

Differential Analysis of Atmospheric Cloud Water Resources between the Southern and Northern Slopes of the Qilian Mountains in Summer: Postprint

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Abstract

Using high spatiotemporal resolution ERA5 reanalysis data provided by the European Centre for Medium-Range Weather Forecasts (ECMWF), this study investigates the spatiotemporal distribution of atmospheric cloud water resources and the differential characteristics between the northern and southern slopes in the Qilian Mountains region during summer, and estimates water vapor condensation efficiency and hydrometeor precipitation efficiency. The results indicate that atmospheric circulation and low-level water vapor field convergence and upward airflow induced by topography play a key role in the distribution of atmospheric cloud water resources in the Qilian Mountains region. (1) Under mean conditions, summer water vapor content on the southern slope is slightly lower than that on the northern slope, while cloud water path is greater on the southern slope than on the northern slope, and the area below 500 hPa on the southern slope is a region enriched with cloud liquid water content. In recent years, water vapor content and cloud liquid water content have shown an increasing trend, with a greater increase rate on the southern slope than on the northern slope; cloud ice water content has shown a decreasing trend, with a faster decrease rate on the northern slope than on the southern slope. (2) During summer daytime, there exists a stationary upward airflow on the northern slope, which can persist into the mid-troposphere, while the low-level of the southern slope is a water vapor flux convergence zone. (3) Under different precipitation circulation patterns, when the flow pattern is westerly or northwesterly, cloud water distribution on the northern slope is more abundant than that on the southern slope, predominantly consisting of water-bearing low clouds; when the flow pattern is southwesterly, cloud water thickness is deeper, and the difference in cloud water between the northern and southern slopes is not significant. (4) The Qilian Mountains region, particularly the southern slope,

has relatively abundant atmospheric cloud water resources, and a considerable portion of hydrometeors does not become precipitation, indicating higher precipitation enhancement potential; however, its cloud water distribution is not fixed and is also related to precipitation circulation patterns. Therefore, the heterogeneity and variability of atmospheric cloud water resource distribution over the Qilian Mountains require more targeted selection of operation areas and methods during development.

Full Text

Analysis of Differences in Atmospheric Cloud Water Resources Between Southern and Northern Slopes of the Qilian Mountains in Summer

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Abstract

Using high spatiotemporal resolution ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), this study investigates the spatiotemporal distribution of atmospheric cloud water resources and the differential characteristics between the southern and northern slopes of the Qilian Mountains during summer, and estimates water vapor condensation efficiency and hydrometeor precipitation efficiency. The results show that: (1) Under average conditions, atmospheric circulation and topographically induced low-level water vapor convergence and updrafts play key roles in the distribution of cloud water resources over the Qilian Mountains. The summer water vapor content on the southern slope is slightly lower than that on the northern slope, while the cloud water path on the southern slope exceeds that on the northern slope, with the region below 500 hPa serving as an enrichment zone for cloud liquid water content. In recent years, water vapor content and cloud liquid water content have shown increasing trends, with greater increases on the southern slope than on the northern slope; cloud ice water content exhibits a decreasing trend, with a more rapid decline on the northern slope than on the southern slope. (2) During summer days, a stationary updraft exists on the northern slope that can extend to the mid-troposphere, while the low-level southern slope constitutes a water vapor flux convergence zone. (3) Under precipitation circulation patterns, when the synoptic situation features westerly or northwesterly flow,

cloud water distribution on the northern slope is more abundant than on the southern slope, predominantly consisting of low-level water-bearing clouds; under southwesterly flow patterns, cloud depth is greater and the north-south slope difference in cloud water is less pronounced. (4) The Qilian Mountains, particularly the southern slope, possess relatively abundant atmospheric cloud water resources, with a substantial portion of hydrometeors failing to precipitate, indicating higher potential for precipitation enhancement. However, the distribution of cloud water is not fixed and is also related to precipitation circulation patterns. Therefore, the non-uniform and variable distribution of cloud water resources over the Qilian Mountains necessitates more targeted selection of operational areas and methods during development.

