Spatiotemporal Characteristics of Atmospheric Water Vapor Content on the Southeastern Margin of the Tarim Basin: Postprint

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Abstract

Water vapor, as an important indicator for evaluating precipitation potential, is of great significance for the scientific development of atmospheric water resources in arid regions. To this end, based on ground-based GPS precipitable water vapor data (GPS-PWV) from three stations and hourly water vapor pressure and precipitation data from 73 surface meteorological observation stations in the southeastern Tarim Basin for the period from January 2021 to December 2024, a surface empirical calculation model (W-e) suitable for local conditions was constructed; the spatiotemporal distribution characteristics of atmospheric water vapor content (W-PWV) in the southeastern Tarim Basin and its relationships with precipitation amount, precipitation duration, and their variations were analyzed. The results show that: (1) On annual and seasonal scales, the high-value areas of W-PWV in the southeastern Tarim Basin are located in the plains, followed by the desert regions, with the mountainous regions having the lowest values. (2) At mountain stations, W-PWV decreases with increasing elevation; autumn is the main period of W-PWV increase, while the period of W-PWV decrease varies with elevation, occurring mainly in spring at stations below 3000 m and in summer at stations above 3000 m. (3) In the 6 h before precipitation, at stations south of 38.5°N and above 1500 m elevation, the rate of change of W-PWV is relatively small, but the precipitation efficiency is relatively high. (4) For different precipitation durations, the W-PWV peak in the study area as a whole and in the mountainous region appears 2–3 h before the onset of precipitation, whereas in the plains the W-PWV peak occurs earlier as precipitation duration increases, and in the desert region, with increasing precipitation duration, the W-PWV peak mostly appears before the start of precipitation.

Spatiotemporal Distribution of Water Vapor in the Southeastern Tarim Basin

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Abstract: Water vapor serves as a crucial indicator for evaluating precipitation potential and holds significant importance for the scientific development of atmospheric water resources in arid regions. Based on ground-based GPS atmospheric precipitable water vapor (GPS-PWV) data from three stations in the southeastern Tarim Basin spanning January 2021 to December 2024, along with hourly water vapor pressure and precipitation records from 73 surface meteorological observation stations, we constructed a localized empirical ground-based calculation model (W-e) to analyze the spatiotemporal characteristics of atmospheric water vapor content (W-PWV) and its relationship with precipitation amount and duration at annual and seasonal scales. The results reveal: (1) High-value W-PWV zones are located in plain regions, followed by desert regions, with mountainous regions exhibiting the lowest values. (2) W-PWV decreases with increasing altitude, with autumn representing the primary growth period across all elevations. The timing of W-PWV reduction varies by altitude: stations below 3000 m show decreases primarily in spring, while those above 3000 m decrease in summer. (3) South of 38.5°N and above 1500 m elevation, the W-PWV variation rate is relatively small, but the precipitation conversion efficiency is substantial. (4) Under different precipitation durations, the W-PWV peak in the study area and mountainous regions consistently appears 2–3 hours before precipitation onset. In plain regions, the W-PWV peak occurs progressively earlier with increasing precipitation duration, whereas in desert regions, the peak tends to appear later as precipitation duration increases.

Keywords: atmospheric water vapor; precipitation conversion efficiency; spatiotemporal characteristics; southeastern Tarim Basin

Introduction

Atmospheric water vapor constitutes a necessary condition for cloud formation and precipitation. Its variation not only directly influences the spatiotemporal distribution patterns of precipitation and their response to climate change but also serves as a critical basis for assessing atmospheric water resource potential. Previous studies have demonstrated that ground-based GPS remote sensing of precipitable water vapor (GPS-PWV) can reliably reflect spatiotemporal variations in atmospheric moisture. However, in some regions, relevant water vapor observations have short time series and limited station coverage, restricting the utilization of GPS-PWV data. Consequently, researchers have employed ground-based empirical relationship methods, combining high-temporal-resolution GPS observations with high-spatial-resolution surface meteorological data to analyze atmospheric water vapor variations across different regions. These studies have revealed seasonal and diurnal water vapor patterns and highlighted differences between precipitation and non-precipitation days, providing important reference information for assessing cloud water resources and forecasting short-duration heavy precipitation.

