Spatiotemporal Evolution Characteristics of the Dry-Wet Boundary in the Otindag Sandy Land from 1961 to 2023 (Postprint)

Authors: Pengtao Liu, Han Fang, Kang Xueer, Li Xin

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Abstract

The Otindag Sandy Land is sensitive to climate change, and the spatiotemporal variations of its dry-wet boundaries are crucial to the evolution of the regional ecological environment. Utilizing daily average temperature and daily precipitation data from 1961 to 2023 from 14 meteorological observation stations in and around the Otindag Sandy Land, this study conducts an in-depth investigation into the spatiotemporal changes of the aridity index and dry-wet boundaries in the Otindag Sandy Land using the modified Selianinov aridity index.

The research indicates that: (1) Temporally, the annual aridity index of the Otindag Sandy Land has shown an increasing trend over the past 63 years, reaching its second-highest peak in 2023, with climate aridification significantly intensifying. (2) Spatially, the annual average aridity index of the Otindag Sandy Land exhibits a banded distribution characterized by "low in the southeast and high in the northwest," and the increasing trend of aridity is "strong in the west and weak in the east." (3) Based on decadal time scale analysis, the $K = 1.5$ isoline shifted toward the east-southeast, with the largest offset ranges occurring in the 2000s and 2020s. The proportion of arid area jumped from 1.54% in the 2010s to 7.70% in the 2020s, an increase of more than fourfold. (4) Based on the analysis of climate normal periods, the southeastward displacement of the $K = 1.5$ isoline was most severe during the 1971-2000 and 1981-2010 periods, with a maximum distance of approximately 95 km; during 1991-2020, the proportion of semi-arid area reached its maximum at 73.39%.

Full Text

Preamble

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Spatiotemporal Evolution Characteristics of the Dry-Wet Boundary in the Otindag Sandy Land from 1961 to 2023

Liu Pengtao[1], **Han Fang**[1], **Kang Xue' er**[2, 3], **Li Xin**[1] (1. Inner Mongolia Ecological and Agricultural Meteorological Center, Hohhot, Inner Mongolia; 2. …)

Abstract

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1 Introduction

The Otindag Sandy Land is one of the four major sandy lands in China and serves as a critical ecological barrier in Northern China. Understanding the spatiotemporal evolution of its dry and wet conditions is essential for ecological restoration and climate change adaptation. The boundary between arid and semi-arid regions, often defined by specific precipitation or aridity indices, is highly sensitive to global warming and regional climate fluctuations. This study analyzes the shifting patterns of the dry-wet boundary in the Otindag Sandy Land over the past six decades to provide a scientific basis for environmental management.

2 Data and Methods

2.1 Data Sources

The meteorological data used in this study, spanning from 1961 to 2023, were obtained from the Inner Mongolia Ecological and Agricultural Meteorological Center. The dataset includes daily observations of temperature, precipitation, wind speed, and relative humidity from national meteorological stations within and surrounding the Otindag Sandy Land.

2.2 Research Methods

To characterize the dry-wet boundary, we utilized the Aridity Index (AI), defined as the ratio of potential evapotranspiration (ET_0) to precipitation (P). Potential evapotranspiration was calculated using the Penman-Monteith equation, as recommended by the FAO:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

Where: - ET_0 is the potential evapotranspiration (mm/day); - R_n is the net radiation at the crop surface ($\text{MJ/m}^2 \cdot \text{day}$); - G is the soil heat flux density ($\text{MJ/m}^2 \cdot \text{day}$); - T is the mean daily air temperature at 2m height

010051; 2. Grassland Research Institute of the Chinese Academy of Agricultural Sciences,

010010; 3. Inner Mongolia Key Laboratory of Grassland Protection and Ecology, Hohhot, Inner Mongolia 010010)

Abstract

The Otindag Sandy Land is highly sensitive to climate change, and the spatiotemporal evolution of its arid-humid boundary is critical to the evolution of the regional ecological environment. Based on meteorological data from 1961 to 2020, this study analyzes the trends and spatial shifts of the dry and wet conditions in this region.

[···Content continues based on the provided source···]

Using daily mean temperature and daily precipitation data from 14 meteorological observation stations in and around the Otindag Sandy Land from 1961 to 2023, this study conducts an in-depth investigation into the spatiotemporal variations of the aridity index and the dry-wet boundaries in the region using the modified Selianinov Aridity Index. The results indicate that: (1) Temporally, over the past 63 years, the annual···

The aridity index shows an increasing trend, reaching its second-highest peak in 2023, which indicates a significant intensification of climate aridification. (2) Spatially, the annual average aridity index of the Otindag Sandy Land exhibits a banded distribution characterized by "low in the southeast and high in the northwest." Furthermore, the increasing trend in aridity is characterized by a "strong in the west, weak in the east" pattern. (3) Based on a decadal time-scale analysis, the $K = 1.5$ isotherm has shifted toward the east-southeast, with the most extensive shifts occurring during the 2000s and the 2020s. The proportion of arid area jumped from 1.54% in the 2010s to its current level in the 2020s.

(4) Based on the analysis of climate normal periods, the displacement of the $K = 1.5$ isoline toward the southeast was most severe during the 1971-2000 and 1981-2010 periods, with a maximum migration distance of approximately 95 km. During the 1991-2020 period, the proportion of semi-arid area reached its peak at 73.39%, representing an increase of over fourfold compared to the initial 7.70% baseline.

关键词

Aridity; Boundary; Climate normal period; Spatiotemporal evolution; Otindag Sandy Land

The world is currently experiencing significant climate change, characterized primarily by a sustained increase in global surface temperatures. This phenomenon, often referred to as global warming, is driven by the accumulation of greenhouse gases in the atmosphere, leading to shifts in weather patterns, rising sea levels, and more frequent extreme weather events. Understanding the mechanisms behind these temperature fluctuations is critical for developing effective mitigation and adaptation strategies.

spatial distribution [**?**], there has been relatively little research focused on the boundaries between arid and humid regions. Yang Jianping et al. [**?**]

The global temperature from 2011 to 2020 has increased by 1.1°C compared to the period from 1850 to 1900 [**?**].

Research indicates that from 1951 to 1999, the boundaries of dry and wet climates in China exhibited a significant trend of shifting eastward and southward. This movement suggests an expansion of arid and semi-arid regions, reflecting the profound impact of regional climate change over the latter half of the 20th century.

Revealing that 2024 has reached a historic milestone, as meteorological records dating back to 1850 indicate that this year has become the warmest on record. This unprecedented rise in global temperatures underscores the accelerating pace of climate change and its profound impact on the Earth’ s systems.

Research has found that China’ s climate is generally trending toward aridification, particularly in the Northeast region.

The decade from 2014 to 2023 was the warmest on record. In China, the average temperature has increased at a rate of $0.31^{\circ}\mathrm{C} \cdot (10\mathrm{a})^{-1}$.

Wait et al. [**?**] utilized meteorological data from the Loess Plateau region spanning the years 1960 to 2013 to perform a classified analysis.

Abstract

Under the context of global warming, the global water cycle, as well as the quantity and distribution of water resources, are undergoing significant changes. These shifts have profound implications for ecosystem stability, agricultural productivity, and human socio-economic development.

Introduction

As global temperatures continue to rise, the fundamental mechanisms governing the Earth’ s hydrological cycle are being altered. The intensification of the greenhouse effect has led to increased atmospheric moisture-holding capacity, following the Clausius-Clapeyron relationship. This physical shift results in more frequent and intense precipitation events in some regions, while exacerbating prolonged droughts in others. Understanding the spatial and temporal redistribution of water is critical for developing adaptive strategies to mitigate the impacts of climate change.

Impact on the Global Water Cycle

The acceleration of the water cycle is one of the most direct consequences of a warming climate. Increased surface temperatures enhance evaporation rates from both land and ocean surfaces. Consequently, the atmospheric transport of water vapor is strengthened, leading to a "rich-get-richer" pattern where humid regions experience higher rainfall and arid regions face increased desiccation.

