A Preliminary Study on Variation Characteristics of Potential Evapotranspiration and Grey Model Prediction in Tibet: Postprint

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Abstract

Based on daily meteorological data from 38 weather stations in the Tibet region from 1981 to 2019, the Penman-Monteith model, trend analysis, Morlet wavelet analysis, Mann-Kendall test, Empirical Orthogonal Function (EOF) method, and grey model were employed to investigate the spatiotemporal evolution patterns of potential evapotranspiration (ET0) and future trends of ET0. The results indicate: On the temporal scale, the average ET0 in the Tibet region was 597.12 mm, showing a significant decreasing trend from 1981 to 2001 and a significant increasing trend from 2002 to 2019 ($P<0.01$). The annual average ET0 in the entire Tibet region and its five major climatic zones all exhibited an increasing trend (except for the southeast), with a 33-year periodic oscillation as the first dominant period. On the spatial scale, annual ET0 primarily exhibited a distribution pattern of gradual decrease from the central region toward the southwest and southeast, with high-value centers concentrated along the river valley line and low-value centers located in the southern region. Stations where abrupt changes in annual ET0 occurred were mainly distributed in the southern marginal areas, along the river valley line, and in the northeast, with the timing of these changes concentrated in the 1980s. The constructed GM(1,1) prediction model achieved an average prediction accuracy of 87.85%, which can be used for medium- and long-term forecasting of annual ET0 time series in Tibet. The prediction results show that, except for a significant decline in the predicted values of annual ET0 in the southeast, all other regions exhibit an upward trend.

Full Text

A Preliminary Study on Variation Characteristics and Grey Model Prediction of Potential Evapotranspiration in Tibet

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Abstract

This paper investigates the spatiotemporal evolution patterns and future trends of potential evapotranspiration (ET_0) in Tibet using daily meteorological data from 38 stations spanning 1981–2019. We employ the Penman-Monteith model, trend analysis, Morlet wavelet analysis, Mann-Kendall tests, empirical orthogonal function (EOF) decomposition, and grey system modeling. The results reveal that, temporally, the average ET_0 in Tibet is 597.12 mm, showing a significant decreasing trend from 1981 to 2001 and a significant increasing trend from 2002 to 2019 ($P < 0.01$). Spatially, high-value ET_0 zones in both periods are concentrated in the central-western Nagqu region and along the Yarlung Zangbo River valley. EOF decomposition indicates that the first mode (EOF1), explaining 51.5% of variance, exhibits high spatial consistency with a high-value center along the river valley and low values in the south. The second mode reveals an opposite pattern between central-western (positive) and southeastern (negative) Tibet. Stations with positive Kendall trend coefficients are concentrated in central-western Nagqu and the southern marginal zone, where a warming-drying climate is evident. Abrupt changes in annual ET_0 primarily occurred in the 1980s at stations in the southern marginal zone, along the river valley, and in the northeast, with two mutations detected at Nagqu and Dangxiong stations. Wavelet analysis identifies a 33-year primary cycle for the entire region and river valley areas, with secondary cycles varying by subregion. The constructed grey model GM(1,1) demonstrates satisfactory performance for medium- to long-term ET_0 prediction, with an average accuracy of 87.85%. Forecasts indicate that ET_0 will continue rising across all regions except the southeast, where a significant decline is projected.

Keywords: Penman-Monteith model; potential evapotranspiration; spatiotemporal analysis; grey model; Tibet

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1.1 Study Area and Data Sources

