Analysis of Spatiotemporal Variation of Reference Crop Evapotranspiration in Karst and Non-Karst Regions: A Case Study of Guangxi Zhuang Autonomous Region (Postprint)

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Abstract

Reference crop evapotranspiration (ET0) is a key factor in determining the water demand of vegetation ecosystems, and analysis of its spatiotemporal distribution characteristics and main influencing factors is of great significance for formulating vegetation restoration strategies and regional water resource allocation schemes. Based on the FAO-56 Penman-Monteith formula and daily data from 25 meteorological stations in Guangxi from 1960 to 2010, this paper calculated ET0 for each station. On this basis, GIS-based Kriging interpolation, Spearman rank correlation method, and path analysis method were used to analyze the spatiotemporal variation characteristics of ET0 and its influencing factors in karst and non-karst areas of Guangxi. The results show that the multi-year average ET0 at various stations in Guangxi over the past 51 years is 1,138 mm · a ^{1}; the spatial distribution exhibits a decreasing characteristic from south to north and from low latitudes to high latitudes, with high-value areas mainly distributed in non-karst regions and low-value areas mainly distributed in karst regions. The cumulative anomaly curves of annual ET0 in both karst and non-karst areas show an "N" -shaped distribution; they were highest in the 1970s, lowest in the 1990s, and have rebounded since the 21st century, but remain below the 51-year average. Additionally, the interannual variation of ET0 in karst areas is smaller than that in non-karst areas. Sunshine duration, wind speed, and mean temperature are the main meteorological factors affecting annual ET0 variation in non-karst areas, while relative humidity indirectly exerts a greater influence on annual ET0 variation in karst areas through interactions with other meteorological factors. At the seasonal scale, sunshine duration and mean temperature are the most important influencing factors of ET0 in all seasons, showing a positive correlation with ET0; the indirect effect coefficient of wind speed on ET0 is negative in winter and spring in karst areas,

a phenomenon not observed in non-karst areas. Understanding the variation trends of ET0 in different regions is a necessary measure for calculating water demand quotas for vegetation ecosystems.

Full Text

Spatio-Temporal Variation in Reference Evapotranspiration in Recent 50 Years in Karst and Non-Karst Areas in Guangxi Zhuang Autonomous Region

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Abstract: Reference evapotranspiration (ET) is a critical factor for determining water requirements in vegetation ecosystems. Analysis of its spatio-temporal distribution characteristics and main influencing factors is of great significance for developing vegetation restoration strategies and regional water resource allocation schemes. Based on daily meteorological data from 25 stations in Guangxi from 1960 to 2010, this study calculated ET using the FAO-56 Penman-Monteith equation. The spatio-temporal variation characteristics of ET and their influencing factors in karst and non-karst areas of Guangxi were analyzed using GIS-based Kriging interpolation, Spearman rank correlation, and path analysis methods.

The results showed that the multi-year average ET at each station in Guangxi over the 51-year period was 1,138 mm · a ^{1}. Spatial distribution exhibited a decreasing trend from south to north and from low to high latitudes, with high-value areas mainly distributed in non-karst regions and low-value areas primarily in karst regions. The cumulative anomaly curves of annual ET in both karst and non-karst areas showed an "N-shaped" distribution: highest in the 1970s, lowest in the 1990s, and recovering somewhat since the 21st century, though still below the 51-year average. Additionally, interannual variation in ET was smaller in karst areas than in non-karst areas. Sunshine duration, wind speed, and mean temperature were the main meteorological factors affecting annual ET variation in non-karst areas, while relative humidity indirectly exerted greater influence on annual ET variation in karst areas through interactions with other meteorological factors. At the seasonal scale, sunshine duration and mean temperature were the most important factors affecting ET in all seasons, positively correlated with ET . Wind speed showed negative indirect effect coefficients on ET in karst areas during winter and spring, a phenomenon not

observed in non-karst areas. Understanding ET variation trends in different regions is a necessary measure for calculating ecological water demand quotas.

