Spatiotemporal variations of total atmospheric water content over Tibet from 1980 to 2024 - postprint

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Abstract

The Second Tibetan Plateau Scientific Expedition and Research has revealed the scientific facts of the imbalance of the "Asian Water Tower" and the warming-wetting trend. Tibet is a sensitive and key region for climate and eco-environmental changes. Understanding the spatiotemporal variation patterns of total atmospheric water content is of great significance for safeguarding the ecological security barrier of Tibet and advancing the construction of an ecological civilization highland. Using ERA5 reanalysis data for 1980-2024, and applying the regional averaging method, EOF decomposition, Mann-Kendall test, and linear trend analysis, this study investigates the spatiotemporal characteristics of total atmospheric water content over Tibet. The results show that: (1) Total atmospheric water content over Tibet exhibits pronounced spatial heterogeneity, with the annual mean total atmospheric water content dropping sharply from a maximum of 38.3 mm in southeastern Tibet to a minimum of 2.0 mm in northwestern Tibet, and with the strongest spatial variability occurring in southeastern Tibet. (2) Based on EOF decomposition, among the first three spatial modes, only the first mode in summer, autumn, and winter reflects a spatially coherent pattern across the whole of Tibet, and the evolution of the corresponding temporal coefficients indicates an increasing trend in total atmospheric water content; all other spatial modes exhibit opposite spatial patterns of change. (3) In terms of spatial trend patterns, summer and autumn show a significant increasing trend in total atmospheric water content over most areas of Tibet, with summer increases exceeding 0.3 mm $\cdot$ $(10a)^{-1}$ across the majority of the region. (4) Regionally averaged total atmospheric water content displays a significant increasing trend in spring, summer, autumn, and on the annual scale, and this increasing trend can be characterized as an abrupt change, with the specific onset years being 2003, 2006, 2016, and 2006, respectively.

Spatiotemporal Changes in Atmospheric Total Water Content in Xizang from 1980 to 2024

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Abstract

The Second Scientific Expedition on the Qinghai-Xizang Plateau revealed the scientific fact of the Asian Water Tower' s imbalance and warming-wetting trend. Xizang is a sensitive and critical region for climate and eco-environmental changes. Mastering the spatiotemporal variation patterns of atmospheric total water content is of great significance for constructing ecological security barriers and highland ecological civilization in Xizang. Based on ERA5 reanalysis data from 1980 to 2024, this study investigates the spatiotemporal variation characteristics of atmospheric total water content in Xizang using regional averaging, EOF decomposition, Mann-Kendall testing, and linear trend analysis. The results show that: (1) The annual-mean atmospheric total water content exhibits significant spatial heterogeneity, decreasing sharply from a maximum of 38.3 mm in southeastern Xizang to a minimum of 2.0 mm in northwestern Xizang, with the most intense spatial variation occurring in southeastern Xizang. (2) Among the first three EOF spatial modes, only the first modes of summer, autumn, and winter show consistent variation across the entire Xizang region, while other modes exhibit opposite spatial patterns. The temporal coefficients of the first modes suggest an increasing trend in atmospheric total water content. (3) In terms of spatial trend patterns, most regions of Xizang show significant increasing trends in atmospheric total water content during summer and autumn, with increases exceeding 0.3 $\mathrm{mm} \cdot (10\mathrm{a})^{-1}$ in most areas. (4) The regionally averaged atmospheric total water content shows significant increasing trends in spring, summer, autumn, and annually, which can be identified as abrupt changes starting in 2003, 2006, 2016, and 2006, respectively.

Keywords: atmospheric total water content; spatiotemporal distribution; variation characteristics; ERA5; Xizang

1. Introduction

The Qinghai-Xizang Plateau and its surrounding areas, known as the “Asian Water Tower,” constitute an important ecological security barrier and strategic resource reserve base in China. The plateau plays a crucial role in maintaining climate system stability, water resource supply, and biodiversity protection. As the source of many major Asian rivers—including the Yangtze, Yellow, Indus, Lancang (Mekong), and Ganges—the plateau’ s unique cross-hemispheric atmospheric water cycle constructs the Asian Water Tower and a unique atmospheric-hydrological functional system in surrounding regions. Research indicates that the plateau is a key region for global energy and water vapor exchange, and its special atmospheric water circulation significantly influences weather and climate systems in China, East Asia, and globally.

