Analysis of Water Vapor Sources in the Muztagh Peak Region of East Kunlun (Postprint)

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Abstract

Precipitation constitutes a crucial supply for mountain glaciers, with water vapor sources being intimately linked to precipitation amounts. This study selects the modern glacier distribution area of Muztagh Peak in the eastern Kunlun Mountains and employs the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model in conjunction with Global Data Assimilation System (GDAS) data to conduct backward trajectory analysis of water vapor sources in the Muztagh Peak region from 2005 to 2022, examining their seasonal variations and elucidating the water vapor sources and their patterns in this area. The results demonstrate that water vapor sources in the Muztagh Peak region primarily extend toward the Eurasian interior along the mid-latitude westerlies, diverging into three pathways in the western Tibetan Plateau: entering the Tibetan Plateau of China via the Tianshan Mountains, the Pamir Plateau, and from the upper troposphere. Indian Ocean water vapor moves northward across the Himalayas or turns northwestward and eastward to merge with the westerly circulation before entering the plateau hinterland. The Muztagh Peak region is predominantly controlled by terrestrial water vapor originating from the Pamir Plateau and Tianshan Mountains, which accounts for 62.52% of the total; oceanic water vapor comprises upper-level westerly water vapor (Atlantic water vapor) and Indian Ocean water vapor, representing 37.48% of the total, with the proportion of oceanic water vapor exhibiting an annual increase. From a multi-year seasonal average perspective, in addition to the aforementioned sources, locally recycled water vapor in summer constitutes a substantial proportion, reaching 22.64% of the total. The findings of this study will provide an important reference for understanding the water cycle in the Muztagh Peak region of the eastern Kunlun Mountains.

Full Text

Analysis of Water Vapor Sources in the Ulugh Muztagh Area of the East Kunlun Mountains

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Abstract

Precipitation serves as a crucial supply for mountain glaciers, and its amount is closely related to water vapor sources. This study selects the modern glacier distribution area of Ulugh Muztagh in the eastern Kunlun Mountains and conducts backward trajectory analysis of water vapor sources in the region from 2005 to 2022 based on the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model and the Global Data Assimilation System (GDAS). The study explores seasonal variations and reveals the sources and patterns of water vapor in the Ulugh Muztagh area. Results show that water vapor sources in the Ulugh Muztagh area mainly extend to the Eurasian interior along the midlatitude westerly belt, dividing into three routes in the western Qinghai-Tibet Plateau: from the Tianshan Mountains, the Pamir Plateau, and from the high-altitude stratosphere into China's Qinghai-Tibet Plateau. Indian Ocean water vapor moves northward over the Himalayas or turns northwestward to merge with the westerly circulation into the plateau's hinterland. The Ulugh Muztagh area is primarily controlled by land-source water vapor entering from the Pamir Plateau and Tianshan Mountains, accounting for 62.52% of the total water vapor. Sea-source water vapor consists of high-altitude water vapor from the westerly belt (Atlantic water vapor) and Indian Ocean water vapor, accounting for 37.48% of the total, with its proportion increasing year by year. Analysis from a multiyear seasonal average perspective shows that, in addition to the aforementioned sources, locally recycled water vapor constitutes a relatively high proportion in summer, reaching 22.64% of the total. The findings of this study will provide important reference for understanding the water cycle processes in the Ulugh Muztagh area of the East Kunlun Mountains.

Keywords: Ulugh Muztagh; HYSPLIT model; water vapor sources; East Kunlun

Introduction

The Third Pole region, centered on the Qinghai-Tibet Plateau, serves as the source of numerous major rivers [citation]. Precipitation constitutes a vital supply for water resources in the Qinghai-Tibet Plateau region, with local precipitation closely related to water vapor sources. Numerous studies on water vapor sources in the Qinghai-Tibet Plateau indicate that precipitation moisture primarily originates from westerly water vapor transport, monsoon circulation, and local circulation, with significant seasonal and regional variations [citation]. For instance, in the northwestern water source region controlled by the westerlies and the southeastern area influenced by monsoon circulation, the monsoon water vapor contribution ratio varies significantly, while locally sourced water vapor from the Qinghai-Tibet Plateau contributes 14%-16% [citation]. However, in the central and northern regions of the Qinghai-Tibet Plateau, local circulation remains significantly important to precipitation contributions. Studies based on deuterium excess records from two ice cores in the northwestern Qinghai-Tibet Plateau have estimated local water cycling over recent decades, indicating that nearly half of the precipitation in the northwestern plateau is supplied by locally recycled water vapor [citation]. Therefore, research on westerly transport, monsoon circulation, and local water vapor cycling in the Qinghai-Tibet Plateau has quantitatively demonstrated the critical roles of both external and local moisture in precipitation over northern Tibet.

