance evaluation and case-based validation

To evaluate the performance of our improved retrieval algorithm, we first present an example case (Fig. S1) illustrating its robustness under complex vertical conditions, and then conduct a case-based validation using independent radiosonde observations. The validation focuses on cloud types that are typically challenging for retrieval, including low-level thin cloud, thin mid-level cloud, thick high-level cloud, multi-layer cloud, and deep precipitating cloud. Six representative cases covering these categories were selected.

For each of the six cases, we constructed standardized three-panel comparative plots and integrated them into a unified supplementary figure (Fig. S2). The left panel shows the statistical distribution of 30-minute MMCR reflectivity samples, overlaid with three height-dependent detection thresholds (S_0 , S_1 , S_2) for signal reliability validation. The middle panel presents the 30-minute time-height cross-section of MMCR radar reflectivity, with markers indicating our retrieved CBH and CTH. The right panel illustrates cloud layers diagnosed from collocated radiosonde profiles using the relative-humidity-gradient method proposed by Xu et al. (2023), with green shading denoting the identified cloud boundaries.

The detailed validation results are summarized as follows:

Case 1 (low-level thin cloud): Panels a1 and b1 show a distinct single-layer boundary-layer cloud situated at an altitude of roughly 500 m, with a vertical extent of only 200–300 m. Our variance-based ground clutter suppression effectively isolates this shallow cloud signal from low-level ground interference (b1). The CBH and CTH retrieved from MMCR match the near-surface saturated humidity layer diagnosed by collocated radiosonde profiles (c1), with nearly negligible vertical offsets between radar and radiosonde cloud boundaries. This close agreement validates the effectiveness of our variance-based criteria for distinguishing true cloud echoes from ground clutter.

Case 2 (mid-level thin cloud): This single-layer cloud continuously occupies the 4–6 km altitude range with weak-to-moderate radar reflectivity (a2, b2). The height-dependent thresholds, combined with a -20 dBZ minimum reflectivity cutoff, effectively isolate these faint mid-level cloud echoes from background noise. The excellent agreement between MMCR-retrieved cloud boundaries (CBH/CTH) and radiosonde-derived cloud boundaries, with nearly negligible vertical offsets (c2), confirms that this cutoff reliably retains true cloud signals while excluding noise.

Case 3 (high-level thick cloud): This single-layer cloud extends from roughly 9 to 12 km with relatively weak-to-moderate reflectivity (a3, b3). After variance-based clutter suppression removes spurious low-level noise (4–6 km), the -20 dBZ reflectivity threshold is applied to isolate genuine cloud signals. The resulting

65 MMCR-retrieved CBH and CTH align closely with the radiosonde-diagnosed saturated upper-tropospheric humidity band, with vertical offsets consistently within 0.5 km (c3), which further confirms that the -20 dBZ threshold effectively filters out noise without erroneously removing authentic cloud signals.

Case 4 (multi-layer cloud, first scenario): This case consists of vertically
70 overlapping mid-level cloud echoes characterized by extensive moderate-to-strong radar reflectivity signals (panels a4, b4). The combination of height-dependent sensitivity thresholds and variance-based ground clutter filtering reliably isolates genuine cloud echoes from low-altitude ground interference and instrumental background noise. The time–height cross-section (b4) reveals that the cloud vertical
75 structure evolves rapidly over the half-hour observation window, with the number of distinct cloud decks varying from one to three layers. Our algorithm accurately tracks these individual cloud layers during their formation, merging and dissipation processes, and marks the CBH and CTH of each layer with dedicated symbols, which validates the robustness of our rules for thin-cloud merging and elimination. In
80 comparison, the radiosonde humidity profile (green shaded saturated region in c4) only provides a single instantaneous snapshot and fails to capture such temporal variability; it merely presents a unified continuous saturated layer that integrates all vertically separated cloud decks.