Atmospheric total water content refers to the sum of all gaseous, liquid, and solid water in an atmospheric column, including precipitating water substances. Massive atmospheric total water content constitutes the material basis of atmospheric water cycling, and anomalies in atmospheric total water content inevitably cause changes in local atmospheric water cycle processes. Water cycling is one of the most important material cycles on Earth. Atmospheric water substances absorb or release latent heat through phase changes, with cloud water condensation latent heat release driving atmospheric circulation and requiring energy. From a weather modification perspective, atmospheric total water content includes water vapor and cloud water, leading to concepts of hydrometeors and cloud water resources.

Based on the above discussion, this study analyzes the spatiotemporal variation patterns of atmospheric total water content in Xizang under climate change. The findings provide important references for research on water cycling, extreme precipitation, evapotranspiration, and weather modification, and are of great significance for constructing ecological security barriers and highland ecological civilization in Xizang.

1.1 Data Sources

This study analyzes spatiotemporal variation characteristics of atmospheric total water content in Xizang using ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF). The dataset used is the monthly total column water (TCW) from 1980 to 2024, with a horizontal spatial resolution of 0.25°$×$0.25°. ERA5 is the fifth-generation global atmospheric reanalysis for climate and weather, representing one of the most advanced and widely used global atmospheric reanalysis datasets currently available. Compared with its predecessor (ERA-Interim) and other reanalysis datasets, ERA5 shows significant improvements in spatiotemporal resolution, data accuracy, assimilation technology, and variable richness, demonstrating superior performance. This dataset has been widely applied in meteorology, hydrology, oceanography, energy, and ecological environment research. Studies have validated the applicability of ERA5 data through comparisons with surface observations, upper-air observations, and satellite data.

Atmospheric total water content (TCW) refers to the sum of water vapor, cloud liquid water, cloud ice water, rain, and snow in an atmospheric column extending from the Earth' s surface to the top of the atmosphere. Expressed as mass per unit area ($\mathrm{kg} \cdot \mathrm{m}^{-2}$), it is equivalent to the thickness of a water layer formed if all atmospheric water content were condensed to the surface (where $1\ \mathrm{kg} \cdot \mathrm{m}^{-2} = 1\ \mathrm{mm}$). TCW reflects the water storage capacity of the atmospheric column and is crucial for studying water cycling, extreme precipitation, and evapotranspiration processes. The higher-version model used in ERA5 incorporates rainfall, snowfall, and all cloud phases, providing more complete coverage of atmospheric water substances. TCW is calculated by integrating the mixing ratios of each component:

$$TCW = \frac{1}{g} \int_{p_{surf}}^{0} (q_{vap} + q_{cliq} + q_{cice} + q_{rain} + q_{snow}) dp$$

where q represents the mixing ratio of each component ($\mathrm{kg} \cdot \mathrm{kg}^{-1}$), p is pressure (Pa), and g is gravitational acceleration. For discrete model levels, the commonly used formula is:

$$TCW \approx \frac{1}{g} \sum_{i} q_i \Delta p_i$$

where Δp_i is the pressure difference of model layer i, and q_i is the sum of mixing ratios of water vapor, cloud liquid water, cloud ice water, rain, and snow in that layer.

1.2 Research Methods

Regional Averaging Method: The regional average over the Xizang geographical domain is calculated by averaging only the grid values within Xizang boundaries after processing.

