



Continuous Remote Sensing Observations of Hydrometeor Sedimentation Evolution during the Transition from Ice Cloud to Precipitating Mixed-Phase Cloud

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Abstract

Hydrometeor growth and sedimentation in mixed-phase clouds are key processes linking cloud evolution to surface precipitation, yet continuous observations of when fast-sedimenting hydrometeors establish effective downward transport remain limited. We combine observations from a millimeter-wave cloud radar, multiwavelength polarization lidar, microwave radiometer, and radiosondes to investigate the evolution of a cloud system from a high-level ice cloud to a stratiform mixed-phase cloud and ultimately to short-lived light precipitation. High-level ice hydrometeors developed and began to sediment under ice-saturated or ice-supersaturated conditions. As they descended into warmer cloud layers containing liquid water, radar reflectivity and hydrometeor terminal fall velocity increased concurrently with Doppler spectral broadening, consistent with further hydrometeor growth and enhanced sedimentation. The mixed-phase cloud subsequently persisted for nearly 8 h, while liquid water and fast-sedimenting spectral components were sustained without continuous surface precipitation. We define the high-velocity spectral energy fraction (F_{fast}) and combine it with the linear radar reflectivity factor to construct a Hydrometeor Sedimentation Index (HSI). F_{fast} was present well before surface precipitation, whereas HSI increased markedly later and extended toward lower altitudes, showing a clearer temporal correspondence with short-lived light precipitation. The concurrent enhancement of fast-sedimenting spectral contributions and strong radar echo signal, together with their downward extension, was a key observational feature of the transition to precipitation. These results provide a process-oriented framework for using continuous Doppler spectral observations to characterize hydrometeor sedimentation evolution and the cloud-to-precipitation transition in mixed-phase clouds.

Keywords: Mixed-Phase Cloud; Hydrometeor sedimentation; Cloud-to-precipitation transition; Multi-source remote sensing; Doppler spectra

Introduction

Mixed-phase clouds are widespread in the atmosphere and are characterized by the coexistence of ice particles and supercooled liquid water over temperatures ranging from 0 to approximately -38°C . The partitioning between ice and liquid phases affects cloud radiative properties and lifetime and also plays a direct role in precipitation formation at mid- and high latitudes, making mixed-phase cloud microphysics an important source of uncertainty in weather and climate models (Morrison et al., 2012; McCoy et al., 2015; Korolev et al., 2017; Wang et al., 2024). Global satellite observations further indicate that a substantial fraction of precipitation at mid- and high latitudes is closely linked to ice-phase processes, highlighting the importance of ice hydrometeor growth and their subsequent transformation into precipitating particles (Field and Heymsfield, 2015; Mülmenstädt et al., 2015).

Precipitation formation in mixed-phase clouds involves a suite of coupled microphysical processes, including ice nucleation, depositional growth, aggregation, riming, and secondary ice production (Field et al., 2017; Korolev and Leisner, 2020). As ice particles are transported downward by gravitational sedimentation into environments containing supercooled



liquid water, their growth conditions can change substantially: in addition to vapor deposition and aggregation, they may undergo riming through the collection of supercooled droplets, increasing particle mass, density, and fall velocity (Moisseev et al., 2017; Pfizenmaier et al., 2018; Kneifel and Moisseev, 2020; Mahernndl et al., 2024). The Wegener–Bergeron–Findeisen process and competitive growth between the ice and liquid phases can also regulate liquid-water depletion, ice growth, and the persistence of mixed-phase conditions (Omanovic et al., 2024). The transition from mixed-phase cloud to precipitation is therefore not governed by a single microphysical process, but by the combined effects of ice-particle growth, liquid-water supply, and hydrometeor sedimentation.

These processes exhibit substantial spatial and temporal heterogeneity, making their continuous observation challenging. Aircraft in situ measurements provide direct information on ice-crystal morphology, particle size distributions, and liquid water content and are therefore essential for investigating mixed-phase cloud microphysics (Verlinde et al., 2007; Huang et al., 2021; Yang et al., 2020); however, their limited flight tracks and sampling durations generally preclude continuous tracking of an individual cloud system from ice-particle formation and sedimentation to the occurrence of surface precipitation. Satellite active remote sensing platforms such as CloudSat and CALIPSO provide large-scale information on cloud phase and the vertical structure of precipitation (Stephens et al., 2018; Mace et al., 2021), but their snapshot-like overpasses cannot resolve the continuous microphysical evolution of an individual cloud system over several hours. Resolving the continuous evolution of hydrometeors from high-level ice clouds into precipitating particles therefore requires ground-based observations with high temporal and vertical resolution.

Ground-based millimeter-wave cloud radar (MMCR) provides an important tool for investigating this process. MMCR not only provides continuous measurements of radar moments such as reflectivity factor (Z_e), Doppler velocity, and spectral width (SW), but also retains the contributions of hydrometeors with different radial velocities within the Doppler power spectrum (Kollias et al., 2014a, b). Conventional radar moments primarily characterize the bulk scattering properties and mean motion of hydrometeors within the radar sampling volume, whereas Doppler spectra provide additional information on the spectral structure of particle populations with different sedimentation velocities. Previous studies have used Doppler spectra to distinguish velocity modes associated with supercooled liquid water and ice particles in mixed-phase clouds (Luke et al., 2010) and to investigate riming, aggregation, and the evolution of distinct ice-particle populations through spectral-peak shifts, spectral broadening, and multimodal structures (Kalesse et al., 2016; Kneifel et al., 2016; Pfizenmaier et al., 2018; Oue et al., 2018). These studies demonstrate that Doppler spectra provide more direct information on particle-population dynamics than Z_e or mean Doppler velocity alone, offering a valuable basis for tracking changes in the growth and sedimentation state of ice hydrometeors.

Importantly, the growth of ice particles does not necessarily manifest as a monotonic change in any single radar variable. Aggregation can substantially increase particle size, whereas riming can increase particle mass while also enhancing particle density and terminal fall velocity; consequently, Z_e and Doppler velocity may respond differently to different growth mechanisms (Mason et al., 2018; Kneifel and Moisseev, 2020). Multifrequency Doppler spectral studies have further shown that radar spectra can reveal distinct scattering and sedimentation signatures associated with different particle populations and growth states (Kneifel et al., 2016). Extracting the contribution of fast-sedimenting hydrometeors from Doppler spectra and combining it with hydrometeor scattering intensity may therefore provide a more effective description of the transition from hydrometeor growth to effective downward sedimentation than any single radar-moment variable alone.



1 MMCR alone, however, cannot uniquely constrain hydrometeor phase or the associated liquid-water environment, and
 2 complementary remote-sensing observations are therefore required. Polarization lidar is highly sensitive to small cloud
 3 particles and can use depolarization signatures to distinguish nonspherical ice crystals from nearly spherical liquid droplets,
 4 while multiwavelength backscatter measurements can provide additional information on changes in particle size (Hu et al.,
 5 2009). Microwave radiometers provide continuous retrievals of liquid water path (LWP) and column-integrated water vapor,
 6 offering independent constraints on the presence of liquid water in mixed-phase clouds and the background moisture
 7 environment (Turner, 2007; Cadetdu et al., 2017). Long-term ground-based observations have shown that the combined
 8 use of radar, lidar, microwave radiometer, and radiosonde measurements can simultaneously constrain the macrophysical
 9 structure of mixed-phase clouds, ice-particle sedimentation, liquid water, and the thermodynamic environment (Shupe et
 10 al., 2006; Illingworth et al., 2007; Shupe et al., 2008a). Such multi-instrument synergy is particularly important for
 11 distinguishing the presence of a mixed-phase environment from the establishment of effective hydrometeor transport
 12 toward surface precipitation.

13 The presence of liquid water cannot be equated directly with precipitation formation. Persistent supercooled liquid water
 14 can provide favorable conditions for further ice-particle evolution, but the formation of surface precipitation also depends
 15 on whether ice hydrometeors grow to a state with sufficient sedimentation capability. Ground-based observations have
 16 shown that mixed-phase clouds can persist for extended periods while producing continuous but weak ice-phase
 17 precipitation (Shupe et al., 2006; Morrison et al., 2012; Silber et al., 2021); studies of riming further indicate that higher
 18 LWP can enhance specific ice-growth processes, although liquid-water amount alone does not uniquely determine the
 19 extent of ice-particle growth or the resulting precipitation output (Moisseev et al., 2017; Maherndl et al., 2024). For weakly
 20 precipitating mixed-phase clouds, the key question is therefore not simply whether supercooled liquid water is present, but
 21 when ice hydrometeors transition from a persistent, slowly sedimenting state to particle populations with stronger
 22 sedimentation capability and more effective downward transport into lower levels.

