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## Research Article

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# Spatially Divergent Modulations of Cloud Microphysical Processes on Precipitation Formation Pathways over Southwest China: Insights from Reanalysis and Satellite Datasets

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## Abstract

Relationships between cloud microphysical processes and precipitation exhibit pronounced spatial heterogeneity across Southwest China, where complex terrain produces strong contrasts in moisture, cloud structure, and dynamics. Using GPM IMERG precipitation, MERRA-2 reanalysis, and ERA5 high cloud cover data during 2000-2023, this study investigated six cloud microphysical process rates across four representative regions through spatial, seasonal, precipitation intensity, hydrometeor, and dynamical analyses. Cloud water autoconversion and accretion of cloud water by rain and snow showed the strongest positive relationships with precipitation and represent major pathways for precipitation particle formation and growth. Cloud water freezing primarily provides initial ice particles for ice phase growth, whereas cloud water and rainwater evaporation are modulated by hydrometeor availability and environmental humidity. The western Tibetan Plateau is characterized by limited liquid cloud water and weak accretion of cloud water by rain, with ice phase processes becoming more prominent during the cold season. The eastern Tibetan Plateau supports both liquid and ice phase growth under abundant moisture and midlevel ascent, with stronger contributions from ice phase processes in the cold season. The Sichuan Basin exhibits active low level warm cloud processes, with accretion of cloud water by rain playing an important role under abundant liquid cloud water and low level ascent. Over the Yunnan-Kweichow Plateau, liquid and ice phase pathways vary seasonally, and heavier precipitation is associated with weaker cloud water evaporation. These results reveal distinct precipitation formation pathways and provide insights into improving cloud microphysical parameterizations over complex terrain.

**Keywords** Cloud microphysical processes; Cloud-precipitation relationship; Southwest China; Hydrometeor particles

## 1 Introduction

Southwest China, including the Tibetan Plateau (TP), Sichuan Basin (SCB), and Yunnan-Kweichow Plateau (YKP), is characterized by substantial topographic relief and marked spatial heterogeneity in precipitation. The region is jointly influenced by

the South Asian monsoon, East Asian monsoon, the westerlies, and the thermal and dynamical effects of the TP. Warm season precipitation dominates the annual total and exhibits pronounced regional differences (Li et al. 2011; Zhang et al. 2014). Summer precipitation over the TP frequently occurs in the form of weak convective precipitation and exhibits distinct deep and shallow precipitating cloud structures (Fu et al. 2006; Gao et al. 2016; Pan and Fu 2015), whereas the SCB and its surroundings frequently experience heavy precipitation associated with the Southwest Vortex, Plateau vortices, basin circulation, and orographic lifting (Huang and Cui 2015; Qian et al. 2015). Over the YKP, summer precipitation is strongly influenced by warm and humid airflow from the Indian and Pacific Oceans together with the thermal and dynamical effects of the plateau (Tuo et al. 2024). These regional contrasts indicate that precipitation formation over Southwest China is jointly shaped by large scale moisture transport, dynamical lifting, and cloud microphysical processes under complex terrain.

Cloud macrophysical and microphysical properties over Southwest China show pronounced spatial variations. Owing to its high elevation and low temperature environment, cloud systems over the TP generally develop at higher altitudes, with cloud thickness, cloud water content, and phase composition differing markedly from those in lower elevation regions. Previous studies have further documented a higher frequency of ice clouds and lower precipitation efficiency of liquid clouds over the TP and its surroundings (Yan et al. 2018; Hua et al. 2020; Wang et al. 2015). The SCB is characterized by high cloud cover, with more cloud cover in winter and extensive midlevel clouds and deep cloud systems throughout the year (Zhao et al. 2019). Under the effects of complex terrain and the quasi-stationary front, cloud cover, cloud height, and cloud particle size over the YKP also show pronounced spatial variations, while warm season moisture favors the development of deep cloud systems (Cai et al. 2022; Yu et al. 2023). These regional differences in cloud vertical structure and hydrometeor distribution provide distinct environments for liquid and ice phase microphysical processes, contributing to regional differences in cloud microphysical controls on precipitation.

Cloud particle size, cloud droplet number concentration, liquid and ice water paths, cloud top height, and cloud phase can all influence precipitation formation and intensity. In general, larger cloud droplets favor collision-coalescence growth, whereas high cloud droplet number concentrations can suppress warm cloud microphysical processes (Rosenfeld and Gutman 1994; Wood 2005). In addition to these spatial variations in cloud properties, recent studies have revealed pronounced regional differences in cloud precipitation relationships across Southwest China. Wang et al. (2024) found that ice water path and cloud-top height were significantly positively correlated with precipitation across all topographic regions, whereas liquid water path was positively correlated with precipitation only over the ETP and YKP. The effective radius of liquid droplets was positively correlated with precipitation over the ETP, YKP, and SCB, while the effective radius of ice particles showed negative correlations over the WTP and ETP. Thermodynamic controls also varied regionally; higher convective available potential energy and low level relative humidity favored precipitation, with stronger effects over the ETP.

Precipitation formation involves multiple liquid phase, mixed phase, and ice phase cloud microphysical processes. Convective precipitation is generally dominated by warm cloud processes, but ice phase and mixed phase processes can substantially affect precipitation evolution through hydrometeor conversion and latent heat from phase changes (Sun et al. 2016; Korolev et al. 2017; Kanji et al. 2017). Cloud microphysical processes not only control hydrometeor formation and growth, but also feed back on atmospheric dynamics through latent heat release and water vapor redistribution (Hazra et al. 2016, 2017). Numerical simulations over Southwest China have shown that accretion of cloud water by raindrops and graupel melting are important pathways for rainwater formation during torrential rainfall in Sichuan (Huang and Cui 2015). Tibetan Plateau vortices and the Southwest Vortex can strengthen upward motion and favor the growth of ice phase particles (Liu et al. 2018). Latent heat from phase changes further strengthens low level convergence and vertical motion, promoting the development of the Southwest Vortex and heavy precipitation (Wu et al. 2022; Li et al. 2024).

Collectively, previous studies indicate that precipitation formation over the complex terrain of Southwest China is jointly regulated by cloud microphysical processes and thermodynamic and dynamic conditions.

Based on this understanding, this study focuses on the spatial distributions and seasonal variations of precipitation and six cloud microphysical process rates over Southwest China during 2000-2023, and examines the relationships between different microphysical processes and precipitation. Together with variables including vertical velocity, cloud liquid water mass mixing ratio, cloud ice mass mixing ratio, and high cloud cover, we further investigate these relationships under different terrain, dynamical conditions, and vertical hydrometeor structures. The aim is to improve understanding of the physical mechanisms linking clouds and precipitation in Southwest China.

## **2 Data and Methods**

### **2.1 Study region**

The study region covers the major topographic units of Southwest China, including the TP, SCB, and YKP (Fig. 1). Strong elevation contrasts distinguish the high elevation TP from the lower elevation SCB and YKP, resulting in distinct cloud and precipitation characteristics. The western and eastern parts of the TP also differ substantially in moisture availability, cloud structure, and precipitation characteristics. Based on these regional differences reported in previous studies (Zhao et al. 2022; Chen and Zhou 2015; Li et al. 2012), four regions of interest were selected for comparison, the western Tibetan Plateau (WTP), eastern Tibetan Plateau (ETP), Sichuan Basin (SCB), and Yunnan-Kweichow Plateau (YKP). Their locations and topographic characteristics are shown in Fig. 1.

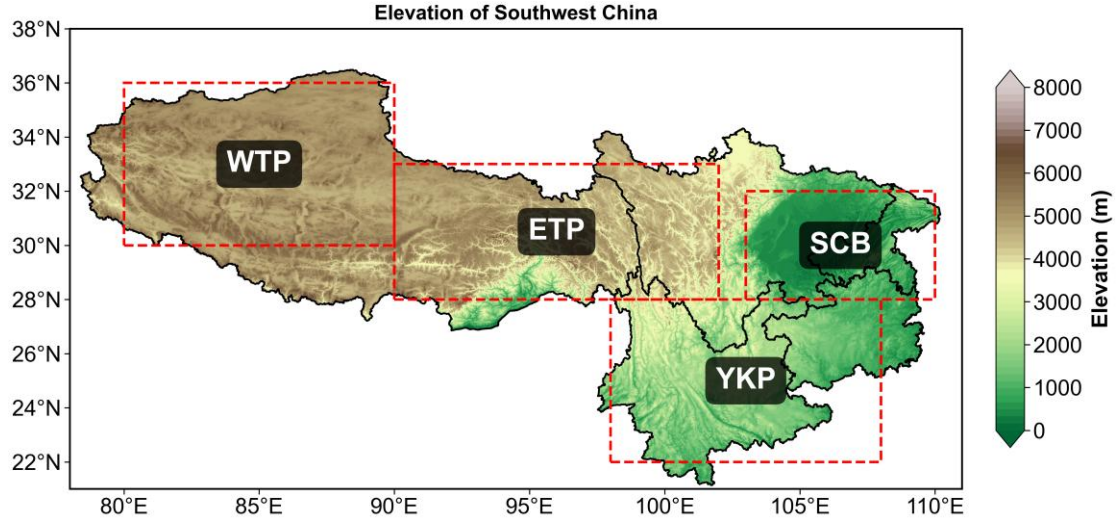


**Fig. 1** Topography of Southwest China (unit: m) and the four regions of interest: western Tibetan Plateau (WTP), eastern Tibetan Plateau (ETP), Sichuan Basin (SCB), and Yunnan-Kweichow Plateau (YKP)

## 2.2 Data

Precipitation data were derived from the Integrated Multi-satellitE Retrievals for GPM (IMERG) Final Run V07B product provided by the Global Precipitation Measurement (GPM) mission (Huffman et al. 2020). The product provides precipitation estimates at a spatial resolution of  $0.1^\circ \times 0.1^\circ$  and a half-hourly temporal resolution. Daily precipitation data from 2000 to 2023 were used in this study. Previous evaluations have shown that IMERG effectively captures precipitation diurnal cycles over the TP and extreme precipitation characteristics over China. It also represents the main spatial characteristics of precipitation over Southwest China at climatological and interannual scales (Fang et al. 2019; Zhang et al. 2024; Jia et al. 2025).

Cloud microphysical process rates, together with dynamical and hydrometeor variables, were derived from NASA's Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) reanalysis (Gelaro et al. 2017). MERRA-2 has a horizontal resolution of  $0.5^\circ \times 0.625^\circ$ . The cloud microphysical process rates and bias-corrected total precipitation rate (PRECTOTCORR) are available at an hourly temporal resolution, while the three-dimensional hydrometeor and dynamical variables are provided at a 3-hourly temporal resolution. The study period covers 2000-2023. The variables analyzed include six cloud microphysical process rates, including

161 autoconversion loss of cloud water (AUTCNVRN), accretion loss of cloud water to rain  
162 (COLCNVRN), accretion loss of cloud water to snow (COLCNVSN), net freezing of  
163 cloud condensate (FRZCL), evaporation loss of cloud water (EVPCL), and evaporation  
164 loss of precipitating water (EVPRN). Additional variables include cloud liquid water  
165 mass mixing ratio (QL), cloud ice mass mixing ratio (QI), and pressure vertical velocity  
166 (OMEGA). Because long term, large scale process rates are difficult to obtain directly  
167 from observations (Morrison et al. 2020), this study uses the parameterized cloud  
168 microphysical process diagnostics provided by MERRA-2.

169 High cloud cover (HCC) was derived from the ERA5 reanalysis produced by the  
170 European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al.  
171 2020), with an original horizontal resolution of  $0.25^{\circ} \times 0.25^{\circ}$  and an hourly temporal  
172 resolution for the period 2000-2023. ERA5 defines HCC as the fraction of cloud cover  
173 in regions where pressure is below 0.45 times the surface pressure (Wu et al. 2023).  
174 Previous studies have shown that the global spatial distribution of high cloud cover in  
175 ERA5 is generally consistent with that from MODIS satellite cloud products,  
176 supporting its use for analyzing high cloud cover characteristics at climatic scales (Wu  
177 et al. 2023).

## 178 **2.3 Methods**

179 To match the spatial and temporal resolutions of the datasets, we used the  $0.1^{\circ} \times 0.1^{\circ}$   
180 spatial resolution and daily temporal resolution of the GPM IMERG precipitation  
181 product as the common standard. MERRA-2 and ERA5 data were interpolated to  
182  $0.1^{\circ} \times 0.1^{\circ}$  and processed at the daily scale. Monthly, warm season, and cold season  
183 means were then calculated. The warm season was defined as May-October, and the  
184 cold season as November-April of the following year.

185 An IMERG daily mean precipitation rate  $>0.1$  mm/day was defined as effective  
186 precipitation. To compare cloud microphysical process rates under different  
187 precipitation intensities, daily precipitation samples were divided into five classes: 0.1-  
188 1 mm/day, 1-10 mm/day, 10-25 mm/day, 25-50 mm/day, and  $>50$  mm/day.

To characterize the dynamical background of each region, we used the 2000-2023 climatological warm and cold season OMEGA profiles for each region of interest (Fig. S1) to identify the pressure level with the strongest upward motion. The mean  $-\omega$  over this level and the adjacent level above and below was used as the intensity of upward motion.

