# Spatiotemporal Variation Characteristics and Influencing Factors of Actual Evapotranspiration in the Northeastern Qinghai-Tibet Plateau (Postprint)

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## Abstract

Investigating the spatiotemporal variation characteristics of actual evapotranspiration and its influencing factors in the northeastern Tibetan Plateau is of great significance for rational utilization of regional water resources and ecological environment management. Taking Qinghai Province, located in the northeastern Tibetan Plateau, as the study area, this study analyzed the spatiotemporal patterns, change processes, and influencing factors of actual evapotranspiration in the region over the past 20 years using actual evapotranspiration (MOD16 ET) data from MOD16 remote sensing products from 2001 to 2020. The results show: (1) From 2001 to 2020, the multi-year average actual evapotranspiration in Qinghai Province was 260 $\mathrm{mm \cdot a^{-1}}$, with interannual variation showing a fluctuating increasing trend, the fluctuation cycle exhibiting an increasing trend, and the average interannual change rate being 2%. Areas with increasing actual evapotranspiration accounted for 69.69% of the total area, while decreasing areas accounted for 16.51%, with the Qilian Mountains region and the eastern part of the River Source Ecological Zone showing an increasing trend in actual evapotranspiration. Seasonal variation in actual evapotranspiration in Qinghai Province was significant, with the highest values in summer, the lowest in winter, and similar values in spring and autumn. (2) From 2001 to 2020, actual evapotranspiration in Qinghai Province exhibited a spatial distribution pattern of low values in the northwest and high values in the southeast; significant differences existed among various ecological zones, with the Three-River Source Region and Qilian Mountains being the areas with the highest actual evapotranspiration in Qinghai Province, while the Qaidam Basin Ecological Zone had the lowest actual evapotranspiration. The ranking of actual evapotranspiration for major vegetation cover types was as follows: shrubland > forestland > grassland > cropland. (3) From 2001 to 2020, the fluctuating changes in actual evapotranspiration in

Qinghai Province were basically consistent with changes in annual mean temperature; the increase in actual evapotranspiration was generally consistent with the fluctuating increasing trend of annual total precipitation, but its peak lagged behind changes in annual total precipitation. (4) Areas with positive correlation between actual evapotranspiration and annual mean temperature accounted for 73% of the total study area, those with positive correlation with annual total precipitation accounted for 56%, those with positive correlation with sunshine hours accounted for 43%, and those with positive correlation with average wind speed accounted for 44%. Actual evapotranspiration in Qinghai Province is primarily controlled by temperature and precipitation, while also being influenced by sunshine hours and wind speed, with significant regional differences in the climatic factors affecting changes in actual evapotranspiration.

## Full Text

## Spatiotemporal Variation Characteristics and Influencing Factors of Actual Evapotranspiration in the Northeastern Qinghai-Xizang Plateau

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**Abstract:** Investigating the spatiotemporal variation characteristics and influencing factors of actual evapotranspiration (ET) in the northeastern Qinghai-Xizang Plateau is of great significance for rational water resource utilization and ecological environment management in the region. Using Qinghai Province, located in the northeastern part of the plateau, as the study area, we analyzed the spatiotemporal patterns, variation trends, and influencing factors of actual ET from 2001 to 2020 based on MOD16 ET data from remote sensing products. The results show that: (1) The average annual actual ET in Qinghai Province from 2001 to 2020 was 260 $mm \cdot a^{-1}$, with a fluctuating increasing trend over time. The fluctuation period showed an increasing trend, with an average interannual change rate of 2%. Areas with increasing ET accounted for 69.69% of the total area, while decreasing areas accounted for 16.51%. Notably, the Qilian Mountains and the eastern part of the river source ecological zone exhibited increasing ET trends. Seasonal variation was significant, with summer ET being the highest, winter the lowest, and spring and autumn being similar. (2) Spatially, ET showed a pattern of low values in the northwest and high values in the southeast. Different ecological zones showed large variations, with the Three River Source area and Qilian Mountains having the highest ET, while the Qaidam Basin ecological zone had the lowest. The ranking of ET among major vegetation types was: shrubland > forest > grassland > cropland. (3) The fluctuating changes in ET were basically consistent with variations in annual average temperature. The increase in ET largely corresponded to the increasing

