

Postprint: Geographical Environment and Its Changes over the Past 30 Years in the Southern Margin of the Tibetan Plateau

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Abstract

The southern margin of the Tibetan Plateau is located in the transitional zone between the Tibetan Plateau and the South Asian subcontinent, serving as the convergence area of the westerlies and the South Asian monsoon, and is highly sensitive to climate and environmental changes. This study comprehensively employs satellite remote sensing and ground-based observations to analyze the natural and human geographical environment conditions and their changes in the southern margin of the Tibetan Plateau since the 1980s, including land use/cover, vegetation, precipitation, temperature, population, and nighttime lights. The results show that forest is the dominant land use/cover type in the southern margin of the Tibetan Plateau (48.62%); vegetation is mainly distributed in the southern foothills of the Himalayas and the eastern region, with vegetation conditions in the east being significantly better than those in the central and western regions; regional precipitation is concentrated during the South Asian summer monsoon period from June to September each year, exhibiting a pattern of higher precipitation in the south than in the north, and in the east than in the west; temperature is lower in the north and higher in the south, with substantial spatial variation; except for the southern margin, the overall population density is low, and the nighttime light coverage rate was only about 10% in 2013. Over the past 30 years, the regional environment of the southern margin of the Tibetan Plateau has undergone significant changes. In terms of the natural environment, regional temperature has increased significantly, with faster warming in high-altitude areas and at night; precipitation in the central and eastern regions has decreased significantly, while precipitation in some western areas has increased; driven by changes in temperature and precipitation, the maximum leaf area index (LAI) of vegetation in the central and western regions has generally increased, while it has slightly decreased in the eastern region. In terms of the human environment, human activities in the central and southern

parts of the region have intensified in recent years, with an increase in settlements within the region and increased population density in India and Nepal in the central and southern parts; the area covered by nighttime lights expanded 2.5 times from 1992 to 2013, with over 85% of the expansion occurring within India.

Full Text

Study on the Status and Changes of the Geographical Environment in the Southern Margin of the Tibetan Plateau since the 1980s

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Abstract

The southern margin of the Tibetan Plateau is located in the transitional zone between the plateau and the South Asian subcontinent, representing a convergence region of the westerlies and the South Asian summer monsoon that is highly sensitive to climate and environmental changes. This study comprehensively utilizes satellite remote sensing and ground-based observations to analyze the natural and human geographical environment conditions—including land use/cover, vegetation, precipitation, temperature, population, and nighttime lights—and their changes in the southern margin of the Tibetan Plateau since the 1980s. The results show that forests dominate the land cover (48.62%). Vegetation is mainly distributed along the southern foothills of the Himalayas and in the eastern part of the region, with significantly better conditions in the east than in the central-west. Precipitation concentrates during the South Asian summer monsoon period from June to September, showing a pattern of higher amounts in the south than north and in the east than west. Temperature decreases from south to north with substantial spatial variation. Except for the southern edge, overall population density is low, with nighttime light coverage at only about 10% in 2013. Over the past 30 years, the regional environment has undergone significant changes. In terms of the natural environment, regional temperature has risen markedly, with more rapid warming at high altitudes and during nighttime. Precipitation has decreased significantly in the central and eastern parts while increasing in some western areas. Under the influence of temperature and precipitation changes, the maximum leaf area index (LAI) has generally increased in the central-western region but slightly decreased in the east. Regarding the human environment, human activities have intensified in the central-southern part of the region in recent years, with increasing residential areas and rising population density in India and Nepal. From 1992 to 2013, the area covered by nighttime lights expanded by 2.5 times, with over 85% of this expansion occurring in India.

Keywords: Tibetan Plateau, southern margin, climate, land surface conditions, human activity, changes

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Introduction

The Tibetan Plateau is the world's highest mega-scale tectonic landform unit, known as the "Third Pole," characterized by unique natural and human environments. Its dramatic uplift has altered atmospheric circulation patterns across Asia, 促成了地球上最强大的亚洲季风系统, 并对北半球的环流产生重要影响 [1,2]. The plateau's special underlying surface and atmospheric processes make it a globally sensitive region for climate and environmental change. Under the influence of climate change and human activities, the plateau's cryosphere—including glaciers, permafrost, and snow cover—has undergone dramatic changes[3-6], while ecosystem structure and function as well as population numbers and structure of key species have also experienced profound transformations[7], exerting substantial impacts on regional water cycles and ecological conditions and presenting new challenges for socioeconomic development and disaster prevention[8,9].