### 3 Results and Discussion

#### 3.1 Spatiotemporal Characteristics of Precipitation and Microphysical Process Rates

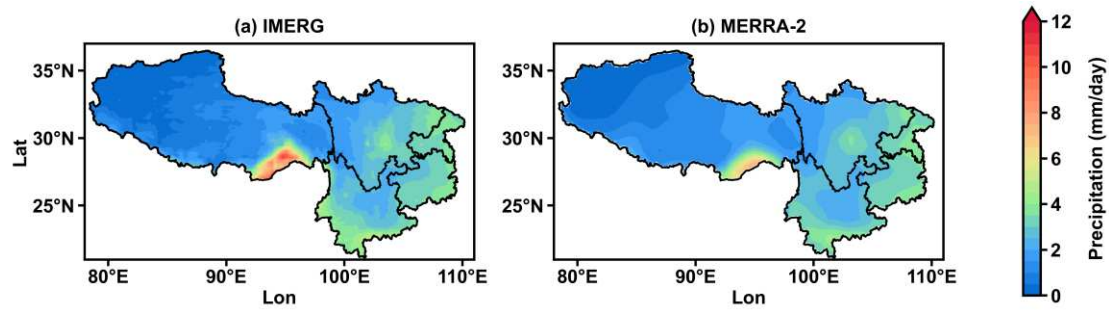


**Fig. 2** Spatial distribution of mean precipitation over Southwest China during 2000-2023: (a) IMERG precipitation and (b) MERRA-2 total precipitation (unit: mm/day)

Fig. 2 presents the spatial distributions of climatological mean daily precipitation over Southwest China for 2000-2023 derived from IMERG and MERRA-2 bias-corrected total precipitation (PRECTOTCORR). Both datasets reveal pronounced spatial heterogeneity in precipitation, with relatively low values over the WTP and high values occurring along the southeastern margin of the TP and in the southern YKP. Climatological mean daily precipitation is below 2 mm/day over most of the WTP but exceeds 8 mm/day along the southeastern margin. Most of the SCB and YKP exhibit precipitation values of 2-5 mm/day, while values exceed 5 mm/day over the southern YKP. This spatial pattern is primarily governed by monsoonal moisture transport and orographic effects (Yuan et al. 2019; Li et al. 2012). The WTP is characterized by limited moisture availability and consequently low precipitation (Zhang et al. 2013; Maussion et al. 2014). In contrast, the southeastern margin serves as a major pathway for South Asian monsoon moisture entering the Plateau, where orographic lifting

promotes condensation and precipitation formation, resulting in substantially higher precipitation (Houze 2012; Wang et al. 2015). Precipitation over the SCB is jointly influenced by low level moisture convergence, the Southwest Vortex, and terrain-induced lifting (Qian et al. 2015; Shen et al. 2022). The YKP lies close to major moisture transport pathways from the Bay of Bengal and the South China Sea. Complex terrain modulates low level moisture transport and amplifies orographic lifting, resulting in relatively high precipitation over the southern plateau and along some windward slopes (Shi et al. 2017; Wang et al. 2024).

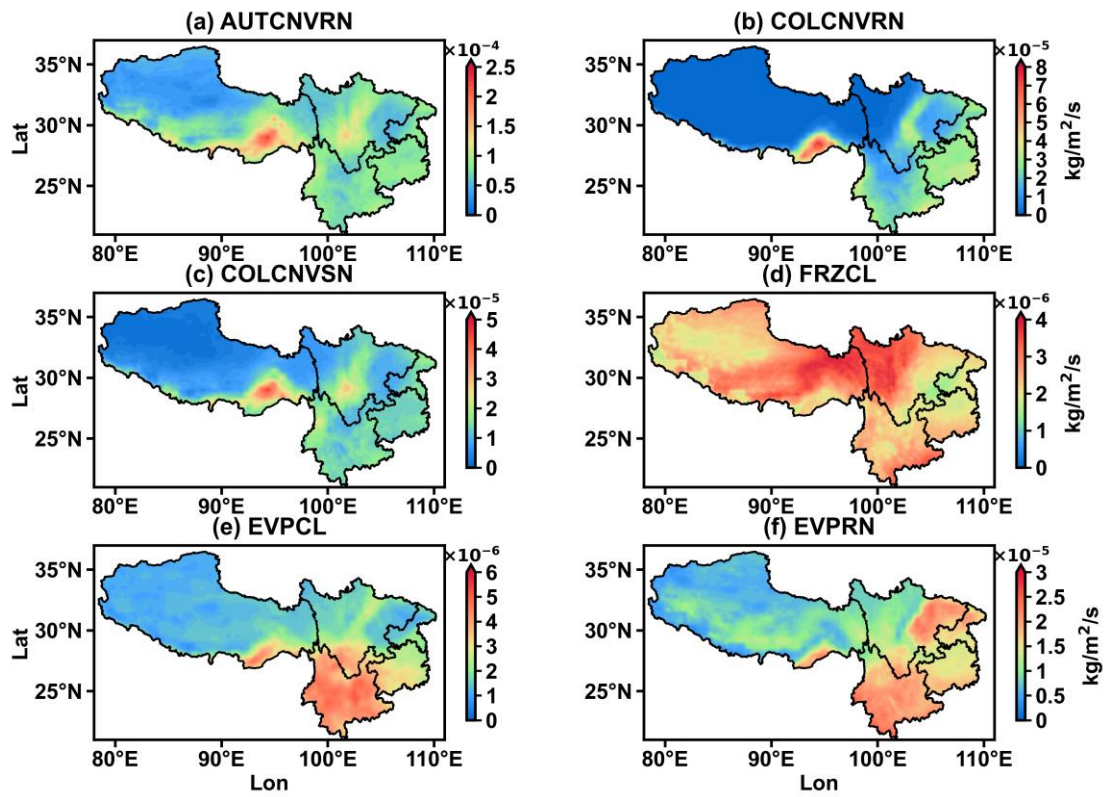


**Fig. 3** Spatial distributions of mean microphysical process rates over Southwest China during 2000 – 2023: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN (unit:  $\text{kg/m}^2/\text{s}$ )

Fig. 3 presents the spatial distributions of the mean rates of six cloud microphysical processes over Southwest China during 2000–2023. Cloud water autoconversion (AUTCNVRN) averages approximately  $0.5 \times 10^{-4} \text{ kg/m}^2/\text{s}$  over the WTP and increases markedly along the southeastern margin of the Plateau, where local values exceed  $2 \times 10^{-4} \text{ kg/m}^2/\text{s}$ . Values are also relatively high over the western SCB and parts

of the YKP. Cloud water autoconversion is an important warm cloud microphysical process that converts small cloud droplets into raindrops (Cheng et al. 2007; Tao et al. 2012; Hazra et al. 2013, 2015). Therefore, high AUTCNVRN magnitudes are generally linked to elevated cloud water content. Over the WTP, insufficient water vapor and low liquid cloud water content substantially suppress this process. The highest rates of accretion of cloud water by raindrops (COLCNVRN) occur mainly along the southeastern margin of the TP, where local values exceed  $6 \times 10^{-5} \text{ kg/m}^2/\text{s}$ . The western SCB and parts of the YKP are secondary high value areas, while the WTP exhibits generally weak magnitudes. As a key warm phase hydrometeor growth process, cloud water accretion by raindrops features higher collision-coalescence efficiency under broad cloud droplet and raindrop size distributions (Beard and Ochs 1984; Vohl et al. 2007). Fig. 3c shows a pronounced maximum in accretion of cloud water by snow particles (COLCNVSN) along the southeastern margin of the TP, with local values exceeding  $4 \times 10^{-5} \text{ kg/m}^2/\text{s}$ . Values are also relatively high over the western SCB and parts of the YKP, whereas the WTP shows distinctly weaker process rates. This process requires the coexistence of snow particles and supercooled cloud water. Intense orographic lifting and persistent water vapor transport along the southeastern margin provide favorable environmental conditions for its occurrence.

Fig. 3d shows that net freezing of cloud condensate (FRZCL) is enhanced over the ETP and southern YKP, with magnitudes ranging from approximately  $2 \times 10^{-6}$  to  $4 \times 10^{-6} \text{ kg/m}^2/\text{s}$ , and relatively suppressed across the SCB. FRZCL corresponds to the freezing of supercooled cloud water into ice hydrometeors. Elevated FRZCL magnitudes over the ETP and southern YKP indicate more active in-cloud freezing processes in these areas. Fig. 3e shows that cloud water evaporation (EVPCL) is generally stronger in the south than in the north. Values are mostly below  $2 \times 10^{-6} \text{ kg/m}^2/\text{s}$  over the SCB and WTP, but range from  $4 \times 10^{-6}$  to  $6 \times 10^{-6} \text{ kg/m}^2/\text{s}$  over the YKP and southeastern margin of the TP. Cloud water evaporation is jointly determined by liquid cloud water availability and in-cloud humidity conditions, and the enhanced EVPCL over these regions reflects vigorous cloud water evaporative processes. Rainwater evaporation (EVPRN; Fig. 3f)

is pronounced over the SCB and YKP, while weak values dominate the TP domain. Spatially elevated EVPRN magnitudes broadly coincide with regions of abundant precipitating hydrometeors.

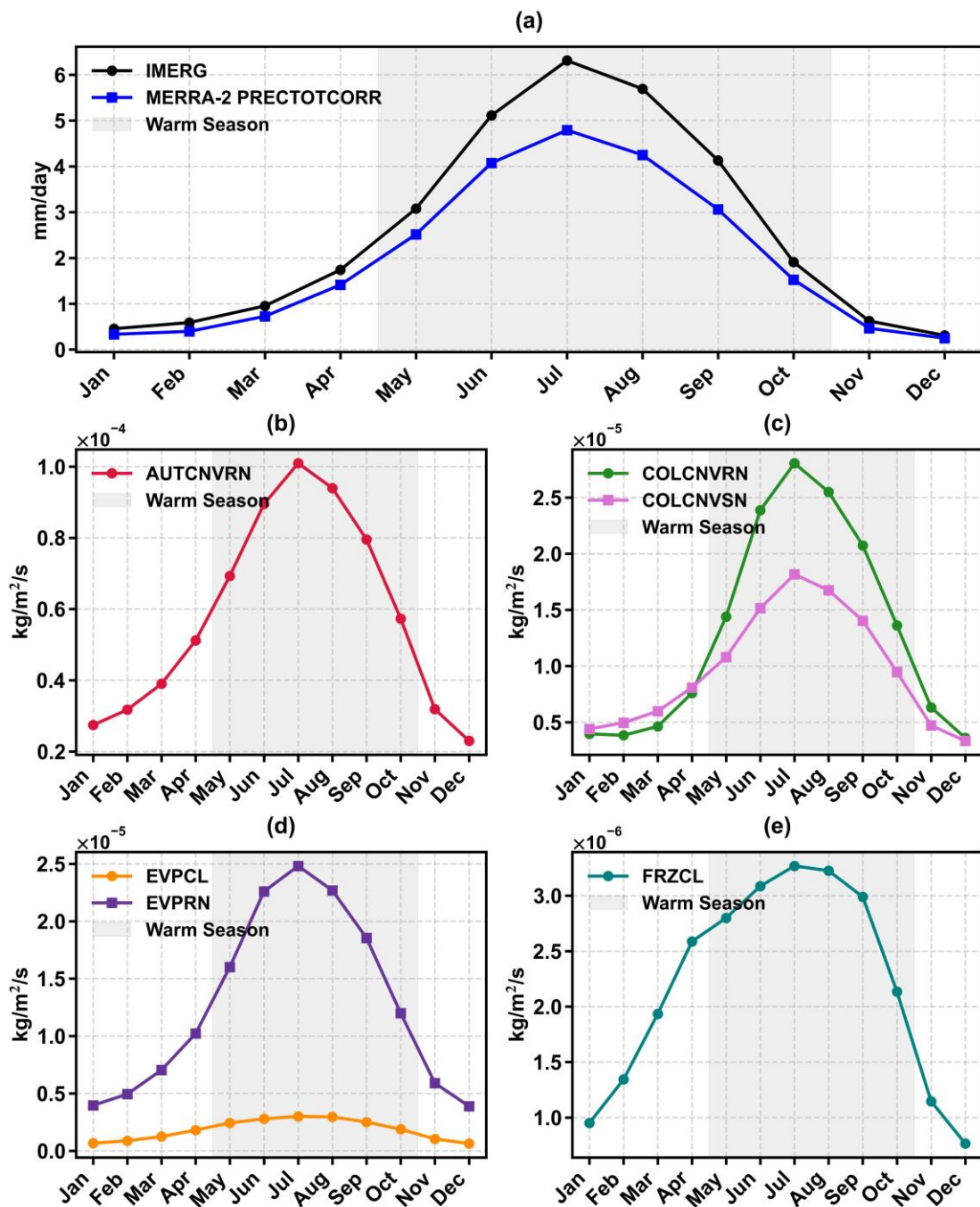


**Fig. 4** Monthly distributions of precipitation and cloud microphysical process rates over Southwest China during 2000-2023: (a) IMERG and MERRA-2 precipitation, (b) AUTCNVRN, (c) COLCNVRN and COLCNVSN, (d) EVPCL and EVPRN, and (e) FRZCL. Shading denotes the warm season (May-October). Units: precipitation, mm/day; microphysical process rates, kg/m<sup>2</sup>/s

Fig. 4 shows the climatological monthly distributions of precipitation and cloud

microphysical process rates over Southwest China during 2000-2023. Both IMERG and MERRA-2 precipitation show a clear warm season peak. Precipitation begins to increase during April-May, peaks around July at approximately 6.3 and 4.8 mm/day, respectively, and gradually decreases after September. In summer, surface sensible heating and tropospheric heating strengthen over the TP and adjacent regions, while the South Asian and East Asian summer monsoons gradually develop. Water vapor transport originating from the Bay of Bengal, the South China Sea, and low latitude regions intensifies. After reaching the southeastern margin of the plateau and the YKP, the low level warm and humid airflow is lifted by terrain, promoting cloud formation and precipitation (Qian et al. 2015; Shi et al. 2017; Wang et al. 2024). Around July, the combined effects of monsoonal water vapor transport, thermal instability, and orographic lifting are strongest, producing the annual precipitation peak. After September, the monsoon circulation and water vapor transport weaken, suppressing cloud vertical development and reducing hydrometeor content, which consequently leads to decreased precipitation (Maussion et al. 2014; Cheng et al. 2019).