Keywords: Qilian Mountains; north-south slope difference; cloud water resources

1. Study Area Overview and Data

1.1 Overview of the Qilian Mountains Region

The Qilian Mountains are located on the northeastern edge of the Tibetan Plateau, bordered by the Hexi Corridor to the north and surrounded by Gobi Desert. Geographically situated at 94°–104°E, 36°–40°N, the range comprises several parallel mountain ridges and valleys oriented west-northwest to east-southeast, with average elevations of 1700–5800 m. Broadly defined, the southern slope refers to the Qinghai side of the Qilian Mountains, while the northern slope refers to the Gansu side. This study focuses on the southern and northern slopes of the Lenglongling section as the primary research area (99.5°–101°E, 37.5°–39°N), where the main peak reaches 5000 m. The northern slope features steep terrain that rapidly descends to the Hexi Corridor at approximately 1500 m, while the southern slope is relatively gentle with smaller elevation differences.

1.2 Data and Applicability

The data used include: (1) ERA5 reanalysis data (spatial resolution 0.25°×0.25°, temporal resolution 1 hour, vertical levels from 1000–100 hPa). This dataset is generated by the ECMWF CY41R2 Integrated Forecast System (IFS) global spectral model, which incorporates improved four-dimensional variational data assimilation and additional historical observations, particularly satellite data, with enhanced surface parameterization and cloud-precipitation schemes. (2) Sounding data from 5 stations around the Qilian Mountains.

Formulas used in the study:

- Precipitable Water (PW): $PW = -\frac{1}{g} \int_{P_s}^{100hPa} q dP$
- Total water vapor flux (Q): $Q = -\frac{1}{g} \int_{P_s}^{100hPa} \mathbf{V}q dP$

- Zonal water vapor flux (Q_λ): $Q_\lambda = -\frac{1}{g} \int_{P_s}^{100hPa} uq dP$
- Meridional water vapor flux (Q_ϕ): $Q_\phi = -\frac{1}{g} \int_{P_s}^{100hPa} vq dP$
- Single-layer water vapor flux divergence (A): $A = -\frac{1}{g} \nabla \cdot (\mathbf{V}q)$

where q is specific humidity, \mathbf{V} is wind vector, u and v are zonal and meridional wind components, P is pressure, P_s is surface pressure varying with longitude and latitude, and g is gravitational acceleration. Water vapor transport above 100 hPa is negligible, so the integration height is set to 100 hPa.

- Grid-averaged cloud liquid (ice) water content (l): $l = \frac{1}{V} \int_V \frac{\rho_w}{\rho} dV$ where ρ_w is cloud liquid (ice) water density and ρ is moist air density. Cloud water path is the vertical integral of cloud liquid (ice) water content.

Estimation of condensation and precipitation efficiency:

Using the Cloud Water Resource Monitoring and Evaluation Method established by the Chinese Academy of Meteorological Sciences, the balance equations for water vapor and hydrometeors in a region are:

$$\begin{aligned} Q_v &= Q_{v0} + Q_{vip} + Q_{ev} - Q_c - R \\ Q_h &= Q_{h0} + Q_{hip} + Q_c - Q_e - R \end{aligned}$$

where Q_v is total water vapor, Q_{v0} is initial water vapor, Q_{vip} is water vapor input, Q_{ev} is surface evaporation, Q_e is evaporation, Q_h is total hydrometeors, Q_{h0} is initial hydrometeors, Q_{hip} is hydrometeor input, Q_c is condensation, Q_{tc} is total condensation, and R is total precipitation.

- Water vapor condensation efficiency (P_c): $P_c = \frac{Q_{tc}}{Q_v}$
- Hydrometeor precipitation efficiency (E_h): $E_h = \frac{R}{Q_h}$

Comparison of ERA5 grid data with sounding station specific humidity data shows correlation coefficients of 0.92–0.98 (all passing 99% significance test), indicating ERA5 reanalysis data is suitable for analyzing water vapor characteristics over the Qilian Mountains.

Correlation test of specific humidity between ERA5 grid data and sounding stations

2. Summer Distribution of Water Vapor and Cloud Water

2.1 Summer Water Vapor Distribution

Summer water vapor distribution over the Qilian Mountains shows higher values in the southeast than northwest, and greater amounts over plains and valleys than mountain slopes (Fig. 2). Water vapor content ranges 7–10 mm over most areas east of 100°E, with low-value centers below 7 mm in the western mountains. The Qinghai Lake to Huangshui River valley area on the southern slope and the region from the rapid terrain descent on the northern slope to

the Hexi Corridor exhibit east-southeast oriented moisture tongues extending to 14 mm. Overall, water vapor content is higher on the northern slope than the southern slope. The entire region shows increasing trends (Fig. 2b) at rates of $0.1\text{--}0.4 \text{ mm} \cdot (10\text{a})^{-1}$, with greater increases in the western mountains than the east, and on the southern slope than the northern slope.

