

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

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Abstract

Cloud vertical structure (CVS) plays a fundamental role in regulating the Earth's radiation budget and hydrological cycle, yet its representation in numerical weather prediction and climate models remains highly uncertain, largely due to limited high-resolution regional observations. Using a newly established national network of 80 Ka-band millimeter-wave cloud radars (MMCRs), here we present the first high-spatiotemporal-resolution (~~30-m~~ vertical resolution of 30 m, ~~1-min~~ temporal resolution of 1 min) characterization of CVS across China based on for one year (2024) of observations, and quantify its thermodynamic, dynamical, and land-surface controls. Cloud boundaries are retrieved using an improved algorithm that integrates height-dependent radar sensitivity with variance-based clutter suppression. Results show that the national annual mean cloud occurrence frequency is $56.7\% \pm 7.2\%$, dominated by single-layer clouds ($34.7\% \pm 4.0\%$), followed by two-layer ($14.7\% \pm 3.2\%$) and multi-layer clouds ($7.1\% \pm 2.4\%$). Spatially, single-layer clouds prevail over arid northwestern China, whereas multi-layer clouds are more frequent in humid southeastern region. Cloud base height (CBH) exhibits strong seasonality (summer > spring > autumn > winter), with notably distinct low CBH over the Tibetan Plateau. Diurnally, summer clouds show exhibit a pronounced afternoon peak between 3 and 9 km, while winter clouds are remain largely confined below 3 km and with a peak near sunrise-peak. Thermodynamic conditions exert the primary control on CVS. Higher 2 m specific humidity at 850 hPa promotes deeper cloud development and elevates-raises cloud top height (CTH), whereas enhanced lower-tropospheric stability suppresses vertical cloud growth and lowers both CBH and CTH. Dynamical forcing further modulates cloud structure: stronger 700-hPa vertical wind shear (VWS) generally inhibits vertical cloud development, reducing CBH, CTH and cloud thickness, although while moderate shear VWS can enhance organization under unstable conditions. Joint dependence analyses reveal that moisture, stability, and shear act in a coupled manner, with moisture being the dominant driver and stability and shear serving as strong regulators. In addition, land-surface characteristics significantly influence CBH, particularly especially for afternoon single-layer low clouds, whose which exhibit a mean CBH is 41.521.7% higher

than the all-~~cloud~~hour low clouds-average, with the strongest enhancement over evergreen deciduous broadleaf forests (+~~55.9~~41.7%). These findings provide the first observationally constrained, national-scale assessment of CVS based on this radar network, over China and-offering quantitative benchmarks for evaluating and improving cloud parameterization-~~schemes~~ in weather and climate models.

55 1. Introduction

Clouds are a crucial component of the Earth-atmosphere system and exert strong influence on both global and regional climate, as well as the hydrological cycle (Ramanathan et al., 1989; Stephens et al., 2005; Williams et al., 2006; Bony et al., 2015; Voigt et al., 2021). By reflecting and scattering incoming solar shortwave radiation and absorbing outgoing longwave radiation, clouds substantially modulate the radiation budget at the top of the atmosphere, within the atmosphere, and at the surface (Wielicki et al., 1995; Muehlbauer et al., 2014; Xu et al., 2021; Li et al., 2023). Cloud macrophysical characteristics—including cloud fraction, cloud base height (CBH), cloud top height (CTH), cloud thickness (CT), and the number of vertical layers—strongly influence cloud radiative forcing and precipitation processes (Weare, 2000; Wild, 2012; George et al., 2018; Zhang et al., 2019). Despite decades of research, climate models continue to exhibit substantial biases in simulating these cloud macrophysical properties, contributing significantly to considerable uncertainties in climate projections (Cesana and Waliser, 2016; IPCC, 2021; Cesana et al., 2022). For instance, many global climate models tend to overestimate high-level clouds in moist environments while underestimating low-level clouds in dry environments (Cesana and Waliser, 2016). Improving the representation of cloud vertical structure (CVS) is therefore essential for reducing model uncertainty and enhancing the reliability of weather and climate simulations.

Satellite observations provide broad spatial coverage of cloud macrophysical properties. Passive sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multiangle Imaging Spectroradiometer (MISR) have been widely used to retrieve CTH and related properties. Based on two decades (2002–2021) of MODIS data, Richardson et al. (2022) reported an increasing trend in tropical-mean high-cloud altitude of $6.9 \pm 2.7 \text{ m yr}^{-1}$, which is statistically consistent with climate model

projections. Using MISR-derived CTHs, Chae and Sherwood (2010) investigated the relationship between atmospheric environmental stability and tropical deep convective cloud altitude over the western Pacific, finding altitude variations of approximately 2 km associated with higher convective available potential energy (CAPE). More recently, Mitra et al. (2023) combined MODIS and MISR data to improve CTH retrieval for thin cirrus overlying low-level clouds. However, passive sensors generally lack the capability to resolve cloud vertical structure comprehensively, particularly CBH and multi-layer configurations.

Active satellite instruments, including the Cloud Profiling Radar (CPR) aboard CloudSat and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard CALIPSO, have greatly advanced CVS observations (e.g., Stephens et al., 2002; Mace et al., 2007; Marchand et al., 2008; Huang et al., 2015). Using combined CloudSat and CALIPSO data, Oreopoulos et al. (2017) identified single-layer low and high clouds as the most frequent global CVS types, accounting for approximately 53% of cloudy scenes. Over China, Chi et al. (2022) documented strong regional and seasonal variability in CBH and CTH.

Nevertheless, active satellite retrievals have limitations. Compared with surface-based observations, CloudSat–CALIPSO products underestimate low clouds occurrence, ~~missing~~failing to detect approximately 25% of clouds with bases below 600 m and roughly 9% of clouds with bases between 600 ~~m~~ and 1000 km (Liu, 2022). Moreover, their narrow swath width and 16-day revisit cycle of CloudSat and CALIPSO restrict temporal sampling and limit the ability to resolve diurnal variability.

Radiosonde observations provide high-vertical-resolution temperature and humidity profiles, allowing for the retrieval of CVS. Threshold-based methods have been widely used for CVS retrieval, including the dew-point depression technique (Poore et al., 1995), fixed relative humidity thresholds (Wang and Rossow, 1995), second-derivative methods (Chernykh and Eskridge, 1996), and dynamic altitude-dependent RH thresholds (Zhang et al., 2010). Xu et al. (2023) developed an improved retrieval method incorporating humidity and temperature gradients, revealing regional differences in low-cloud occurrence across East Asia, Europe and North America. However, these sounding measurements are

typically conducted twice daily at 0000 UTC and 1200 UTC (Guo et al., 2016, 2019; Zhou et al., 2020), making them insufficient to capture the full diurnal evolution of CVS.

Compared with radiosonde observations, ground-based Ka-band millimeter-wave cloud radar (MMCR) enables continuous monitoring of CVS (Shupe et al., 2008). Owing to its high spatiotemporal resolution and strong penetration capability (Moran et al., 1998; Hollars et al., 2004), MMCR has been widely applied to analyze diurnal and seasonal variations in CVS (Zhao et al., 2017; Zhou et al., 2019; Chen et al., 2022). However, most MMCR based studies on CVS have been limited to individual sites or small regions, leaving a systematic national-scale characterization of CVS largely unexplored. Previous research has highlighted that cloud vertical development is jointly influenced by atmospheric thermal conditions, dynamical processes, and land-surface characteristics (Richardson, 2007; Chen et al., 2015; Fu et al., 2020). Specifically, lower-tropospheric stability (LTS) and low-level humidity are key thermodynamic factors regulating boundary-layer development and CBH, while vertical wind shear (VWS) modulates CTH and CT by influencing the vertical development of clouds (Helfer et al., 2020; Wang et al., 2020; Yang et al., 2022; Xu et al., 2025). Land cover types further modulate cloud formation and CVS by altering surface energy partitioning and moisture fluxes (Wang et al., 2021). Despite these advances, most studies have focused on isolated factors or localized regions. To our knowledge, few ~~prior no previous studies have ever provided~~ a national-scale, high-frequency characterization of CVS across China ~~using based on~~ a coordinated ground-based radar network remains lacking, ~~nor systematically quantified and~~ the combined thermodynamic, dynamical, and land-surface controls have yet to be systematically quantified.

To address this gap, we present the first attempt to retrieve high-spatiotemporal-resolution vertical structures of clouds across China using one year (2024) of MMCR observations from a national network of 80 stations. The retrieved CVS metrics include cloud layer number, CBH, CTH, and CT for each detected cloud layer. An improved retrieval algorithm incorporating height-dependent radar sensitivity curves and a variance-based clutter suppression method is developed to enhance detection reliability. Unless otherwise specified, CBH refers to the base height of the lowest cloud layer, CTH denotes the top

of the highest cloud layer, and CT represents the total cloud thickness, defined as the difference between
130 the highest CTH and lowest CBH across all detected layers. For multi-layer cloud conditions, this
definition includes the clear-sky gaps between individual cloud layers.

The remainder of this paper is organized as follows: Section 2 describes the observational data and
methodology used for CVS retrieval. Section 3 presents the spatial, vertical, seasonal, and diurnal
characteristics of CVS and analyzes its thermodynamic, dynamical, and land-surface controls. Section 4
135 summarizes the main findings and discusses their implications for weather and climate modeling.

2. Data and methods

2.1 Study area

China spans a vast territory across broad latitudinal and longitudinal ranges, leading to pronounced
spatial heterogeneity in both atmospheric and surface conditions. The climate is predominantly governed
140 by the Asian monsoon systems and the topographic forcing of the Tibetan Plateau, which together result
in substantial regional variations (Ye and Gao, 1979; Domroes and Peng, 1988; Ding and Murakami,
1994). In eastern China, a distinct north–south gradient is evident: southern regions are characterized by
year-round warm and humid conditions, while northern areas experience colder winters and pronounced
seasonal temperature variability. In contrast, western China, an area dominated by high-elevation terrain
145 such as the Tibetan Plateau, is typified by relatively low temperatures, strong radiative cooling, and
limited moisture availability (Shi and Wang, 2020). Across this diverse landscape, meteorological
variables exhibit strong seasonal cycles: precipitation and air temperature peak in summer (June–July–
August) and reach minima in winter (December–January–February), sunshine duration follows a similar
seasonal pattern, with maximum values occurring in summer. Wind speeds are generally highest in spring
150 (March–April–May), whereas relative humidity remains consistently elevated in southern China and
shows comparatively modest seasonal variation. Autumn (September–October–November) does not
display equally distinct seasonal extremes in these meteorological variables.

2.2 Data

2.2.1 Ka-band millimeter-wave cloud radar observations

The MMCRs retrieve cloud macrophysical properties by detecting the scattering signals of cloud particles at millimeter wavelengths (Hobbs et al., 1985; Kollias et al., 2007). Capable of continuously monitoring cloud vertical structure with high spatiotemporal resolution (Clothiaux et al., 2000; Mace et al., 2001; Hollars et al., 2004), the MMCRs employed in this study operates with a vertical resolution of 30 m, a temporal resolution of 1 minute, and a maximum detection height of 18 km above ground level (AGL). Compared to conventional weather radars, the shorter wavelength of the MMCRs enhances their sensitivity to small cloud particles, making them particularly effective for observing non-precipitating and weakly precipitating clouds, as well as for penetrating multi-layer cloud systems (Moran et al., 1998; Kollias et al., 2007). This penetrative ability enables MMCRs to obtain detailed vertical cloud profiles, especially for thick, dense, and multi-layered clouds.

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.

2.2.32 Radar wind profiler measurements

The radar wind profiler (RWP) is a ground-based remote sensing instrument designed to measure ~~wind~~-vertical profiles of wind within the planetary boundary layer (PBL) and the lower free atmosphere (Liu et al., 2020). By transmitting electromagnetic beams in multiple directions and analyzing the returned signals, ~~the~~ RWP provides a comprehensive set of atmospheric variables, including horizontal wind speed and direction, vertical velocity, radial velocity, Doppler spectral width, signal-to-noise ratio (SNR), and the refractive index structure parameter (C_n^2) (Liu et al., 2020). These measurements typically cover altitudes from 150 m to 5.0 km AGL, with a vertical resolution of 120 m and a temporal interval of 6 minutes (McCaffrey et al., 2017; Ruan et al., 2014). Compared to conventional radiosonde observations and reanalysis datasets, RWPs offer significantly higher temporal resolution, thereby facilitating high-resolution, continuous monitoring of temporal variations in atmospheric wind profiles. In this study, ~~700 hPa vertical wind shear (VWS700)~~ was derived from the RWP—observed wind speed and direction profiles. The magnitude of VWS at a given height is calculated as using the following formula:

$$SVWS = \left[\left(\frac{\partial u}{\partial h} \right)^2 + \left(\frac{\partial v}{\partial h} \right)^2 \right]^{1/2} \quad (1)$$

where ~~S~~ denotes the vertical wind shear, and u and v represent the zonal and meridional components of the horizontal wind, respectively. To account for the large topographic relief across China, we adopt a terrain-following criterion for selecting the pressure level at which VWS is evaluated: for stations with surface elevation < 3 km (covering most of eastern and central China), VWS is computed from the wind profile at the 700 hPa level; for stations with surface elevation $\geq$ 3 km (typical of the Tibetan Plateau), VWS is computed from the wind profile at the 500 hPa level. This ensures that the derived VWS consistently characterizes the lower-to-mid tropospheric shear relevant to cloud development under different topographic conditions.

Although RWP observations offer high temporal resolution, they are subject to notable uncertainties. Despite these advantages, RWP measurements are subject to notable uncertainties. Data quality is often degraded below approximately 0.5 km AGL due to near-surface clutter, while significant beam attenuation limits reliable detection above about 5.0 km AGL. Therefore, rigorous quality control is

essential before deriving dynamic variables from RWP data. ~~In practice, only observations within the 0.5–5.0 km height range are generally considered suitable for reliable analysis, which ensures the accuracy of WS700 calculations (consistent with the height range of the lower free atmosphere targeted by RWP measurements), and our analysis is consequently restricted to the 0.5–5.0 km height range.~~

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 $\geq$ 3 km).

2.2.3 ERA5 reanalysis

ERA5, the latest global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), was released in 2017 and provides continuous meteorological data from January 1950 to the present (Bell et al., 2021). Generated using a 4-dimensional variational (~~4D-Var~~) data assimilation system, ERA5 offers comprehensive, high-resolution, and large-scale meteorological fields that are well suited for climatic research, with temporal and spatial resolutions of up to 1 hour and $0.25^{\circ} \times 0.25^{\circ}$ (approximately 31 km), respectively (Hersbach et al., 2020). ERA5's fine resolution facilitates improved representation of vertical profiles and diurnal variations in key atmospheric variables, particularly over land areas (Dai, 2023). In this study, we use ERA5 data for 2024 to examine the impacts of LTS and specific humidity on CVS. For this purpose, hourly 2 m air temperature (T_{2m}).

230 atmospheric temperature at the 1000 hPa and 700 hPa level ($T_{700\text{hPa}}$) and at the 500 hPa level ($T_{500\text{hPa}}$),
 2 m dewpoint temperature ($T_{d,2\text{m}}$), and surface pressure (p_{surface}) and specific humidity at 850 hPa
 (q850) are extracted for all 80 selected MMCR stations. The 2 m specific humidity ($q_{2\text{m}}$) is calculated
 from $T_{d,2\text{m}}$ and p_{surface} using standard psychrometric formulas. Because $q_{2\text{m}}$ is defined at 2 m
 above the surface, it inherently follows the topography, making it a physically consistent measure of low-
 235 level moisture across all terrain heights, including the Tibetan Plateau.