All six cloud microphysical process rates are higher in the warm season than in the cold season, with peaks mainly in July to August. AUTCNVRN, COLCNVRN, COLCNVSN, and EVPRN all peak in July at approximately  $1.0 \times 10^{-4}$ ,  $2.8 \times 10^{-5}$ ,  $1.8 \times 10^{-5}$ , and  $2.5 \times 10^{-5}$  kg/m<sup>2</sup>/s, respectively. FRZCL reaches approximately  $3.3 \times 10^{-6}$  kg/m<sup>2</sup>/s in July, whereas EVPCL remains near  $3.0 \times 10^{-6}$  kg/m<sup>2</sup>/s in July to August. During the warm season, enhanced monsoon water vapor transport, favorable thermal conditions, and intensified orographic lifting favor vigorous cloud development. Accordingly, the contents of liquid cloud water, rainwater, and ice phase hydrometeors increase, facilitating raindrop formation, liquid phase growth, ice phase growth, and relevant phase change processes. During the cold season, insufficient water vapor and limited cloud development reduce the rates of these processes (Qian et al. 2015; Shi et al. 2017; Wang et al. 2024). Overall, the monthly variations in the microphysical processes are generally consistent with those in precipitation, reflecting more favorable moisture and cloud development conditions during the warm season.

### 3.2 Relationships between Microphysical Process Rates and Precipitation

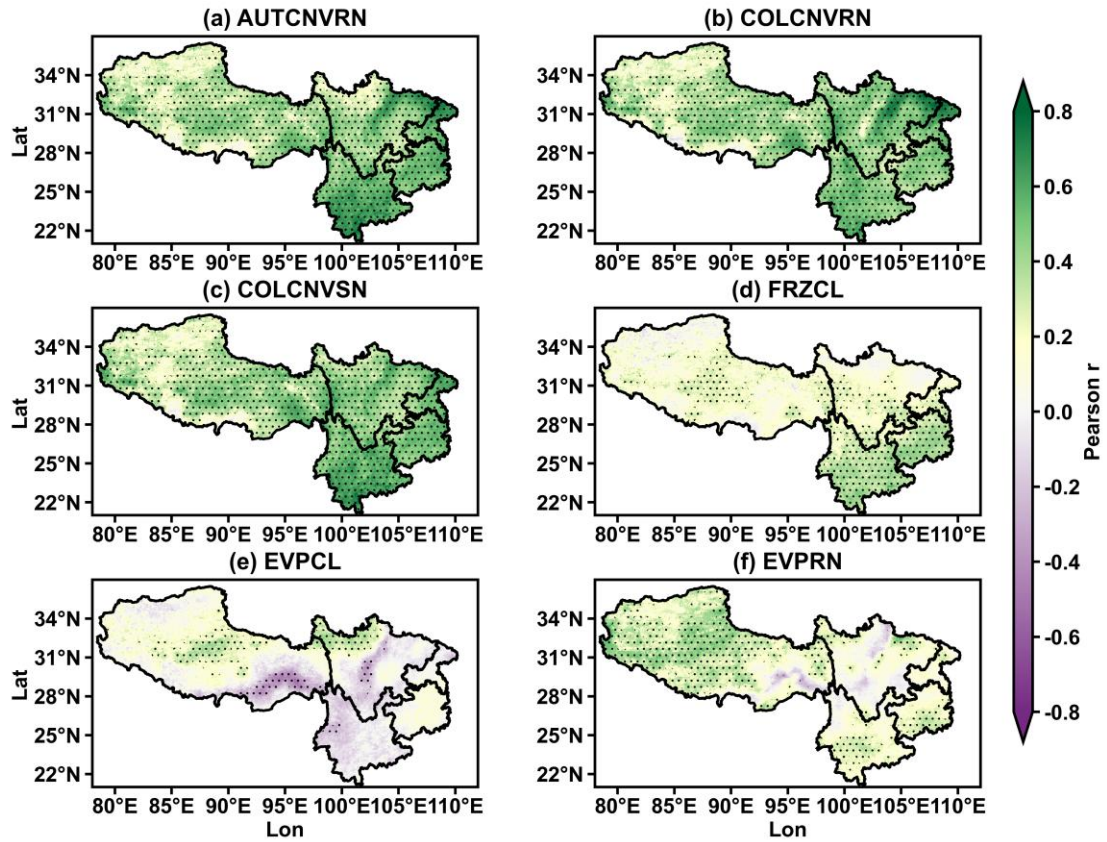


**Fig. 5** Spatial distributions of Pearson correlation coefficients between monthly anomalies in cloud microphysical process rates and precipitation over Southwest China during 2000-2023. Correlations were calculated from monthly anomaly series after removing the climatological annual cycle and linear trend: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. The dot in the grid indicates significance at the 99% confidence level

Fig. 5 shows the spatial distributions of Pearson correlation coefficients between monthly anomalies of cloud microphysical process rates and precipitation over Southwest China during 2000-2023. AUTCNVRN is positively correlated with precipitation anomalies over most of the study region (Fig. 5a). Regions with statistically significant correlations at the 99% confidence level are mainly located in the SCB, YKP, and along the southeastern margin of the TP, with the strongest correlations occurring along the southeastern margin. AUTCNVRN is a key process in the formation of initial raindrops within warm clouds. When liquid cloud water content is high and the cloud droplet size distribution extends toward larger sizes, cloud water autoconversion is enhanced, providing more initial raindrops for subsequent growth

(Stephens and Haynes 2007; Gettelman et al. 2013; Hazra et al. 2016). The SCB and YKP are characterized by relatively abundant liquid cloud water, while the southeastern margin of the TP is an important pathway for monsoonal moisture entering the Plateau. These conditions are favorable for cloud water autoconversion and correspond to its stronger positive correlation with precipitation in these regions. In contrast, limited moisture availability and low liquid cloud water content over the WTP constrain cloud water autoconversion, resulting in its relatively weak correlation with precipitation.

COLCNVRN is significantly positively correlated with precipitation anomalies over most of the study region, with the strongest correlations mainly occurring in the SCB and YKP (Fig. 5b). Accretion of cloud water by raindrops requires both liquid cloud water and pre-existing raindrops. The strong positive correlations in the SCB and YKP suggest that abundant liquid cloud water and raindrops provide favorable conditions for continued accretion growth, thereby promoting rainwater growth and precipitation formation. Numerical simulations of heavy rainfall over the SCB have also shown that accretion of cloud water by raindrops is an important process for rainwater growth in this region (Huang and Cui 2015; Huang et al. 2016). In contrast, the weaker correlation over the WTP is consistent with its lower cloud water content and limited availability of raindrops, which restrict sustained collision-coalescence growth.

Significant positive correlations between COLCNVSN and precipitation anomalies are mainly found over the ETP, SCB, and YKP (Fig. 5c). COLCNVSN is an important ice phase growth process for precipitation formation. Its significant positive correlation with precipitation indicates that ice particle growth is important not only over the plateau, but also for precipitation formation in the SCB and YKP. Numerical simulations over the TP and aircraft observations have found that snow, graupel, and supercooled cloud water can coexist, allowing riming to rapidly increase the mass of ice phase particles (Gao et al. 2018; Zhao et al. 2023). These snow and graupel particles can subsequently contribute to surface precipitation through melting. The significant positive correlations therefore indicate that abundant supercooled cloud water and well-

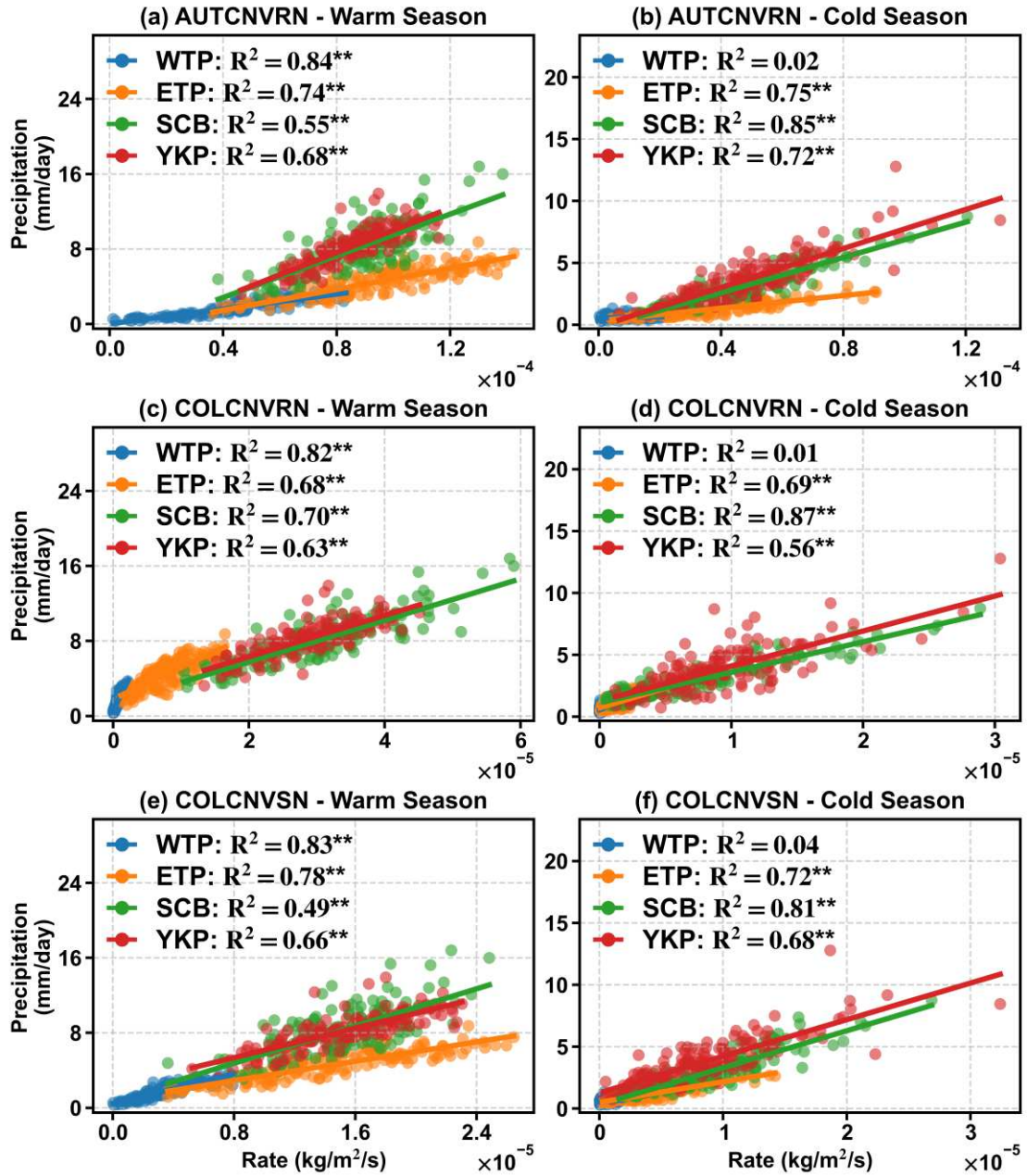
developed cloud systems in these regions support sustained snow particle growth, making ice phase processes an important pathway for precipitation formation.

FRZCL is generally weakly correlated with precipitation anomalies (Fig. 5d), with significant positive correlations mainly occurring over the YKP and along the southeastern margin of the TP. Ice particles produced by freezing must undergo subsequent growth through processes such as deposition, aggregation, and riming before developing into larger precipitating ice phase hydrometeors that may eventually melt into rainwater (Korolev et al. 2017; Gao et al. 2018). Therefore, FRZCL represents an initial stage of ice phase development, and its correlation with precipitation is generally weaker than that of subsequent ice phase growth processes, such as COLCNVSN.

The correlation between EVPCL and precipitation anomalies exhibits pronounced spatial variability (Fig. 5e). Negative correlations occur along the southeastern margin of the TP, west of the SCB, and in parts of the YKP. In these relatively dry or less saturated cloud environments, enhanced cloud water evaporation increases cloud water loss and may reduce the liquid water available for subsequent raindrop formation and growth. Under weak precipitation conditions, shallower clouds and drier environments can further enhance entrainment evaporation, leading to stronger cloud water depletion. In contrast, stronger precipitation systems are generally associated with moister and more saturated cloud environments, where evaporation is relatively limited. Positive correlations dominate in other regions, suggesting that cloud water evaporation and precipitation can increase simultaneously when abundant liquid cloud water and well-developed cloud systems are present. The spatial variability in the EVPCL-precipitation relationship therefore reflects the combined effects of cloud water availability and in-cloud humidity conditions (Baker et al. 1980; de Rooy et al. 2013; Hazra et al. 2016).

EVPRN is positively correlated with precipitation anomalies over most of the study area (Fig. 5f). Positive correlations dominate over the WTP, YKP, and parts of the SCB, whereas weak negative correlations are present over the ETP. Higher EVPRN values may occur in regions with abundant rainwater, where evaporation and surface

precipitation increase simultaneously, producing positive correlations between EVPRN and precipitation. The fraction of rainwater lost through evaporation is further controlled by subcloud relative humidity and raindrop size (Rosenfeld and Mintz 1988; Schlesinger et al. 1988). The weak negative correlation over the ETP suggests greater rainwater loss through evaporation under locally unsaturated subcloud conditions.