Empirical Orthogonal Function (EOF) Decomposition: EOF decomposition has no fixed functions and offers advantages including fast convergence, concentration of variable field information into a few modes, and physically meaningful spatial structures. It is widely applied in atmospheric science research. The natural orthogonal expansion of a meteorological field decomposes X into a time function Z and a spatial function V, i.e., $X = VZ$. The empirical orthogonal functions are tested for significance using eigenvalue error ranges. At the α significance level, the error range for eigenvalue λ_j is:

$$e_j = \lambda_j \sqrt{\frac{2}{n}}$$

where n is the sample size, and e_j is the error of the jth eigenvalue λ_j. Eigenvalues satisfying $\lambda_j - e_j > \lambda_{j+1} + e_{j+1}$ are considered distinct. When $\lambda_j - e_j \geq \lambda_{j+1} + e_{j+1}$, the empirical orthogonal functions corresponding to these two eigenvalues are considered valuable signals.

Mann-Kendall Test: The Mann-Kendall test is a non-parametric statistical test commonly used for abrupt change detection. Its advantages include simple calculation, clear identification of when abrupt changes begin, and indication of change regions.

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2. Results and Analysis

2.1 Spatial Distribution of Atmospheric Total Water Content in Xizang

Figure 1 shows that the seasonal mean spatial fields of atmospheric total water content in Xizang exhibit a consistent pattern decreasing from southeastern to northwestern Xizang, with the most intense spatial variation in southeastern Xizang. Regional averages are highest in summer, followed by autumn, spring, and winter (Table 1). In spring, the maximum value reaches 35.6 mm in southeastern Xizang, decreasing to 1.4 mm in northwestern Xizang, with a regional average of 5.2 mm. Summer, autumn, and winter spatial fields show maximum values of 59.3 mm, 38.2 mm, and 19.9 mm, respectively, decreasing to 4.3 mm, 4.0 mm, and 0.6 mm in northwestern Xizang, with regional averages of 11.0 mm, 7.5 mm, and 1.9 mm, respectively. Additionally, the annual-mean atmospheric total water content shows a maximum of 38.3 mm in southeastern Xizang, decreasing to a minimum of 2.0 mm in northwestern Xizang, with a regional average of 5.5 mm.

The spatial distribution pattern of atmospheric total water content in Xizang is similar to the spatial distribution of precipitation, related to topographic forcing (blocking, disturbance, etc.) by mountains and water vapor transport. Simulation results of complex terrain effects on water vapor transport and precipitation over the Xizang Plateau show that, compared with flat terrain areas, steep slopes of the Himalayas shift uplifted airflow northward, thereby shifting precipitation northward. Complex terrain reduces inward and outward water transport, with numerous small-scale valleys forming channels for water vapor transport across the Himalayas, further facilitating northward precipitation shift and increasing the net water transport to the Xizang Plateau by about 25%. Additionally, windward and leeward slopes critically affect precipitation, particularly pronounced in the Xizang Plateau under the influence of the southwest monsoon. These factors collectively form the spatial distribution pattern of atmospheric total water content in Xizang.

To further understand the spatial distribution, we calculated the coverage area and area percentage of different threshold values for seasonal mean atmospheric total water content in Xizang. Results show that the threshold ranges with largest coverage areas are 7.5-10.0 mm in spring (35.0%-62.8% of total area), 2.5-5.0 mm in summer (~75.8$×10^{4}$ km^2, 62.8%), 1.0-2.5 mm in autumn (48.5$×10^{4}$ km^2, 42.2%), and 1.0-2.5 mm in winter (40.2%). Conversely, the smallest coverage areas occur at 35.0-50.0 mm in spring (0.14$×10^{4}$ km^2, <0.1%), 35.0-50.0 mm in summer (1.22$×10^{4}$ km^2, 1.0%), 7.5-10.0 mm in autumn (0.14$×10^{4}$ km^2, 0.1%), and 2.5-5.0 mm in winter (0.14$×10^{4}$ km^2, 0.1%). These data further confirm the significant seasonal and spatial heterogeneity of atmospheric total water content in Xizang.

2.2 Spatiotemporal Characteristics of Atmospheric Total Water Content in Xizang

To understand spatiotemporal distribution, we performed EOF decomposition on seasonal atmospheric total water content in Xizang, obtaining four spatial modes with eigenvalues, error ranges, and variance contributions (Table 2). Significance testing shows that the first three modes for all four seasons pass the 95% confidence level.

