Impact of Glacier Underlying Surface on Summer Cloud Structure and Cloud Water Content: A Case Study of Shule South Mountain in the Qilian Mountains (Postprint)

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Abstract

Cloud water content and cloud structural parameters are fundamental to weather forecasting and analysis of water cycle processes in alpine regions. Based on 2012–2015 summer CloudSat satellite remote sensing data including 2B-CLDCLASS, 2B-GEOPROF, and 2B-GEOPROF-LIDAR, combined with China' s Second Glacier Inventory data and meteorological data, an analysis was conducted on the characteristics of cloud water content and cloud types in glacier-covered and non-glacier-covered areas of the Shule South Mountain region in the Qilian Mountains. The results indicate that: (1) The vertical distribution of cloud water content is influenced by the underlying surface and cloud type, primarily manifested as deep convective clouds being the dominant precipitation cloud type over glacier-covered mountains, while nimbostratus clouds are the dominant precipitation cloud type over non-glacier-covered mountains. (2) In the Shule South Mountain region, high water content is mainly distributed in mid- and low-level clouds below 5 km, and vertical air motion is more active in glacier areas than in non-glacier areas. (3) The average cloud water content in the Shule South Mountain glacier area is 0.07 $g \cdot m^{-3}$, while that in the non-glacier area is 0.17 $g \cdot m^{-3}$. The spatial variation of cloud water can, to a certain extent, reflect the distribution of precipitation and water vapor.

Full Text

Abstract

Cloud water content and cloud structural parameters are fundamental for weather forecasting and analyzing water cycle processes in alpine regions. Based on CloudSat satellite remote sensing data (2B-CLDCLASS, 2B-GEOPROF, and 2B-GEOPROF-LIDAR products) from 2012–2015, combined with China's second glacier inventory data and meteorological observations, this study analyzes the characteristics of cloud water content and cloud types over glacial and non-glacial areas of Shulenan Mountain in the Qilian Mountains. The results show that: (1) The vertical distribution of cloud water content is significantly influenced by the underlying surface and cloud types. Precipitation clouds over glaciated high mountains are predominantly deep convective clouds, whereas those over non-glaciated high mountains are mainly nimbostratus. (2) High water content in the Shulenan Mountain area is primarily distributed in middle- and low-level clouds below 5 km, with more active vertical airflow motion in glacial areas compared to non-glacial areas. The average cloud water content in the glacial area is $0.07\ \mathrm{g \cdot m^{-3}}$, while in the non-glacial area it is $0.17\ \mathrm{g \cdot m^{-3}}$. (3) Spatial variation in cloud water content can, to a certain extent, reflect the distribution patterns of precipitation and water vapor.

Keywords: cloud structure; cloud water content; glacial underlying surface; CloudSat; Shulenan Mountain of Qilian Mountains

Introduction

Clouds are crucial components of the Earth-atmosphere circulation system, playing an important regulatory role in radiation balance and water cycling. The vertical structure of clouds (such as cloud height, thickness, and layer number) and microphysical parameters (such as ice water content, cloud droplet number concentration, and effective particle radius) are prerequisites for artificial precipitation enhancement. However, influenced by underlying surface types, terrain conditions, and weather systems, the uncertainties they generate represent one of the greatest obstacles in studying cloud-climate interactions. Therefore, identifying the distribution characteristics of cloud structure and cloud water content and their relationships with water vapor and precipitation is essential for understanding regional water cycle processes, developing cloud precipitation potential, and improving precipitation efficiency.

Clouds are closely related to water vapor and precipitation, and their vertical structural characteristics are important for weather, climate, and weather modification. As a key factor in atmospheric cloud-radiation feedback, cloud amount can reflect the abundance of regional cloud water resources and serves as an important parameter for implementing artificial weather modification. When cloud amount, cloud water content, and cloud thickness are all large, conditions are favorable for precipitation formation and catalytic precipitation enhancement. In northwestern China, the multi-year average distribution of atmospheric cloud water resources shows characteristics of following the terrain distribution. High-value areas of total cloud amount, middle cloud amount, total optical thickness, and total cloud water path are all concentrated in the Tianshan, Kunlun, and Qilian Mountains, while low-value centers are generally distributed in the Tarim Basin–western Inner Mongolia Gobi Desert–northwestern Loess Plateau region. Moreover, in the western region, precipitation increases with cloud amount. The water vapor and precipitation in the Qilian Mountains region are mainly influenced by the westerlies, southern monsoons (South Asian monsoon and plateau monsoon), and East Asian monsoons, with precipitation increasing from west to east, forming a "water vapor sink" across the entire Qilian Mountains region in summer. Research shows that high cloud amount areas in the Qilian Mountains are consistent with high precipitation areas.

