

S1 Observation site and multi-instrument platform

The observations were conducted at the Jinghe Meteorological Station in Xi'an, Shaanxi Province, China (108°58' E, 34°26' N). The station is located in the central Guanzhong Plain, with the Loess Plateau to the north and the Qinling Mountains to the south, representing a typical mountain–basin terrain setting. The region has a warm-temperate, semi-humid continental monsoon climate, and regional moisture transport and cloud development are influenced by both large-scale circulation and local topography, making the site suitable for continuous ground-based observations of the vertical structure of clouds and precipitation. A multi-instrument observational platform is deployed at the Jinghe station, including a Ka-band millimeter-wave cloud radar (MMCR), a multiwavelength polarization lidar, a microwave radiometer (MWR), a radiosonde system, and surface precipitation instruments (Fig. S1). The instruments are co-located within the same observational site: MMCR and MWR are separated by approximately 3 m, the radar and lidar by approximately 50 m, and the radiosonde launch point is located about 10 m from lidar. The short distances between the instruments support the multi-instrument analysis of the continuous evolution of the stratiform mixed-phase cloud examined in this study.

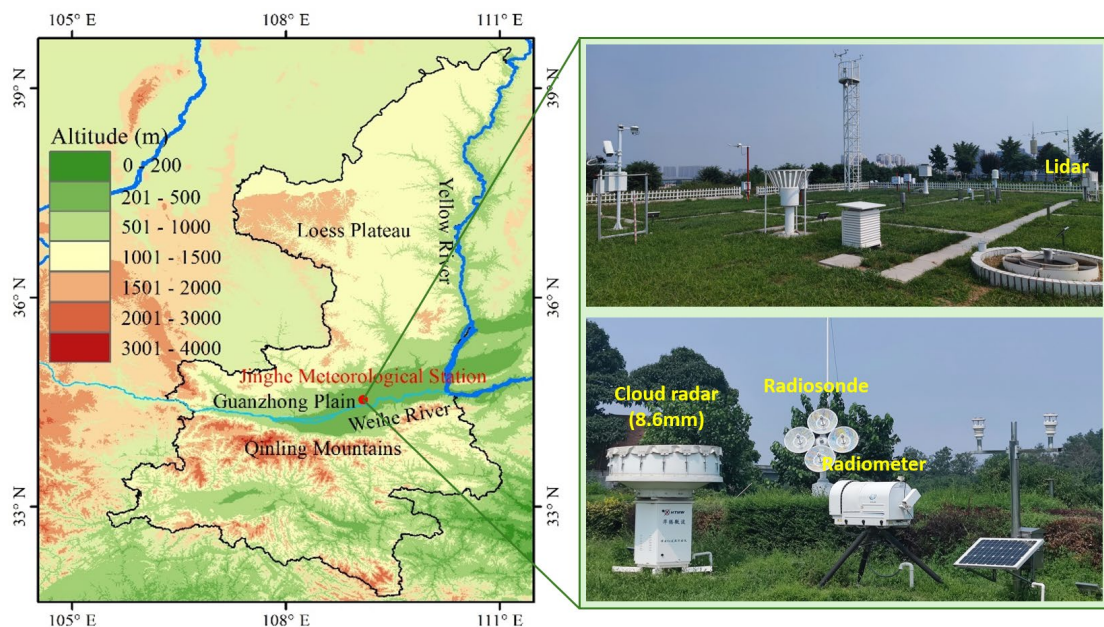


Figure S1. Location of the observation site and the multi-instrument observational platform, including the ground-based lidar, MMCR, MWR, surface precipitation sensor, rain gauge, and radiosonde system.

S2 Multi-instrument observations

To characterize the cloud structure, hydrometeor radar scattering and sedimentation characteristics, and the water-vapor and liquid-water environment during this stratiform mixed-phase cloud event, observations from a multiwavelength lidar, MMCR, MWR, and radiosondes were jointly analyzed. These instruments provide complementary measurements in terms of observed variables and detection characteristics, and the instruments and observational quantities used in this study are described below.

