Variation Characteristics and Influencing Factors of Atmospheric Vapor Pressure Deficit in the Kaidu-Kongque River Basin, Xinjiang over the Past 60 Years: Postprint

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Abstract

Based on monthly temperature and relative humidity observational data from 1961 to 2021 in the Kaidu-Kongque River Basin, Xinjiang, this study analyzes the variation trends of atmospheric vapor pressure deficit, saturated vapor pressure, and actual vapor pressure in the Kaidu-Kongque River Basin, explores the variation characteristics of atmospheric vapor pressure deficit under mountain, oasis, and desert environments, and reveals the influencing factors of atmospheric vapor pressure deficit variation. The results show that: (1) From 1961 to 2021, the annual and seasonal atmospheric vapor pressure deficit in the Kaidu-Kongque River Basin showed an overall increasing trend with phased variation characteristics, with an abrupt change occurring in 1997, shifting from a decreasing trend during 1961–1996 to an increasing trend during 1997–2021, indicating intensified atmospheric drought after 1997, particularly in spring. (2) The variation trend of atmospheric vapor pressure deficit under different environments is consistent with the variation trends of temperature and actual vapor pressure, with the largest growth rate of atmospheric vapor pressure deficit occurring in the desert environment, followed by oasis and mountain environments. (3) Atmospheric vapor pressure deficit is positively correlated with temperature variation and negatively correlated with relative humidity variation; the rapid temperature increase and sharp relative humidity decrease since 1997 are the main causes of the accelerated rise in atmospheric vapor pressure deficit; furthermore, the growth rate of actual vapor pressure is smaller than that of saturated vapor pressure. The research findings contribute to a deeper understanding of atmospheric drought processes and their response relationships to climate change.

Full Text

Preamble

Changes in Atmospheric Vapor Pressure Deficit and Its Influencing Factors in the Kaidu-Kongque River Basin, Xinjiang over the Past 60 Years

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Abstract: Based on monthly temperature and relative humidity observations from 1961 to 2021 in the Kaidu-Kongque River Basin of Xinjiang, this study analyzes the changing trends of atmospheric vapor pressure deficit (VPD), saturated vapor pressure, and actual vapor pressure. We examine VPD variation characteristics across mountainous, oasis, and desert environments and identify the key factors influencing these changes. The results show that: (1) Annual and seasonal VPD exhibited an overall upward trend with distinct phase changes, with an abrupt shift occurring in 1997. The trend reversed from a decline during 1961–1996 to a significant increase during 1997–2021, indicating intensified atmospheric drought after 1997, particularly pronounced in spring. (2) VPD trends across different environments align with temperature and actual vapor pressure changes, with the most rapid increase observed in desert environments, followed by oasis and mountainous areas. (3) VPD changes are positively correlated with temperature and negatively correlated with relative humidity. The accelerated rise in temperature coupled with rapid decline in relative humidity since 1997 represents the primary driver of increasing VPD, compounded by the fact that the growth rate of actual vapor pressure lags behind that of saturated vapor pressure. These findings contribute to a deeper understanding of atmospheric drought processes and their response to climate change.

Keywords: Vapor Pressure Deficit (VPD); actual vapor pressure; variation characteristics; influencing factors; Kaidu-Kongque River Basin

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Introduction

Atmospheric vapor pressure deficit (VPD) represents the difference between saturated vapor pressure (es) and actual vapor pressure (ea) at a given temperature, reflecting the degree of water vapor saturation in the atmosphere and indicating air dryness. According to IPCC assessment reports, limiting global warming to 1.5°C presents unprecedented challenges. Global surface temperatures have risen by 1.1°C, leading to increased saturated vapor pressure and consequently driving continuous growth in VPD. As a key indicator of atmospheric drought and an important climate regulator of ecosystem photosynthesis, VPD reflects atmospheric aridity and plant evapotranspiration stress, significantly influencing plant transpiration and grassland carbon flux variations in semi-arid regions. Research demonstrates that increased atmospheric water vapor deficit affects global vegetation growth, with extreme heat critically impacting corn yields in the United States. In forest ecosystems, atmospheric moisture demand more strongly limits soil hydraulic conductivity and evapotranspiration than soil moisture. These findings underscore VPD's crucial role in climate and ecosystem dynamics.

Xinjiang, located in the arid northwestern interior of China and the Eurasian continent, is highly sensitive to climate change and represents a typical ecologically vulnerable region. While global warming is unequivocal, Xinjiang's climate "warming and wetting" trend has attracted widespread attention. Studies indicate that Xinjiang experienced a significant dry-to-wet transition during 1961–2015, with increased annual precipitation and reference crop evapotranspiration, alleviating drought conditions. However, seasonal patterns reveal complex changes: spring has become significantly drier, autumn significantly wetter, while summer and winter show wetting trends. For the Kaidu-Kongque River Basin specifically, research shows rising extreme temperature indices, decreasing diurnal temperature range and extreme low temperature indices, but no significant changes in extreme precipitation indices, though consecutive dry days have significantly decreased.