23 Multi-instrument ground-based remote sensing provides a promising means of addressing this problem, although
 24 individual instruments remain subject to distinct observational limitations. Lidar is highly sensitive to small ice crystals
 25 and liquid cloud droplets, but its performance is strongly limited by optical attenuation; in optically thicker mixed-phase
 26 clouds, the signal may be substantially attenuated within only a shallow portion of the cloud layer. MMCR has greater
 27 penetration capability and is more sensitive to larger ice particles and precipitating hydrometeors (Shupe et al., 2008a;
 28 Luke et al., 2010; Mace et al., 2021). Luke et al. (2010) explicitly showed that MMCR can detect regions of mixed-phase
 29 clouds that lidar cannot penetrate because of extinction. Radar and lidar are therefore strongly complementary in terms of
 30 particle-size sensitivity, phase information, and penetration capability. On this basis, we selected a weakly precipitating
 31 stratiform-cloud case from the long-term joint observational record; the relatively weak precipitation and favorable optical
 32 conditions allowed lidar measurements to remain available through the main stages of cloud evolution, enabling the optical
 33 signatures of ice particles to be combined with millimeter-wave radar observations of hydrometeor scattering and Doppler
 34 spectra to continuously track the evolution of the ice phase.

35 Although previous studies have examined mixed-phase clouds from the perspectives of cloud phase, supercooled liquid
 36 water, riming, ice-particle growth, and precipitation, and have demonstrated the high sensitivity of Doppler radar
 37 observations to particle-growth processes (Kalesse et al., 2016; Pfitzenmaier et al., 2018; Kneifel and Moisseev, 2020),
 38 continuous observational constraints remain limited for the full evolution of a weak-precipitation event, including how



high-level ice particles begin to sediment, how they evolve after entering a mixed-phase environment, and when fast-sedimenting hydrometeors establish effective downward transport that ultimately reaches the surface as precipitation. In particular, conventional Z_e and mean Doppler velocity primarily emphasize hydrometeor scattering and bulk motion, respectively, while a simple metric that jointly captures enhanced hydrometeor scattering and changes in the contribution of fast-sedimenting particles is still lacking.

To address this issue, we combine observations from MMCR, a multiwavelength polarization lidar, a microwave radiometer, and radiosondes with ERA5 reanalysis to investigate a weakly precipitating stratiform mixed-phase cloud event observed over Xi'an, China, on 6–7 June 2021. We focus on the formation and initial sedimentation of high-level ice particles, changes in their growth environment during downward transport, and the evolution of fast-sedimenting hydrometeors toward lower levels during the persistence of the mixed-phase cloud. On this basis, we define the high-velocity spectral energy fraction (F_{fast}) from the Doppler spectrum and combine it with Z_e to construct a Hydrometeor Sedimentation Index (HSI), which jointly characterizes changes in hydrometeor scattering and the contribution of fast-sedimenting spectral components. The study aims to characterize, from continuous multi-instrument remote-sensing observations, the evolution of hydrometeors from their initial growth and sedimentation through enhanced sedimentation to effective downward transport associated with the occurrence of surface precipitation in this weakly precipitating event.

2 Data and methods

2.1 Observations

The observations were conducted at the Jinghe Meteorological Station (34°26' N, 108°58' E) in Xi'an, Shaanxi Province, China, located in the central Guanzhong Plain between the Loess Plateau to the north and the Qinling Mountains to the south. Influenced by the surrounding mountain–basin topography, the region exhibits distinct characteristics of moisture transport and vertical motion, with stratiform clouds and associated light-precipitation events occurring frequently. This study combines collocated observations from MMCR, a multiwavelength polarization lidar, a microwave radiometer, and radiosondes. MMCR provides Z_e , Doppler velocity (V_r), and SW, together with retrieved in-cloud vertical air velocity (w) and hydrometeor terminal fall velocity (V_t). The multiwavelength polarization lidar provides the 1064 nm range-squared-corrected signal (RSCS), the 532 nm volume depolarization ratio, and multiwavelength color ratios to characterize cloud structure and the optical properties of ice particles (Di et al., 2024). The microwave radiometer provides LWP and column-integrated water vapor (Vint), which characterize the liquid-water and moisture environment. Radiosonde measurements provide vertical profiles of thermodynamic variables, including temperature and humidity. The retrieval methods for in-cloud w and V_t are described in detail by Yuan et al. (2026) and are therefore not repeated here. Technical specifications of the instruments, data preprocessing procedures, and multi-instrument data matching are described in Supplement Sects. S1–S3.

2.2 Case selection

Because lidar signals can be strongly attenuated in optically thick clouds, case selection emphasized periods during which both MMCR and the multiwavelength lidar provided continuous and reliable observations. From the long-term joint observational record, a long-lasting stratiform light-precipitation event on 6–7 June 2021 was selected for detailed analysis. During this event, MMCR continuously captured the vertical evolution of cloud structure and sedimenting hydrometeors,



while lidar retained usable backscatter and depolarization measurements throughout the main stages of cloud development. The weak precipitation intensity and relatively favorable optical conditions allowed the two active remote-sensing systems to provide complementary information, enabling continuous analysis of high-level ice-cloud development, downward transport of ice particles, and the subsequent transition to mixed-phase conditions.

2.3 ERA5 reanalysis

To characterize the large-scale circulation and thermodynamic environment associated with this stratiform light-precipitation event, we use the fifth-generation atmospheric reanalysis (ERA5) from the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA5 data have a horizontal resolution of $0.25^\circ \times 0.25^\circ$ and a temporal resolution of 1 h. ERA5 fields over $100\text{--}115^\circ$ E and $28\text{--}40^\circ$ N from 19:00 China Standard Time (CST; UTC+8) on 6 June to 11:00 CST on 7 June 2021 are analyzed to characterize the large-scale environment at different atmospheric levels during the formation and maintenance of the cloud system. Specifically, 850 hPa specific humidity, horizontal winds, and moisture transport are used to examine low-level warm and moist airflow and moisture supply. Relative humidity and vertical velocity at 750 hPa are used to characterize moisture conditions and large-scale vertical motion near the cloud layer. Temperature, geopotential height, and horizontal winds at 500 hPa are used to characterize the mid-tropospheric circulation and the influence of cold-air advection. Winds and wind speed at 300 hPa are used to characterize the upper-level jet and the associated dynamical environment. These ERA5 fields are used primarily to provide the large-scale context for the development and persistence of the cloud system, whereas the evolution of hydrometeors within the cloud is analyzed mainly using the ground-based multi-instrument observations.

2.4 Doppler spectral analysis and HSI

2.4.1 High-velocity spectral energy fraction

The Doppler power spectrum measured by MMCR represents the contributions of hydrometeors with different radial velocities to the radar return within a single range gate. Compared with spectral-moment quantities such as radar reflectivity factor and mean Doppler velocity, the Doppler spectrum retains information on the velocity-space distribution of hydrometeors and thus provides additional information on the spectral contributions of particles with different sedimentation velocities. To quantify changes in fast-sedimenting spectral components during the cloud-to-precipitation transition, we calculate F_{fast} from the linear-scale Doppler spectral power $S(v)$ after noise estimation and identification of the valid meteorological spectrum. For MMCR used in this study, negative velocities denote downward motion and positive velocities denote upward motion. For each valid Doppler spectrum, V_L and V_R denote the two velocity boundaries of the meteorological spectrum, and V_c denotes the threshold velocity used to identify fast-sedimenting spectral components. Based on the numerical definition of Doppler velocity, spectral components satisfying $v \leq V_c$ are defined as fast-sedimenting components. Accordingly, F_{fast} is defined as the fraction of spectral power contained within the fast-sedimentation velocity range relative to the total power of the valid meteorological spectrum:

$$F_{fast} = \frac{\int_{V_c}^{V_R} S(v) dv}{\int_{V_L}^{V_R} S(v) dv} \quad (1)$$

Here, $S(v)$ denotes the Doppler spectral power on a linear scale, and V_L and V_R denote the left and right velocity



boundaries of the valid meteorological spectrum, respectively. During this event, the dominant hydrometeor population was primarily concentrated at weakly negative Doppler velocities, whereas the Doppler spectrum extended markedly toward more negative velocities during the later stage of the cloud-to-precipitation transition; accordingly, a velocity of approximately $-1.0 \text{ m} \cdot \text{s}^{-1}$ was selected as the threshold separating the dominant sedimenting spectral components from the faster-sedimenting components. This threshold is used only to identify relatively fast-sedimenting components within the Doppler spectrum; it does not represent the terminal fall velocity of any specific hydrometeor type and should not be interpreted as a universal physical threshold for the cloud-to-precipitation transition.