To quantify the thermal stratification of the lower troposphere, the traditional definition of LTS
 definition, calculated as ($LTS = \theta_{700\text{hPa}} - \theta_{1000\text{hPa}}$, Wood and Bretherton, 2006), was is
 infeasible inapplicable over for high terrain because the elevation regions. This is because the
 1000 hPa level surface lies below the ground surface over high terrain underground, making $\theta_{1000\text{hPa}}$ the
 240 corresponding potential temperature undefined. Similar to the terrain-following criterion for calculating
 VWS, Accordingly, we propose a unified and terrain-following LTS definition applicable to all study
 stations: derived following the formulation proposed by Wood and Bretherton (2006), which is defined
 as the difference in potential temperature between the 700 hPa and 1000 hPa pressure levels:

$$LTS_{\text{sfc}} = \theta_{\text{lev}700\text{hPa}} - \theta_{1000\text{hPa surface}} \quad (2)$$

245 Where $\theta_{\text{lev}700\text{hPa}}$ ($\theta_{700\text{hPa}}$ or $\theta_{500\text{hPa}}$) is the potential temperature at 700 hPa or 500 hPa, chosen
 such that the pressure level remains above the surface, calculated from T_{700} and the temperature
 and pressure of 700 hPa at that level using the standard potential temperature equation standard
 formula, and θ_{surface} denotes the surface potential temperature, which is also derived from $T_{2\text{m}}$ and
 p_{surface} of ERA5 2m reanalysis and p_{surface} using the standard potential temperature equation.

250 The standard potential temperature equation is as follows, calculated using the following formula:

$$\theta_{\text{lev surface}} = T_{2\text{m}} \left(\frac{p_0}{p_{\text{lev surface}}} \right)^{\frac{R}{C_p}}, \quad p_0 = 1000 \text{ hPa} \quad (3)$$

where $T_{2\text{m}}$ represents 2m air tempertaure in Kelvin (K), and p_{surface} represent denotes the air
 temperature and atmospheresurface pressure in hectopascals (hPa), at the given pressure level,
 respectively; $p_0 = 1000 \text{ hPa}$ is the reference pressure; R is the specific gas constant for dry air; and C_p
 255 is the specific heat capacity at constant pressure. For low-elevation areas stations with surface pressure

elsewhere $p_{levsurf} \approx 1000$ is the 700 hPa level or 500 hPa or surface pressure.; Over low terrain, $\theta_{surface}$ closely approximates θ_{1000} is approximately equivalent to the potential temperature at 1000 hPa.; thus ~~Therefore, the newly defined LTS_{surf}~~ this definition closely approximates the ~~conventional~~ traditional LTS ($\theta_{700hPa} - \theta_{sfc}$) in lowland regions. Over high terrain, this adopting the 500 hPa level as the reference keeps the analysis-definition remains physically meaningful and allows ensures consistency analysis across all stations.

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 ($0.1^\circ \times 0.1^\circ$, ~ 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.

2.3 CVS retrieval methods based on MMCR data

MMCR identifies cloud boundaries by detecting radar backscatter from hydrometeors, including liquid droplets and ice crystals within clouds. However, due to its short operating wavelength, MMCR is also sensitive to non-meteorological echoes, such as near-surface dust, insect swarms, and atmospheric turbulence, as well as random noise arising from instrumental instabilities and signal processing artifacts (Ulaby et al., 1981; Zhou, 2008). These interfering signals can degrade the reliability of cloud boundary detection and introduce biases in retrieved CVS.

In the literature, ~~A commonly used approach for retrieving CVS is~~ the reflectivity threshold approach method is a widely used approach for, which distinguishes cloud signals from background noise and clutter using a fixed reflectivity cutoff. Based on the operational characteristics of MMCR,

~~observations from the U.S. Atmospheric Radiation Measurement (ARM) program,~~ Clothiaux et al. (1999) reported that radar reflectivity (Z) for ~~various cloud types—including~~ 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).

However, the fixed threshold neglects the height-dependent sensitivity of radar measurements. Because radar detectability decreases with range, weak high-altitude cloud signals may fall below a constant threshold, while near-surface clutter may be misclassified as clouds. Such biases can lead to inaccurate estimates of cloud occurrence and vertical structure.

To address these limitations, this study introduces an improved CVS retrieval technique that integrates (1) theoretical radar sensitivity curves accounting for height-dependent detection capability and (2) a variance-based clutter suppression method adapted from Kalapureddy et al. (2018). By combining physically constrained sensitivity thresholds with statistical filtering of reflectivity variability, this approach enhances cloud detection robustness across different altitudes and cloud regimes.

The retrieval procedure consists of the following steps:

First, a height-dependent noise-equivalent reflectivity (NER) threshold curve (denoted as $Z_{th}(j)$) is established to replace the fixed threshold. This curve is tailored to typical atmospheric conditions over China and defined as:

$$Z_{th}(j) = \sqrt{1.2 \times j} - 42.0 \quad (4)$$

where j represents the vertical range bin index (or corresponding height level). This formulation accounts for the progressive reduction in radar sensitivity with increasing height.

For a given time t , the measured reflectivity $Z(j, t)$ at height level j is classified as a potential cloud signal if:

$$Z(j, t) \geq Z_{th}(j) \quad (5)$$

Otherwise, the signal is classified as noise. This step generates a preliminary binary indicator $I(j, t)$, where $I = 1$ denotes potential cloud signals and $I = 0$ denotes noise. The resulting non-noise layers provide the initial candidates for cloud detection while removing the majority of random noise.

To further refine the non-noise regions, contiguous segments where $I(j, t) = 1$ are identified as
 310 candidate cloud-containing layers. Although the NER threshold removes most random noise, residual
 non-meteorological clutter may remain. To further distinguish true cloud signals from clutter, a variance-
 based method is applied within the identified non-noise layers. This method exploits the physical property
 that cloud hydrometeors are generally more spatially homogeneous and temporally coherent than clutter
 sources (Kalapureddy et al., 2018). As a result, the temporal variability of reflectivity within cloud-
 315 dominated layers is typically lower than that within clutter-contaminated layers.

A 3-minute sliding time window is applied at each height level within the non-noise layers. Within
 each window, the standard deviation of reflectivity across consecutive profiles is calculated, forming a
 variability sequence A_i . The mean (μ) and standard deviation (σ) of this sequence are then calculated as:

$$\mu = \frac{1}{3} \sum_{i=0}^2 A_i \quad (6)$$

$$\sigma = \left[\frac{1}{3} \left(\sum_{i=0}^2 (A_i - \mu)^2 \right) \right]^{\frac{1}{2}} \quad (7)$$

A dual-threshold criterion is applied to identify moist (cloud) layers: if $\mu < 2.0$ dBZ, and $\sigma < 1.0$
 dBZ. If both conditions are satisfied, the signal at that height is identified as part of a moist layer. The
 base and top height levels of moist (cloud) layers are determined by identifying vertically contiguous bins
 meeting this criterion. Otherwise, the segment is filtered out as clutter.

325 Finally, the cloud detection step is conducted to retrieve the CBH and CTH of each identified cloud
 layer by verifying the radar reflectivity within previously detected moist layers. This step yields the final
 CVS. Specifically, any candidate moist layer with a maximum reflectivity lower than -20 dBZ is
 excluded, as such weak backscatter signals are unlikely to represent physically meaningful cloud layers
 and may instead reflect residual noise or sub-detection-limit echoes. This reflectivity threshold is selected
 330 to balance sensitivity to thin non-precipitating clouds and robustness against noise contamination.

Given the high temporal resolution (1 min) of the MMCR observations, loosely connected cloud
 elements may occasionally be misidentified as multiple discrete layers. To reduce artificial layer
 fragmentation, an additional quality-control procedure is applied to the initially detected cloud boundaries.
 For each identified cloud layer, both its geometric thickness and the vertical separation distance to

335 adjacent layers are calculated. If a cloud layer is thinner than 7 range bins (equivalent to 210 m at the 30 m vertical resolution of the MMCR), the following criteria are applied:

- If the separation distance to the nearest adjacent cloud layer exceeds 24 range bins (720 m), the thin layer is considered isolated and is discarded.
- If the separation distance is less than or equal to 24 range bins, the thin layer is merged with the
340 nearest adjacent cloud layer.

This procedure reduces spurious detections while preserving physically coherent multi-layer structures. The complete CVS retrieval workflow is illustrated in the flowchart (Fig. 2). The algorithm is capable of detecting cloud layers across a wide range of altitudes and configurations, ~~including single-layer, multi-layer, shallow, and deep convective structures~~. An example case demonstrating the
345 robustness of the retrieval under complex vertical conditions is provided in Fig. S1.

To evaluate the performance of our improved retrieval algorithm for various cloud categories (including low-level thin cloud, mid-level thin cloud, high-level thick cloud, multi-layer cloud, and deep precipitating cloud), we conducted case-based validation against collocated radiosonde observations (Fig. S2). Comparisons reveal good agreement between radar-retrieved cloud boundaries and cloud limits derived from radiosonde profiles processed following the algorithm proposed by Xu et al. (2023). Vertical discrepancies of CBH and CTH are nearly negligible for thin low-level and mid-level clouds, constrained within 0.5 km for thick high-level clouds, and limited to 1 km for precipitating cloud systems.

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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.

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3. Results and discussion

This section presents the spatial, vertical, seasonal, and diurnal characteristics of cloud vertical structure across China, followed by an analysis of the thermodynamic, dynamical, and land-surface controls governing cloud development. Unless otherwise specified, statistics are derived from all valid MMCR observations in 2024 across the 80 selected stations.

3.1 Spatial distribution of cloud layer occurrence frequency

Figure 3 ~~illustrates presents~~ the spatial ~~distributions patterns~~ of annual mean occurrence frequency~~ies~~ ~~for under total all-sky conditions clouds and for clouds classified by vertical layer number (single-layer, two-layer, and multi-layer; the latter defined as three to five layers)~~ across China ~~under all-sky conditions~~ in 2024, ~~including total cloud occurrence and clouds categorized by vertical layer number (single-layer, two-layer, and multi-layer clouds; multi-layer clouds are defined as systems containing three to five cloud layers)~~. The national mean total cloud occurrence ~~frequency~~ is $56.7\% \pm 7.2\%$, with ~~regional individual station~~ values ranging from 40% to 70% (Fig. 3a). 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. potentially reflecting the reported declining trend in total cloud fraction over East Asia in recent years (Zhou et al., 2022).~~ The probability density function (PDF) of total cloud occurrence frequency exhibits a non-uniform distribution, with high probabilities concentrated toward the upper end of the frequency range. Roughly 82% of observed stations show total cloud frequencies above 50%, demonstrating that cloudy conditions prevail across the majority of the MMCR network.

When classified by vertical cloud structures (Figs. 3b–d), occurrence frequencies range from 25% to 40% for single-layer clouds, 10% to 16% for two-layer clouds, and 1% to 12% for multi-layer clouds. The PDF ~~for of~~ single-layer clouds ~~shows displays~~ a relatively continuous distribution, with a prominent peak concentration of stations at higher occurrence frequencies. In contrast, the PDF for two-layer clouds exhibits a more discontinuous pattern, with probability mass ~~clustered concentrated within~~ the high-frequency interval range. Nationally averaged occurrence frequencies decrease systematically with increasing layer number, with mean values of $34.8\% \pm 4.0\%$ for single-layer clouds, $14.7\% \pm 3.2\%$ for two-layer clouds, and $7.1\% \pm 2.4\%$ for multi-layer clouds.

These ~~results statistics~~ indicate that single-layer clouds constitute the dominant vertical structure over China. ~~This overall distribution is broadly consistent with CALIPSO-based estimates reported by~~ Pan et al. (2016), ~~although differences in magnitude likely reflect differences in observational platforms and sampling characteristics, accounting for approximately 62% of all cloudy occurrences.~~

Spatially, the highest total occurrence frequencies are ~~observed concentrated~~ over the southeastern Tibetan Plateau and the Sichuan Basin (Fig. 3a). Notably, stations with the most prominent total cloud frequency signals are concentrated within this topographically complex region, where the peak cloud occurrence across all observation sites emerges. In contrast, stations distributed across northwest China display highly variable total cloud occurrence levels, covering a wide spectrum from low to moderately high frequencies. Multiple monitoring sites in inland northwest China exhibit cloud occurrence levels comparable to the average cloudiness found across southeastern cloud-abundant zones. This spatial pattern agrees with previous satellite-based studies (e.g., Pan et al., 2015; Yin et al., 2015) and ~~can be attributed is plausibly linked~~ to topographic lifting and enhanced moisture convergence associated with complex terrain. However, the spatial contrast between northwestern and southeastern China observed by MMCRs differs somewhat from satellite-derived cloud fraction patterns. In particular, point-based MMCR observations indicate relatively higher total cloud occurrence frequencies at some stations in northwestern China ~~compared with southeastern regions (Fig. 3ba)~~. This apparent discrepancy likely ~~arises stems~~ from the fundamental distinction between the two differences in ~~observingational sampling approaches as mentioned above: satellite products represent areal cloud fraction over large grid~~

cells, whereas MMCR measurements capture local, vertically resolved cloud occurrence. In addition, northwestern China is often characterized by persistent, optically thin cloud layers, while southeastern China experiences more intermittent but vertically extensive convective systems. These differing cloud regimes, and direct quantitative comparisons between the spatial patterns derived from the two platforms should be interpreted with appropriate caution may contribute to the observed spatial contrasts.

Single-layer clouds occur more frequently in northwestern China than in the relative to southeastern regions (Fig. 3b), whereas multi-layer clouds exhibit the opposite pattern, with higher frequencies in the southeast and lower frequencies in the northwest, 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 contrast divergence likely reflects differences in moisture availability and atmospheric instability. Southeastern China, influenced by abundant water vapor transport and stronger intense solar heating, both of which favors deep convection development and the development formation of vertically complex, multi-layered cloud systems (Chi et al., 2022). In contrast, By comparison, dry, stable boundary-layer the comparatively dry and stable conditions in northwestern China suppress vertical motion and cloud development, leading to promote simpler, predominantly single-layer clouds structures 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 suggesting a more transitional vertical structure state between the 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.

3.2 Horizontal distribution of cloud height

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 $4\text{--}5\text{ W m}^{-2}$ 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). ~~CBH plays a particularly important role in regulating near-surface radiation and turbulent energy exchange, while also linking surface–atmosphere interactions to cloud formation processes.~~ Accurate characterization of CBH is therefore essential for both regional weather forecasting and climate change assessments (e.g., Stephens et al., 2012; Mülmenstädt et al., 2018; An et al., 2019).

Figure 4 presents the horizontal distribution of seasonal mean CBH across China in 2024. CBH exhibits pronounced seasonal variability. In summer, CBH is generally elevated, with 84% of stations exceeding 3 km and approximately 10% reaching values up to 5 km (Fig. 4b). Spring (Fig. 4a) displays a similar spatial distribution but with lower magnitudes, with most CBH values (67%) concentrated between 2.5 km and 4 km. In contrast, autumn and winter (Figs. 4c-d) are characterized by substantially

465 lower CBH, predominantly within the 2–3 km range, and only a small fraction of stations exceeding 4 km. The seasonal mean CBH follows the order: summer (3.95 ± 0.88 km) > spring (3.24 ± 0.77 km) > autumn (2.78 ± 0.62 km) > winter (2.15 ± 0.89 km). This seasonal progression is consistent with previous studies (e.g., [ZhangShupe et al., 2014](#); Chi et al., 2022; Xu et al., 2023) and reflects the strong modulation of cloud formation by radiative forcing and boundary-layer dynamics. Enhanced solar heating in summer
470 deepens the PBL and promotes stronger turbulent mixing, favouring higher cloud bases. In contrast, reduced insolation and increased static stability in winter suppress boundary-layer growth, resulting in lower CBH (Zhang et al., 2018).

Spatially, elevated summer CBHs (>3 km) dominate much of eastern China. While the East Asian summer monsoon enhances moisture transport from the Pacific (Ding and Chan, 2005; Li et al., 2016),
475 increased surface heating and boundary-layer development over land can elevate condensation levels despite enhanced humidity. This highlights the competing influences of moisture supply and boundary-layer dynamics on CBH.