Water vapor source tracing methods have matured considerably, such as using hydrogen and oxygen stable isotopes to trace climatic characteristics and water vapor sources, thereby obtaining contribution rates of different moisture sources to local precipitation [citation]. Additionally, methods employing various algorithms and models to track and quantify water vapor sources have gained widespread application. For example, the Water Accounting Model used to trace and quantitatively analyze water vapor in the Qinghai-Tibet Plateau revealed important insights about moisture contributions [citation]. Lagrangian and Eulerian methods have both been extensively applied in water vapor source tracking models [citation]. The Lagrangian method can provide more information about humidity changes during water vapor transport, and continuous model improvements have significantly advanced water vapor source research. For instance, using the Lagrangian method to analyze and compare water vapor sources in the Qinghai-Tibet Plateau during summer (July) and winter (January) found that both the westerlies and Indian summer monsoon contribute significantly to precipitation in the northern and southern plateau, respectively, with distant moisture sources for the northern plateau concentrated in westerly-dominated regions [citation]. Studies have shown that water vapor in the Muztagh Ata region of the northwestern Qinghai-Tibet Plateau primarily originates from Siberia (land source) and the North Atlantic and surrounding areas (sea source) transported by the westerlies, with supplementary local water vapor along the path [citation]. Research on water vapor sources in the Golmud River basin on the northern slope of the Kunlun Mountains also found that water vapor mainly consists of sea-source water vapor carried by the westerly circulation, with some contribution from land-source water vapor [citation].

The Kunlun Mountains are located on the northern edge of the Qinghai-Tibet Plateau. The Ulugh Muztagh area is situated in the uninhabited region of the Altun Mountain Nature Reserve, with difficult access and limited ground observation data, resulting in limited understanding of its hydrological processes, particularly the extremely complex water vapor sources. Therefore, investigating water vapor sources in this region will contribute to understanding the local water cycle processes.

Ulugh Muztagh is located in the northern part of the Qinghai-Tibet Plateau and represents the highest peak in the eastern Kunlun Mountains, as well as the most glaciated area in the eastern Kunlun region. For research on water vapor sources in the Ulugh Muztagh area, beyond the consensus that moisture primarily originates from the westerly airflow, studies on local water vapor and other moisture sources remain relatively scarce, necessitating in-depth analysis through model calculations [citation]. In view of this, this paper focuses on the Ulugh Muztagh region. Considering the scarcity of ground observation data and precipitation samples in the area, we selected the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model to conduct backward trajectory tracking calculations for water vapor sources in the Ulugh Muztagh area from 2005 to 2022, and performed cluster analysis on the trajectories. Combined with precipitation data from the Ayak Meteorological Station, we explore the water vapor sources and their contributions in the Ulugh Muztagh area, revealing the water cycle processes in this region of the East Kunlun Mountains.

1 Study Area Overview

Ulugh Muztagh (36°16'~36°42'N, 87°5'~87°39'E) is located on the northern edge of the Qinghai-Tibet Plateau and represents the largest modern glacier development area in the eastern Kunlun Mountains. Ulugh Muztagh is perennially influenced by continental air masses, with significant interannual and diurnal temperature variations [citation]. The northward shift of the westerlies marks the arrival of the rainy season in the Ulugh Muztagh area [citation]. Water vapor sources are comprehensively influenced by westerly circulation, monsoon circulation, and local water cycling, making them rather complex. Particularly in the Ulugh Muztagh area of the East Kunlun Mountains, located in the uninhabited region of the Altun Mountain Nature Reserve with difficult access, ground observation data is scarce [Figure 1: see original paper].

Studies have shown that annual precipitation near the snow line is approximately 300 mm, and the glaciers are primarily summer-accumulation type [citation]. According to China's second glacier inventory, the Ulugh Muztagh glacier system comprises multiple glaciers covering a total area exceeding [value] km^2, with glaciers radiating outward from the peak in a dendritic pattern [citation]. The highest elevation of Ulugh Muztagh is approximately 6973 m, with the snow line at about 5500-5750 m.

2 Data and Methods

2.1 Observation Data

The Ayak Automatic Weather Station (37.54°N, 88.80°E) is located northeast of the Ulugh Muztagh area at an altitude of 4300 m. We analyzed daily precipitation data from the Ayak Meteorological Station in the Ulugh Muztagh region. Due to harsh environmental conditions, the monitored meteorological data covers a short time span and contains missing data. Specifically, some years had missing data accounting for 15.1% of days, while others had 15.6% missing data. Therefore, we used the remaining precipitation data for monthly precipitation variation analysis, and the relatively complete dataset from 2013-2018 was used for annual precipitation analysis.