Because the Doppler power spectra are obtained using a 256-point fast Fourier transform, the velocity coordinate is discretely sampled and does not contain a bin exactly at $-1.0 \text{ m} \cdot \text{s}^{-1}$. The 139th spectral bin, which is closest to this target value, was therefore selected for the calculation, corresponding to $V_c = -1.09 \text{ m} \cdot \text{s}^{-1}$. Spectral components satisfying $v \leq V_c$ are consequently defined as fast-sedimenting components, corresponding to the negative-velocity portion of the valid meteorological spectrum beyond V_c (Fig. 1). The rationale for selecting this threshold and the corresponding sensitivity tests are provided in Supplement Sect. S4.

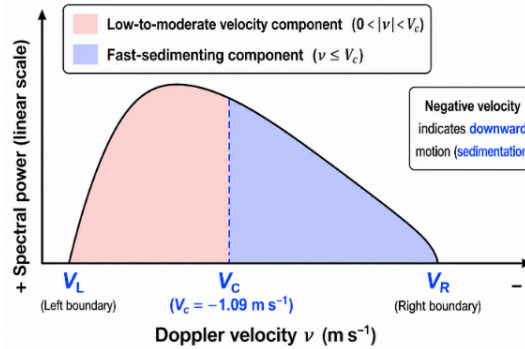


Figure 1. Schematic illustration of the calculation of the high-velocity spectral energy fraction (F_{fast}). V_L and V_R denote the left and right velocity boundaries of the valid meteorological Doppler spectrum, respectively, and $V_c = -1.09 \text{ m} \cdot \text{s}^{-1}$ is the threshold used to identify fast-sedimenting spectral components. Negative velocities denote downward motion in this study; therefore, the shaded region satisfying $v \leq V_c$ represents the spectral energy associated with fast-sedimenting components.

2.4.2 HSI

F_{fast} is a normalized spectral energy fraction that represents the relative contribution of fast-sedimenting components to the total valid Doppler spectrum, but it does not account for the overall radar scattering contribution of hydrometeors within the range gate. For example, when the total spectral power is weak, a relatively large F_{fast} may still occur even if only a small amount of spectral power is present within the fast-sedimentation velocity range. Therefore, F_{fast} alone cannot distinguish between a high relative contribution of fast-sedimenting spectral components and an enhancement of fast-sedimenting hydrometeors with strong radar scattering contributions.

To jointly account for the relative contribution of fast-sedimenting spectral components and the overall radar scattering characteristics of hydrometeors, we combine F_{fast} with the linear form of radar reflectivity factor and define HSI as:

$$\text{HSI} = F_{fast} Z_{lin} = F_{fast} \times 10^{Z_e/10} \quad (2)$$



Here, Z_e is the radar reflectivity factor expressed in dBZ, and $Z_{lin}=10^{Z_e/10}$ is its corresponding linear form. F_{fast} represents the relative contribution of fast-sedimenting spectral components within the valid Doppler spectrum, whereas Z_{lin} represents the overall radar scattering level of hydrometeors within the range gate. A higher HSI therefore indicates the concurrent presence of a larger relative contribution from fast-sedimenting spectral components and stronger hydrometeor radar scattering.

Based on the above definition, HSI can be regarded as an integrated measure of the radar scattering contribution associated with the fast-sedimentation velocity range within the valid Doppler spectrum. HSI increases when the relative contribution of fast-sedimenting spectral components increases concurrently with stronger overall hydrometeor radar scattering within the range gate. It should be emphasized that millimeter-wave radar reflectivity depends not only on hydrometeor number and size but also on particle shape, density, and scattering properties. Therefore, HSI cannot be interpreted directly as the particle size, mass, mass flux, or precipitation rate of fast-sedimenting hydrometeors. In this study, HSI is used solely as a process diagnostic to examine the covariation between the contribution of fast-sedimenting spectral components and hydrometeor radar scattering during the same cloud event.

To further characterize the temporal evolution of HSI over the entire cloud column, HSI is vertically integrated over the altitude range containing valid meteorological radar echoes:

$$HSI_{int}(t) = \int_{z_b(t)}^{z_t(t)} HSI(z, t) dz \quad (3)$$

Here, z_b and z_t denote the lower and upper boundaries, respectively, of the valid meteorological radar echoes at time t . In practice, the vertical integration is calculated in discrete form as:

$$HSI_{int}(t) = \sum_{i=1}^{N(t)} HSI(z_i, t) \Delta z \quad (4)$$

Here, $\Delta z = 30$ m is the radar range resolution, and $N(t)$ denotes the number of range gates containing valid meteorological echoes at time t ; only these valid range gates are included in the calculation. HSI_{int} provides a column-integrated diagnostic of the relative contribution of fast-sedimenting spectral components, the associated radar scattering level, and their vertical extent; an increase in HSI_{int} may therefore result from stronger local HSI values, a greater vertical extent of elevated HSI, or both. HSI_{int} is subsequently averaged over 0.5 h intervals to reduce short-timescale variability and emphasize changes among different stages of cloud evolution. This metric is used to compare relative changes among the high-level ice-cloud stage, the transition from ice cloud to mixed-phase cloud, and the persistent mixed-phase stage, and to examine the temporal correspondence between the downward extension of radar signatures associated with fast-sedimenting hydrometeors and the occurrence of light surface precipitation.

3 Results and analysis

3.1 Synoptic environment and cloud overview

To characterize the large-scale environmental background of this stratiform light-precipitation event, ERA5 reanalysis data were used to examine moisture, humidity, vertical motion, and circulation at different pressure levels from 19:00 CST on 6 June to 11:00 CST on 7 June 2021 (Fig. 2). Overall, relatively persistent moisture and dynamical conditions were maintained over Xi'an and the surrounding region, providing a favorable large-scale environment for the sustained



1 development of the stratiform cloud system. At 850 hPa (Fig. 2a1–d1), relatively high specific humidity persisted near the
 2 observation site together with sustained southerly to southeasterly flow, indicating a persistent supply of warm and moist
 3 air in the lower troposphere. At 750 hPa (Fig. 2a2–d2), relative humidity remained generally high over the study region
 4 and was accompanied by weak upward motion, indicating moist conditions with weak large-scale ascent near the cloud
 5 layer. At 500 hPa (Fig. 2a3–d3), the study region was characterized by relatively low temperatures and the influence of the
 6 mid-tropospheric circulation. At 300 hPa (Fig. 2a4–d4), strong upper-level winds persisted over the study region. Taken
 7 together, the event occurred under a large-scale environment characterized by persistent low-level moisture transport, high
 8 mid-level humidity, weak ascent, and the influence of the mid- to upper-tropospheric circulation, which favored the
 9 prolonged maintenance and subsequent evolution of the cloud system.