Over the Tibetan Plateau, CBH is distinctly lower (approximately 2.5 km above ground level) during spring and summer compared with surrounding regions. This regional feature reflects unique
480 thermodynamic conditions associated with high elevation. Although strong surface heating enhances buoyancy and deepens the PBL, lower ambient temperatures reduce the lifting condensation level (LCL) for a given near-surface relative humidity, facilitating the frequent formation of low-level clouds (Wang et al., 2020). The combined effects of terrain-induced lifting, enhanced vertical moisture transport, and lower LCL contribute to the relatively low CBH over the Plateau.

485 CTH exhibits similar seasonal variability (Fig. S23), 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. S23, 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
490 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 [in summer](#). 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
495 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. S34). [Figure S3 shows that](#)
500 [In summer, the thickest clouds \(\$\sim 4\$ km\) occur over southern China and the eastern Tibetan Plateau margins, whereas winter clouds are uniformly thin \(\$\sim 2\$ km\) 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
505 stratification.

3.3 Vertical distribution of cloud

Figure 5 presents the annual and seasonal mean vertical occurrence frequencies of CBH, CTH, and the combined cloud vertical profiles across China in 2024. These profiles provide insights into the climatological structures of clouds and the mechanisms governing their seasonal variability.

510 3.3.1 Vertical distribution of CBH

As shown in Fig. 5a, CBH occurrence frequency exhibits a pronounced unimodal distribution, with notable seasonal modulation. Across all seasons, the highest frequencies occur below 1 km, indicating the predominance of low-level cloud bases over continental China. This result is consistent with previous ground-based radar and lidar observations in mid-latitude continental regions, which [documented](#) the
515 frequent occurrence of low cloud bases in boundary-layer cloud regimes (e.g., Clothiaux et al., 2000; Wang and Sassen, 2001).

Distinct seasonal contrasts are evident. Above 6 km, CBH frequencies are highest in summer, whereas below 3.0 km, they peak in winter. 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~~contrast reflects differences in thermodynamic instability, large-scale circulation, and the associated cloud types (Shupe et al., 2011).~~ In summer, enhanced surface heating and abundant moisture supply associated with the East Asian summer monsoon promote deep boundary-layer development and vigorous convection, allowing cloud bases to form at higher altitudes, particularly for convective and high-level cloud systems (Ding and Chan, 2005; Mace et al., 2006). In winter, reduced insolation and colder temperatures lower the lifting condensation level (LCL) and suppress boundary-layer mixing. Moreover, the East Asian winter monsoon advects cold, dry air southward, strengthening static stability and limiting vertical development (Zhang et al., 1997). Under these conditions, condensation frequently occurs within shallow boundary layers, favoring low-base stratiform clouds such as stratus and stratocumulus (Klein and Hartmann, 1993).

3.3.2 Vertical distribution of CTH

In contrast to CBH, the vertical occurrence frequency of CTH exhibits a prominent bimodal distribution, with one peak occurring between 1.0 and 3.0 km and a second peak between 6 and 12 km (Fig. 5b). This bimodal pattern indicates the coexistence of two dominant cloud regimes over China: shallow low-topped clouds and deep convective or high-level cloud systems. The presence of both peaks reflects the diversity of synoptic environments and climatic regimes across the region.

The two modes exhibit distinct seasonal behavior. The high-altitude peak (6–12 km) is most pronounced in summer, particularly above 9 km. This enhancement is consistent with a deeper troposphere, stronger convective instability, and more frequent deep convection during the warm season. Intense surface heating combined with monsoonal moisture transport supports strong updrafts capable of transporting cloud tops into the upper troposphere (Johnson et al., 1999; Holloway and Neelin, 2009). In contrast, the low-altitude peak (1–3 km) dominates in winter, when stable stratification restricts vertical

cloud growth and favors shallow stratiform cloud types (Klein and Hartmann, 1993; Wood and Bretherton, 2006).

3.3.3 Combined vertical cloud profiles

545 The combined vertical distribution derived from CBH and CTH (Fig. 5c) further illustrates seasonal contrasts in overall cloud depth. During summer, clouds occupy a broad vertical range, frequently extending from near the surface to above 9 km. This structure reflects the prevalence of deep convective systems supported by strong surface heating, enhanced instability, and abundant moisture supply (Houze, 2018). In winter, by contrast, cloud occurrence is largely confined below 6 km, and the vertical extent is
550 substantially reduced. This shallow structure is consistent with the dominance of low-level stratiform clouds under cold, dry, and stable atmospheric conditions, where limited vertical mixing suppresses deep convection (Shupe et al., 2011; Pan et al., 2023).

3.4 Diurnal variation of cloud occurrence frequency at different heights

555 Compared with conventional radiosonde measurements, the MMCR provides much higher temporal resolution (1 min), enabling detailed characterization of the diurnal evolution of cloud vertical structure. Based on the retrieved CVS dataset, Figure 6 shows the annual mean diurnal variations of height-resolved cloud occurrence frequencies, along with the corresponding annual mean vertical profiles. Cloud occurrence frequencies were calculated at 1-hour intervals with a vertical resolution of 30 m, and the time refers to local time (LT).

560 3.4.1 Annual mean diurnal cycle

 The annual mean diurnal variability extends primarily from 0.5 to 9 km, with the strongest fluctuations occurring below 3 km (Fig. 6b). Two prominent peaks in cloud occurrence frequency are identified: one in the morning (0600–0800 LT) and another in the afternoon (1400–1800 LT). These two peaks may be associated with seasonal influences. These peaks reflect the combined influence of
565 nocturnal PBL processes and daytime convective development.

The morning peak is likely associated with nocturnal radiative cooling in the PBL, which enhances relative humidity and promotes the formation of low-level clouds under stable stratification. In contrast, the afternoon maximum corresponds to enhanced surface heating and increased boundary-layer instability, which favour convective cloud development. This diurnal pattern is broadly consistent with previous studies showing early-morning peaks in low cloud occurrence and late-afternoon maxima in convective activity (Li et al., 2008).

3.4.2 Seasonal modulation of the diurnal cycle

Figure 7 further shows seasonal mean diurnal variations in height-resolved cloud occurrence frequencies, along with the corresponding ~~annual~~-seasonal mean vertical profiles. The amplitude and vertical extent of diurnal variability differ markedly by season.

In summer (Fig. 7b), cloud occurrence variability spans a broad vertical range (approximately 1–10 km), substantially larger than in winter (Fig. 7d). This enhancement likely reflects the combined effects of strong surface heating and the East Asian summer monsoon-(EASM). Enhanced solar radiation increases near-surface buoyancy and promotes vigorous convection, while monsoonal moisture transport provides the thermodynamic support necessary for deep cloud development. These conditions favour the frequent formation of deep convective clouds and produce pronounced diurnal variability extending into the upper troposphere (~~Houze, 2014;~~ Wood, 2012; Houze, 2014).

The summer vertical profile exhibits a distinct two-layer structure. A lower layer (1–2 km) shows relatively weak diurnal variation, while an upper layer (3–9 km) displays a pronounced cycle. Within the upper layer, cloud occurrence reaches a minimum in the early morning (0600–0800 LT) and peaks in the late afternoon to early evening (1600–2000 LT). This pattern reflects the strong control of solar heating on convective instability: daytime heating destabilizes the planetary boundary layer, initiates moist convection, and drives the formation of cumuliform and deep convective clouds, leading to enhanced cloud occurrence in the afternoon (Betts, 2009; Zhang and Klein, 2013). At night, the absence of solar heating reduces convective turbulence and suppresses vertical moisture transport, thereby weakening upper-level cloud development.

In winter, the diurnal variability of cloud vertical distribution is considerably weaker and largely confined below 3 km. Cloud occurrence is most frequent between 0.5 and 3 km, consistent with the typical altitude range of liquid-phase stratiform clouds (Xu et al., 2023). A near-sunrise maximum (0600–0800 LT) is evident, in agreement with previous findings (Betts and Tawfik, 2016). This wintertime enhancement likely results from minimum near-surface air temperatures around sunrise under stable boundary-layer conditions, which increase relative humidity and favour cloud formation (Dai, 2001; Eastman and Warren, 2014).

Spring and autumn exhibit transitional behavior between summer and winter. In spring (Fig. 7a), the vertical range of cloud variability expands relative to winter, with cloud tops occasionally reaching 7–8 km. An afternoon peak in mid-tropospheric cloud occurrence (3–6 km) is evident between 1400 and 1800 LT, reflecting strengthening solar heating and increasing convective instability. In autumn (Fig. 7c), cloud tops gradually lower and the diurnal amplitude weakens. Cloud occurrence becomes more evenly distributed throughout the day, particularly below 4.3 km, as solar radiation declines and atmospheric stratification strengthens. Overall, these transitional seasons illustrate the progressive adjustment of the cloud diurnal cycle to evolving surface heating and large-scale circulation, broadly consistent with the broader seasonal evolution documented over China (Yu et al., 20071).

3.5 Impact of atmospheric ~~thermodynamic~~thermodynamic and dynamical factors on CVS

~~The vertical structure of clouds~~CVS ~~over China is regulated~~modulated by ~~the combination of~~integrated effects of thermodynamic stratification, moisture availability, and dynamical forcing. To ~~quantitatively~~elucidate their dominant regulatory mechanisms over China~~these controls~~, we examine the ~~relationships~~correlations between three ~~core~~key CVS metrics—(CBH, CTH, and CT)—and key atmospheric variables, including LTS_{surf} and q_{2m} from ERA5, and VWS~~retrieved from RWP observations. All analyses are performed based on~~using temporally and spatially collocated ~~ERA5 reanalysis data~~datasets. Recognizing that atmospheric controlling factors rarely operate independently, we further investigate the joint regulation of CVS by paired variables.

Across China, thermodynamic factors exert primary control on cloud vertical development, while dynamical forcing modulates cloud organization and geometric extent.

3.5.1 *Impact of atmospheric thermodynamic and dynamical thermodynamic factors on CBH* Cloud base height

Figure 8 displays illustrates the spatial distributions of annual mean correlation coefficients between CBH and three atmospheric variables. For the q_{2m} , positive correlations between CBH and q_{2m} dominate are found at 92.43.8% of all observation stations (Fig. 8a), while only 6.3% of stations show negative correlations. This widespread positive relationship indicates that climatologically moister low-level environments with enhanced low level moisture are generally associated with accompanied by higher cloud bases in the climatological mean. Importantly/Notably, this relationship/positive correlation does not imply that increased surface moisture directly lifts/raises the lifting condensation level (LCL); rather, Instead, it reflects the co-variability of low-level moisture and convective instability. Seasonal composite analyses further verify that this positive relationship between CBH and q_{2m} is most pronounced in summer (85% of stations), and weakest in spring (64.6%), with winter (74.7%) and autumn (66.3%) falling in between (Fig. S6 a-d). Such seasonal contrast demonstrates that the CBH is governed by boundary layer depth and convective regimes, instead of a straightforward moisture-driven effect on cloud base height. Under moist and unstable conditions, more deeper PBL developed/more PBL and stronger thermally driven updrafts act to elevate cloud bases, particularly for cumulus and convective cloud regimes/systems (Betts, 2004; Zhang and Klein, 2013). This relationship is statistically robust and spatially coherent/consistent across most regions, particularly over southern/southeast China and the eastern margins of the Tibetan Plateau, where moist convection frequently regulates/controls cloud vertical development.

The few/sparse negative correlations (7.66.36.3%), scattered over arid/northwestern China, are likely reflect/governed by the dominance of persistent large-scale subsidence, which decouples local moisture variability/fluctuations from cloud formation and evolution processes (Wood, 2012; Myers and Norris, 2013/Riemann-Campe et al., 2011).

In ~~contrast~~contrast, CBH exhibits predominantly negative correlations with LTS_{surf} ~~LTS~~ across 97.5% of stations (~~72.5% of stations~~; Fig. 8b), ~~with only 2.5% of stations showing positive correlations~~. The strong negative correlations are ~~most notably concentrated~~ over the southeastern coastal regions of China and the Sichuan Basin. A ~~H~~higher LTS_{surf} ~~LTS~~ value indicates ~~stronger~~intensified lower-tropospheric stratification in the lower-troposphere, which suppresses boundary-layer growth and favours shallow stratiform clouds with lower cloud bases (Klein and Hartmann, 1993; Wood and Bretherton, 2006). Conversely, reduced LTS_{surf} ~~LTS~~ enhances instability, ~~promotes~~facilitating ~~deeper~~intense turbulent mixing in the boundary layer, and ~~promoting~~supports the development of ~~higher cloud bases associated with convective clouds~~with higher cloud bases (Slingo, ~~2007~~1987). Seasonal composite analyses further verify that this negative relationship is most widespread in autumn (80.0% of stations) and summer (73.8%), and relatively less so in winter (63.3%) and spring (62.0%) (Fig. S6 e-f). This seasonality indicates that the CBH- LTS_{surf} coupling is modulated by the prevailing convective and boundary-layer regimes. The more consistent negative correlations in summer and autumn align with the dominance of deep convection and stable stratiform conditions (Zhang and Klein, 2013; Guo et al., 2016), respectively, whereas the weaker connection in spring and winter suggests that synoptic transients may at times override the local stability control (Taszarek et al., 2019). This seasonal differentiation confirms that, while LTS_{surf} exerts a primary thermodynamic control on CBH, its influence is conditioned by the seasonal evolution of boundary layer and cloud regimes (Zhang and Klein, 2013).

~~In contrast~~, At the national scale, CBH exhibits a predominantly negative correlation with VWS across 77.8% of observation stations ~~no coherent national-scale relationship with WS700~~ (Fig. 8c), . This widespread negative correlation indicates that stronger vertical wind shear is generally associated with lower cloud bases. Physically, enhanced VWS promotes the entrainment of drier environmental air into the cloud layer, which intensifies droplet evaporation, reduces buoyancy, and suppresses deep convective development, lowering effective cloud bases ~~with nearly equal proportions of positive (52.2%) and negative (47.8%) correlations~~. This near-symmetric distribution suggests that vertical wind shear exerts a context-dependent influence on CBH (Jiang et al., 2012). In some regions (e.g., northern China), stronger shear may enhance convective organization and elevate inflow layers, leading to higher cloud

670 ~~bases~~ (Weisman and Rotunno, 2000). ~~In~~ The sparse positive correlations (22.2%) likely reflect localized
regimes where moderate shear organizes convection and helps sustain updrafts, or where shear-induced
low-level convergence promotes cloud formation under specific instability conditions (Houze, 2018).
~~Overall, the absence of a uniform signal indicates that dynamical shear does not systematically control~~
~~CBH at the national scale.~~

675 Seasonal composite analyses confirm the robustness of this negative relationship, with the proportion
of stations showing negative correlations ranging from 56.5% in summer to 70.0% in winter (Fig. S6 i-l).
This seasonal consistency, albeit weaker than that observed for thermodynamic factors (q_{2m} and
 LTS_{surf}), reinforces the interpretation that VWS plays a secondary modulating role in controlling CBH,
conditioned by the prevailing convective regime.

680 To further explore the joint constraints of atmospheric factors on CBH, we analyze the paired
dependence of CBH on q_{2m} , LTS_{surf} , and VWS (Fig. 9). For the q_{2m} - LTS_{surf} combination (Fig. 9a),
CBH generally increases with increasing q_{2m} , while the magnitude of this sensitivity is strongly
modulated by atmospheric stability. Under low LTS_{surf} (unstable) conditions, the highest CBH values
occur in moisture-abundant environments, consistent with deep boundary layers and active convective
685 cloud development (Zhang and Klein, 2013). In contrast, under high LTS_{surf} (stable) conditions, CBH
remains consistently low across nearly the entire moisture range, suggesting that strong lower-
tropospheric stratification dominates the cloud base variation, confining cloud development to low-base
stratiform clouds regardless of moisture availability (Klein and Hartmann, 1993; Wood and Bretherton,
2006).

690 The LTS_{surf} -VWS relationship (Fig. 9b) further illustrates this conditional modulation effect. In low
 LTS_{surf} environments, CBH tends to increase with increasing wind shear, consistent with the role of wind
shear in organizing convection and modulating inflow structure under unstable conditions (Weisman and
Rotunno, 2000). Under high LTS_{surf} environments, CBH remains uniformly low and shows weak
sensitivity to shear, reinforcing the conclusion that stability exerts the primary constraint on cloud-base
695 variability.