Tibet, located in southwestern China and constituting the main body of the Qinghai-Tibet Plateau, spans 26°50 –36°53 N and 78°25 –99°06 E. The region is characterized by low temperatures, small accumulated temperature, large diurnal temperature variations, distinct wet and dry seasons, mean annual temperatures of -2.4 to 12.1°C, annual precipitation of 66.3-894.5 mm, and annual sunshine duration of 1443.5-3574.3 hours. Meteorological data were obtained from the Tibet Meteorological Bureau, comprising daily records from 38 stations (1981-2019) including mean, maximum, and minimum temperatures, average wind speed, sunshine hours, and mean relative humidity. Following Wen and Liu' s climate regionalization, Tibet is divided into five climatic zones: central-western Nagqu (Nagqu, Bango, Xainza, Damxung, Amdo, Shiquanhe, Burang, Gerze), the Yarlung Zangbo River valley (Lhasa, Zedang, Xigaze, Gyantse, Nagarze, Lhatse, Nyemo, Gonggar, Maizhokunggar, Gyaca, Namling), the southern marginal zone (Nyalam, Tingri, Lhünzê, Cona, Pali), the northeast (Qamdo, Dêngqên, Sog, Lhari, Biru, Lhorong, Riwoqê), and the southeast (Nyingchi, Bomi, Zayü, Markam, Mainling, Baxoi) [Figure 1: see original paper].

1.2.1 Penman-Monteith Model

Potential evapotranspiration was calculated using the Penman-Monteith equation recommended by the Food and Agriculture Organization (FAO) in 1998:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}$$

where ET_0 is potential evapotranspiration ($\mathrm{mm \cdot d^{-1}}$), R_n is net radiation at the surface ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), G is soil heat flux ($\mathrm{MJ \cdot m^{-2} \cdot d^{-1}}$), Δ is the slope of the saturation vapor pressure curve ($\mathrm{kPa \cdot °C^{-1}}$), T is mean temperature (°C), U_2 is wind speed at 2 m height ($\mathrm{m \cdot s^{-1}}$), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), and γ is the psychrometric constant ($\mathrm{kPa \cdot °C^{-1}}$). Specific formulas for each parameter follow Allen et al. (1998).

1.2.2 Wavelet and Abrupt Change Analysis

The Mann-Kendall test, a nonparametric statistical method resistant to outliers and requiring no specific distribution, was used for trend significance and abrupt change detection. The Morlet wavelet function was applied to analyze periodicity in $\mathrm{ET_0}$ time series.

1.2.3 Empirical Orthogonal Function (EOF)

EOF decomposition, also known as natural orthogonal function analysis, employs no fixed functional form—its patterns are determined by the data field itself. This method converges rapidly and effectively reveals the fundamental structure of meteorological fields. It can decompose spatial variations across different stations or analyze multiple temporal and vertical elements at a single station. The resulting temporal and spatial components are orthogonal, allowing the original matrix to be approximated using the first few spatial modes with large variance contributions.

1.2.4 Grey Model Prediction

Grey prediction models are suitable for systems with limited sample sizes and irregular distributions, offering high accuracy with minimal computational effort. The GM(1,1) model construction involves accumulated generating operations, matrix formation, parameter estimation, and forecasting. This approach has been increasingly applied to short-, medium-, and long-term system predictions.

2.1.1 Variation Characteristics of ET_0 in Tibet

The multi-year average ET_0 values are similar in central-western Nagqu (663.25 mm) and the river valley (728.91 mm), while the southern marginal zone and southeast show comparable lower values (510.14 mm and 537.42 mm, respectively). The regional average is 597.12 mm. Tibet experienced a significant decreasing trend from 1981 to 2001 and a significant increasing trend from 2002 to 2019 ($P < 0.01$), with rates of -88.41 mm$\cdot$(10a)$^{-1}$ and +109.70 mm$\cdot$(10a)$^{-1}$, respectively. High-value zones in both periods are concentrated in central-western Nagqu and along the river valley [Figure 2: see original paper].

2.1.2 EOF Analysis of Annual ET_0

EOF decomposition of standardized annual ET_0 values shows the first three eigenvectors have non-overlapping error ranges and pass North' s significance test. The first mode (EOF1) explains 51.5% of variance with positive values across the entire region, indicating highly consistent spatial variation. The high-value center lies along the river valley, with low values in the south, decreasing gradually from the central region toward the southwest and southeast [Figure 3: see original paper]. The corresponding time coefficient oscillates between positive and negative values, reflecting significant interannual variability. Positive coefficients during 2002–2019 indicate increasing ET_0, consistent with observed trends.