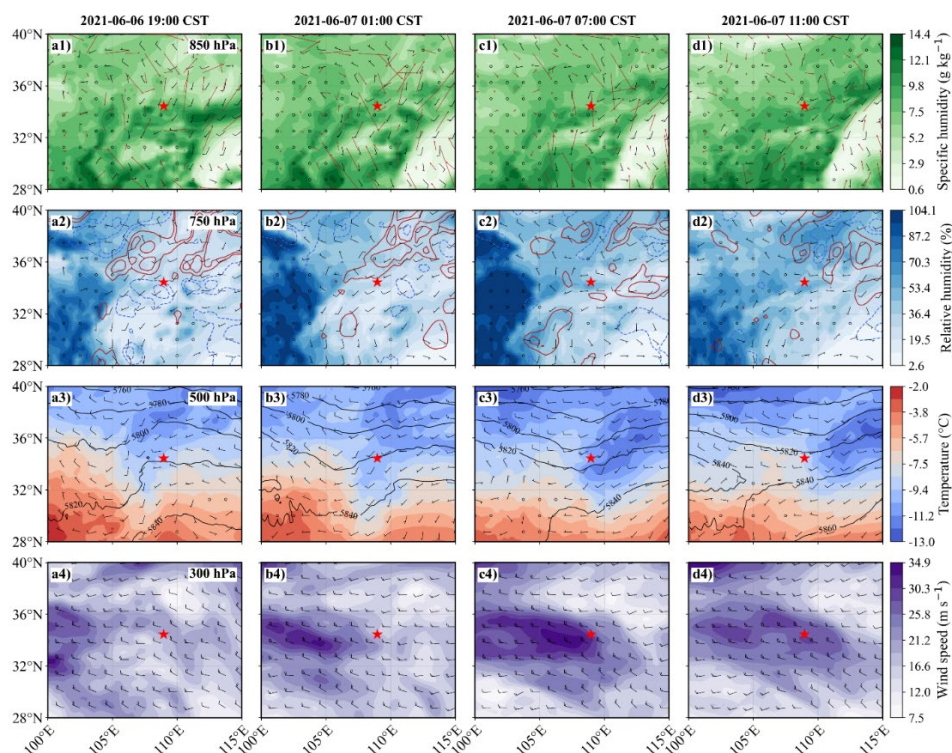
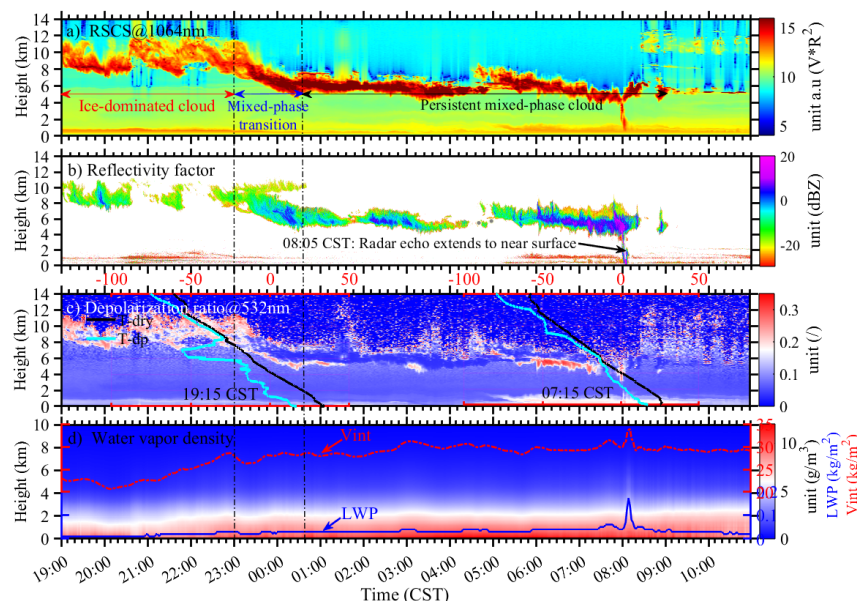


Figure 2. Evolution of the large-scale atmospheric circulation from 19:00 CST on 6 June to 11:00 CST on 7 June 2021 based on ERA5 reanalysis. First row (a1–d1): 850 hPa specific humidity (shading), horizontal winds (wind barbs), and moisture flux (red vectors). Second row (a2–d2): 750 hPa relative humidity (shading), horizontal winds (wind barbs), and pressure vertical velocity (contours), with red solid contours ($< -0.2 \text{ Pa s}^{-1}$) indicating ascent and blue dashed contours ($> 0.2 \text{ Pa s}^{-1}$) indicating subsidence. Third row (a3–d3): 500 hPa temperature (shading), geopotential height (black contours; gpm), and horizontal winds (wind barbs). Fourth row (a4–d4): 300 hPa wind speed (shading) and horizontal winds (wind barbs). The red star marks the observation site.

Multi-instrument ground-based remote sensing further captured the continuous evolution of the cloud system as it extended from upper to lower levels and eventually produced light precipitation (Fig. 3). From 19:00 to 23:00 CST, the cloud was mainly located at approximately 8–12 km, with relatively continuous high-level cloud signals observed by lidar and generally weak echoes detected by MMCR (Fig. 3a–b). Lidar depolarization ratio was also relatively high within this



1 altitude range, and, together with the radiosonde temperature profile, indicated that this stage was dominated by ice-phase
 2 cloud particles (Fig. 3c). Accordingly, the period from 19:00 to 23:00 CST is defined as the ice-dominated cloud stage.
 3 After 23:00 CST, the cloud system began to extend markedly toward lower altitudes, while MMCR echoes gradually
 4 intensified and extended downward, with the cloud base rapidly descending from approximately 8 to 6 km (Fig. 3a–b).
 5 Concurrently, pronounced changes occurred in lidar depolarization ratio and the vertical cloud structure (Fig. 3c), indicating
 6 changes in the scattering characteristics of cloud particles and the internal structure of the cloud system. By approximately
 7 00:30 CST, the main cloud layer had developed downward from its earlier high-level structure to approximately 5–7 km.
 8 Based on the concurrent changes in cloud altitude, radar echoes, and lidar depolarization characteristics, the period from
 9 23:00 to 00:30 CST is defined as the mixed-phase transition stage.
 10 From 00:30 to 08:30 CST, the main cloud layer remained primarily at approximately 5–7 km and exhibited a relatively
 11 stable stratiform structure (Fig. 3a–c). Microwave radiometer observations show that Vint remained relatively high during
 12 this period, while LWP persisted and increased markedly near 08:00 CST (Fig. 3d), indicating sustained moisture and
 13 liquid-water conditions within the cloud system. Accordingly, the period from 00:30 to 08:30 CST is defined as the
 14 persistent mixed-phase cloud stage. At approximately 08:05 CST, MMCR echoes extended markedly toward near-surface
 15 levels (Fig. 3b), coinciding with the occurrence of short-lived light precipitation at the surface.



16
 17 **Figure 3.** Multi-instrument ground-based remote-sensing observations of the cloud-system evolution on 6–7 June 2021. (a) 1064 nm
 18 RSCS from the multiwavelength lidar. (b) Ze from MMCR. (c) 532 nm lidar volume depolarization ratio, with radiosonde temperature
 19 profiles at 19:15 and 07:15 CST overlaid; the cyan and black curves indicate the corresponding moist- and dry-adiabatic temperature
 20 profiles, respectively. (d) Water-vapor density retrieved by the microwave radiometer, with Vint (red dashed line) and LWP (blue solid
 21 line). Vertical dashed lines separate the ice-dominated cloud stage, mixed-phase transition stage, and persistent mixed-phase cloud stage.
 22 At approximately 08:05 CST, the radar echo extended toward near-surface levels, coinciding with the occurrence of short-lived light
 23 precipitation at the surface.

24 The cloud system exhibited a clear sequence of three stages: an ice-dominated cloud stage (19:00–23:00 CST), a mixed-
 25 phase transition stage (23:00–00:30 CST), and a persistent mixed-phase cloud stage (00:30–08:30 CST). The following



sections examine the evolution of radar reflectivity, hydrometeor motion, and Doppler spectral characteristics during these three stages and further investigate their relationship with the development of light precipitation.

3.2 Development and sedimentation of ice particles during the ice-dominated cloud stage

The dynamical and sedimentation characteristics of hydrometeors exhibited pronounced spatial and temporal variability within the cloud. SW was relatively small over most of the cloud but increased markedly in the middle and lower portions and in several localized regions (Fig. 4b), indicating greater variability in hydrometeor velocities. w was characterized mainly by weak ascending and descending motions with alternating spatial patterns (Fig. 4c). In contrast, V_t , after correction for vertical air motion, was predominantly negative within the cloud, with more negative values occurring in some regions (Fig. 4d). This indicates that, despite variations between weak ascending and descending air motions, the ice hydrometeors exhibited a clear gravitational sedimentation signature.

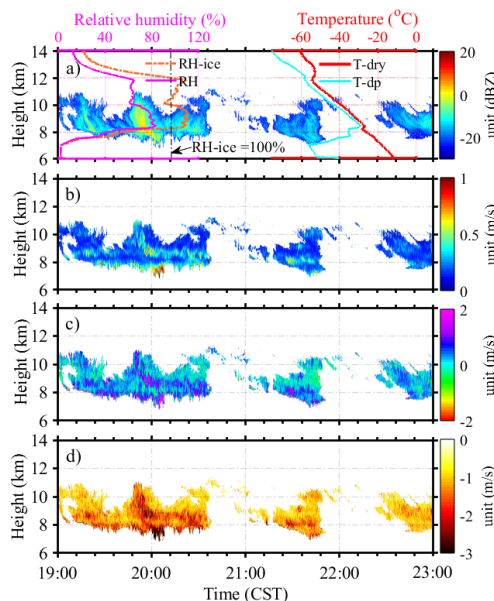


Figure 4. Radar and dynamical characteristics of hydrometeors during the ice-dominated cloud stage (19:00–23:00 CST). (a) Radar reflectivity factor (Z_e); (b) Doppler spectral width (SW); (c) in-cloud vertical air velocity (w); and (d) hydrometeor terminal fall velocity (V_t) after correction for vertical air motion. Positive and negative w indicate upward and downward air motions, respectively, while negative V_t indicates downward hydrometeor sedimentation.