Keywords: Reference evapotranspiration; Penman-Monteith equation; Karst area; Non-karst area; Meteorological factor; Path analysis

Introduction

Evapotranspiration represents the water consumed by ecosystems to maintain biological survival, comprising both soil and vegetation evaporation and plant transpiration. Due to its crucial linking role in the soil-vegetation-atmosphere system, it has received widespread attention from global change researchers. Reference crop evapotranspiration (ET) is a meteorological factor representing atmospheric evaporation capacity and an important parameter in regional water and energy balance studies. Accurate estimation of ET is not only an important basis for formulating regional vegetation ecological water demand quotas and optimizing water resource allocation decisions but has also become a key link in monitoring agricultural drought and improving regional water use efficiency.

The FAO-recommended Penman-Monteith formula (hereinafter referred to as FAO-PM) comprehensively considers various factors affecting ET with high accuracy, achieving good results across different climate zones and demonstrating universal applicability. Against the background of global climate change, numerous scholars have conducted extensive research on the spatio-temporal variation characteristics of ET and its influencing factors. Hulme et al. suggested that global warming and rising temperatures would promote increased ET . However, other studies have shown that, except in individual regions, pan-evaporation observed ET in the Northern Hemisphere has exhibited a decreasing trend over the past several decades. The changing trend of ET in China over recent decades has also been evident. Liu et al. analyzed the sensitivity of ET to meteorological factors across China' s ten major river basins, finding that ET showed a decreasing trend in eight of the ten basins, with northern basins being sensitive to water vapor pressure and southern basins sensitive to maximum temperature. Zhang et al. analyzed the sensitivity of ET to meteorological factors in the Huangshui River basin and surrounding areas, discovering that the spatio-temporal distribution characteristics of ET were correlated with altitude—ET was more sensitive to actual water vapor pressure in high-altitude areas and more sensitive to temperature in low-altitude areas. These results demonstrate that due to differences in geographical environments, ET variations and their causes exhibit regional differences, with influencing factors varying by location. Therefore, ET research must be conducted regionally.

Karst areas mainly refer to carbonate rock outcrop regions and areas dominated by carbonate rock composition. The Southwest China karst region is one of the three largest concentrated karst distribution areas globally, with a sensitive and fragile ecological environment, frequent drought and flood disasters, and unstable agricultural production. Against the backdrop of global climate change, precipitation in Southwest China has shown a decreasing trend over the past 60 years, and the frequent occurrence of extreme events makes research on ET changes in this region more urgent. Gao et al. and Xu et al. found that annual ET in Guizhou Province showed an overall decreasing trend, with reduced sunshine duration being the main cause of ET decline. Dai et al. found that the dominant meteorological factor affecting ET in Guizhou was sunshine duration, which was positively correlated with ET , while geographical latitude showed a significant negative correlation with ET . Guan et al. concluded that 95% of stations in Guangxi showed decreasing ET trends from 1951-2001, and the proportion of stations with increasing ET trends would increase in the future compared to 1951-2001. Hu et al. clarified that reduced sunshine duration and wind speed were the main causes of ET changes in Northwest Guangxi. Currently, research distinguishing between karst and non-karst areas remains scarce. Conducting comparative studies on ET variation characteristics and influencing factors in karst and non-karst areas, and explaining the differences in ET under these two geomorphological backgrounds, is of great significance for agricultural development and rational water resource allocation in karst and non-karst areas of Southwest China.

Based on 51 years of daily meteorological data from 25 stations, this paper analyzes the spatio-temporal distribution characteristics of ET in Guangxi and uses correlation analysis, path analysis, and other methods to explore the relationships between meteorological factors and ET , aiming to reveal the main meteorological factors influencing ET changes in karst and non-karst areas and provide scientific basis for evaluating and predicting climatic dry-wet conditions and restoring the fragile ecological environment in karst areas.