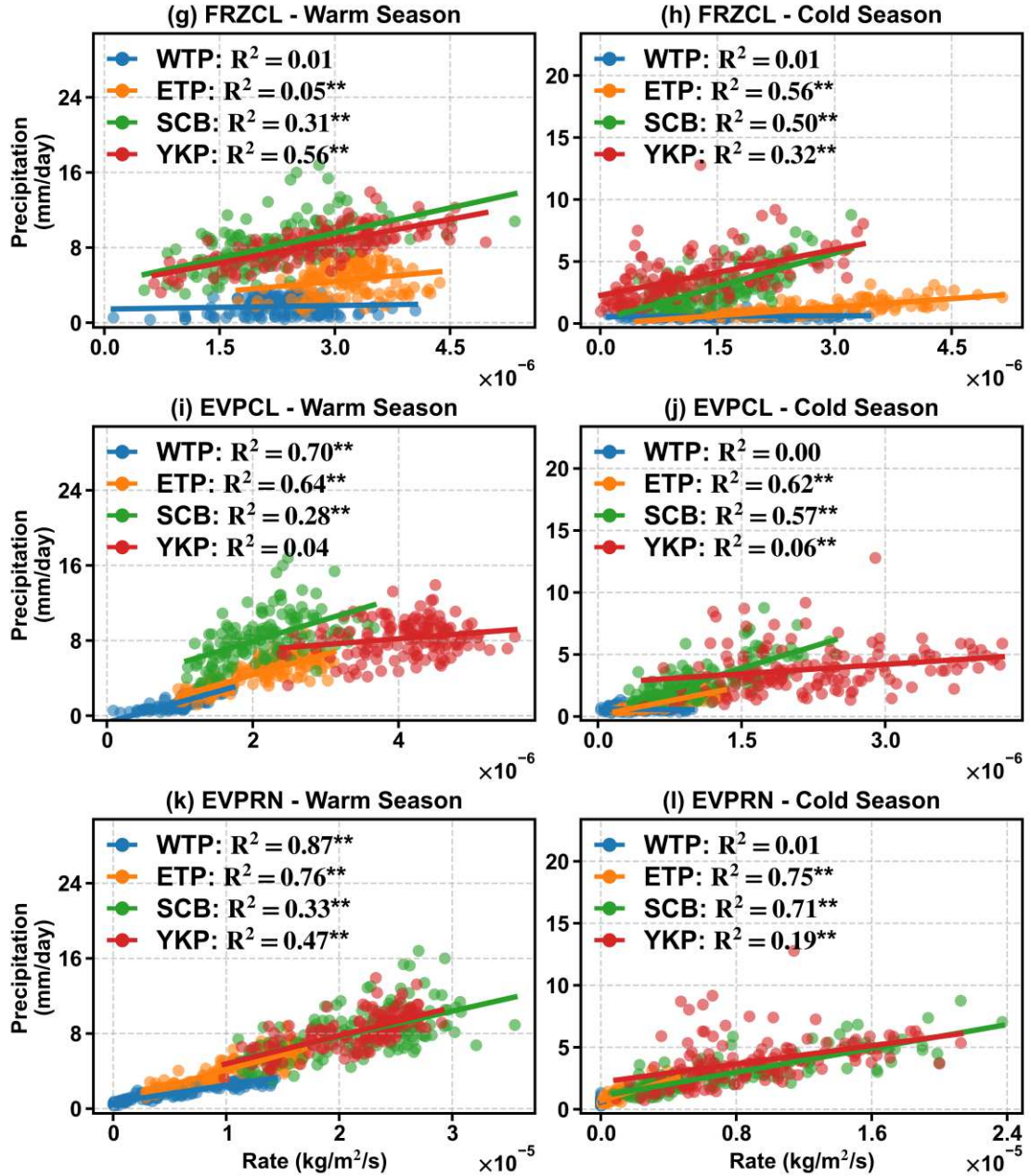


**Fig. 6** Scatter relationships and fitted curves between monthly mean precipitation rates and cloud microphysical process rates in the four regions of interest during the warm season (left column) and cold season (right column): (a, b) AUTCNVRN, (c, d) COLCNVRN, (e, f) COLCNVSN, (g, h) FRZCL, (i, j) EVPCL, and (k, l) EVPRN. Double asterisks indicate significance at the 99% confidence level

Fig. 6 compares the scatterplots and linear relationships between monthly mean precipitation and the six cloud microphysical process rates across the four regions during the warm and cold seasons. AUTCNVRN, COLCNVRN, and COLCNVSN are significantly positively correlated with precipitation in all four regions during the warm season. During the cold season, significant relationships persist over the ETP, SCB, and

YKP but generally weaken or disappear over the WTP (Fig. 6a–f). AUTCNVRN shows its strongest relationship during the warm season over the WTP ( $R^2=0.84$ ), although both variables remain within relatively low ranges. COLCNVRN is strongly related to precipitation over the SCB in both seasons, with  $R^2$  reaching 0.87 during the cold season. The abundant liquid cloud water in the lower and middle troposphere over the SCB provides favorable conditions for sustained raindrop growth through collision and coalescence. COLCNVSN also shows strong relationships during the warm season over the WTP and ETP ( $R^2=0.83$  and 0.78, respectively), indicating that ice phase particle growth is closely associated with precipitation over the Tibetan Plateau. The marked weakening of these relationships over the WTP during the cold season is consistent with its limited liquid cloud water and generally weak microphysical process rates.

FRZCL shows weaker and more spatially variable relationships with precipitation than the three principal growth processes (Fig. 6g, h). Significant positive correlations occur over the ETP, SCB, and YKP, with the strongest relationship during the warm season over the YKP ( $R^2=0.56$ ), whereas the WTP shows no significant correlation in either season. EVPCL and EVPRN also exhibit predominantly positive correlations with precipitation, although the relationships vary considerably among regions and seasons (Fig. 6i–l). EVPCL is significantly positively correlated with precipitation over the WTP, ETP, and SCB during the warm season, while positive relationships during the cold season are mainly found over the ETP and SCB. EVPRN is significantly positively correlated with precipitation in all four regions during the warm season, but the relationship weakens over the WTP and YKP during the cold season. These positive correlations likely reflect the common dependence of evaporation and precipitation on hydrometeor availability. Stronger precipitation systems generally contain more liquid hydrometeors and therefore provide more rainwater available for evaporation. Regional and seasonal variations in these relationships may be further influenced by environmental humidity and entrainment and mixing.

Overall, the WTP exhibits the strongest seasonal contrast, with the relationships between most microphysical processes and precipitation weakening markedly during

the cold season. Over the ETP, both liquid phase and ice phase processes remain significantly related to precipitation in both seasons. The SCB shows particularly strong relationships for AUTCNVRN and COLCNVRN, while COLCNVSN also remains significantly related to precipitation. The YKP exhibits significant relationships for both liquid phase and ice phase processes, indicating the involvement of multiple precipitation growth pathways. These regional contrasts are consistent with differences in liquid cloud water availability and the relative importance of liquid and ice phase processes across Southwest China (Wang et al. 2024).

### **3.3 Cloud Microphysical Processes under Different Precipitation Intensities**

To further reveal how cloud microphysical process rates evolve across precipitation events of different intensities, daily precipitation samples were divided into five classes: 0.1-1 mm/day, 1-10 mm/day, 10-25 mm/day, 25-50 mm/day, and >50 mm/day. The distributions of cloud microphysical process rates were then calculated separately for the four regions of interest.

## WTP

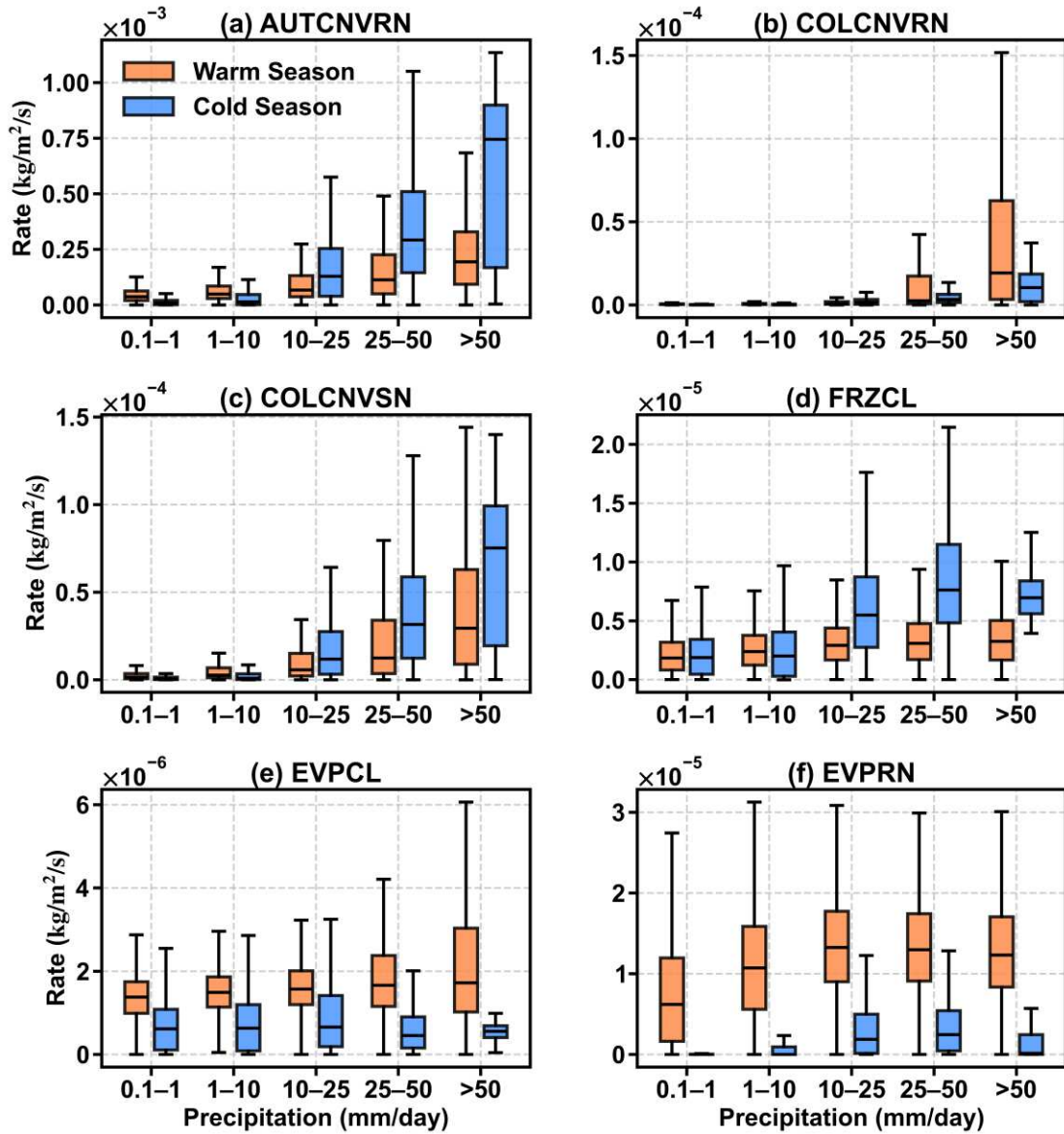


**Fig. 7** Boxplots of microphysical process rates in different precipitation intensity classes over the WTP: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; microphysical process rates, kg/m²/s

Fig. 7 shows the statistical distributions of the six cloud microphysical process rates across different precipitation classes over the WTP. AUTCNVRN occurs across all precipitation classes, with relatively high process rates concentrated mainly in cold season samples with daily precipitation exceeding 25 mm/day. This indicates that cloud water autoconversion plays a more prominent role in moderate and heavy precipitation during the cold season (Fig. 7a). In contrast, COLCNVRN is generally weak and becomes pronounced only in warm season samples above 25 mm/day and in the highest

precipitation class during the cold season (Fig. 7b). The WTP has the lowest liquid water path among the four regions and generally smaller effective cloud particle radii (Wang et al. 2024). Weak convective and stratiform precipitation over the Plateau is also dominated by small raindrops, whereas medium and large raindrops occur mainly during stronger precipitation events (Chen et al. 2017; Liu et al. 2024). Because collision-coalescence efficiency depends strongly on cloud droplet and raindrop sizes (Beard and Ochs 1984; Vohl et al. 2007), limited cloud water availability and relatively small particle sizes constrain COLCNVRN. Initial raindrop formation over the WTP therefore relies primarily on AUTCNVRN. During the warm season, increased liquid cloud water and a broader raindrop size distribution can enhance COLCNVRN, thereby favoring raindrop growth and the development of heavier precipitation. High COLCNVSN values are concentrated mainly in cold season samples with daily precipitation exceeding 25 mm/day, indicating that the accretion of supercooled cloud water by snow particles provides an efficient pathway for increasing the mass of ice phase hydrometeors and contributes to the development of stronger precipitation (Fig. 7c). FRZCL exhibits relatively high rates in cold season samples above 10 mm/day and is most pronounced in the 25-50 mm/day class. Together with the increase in COLCNVSN at higher precipitation intensities, this indicates stronger involvement of freezing and subsequent ice particle growth in moderate and heavy cold season precipitation over the WTP. In contrast, EVPCL and EVPRN are mainly higher in the warm season than in the cold season, with limited differences across precipitation classes (Fig. 7e, f). This indicates that evaporation processes mainly reflect the seasonal temperature and humidity environment and are not the primary factors that distinguish precipitation intensity over the WTP.

