Changes in Reference Evapotranspiration and Its Attribution on the Tibetan Plateau from 1971 to 2014: Postprint

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Abstract

Investigating spatiotemporal variation patterns of reference evapotranspiration and identifying its driving factors are important approaches to understanding regional hydrological processes and their responses to climate change. Based on the modified FAO 56 Penman-Monteith formula and daily meteorological observation data from 75 stations on the Tibetan Plateau, this study analyzed the turning point characteristics of reference evapotranspiration changes on the plateau from 1971 to 2014, and examined the interannual and seasonal variation trends and their dominant factors before and after the turning point. The results indicate that reference evapotranspiration on the Tibetan Plateau exhibited a sharp decreasing trend from 1971 to 1996 [-27.07 mm · (10a)-1], while showing a significant increasing trend from 1997 to 2014 [40.16 mm · (10a) -1], particularly pronounced in the region south of 30°N. This pattern is closely related to the interannual turning point in the changing trends of climatic factors affecting reference evapotranspiration. Specifically, decreasing wind speed was the primary factor contributing to the reduction in annual reference evapotranspiration on the plateau from 1971 to 1996, especially in the northern plateau; the decrease in relative humidity greatly promoted the significant increase in reference evapotranspiration in the main body of the plateau (excluding the northern edge) from 1997 to 2014. Furthermore, at the seasonal scale, the dominant contributor to reference evapotranspiration changes in spring, autumn, and winter shifted from decreasing wind speed in the earlier period to decreasing relative humidity from 1997 to 2014; the dominant factor affecting summer reference evapotranspiration on the plateau was the increase in relative humidity from 1971 to 1996, which subsequently shifted to the increase in sunshine duration from 1997 to 2014.

Full Text

Preamble

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Abstract

Exploring the spatiotemporal variation of reference evapotranspiration over the Tibetan Plateau and its driving factors is essential for deepening the understanding of regional hydrological processes and their response to climate change. Daily data from 75 meteorological stations across the plateau were utilized to analyze the spatiotemporal changes in evapotranspiration based on the modified FAO56 Penman-Monteith formula, and the contribution of climatic factors to the variation during the period of 1971–2014 was discussed. The main conclusions are summarized as follows: Annual reference evapotranspiration over the Tibetan Plateau tended to increase, especially in regions south of 33°N from 1997 to 2014, with an average linear trend of 40.16 mm · (10a) ^{1}. However, it decreased remarkably at a rate of -27.07 mm · (10a) ^{1} from 1971 to 1996, and the dominant climatic factor resulting in the decrease was the reduction of wind speed, particularly in the northern plateau. Reduction of relative humidity played a crucial role in increasing reference evapotranspiration from 1997 to 2014. In addition, the biggest contribution factor to the seasonal variation of reference evapotranspiration shifted from the reduction of wind speed (from 1971 to 1996) to the decrease of relative humidity (from 1997 to 2014), and the dominant factor to the summer variation of reference evapotranspiration shifted from the increase of relative humidity (from 1971 to 1996) to the increase of annual mean relative sunshine duration (from 1997 to 2014).

Keywords: reference evapotranspiration; climatic factor; spatial difference; Tibetan Plateau

1.2.2 Calculation of Reference Evapotranspiration

The standardized regression coefficients of climatic factors affecting annual and seasonal reference evapotranspiration over the Tibetan Plateau were analyzed. The FAO56 Penman-Monteith equation was applied to calculate reference evapotranspiration (ET) using daily meteorological data from 75 stations across the plateau during 1971–2014.

The net radiation components were calculated as follows:

(1) Net longwave radiation (R) was computed using the formula:

$$R_{nl} = \left[\sigma \frac{T_{max,k}^4 + T_{min,k}^4}{2}\right] \times (0.34 - 0.14\sqrt{e_a}) \times \left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

where is the Stefan-Boltzmann constant (4.903×10 MJ · m^{2} · d^{1} · K), T , and T , are maximum and minimum absolute temperatures (K), e is actual vapor pressure (kPa), R is measured solar radiation, and R is clear-sky solar radiation.

(2) Soil heat flux (G ,) was estimated by:

$$G_{month,i} = 0.07(T_{month,i+1} - T_{month,i-1})$$

For the first and last months, the calculation was adjusted as:

$$G_{month,i} = 0.14(T_{month,i} - T_{month,i-1})$$

where G , is soil heat flux for month i (MJ · m^{2} · d^{1}), and T , , T , , T , are mean air temperatures for the previous, current, and next months.

