Evapotranspiration Characteristics and Attribution Analysis in the Semi-arid Region of Inner Mongolia (Postprint)

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Abstract

Investigating the variation characteristics of evapotranspiration (ET) and its influencing factors is crucial for the effective utilization of regional water resources. This study, based on the BEPS (Boreal Ecosystem Productivity Simulator) model and combined with remote sensing and meteorological data, simulated the ET variation characteristics in the semi-arid region of Inner Mongolia from 1981 to 2018 and quantified the contributions of its influencing factors. The study found that ET in the semi-arid region of Inner Mongolia exhibited a fluctuating upward trend at a rate of 1.75 mm · a^{-1} from 1981 to 2018 (P<0.05); simultaneously, ET variation showed interdecadal differences, with an obvious abrupt change occurring in 1997, and ET increased at a rate of 1.70 mm · a^{-1} from 1998 to 2018 (P<0.05). Vapor pressure deficit (VPD) and LAI increased significantly at rates of 0.002 hPa and 0.01 per year, respectively, after 1997 (P<0.05), compensating for the adverse effects of other factors and leading to a significant increase in ET. Path analysis and regression analysis results indicated that ET variation was primarily driven by the direct effect of VPD, with the coefficient of determination of the path analysis reaching 0.95. Areas where VPD dominated ET variation accounted for 93.56% of the semi-arid region of Inner Mongolia, explaining 24.83%~90.46% of ET variation. Meanwhile, VPD was also the main influencing factor of ET variation across five land use types—cropland, forestland, grassland, urban areas, and bare land—explaining on average more than 45% of ET variation.

Full Text

Evapotranspiration Characteristics and Attribution Analysis in Semi-arid Regions of Inner Mongolia

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Abstract

Understanding the variation characteristics of evapotranspiration (ET) and its influencing factors is crucial for effective regional water resource utilization. This study simulated ET in the semi-arid region of Inner Mongolia from 1981 to 2018 using the Boreal Ecosystem Productivity Simulator (BEPS) model combined with remote sensing and meteorological data, and quantified the contributions of various driving factors. The results indicate that ET exhibited a fluctuating upward trend at a rate of 1.75 mm · a^{-1} (P<0.05) during the study period. Notably, ET changes displayed interdecadal differences with a significant mutation occurring in 1997. After this mutation point, ET increased substantially at 1.70 mm · a^{-1} (P<0.05) from 1998 to 2018. Atmospheric water demand, characterized by vapor pressure deficit (VPD), and vegetation dynamics, represented by leaf area index (LAI), emerged as the primary driving factors after 1997, increasing significantly at rates of 0.002 hPa · a^{-1} and 0.01 a^{-1}, respectively (P<0.05). The positive effects of VPD and LAI compensated for adverse impacts from other factors, ultimately driving the significant ET increase. Path analysis and regression results demonstrate that VPD was the dominant factor controlling ET variability, directly driving changes across 93.56% of the study area and explaining 24.83%-90.46% of ET variation, with a path analysis determination coefficient of 0.95. VPD also served as the principal influencing factor across all five land use types—cultivated land, forestland, grassland, urban land, and bare land—with average contribution rates exceeding 45%.

Keywords: evapotranspiration; vapor pressure deficit; BEPS model; leaf area index; Inner Mongolia

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Introduction

Evapotranspiration (ET) represents the transfer of water from land surfaces to the atmosphere and constitutes a critical link between terrestrial water and energy balance. Global ET has exhibited an overall upward trend due to climate change and anthropogenic influences, accelerating the water cycle and consequently affecting regional water resource availability. Accurate simulation and quantification of regional-scale ET and its driving factors are therefore essential for understanding climate change impacts on terrestrial water cycles.