trend of precipitation, though the peak lagged behind precipitation changes. (4) Areas with positive correlations between ET and annual average temperature, annual total precipitation, sunshine duration, and average wind speed accounted for 73%, 56%, 43%, and 44% of the total study area, respectively. Temperature and precipitation were the primary controlling factors, while sunshine duration and wind speed also exerted notable influences. Significant regional differences existed in the climate factors affecting ET changes.

**Keywords:** evapotranspiration; spatiotemporal variation; influencing factors; northeastern Qinghai-Xizang Plateau; Qinghai Province

# 1 Data and Methods

## 1.1 Study Area Overview

Qinghai Province is located in the northeastern part of the Qinghai-Xizang Plateau, forming an important component of the plateau. The terrain is high in the west and low in the east, with numerous mountain ranges including the Kunlun Mountains running through the central region, the Tanggula Mountains in the south, and the Qilian Mountains spanning Qinghai and Gansu Province in the north. Between these mountains are interspersed plateaus, basins, and valleys. The region is characterized by 纵横交错的河流 and widespread distribution of lakes and marshes, serving as the source area for the Yellow River, Yangtze River, and Lancang River. The climate is a typical plateau continental climate with low precipitation concentrated in specific periods, large diurnal temperature variations, low annual average temperatures, long cold winters, and short cool summers.

The average annual precipitation is low with significant spatial variation, increasing from northwest to southeast. The Qaidam Basin in the northwest receives less than 50 mm of annual precipitation, while the alpine meadow steppe ecological zone in the southeast can receive up to 500 mm. Land cover types mainly include grassland, water bodies, ice/snow, bare land, forest, and cropland (Figure 1). Based on functional and geographic characteristics of ecosystems, Qinghai Province is divided into 5 primary ecological zones and 11 secondary ecological zones (Figure 1). The primary zones include: Altun Mountain ecological zone (I), Qaidam Basin ecological zone (II), Qilian Mountains ecological zone (III), Northern Qiangtang alpine desert steppe ecological zone (IV), and River Source ecological zone (V).

## 1.2 Data and Processing

**MOD16 ET Data:** The MOD16 ET data were downloaded from https://ladsweb.modaps.eosdis.nasa.gov/ with a spatial resolution of 500 m and an 8-day temporal resolution. Using ENVI 5.3 remote sensing image processing software, we performed projection conversion and image mosaicking on the original MOD16 ET data, and clipped the study area based on Qinghai Province boundary data from http://ngcc.sbsm.gov.cn/. Since MOD16 data lack ET data for deserts, Gobi areas, bare rock, and water bodies, lakes, water areas, deserts, Gobi areas, and bare rock regions within Qinghai Province were excluded from calculations.

**Meteorological Data:** Meteorological data were obtained from the China Meteorological Science Data Center (http://cdc.nmic.cn/), including annual total precipitation, annual average temperature, sunshine duration, and average wind speed data from 18 national meteorological stations in the study area from 2001 to 2020. MODIS DEM data were obtained from the Geospatial Data Cloud Platform (http://www.gscloud.cn/) with a resolution of 500 m. Using ArcGIS 10.5, we first analyzed the regression relationships between annual precipitation, temperature, sunshine duration, wind speed and elevation, latitude, and longitude, then performed spatial interpolation to obtain spatial distribution data of these meteorological factors at 500 m resolution consistent with the MOD16 ET data for analyzing ET influencing factors.

**Land Cover Data:** The land cover dataset (storage and sharing platform) was obtained from an open research dataset (https://doi.org/10.5281/zenodo.4417810), including farmland, forest, shrubland, grassland, water bodies, ice/snow, bare land, impervious surfaces, and wetlands. Qinghai Province ecological zoning data were obtained from the China Terrestrial Ecosystem Database (http://www.ecosystem.csdb.cn/).