For the q_{2m} -VWS pairing (Fig. 9c), CBH increases primarily with q_{2m} , while wind shear plays a secondary modulating role. The highest CBH values occur when abundant low-level moisture coincides with weak-to-moderate wind shear, indicating that abundant low-level moisture acts as the primary driver for elevated cloud bases, while weak shear does not exert the suppressing effect typically associated with strong wind shear. This is consistent with the national-scale negative correlation between CBH and VWS shown in Fig. 8c, where strong shear environments tend to suppress cloud-base height.

3.5.2 *Impact of atmospheric thermodynamic and dynamical factors on CTH* Cloud top height

Cloud top height (CTH) exhibits broadly similar but more pronounced thermodynamic sensitivity (Fig. 9). Single-variable correlations for q_{2m} (Fig. 9a) show that q_{2m} is positively correlated with CTH at 96.3% of stations, indicating that abundant low-level moisture sustains buoyant ascent and supports deeper cloud development. This relationship is most pronounced over southern China and the eastern Tibetan Plateau margins, where active abundant low-level moisture sustains buoyant ascent and deeper cloud development moist convection prevails. Higher specific humidity provides ample moisture supply to convective systems, enabling air parcels to maintain positive buoyancy over deeper layers and reach higher levels before encountering their level of neutral buoyancy (Johnson et al., 1999; Holloway and Neelin, 2009). The few negative correlations (3.7%), scattered over arid northwestern China, likely reflect the dominance of large-scale subsidence that inhibits suppresses deep convective development regardless of local moisture availability (Riemann-Campe et al., 2011).

CTH is predominantly negatively correlated with LTS_{surf} (65.8% of stations; Fig. 9b), particularly over coastal southeastern China, the Sichuan Basin, and the Yangtze River valley. The explanation parallels that for CTH: higher LTS_{surf} suppresses vertical cloud growth, favouring shallow cloud formations with lower cloud tops (Klein and Hartmann, 1993; Wood and Bretherton, 2006), while lower-reduced LTS_{surf} enables vigorous deeper convective development that extends to higher altitudes (Slingo, 1987). The small fraction of positive correlations (34.2% of stations), primarily mainly over the Tibetan Plateau and parts of northern China, may reflect situations where

LTS_{surf} variations are coupled with large-scale dynamical lifting or orographic forcing (Medeiros et al., 2010). Seasonally, the proportion of negative correlations is highest in autumn (67.5%) and lowest in summer (55.0%), consistent with the seasonal prevalence of stable stratiform conditions versus deep convection. This seasonal modulation reinforces the interpretation that stability control on cloud top height is conditioned by the dominant cloud type and boundary-layer regime (Klein and Hartmann, 1993; Wood and Bretherton, 2006; Zhang and Klein, 2013).

By comparison, CTH shows a predominantly negative correlation with VWS_{700} (69.6% of stations; Fig. 910c), with negative correlations concentrated over southern China, the Tibetan Plateau margins, and northeastern China. This pattern indicates that stronger vertical wind shear tends to suppress vertical cloud development, thereby CTH through enhanced entrainment mixing, disruption of coherent updrafts, and increased upper-level turbulence that spreads anvils horizontally lowering cloud top heights. Several mechanisms may explain this relationship: (1) Enhanced entrainment mixing near cloud edges, which dilutes buoyancy and limits vertical growth; (2) Disruption of vertically coherent updrafts during early convective stages; and (3) Increased upper-level turbulence that spreads anvils horizontally rather than vertically (Sathiyamoorthy et al., 2004). These processes reduce maximum cloud top altitude and favour layered cloud structures (Yang et al., 2022). However,

Positive correlations (30.4% of stations), scattered mainly over northwestern China, show positive correlations, may reflect environments where moderate shear organizes convection into longer-lived systems capable of deeper vertical development—consistent with the “optimal shear” framework (Weisman and Rotunno, 2000).

The joint dependence of CTH on paired variables (Fig. 11) further clarifies this conditional behaviour. Under low LTS_{surf} (unstable) and high q_{2m} (moist) conditions (Fig. 11a), CTH reaches its maximum values, confirming that both instability and moisture are necessary for deep convection. Compared with CBH, the sensitivity of CTH to moisture under unstable conditions is more gradual, suggesting that processes aloft—such as entrainment, detrainment, and upper-level thermodynamic structure—exert additional modulation on maximum CTH (Holloway and Neelin, 2009).

The LTS_{surf} -VWS pairing (Fig. 11b) shows that CTH is greatest under low LTS_{surf} with weak-to-moderate wind shear, directly illustrating the “optimal shear” effect, whereby moderate shear organizes rather than suppresses deep convection (Weisman and Rotunno, 2000). Under high LTS_{surf} , CTH remains low regardless of wind shear magnitude, reaffirming that stable stratification acts as the primary constraint on cloud top development.

For the q_{2m} -VWS combination (Fig. 11c), the joint patterns reinforce that CTH is more tightly coupled to q_{2m} than to VWS: the largest CTH occurs when abundant moisture coincides with weak wind shear. Conversely, reducing wind shear under low-humidity conditions is insufficient to significantly elevate cloud tops, confirming that moisture availability, rather than wind shear, is the fundamental driver for deep convective cloud development. Wind shear thus primarily serves as a constraining, rather than an elevating factor.

3.5.3 *Impact of atmospheric thermodynamic and dynamical factors on CT* Cloud thickness

Cloud thickness exhibits distinct correlation patterns that differ from those of CBH and CTH (Fig. 102). For q_{2m} -CT (Fig. 102a), positive correlations dominate across 67.5% of stations, indicating that abundant low-level moisture favours 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 (32.5% of stations), scattered over arid northwestern China and parts of Inner Mongolia, may reflect environments where moisture is insufficient to support deep convective development, or where enhanced low-level moisture triggers early precipitation that limits further vertical growth. 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} -CT (Fig. 102b), cloud thickness exhibits a predominantly 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. (67.155.0 % of stations), (Slingo, 1987; Medeiros et al., 2010) concentrated over southern China, the Sichuan Basin, and the Yangtze River valley. This contrasts with the negative LTS correlations observed for CBH and CTH. The positive relationship arises because moderate to high LTS is often associated with stratiform cloud regimes, which, while having limited vertical extent individually, can develop considerable geometric thickness through layered cloud structures and persistent moisture supply (Klein and Hartmann, 1993; Wood and Bretherton, 2006). NegativePositive correlations (32.945.0 % of stations), concentrated over northern China, the Sichuan Basin, and the Yangtze River valley. This contrasts with the negative LTS correlations observed for CBH and CTH. The positive relationship arises because moderate to high LTS is often associated with stratiform cloud regimes, which, while having limited vertical extent individually, can develop considerable geometric thickness through layered cloud structures and persistent moisture supply (Klein and Hartmann, 1993; Wood and Bretherton, 2006). primarily over the Tibetan Plateau and parts of northern China, reflect situations where low LTS enhances atmospheric instability and promotes deep convection, but the resulting clouds exhibit highly variable thickness depending on convective stage and precipitation processes (Slingo, 1987; Medeiros et al., 2010).

Cloud thickness shows a predominantly negative correlation with $\nabla W S_{700}$ (78.33.9% of stations; Fig. 102c), indicating that stronger vertical wind shear generally suppresses vertical cloud development. with a Negative correlations are widespread across southern China, the Tibetan Plateau margins, northeastern China, and the North China Plain. This strong negative relationship indicates that

stronger vertical wind shear suppresses vertical cloud development, reducing cloud thickness. Multiple mechanisms operate across different atmospheric layers. Large eddy simulations demonstrate that vertical wind shear—particularly backward shear (surface easterlies becoming upper westerlies)—limits vertical cloud development in trade wind cumulus convection, leading to shallower cloud layers (Helfer et al., 2020). Wind shear across the cloud-top interface enhances entrainment mixing and turbulent kinetic energy production, diluting cloud cores and suppressing vertical growth (Mellado and Stevens, 2014). Strong upper-level shear limits upward deep convective development by enhancing turbulence over cloud tops and extending anvils horizontally (Sathiyamoorthy et al., 2004) and disrupts organized updraft structures (Bi et al., 2023). Positive correlations (21.76.1% of stations), scattered across limited areas of northwestern China, may reflect environments where moderate shear organizes convection into longer-lived systems capable of that achieve greater vertical development through enhanced moisture convergence—consistent with the concept of "optimal" shear—"concept for organized deep convection (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 enhance 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 function as strong regulators that either suppress or facilitate vertical development depending on their specific magnitudes.

—3.6 Joint thermodynamic–dynamic controls

Because atmospheric controls rarely operate in isolation, we further examine the joint regulation of CVS by paired thermodynamic and dynamical variables. This bivariate analysis reveals that moisture availability establishes the fundamental precondition for vertical cloud development, while instability and wind shear determine the efficiency with which that moisture is converted into vertical growth. Under high humidity and low LTS conditions, clouds attain maximum CBH, CTH, and CT. In contrast, high LTS suppresses vertical development regardless of moisture or shear intensity, demonstrating the dominant stabilizing control of stratification. Wind shear exhibits a nonlinear influence: moderate shear enhances convective organization under unstable conditions, whereas strong shear inhibits vertical cloud growth through enhanced mixing. This joint dependence confirms that thermodynamic forcing provides the primary control on CVS across China, with dynamical processes acting as modulators.

3.6.1 Cloud base height

Figure 11 illustrates the joint dependence of CBH on paired atmospheric variables. For the q_{2m} - q_{850} -LTS combination (Fig. 11a), CBH generally increases with q_{850} , but the sensitivity depends strongly on stability. Under low LTS (unstable) conditions, CBH reaches its highest values when moisture

855 is abundant, consistent with environments favouring deep boundary layer development and convective cloud regimes. Under high LTS (stable) conditions, CBH remains low across nearly all humidity bins, indicating that strong stratification limits boundary layer growth and favours low base stratiform clouds regardless of moisture availability.

860 The LTS-WS700 relationship (Fig. 11b) further demonstrates this conditional behavior. Under low LTS, CBH tends to increase with increasing shear, consistent with the role of shear in organizing convection and modulating inflow structure in unstable environments (Weisman and Rotunno, 2000). Under high LTS, CBH remains uniformly low and exhibits weak sensitivity to shear, again emphasizing that stability constrains cloud base variability.

865 For the $q_{zm}q850$ -WS700 pairing (Fig. 11c), CBH increases primarily with $q_{zm}q850$, while shear acts as a secondary modulator. The largest CBH values occur when high moisture coincides with moderate-to-strong shear, suggesting that organized convection and enhanced mixing in such environments can support higher cloud bases. When $q_{zm}q850$ is low, increasing shear alone produces only limited increases in CBH, indicating that moisture availability remains a prerequisite for elevated cloud bases.

870 3.6.2 Cloud top height

875 The joint dependence of CTH on paired variables (Fig. 12) is broadly consistent with that of CBH, but with greater sensitivity to deep convective environments. For the $q_{zm}q850$ -LTS combination (Fig. 12a), CTH maximizes under high humidity and low LTS, consistent with vigorous vertical development supported by strong buoyancy and ample moisture supply (Johnson et al., 1999). Compared with CBH, the dependence of CTH on humidity under unstable conditions is more gradual, indicating that processes aloft—such as entrainment, detrainment, and upper-level thermodynamic structure—also influence maximum cloud-top altitude.

880 The LTS-WS700 pairing (Fig. 12b) indicates that CTH is largest under low LTS with moderate-to-strong shear, consistent with the concept of “optimal shear” conditions that favour organized deep convection (Weisman and Rotunno, 2000). Under high LTS, CTH remains low across all shear bins, reaffirming that stable stratification suppresses vertical development irrespective of dynamical forcing.

For the q_{850} –WS700 combination (Fig. 12c), CTH increases with both humidity and shear, with the highest values occurring when high q_{2m} – q_{850} coincides with strong shear. This behavior is consistent with shear-enhanced convective organization when sufficient moisture is available, whereas under low humidity, increasing shear alone does not substantially elevate cloud tops.

3.6.3 Cloud thickness

Cloud thickness exhibits distinct joint-dependence characteristics (Fig. 13), reflecting its integrated sensitivity to both cloud-base and cloud-top processes. For the q_{2m} – q_{850} –LTS combination (Fig. 13a), the thickest clouds occur under high humidity and low LTS. CT shows a particularly strong dependence on stability when humidity is high, indicating that instability is critical for realizing large vertical extent once moisture requirements are satisfied.

The LTS–WS700 relationship (Fig. 13b) shows that maximum CT tends to occur under low LTS combined with moderate shear. The thickest clouds generally develop under low LTS combined with moderate vertical wind shear. Consistent with the inhibitory effect of strong shear concluded in Section 3.5.3, intense shear under unstable atmospheric conditions markedly reduces CT magnitude. The physical suppression of cloud vertical growth by excessive wind shear has been well documented in previous numerical studies. Large-eddy simulations demonstrate that vertical wind shear—particularly backward shear (surface easterlies becoming upper westerlies)—limits vertical cloud development in trade wind cumulus convection, leading to shallower cloud layers (Helfer et al., 2020). Wind shear across the cloud-top interface enhances entrainment mixing and turbulent kinetic energy production, diluting cloud cores and suppressing vertical growth (Mellado and Stevens, 2014). Strong upper-level shear limits upward deep convective development by enhancing turbulence over cloud tops and extending anvils horizontally (Sathiyamoorthy et al., 2004) and disrupts organized updraft structures (Bi et al., 2023). Strong shear thus exerts dual regulatory effects on cloud development: moderate shear organizes convective systems and sustains cloud evolution, whereas excessive shear enhances interfacial entrainment and turbulent detrainment, restricting net cloud vertical depth. In contrast, strong shear under unstable conditions is associated with reduced CT, consistent with the dual role of shear: moderate shear can enhance organization, whereas excessive shear increases entrainment mixing and promotes detrainment that limits

net cloud depth (Mellado and Stevens, 2014; Helfer et al., 2020). Under high LTS, CT remains uniformly small and exhibits weak sensitivity to shear, again indicating that stability strongly constrains vertical development.

For the q_{zm} - q_{850} -WS700 combination (Fig. 13c), CT increases primarily with q_{zm} - q_{850} , while shear influences CT more strongly under high humidity conditions. When humidity is low, CT remains limited across all shear bins; when humidity is high, CT increases with shear up to moderate-strong values. These joint results further support the view that moisture availability is a necessary precondition for substantial cloud depth, while wind shear regulates the realized vertical extent by modulating organization and mixing.

3.7.6 The land surface modulation of cloud vertical structure

In addition to 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). BecauseSince CBH is closely linked tightly coupled to PBL thermodynamics, it providesserves 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 influences, we compare CBH across land-cover types for under two conditions: (i) all-hour low clouds and (ii) afternoon (1400–1800 LT) single-layer low clouds (Fig. 14), which are expected to exhibit stronger coupling to surface forcing during peak daytime heating. The afternoon subset captures the period of strongest coupling, when the boundary layer is fully developed and land-atmosphere fluxes are maximized.

3.76.1 All-hour low-cloud conditions

Under all-hour cloud conditions, CBH of low clouds exhibits substantial variability depends systematically on underlying land cover type across land cover types, with interquartile ranges typically spanning approximately 1–6 km (Fig. 14, left panels). Barren land (type 10) shows the highest median CBH (1.32 km), consistent with limited surface moisture availability and a tendency toward higher lifting condensation elevated LCLs, and fewer low-base clouds. In contrast, Densely vegetated surfaces (types 2–7) 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 (type 3, 0.72 km), and croplands (type 7, 0.72 km) generally exhibit lower median CBH. Among these, evergreen broadleaf forest (type 2) and deciduous broadleaf forest (type 3) show the lowest median CBH, while grasslands (type 6) and Water bodies (type 01, 1.02 km) and urban and built-up lands (type 8, 0.90 km) fall in the intermediate range display moderately low values.