China' s water resources exhibit significant spatiotemporal heterogeneity, particularly in northwestern arid regions where water scarcity has become a critical factor limiting high-quality economic and social development. Atmospheric water resources, which can be directly intervened and utilized through artificial means, hold substantial development potential. Therefore, scientific analysis of atmospheric water vapor distribution and evolution, along with timely monitoring of atmospheric water resource conditions, is essential for guiding weather modification operations, accelerating atmospheric water resource development, and alleviating water shortages.

The southeastern Tarim Basin borders the Taklamakan Desert to the north, the Kunlun and Altyn Mountains to the south, and connects to the Qaidam Basin in the east. This region features complex underlying surfaces including high mountains, Gobi deserts, and oases, representing one of Xinjiang's most environmentally harsh areas and a crucial transportation corridor. Located deep within the continent, the southeastern Tarim Basin experiences an arid climate with scarce precipitation. Under the combined influence of unique topography and atmospheric circulation, complex water vapor transport pathways have formed, making the region highly sensitive to climate change. Consequently, water vapor variations in this area significantly impact regional water security, ecological balance, and local economic development and livelihoods.

Previous studies on atmospheric water vapor in the southeastern Tarim Basin have primarily relied on single-station analysis due to limitations in observation methods and data availability. The applicability of reanalysis-derived precipitable water vapor products has not been validated in this region. Moreover, ground-based GPS water vapor observations have short time series and limited station coverage, failing to encompass the entire southeastern Tarim Basin. Consequently, research on the spatial distribution of atmospheric water vapor and its relationship with precipitation remains relatively scarce in this region and its surroundings.

As global warming intensifies, climate in arid and semi-arid regions has shifted from warm-dry to warm-wet conditions. However, increasing temperatures and evaporation rates continue to exacerbate water scarcity issues. Clarifying the relationship between atmospheric water vapor and precipitation in the southeastern Tarim Basin is crucial for understanding hydrological cycles and guiding scientific development of atmospheric water resources. This study utilizes ground-based GPS-PWV data, hourly surface water vapor pressure, and precipitation observations to construct an empirical model (W-e) for atmospheric water vapor content applicable to this region. By analyzing the distribution characteristics of W-PWV and its relationship with precipitation in this arid region, we aim to provide valuable reference for meteorological services and weather modification operations in arid areas.

1. Data and Methods

1.1 Data Selection

The study employs sounding, ground-based GPS atmospheric water vapor data, and surface meteorological observations from January 2021 to December 2024. Precipitable water vapor (PWV) data from radiosonde observations at Ruoqiang station were obtained from the University of Wyoming (weather.uwyo.edu). Hourly water vapor pressure and precipitation data were provided by the Xinjiang Meteorological Information Center. To ensure data quality, stations were required to have observational records exceeding 75% of total annual hours. Statistical analysis shows that cumulative observation hours at Ruoqiang (collocated with the sounding station), Qiemo, and Tazhong stations all exceed 75% of total hours, with most other stations reaching approximately 95%. Overall data completeness is satisfactory. For subsequent analyses, all stations were processed using identical annual, monthly, daily, and hourly averaging procedures to represent the study area, with missing data excluded from calculations.

Seasons are defined as spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). Based on underlying surface characteristics and elevation, stations are classified into three types: desert stations (within the Taklamakan Desert), plain stations (surrounding the desert), and mountain stations (Kunlun-Altyn Mountain region) (Table 1,).

Table 1 Classification basis for stations in the study area

Region/Station Type	Classification Criteria
Desert stations	Located in the Taklamakan Desert interior; surface dominated by desert and sand dunes with no vegetation; relatively flat terrain; elevation <1100 m
Plain stations	Located around the Taklamakan Desert; surface dominated by grassland and cropland with surrounding trees and herbaceous vegetation; flat, open terrain; elevation <1500 m

Region/Station Type	Classification Criteria
Mountain stations	Located in the Kunlun-Altyn Mountains and surrounding areas; surface dominated by Gobi and rock with surrounding shrubs and herbaceous vegetation; complex terrain; elevation >1500 m

Note: Base map produced using standard map from Ministry of Natural Resources, map approval number GS(2023)2767, with no modifications to boundaries.

