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Research Article

Spatial-Temporal Patterns and Controls of Evapotranspiration across the Tibetan Plateau (2000–2012)

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Evapotranspiration (ET) is a key factor to further our understanding of climate change processes, especially on the Tibetan Plateau, which is sensitive to global change. Herein, the spatial patterns of ET are examined, and the effects of environmental factors on ET at different scales are explored from the years 2000 to 2012. The results indicated that a steady trend in ET was detected over the past decade. Meanwhile, the spatial distribution shows an increase of ET from the northwest to the southeast, and the rate of change in ET is lower in the middle part of the Tibetan Plateau. Besides, the positive effect of radiation on ET existed mainly in the southwest. Based on the environment gradient transects, the ET had positive correlations with temperature ($R > 0.85$, $p < 0.0001$), precipitation ($R > 0.89$, $p < 0.0001$), and NDVI ($R > 0.75$, $p < 0.0001$), but a negative correlation between ET and radiation ($R = 0.76$, $p < 0.0001$) was observed. We also found that the relationships between environmental factors and ET differed in the different grassland ecosystems, which indicated that vegetation type is one factor that can affect ET. Generally, the results indicate that ET can serve as a valuable ecological indicator.

1. Introduction

With a variable global climate, evapotranspiration, which has not escaped our concern, is seen as the crux to comprehending soil-vegetation-atmosphere interactions [1]. The word evapotranspiration is composed of evaporation and transpiration. The former is the process by which water from the Earth's surface waters changes from liquid to vapour and goes into the atmosphere, and the latter refers to the process by which the water in plants passes through the stomata and spreads to the exterior [2]. Evaporation is a component not only of the surface heat balance but also of the hydrological cycle [3]; it has the functions of regulating temperature, increasing humidity, and affecting the ecological environment, and it thus affects the sustainable development of society and economy [4]. Approximately 60% to 65% of the Earth's precipitation reenters the atmosphere via evaporation [5, 6]. Moreover, a close relationship between evapotranspiration and meteorological variables (temperature, precipitation, radiation, and wind speed and humidity) has been reported [7–9]. Therefore, the variation in evapotranspiration is a vital indicator for the drivers of climate change [10, 11], and it can serve as a valuable tool in investigations of ecological environment change and the impacts that human activities have on it.

Many methods and significant comparative analyses for evaluating evapotranspiration have been carried out at the global scale for many years [12–17]. The most common way is to use remote sensing data to calculate the evapotranspiration by employing the surface energy balance with parameters such as meteorological data [18], which has been used in China, including in the northwest of Yunnan province [19]. Long-term estimation methods of evapotranspiration mainly involve water balance [20–22], combination, and complementary methods [23, 24], and measurement methods mainly involve sap flow, lysimeter, and eddy covariance methods, which underestimate the measurement [25]. Analyses of the spatial distribution of global ET have shown an overall increasing trend from high-altitude or high-latitude cold areas to low-latitude regions such as tropical rain forest, which show high year-round ET values with lower seasonal variability than the temperate or subarctic climes [26, 27]. Evapotranspiration has increased, which is attributed to increases in precipitation (in Poyang Lake watershed) [28], incident solar radiation (in China or tropical ecosystems) [29], wind speed, and sunshine duration (in arid region of China) [30]. The effect of temperature on evapotranspiration has also been discussed in Australia [31], India [32], Iran [33], and North China [34]. The evaporation paradox explains that pan evaporation has decreased despite the increase in annual temperature, but it does not exist in northeast and southwest China [11, 35].

The mean annual temperature in the Tibetan Plateau has had significant changes with a remarkable warming trend since the 1980s [36, 37]. The temperature in the region has risen at an average of 0.05°C per year from 1981 to 2010, and a warming trend of 0.02°C per year was observed in the 30 years before 2000 [38]. The daytime temperature is greater than 10°C in the growing season from June to September [39, 40]. Glaciers melt, ice lakes increase, and glacial debris flows become active under global warming [41]. There are special climatic conditions and natural environments in the Tibetan Plateau that are sensitive to global change [42]. The Tibetan Plateau contains the headwaters of the Yangtze River, Yellow River, and other rivers, which are the main rivers of China; hence, the alpine ecosystem here has significant functions [43].

Consequently, the comprehensive study of changes of actual evapotranspiration (ET) and the relationships between ET and environmental factors is important for the Tibetan Plateau. Recently, a paper using a modified model to estimate ET with a more accurate temporal and spatial distribution has been published; the better quality is attributed to local validating parameters and different input driving variables [44]. The aim of this paper is to examine the spatial-temporal patterns of ET, with an emphasis on the relationships between ET and environmental factors such as temperature, precipitation, solar radiation, and NDVI at different scales. Further, the above issues are discussed in different ecosystems, such as alpine meadows, alpine steppes, desert steppes, and forests, across the Tibetan Plateau (with the exception of barren land in the north) from 2000 to 2012.

2. Materials and Methods

2.1. Study Area. Our study area, between 73°19′–104°47′E and 26°00′–39°47N, which covers an area of 2.5 million km^2, is the highest plateau in the world, and it has been called the *roof of the world* and the *third pole of the Earth* [45, 46]. The Tibetan Plateau, located in southwest China, features several climate types. It not only has the characteristics of the hot and rainy equatorial region and the north with a cold and dry climate but also has a number of microclimates and the plateau alpine zone with its obvious vertical distribution of climate [47, 48]. The unique atmospheric conditions, topography (such as high elevation), and weather systems result in all sorts of chaos and strange plateau climate zones that are fragile and vulnerable to the effects of global climate change [42, 48]. Alpine steppes and alpine meadows cover most of the study area, with forests occurring mainly in the south and southeast of the plateau and large tracts of bare land such as desert steppes occurring in the northwest (Figure 1).

2.2. Data Compilation. The remote sensing data used in this paper are from the moderate resolution imaging spectroradiometer (MODIS) imagery provided by the United States National Aeronautics and Space Administration (NASA). The MOD16 global ET product provides vital information for water resource management by calculating the regional water and energy balance. The NDVI data are retrieved from atmosphere-corrected and bidirectional surface reflectance. From the two highest NDVI values for the demand of cloud-free images or better photographing quality images, it selects the closest-to-nadir pixel. All of the MODIS data can be downloaded for free at the NASA website (https://modis.gsfc.nasa.gov).

Temperature, precipitation, and radiation data were downloaded from the China Meteorological Administration; they were collected from 127 meteorological observatories around and within the research region from 2000 to 2012 (China Meteorological Data Sharing Service System, available online: http://data.cma.cn/). To acquire detailed temperature, precipitation, and radiation factors for each sampling site and pixel, we resampled the interpolated data in ArcGIS (v. 10.2), in which the meteorological data were interpolated at 5 km × 5 km resolution via the kriging method.