(3) Net radiation (R) was obtained from:

$$R_n = R_{ns} + R_{nl} + G$$

where R is net shortwave radiation, R is net longwave radiation, and G is soil heat flux.

Spatial interpolation was performed using ArcGIS 9.3 with the Kriging method to generate spatial distribution maps of ET and its trends.

2.1.1 Temporal Variations in Annual ET

The average annual reference evapotranspiration over the Tibetan Plateau during 1971-2014 was 917.15 mm, with a maximum of 1408.29 mm and minimum of 672.61 mm. An abrupt change occurred around 1997, after which ET showed a significant increasing trend. The cumulative anomaly curve revealed that 1997 was the turning point, with ET decreasing before and increasing after this year.

During 1971-1996, ET exhibited a significant decreasing trend of -27.07 mm · (10a)^{1} ($P < 0.05$). In contrast, during 1997-2014, ET showed a significant increasing trend of 40.16 mm · (10a)^{1} ($P < 0.05$). This shift indicates a fundamental change in the hydroclimatic regime over the plateau.

2.1.2 Spatial Patterns of Annual ET Trends

The spatial distribution of linear trends in annual ET at 75 meteorological stations shows distinct patterns. During the entire study period (1971-2014), 31 stations exhibited statistically significant trends ($P < 0.05$), with 15 stations showing negative trends (-49.99 to -10.00 mm · (10a)^{1}) and 16 stations showing positive trends (10.01-50.00 mm · (10a)^{1}). The ratio of negative to positive significant trends was 4:9:18 across different magnitude categories.

During 1971-1996, negative trends dominated, particularly north of 33°N. During 1997-2014, positive trends became dominant, especially south of 33°N, where the strongest increases exceeded 50.01 mm·(10a) ^{1}. The spatial pattern reversed after 1997, with the ratio of strong positive to negative trends becoming 3:24:19.

2.1.3 Seasonal Variations in ET

Seasonal analysis reveals that during 1971–1996, spring, summer, autumn, and winter ET all showed decreasing trends, with rates of -9.18, -9.56, -4.49, and -2.60 mm·(10a) ^{1}, respectively. Spring and summer exhibited the strongest declines, with widespread negative trends across the plateau, particularly in the range of -49.99 to -10.00 mm·(10a) ^{1}.

During 1997–2014, all seasons showed increasing trends: 10.52 mm·(10a) ^{1} in spring, 11.29 mm·(10a) ^{1} in summer, 7.75 mm·(10a) ^{1} in autumn, and 6.84 mm·(10a) ^{1} in winter. Spring and summer increases were most pronounced, with extensive areas showing trends exceeding 50.00 mm·(10a) ^{1}. The spatial patterns indicate that the post-1997 increase was strongest in the southern plateau during spring and summer.

3.1 Discussion of the FAO56 Penman-Monteith Method

The FAO56 Penman-Monteith equation is considered the standard method for calculating reference evapotranspiration. Using 40 years of data from 75 stations across the Tibetan Plateau, this study analyzed ET trends and their sensitivity to climate change. The method accounts for the combined effects of energy supply and atmospheric evaporative demand, making it suitable for high-elevation regions with complex terrain.

Previous studies have shown varying results for ET trends on the Tibetan Plateau. Chen et al. [18] reported decreasing ET during 1961–2000, while Zhang et al. [19] found increasing trends after the 1990s. These discrepancies highlight the importance of analyzing sub-periods to identify regime shifts. The turning point around 1997 identified in this study corresponds to a documented climate shift over the plateau, characterized by warming and changes in atmospheric circulation patterns.

3.2 Driving Factors of ET Variation

The dominant factors controlling ET variation changed between the two sub-periods. During 1971–1996, wind speed reduction was the primary cause of ET decrease, particularly in the northern plateau where wind speeds declined most significantly. This "wind stilling" phenomenon has been widely observed across China and globally.

During 1997–2014, decreasing relative humidity became the dominant factor driving ET increase. The standardized regression coefficients show that relative humidity had the strongest influence on ET trends during this period. In summer, the dominant factor shifted from increasing relative humidity (1971–

1996) to increasing sunshine duration (1997-2014), suggesting changes in cloud cover and atmospheric moisture content.

Temperature showed positive correlations with ET throughout the study period, but its relative importance was secondary to wind speed and humidity. The combined effects of these climatic factors created the observed spatiotemporal patterns, with the southern plateau experiencing the most dramatic post-1997 increases due to synergistic effects of warming, reduced humidity, and increased solar radiation.

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