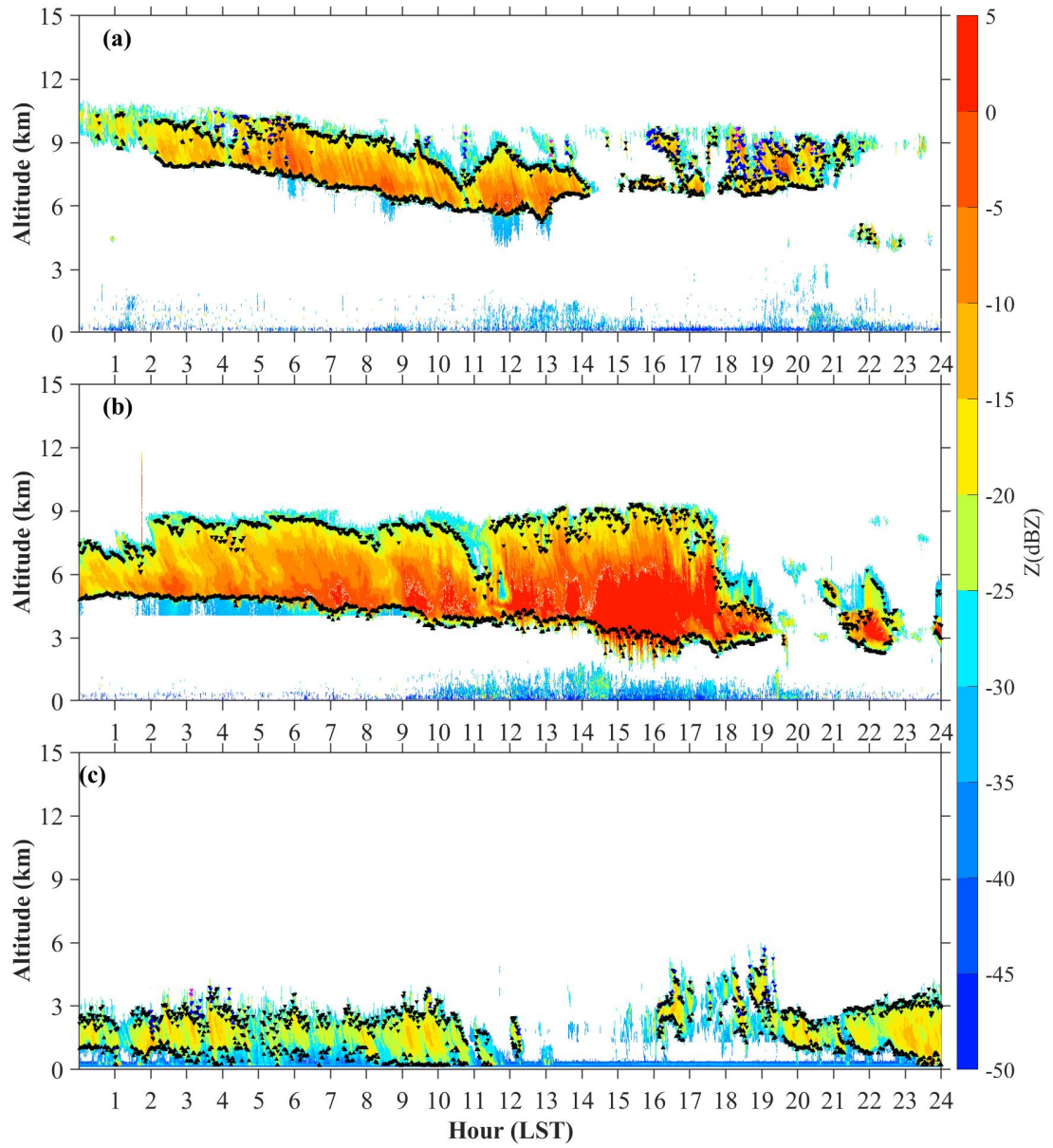
Case 5 (multi-layer cloud, second scenario): This analogous multi-layer case
85 (panels a5, b5, c5) further validates the robustness of our retrieval scheme under complex multi-layer conditions. As in Case 4, our algorithm successfully resolves vertically stacked thin-to-moderate cloud layers, avoids false detection amid overlapping echoes.

Case 6 (deep precipitating cloud): This case features a deep precipitating cloud
90 extending from near-surface to ~11 km with strong reflectivity (a6, b6). Height-dependent thresholds and variance-based clutter filtering reliably separate cloud and precipitation signals from ground interference, and the algorithm correctly identifies the continuous cloud boundaries (CBH/CTH) throughout the observation period. The collocated radiosonde profile (c6) shows a deep saturated layer, which
95 matches the MMCR-retrieved cloud extent closely, with only minor vertical differences (within 1 km). This confirms that the retrieval framework remains robust and produces credible cloud boundaries even for deep, heavily precipitating systems.

References:

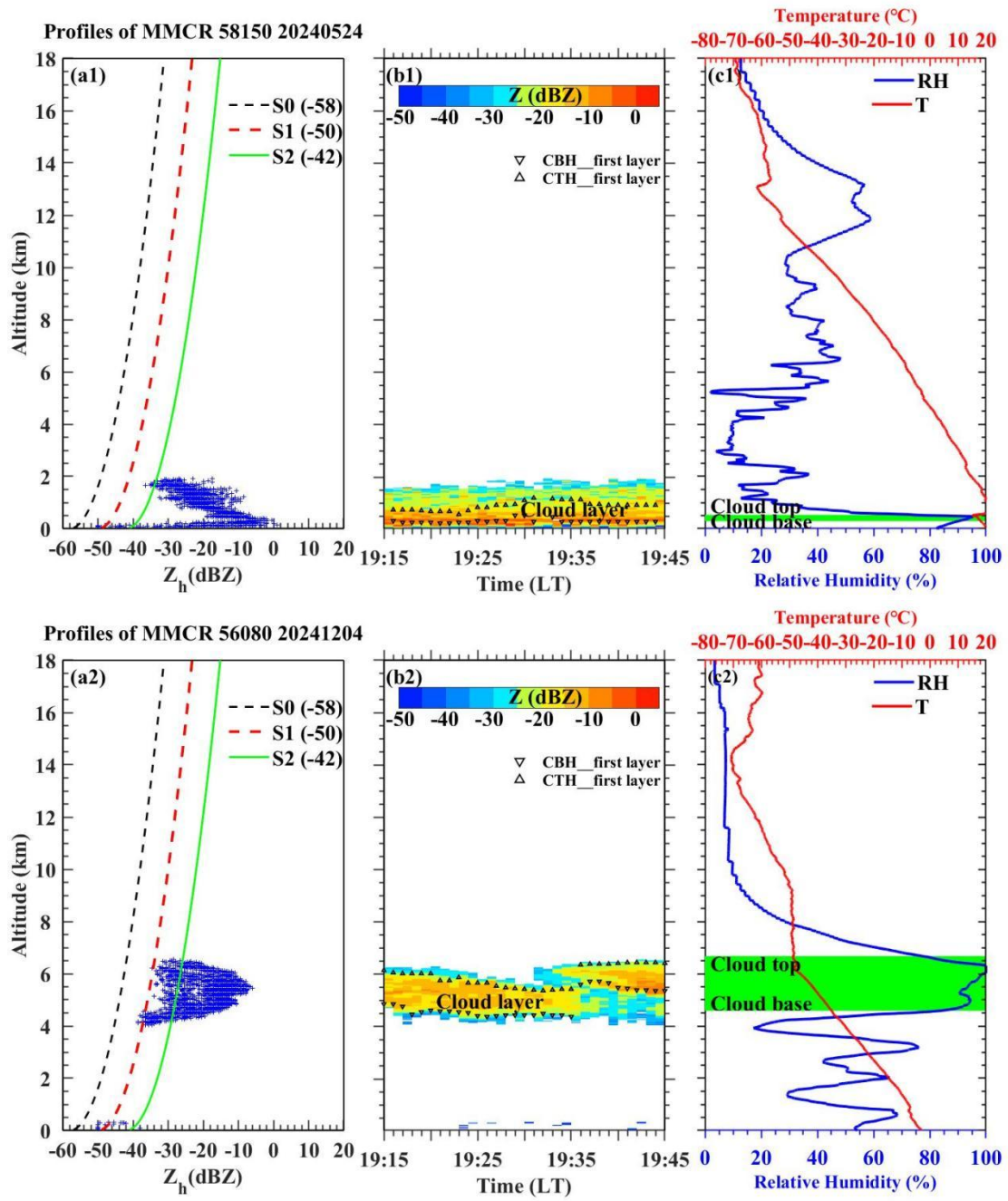
100 Xu, H., Guo, J., Tong, B., Zhang, J., Chen, T., Guo, X., Zhang, J., and Chen, W.: Characterizing the near-global cloud vertical structures over land using high-resolution radiosonde measurements, *Atmos. Chem. Phys.*, 23, 15011–15038, <https://doi.org/10.5194/acp-23-15011-2023>, 2023.

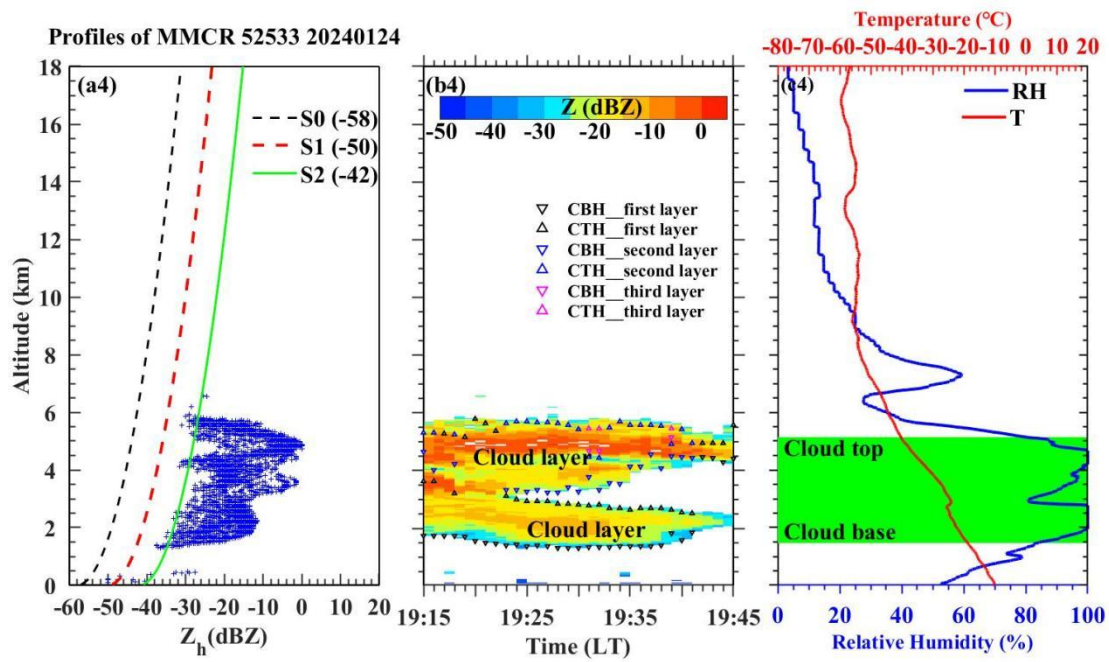
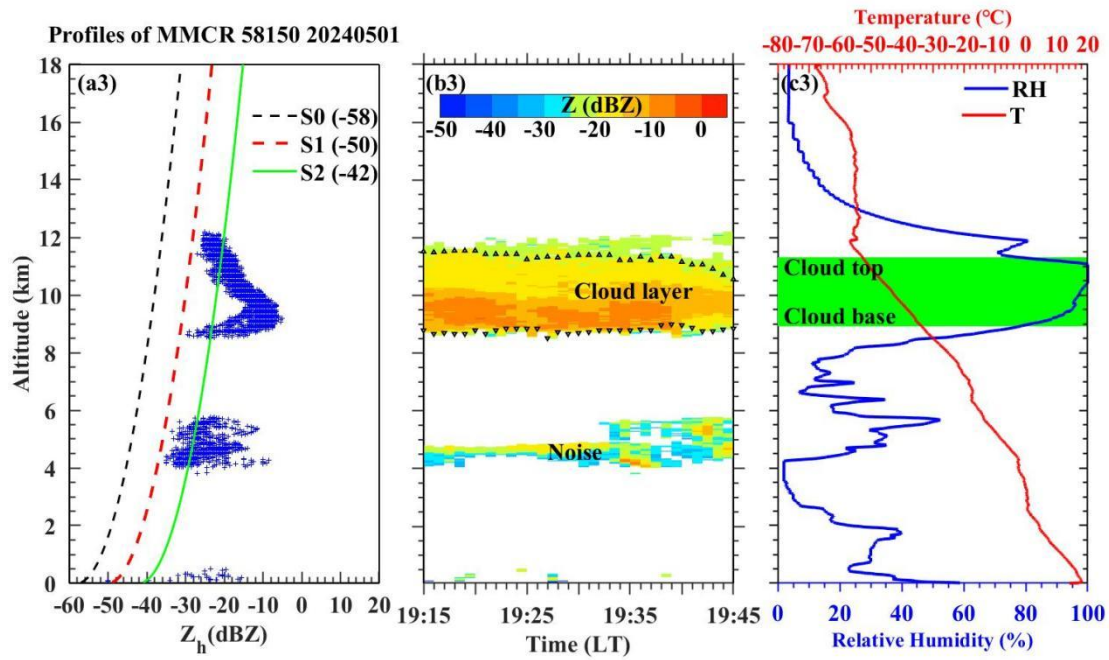
▲ CBH(first layer) ▼ CTH(first layer) ▲ CBH(second layer) ▼ CTH(second layer) ▲ CBH(third layer) ▼ CTH(third layer)