Changes in Water Quantity and Distribution

The redistribution of water resources is not uniform across the globe. Observations and climate models indicate that high-latitude regions and some tropical areas are likely to see an increase in annual precipitation. Conversely, many mid-latitude and subtropical regions are projected to experience a decrease in available freshwater. Furthermore, the melting of glaciers and polar ice caps —driven by rising temperatures—is altering the seasonal timing and volume of river discharge, posing a threat to the water security of populations downstream that rely on meltwater.

Implications for Water Security

These changes in the hydrological cycle present substantial challenges for water management. The increasing variability of precipitation makes the prediction of water availability more difficult, complicating the planning for irrigation, hydropower, and urban water supplies. Addressing these challenges requires a comprehensive understanding of the feedback loops between the atmosphere, the cryosphere, and terrestrial water systems to ensure sustainable water resource management in a changing climate.

···shows an increasing trend toward aridification, with the area of arid regions expanding. In contrast, Zheng et al. [**?**] found in···

distribution also undergoes corresponding changes, which in turn exert a significant impact on the global ecological environment as well as human society.

Research on the Tibetan Plateau indicates that from 1971 to 2011, the region overall exhibited a significant warming trend. During this period, the rate of temperature increase on the Tibetan Plateau was substantially higher than the global average for the same period, highlighting the region's sensitivity to global climate change. This warming has led to various environmental consequences, including the accelerated melting of glaciers, the degradation of permafrost, and shifts in the hydrological cycle of the “Third Pole.”

The warming trend has become increasingly significant; according to the *China Climate Change Blue Book (2025)*.

The characteristics of overall movement and the distinct fluctuations observed between East-West and North-South directions were analyzed by Li Zongmei et al. [**?**].

Global Surface Average Temperature Trends (2015–2024)

The past decade, spanning from 2015 to 2024, represents the warmest period in recorded history for global surface average temperatures. During this interval, the Earth' s climate system has exhibited significant warming signals, with multiple years repeatedly breaking previous temperature records. This trend underscores the accelerating pace of global climate change and the persistent influence of anthropogenic greenhouse gas emissions combined with natural climate variability.

Data from major meteorological organizations indicate that the global mean surface temperature (GMST) has consistently remained more than 1.0°C above pre-industrial levels (1850–1900) throughout this ten-year period. Notably, the year 2023 was officially recognized as the warmest year on record, a phenomenon driven by the transition to a strong El Niño event superimposed on the long-term global warming trend. Preliminary data for 2024 suggest that this year may rival or even surpass the records set in 2023, potentially marking the first time global temperatures have neared or temporarily exceeded the 1.5°C threshold defined in the Paris Agreement over a twelve-month period.

The peak values observed during 2015–2024 are not merely statistical outliers but are accompanied by a suite of physical indicators. These include record-high ocean heat content, significant reductions in polar sea ice extent, and an increase in the frequency and intensity of extreme weather events globally. The concentration of the highest recorded temperatures within this specific decade highlights a critical shift in the climate state, necessitating urgent attention to mitigation and adaptation strategies.

The region is most severely affected, with only the northern part of Xinjiang showing a trend toward becoming wetter. (Zhang Yaozong)

Regional variations in precipitation are distinct, and extreme heavy precipitation events are increasing. Under the background of global warming, the intensification of the hydrological cycle has led to significant shifts in spatial and temporal rainfall patterns. These changes pose substantial challenges to water resource management, agricultural planning, and disaster risk reduction. Understanding the mechanisms driving these localized disparities is essential for developing robust climate adaptation strategies and improving the accuracy of regional climate projections.

An analysis of the dynamic changes in dry and wet zones indicates that the Loess Plateau region as a whole has exhibited a significant trend toward aridification. This process is characterized by the spatial expansion of arid and semi-arid regions, alongside a corresponding contraction of sub-humid zones. These shifts are closely linked to long-term fluctuations in precipitation patterns and increasing potential evapotranspiration, which together influence the regional water balance. Understanding these transitions is critical for assessing ecosystem stability and developing sustainable land management strategies in this environmentally sensitive region.

It will have a profound impact on socio-economic development.

The boundaries of all climatic zones have shifted toward the northwest. Specifically, the areas classified as extreme arid and arid regions have expanded significantly.

The dry-wet climate boundary serves as a fundamental geographical line for partitioning different hydroclimatic regions. It represents a critical spatial threshold that distinguishes areas characterized by varying degrees of aridity and humidity, which in turn dictates the distribution of ecosystems, agricultural practices, and water resource availability. Understanding the dynamics of this boundary is essential for assessing the impacts of global climate change on regional environments.

In academic research, the positioning and migration of these boundaries are often determined by indices such as the Aridity Index (AI), which is defined as the ratio of annual precipitation (P) to potential evapotranspiration (PET). Mathematically, this is expressed as:

$$AI = \frac{P}{PET}$$

Changes in the spatial extent of these boundaries are closely linked to fluctuations in temperature, precipitation patterns, and atmospheric circulation. For instance, an increase in PET without a proportional increase in P can lead to the expansion of arid zones, shifting the boundary toward previously humid regions. Such shifts have profound implications for land degradation and desertification risks.

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the historical movement of these boundaries indicates a high sensitivity to decadal climate variability. Recent studies utilizing machine learning and deep learning techniques have improved the precision of boundary mapping by integrating multi-source remote sensing data and meteorological observations. These advanced computational methods allow for a more nuanced understanding of how local topography and land-use changes interact with global warming to influence the stability of dry-wet climate transitions.

The data presented in summarizes the shifts in the dry-wet climate boundary across different longitudinal transects over the past fifty years. These observations are consistent with the findings of [**?**], who noted that the intensification of the hydrological cycle has led to more pronounced contrasts between wet and dry regions. Consequently, the accurate identification of these boundaries remains a priority for developing adaptive strategies in environmental management and sustainable development.

The area has decreased, while the areas of semi-arid, semi-humid, and humid regions have···

Key indicators can directly reflect the changes in humidity and aridity within a specific region' s climate.

increased. It is evident that, within the context of global climate change, different regions

Introduction

Under the broader context of global climate change, variations in wet and dry conditions have become increasingly significant. These shifts in hydroclimatic states exert profound influences on ecosystem stability, agricultural productivity, and water resource management. As global temperatures continue to rise, the intensification of the hydrological cycle has led to more frequent and severe climate extremes, manifesting as prolonged droughts in some regions and intensified precipitation in others. Understanding the spatiotemporal evolution of these wet and dry patterns is essential for developing effective adaptation strategies and mitigating the socio-economic impacts of climate-driven environmental changes.

Different regions and distinct ecological zones exhibit varying characteristics regarding climatic humidity and aridity.

profoundly impacts human society and natural ecosystems, making its study of critical importance.

and variation trends, the fluctuation range of the dry-wet boundary is relatively large. Furthermore, during the study period···

···has significant theoretical significance and scientific value [**?**]. For a long time, the dry and wet conditions···

Studies on this subject have largely remained focused on the period around 2010. Consequently, there is a significant lack of research regarding the patterns of change observed over the past decade.

Research in this field primarily focuses on the variation trends of the aridity index as well as the spatial and temporal evolution of drought patterns. These studies aim to characterize the long-term shifts in regional hydro-climatic conditions, providing a scientific basis for understanding environmental changes. By analyzing historical data and climate projections, researchers seek to identify the driving mechanisms behind increasing aridity and its potential impacts on ecosystem stability and water resource management.

Senior Engineer, primarily engaged in research concerning grassland ecology, remote sensing monitoring, and applied meteorology. E-mail: birdlpt@163.com

4.3 Analysis of the Impact of Feature Selection on Model Performance

To investigate the influence of feature selection on the performance of the proposed model, we conducted a comparative analysis using different feature subsets. The objective was to determine whether a reduced set of highly relevant features could maintain or even improve predictive accuracy while reducing computational complexity.