Previous decades have witnessed numerous studies investigating ET changes and associated drivers. However, due to spatial heterogeneity in influencing factors and regional climate background differences, no consensus has been reached regarding the primary factors causing ET variation. Recently, atmospheric water demand (vapor pressure deficit, VPD) and vegetation dynamics have garnered widespread attention as two crucial influencing factors. Global greening has contributed substantially to terrestrial ET increase, with studies indicating that vegetation greening accounts for up to 1.75 $\mathrm{mm} \cdot \mathrm{a}^{-1}$ of the global ET increase. Climate warming enhances saturated vapor pressure while reducing oceanic moisture transport, leading to decreased actual vapor pressure and intensified atmospheric drought. In arid and semi-arid regions, persistent warming exacerbates VPD impacts on ET, with water-limited, low-yield grassland areas exhibiting the highest sensitivity to such climate change effects.

The semi-arid region of Inner Mongolia, dominated by grassland ecosystems, is characterized by ecological fragility and high sensitivity to climate change and human disturbance. The region experiences severe water scarcity with uneven spatiotemporal distribution and ranks among the fastest warming areas globally. Analyses of terrestrial water storage and other indicators have revealed intensifying drought trends in Inner Mongolia' s semi-arid zone. Under current climate conditions, clarifying ET variation patterns and their driving mechanisms is critical for scientific water resource scheduling and risk management in response to potential extreme events caused by accelerated water cycling.

This study combines long-term flux and meteorological observations with the BEPS (Boreal Ecosystem Productivity Simulator) model to simulate ecosystem ET in Inner Mongolia' s semi-arid region from 1981 to 2018. By analyzing spatiotemporal ET variation characteristics and responses to climatic and vegetation changes, we aim to quantify ET variation patterns and identify primary influencing factors, thereby providing scientific significance for effective water resource development and ecological environmental protection.

1.1 Study Area Overview

Based on the climate zoning map compiled by the China Meteorological Administration, we selected the semi-arid region of Inner Mongolia in northwestern China (107.66°-121.90°E, 37.62°-46.83°N) as our study area [Figure 1: see original paper]. This region represents a typical agro-pastoral ecotone with fragile ecological environments and high sensitivity to climate change responses. Grassland constitutes the primary land cover type, accounting for the majority of the total area and mainly distributed across the Inner Mongolia Plateau. Forestland (FOREST) is primarily located in the southern plateau region and the southern

Greater Khingan Mountains. Cultivated land occupies approximately 9.82% of the area, distributed mainly in the southern plateau and southwestern Songliao Plain.

1.2 Data Sources

Meteorological data were obtained from the National Meteorological Science Data Center (data.cma.cn), including daily average temperature (°C), precipitation (mm), relative humidity (%), sunshine hours (h), and wind speed ($m \cdot s^{-1}$). All data underwent rigorous quality control and standardization processing. VPD datasets were calculated from these meteorological variables. Soil moisture data were derived from the European Centre for Medium-Range Weather Forecasts (ECMWF) soil moisture grid dataset (https://cds.climate.copernicus.eu), which uses volumetric soil water content ($m^3 \cdot m^{-3}$) in the 0–5 cm surface soil layer to represent soil moisture conditions. Leaf area index (LAI) data were acquired from the GLOBMAP LAI V3 product of the Resources and Environmental Science Data Center (https://www.resdc.cn/), with LAI values representing annual vegetation growth status. All datasets were processed to WGS1984 coordinate system with 1 km spatial resolution.

The spatially explicit ET dataset was simulated using the BEPS model, which operates on a daily time step. The BEPS model is a remote sensing-based ecological process model (dual-leaf, dual-source model) built upon the foundation of the FOREST physiological ecology model. ET calculation in BEPS incorporates four components: canopy interception evaporation, canopy transpiration, soil surface evaporation, and surface snow sublimation. The model comprehensively considers environmental factors (soil moisture, meteorological elements), vegetation structure, and plant physiological processes affecting ET. Previous studies have demonstrated that BEPS can accurately estimate ET and reveal the influence mechanisms of climate change and vegetation dynamics, leading to its widespread application.

