Variation Characteristics and Dominant Factors of Potential Evapotranspiration in Different Arid and Humid Regions of Inner Mongolia: A Postprint Analysis

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Abstract

Analyzing the spatiotemporal variations of potential evapotranspiration and its sensitivity to meteorological factors in different dry-wet zones facilitates the optimization of water resource management for agriculture, animal husbandry, and forestry, as well as water resources planning and allocation, and the prediction of climate change impacts on water resources. Given the diverse dry-wet conditions and climatic characteristics in Inner Mongolia, a region experiencing significant climate change, this study calculated potential evapotranspiration (ET0) from 1961 to 2023 at 76 meteorological stations using the FAO Penman-Monteith equation, along with sensitivity coefficients to air temperature, wind speed, water vapor pressure, and sunshine duration. The dominant factors driving ET0 variation and the quantitative response of ET0 to climate change in different dry-wet zones were investigated. The results indicate: (1) Spatially, ET0 generally exhibits a decreasing trend from west to east meridionally and from south to north zonally; the ET0 trend is not significant in arid and semi-arid zones, while ET0 shows an increasing trend in semi-humid zones. (2) Across all dry-wet zones, ET0 exhibits the highest sensitivity to maximum air temperature, followed by water vapor pressure, wind speed, and minimum air temperature, with the lowest sensitivity to sunshine duration. (3) The trends of sensitivity coefficients for meteorological factors are consistent across different dry-wet zones: temperature and water vapor pressure sensitivity coefficients show decreasing trends, while wind speed and sunshine sensitivity coefficients show increasing trends, with water vapor pressure and wind speed sensitivity coefficients changing significantly. (4) Changes in maximum and minimum air temperature positively contribute to ET0 variation, whereas changes in wind speed, water vapor pressure, and sunshine negatively contribute; sunshine has the smallest contribution to ET0 variation in all dry-wet zones, wind speed is the dominant factor of ET0 variation in arid and semi-arid zones, and maximum air temperature is the dominant factor in semi-humid zones.

Full Text

Changes Characteristics and Dominant Factors of Potential Evapotranspiration in Different Dry and Wet Zones of Inner Mongolia

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Abstract

Analyzing the spatiotemporal variations of potential evapotranspiration and its sensitivity to meteorological factors across different dry and wet zones is crucial for optimizing water resource management in agriculture, animal husbandry, and forestry, as well as for water resource planning and allocation and predicting climate change impacts on water resources. Given the diverse dry-wet conditions and climatic characteristics of Inner Mongolia, a region experiencing significant climate change, this study calculated potential evapotranspiration (ET_0) using the FAO Penman-Monteith formula and its sensitivity coefficients to maximum temperature, wind speed, water vapor pressure, and sunshine hours based on daily meteorological data from 76 stations in Inner Mongolia from 1961 to 2023. The dominant factors driving ET_0 changes under climate change and their quantitative responses were investigated. The results show that: (1) Spatially, ET_0 generally decreases from west to east longitudinally and from south to north latitudinally. The trend is not significant in arid and semi-arid zones, while a significant increasing trend is observed in semi-humid zones. (2) ET_0 exhibits the highest sensitivity to maximum temperature, followed by water vapor pressure, wind speed, and minimum temperature, with sunshine hours being the least sensitive factor. (3) The sensitivity coefficients of all meteorological factors show consistent trends across different dry-wet zones: temperature and vapor pressure sensitivity coefficients decrease, while wind speed and sunshine sensitivity coefficients increase, with significant changes in vapor pressure and wind speed sensitivity coefficients. (4) Maximum and minimum temperatures positively contribute to ET_0 changes, whereas wind speed, water vapor pressure, and sunshine hours contribute negatively. Sunshine hours have the smallest contribution across all zones. Wind speed is the dominant factor in arid and semi-arid zones, while maximum temperature is the dominant factor in semi-humid zones.

