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Comparative Analysis of Water Vapor Characteristics of Two Extreme Rainstorm Events in the Northern Foothills of the Kunlun Mountains: Postprint

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Abstract

Using upper-air and surface observational data, surface automatic weather station rainfall data, and National Centers for Environmental Prediction (NCEP) reanalysis data, the circulation patterns, mesoscale systems, water vapor transport, and budget characteristics of two extreme rainfall events in the Hotan region at the northern foot of the Kunlun Mountains—one from May 5-7, 2020 (referred to as the "05 · 06" event) and another from June 14-17, 2021 (referred to as the "06 · 15" event)—were analyzed through water vapor flux diagnostic analysis, backward trajectory models, and other methods. The results indicate that: (1) The two rainfall events shared common characteristics: the influencing system was a Central Asian low vortex in both cases, with water vapor transport originating from the Caspian Sea and Aral Sea regions; the low-level easterly jet in the troposphere played a significant role, with the strongest water vapor convergence concentrated at 700-850 hPa. (2) The two rainfall events also exhibited significant differences: the South Asian High in the "05 · 06" event exhibited a zonal distribution, with water vapor transport pathways being western and easterly, among which the western pathway was most pronounced, contributing 88% of water vapor input through the western boundary; the South Asian High in the "06 · 15" event exhibited a dipole pattern, with water vapor transport pathways being northern and southern, as water vapor from the Arabian Sea and Bay of Bengal was transported northward by southerly airflow, with the southern pathway transport volume far exceeding other pathways, contributing 78% of water vapor input through the southern boundary. (3) Increases in precipitable water (PW) over Hotan, particularly when exceeding average conditions, are indicative of heavy rainfall occurrence; when PW $\geq$ 20 mm, rainstorm or extreme rainstorm events may occur.

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Full Text

Comparative Analysis of Water Vapor Characteristics of Two Extreme Rainstorms on the Northern Slope of Kunlun Mountains

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Abstract: On the basis of the meteorological observation data and the National Centers for Environmental Prediction reanalysis data and using water vapor flux diagnosis analysis and the hybrid single-particle lagrangian integrated trajectory model, two extreme rainstorms that occurred on May 5–7, 2020 (the "05・06" rainstorm), and June 14–17, 2021 (the "06・15" rainstorm), in the Hotan Prefecture, Xinjiang in the north slope of Kunlun Mountains, China were analyzed to study the transport mechanism of water vapor and its budget in the process. The results revealed that (1) the influence system of the two rainstorms was the Central Asian vortex, and they both received water vapor from the Caspian Sea and Aral Sea. During the two rainstorms, there was a clear easterly jet in the lower troposphere, and the strongest water vapor convergence was at the level of 700-850 hPa. (2) The difference between the two rainstorms was that in the "05・06" rainstorm, the South Asia High was banded. Its water vapor transport path was from the west and east, and mainly from the west, because the west path contributed 88% of the total water vapor transport. However, in the "06・15" rainstorm, the South Asia High was bimodal. Its water vapor transport path was from the north and south, and mainly from the south, which contributed 78% of the total water vapor transport. (3) The southerly flow from the Arabian Sea and Bay of Bengal transported water vapor to the north. When the atmospheric precipitable water in the Hotan region increases, particularly exceeding the average state, heavy precipitation may occur. Rainstorm or extreme rainstorm is more likely to occur when the precipitable water is $ $20 mm.

Keywords: extreme rainstorm; north slope of Kunlun Mountains; water vapor source; water vapor transport; vapor budget

Introduction

Meteorologists have conducted extensive research on the formation mechanisms of extreme rainstorms in different regions. Previous studies have shown that extreme rainstorms in China typically occur under specific circulation patterns with favorable configurations of upper, middle, and lower-level jets, where mesoscale convergence and convection serve as direct causes. For instance, extreme rainstorms in the Yangtze River basin often form in convergence zones between low-level southwestern and southeastern jets south of shear lines, while those in the Sichuan Basin are associated with "high east, low west" and "dual high shear" patterns. In Hubei, southwestern water vapor transport channels converge strongly over the rainstorm area, while in Ningxia, precipitation events west of Liupan Mountain are preceded by atmospheric water vapor content exceeding 12.0 mm. Research on southern Xinjiang has identified the Central Asian trough (vortex) as a favorable environmental background field for heavy precipitation, with water vapor from the Caspian Sea, Aral Sea, Bay of Bengal, and South China Sea providing abundant moisture sources through western, southern, and eastern pathways.