These contrasts can be interpreted in terms of land-cover biophysical properties explained by the biophysical properties of the land cover. Forests sustain high evapotranspiration, which moistens the boundary layer and lowers the lifting condensation level, favoring lower cloud bases (Spracklen et al., 2012; Zhang et al., 2024). In addition, lower canopy albedo and greater surface roughness can enhance turbulent exchange, influencing boundary layer growth and cloud formation. Collectively, these mechanisms favour cloud formation and can contribute to lower cloud bases over forests relative to sparsely vegetated or barren surfaces. This interpretation is consistent with observational and modeling studies demonstrating that land-use and land-cover change can modify CBH by altering the partitioning between sensible and latent heat fluxes and the resulting boundary layer thermodynamics 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).

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%).

Two factors likely contribute to these systematic differences. First, single-layer cloud regimes often occur under relatively dry or weakly forced conditions, which can be associated with higher condensation levels than multi-layer or deep convective regimes. Second, peak daytime heating in the afternoon deepens the boundary layer and can raise cloud bases through enhanced turbulent mixing and increased boundary layer temperature. The amplified land-cover contrasts during afternoon hours may also reflect enhanced sensitivity of boundary layer evolution to surface heterogeneity under strong insolation. Heterogeneous landscapes can generate mesoscale circulations and spatial gradients in moisture and heat fluxes that modulate cloud initiation and cloud base height. The systematically higher afternoon CBH primarily reflects the deepening of the boundary layer and the associated rise in the lifting condensation level 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 ~~that land cover type exerts~~ 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 ~~using distributed sensor networks~~; Trivedi et al., 2025), suggesting that land-surface modulation of low cloud vertical structure ~~may be~~ is a robust feature across diverse geographic settings.

4. Summary and conclusions

This study presents the first national-scale, high-spatiotemporal-resolution characterization analysis of ~~cloud vertical structure (CVS)~~ across China based on observations from a coordinated network of 80 Ka-band cloud radars during 2024. ~~The dataset provides~~ an unprecedentedly detailed snapshot (30 m vertical, 1 min temporal resolution) of cloud vertical structures for examining the spatial distribution, seasonal evolution, diurnal variability, and their governing controls factors. ~~of cloud vertical structure. Our results demonstrate pronounced spatial, seasonal, and diurnal variability in CVS, reflecting strong modulation by monsoonal circulation, thermodynamic stratification, and regional terrain.~~

The ~~national~~ annual mean cloud occurrence frequency is $56.7 \pm 7.2\%$, with single-layer clouds dominating ($34.7 \pm 4.0\%$), followed by two-layer ($14.7 \pm 3.2\%$) and multi-layer clouds ($7.1 \pm 2.4\%$). Spatially, single-layer clouds are more prevalent over arid northwestern China, whereas multi-layer clouds occur more frequently in humid southeastern regions. ~~This contrast highlights the regulatory, highlighting the~~ role of moisture availability ~~and atmospheric instability~~ in shaping cloud vertical complexity.

Cloud height exhibits clear seasonal modulation. CBH follows the order of summer > spring > autumn > winter, with systematically lower values over the ~~consistent with seasonal variations in solar~~

heating and boundary layer development. The Tibetan Plateau shows systematically lower CBH in spring and summer, reflecting the combined influence of lower ambient temperatures, terrain-induced lifting, and unique boundary layer thermodynamics in spring and summer. Vertically, CBH displays a unimodal distribution dominated by low-level clouds, ~~whereas~~ while CTH exhibits a bimodal structure, ~~indicating~~ reflecting the coexistence of shallow stratiform and deep convective cloud regimes across China.

Diurnal variations in CVS are strongly seasonally dependent. In summer, upper-level cloud occurrence (3–9 km) peaks during the late afternoon (1600–2000 LT), driven by enhanced surface heating and convective instability. In winter, clouds are largely confined below 3 km and exhibit a near-sunrise maximum (0600–0800 LT), consistent with nocturnal radiative cooling and stable boundary-layer conditions. Spring and autumn display transitional behavior between these two regimes.

Thermodynamic conditions exert the dominant control on CVS. Both CBH and CTH are positively correlated with q_{2m} and negatively correlated with LTS_{surf} , indicating that abundant moisture and reduced stability favor deeper vertical development. VWS plays a secondary but systematic role. CTH and CT are predominantly negatively correlated with shear, suggesting that with strong shear generally suppresses vertical cloud growth through enhanced entrainment and disruption of organized updrafts. Joint analyses further reveal that high humidity combined with low LTS_{surf} maximizes cloud vertical development, whereas high LTS_{surf} constrains CVS regardless of moisture or shear conditions. Wind shear exhibits nonlinear behavior; with moderate shear occasionally supporting organized convection under unstable conditions, whereas but strong shear generally limits vertical extent.

Land cover type exerts a measurable influence on cloud base height, particularly for afternoon single-layer low clouds. The, whose median CBH of afternoon single-layer clouds is approximately 41.521.7% higher than that under all-cloud hour low cloud conditions, reflecting enhanced boundary layer growth during peak daytime heating. Among land cover types, barren lands exhibit the highest CBH, likely due to limited surface moisture supply, while forested regions display the lowest CBH, consistent with enhanced evapotranspiration, moisture recycling, and surface-atmosphere coupling. The largest relative

enhancement in afternoon CBH occurs over deciduous broadleaf forests (+55.941.7%), underscoring the amplification of land–atmosphere feedback under strong solar forcing.

Overall, this study provides a high-resolution, observationally constrained ~~datasets~~snapshot of cloud vertical structure across China and establishes a quantitative framework linking CVS metrics to thermodynamic, dynamical, and land-surface controls, ~~as shown in the schematic diagram~~ (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. 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. Additionally, while the seasonal stratification in this study captures the dominant large-scale regime shifts (e.g., monsoon), a dedicated analysis using objective weather-typing techniques would further isolate the effects of synoptic weather regimes on CVS, which is beyond the scope of the current study. These findings offer valuable observational constraints for evaluating and improving cloud parameterization schemes in numerical weather prediction and climate models. 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.

Code/Data availability. The authors would like to acknowledge the National Meteorological Information Centre (NMIC) of CMA (<http://data.cma.cn/en>, CMA, 2024) for providing the Ka-band millimeter-wave

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Author contribution. JG conceptualized this study. HX, JG, and JD carried out the analysis with comments from other co-authors. HX wrote the paper with contribution from JG, RY, DM, JZ, JC, NL, LZ, YZ, and TC provided useful suggestions for the study. BT contributed to the big data analysis. All authors contributed to the improvement of paper.

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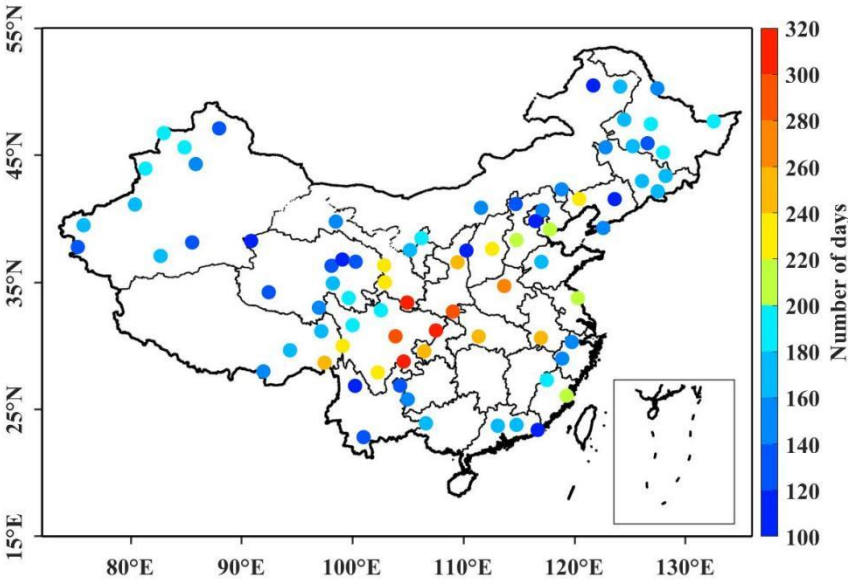
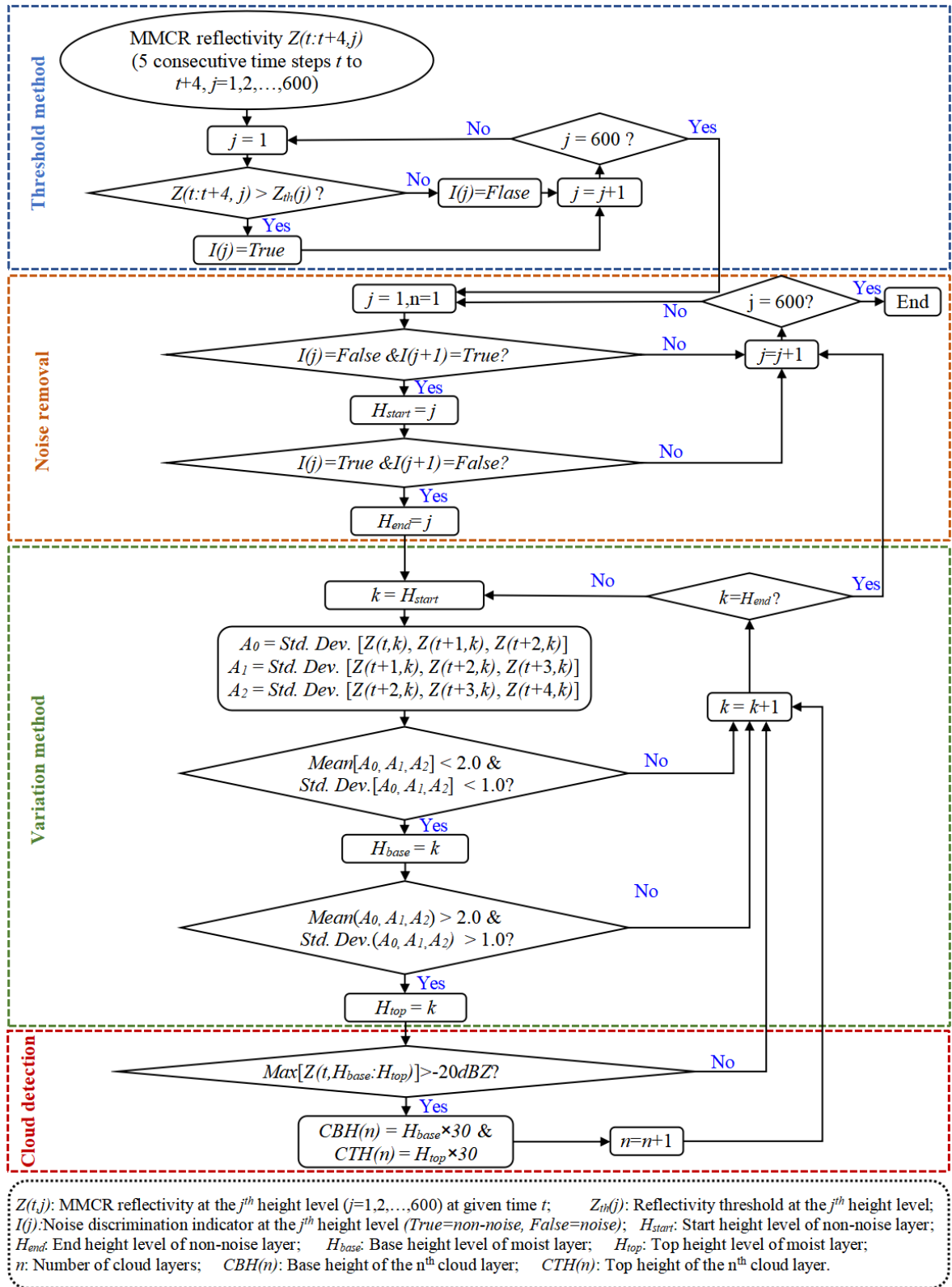


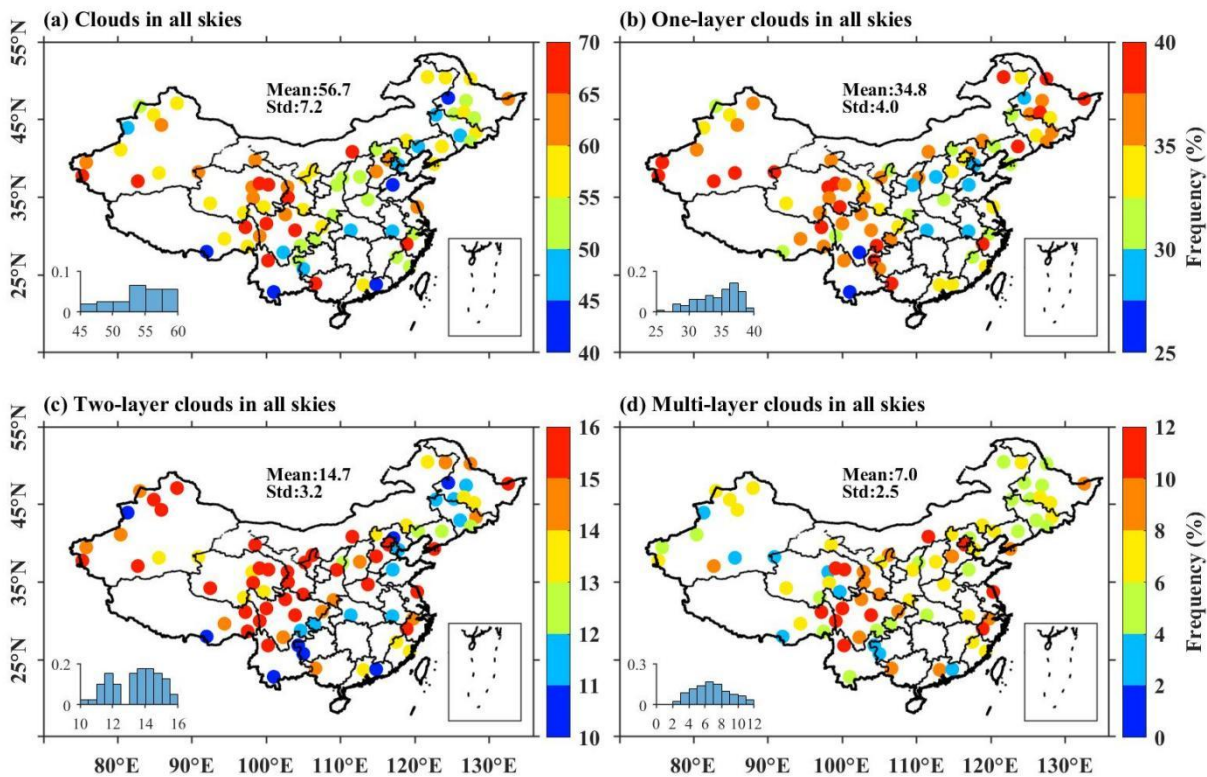
Figure 1. Geographical distribution of millimeter-wave cloud radar (MMCR) stations across mainland China in 2024. A total of 120 MMCR stations were in nationwide operation during this period. For rigorous data quality control, stations with fewer than 100 valid annual observation days were excluded from the subsequent analysis. Consequently, 80 stations that met this quality criterion are displayed in the map, where the color of each station marker denotes the total number of days with valid observational records at the corresponding site.

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$Z(t,j)$: MMCR reflectivity at the j^{th} height level ($j=1,2,\dots,600$) at given time t ; $Z_{th}(j)$: Reflectivity threshold at the j^{th} height level;
 $I(j)$: Noise discrimination indicator at the j^{th} height level ($True=non-noise, False=noise$); H_{start} : Start height level of non-noise layer;
 H_{end} : End height level of non-noise layer; H_{base} : Base height level of moist layer; H_{top} : Top height level of moist layer;
 n : Number of cloud layers; $CBH(n)$: Base height of the n^{th} cloud layer; $CTH(n)$: Top height of the n^{th} cloud layer.

