Spatiotemporal Distribution Characteristics of Cloud Water Resources in Qinghai Province from 2014 to 2018: Postprint

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Abstract

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t, being most abundant in the southern and southeastern parts of the Three-River Source region, reaching up to 2000 kg·m-2. The Qilian Mountains southern foothills to Xining extension belt represents a secondary high zone, while the total cloud water resources in the Qaidam Basin are relatively low. The EOF decomposition of cloud water resources shows a main spatial distribution with stepwise variation of more in the northeast and less in the southwest. Based on the transport characteristics of water vapor and condensate and the distribution of cloud water resources, combined with different regions and terrains, conducting targeted weather modification operations is highly necessary.

Full Text

Preamble

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Spatiotemporal Distribution Characteristics of Cloud Water Resources in Qinghai Province from 2014 to 2018

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Abstract: Based on ERA5 hourly reanalysis data with a horizontal resolution of 0.25°$×0.25°, thisstudyanalyzesprecipitation, watervapor, hydrometeors, andatmosphericcloudwaterresou
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theQaidam–QinghaiLake–HehuangValleybandinthenorth, theHohXil–Zhiduo–Zaduobandinthesouthwest, tons, being most abundant in the southern and southeastern Sanjiangyuan region, reaching up to 2000 kg · m^{-2}. The region from the southern foothills of the Qilian Mountains to the Xining extension zone represents the second-highest area, while the Qaidam Basin has relatively low total cloud water resources. In EOF decomposition, the main spatial distribution shows a stepwise pattern with more resources in the northeast and fewer in the southwest. Targeted weather modification operations based on water vapor and hydrometeor transport characteristics, combined with regional and topographical features, are urgently needed.

Keywords: cloud water resources; water vapor transport; precipitation efficiency; EOF analysis

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1 Study Area Overview and Methods

1.1 Study Area Overview

Qinghai Province is located between 89.50°E–103.00°E and 31.50°N–39.25°N in the northeastern part of the Qinghai-Tibet Plateau, covering a total area of 72$×10^{4}$ km^2. The overall terrain slopes from high in the west to low in the east, with high elevations in both north and south and lower elevations in the central region. The eastern area forms a transitional zone from the Qinghai-Tibet Plateau to the Loess Plateau. The Qilian Mountains and Qinghai Lake are located in the north and east, while the sources of the Yellow River, Yangtze River, and Lancang River (the "Sanjiangyuan" region) lie to the south. The province features three distinct landform types: Qinghai-Tibet Plateau, inland arid basin, and Loess Plateau, and experiences a plateau continental climate.

[Figure 1: see original paper]

1.2 Methods

This study utilizes ERA5 hourly reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) with a horizontal resolution of 0.25°$×$0.25° and temporal coverage from 2014 to 2018. The CCR-MEM (Cloud Water Resources Monitoring Method) is employed for hourly grid-based assessment of atmospheric cloud water resources in Qinghai Province. Key physical quantities include total water vapor content, total hydrometeor content, water vapor condensation efficiency, hydrometeor precipitation efficiency, total water substance precipitation efficiency, water vapor and hydrometeor renewal cycles, and total cloud water resources.

The water vapor content is calculated as:

$$W = -\frac{1}{g}\int_{P_s}^{P_z} q\,dp$$

where W represents water vapor content ($\mathrm{kg \cdot m^{-2}}$), g is gravitational acceleration, q is specific humidity at each level ($\mathrm{kg \cdot kg^{-1}}$), P_z is atmospheric pressure at height z (hPa), and P_s is surface pressure (hPa).

Water vapor transport flux, representing the mass of water vapor passing through a unit area per unit time, is calculated as:

$$Q = \frac{1}{g} \int_{P_s}^{P_z} V_n q \, dp$$

where Q is water vapor transport flux ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$) and V_n is the wind component perpendicular to the regional boundary ($\mathrm{m \cdot s^{-1}}$). Other physical quantities and their calculation methods are summarized in .

Empirical Orthogonal Function (EOF) analysis, also known as Principal Component Analysis (PCA), is applied to investigate spatiotemporal distribution characteristics of cloud water resources. First introduced by Pearson, EOF analysis decomposes spatiotemporal fields where spatial modes reflect distribution patterns and temporal coefficients (principal components) indicate temporal weighting variations.

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2 Results

2.1 Spatiotemporal Distribution Characteristics of Cloud Water Resources and Related Physical Quantities

Precipitation Distribution: Annual average precipitation in Qinghai Province shows a clear southeast-to-northwest decreasing gradient [Figure 2: see original paper]. The Sanjiangyuan region receives nearly 550 mm annually, with some areas exceeding 600 mm. Precipitation in the Qilian Mountains increases westward overall, with the southern foothills (Qilian and Menyuan) receiving approximately 450 mm, while Datong Mountain, Shule Nanshan, and Daban Mountain exceed 500 mm. The Qaidam Basin, surrounded by high mountains, receives less than 50 mm annually. Precipitation distribution is extremely uneven and does not increase monotonically with altitude, as the altitude gradient effect of precipitation on the Qinghai-Tibet Plateau is jointly influenced by complex terrain and water vapor sources.