1.2 Research Methods

1.2.1 GPS-PWV Data Applicability Analysis Statistical methods including root mean square error (RMSE), mean absolute deviation (MAD), mean bias (MB), and coefficient of determination (R^2) were employed to validate the applicability of GPS-PWV data. Using Ruoqiang station as a representative site, we compared GPS-PWV and radiosonde-derived PWV (RS-PWV) at 08:00 and 20:00 BT to verify model accuracy and ensure scientific rigor. The formulas are:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)^2}$$

$$\mathrm{MAD} = \frac{1}{n}\sum_{i=1}^{n}|x_i - y_j|$$

$$\mathrm{MB} = \frac{1}{n}\sum_{i=1}^{n}(x_i - y_i)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}\right]^2$$

where x_i represents the GPS-PWV average, y_i represents the RS-PWV calculated from sounding data, $\bar{x}$ and $\bar{y}$ are the respective mean values, and σ_x and σ_y are the standard deviations.

Comparison of GPS-PWV and RS-PWV at Ruoqiang station at 08:00 and 20:00 (with 1,096 and 1,093 matched samples, respectively) revealed R^2 values of 0.96 and 0.94, mean absolute deviations of 1.4 mm and 1.5 mm, mean biases of 0.2 mm and 2.2 mm, and RMSE values of 1.9 mm and 2.8 mm. These results demonstrate good consistency between GPS-PWV and RS-PWV at Ruoqiang station, indicating that GPS-PWV can effectively compensate for the spatiotemporal limitations of sounding data.

1.2.2 Model Calculation Method Based on previous research, the formula for calculating atmospheric water vapor content W from surface water vapor pressure e can be simplified as $W = a \times e$, where a is an undetermined coefficient. Linear regression between ground-based GPS-PWV and surface water vapor pressure at collocated stations (Ruoqiang, Qiemo, and Tazhong) shows good correspondence (Table 2,), with correlation coefficients of 0.95, 0.93, and 0.92, respectively. The scatter plots reveal a strong linear relationship between atmospheric water vapor content and surface water vapor pressure, with an R^2 of 0.90 (Figure 3, [Figure 3: see original paper]). The relationship is expressed as:

$$W = 1.8 \times e$$

Using this formula, atmospheric water vapor content W (hereafter referred to as W-PWV) can be derived from surface water vapor pressure at each station in the study area.

Table 2 Comparison of W-PWV and RS-PWV at Ruoqiang station at 08:00 and 20:00 from 2021–2024

Time	R^2	MB (mm)	MAD (mm)	RMSE (mm)
08:00	0.96	0.2	1.4	1.9
20:00	0.94	2.2	1.5	2.8

1.2.3 Relationship Between Water Vapor Content and Precipitation Evolution The abrupt change process of water vapor content shows good correlation with precipitation events, with dramatic changes in atmospheric moisture occurring before and after precipitation at observation stations. The hourly maximum W-PWV value provides certain indicative significance for short-term forecasting of precipitation onset. A precipitation event is defined as occurring when precipitation $ $0.1 mm with intervals exceeding 2 hours, with the duration defined as precipitation length. The period from 6 hours before precipitation onset until precipitation cessation is considered precipitation-influenced time, with other periods being non-precipitation-influenced time. The difference between the time of maximum W-PWV occurrence and precipitation onset is recorded as the lead time.

To scientifically guide atmospheric water resource development, the relationship between atmospheric water vapor variation and precipitation amount can be analyzed by calculating the ratio of cumulative precipitation to cumulative atmospheric water vapor content during precipitation events:

$$P = \frac{\mathrm{PS}}{\mathrm{PW}} \times 100\%$$

where P represents precipitation conversion efficiency (%), PS represents observed precipitation amount (mm), and PW represents atmospheric water vapor content (mm).

2. Results and Analysis

2.1 Model Validation and Assessment

The time series comparison shows consistent distribution patterns between GPS-PWV and W-PWV (Figure 4, [Figure 4: see original paper]). Both show rapid decline from January to February, gradual increase from March to July, rapid growth from August to September, and maintenance at low levels from October to December. Overall, the W-e model based on GPS-PWV and surface water vapor pressure demonstrates scientific validity and rationality, with calculated W-PWV results effectively reflecting temporal water vapor characteristics in the southeastern Tarim Basin.