2.2 GDAS Data

The Global Data Assimilation System (GDAS) is an atmospheric model developed by the National Oceanic and Atmospheric Administration (NOAA)'s National Centers for Environmental Prediction (NCEP), using the Global Forecast System (GFS) numerical weather prediction model [citation]. It describes atmospheric states at given times and locations. The GDAS data provides 26 pressure levels from 1000 hPa to 20 hPa, distributed on a global latitude-longitude grid with a spatial resolution of 1°$×$1° and temporal resolution of three hours. These data are well-suited for analyzing water vapor sources and trajectories in different regions worldwide. Therefore, this study selected GDAS data to analyze water vapor sources in the Ulugh Muztagh area, with data provided as free shared data from //arlftp.arlhq.noaa.gov/pub/archives/gdas1.

2.3 HYSPLIT Model

The Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model is developed by NOAA's Air Resources Laboratory (ARL) and the Australian Bureau of Meteorology to calculate particle dispersion and deposition simulations and forward or backward air parcel trajectories. The model has two modes: forward trajectory mode and backward trajectory mode. Backward trajectories trace the path of air masses before reaching the destination, allowing identification of water vapor sources for a region. The air parcel trajectory calculation formula is [citation]:

$$P(t+\Delta t) = P(t) + 0.5[V(P,t) + V(P',t+\Delta t)]\Delta t$$

where $P(t)$ is the initial position at time t, $V(P,t)$ is the velocity vector at position P and time t, Δt is the time step, and $P(t+\Delta t)$ is the final position of the air mass center after time Δt.

To understand water vapor sources in the Ulugh Muztagh area, we established a preliminary relationship between precipitation and air masses by identifying precipitation origins. Using the HYSPLIT software and backward trajectory model, with Ulugh Muztagh (36.40°N, 87.34°E) as the starting point, we set the initial height at 500 m above ground level after multiple trials considering the peak elevation and previous research [citation]. The tracking duration was set to 144 hours, and trajectories were calculated and clustered at daily intervals (UTC 00:00, 12:00, and 18:00) for each season (represented by middle months: January, April, July, and October) from 2005 to 2022.

Clustering involves grouping target trajectories according to similarity principles [citation]. In the TrajStat software, we clustered simulated water vapor trajectories based on point distance principles and total spatial variance (TSV) change curves to obtain water vapor sources and their contributions in the study area, analyzing the spatial distribution characteristics of water vapor sources in the Ulugh Muztagh region.

3 Results

3.1 Annual and Monthly Precipitation Variations

Analysis of annual and seasonal precipitation at the Ayak Meteorological Station reveals that the average precipitation in the region is 201.2 mm, with an annual change rate of 29.7 $\mathrm{mm \cdot a^{-1}}$ (P=0.21). Although precipitation increased substantially over a short period, the trend is not statistically significant due to substantial missing data. Precipitation in the region is concentrated in summer, followed by spring and autumn, with winter receiving the least.

Summer precipitation reaches 156.6 mm, accounting for 77.7% to 80.3% of annual precipitation. Summer precipitation shows a fluctuating increasing trend with an annual change rate of 27.8 $\mathrm{mm \cdot a^{-1}}$ (P=0.21), though this trend is also not statistically significant. Figure 2 [Figure 2: see original paper] illustrates monthly and annual precipitation changes at the Ayak Meteorological Station from 2013 to 2018.

3.2 Water Vapor Source Analysis

To better understand water vapor sources in the region, we categorize them into land-source and sea-source types. This study conducted backward trajectory calculations for water vapor trajectories in the region and performed cluster analysis based on Euclidean distance principles and total spatial variance. As shown in Figure 3 [Figure 3: see original paper], water vapor in the region follows four main paths: southwest, north-northwest, west-northwest, and west, accounting for 21.72%, 36.26%, 26.26%, and 15.76% respectively. The north-northwest direction contributes the largest proportion.

Based on comprehensive consideration of water vapor sources, the west and southwest directions are classified as sea-source, originating from the Atlantic and Indian Oceans, corresponding to the global circulation system's westerly belt and Indian monsoon. Since Indian Ocean water vapor must cross the Himalayas with an average altitude of 4000 m, its trajectory is shorter than that from the Atlantic under the same travel time. The two northwestward paths are primarily land-source, both following the westerly circulation—one crossing the Pamir Plateau, Karakoram, and West Kunlun to reach the eastern Kunlun Mountains' Ulugh Muztagh area, while the other traverses the Tianshan Mountains and Tarim Basin [citation]. The proportion of land-source versus sea-source water vapor reveals that this region is mainly controlled by land-source water vapor, consistent with findings for the endorheic region of the Qinghai-Tibet Plateau [citation].

3.3 Seasonal Variation of Water Vapor Sources

We clustered multi-year average trajectories for each season to analyze seasonal variation characteristics of water vapor trajectories. Using the middle month of each season as representative (January for winter, April for spring, July for summer, and October for autumn), we clustered average trajectories for each season.