Recent VPD research has primarily focused on global or national scales, with limited studies at the watershed scale. While climate change studies in the Kaidu-Kongque River Basin have advanced, VPD research remains scarce despite its important implications for regional atmospheric drought and vegetation water status. This study analyzes trends in VPD and related variables (temperature, relative humidity, saturated and actual vapor pressure) from 1961 to 2021 in the Kaidu-Kongque River Basin, examines VPD variation characteristics across mountainous, oasis, and desert environments, and identifies key influencing factors. The results provide valuable insights for improving scientific understanding of regional climate change and atmospheric drought processes.

1. Data and Methods

1.1 Data Sources

The Kaidu-Kongque River Basin, an important component of the Tarim River system, is located in Bayingolin Mongol Autonomous Prefecture, Xinjiang, covering parts of Hejing, Hoshud, Yanqi, Baghrash, Korla, and Yuli counties. The basin extends from 82°57 –90°39 E to 40°25 –43°21 N, with the Kaidu River in the northwest and Kongque River in the southwest. Elevation varies dramatically from 700–4800 m, with a multi-year average temperature of 7.3–10.9°C and annual precipitation of 47.3–270.0 mm concentrated in summer. The region exhibits significant warming and fluctuating precipitation increases.

This study utilizes monthly temperature and relative humidity observations from 1961 to 2021 at eight meteorological stations: Bayinbuluke, Baluntai, Hejing, Hoshud, Yanqi, Korla, Yuli, and Tikanlik [Figure 1: see original paper]. These stations represent three distinct environments: mountainous (Bayinbuluke, Baluntai), oasis (Hejing, Hoshud, Yanqi, Korla), and desert (Yuli, Tikanlik). All meteorological data underwent strict quality control and are suitable for climate change analysis.

1.2 Methods

1.2.1 Calculation of VPD, Saturated Vapor Pressure, and Actual Vapor Pressure VPD is defined as the difference between saturated and actual vapor pressure. We calculated monthly saturated vapor pressure (es), actual vapor pressure (ea), and VPD for each station using the following formulas:

$$es = 0.611 \exp\left(\frac{17.27 \times Ta}{Ta + 237.5}\right)$$

$$ea = es \times \frac{RH}{100}$$

$$VPD = es - ea$$

where es is saturated vapor pressure (kPa), ea is actual vapor pressure (kPa), Ta is air temperature (°C), RH is relative humidity (%), and VPD is vapor pressure deficit (kPa).

1.2.2 Statistical Analysis We employed the non-parametric Sen's slope estimator to analyze linear trends in VPD, saturated vapor pressure, actual vapor pressure, temperature, and relative humidity. The Mann-Kendall method was used for change-point detection and significance testing of trends, with $p < 0.05$ considered statistically significant. Partial correlation analysis was applied to determine the influence of climatic factors on VPD changes. The partial correlation coefficient was calculated as:

$$R_{xy,z} = \frac{R_{xy} - R_{xz}R_{yz}}{\sqrt{(1 - R_{xz}^2)(1 - R_{yz}^2)}}$$

where x represents VPD (dependent variable), and y and z represent temperature and relative humidity (independent variables). R_{xy,z} denotes the partial correlation between x and y while controlling for z; R_{xy}, R_{xz}, and R_{yz} are simple correlation coefficients between respective variable pairs.

2. Results

2.1 Trends in Temperature and Relative Humidity

Annual mean temperature in the Kaidu-Kongque River Basin increased at a rate of 0.217°C · decade^{-1} from 1961 to 2021, with significant spatial variation [Figure 2: see original paper]. The desert region exhibited the greatest warming (0.282°C · decade^{-1}), substantially exceeding the basin average, followed by the oasis region (0.216°C · decade^{-1}). The mountainous region showed the smallest increase (0.154°C · decade^{-1}). All sub-regions experienced warming across all seasons, with winter showing the most pronounced trend (0.309°C · decade^{-1}), followed by spring (0.257°C · decade^{-1}). Summer and autumn trends were similar at 0.169°C · decade^{-1} and 0.129°C · decade^{-1}, respectively .

Relative humidity trends showed contrasting patterns across environments [Figure 3: see original paper]. The oasis region experienced a slight increase (0.122% · decade^{-1}), while mountainous and desert regions exhibited decreasing trends of -0.085% · decade^{-1} and -0.207% · decade^{-1}, respectively. Seasonally, summer, autumn, and winter relative humidity increased across the basin, while spring showed a decreasing trend .