1 Materials and Methods

1.1 Study Area Overview

Guangxi (20°54 -26°24 N, 104°26 -112°04 E) is located in Southwest China, on the southeastern edge of the Yunnan-Guizhou Plateau at China' s second topographic step. It is surrounded by mountains and plateaus, with flat land in the central and southern parts, and terrain sloping from northwest to southeast. The region has a subtropical monsoon climate with warm temperatures and abundant heat. Annual mean temperature ranges from 16.0°C to 23.0°C, increasing from north to south and decreasing from valley plains to hilly mountainous areas. Precipitation is abundant with concurrent rainfall and heat, with annual precipitation exceeding 1,070 mm, mostly between 1,500–2,000 mm in most areas. Seasonal precipitation distribution is uneven, with the rainy season from April to September accounting for 70%-85% of annual precipitation. Sunshine is moderate, less in winter and more in summer. Karst landforms are widely distributed in Guangxi, covering 41% of the total area, concentrated in Southwest, Northwest, Central, and Northeast Guangxi.

1.2 Data Sources

Meteorological data for the study area were obtained from the China Meteorological Data Service Center (http://www.nmic.gov.cn/). Daily data from 1960–2010 were collected for 25 meteorological stations [Figure 1: see original paper], including daily mean temperature (T), maximum temperature (T), minimum temperature (T), wind speed at 2 m height (u), sunshine duration (n), and relative humidity (RH). The data records are relatively complete with high quality; missing data and invalid values were interpolated using values from neighboring stations or adjacent years. A meteorological station was considered a karst station if the karst landform area in its county (city) exceeded 30%. Among the 25 stations, 11 were karst stations and 14 were non-karst stations, which can well represent the distribution and variation of ET in Guangxi' s karst and non-karst areas.

2.1 FAO-56 Penman-Monteith Equation

The FAO-PM formula is based on energy balance and water vapor diffusion theory, comprehensively considering crop physiological characteristics and aerodynamic parameter changes. Its expression is:

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

where ET is reference crop evapotranspiration (mm · d ¹), R is net radiation at the surface (MJ · m ² · d ¹), G is soil heat flux (MJ · m ² · d ¹), T is mean daily temperature at 2 m height (°C), u is wind speed at 2 m height (m · s ¹), e is saturation vapor pressure (kPa), e is actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure curve (kPa · °C ¹), and is the psychrometric constant (kPa · °C ¹).

2.2 Cumulative Anomaly Method

The cumulative anomaly method is a commonly used approach to visually identify trends through curves. For a sequence X, the cumulative anomaly at time t is expressed as:

$$\bar{X}_t = \sum_{i=1}^{t}(X_i - \bar{X}), \quad t = 1, 2, \dots, n$$

By calculating cumulative anomaly values for all n time points, a cumulative anomaly curve can be plotted for trend analysis.

2.3 Spearman Rank Correlation Test

The Spearman rank correlation test primarily examines whether a time series has a trend by analyzing the correlation between sequence x and its time order i. During calculation, the time series x is represented by its rank M , and the rank correlation coefficient is:

$$r = 1 - \frac{6\sum_{i=1}^{n}(M_i - i)^2}{n(n^2-1)}$$

where n is the series length (i.e., number of years). When rank M is close to time order i, the rank correlation coefficient r is large and the trend is significant. The t-test method is typically used to examine whether the trend in hydrological series is significant. The test statistic T is calculated as:

$$T = r\sqrt{\frac{n-2}{1-r^2}}$$

where T follows a t-distribution with (n-2) degrees of freedom. The null hypothesis is that the series has no trend. Based on the rank correlation coefficient, the T statistic is calculated, and a significance level   is selected to find the critical value t / from the t-distribution table. When T   t / , the null hypothesis is rejected and the trend is considered significant; otherwise, the null hypothesis is accepted and the trend is not significant.

2.4 Path Analysis

Path analysis was proposed by quantitative geneticist Sewall Wright in 1921. It can directly quantify the relative importance of independent variables without being affected by measurement units or variation degrees of independent variables, while obtaining both direct and indirect effects of independent variables on dependent variables, thereby analyzing inter-variable relationships and the manner and degree of independent variable effects on dependent variables. This study used SPSS (regression analysis) to conduct path analysis to identify the main meteorological factors affecting ET changes.