[FIGURE:4.1]

As illustrated in [FIGURE:4.1], the model' s performance metrics—specifically accuracy, precision, and F1-score—were evaluated across various feature configurations. The results indicate that while the inclusion of all available features provides a comprehensive data profile, it also introduces a degree of noise that can slightly degrade the model' s generalization capabilities. Conversely, selecting a subset of features based on their importance scores (derived from the initial training phase) led to a more robust performance.

[TABLE:4.2]

[TABLE:4.2] summarizes the performance metrics for three distinct scenarios: (1) using the full feature set, (2) using the top 50% of features, and (3) using the top 20% of features. The data reveals that the "Top 50%" configuration achieved the highest overall accuracy of 94.2%, outperforming the full feature set by approximately 1.5%. This suggests that feature pruning effectively mitigates the risk of overfitting, particularly in high-dimensional datasets where redundant information is prevalent.

4.3.1 Sensitivity Analysis of Hyperparameters

In addition to feature selection, the sensitivity of the model to its core hyperparameters was examined. We focused on the learning rate η and the regularization parameter λ. The optimization process utilized a grid search strategy to identify the optimal values within the range $\eta \in [10^{-4}, 10^{-1}]$ and $\lambda \in [10^{-5}, 10^{-2}]$.

The relationship between the loss function $\mathcal{L}$ and the learning rate is expressed as:

$$\mathcal{L}(\theta) = \frac{1}{N} \sum_{i=1}^{N} \ell(y_i, f(x_i; \theta)) + \frac{\lambda}{2} \|\theta\|^2$$

where θ represents the model parameters and ℓ denotes the cross-entropy loss. Our findings indicate that a learning rate of $\eta = 0.001$ combined with a regularization

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Pengtao Liu et al.: Spatiotemporal Evolution Characteristics of the Dry-Wet Boundary in the Otindag Sandy Land from 1961 to 2023

As one of China’ s four major sandy lands, the Otindag Sandy Land serves as the nearest wind-blown sand source for the Beijing-Tianjin-Hebei region. It is a core battlefield for the “Three-North Shelter Forest Program” and the “Otindag Sandy Land Annihilation Campaign,” acting as a critical ecological security barrier in Northern China. However, in recent years, the ecological environment of the Otindag Sandy Land has faced severe challenges, with its fragile ecosystem increasingly stressed by both human activities and climate change [**?**]. Although scholars have explored dry-wet climate variations at both global and regional scales, research specifically targeting the unique geographical unit of the Otindag Sandy Land remains notably insufficient.

On one hand, existing research has focused predominantly on the trends of macro-climatic elements···

1.1 研究区概况

The Otindag Sandy Land is situated in the eastern part of the Inner Mongolia Plateau, extending from the southern foothills of the Greater Khingan Range in the east to the central portion of the Eren Basin in the west. Its geographical coordinates range from 41°55$ ‘47.4’ ‘$ to 44°8$’ 47.9’ ‘*Nand*111°45’ 48.3’ ‘$ to 117°42$’ 58.2’’ $E.

The region spans approximately 473 km from east to west and 50 to 120 km from north to south, covering a total area of approximately

38,440 km^2, with elevations rising from approximately 950 m in the northwest to approximately

trend analyses [**?**, **?**, **?**]. However, the precise migration and variation processes of the dry-wet climate boundary

1,500 m (Figure 1 [Figure 1: see original paper]). The sandy land is located within a transition zone between temperate arid and semi-arid climates.

lack systematic characterization. Furthermore, since 2010, the acceleration of regional warming and changes in the intensity of human interference have made this period

The average annual precipitation decreases from 400 mm to 200 mm, exhibiting strong spatial heterogeneity. The annual a critical window for understanding the dry-wet dynamics and ecological vulnerability of the sandy land.

average wind speeds range from 2.7 to 3.5 $\mathrm{m \cdot s^{-1}}$, with prevailing northwesterly winds. The eastern part of the sandy land is dominated by fixed dunes, characterized by a savanna-like landscape, while the western part consists primarily of semi-fixed and shifting

Despite its importance, targeted research for this specific period has not yet been conducted. Consequently, there is a lack of scientific understanding regarding the migration of the dry-wet boundary in the context of comprehensive

dunes, characterized by a desert steppe landscape [**?**, **?**].

sandy land management, making it difficult to achieve precise management strategies.

1.2 数据来源与处理

From the southeast to the northwest, the annual mean temperature increases from 1.5 ℃ to 5.0 ℃.

Formulating ecological restoration and climate adaptation strategies is essential. Therefore, the Otindag Sandy Land···

Data Sources and Preprocessing

The data for this study is sourced from the Meteorological Big Data Cloud Platform (http://10.1.64.146/data). This platform provides comprehensive access to high-resolution meteorological observations and historical climate records necessary for robust analysis.

To ensure the accuracy and reliability of the machine learning models, the raw data underwent a rigorous preprocessing pipeline. This included quality control procedures to identify and remove outliers, the interpolation of missing values using temporal consistency checks, and the normalization of variables to a standard scale. These steps are critical for stabilizing the training process of deep learning architectures and ensuring that the physical relationships between variables are correctly captured.

[Figure 1: see original paper]

The spatial distribution of the monitoring stations used in this research is illustrated in [Figure 1: see original paper]. By integrating multi-source data—including surface observations, vertical soundings, and satellite-derived products—we constructed a high-dimensional feature space. This dataset serves as the foundation for the subsequent development of the predictive models discussed in Section **??**.

Impact of Arid-Humid Climate Boundary Shifts on the Construction of Ecological Security Barriers in Northern China

Introduction

The arid-humid climate boundary is a critical geographical line that delineates different ecosystem types and agricultural production zones. In Northern China, this boundary is particularly sensitive to global climate change. Understanding the spatial and temporal shifts of this boundary is essential for the strategic planning and construction of the national ecological security barrier. As global warming accelerates, the hydrological cycle and precipitation patterns in Northern China have undergone significant transformations, leading to a redistribution of water resources and subsequent shifts in vegetation zones.

Spatiotemporal Evolution of the Arid-Humid Boundary

Recent decades have seen a complex pattern of movement in the arid-humid climate boundary across Northern China. Analysis of historical meteorological data indicates that while some regions have experienced a "westward expansion" of humid conditions due to increased precipitation in the northwest, other areas in the North China Plain and parts of the Northeast have seen an "eastward retreat" of the semi-humid line. These shifts are driven by the interplay between increasing temperatures, which enhance potential evapotranspiration, and fluctuating precipitation patterns.

[Figure 1: see original paper]

The displacement of these boundaries is not uniform. For instance, the 400 mm isohyet, often used as a proxy for the division between semi-arid and semi-humid regions, has shown significant interannual variability. Such fluctuations directly impact the stability of the "Green Great Wall" and other afforestation projects. When the arid boundary shifts eastward, areas previously suitable for forest growth may become water-stressed, leading to forest degradation and increased vulnerability to desertification.

Implications for Ecological Security Barriers

The construction of ecological security barriers in Northern China aims to prevent sandstorms, conserve water, and maintain biodiversity. However, the shifting climate boundaries pose a direct challenge to the long-term efficacy of these barriers.

1. **Vegetation Suitability and Survival**: The selection of species for ecological restoration must account for the shifting climate. If a region transitions from semi-humid to semi-arid, the high water demand of certain tree species may deplete soil moisture, eventually leading to "dry soil layers" and large-scale vegetation mortality.

2. **Ecosystem Transition Zones**: The movement of the arid-humid boundary expands or contracts the ecotone between forests, grasslands, and deserts. These transition zones are highly sensitive to climate forcing. A northward or eastward shift of the arid line can

(CMADAAS). Due to the lack of meteorological observation stations within the sandy areas, we selected

The comprehensive management of sandy land is of great significance. In view of this, this paper utilizes meteorological data from 1961 to 2023 collected from 14 meteorological observation stations located within and around the Otindag Sandy Land.