S2.1 Multiwavelength lidar

A multiwavelength polarization Mie-scattering lidar was used for continuous vertical observations of the cloud. Lidar operates at three wavelengths of 1064, 532, and 355 nm, with parallel- and cross-polarized detection channels at 532 nm.

1 The system mainly consists of a laser transmitter, telescope receiver, spectral separation unit, photodetection unit, data
2 acquisition system, and data-processing terminal, with the main technical specifications summarized in [Table S1](#). The
3 parallel- and cross-polarized channels at 532 nm were used to derive depolarization information for cloud particles ([Wang
4 et al., 2024](#)). In addition, the particle color ratio was calculated from the backscatter coefficients at 1064 and 355 nm to
5 characterize wavelength-dependent differences in particle backscattering ([Wang et al., 2024](#)). The receiving telescope has
6 an aperture of 400 mm, and the original range resolution is 3.75 m.

7 This study primarily uses the 1064 nm range-squared-corrected signal (RSCS) and the 532 nm volume depolarization
8 ratio. The 1064 nm RSCS is sensitive to relatively small cloud particles and is mainly used to characterize the vertical
9 cloud structure and its temporal evolution. The 532 nm volume depolarization ratio is used to characterize the polarization
10 scattering properties of cloud particles, while the color ratio provides complementary information on changes in particle
11 scattering characteristics during different stages of the event. Lidar observations mainly complement MMCR by providing
12 information on cloud structure and particle optical properties in regions where the radar response to weakly scattering small
13 particles is relatively limited.

14 Table S1. Main technical specifications of lidar.

No.	Component	Main specifications
1	Transmitter	Laser: Nd:YAG laser Pulse energy: 500 mJ at 1064 nm 200 mJ at 532 nm 240 mJ at 355 nm
2	Receiver	Cassegrain telescope; aperture: 400 mm
3	Spectral separation unit	Interference-filter bandwidth: 0.5 nm
4	Detection unit	Detector: PMT/APD Acquisition mode: analog detection
5	Other specifications	Range resolution: 3.75 m Pulse accumulation: 2000 Number of sampling points: 8000

15 **S2.2 Ka-band millimeter-wave cloud radar**

16 An HT101 all-solid-state MMCR was used for continuous vertical observations of clouds and hydrometeors. The radar
17 operates at 35 GHz±200 MHz in a vertically pointing mode, with a temporal resolution of 5 s and a range resolution of 30
18 m; its main technical specifications are summarized in [Table S2](#). The radar continuously provides radar reflectivity factor
19 (Z_e), Doppler velocity, spectral width (SW), and Doppler power spectra, and is calibrated annually to maintain the stability
20 and reliability of the observations.

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Table S2. Main technical specifications of MMCR.

No.	Parameter	Technical specification
1	Radar system	Coherent pulse-Doppler radar solid-state transmitter pulse compression
2	Operating frequency	35 GHz $\pm$ 200 MHz (Ka band)
3	Scanning mode	Vertically pointing
4	Horizontal and vertical beamwidth	0.4° $\times$ 0.4°
5	Antenna gain	53 dB
6	Pulse repetition frequency	6500 Hz
7	Peak power	≥ 20 W
8	Observed variables	Radar reflectivity factor (Z_e)
		Doppler velocity (V_r)
		Spectral width (SW)
9	Measurement range	Doppler power spectrum
		Height: 0.15–15 km
		Z_e : -45 to +30 dBZ
10	Temporal and range resolution	V_r : -15 to 15 m s ⁻¹
		SW: 0–15 m s ⁻¹
11	Pulse width	Temporal resolution: 5 s
12	FFT points	Range resolution: 30 m

MMCR is the primary instrument used in this study to analyze hydrometeor radar scattering, motion, and Doppler spectral evolution. Here, Z_e is used to characterize the overall radar scattering properties of hydrometeors within the radar resolution volume, while SW describes the spread of the Doppler velocity distribution. The Doppler power spectrum further retains the relative contributions of spectral components at different radial velocities to the radar return and provides the basis for calculating the high-velocity spectral energy fraction (F_{fast}) and the Hydrometeor Sedimentation Index (HSI).