Keywords: potential evapotranspiration; sensitivity coefficient; dominant factor; dry and wet zones; Inner Mongolia

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1 Introduction

Evapotranspiration is a critical component of the hydrological cycle and an important element in assessing the impacts of global change on water resources and management. It serves as a fundamental basis for evaluating agricultural water use efficiency and plays a vital role in regional and global water-heat balance calculations. Together with precipitation, it determines regional dry-wet conditions and influences the formation and evolution of geographical environments, making it essential for sustainable water resource management. Due to limited direct evapotranspiration observations, potential evapotranspiration (ET_0) is commonly used to estimate actual evapotranspiration. ET_0 represents the evapotranspiration capacity under sufficient water supply conditions. The most widely applied method for calculating ET_0 is the FAO Penman-Monteith equation, revised by the Food and Agriculture Organization in 1998. This equation incorporates multiple meteorological elements including temperature, wind speed, water vapor pressure, and radiation, making it applicable across different climate types and widely used in hydrological and water resource assessments under climate change scenarios.

Analyzing ET_0 sensitivity to meteorological factors facilitates quantitative investigation of climate change impacts on regional water cycles and provides valuable guidance for water management planning in agriculture, animal husbandry, and forestry. Current ET_0 research primarily focuses on three aspects: spatial variation characteristics, temporal variation characteristics, and factor sensitivity analysis. Regarding spatial patterns, Li et al. analyzed ET_0 variations on the northern slope of the Kunlun Mountains in Xinjiang from 1979 to 2021, finding a decreasing trend from the southern Tarim Basin margin southward. Feng et al. calculated ET_0 in the Xiliao River Basin and identified an overall increasing trend. Li et al. studied the central arid zone of Ningxia and found longitudinal decreasing patterns in Yanchi County and latitudinal increasing patterns in Tongxin and Haiyuan counties. Concerning temporal trends, Zhou et al. reported that ET_0 in the Three-River Headwaters region increased at a rate of $0.69 \text{ mm} \cdot \text{a}^{-1}$ from 1961 to 2019. Wang et al. found that annual ET_0 in the Tabu River Basin showed a non-significant increasing trend at $4.09 \text{ mm} \cdot (10\text{a})^{-1}$ after a substantial increase post-1993. Wu et al. observed a decreasing ET_0 trend in the Hexi Corridor from 1960 to 2020, with values significantly lower after 2013 and peaking in 1960.

In terms of factor sensitivity, studies have identified maximum temperature as the most sensitive meteorological factor for ET_0 in the Yangtze River Basin, Haihe River Basin, and Northeast China. However, other research indicates varying dominant factors across regions: relative humidity in some areas, sunshine hours in the North China Plain, and minimum temperature in the Tarim Basin during the growing season. These discrepancies highlight that ET_0 spatiotemporal variations and dominant factors differ across periods and regions.

Most studies have not conducted in-depth analyses of ET$_0$ characteristics and influencing factors for different climate type zones, particularly regarding differences between dry-wet zones, which are crucial for regional water-heat balance and indirectly affect ET$_0$ variations.

China is a sensitive and significantly affected region of global climate change, with Inner Mongolia experiencing particularly pronounced impacts. Since the 1960s, Inner Mongolia has experienced significant warming, enhanced precipitation extremes, and frequent droughts, leading to severe water shortages and prominent water-heat balance issues that threaten ecosystem and economic sustainability. While existing climate research in this region has focused on climate change characteristics and resulting dry-wet conditions, studies on ET$_0$ evolution remain limited. Therefore, this study selected 76 meteorological stations across Inner Mongolia, calculated ET$_0$ sequences using the Penman-Monteith formula, analyzed spatiotemporal variation characteristics using trend analysis and spatial analysis, investigated ET$_0$ sensitivity to meteorological factors using the sensitivity coefficient method, evaluated contributions of various factors using variance analysis, and conducted attribution analysis to provide references for water resource management in different dry-wet zones of Inner Mongolia.