The second mode (EOF2) explains 12.1% of variance, showing opposite patterns between central-western Tibet (positive) and the southeast (negative). Positive values dominate Ngari, central-western Shigatse, and most of Nagqu. The time coefficient reveals that before the mid-1990s, ET_0 decreased in central-western Tibet while increasing in the southeast; after the mid-1990s, this pattern reversed.

The third mode (EOF3) explains 8.1% of variance, featuring positive centers in central-southern and southeastern Tibet and a negative center in the northwest. Positive values are concentrated in Qamdo, Nyingchi, central Shigatse, and eastern Shannan.

2.2.1 Trend Analysis of Annual ET_0

Spatial distribution of Kendall trend coefficients shows 21 stations with negative values, including significant decreases at Gonggar, Lhünzê, and Baxoi (coefficients < -1.96). Positive coefficients occur at 17 stations, primarily in central-western Nagqu and the southern marginal zone. Significant increasing trends ($P < 0.05$) are observed at Shiquanhe, Nyalam, Lhasa, Pali, Sog, and Mainling. The predominance of positive coefficients aligns with findings of warming-drying trends in northern and northwestern Tibet, where temperature rises increase evaporation and drought risk.

2.2.2 Abrupt Change Analysis

Mann-Kendall tests combined with moving t-tests and Yamamoto methods identified abrupt changes at 13 stations, mostly in the 1980s. The southern marginal zone shows the highest sensitivity, with all its stations experiencing upward ET_0 mutations (except Lhünzê). Mutations also occurred along the river valley and in the northeast. Only Nagqu and Damxung stations experienced two mutations; most other stations showed one or none. Non-mutated stations are concentrated in central-western Nagqu [Figure 4: see original paper].

2.3 Periodic Variation Characteristics

Wavelet analysis reveals pronounced oscillations at 30–35-year scales for the entire region and river valley, with alternating positive-negative phases indicating "high" and "low" periods. Shorter 3–8-year scales show dense alternations. Wavelet variance tests identify a 33-year primary cycle and an 11-year secondary cycle for both the whole region and river valley.

Central-western Nagqu exhibits alternating patterns at 20–25-year and 3–8-year scales, with primary and secondary cycles of 22 years and 3 years, respectively. The southern marginal zone shows dense alternations at 30–35-year and 8–12-year scales (primary cycles of 8 and 12 years). The northeast displays an 8-year primary cycle, while the southeast shows primary cycles of 22 and 12 years [Figure 5: see original paper].

2.4 Grey Prediction Model

The GM(1,1) model requires grey parameters $a \in [-2, 2]$ and smooth level ratios $\sigma(k) \in [0.1353, 7.389]$. All stations satisfy these conditions. After excluding 5 unqualified stations, models were constructed for the remaining sites. Prediction accuracy exceeds 80% at 33 stations (87% of total), with average accuracy of 87.85%, confirming the model' s suitability for medium- to long-term ET_0 forecasting in Tibet .

Forecasts indicate that ET_0 will continue rising across all regions except the southeast, where a significant decline is projected. The southern marginal zone shows the fastest increase, consistent with Zhao et al.' s (2018) projections of enhanced evapotranspiration under future climate scenarios, particularly in southern Shigatse.

Discussion

The increasing ET_0 trend after 2002 aligns with studies in the Xilin River Basin, Zoigê Wetland, and northern Tibet, though regional differences exist. Central-western Tibet' s high evapotranspiration centers correspond to arid and semi-arid zones with sparse vegetation, while lower values in the southeast reflect forest and grassland coverage with humid/semi-humid conditions. The 33-year cycle differs from some regional studies, likely due to Tibet' s unique plateau climate. The 1980s concentration of abrupt changes matches findings from other Tibetan studies, though variations in study periods and station selection can lead to differing conclusions.

While the GM(1,1) model demonstrates good applicability, only a few stations achieved first-grade accuracy, indicating room for residual correction improvements. Future research should incorporate longer time series and denser observational networks to enhance prediction reliability.

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