# Glacier Variations in the Pumqu Basin during 1990-2020 and Their Response to Climate Change: Postprint

**Authors:** Tang Yuanhang, Li Mengqi, Deng Ling

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## Abstract

Based on Landsat series imagery, Digital Elevation Model (DEM), and other datasets, glacier boundary information in the Pengqu River basin from 1990 to 2020 was extracted using remote sensing image processing and visual interpretation methods to investigate the distribution and variation of glacier area and its response to climate change over the past 30 years. The results indicate that: (1) From 1990 to 2020, the glacier area in the study region continuously decreased, with a retreat rate of $1.52\% \cdot a^{-1}$. Comparison of glacier retreat characteristics across different periods reveals that glacier retreat in the Pengqu River basin accelerated during the study period. (2) From 1990 to 2020, glacier distribution area exhibited a trend of initial increase followed by decrease with increasing altitude, with the maximum glacier distribution area occurring between 5900-6100 m. (3) From 1990 to 2020, glaciers on all aspects displayed a retreat trend, with the highest retreat rate on south-facing slopes and the lowest on north-facing slopes. (4) Similar to aspect, glaciers across different slope gradient categories also showed a retreat trend, with glacier retreat primarily concentrated within the 15°-45° range, and the fastest retreat rate occurring between 30°-35°. (5) Comprehensive analysis of regional temperature and precipitation data demonstrates that glacier area changes in the study region are influenced by climatic conditions; increasing temperature and decreasing precipitation may be the primary causes of accelerated glacier retreat, with the former exerting a greater influence on glacier retreat.

## Full Text

### Glacier Change and Its Response to Climate Change in the Pumqu Basin from 1990 to 2020

**TANG Yuanhang, LI Mengqi, DENG Ling, WANG Xiaoli**

Key Laboratory of GIS Application, College of Geography and Tourism, Chongqing Normal University, Chongqing 401331, China

**Abstract**

This study examines the distribution and change of glacier area in the Pumqu Basin, Tibet, China over the last 30 years as well as its response to climate change. The purpose of this study is to develop a more intuitive and comprehensive understanding of the total change characteristics of glaciers in the Pumqu Basin and the spatial distribution pattern and dynamic change differences between various slope directions and slopes over time. The Pumqu Basin is located on the southern margin of the Qinghai-Tibet Plateau. The Pumqu Basin has experienced crustal uplift, and the precipitation in the basin is large. The glaciers in this area have a large distribution area, diverse types, complex terrain, and climate conditions, and the ecological environment is sensitive and fragile. Currently, research on the Pumqu Basin mostly focuses on the analysis of the regional ice lake area change and the potential collapse of ice lakes. Although there are some studies on glacier change in the Pumqu Basin, the research period sequence is short, and there are few studies on the relationship between glacier and climate change in the Pumqu Basin. The glacier boundary of the Pumqu Basin from 1990 to 2020 is extracted by remote sensing image processing and visual interpretation methods based on the long-time series of Landsat remote sensing image data and Digital Elevation Model, and the Pumqu Basin is studied from many angles. The results showed that: (1) the glacier area in the study area continued to decrease; the retreat rate of the glacier area in the study period was 1.52 $\% \cdot a^{-1}$ from 1990 to 2020; and the melting rate increased year by year. (2) The distribution area of glaciers increases first and then decreases with elevation, and the distribution area between 5900 m and 6100 m is the largest. (3) Glaciers in all slope directions showed a retreat trend, with the biggest and smallest retreat rates on the south and north slopes, respectively, during the period of 1990–2020. (4) In addition, the glacier with different slope grades shows a retreating trend. Glacier retreat primarily occurs in the range of 15° to 45°, with a maximum slope of between 30° and 35°. The maximum rate of retreat is between 30° and 35°. (5) Comprehensive analysis of regional temperature and precipitation data shows that climatic conditions influence glacier area change in the study area, with increasing temperatures and decreasing precipitation likely to be the primary causes of glacier retreat.

