Spatiotemporal Variation Characteristics of Atmospheric Water Deficit in Xinjiang Over the Past 60 Years: Postprint

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Date: 2023-02-27T00:00:00+00:00

Abstract

Against the backdrop of increasing global terrestrial atmospheric water deficit (VPD) that will continue to intensify, whether the atmospheric environment in Xinjiang is trending toward aridification warrants investigation. Using surface meteorological observation data from 1961–2020 and employing methods such as linear trend analysis and Mann-Kendall test, this study examines the distribution and spatiotemporal evolution characteristics of VPD in Xinjiang. The results indicate: (1) Over the past 60 years, VPD in Xinjiang has exhibited a significant increasing trend overall, with an increase rate of 0.015 kPa · (10a)-1. An abrupt change in VPD occurred in 2005, characterized by weak fluctuation before the breakpoint and an increasing trend thereafter. (2) VPD in all seasons shows a predominant increasing trend, with larger increases in spring and summer and the smallest increase in winter. The abrupt change characteristics of VPD in spring and autumn are relatively consistent with the annual variation, while in summer it occurs slightly later (breakpoint in 2006). (3) In terms of spatial distribution, VPD displays a distinct pattern of "low in mountainous areas, high in basins" . Spatiotemporal evolution analysis reveals that VPD exhibits an increasing trend across vast areas of Xinjiang (at nearly 83.65% of meteorological stations), while stations showing a decreasing VPD trend are mainly distributed on the northern piedmont of the eastern Tianshan Mountains and the northern and northwestern margins of the southern Xinjiang basin. At the seasonal scale, spring shows the highest proportion of stations with increasing VPD (96.15%), representing the period with the most extensive atmospheric water stress across Xinjiang, whereas atmospheric water vapor content remains relatively stable in winter.

Spatiotemporal Variations of Vapor Pressure Deficit in Xinjiang in Recent 60 Years

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Abstract

Research has confirmed that global terrestrial vapor pressure deficit (VPD) has increased and will continue to intensify. Against this backdrop, whether the atmospheric environment in Xinjiang is trending toward aridification warrants investigation. Using ground meteorological observation data from 1961 to 2020, this study employs linear trend analysis and Mann-Kendall testing to examine the distribution and spatiotemporal evolution characteristics of VPD in Xinjiang. The results indicate: (1) The annual mean VPD in Xinjiang shows a significant increasing trend with a rate of 0.015 $\text{kPa}\cdot(10\text{a})^{-1}$. An abrupt change occurred around 2005, characterized by weak fluctuating changes before the mutation and a persistent increasing trend thereafter. (2) Seasonal VPD intensity varies significantly, though all seasons exhibit increasing trends. Spring and summer show larger increases, while winter shows the smallest 增幅. The abrupt change characteristics in spring and autumn align closely with annual variations, while summer’ s abrupt change occurred slightly later (in 2006). (3) Spatially, VPD displays a distinct pattern of “low in mountains and high in basins.” The long-term evolution trend shows spatial heterogeneity, with approximately 83.65% of meteorological stations showing increasing VPD. Stations with decreasing trends are mainly distributed along the northern foothills of the eastern Tianshan Mountains and the northern/northwestern edges of the Tarim Basin. On the seasonal scale, spring has the highest proportion of stations with increasing trends (96.15%), indicating it is the period when atmospheric moisture stress affects the widest area in Xinjiang. In contrast, winter VPD remains relatively stable. This study reveals the evolution of VPD in Xinjiang under the significant climate shift from warm-wet to warm-dry conditions, providing a reference for reducing uncertainties in predicting changes in ecosystem structure and function.

Keywords: vapor pressure deficit (VPD); variation trend; abrupt change analysis; spatiotemporal evolution; Xinjiang