2.3. Data Analysis. The mean annual temperature, precipitation, and radiation were calculated using meteorological data from 2000 to 2012. We obtained precipitation values between 19.54 and 1676 mm, temperature values between −3.58°C and 15.86°C, and radiation values between 4539 and 7235 MJ m^{-2} from the spatial distribution across the Tibetan Plateau. Using cross-validation, we compared the observed and predicted values (from meteorological station and kriging process, resp.) for temperature (R^2 = 0.98), radiation (R^2 = 0.73), and precipitation (R^2 = 0.92) and found similar spatial distributions and approximate numerical ranges as those obtained in another report in the study area [49].

We obtained the annual and monthly ET distributions over the last 10 years using a raster calculator in ArcGIS. Because the quality of the MOD16 global ET product is not particularly high, we made a comparative analysis of our result with those from other studies. The spatial change rate of ET and the spatial correlation between ET and four environmental factors—temperature, precipitation, radiation, and NDVI—were also obtained with a raster calculator by using least squares [50].

$$\beta = \frac{n\sum xy - \sum x \sum y}{n\sum x^2 - (x)^2}$$

$$r = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n\sum_{i=1}^{n} x_i^2 - \left(\sum_{i=1}^{n} x_i\right)^2} - \sqrt{n\sum_{i=1}^{n} y_i^2 - \left(\sum_{i=1}^{n} y_i\right)^2}}. \quad (1)$$

Factor n is the number of years during the study and x and y are the year and ET, respectively, in the first formula.

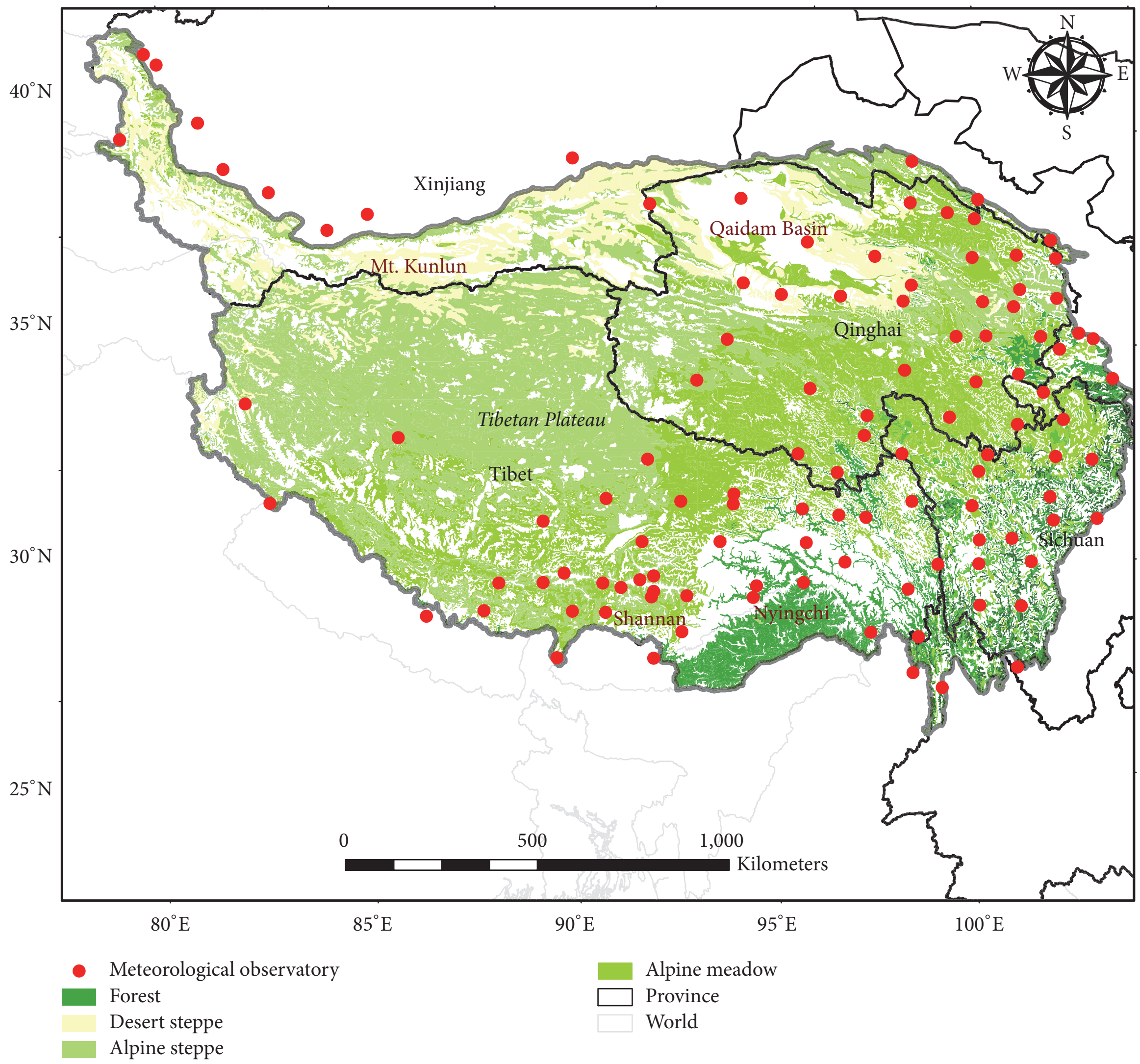

Figure 1: The study area across Tibetan Plateau. The ecosystems contained alpine meadow, alpine steppe, desert steppe, and forest.

In the latter, n is the same, x_i is the environmental factor (temperature, precipitation, radiation, and NDVI), and y_i is the ET.

3. Results

3.1. Spatial-Temporal Patterns of ET across the Tibetan Plateau. The mean value of ET gradually increased to the maximum at approximately 60 mm in July and then decreased throughout the year (Figure 2(a)), and the minimum ET of approximately 30 occurred in January or December. The annual value had a stationary trend (the average rate of change was $-2.8\,\mathrm{mm\,yr^{-1}}$), fluctuating between 450 and 500 mm from 2000 to 2012, except in 2006 and 2007, which had an obvious decline to the minimum value, 427 mm (Figure 2(b)).