Flux observation data were obtained from the AsiaFlux database (http://www.asiaflux.net), including monthly flux data from two typical semi-arid grassland stations at Xilinhot and Duolun, with station locations shown in [Figure 1: see original paper]. The energy balance closure of these flux datasets exceeded 90%, meeting energy non-closure requirements and indicating good data quality.

1.3 Methods

1.3.1 Mutation Detection and Trend Analysis We employed two different mutation detection methods—Sequential t-test Analysis of Regime Shifts (STARS) and cumulative anomaly method—to examine ET data mutations in Inner Mongolia' s semi-arid region. Cross-validation using both methods effectively improves mutation detection accuracy. We selected the consistent mutation year identified by both methods as the mutation point and conducted segmented studies of ET changes.

The cumulative anomaly method is a nonlinear statistical approach that can intuitively identify data evolution trends and mutation points through cumulative curves. STARS is a method based on sequential t-tests that detects changes in sequence mean fluctuation levels and variances, capable of real-time monitoring of signals when systems rapidly transition from one relatively stable state to another. This method has been widely applied in climate and ecosystem mutation detection studies. The Regime Shift Index (RSI) is calculated as:

$$RSI_j = \sum_{i=0}^{l} \frac{x_i^*}{\sigma_l}, \quad x_i^* = \begin{cases} x_i - \bar{x} & \text{if } i \leq j \\ 0 & \text{if } i > j \end{cases}$$

where l represents the cutoff length set for sequence x, similar to cutoff points in low-pass filtering; $\bar{x}$ is the mean of regime R; σ_l^2 is the mean variance of sequence x over cutoff length l; and t is the t-distribution value corresponding to degrees of freedom at a given probability level. If RSI is negative, no mutation exists in year j; if RSI is positive, a regime shift occurs in year j.

We applied the Theil-Sen method for ET trend analysis, a non-parametric approach commonly used for meteorological time series trend detection. The Theil-Sen method calculates ET change rate β as:

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

where x_i and x_j are sequence values in years i and j, respectively. If $\beta > 0$, the sequence shows an upward trend; if $\beta < 0$, it shows a downward trend. The Mann-Kendall method was used for significance testing.

1.3.2 Evapotranspiration Influencing Factor Analysis ET changes are driven by multiple factors including solar radiation, air temperature, humidity, wind speed, water supply, and vegetation physiological characteristics. Due to the complexity and correlation among influencing factors, we first employed partial correlation analysis and path analysis to select appropriate factors as independent variables for regression analysis from among temperature, precipitation, relative humidity, wind speed, solar radiation, soil moisture, and LAI.

Path analysis decomposes the correlation between independent and dependent variables into direct and indirect effects based on multiple linear regression, using direct and indirect path coefficients to characterize factor impacts. In this study, ET served as the dependent variable and passed the Shapiro-Wilk normality test, confirming its suitability for path analysis. The larger the absolute value of the decision coefficient, the stronger the factor' s influence; positive decision coefficients indicate promotional effects, while negative values indicate inhibitory effects.

Building upon this foundation and minimizing inter-factor correlation effects, we used stepwise multiple regression analysis to investigate the primary drivers of ET change and quantify each environmental factor’ s relative contribution. Original data and environmental variables were normalized using:

$$x_{\text{norm}} = \frac{x_i - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}$$

where x_{norm} is the normalized variable, x_i is the ith variable in sequence x, and x_{min} and x_{max} are the minimum and maximum values, respectively. Stepwise regression established models describing relationships between normalized ET (dependent variable Y) and influencing factors (independent variables X). The relative contribution θ of factor X to Y change was calculated as:

$$\Delta Y = a\Delta X_1 + b\Delta X_2 + c\Delta X_3 + \cdots$$

where a, b, and c are regression coefficients, and θ represents the relative contribution of X to Y variation.