However, research specifically focused on the Hotan region remains limited. Located on the northern slope of Kunlun Mountains and the southern edge of the Taklamakan Desert, Hotan covers an area of 24.78×10^{4} km^{2}, with desert and Gobi comprising 63.0% of its territory. The region experiences an arid climate with scarce water resources, extremely harsh natural conditions, and fragile ecological environments, with annual average precipitation below 50 mm. In recent years, under a warming and humidifying climate background, Hotan has experienced frequent spring and summer rainstorms, with some single events producing precipitation exceeding the annual average and even reaching multiples of it. While extreme rainstorm events in southern Xinjiang benefit oasis farmland and mountain pastures by replenishing water and increasing river runoff, they also cause severe flooding and secondary disasters with significant impacts on production and livelihoods. This study compares two extreme rainstorm events in Hotan—the "05 · 06" event (May 5-7, 2020) and the "06 · 15" event (June 14-17, 2021)—to analyze their circulation patterns, water vapor sources, transport pathways, and budgets, thereby enhancing understanding of rainstorm mechanisms on the northern slope of Kunlun Mountains and providing scientific references for forecasting and early warning.

1. Data and Methods

This study utilizes upper-air and surface observation data, automatic weather station precipitation data, and NCEP reanalysis data with $1°\times1°$ spatial resolution. Water vapor flux diagnostic analysis and the HYSPLIT (Hybrid Single-Particle Lagrangian Integrated Trajectory) model were employed to analyze water vapor sources and transport pathways. The HYSPLIT model, developed by Draxler et al., is a comprehensive system for particle trajectory, diffusion, and deposition analysis that uses a Lagrangian approach for advection and diffusion calculations. Its backward trajectory model traces air mass origins, enabling analysis of atmospheric moisture source directions.

For water vapor budget calculations, the study domain was defined as 74°-85°E, 31°-40°N. Water vapor input, output, and net budget were calculated for the lower troposphere (surface-700 hPa), middle troposphere (700-500 hPa), upper troposphere (500-300 hPa), and the entire atmospheric column (surface-300 hPa), with positive values indicating net inflow and negative values indicating net outflow.

2. Analysis of the Two Rainstorm Processes

2.1 Overview of the Two Rainstorm Processes

The "05 • 06" Process: From May 5 20:00 to May 7 20:00, heavy precipitation occurred primarily in the Kashgar region of western southern Xinjiang and Hotan. Cumulative precipitation in Hotan reached 24.1–48.0 mm at 12 stations, with maximum precipitation at Cele Station. Cele recorded 37.7 mm on May 6, ranking second historically for the same period, spring season, and annual maximum daily precipitation. During 18:00–7 03:00, Cele Station received 65.3 mm, constituting a 200-year return period extreme precipitation event. The maximum hourly intensity reached 19.9 mm • h^{-1} (19:00–20:00). Lop Station recorded a maximum daily precipitation of 21.8 mm, ranking second historically.

The "06•15"Process: From June 15 20:00 to June 17 20:00, heavy precipitation concentrated in Kashgar, Kizilsu Kirghiz Autonomous Prefecture, and Hotan. Cumulative precipitation in Hotan reached 24.1–48.0 mm at 24 stations, with 12 stations reporting 48.1–96.0 mm and 2 stations exceeding 96.0 mm. The rainstorm center at Lop Station recorded 74.1 mm, establishing a new historical extreme (Table 1). Lop, Moyu, and Hotan stations all experienced 200-year return period extreme precipitation, breaking historical records and exceeding their annual average precipitation. Lop recorded the maximum hourly intensity of 20.6 mm • h^{-1} (21:00–22:00). The rainstorm caused urban waterlogging, flash floods, and geological disasters, resulting in direct economic losses.

shows the number of stations with different precipitation levels for both events.