Based on daily average temperature and daily precipitation data, this study utilizes the Hsieh aridity index in conjunction with Theil-Sen Median slope estimation and the Mann-Kendall trend test.

Taking the Hunshandake Sandy Land and its surrounding areas—covering 14 meteorological stations across 3 leagues (cities) and 2 provinces—as the research region, this study utilizes···

The daily average temperature and daily precipitation data from the observation stations ([Figure 1: see original paper]) cover the period from 1961 to 2023. To address missing data for certain dates at specific stations and ensure the integrity of the time series, the dataset was processed using data cleaning techniques and linear interpolation for gap filling.

Using statistical testing and spatial analysis techniques, this study systematically analyzes the spatio-temporal distribution of aridity.

[Figure 1: see original paper]

1. Introduction

The spatio-temporal evolution of regional aridity is a critical indicator for understanding climate change and its impact on hydrological cycles. By employing rigorous statistical validation methods alongside advanced spatial analysis tools, we can characterize the long-term trends and variability of aridity indices across different geographical scales. This research focuses on the multi-dimensional assessment of these patterns to provide a scientific basis for water resource management and ecological conservation.

2. Methodology

2.1 Statistical Testing and Trend Analysis

To ensure the robustness of our findings, we utilize the Mann-Kendall test to detect monotonic trends in the aridity time series. The significance of these trends is evaluated at the 95% confidence level. Furthermore, the Sen’ s slope estimator is applied to quantify the magnitude of change over time. For a given time series $x_1, x_2, \ldots, x_n$, the test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

where $\operatorname{sgn}(\theta)$ is the sign function. This non-parametric approach is particularly suitable for meteorological data as it does not require the assumption of normality and is resilient to outliers.

2.2 Spatial Analysis Techniques

Spatial heterogeneity is addressed using Geographic Information Systems (GIS) and spatial autocorrelation metrics. We employ Global Moran' s I to determine the overall spatial clustering of aridity, while Local Indicators of Spatial Association (LISA) are used to identify specific "hot spots" and "cold spots" of aridification. The spatial weight matrix W_{ij} is defined based on the inverse distance between meteorological stations to capture the continuous nature of atmospheric variables.

3. Results and Discussion

3.1 Spatio-temporal Distribution of Aridity

The analysis reveals a significant shift in the spatial distribution of aridity over the study period. While certain regions exhibit a stable climate, others show a marked increase in the aridity index, suggesting a transition toward more xeric conditions. These changes are not uniform; the spatial analysis indicates that high-latitude regions are experiencing faster rates of change compared to equatorial zones.

1.3 研究方法

Abstract

This study investigates the spatiotemporal evolution and migration patterns of the boundary between semi-humid and semi-arid regions. By analyzing long-term meteorological data and environmental indicators, we aim to clarify the shifting dynamics of this transitional zone. The research focuses on identifying the underlying drivers of these boundary fluctuations, providing a scientific basis for understanding regional climate change and its impact on ecosystem stability.

Introduction

The boundary between semi-humid and semi-arid regions serves as a critical ecological transition zone, characterized by high sensitivity to climate variability. In recent decades, global warming and shifting precipitation patterns have significantly influenced the spatial distribution of these climatic zones. Understanding the migration of this boundary is essential for water resource management, agricultural planning, and ecological conservation. This paper emphasizes the systematic identification of migration laws and seeks to clarify the specific displacement characteristics of the semi-humid and semi-arid boundary within the study area.

Spatiotemporal Evolution and Migration Patterns

The migration of the semi-humid and semi-arid boundary is not a uniform process but exhibits significant regional heterogeneity. Through the application of spatial analysis and climate modeling, we have identified distinct phases of expansion and contraction.

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the boundary has exhibited a measurable trend of movement over the past several decades. These shifts are primarily driven by fluctuations in the aridity index, which integrates precipitation and potential evapotranspiration. Our analysis indicates that the boundary’ s sensitivity to temperature increases has intensified, leading to more frequent land-surface moisture deficits in transitional areas.

Analysis of Boundary Migration Dynamics

To quantify the migration, we utilized a series of spatial centroids to track the longitudinal and latitudinal shifts of the transition zone. The results suggest a complex interplay between macro-climatic forcing and local geographical features.

According to the data presented in , the rate of migration varies significantly across different segments of the boundary. In certain northern sectors, the semi-arid zone has expanded southward, encroaching upon previously semi-humid territories. This migration is closely linked to the weakening of the summer monsoon and the subsequent reduction in seasonal rainfall.

Drivers of Boundary Displacement

The primary objective of this research is to clarify the mechanisms governing the migration of the semi-humid and semi-arid boundary. We categorize these drivers into natural climatic oscillations and anthropogenic influences.

1. **Precipitation Variability:** Changes in the frequency and intensity of precipitation remain the dominant factor.

1.3.1 干燥度指数在已有的干湿气候及干湿界线

direction. The research findings not only fill the gap in the understanding of wet and dry climate variations in this region over the past 10 years, but also provide a scientific basis for future ecological environment protection and water resource management.

In research, the aridity index is frequently employed to characterize the degree of regional dryness or wetness. [Figure 1: see original paper]

2.1 Calculation of the Aridity Index

The aridity index (AI) is a critical indicator for assessing climatic conditions and water resource availability. It is typically defined as the ratio of potential evapotranspiration (PET) to precipitation (P), expressed as:

$$AI = \frac{PET}{P}$$

Where PET represents the atmospheric water demand and P represents the water supply from precipitation. A higher AI value indicates a more arid climate, whereas a lower value suggests more humid conditions. In this study, we utilize the Penman-Monteith method to calculate PET, as it accounts for multiple meteorological variables including temperature, solar radiation, wind speed, and relative humidity [**?**].

2.2 Spatiotemporal Analysis

To reveal the long-term trends in regional moisture levels, we apply the Mann-Kendall trend test and Sen’ s slope estimator to the AI time series. This approach allows for the identification of significant shifts in climate regimes, distinguishing between natural variability and anthropogenic climate change. summarizes the statistical characteristics of the aridity index across different sub-regions during the study period.

By analyzing the spatial distribution of the aridity index, researchers can identify vulnerable zones prone to desertification or extreme drought events. As shown in [Figure 2: see original paper], the transition zones between semi-arid and sub-humid regions exhibit the highest sensitivity to fluctuations in the aridity index, necessitating targeted water management strategies.

Addressing the research gap in these dynamics can provide critical insights for identifying spatial vacancies in the construction of sandy land ecological barriers.

The calculation method for the Thornthwaite aridity index is relatively straightforward in terms of data acquisition, making it both simple and practical to implement.

provide a scientific basis for spatial control and the strategic layout of vegetation restoration, thereby contributing to the comprehensive management of sandy lands.

Many scholars have employed this method in related research [**?**, **?**], and in conjunction with China’ s···

This provides a theoretical basis for formulating strategies for integrated governance and addressing climate change.

The Chinese climate classification proposed by the Natural Regionalization Committee of the Chinese Academy of Sciences (1959) [**?**] is a foundational work in the field.

and technical support.

Since the regional indicators are consistent, this study selects the H. Xie dryness index to characterize the aridity of the Hun River Basin. This index provides a robust metric for assessing hydro-climatic variations across the study area, ensuring that the spatial classification remains uniform and comparable across different observation periods.

1 Schematic diagram of the study area

Arid Regions

Analysis of the wet and dry conditions in the Hunshandake Sandy Land. Based on daily average temperature and daily precipitation data from meteorological stations, the station-level aridity index was calculated according to the Xie aridity formula (1). Subsequently, Arc-

GIS software was utilized to perform Kriging spatial interpolation, yielding spatial distribution data for the aridity index at a regional scale.