105 **Figure S1.** Examples of cloud vertical structure (CVS) detection for three selected cases: (a) high cloud, (b) middle cloud, and (b) low cloud.

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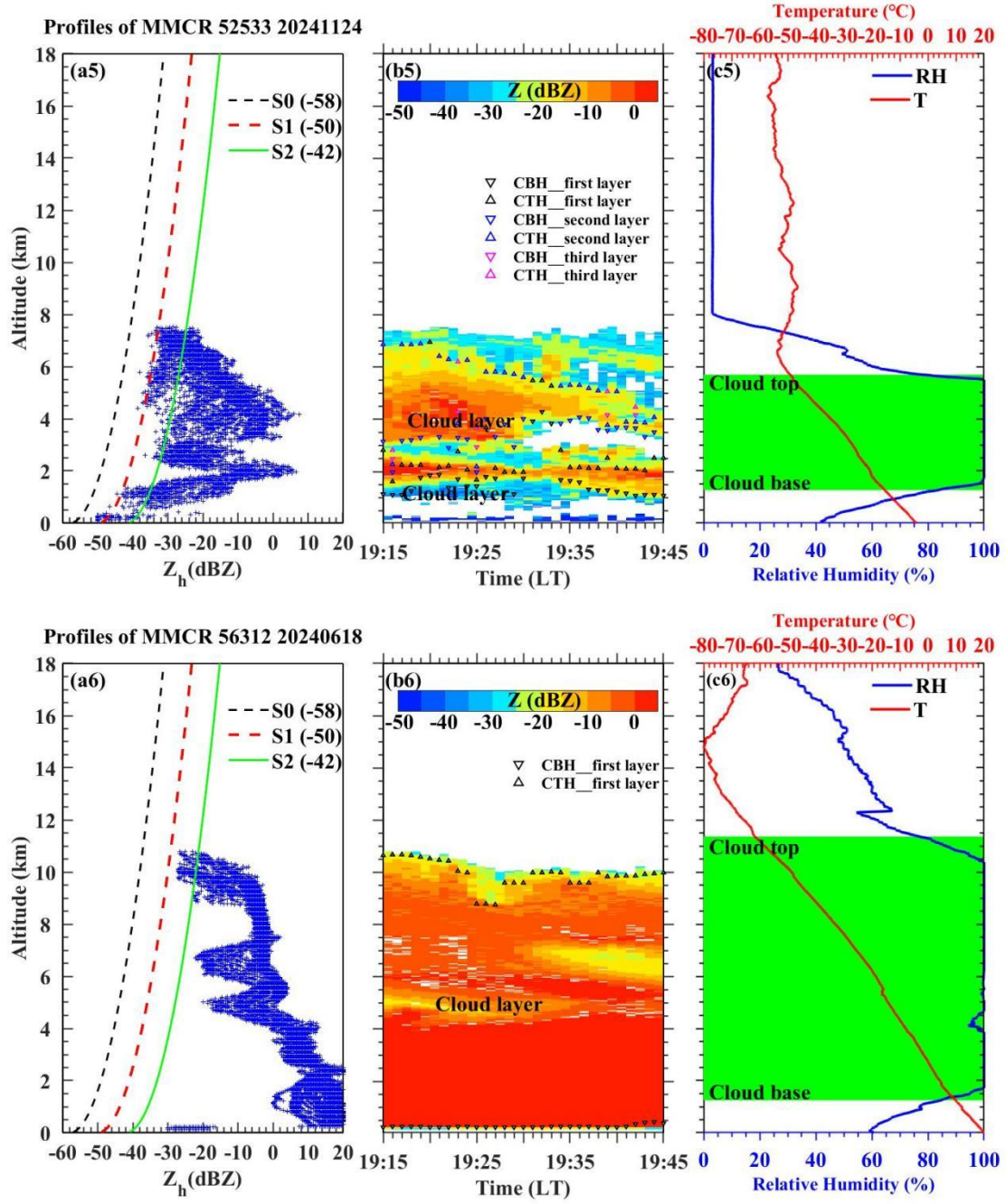