For a vertically pointing MMCR, the observed Doppler velocity contains contributions from both gravitational sedimentation of hydrometeors and vertical air motion within the cloud. The method developed in our previous study was applied to retrieve the in-cloud vertical air velocity (w) from MMCR Doppler spectra and subsequently derive the hydrometeor terminal fall velocity (V_t) (Yuan et al., 2026). The theoretical basis, retrieval algorithm, quality-control procedure, and error analysis of this method have been described in detail in Yuan et al. (2026) and are therefore not repeated here. Throughout this study, upward motion is defined as positive and downward motion as negative; therefore, negative V_t denotes downward hydrometeor sedimentation.

S2.3 Microwave radiometer

An MW967KA MWR was used to obtain information on water vapor and liquid water during the cloud event. The instrument retrieves atmospheric temperature, humidity, water vapor, and liquid-water properties from brightness-temperature measurements at multiple microwave channels, with its main technical specifications summarized in Table S3. The MWR provides retrievals over an altitude range of 0–10 km with a temporal resolution of 2 min. This study mainly uses the column-integrated water vapor (V_{int}) and liquid water path (LWP) retrieved from MWR. V_{int} is used to characterize the atmospheric water-vapor background and its temporal variation throughout the cloud event, while LWP represents the presence and temporal evolution of liquid water within the atmospheric column. These two quantities are

mainly used to characterize Vint and LWP during the persistent mixed-phase cloud stage.

Table S3. Main technical specifications of MWR.

No.	Parameter	Technical specification
1	Measurement range	0 m –10 km
2	Vertical resolution	25 m (0 m–500 m)
		50 m (500 m–2000m)
		250 m (2 km –10 km)
3	Temporal resolution	2 min

S2.4 Radiosonde

An L-band upper-air sounding system was used to obtain vertical profiles of temperature, relative humidity, and wind above the observation site. Routine radiosonde launches at the Jinghe station are conducted daily at 07:15 and 19:15 China Standard Time (CST; UTC+8), with measurements extending to approximately 30 km altitude. This study mainly uses the radiosonde observations at 19:15 CST on 6 June and 07:15 CST on 7 June 2021 to characterize the thermodynamic and moisture environments during the high-level ice-cloud stage and the persistent mixed-phase cloud stage, respectively. The radiosonde data were provided by the Xi'an Meteorological Bureau and subjected to quality-control procedures, including valid-range checks and removal of gross errors. The radiosonde temperature profiles were used to characterize the thermal environment of the cloud layers, while relative humidity and humidity with respect to ice were used to assess the moisture conditions associated with the formation and maintenance of the high-level ice cloud. The radiosonde profiles were also used to determine the altitudes of the 0, –20, and –40 °C isotherms, providing reference levels for the thermodynamic analysis of different stages of cloud evolution.

S3 Data preprocessing and multi-instrument matching

Because the instruments have different temporal and spatial resolutions, data matching was performed according to the requirements of each multi-instrument analysis. All observations are reported in CST, and the analysis period extends from 19:00 CST on 6 June to 11:00 CST on 7 June 2021. MMCR, multiwavelength lidar, and MWR are co-located at the Jinghe Meteorological Station and therefore provide coordinated observations of the same local cloud system. MMCR has temporal and range resolutions of 5 s and 30 m, respectively, while the original range resolution of lidar is 3.75 m.

For the time–height analysis of the continuous cloud evolution, each instrument retains its original temporal and spatial resolutions without additional temporal or spatial interpolation. MMCR, lidar, and MWR observations are processed and presented at their respective sampling resolutions to preserve the original characteristics of each dataset. For joint probability-density and two-dimensional distribution analyses involving variables from different instruments, the corresponding observations are matched in time and height. Specifically, the observations are mapped onto a common 5 s temporal grid and a 3.75 m vertical grid, and matched samples are extracted within the common valid observational domain. This procedure is used only to establish temporal and spatial correspondence among measurements from different instruments and does not alter the actual measurement resolution of the individual instruments.