With the development of satellite remote sensing technology, research on cloud structure and cloud water content has been greatly improved. For instance, Yang and Wang used CloudSat satellite data to analyze the vertical distribution characteristics of cloud water content over China and found that the Tibetan Plateau terrain and East Asian summer monsoon significantly affect the monthly average cloud water content distribution. Li et al. used spaceborne lidar data to study the vertical distribution characteristics of clouds and found that double-layer clouds account for the largest proportion of multi-layer cloud distribution in East Asia, with cloud top and base heights showing significant seasonal variations and obvious regional characteristics. Wang et al. analyzed the cloud structure characteristics during heavy snowfall in northern Xinjiang using CloudSat data and found that before and during snowfall, cloud types were mainly stratus, cumulus, altostratus, and deep convective clouds, with the mean values of ice particle effective radius and ice water content before snowfall being larger than those during snowfall.

These studies have mostly focused on analyzing cloud parameter characteristics and the relationships between cloud parameters and various meteorological elements, lacking research on the relationship between underlying surface types and regional clouds. As research has deepened, underlying surface characteristics (such as vegetation coverage and surface albedo) have been found to affect local atmospheric water resources. In alpine glacier regions, due to differences in temperature and humidity fields between the underlying surface and the surrounding environment, glaciers form cold islands and high-humidity centers, intensifying turbulence and convection over glaciers and forming multiple precipitation processes, thereby increasing precipitation. To further understand the relationship between regional cloud structure, cloud water content distribution characteristics, and different underlying surfaces, this study selects Shulenan Mountain (38°–39°N, 96°30’ –98°30’ E), one of the glacier development centers of the Qilian Mountains, as the research area. It analyzes the distribution characteristics of cloud structure and cloud water content over glacial and non-glacial areas and the conversion of atmospheric water resources, thereby providing a theoretical basis for improving understanding of the complex relationship between clouds and climate.

1 Data and Methods

1.1 Data Sources

The data sources used in this study mainly include: (1) 2B-CLDCLASS, 2B-GEOPROF, and 2B-GEOPROF-LIDAR retrieval data from the CloudSat satellite' s Cloud Profiling Radar (CPR), obtained from the CloudSat Data Processing Center (http://www.cloudsat.cira.colostate.edu). Compared with traditional satellite remote sensing data, this data has higher accuracy. (2) China' s second glacier inventory data, obtained from the Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn). (3) ERA-Interim reanalysis monthly mean data with a spatial resolution of 0.125°\$×0.125°, *obtainedfromtheEuropeanCentreforMedium − RangeWeatherForecasts(http : //data.ecmwf.int/data).(4)Precipitationdatafromthe"MeteorologicalandE SurfaceAtmosphereoverChina"withatemporalresolutionof1dayandhorizontalspatialresolutionof*0.1°×\$0.1° obtained from the Cold and Arid Regions Science Data Center (http://westdc.westgis.ac.cn).

1.2 Data Processing

1.2.1 CloudSat Satellite Data Processing For the GEOPROF product processing, data with CPR_{{{Cloud}}*{{Mask}}}\$ \$20 were selected, where Cloud*{Mask} values mainly include: 0, 1, 2, 3, 4, 5, representing no cloud detected, data corruption, surface clutter, weak detection signal, and cloud detected, respectively, with larger values indicating more accurate detection. The CLDCLASS product provides cloud types for each layer, represented by: cirrus, cirrostratus, deep convective clouds, etc. To reduce random errors, the cloud water content at various height levels over Shulenan Mountain was averaged zonally before analysis, with cloud water content being the sum of liquid water content and ice water content.

[Figure 1: see original paper]

1.2.2 Atmospheric Water Vapor Content Calculation Atmospheric water vapor content (W) is calculated as:

$$W = (1/g)\ {}_{0}\hat{}P_{0}\ q\ dP$$

where W is the total water vapor content per unit area in the entire atmospheric column (kg·m^{-2}), g is gravitational acceleration (m·s^{-2}), is water density (kg·m^{-3}), P is atmospheric pressure (hPa), q is specific humidity (kg·kg^{-1}), and P_0 and Pz represent surface pressure and pressure at height Z, respectively. When the atmospheric layer is relatively thin, the specific humidity distribution with height in each layer can be considered linear. The formula can be rewritten as:

$$W = 0.01\ \Sigma\ (\bar{q}\ \ \Delta P\ )$$

where $\bar{q}$ is the average specific humidity in the i-th layer (kg·kg^{-1}) and ΔP is the layer thickness (hPa).