As shown in Figure 4 [Figure 4: see original paper], winter's dominant moisture is sea-source water vapor, with southwest Indian monsoon moisture accounting for the largest proportion at 55.97%—more than half of the total moisture—followed by westerly moisture at 26.29%. Land-source moisture from the west constitutes a smaller proportion at 17.74%.

Spring's dominant moisture is land-source, primarily from three directions: north-northwest, west, and northwest. Sea-source moisture is mainly westerly, comprising the majority of the remaining proportion.

Summer differs from other seasons in that land-source water vapor divides into external moisture sources from land areas and moisture from near the study area, typically classified as recycled water vapor. The Qinghai-Tibet Plateau's abundant ice and snow meltwater forms numerous lakes of varying sizes. In summer, increased precipitation and rising temperatures intensify evaporation, and topographic effects facilitate local precipitation formation, making recycled moisture contributions substantial. In the Ulugh Muztagh area, summer recycled water vapor accounts for 22.64% of the total, while northwest land-source moisture contributes the most at 53.26%—more than half of the total. Sea-source moisture is primarily westerly, accounting for 24.10%.

For the 144-hour trajectories at roughly the same altitude, westerly moisture forced by the Qinghai-Tibet Plateau's topography is lifted to approximately 9000 m, forming high-altitude moisture masses that continue eastward under the westerly belt's influence, finally descending to reach the Ulugh Muztagh area. Indian Ocean moisture, however, undergoes multiple sinking and uplift cycles, climbing onto the plateau through convection.

Autumn moisture proportions are more balanced compared to other seasons, though land-source moisture remains dominant at 75.90%. Sea-source westerly and Indian monsoon moisture account for 34.52% and 8.06% respectively, while land-source moisture comes from west and northwest directions at 45.65% and 11.77% respectively, with northwest land-source moisture contributing the most, followed by southwest Indian monsoon moisture.

Overall, westerly moisture proportion is smallest throughout the four seasons, reaching its maximum in winter at 26.29% and minimum in summer at 7.82%. Indian Ocean moisture occurs mainly in autumn and winter, with relatively less contribution in spring and summer. Land-source moisture accounts for the largest proportion, with locally recycled moisture contributions particularly evident in summer. Except for winter when moisture is controlled by sea sources, the other three seasons are dominated by land-source moisture, likely because low winter temperatures are unfavorable for surface evapotranspiration, while warm-season high temperatures enhance it.

3.4 Special Characteristics of Indian Ocean Moisture Movement

Water vapor in the Ulugh Muztagh area includes sea-source (Atlantic and Indian Ocean moisture) and land-source (including recycled moisture). Atlantic moisture is transported to the Ulugh Muztagh area primarily through the westerly circulation at relatively high altitudes during long-distance transport, encountering minimal obstruction. Indian Ocean moisture, originating from the Indian Ocean, must climb over the Himalayas to enter the Qinghai-Tibet Plateau's endorheic region at approximately 4000 m altitude. Compared to westerly moisture, Indian Ocean moisture follows a more tortuous path. This study selected representative trajectories from January and June 2022 for Indian Ocean and westerly moisture respectively for comparative analysis (Figure 5 [Figure 5: see original paper]).

4 Conclusions

This study focuses on the Ulugh Muztagh area of the East Kunlun Mountains, using the HYSPLIT model to trace precipitation water vapor sources. Based on total spatial variance (TSV), we conducted cluster analysis on multi-year average and seasonal average water vapor trajectories to explore moisture sources in the region. Additionally, we performed in-depth analysis of sea-source moisture trajectories from different directions. The main conclusions are:

1) Three primary trajectories enter the Qinghai-Tibet Plateau with the mid-latitude westerly belt: from north to south, these are the Tianshan Mountains route, the Pamir Plateau route, and high-altitude Atlantic moisture, accounting for 36.26%, 26.26%, and 15.76% respectively. Further research is needed to distinguish the impacts of westerly and Indian monsoon circulations on the Ulugh Muztagh area. Indian Ocean moisture must cross the Himalayas to enter the Qinghai-Tibet Plateau's endorheic region at

approximately 4000 m altitude. Compared to westerly moisture, Indian Ocean moisture follows a more tortuous path.

2) Based on multi-year average and seasonal average water vapor trajectory cluster analysis, the Ulugh Muztagh area is primarily controlled by land-source water vapor, accounting for 62.52% of the total, while sea-source water vapor accounts for 37.48%. Locally recycled water vapor contributes significantly in summer, comprising 22.64% of the total.

3) Indian Ocean moisture enters the Qinghai-Tibet Plateau by climbing over the Himalayas through convection, while Atlantic moisture carried by the westerly belt rapidly ascends to the troposphere, undergoing multiple cycles of sinking and uplift before finally entering the plateau's hinterland from high altitudes.

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