## ETP

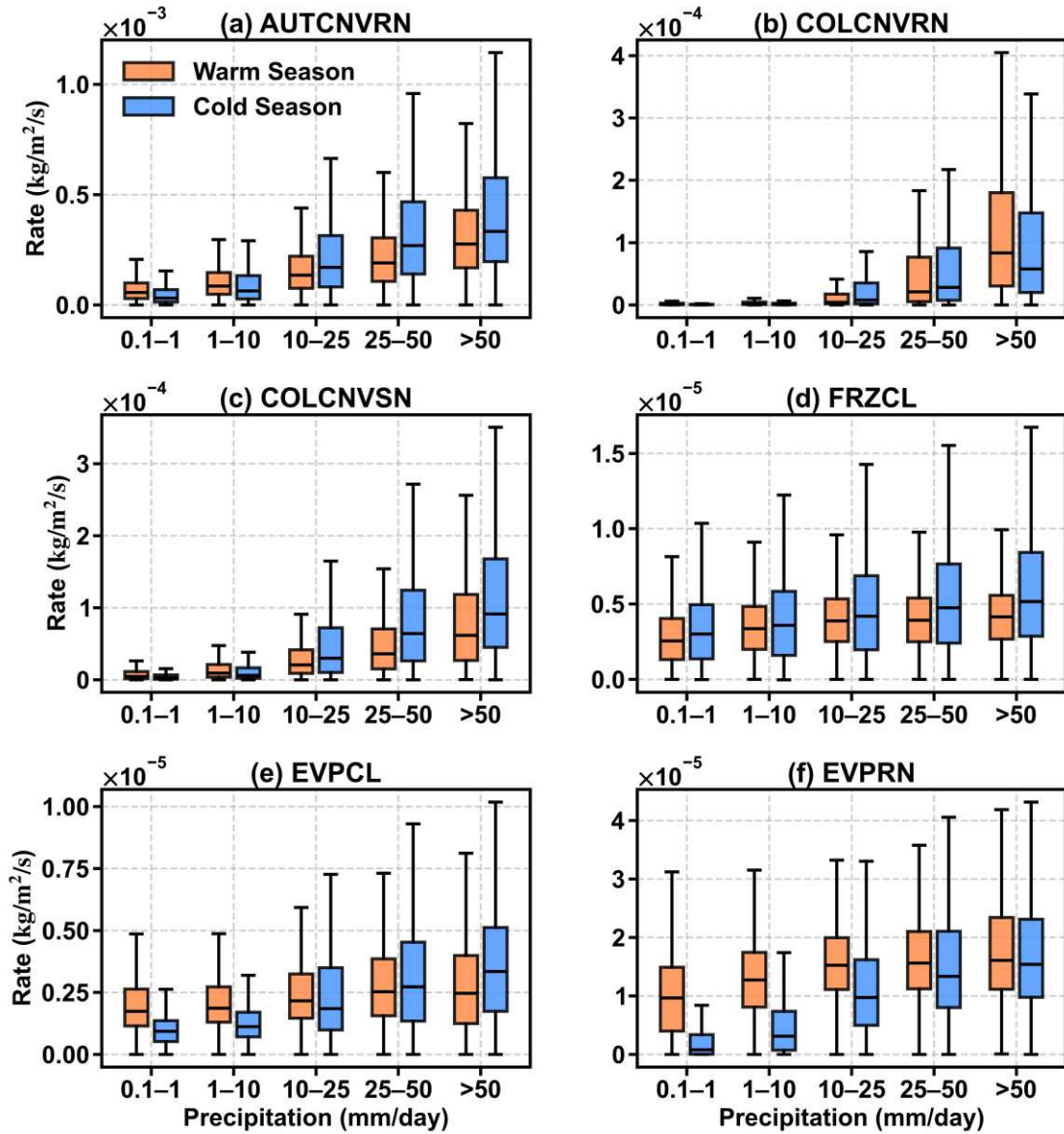


**Fig. 8** Boxplots of microphysical process rates in different precipitation intensity classes over the ETP: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; microphysical process rates, kg/m<sup>2</sup>/s

Fig. 8 shows the statistical distributions of the six cloud microphysical process rates across different precipitation classes over the ETP. Compared with the WTP, the ETP is characterized by greater liquid cloud water content and larger cloud droplet effective radii, allowing both initial raindrop formation and subsequent liquid phase growth to remain active. High AUTCNVRN values occur mainly in the moderate and heavy precipitation classes. Process rates in cold season samples with daily precipitation exceeding 10 mm/day are generally higher than those in the warm season,

indicating stronger cloud water autoconversion during stronger cold season precipitation (Fig. 8a). COLCNVRN becomes pronounced in samples above 10 mm/day and reaches its highest level in the warm season >50 mm/day class (Fig. 8b). The greater liquid water path and larger cloud droplet effective radius over the ETP (Wang et al. 2024) favor both initial raindrop formation and efficient collision-coalescence growth. AUTCNVRN and COLCNVRN therefore jointly contribute to the formation and subsequent growth of raindrops.

Heavy cold season precipitation over the ETP also involves enhanced ice phase processes. High COLCNVSN values are concentrated mainly in the moderate and heavy precipitation classes during the cold season, particularly in samples exceeding 50 mm/day, indicating that accretion of supercooled cloud water by snow particles can rapidly increase the mass of ice phase hydrometeors (Fig. 8c). Aircraft observations over the southern ETP have shown that snow, graupel, and supercooled cloud water can coexist within mixed phase clouds, where riming promotes rapid growth of ice phase hydrometeors (Zhao et al. 2023). This is consistent with the pronounced increase in COLCNVSN toward the higher precipitation classes shown in Fig. 8c. FRZCL is also relatively strong during the cold season, but its contrast across precipitation classes is weaker than that of COLCNVSN, indicating that precipitation intensity variations are more clearly associated with subsequent snow particle growth than with freezing. EVPCL and EVPRN also exhibit relatively high values in some heavy precipitation samples, but their variations among precipitation classes are less distinct than those of the major hydrometeor formation and growth processes (Fig. 8e, f).

## SCB

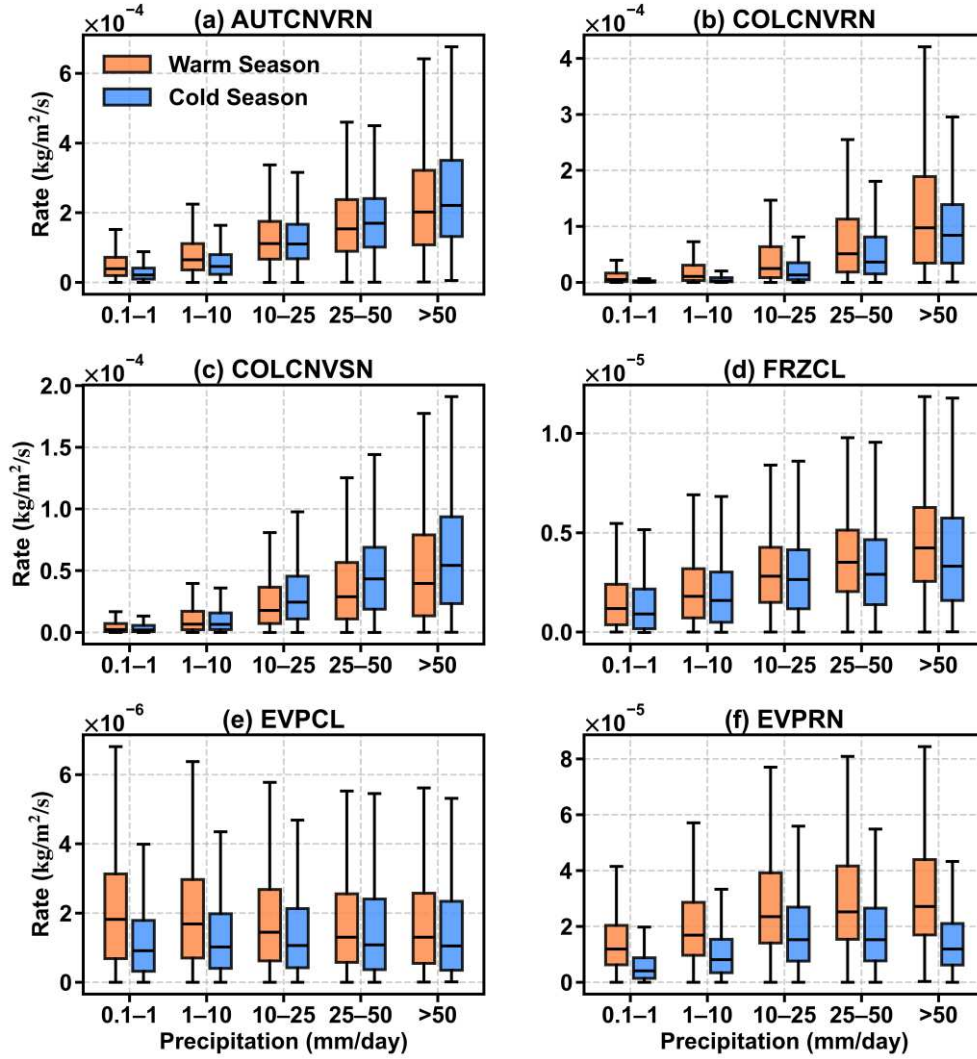


**Fig. 9** Boxplots of microphysical process rates in different precipitation intensity classes over the SCB: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; microphysical process rates, kg/m<sup>2</sup>/s

Fig. 9 shows the statistical distributions of the six cloud microphysical process rates across different precipitation classes over the SCB. In Fig. 9a, relatively high AUTCNVRN values occur mainly in the moderate and heavy precipitation classes, indicating that cloud water autoconversion not only provides initial raindrops for precipitation development over the SCB, but also intensifies during moderate and heavy precipitation.

Fig. 9b shows that high COLCNVRN values are concentrated mainly in warm season samples with daily precipitation exceeding 25 mm/day and reach their maximum

in the >50 mm/day class. This indicates that accretion of cloud water by raindrops is the most prominent liquid phase growth process associated with moderate and heavy warm season precipitation over the SCB. Compared with the Plateau regions, the SCB is characterized by a broader raindrop size distribution and a larger fraction of large raindrops, which favor higher collision-coalescence efficiencies (Liu et al. 2024). The combination of abundant low level liquid cloud water and a favorable raindrop size distribution supports efficient accretion growth, thereby contributing to the development of moderate and heavy warm season precipitation. COLCNVSN is relatively strong during the cold season, whereas FRZCL remains comparatively weak, indicating a more limited role of cloud water freezing in distinguishing precipitation intensity over the SCB.

EVPCCL does not increase toward the higher precipitation classes and even decreases slightly, suggesting that reduced cloud water evaporation helps retain more liquid cloud water for initial raindrop formation and subsequent growth (Fig. 9e). In contrast, the relatively high EVPRN values in the moderate and heavy precipitation classes during the warm season mainly reflect greater rainwater availability for evaporation (Fig. 9f).

# YKP

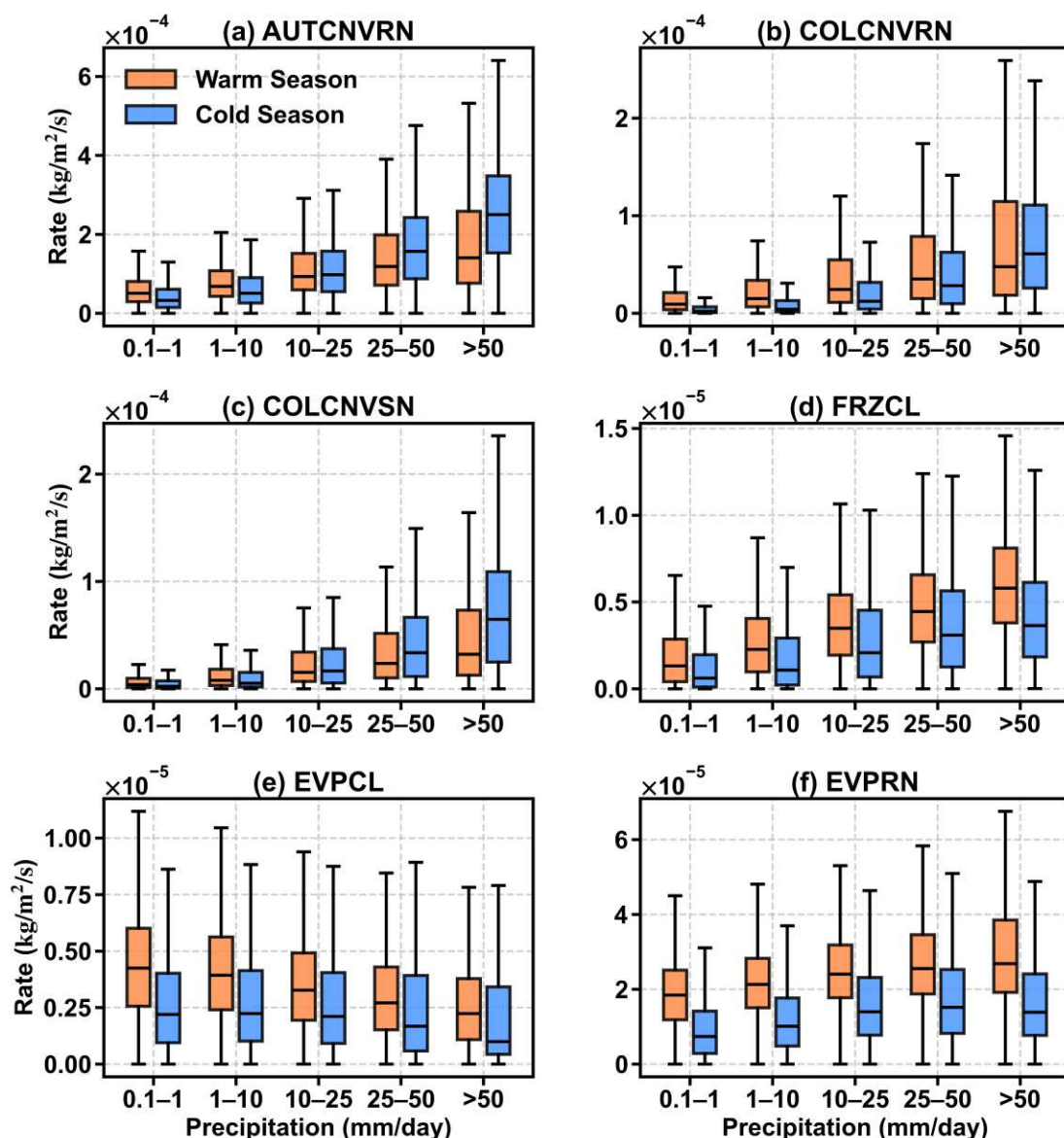


**Fig. 10** Boxplots of microphysical process rates in different precipitation intensity classes over the YKP: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; microphysical process rates, kg/m<sup>2</sup>/s

Fig. 10 shows the statistical distributions of the six cloud microphysical process rates across different precipitation classes over the YKP. Liquid phase processes over the YKP exhibit pronounced seasonal differences. High AUTCNVRN values occur mainly in the moderate and heavy precipitation classes. Process rates in cold season samples with daily precipitation exceeding 25 mm/day are generally higher than those in the warm season, indicating that cloud water autoconversion makes a greater contribution to initial raindrop formation during stronger cold season precipitation (Fig.

10a). COLCNVRN is already relatively strong in the low and moderate precipitation classes during the warm season, whereas high values during the cold season are mainly confined to the highest precipitation class (Fig. 10b). This suggests that abundant liquid cloud water in the middle and lower troposphere supports sustained accretion growth during the warm season, whereas efficient accretion growth during strong cold season precipitation requires a greater availability of both cloud water and pre-existing raindrops.