Figure S2. Comparison of six representative cases between MMCR-retrieved CVS and collocated radiosonde cloud layers. The first column of panels shows height-dependent detection thresholds S0, S1, and S2 (with their respective threshold values indicated in brackets) overlaid with instantaneous radar reflectivity samples. The middle column presents time-height cross-sections of MMCR reflectivity factor Z (dBZ), with inverted triangles and triangles marking the retrieved cloud base height (CBH) and cloud top height (CTH), respectively. The right column displays radiosonde profiles of relative humidity (RH, blue curve) and temperature (T, red curve); green horizontal bars denote cloud boundaries diagnosed via the humidity-gradient method of Xu et al. (2023). Each row (rows 1-6) corresponds to one validation case.

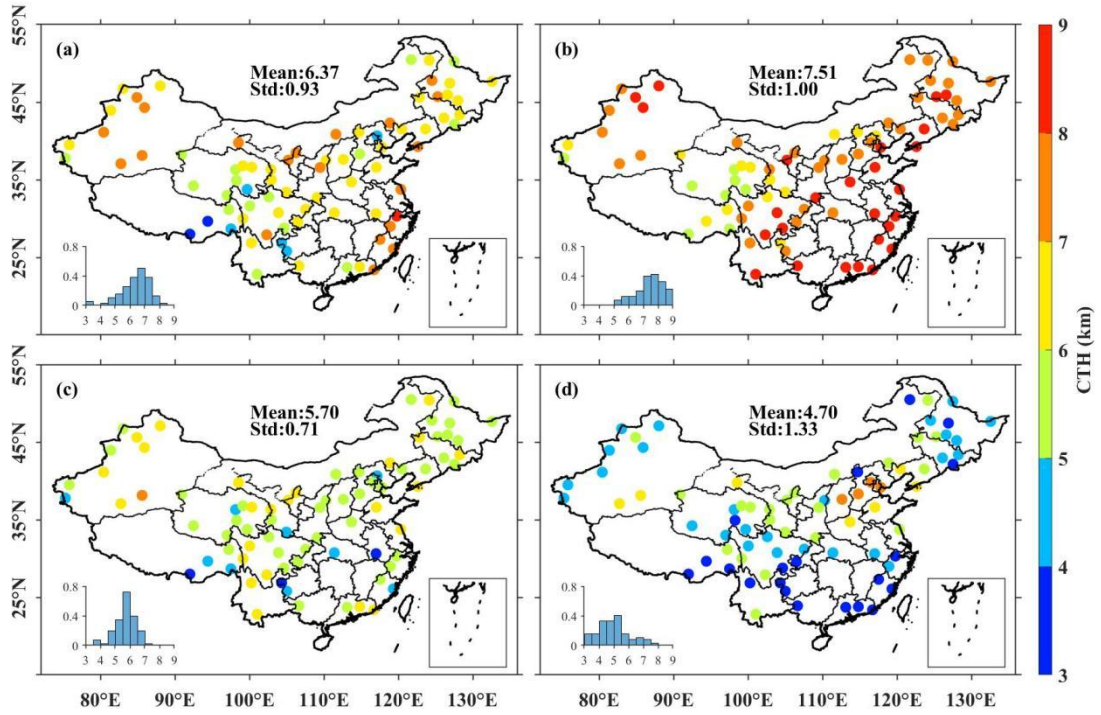


Figure S3. Seasonal geographic distribution of CTH over China in 2024, derived from the 80 MMCR stations of the same network referenced in Figure 1. The four panels correspond to (a) spring (March–April–May), (b) summer (June–July–August), (c) autumn (September–October–November), and (d) winter (December–January–February). Note that each panel presents a histogram illustrating the probability distribution of cloud occurrence frequency, with the corresponding mean value and standard deviation provided for each distribution.