3 Results and Analysis

3.1 Spatial Distribution Characteristics of Reference Evapotranspiration

The 51-year average ET at 25 meteorological stations in Guangxi was 1,138 mm·a[1]. The spatial distribution of multi-year ET in Guangxi was obtained using Kriging interpolation in ArcGIS software [Figure 2: see original paper]. The results show that multi-year ET across Guangxi ranged from 1,018 to 1,343 mm · a^{1}, generally decreasing from south to north and from low to high latitudes. High-value areas were located in coastal non-karst regions in the south with higher temperatures and abundant precipitation, while sub-high-value areas were in the western Tiandong region with sufficient sunlight and relatively flat terrain. Low-value areas were mainly distributed in karst mountainous regions in northern and northwestern Guangxi with higher altitudes, with values below 1,108 mm · a^{1}.

Seasonal spatial distributions of ET showed significant differences [Figure 3: see original paper]. In spring, ET across Guangxi ranged from 256 to 342 mm · a^{1}, generally decreasing from west to east, with high-value areas mainly in the vast northwestern Guangxi region, decreasing from the non-karst areas of Baise and Tiandong toward surrounding karst areas. Summer ET was the highest annually, ranging from 345 to 434 mm · a^{1}, with average values of 377 mm · a^{1} in karst areas and 403 mm · a^{1} in non-karst areas, showing a decreasing trend from southeast to northwest. Autumn ET ranged from 224 to 372 mm · a^{1}, with spatial characteristics similar to annual ET except for slight differences in northeastern Guangxi. Winter ET ranged from 134 to 226 mm · a^{1}, generally decreasing from south to north, with a sub-high-value area appearing in the Tiandong region of northwestern Guangxi. These results indicate that spring ET spatial distribution differed greatly from other seasons, primarily because in spring, western Guangxi had longer sunshine duration, higher temperatures, and lower relative humidity compared to other regions. Southern coastal non-karst areas were high-value zones in all seasons, related to their much longer sunshine duration than other regions in Guangxi.

3.2.1 Multi-Year Monthly Average Evapotranspiration Trends

The multi-year monthly average ET variation trends in Guangxi's karst and non-karst areas are shown in [Figure 4: see original paper]. Both showed consistent trends, following a unimodal parabolic curve with maximum values in July and minimum values in January. The multi-year monthly average ET in karst areas ranged from 40 to 104 mm, a difference of 64 mm, while in non-karst areas it ranged from 60 to 155 mm, a difference of 95 mm. The monthly ET range in karst areas was smaller than in non-karst areas. Additionally, both the multi-year monthly average ET and its rate of change were smaller in karst areas than in non-karst areas.

3.2.2 Annual Evapotranspiration Trends

Interannual variations in cumulative ET anomalies were substantial in both karst and non-karst areas [Figure 5: see original paper]. The annual ET cumulative anomaly curves showed an "N-shaped" distribution, roughly divided into four stages: (1) 1960–1967, when ET showed a clear increasing trend, with smaller increases in karst areas than non-karst areas; (2) 1967–1980, a relatively stable stage with small fluctuations; (3) 1980–2002, when ET showed a decreasing trend, with smaller declines before 1992, a slight increase around 1985, and a significant decreasing trend after 1992, with smaller decreases in karst areas; and (4) 2002–2010, when ET showed an increasing trend but remained below the average, with similar changes in karst and non-karst areas.

To further analyze trends at individual stations, Spearman rank correlation coefficients were calculated for all 25 stations . Among 11 karst stations, 6 (54.55%) showed decreasing ET trends, with 3 (27.27%) being significantly decreasing; 5 (45.45%) showed increasing trends, with 2 (18.18%) being significantly increasing. Among 14 non-karst stations, 8 (57.14%) showed decreasing trends, with 4 (28.57%) being significantly decreasing; 6 (42.86%) showed increasing trends, with 1 (7.14%) being significantly increasing. These results show that more stations in Guangxi showed decreasing than increasing ET trends, with decreasing stations being predominantly significantly decreasing, while increasing stations mainly showed non-significant increases. The decreasing and increasing trends and their significance were similar between karst and non-karst areas, though the proportion of significantly increasing stations was slightly higher in karst areas.