1480 **Figure 2.** Flowchart for identifying the cloud vertical structure (CVS) from high-temporal-resolution
MMCR measurements. This flowchart comprises four sequential key steps in the CVS retrieval process:
first, the threshold method involves comparing the MMCR reflectivity $Z(t:t+4, j)$ against the height-
dependent threshold $Z_{th}(j)$ to generate the noise discrimination indicator $I(j)$, which distinguishes non-
noise and noise layers; subsequently, the noise removal step identifies the start (H_{start}) and end (H_{end})
1485 height levels of non-noise layers based on the indicator $I(j)$; then, the variation method determines the
base (H_{base}) and top (H_{top}) height levels of moist layers by calculating the statistical variation (including
standard deviation and mean) of reflectivity within the identified non-noise layers; finally, the cloud
detection step retrieves the base height ($CBH(n)$) and top height ($CTH(n)$) of each cloud layer by
verifying the reflectivity magnitude of the moist layers, thereby yielding the final cloud vertical structure.



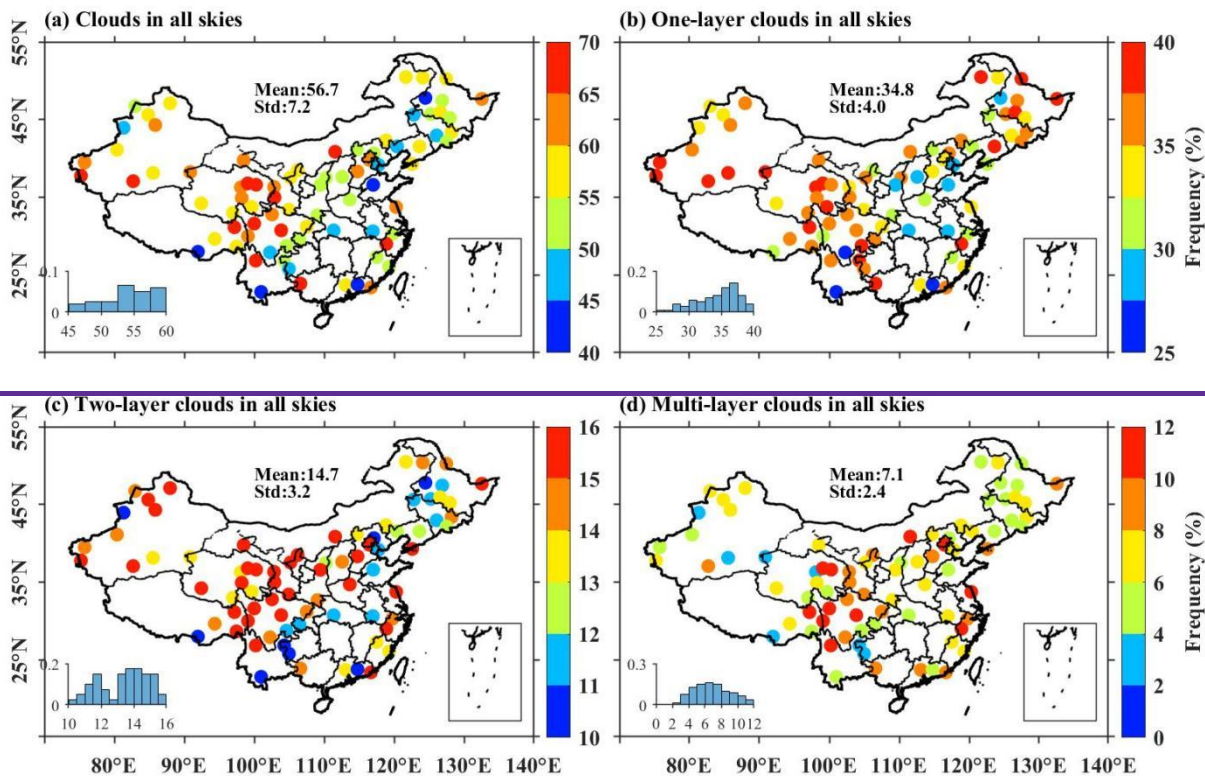


Figure 3. Spatial distribution of annual mean cloud occurrence frequency for different cloud layering classifications: (a) all clouds, (b) single-layer clouds, (c) two-layer clouds, and (d) multi-layer clouds (three-, four-, and five-layer clouds) under all-sky conditions in 2024. The data are derived 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.

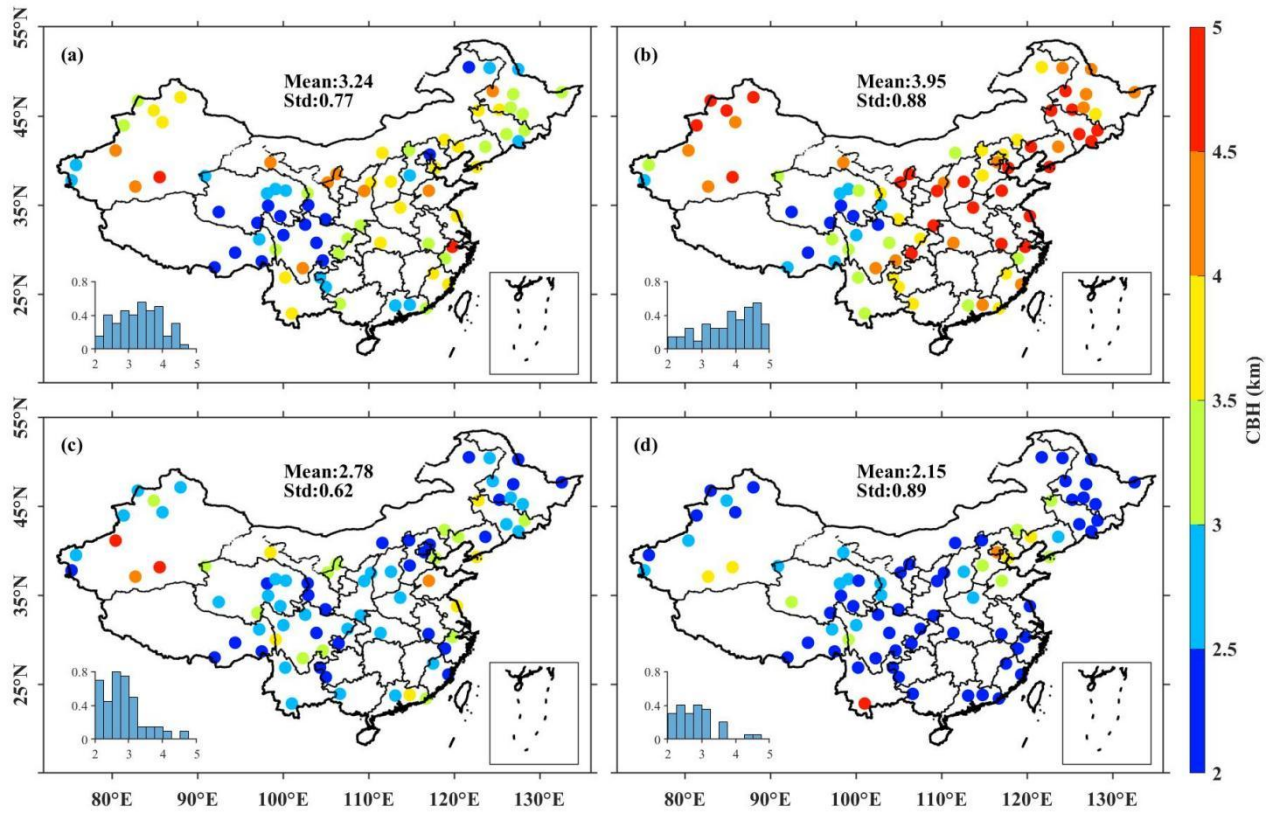


Figure 4. Seasonal geographic distribution of cloud base height (CBH) over China in 2024, derived from the 80 MMCR stations of the same network referenced in Figure 1. The four panels correspond to (a) spring (March - April - May), (b) summer (June - July - August), (c) autumn (September - October - 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.

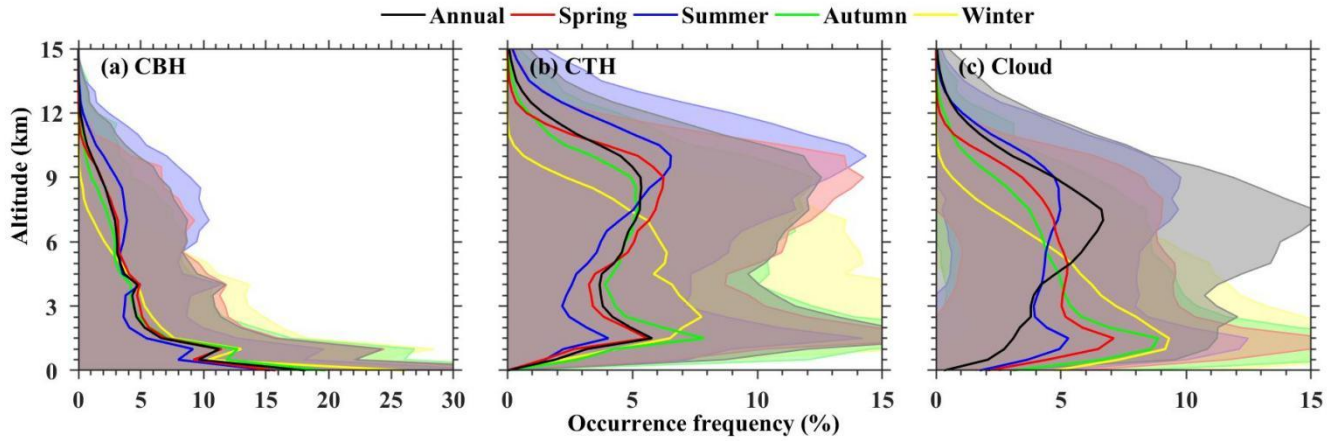


Figure 5. Vertical distributions of annual and seasonal mean occurrence frequencies of (a) CBH and (b) cloud top height (CTH), and (c) overall cloud occurrence across China in 2024. The annual mean is plotted in black, while seasonal means for spring, summer, autumn, and winter are shown in red, blue, green, and yellow, respectively. Data samples are binned at a vertical resolution of 200 m. At each altitude, cloud occurrence frequency is defined as the ratio of cloudy samples at that altitude to the total number of cloudy samples across all altitudes. Solid lines denote mean values, and shaded areas represent the corresponding standard deviations.

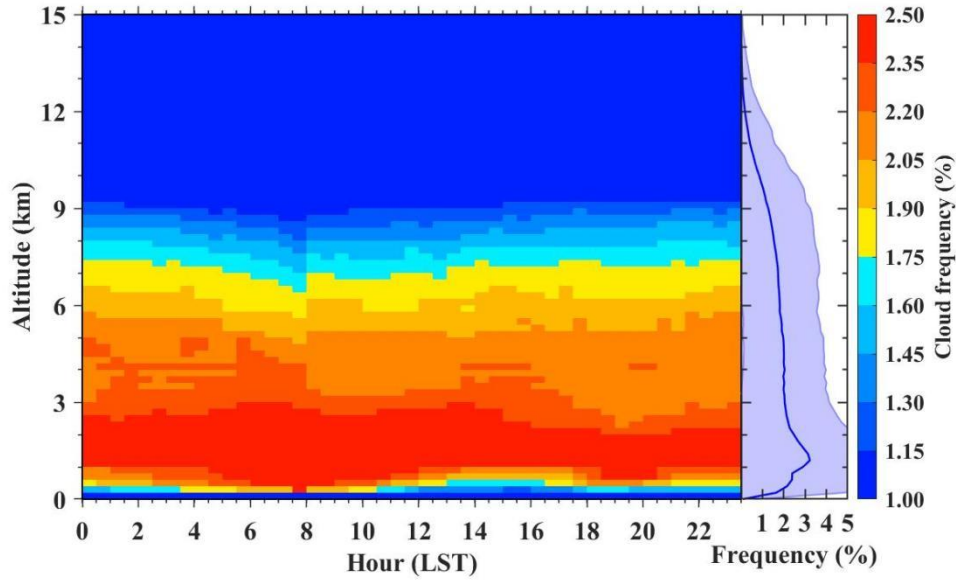


Figure 6. Annual mean diurnal cycle of height-resolved cloud occurrence frequency and corresponding vertical profiles derived from measurements at all 80 MMCR stations (Figure 1) across China in 2024. Data samples are binned at a vertical resolution of 200 m and a temporal resolution of 30 minutes. Cloud occurrence frequency at a given altitude is defined as the ratio of cloudy samples at that altitude to the total number of cloudy samples across all altitudes. Also presented are the corresponding vertical probability distributions of clouds.

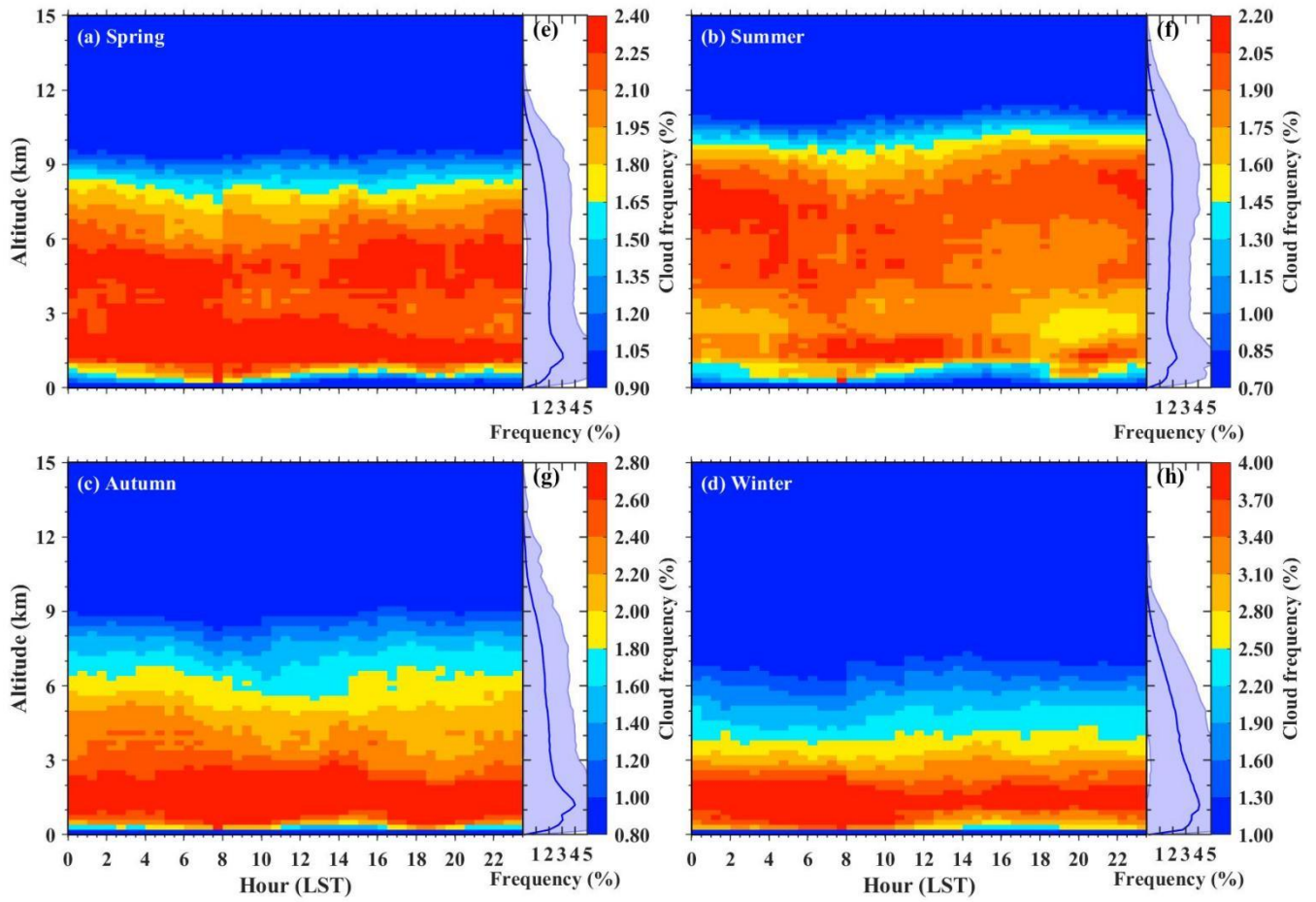


Figure 7. Similar to Figure 6, but for the seasonal mean diurnal cycle of height-resolved cloud occurrence frequency and corresponding vertical profiles over China in (a) spring, (b) summer, (c) autumn, and (d) winter.

