Postprint: Variation Analysis of Evapotranspiration and Its Components in Alpine Meadows of the Qinghai-Tibet Plateau Based on the SWH Model

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Abstract

Evapotranspiration was estimated for the Naqu, Namco, and Southeast Tibet stations on the Qinghai-Tibet Plateau using the Shuttleworth-Wallace Hu (SWH) dual-source evapotranspiration model. Based on good validation results, the variation characteristics of evapotranspiration on the Qinghai-Tibet Plateau and the main influencing factors at each station were analyzed. The results demonstrate that the SWH model exhibits good applicability at the three alpine meadow stations on the Qinghai-Tibet Plateau. Annual evapotranspiration ranges between 388–732 mm, with an intra-annual distribution characterized by an initial increase followed by a decrease. The components of evapotranspiration differ significantly among the three stations: soil evaporation contributes 53% and 56% to total evapotranspiration at Naqu and Namco stations, respectively, while evapotranspiration at the Southeast Tibet station is contributed almost entirely by vegetation transpiration, accounting for up to 95%. Vegetation leaf area index is the most important influencing factor for evapotranspiration at all three stations, and saturated vapor pressure deficit also exerts a relatively large influence on evapotranspiration at the Southeast Tibet station. The research results can provide a scientific basis for studies on the spatiotemporal patterns of evapotranspiration and its components and the water cycle processes on the Qinghai-Tibet Plateau.

Full Text

Preamble

Variations of Evapotranspiration and Its Components in Alpine Meadow on the Tibetan Plateau Based on the SWH Model

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Abstract: This study employs the SWH dual-source evapotranspiration model to estimate evapotranspiration at three alpine meadow stations on the Tibetan Plateau: the Nagqu Station of Plateau Climate and Environment, the Nam Co Monitoring and Research Station for Multisphere Interactions, and the Southeast Tibet Observation and Research Station for the Alpine Environment. Following robust validation of the model results, we analyze the spatiotemporal characteristics of evapotranspiration variations across the plateau and identify the primary influencing factors at each station. The results demonstrate that the SWH model exhibits good applicability at the three meadow stations. Annual evapotranspiration ranges from 388 mm to 732 mm, showing an initial increase followed by a decrease in its interannual distribution. The stations exhibit substantial differences in evapotranspiration components: soil evaporation contributes 53% and 56% of total evapotranspiration at the Nagqu and Nam Co stations, respectively, while evapotranspiration at the Southeast Tibet Station is almost entirely contributed by vegetation transpiration (95%). The leaf area index represents the most critical factor affecting evapotranspiration at all three stations, while vapor pressure deficit also significantly influences evapotranspiration at the Southeast Tibet Station. These findings provide a scientific basis for investigating the spatiotemporal patterns of evapotranspiration and its components, as well as the water cycle processes over the Tibetan Plateau.

Keywords: evapotranspiration; evapotranspiration components; SWH model; Qinghai-Tibet Plateau

1. Introduction

The Tibetan Plateau, located in southwestern China, is the world' s highest, largest, and most topographically complex plateau, earning it the monikers "Roof of the World"and "Third Pole"[?, ?]. Approximately 63.5% of the plateau's surface is covered by alpine desert steppe, alpine grassland, and meadow ecosystems. Under global warming, the plateau has experienced pronounced changes in climate and environment, with water resources showing a persistent declining trend. These dramatic alterations in the water cycle profoundly affect regional water and heat balances across the plateau and its surrounding areas [?, ?]. Evapotranspiration, the sum of soil evaporation and vegetation transpiration, constitutes the primary process of energy exchange between the land surface and atmosphere and plays a decisive role in terrestrial water cycling, carbon cycling, and energy balance [?]. During the water cycle, approximately 60% of precipitation over land returns to the atmosphere through evapotranspiration

[?]. Quantifying evapotranspiration and separating its components are prerequisites for obtaining complete evapotranspiration data and represent important pathways for deepening our understanding of water cycle processes.