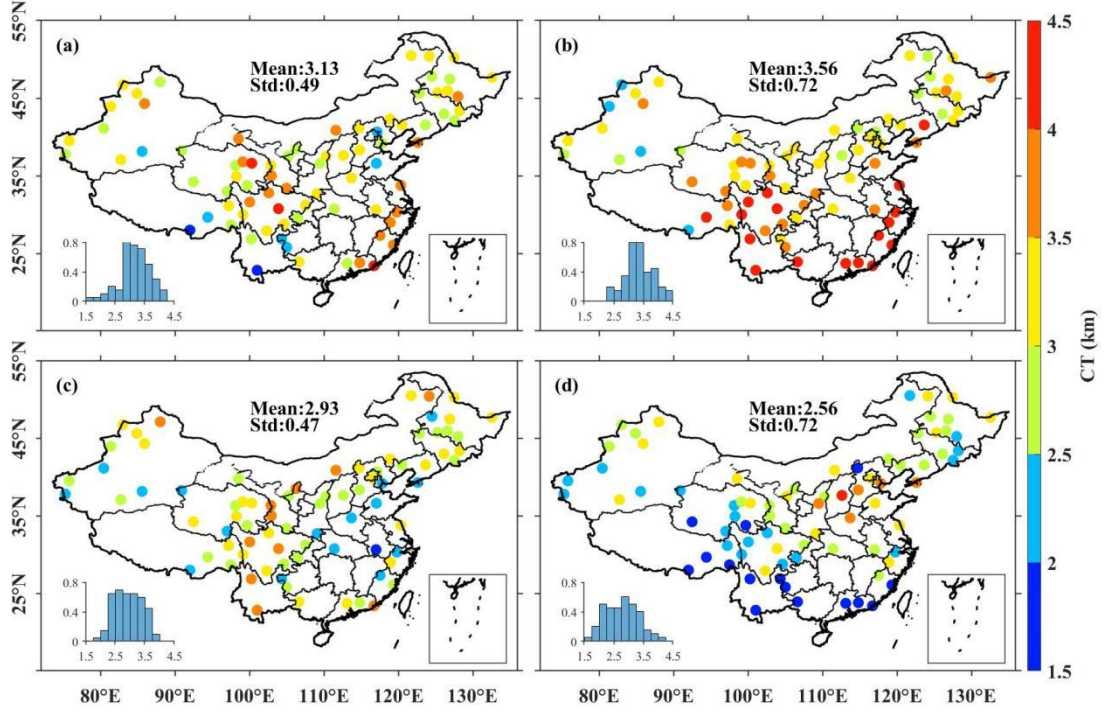


Figure S4. Seasonal geographic distribution of cloud thickness (CT) over China in 2024, derived from the 80 MMCR stations of the same network referenced in Figure 1. The four panels correspond to (a) spring, (b) summer, (c) autumn, and (d) winter. Note that each panel presents a histogram illustrating the probability distribution of cloud occurrence frequency, with the corresponding mean value and standard deviation provided for each distribution.