1 Introduction

Vapor pressure deficit (VPD) refers to the difference between saturation vapor pressure and actual vapor pressure at a given temperature, representing atmospheric moisture stress and serving as an effective indicator of atmospheric drought. Recent studies indicate that under the combined influence of continuously rising temperatures and decreasing ocean evaporation, global terrestrial VPD has increased exponentially since the late 1990s, exceeding 11.26% of global vegetated areas. Research has confirmed that atmospheric moisture stress is a crucial meteorological factor affecting terrestrial vegetation growth. Compared with soil moisture and precipitation, plant physiological characteristics and growth conditions may be more sensitive to atmospheric moisture stress. As an important driver of plant water demand, increasing VPD has significantly impacted vegetation growth and productivity. High VPD may trigger stomatal closure to prevent water loss, leading to reduced stomatal conductance and xylem hydraulic conductivity, thereby weakening photosynthesis and plant growth. Simultaneously, under high VPD conditions, plant transpiration rates and underlying surface soil moisture loss rates increase, subjecting vegetation growth to more severe water stress, limiting carbon absorption and water use, and causing vegetation mortality. The persistent growth of VPD reduces global vegetation growth, leading to decreased primary productivity worldwide and negatively impacting global gross primary productivity (GPP). The regulatory effects of VPD on global terrestrial carbon sinks, its limiting effects on forest carbon uptake and transpiration, and its negative impacts on gross primary productivity in typical grassland ecosystems in China have been successively confirmed. Therefore, clarifying the spatiotemporal evolution characteristics of VPD under climate change is crucial for managing drought risks and reducing uncertainties in predicting future land carbon sequestration and climate change. However, current VPD research primarily focuses on global or national scales, with insufficient detailed revelation of evolution patterns at regional scales.

Xinjiang, located deep in the Eurasian continent far from oceans, constitutes the main body of China' s arid regions. With complex and diverse natural environments and climate types, Xinjiang exhibits extreme disparities in water and heat distribution, making it one of the world' s most ecologically fragile regions where vegetation is highly dependent on water and heat conditions, particularly moisture. Over the past half-century, against the backdrop of global warming, Xinjiang' s climate has undergone an obvious "warm-wet transition" and "wet-dry shift," with significant increases in average and extreme temperatures, and fluctuations in precipitation and evaporation. Changes in temperature and precipitation affect VPD by increasing saturation vapor pressure or altering relative humidity, thereby impacting the fragile regional ecosystem. Therefore, investigating the distribution characteristics and changing trends of atmospheric moisture stress in Xinjiang helps reveal the evolution patterns of atmospheric drought under climate transition, providing references for comprehensively predicting changes in vegetation habitats. This study aims to calculate and evaluate the distribution and evolution trends of VPD in Xinjiang based on ground meteorological observation data to preliminarily understand the dry-wet conditions of Xinjiang' s atmospheric environment.

2 Study Area and Data

2.1 Data Sources and Processing

The original meteorological observation station data used in this study were obtained from the Xinjiang Uygur Autonomous Region Meteorological Information Center, including monthly observations from 105 national benchmark meteorological stations in Xinjiang from 1961 to 2020. The data have undergone strict quality control and meet research accuracy requirements. Stations with continuous missing data for two years or more were removed (totaling 4 stations). For other stations with missing data, multiple regression analysis was applied for interpolation to ensure data continuity and uniformity.

The monthly VPD series for each meteorological station was calculated using the following formula:

$$VPD = 0.611 \times \exp\left(\frac{17.27 \times T_A}{T_A + 237.3}\right) \times (1 - RH)$$

where VPD is vapor pressure deficit (kPa), T_A is air temperature (°C), and RH is relative humidity (%). Monthly VPD series for each station were averaged to obtain seasonal and annual mean series. The annual (seasonal) mean VPD for the entire region represents the average across all meteorological stations.

2.2 Methods

2.2.1 Linear Trend Estimation The linear trend estimation method was used to analyze the temporal variation trends of annual and seasonal VPD. The method is expressed as:

$$Slope = \frac{n \sum iX_i - \sum i \sum X_i}{n \sum i^2 - (\sum i)^2}$$

where X_i is the VPD value in year i, n is the total number of years in the study period, and $Slope$ is the linear regression coefficient. $Slope > 0$ indicates an upward trend over time, with larger values representing greater rates of change. $Slope < 0$ indicates a decreasing trend. This method was also applied to analyze spatiotemporal evolution patterns and rates of change at annual and seasonal scales, with meteorological stations serving as the analytical units.

2.2.2 Mann-Kendall Test The Mann-Kendall test was employed to detect and extract abrupt change information from VPD time series and compare differences in trends before and after mutations. This non-parametric statistical test is largely unaffected by outliers and sample distribution, computationally simple, and capable of both trend detection and abrupt change point identification. It has been widely applied in hydrological and meteorological analyses.

The test was applied to annual and seasonal mean VPD series to identify mutation points and analyze stage characteristics.

2.2.3 Spatial Interpolation The ANUSPLIN software was used for spatial interpolation of meteorological station-scale annual mean VPD series to generate gridded data with 0.5° × 0.5° resolution for visualizing Xinjiang' s atmospheric drought patterns. ANUSPLIN is specialized climate data interpolation software that introduces elevation as a covariate, achieving high interpolation accuracy. Seasons were defined as: spring (March-May), summer (June-August), autumn (September-November), and winter (December-February).