1.1 Study Area

Inner Mongolia is located in northern China between 97°11 E–126°04 E and 37°22 N–53°20 N, covering an area of 1.18$×10^{6}$ km^2 with elevations ranging from 78–3389 m. The terrain is undulating, encompassing arid, semi-arid, and semi-humid zones. Precipitation is less than evaporation, with extreme precipitation events and highly uneven spatiotemporal distribution. The ecological environment is fragile. Since the 1980s, intensified climate change has caused significant warming in Inner Mongolia, making the region highly sensitive to climate change.

1.2 Data Sources and Processing

Daily meteorological data from 76 stations (Fig. 1) were selected, including average pressure (P), maximum temperature (T), minimum temperature (T), average wind speed at 10 m height (U), average water vapor pressure (V), and sunshine hours (N). Data were obtained from the National Comprehensive Meteorological Information Sharing Platform (CIMISS) and underwent continuity and consistency checks. Missing data were interpolated using linear regression.

1.3 Methods

1.3.1 Potential Evapotranspiration Calculation The FAO-recommended Penman-Monteith equation was used to calculate ET$_0$:

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

where ET_0 is potential evapotranspiration ($mm \cdot d^{-1}$); R is net radiation at the surface ($MJ \cdot m^{-2} \cdot d^{-1}$); G is soil heat flux ($MJ \cdot m^{-2} \cdot d^{-1}$); T is mean daily air temperature (°C); Δ is the slope of the saturation vapor pressure curve ($kPa \cdot °C^{-1}$); e is saturation vapor pressure (kPa); e is actual vapor pressure (kPa); γ is the psychrometric constant ($kPa \cdot °C^{-1}$); and u_2 is wind speed at 2 m height ($m \cdot s^{-1}$). Some parameters in the equation lack direct observations and must be estimated from other meteorological elements.

1.3.2 Sensitivity Coefficient Method and Optimization The concept of sensitivity coefficients was first proposed by McCuen (1974):

$$S_i = \lim_{\Delta x_i \to 0} \frac{\Delta ET_0 / ET_0}{\Delta x_i / x_i}$$

where ΔET_0 is the change in potential evapotranspiration; Δx is the change in meteorological factor x ; and S is the dimensionless sensitivity coefficient of ET_0 to x . However, this method has limitations: the sensitivity coefficient remains influenced by the magnitude of x despite dimensionless processing, compromising comparability between different x . Additionally, the sign of x affects continuity—for instance, winter temperatures in northern China are mostly below 0°C, causing temperature sensitivity coefficients to have opposite signs compared to when temperature exceeds 0°C, which is an artifact of temperature values rather than true sensitivity differences.

To address this, the calculation method was optimized by standardizing both ET_0 and x :

$$S_i = \lim_{\Delta x_i \to 0} \frac{\Delta ET_0 / (ET_{0,\max} - ET_{0,\min})}{\Delta x_i / (x_{i,\max} - x_{i,\min})}$$

where ET_0, and ET_0, are the maximum and minimum ET_0 values, and x , and x , are the maximum and minimum values of x . Based on this method, T , T , U, V, and N were selected as key meteorological factors for sensitivity analysis, with ST , ST , SU, SV, and SN representing sensitivity coefficients of ET_0 to each factor.

1.3.3 Contribution of Meteorological Factors to ET_0 Changes ET_0 changes depend not only on sensitivity to meteorological factors but also on the magnitude of factor changes. The contribution of each factor was calculated using the ratio of its climate tendency rate to its multi-year average value, with the largest contributor identified as the dominant factor:

$$C_i = \lim_{\Delta x_i \to 0, \mathrm{Trend}} \frac{\Delta ET_0}{ET_0} = \frac{\mathrm{Trend}_{x_i} \cdot n \cdot S_i}{\overline{x_i}}$$

where Trend is the climate tendency rate of x ; n is the number of statistical years; $\overline{x_i}$ is the multi-year average of x ; and C is the contribution of x to ET_0 changes.