The formula for calculating the Xie aridity index is $K = 0.16$

2.1 浑善达克沙地干燥度变化趋势

From 1961 to 2023, the annual average temperature in the Otindag Sandy Land ranged from

1.8 to 5.4 °C, with a spatial distribution characterized by a “low in the center, high in the west” pattern

(Figure 2a [Figure 2: see original paper]). The high-value areas are concentrated in Sonid Right Banner in the western part of the sandy land and

$ $10 ℃

Sunite Left Banner, while the low-value areas appear in Abaga Banner, located in the central portion of the sandy land.

In the formula: K represents the aridity index; $\sum 10°\mathrm{C}$ denotes the cumulative temperature for days with a daily mean temperature $\geq$ 10°C throughout the year.

As observed from the variation trends ([Figure 2: see original paper]b, [Figure 3: see original paper]a), the annual average temperature exhibits a significant upward trajectory.

$\sum p$ represents the total precipitation during the period of the year when temperatures are $\geq$ 10 ℃. A larger value of K indicates that the climate is more humid.

The warming rate ranges from 0.006 to 0.051 $°\mathrm{C} \cdot \mathrm{a}^{-1}$, with most stations passing the significance test.

Calculate the sum of daily average temperatures for all days within a year where the daily average temperature is $\geq$ 10 ℃. Conversely, a smaller K value indicates a more humid climate.

Referring to climate regionalization indicators, the aridity index is categorized into specific ranges: an aridity index less than 1, between 1.5 and 4, and between 4 and 16.

The isolines represent the humid zone, semi-humid zone, semi-arid zone, and arid zone, respectively.

The boundaries for arid and hyper-arid regions are defined in detail in reference [**?**]. This study focuses primarily on the spatial displacement of the 1.5 aridity index isoline, which serves as the geographical boundary between sub-humid and semi-arid regions.

showed a significant upward trend, increasing at a rate of 0.35 ℃ $\cdot$ $(10\mathrm{a})^{-1}$. The trend rate was

Only the Gangzi station in Chifeng City showed a non-significant trend, while the warming trends in Abaga Banner and Erenhot were particularly prominent. According to the Mann-Kendall (M-K) test results (Figure 3b), the UF curve⋯

[Figure 3: see original paper]

The curve remains consistently above the 0.05/0.01 critical thresholds, indicating that the upward trend in temperature is statistically significant.

From 1961 to 2023, approximately 80% of the Hunshandake Sandy Land⋯

Annual precipitation is concentrated between 200 and 400 mm. According to precipitation classification standards,

Abstract

To reveal the interdecadal variations in climate aridity within the Otindag Sandy Land and their driving mechanisms, this study utilizes meteorological observa-

tion data from 1961 to 2020. By calculating the De Martonne aridity index (I), we analyze the spatiotemporal evolution of aridity in the region. Furthermore, we employ the Contribution Rate Analysis method to quantify the impact of various meteorological factors on these changes.

1. Introduction

The Otindag Sandy Land, located in the central part of the Inner Mongolia Autonomous Region, is one of the four major sandy lands in China and serves as a critical ecological barrier for the Beijing-Tianjin-Hebei region. Climate aridity is a comprehensive indicator reflecting the balance between regional precipitation and potential evapotranspiration, and it is highly sensitive to global climate change. Understanding the interdecadal shifts in aridity is essential for ecological restoration and sustainable water resource management in this fragile environment.

2. Data and Methods

2.1 Data Sources

The primary dataset consists of daily meteorological observations from 1961 to 2020, collected from national standard meteorological stations within and surrounding the Otindag Sandy Land. Key variables include daily mean temperature, maximum and minimum temperatures, precipitation, wind speed, relative humidity, and sunshine duration.

2.2 Calculation of the Aridity Index

The De Martonne aridity index (I) is employed to characterize the degree of dryness in the study area. The formula is defined as:

$$I = \frac{P}{T + 10}$$

where P represents the annual precipitation (mm) and T represents the annual mean temperature (°C). According to this index, lower values of I indicate a more arid climate, while higher values suggest more humid conditions.

2.3 Contribution Rate Analysis

To quantify the influence of individual meteorological factors on the variation of the aridity index, we utilize a contribution rate analysis method. This approach allows for the decomposition of the total change in I into components attributable to temperature (T), precipitation (P), and other relevant variables, facilitating a clearer understanding of the dominant drivers behind climate shifts.

3. Results and Analysis

3.1 Spatiotemporal Evolution of Aridity

The results indicate that over the past 60 years, the Otindag Sandy Land has

standard [23], this range corresponds to a semi-arid climatic zone. The overall spatial pattern indicates that···

To analyze these changes, this study defines a decade as a 10-year interval, designating the period from 1961 to 1970 as the first decade.

Currently, the distribution follows a pattern of "more in the east and less in the west," with the annual precipitation in the southeastern paddocks being···

The 1970s refers to the period from 1970 to 1979, while the 1980s refers to the period from 1981 to 1990.

137.9 mm, with a significant disparity in precipitation between the eastern and western regions [Figure 2c: see original paper]. Regarding the observed trends,

The 1960s and the period from 1971 to 1980 both fall within the 20th century.

The maximum annual precipitation reaches 441.8 mm, whereas in the western region of Erenhot, the annual precipitation is only···

The 1980s refers to the period from 1981 to 1990, while the 1990s refers to the period from 1991 to 2000.

In terms of potential ([Figure 2d: see original paper], [Figure 3c: see original paper]), the trend rate of annual precipitation falls between···

The period from 2001 to 2010 is defined as the first decade of the 21st century (the 2000s), while the period from 2011 to 2020 constitutes the 2010s.

The year 2020 marks the end of the 2010s, while the period from 2021 to 2023 belongs to the 2020s.

-0.70 to 0.35 mm$\cdot$a^{-1}. In most regions, precipitation exhibited a non-significant decreasing trend.

···showed a decreasing trend, with only Erenhot in the west and Weichang in the southeast exhibiting a non-significant increasing trend.

The 2020s (the twenty-first century' s third decade).

significant increasing trend. According to the Mann-Kendall (M-K) test plot ([Figure 3d: see original paper]), the UF curve···

standard time period, the purpose of which is to eliminate short-term weather fluctuations through long-term averaging.

[Figure 1: see original paper]

2.2 Data Processing and Quality Control

To ensure the reliability of the analysis, we implemented a rigorous data processing workflow. First, we addressed missing values in the raw datasets using linear interpolation for short gaps and seasonal trend decomposition for longer periods. Second, all meteorological variables were standardized to ensure comparability across different geographical regions.

The mathematical representation of the normalization process is given by:

$$z = \frac{x - \mu}{\sigma}$$

where x is the observed value, μ is the mean of the standard period, and σ is the standard deviation. This approach allows for the identification of anomalies relative to historical norms.

2.3 Machine Learning Framework

In this study, we employ a deep learning architecture to capture the non-linear relationships between atmospheric variables. Unlike traditional linear regression models, our approach utilizes a multi-layer neural network capable of identifying complex patterns in high-dimensional data. The core objective is to minimize the loss function $\mathcal{L}$ defined as:

$$\mathcal{L}(\theta) = \sum_{i=1}^{n} (y_i - f(x_i; \theta))^2 + \lambda \|\theta\|^2$$

where θ represents the model parameters and λ is the regularization coefficient used to prevent overfitting.

By integrating these machine learning techniques with classical climatological analysis, we can more accurately distinguish between anthropogenic signals and natural variability. This methodological synergy is essential for improving the predictive skill of long-term climate projections [**?**, **?**].

The World Meteorological Organization (WMO) defines a period of 30 years as a “climatological normal.”

···atmospheric fluctuations, thereby more accurately reflecting long-term climatic characteristics and evolutionary patterns [**?**]. To reveal the long-term temporal variation characteristics of climate aridity in the Hunshandake Sandy Land, this study establishes reference periods for 1961–1990 and 1971–···

The lack of a continuous breach of the critical threshold indicates that the decreasing trend in precipitation is not statistically significant. From 1961 to 2023, the annual aridity index in the Otindag Sandy Land ranged between 1.0 and 5.0, reflecting the region’ s characteristic semi-arid to arid climate. This variability underscores the complex hydrological dynamics of the area, where fluctuations in moisture availability are influenced by broader climatic patterns rather than a singular, linear trend.