3 Results

3.1 Temporal Variation Characteristics of VPD in Xinjiang

Linear trend analysis reveals that from 1961 to 2020, the annual mean VPD in Xinjiang showed a significant increasing trend with a rate of 0.015 kPa•$(10a)^{-1}$. The multi-year average was 0.658 kPa, with a maximum of 0.771 kPa in 2020 and a minimum of 0.477 kPa in 1961. To determine whether the trend exhibited stage differences, Mann-Kendall mutation testing was applied to the annual mean VPD series. The test statistic (UF) shows the statistical value calculated from the forward series, while UB represents the value from the reverse series. An increasing trend is indicated when UF > 0, and a decreasing trend when UF < 0. If $|UF| > |U\alpha|$ (where Uα is the critical value at significance level α), the trend is statistically significant. The intersection point between UF and UB within the critical value range indicates the mutation point.

The test results show that VPD underwent an abrupt change in 2005. Before the mutation (1961-2005), VPD showed non-significant fluctuating changes with a rate of -0.001 kPa•$(10a)^{-1}$. After the mutation (2006-2020), the increasing rate accelerated significantly to 0.014 kPa•$(10a)^{-1}$.

Seasonal variations show that mean VPD values from high to low are: summer (1.535 kPa), spring (1.076 kPa), autumn (0.838 kPa), and winter (0.667 kPa). Trend analysis indicates that all seasonal VPD series exhibit significant increasing trends, with spring and summer showing larger increases at rates of 0.027 kPa•$(10a)^{-1}$ and 0.022 kPa•$(10a)^{-1}$, respectively, while winter shows the smallest increase at 0.004 kPa•$(10a)^{-1}$. Seasonal VPD also shows stage characteristics, though mutation times vary slightly. Spring and autumn mutations occurred in 2005, consistent with annual changes. Summer' s abrupt change occurred later in 2006. Winter shows multiple UF-UB intersections without a clear mutation point, reflecting relatively stable VPD during this season.

3.2 Spatial Distribution and Evolution of VPD

3.2.1 Spatial Distribution of Annual Mean VPD Spatial interpolation results based on ANUSPLIN software show distinct spatial heterogeneity in annual mean VPD. Low-value areas (VPD < 0.5 kPa) are mainly distributed in mountainous regions, particularly in the humid and semi-humid Tianshan and Altai Mountains, indicating relatively abundant atmospheric moisture. In contrast, the Gobi, desert, and sandy areas in northern and southern Xinjiang show consistently high VPD (VPD > 0.7 kPa) due to water scarcity and sparse vegetation, indicating varying degrees of atmospheric moisture stress. Piedmont plain areas mostly range between 0.5-0.9 kPa.

3.2.2 Spatial Variation Characteristics From the spatial pattern perspective, VPD shows an overall increasing trend across most of Xinjiang, with 83.65% of stations exhibiting Slope > 0. Among these, 66.35% show statistically significant increases ($p < 0.05$), accounting for 79.31% of all stations with increasing trends. This indicates a widespread intensification of atmospheric drought across Xinjiang during the study period. Stations with decreasing trends account for only 16.35%, scattered along the northern slopes of the eastern Tianshan Mountains and the northern/northwestern edges of the Tarim Basin, with 47.06% of these showing significant decreases.

Seasonally, areas with increasing VPD far exceed those with decreasing trends in all seasons. The proportions of stations with increasing trends in spring, summer, autumn, and winter are 96.15%, 80.77%, 74.04%, and 80.77%, respectively, with over 80% passing significance tests in each season. Spring shows the most extensive atmospheric drought stress across Xinjiang, followed by autumn and winter. Notably, localized areas along the northern foothills of the eastern Tianshan Mountains and the northern edge of the Tarim Basin show reversed trends from increase to decrease in summer, indicating some relief from atmospheric drought intensity in these regions.

4 Discussion

4.1 VPD Accuracy Verification

To verify the reliability of VPD calculated from meteorological station observations, this study obtained global 0.5° × 0.5° gridded temperature and actual vapor pressure data (CRU TS v. 4.05) from the Climatic Research Unit (CRU) at the University of East Anglia. VPD_{CRU} was calculated using the same method and compared with station-based VPD. Correlation analysis shows good linear relationships between the two datasets ($R = 0.690$, $p < 0.001$), with high consistency in interannual variation trends, particularly after 2000 when differences in both magnitude and trend narrowed further. Spatially, both datasets show the distinct pattern of low VPD in mountains and high VPD in basins.