2.2 Spatial Distribution Characteristics of Water Vapor

The annual average W-PWV in the study area ranges from 7.2 to 10.0 mm, with most stations in plain regions (Figure 5, [Figure 5: see original paper]). Western areas contain more stations, with desert stations showing similar values (mostly 7.2–9.0 mm), while mountainous stations have the lowest values, generally below 7.2 mm. W-PWV decreases with increasing longitude east of 85°E and with increasing altitude above 1500 m. Since W-PWV is derived from cumulative water vapor throughout the atmospheric column, and relative column thickness decreases with altitude, high-elevation areas generally exhibit lower water vapor content.

Seasonally, all regional stations show maximum W-PWV in summer (generally >10.0 mm), followed by spring and autumn (mostly 5.0–9.0 mm), with minimum values in winter (all <4.0 mm). This pattern likely relates to enhanced Tibetan Plateau monsoon and northward movement of warm, moist airflow from lower latitudes during summer, while winter experiences minimal water vapor transport due to polar front influence and weakened westerlies.

Further analysis dividing plain stations into eastern and western subgroups and mountain stations by altitude (Table 3,) reveals that both eastern and western plain stations show increasing annual trends, though western stations decrease in spring while eastern stations decrease in summer. Mountain stations show decreasing W-PWV with altitude, with stations below 3000 m decreasing in spring and those above 3000 m decreasing in summer, while all mountain stations increase in autumn and winter, with maximum growth rates in autumn.

Table 3 Annual and seasonal W-PWV changes in various regions of the southeastern Tarim Basin

Region	Annual (mm)	Spring (mm)	Summer (mm)	Autumn (mm)	Winter (mm)
Desert stations	8.0	-0.2	0.3	0.5	0.1
Plain stations (West)	8.5	-0.3	0.2	0.4	0.2
Plain stations (East)	8.2	0.1	-0.1	0.3	0.3
Mountain stations (<2000 m)	6.8	-0.2	0.1	0.4	0.2
Mountain stations (2000–3000 m)	6.2	-0.3	0.0	0.5	0.3
Mountain stations (>3000 m)	5.5	0.0	-0.2	0.6	0.4

2.3 Temporal Variation Characteristics

2.3.1 Monthly and Seasonal Variations Monthly average W-PWV shows a single-peak pattern across the study area and all subregions (Figure 7, [Figure 7: see original paper]), slowly increasing from January to July, rapidly decreasing after September, and maintaining low levels in winter. Maximum and minimum values occur in July and December, respectively, with a difference exceeding 10.0 mm. Mountain regions show smaller monthly variations, consistent with the annual spatial distribution pattern.

The study area and all subregions show maximum change rates in September. During autumn, prevailing northeasterly or easterly winds at middle-lower levels may increase water vapor input from the northeast. Plain regions may experience significant autumn and winter water vapor changes under the climatic background of summer "warm-drying" and winter "cold-wetting" trends in Xinjiang.

2.3.2 Diurnal Variation Diurnal anomaly variations show consistent patterns across regions (Figure 8, [Figure 8: see original paper]), with higher values maintained at night (00:00–10:00) and reaching minimum values at 15:00–18:00. Peak timing varies by season: spring and summer peaks occur at 08:00–10:00 in plain and desert regions, 23:00 in mountain regions, and 09:00–10:00 for the entire study area. Autumn peaks in plain regions and the study area appear at 17:00–19:00, while winter peaks in desert regions and the study area occur at 15:00.

Amplitude analysis reveals summer has the largest diurnal variation across all regions, likely due to large diurnal temperature differences over desert and Gobi surfaces that accelerate daytime evaporation and increase water vapor content, followed by rapid temperature drops after sunset that reduce moisture. Mountain regions show larger peaks in autumn in addition to summer. Spring and summer humidification occurs mainly at night, while winter humidification occurs primarily during daytime. Mountain regions show significant time lags in humidification periods compared to other regions, possibly related to valley winds and seasonal precipitation patterns.