Traditional models for estimating evapotranspiration, such as the Penman-Monteith equation, energy balance models, and the SEBAL model, have achieved satisfactory results [?]. However, these approaches are constrained by the uneven distribution of meteorological stations, making large-scale regional evapotranspiration estimation challenging. While remote sensing products like GLDAS, MODIS16, and GLEAM have resolved the issue of large-scale evapotranspiration estimation [?], they cannot separate evapotranspiration components or conduct quantitative analyses of each component. In 1985, Shuttleworth and Wallace proposed the dual-source Shuttleworth-Wallace evapotranspiration model [?], which enables simultaneous estimation of total evapotranspiration and separation of its components. The SWH model is a physically-based conceptual evapotranspiration model that, after parameterization of resistance terms, demonstrates strong capability in simulating both soil evaporation and vegetation transpiration. It has been widely applied in evapotranspiration estimation research [?].

The SWH model was developed by introducing a soil surface resistance equation, a stomatal conductance model, and a light use efficiency-based Gross Primary Productivity (GPP) model into the Shuttleworth-Wallace framework [?, ?]. This integration enables estimation of canopy stomatal conductance based on meteorological data and GPP, forming an improved SWH model. The model has demonstrated good performance when applied to forest ecosystems at the Changbai Mountain station and grassland ecosystems at the Haibei station [?]. Wu et al. [?] validated SWH model simulations against multi-year evapotranspiration observations at various stations, confirming its robust simulation capabilities at both annual and seasonal scales. Jiang et al. [?] estimated and partitioned evapotranspiration across the Yellow River Basin from 1982 to 2015. These studies collectively demonstrate that the SWH model can effectively simulate land surface evapotranspiration at both site and regional scales while separating its components, providing a valuable tool for comprehensive analysis of ecosystem evapotranspiration processes.

The Tibetan Plateau, often called the "Water Tower of Asia," serves as the source region for several major Asian rivers. Precipitation and evapotranspiration on the plateau determine freshwater supply for nearly 2 billion people. As a critical component of water and energy balance, Tibetan Plateau evapotranspiration and its variations have attracted widespread attention, yet refining the evapotranspiration process remains a research priority. Furthermore, quantifying evapotranspiration and partitioning its components holds significant strategic importance for understanding plateau water cycle processes, ecosystem responses, climate change adaptation strategies, and national security. This study evaluates the accuracy of the SWH model in simulating evapotranspiration on the Tibetan Plateau, analyzes variations in evapotranspiration and its components based on simulation results, and explores the primary factors influencing evapotranspiration changes, thereby providing a scientific foundation for regional-scale evapotranspiration estimation and spatiotemporal pattern analysis on the plateau.

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2. Data and Methods

2.1 Data Sources

This study utilizes hourly-scale continuous meteorological and environmental observation data from 2005 to 2016 at the Nagqu, Nam Co, and Southeast Tibet stations, obtained from the National Tibetan Plateau Data Center (http://data.tpdc.ac.cn) [?]. Vegetation Leaf Area Index (LAI) data were derived from the Chinese Academy of Sciences Resource and Environmental Science Data Center (http://www.resdc.cn) and the GLOBMAP LAI Version 3 product. The GLOBMAP product, based on fused AVHRR and MODIS data, has a spatial resolution of 0.08°$×$0.08° and a temporal resolution of 8 days. Further temporal scaling processing was applied to align model driver data, resulting in all input and output data being at daily resolution.

For model validation, this study employs two evapotranspiration products: the China Land GPR product and the Tibetan Plateau ETa dataset. The GPR product contains monthly terrestrial evapotranspiration across China at 0.01°$×0.01°*spatialresolution*, *whiletheETadatasetprovidesmonthlylandsurfaceevapotranspirationovertheT*
//data.tpdc.ac.cn)[?].*Linearregressionanalysiswasconductedbetweenmodel* −
simulatedevapotranspirationandproductdata, *withcoefficientofdetermination*(*R*^{2}$), mean absolute error (MAE), root mean square error (RMSE), and mean relative error (MRE) used as evaluation metrics.