[Figure 1: see original paper] illustrates the hourly precipitation at heavy precipitation stations for both processes.

2.2 Upper- and Lower-Level Circulation Configurations

2.2.1 500 hPa Circulation Pattern The "05 • 06" Process: Prior to precipitation, the Eurasian circulation exhibited a "two ridges, one trough" pattern, with ridges over the Caspian Sea, Aral Sea, and Lake Baikal, and a trough over Balkhash Lake. Xinjiang was situated in the southwestern flow ahead of the trough. As the upstream ridge developed, the trough slowly moved eastward and southward into northern Xinjiang by May 6 08:00, with a cold center of -28°C. By May 6 20:00, the trough entered northern Xinjiang, with the cold center maintaining -28°C. Some cold air crossed the Tianshan Mountains into southern Xinjiang. By May 7 08:00, as the Caspian-Aral Sea ridge developed northeastward, the West Siberian trough deepened and split: the northern section formed a vortex near Lake Baikal, while the southern section formed a weak vortex near Tashkurgan, with Lop located near a shear line between northerly and southerly winds. By May 7 20:00, the northern trough moved out of Xinjiang, while the Central Asian trough continued pressing southward, affecting western southern Xinjiang. Hotan was positioned between the westerly flow ahead of the Central Asian vortex and the easterly flow behind the West Siberian trough base, creating an "east-west pincer" pattern.

The "06 • 15" Process: Prior to precipitation, the Eurasian circulation also showed a "two ridges, one trough" pattern, with ridges over the Ural Mountains and Lake Baikal and a deep trough over West Siberia. The circulation exhibited strong meridionality. From June 15 20:00 to June 16 20:00, as the Iranian subtropical high developed and the West Pacific subtropical high extended westward and northward, the vortex near Tashkurgan deepened and intensified, moving into southwestern Xinjiang. By June 17, the vortex weakened into a trough and moved out of southern Xinjiang, ending the precipitation.

In summary, both processes exhibited typical southern Xinjiang heavy precipitation circulation configurations, with the "06 • 15" process showing more pronounced features.

2.2.2 Low-Level Easterly Flow **The "05 • 06" Process:** At 700 hPa, a shear line existed between Kashgar and Aksu on May 6 20:00, with Cele in a warm tongue zone. By May 7 08:00, the shear line persisted with increased wind speeds. At 850 hPa, a shear line was present between Hotan and Ruoqiang on May 6 20:00, with Ruoqiang' s easterly winds reaching 6 $m \cdot s^{-1}$. By May 7 08:00, Ruoqiang' s easterly winds increased to 12 $m \cdot s^{-1}$, forming convergence over eastern southern Xinjiang. By May 7 20:00, Ruoqiang' s easterly winds further increased to 18 $m \cdot s^{-1}$, with the convergence line between Minfeng and Ruoqiang.

The "06 • 15" Process: At 700 hPa on June 15 20:00, northerly winds prevailed from Kashgar to Hotan while easterly winds occurred from Ruoqiang to Minfeng, forming a shear line between Hotan and Minfeng. By June 16 08:00, the shear line remained with increased wind speeds. At 850 hPa on June 15 20:00, northerly winds were present from Kashgar to Minfeng while Ruoqiang maintained easterly winds at 12 $m \cdot s^{-1}$. By June 16 08:00, Ruoqiang' s easterly winds increased to 18 $m \cdot s^{-1}$, forming convergence over eastern southern Xinjiang.

During both rainstorms, the 850 hPa easterly jet was stronger than at 700 hPa, with jet axis wind speeds exceeding 18 $m \cdot s^{-1}$. The "06 • 15" process featured stronger easterly flow, whose convergence with northwesterly winds rapidly concentrated and lifted low-level moisture, producing the extreme rainstorm in Hotan.

2.3 Water Vapor Characteristics

2.3.1 Water Vapor Sources and Transport Intensity Abundant water vapor transport is essential for heavy precipitation. To analyze water vapor sources and transport, vertically integrated water vapor flux was calculated for each layer and from the surface.