**Eddy Covariance Dataset:** The eddy covariance dataset was obtained from the National Tibetan Plateau Science Data Center (https://data.tpdc.ac.cn/), including observation data from 2 eddy covariance stations. The Aru station (100°27 51 E, 38°02 50 N, 3033 m) has subalpine meadow underlying surface with data from 2008-2020. The temperate grassland station (100°14 05 E, 37°14 50 N, 3210 m) has temperate grassland underlying surface with data from 2016-2020. First, the mean diurnal variation method was used to gap-fill missing eddy covariance data. The 30-minute interval actual ET data were processed into 8-day intervals starting from January 1, 2001, consistent with MOD16 ET data.

### 1.3 Methods

**1.3.1 Interannual Trend Analysis** The linear regression model can reflect variable trends over a time period to some extent. Based on the linear regression model at the pixel scale, we analyzed the interannual variation trend of actual ET in Qinghai Province. The trend slope ($\delta$) was calculated as:

$$\delta = \frac{n \times \sum_{i=1}^{n}(i \times ET_i) - \sum_{i=1}^{n} i \sum_{i=1}^{n} ET_i}{n \times \sum_{i=1}^{n} i^2 - (\sum_{i=1}^{n} i)^2}$$

where $ET_i$ is the actual ET in year $i$ ($\mathrm{mm \cdot a^{-1}}$); $n$ is the study period length.

The interannual trend reflects the degree of ET change over time: when $\delta > 0$, ET is increasing; when $\delta < 0$, ET is decreasing.

**1.3.2 Correlation Analysis with Climate Factors** To quantitatively analyze the correlation between actual ET and annual precipitation, temperature, sunshine duration, and wind speed in Qinghai Province, we analyzed the relationships at the pixel scale using:

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}}$$

where $x_i$ is the actual ET in year $i$ ($\mathrm{mm \cdot a^{-1}}$); $y_i$ is the annual precipitation (mm), annual average temperature (°C), sunshine duration (h), or average wind speed ($\mathrm{m \cdot s^{-1}}$); $\bar{x}$ and $\bar{y}$ are the multi-year averages; $r_{xy}$ is the correlation coefficient. When $r_{xy} > 0$, ET increases with the climate factor; when $r_{xy} < 0$, ET decreases with the climate factor.

### 1.4 MOD16 ET Data Validation

To verify the reliability of MOD16 ET data, we compared them with ground observation data from eddy covariance stations in Qinghai Province. The coefficient of determination ($R^2$) between MOD16 ET data and ground observations at the two stations were 0.65 and 0.71, respectively, with root mean square errors (RMSE) of 3.3 $\mathrm{mm \cdot (8d)^{-1}}$ and 5.4 $\mathrm{mm \cdot (8d)^{-1}}$. These results indicate that MOD16 ET data have good applicability in the northeastern Qinghai-Xizang Plateau region.

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## 2 Results and Analysis

### 2.1 Spatiotemporal Variation Characteristics of Actual Evapotranspiration

**2.1.1 Interannual Variation Characteristics** The interannual variation and relative change rate of actual ET in Qinghai Province from 2001 to 2020 are shown in Figure 3. Annual average ET fluctuated between 219-286 $\mathrm{mm \cdot a^{-1}}$, with a multi-year average of 260 $\mathrm{mm \cdot a^{-1}}$. Overall, ET showed a fluctuating increasing trend with gradually lengthening fluctuation periods, which can be divided into three stages: (1) 2001-2012: ET increased from 2001 to 2008, peaked in 2008, then decreased to a trough in 2012, with an average of 246.32 $\mathrm{mm \cdot a^{-1}}$; (2) 2012-2017: ET increased steadily from 2012, peaked in 2017, then decreased again, with an average of 256.33 $\mathrm{mm \cdot a^{-1}}$; (3) 2017-2020: ET increased steadily from 2017 to 2020, with an average of 264.11 $\mathrm{mm \cdot a^{-1}}$.