Water Vapor and Hydrometeor Distribution: Water vapor distribution differs markedly from precipitation, forming three primary bands: the Qaidam-Qinghai Lake-Hehuang Valley band in the north, the Hoh Xil-Zhiduo-Zaduo band in the southwest, and the Bayan Har Mountains-Yellow River bend region in the southeast. The maximum annual average water vapor content occurs in the Qinghai Lake basin, while minima appear along the northern margin of the Qaidam Basin, Kunlun Mountains, and Qilian Mountains, indicating strong correlation between water vapor transport corridors and topography. Controlled by prevailing westerly and easterly flows throughout the year, the northern band receives water vapor entering from north of the Altun Mountains, flowing through the Qaidam Basin, Qinghai Lake, and the Hehuang Valley. In summer, southerly winds and the lake's topographic effects create pronounced water vapor enrichment over Qinghai Lake. The Sanjiangyuan bands receive southwestern airflow driven by the East Asian and Indian Ocean monsoons.

Hydrometeor distribution resembles precipitation, being higher in the southeast and lower in the northwest, with relative enrichment on windward slopes of the Datong Mountains, Shule Nanshan, Daban Mountain, Qinghai Nanshan, Laji Mountains, and Amne Machin. Unlike water vapor, the Qaidam–Qinghai Lake–Hehuang Valley band shows the lowest hydrometeor values in Qinghai. This results from: (1) pronounced subsidence in the enclosed Qaidam Basin lacking favorable updraft conditions, and (2) abundant sandy aerosols (mainly saline-alkaline components) that compete for water vapor, inhibiting hydrometeor growth. In contrast, the southern Qilian foothills, despite lower water vapor, experience strong orographic lifting that promotes condensation.

Transport Flux: Annual average water vapor transport flux reaches 1200 $g \cdot s^{-1}$, primarily entering from southern, southwestern, and northwestern boundaries. Hydrometeor transport flux is only 30 $g \cdot s^{-1}$, entering mainly from the western and southern Lancang and Yangtze River source regions and exiting through the Qilian Mountains, eastern agricultural areas, and eastern Sanjiangyuan. The input-output difference for hydrometeors is an order of magnitude smaller than for water vapor.

Renewal Cycles: Water vapor renewal cycles average 5–6 days across most regions, except in the central and northwestern Qaidam Basin where cycles slow to 200 days. Hydrometeor renewal is significantly faster, averaging 8–14 hours in most areas, with the fastest renewal (5–6 hours) in eastern agricultural zones and the Qinghai Lake basin. The slowest hydrometeor renewal occurs in northwestern Qaidam Basin (~20 hours).

Precipitation Efficiency: Average water vapor and hydrometeor precipitation efficiencies are 0.3% and 14%, respectively [Figure 3: see original paper]. Both show a general west-high, east-low pattern. Water vapor condensation efficiency is lowest in the Qaidam Basin (0.2%) and highest in the Yangtze and Lancang River source regions (0.4%), with relatively high values also in Sanjiangyuan.

Correlation Analysis: Cloud water resources show strong correlations with hydrometeor content (0.85), precipitation amount (0.78), and water vapor precipitation efficiency (0.71), indicating that regions with higher precipitation efficiency and hydrometeor content possess greater cloud water resources. No clear linear relationship exists with renewal cycles, but areas with cloud water resources exceeding 2000 $kg \cdot m^{-2}$ have water vapor renewal cycles under 6 days and hydrometeor renewal cycles under 14 hours.

2.2 Seasonal Characteristics of Total Cloud Water Resources

Seasonal analysis reveals distinct patterns [Figure 6: see original paper]:

Spring (March–May): Cloud water resources are relatively high in western Sanjiangyuan (210 $kg \cdot m^{-2}$) and in windward valleys of the central-eastern Qilian Mountains and eastern agricultural areas. Northwestern Qaidam Basin shows lower values (90 $kg \cdot m^{-2}$). Resources increase temporally, with notable increases in the central-eastern Qilian Mountains and northwestern Yellow River source region.

Summer (June–August): The most resource-abundant season, with peak values reaching 360 $kg \cdot m^{-2}$ across extensive areas. High-value zones cover Sanjiangyuan and the central-eastern Qilian Mountains, with western Hoh Xil and windward slopes of eastern agricultural areas also showing enrichment. The eastern Yellow River source region reaches the highest values. The main high-value area shifts northeastward, extending to northwestern Yellow River source region, blocked by the Kunlun and Burhan Budai Mountains.