Ice phase processes become particularly important for strong cold season precipitation over the YKP. High COLCNVSN values occur mainly in samples with daily precipitation exceeding 25 mm/day and are most pronounced in the cold season >50 mm/day class, indicating that accretion of supercooled cloud water by snow particles constitutes an important ice phase growth pathway for strong cold season precipitation (Fig. 10c). FRZCL is generally stronger during the warm season and exhibits relatively high rates in the moderate and heavy precipitation classes, whereas COLCNVSN is most pronounced in strong cold season precipitation. This contrast indicates a clear seasonal difference between cloud water freezing and subsequent snow particle growth over the YKP.

Compared with the other regions, EVPCL exhibits the most distinct sensitivity to precipitation intensity over the YKP. High EVPCL values are concentrated mainly in the lower precipitation classes, whereas moderate and heavy precipitation are associated with weaker cloud water evaporation (Fig. 10e). Reduced cloud water evaporation is associated with greater liquid cloud water availability for subsequent raindrop formation and growth, consistent with stronger precipitation. This precipitation class dependence is also consistent with the negative correlations between EVPCL and precipitation anomalies found in parts of the YKP in Fig. 5e. EVPRN is relatively high in the moderate and heavy precipitation classes during the warm season (Fig. 10f), primarily reflecting the greater availability of rainwater for evaporation when rainwater content is high. Its direct microphysical effect, however, remains the loss of rainwater through evaporation.

Overall, Figs. 7-10 show that all four study regions can generate initial raindrops through AUTCNVRN, but the subsequent processes affecting heavy precipitation differ markedly. Because the WTP has low liquid cloud water content and small particle sizes, sustained liquid phase growth is weak, and is more closely associated with net cloud condensate freezing and the accretion of supercooled cloud water by snow particles. The ETP supports strong initial raindrop formation, liquid phase collection growth, and cold season ice phase growth. The SCB is characterized by sustained raindrop growth associated with COLCNVRN. The YKP shows a pronounced seasonal transition, with precipitation intensity closely related to cloud water evaporation.

### 3.4 Cloud Macrophysical Structure, Cloud Condensate Background, and Dynamical Factors

#### 3.4.1 Cloud Cover and Vertical Distribution of Hydrometeors

To further understand the hydrometeor and cloud conditions through which cloud microphysical processes influence precipitation formation, we analyzed the seasonal variations, spatial distributions, and vertical structures of high cloud cover (HCC), cloud liquid water mass mixing ratio (QL), and cloud ice mass mixing ratio (QI).

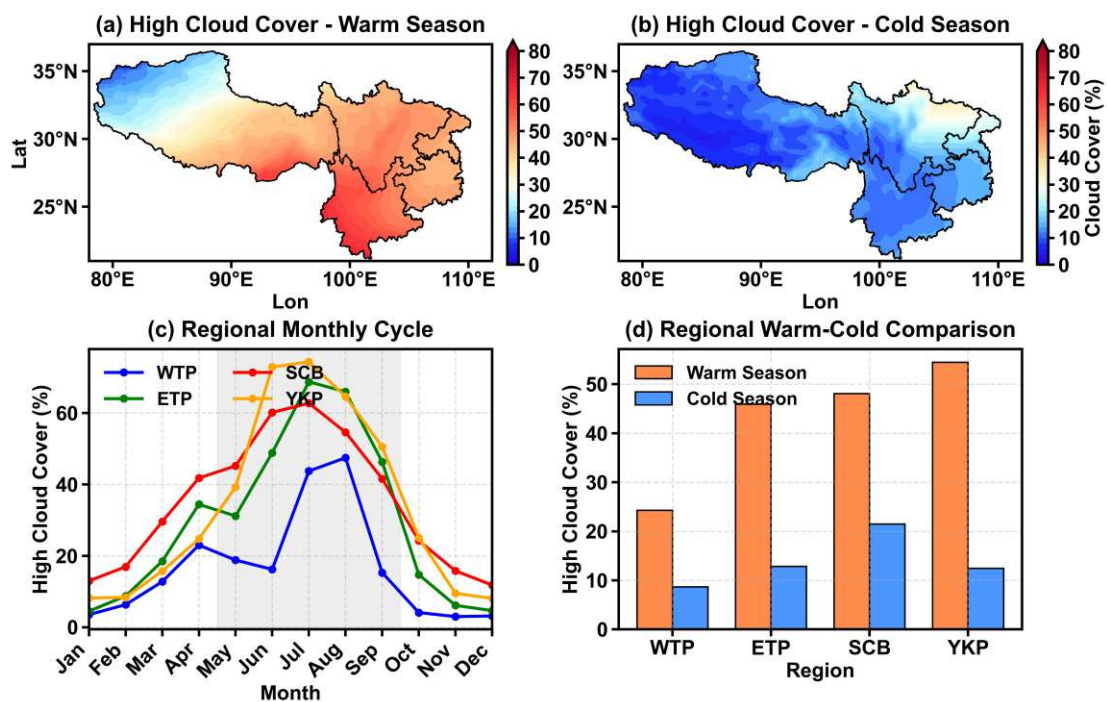


**Fig. 11** Seasonal distributions, regional monthly cycles, and warm versus cold season contrasts in high

cloud cover (HCC) over Southwest China: (a) warm season mean spatial distribution of HCC, (b) cold season mean spatial distribution of HCC, (c) regional monthly mean HCC in the four regions of interest, and (d) comparison of warm and cold season mean HCC in the four regions

Fig. 11 shows the warm and cold season spatial distributions of HCC over Southwest China, together with its monthly distribution and seasonal differences in the four study regions. During the warm season, HCC is generally higher in the southeast and lower in the northwest. High values occur mainly over the YKP, southeastern ETP, SCB, and western margin of the SCB, whereas the WTP has markedly lower values (Fig. 11a). The higher HCC over the YKP, ETP, and SCB indicates greater high cloud coverage during the warm season, consistent with their relatively abundant water vapor, orographic lifting, and convective cloud development. Previous studies have shown frequent warm season mesoscale convective systems over the TP and YKP, which can produce pronounced high level cloud structures (Kukulies et al. 2021; Guo et al. 2022). HCC in all four regions peaks during June-August (Fig. 11c), with the highest cloud cover over the YKP, followed by the ETP and SCB. The WTP shows a clear increase only in July-August. Although the WTP is characterized by high elevation and low temperature, its insufficient water vapor and low liquid cloud water content restrict the development of deep clouds and extensive anvil clouds. The relatively narrow and thin anvils of deep convective systems over the TP also reflect the constraint of environmental water vapor on cloud development (Zhao et al. 2024). During the cold season, HCC decreases markedly throughout the study region, although relatively high local values remain over the northern SCB and southeastern margin of the TP (Fig. 11b). This indicates that high level clouds remain relatively common over the SCB during the cold season.

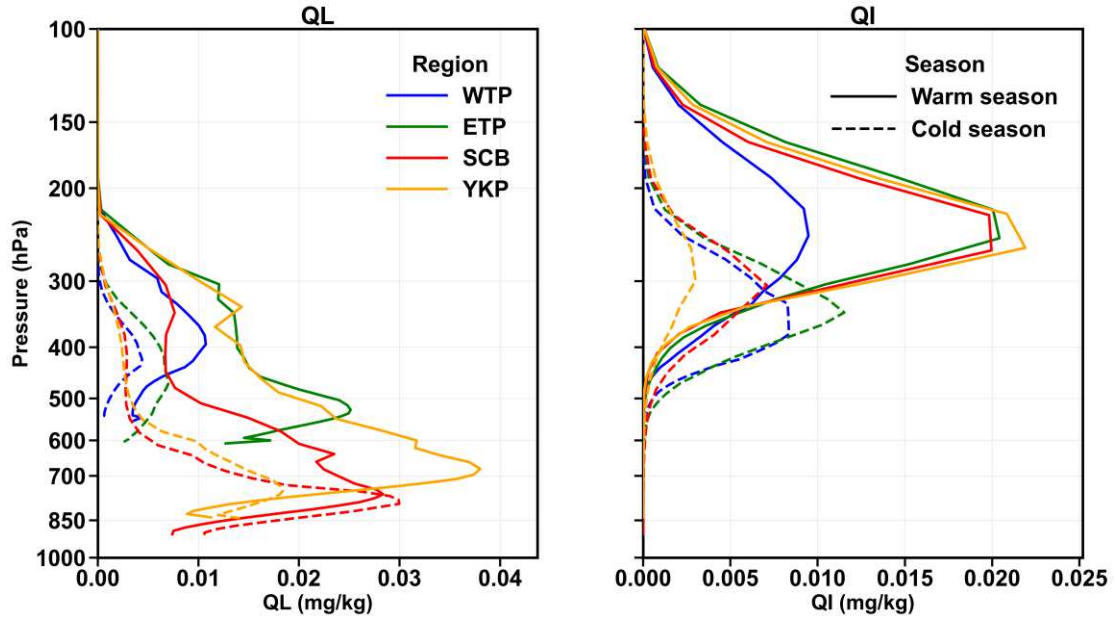


**Fig. 12** Mean vertical profiles of (a) cloud liquid water mass mixing ratio and (b) cloud ice mass mixing ratio (unit: mg/kg)

Fig. 12 shows the mean warm and cold season vertical profiles of cloud liquid water mass mixing ratio (QL) and cloud ice mass mixing ratio (QI) in the four study regions during 2000-2023. Overall, QL is mainly distributed in the lower and middle troposphere, whereas high QI values are mainly located in the middle and upper troposphere. The pressure levels of the peaks differ markedly among the study regions.

During the warm season, the YKP and SCB have the highest QL values, with high values concentrated at approximately 600-750 hPa and 700-850 hPa, respectively. This indicates abundant liquid cloud water in the lower and middle troposphere over both regions. Previous studies have shown that liquid cloud water content and liquid cloud thickness over the SCB are generally greater than those over the TP, and that liquid cloud water plays an important role in cloud and precipitation processes over the basin (Cao et al. 2022). QL over the ETP is mainly distributed at approximately 450-550 hPa, with a peak markedly higher than those over the SCB and YKP. The WTP has the lowest QL values, with a peak near 400 hPa. This is consistent with the generally low AUTCNVRN and COLCNVRN values and low precipitation over the WTP described above. CloudSat and CALIPSO observations have also shown clear differences in cloud vertical structure between the TP and surrounding low-elevation regions, strongly

modulated by terrain and water vapor conditions (Yan et al. 2016; Yan and Liu 2019). During the cold season, QL generally decreases in all regions. However, the SCB retains high QL at approximately 750-900 hPa, and some low level values even exceed those in the warm season, indicating abundant low level liquid cloud water during the cold season. In contrast, QL decreases further over the plateau regions, and liquid cloud water is confined to a narrower vertical range.

The vertical distribution of QI is shown in Fig. 12b. During the warm season, QI over the ETP, SCB, and YKP exhibits pronounced maxima at approximately 200-300 hPa. The ETP is characterized by relatively high QL at middle levels, whereas the SCB and YKP exhibit higher QL at lower and middle levels, together with pronounced QI at upper levels. These distributions indicate abundant liquid cloud water and cloud ice in these regions during the warm season. The frequency of mixed phase clouds over the TP is also highest in summer, indicating that the warm season favors the coexistence of liquid and ice phase hydrometeors (Yan et al. 2020). This vertical configuration provides favorable hydrometeor conditions for the enhanced COLCNVSN and FRZCL over the ETP and YKP described above. Warm season QI is markedly lower over the WTP, consistent with its generally low hydrometeor content. During the cold season, QI generally decreases in all regions, and the high value layer descends from approximately 200-300 hPa in the warm season to approximately 300-400 hPa. Some cloud ice remains in the middle and upper troposphere over the ETP and WTP, whereas QI decreases markedly over the YKP. This indicates reduced upper level cloud ice and cloud development over the YKP during the cold season.

Overall, both QL and QI are low over the WTP, where microphysical processes are limited by water vapor and hydrometeor conditions. The ETP is characterized by pronounced QL at middle levels and QI at upper levels. The SCB exhibits high QL at lower levels, whereas the YKP combines abundant QL at lower and middle levels with QI at upper levels during the warm season. These spatial differences provide the vertical hydrometeor background for the distinct liquid and ice phase processes in the four study regions.

### 3.4.2 Joint effects of Dynamical Factors and Cloud Microphysical Processes on Precipitation Formation

Based on the vertical structures of QL and QI, representative ascent levels were selected for the warm and cold seasons in the four study regions. The joint variations in vertical velocity, the six process rates, and precipitation were compared to further explain spatial differences in the relationships between cloud microphysical processes and precipitation (Figs. 13–16; cold season results are shown in Figs. S2–S5). The representative ascent levels are located in the middle troposphere over the WTP and ETP and in the lower troposphere over the SCB and lower to middle troposphere over the YKP. They are generally near or below the QL maxima.