The radiosonde observations were not included in the temporal and spatial interpolation or collocation of the continuous

remote-sensing datasets; instead, temperature and humidity profiles from the actual launch times were used to characterize the thermodynamic and moisture environments of the corresponding cloud stages. Relative humidity with respect to ice (RH_{ice}) was further calculated from the radiosonde temperature and relative-humidity measurements to characterize the saturation state with respect to ice in subfreezing cloud layers. The calculation of RH_{ice} follows the method used in our previous study published in *Remote Sensing* (Yuan et al. 2022). Before the multi-instrument analysis, basic quality control was applied to all datasets to remove missing values, invalid measurements, and obvious outliers. For cross-instrument statistical analyses, only samples with valid observations from all relevant instruments at the same time and height were retained.

S4 Sensitivity of HSI to the velocity threshold

To evaluate the sensitivity of the Hydrometeor Sedimentation Index (HSI) to the choice of the fast-sedimentation velocity threshold V_c , F_{fast} and HSI were recalculated using $V_c = -0.54, -0.87, -1.09, -1.31, -1.52$, and -1.63 m s^{-1} , and the temporal evolution of the 0.5 h mean vertically integrated HSI was compared (Fig. S2). As V_c increased, the magnitude of the vertically integrated HSI generally decreased because the more restrictive velocity threshold reduced the amount of Doppler spectral energy included in the fast-sedimenting component. However, the main temporal evolution of HSI remained consistent across the different thresholds: values were generally low during the high-level ice-cloud stage, showed localized enhancement during the mixed-phase transition stage from 23:00 to 00:30 CST, returned to relatively low levels during the early part of the persistent mixed-phase cloud stage, and increased markedly after approximately 05:30 CST, reaching the most pronounced levels of the event around 08:00 CST before decreasing rapidly. After normalization by the respective maximum value for each threshold, this common temporal evolution remained evident (Fig. S2b). Therefore, the choice of V_c affects the absolute magnitude and rate of increase of HSI, whereas the pronounced enhancement of HSI before the occurrence of surface precipitation remains robust across the range of thresholds tested.

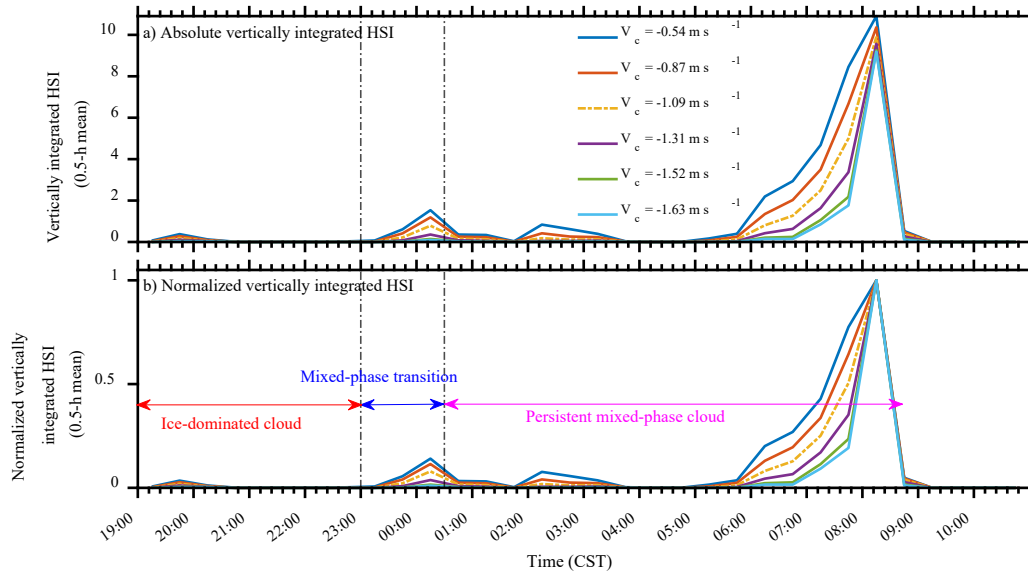


Figure S2. Sensitivity of vertically integrated HSI to the fast-sedimentation velocity threshold V_c . (a) 0.5 h mean vertically integrated HSI for different V_c values. (b) Corresponding normalized HSI. Dashed lines indicate the boundaries between the three cloud stages.