[Figure 1: see original paper]

2.2 SWH Evapotranspiration Model

The SWH model, developed through parameterization of resistance terms, canopy stomatal conductance estimation, and other improvements, exhibits strong simulation capability for soil evaporation and vegetation transpiration across diverse ecosystems [?, ?]. By adopting ecosystem-specific parameter values for key parameters, the model achieves robust performance in different ecosystems and can be widely applied to evapotranspiration estimation in various land cover types [?, ?].

The core equations of the SWH model are as follows:

$$PM_c = \frac{\Delta \cdot R_{nc} + \rho \cdot c_p \cdot \frac{VPD}{r_{ac}}}{\Delta + \gamma \cdot \left(1 + \frac{r_{sc}}{r_{ac}}\right)}$$

$$PM_s = \frac{\Delta \cdot R_{ns} + \rho \cdot c_p \cdot \frac{VPD}{r_{as}}}{\Delta + \gamma \cdot \left(1 + \frac{r_{ss}}{r_{as}}\right)}$$

$$ET = c_c \cdot PM_c + c_s \cdot PM_s$$

where PM_c and PM_s represent the Penman-Monteith equations for canopy and soil, respectively; ET is evapotranspiration; c_c and c_s are weighting coefficients for vegetation transpiration and soil evaporation, respectively; Δ is the slope of the saturation vapor pressure curve; γ is the psychrometric constant; ρ is air density; c_p is specific heat at constant pressure; VPD is vapor pressure deficit; R_{nc} and R_{ns} are net radiation absorbed by the canopy and soil surface, respectively; r_{ac}, r_{as}, r_{sc}, and r_{ss} are aerodynamic resistance between the surface and canopy height, aerodynamic resistance between canopy height and reference height, canopy boundary layer resistance, canopy stomatal resistance, and soil surface resistance, respectively.

Model driver data include meteorological environmental variables (average air temperature T_a, relative humidity RH, vapor pressure deficit VPD, wind speed u, soil moisture SM, soil heat flux G, photosynthetically active radiation PAR) and remote sensing data (LAI). The model calculates five resistance terms through these drivers and subsequently computes soil evaporation and vegetation transpiration to obtain total evapotranspiration. Detailed model descriptions are provided in Hu et al. [**?**] and Wu et al. [**?**]. Key parameter values in this study follow established literature, with parameters c_c and c_s set at 0.8 and 0.2, respectively.

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3. Results and Analysis

3.1 SWH Model Simulation Evaluation

Primary input data for the SWH model are illustrated in Figure 2. The three stations show broadly similar patterns in all variables, exhibiting clear intra-annual and interannual variations over time, though individual elements differ substantially. Nam Co station consistently shows higher LAI values than Nagqu and Southeast Tibet stations. Nagqu station exhibits significantly higher VPD than the other two stations, with Southeast Tibet station showing the lowest VPD. PAR fluctuations are most pronounced at Southeast Tibet station, while other variables show relatively smaller differences. Soil moisture and soil heat flux variations are minimal at Southeast Tibet station, whereas Nagqu and Nam Co stations display more substantial fluctuations.

[Figure 2: see original paper]

Model validation results are presented in Figure 3. The SWH model demonstrates good agreement with GPR and ETa data across the Tibetan Plateau.