In spring, the first EOF mode shows opposite spatial distribution between east-central northern Xizang and other regions—when atmospheric total water content increases in east-central northern Xizang, it decreases elsewhere, with relatively strong intensity changes in north-central Nyingchi City (Figure 3a). The second mode shows consistent variation across most of Xizang, with weak opposite variation only in central western Xizang and stronger intensity changes in southeastern Xizang (Figure 3b). The third mode also shows consistent variation across most of Xizang, with weak opposite variation in south-central Xizang (Figure 3c). The first mode accounts for 59.4% of variance, with its temporal coefficient showing more negative-phase years before the 1980s and more positive-phase years after the 1990s, suggesting an increasing trend. The cumulative variance contribution of the first three modes reaches 89.5%, indicating they well represent the spatial distribution characteristics of spring atmospheric total water content in Xizang.

In summer, the first EOF mode shows consistent spatial variation across Xizang (Figure 3d). The second mode shows opposite variation between western Xizang and other regions (Figure 3e). The third mode shows opposite variation between eastern and western Xizang with good symmetry (Figure 3f). The first mode accounts for 62.8% of variance, with its temporal coefficient showing more negative-phase years before 2000 and more positive-phase years after 2000, implying an increasing trend in summer atmospheric total water content. The cumulative variance contribution of the first three modes reaches 89.7%.

In autumn, the first mode shows consistent variation across Xizang (Figure 3g). The second mode shows opposite variation between eastern and western Xizang (Figure 3h). The third mode shows opposite variation between south-central Xizang plus parts of northwestern Xizang and other regions (Figure 3i). The first mode accounts for 70.7% of variance, with temporal coefficient characteristics similar to summer but weaker intensity, also implying an increasing trend. The cumulative variance contribution reaches 90.9%.

In winter, the first mode shows consistent spatial variation across Xizang (Figure 3j). The second mode shows opposite variation between north-central Xizang and other regions, with strong spatial variation in southeastern Xizang (Figure 3k). The third mode shows opposite variation between eastern and western Xizang (Figure 3l). The first mode accounts for 57.0% of variance, with temporal coefficients showing sustained 3–5 year positive/negative phase variations. The cumulative variance contribution reaches 87.5%.

Overall, among the first three spatial modes for the four seasons, only the first modes of summer, autumn, and winter show consistent variation across Xizang (simultaneous increase or decrease), while other modes show opposite spatial distributions. The first modes have variance contributions of 57%–70%, with temporal coefficients of summer and autumn first modes showing obvious positive-phase enhancement trends, implying increasing atmospheric total water content.

2.3 Trend Analysis

2.3.1 Seasonal and Annual Linear Trends To understand interannual variation trends, we calculated regional averages from annual seasonal and annual spatial fields, obtaining five time series. Linear regression was performed to estimate trends, yielding regression coefficients and constants (Figure 4). All five series show increasing trends, with regression coefficients of 0.05, 0.12, 0.08, 0.02, and 0.07 $\text{mm} \cdot (10\text{a})^{-1}$ for spring, summer, autumn, winter, and annual means, respectively. Correlation coefficients with time are 0.37, 0.67, 0.53, 0.15, and 0.55, respectively. Significance testing shows that spring, summer, autumn, and annual trends pass the 99.9% significance level, while the winter trend does not pass significance testing, indicating the winter increase is not statistically significant.

2.3.2 Abrupt Change Detection To better understand the trend changes, we applied the Mann-Kendall test to regionally averaged time series for four seasons and the annual mean, calculating and plotting UF and UB curves (Figure 5). The UF curves show that atmospheric total water content in all seasons experienced a fluctuating pattern of initial decrease followed by increase, with more years showing increase than decrease. Spring has maintained an increasing trend since 1998, exceeding the significance level after 2012. Based on the intersection point of UF and UB curves, this increase can be identified as an abrupt change beginning in 2003 (Figure 5a). Summer has maintained an increasing trend since 2000, exceeding significance after 2008, with the UF and UB curves intersecting in 2006, indicating an abrupt change beginning in 2006 (Figure 5b). Autumn has maintained an increasing trend since 2000, oscillating near the significance level until 2012 when it stably exceeds the level, with the UF and UB curves intersecting in 2016, indicating an abrupt change beginning in 2016 (Figure 5c). Winter has increased since 2000 but only stabilized after 2013, without exceeding significance level, with multiple UF and UB intersections preventing determination of an abrupt change (Figure 5d).