The southern margin of the Tibetan Plateau extends along the southern foothills of the Himalayas, forming a transitional zone between the South Asian subcontinent and the Tibetan Plateau where the westerlies, South Asian monsoon, and East Asian monsoon converge. This region features extremely complex topography, climate, and ecological environments, with elevation dropping rapidly from over 4,500 meters in the Himalayas to approximately 200 meters in the plains, and climate ranging from alpine cold conditions to tropical monsoon climates. Land cover exhibits significant vertical zonation, including forests, croplands, grasslands, and snow/ice. Investigating the geographical environment and hu-

man conditions and their changes in the southern margin of the Tibetan Plateau contributes to understanding the response and adaptation of the plateau and adjacent regions to climate change, particularly variations in the westerlies and Asian monsoon systems.

Data and Methods

This study integrates ground-based observations and satellite remote sensing techniques to analyze natural and human conditions—including land use/cover, vegetation, temperature, precipitation, population, and nighttime lights—in the southern margin of the Tibetan Plateau over the past 30 years, characterizing the region' s geographical environment status and changes.

(1) Land Use/Cover Data. We used Landsat satellite observations and Google Earth high-resolution imagery, combined with the global 30-meter land cover classification product GlobeLand 30, to analyze land cover and land use conditions in the region. Landsat data employed clear-sky observations from TM and ETM+ sensors around 1990 and 2015, with a resolution of 30 meters. GlobeLand 30 is a global 30-meter resolution land cover dataset derived from Landsat and environmental satellite imagery using the POK (Pixel-Object-Knowledge) classification method that integrates pixel-based, object-oriented, and expert knowledge approaches, achieving an overall classification accuracy of over 80%[10]. This study utilized the 2010 classification results.

(2) Vegetation Leaf Area Index Data. The GLOBMAP leaf area index (LAI) product was employed to analyze regional vegetation conditions and changes. This product provides globally consistent LAI data since 1981, generated from AVHRR and MODIS data[11], with a spatial resolution of 8 kilometers and temporal resolutions of 15 days for 1981-1999 and 8 days for 2000-2016. The product first applies an improved GLOBCARBON LAI algorithm to retrieve LAI from MODIS data, then establishes an AVHRR SR-MODIS LAI relationship for each pixel using overlapping observations from both sensors, enabling retrospective retrieval from historical AVHRR data. GLOBMAP resolves inconsistencies in retrieval results caused by differences between the two sensors.

(3) Climate Data. We analyzed precipitation and temperature conditions and their changes using TRMM satellite daily precipitation product 3B42Daily, MODIS land surface temperature product MOD11A2, and meteorological station observations in the study region. The TRMM daily precipitation product provides daily precipitation at 0.25-degree spatial resolution from 1989 to 2016[12]. MODIS land surface temperature product MOD11A2 provides daytime and nighttime land surface temperatures during satellite overpasses every 8 days at 1-km spatial resolution from 2000 to 2016[13]. Ground observations included daily precipitation and daily maximum, minimum, and mean temperature data from 1980 to 2016 obtained from five stations in the China Meteorological Administration' s Surface Climate Data Daily Dataset (V3.0) and

five stations from NOAA NCDC in India and Nepal. The five Chinese stations (Pulan 556960, Nielaer 557730, Cuona 556900, Longzi 556550, and Pali 554370) are located on the northern side of the study region at elevations above 3,500 meters, while the Nepal and India stations (DEHRADUN 421110, LILABARI 423090, DIBRUGARH 423140, TEZPUR 424150, and TRIBHUVAN 444540) are located on the southern side at elevations below 1,500 meters.

(4) Population Data. We used the Gridded Population of the World, Version 4 (GPWv4) from the Center for International Earth Science Information Network (CIESIN) at Columbia University to characterize regional population density distribution[14]. This dataset combines census data with population distribution models to generate globally continuous population distribution at approximately 1-km spatial resolution at the equator, updated every five years from 2000 to 2020. This study used data from 2005 and 2015.

(5) Nighttime Light Data. DMSP-OLS nighttime light data (Version 4) were used to describe the expansion of human activities in the region. The data include three products: number of cloud-free observations, average visible band digital number values, and stable light images. This study used the stable light product, which has undergone cloud removal and elimination of background noise and transient light sources (volcanic gas, forest fires, aurora, etc.)[15]. Pixel values range from 0 to 63, with data available annually from 1992 to 2013 at 1-km spatial resolution.