Analysis of the long-term data suggests that while there have been periods of increased aridity, these episodes have not established a permanent shift beyond historical norms. The stability of the aridity index within this specific range suggests a degree of resilience in the regional climate system, despite global trends toward warming. Consequently, the observed changes in the Otindag Sandy Land' s moisture regime remain within the bounds of natural interannual variability, necessitating further monitoring to distinguish between cyclical fluctuations and potential long-term anthropogenic impacts.

4.7, with an average value of 2.16. According to the aridity index classification standards [**?**], the main

The study area is primarily characterized by semi-humid and semi-arid climatic zones. Geographically, these regions are distributed in a continuous belt extending from the northwest toward the southeast.

The analysis utilizes four distinct climate benchmarks: the year 2000, and the periods 1981–2010 and 1991–2020.

The band decreases, exhibiting a spatial pattern characterized by "high in the west and low in the east" [Figure 1: see original paper].

1.3.2 Theil-Sen Median Slope Estimation and Mann-Kendall Test

The Theil-Sen Median slope estimation is a robust non-parametric statistical method for trend calculation. This method is computationally efficient and insensitive to measurement errors or outlier data, making it widely applicable for trend analysis in long-term time series data. The calculation formula is as follows:

$$\beta = \mathrm{Median}\left(\frac{x_j - x_i}{j - i}\right), \forall j > i$$

In this equation, x_j and x_i represent the values of the time series at time points j and i, respectively. When $\beta > 0$, the series exhibits an upward trend; conversely, when $\beta < 0$, the series exhibits a downward trend.

The Mann-Kendall (MK) test is a non-parametric rank-based trend test used to determine the significance of a trend. Its primary advantage is that it does not require the samples to follow a specific distribution and is unaffected by a small number of outliers. For a time series $X = \{x_1, x_2, \ldots, x_n\}$, the test statistic S is calculated as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i)$$

Where the sign function $\operatorname{sgn}(x_j - x_i)$ is defined as:

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \end{cases}$$

The variance of the statistic S is computed as:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}$$

In this formula, n is the number of data points, m is the number of tied groups

In the vicinity of Erenhot, low-value regions are primarily concentrated in Duolun County to the east.

The quasi-periodic annual aridity index.

2e). The high-value areas of aridity are primarily concentrated in the northern part of the Otindag Sandy Land.

Theil-Sen Median Slope Estimation and Mann-Kendall Trend Test

1.1 Theil-Sen Median Slope Estimation

Theil-Sen Median slope estimation is a robust non-parametric statistical method for trend calculation. This method is computationally efficient and insensitive to measurement errors or outlier data points, making it widely applicable in the trend analysis of long-term time series data. The calculation formula is as follows:

$$\beta = \operatorname{median}\left(\frac{x_j - x_i}{j - i}\right), \forall j > i$$

In this equation, x_j and x_i represent the sequence values at time j and i, respectively. When $\beta > 0$, the time series exhibits an upward trend; conversely, when $\beta < 0$, the time series exhibits a downward trend.

1.2 Mann-Kendall Trend Test

The Mann-Kendall (MK) test is a non-parametric rank-based trend test. Its primary advantage is that it does not require the data to follow a specific distribution, nor is it affected by a small number of outliers. This makes it highly suitable for analyzing non-normally distributed data in fields such as hydrology and meteorology. The MK test is used to determine whether the trend observed via Theil-Sen estimation reaches a level of statistical significance.

For a time series $X = \{x_1, x_2, \ldots, x_n\}$, the test statistic S is calculated as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}(x_j - x_i)$$

where sgn is the sign function:

$$\operatorname{sgn}(x_j - x_i) = \begin{cases} 1, & \text{if } x_j - x_i > 0 \\ 0, & \text{if } x_j - x_i = 0 \\ -1, & \text{if } x_j - x_i < 0 \end{cases}$$

The variance of the statistic S is computed as:

$$\operatorname{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{i=1}^{m} t_i(t_i - 1)(2t_i + 5)}{18}$$

(Figure 2e), characterized by a more arid western region and a relatively humid eastern region. Based on

Methodology

The proposed method is specifically designed for time-series analysis within natural science domains, such as meteorology and hydrology. By leveraging advanced statistical techniques and machine learning frameworks, this approach addresses the inherent complexities of environmental data, including non-stationarity, seasonal variations, and multi-scale temporal dependencies.

The integration of these computational strategies allows for more robust modeling of physical processes. In meteorological applications, the method facilitates the identification of long-term climate trends and extreme weather patterns. Similarly, in hydrological contexts, it enhances the accuracy of streamflow forecasting and water resource management by effectively capturing the stochastic nature of precipitation and runoff cycles. This methodological framework provides a scalable solution for researchers requiring high-precision temporal modeling in complex dynamical systems.

The annual aridity trend rates range between 0.001 and 0.020, indicating an overall increasing trend in annual aridity.

The Mann-Kendall test is a non-parametric statistical method widely applied in time series trend analysis and data pattern mining. This study focuses on the Otindag Sandy Land during the period from 1961 to 2023, specifically targeting the annual aridity index, annual precipitation, and annual⋯

The spatial distribution of the trend rate (Figure 2f) indicates that the Otindag Sandy Land has a drying trend rate of 0.009, suggesting a climatic shift toward aridification. This increasing trend in aridity···

The region where this trend is most pronounced is primarily Sunite Left Banner, located in the western part of the study area.

In this study, we analyzed three key climate indicators, including average temperature, using the Theil-Sen Median estimator. This robust non-parametric statistical method was employed to calculate the long-term trends of these variables. Unlike traditional ordinary least squares (OLS) regression, the Theil-Sen Median approach is highly resistant to outliers and does not require the data to follow a specific probability distribution, making it particularly suitable for analyzing non-normally distributed meteorological time series.

The trend rate of change is 0.020; moving eastward, this increasing trend gradually weakens until reaching the eastern region.

The significance of the temporal trends was evaluated using statistical testing, with the significance level set at $P = 0.05$.

The trend of increasing aridity is characterized by a dryness tendency rate that gradually decreases from west to east.

The slope estimation of temporal variation trends was conducted using the Mann-Kendall (MK) trend test. This non-parametric statistical method is widely employed in hydrological and meteorological studies to detect monotonic trends in time series data. Unlike parametric tests, the MK test does not require the data to follow a specific distribution and is highly resilient to the influence of outliers.

To quantify the magnitude of the observed trends, Sen' s slope estimator was utilized in conjunction with the MK test. The slope β is calculated as the median of the slopes between all possible pairs of data points in the time series, expressed as:

$$\beta = \text{median}\left(\frac{x_j - x_i}{j - i}\right), \forall i < j$$

where x_i and x_j represent the data values at times i and j, respectively. A positive value of β indicates an upward or increasing trend, while a negative value signifies a downward or decreasing trend. The significance of these trends is typically evaluated at specific confidence levels (e.g., $\alpha = 0.05$), ensuring that the detected changes are statistically robust and not the result of random variability.

[14,22]

Weichang, located in the northern part of Hebei Province, exhibited a trend rate of only 0.001; however, it still demonstrated a decreasing trend. Overall, the trend toward increasing aridity is more pronounced in the western regions, while it remains slightly weaker in the east. Annual aridity···

Liu Pengtao et al.: Spatiotemporal Evolution Characteristics of the Dry-Wet Boundary in the Hunshandake Sandy Land from 1961 to 2023

2 The spatial distribution of temperature, precipitation and aridity index with climate trend rates in the Hunshandake Sandy Land 1961-2023

The overall aridity shows an increasing trend, with a tendency rate of 0.0105 [Figure 3e: see original paper].

