Response Relationship Between Potential Evaporation and Air Temperature and Its Influencing Factors in the North and South of the Qinling Mountains: Postprint

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Abstract

Evaporation constitutes a crucial component of the hydrological cycle, and refining the response relationship between evaporation variation and meteorological elements holds significant implications for water resources, ecological restoration and reconstruction, and sustainable socioeconomic development in China' s critical ecological transition zones. Based on observational data from 70 meteorological stations spanning 1970–2017, supplemented by trend analysis and wavelet coherence methods, this study examines the variation characteristics of temperature and potential evapotranspiration (ET0) across the northern and southern regions of the Qinling Mountains, and investigates the response relationship between meteorological elements and ET0. The results demonstrate that based on the moving correlation method, both sliding window adjustments and detrended series reveal a positive correlation between temperature and ET0, indicating that rising temperatures in the Qinling region correspond to increased ET0; however, significant spatiotemporal differences exist in the temperature-ET0 correlation. Using 1993 as a temporal threshold, the correlation exhibited an increasing trend in the pre-1993 period but gradually weakened thereafter; spatially, the western Qinling region represents a weak correlation zone between temperature and ET0. Regarding dominant factors, ET0 demonstrates greater sensitivity to solar radiation variability, while wind speed does not constitute the primary driver of regional ET0 variation, thereby resulting in a less pronounced "evaporation paradox" phenomenon. The multi-factor control of ET0 variation accounts for the observed spatiotemporal differences in the ET0-temperature response relationship across the Qinling region.

Full Text

Spatiotemporal Relationship Between Potential Evaporation and Temperature in the South and North of the Qinling Mountains and Its Influential Factors

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Abstract

Evaporation is a crucial component of the hydrological cycle. A detailed analysis of the relationship between evaporation changes and meteorological factors is of great significance for water resources management, ecological restoration and reconstruction, and sustainable socio-economic development in China' s important ecological transition zones. Based on observational data from 70 meteorological stations in the south and north of the Qinling Mountains from 1970 to 2017, this study employs trend analysis and wavelet coherence methods to analyze temperature and potential evaporation (ET_0) variations and investigate the response relationship between meteorological elements and ET_0. The results indicate that, using the sliding correlation method, both original and detrended sequences consistently show a positive correlation between temperature and ET_0, suggesting that the "evaporation paradox" phenomenon is not prominent in the Qinling region. However, the correlation exhibits spatiotemporal differences: temporally, 1993 serves as a critical turning point, with correlations initially strengthening and then weakening; spatially, the western Qinling region represents a weak correlation zone between temperature and ET_0. In terms of dominant factors, ET_0 is more sensitive to solar radiation changes, while wind speed is not the primary factor controlling regional ET_0 variations. The combined effects of multiple meteorological elements drive ET_0 changes, which explains the complexity of temperature-ET_0 response relationships in the Qinling region.

Keywords: climate change; potential evaporation; evaporation paradox; trend analysis; south and north of Qinling Mountains

1 Study Area

The Qinling Mountains, an east-west oriented mountain range in central China, feature steep northern slopes and gentle southern slopes. Due to the barrier effect of the Qinling Mountains on water and heat, distinct climates and natural environments have formed on either side. The area north of the Qinling belongs to the warm temperate semi-humid climate zone, with deciduous broad-leaved forests as the dominant vegetation; the area south of the Qinling belongs to the north subtropical humid climate zone, characterized by mixed evergreen and deciduous broad-leaved forests [26]. From a climatic analysis perspective, using the watershed as the boundary cannot accurately summarize the climate characteristics of the region. Therefore, this study adopts the line from "Lüeyang-Heiheba-Madao-Jinshuihe-Ningshan-Chaijiaping-Shanyang-Zhulanguan-Shangnan"as the boundary between the north subtropical and warm temperate zones, which conforms to biological succession patterns while maintaining the vertical differentiation 规律 of the Qinling region [26]. Accordingly, this paper selects the watershed and the 1000 m contour on the southern foothills of the Qinling as boundaries, dividing the region into three sub-regions: north of the Qinling, the southern Qinling slope, and the Hanjiang River Valley [27].