Fig. 5 further shows the statistical distributions of hydrometeor properties during this stage. Z_e was concentrated mainly between approximately -25 and -10 dBZ and at altitudes of 8 – 10 km (Fig. 5a), while V_t occurred predominantly between approximately -1.5 and -0.5 $\text{m}\cdot\text{s}^{-1}$ (Fig. 5b). The two-dimensional Z_e - V_t distribution shows that the high-probability region generally extends toward more negative V_t as Z_e increases (Fig. 5c), indicating that hydrometeors with higher radar reflectivity generally correspond to larger terminal fall velocities. The two-dimensional distribution of V_t and depolarization ratio is concentrated mainly at depolarization ratios of approximately 0.15 – 0.25 and V_t values of approximately -1.5 to -0.5 $\text{m}\cdot\text{s}^{-1}$ (Fig. 5d), indicating that the sedimenting hydrometeors retained pronounced nonspherical ice-particle characteristics.

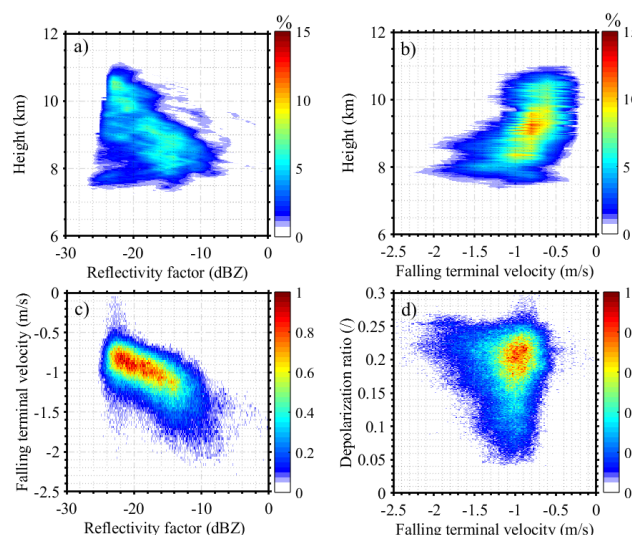


Figure 5. Statistical distributions of hydrometeor properties during the ice-dominated cloud stage (19:00–23:00 CST). (a) Contoured frequency by altitude diagram (CFAD) of radar reflectivity factor (Z_e); (b) CFAD of hydrometeor terminal fall velocity (V_t); (c) normalized two-dimensional probability density distribution of Z_e and V_t ; and (d) normalized two-dimensional probability density distribution of the 532 nm volume depolarization ratio and V_t . Colors in (a) and (b) indicate frequency of occurrence (%), whereas colors in (c) and (d) indicate normalized probability density.

Taken together, the spatial–temporal and statistical characteristics indicate enhanced radar reflectivity and sedimentation of high-level ice hydrometeors under cold and humid conditions, with higher Z_e generally corresponding to larger $|V_t|$. These observational features are consistent with the continued development of ice hydrometeors within the cloud and the emergence of different sedimentation states. Because the available observations do not allow the relative contributions of individual microphysical growth processes, such as vapor deposition and aggregation, to be quantitatively separated, no further attribution to specific growth mechanisms is made here. The period from 19:00 to 23:00 CST therefore represents a stage of high-level ice-hydrometeor development and initial sedimentation, providing an ice-phase source for the subsequent downward transport of hydrometeors to lower altitudes.

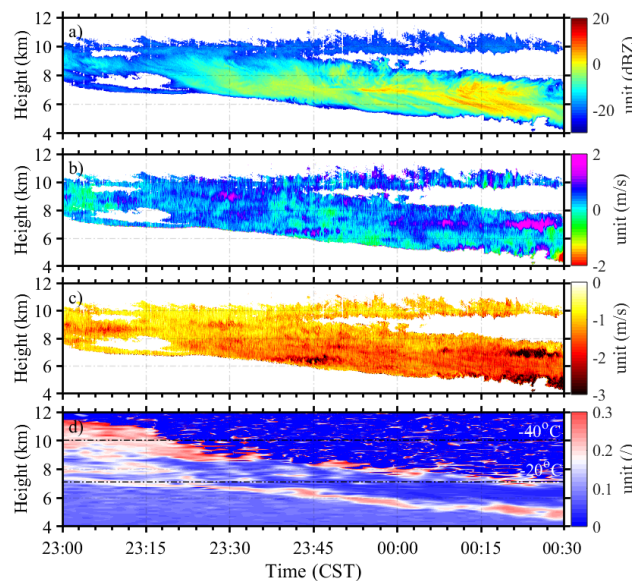
3.3 Enhanced ice-particle sedimentation and transition to mixed-phase conditions

The period from 23:00 to 00:30 CST marks a pronounced transition in both cloud structure and hydrometeor sedimentation. Compared with the preceding high-level ice cloud located mainly above 8 km, MMCR echoes rapidly extended toward lower altitudes, with the lower echo boundary descending from approximately 8 km to 5–6 km and Z_e increasing markedly in the middle and lower portions of the cloud (Fig. 6a). During the same period, vertical air motion was dominated by weak ascending and descending motions (Fig. 6b), whereas V_t became more negative and extended to lower altitudes as the cloud developed downward (Fig. 6c). Thus, this stage was characterized not only by a downward shift in the cloud boundaries but also by marked changes in radar reflectivity and hydrometeor sedimentation.

As hydrometeors were transported toward lower altitudes, the thermodynamic and phase environment through which they moved also changed substantially. Lidar observations show that, after 23:00 CST, the depolarization ratio decreased markedly in the middle and lower portions of the cloud and that the region of reduced depolarization progressively extended



1 downward (Fig. 6d). The temperature profiles indicate that these changes occurred mainly within subfreezing cloud layers,
 2 while the LWP observations in Fig. 3 show the persistent presence of liquid water during the same period. Taken together,
 3 these observations indicate that the sedimenting ice hydrometeors progressively entered warmer cloud layers containing
 4 liquid water during their downward transport, while the cloud evolved from an ice-dominated state toward mixed-phase
 5 conditions in which ice and liquid water coexisted.



6
 7 **Figure 6.** Evolution of cloud structure and hydrometeor dynamical characteristics during the mixed-phase transition stage (23:00–00:30
 8 CST). (a) Radar reflectivity factor (Z_e); (b) in-cloud vertical air velocity (w); (c) hydrometeor terminal fall velocity (V_t) after correction
 9 for vertical air motion; and (d) 532 nm volume depolarization ratio. Positive and negative w indicate upward and downward air motions,
 10 respectively, whereas negative V_t denotes downward hydrometeor sedimentation. The white dash-dotted lines in (d) indicate the -20°C
 11 and -40°C isotherms.

12 The Doppler power spectra further reveal the evolution of hydrometeor velocity distributions during this transition (Fig.
 13 7a1–a4). At 23:00 CST, most of the spectral energy remained concentrated at higher altitudes; thereafter, it progressively
 14 extended downward while also shifting toward more negative velocities. By 00:30 CST, stronger spectral signals had
 15 extended to approximately 5 km and were accompanied by pronounced spectral broadening. This indicates that the
 16 transition involved not only the downward transport of hydrometeors but also a continuing redistribution of spectral energy
 17 across the velocity range, reflecting marked changes in the relative contributions of components with different
 18 sedimentation velocities.

19 This evolution is more clearly evident in the two-dimensional Z_e – V_t distributions (Fig. 7b1–b3). During 23:00–23:30
 20 CST, the high-probability region was concentrated mainly at relatively weak Z_e and V_t values near $-0.8\text{ m}\cdot\text{s}^{-1}$. The
 21 distribution subsequently extended toward higher Z_e and more negative V_t . By 00:00–00:30 CST, hydrometeors
 22 characterized by higher radar reflectivity and larger terminal fall velocities became more prevalent. Thus, as the cloud
 23 developed downward, the hydrometeor population evolved from a state characterized by relatively weak radar reflectivity
 24 and smaller terminal fall velocities toward one with stronger reflectivity and more pronounced sedimentation.