2 Results and Analysis

2.1 Spatial Distribution Characteristics of ET_0

Spatial analysis of multi-year average ET_0 reveals a general pattern decreasing from west to east longitudinally and from south to north latitudinally (Fig. 2). High values occur at Guazihu Station in Alxa League (1741.6 mm), while low values occur at Tulihe Station in Hulun Buir City (624.5 mm)—a difference of 1117.1 mm. This distribution correlates with geographical location and surface cover types: desert and desertified grassland areas have very high ET_0 exceeding 1200 mm, while forest and meadow grassland areas have low ET_0 below 800 mm.

2.2 Variation Characteristics of ET_0 and Meteorological Factors

Mann-Kendall trend analysis shows that ET_0 exhibits a significant increasing trend in all dry-wet zones, with greater increases in semi-humid zones (Table 1). Maximum and minimum temperatures show significant warming trends, with minimum temperatures rising more prominently, indicating clear warming in Inner Mongolia under global climate change. Wind speed shows a significant decreasing trend, with larger reductions in arid and semi-arid zones. Water vapor pressure shows slight decreasing trends, with greater decreases in semi-humid zones. Sunshine hours decrease slightly in arid and semi-arid zones but remain essentially unchanged in semi-humid zones. ET_0 trends are not significant in arid and semi-arid zones but increase in semi-humid zones.

2.3 Sensitivity Coefficient Analysis

2.3.1 Interannual Variation of Sensitivity Coefficients Sensitivity coefficients of all meteorological factors show some interannual fluctuation (Fig. 3). The variances of ST , ST , SU, SV, and SN are 2.3\$$\times10^{\{-6\}, 1.7\times10}$\{-6\}, $1.2\times10^{\{-5\}, 1.1\times10}$\{-5\}, *and*3.6×10^\{-6\}\$, respectively, indicating small interannual variations. All zones show consistent trends: ST and ST (negative values) decrease, while SU and SN increase. The magnitude of change ranks as: SV > SU > SN > ST > ST , with SV and SU showing larger tendency rates, indicating strengthening positive sensitivity to wind speed and weakening negative sensitivity to vapor pressure.

2.3.2 Intra-annual Variation of Sensitivity Coefficients Monthly variations of meteorological factors and sensitivity coefficients show high correlation (Fig. 4). Except for SU' s bimodal pattern, all show unimodal changes. ST and ST follow temperature patterns, with greater sensitivity at higher temperatures. SU peaks in spring and autumn, followed by summer, with winter minimums, roughly matching annual wind speed variations. SV remains negative year-round, indicating ET_0 decreases as vapor pressure increases, with maximum negative values in summer when vapor pressure is highest. N and SN show consistent trends but different magnitudes: despite shorter sunshine hours in winter, SN approaches zero, indicating very low winter sensitivity. Seasonally, spring and autumn are most sensitive to temperature and wind speed, summer is most sensitive to temperature, and winter is least sensitive to sunshine hours. Overall, the ranking of sensitivity coefficients is: ST $>$ ST $>$ |SV| $>$ SU $>$ SN.

2.3.3 Spatial Variation of Sensitivity Coefficients Spatial distributions of sensitivity coefficients show distinct regional patterns (Fig. 5). ST exhibits three high-value centers in western Hulun Buir, southern Tongliao, and western Xilingol League, and three low-value centers in Alxa League, Hohhot, and northern Chifeng. SU decreases gradually from west to east to northeast, with high-low differences reaching 0.05, closely related to surface cover types. SV (negative values) shows the opposite pattern to SU, with high-sensitivity areas in Hulun Buir and low-sensitivity areas in Alxa League, correlating with local moisture conditions. SN high-value centers are located south of the Hetao region to Hohhot, with relatively low values elsewhere. Overall, central areas are highly sensitive to temperature, western areas are highly sensitive to wind speed but lowly sensitive to vapor pressure, northeastern areas show the opposite pattern, and central-western areas are highly sensitive to sunshine hours.