The comparison of ET dynamics in different ecosystems indicated that the ET values in the forest had the least interannual variability (the average rate of change rate was $-0.45\,\mathrm{mm\,yr^{-1}}$) and highly outperformed the others (Figure 2). The ET values showed a similar tendency to fluctuate in the different ecosystems, particularly in alpine meadow and all ecosystems. Moreover, ET in alpine steppe and desert steppe was the least susceptible to seasonal effects, which fluctuated between $20\,\mathrm{mm\,mon^{-1}}$ and $30\,\mathrm{mm\,mon^{-1}}$. Based on the value of ET, the fact was discovered expressly that the ecosystems could be divided into the following three groups, ordered from high to low ET values: forest (approximately $660\,\mathrm{mm\,yr^{-1}}$), alpine meadow and all ecosystems (between $450\,\mathrm{mm\,yr^{-1}}$ and $550\,\mathrm{mm\,yr^{-1}}$), and alpine steppe and desert steppe (between $250\,\mathrm{mm\,yr^{-1}}$ and $350\,\mathrm{mm\,yr^{-1}}$).

The spatial distribution of ET over the Tibetan Plateau shows an increase from the northwest to the southeast in Figure 3(a). The highest ET regions were in the south of Shannan Prefecture and Nyingchi in Tibet, with ET values ranging from $888\,\mathrm{mm\,yr^{-1}}$ to $1340\,\mathrm{mm\,yr^{-1}}$. The lowest ET regions were in the western part of the Tibetan Plateau and

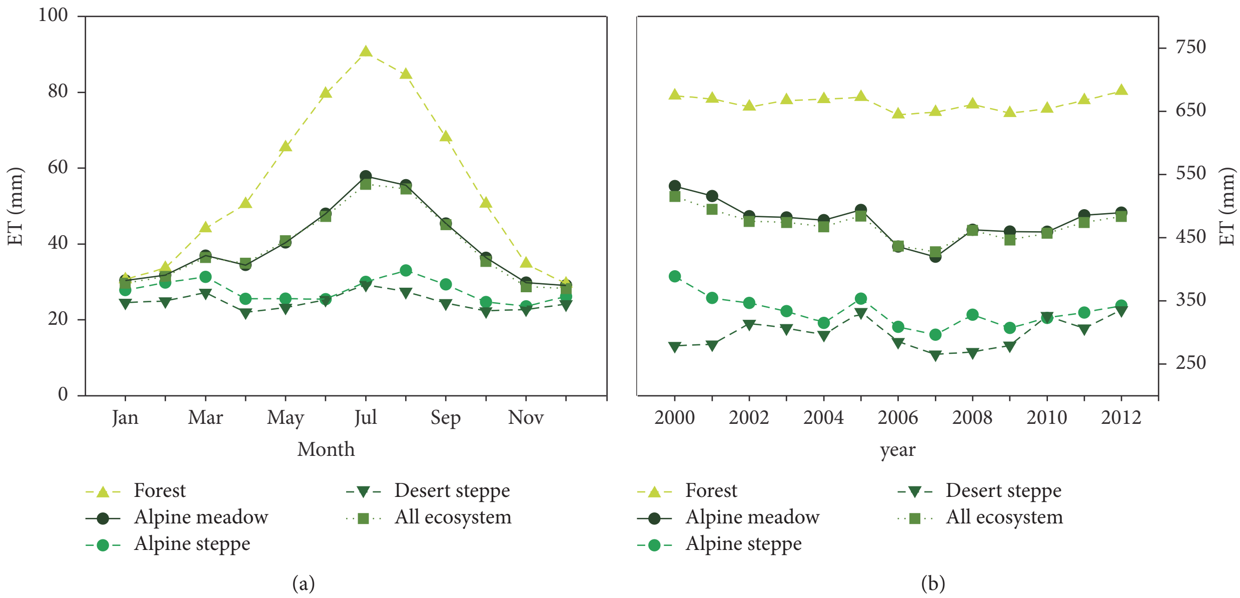

Figure 2: Temporal patterns of ET across the Tibetan Plateau. Graphs (a) and (b) represent variation ET of months January–December and years 2000–2012, respectively.

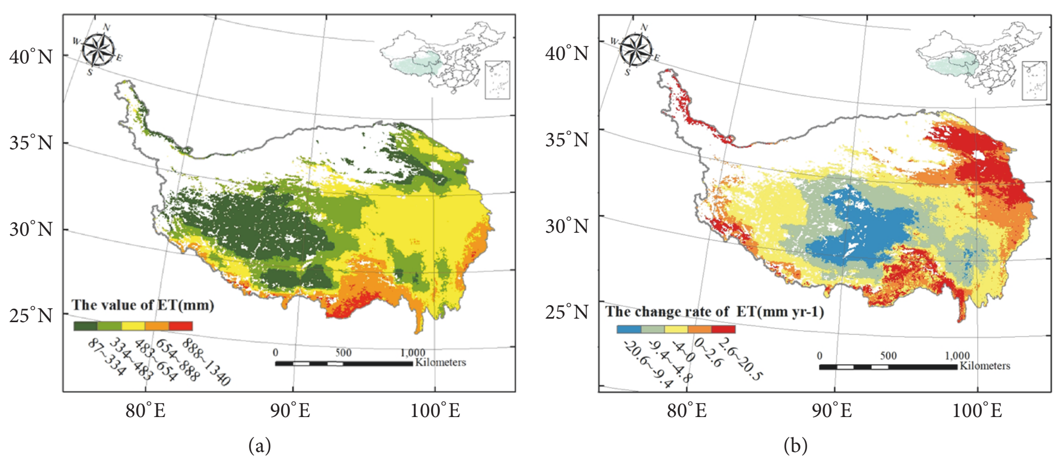

Figure 3: Spatial patterns and dynamics of ET across the Tibetan Plateau. Graphs (a) and (b) represent distribution and variation of ET, respectively.

northern Tibet, with ET values ranging from 87.4 mm yr^{-1} to 334.2 mm yr^{-1}. The change rate of ET was positive in the edge areas, except north and southeast of the Tibetan Plateau, forming an almost ring-like distribution (Figure 3(b)). In addition, the most important negative change region emerged in the middle part of the Tibetan Plateau, which included almost all of Tibet and had a value lower than −94 mm per 10 years.

The spatial pattern of ET and ecosystems was consistent in the Tibetan Plateau; where there was forest or desert steppe, there was a higher or lower ET, respectively, which is fairly similar to the change rate of ET. However, unlike the distribution of ET value, the change rate of ET in alpine steppe and alpine meadow was complex and had a widespread area that included all rate classifications.