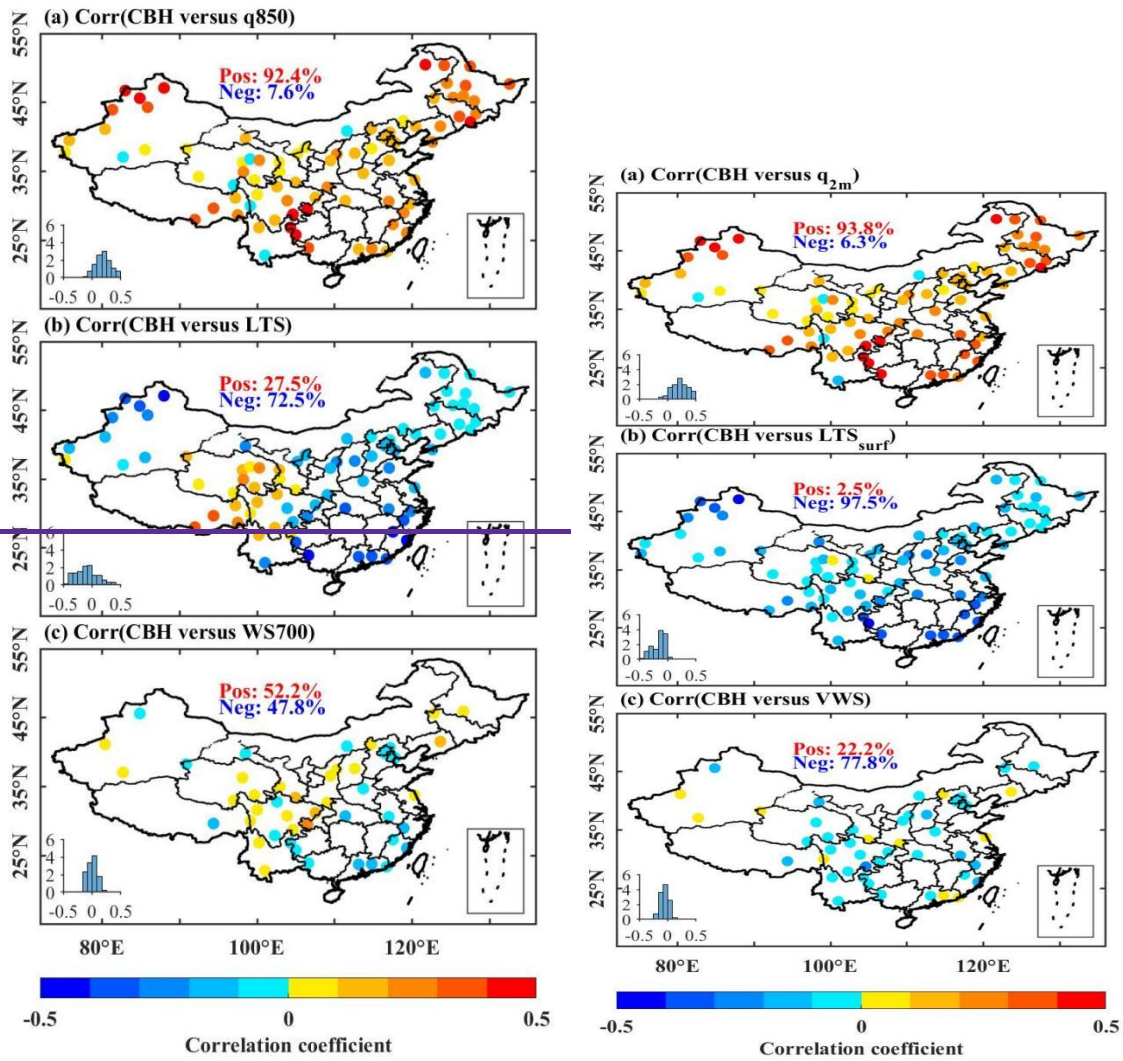


Figure 8. Spatial distributions of correlation coefficients of CBH, ~~CTH~~, and ~~cloud thickness (CT)~~ with lower-tropospheric stability (LTS), 2 m specific humidity ~~at 850 hPa~~ (q_{2m} ~~q850~~), and ~~700 hPa~~ vertical wind shear (~~VWS700~~) across China (2024). Here, LTS_{surf} is defined as the difference between potential temperature at the reference pressure level (700 hPa for low-elevation sites and 500 hPa for high-elevation sites) and surface potential temperature. The VWS is calculated at the same reference levels following the elevation-dependent scheme described in Section 2.2.3. 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.

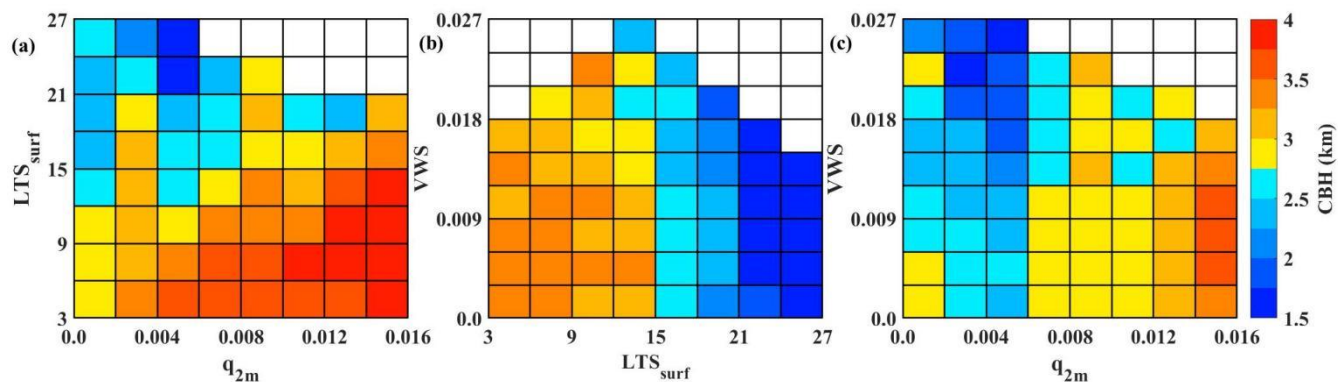


Figure 9. Bivariate regulation of CBH by thermodynamic and dynamical factors across China in 2024, based on observations from 80 MMCR stations. Each panel illustrates the response of CBH to the combined modulating effects of a specific pair of key atmospheric factors: (a) LTS_{surf} and q_{2m} , (b) VWS and LTS_{surf} , and (c) VWS and q_{2m} . All ERA5 reanalysis variables were spatially and temporally matched with MMCR data to ensure the validity and reliability of this bivariate joint dependence analysis.

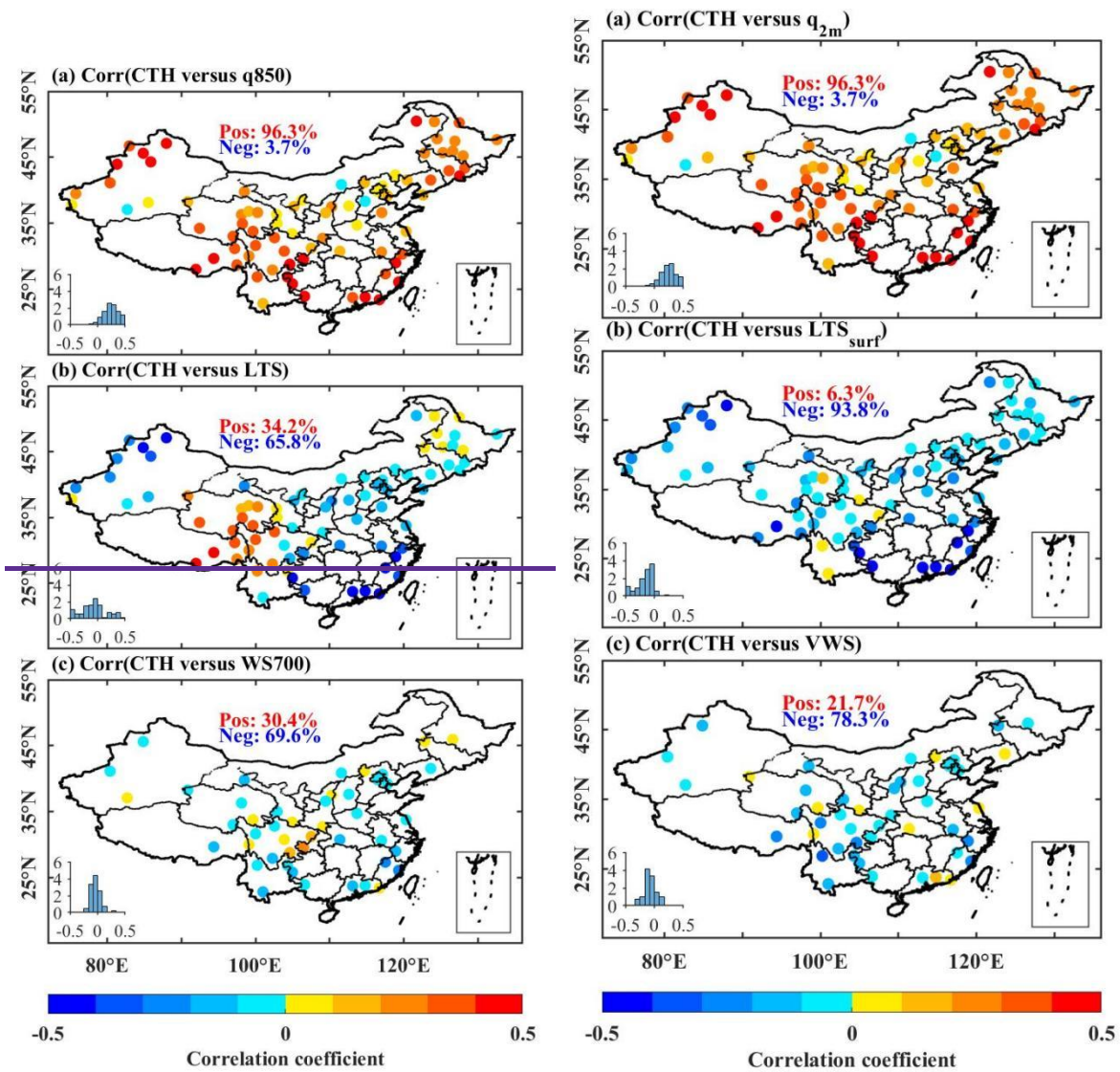
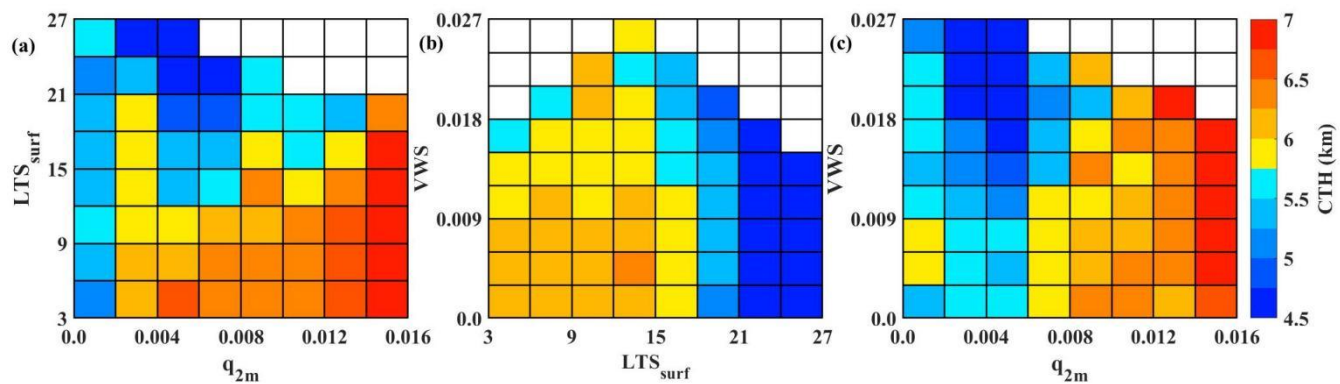


Figure 910. Similar as Figure 8, but for the CTH.



1555 **Figure 11.** Similar as Figure 9, but for CTH.

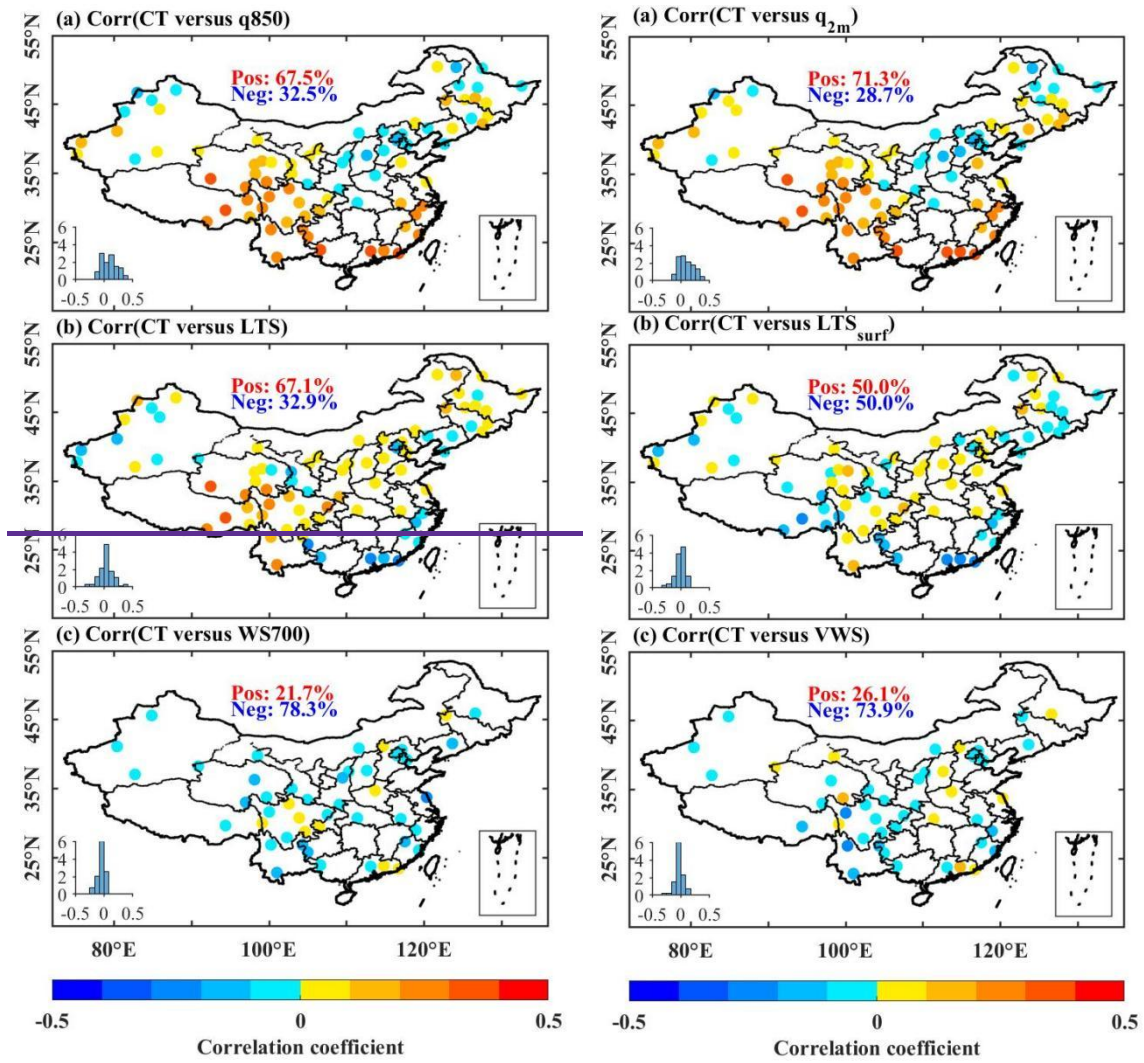


Figure 102. Similar as Figure 8, but for CT.