2.1 ET Dataset Validation

We validated BEPS model performance by comparing simulated ET with monthly observed ET data from the Xilingol and Duolun stations from 2005 to 2010 [Figure 2: see original paper]. The BEPS-simulated ET showed good agreement with observations at both stations, with fitted curve slopes reaching 0.81 at Xilingol station ($R^2 = 0.81$) and 0.90 at Duolun station ($R^2 = 0.90$). These results indicate that the BEPS model can accurately simulate ET in Inner Mongolia’ s semi-arid region.

2.2.1 Mutation Year of ET

Based on STARS and cumulative anomaly tests, ET in Inner Mongolia’ s semi-arid region experienced a significant mutation in 1997 [Figure 3: see original paper]. The cumulative anomaly curve identified 1997 as the inflection point, with predominantly negative anomalies before this year (-37.56 to -6.29 $\text{mm} \cdot \text{a}^{-1}$) and positive anomalies afterward (10.58 to 52.95 $\text{mm} \cdot \text{a}^{-1}$). Although the turning point after 2000 was less distinct and spanned a shorter period, comprehensive analysis using both mutation detection methods confirms that ET underwent a clear regime shift in 1997. Consequently, we divided the study period into two sub-periods: 1981–1996 and 1998–2018.

2.2.2 Spatial-Temporal Distribution Characteristics

From 1981 to 2018, ET in Inner Mongolia’ s semi-arid region exhibited a fluctuating upward trend at 1.75 $\text{mm} \cdot \text{a}^{-1}$ ($P<0.05$, $R^2 = 0.73$). The lowest annual ET total was 286.14 mm in 1981, while the spatial distribution of multi-year average ET showed a pattern of low values in the central region and higher values on both sides, closely related to land use types. Areas with average ET below 300 mm accounted for 50.44% of the study area, primarily distributed in grasslands and unused lands of the Inner Mongolia Plateau. Regions with ET between 300-350 mm comprised 28.17% of the area, mainly in southern plateau grasslands. The 350–400 mm ET zone covered 15.98% of the area, distributed in forestlands and croplands of the southern Greater Khingan Mountains and Songliao Plain. Areas with ET exceeding 400 mm represented 5.41% of the region, located in forestlands of the southern Greater Khingan Mountains and southern Inner Mongolia Plateau [Figure 4: see original paper].

Trend analysis revealed that 99.70% of the study area experienced increasing ET trends. Specifically, 69.81% of the region showed increases at 0-1 $mm \cdot a^{-1}$, 24.75% at 1-2 $mm \cdot a^{-1}$, and 5.13% at rates exceeding 2 $mm \cdot a^{-1}$. The latter high-increase areas were concentrated in eastern and southern forestlands and croplands.

2.3 Changes in ET Influencing Factors Before and After Mutation

Analysis of ET and its influencing factors across different periods revealed that from 1981 to 2018, temperature increased significantly at 0.05°C $\cdot a^{-1}$ ($P<0.01$), precipitation decreased at -1.70 $mm \cdot a^{-1}$ ($P<0.05$), VPD increased significantly at 0.002 $hPa \cdot a^{-1}$ ($P<0.01$), wind speed decreased at -0.01 $m \cdot s^{-1} \cdot a^{-1}$ ($P<0.05$), and LAI increased significantly at 0.01 a^{-1} ($P<0.01$). Comparing pre- and post-mutation periods, both VPD and LAI showed significant increasing trends after 1997, with acceleration rates of 0.002 $hPa \cdot a^{-1}$ and 0.01 a^{-1}, respectively. The vegetation greening trend and intensified atmospheric water demand both favored ET increase. However, after 1997, the increasing rate of solar radiation (SD) slowed, and soil moisture (SMV) showed a significant decreasing trend, both of which were unfavorable for ET increase. Overall, the positive impacts of VPD and LAI dominated ET changes around the mutation point.