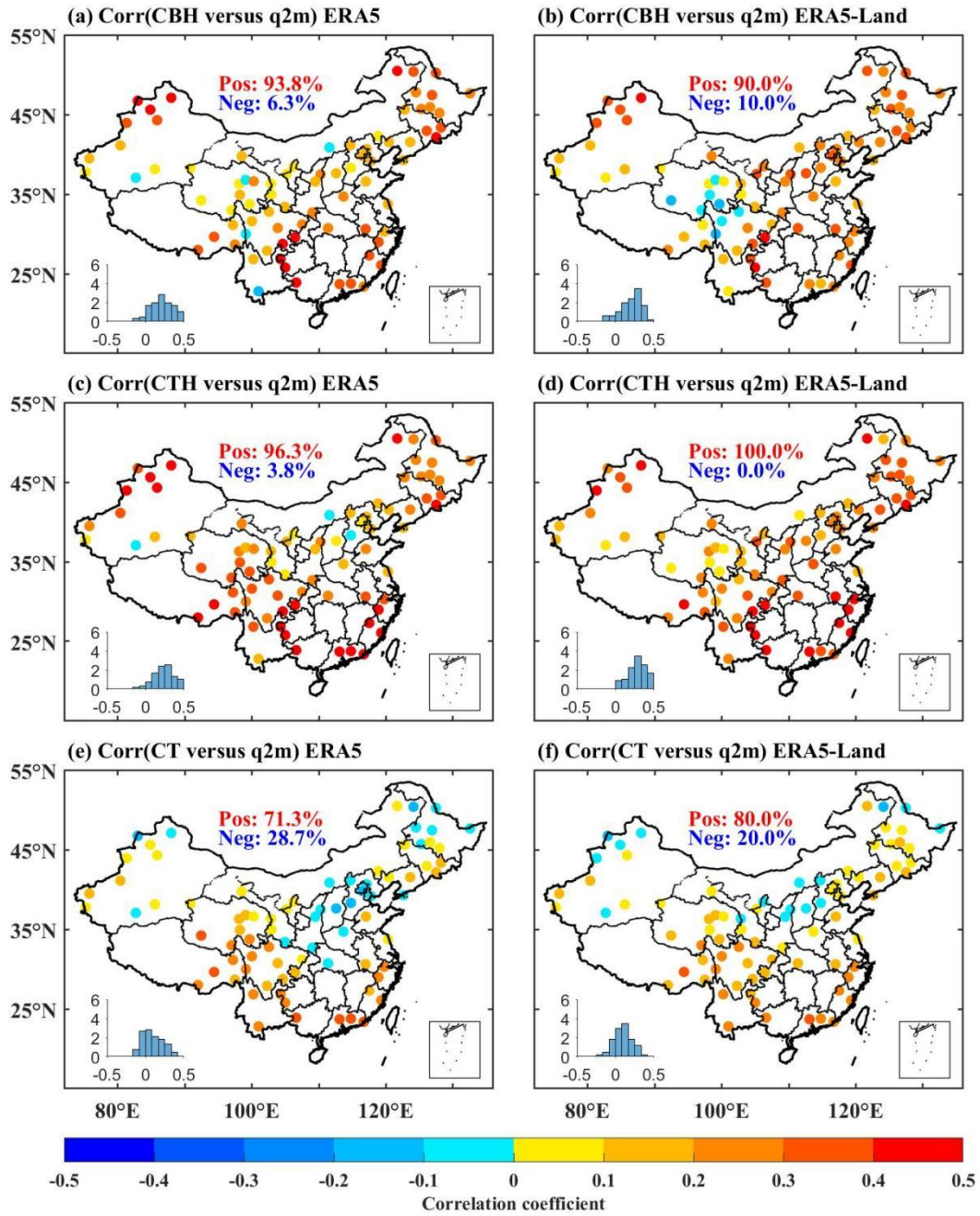


Figure S5. Comparison of the spatial correlations of CBH, CTH, and CT with 2m specific humidity (q_{2m}) from ERA5 and ERA5-land across China (2024). All atmospheric variables were spatially and temporally matched with the MMCR CBH observational data to ensure the reliability of the correlation analysis. In each panel, the probability distribution of the correlation coefficient is illustrated by a histogram, and the abbreviations “Pos” and “Neg” denote the percentages of statistically significant positive and negative correlation coefficients across the entire study domain, respectively.

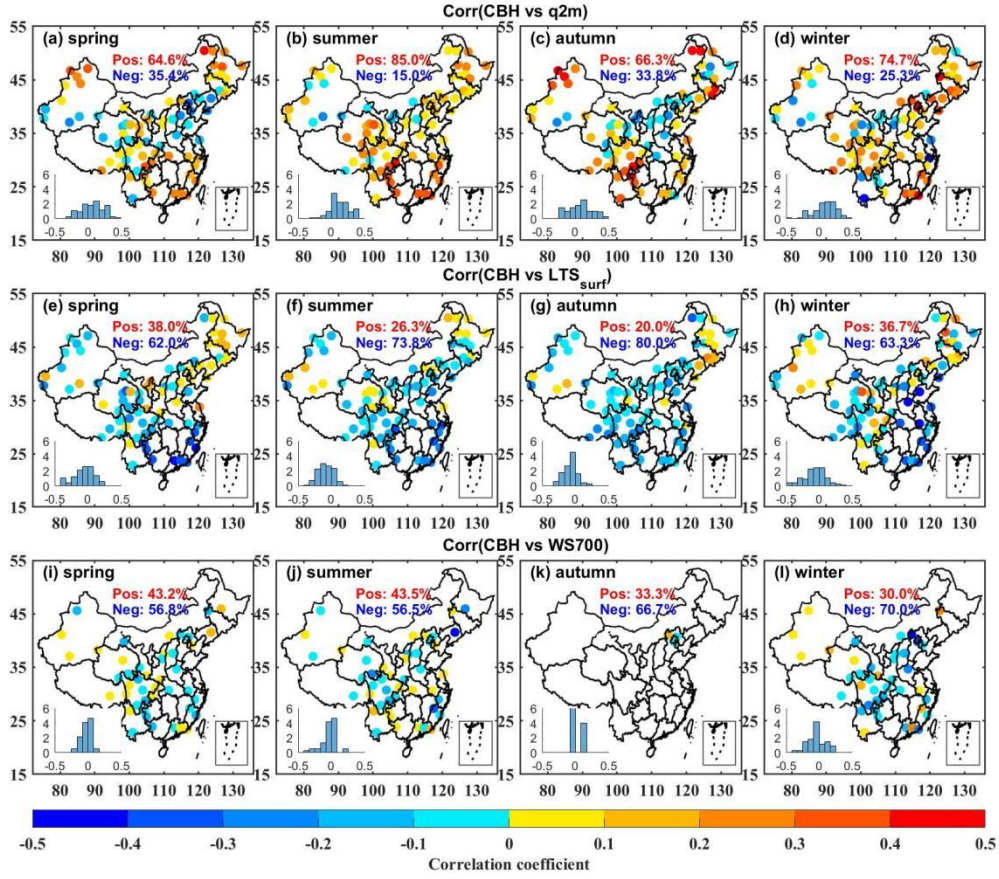


Figure S6. Seasonal mean spatial correlations of CBH with (a-d) q_{2m} , (e-h) lower-tropospheric stability (LTS_{surf}), and (i-l) vertical wind shear (VWS) across China in 2024. All atmospheric variables were spatially and temporally matched with the MMCR CBH observations. In each panel, the histogram shows the probability distribution of the correlation coefficients, and the labels “Pos” and “Neg” indicate the percentages of stations with statistically significant positive and negative correlations, respectively.