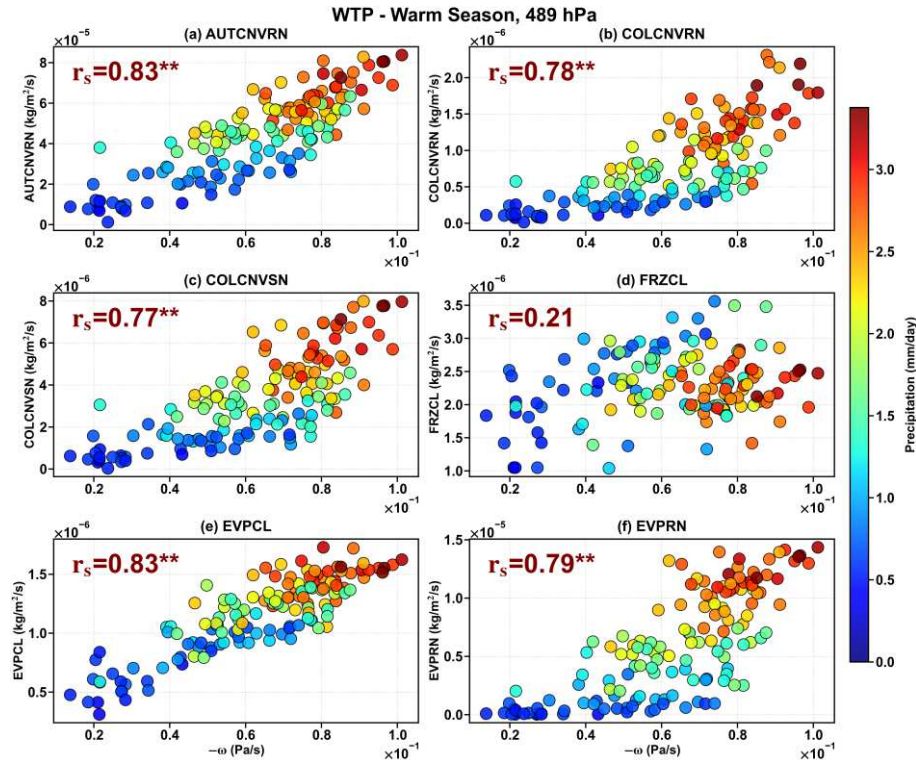


**Fig. 13** Three dimensional scatterplots of vertical velocity, microphysical process rates, and precipitation over the WTP during the warm season: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; vertical velocity, Pa/s; microphysical process rates,  $\text{kg/m}^2/\text{s}$ . Double asterisks indicate significance at the 99% confidence level

Fig. 13 shows the relationships between representative layer upward motion intensity and the six cloud microphysical process rates over the WTP. During the warm

season, AUTCNVRN, COLCNVRN, and COLCNVSN are all significantly positively correlated with midlevel ascent, with  $r_s$  values of 0.83, 0.78, and 0.77, respectively. These results indicate that initial raindrop formation and subsequent rain and snow particle growth are strongly associated with variations in midlevel dynamical lifting over the WTP. Limited moisture availability and low liquid cloud water constrain sustained cloud development over the WTP. Under these conditions, the strong correlations found here between upward motion and the major microphysical process rates suggest a pronounced dynamical dependence of cloud microphysical activity (Wang et al. 2024). The strong positive correlations of AUTCNVRN and COLCNVRN with upward motion are consistent with enhanced lifting favoring adiabatic cooling and condensation, thereby increasing the liquid cloud water supply for initial raindrop formation and subsequent accretion growth. COLCNVSN also increases with strengthening upward motion, suggesting that stronger midlevel lifting favors cloud development and the maintenance of supercooled cloud water, thereby providing favorable conditions for snow particles to grow through the accretion of cloud water.

FRZCL shows no significant correlation with upward motion ( $r_s=0.21$ ), indicating a weak association with representative layer ascent. Temperature, supercooled cloud water availability, and ice nucleation conditions may further modulate its variability. EVPCL and EVPRN are also significantly positively correlated with upward motion, with  $r_s$  values of 0.83 and 0.79, respectively. Well-developed cloud systems generally contain more cloud water and rainwater available for evaporation, corresponding to higher EVPCL and EVPRN. The precipitation gradient in Fig. 13 further shows that samples with stronger upward motion and higher AUTCNVRN, COLCNVRN, and COLCNVSN generally correspond to larger precipitation, whereas no similarly clear gradient is evident for FRZCL. This suggests that midlevel dynamical lifting over the WTP is more closely associated with the generation and growth of precipitating hydrometeors than with cloud water freezing.

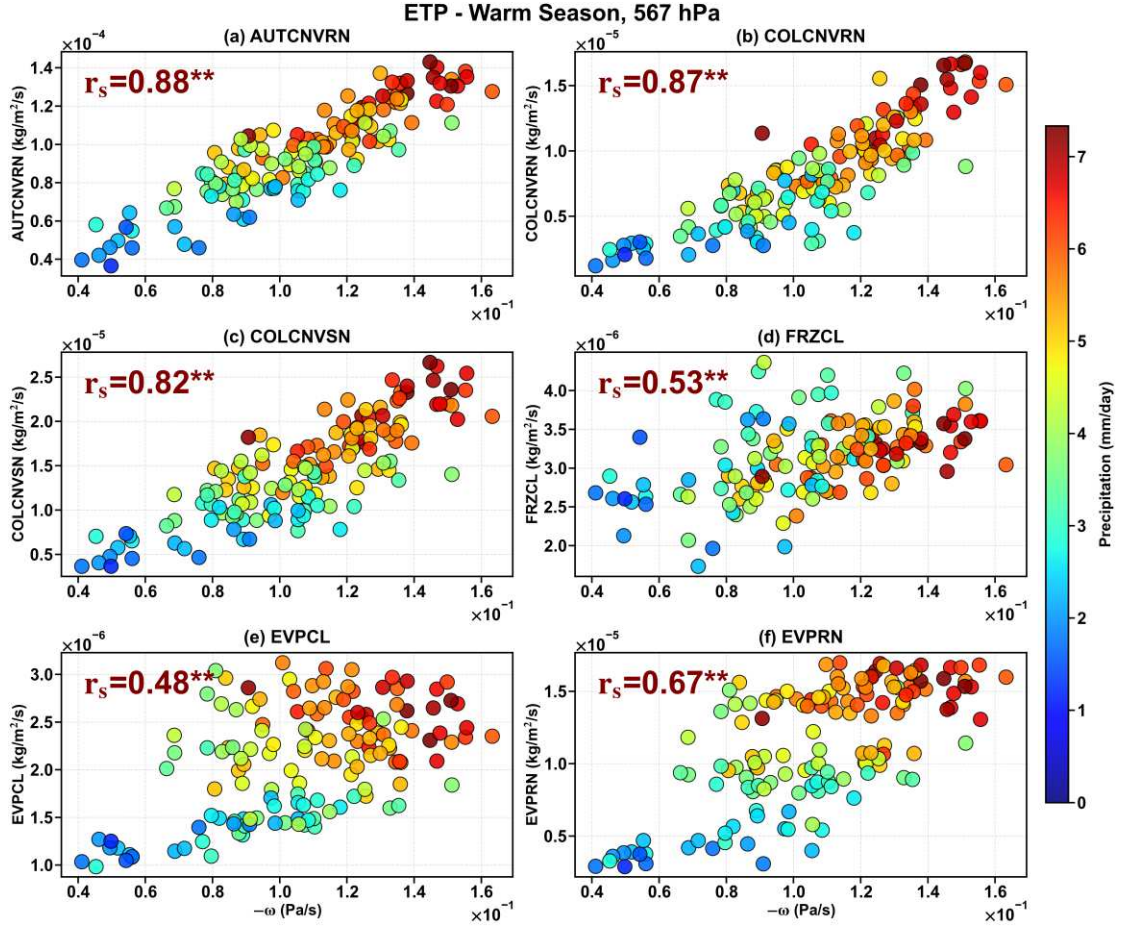


**Fig. 14** Three dimensional scatterplots of vertical velocity, microphysical process rates, and precipitation over the ETP during the warm season: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; vertical velocity, Pa/s; microphysical process rates, kg/m<sup>2</sup>/s. Double asterisks indicate significance at the 99% confidence level

Fig. 14 shows the relationships between upward-motion intensity and the six cloud microphysical process rates over the ETP. During the warm season, all six microphysical processes are significantly positively correlated with upward motion near the representative level of 567 hPa (Fig. 14). AUTCNVRN increases markedly with strengthening upward motion, and high precipitation values occur primarily under conditions of strong ascent and high autoconversion rates. Compared with the WTP, the ETP has greater monsoonal moisture availability, while the topography of the eastern and southern ETP favors moisture uplift. Midlevel ascent therefore promotes adiabatic cooling and water vapor condensation under relatively moisture rich conditions (Wang et al. 2024). Consequently, cloud water autoconversion over the ETP is not only

sensitive to variations in dynamical lifting but also sustained by abundant liquid cloud water. COLCNVRN is also strongly positively correlated with upward motion, indicating that under conditions of abundant cloud water and raindrops, enhanced midlevel ascent provides favorable conditions for the accretion of cloud water by raindrops. COLCNVSN likewise increases markedly with strengthening upward motion. The ETP has favorable midlevel conditions for the coexistence of snow particles and supercooled cloud water, allowing stronger ascent to support enhanced ice particle growth through the accretion of supercooled cloud water by snow. The preceding analyses showed that both liquid and ice phase processes over the ETP are positively related to precipitation. The results in Fig. 14 further demonstrate that both pathways are closely linked to midlevel dynamical lifting. FRZCL is also significantly positively correlated with upward motion, although more weakly than AUTCNVRN, COLCNVRN, and COLCNVSN, indicating that cloud water freezing varies with midlevel ascent but is less strongly coupled to it than the major formation and growth processes. EVPCL and EVPRN are likewise positively correlated with upward motion, suggesting that enhanced hydrometeor growth and evaporation may occur concurrently in well-developed precipitation systems.

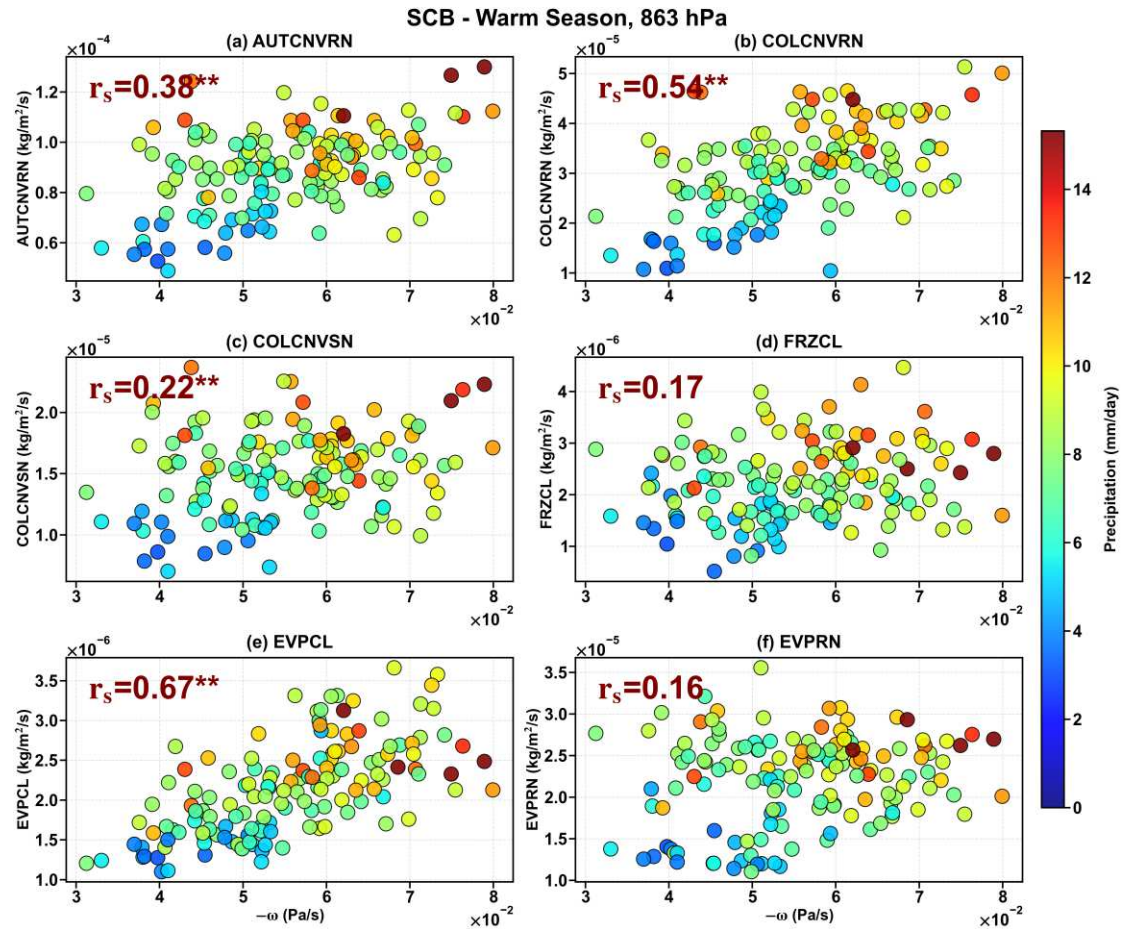


**Fig. 15** Three dimensional scatterplots of vertical velocity, microphysical process rates, and precipitation over the SCB during the warm season: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; vertical velocity, Pa/s; microphysical process rates,  $\text{kg/m}^2/\text{s}$ . Double asterisks indicate significance at the 99% confidence level

Fig. 15 shows the relationships between representative layer upward-motion intensity and the six cloud microphysical process rates over the SCB. During the warm season, the representative ascent layer over the SCB is centered near 863 hPa, substantially lower than those over the WTP and ETP. All six processes are generally positively related to upward motion at this level, although the strength and statistical significance of these relationships vary considerably. Overall, the relationships are weaker than those over the Plateau regions, suggesting that cloud microphysical processes over the SCB are less closely linked to a single low level upward-motion index. Among the six processes, EVPCL shows the strongest relationship with upward motion ( $r_s=0.67$ ), followed by COLCNVRN. AUTCNVRN exhibits a moderate

relationship, whereas COLCNVSN, FRZCL, and EVPRN are only weakly related to low level ascent.

Both AUTCNVRN and COLCNVRN are significantly positively correlated with low level upward motion, with COLCNVRN showing a markedly stronger correlation than AUTCNVRN. The SCB is characterized by relatively high liquid cloud water content in the lower and middle troposphere. Enhanced low level ascent promotes adiabatic cooling and water vapor condensation, increasing the availability of liquid cloud water and thereby providing favorable conditions for the accretion of cloud water by raindrops. Fig. 9 further showed that COLCNVRN is markedly enhanced in the moderate and heavy precipitation classes during the warm season. These results suggest that stronger low level ascent is generally associated with greater liquid cloud water availability, thereby enhancing liquid phase growth and its contribution to precipitation formation.