3.3 Analysis of Influencing Factors on Reference Evapotranspiration

ET reflects regional atmospheric evaporation capacity and is influenced by multiple environmental factors. This study conducted correlation and path analyses between meteorological factors (sunshine duration, wind speed, mean temperature, relative humidity) and annual/seasonal ET at 25 stations, calculating direct and indirect effect coefficients [TABLE:2, TABLE:3].

For Guangxi as a whole, sunshine duration, wind speed, and mean temperature had large impacts on annual ET , with positive correlations (correlation coefficients of 0.845, 0.759, and 0.664, respectively). Relative humidity had a smaller impact, with a negative correlation. In non-karst areas, the correlation between meteorological factors and annual ET was similar to the overall results, with correlation coefficients of 0.862, 0.797, 0.679, and -0.076 for sunshine duration, wind speed, mean temperature, and relative humidity, respectively. In karst areas, relative humidity showed a strong negative correlation with annual ET (correlation coefficient of -0.526). Path analysis results revealed that the direct effect coefficient of relative humidity on annual ET in karst areas was not large, even smaller than in non-karst areas. The large negative correlation coefficient mainly resulted from indirect effects of other meteorological factors interacting with relative humidity, with an indirect effect sum of -0.349. Additionally, the indirect effect coefficients among sunshine duration, wind speed, and mean temperature in karst areas were all smaller than in non-karst areas, indicating that interactions among these three meteorological factors were weaker in karst areas.

Correlation and path analyses were conducted separately for meteorological factors and ET in each season in karst and non-karst areas . Overall, sunshine duration and mean temperature were the most important factors affecting ET in all seasons, positively correlated with ET . Relative humidity was significantly negatively correlated with ET , with indirect effects on ET in karst areas exceeding direct effects in all seasons. Furthermore, wind speed showed negative indirect effect coefficients on ET in karst areas during winter and spring, possibly because increased wind speed led to decreased mean temperature, thereby reducing ET and offsetting the positive direct effect of wind speed on ET . This phenomenon was not observed in non-karst areas.

Discussion

4.1 Spatio-Temporal Variation Characteristics of Reference Evapotranspiration

The spatio-temporal distribution characteristics showed that ET in karst areas was lower than in non-karst areas, which is related to non-karst areas being mainly located in southern coastal regions with longer sunshine duration. This indicates that ET is influenced by geographical location to some extent. However, compared with inland karst areas far from the sea, the Tiandong region (non-karst), which is also inland and surrounded by mountains but has relatively flat terrain, showed high ET , demonstrating that topography and landforms also significantly affect ET levels. Therefore, differentiated approaches should be adopted in water resource utilization and management.

From 1960–2010, ET in Guangxi showed an overall decreasing trend, with cumulative ET anomalies reaching maximum values in the 1970s, gradually decreasing thereafter, reaching minimum values in the 1990s, and increasing rapidly after 2002. The recent increase in cumulative ET anomalies indicates enhanced atmospheric evaporation capacity in Guangxi, increased vegetation transpiration and crop water requirements. If ET continues to increase without timely effective measures to guarantee ecological water demand, it will exacerbate rocky desertification in karst areas, trigger agricultural drought across Guangxi, and even threaten domestic water supply. Zhang et al. pointed out that ET in Southwest China decreased sharply from the late 1970s to the early 21st century, then increased dramatically after 2004, consistent with our findings. This shows that ET variation characteristics differ across periods in the same region, making it necessary to conduct segmented discussions on ET variation characteristics and causes for different decades to scientifically and objectively understand the role of ET changes in water resource management under different climate change stages. While cumulative anomalies reveal interannual ET trends for Guangxi as a whole, they cannot reflect trends at individual stations. This study used the Spearman rank correlation method to calculate correlation coefficients for multi-year average ET at each station in Guangxi, quantitatively analyzing trends at each station. The results showed that slightly more stations showed decreasing than increasing trends, with increasing stations mainly showing non-significant increases, similar to Guan et al.' s study of 20 meteorological stations in Guangxi but differing from Zhang and Shen' s conclusion that significantly increasing stations slightly outnumbered significantly decreasing stations across China, reflecting regional characteristics of climate change.