At Nagqu, Nam Co, and Southeast Tibet stations, R^2 values between simulated ET and GPR data are 0.74, 0.71, and 0.73, respectively, with RMSE values of 9.55 $\mathrm{mm \cdot d^{-1}}$, 7.75 $\mathrm{mm \cdot d^{-1}}$, and 14.33 $\mathrm{mm \cdot d^{-1}}$. Comparisons with ETa data yield R^2 values of 0.71, 0.68, and 0.70, with RMSE values of 10.10 $\mathrm{mm \cdot d^{-1}}$, 9.18 $\mathrm{mm \cdot d^{-1}}$, and 13.25 $\mathrm{mm \cdot d^{-1}}$. Monthly variations (Figure 4) reveal that while the model shows slight underestimation or overestimation relative to validation products, overall patterns are smooth and stable. The differing validation accuracy between GPR and ETa products likely reflects variations in spatial resolution, observation methods, and data fusion algorithms. These validation analyses confirm that the SWH model exhibits good applicability at site scales on the Tibetan Plateau and can be reliably used for evapotranspiration simulation at the three meadow stations.

[Figure 3: see original paper] [Figure 4: see original paper]

3.2 Evapotranspiration Variations Across Temporal Scales

Daily evapotranspiration at all three stations shows a unimodal trend of initial increase followed by decrease. Daily ET ranges from 0.0 to 4.9 mm, with mean values of 1.2 mm, 1.9 mm, and 1.4 mm at Nagqu, Nam Co, and Southeast Tibet stations, respectively. Nagqu station exhibits relatively stable daily ET with smaller fluctuations compared to the other stations, while Southeast Tibet station shows the most dramatic variations and Nam Co station displays the largest fluctuation range.

Monthly ET variations (Figure 6) reveal that all three stations experience increases from January to July, with maximum values occurring in July (Nagqu: 85 mm; Nam Co: 77 mm; Southeast Tibet: 97 mm). Overall, Southeast Tibet station shows higher monthly ET than the other two stations. The intra-annual monthly variation pattern aligns well with the vegetation growing season (May-September). Seasonal variations (Figure 7) indicate that Nagqu station shows minimal fluctuation across seasons, with almost no change in winter. Nam Co station exhibits unstable seasonal variations, most pronounced in winter. Southeast Tibet station shows slowly increasing trends in spring and summer, with more obvious fluctuations in autumn and winter.

[Figure 5: see original paper] [Figure 6: see original paper] [Figure 7: see original paper]

3.3 Separation of Evapotranspiration Components

The SWH model partitions annual and seasonal evapotranspiration into soil evaporation (E) and vegetation transpiration (T) components. Interannual variations in ET components are minimal, showing slight increases or remaining stable. Annual ET ranges from 388-479 mm at Nagqu, 450-658 mm at Nam Co, and 674-732 mm at Southeast Tibet.

Daily variations in E and T are illustrated in Figure 8. At Nagqu station, daily E ranges from 0.0-1.1 mm and daily T from 0.0-2.9 mm. During the non-growing season, E and T show similar trends, while during the growing season they exhibit opposite patterns–T increases continuously while E decreases. The ratio of daily soil evaporation to total evapotranspiration (E/ET) at Nagqu ranges from 0.07-0.88, averaging 0.53. At Nam Co station, daily E shows large fluctuations (0.0-2.5 mm) with a mean of 1.3 mm, while daily T ranges from 0.0-1.3 mm with more stable patterns. The E/ET ratio at Nam Co varies between 0.00-0.89, averaging 0.56. Southeast Tibet station shows minimal daily E (approximately 0.1 mm) with E/ET ratios of only 0.02-0.11, indicating that nearly all evapotranspiration originates from vegetation transpiration.

Monthly component variations show that at Nagqu station, monthly E remains relatively stable (22 mm in July) while monthly T displays unimodal variation, peaking at 76 mm in July. Nam Co station exhibits stable monthly E (30 mm) with monthly T showing an initial decrease followed by increase, reaching a maximum of 49 mm in July. Southeast Tibet station shows minimal and stable monthly E (2.4 mm) while monthly T follows a clear unimodal pattern, peaking at 95 mm in July.