[Figure 1: see original paper]

2.2 Research Methods

2.2.1 Penman-Monteith Equation

The Food and Agriculture Organization (FAO) of the United Nations defines potential evaporation as the evapotranspiration rate from a reference surface of 0.12 m height, with an albedo of 0.23, surface resistance of 70 $\mathrm{s \cdot m^{-1}}$, and assuming adequate water supply and vigorous growth of green grass cover [28]. This study employs the Penman-Monteith equation to calculate $\mathrm{ET_0}$ for the south and north of the Qinling Mountains. The specific calculation formula is provided in reference [28].

2.2.2 Wavelet Coherence Analysis

Wavelet analysis represents a breakthrough for traditional linear stationary signal processing, enabling multi-scale signal decomposition with adaptive resolution, thereby overcoming limitations of Fourier analysis [29]. Wavelet coherence combines wavelet analysis with cross-spectrum to examine the relationship between two time series in the time-frequency domain, with red noise testing enhancing result reliability [30]. The wavelet coherence analysis formula is as follows:

$$R_n^2(s) = \frac{|S(s^{-1}W_n^{XY}(s))|^2}{S(s^{-1}|W_n^X(s)|^2) \cdot S(s^{-1}|W_n^Y(s)|^2)}$$

where S is the smoothing operator; s is the scale factor; $W_n^X(s)$ and $W_n^Y(s)$ are the wavelet transforms of X and Y, respectively; and $W_n^{XY}(s)$ is the wavelet cross-spectrum.

2.2.3 Relationship Between Potential Evaporation and Meteorological Elements

The uncertainty of the "evaporation paradox" stems not only from research methodologies but also from the combined effects of multiple meteorological factors such as wind speed, sunshine duration, relative humidity, and temperature [31]. Therefore, this study constructs a comprehensive correlation coefficient to re-examine the relationship between meteorological elements and ET_0 in the Qinling region, reflecting differences in influencing factors across various sub-regions. The specific calculation formula is as follows:

$$P = 0.2 \times \mathrm{Avg} + 0.3 \times \mathrm{Std} + 0.5 \times \mathrm{Prop}$$

where P is the comprehensive correlation coefficient representing regional differences in ET_0 influencing factors; Avg is the average correlation coefficient between ET_0 and meteorological elements across all stations in the region, reflecting the average state of correlation (higher values indicate better correlation); Std is the standard deviation of correlation coefficients between ET_0 and meteorological elements across stations, reflecting the degree of dispersion within the region (larger Std values indicate greater uncertainty in the relationship between meteorological elements and ET_0); and Prop is the proportion of stations where correlations pass the 0.05 significance level (higher Prop values indicate better regional correlation between ET_0 and meteorological factors). Standard deviation is a negative indicator, while mean and station proportion are positive indicators, with standardization applied to eliminate dimensional differences.

3 Results

3.1 Background of Temperature and ET_0 Changes in the South and North of the Qinling Mountains

From 1970 to 2017, temperature in the Qinling region showed an increasing trend, while ET_0 maintained decadal fluctuations, with both exhibiting regional synchrony in interdecadal variations (Fig. 2). Specific patterns are as follows:

Temperature Changes: From 1970 to 2017, the annual mean temperature north of the Qinling increased at a rate of $0.323°\mathrm{C} \cdot (10\mathrm{a})^{-1}$, higher than that of the southern Qinling slope $[0.241°\mathrm{C} \cdot (10\mathrm{a})^{-1}]$ and the Hanjiang River Valley $[0.214°\mathrm{C} \cdot (10\mathrm{a})^{-1}]$, indicating that under climate change, the warming rate in the warm temperate zone north of the Qinling exceeds that in the mountainous warm temperate zone and Hanjiang Valley south of the Qinling. In terms of latitudinal patterns, the warming rate is higher in high-latitude and mountainous areas than in low-latitude valleys and plains (Fig. 2a). Regarding decadal variations, using a 9-year moving average to filter interdecadal fluctuation information from temperature curves, the three sub-regions show synchronous decadal fluctuations that can be divided into three stages: 1970–1985 formed a low trough; 1986–1993 showed initial temperature rise followed by decline; 1994–2013 was a period of rapid temperature increase, with most years after 2000 above the positive anomaly; and 2014–2017 maintained high-level fluctuations with a slight decline. Compared with global temperature changes, the Qinling region showed slowed temperature growth after 2000, even exhibiting a declining trend consistent with the warming hiatus characteristic. Notably, after 2015, temperatures in the region rose rapidly with frequent extreme high-temperature events, suggesting that following a brief warming hiatus, regional temperatures may have entered a new acceleration phase.