2.2 Trends in VPD, Saturated Vapor Pressure, and Actual Vapor Pressure

Annual VPD in the Kaidu-Kongque River Basin increased at 0.007 kPa · decade^{-1}, with significant inter-environmental differences [Figure 4: see original paper]. The desert region showed the fastest growth (0.018 kPa · decade^{-1}), followed by the oasis (0.003 kPa · decade^{-1}) and mountainous regions (0.002 kPa · decade^{-1}). Seasonal VPD trends varied, with spring showing the most rapid increase (0.015 kPa · decade^{-1}), followed by summer (0.007 kPa · decade^{-1}). Winter and autumn showed smaller increases of 0.003 kPa · decade^{-1} and 0.002 kPa · decade^{-1}, respectively [FIGURE:5, TABLE:2].

The accelerated VPD increase in desert environments likely reflects the highest temperatures and lowest relative humidity, making temperature and actual vapor pressure changes more pronounced than in mountainous and oasis settings. Seasonal VPD trends across all sub-regions mirrored annual patterns, with winter showing the smallest increase. Except for summer in certain regions, spring exhibited the greatest VPD increase in most areas.

An abrupt change in VPD occurred in 1997 [Figure 7: see original paper]. During 1961–1996, annual VPD decreased at -0.023 kPa · decade^{-1}, while during 1997–2021 it increased at 0.029 kPa · decade^{-1}. Seasonal analysis reveals that spring, summer, and autumn VPD decreased during 1961–1996 (summer showing the fastest decline at -0.05 kPa · decade^{-1}) but increased during 1997–2021, with spring showing the most rapid increase (0.05 kPa · decade^{-1}) [Figure 6: see original paper].

VPD changes are primarily influenced by saturated and actual vapor pressure. Both es and ea showed significant increasing trends, with es increasing at 0.018 kPa · decade^{-1} and ea at 0.009 kPa · decade^{-1} [Figure 8: see original paper]. Saturated vapor pressure increased most rapidly in summer (0.029 kPa · decade^{-1}) and spring (0.023 kPa · decade^{-1}) [FIGURE:9, TABLE:3]. Actual vapor pressure also increased across all seasons, with summer showing the fastest growth (0.011 kPa · decade^{-1}) [Figure 10: see original paper]. Critically, the growth rate of actual vapor pressure consistently lagged behind that of saturated vapor pressure, contributing to VPD increase.

2.3 Relationships Between VPD and Temperature/Relative Humidity

Temperature and relative humidity significantly influence VPD, but their relative contributions require clarification. Correlation analysis reveals significant relationships between VPD and both temperature (positive) and relative humidity (negative) [Figure 11: see original paper]. The correlation between VPD and temperature is strongest in spring (r = 0.74–0.81), while VPD-relative humidity correlation peaks in summer (r = -0.83 to -0.92).

Partial correlation analysis shows that the relationship between VPD and temperature is strongest in summer (partial r = 0.92–0.99), as is the VPD-relative humidity relationship (partial r = -0.98 to -1.0). Overall, VPD shows stronger partial correlation with relative humidity than with temperature, indicating that relative humidity contributes more significantly to VPD changes in the Kaidu-Kongque River Basin.

3. Discussion and Conclusions

This study analyzed routine meteorological observations from 1961 to 2021 to investigate VPD trends and influencing factors in the Kaidu-Kongque River Basin. The main conclusions are:

(1) Annual and seasonal VPD increased significantly from 1961 to 2021, with an abrupt shift in 1997. The trend reversed from decreasing during 1961–1996 to increasing during 1997–2021, indicating intensified atmospheric drought, particularly in spring.

(2) VPD trends align with temperature and actual vapor pressure changes across all environments, with the most rapid increase in desert regions, followed by oasis and mountainous areas. Seasonal patterns show consistent increases across all sub-regions, with winter showing the smallest 增幅.

(3) VPD changes are positively correlated with temperature and negatively correlated with relative humidity. The rapid temperature increase and relative humidity decline since 1997 are the primary drivers of accelerated

VPD growth. The contribution of relative humidity to VPD changes is more significant than that of temperature. The growth rate of actual vapor pressure lags behind that of saturated vapor pressure, further driving VPD increase.

The rapid VPD increase in the Kaidu-Kongque River Basin intensifies atmospheric drought, increases vegetation evapotranspiration, and consequently affects photosynthesis, posing greater ecological risks. Enhanced evaporation also leads to soil water loss, potentially causing shallow-rooted plant mortality and reduced species diversity. These findings underscore the importance of monitoring watershed-scale VPD changes and highlight the critical role of VPD in climate and ecosystem research, particularly regarding its impacts on arid region vegetation.

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