Autumn (September–November): Distribution resembles spring, with peak values of 320 $kg \cdot m^{-2}$ in the Qilian Mountains, Qinghai Lake basin, and eastern agricultural areas. Western Hoh Xil also shows significant increases (up to 240 $kg \cdot m^{-2}$). High values in the Qilian Mountains and at the Hoh Xil-Lancang/Yangtze source junction decrease significantly over time.

Winter (December–February): Similar to autumn but with reduced values. Peak cloud water reaches 150 $kg \cdot m^{-2}$, primarily in western Sanjiangyuan and southeastern Qaidam Basin.

2.3 EOF Analysis of Total Cloud Water Resources

EOF analysis of 2014–2018 cloud water resources reveals primary spatial distribution patterns [Figure 7: see original paper]. The first two eigenvectors cumulatively explain 85% of variance, with North' s test confirming effective separation.

First Eigenvector: Shows uniform positive anomalies across Qinghai, reflecting the dominant distribution pattern that approximates precipitation distribution—more in the northeast, less in the southwest. High positive anomalies appear in the southern Qilian foothills, Sanjiangyuan, and southern Hoh Xil, corresponding to high-value cloud water resource zones. Temporal coefficients show a unimodal annual cycle, lowest in winter and peaking in July–August.

Second Eigenvector: Displays a dipole pattern with positive anomalies in the north (especially the southern Qilian foothills) and negative anomalies in the south (most prominent in northwestern Amne Machin). Temporal coefficients are negative in June–August and positive in other months, indicating strong seasonal contrast. This pattern shows that the southern Qilian foothills have abundant cloud water resources in summer under the influence of southerly and southwesterly flows, while Sanjiangyuan experiences relative scarcity except in summer when southwestern airflow is crucial.

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3 Conclusions

Using ERA5 reanalysis data ($0.25° \times 0.25°$) and CCR-MEM/EOF methods, this study analyzes precipitation, water vapor, hydrometeors, and atmospheric cloud water resources in Qinghai Province from 2014 to 2018. Main conclusions are:

1) **Precipitation Pattern:** Annual precipitation decreases stepwise from southeast to northwest, with higher values in western Sanjiangyuan and the southern Qilian foothills. The Qaidam Basin receives less than 50 mm annually. Precipitation distribution is extremely uneven and does not increase with altitude, as the altitude gradient effect is jointly controlled by complex terrain and water vapor sources.

2) **Water Vapor and Hydrometeor Characteristics:** Water vapor distributes in three bands: Qaidam–Qinghai Lake-Hehuang Valley, Hoh Xil-Zhiduo–Zaduo, and Bayan Har Mountains–Yellow River bend. Hydrometeor distribution resembles precipitation, being higher in the southeast and lower in the northwest, with enrichment on windward slopes and in the Qilian Mountains and Qinghai Lake basin. Water vapor enters primarily from southern, southwestern, and northwestern boundaries with transport flux of 1200 $\mathrm{g \cdot s^{-1}}$ and renewal cycles of ~6 days. Hydrometeors enter mainly from western and southern Lancang/Yangtze source regions, exiting through the Qilian Mountains, eastern agricultural areas, and eastern Sanjiangyuan with flux of 30 $\mathrm{g \cdot s^{-1}}$ and renewal cycles of ~10 hours. Average precipitation efficiencies are 0.3% for water vapor and 14% for hydrometeors, with condensation efficiency lowest in the Qaidam Basin (0.2%) and highest in the Yangtze/Lancang source regions (0.4%).

3) **Cloud Water Resources:** Total cloud water resources reach 708×10^{8} tons annually, showing substantial development potential. The highest annual average values (up to 2000 $\mathrm{kg \cdot m^{-2}}$) occur in southern and southeastern Sanjiangyuan, with the southern Qilian foothills to Xining extension zone as the second-highest area. The Qaidam Basin has relatively low values (900 $\mathrm{kg \cdot m^{-2}}$). Summer is the most abundant season, with the Qilian Mountains, Qinghai Lake basin, eastern agricultural areas, and Sanjiangyuan showing significant increases—peaking at 330 $\mathrm{kg \cdot m^{-2}}$ in western Qilian Mountains and 320 $\mathrm{kg \cdot m^{-2}}$ in the Lancang/Yangtze source regions and Bayan Har Mountains.

4) **EOF Analysis:** Spatial distribution shows a stepwise northeast-southwest gradient, with high positive anomalies in the southern Qilian foothills, Sanjiangyuan, and southern Hoh Xil. The first eigenvector

reflects uniform changes across the province, while the second shows a summer dipole pattern with more resources in the east/south and less in Sanjiangyuan (except summer).

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Note: Figure translations are in progress. See original paper for figures.