In contrast, COLCNVSN is only weakly positively correlated with low level upward motion, while FRZCL does not reach statistical significance. Accretion of cloud water by snow and cloud water freezing primarily occur in subfreezing or mixed phase cloud layers, whereas upward motion near 863 hPa mainly characterizes lower tropospheric dynamical conditions over the basin. Consequently, this low level ascent index cannot fully characterize mid and upper level cloud development, the transport and maintenance of supercooled cloud water, or the growth of ice phase hydrometeors. Previous observations have shown pronounced vertical variations in precipitation structure over the SCB and its surrounding terrain, reflecting the influence of orographic lifting and multilevel dynamical structure (Shen et al. 2022). The weaker relationships of the ice phase processes with low level upward motion may therefore reflect their occurrence at higher levels, where the dynamical structure differs from that represented by the 863 hPa ascent.

EVPCl is significantly positively correlated with low level upward motion, indicating that enhanced ascent favors greater liquid cloud water availability and consequently increases the amount of cloud water available for evaporation. EVPRN,

in contrast, is only weakly related to upward motion, suggesting that rainwater evaporation is controlled primarily by rainwater availability and subcloud environmental conditions and is therefore less directly linked to low level ascent.

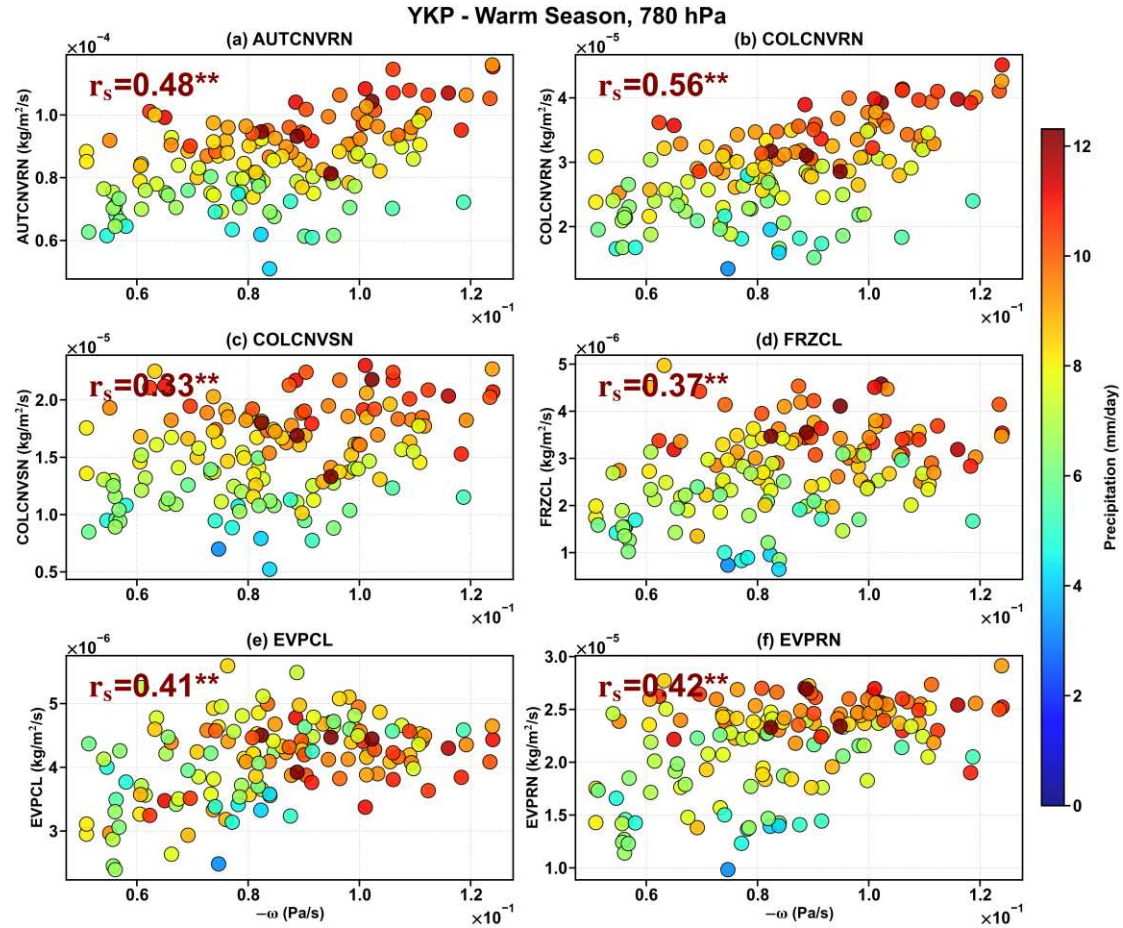


**Fig. 16** Three dimensional scatterplots of vertical velocity, microphysical process rates, and precipitation over the YKP during the warm season: (a) AUTCNVRN, (b) COLCNVRN, (c) COLCNVSN, (d) FRZCL, (e) EVPCL, and (f) EVPRN. Units: precipitation, mm/day; vertical velocity, Pa/s; microphysical process rates, kg/m<sup>2</sup>/s. Double asterisks indicate significance at the 99% confidence level

Fig. 16 shows the relationships between representative layer upward-motion intensity and the six cloud microphysical process rates over the YKP. During the warm season, the representative ascent layer over the YKP is centered near 780 hPa, and all six processes are positively related to upward motion at this level. Among them, COLCNVRN shows the strongest relationship with upward motion, followed by AUTCNVRN.

Both AUTCNVRN and COLCNVRN increase with strengthening upward motion,

with COLCNVRN showing the stronger relationship. The YKP is located southeast of the TP and is strongly influenced by monsoonal circulation. Its complex terrain modifies regional moisture transport and dynamical lifting, resulting in pronounced spatial and temporal variations in moisture availability and vertical motion (Shi et al. 2017). Under relatively favorable moisture conditions, lower to midlevel ascent promotes adiabatic cooling and water vapor condensation, thereby increasing the availability of liquid cloud water for cloud water autoconversion and the accretion of cloud water by raindrops. Combined with the significant positive relationship between COLCNVRN and precipitation described above, these results indicate that accretion of cloud water by raindrops is an important liquid phase pathway through which lower to midlevel dynamics influence precipitation formation over the YKP.

COLCNVSN and FRZCL are also positively related to upward motion, although their relationships are weaker than those of AUTCNVRN and COLCNVRN. Upward motion near 780 hPa reflects the dynamical background of lower to midlevel cloud development over the YKP. However, accretion of supercooled cloud water by snow and cloud water freezing are additionally influenced by temperature in the middle and upper troposphere, the vertical distribution of supercooled cloud water, and the vertical development of cloud systems. Consequently, these two ice phase processes show weaker relationships with upward motion at the representative layer. Compared with the SCB, the representative ascent layer over the YKP is located at a higher altitude and can therefore capture, to some extent, the dynamical conditions associated with cloud development into the middle troposphere. This may explain why the ice phase processes still exhibit positive relationships with upward motion. EVPCL and EVPRN show weak to moderate positive correlations with upward motion, suggesting that, in addition to hydrometeor availability, evaporation processes are also associated with variations in local humidity conditions and the surrounding cloud environment under complex terrain.

The relationships among representative layer upward motion, cloud microphysical process rates, and precipitation during the cold season are shown in Figs. S2-S5. The

warm and cold season results reveal pronounced spatial and seasonal differences in the relationships between dynamical lifting and cloud microphysical processes across the four study regions. Over the WTP, AUTCNVRN, COLCNVRN, and COLCNVSN are strongly related to midlevel upward motion during the warm season, whereas these relationships weaken during the cold season and FRZCL and EVPCL become relatively more prominent. This seasonal transition suggests that reduced liquid water availability during the cold season weakens the dynamical control on initial raindrop formation and subsequent liquid phase growth, while freezing and cloud water evaporation become relatively more sensitive to variations in the cloud environment. Over the ETP, all six processes are significantly positively correlated with midlevel upward motion in both seasons, with particularly strong relationships for liquid phase processes and ice phase growth. Over the SCB, except for EVPCL, most processes are only weakly to moderately related to low level upward motion near 863 hPa, indicating that a single low level dynamical index cannot fully represent the multilayer cloud development over the basin. The YKP exhibits the strongest seasonal contrast: AUTCNVRN and COLCNVRN are more strongly related to upward motion during the warm season, whereas FRZCL, EVPCL, and EVPRN show stronger relationships during the cold season.

#### **4 Conclusions and Discussion**

This study systematically investigated the spatial and seasonal relationships between six cloud microphysical process rates and precipitation across four representative topographic regions of Southwest China, including the WTP, ETP, SCB, and YKP. Based on long-term GPM IMERG, MERRA-2, and ERA5 datasets spanning 2000-2023, this study examined the regional characteristics of major precipitation related microphysical pathways and their relationships with environmental and atmospheric dynamical conditions.

The results reveal that precipitation formation over the complex terrain of Southwest China is associated with spatially distinct microphysical pathways rather

than a single uniform dominant mechanism. Among the six analyzed microphysical processes, cloud water autoconversion, accretion of cloud water by raindrops, and accretion of cloud water by snow particles exhibit the most consistent positive correlations with precipitation, representing the principal pathways associated with the formation and growth of precipitating hydrometeors. In contrast, cloud water freezing, cloud water evaporation, and rainwater evaporation show more spatially and seasonally variable relationships with precipitation and are more strongly influenced by regional hydrometeor availability and environmental conditions.

Pronounced regional and seasonal differences are evident among the four study regions. The WTP is characterized by limited moisture supply and restricted liquid phase growth, while ice phase processes become relatively more important, particularly during the cold season. The ETP is characterized by greater moisture availability and midlevel ascent, which support the concurrent development of liquid and ice phase pathways, with ice phase processes becoming more prominent during the cold season. In the SCB, abundant low level liquid cloud water and low level ascent favor efficient warm cloud growth, with COLCNVRN showing the strongest relationship with precipitation among the four regions, especially during stronger warm season precipitation. The YKP exhibits both liquid and ice phase growth, with their relative prominence varying seasonally, while cloud water evaporation tends to weaken at higher precipitation intensities, indicating reduced cloud water loss during stronger precipitation. Across the four regions, warm season conditions generally favor stronger microphysical activity under greater moisture availability and cloud development, whereas reduced liquid cloud water during the cold season increases the relative importance of ice phase processes in some regions. Overall, regional differences in moisture availability, cloud hydrometeor vertical structure, topography, and atmospheric dynamics jointly shape the spatially distinct microphysical pathways associated with precipitation over Southwest China.

The consistent positive relationships of AUTCNVRN, COLCNVRN, and COLCNVSN with precipitation reflect their roles in the formation and subsequent

growth of precipitating hydrometeors. Cloud water autoconversion provides initial raindrops, whereas accretion by raindrops and snow particles supports further liquid and ice phase growth. Similar pathways have been identified in previous modeling and observational studies (Cheng et al. 2007; Tao et al. 2012; Hazra et al. 2016; Huang and Cui 2015; Huang et al. 2016). These correlations characterize the statistical relationships between individual microphysical processes and precipitation under varying environmental conditions, with their magnitude jointly influenced by moisture supply, cloud depth, hydrometeor availability, and vertical motion.

The contrast between the WTP and ETP emphasizes the role of moisture availability in regulating Plateau microphysics. Over the WTP, limited moisture and low liquid cloud water restrict sustained collision-coalescence growth, whereas ice phase processes become relatively more prominent under colder conditions. Observations and simulations over the Tibetan Plateau have documented the coexistence of liquid and ice hydrometeors and active mixed phase development (Gao et al. 2018; Chang et al. 2019; Qiu et al. 2019; Xu et al. 2020). In contrast, greater moisture availability and midlevel ascent over the ETP favor the concurrent development of liquid and ice phase processes. The stronger ice phase relationships there may therefore reflect both ice particle growth and the common response of precipitation and ice phase processes to deeper clouds and stronger dynamical forcing.

The SCB and YKP show different responses under relatively moisture rich conditions. In the SCB, abundant low level liquid cloud water favors efficient collision-coalescence, consistent with simulations showing an important role of cloud water accretion in Sichuan heavy rainfall (Huang and Cui 2015; Huang et al. 2016). Ice phase processes become more evident during stronger precipitation in our analysis, indicating that intense SCB precipitation can involve both liquid and ice phase growth. This is consistent with TRMM observations of two Southwest China Vortex events over the eastern SCB, in which both warm rain and ice particle contributions were identified (Xiang et al. 2021). Over the YKP, the weakening of cloud water evaporation at higher precipitation intensities suggests reduced cloud water loss during stronger precipitation,

while regional moisture and circulation variability provide an important environmental background (Li and Yu 2014; Cai et al. 2022; Yu et al. 2023; Wang et al. 2024).

Several uncertainties should be considered when interpreting these results. MERRA-2 microphysical process rates are model-diagnosed quantities rather than direct observations, and their magnitudes depend on parameterizations of autoconversion, accretion, freezing, and ice growth (Gelaro et al. 2017; Khain et al. 2015; Morrison et al. 2020). In addition, the selected variables do not represent a complete microphysical budget, particularly for the ice phase pathway, which also includes deposition, aggregation, graupel formation, sedimentation, and melting. The present analysis therefore identifies the relative prominence and environmental dependence of selected microphysical pathways rather than their exact quantitative contributions to surface precipitation. Nevertheless, the consistency of the relationships across spatial, seasonal, precipitation intensity, and dynamical analyses provides a coherent framework for understanding regional differences in cloud-precipitation processes over the complex terrain of Southwest China.

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## Statements and Declarations

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**Conflict of interest** The authors declare no conflict of interest.

**Author contributions** All authors contributed to the conception and design of the study. Heng Shen and Pengguo Zhao analyzed the data, visualized the results, and drafted the first version of the manuscript. All authors discussed the analysis method, improved the original manuscript, and approved the final manuscript.

**Data availability** GPM IMERG Final Run Version 07 precipitation data are available from the NASA Goddard Earth Sciences Data and Information Services Center (GES DISC) at [https://disc.gsfc.nasa.gov/datasets/GPM\\_3IMERGDF\\_07/summary](https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGDF_07/summary). MERRA-2 reanalysis fields are available from NASA GES DISC at <https://disc.gsfc.nasa.gov/datasets?keywords=MERRA-2>. ERA5 high cloud cover data are available from the Copernicus Climate Data Store (CDS) at <https://cds.climate.copernicus.eu/>.

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