This study employed geographic information system (GIS) spatial analysis, change detection, and linear trend analysis methods to investigate the distribution and temporal changes of natural and human geographical elements in the region. Specific methods are as follows:

(1) Land Use/Cover. Using 2010 GlobeLand30 data, we obtained 30-meter land use/cover classification maps for the study region and analyzed the spatial distribution characteristics of different cover types by country. For typical change areas in southern Tibet, we used Landsat TM/ETM+ imagery and Google Earth high-resolution images with manual visual interpretation to obtain distributions of residential areas and airports in 1990 and 2015 and analyze their changes.

(2) Vegetation Conditions. Using 1981-2016 GLOBMAP LAI data, we obtained maximum LAI distribution maps for each year (excluding 1981 due to incomplete data). Linear fitting was performed on the 35-year maximum LAI time series from 1982-2016 to analyze vegetation status and growth trends at each pixel.

(3) Climate Elements. Using TRMM data from 1998-2016, we calculated mean annual precipitation and performed linear fitting on annual precipitation to analyze interannual changes. Using MODIS land surface temperature data from 2000-2016, we calculated annual mean daytime and nighttime surface temperatures and mean diurnal temperature range, performing linear fitting on annual results to analyze surface temperature changes. Additionally, based on

daily meteorological station observations since 1980, we calculated annual and monthly precipitation, annual mean temperature, annual maximum and minimum temperatures, and monthly mean, maximum, and minimum temperatures to analyze interannual changes in precipitation and temperature. In station analyses, we separately analyzed elevations above 3,500 meters and below 1,500 meters. Due to numerous missing observations at Nepal and India stations, particularly before 1995, which severely affected reliability of interannual analysis, we retained only the DEHRADUN 421110 station for temporal analysis.

(4) Human Activities. We analyzed population changes by comparing population density distribution maps from 2005 and 2015. Using DMSP-OLS nighttime light data from 1992–2013, we applied linear trend fitting to obtain slope values of light digital numbers, representing patterns of artificial construction changes. Positive slopes indicate brightening nighttime lights and expanding artificial construction, while negative slopes indicate dimming lights and shrinking construction.

Results

3.1.1 Terrain

The southern margin of the Tibetan Plateau is a high mountain-plain transition zone with high elevation in the north and low in the south, featuring dramatic elevation differences. [Figure 1: see original paper] shows the digital elevation model (DEM) distribution. From north to south, the northern region comprises the towering Himalayas, mostly above 4,000 meters, including Mount Everest—the world’s highest peak—on the China-Nepal border in the central region. The southern region is the South Asian subcontinent with flat terrain, mostly below 200 meters elevation. Within a north-south width of less than 200 kilometers, elevation drops by more than 4,000 meters and even over 6,000 meters, with numerous peaks exceeding 5,000 and 7,000 meters in the north, creating deep valleys and steep slopes with extremely complex topography. From west to east, the western and central regions are dominated by the transverse Himalayas, while the eastern region lies at the Himalayan terminus where the Yarlung Zangbo Grand Canyon is located, with relatively lower elevations mostly below 4,000 meters.

3.1.2 Land Use/Cover

[Figure 2: see original paper] illustrates land use/cover distribution in the study region, while presents the area and proportion of each land use/cover type for the entire region and by country. Forests dominate land use/cover in the southern margin of the Tibetan Plateau, with a total forest area of 211,800 km², accounting for 48.62% of the total land area, followed by cropland (82,400 km², 18.92%) and grassland (75,600 km², 17.35%). Bare land and permanent snow/ice also occupy substantial areas of 37,500 km² (8.62%) and 24,100 km² (5.52%), respectively. Residential land covers only 2,000 km², representing just 0.46% of the

total area.

The study region encompasses four countries: India, Nepal, Bhutan, and China. In western India and Nepal, forests and croplands dominate, together accounting for 62.79% and 71.58% of each country's area within the study region, respectively. In contrast, eastern Bhutan and China are dominated by forests and grasslands, which combined represent 93.19% and 89.51% of each country's area, respectively.

Examining distribution by country, India has 42,300 km² of forest and 24,300 km² of cropland within the study region, representing 39.89% and 22.90% of its area, respectively. Grassland and bare land areas are also substantial at 16,600 km² and 13,200 km², accounting for 15.62% and 12.42%, respectively. Residential area totals 458 km² (0.43%), the highest proportion among the four countries. Nepal contains 65,400 km² of forest and 37,000 km² of cropland, representing 45.71% and 25.87% of its area, respectively, plus 23,600 km² of grassland (16.5%). Nepal's residential area proportion ranks second after India at 382 km² (0.27%).

Bhutan is dominated by forest distribution, with 28,300 km² of forest covering 76.14% of its area in the region—far exceeding other cover types. Grassland is the second major type at 6,300 km² (17.05%). Bhutan has the smallest residential area proportion at only 0.01%.