2.4 Analysis of ET Change Influencing Factors

ET is influenced by multiple climatic factors and vegetation dynamics. Correlation analysis for the entire region showed significant positive correlations between VPD and ET ($P<0.01$) and between temperature and ET ($P<0.05$). Although the LAI-ET correlation was not statistically significant, the correlation coefficient reached 0.06. Precipitation and wind speed showed significant negative correlations with ET ($P<0.05$). Soil moisture exhibited a negative effect on ET, while increased VPD enhanced the water vapor gradient, promoting ET increase ($P<0.01$).

Since correlation analysis cannot separate inter-variable correlations, we conducted path analysis using synchronous observation data as independent variables and regional ET as the dependent variable [Figure 5: see original paper]. Considering both direct and indirect contributions, factors influencing ET change ranked as VPD > TA > WD > PRE > LAI > SD > SMV in total effect. Direct effects ranked as VPD > TA > WD > PRE > SD > SMV, while total indirect effects ranked as LAI > TA > SMV > PRE > VPD > WD > SD. VPD showed the largest decision coefficient (0.95) with direct effect coefficient of 0.97, indicating dominance through direct influence. Temperature ranked second with a decision coefficient of 0.87, also primarily through direct effects. LAI had the third-largest decision coefficient (0.86), but with indirect effects far exceeding direct effects (0.68 vs. 0.18). Solar radiation contributed mainly through indirect effects (0.39 vs. -0.02), primarily derived from VPD. Based on physical meaning, correlation analysis, and path analysis results, we selected VPD, temperature, LAI, precipitation, wind speed, and soil moisture as primary ET influencing factors for contribution rate analysis.

Stepwise multiple regression analysis quantified the driving factors and their relative contributions to ET change [Figure 6: see original paper]. Overall, VPD dominated regional ET change across 93.56% of the study area, explaining 24.83%-90.46% of ET variation with an average contribution exceeding 45%. During 1981–1996, VPD dominated 65.79% of the region, explaining 37.65%–38.61% of ET change. During 1998–2018, VPD's dominance expanded to 76.46% of the area, with contribution rates of 43.61%–45.26%. Temperature was the second major contributor, dominating 12.74% of the region during 1981–1996 and 15.44% during 1998–2018, with average contribution rates of 37.84%–40.79%. LAI contributions were relatively small, dominating 4.14% and 1.89% of the region in the two periods, respectively, with average contribution rates of 1.83%–9.82%.

2.5 Contribution Rates of Influencing Factors Across Land Use Types

We quantified the contributions of influencing factors to ET change across different land use types using stepwise multiple regression analysis . VPD was the dominant factor for ET change across all land use types, followed by temperature. VPD dominated the largest areas in bare land and grassland (96.14% and 95.18%, respectively), and the smallest area in cultivated land (86.10%). The average contribution rate of VPD exceeded 45% across all land use types. Temperature was the secondary dominant factor in cultivated land and urban land (8.26% and 9.82% of area, respectively), with average contribution rates of 37.65%–38.61%. Other factors played minor roles in dominating ET change (all <5%).

3.1 Model Uncertainty Analysis

We validated BEPS model performance using site-based flux observation ET data. Comparison between observed and BEPS-simulated ET at Xilingol and Duolun stations from 2005 to 2010 showed good agreement with determination coefficients (R^2) of 0.81-0.90. Existing studies report R^2 values of 0.5-0.8 when validating various ET models using site and literature data, indicating that our BEPS simulations achieve accurate ET modeling precision. The simulated multi-year average ET in our study ranged from 286.14 to 376.65 mm, consistent with previous research showing Inner Mongolia ET between 200–450 mm. Our results align closely with studies using the WaVEM model for Horqin Sandy Land ET (300–400 mm) and MOD16 data for Xilingol grassland (218.08 mm), though MOD16 products are known to underestimate ET in degraded or desert grasslands (150.90–207.50 mm). These comparisons confirm that BEPS simulations are consistent with actual conditions and possess robust capability for accurate terrestrial ecosystem ET simulation.