2.2 Summer Cloud Water Distribution

Summer cloud water path distribution generally mirrors water vapor patterns (Fig. 3), with more in the southeast than northwest, and significantly more over the mountains than surrounding areas. The easternmost mountain ridge is a high-value zone, reaching $120 \text{ g} \cdot \text{m}^{-2}$. Overall, cloud water path is slightly higher on the southern slope than the northern slope, decreasing rapidly with elevation on the northern slope. Most mountain areas show increasing trends in cloud water path (Fig. 3b) at $2\text{--}4 \text{ g} \cdot \text{m}^{-2} \cdot (10\text{a})^{-1}$, except for a weak decreasing trend in the central-eastern section east of 100°E . The southern slope shows rising cloud water path while the northern slope exhibits a weak declining trend.

Cloud liquid water content and cloud ice water content distributions are consistent with cloud water path patterns (Fig. 3c, 3e), with slightly higher liquid water content on the southern slope below 500 hPa. Their trends are opposite (Fig. 3d, 3f): liquid water content increases throughout the region, especially in the west at $2\text{--}4 \text{ g} \cdot \text{m}^{-2} \cdot (10\text{a})^{-1}$ with greater increases on the southern slope; ice water content decreases, particularly in the eastern northern slope at $2\text{--}4 \text{ g} \cdot \text{m}^{-2} \cdot (10\text{a})^{-1}$. Thus, the rising cloud water path on the southern slope is dominated by increasing liquid water content, while the declining cloud water path on the northern slope and central-eastern mountains is dominated by decreasing ice water content.

Vertical cross-sections along 38.3°N and 100°E show that cloud liquid water content maxima (greater than $0.025 \text{ g} \cdot \text{kg}^{-1}$) are concentrated below 300 hPa over the mountains and southern slope lowlands, reaching $0.055 \text{ g} \cdot \text{kg}^{-1}$ in valleys on the southern slope of Lenglongling at 500–600 hPa. Cloud ice water content is mainly distributed between 500–200 hPa, with high values (greater than $0.03 \text{ g} \cdot \text{kg}^{-1}$) centered around 300 hPa, showing no significant difference between slopes. The vertical distribution characteristics are consistent with previous studies showing two height peaks for liquid water content in East Asia (0.5–1.0 km and 3.5–4.5 km) and ice water content centered near 8 km, with higher centers over the Tibetan Plateau due to elevated terrain and vigorous convection.

[Figure 2: see original paper] Distribution and variation trend of precipitable water vapor over the Qilian Mountains in summer (June–August) 1979–2019

[Figure 3: see original paper] Distribution and variation trend of cloud water path, cloud liquid water content, and cloud ice water content over the Qilian Mountains in summer (June–August) 1979–2019

[Figure 4: see original paper] Vertical profile distribution of cloud liquid water content and cloud ice water content along 38.3°N and 100°E in summer (June–August) over the Qilian Mountains 1979–2019

3. Differences in Cloud Water Resources Between Southern and Northern Slopes

3.1 Summer Water Vapor Transport

The entire mountain range experiences west-to-east water vapor flux of 40–50 $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$. Meridional transport is south-to-north (Fig. 5), with maximum flux centers in the southeastern mountains reaching 5 $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$. Weak southward water vapor flux occurs along the Hexi Corridor near the northern slope, particularly in the central-eastern section where values reach -5 $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$. Zonal flux far exceeds meridional flux by about an order of magnitude.

Trend analysis shows decreasing zonal flux throughout the region at -4 to -2 $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot (10\text{a})^{-1}$, indicating weakening westerly moisture transport, especially on the central-eastern southern slope. Meridional flux shows increasing trends, particularly over the Hexi Corridor to northern slope area at about 3 $\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1} \cdot (10\text{a})^{-1}$. Thus, moisture sources primarily depend on mid-latitude westerlies, though this transport is weakening. Summer monsoons, blocked by topography, deliver limited moisture to the central-eastern southern slope, but this maritime moisture plays an important role in distribution. The southward flux near the northern slope in the central-eastern Hexi Corridor shows an increasing trend, converging with northward flux from the southern slope at the mountains, contributing importantly to cloud water distribution in the central-eastern section.