Based on the interannual change rate, the study area was divided into seven categories: significant decrease (< -5%), moderate decrease (-5% to -2.7%), slight decrease (-2.7% to -0.5%), basically unchanged (-0.5% to 0.5%), slight increase (0.5% to 2.7%), moderate increase (2.7% to 5%), and significant increase (> 5%). These categories accounted for 0.25%, 1.70%, 14.55%, 13.81%, 31.39%, 13.34%, and 24.95% of the total area, respectively. Areas with increasing ET accounted for 69.69% of the total area, with significant and moderate increases concentrated in the Qilian Mountains ecological zone and eastern river source ecological zone. Decreasing areas accounted for 16.51% of the total area, with slight decreases mainly in the Yangtze River source region.

**2.1.2 Seasonal Variation Characteristics** Seasonal variation of actual ET in Qinghai Province was significant (Figure 5). Spring (March-May) average ET was 61.22 $mm \cdot a^{-1}$, with high values in the Yellow River source and southeastern Yangtze River source regions. As temperatures rose and precipitation increased, vegetation growth led to higher ET than in winter. Summer (June-August) had the highest average ET at 102.53 $mm \cdot a^{-1}$, with temperature, precipitation, and solar radiation all reaching annual peaks and vegetation thriving. Autumn (September-November) average ET was 57.81 $mm \cdot a^{-1}$, slightly lower than spring as temperatures and precipitation decreased and vegetation senesced. Winter (December-February) had the lowest ET at 38.48 $mm \cdot a^{-1}$ due to low temperatures and precipitation. The seasonal ranking was: summer (102.53 mm) > spring (61.22 mm) > autumn (57.81 mm) > winter (38.48 mm).

**2.1.3 Spatial Distribution Characteristics** The spatial distribution of multi-year average actual ET in Qinghai Province from 2001 to 2020 showed a clear pattern of low values in the northwest and high values in the southeast (Figure 6). Significant regional differences existed among ecological zones (Table 1). The Altun Mountain ecological zone (I) had relatively low ET at 91.56 $mm \cdot a^{-1}$ due to dry climate, high temperatures, and sparse vegetation. The Qaidam Basin ecological zone (II) had the lowest ET at 64.75 $mm \cdot a^{-1}$ due to harsh climate, low precipitation, sparse vegetation, and severe grassland degradation. The Qilian Mountains ecological zone (III) had relatively high ET at 326.58 $mm \cdot a^{-1}$, being a national nature reserve with extensive grassland and forest, adequate precipitation, and suitable temperatures. The Northern Qiangtang alpine desert steppe ecological zone (IV) had moderate ET at 227.95 $mm \cdot a^{-1}$ due to poor water-heat conditions and low vegetation coverage. The River Source ecological zone (V) had the highest ET at 388.82 $mm \cdot a^{-1}$, with high vegetation coverage, abundant precipitation, and meltwater from alpine snow and ice promoting strong transpiration.

**2.1.4 Actual Evapotranspiration Characteristics of Different Vegetation Types** Affected by natural conditions and human activities, different vegetation cover types showed distinct ET characteristics. Grassland, the dominant vegetation type covering 66.22% of Qinghai Province, had an average ET of 363.61 $mm \cdot a^{-1}$. Forest land, covering only 0.61% of the area, had high ET at 421.70 $mm \cdot a^{-1}$. Shrubland, covering 0.17%, had the highest ET at 427.13 $mm \cdot a^{-1}$. Cropland, covering 0.84%, had an average ET of 323.75 $mm \cdot a^{-1}$. The ranking of ET by vegetation type was: shrubland (427.13 $mm \cdot a^{-1}$) > forest (421.70 $mm \cdot a^{-1}$) > grassland (363.61 $mm \cdot a^{-1}$) > cropland (323.75 $mm \cdot a^{-1}$).