Potential Evaporation Changes: From 1970 to 2017, ET_0 in all three sub-regions of the Qinling area showed decreasing trends, though the magnitude varied. The southern Qinling slope exhibited the most significant decline, with rates as follows: north of the Qinling [-0.37 $mm \cdot (10a)^{-1}$], southern Qinling slope [-10.78 $mm \cdot (10a)^{-1}$], and Hanjiang River Valley [-5.73 $mm \cdot (10a)^{-1}$], all passing significance tests. Contrary to temperature changes, the decline magnitude was greater in low-latitude valley areas than in high-latitude mountainous regions (Fig. 2b). The three sub-regions showed synchrony in ET_0 changes: 1970–1985 maintained stable fluctuations followed by continuous decline; 1986–1993 was a period of rapid ET_0 increase, forming a trough in the 1990s; 1994–2013 was a period of continuous decline corresponding to the warming hiatus, forming a trough in 2012; and after 2013, ET_0 in all three sub-regions showed an increasing trend.

[Figure 2: see original paper]

3.2 Spatiotemporal Response Relationship Between Temperature and ET_0

3.2.1 Temporal Response Relationship In classical analysis, linear trend forms the basis for discussing the evaporation paradox, but linear trend analysis is greatly influenced by the study period. Using sliding correlation as an entry point and selecting 11-year and 21-year windows to compare correlation differences between detrended and original sequences, this study re-examines the evaporation paradox in the Qinling region from a new perspective (Fig. 3). The results show:

From 1970 to 2017, temperature and ET_0 in different sub-regions of the Qinling area showed significant positive correlations, passing the 0.05 significance level, indicating that regional temperature increases are generally accompanied by ET_0 increases, with no evaporation paradox phenomenon. However, the strength of the positive correlation shows 阶段性 changes. Before the early

1990s, all three sub-regions maintained a "double-peak structure," indicating that the temperature-ET_0 relationship underwent an "enhancement-weakening-enhancement" process. After the 1990s, the positive correlation between temperature and ET_0 in the north and southern slope of the Qinling gradually weakened, even failing the 0.05 significance test in 2012, while the Hanjiang River Valley maintained stable positive correlation. This declining correlation pattern becomes more pronounced after filtering linear trends, particularly for the north and southern slope of the Qinling, where temperature-ET_0 correlations showed rapid decline after 2000.

Comparing detrended sliding correlations reveals that the correlation changes in all three sub-regions are synchronous, showing an "increase-decrease-increase" pattern. Taking 1993 as a node, detrended correlations increased significantly before this point but weakened afterward. Notably, during the 1960s–1990s, many regions worldwide experienced decreased solar radiation monitoring, a phenomenon called "global dimming." After eliminating the impact of radiation instrument replacement at Chinese meteorological stations around 1990, the decreasing radiation trend continued until 2015, with China' s radiation increase rate at 6.13$\pm 1.77 W\cdot m^{\{-2\}\cdot(10a)}\{-1\}$ after 2015. Radiation changes significantly impact evaporation, particularly evident in the sliding response relationship between temperature and ET_0 in the north and southern slope of the Qinling, where the response relationship gradually strengthened after 1998.

[Figure 3: see original paper]

3.2.2 Spatial Response Relationship Whether using original or detrended sequences, analyzing sliding correlations based on regional station averages tends to mask internal patterns within sub-regions and overlook spatial heterogeneity. Therefore, this study uses the ANUSPLIN climate data interpolation software to spatially interpolate correlation coefficients and trends between temperature and ET_0 in the Qinling region, incorporating latitude, longitude, and elevation information.