[Figure 8: see original paper]

3.4 Analysis of Evapotranspiration Influencing Factors

Evapotranspiration is influenced by numerous factors including air temperature, precipitation, wind speed, sunshine duration, and vegetation condition, with complex interactions among them. Correlation analysis between ET and major drivers at each station identified factors with $R^2 > 0.3$ for further analysis. Hierarchical regression models examined the degree and importance of influencing factors (Table 1). When considering single factors alone, results were unsatisfactory; however, when integrating multiple major factors, R^2 exceeded 0.75 for all stations.

Standardized coefficients reveal that leaf area index (LAI) has the greatest influence on evapotranspiration across all stations, significantly larger than other factors. LAI affects evapotranspiration primarily by influencing vegetation growth and transpiration processes. Previous studies have shown conflicting results regarding vapor pressure deficit (VPD) effects. Grossiord et al. [?] found that increasing VPD reduces stomatal conductance but enhances transpiration under certain thresholds. Zhang et al. [?] demonstrated that actual daily evapotranspiration correlates significantly and positively with air temperature, ground temperature, net radiation, and soil moisture. This study finds VPD also significantly affects evapotranspiration at Southeast Tibet station. These similarities and differences with previous research likely reflect variations in study scope, driver data, and model methodologies.

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4. Discussion

Previous studies have established vegetation transpiration as the dominant component of global evapotranspiration [?]. However, Kool et al. [?] demonstrated that soil evaporation constitutes an important component in arid and semi-arid regions. Wang et al. [?] calculated that 40-60% of Tibetan Plateau evapotranspiration originates from soil evaporation. Jiang et al. [?] similarly quantified evapotranspiration components using the SWH model, finding soil evaporation dominates except in semi-humid regions with high canopy cover in southeastern Tibet. These findings align with our component separation results.

The SWH model' s output represents daily mean values due to remote sensing data temporal resolution limitations, which cannot capture diurnal ET variations and introduces some uncertainty in daily-scale analysis. The model only partitions evapotranspiration into soil evaporation and vegetation transpiration, omitting canopy interception evaporation. Future research should incorporate canopy evaporation to more accurately characterize the complete evapotranspiration process on the Tibetan Plateau.

Although all three stations feature alpine meadow underlying surfaces, environmental and climatic conditions differ substantially. The Nagqu and Nam Co stations are influenced by river and lake systems, showing smaller evapotranspiration than Southeast Tibet station, which is affected by both alpine meadows and temperate coniferous forests. Our simulations used grassland ecosystem parameters, which may cause some divergence from actual ET variations. Future application of the SWH model across the entire Tibetan Plateau must address how to account for regional environmental and climatic heterogeneity impacts on model results.

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5. Conclusions

This study evaluates the SWH dual-source evapotranspiration model at three Tibetan Plateau stations and draws three main conclusions. First, the SWH model demonstrates good applicability at the Nagqu, Nam Co, and Southeast Tibet stations, accurately estimating evapotranspiration and enabling reliable investigation of ET variations at these sites. Second, all three stations exhibit unimodal ET patterns with initial increases followed by decreases. Daily ET ranges from 0.0-4.9 mm (peaking in July-August), while monthly ET varies between 8-97 mm (peaking in July). Despite similar underlying surfaces, ET differs among stations due to variations in elevation, topography, monsoon influence, and vegetation condition. Third, the stations show marked differences in ET components. At Nagqu station, daily soil evaporation (E) and transpiration (T) range from 0.0-1.1 mm and 0.0-2.9 mm, respectively, with E/ET averaging 0.53. Nam Co station shows more volatile component partitioning, with daily E and T ranging from 0.0-2.5 mm and 0.0-1.3 mm, respectively, and E/ET averaging 0.56. Southeast Tibet station exhibits minimal soil evaporation (approximately

0.1 mm) with E/ET ratios of only 0.02-0.11, indicating that vegetation transpiration dominates total evapotranspiration. Finally, while the dominant factors are similar across stations, leaf area index emerges as the primary control on evapotranspiration at all sites, though vapor pressure deficit also represents a non-negligible influence at Southeast Tibet station.

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