3.2. Variations of ET with Environmental Factors across the Tibetan Plateau. The spatial correlation and significance between ET and four environmental factors (temperature, precipitation, radiation, and NDVI) were calculated and are shown in Figures 4 and 5. Compared with several other environmental factors, the area in which there was a positive correlation between precipitation and ET was the largest, followed by NDVI, radiation, and temperature. The strong positive correlation between ET and precipitation emerged mainly in the east and southwest parts of the Tibetan Plateau, where most of the area is dominated by the positive correlations (Figure 4(b)). The significant correlations were also distributed in this region (Figure 5(b)). There were no obvious spatial distribution characteristics in the positive correlations between ET and NDVI, although a few areas

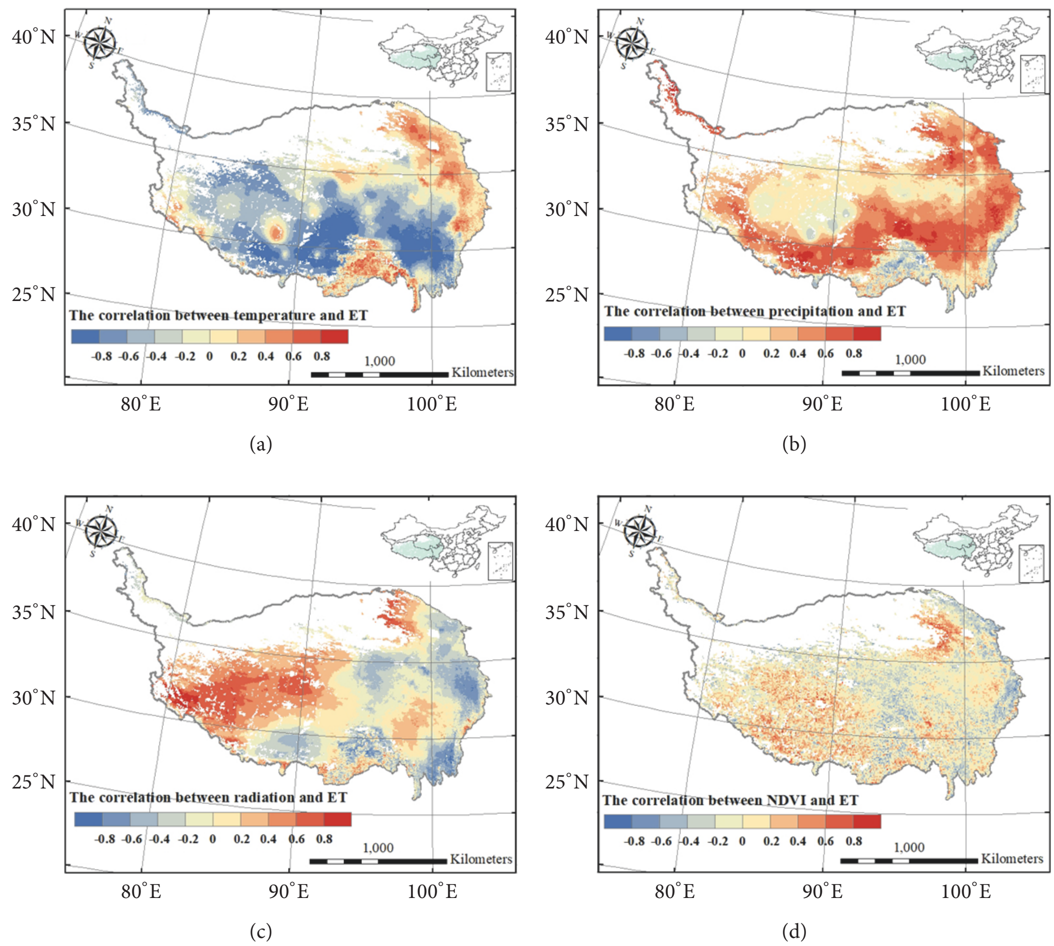

Figure 4: Responses of ET to variation of four environmental factors across the Tibetan Plateau. Graphs (a), (b), (c), and (d) represent the variation with temperature, precipitation, radiation, and NDVI, respectively.

of significant correlations were spread throughout the study area (Figures 4(d) and 5(d)). The areas of the positive correlations between ET and radiation were distributed in the southwest Tibetan Plateau, negative correlations were distributed in the east and south of the area (Figure 4(c)), and significant correlations were distributed in the west of Tibet and, secondarily, southeast of Tibetan Plateau (Figure 5(c)). The areas with significant correlations of ET with temperature were larger than those with precipitation, radiation, and NDVI, and the area that had a negative correlation was distributed in Tibet and western Sichuan (Figures 4(a) and 5(a)).

Figure 6 shows the proportion of significant to nonsignificant correlations in the grassland ecosystems. There were fewer regions with significant correlations. The percentage of significant changes of ET with temperature (negative significant) and precipitation (positive significant) was higher than those with radiation and NDVI. In these cases, with four environmental factors, only the correlation of ET with temperature in alpine steppes was approximately 40% (positive significant and negative significant together accounting for 36 percent).

3.3. Variations of ET with Typical Environmental Gradients. To examine the responses of ET to the changing environmental conditions, gradient transects of temperature, precipitation, radiation, and NDVI were constructed (Figure 7). There were two gradients (gradients a and b) in each environmental condition, except the last one, which contained a random selection of sites of NDVI.

The ET had consistent linear correlations with temperature and precipitation in both gradients a and b (Figures 8(a)(A), 8(a)(B), 8(b)(A), and 8(b)(B)). There were positive linear correlations between temperature and ET with $R = 0.88$, $p < 0.0001$, in gradient a and $R = 0.85$, $p < 0.0001$, in gradient b and between precipitation and ET in the two precipitation gradients ($R = 0.89$, $p < 0.0001$, and $R = 0.94$, $p < 0.0001$, resp.). Nevertheless, the linear correlations between ET and radiation differed from temperature and precipitation; it had opposing linear relationships in the two radiation gradients ($R = 0.95$, $p < 0.0001$; $R = 0.76$, $p < 0.0001$) (Figures 8(c)(A) and 8(c)(B)). In addition, a positive linear correlation existed between NDVI and ET ($R = 0.75$, $p < 0.0001$) in the randomly selected sites of NDVI (Figure 9).