From 1970 to 2017, temperature and ET_0 in the Qinling region showed overall positive correlation, but with spatial differentiation (Fig. 4). Low correlation zones were mainly located in the high-altitude western section of the southern Qinling slope, while high correlation zones were in the Guanzhong Plain and eastern Hanjiang River Valley. Overall, the spatial homogeneity of station correlations in the southern Qinling slope was lower than that north of the Qinling, which is the main reason why temperature-ET_0 correlations in the southern slope are lower than in the northern region and Hanjiang River Valley.

Comparing detrended sequences, the main change in the original correlation pattern is that correlations in the western section of the southern Qinling slope and Guanzhong Plain decreased slightly, but the spatial pattern of "high in the southeast, low in the northwest" remained unchanged. This reaffirms that understanding the evaporation paradox in the Qinling region requires attention to both decadal correlation characteristics and spatial pattern evolution in different regions and stages.

In terms of spatial variation trends, regardless of sliding window adjustments or detrending analysis, temperature and ET_0 in the Qinling region maintain positive correlation. The correlation is more stable in the Guanzhong Plain north of the Qinling and the Hanjiang River Valley, while less stable in the southern Qinling slope, with the western Qinling region being a weak correlation zone between temperature and ET_0. Regarding trend patterns, the correlation between temperature and ET_0 in the Qinling region shows a spatial characteristic of "weakening in high-correlation zones and strengthening in low-correlation zones" (Fig. 5). Areas with enhanced correlation are mainly located on both sides of the Jialing River Basin in the western Qinling, as well as in the Daba and Micang Mountains. The spatial trend pattern of temperature-ET_0 correlation remains stable and is not affected by sliding window periods or trend removal.

[Figure 4: see original paper]

[Figure 5: see original paper]

3.3 Response Relationship Between ET_0 and Meteorological Elements

Analysis of correlations between meteorological elements and ET_0 reveals that ET_0 shows positive correlations with maximum temperature, mean temperature, sunshine duration, and mean wind speed, and negative correlation with relative humidity. That is, when temperatures are higher, sunshine duration increases, mean wind speed increases, and relative humidity decreases in the Qinling region, ET_0 tends to be larger (Table 1).

Examining the average (Avg) and standard deviation (Std) of correlation coefficients between temperature and ET_0 at each station from 1970 to 2017 shows that, whether using original or detrended sequences, the correlation coefficient between sunshine duration and ET_0 not only has a high mean value but also the smallest regional standard deviation, indicating that sunshine duration is the dominant factor influencing ET_0 in the Qinling region. Attention to solar radiation changes is crucial for understanding ET_0 variations in this area.

Integrating three dimensions—mean value, standard deviation, and proportion of significantly correlated stations (Prop)—yields the ranking of meteorological elements influencing ET_0 in the Qinling region. From the perspective of original sequences, the dominant meteorological elements for ET_0 in different sub-regions are: north of the Qinling: mean temperature < relative humidity < mean wind speed < sunshine duration; southern Qinling slope: maximum temperature < mean temperature < relative humidity < mean wind speed < sunshine duration; Hanjiang River Valley: maximum temperature < mean wind speed < mean temperature < relative humidity < sunshine duration.

Detrended sequence results show that for the region north of the Qinling, the Avg of mean temperature increased from 0.18 in the original sequence to 0.69, while the Std decreased from 0.16 to 0.11, causing the ranking of mean temperature correlation to rise to second place. This indicates that after removing linear trends, the influence of solar radiation and temperature changes on ET_0 in the region north of the Qinling gradually increases. For the southern Qinling slope and Hanjiang River Valley, sunshine duration and relative humidity remain the main factors affecting regional ET_0 changes, though the Hanjiang River Valley, influenced by topography, shows relatively greater impact from mean wind speed, which ranks second in correlation.

In China, decreasing wind speed is the main cause of the evaporation paradox, particularly in northwestern and northern regions where wind speed contributions far exceed those of radiation, temperature, and relative humidity changes. Simultaneously, decreasing solar radiation and relative humidity inhibit evaporation trends, offsetting the ET_0 increase caused by temperature rises and highlighting the phenomenon of ET_0 decline due to wind speed reduction [32]. Combined with this study' s results, in the Qinling region located in the warm temperate and north subtropical zones, wind speed is not the dominant factor controlling regional ET_0 changes; ET_0 is more sensitive to solar radiation changes, resulting in a less prominent evaporation paradox phenomenon, consistent with conclusions from evaporation pan attribution studies.