### 2.2 Relationship Between Actual Evapotranspiration and Climate Factors

**2.2.1 Interannual Variation Characteristics with Temperature and Precipitation** The fluctuating changes in actual ET were basically consistent with variations in annual average temperature (Figure 7). The increase in ET largely corresponded to the increasing trend of precipitation, though the peak lagged behind precipitation changes. ET changes were constrained by temperature variations and influenced by precipitation. In the eastern Yangtze River source region, Yellow River source region, and Lancang River source region with relatively high precipitation and low temperatures, ET was mainly controlled by temperature and also affected by sunshine duration and wind speed. In the Yangtze River source region with relatively low precipitation and temperature, ET was controlled by both temperature and precipitation. In the Gonghe Basin and Haidong-Gannan region with low precipitation and high temperatures, ET was mainly controlled by precipitation while also affected by sunshine duration and wind speed. In the eastern Qaidam Basin desert region with low precipitation and high temperatures, ET was primarily controlled by precipitation.

**2.2.2 Correlation Between Actual Evapotranspiration and Climate Factors** The spatial correlations between actual ET and climate factors are shown in Figure 8. Areas with positive correlations between ET and annual average temperature accounted for 73% of the study area, with high correlation zones in the Yellow River source, Yangtze River source, and Lancang River source regions. Areas with positive correlations with annual precipitation accounted for 56% of the area, with significant positive correlations ($P < 0.05$) in 18% of the area, mainly concentrated in the Qilian Mountains, Gonghe Basin, Haidong-Gannan region, and northwestern Yangtze River source region. Areas with positive correlations with sunshine duration accounted for 43% of the area, with significant positive correlations in 13% of the area, mainly in the Yangtze River source region. Areas with positive correlations with average wind speed accounted for 44% of the area, with significant positive correlations in 14% of the area, mainly in the river source ecological zone.

Comprehensive analysis shows that actual ET in Qinghai Province is primarily controlled by temperature and precipitation, while also influenced by sunshine duration and wind speed. The influencing factors showed significant regional differences.

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## 3 Conclusions

(1) The average annual actual evapotranspiration in Qinghai Province from 2001 to 2020 was 260 $\mathrm{mm \cdot a^{-1}}$, showing a fluctuating increasing trend with lengthening fluctuation periods and an average change rate of 2%. Areas with increasing ET accounted for 69.69% of the total area, with significant increases concentrated in the Qilian Mountains and eastern river source ecological zone. Decreasing areas accounted for 16.51%, mainly with slight decreases in the Yangtze River source region. Overall, ET enhancement occurred in the Qilian Mountains and eastern river source ecological zone.

(2) Actual ET showed significant seasonal variation, with the highest in summer and lowest in winter, and similar values in spring and autumn. Spatially, ET distribution was low in the northwest and high in the southeast, with large differences among ecological zones. The ranking of average ET by ecological zone was: River Source zone (388.82 $\mathrm{mm \cdot a^{-1}}$) > Qilian Mountains zone (326.58 $\mathrm{mm \cdot a^{-1}}$) > Northern Qiangtang zone (227.95 $\mathrm{mm \cdot a^{-1}}$) > Altun Mountains zone (91.56 $\mathrm{mm \cdot a^{-1}}$) > Qaidam Basin zone (64.75 $\mathrm{mm \cdot a^{-1}}$). By vegetation type, the ranking was: shrubland > forest > grassland > cropland.

(3) The fluctuating changes in actual ET were basically consistent with temperature variations. ET increase corresponded to precipitation increase, with peaks lagging behind precipitation changes. Areas positively correlated with temperature, precipitation, sunshine duration, and wind speed accounted for 73%, 56%, 43%, and 44% of the study area, respectively.

(4) Temperature and precipitation were the primary controlling factors of ET, with significant regional differences in influencing factors. In high-precipitation, low-temperature regions, ET was mainly controlled by temperature and also affected by sunshine and wind. In low-precipitation, low-temperature regions, ET was controlled by both temperature and precipitation. In low-precipitation, high-temperature regions, ET was mainly controlled by precipitation while also affected by sunshine and wind.

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