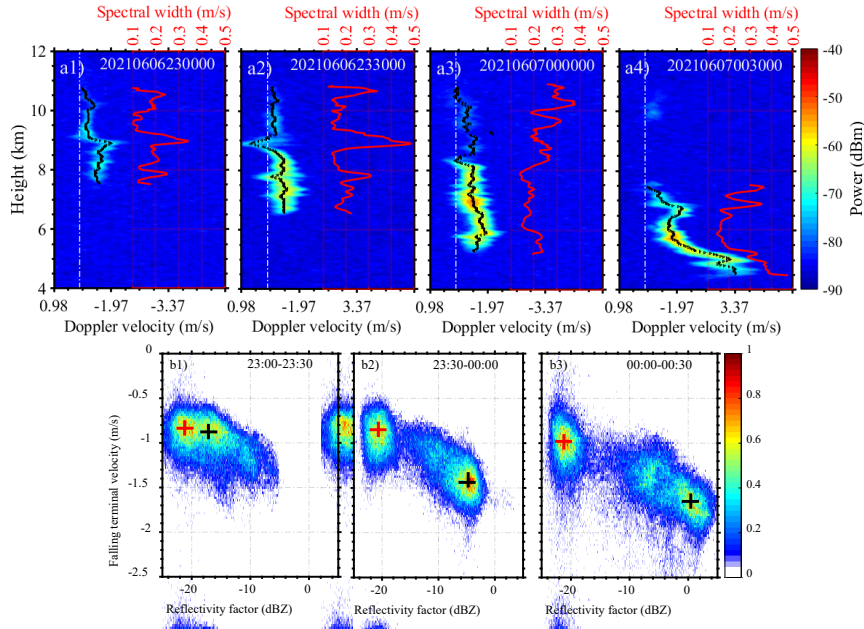


Figure 7. Evolution of Doppler spectra and the Z_e – V_i relationship during the mixed-phase transition stage (23:00–00:30 CST). (a1–a4) Vertical profiles of Doppler power spectra at 23:00, 23:30, 00:00, and 00:30 CST, respectively. Colors indicate spectral power, black dotted curves denote the spectral peak velocity at each height, and red curves indicate Doppler spectral width (SW). (b1–b3) Normalized two-dimensional density distributions of Z_e and V_i during 23:00–23:30, 23:30–00:00, and 00:00–00:30 CST, respectively. Colors indicate normalized density. Black crosses denote manually marked representative centers of the high-density regions.

Accordingly, three concurrent changes occurred during 23:00–00:30 CST: rapid downward extension of the cloud, simultaneous enhancement of hydrometeor radar reflectivity and sedimentation, and an increasing liquid-phase contribution within subfreezing cloud layers. The concurrent changes in Z_e , V_i , the Doppler spectra, and depolarization ratio indicate that the high-level ice hydrometeors that had already begun to sediment during the preceding stage continued to evolve during their downward transport and progressively exhibited stronger radar reflectivity and more pronounced sedimentation. This period therefore represents a key transition between the initial sedimentation of high-level ice hydrometeors and the subsequent persistent mixed-phase cloud stage.

3.4 Maintenance of the mixed-phase cloud and precipitation initiation

After 00:30 CST, the cloud system transitioned from the rapid downward development observed during the preceding stage to a relatively stable period of mixed-phase cloud maintenance. The main cloud layer remained at approximately 5–7 km for an extended period, with no further rapid lowering of the cloud base comparable to that observed during 23:00–00:30 CST (Fig. 8a). Despite the relatively stable cloud geometry, radar reflectivity and hydrometeor sedimentation continued to exhibit pronounced variability. In particular, during the later part of this stage, regions of enhanced Z_e became increasingly widespread, V_i shifted toward more negative values, and SW increased markedly in the middle and lower portions of the cloud (Fig. 8a–c). These changes indicate that, despite the relatively stable cloud geometry, hydrometeor radar reflectivity, sedimentation characteristics, and velocity distributions continued to evolve.

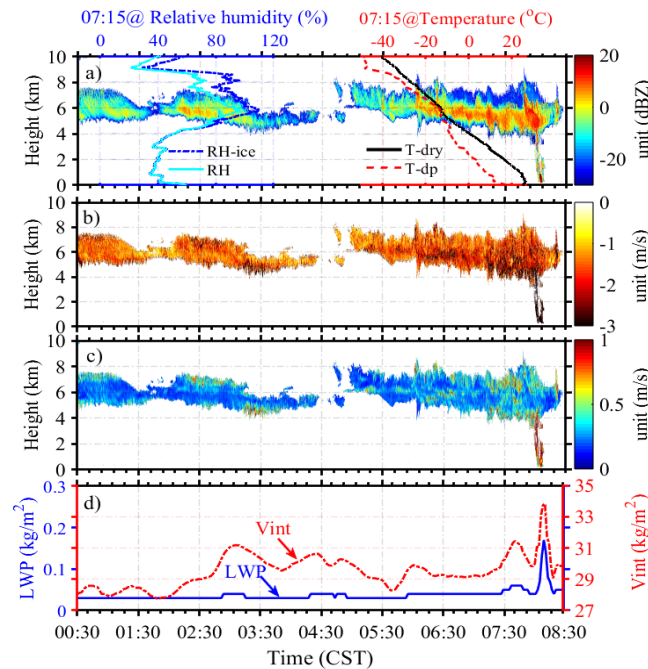


Figure 8. Evolution of hydrometeor properties and water-vapor–liquid-water conditions during the persistent mixed-phase cloud stage (00:30–08:30 CST). (a) Radar reflectivity factor (Z_e), with the 07:15 CST radiosonde relative-humidity and temperature profiles overlaid; (b) hydrometeor terminal fall velocity (V_t) after correction for vertical air motion; (c) Doppler spectral width (SW); and (d) liquid water path (LWP; blue line) and column-integrated water vapor (V_{int} ; red dashed line) retrieved from the microwave radiometer.

This stage was also characterized by sustained water-vapor and liquid-water conditions. Microwave radiometer observations show that, during 00:30–08:30 CST, V_{int} remained generally high, while LWP persisted with some variability and exhibited a pronounced peak near 08:00 CST (Fig. 8d). The 07:15 CST radiosonde profile further indicates that the main cloud layer remained in a humid, subfreezing environment (Fig. 8a). Together with the ice–liquid coexistence established during the preceding stage, these observations indicate that the cloud maintained moisture and liquid-water conditions favorable for the persistence of mixed-phase conditions and continued hydrometeor evolution over several hours.

The Doppler power spectra further reveal that hydrometeor sedimentation continued to evolve markedly despite the relatively stable cloud geometry. At 7 and 5 km, the spectral energy during the earlier part of this stage was concentrated within a relatively limited velocity range. After 05:30 CST, the spectral energy progressively extended toward more negative velocities, accompanied by an increasing contribution from the fast-sedimenting end of the spectrum (Fig. 9a, b). This change was particularly pronounced at 5 km, indicating that the contribution of fast-sedimenting hydrometeors not only increased within the cloud but also progressively extended toward lower altitudes. Consistently, F_{fast} calculated using $V_c = -1.09 \text{ m s}^{-1}$, remained generally low during the earlier part of the stage, whereas regions of elevated F_{fast} became more frequent after 06:00 CST and were concentrated mainly in the middle and lower portions of the cloud (Fig. 9c).

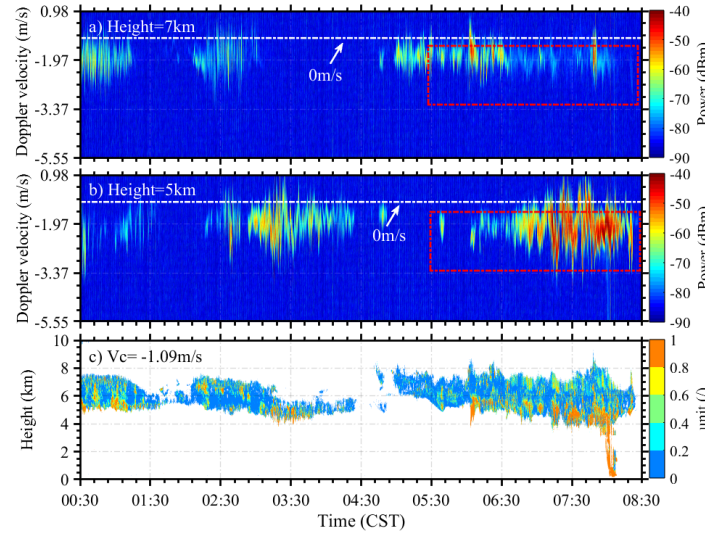


Figure 9. Evolution of Doppler spectra and fast-sedimenting spectral components during the persistent mixed-phase cloud stage (00:30–08:30 CST). (a, b) Time series of Doppler power spectra at 7 and 5 km, respectively. Negative Doppler velocities indicate downward motion. Colors indicate spectral power, the white dash-dotted lines denote 0 m·s⁻¹, and the red dashed boxes highlight regions where fast-sedimenting spectral components became more pronounced during the later part of the stage. (c) Height–time distribution of the high-velocity spectral energy fraction (F_{fast}), calculated using $V_c = -1.09$ m·s⁻¹ as the threshold for identifying fast-sedimenting spectral components. Colors indicate F_{fast} .