2.4 Relationship Between Water Vapor and Precipitation

2.4.1 Variations Under Precipitation and Non-Precipitation Influence Under precipitation influence, diurnal variation trends in plain regions are similar to the study area, decreasing slightly from 00:00 to 09:00, reaching a minimum at 09:00, then increasing slightly to a peak at 18:00 (Figure 9, [Figure 9: see original paper]). Mountain regions show minimum values 3 hours later and peaks 2 hours earlier. Desert regions show no significant difference compared to precipitation-influenced conditions. Under non-precipitation influence, plain regions and the study area show stable variations, while desert and mountain regions exhibit single-peak patterns with "daytime decrease and nighttime increase" characteristics.

2.4.2 Relationship with Precipitation Conversion Efficiency and Duration Analysis of the relationship between W-PWV variation rate and precipitation conversion efficiency shows that conversion efficiency decreases significantly with increasing W-PWV variation rate (Figure 10, [Figure 10: see original paper]). For every 1.0 $\mathrm{mm \cdot h^{-1}}$ increase in variation rate, precipitation conversion efficiency decreases by 0.24%. Spatially, variation rate increases with latitude and decreases with altitude, while conversion efficiency shows the opposite pattern. Stations south of 38.5°N and above 1500 m generally exhibit low variation rates and high conversion efficiencies.

The lead time of maximum W-PWV relative to precipitation onset increases with precipitation duration in plain regions but decreases in desert regions. In mountain regions, maximum W-PWV consistently appears 2–3 hours before precipitation across different duration categories. In plain regions, for precipitation events lasting 2–5 hours, maximum W-PWV appears about 2 hours before onset, while for events exceeding 6 hours, it appears about 5 hours before onset. In desert regions, the opposite pattern occurs, with lead times decreasing as precipitation duration increases.

3. Discussion

The W-e model constructed using ground-based GPS water vapor and surface water vapor pressure data reveals spatiotemporal W-PWV characteristics across different underlying surfaces in the study area. Annual and monthly W-PWV values in desert stations are similar to those in plain stations but significantly higher than in mountain stations, consistent with previous research findings. This pattern may result not only from altitude-related differences in atmospheric column thickness but also from frequent sunny weather and shallow groundwater tables in desert and plain areas that provide substantial surface evaporation. Additionally, atmospheric moisture concentrates in the lower troposphere, making overhead water vapor more abundant than in surrounding mountainous areas.

The core methodology of weather modification involves altering cloud microphysical structures without changing macroscale precipitation mechanisms to enhance rainfall, indicating that suitable target clouds are those already precipitating or likely to precipitate. Since higher precipitation conversion efficiency regions in arid areas are more likely to produce suitable operational cloud systems, the temporal characteristics of W-PWV and its evolution with precipitation suggest that intensive weather modification operations conducted during summer and autumn in areas south of 38.5°N and above 1500 m could further promote atmospheric water resource development.

This preliminary analysis of local water vapor variation processes based on precipitation, topography, and three variables should be expanded in future research to include additional environmental variables such as temperature and wind speed for deeper mechanistic analysis, providing scientific support for understanding water cycle processes in extremely arid regions.

4. Conclusions

(1) The W-e model effectively calculates annual and seasonal average W-PWV values. Low-value zones are located in high-altitude mountain regions of the southeastern Tarim Basin, while high-value zones occur in plain regions, with desert regions showing intermediate values. This indicates that atmospheric water vapor content is significantly influenced by altitude but less affected by underlying surface differences.

(2) The southeastern Tarim Basin and its plain regions show similar temporal evolution trends, particularly during summer when precipitation is

concentrated. However, mountain and desert regions exhibit significantly different trends from plain areas, demonstrating strong regional specificity and indicating that underlying surface differences substantially influence temporal water vapor variations.

(3) Under different precipitation durations, maximum W-PWV appearance times are relatively consistent between the study area and mountain regions but differ in desert regions. In plain regions, the lead time of maximum W-PWV increases with precipitation duration, indicating that topographic and geomorphological factors significantly influence the impact of atmospheric water vapor on precipitation in the southeastern Tarim Basin.

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