This comparison confirms that VPD series calculated from Xinjiang meteorological station observations are reliable for regional atmospheric drought assessment. However, some differences exist: VPD_{CRU} values are generally higher than station values before 1990, and CRU data show smaller spatial variability. These discrepancies likely stem from differences in base data, processing methods, and spatial resolution.

4.2 VPD Distribution and Evolution Patterns

The spatial distribution pattern of VPD is influenced by topography and land cover types. Northern Xinjiang’ s mountainous areas have abundant precipitation and high vegetation coverage. Vegetation transpiration enhances atmospheric humidity, while vegetation’ s regulatory effect on surface temperature inhibits saturation vapor pressure increase, maintaining relatively stable regional VPD. Southern Xinjiang’ s mountainous areas are dominated by snow and ice cover; warming-induced accelerated melting likely prevents atmospheric moisture deficiency. Additionally, high vegetation or snow/ice coverage in mountainous areas increases surface water content and water-holding capacity, sustaining evapotranspiration and replenishing atmospheric moisture. In contrast, the Gobi, desert, and sandy areas in the basins have sparse vegetation, scarce water resources, high temperatures, low precipitation, strong sunshine, and intense evaporation, resulting in very low relative humidity and consequently high VPD.

Trend analysis shows that VPD in Xinjiang increased significantly during the study period. Under global warming, Xinjiang’ s temperature has risen continuously and substantially, while precipitation increases have slowed since the late 20th century, with potential evapotranspiration intensifying. Since the 21st century, drought frequency has increased in southern and eastern Xinjiang, atmospheric moisture sources have decreased, and drought severity has increased. Meanwhile, the Tianshan Mountains and Pamir Plateau have shown “wetting” trends, leading to localized VPD decreases. Seasonally, spring and summer VPD increases are more prominent, while winter shows the weakest increase. Studies indicate that “warming-drying” phenomena were common in Xinjiang during spring and summer over the past half-century, while winter tended toward “cooling-wetting.” These seasonal climate differences directly affect the temporal heterogeneity of VPD trends. Other climate-induced factors, such as accelerated snow/ice melt, surface runoff changes, and vegetation growth variations, may also contribute to spatiotemporal differences in VPD evolution and warrant further investigation.

The VPD trend shows clear stage characteristics. During the first stage (1961-2005), increased precipitation largely compensated for moisture loss caused by rising temperatures, maintaining weak VPD fluctuations. During the second stage (2006-2020), temperatures remained high while precipitation growth rates decreased substantially, weakening the “warm-wetting” process and triggering a “wet-dry shift” transition. The moisture supplementation effect of precipitation on surface and atmospheric water content weakened significantly, leading to gradually increasing atmospheric drought. Thus, Xinjiang’ s VPD conditions are closely linked to its climate transition.

5 Conclusions

Based on meteorological station observation data, this study analyzed the distribution and spatiotemporal evolution of VPD in Xinjiang from 1961 to 2020. The main conclusions are:

1. The annual mean VPD in Xinjiang showed a significant increasing trend with a rate of 0.015 $\text{kPa} \cdot (10\text{a})^{-1}$. An abrupt change occurred around 2005, with weak fluctuating changes before the mutation and a persistent increasing trend thereafter.
2. Seasonal mean VPD values from high to low were summer, spring, autumn, and winter. All seasonal VPD series showed increasing trends, with spring and summer having larger increases (0.027 and 0.022 $\text{kPa} \cdot (10\text{a})^{-1}$, respectively) and winter having the smallest increase (0.004 $\text{kPa} \cdot (10\text{a})^{-1}$). Spring VPD increases were most extensive, affecting 96.15% of stations.
3. VPD spatial distribution and evolution showed heterogeneity. VPD was generally low in mountains and high in the Gobi, desert, and sandy areas of northern and southern Xinjiang. Approximately 83.65% of stations showed increasing VPD trends, with only localized areas along the northern foothills of the eastern Tianshan Mountains and the northern/northwestern edges of the Tarim Basin showing decreasing trends.
4. Comparison with CRU gridded data confirmed the reliability of station-based VPD calculations. Land cover type, vegetation coverage, climate transition stages, and regional climate differences, along with climate-induced changes in glaciers and surface runoff, are potential factors causing heterogeneity in VPD spatial distribution and evolution patterns.

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