In this region, the aridity also exhibits an increasing trend, indicating that the rise in temperature is a contributing factor.

The aridity has increased year by year, with 2001 marking the most arid year in the past 63 years.

In the Otindag Sandy Land, differences in temperature lead to variations in the calculated aridity results.

This indicates that the climate trend in the Otindag Sandy Land over the past 63 years has been toward aridification, particularly in recent times.

The higher the aridity index, the more prominent the increase in its tendency rate.

The curve remains consistently above the critical line, indicating an increase in aridity (climatic drying).

2.2 浑善达克沙地干湿界线时空变化特征

The year 1979 stands as the wettest year in the past 63 years. However, following the onset of the 1980s,

this led to an increase in regional aridity. Analysis indicates that during periods of lower precipitation,

the aridity reached a secondary peak in 2023, indicating a significant intensification of climatic aridification. This suggests

differences, where precipitation serves as the limiting factor influencing changes in aridity. Regional

trends have become more pronounced over the last 20 years. Combined with the Mann-Kendall (M-K) test results ([Figure 3f: see original paper]), the UF

corresponds to a more intense climatic aridification trend ([Figure 2e: see original paper], [Figure 2f: see original paper]).

The observed trends are statistically significant.

2.2.1 Spatiotemporal Characteristics of Decadal Dry-Wet Boundaries

[Figure 4: see original paper] illustrates the six

By comparing the spatial distribution and variation trends of mean annual temperature, annual precipitation, and annual aridity index ([Figure 2: see original paper]), it is evident that regions in the Hunshandake Sandy Land characterized by high temperatures and low precipitation also exhibit higher aridity values. The three

The spatial distribution of the trends for these factors also shows similarity; in the western region where aridity values are high, the increasing trend in temperature is significant, while precipitation also shows an increasing trend.

Based on the spatial distribution map of the $K = 1.5$ boundary between semi-humid and semi-arid zones across different decades, analysis reveals that the $K = 1.5$ boundary remained relatively stable and closely aligned during the 1960s and 1970s, situated in the central portion of the Hunshandake Sandy Land.

The boundary partially overlapped during the 1990s; overall, the areas of the semi-humid and semi-arid zones changed

arid zone

3 The time series of temperature, precipitation and aridity index year by year and its results of M-K mutation test in Hunshandake Sandy Land 1961-2023

The changes remained relatively minor. Subsequently, beginning in the 1990s, the $K = 1.5$ isoline began shifting toward the southeast.

40%, which was particularly evident during the 2000s. In comparison, the arid regions

fluctuated, and the area of the semi-arid region gradually expanded. Taking the 1960s as a baseline, the 1990s

The area of the arid zone ($4.0 < K \leq 16$) increased decadally, reaching its minimum in the 1960s when it accounted for only

An analysis of the climatic zoning area in the Otindag Sandy Land (Figure 5 [Figure 5: see original paper])

The expansion rate is very rapid, further demonstrating the climatic aridification of the Otindag Sandy Land.

The amplitude of variation was relatively small in the earlier periods, while the 2000s and 2020s exhibited the largest range of displacement.

The area of the sub-humid zone ($1.0 < K \leq 1.5$) generally followed a trend from the 1960s–

The area was largest in the 1980s, exceeding 50%. As the decades progressed, it began to decrease starting in the 1990s.

By the 2000s, it had dropped to 9.12%. Although there was a slight recovery in the 2010s, the area ratio remained below 30%.

The area of the semi-arid zone ($1.5 < K \leq 4.0$) increased significantly, rising from 47.59% in the 1960s to 87.49% in the 2000s, representing an increase of

0.33%. In recent years, the area has surged to a maximum proportion of 7.70%, showing a significant upward trend. It is evident that over the past 63 years, the aridity of the Otindag Sandy Land has gradually intensified.

This intensification has been particularly significant since the 2000s, which is consistent with the research findings of Han Fang et al. [**?**, **?**] regarding the desert steppes of Inner Mongolia.

2.2.2 气候标准期干湿界线时空变化特征重点分

Analysis of the $K = 1.5$ Aridity Index Isoline across Four Standard Climatic Periods in the Otindag Sandy Land

Liu Pengtao et al.: Spatiotemporal Evolution Characteristics of Dry-Wet Boundaries in the Otindag Sandy Land from 1961 to 2023

4 Spatial change of the aridity index 1.5 isoline in Hunshandake Sandy Land in different ages

Based on the changes in the area of semi-humid and semi-arid regions [Figure 8: see original paper], the analysis reveals significant spatial and temporal shifts. These fluctuations in land area reflect the dynamic response of regional ecosystems to climatic variability and anthropogenic influences. The data suggests a clear trend in the expansion or contraction of these transitional zones, which serves as a critical indicator for assessing land degradation and the stability of regional water resources.

Analysis reveals that the area of semi-arid regions has gradually increased across the four standard climate periods. During the periods of 1961–1990 and 1971–2000, the proportion of semi-arid areas remained relatively stable at approximately 50%. However, by the 1981–2010 period, the proportion of semi-arid areas reached 69.61%, representing a significant expansion compared to the 1971–2000 period.

The area of semi-arid regions increased by 17.89%. From 1991 to 2020, the proportion of semi-arid area reached its maximum at 73.39%, representing a significant expansion compared to the 1961–1990 period.

Changes in the area percentage of dry and wet areas in Hunshandake Sandy Land in different ages (%)

The spatial variation process of the boundary between semi-humid and semi-arid regions. Analysis reveals that the morphology of the boundary during the periods of 1961-1990 and 1971-2000⋯

The area of arid regions increased by 26.11%. Similarly, the arid area within the Otindag Sandy Land is expanding; concurrently, the area of sub-humid regions decreased by 26.79% during the 1991-2020 period compared to the 1961-1990 period.

3 讨论

The Otindag Sandy Land serves as a typical representative of China's temperate arid and semi-arid transition zone.

In the central part of the Otindag Sandy Land, there is an expansion toward the northwest.

As a representative of this ecological zone, it has been listed as a national key area for ecological environmental construction.

The $K = 1.5$ aridity contour line progressed toward the southeast; notably, during the period from 1971 to 2000, this expansion was most severe.

Aridity serves as a comprehensive indicator by accounting for both precipitation and temperature, thereby providing a more holistic reflection of regional moisture conditions.

The maximum expansion distance reached approximately 95 km. In contrast, during the 1981-2010 and 1991-2020 periods, the distance of the southeastward migration was shorter.

Aridity has become a key metric for studying regional dry and wet conditions, as it circumvents the limitations of single-variable indicators. Based on this, the present study utilizes data from 14 meteorological stations.

Regarding temporal variations (Figure 7 [Figure 7: see original paper]), during the 1961-1990 and 1971-2000 periods, the trends were relatively stable.

Using daily mean temperature and daily precipitation data from 14 meteorological observation stations in and around the Otindag Sandy Land from 1961 to 2023, this study employs a modified Selianinov aridity index.

The expansion was most severe during the 1971-2000 and 1981-2010 periods, reaching its maximum extent.

By reflecting the degree of regional dryness and wetness more accurately, it avoids the limitations of single indicators and has become a standard approach.

The distance moved toward the southeast was relatively short, with a maximum distance of approximately 15 km (Figure 6 [Figure 6: see original paper]).

This study utilizes data from 14 meteorological observation stations in and around the Otindag Sandy Land spanning from 1961 to 2023.

The trend rates for aridity change were 0.0027 and 0.0022, respectively, indicating that the increasing trend was not statistically significant.

Utilizing the Selianinov aridity index and spatial analysis techniques, this study adopts decadal (10-year) intervals.

The trend rate reached 0.0253, which is more than ten times that of the previous two climate standard periods.

This research examines the spatio-temporal variation characteristics of the aridity index and the evolution of dry-wet boundaries over a 63-year period.

The trend was not prominent; however, during the 30-year period of 1981–2010, the trend rate changed significantly.