The vertical structure of the Doppler spectra at different times further illustrates this evolution (Fig. 10). At 05:30 CST, the stronger spectral energy was largely confined to the interior of the cloud. After 06:30 CST, the spectral distribution progressively broadened, accompanied by a more pronounced contribution from fast-sedimenting spectral components. By 07:50 CST, the fast-sedimenting spectral components had extended further toward lower altitudes. Near 08:00 CST, the Doppler spectral structure changed most markedly, with enhanced spectral energy at more negative velocities extending toward near-surface levels (Fig. 10a–d). This evolution corresponds to the late-stage changes in Z_e , V_t , and SW shown in Fig. 8, indicating a pronounced reorganization of hydrometeor velocity distributions and sedimentation characteristics prior to the occurrence of surface precipitation.

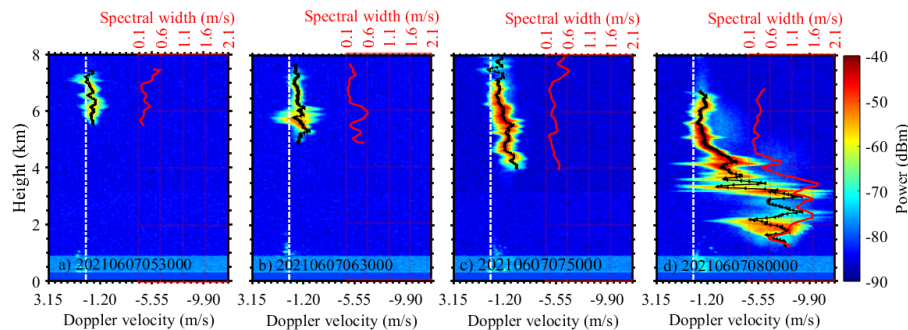


Figure 10. Evolution of the vertical structure of Doppler power spectra during the later part of the persistent mixed-phase cloud stage. (a–d) Vertical profiles of Doppler power spectra at 05:30, 06:30, 07:50, and 08:00 CST, respectively. Colors indicate spectral power, black dotted curves denote the spectral peak velocity at each height, red curves indicate Doppler spectral width (SW), and white dash-dotted lines denote 0 m·s⁻¹. Negative Doppler velocities indicate downward motion.



Therefore, during 00:30–08:30 CST, although the cloud maintained a relatively stable geometry and persistent mixed-phase conditions for several hours, the sedimentation state of the hydrometeors continued to evolve. During the earlier part of this stage, fast-sedimenting spectral components were generally weak. During the later part of the stage, particularly after 06:00 CST, spectral energy associated with fast-sedimenting components progressively increased and extended into the middle and lower portions of the cloud. By approximately 08:00 CST, a pronounced low-level fast-sedimentation signal had developed, corresponding in time with the subsequent extension of radar echoes toward near-surface levels. These results indicate that one of the most prominent changes preceding the occurrence of light surface precipitation was the increasing contribution of fast-sedimenting hydrometeors together with their downward extension toward lower levels.

3.5 Evolution of hydrometeor growth and sedimentation during the cloud-to-precipitation transition

To provide an integrated comparison of changes in hydrometeor sedimentation throughout the cloud-to-precipitation transition, Fig. 11 shows the evolution of F_{fast} , HSI, and its 0.5 h mean vertically integrated value. F_{fast} represents the relative contribution of fast-sedimenting spectral components to the total valid spectral energy, whereas HSI additionally incorporates the linear radar reflectivity factor to characterize the covariation between the contribution of fast-sedimenting spectral components and hydrometeor radar scattering intensity. Their combined analysis therefore helps distinguish the mere presence of fast-sedimenting spectral components from conditions in which their contribution increases concurrently with stronger radar scattering.

During the ice-dominated cloud stage, non-negligible F_{fast} was already present at altitudes of 8–11 km (Fig. 11a), whereas HSI and its vertically integrated value remained generally low (Fig. 11b–c). This indicates that fast-sedimenting spectral components were already present during the ice-dominated cloud stage, but their associated radar scattering contribution remained relatively limited. After 23:00 CST, as the cloud rapidly extended toward lower altitudes, elevated F_{fast} progressively spread into the 5–8 km layer, while HSI also increased and showed localized enhancements during the mixed-phase transition stage. These changes are consistent with the enhanced Z_e , the shift of V_i toward more negative values, and the reorganization of the Doppler spectral structure described in Sect. 3.3. This indicates that, during the transition from the high-level ice cloud to mixed-phase conditions, changes in fast sedimentation and radar scattering occurred concurrently.

After the cloud entered the persistent mixed-phase stage, F_{fast} remained present within the cloud for an extended period, whereas HSI did not remain correspondingly high. In particular, during approximately 01:00–05:30 CST, although V_{int} remained generally high and LWP persisted, both HSI and its vertically integrated value remained relatively low. After 06:00 CST, HSI increased markedly, and the most pronounced high-value region of the entire event developed during 07:00–08:30 CST, concentrated mainly in the middle and lower portions of the cloud and progressively extending downward (Fig. 11b). Meanwhile, the 0.5 h mean vertically integrated HSI increased rapidly and reached its highest value of the event near 08:00 CST (Fig. 11c), showing a clear temporal correspondence with the downward extension of radar echoes toward near-surface levels and the occurrence of light surface precipitation. Notably, although LWP also increased markedly near 08:00 CST, liquid water had already been present for several preceding hours; therefore, the persistence of LWP did not show a one-to-one temporal correspondence with the onset of surface precipitation.

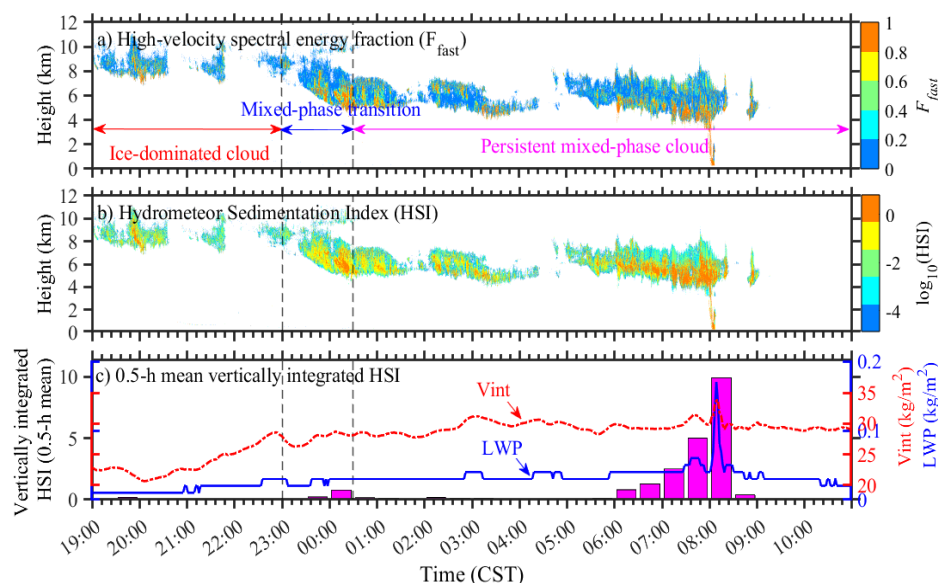


Figure 11. Integrated evolution of fast-sedimenting spectral components and hydrometeor sedimentation during the cloud-to-precipitation transition. (a) Height–time distribution of F_{fast} ; (b) height–time distribution of HSI; and (c) 0.5 h mean vertically integrated HSI, together with V_{int} (red dashed line) and LWP (blue line). The arrows in (a) indicate the ice-dominated cloud stage, mixed-phase transition stage, and persistent mixed-phase cloud stage, while the vertical dashed lines mark the boundaries between these stages.