1.2.3 Precipitation Conversion Efficiency Precipitation conversion efficiency (PCE) is the ratio of precipitation produced in precipitating cloud systems to atmospheric water vapor content. Generally, for a given atmospheric water vapor content, lower precipitation conversion efficiency indicates greater potential for cloud water resource development. The calculation formula is:

$\mathrm{PCE} = (\mathrm{Pr}/\mathrm{W}) \times 100\%$

where PCE is the precipitation conversion efficiency in a certain area during a certain period (%), Pr is the total precipitation during that period (mm), and W is the total atmospheric water vapor content (precipitable water) during the same period (mm).

2 Results and Analysis

2.1 Current Status of Glaciers in Shulenan Mountain

According to China’ s second glacier inventory, Shulenan Mountain has 432 glaciers covering a total area of 432.54 km^2. Statistical analysis shows that glaciers with areas <1.0 km^2 dominate, totaling 329 glaciers and accounting for 76.32% of the total glacier number in Shulenan Mountain. Glaciers with areas between 1-10 km^2 number 56, accounting for 13.00% of the total, while glaciers \$ $10km$^{2}\$ number only 14, accounting for 3.24% of the total. The largest glacier is the No. 5 Glacier (ID: 5Y445G0020) with an area of 240.66 km^2. In terms of orientation (Fig. 3), both glacier number and area are largest for north-facing glaciers, followed by northeast- and northwest-facing orientations. North-facing glaciers (including northeast and northwest) total 298, accounting for 69.14% of the total glacier number. The combined area of north-, northeast-, and northwest-facing glaciers is 307.39 km^2, representing 71.09% of the total glacier area. Southwest-facing glaciers rank second with an area of 39.95 km^2, accounting for 9.24% of the total glacier area.

[Figure 2: see original paper] [Figure 3: see original paper]

2.2 Spatial Distribution of Summer Cloud Water Content and Cloud Types in Shulenan Mountain

2.2.1 Spatial Distribution of Summer Cloud Water Content Figure 4 shows the zonal-vertical profile of cloud water content over Shulenan Mountain in summer 2012–2015. White areas indicate no cloud water content, likely due to data gaps. The maximum height of cloud water content in the vertical direction reaches 14 km, indicating that water vapor can extend throughout the troposphere and into the lower stratosphere. The overall convective development height in the area west of Har Lake is higher than that in the area east of Har Lake, reflecting the active vertical motion of airflow in the glacial area.

High-value zones of cloud water content (>1 $\mathrm{g \cdot m^{-3}}$) are mostly distributed below 5 km, indicating that high water content in the Shulenan Mountain area is mainly concentrated in middle- and low-level clouds, with a maximum value of approximately 1.87 $g \cdot m^{-3}$. Near Har Lake (38.2°N), cloud water content is relatively high, which is directly related to the water body underlying surface and strong evaporation in summer, resulting in abundant water vapor over the lake. In contrast, the piedmont area of Shulenan Mountain north of Har Lake (38.5°N) shows significantly lower cloud water content than areas to its south or north. This is because the large horizontal temperature gradient at the edge of the high mountain glacier area creates strong thermal wind, which increases the vertical wind shear with height and accelerates the flow of warm, moist air masses from non-glacial to glacial underlying surfaces. This creates a "suction" effect on warm, moist air masses, increasing precipitation over the glacier surface while reducing cloud water content in surrounding areas.

A distinct high-value zone exists between 38.4°N-38.6°N in Area A, with maximum cloud water content reaching 0.17 $g \cdot m^{-3}$, showing an increasing trend from west to east across Shulenan Mountain. Area A is mainly located in the northwestern section of Shulenan Mountain with extensive glacier distribution (glacial area), while Area B is in the southeastern section with minimal glacier cover (non-glacial area). Although both areas belong to the same mountain system, their cloud water content and cloud type distributions show significant spatial differences, reflecting the complexity of mountain climate and the influence of different underlying surfaces (glacial vs. non-glacial) on cloud properties.

[Figure 4: see original paper]

2.2.2 Cloud Types and Height Structure Statistics of cloud types in different regions of Shulenan Mountain in summer 2012-2015 (Table 1) reveal that deep convective clouds are the main precipitation cloud type in Area A (glacial area), while Area B (non-glacial area) precipitation is dominated by nimbostratus, followed by stratus and stratocumulus. The vertical distribution differences in cloud water content are also influenced by regional cloud type variations.