**Keywords:** glacier variations; motivation analysis; remote sensing; Pumqu Basin; geographic information system (GIS)

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## 1 Study Area Overview

The Himalayan Mountains host numerous glaciers, with the Pumqu Basin being one of the prominent regions. The Pumqu Basin (27°49 ~29°05 N, 85°38 ~88°57 E) is situated on the southern Tibetan Plateau, in southwestern Tibet Autonomous Region, bordering Nepal. The basin extends from the Himalayas in the south to the Gangdise Mountains in the north, and borders Paiku Co in the west. Most of the basin lies on the northern side of the Himalayas, where a distinct foehn effect results in low temperatures, scarce rainfall, and high evaporation. A smaller portion lies on the southern side, where the Indian Ocean warm and humid airflow brings abundant precipitation. Due to the high altitude, complex terrain, and favorable topographic and climatic conditions in this high-cold region of the Himalayas, the Pumqu Basin has developed extensive glaciers with a total area of approximately 1400 $km^2$. These glaciers are relatively dense and concentrated along the Himalayan mountain range along the national border, forming an important solid reservoir for the economic and social development of surrounding areas. In recent years, under the influence of global warming and intense solar radiation, glaciers in the Pumqu Basin have been retreating and melting at an accelerated rate, leading to an increase in the number and area of glacial lakes in surrounding areas. Given the already well-developed river system in the basin, this may bring many serious natural disasters, such as floods caused by glacial lake outbursts.

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## 2 Data Sources and Methods

### 2.1 Data Sources

**2.1.1 Remote Sensing Imagery and DEM Data** The remote sensing data used in this study were obtained from the United States Geological Survey (USGS). The Landsat series satellite data were sourced from the Geospatial Data Cloud (http://www.gscloud.cn/). This data has undergone orthorectification using the GLS2005 global land control point system and high-precision terrain correction using DEM data. The geodetic correction in this study is based on precise DEM data and ground control points, meeting the requirements for glacier monitoring using remote sensing. The DEM data used in this study is the ASTER GDEM data provided by the Geospatial Data Cloud. Since snow cover and cloud cover can obstruct remote sensing lines of sight or cause unclear glacier boundaries, this study selected image data that are clear with no or few clouds in summer. However, in practice, we retained some images from around July with high cloud cover but minimal impact on glacial areas and good overall quality. The final remote sensing images selected for this study are listed in Table 1.

**2.1.2 Meteorological Grid Data and Other Data** Due to the limited number of meteorological stations in the Pumqu Basin region, this study ultimately selected annual temperature and precipitation grid data from the Climate Research Center of the Department of Geography at the University of Delaware for the period 1970-2017. This data provides a more accurate description of meteorological conditions in the Pumqu Basin through ground station observations, enabling more realistic conclusions. To verify the accuracy of the grid data, this study also collected data from three meteorological stations near the Pumqu Basin for comparison. In addition, this study validated the 2020 glacier boundary extraction results using the Second Glacier Inventory data.

### 2.2 Research Methods

This study employed the high-precision ratio threshold method to extract glacier boundaries. This method involves calculating band ratios to generate ratio images, setting thresholds for decision tree classification, and obtaining preliminary glacier boundary extraction results after binary processing of the ratio images. After repeated experimentation with the data, the final threshold for Landsat OLI images was set at 2.0, and for Landsat TM/ETM+ images at 2.2. To ensure data accuracy, this study conducted visual interpretation of each glacier boundary obtained from the ratio threshold method. The distinction between glaciers and snow was primarily based on glacier morphology, with glacier tongues being relatively smooth and regular in shape, while snow cover is more scattered. For each glacier, Google Earth historical data was used for visual interpretation.

### 2.3 Accuracy Assessment

To verify the accuracy of glacier boundaries, this study performed a buffer zone analysis on the study area boundary from 1990 to 2020. The error rate was obtained by dividing the buffer zone area by the total area. The error rate was small and met the precision requirements of this study.

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## 3 Results

### 3.1 Glacier Distribution Area and Change Characteristics

The glaciers in the Pumqu Basin showed an overall retreat trend from 1990 to 2020, though the retreat rate varied across different periods. The glacier area decreased from 1248.70 $km^2$ in 1990 to 1209.19 $km^2$ in 2000, 1152.25 $km^2$ in 2010, and 1068.10 $km^2$ in 2020. Over the 30-year period, the glacier area retreated by 180.60 $km^2$, with an average annual retreat rate of 1.52 $\% \cdot a^{-1}$. Comparing glacier distribution areas across different periods, the average annual retreat rate was 0.32 $\% \cdot a^{-1}$ from 1990-2000, 0.47 $\% \cdot a^{-1}$ from 2000-2010, and 0.73 $\% \cdot a^{-1}$ from 2010-2020. The period from 2010-2020 had the highest average annual retreat rate, indicating accelerated glacier retreat in the Pumqu Basin, particularly in the last decade.