At 650 hPa, central-eastern moisture transport extends to approximately 100°E, considered the average limit of summer monsoon reach. This southeasterly transport shows an increasing trend with maximum rates of 20 $\text{g} \cdot \text{cm}^{-1} \cdot \text{hPa}^{-1} \cdot \text{s}^{-1} \cdot (10\text{a})^{-1}$, supplementing westerly transport. Summer monsoon moisture transport concentrates in low-mid levels, creating an east-high, west-low moisture distribution pattern.

3.2 Summer Water Vapor Flux Divergence and Mean Airflow

Daytime cross-sections along 38.3°N show the eastern slope as a water vapor flux divergence zone, while the western slope below 550 hPa is a convergence zone with maximum intensity of $-1.2 \times 10^{-3} \text{ g} \cdot \text{hPa}^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$. An easterly updraft appears from 103°E, extending westward to heights above 400 hPa. At night, the eastern slope low-level becomes a convergence zone while the western slope becomes a divergence zone, with weak subsidence dominating the eastern slope.

Along 100°E, the northern slope is a divergence zone while the southern slope below 550 hPa is a convergence zone with center intensity of $-2.4 \times 10^{-3} \text{ g} \cdot \text{hPa}^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$. A northerly updraft along the northern slope extends into the southern slope above 400 hPa, with vertical velocity reaching $0.3 \text{ Pa} \cdot \text{s}^{-1}$ at the peak. Nighttime patterns are similar to zonal cross-sections.

Thus, a stationary daytime updraft exists on the northern slope during summer, carrying relatively abundant moisture upslope to the southern slope, persisting into the mid-troposphere. The southern slope low-level is a water vapor flux convergence zone within 37.5°–38.5°N. High cloud liquid water content corresponds to low-level convergence, while the updraft extending from peak to southern slope corresponds to high cloud water content throughout the layer. Topographically induced convergence redistributes moisture, and together with the stationary updraft, determines the north-south slope differences in cloud water content.

[Figure 5: see original paper] Distribution and variation trend of latitudinal and meridional water vapor transport flux over the Qilian Mountains in summer (June–August) 1979–2019

[Figure 6: see original paper] Distribution of water vapor fluxes and mean wind field, and variation trend of water vapor fluxes at 650 hPa in summer (June–August) over the Qilian Mountains 1979–2019

[Figure 7: see original paper] Physical quantity fields along 38.3°N and 100°E in day and night over the Qilian Mountains in summer (June–August) 1979–2019

4. Differences Under Typical Summer Precipitation Circulation Patterns

Analysis of summer precipitation circulation patterns over the Qilian Mountains reveals two main types: cold-air-dominated westerly flow and warm-moist-air-dominated southerly flow. Using 500 hPa geopotential height (H) at 30°–45°N, 110°E as a classification standard: $H > 20 \text{ gpm}$ indicates southwesterly flow type, $H < 20 \text{ gpm}$ indicates westerly or northwesterly flow type.

Under westerly/northwesterly patterns, cloud liquid water content dominates the lower layers, significantly greater on the northern slope than southern slope, with cloud ice water content mainly above 400 hPa at $0.03 \text{ g} \cdot \text{kg}^{-1}$. Under southerly patterns, both slopes have substantial low-level cloud water, with liquid water extending to 400 hPa and ice water centered at 300 hPa exceeding $0.05 \text{ g} \cdot \text{kg}^{-1}$. Thus, under westerly/northwesterly patterns, the northern slope has more abundant cloud water, primarily low-level water-bearing clouds; under southwesterly patterns, cloud depth is greater with larger ice water content, and north-south differences are less pronounced.

[Figure 8: see original paper] Vertical profile distribution of cloud liquid water

content and cloud ice water content under westerly/northwesterly and southwesterly flows along 38.3°N in summer (June–August) over the Qilian Mountains 1979–2019

5. Artificial Precipitation Enhancement Potential in the Qilian Mountains

Atmospheric water vapor condensation efficiency and hydrometeor precipitation efficiency are important indicators for assessing precipitation enhancement potential. Generally, clouds with high condensation efficiency but low precipitation efficiency have greater enhancement potential. The Qilian Mountains show significantly higher efficiencies than surrounding areas: condensation efficiency exceeds 0.8% on the southern slope and 0.3% on the northern slope; precipitation efficiency is 20%–30% on the southern slope and 10%–20% on the northern slope. The southern slope possesses relatively abundant atmospheric water resources with substantial hydrometeors not converting to precipitation, indicating development potential.