2.2.3 Relationship Between Summer Cloud Water Content and Precipitation Cloud presence is a prerequisite for precipitation. Through interaction with atmospheric circulation, clouds can indirectly establish physical connections with regional precipitation. Analysis of summer average precipitation and precipitation conversion efficiency in Shulenan Mountain from 2012-2015 shows that precipitation generally increases from northwest to southeast, with southern slopes receiving more precipitation than northern slopes, and Area A receiving more precipitation than Area B. This pattern aligns with the spatial distribution of cloud water content (Fig. 5). The relationship between precipitation and atmospheric water vapor content can be expressed through precipitation conversion efficiency, which intuitively reflects the potential for developing atmospheric cloud water resources in a region. The precipitation conversion efficiency in Shulenan Mountain also increases from west to east, indicating that cloud water resource development potential decreases from west to east. Combined with atmospheric water vapor conversion patterns in the Qilian Mountains region, this suggests that water vapor carried by westerlies contributes less to precipitation, while water vapor from eastern monsoons contributes more. This also demonstrates that spatial variation in cloud water content can, to some extent, reflect the distribution of precipitation and water vapor.

[Figure 5: see original paper]

2.3 Effects of the Special Glacial Underlying Surface on Summer Cloud Water Content in Shulenan Mountain

To further analyze the influence of glacial underlying surfaces on cloud water content, Area A with extensive glacier distribution is designated as the glacial area, while Area B with minimal glacier cover is designated as the non-glacial area (Fig. 1). Analysis of the vertical distribution of cloud water content over these two regions (Fig. 6) reveals that the vertical profile of cloud water content in the glacial area shows double peaks at different heights, with the primary peak near 4 km and a secondary peak near 7 km. In contrast, the non-glacial area shows a single-peak vertical profile with the maximum peak near 5 km. This pattern helps explain why the first major precipitation height zone typically occurs at mid-mountain belts for a given mountain elevation, while a second precipitation height zone exists in glacial areas.

The average cloud water content in the glacial area ($0.07\ \text{g} \cdot \text{m}^{-3}$) is lower than that in the non-glacial area ($0.17\ \text{g} \cdot \text{m}^{-3}$). Due to the cold storage effect of glaciers, the saturated water vapor pressure over glacial surfaces is lower, making water vapor more likely to condense and precipitate when passing over glacial areas. This result is consistent with analyses of temperature and humidity evolution during precipitation processes. Deep convective clouds occur with a frequency of 42.3% in the glacial underlying surface (Area A), while nimbostratus dominates the non-glacial underlying surface (Area B) with a frequency of 38.7%, further demonstrating the active vertical motion of airflow in glacial areas.

[Figure 6: see original paper]

3 Conclusions

The vertical distribution of summer cloud water content in the Shulenan Mountain region of the Qilian Mountains is significantly influenced by atmospheric circulation and underlying surfaces. Understanding the spatiotemporal distribution characteristics of cloud water content is crucial for weather forecasting, weather modification, and water cycle analysis. Based on analysis of cloud water content variations over Shulenan Mountain during summers 2012–2015, the following conclusions are drawn:

(1) In summer, cloud water content over Shulenan Mountain can develop up to 14 km in the vertical direction, reaching the entire troposphere and lower stratosphere. The convective development height in the area west of Har Lake is higher than that in the area east of Har Lake, reflecting the active vertical motion of airflow in glacial areas. High-value zones of average cloud water content are mainly concentrated below 5 km, with a maximum value of approximately 1.87 $g \cdot m^{-3}$, indicating that high water content is primarily distributed in middle- and low-level clouds. Deep convective clouds are the main precipitation cloud type in the glacier-covered area west of Har Lake, while nimbostratus dominates the area east of Har Lake with less glacier cover.

(2) Statistical analysis of average precipitation in the study area shows that precipitation increases from northwest to southeast across Shulenan Mountain, consistent with the spatial distribution of cloud water content. Generally, southern slopes receive more precipitation than northern slopes, and the eastern mountain area receives more than the western area. The development potential of cloud water resources gradually decreases from west to east, indicating that spatial variation in cloud water content can, to some extent, reflect the distribution patterns of precipitation and water vapor.

(3) In the glacier-covered mountainous area west of Har Lake, deep convective clouds are the main precipitation cloud type, while in the non-glaciated mountainous area east of Har Lake, nimbostratus dominates. The vertical profile of cloud water content in the glacial area shows double peaks at approximately 4 km and 7 km, while the non-glacial area shows a single peak near 5 km. The average cloud water content over glacial surfaces (approximately 0.07 $g \cdot m^{-3}$) is lower than that over non-glacial areas (approximately 0.17 $g \cdot m^{-3}$), indicating that due to the cold storage effect of glacial underlying surfaces, saturated water vapor pressure decreases and water vapor is more likely to condense and precipitate when passing over glacial areas, reflecting the glacier' s traction effect on water vapor transport.

The CloudSat satellite remote sensing data used in this study are internationally recognized high-precision, multi-parameter retrieval data for cloud characteristics. However, the limited study period and small research area may have narrowed regional differences in cloud characteristic parameters. Future research should incorporate more high-quality cloud product data to investigate the relationships between different underlying surfaces, clouds, and various meteorological elements.

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