For the annual-mean series (Figure 5e), atmospheric total water content also experienced initial decrease followed by increase, maintaining an increasing trend since 2000 and exceeding significance after 2008. The UF and UB curves intersect in 2006, indicating an abrupt change beginning in 2006.

According to the Clausius-Clapeyron equation, atmospheric water-holding capacity increases exponentially with temperature. Studies show that a 0.2°C increase in tropical southeastern Indian Ocean surface temperature since 2001 caused anomalous upward motion and enhanced low-level convergence, with warmer air accommodating more water vapor. The South Asian summer monsoon index shows a strengthening trend, indicating increased Indian summer monsoon precipitation intensity and more water vapor transport from the Indian Ocean and Bay of Bengal to Xizang. These mechanisms provide preliminary physical explanations for the increasing trends and abrupt changes in spring, summer, autumn, and annual atmospheric total water content in Xizang.

2.3.3 Spatial Variation Trends To understand spatial field variation characteristics, we calculated regression coefficients for grid-point time series across Xizang, showing spatial distributions of temporal trends. Areas passing the 95% confidence level are shaded gray (Figure 6).

In spring, most of north-central Xizang shows significant increasing trends, with values gradually increasing from northwest to southeast from less than 0.05 to over 0.2 mm $\cdot$ $(10a)^{-1}$. The maximum center is located in a small area from southern Lhasa to northern Shannan. Southeastern Xizang and parts of western Xizang show non-significant increasing trends (Figure 6a).

In summer, most of Xizang shows significant increasing trends, except for a small area in south-central Nyingchi City in southeastern Xizang. Increasing values exceed 0.3 mm $\cdot$ $(10a)^{-1}$ in most areas, with central western Xizang exceeding 0.4 mm $\cdot$ $(10a)^{-1}$ (Figure 6b).

In autumn, most of Xizang shows significant increasing trends, except for small areas in southern Nyingchi City and southeastern Shannan City. Increasing values range from less than 0.1 mm $\cdot$ $(10a)^{-1}$ in northwestern Xizang to over 0.2 mm $\cdot$ $(10a)^{-1}$ in southeastern Xizang, with a small area in southern Shannan exceeding 0.4 mm $\cdot$ $(10a)^{-1}$ (Figure 6c). The spatial trend patterns in summer and autumn correspond to the first EOF modes and temporal coefficient characteristics.

In winter, most of Xizang shows no significant increase or decrease, with significant increasing areas of less than 0.05 mm $\cdot$ $(10a)^{-1}$ only in northern Chamdo, eastern Nagqu, southeastern Lhasa, western Nyingchi, northern Shannan, and southeastern Xigazê. Southern Shannan and southwestern Nyingchi even show decreasing areas, though not significant (Figure 6d).

3. Discussion

From 1980 to 2024, the spatial distribution of atmospheric total water content in Xizang shows a consistent pattern decreasing from southeast to northwest. Regional average seasonal and annual trends show that larger atmospheric total water content corresponds to more significant increasing trends, while the small atmospheric total water content in winter shows non-significant increasing trends. Spatial trend patterns show similar characteristics, with larger values showing more significant increasing trends. In summer, central western Xizang shows increasing trends up to 0.4 mm $\cdot$ $(10a)^{-1}$. However, in small areas of southeastern Xizang, annual and seasonal increasing trends are non-significant, with even decreasing trends in winter.

The spatial distribution pattern is consistent with the "east-west dipole pattern" of water resources distribution on the Qinghai-Xizang Plateau proposed by Bao et al. and the diversified characteristics of warming-wetting trends across the plateau based on surface precipitation observations by Li et al. The spatial trend patterns relate to conclusions by Li Lin that precipitation efficiency is highest in summer and lowest in winter.