4.2 Influencing Factors of Spatio-Temporal Variation in Reference Evapotranspiration

Zhao et al. found that ET in the Haihe River basin was most sensitive to mean relative humidity, while reduced wind speed and shortwave radiation were the main causes of ET decline in eastern and southern Haihe. Cao et al. found that sunshine duration and wind speed were the dominant factors affecting ET changes in Anhui Province. Shi et al. concluded that wind speed was the main factor causing ET changes at most meteorological stations on the Loess Plateau. These studies demonstrate that dominant factors of ET differ across regions. In this study, sunshine duration, wind speed, and mean temperature had large impacts on annual ET in Guangxi and non-karst areas, with relative humidity having smaller impacts, similar to Tian et al.' s results in Guizhou. In karst areas, all meteorological factors showed strong correlations with annual ET , with relative humidity affecting ET mainly through influencing other meteorological factors. Path analysis results indicated that interactions among sunshine duration, wind speed, and mean temperature were weaker in karst areas than in non-karst areas, possibly because their interrelationships were more complex due to microtopography. Additionally, in karst areas during winter and spring, increased wind speed may have decreased mean temperature, thereby reducing ET and offsetting the positive direct effect of wind speed, demonstrating that ET is affected not only by direct effects of meteorological factors but also by their mutual constraints and interactions.

This study further demonstrates that ET changes and their influencing factors have regional differences. Even in karst and non-karst areas within the same region, ET influencing factors differ. Therefore, ET research must be conducted regionally to fully understand variation trends and influencing factors in each region, which helps assess changes in water resource demand under future climate change and provides important guidance for developing reasonable vegetation restoration strategies, disaster prevention and mitigation, and productivity improvement.

Conclusions

Based on the FAO-56 Penman-Monteith equation and daily data from 25 meteorological stations in Guangxi from 1960–2010, this study analyzed the spatio-temporal variation characteristics of ET and their influencing factors in karst and non-karst areas of Guangxi. The main conclusions are:

1. The 51-year average ET at Guangxi stations ranged from 1,018 to 1,343 mm · a^{1}, with a mean of 1,138 mm · a^{1}. ET in non-karst areas was generally higher than in karst areas. Except for spring when high ET values were concentrated in western karst areas, high ET values in other seasons were mainly concentrated in southern coastal non-karst areas. Seasonal

ET variation trends were consistent between karst and non-karst areas, being highest in summer, similar in spring and autumn, and lowest in winter. Annual ET cumulative anomaly curves showed an "N-shaped" distribution, highest in the 1970s, lowest in the 1990s, recovering somewhat since the 21st century but still below the average. Additionally, interannual ET variation was smaller in karst areas than in non-karst areas.

2. Path analysis between ET and meteorological factors showed that main influencing factors differed by region and season. Relative humidity had little impact on annual ET in non-karst areas but indirectly exerted greater influence on annual ET in karst areas through interactions with other meteorological factors. At the seasonal scale, sunshine duration and mean temperature were the most important factors affecting ET in both karst and non-karst areas in all seasons. Additionally, wind speed showed negative indirect effect coefficients on ET in karst areas during winter and spring, a phenomenon not observed in non-karst areas.

In reality, ET changes are influenced not only by sunshine duration, wind speed, temperature, and relative humidity but also by other climatic factors, underlying surface conditions, vegetation cover, human activities, and other factors. Further research is needed on the impacts of these factors on regional evapotranspiration to comprehensively understand the dominant factors causing regional evapotranspiration differences.

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