### 3.2 Glacier Distribution Characteristics at Different Altitudes

Glacier distribution area in the study area showed significant variation with altitude, following a clear pattern: glacier distribution area increased with altitude up to a certain height, then gradually decreased. The minimum glacier distribution area occurred at 4700-4900 m, while the maximum occurred at 5900-6100 m. In 2020, the minimum glacier distribution area was 8.44 $km^2$ and the maximum was 211.79 $km^2$. This distribution pattern is primarily influenced by topography and climatic conditions. Within the troposphere, temperature decreases with increasing altitude, while moisture content first increases then decreases with altitude, causing glacier distribution area to first increase then decrease with altitude.

### 3.3 Glacier Distribution and Change Characteristics by Slope Aspect

From 1990 to 2020, glaciers on all slope aspects in the Pumqu Basin showed retreat trends, with the retreat trend gradually intensifying. The south-facing slope had the largest glacier retreat rate at 22.62%, followed by southeast-facing and east-facing slopes at 19.65% and 19.33% respectively. The north-facing slope had the smallest retreat rate at 10.41%, followed by northwest-facing, northeast-facing, and west-facing slopes at 16.84%, 9.74%, and 12.69% respectively. In terms of distribution area, north-facing slopes had the largest glacier area, accounting for 19.99%, 20.22%, 19.77%, and 17.27% of total glacier area in 1990, 2000, 2010, and 2020 respectively. Although the glacier area on north-facing slopes showed a decreasing trend, its proportion of total glacier area showed an increasing then decreasing trend. Southwest-facing slopes had the smallest glacier distribution area, accounting for 7.15%, 7.33%, 7.27%, and 5.70% of total glacier area in the respective periods, showing a clear decreasing trend in both area and proportion.

### 3.4 Glacier Distribution and Change Characteristics by Slope Gradient

This study divided glacier surface slopes into categories at 5° intervals. From 1990 to 2020, glaciers in the study area were most extensively distributed in the 5°-10° slope range, followed by decreasing distribution in subsequent ranges. The 45°-50° slope range had slightly more glacier distribution area than the 50°-55° range, but still less than the 5°-25° range. Overall, glaciers in the Pumqu Basin are mostly distributed in gentle terrain (5°-25°). All slope categories showed retreat trends, with retreat rates first increasing then decreasing with slope gradient. Glacier retreat was mainly concentrated in the 15°-45° range, with the maximum retreat rate occurring in the 30°-35° range at 18.41%. The minimum retreat rate occurred in the 0°-5° range at 8.95%. The retreat rate in 1990-2000 was similar across different slopes, with slightly higher rates in medium and high slopes (35°-55°). In 2000-2010, the retreat rate increased with slope up to 35°, then decreased with further slope increase, approaching zero after 50°-55°. In 2010-2020, the retreat rate showed two peaks: one at 30°-35° (9.99%) and another at 50°-55° (9.10%), with minimal retreat in extremely gentle or extremely steep areas.

### 3.5 Glacier Distribution and Change Characteristics by Size Class

**3.5.1 Distribution and Change Characteristics of Glacier Numbers** Glaciers in the Pumqu Basin are dominated by small-scale glaciers. Glaciers $ 0.2km^{2}$ numbered 268, 286, 283, and 294 in 1990, 2000, 2010, and 2020 respectively, accounting for 59.13%, 67.88%, 71.45%, and 74.24% of the total number in each period. Glaciers $ 20km^{2}$ numbered only 9, 8, 7, and 4 respectively, accounting for just 1.45%, 1.03%, 0.79%, and 1.01% of the total. No glaciers in the study area exceeded 100 $km^2$. Overall, glacier numbers showed an increasing trend from 1990 to 2020, increasing by 31 glaciers. However, only glaciers in the 10-20 $km^2$ size class showed an increasing trend (from 9 to 14), while all other size classes showed decreasing numbers. Glaciers in the 1-2 $km^2$ size class decreased the most (by 12), while glaciers in the 20-50 $km^2$ size class decreased the least (by 1). The analysis reveals that larger glaciers show smaller fluctuations in number.