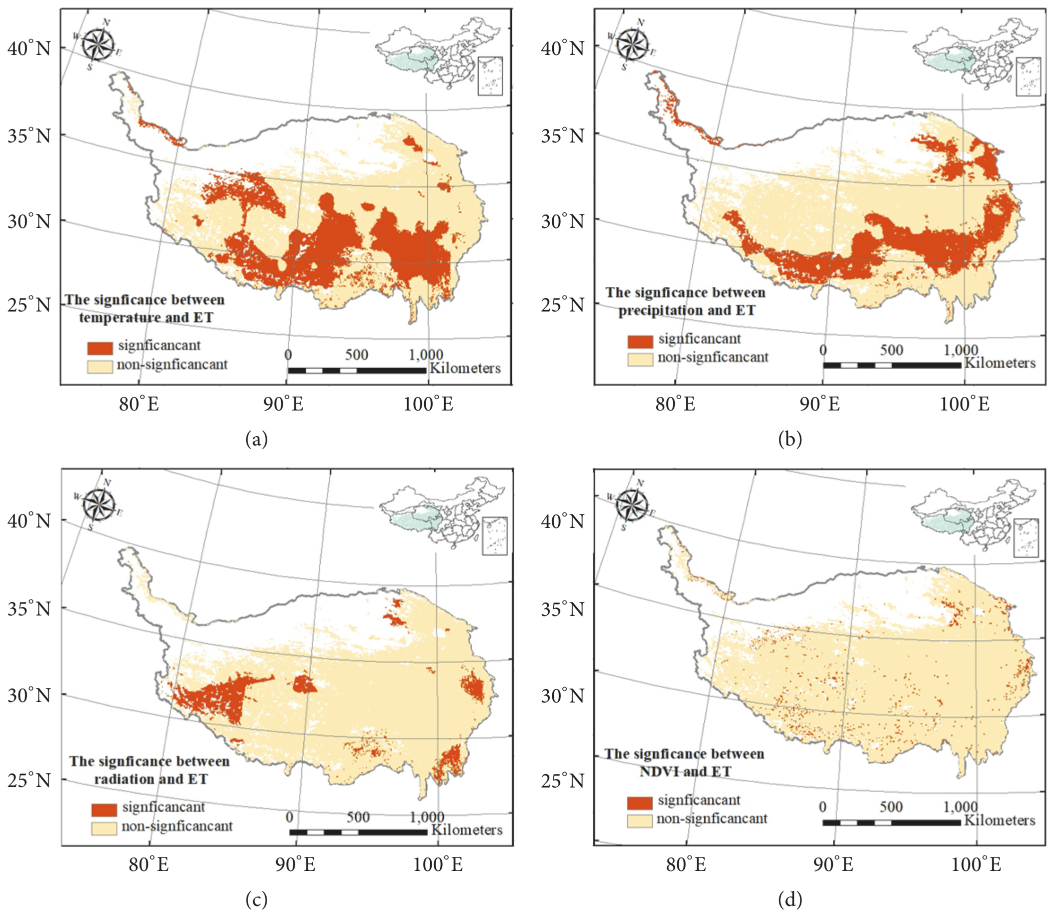

FIGURE 5: The significant changes of ET with four environmental factors across the Tibetan Plateau. Graphs (a), (b), (c), and (d) represent the variations with temperature, precipitation, radiation, and NDVI, respectively.

4. Discussion

4.1. Dynamics of ET. The spatial distribution of ET over Tibetan Plateau in our study shows a decrease from the southeast to the northwest. These results are consistent with those obtained using the Lund-Potsdam-Jena Dynamic Global Vegetation Model [43]. Much previous research has demonstrated a positive correlation between temperature and ET in study areas such as the Guanzhong region of Shanxi [51], northeast China [52], and the Songhua River basin [53]. However, the most important factor in the change of ET is precipitation [43] in the Tibetan Plateau and northwest Yunnan [19], which is in agreement with our study both in temporal distribution and in spatial distribution (Figures 2 and 4(b)). The ET value is highest in the summer, when the precipitation is also largest [54]. Moreover, our study discovered that the value was nearly constant, fluctuating between 450 and 500 mm from 2000 to 2012, with the exception of the obvious decline in 2006. Similarly, the precipitation was reduced in 2006 [55]. The growth trend of ET in the spatial distribution from northwest to southeast is almost similar to that of precipitation. Comparisons of ET in different ecosystems indicated that the ET value in the forest was much higher than that in other areas. Forests occur mainly in western Sichuan, the southern mountain regions of Tibet, and deep ravine areas, that is, in regions where the larger values of ET are distributed [37]. After forest, the values in alpine meadow are higher than those in alpine steppe, which in turn are higher than those in desert steppe, which mainly occurs in the Qaidam Basin and on Mt. Kunlun.

As the climate changes, we are seeing a decline of ET in many parts of the world, except in China and southern India [16]. The change of ET was positive in the edge area, except at the northern and southeastern edge of the Tibetan Plateau. ET increased in this region, partly due to the increase in precipitation [50, 56–58]. However, ET decreased in the middle part of the Tibetan Plateau, including almost all of Tibet. Alpine meadow occurs almost entirely here as well. The temperatures in the area are lower than those in other grassland ecosystems because of the high altitude, which is probably one of the factors that limit ET. The distribution (Figure 4(a)) of spatial correlation between ET and temperatures indicates that increase in temperatures was correlated to decrease in ET, but the sunshine duration, humidity, and wind speed all showed decreasing trends from 1981 to 2010 which was one of the reasons [43]. The cause of