Since simple linear correlations may overlook multi-timescale effects between meteorological elements and ET_0, this study uses wavelet coherence analysis to verify the relationship between ET_0 and various meteorological elements in the time-frequency domain (Fig. 6). The results show: (1) The relationship between ET_0 and meteorological elements in the Qinling region confirms the above analysis, with ET_0 showing positive correlations with sunshine duration, mean temperature, maximum temperature, and mean wind speed, and negative correlation with relative humidity; (2) The response has periodic characteristics. Taking the region north of the Qinling as an example, sunshine duration, mean temperature, and maximum temperature show medium-to-long scale cycles of 4–12 years, while short-scale cycles are 2–4 years; (3) For the Hanjiang River Valley, the response relationship between wind speed and ET_0 shows sporadic point distribution, while relative humidity' s response to ET_0 has full-time domain characteristics, indicating that relative humidity' s influence on ET_0 is persistent and continuous; (4) Comparison of wavelet coherence results between detrended and original sequences shows consistent patterns, indicating that under nonlinear methods, meteorological element trend information has relatively minor impact on ET_0 attribution.

[Figure 6: see original paper]

4 Conclusions and Outlook

Based on observational data from 70 meteorological stations for temperature, potential evaporation, sunshine duration, and mean wind speed from 1970 to

2017, this study analyzed the spatiotemporal response relationship between ET_0 and temperature in the south and north of the Qinling Mountains and examined the main factors influencing the spatiotemporal variations in their correlations. The conclusions are as follows:

(1) **Temporal variation characteristics**: From 1970 to 2017, temperature and ET_0 changes in the south and north of the Qinling Mountains were synchronous, jointly demonstrating that regional temperature increases are generally accompanied by ET_0 increases, with no "evaporation paradox" phenomenon. However, the strength of the positive correlation between temperature and ET_0 shows 阶段性 changes, with 1993 serving as a critical turning point when correlations initially strengthened and then weakened.

(2) **Spatial variation characteristics**: Regardless of adjustments to the sliding window or detrending analysis, temperature and ET_0 in the south and north of the Qinling Mountains maintain positive correlation, though the correlation shows spatial differentiation. The western Qinling region is a weak correlation zone between temperature and ET_0. In terms of variation trends, the correlation between temperature and ET_0 in the Qinling region exhibits a spatial pattern of "weakening in high-correlation zones and strengthening in low-correlation zones."

(3) **Dominant influencing factors**: Analysis from two perspectives—comprehensive correlation coefficient and wavelet coherence—reveals that in the Qinling region located in the warm temperate and north subtropical zones, wind speed is not the dominant factor controlling regional ET_0 changes; ET_0 is more sensitive to solar radiation changes, resulting in a less prominent evaporation paradox phenomenon. For the southern Qinling slope and Hanjiang River Valley, sunshine duration and relative humidity are the main factors influencing regional ET_0 changes, while the Hanjiang River Valley, influenced by topographic factors, shows relatively greater impact from mean wind speed.

Regarding future research directions on temperature and ET_0 changes in the Qinling region, several aspects warrant further exploration: (1) **Validation with actual evaporation data**: In actual evaporation observations, the replacement of evaporation pans with E601B pans around 1998 caused data discontinuity, and substantial missing data constrain current evaporation trend and attribution studies. Using models such as the Penman-V3 model to simulate actual evaporation changes could provide new approaches for future research [33]. (2) **Evapotranspiration retrieval models**: Traditional evapotranspiration observations rely primarily on ground stations, which are limited by sparse distribution and short time series, making large-scale spatiotemporal distribution studies difficult. Remote sensing data with multi-spatiotemporal resolution provides technical means for large-scale evapotranspiration prediction [34]. (3) **Response between evaporation changes and circulation**: Climate change in the south and north of the Qinling Mountains is jointly influenced by sea temperature anomalies in the Bay of Bengal, South China Sea, and western Pacific. Identifying key ocean regions and exploring the response relationship between sea temperature anomalies and regional evaporation changes to extract predictable and early-warning information will be crucial for understanding evaporation-water resources-ecosystem responses [35].

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