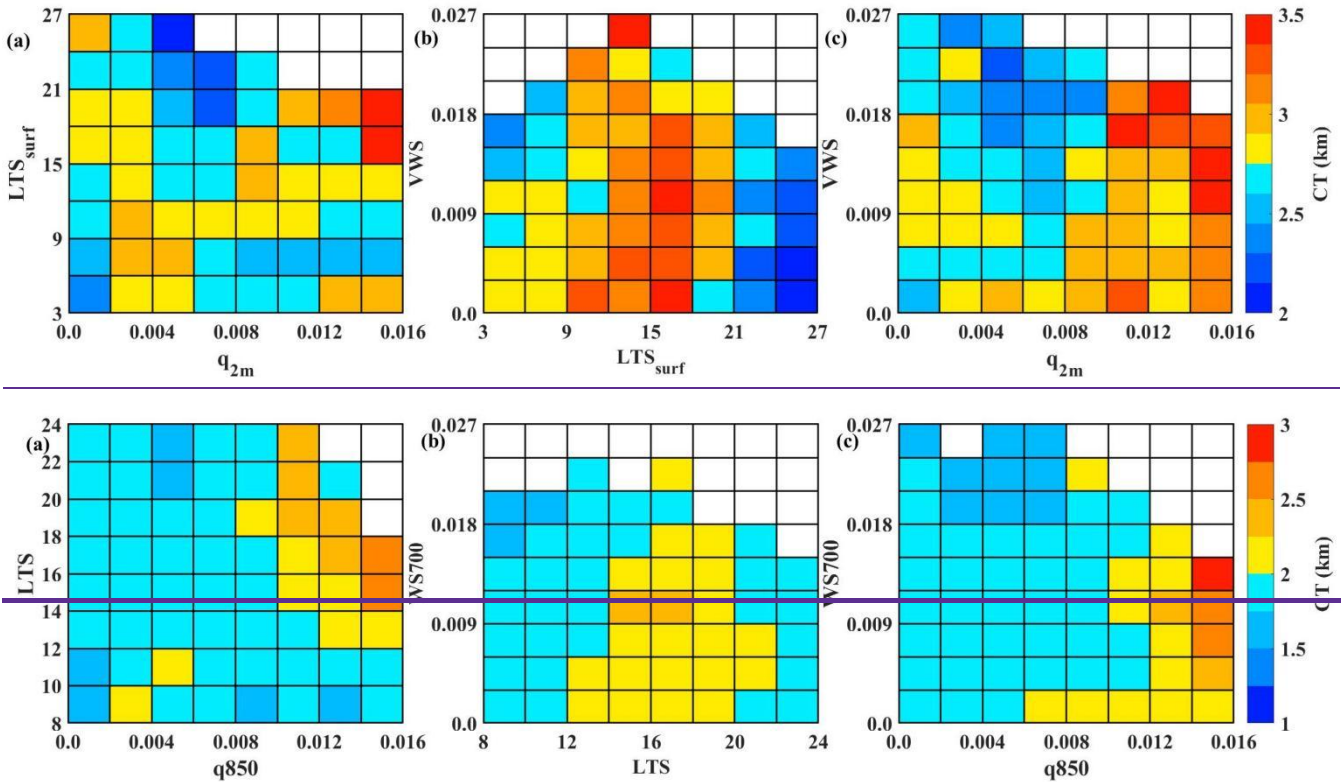
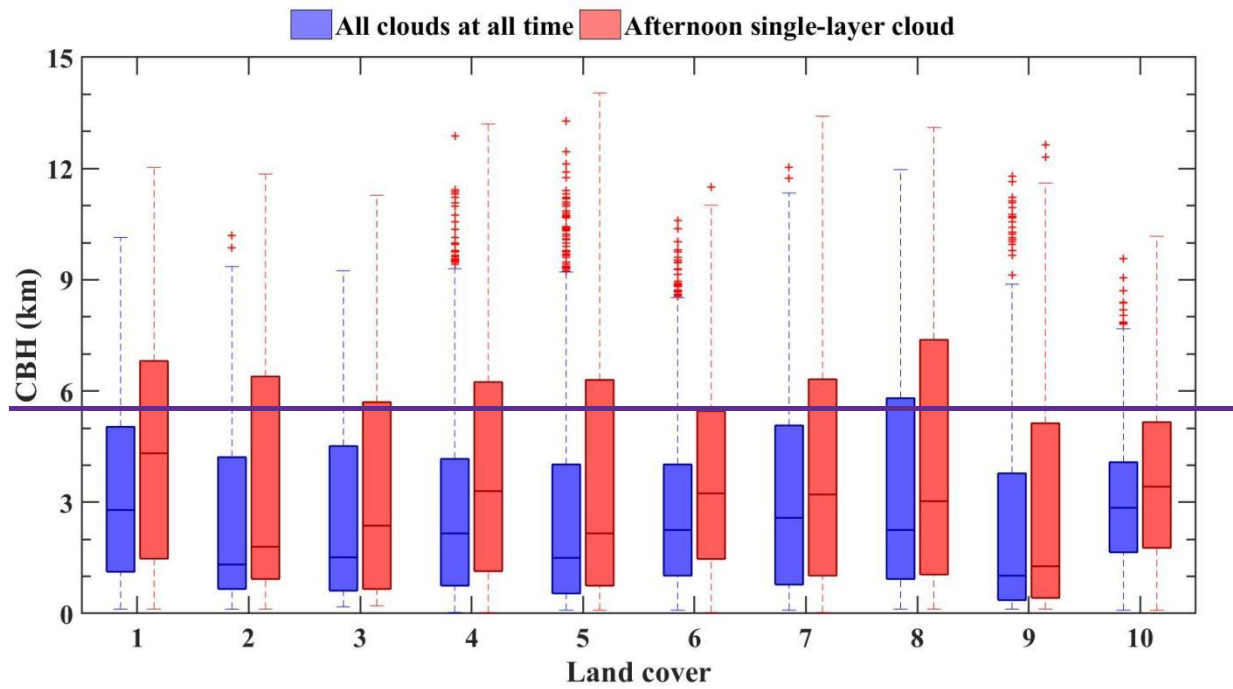


Figure 11. Bivariate regulation of CBH by thermodynamic and dynamical factors across China in 2024, based on observations from 80 MMCR stations. Each panel illustrates the response of CBH to the combined modulating effects of a specific pair of key atmospheric factors: (a) LTS and q850, (b) WS700 and LTS, and (c) ws700 and q850. All ERA5 reanalysis variables were spatially and temporally matched with MMCR data to ensure the validity and reliability of this bivariate joint dependence analysis.

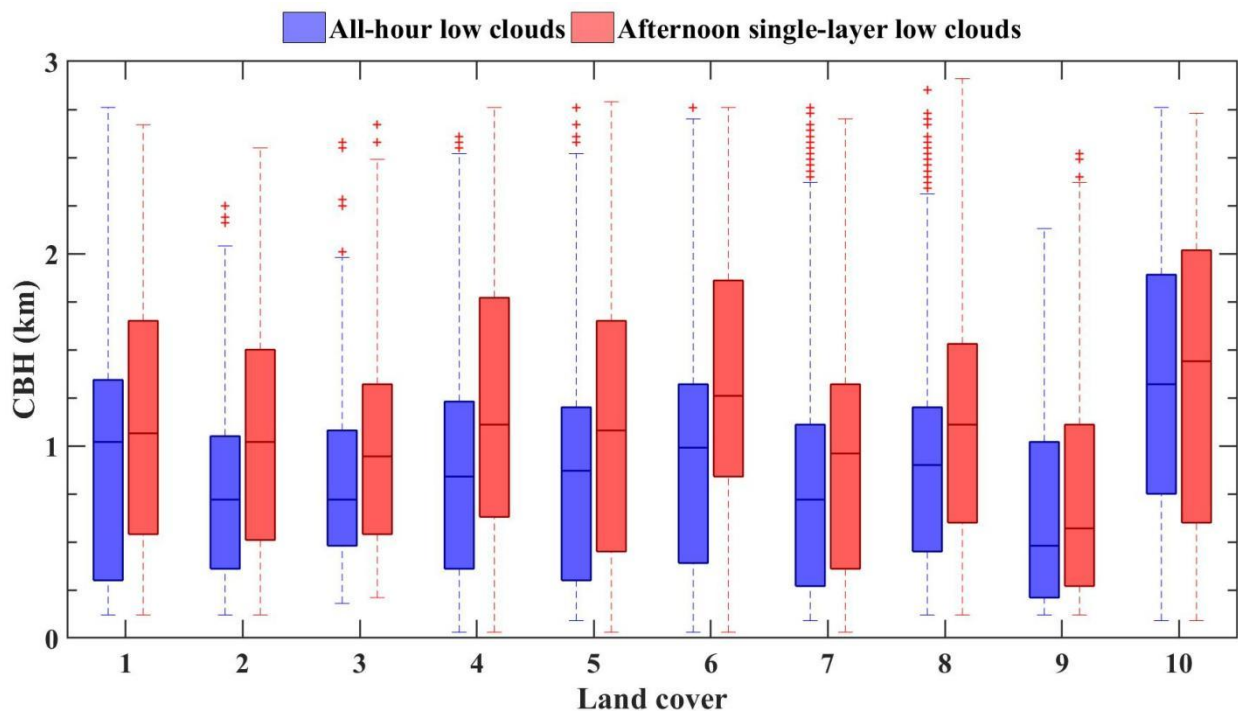
1570 ~~Figure 12. Similar as Figure 11, but for CTH.~~

Figure 13. Similar as Figure ~~11~~9, but for CT.

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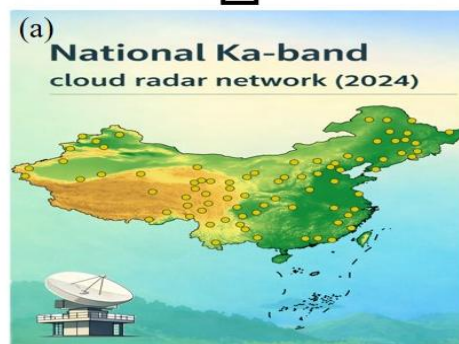
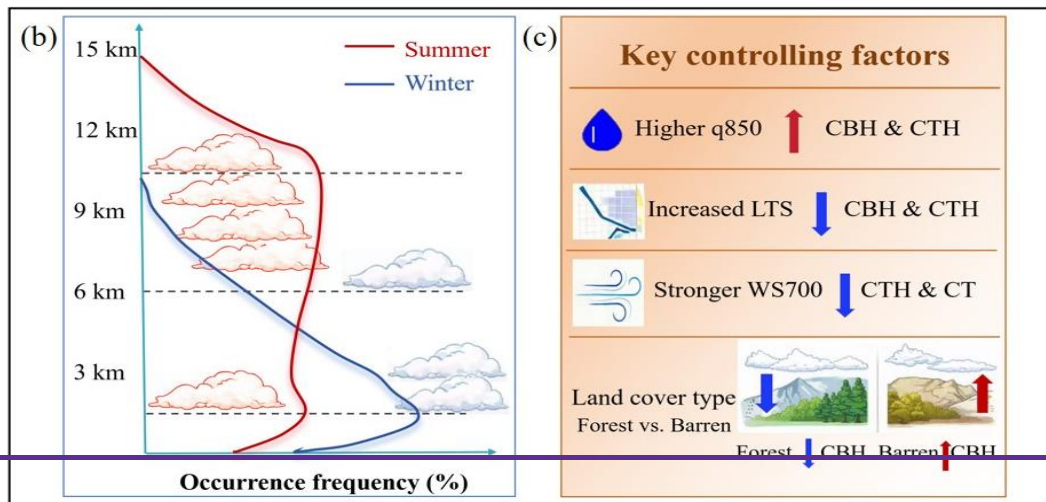


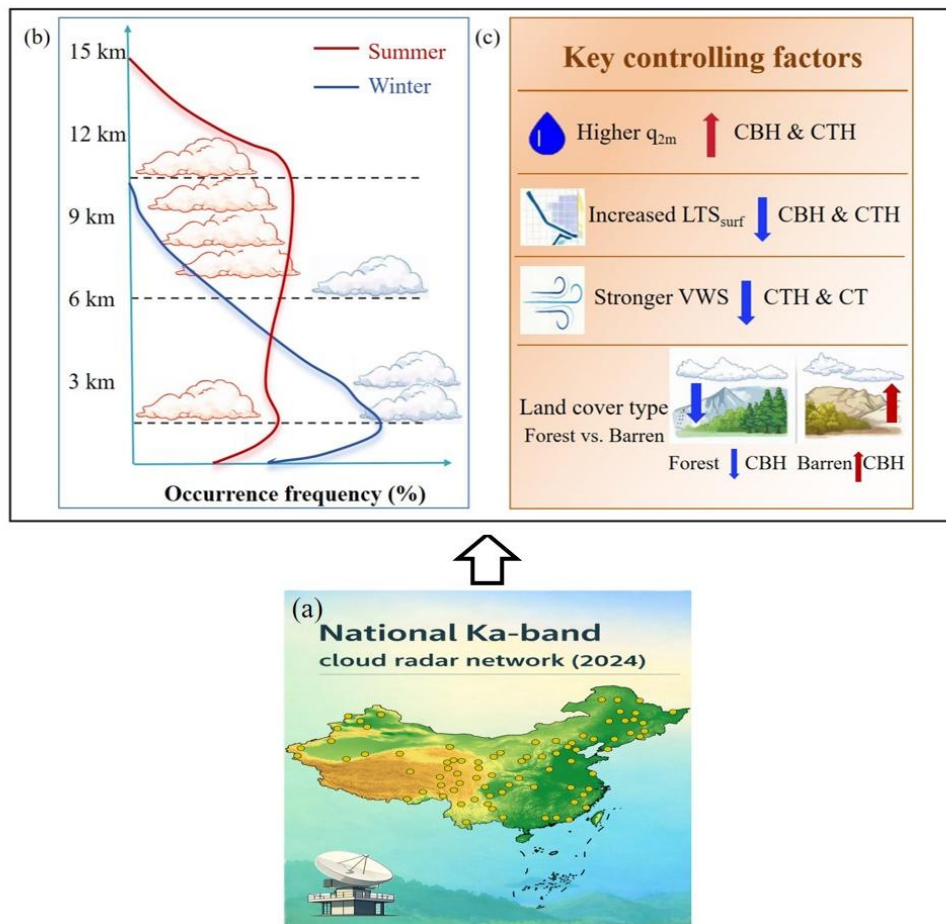
1: Water Bodies 2: Evergreen Broadleaf Forests 3: Deciduous Broadleaf Forests 4: Woody Savannas 5: Savannas
6: Grasslands 7: Croplands 8: Urban and Built-up Lands 9: Cropland/Natural Vegetation Mosaics 10: Barren



1: Water Bodies 2: Evergreen Broadleaf Forests 3: Deciduous Broadleaf Forests 4: Woody Savannas 5: Savannas
6: Grasslands 7: Croplands 8: Urban and Built-up Lands 9: Cropland/Natural Vegetation Mosaics 10: Barren

Figure 14. Land-surface influence on CBH across China in 2024, based on 80 MMCR stations. Blue bars indicate all-sky-hour low cloud conditions, 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://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/products/MCD12C1>).





1585 **Figure 15.** Schematic diagram showing (a) the national Ka-band cloud radar MMCR network MMCR
 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).

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