Overall, fast-sedimenting spectral components appeared well before the occurrence of surface precipitation, whereas the most prominent change preceding the light precipitation was a marked increase in HSI together with its downward extension into the middle and lower portions of the cloud. This indicates that F_{fast} and HSI represent two distinct but complementary observational states: the former characterizes the relative contribution of fast-sedimenting spectral components to the total valid spectral energy, whereas the latter additionally characterizes the concurrent variation in fast-sedimenting spectral contribution and hydrometeor radar scattering intensity. Therefore, identifying the presence of fast-sedimenting spectral components alone is insufficient to fully characterize this cloud-to-precipitation transition. In contrast, the concurrent enhancement of fast-sedimenting spectral contributions and stronger radar scattering, together with their downward extension, showed a clearer temporal correspondence with the occurrence of light surface precipitation.

4 Discussion

The observations show that the radar reflectivity and sedimentation characteristics of high-level ice hydrometeors did not remain unchanged during their downward transport. During the high-level ice-cloud stage, low temperatures, high humidity, and locally ice-saturated or ice-supersaturated conditions provided a favorable environment for the development of ice hydrometeors; subsequently, as they entered a warmer mixed-phase environment, increases in Z_e and $|V|$, broadening of the Doppler spectra, and changes in depolarization ratio occurred concurrently. Previous studies have shown that vapor deposition, aggregation, and interactions between ice particles and supercooled liquid droplets can alter ice-particle size, mass, and sedimentation characteristics, with corresponding changes in Doppler spectra (Kalesse et al., 2016; Pfitzenmaier et al., 2018; Kneifel and Moisseev, 2020). Therefore, the coordinated changes observed in these parameters are consistent



with continued growth of sedimenting ice hydrometeors during their downward transport. However, the available ground-based remote-sensing observations do not allow the relative contributions of processes such as vapor deposition, aggregation, and riming to be quantitatively distinguished. Accordingly, these changes are not attributed here to any single microphysical mechanism; instead, the interpretation is limited to the conclusion that, after entering the mixed-phase environment, the radar reflectivity, velocity distribution, and sedimentation characteristics of ice hydrometeors continued to evolve.

A notable feature of this event is that the mixed-phase cloud persisted for nearly 8 h, whereas light surface precipitation occurred only briefly during the later stage. Previous ground-based observations have shown that supercooled liquid water can persist within mixed-phase clouds and coexist with sedimenting ice hydrometeors (Shupe et al., 2006; Silber et al., 2021). In the present event, Vint remained generally high and LWP persisted through most of the persistent mixed-phase stage, yet surface precipitation did not occur concurrently. A clearer temporal correspondence with the occurrence of surface precipitation was observed for the late-stage enhancement of fast-sedimenting spectral energy and its downward extension toward lower altitudes. This suggests that, for this case, sustained water vapor and liquid water were more likely to provide the environmental conditions supporting mixed-phase cloud persistence and continued hydrometeor evolution, whereas the increasing contribution of strongly sedimenting hydrometeors and their sustained downward transport toward lower levels constituted a more direct observational signature of the transition from in-cloud hydrometeors to light surface precipitation. This result does not imply that liquid water was unimportant for precipitation formation; rather, its persistent presence alone was insufficient to explain the specific timing of surface precipitation in this event.

F_{fast} and HSI further highlight the temporal differences described above. Doppler spectra retain the contributions of hydrometeors with different velocities to the radar return and therefore provide information on hydrometeor velocity distributions and spectral structure beyond that available from conventional radar moments (Kalesse et al., 2016; Kneifel et al., 2016; Pfitzenmaier et al., 2018). In this event, F_{fast} was already present during both the high-level ice-cloud stage and the persistent mixed-phase stage, whereas the most pronounced enhancement in HSI occurred mainly during the later part of the event and was accompanied by a downward extension of elevated HSI into the middle and lower portions of the cloud. This indicates that the presence of fast-sedimenting spectral components and the concurrent enhancement of fast-sedimenting spectral contribution and stronger radar scattering represent two distinct observational states. By definition, HSI provides an integrated measure of the spectral contribution within the fast-sedimentation velocity range together with the corresponding radar scattering level. HSI is therefore not intended to replace Z_e , V_i , or the Doppler spectra, but rather to serve as a process diagnostic for identifying concurrent changes in fast-sedimenting spectral contribution and radar scattering. For this case, this concurrent enhancement and its downward extension showed a clearer temporal correspondence with the occurrence of light surface precipitation than F_{fast} alone. However, this relationship should be interpreted as an observational temporal correspondence rather than as evidence that HSI constitutes a causal criterion for precipitation initiation.

5 Conclusions

This study combines observations from MMCR, a multiwavelength lidar, a microwave radiometer, and radiosondes to investigate the continuous evolution of a stratiform mixed-phase cloud system from a high-level ice cloud to short-lived light precipitation, with particular emphasis on changes in hydrometeor radar scattering, sedimentation, and Doppler



1 spectral characteristics across different stages of the event. The main conclusions are as follows.

2 (1) The high-level ice-cloud stage was characterized primarily by the growth and initial sedimentation of ice particles.

3 During the early stage of the event, the cloud was mainly located at 8–11 km, where ice-saturated or ice-supersaturated

4 conditions provided a favorable environment for the growth of ice particles. As the cloud system evolved, both Z_e and

5 V_i generally increased, indicating progressive changes in the radar scattering and sedimentation characteristics of ice

6 particles, although stronger sedimentation remained largely confined to localized regions within the cloud.

7 (2) The transition from ice cloud to mixed-phase cloud was accompanied by pronounced enhancements in hydrometeor

8 radar scattering and sedimentation characteristics. During 23:00–00:30 CST, the cloud lower boundary rapidly

9 descended from approximately 8 km to 5–6 km. As sedimenting ice particles entered warmer cloud layers containing

10 liquid water, Z_e and $|V_i|$ increased and the Doppler spectra broadened. These coordinated changes are consistent with

11 continued hydrometeor growth in the mixed-phase environment. At the same time, hydrometeors characterized by

12 stronger radar scattering and more pronounced sedimentation became increasingly evident and progressively extended

13 toward lower altitudes.

14 (3) The prolonged maintenance of mixed-phase conditions did not correspond to continuous surface precipitation; instead,

15 the late-stage concurrent enhancement of fast-sedimenting spectral contributions and hydrometeor radar scattering

16 showed a clearer temporal correspondence with the occurrence of light precipitation. The mixed-phase cloud persisted

17 for nearly 8 h, during which Vint and LWP remained present and fast-sedimenting components could be identified in

18 the Doppler spectra for extended periods, whereas surface precipitation was absent during most of this time. Joint

19 analysis of F_{fast} and HSI further shows that fast-sedimenting spectral components were already present before the

20 occurrence of surface precipitation, whereas the most pronounced enhancement in HSI was concentrated in the later

21 stage of the event. At the same time, elevated HSI progressively extended into the middle and lower portions of the

22 cloud, and the 0.5 h mean vertically integrated HSI reached relatively high values around the onset of light surface

23 precipitation. Therefore, the presence of fast-sedimenting spectral components alone was insufficient to characterize

24 the cloud-to-precipitation transition in this event. The concentrated enhancement of fast-sedimenting hydrometeors

25 associated with stronger radar scattering, together with their downward extension toward lower altitudes, was one of

26 the most prominent observational changes preceding the occurrence of light surface precipitation.

27 This stratiform mixed-phase cloud underwent a continuous evolution from the growth and initial sedimentation of high-

28 level ice particles, through enhanced hydrometeor radar scattering and sedimentation during the transition to mixed-phase

29 conditions, to continued hydrometeor evolution within the persistent mixed-phase cloud; during the later stage, fast-

30 sedimenting spectral contributions and stronger radar scattering increased concurrently and extended toward lower altitudes,

31 coinciding with the occurrence of short-lived light surface precipitation. Sustained water vapor and liquid water provided

32 a favorable environment for the prolonged maintenance of the mixed-phase cloud and continued hydrometeor evolution,

33 but their persistent presence alone was not synchronized with the onset of surface precipitation. The HSI developed in this

34 study provides a process diagnostic for identifying concurrent changes in fast-sedimenting spectral contributions and

35 hydrometeor radar scattering, while its applicability under different mixed-phase cloud conditions requires further

36 evaluation using additional observational cases.



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Code and data availability

The processed observational data and MATLAB code supporting this study and required to reproduce Figs. 3–11 and Fig. S2 are publicly available from Zenodo at <https://doi.org/10.5281/zenodo.23408290> (Yuan, 2026). The repository contains figure-specific plotted data and reproduction programs, including the processed Ka-band millimetre-wave cloud radar, lidar, microwave-radiometer, and radiosonde products used in this study.

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