2.4 Analysis of ET_0 Change Influencing Factors

Using the contribution formula, the impacts of meteorological factors on ET_0 changes were analyzed (Table 2). In arid and semi-arid zones, factor contributions rank as: U $>$ T $>$ T $>$ V $>$ N. Wind speed changes contribute -7.63% and -10.04% in these zones, respectively, while temperature changes contribute 6.81%, 7.05%, and 4.40%. Vapor pressure contributions are relatively small (5.02% and 3.34%), and sunshine hours contribute minimally (-2.06% and -1.43%). In semi-humid zones, the ranking differs: T $>$ V $>$ T $>$ U $>$ N. Maximum temperature contributes 10.57% to ET_0 changes, while wind speed, vapor pressure, minimum temperature, and sunshine hours contribute negatively (-6.12%, -5.01%, -1.17%, and -1.08%, respectively). The calculated ET_0 changes match actual changes with relative errors within 5%. Wind speed is the dominant factor in arid and semi-arid zones, while maximum temperature dominates in semi-humid zones.

3 Discussion

Previous studies analyzing ET_0 changes across China using 740 stations found decreasing trends at rates of 4.43 $\mathrm{mm} \cdot (10\mathrm{a})^{-1}$ nationally and 6.75 $\mathrm{mm} \cdot (10\mathrm{a})^{-1}$ in North China. Other research using 599 stations showed decreasing trends in the arid region (including Inner Mongolia). This study, using dry-wet conditions as regional divisions, found different results: non-significant ET_0 changes in arid and semi-arid zones but increases in semi-humid zones. These discrepancies arise from differences in data periods, regional divisions, dry-wet conditions, and geographical factors. Global warming continues to intensify, affecting hydrological cycle speed and intensity and regional evapotranspiration, potentially altering local dry-wet conditions. In water-scarce, drought-prone Inner Mongolia with diverse dry-wet conditions, understanding ET_0 responses to climate change is crucial for water resource management.

This study optimized the sensitivity coefficient calculation method. The monthly sensitivity coefficient variations differ from some previous studies, particularly regarding minimum temperature sensitivity signs. While other studies attempted corrections by taking absolute values of meteorological factors, this did not fundamentally resolve continuity issues. The optimization algorithm developed here has clear physical meaning, effectively avoids sign-related artifacts, and enables more comparable sensitivity analyses.

Under climate change, Inner Mongolia has warmed significantly. Although ET_0 sensitivity to temperature is high and positive, overall ET_0 has not increased substantially, largely because decreasing wind speed offsets temperature effects. The different dominant factors across zones—wind speed in arid/semi-arid zones versus temperature in semi-humid zones—result from larger wind speed tendency rates and higher SU values in arid/semi-arid zones, while temperature sensitivity is highest in semi-humid zones. Future research should quantitatively examine feedback mechanisms among ET_0, topography, vegetation types, soil texture, aerosol concentrations, and atmospheric circulation.

4 Conclusions

(1) ET_0 spatial distribution correlates highly with local precipitation and surface cover types. High-value areas have high temperatures, scarce precipitation, and exposed surfaces, while low-value areas have low temperatures, abundant precipitation, and dense vegetation cover.

(2) All dry-wet zones show consistent trends in meteorological factor sensitivity coefficients: SV and SU change significantly; ET_0 is least sensitive to sunshine hours; the most sensitive factor varies by season and region.

(3) Meteorological factor contributions to ET_0 changes vary significantly across dry-wet zones. Wind speed dominates in arid and semi-arid zones, while maximum temperature dominates in semi-humid zones.

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