The "05 • 06" Process: Water vapor originated primarily from the Mediterranean Sea, Caspian Sea, and Aral Sea. Some moisture entered western southern Xinjiang with the westerly flow ahead of the Central Asian trough, while another portion reached northern Xinjiang via long-distance northerly flow before crossing mountains into western southern Xinjiang. A third portion arrived in eastern Xinjiang and was transported to the rainstorm area via easterly flow. Prior to precipitation (02:00–7 02:00), water vapor flux values exceeded 10×10^{-1} $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$, reaching 15×10^{-1} $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$ during heavy precipitation. At the rainstorm center (Cele Station), maximum water vapor flux divergence reached -10×10^{-6} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}$, concentrated at 700–850 hPa, coinciding with the heavy precipitation period.

The "06 · 15" Process: Water vapor originated from the Norwegian Sea, reaching West Siberia via the Ural Mountains. One portion entered northern Xinjiang and crossed the Tianshan Mountains, while another reached eastern Xinjiang and was transported westward by easterly flow. Moisture from the Bay of Bengal bypassed the western Tibetan Plateau via a southerly path. Prior to precipitation (02:00–7 08:00), water vapor flux values reached 10×10^{-1} $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$, with maximum values of 15×10^{-1} $g \cdot cm^{-1} \cdot hPa^{-1} \cdot s^{-1}$ during heavy precipitation—larger in magnitude and extent than the "05 · 06" process. At Lop Station (80°14 E, 37°03 N), maximum water vapor flux divergence reached -15×10^{-6} $g \cdot cm^{-2} \cdot hPa^{-1} \cdot s^{-1}$ at 600–750 hPa. The stronger mid-to-low level moisture transport was a primary reason for Lop' s greater precipitation intensity.

In summary, the "05 · 06" process featured Mediterranean-Caspian-Aral Sea moisture transported via western and eastern paths, while the "06 · 15" process featured Norwegian Sea and Bay of Bengal moisture via northern and southern paths, with the southern path contributing most significantly.

[Figure 3: see original paper] shows the 700 hPa and 850 hPa wind fields for both processes.

[Figure 4: see original paper] displays the vertically integrated water vapor flux and divergence profiles.

2.3.2 Water Vapor Budget **The "05 · 06" Process:** Analysis of the entire atmospheric column during 02:00–7 20:00 shows water vapor input through western and southern boundaries of 53×10^{6} and 14×10^{6} $kg \cdot s^{-1}$, respectively, and output through eastern and northern boundaries of 27×10^{6} and 40×10^{6} $kg \cdot s^{-1}$. The western boundary contributed 88% of total water vapor input, indicating that moisture transport from the Caspian-Aral Sea to Balkhash Lake region was the dominant source. Input far exceeded output, confirming strong moisture convergence in the rainstorm area.

The "06 · 15" Process: During 08:00–16 08:00, water vapor input through southern and western boundaries was 141×10^{6} and 64×10^{6} $kg \cdot s^{-1}$, respectively, while output through eastern and northern boundaries was 27×10^{6} and 40×10^{6} $kg \cdot s^{-1}$. The southern boundary contributed

78% of total input, demonstrating that the southerly moisture relay transport from the Arabian Sea and Bay of Bengal was extremely abundant. The large excess of input over output indicates substantial moisture convergence.

Both processes showed mid-to-upper level water vapor input through the western boundary before and during precipitation, with low-level input and upper-level output through the eastern boundary during heavy precipitation. The southern boundary showed distinct differences: the "05 • 06" process had upper-level output, while the "06 • 15" process had upper-level input with stronger intensity.

[Figure 5: see original paper] illustrates water vapor transport at each boundary for different tropospheric layers.