In southern Tibet (the easternmost part of the study region) [Figure 2: see original paper], forest distribution is absolutely dominant, covering 57,200 km² or 70.81% of the area, far exceeding other land cover types. Grassland is the second major type at 15,200 km² (18.78%). Since China's southern Tibet region was illegally occupied by India, continuous immigration has gradually increased the population. [Figure 3: see original paper] shows residential area and airport distributions in 1990 and 2015. Residential areas are mainly distributed along river valleys, increasing from approximately 70.63 km² in 1990 to 133.42 km² in 2015, representing 0.16% of southern Tibet's total area—far exceeding the residential proportion in Bhutan. Additionally, nine airports have been constructed in this region, with the northernmost airport located 180 km from Mainling County and 71 km and 56 km from Medog County seat in Tibet.

3.1.3 Vegetation

[Figure 4: see original paper]a and b show maximum leaf area index (LAI) distributions for 1982 and 2016, respectively. Vegetation conditions in the eastern region are significantly better than in the central-western region. Comparing the two maps reveals that although central-western vegetation conditions are poorer than in the east, they show improvement trends in 2016 compared to 1982.

[Figure 4: see original paper]c presents the linear trend of annual maximum LAI from 1982-2016. Overall, vegetation growth conditions in the study region have

improved annually. Specifically, some eastern areas show slopes of zero or negative values, indicating little change or some decrease in vegetation conditions during the 35-year study period, likely related to regional precipitation reduction (see Section 3.2.1). In contrast, all central-western regions show positive slopes, indicating continuous vegetation growth in recent years, possibly related to temperature increases favorable for vegetation growth (see Section 3.2.2).

3.2.1 Precipitation

The southern margin of the Tibetan Plateau is located at the convergence zone of the westerlies, South Asian monsoon, and East Asian monsoon, with the western part mainly influenced by the westerlies and the central-eastern part dominated by the South Asian summer monsoon. [Figure 5: see original paper]a shows the TRMM mean annual precipitation distribution from 1998-2016, revealing a pattern of higher precipitation in the south than north and in the east than west. The towering Himalayas intercept abundant moisture from the Indian Ocean brought by the South Asian summer monsoon, forming heavy rainfall centers in the central and eastern regions where TRMM annual precipitation exceeds 2,000 mm in the 88°E-97°E zone. The western region, under dual influence of the westerlies and South Asian monsoon, also receives over 1,000 mm annually. The southern windward slope intercepts abundant Indian Ocean moisture, with annual precipitation mostly above 1,500 mm, while the northern side, mostly above 3,000 meters, receives less than 800 mm.

Unlike the overall Tibetan Plateau, the study region shows a significant precipitation decreasing trend [Figure 5: see original paper]b. TRMM data fitting for 1989-2016 reveals significant annual precipitation reduction in the central and eastern parts of the study region. Meteorological station observations [Figure 6: see original paper]c also support this finding, showing mean annual precipitation decreasing at a rate of 5.95 mm per decade, likely related to recent weakening of the South Asian summer monsoon[16]. In some western local areas, however, TRMM annual precipitation shows an increasing trend, and precipitation observations at India's DEHRADUN station (30.317°N, 78.033°E) since 1993 have increased at a rate of 267.02 mm per decade, possibly related to westerly enhancement.

Seasonally, precipitation concentrates from June to September, particularly peaking in July-August under South Asian summer monsoon influence. Areas below 1,500 meters in the south average 200-250 mm in July-August, while areas above 3,500 meters in the north still receive 60-80 mm. The western part of the southern margin can also receive westerly precipitation in winter, as evidenced by a small precipitation peak from January to April at Nielaer and Pulan stations in the western part of the region.

3.2.2 Temperature

Due to dramatic elevation differences, temperature decreases from south to north with substantial spatial variation [Figure 7: see original paper]. For stations above 3,500 meters in the northern part of the southern margin, summer (June–August) mean temperature is around 10°C, while areas below 1,500 meters in the south have summer monthly mean temperatures above 25°C [Figure 8: see original paper]. Summer maximum temperature is around 20°C in the north and nearly 40°C in the south. Annual minimum temperature can be below -25°C in the north but mostly above 0°C in the south.