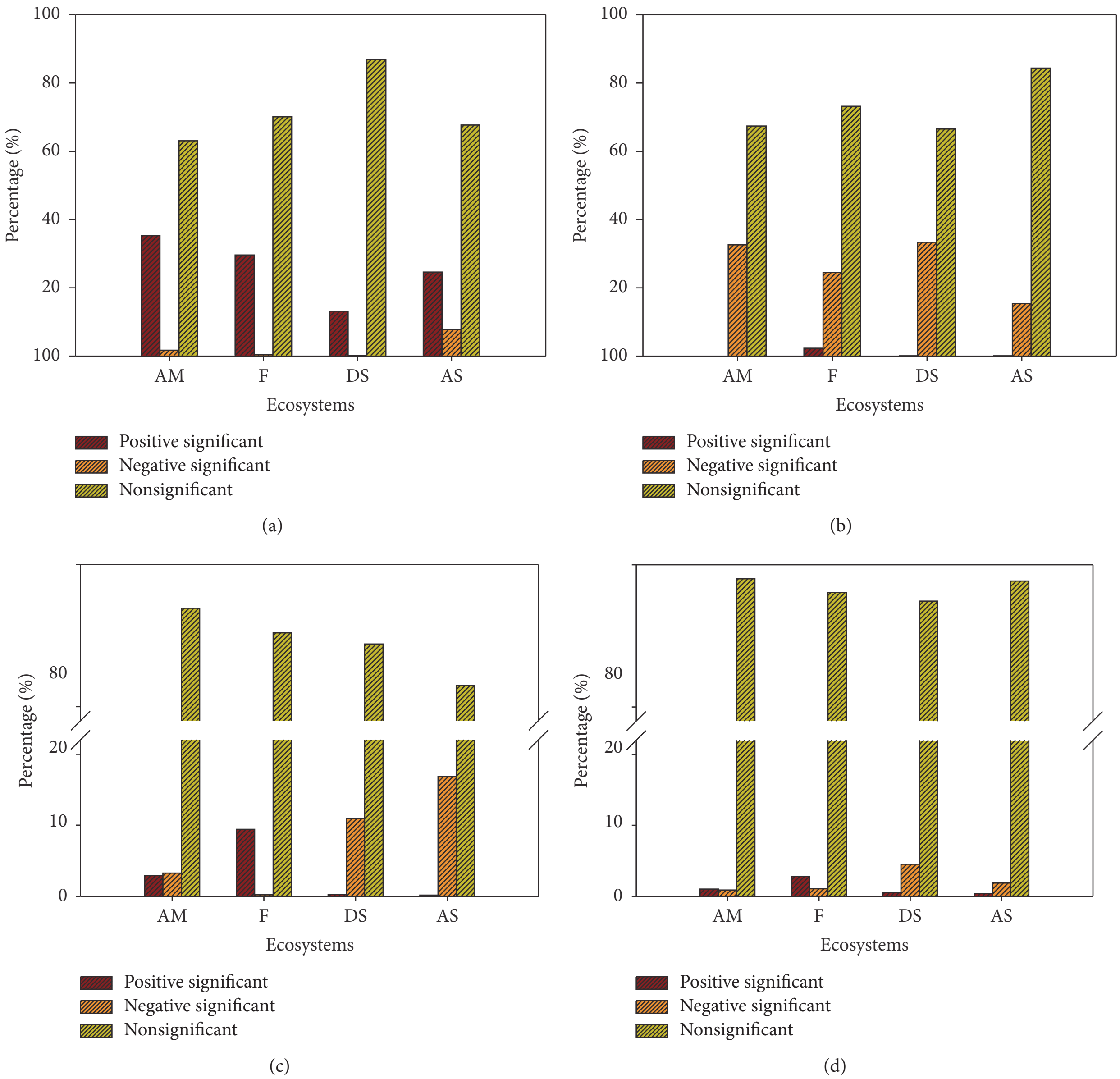

Figure 6: The percentage of significant changes of ET with four environmental factors across the Tibetan Plateau. Graphs (a), (b), (c), and (d) represent the variation with temperature, precipitation, radiation, and NDVI, respectively. Furthermore, alpine meadow, forest, desert steppe, and alpine steppe are represented by AM, F, DS, and AS, respectively.

the reduction in ET also may be human activities, which have been found to alter surface water conditions [59]. In addition, some transformations of alpine grassland in northern Tibet are borne from anthropogenic factors such as migratory grazing activities, roads, and residential distribution [60].

4.2. The Effect of Climate Factors on ET. In general, as the climate varies, ET is likely to be impacted; it is particularly hypersensitive to short-period meteorological conditions [61–64]. Three climate factors were researched in our paper.

The effect of precipitation on ET has been described previously [28]. Precipitation was compared with several other environmental factors; the area of positive correlation was largest across the Tibetan Plateau, where most of the area was dominated by the correlations. Studies also have found that there are an increase in precipitation over the 85% region, where ET increased simultaneously, and a decrease over the 70% region, where ET reduced in the Tibetan Plateau [43]. The reason why higher precipitation may yield greater ET is that more precipitation could augment the water available for ET [17, 65].

ET is correlated with temperature, whether on the Great Plains [15], the Gulf Coast [14], or the Tibetan Plateau [66]. A positive linear correlation of ET and temperature existed in gradients a and b (Figures 8(a)(A) and 8(a)(B)), and the increasing trend in ET exhibited complementary behaviour to reference evapotranspiration due to an increase in the air temperature [67]. The only area of negative correlation in

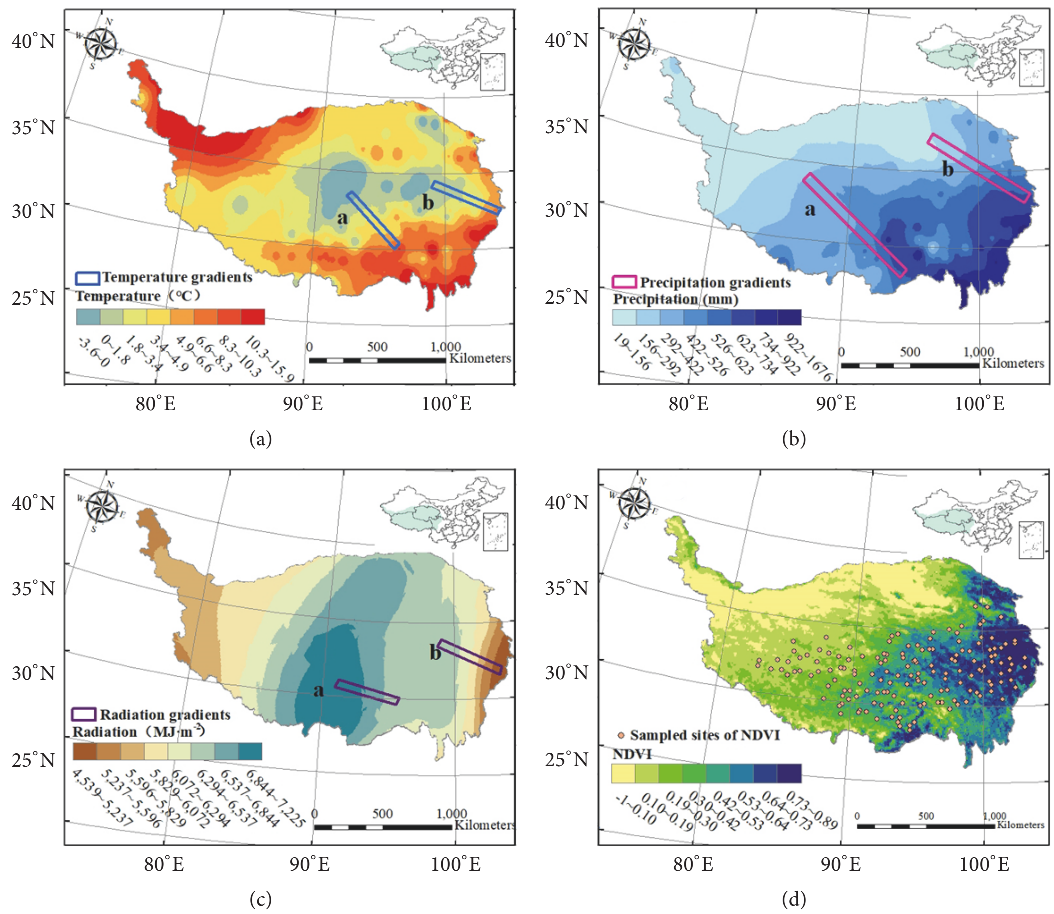

Figure 7: The typical environment gradients of four environmental factors across the Tibetan Plateau. Graphs (a), (b), (c), and (d) represent the gradients of temperature, precipitation, radiation, and NDVI, respectively.