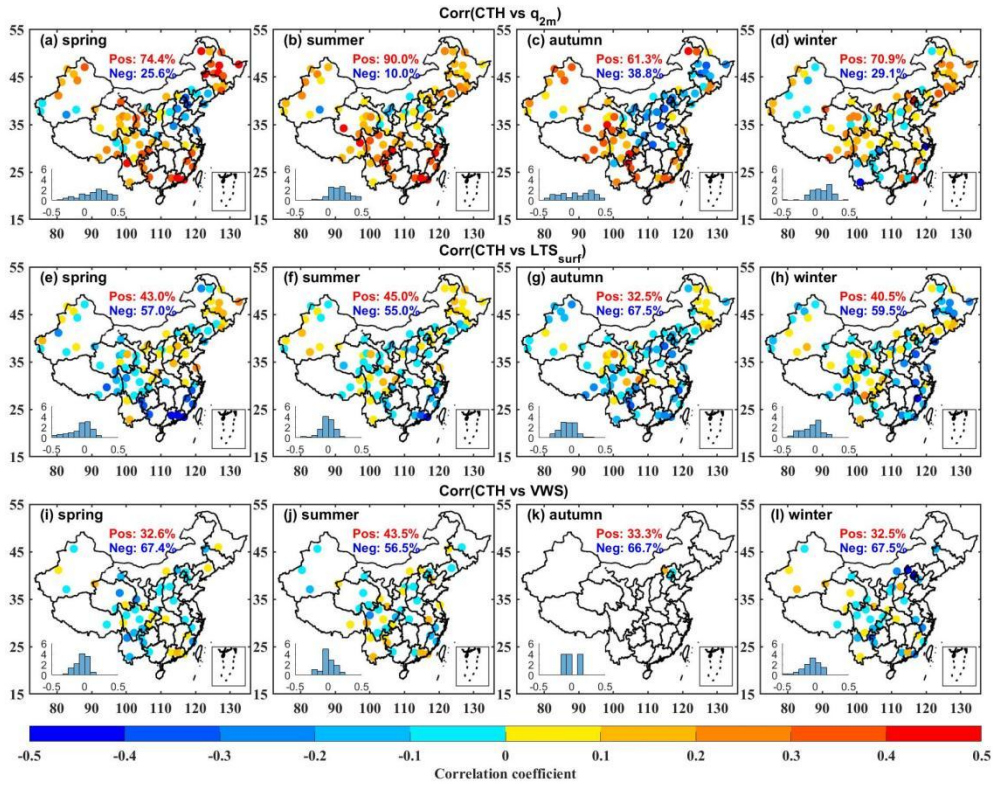


Figure S7. Similar as Figure S6, but for CTH.

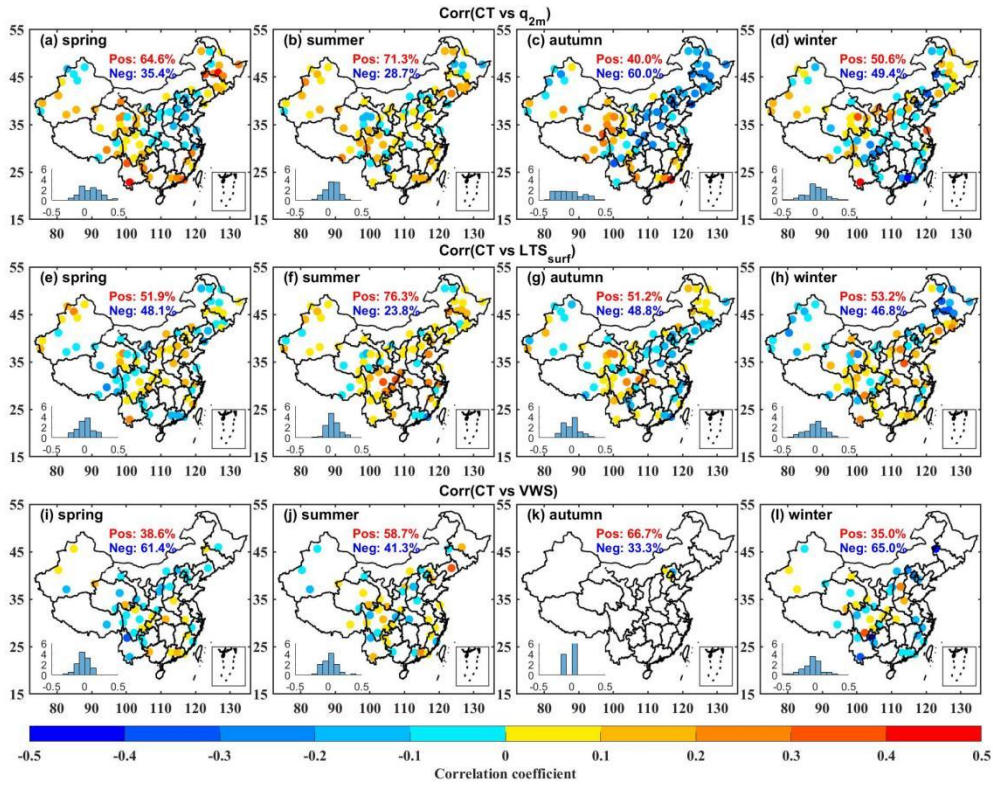


Figure S8. Similar as Figure S6, but for CT.