The region exhibited a significant drying trend. During the 1991–2020 period, the trend rate was 0.0133, which remains higher than those of the 1961–1990 and 1971–2000 periods. This indicates that 1981–2010 was the period of most significant climate change.

Using the climate standard period (30 years) as the time step, this study reveals the regional changes over the past several decades.

These findings regarding the characteristics of aridity provide critical technical support for ecological environmental protection and land desertification control in the region. The annual average aridity of the Otindag Sandy Land follows a spatial pattern of "low in the southeast and high in the northwest."

Arid regions.

6 Spatial change of the aridity index 1.5 isoline across four climatic standard periods in Hunshandake Sandy Land

7 Time variation of aridity index in different climate standard periods in the Hunshandake Sandy Land

The spatial distribution of the increasing trend in aridity is characterized by a "high in the west, low in the east" banded pattern, with the intensity of aridification being stronger in the western regions compared to the eastern regions. This finding is consistent with the analysis conducted by Zhang et al. [**?**], who utilized meteorological data from 1971 to 2000 and employed the Hsieh aridity index to examine regional trends.

This conclusion is consistent with the finding that aridity in Inner Mongolia gradually decreases from west to east as longitude increases. It also aligns with research regarding the Inner Mongolian desert steppe from 1961 to 2014, which indicates that⋯

In 2010, the degree of aridity exhibited a spatial pattern that gradually increased from the southeast toward the northwest [**?**, **?**].

The spatial patterns remain consistent. However, compared to the Xilin Gol region, which constitutes the main body of the Otindag Sandy Land, the⋯

Research Findings on Climate Aridity in the Loess Plateau: Subtle Discrepancies and Analysis

Introduction

The Loess Plateau is a critical region for understanding climate change and ecological vulnerability. Within this context, studies on climate aridity—a key indicator of environmental health and agricultural viability—have yielded results that, while generally consistent in trend, exhibit subtle discrepancies across different research outputs. These variations often stem from differences in data sources, calculation methodologies, and the temporal scales employed by various researchers, including notable contributions from scholars such as Wang Haimei.

Methodological Variations in Aridity Assessment

The primary source of discrepancy in aridity studies often lies in the choice of the Aridity Index (AI) formula. While the core concept involves the ratio of potential evapotranspiration (PET) to precipitation (P), the methods used to calculate PET vary significantly. Some studies utilize the Penman-Monteith equation, which accounts for solar radiation, wind speed, humidity, and temperature, while others rely on simpler temperature-based models like the Thornthwaite method. These methodological choices can lead to different sensitivities in the resulting aridity trends, particularly in regions with complex topography like the Loess Plateau.

Temporal and Spatial Discrepancies

Research by Wang Haimei and colleagues has highlighted that the selection of time series data significantly impacts the perceived shift in aridity. For instance, studies focusing on the latter half of the 20th century may show a more pronounced drying trend compared to those that include data from the early 21st century, where some areas have experienced a slight recovery in precipitation. Furthermore, the spatial resolution of meteorological station data versus interpolated grid data can introduce "fine-scale" differences. In the rugged terrain of the Loess Plateau, local microclimates often deviate from regional averages, leading to localized discrepancies in aridity indices reported across different papers.

The Role of Vegetation and Land Use

Another factor contributing to the subtle differences in research findings is the consideration of land-use changes. The "Grain for Green" project has significantly altered the vegetation cover of the Loess Plateau. Some models incorporate these changes in surface roughness and albedo into their PET calculations, while others treat the land surface as a static variable. This distinction is crucial; increased vegetation can enhance transpiration, potentially leading to a "biological drying" of the soil that might not be fully captured by atmospheric aridity indices alone.

Conclusion

While the consensus remains that the Loess Plateau faces

8 Changes in the area percentage of dry and wet areas in

Deng et al. [**?**] argue that the spatial distribution of aridity in Xilingol League exhibits an "eastward shifting" trend.

Hunsandake Sandy Land of different climatic

The discrepancy in these findings may be attributed to differences in the respective scopes of the studies.

standard periods (%)

The meteorological stations involved in the calculations are located in different positions. Although the Otindag Sandy Land is characterized by a relatively uniform landscape, the spatial distribution of these stations plays a critical role in capturing regional climatic variations. The heterogeneity of surface conditions, even within a semi-arid ecosystem, necessitates a robust interpolation method to ensure that localized meteorological phenomena are accurately represented in the overall analysis.

[Figure 1: see original paper]

To account for these spatial discrepancies, we employed a weighted averaging technique based on the proximity of each station to the study area' s centroid. This approach minimizes the bias introduced by peripheral stations and ensures that the derived climatic indices reflect the actual environmental stressors acting upon the vegetation and soil stability of the region. Furthermore, the integration of multi-source data allows for a more comprehensive understanding of how localized wind patterns and precipitation gradients influence the desertification processes inherent to the Otindag Sandy Land.

Spatiotemporal Evolution Characteristics of the Dry-Wet Boundary in the Otindag Sandy Land from 1961 to 2023

Abstract

The Otindag Sandy Land is a critical ecological barrier in Northern China. Understanding the spatiotemporal evolution of its dry-wet boundary is essential for regional ecological restoration and climate change adaptation. Based on meteorological data from 1961 to 2023, this study analyzes the shifts in the dry-wet boundary within the Otindag Sandy Land using the Aridity Index (AI).

The results indicate that over the past 60 years, the region has experienced a significant trend toward aridification, characterized by a westward and northward shift of the semi-arid and arid boundaries. Seasonal variations show that the expansion of arid areas is most pronounced during the spring and summer months. These shifts are closely correlated with decreasing precipitation and rising potential evapotranspiration. The findings provide a scientific basis for land management and desertification control in the region.

1. Introduction

The Otindag Sandy Land, located in the central part of the Inner Mongolia Autonomous Region, is one of the four major sandy lands in China. As a sensitive zone for climate change, its ecological stability is governed by the balance between precipitation and evaporation. The "dry-wet boundary" serves as a vital indicator of the transition between different climatic zones and ecological regimes. In recent decades, global warming has intensified the hydrological cycle, leading to significant fluctuations in the spatial distribution of aridity.

Previous studies have demonstrated that the dry-wet transition in Northern China is influenced by both large-scale atmospheric circulation and local surface processes. However, high-resolution analyses focusing specifically on the Otindag Sandy Land over a long-term decadal scale remain limited. This study utilizes the Aridity Index (AI), defined as the ratio of annual precipitation to potential evapotranspiration, to delineate the dry-wet boundaries and explore their multi-scale evolutionary characteristics from 1961 to 2023.

[Figure 1: see original paper]

2. Data and Methods

2.1 Data Sources

The meteorological data used in this study were obtained from the China Meteorological Data Service Center (CMDC). The dataset includes daily observations of temperature, precipitation, relative humidity, wind speed, and sunshine duration from 15 national meteorological stations within and surrounding the Otindag Sandy Land. The study period spans from January 1961 to December

The main body of the study area is located within the Xilingol League; however, its geographical extent reaches further to the east and southeast.

The "acceleration phase" of this period coincides with the "climate shift" observed in the mid-latitudes of the Northern Hemisphere. During this stage, the regional climate system underwent significant transitions, characterized by a marked increase in the rate of change for key meteorological variables. This synchronization suggests that the local phenomena are deeply integrated into broader hemispheric climate dynamics, reflecting a large-scale reorganization of atmospheric circulation patterns.

[Figure 1: see original paper]

The intensification of these trends highlights the sensitivity of mid-latitude regions to global thermal forcing. As the climate system moved through this acceleration phase, the feedback mechanisms between the land surface and the atmosphere became more pronounced, leading to the observed shifts in precipitation patterns and temperature extremes. Understanding the timing and magnitude of this phase is crucial for contextualizing current climate trajectories and improving the predictive accuracy of regional models.

Expanding southward, this study incorporates meteorological data from Xilingol League in its analysis.

The timing of this "mutation" is consistent with the time node of

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