the study area was distributed in Tibet and western Sichuan (Figure 4(a)), where alpine meadow is distributed. The reduction in ET was the result of decreasing the atmospheric water demand, and soil available water is the main factor limiting ET during the growing season in arid and semiarid lands [68]. With the temperature rising constantly, the Tibetan Plateau may suffer a shrinkage in water resources over the coming decades [69, 70]. Temperature may not appear to have a significant impact on evapotranspiration when the temperature is sufficiently low [33]. The temperature in the area is less than that in other grassland ecosystems because of the high altitude; this is one of the factors that limit evapotranspiration [32]. With the temperature rising, the expected acceleration of the water circulation caused by an increase in ET and precipitation may not be consistent with the decrease in ET, according to multiple studies [44, 71]. As the climate becomes warmer and drier, water supply will be the main driving factor. Multiple factors can lead to a negative correlation, for example, the decrease in relative humidity or the significant decrease in wind speed and net solar radiation despite the rise in annual temperature. A negative correlation of temperature and ET was also found in the Haihe River Basin [59].

Furthermore, the area with positive correlations between ET and net solar radiation was distributed in the southwest Tibetan Plateau (Figure 4(c)). In these areas, the hydrological cycle and surface climate may be profoundly affected by radiation variation, which is the main energy source on the surface of the Earth [9, 29]. Although negative correlations were distributed in the east and south of the area, linear relationships with opposite signs emerged in the two radiation gradients selected in our study (Figures 8(c)(A) and 8(c)(B)). One possible cause of a low ET is the small amount of energy used in ET, even in high radiation conditions, particularly in alpine meadow [25].

4.3. The Effect of Vegetation Characteristics on ET. The largest values of ET were observed in forest, followed by alpine meadow, alpine steppe, and, finally, desert steppe. Therefore, it is not surprising that the decreased ET from northwest to southeast was coincident with the direction of the ecosystem transitions. Many studies have confirmed this phenomenon and demonstrated the significant impact and correlation between ET and vegetation types, finding that climate factors contributed much of the variability in the observed ET [14, 72]. A positive linear correlation existed between NDVI and

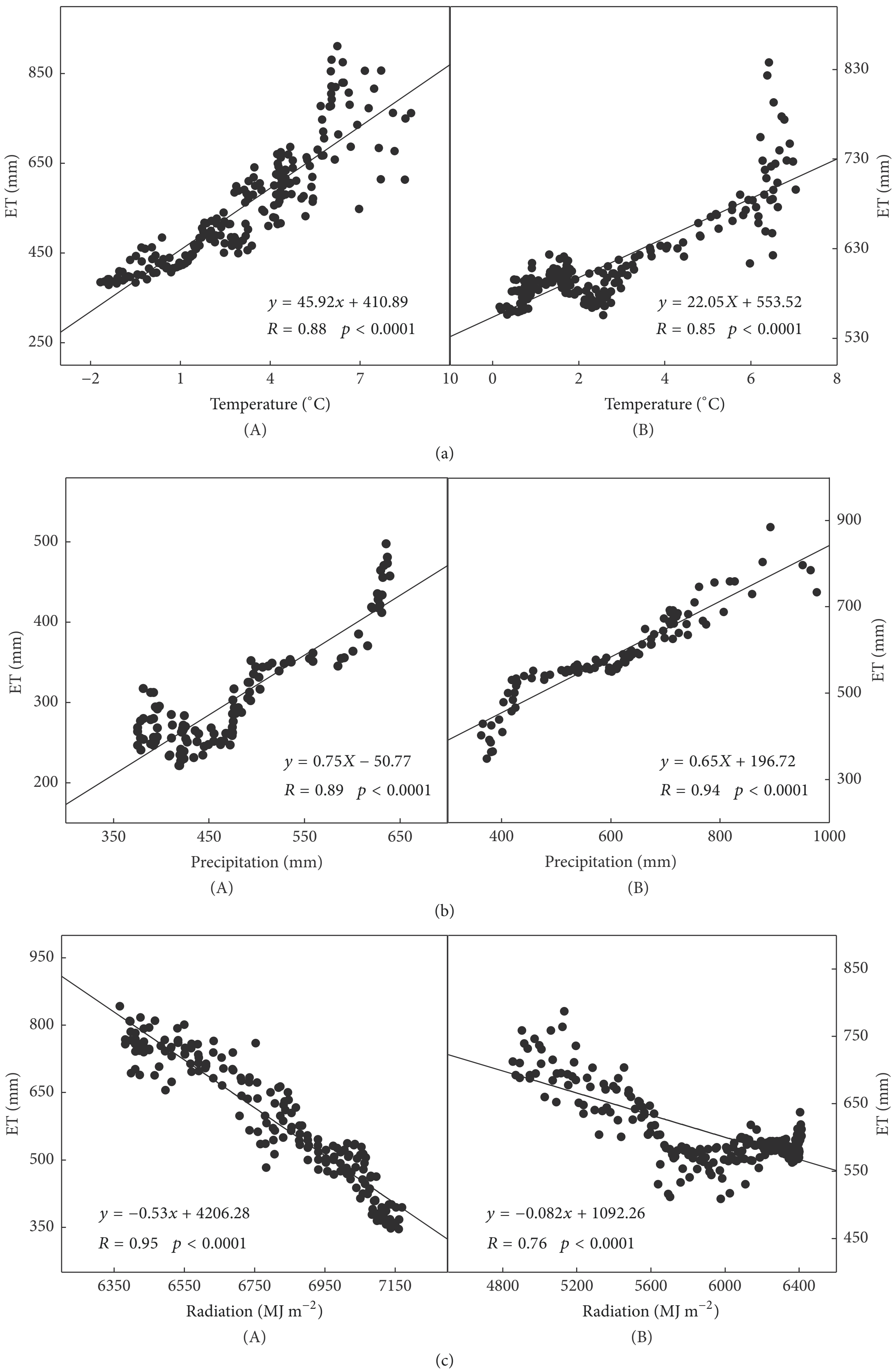

Figure 8: Relationship of three environmental factors with ET. Graphs (a)(A) and (a)(B) represent the relationship between ET with temperature in temperature gradients a and b; graphs (b)(A) and (b)(B) with precipitation in precipitation gradients a and b; and graphs (c)(A) and (c)(B) with radiation in radiation gradients a and b, respectively.