The inconsistent EOF modes may relate to monsoon-induced changes in water vapor transport location onto the plateau. For example, Sun et al. found that under Indian summer monsoon influence, precipitation in eastern and western plateau shows opposite characteristics: in strong (weak) monsoon years, anomalous upward motion strengthens (weakens) in western plateau, causing anomalous water vapor convergence (divergence) and more (less) precipitation, while eastern plateau shows opposite anomalies. This mechanism may form the inconsistent EOF modes of atmospheric total water content in Xizang.

The increasing trends in annual and seasonal atmospheric total water content further confirm the warming-wetting trend of the Qinghai-Xizang Plateau. Abrupt change detection identifies these increases as abrupt changes in spring, summer, autumn, and annually. Monitoring data show that Xizang' s average precipitation increased significantly from 2000 to 2023, with increases of 9.55 mm in spring and 25.3 mm in summer, consistent with our conclusions. Studies show that compared with temperature, precipitation changes on the Qinghai-Xizang Plateau have stronger seasonal and regional differences, with summer precipitation increase being most significant, related to different weather systems and circulation patterns across seasons and regions. Liu and You diagnosed that over eastern China, hydrometeors are mainly contributed by evaporation and vertical water vapor convection from southern subregions, while northern subregions are most significantly contributed by evaporation and horizontal water vapor advection. Whether similar mechanisms exist for the spatiotemporal differences in atmospheric total water content over Xizang requires further investigation.

As the "Asian Water Tower," Xizang' s water resource system is a complex large system, and atmospheric total water content is an important component of Earth' s water resources. This study analyzes spatiotemporal distribution characteristics of atmospheric total water content in Xizang, laying a foundation for subsequent research on regional transport dynamics of atmospheric water substances. In-depth exploration of the causes and mechanisms of spatiotemporal distribution changes in atmospheric total water content under climate change is fundamental for high-precision hydrological modeling and prediction on the plateau.

4. Conclusions

This study uses ERA5 reanalysis data and methods including regional averaging, Empirical Orthogonal Function (EOF) decomposition, and linear trend analysis to examine spatiotemporal distribution and climatic characteristics of atmospheric total water content in Xizang under climate change. The main conclusions are:

1) Influenced by topographic forcing, atmospheric total water content in Xizang shows strong spatial heterogeneity. Seasonal and annual atmospheric total water content consistently decreases from southeastern to northwestern Xizang, with the most intense spatial variation in southeastern Xizang. Annual-mean atmospheric total water content decreases sharply from a maximum of 38.3 mm in southeastern Xizang to a minimum of 2.0 mm in northwestern Xizang.

2) Controlled by Indian summer monsoon water vapor transport changes, seasonal distribution differences in atmospheric total water content are substantial. In spring, the 7.5-10.0 mm threshold range has the largest coverage area (35.0%-62.8%); in summer, 2.5-5.0 mm covers the largest area (~75.8$×10^{4}$ km^2, 62.8%); in autumn, 1.0-2.5 mm covers the largest area (48.5$×10^{4}$ km^2, 42.2%); and in winter, 1.0-2.5 mm covers the largest area (40.2%).

3) After spatiotemporal separation, among the first three spatial modes for the four seasons, only the first modes of summer, autumn, and winter show consistent variation across Xizang (simultaneous increase or decrease), while other modes show opposite spatial distributions. The consistency modes have large variance contributions (57%-70%), and their temporal coefficients show increasing positive signals, implying increasing trends in

atmospheric total water content.

4) In terms of annual and seasonal trends, atmospheric total water content in Xizang shows increasing trends. After testing, spring, summer, autumn, and annual increases pass the 99.9% significance level, while winter increase does not pass significance testing, indicating the winter trend is not statistically significant.
5) In terms of spatial trend patterns, most regions of Xizang show significant increasing trends in summer and autumn, with increases exceeding 0.3 mm $\cdot$ $(10a)^{-1}$ in most areas. Mann-Kendall testing identifies the increasing trends in spring, summer, autumn, and annual atmospheric total water content as abrupt changes beginning in 2003, 2006, 2016, and 2006, respectively.

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