Affected by global warming, regional temperature shows a significant increasing trend [Figure 9: see original paper], confirmed by observational results [Figure 8: see original paper]c and d. Since 1980, stations above 3,500 meters have shown mean annual temperature increasing at 0.35°C per decade, with annual maximum and minimum temperatures rising at 0.03°C and 0.64°C per decade, respectively. Stations below 1,500 meters show mean annual temperature and maximum temperature increasing at 0.22°C and 0.23°C per decade, respectively, while minimum temperature has decreased at 0.41°C per decade. Higher elevation areas show more significant warming, consistent with other studies finding topographic amplification of global warming. Since 2000, both daytime and nighttime surface temperatures have increased, with nighttime warming faster than daytime. The region has a large diurnal temperature range, greater in the north than south, with mean diurnal ranges of 10–15°C, maximum ranges exceeding 20°C, and even over 30°C in northern high-altitude areas, showing a decreasing trend in mean diurnal temperature range.

3.3.1 Population

Except for the southern edge plain area, the study region has low overall population density [Figure 10: see original paper]. The northern high mountain area has the lowest density, generally below 100 people/km². Central mountain areas have densities of 100–200 people/km², with several population clusters (>300 people/km²) appearing in central Nepal. The southern edge plain area shows significantly higher densities, mostly above 400 people/km², with some areas in western India exceeding 1,000 people/km².

Overall, the Tibetan Plateau has significantly lower population density than the southern plain areas, generally below 50 people/km², with large uninhabited areas in the north, while the southern plains of India and Bangladesh are densely populated, with northern India being one of India's high-density population regions. Comparing 2005 and 2015, population density in the northern Tibetan Plateau region and Bhutan changed little during these 11 years. However, density increased in India and Nepal, particularly in major cities. For example, Nepal's capital Kathmandu saw population density increase from approximately 8,000 people/km² in 2005 to over 30,000 people/km² in 2015, indicating intensified human activities in the southern part of the study region.

3.3.2 Nighttime Lights

As shown in [Figure 11: see original paper]a and b, nighttime light coverage in the entire southern margin of the Tibetan Plateau was only 3.1% in 1992. Within the region, the vast majority of light coverage (81.02%) was distributed in India, with smaller portions in Nepal (17.59%) mainly in major cities, Bhutan (1.23%), Bangladesh (0.17%), and no light coverage in China. By 2013, nighttime light coverage in the region reached 10.8% (3.5 times that of 1992), with 84.84% in India, 12.46% in Nepal, 2.27% in Bhutan, 0.28% in Bangladesh, and 0.13% in China.

[Figure 11: see original paper]c shows the linear change trend of nighttime lights from 1992-2013. Among areas with nighttime light coverage, 96.1% showed increasing light intensity, 2.6% showed decreasing trends, and 1.3% remained unchanged. Significantly increasing areas were mainly distributed in India's Himachal Pradesh and Uttarakhand in the western part of the study region, and in Sikkim and West Bengal in the central-eastern region (between Nepal and Bhutan), consistent with Pandey et al.[17]. From 1992-2013, the light-covered area in the southern margin of the Tibetan Plateau expanded by approximately 2.5 times, with India accounting for 85.89% of the total expansion area, Nepal 10.37%, Bhutan 3.41%, Bangladesh 0.33%, and China 0.18%.

Conclusion

This study combines satellite remote sensing and ground observations to analyze terrain, land cover, vegetation, climate, and human activities in the southern margin of the Tibetan Plateau and their changes over the past 30 years. The main findings are as follows:

(1) Land Surface Characteristics. The southern margin of the Tibetan Plateau features dramatic elevation differences and complex terrain, with diverse land use/cover types. Residential land accounts for the smallest proportion but has shown significant growth in areas such as China's southern Tibet. Regional vegetation is dominated by forests, mainly distributed along the southern foothills of the Himalayas and in the eastern part of the region, with vegetation conditions in the east significantly better than in the central-west. Since 1982, vegetation conditions have improved across most areas, with little change or slight decrease in maximum LAI in some eastern regions, while central-western regions have shown widespread increases.

(2) Climate. Precipitation shows a pattern of higher amounts in the south than north and east than west, concentrating from June to September, with western areas also receiving westerly precipitation in winter. Precipitation has decreased significantly in the central and eastern parts while increasing in some western areas. Land surface temperature and air temperature decrease from south to north with substantial spatial differences. Regional temperature has risen significantly, with more rapid warming at high altitudes and during nighttime, and the diurnal temperature range has decreased.

(3) Human Activities. Human activity intensity is relatively low, with low population density that is higher in the south than north. Artificial structures are sparse and nighttime light coverage is limited. However, both population and nighttime lights have increased in recent years, primarily in India and Nepal in the southern part of the study region. From 1992-2013, nighttime light coverage expanded 2.5-fold, from 3.1% to 10.8%, with India accounting for 85.89% of the total expansion area.

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