3.2 Analysis of Pattern Mutation Causes

Multiple mutation detection methods consistently identified a significant ET mutation in 1997, after which ET increased markedly. Global-scale studies have also identified 1997 as a turning point in ET trends, with the phenomenon attributed to the 1997–1998 El Niño event and associated extreme precipitation events. In Inner Mongolia, the 1998 catastrophic flood caused solar radiation deficiency and increased cloud cover, resulting in a negative ET anomaly of -9.39 $mm \cdot a^{-1}$. Some researchers attribute ET changes to global oceanic evaporation transitions, noting that saturated vapor pressure increases with warming while reduced oceanic moisture transport decreases actual vapor pressure, leading to significant VPD increases. This pattern aligns with our finding of a 1997 mutation and subsequent rapid VPD increase (TABLE:1). Additionally, China implemented extensive ecological restoration projects after 1998, including the Three-North Shelter Forest Program and Grain for Green Project, which significantly improved vegetation coverage in arid and semi-arid regions. However, increased artificial forestation accelerates water loss and disrupts regional water balance in water-limited areas. Studies using the Shuttleworth-Wallace model in the Loess Plateau found that transpiration explained most ET increases while evaporation remained unchanged, with vegetation increase dominating 63.82%–78.47% of ET enhancement. Similar vegetation increases in Inner Mongolia’ s semi-arid region represent a major ET driver (TABLE:4). Therefore, ecological engineering should operate within local water resource capacity to ensure sustainable restoration.

3.3 Analysis of ET Influencing Factors

VPD directly influences the water vapor gradient across bare and vegetated surfaces, thereby affecting ET. Its impact is closely related to temperature. In water-limited regions, atmospheric and soil drought often occur simultaneously, but in Inner Mongolia’ s semi-arid region, ET change is dominated by atmospheric drought (FIG:5). Sustained warming intensifies atmospheric drought, steepening the water vapor gradient and increasing water loss from vegetation and bare soil, consequently aggravating regional drought. Although decreasing soil moisture trends in Inner Mongolia may constrain water loss through soil drought, high VPD can trigger vegetation self-regulation mechanisms such as stomatal closure to reduce water loss, partially mitigating ET surge caused by atmospheric drought. This regulatory effect is evident in our results, where cropland and forestland—with stronger regulation capacity—showed smaller VPD impacts than grassland and bare land (TABLE:4).

4 Conclusions

This study simulated ecosystem ET in Inner Mongolia' s semi-arid region from 1981 to 2018 using the BEPS model with remote sensing and meteorological data, and analyzed its spatiotemporal variation characteristics and influencing factors. The main conclusions are as follows:

1. BEPS model simulations agreed well with flux observation data (R^2 = 0.81-0.90), demonstrating robust capability for accurate ET simulation in Inner Mongolia' s semi-arid region.
2. From 1981 to 2018, ET in the study area showed a fluctuating upward trend at 1.75 $mm \cdot a^{-1}$ ($P<0.05$). ET changes exhibited interdecadal differences with a significant mutation in 1997. After 1998, ET increased significantly at 1.70 $mm \cdot a^{-1}$ ($P<0.05$), while ET showed no obvious trend before 1997.
3. VPD was the dominant factor driving ET changes, controlling regional ET variation across 93.56% of the study area and explaining 24.83%-90.46% of ET change, with a path analysis determination coefficient of 0.95 and primarily direct effects.
4. VPD was the primary influencing factor across all land use types (cultivated land, forestland, grassland, urban land, and bare land), dominating 86.10%-96.14% of each type' s area with average contribution rates exceeding 45%. Temperature was the secondary factor, dominating 37.65%-38.61% of the area with average contribution rates of 40.79%. Due to stronger self-regulation, cropland and forestland were less sensitive to VPD than grassland and bare land.

As a key indicator of atmospheric water demand, VPD directly drove ET changes. The significant VPD increase after 1997 compensated for adverse effects from other factors, leading to the significant ET increase observed in Inner Mongolia' s semi-arid region.

References

[References section preserved exactly as provided in the original text]

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