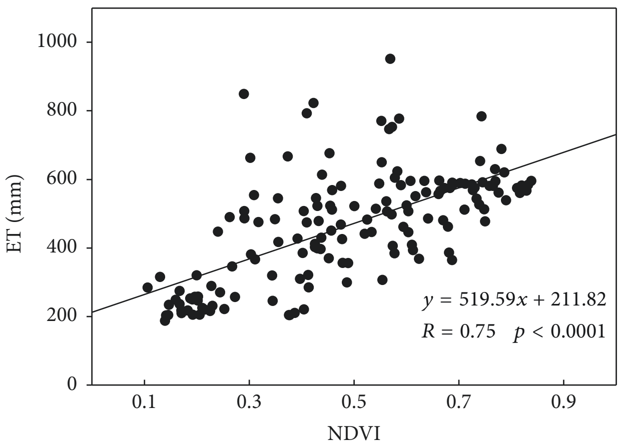

Figure 9: Relationship of NDVI with ET.

ET ($R = 0.75$, $p < 0.0001$) in the randomly selected sites of NDVI (Figure 9).

The aforementioned negative correlation between ET and radiation mostly occurred in alpine meadow. We noted a lower efficiency in the annual radiation budget of alpine meadow compared with the lowland grasslands, which can receive even higher incident radiation [73, 74]. The lower efficiency observed on this plateau is attributed to the much higher net longwave radiation compared with lowland grasslands or the global surface [75]. The subtle connection between biomass and ET is authenticated: the more biomass there is, the more precipitation is used efficiently [76]. In addition, the peak biomass in this alpine meadow lagged approximately 30 days behind the maximum ET [25].

Among all ecosystems, the ET value in a forest is the largest and steadiest. The reason why this kind of situation will appear in a forest is that forests can maintain a good amount of ET, even under a dry weather regime [77]. This may be due to the transpiration of trees, which can maintain ET by using deep roots to absorb underground water, and the grass forces transpiration to rely primarily on the occurrence of precipitation or the presence of top soil water [78]. This explains the small area of negative correlation relationship between ET and precipitation distributed in the southeast Tibetan Plateau, which is covered by forest (Figure 4(b)).

5. Conclusions

Using data from MODIS and meteorological stations in the Tibetan Plateau from 2000 to 2012, spatial-temporal patterns of ET were analysed with least squares regression. In addition, the effects of environmental factors on ET across transect scales and regional scales were explored. A steady trend in ET was detected over the past decade, and the largest value of ET occurred in June of each year. The growth trend of ET in the spatial distribution from northwest to southeast was similar to that of precipitation. The rate of ET increase was higher in the edge area, except at the northern and southeastern edge of the Tibetan Plateau, which was affected by low temperature. In addition, positive linear relationships existed between ET and meteorological variables (temperature, NDVI, and precipitation), with the most obvious effect on ET coming from precipitation. However, the opposite relationship emerged in the two radiation gradients. This apparent disaccord between different grassland ecosystems indicated that vegetation also has a strong influence on ET.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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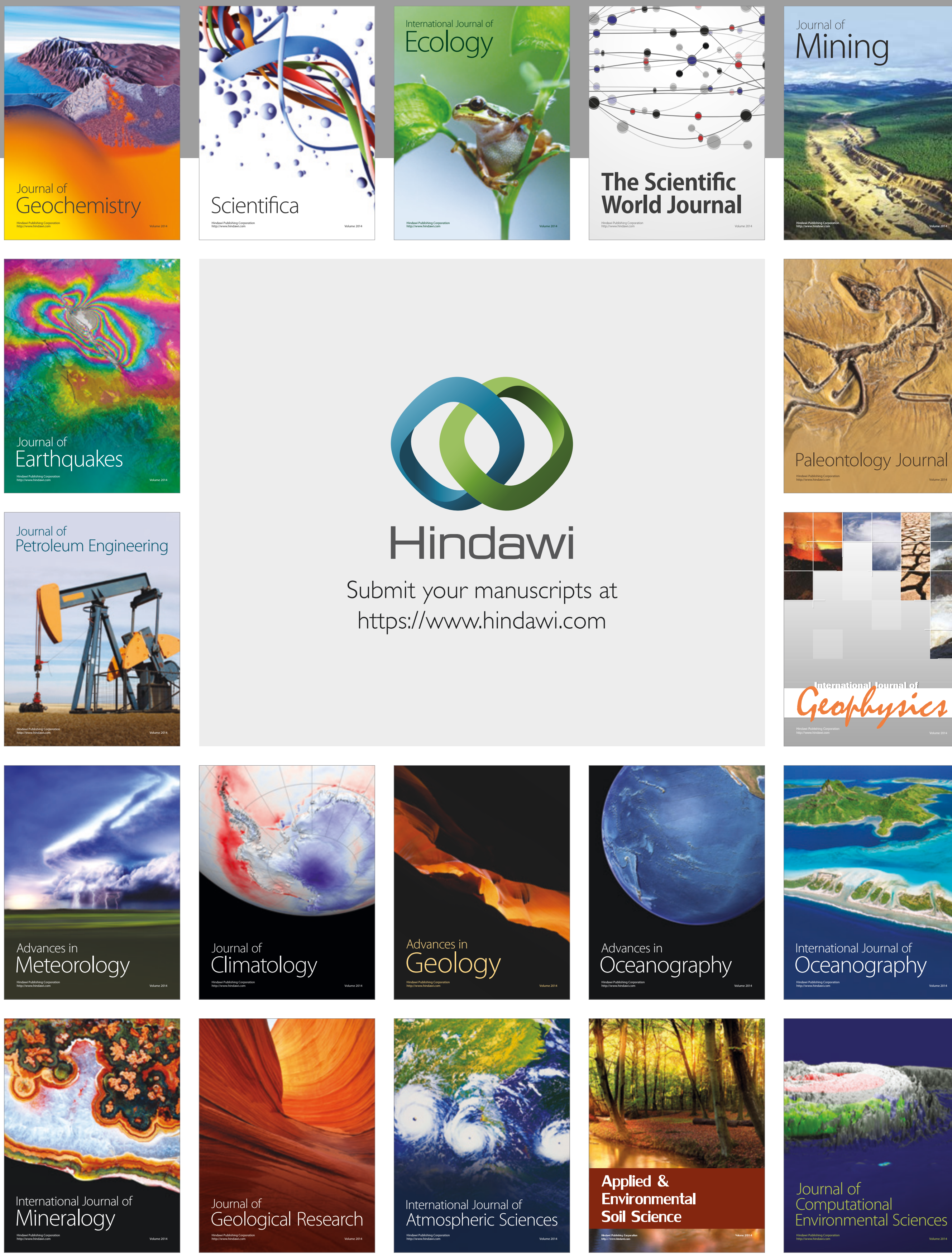
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