While direct comparison with previous studies is difficult due to different regional environments and precipitation mechanisms, reference values show: condensation efficiencies of 0.5% (Guangxi), 0.4% (Beijing), and 4.77% (Qinghai); precipitation efficiencies of 69.7% (Liupanshan), 72.2% (Henan), 44.9% (Beijing), and 44.9% (Qinghai). The Qilian Mountains, especially the southern slope, show considerable space for atmospheric water resource development.

[Figure 9: see original paper] Water vapor condensation efficiency and hydrometeor precipitation efficiency distribution in the Qilian Mountains 2005–2019

6. Discussion

Mountain cloud water distribution is non-uniform and highly variable. For the Qilian Mountains in summer, the southeast-northwest gradient is dominated by atmospheric circulation-driven moisture transport, while the mountain-surrounding and north-south slope differences reflect topographic redistribution of moisture and orographic lifting, particularly evident in arid/semi-arid mountainous regions. The complexity of terrain effects on cloud microphysics under different precipitation patterns is consistent with simulation studies.

Under climate warming, global cloud water resources are increasing significantly, especially at mid-high latitudes. China's cloud water resources show overall increasing trends with regional heterogeneity, increasing west of 105°E but decreasing east of it. The plateau climate zone where the Qilian Mountains are located shows obvious increasing trends. This study extends the analysis period and finds continued increasing trends with regional heterogeneity: rising liquid

water content and decreasing ice water content result in increasing cloud water path on the southern slope but decreasing on the northern slope, consistent with studies showing liquid water positively and ice water negatively correlated with temperature.

Climate warming affects atmospheric circulation, thereby influencing moisture transport required for cloud formation. The weakening westerly moisture transport allows monsoon-carried moisture to penetrate further west and north, consistent with studies on circulation impacts on Northwest China's arid/semi-arid climate. However, cloud formation and distribution are complex processes influenced not only by circulation and topography but also by surface temperature, underlying surfaces (glaciers, lakes, vegetation), and aerosols, with accelerated water cycles under global warming making distribution patterns more complex. This study only discusses circulation and topography; comprehensive understanding of all influencing factors is needed for more effective precipitation enhancement operations. Additionally, with the availability of long-term satellite datasets from active sensors providing complete cloud vertical information, future work should validate these results using such datasets.

7. Conclusions

Based on high-resolution reanalysis data, this study analyzes north-south slope differences and trends in summer cloud water content over the Qilian Mountains, explores their causes, and estimates condensation and precipitation efficiencies using the Cloud Water Resource Monitoring and Evaluation Method. The non-uniform and variable distribution of cloud water resources provides references for targeted selection of operational areas and methods. Main conclusions are:

- 1) Summer water vapor content and cloud water path over the Qilian Mountains show southeast-northwest gradients, but with north-south slope differences: water vapor content is slightly lower on the southern slope while cloud water path is higher, with the region below 500 hPa being an enrichment zone for cloud liquid water. Recently, both water vapor and cloud water path show increasing trends, with greater increases on the southern slope. The rising cloud water path on the southern slope is dominated by increasing liquid water content, while the declining cloud water path on the northern slope and central-eastern mountains is dominated by decreasing ice water content.
- 2) The zonal water vapor flux far exceeds the meridional flux by about an order of magnitude, concentrated in low-mid levels. Western areas depend on westerly transport, while central-eastern areas depend on southeasterly transport, creating an east-high, west-low moisture pattern. During summer days, the southern slope low-level is a convergence zone while the northern slope has a stationary updraft extending to high levels. Topographically induced low-level moisture convergence and updrafts are key

to cloud water distribution.

- 3) Under different precipitation circulation patterns, north-south slope cloud water distribution differs: westerly/northwesterly patterns produce more abundant cloud water on the northern slope, mainly low-level water-bearing clouds; southwesterly patterns produce deeper clouds with greater ice water content and smaller north-south differences.
- 4) Condensation efficiency is about 0.3%–0.8% and precipitation efficiency about 10%–30%. The southern slope has abundant atmospheric water resources with substantial hydrometeors not precipitating, indicating development potential. The non-uniform and variable cloud water distribution requires targeted operational area and method selection.

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