2.3.3 Lagrangian Water Vapor Tracking **The "05 • 06" Process:** HYSPLIT backward trajectory analysis for Cele Station shows three main moisture paths: (1) A western path where particles at 3000 m originated from the Caspian-Aral Sea region, reaching eastern Xinjiang and transported to the rainstorm area at ~2000 m; (2) A northern path where particles at 5000 m originated from the Norwegian Sea, crossed the Ural Mountains, and entered northern Xinjiang before crossing the Tianshan Mountains; (3) An eastern path where particles at 1500 m originated from the Kara Sea, entered eastern Xinjiang via Balkhash Lake, and were transported at ~1000 m.

The "06 • 15" Process: Trajectory analysis for Lop Station reveals three paths: (1) A southern path where particles at 5000 m originated from the Arabian Sea and Bay of Bengal, transported northward along the western Tibetan Plateau, continuously lifting due to weather systems and terrain to reach the upper troposphere; (2) An eastern path where particles at 3000 m originated from the Kara Sea, entered eastern Xinjiang via Balkhash Lake, and crossed the northwestern Tibetan Plateau; (3) A northern path where particles at 1500 m originated from Central Asia, crossing the western Tianshan Mountains.

These trajectory analyses corroborate the water vapor transport pathways identified earlier.

[Figure 6: see original paper] shows the 120-hour backward trajectories at different heights for both rainstorm centers.

2.3.4 Precipitable Water Prior to both rainstorms, atmospheric precipitable water (PW) over southern Xinjiang showed increasing trends. For the "05 • 06" process, PW locally reached 25-30 mm, while for "06 • 15" it reached 30 mm. Analysis of Hotan Station PW data shows values increasing above the average before precipitation, remaining above average throughout the event. The "05 • 06" process maximum was 20 mm, while the "06 • 15" maximum was 25 mm.

Analysis of specific humidity temporal variation at heavy precipitation stations shows values of 6 $g \cdot kg^{-1}$ below 850 hPa during both events. At Cele Station, maximum specific humidity occurred near 650 hPa, while at Lop Station, values gradually increased at 700–850 hPa, reaching a maximum of 9 $g \cdot kg^{-1}$ at 08:00 and 20:00, decreasing as precipitation weakened.

When PW increases above average, particularly exceeding 20 mm, it indicates likely heavy precipitation. Increasing specific humidity in the near-surface layer (850 hPa) signals imminent heavy precipitation.

[Figure 7: see original paper] displays PW and specific humidity distributions for both processes.

3. Conclusions

This comparative analysis of two extreme rainstorms on the northern slope of Kunlun Mountains reveals:

1) Both events were influenced by the Central Asian vortex and featured water vapor from the Caspian Sea and Aral Sea. Significant low-level easterly jets were present, with the strongest water vapor convergence concentrated at 700–850 hPa.
2) Distinct differences existed between the events. The "05 • 06" process featured a banded South Asia High, with dominant western path transport contributing 88% of total moisture. The "06 • 15" process featured a bimodal South Asia High, with dominant southern path transport from the Arabian Sea and Bay of Bengal contributing 78% of total moisture.
3) The southerly moisture transport in the "06 • 15" process was transported over long distances to the northern slope of Kunlun Mountains, representing the primary reason for its greater precipitation intensity. Water vapor flux divergence values in mid-to-low levels and at the rainstorm center were larger than in the "05 • 06" process.
4) Both events showed mid-to-upper level moisture input through the western boundary before and during precipitation, with low-level input and upper-level output through the eastern boundary during heavy precipitation. The southern boundary showed marked differences: the "05 • 06" process had upper-level output, while the "06 • 15" process had upper-level input with greater intensity.
5) When atmospheric precipitable water over southern Xinjiang increases above average, particularly exceeding 20 mm, it provides good indication of future heavy precipitation in Hotan. Increasing specific humidity near 850 hPa signals imminent heavy precipitation.

This study provides preliminary insights into water vapor characteristics and indicators for extreme precipitation in the Hotan region. However, further research is needed to fully understand the formation mechanisms of extreme rainstorms on the northern slope of Kunlun Mountains. Future work will focus on improving location-, time-, and quantity-specific forecasting of southern Xinjiang rainstorms, investigating heavy precipitation mechanisms, and applying satellite-retrieved data and high-resolution numerical model simulations to enhance forecasting and early warning capabilities.

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