**3.5.2 Distribution and Change Characteristics of Glacier Area** The largest glacier area distribution in the Pumqu Basin was in the 20-50 $km^2$ size class, with areas of 326.99 $km^2$, 306.74 $km^2$, 287.96 $km^2$, and 244.88 $km^2$ in 1990, 2000, 2010, and 2020 respectively, accounting for 26.19%, 25.37%, 24.99%, and 22.93% of total glacier area in each period. The second largest was the 10-20 $km^2$ size class, with areas of 251.95 $km^2$, 231.14 $km^2$, 214.47 $km^2$, and 192.87 $km^2$, accounting for 20.18%, 19.11%, 18.61%, and 18.06% respectively. The smallest distribution area was in the $ 0.2km^{2}$ size class, with areas of 29.86 $km^2$, 30.94 $km^2$, 32.13 $km^2$, and 30.94 $km^2$, accounting for 2.39%, 2.56%, 2.79%, and 2.90% respectively. Among the different size classes, only glaciers $ 0.2km^{2}$ showed an increasing trend in area (increasing by 1.08 $km^2$). All other size classes showed decreasing trends. The 10-20 $km^2$ size class had the largest area reduction (66.83 $km^2$), followed by the 20-50 $km^2$ size class (58.86 $km^2$). The analysis shows that smaller glaciers exhibit smaller area fluctuations compared to larger glaciers. Overall, glacier size class shows an inverse relationship with glacier fluctuations: larger glaciers have smaller fluctuations, while smaller glaciers have larger fluctuations.

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## 4 Discussion

Slope aspect, slope gradient, and glacier area are important topographic factors affecting glacier response to climate change. Analysis of glaciers with different slope aspects and gradients reveals that glacier response to climate change has a certain lag period, with smaller glaciers having shorter lag periods. Previous studies selected typical regions and used median area indicators to study the entire Himalayan glacier system, finding that the average glacier size in the Himalayas is 7.78 $km^2$, while the average glacier size in the Pumqu Basin is 1.51 $km^2$. Therefore, using a lag period of 5-10 years, this study analyzed climate data from 1970-2017. To more fully reflect climate change characteristics in the study area, annual average temperature and annual precipitation data were used to represent climate variations within different periods.

From 1970-2017, the annual average temperature in the Pumqu Basin showed an overall fluctuating trend, reaching a maximum of 2.5°C and a minimum of 0.6°C. Annual precipitation showed large fluctuations, with smaller variations from 1970-1990, peaking at 1773.4 mm in 1990, then dropping sharply to a valley of 1330.8 mm in 1995 before rising significantly. In the corresponding period (1990-2000), glaciers in the Pumqu Basin showed a retreat trend with an average annual retreat rate of 0.32 $\% \cdot a^{-1}$. From 2000-2010, both annual average temperature and annual precipitation were higher than in the previous period. In the corresponding period (2000-2010), glaciers in the Pumqu Basin retreated at an annual rate of 0.47 $\% \cdot a^{-1}$. Analysis suggests that although precipitation was higher in this stage, temperature increased significantly, which may be the main climatic reason for accelerated glacier retreat.

From 2010-2017, the annual average temperature in the Pumqu Basin was higher than in the previous period, showing an overall trend of fluctuating decline followed by increase, with a maximum of 2.1°C and a minimum of 0.7°C. Annual precipitation in this stage was lower than in the previous period, first declining to 1479.58 mm then rising to a peak of 1706.91 mm. In the corresponding period (2010-2020), glaciers in the Pumqu Basin retreated at an annual rate of 0.73 $\% \cdot a^{-1}$, higher than in the previous two periods. Based on temperature and precipitation characteristics, the glacier retreat rate in the Pumqu Basin may continue to increase year by year. Overall, glaciers in the Pumqu Basin have accelerated retreat from 1990-2020, with the acceleration trend becoming more significant in the last decade.

Previous studies on glacier changes in the Pumqu Basin include Wei et al., who used topographic map data from around 1970 and Landsat TM/ETM+ imagery to find a retreat rate of 0.29 $\% \cdot a^{-1}$ from 1970-2000. Ji et al. used Landsat imagery and ASTER GDEM data to study glacier distribution and changes from 1990-2015, finding accelerated glacier retreat in the region, with the latter period (2000-2015) showing a retreat rate much greater than the earlier period (1990-2000). The results of this study are consistent with previous research. Compared with similar studies in this region, this research has a longer time series. For small-scale glacier studies, the combination of manual visual interpretation, remote sensing, and GIS technology is a scientific and comprehensive approach. Therefore, this study provides supplementary information for regional glacier change and glacial lake prediction, and is important for glacier change forecasting and disaster prevention.

## 5 Conclusions

Based on Landsat series remote sensing imagery, DEM data, and meteorological grid data, this study extracted glacier boundaries in the Pumqu Basin from 1990-

2020 using the ratio threshold method combined with visual interpretation. The distribution and changes of glaciers and their response to climate change were analyzed, leading to the following conclusions:

1) Glaciers in the Pumqu Basin showed accelerated retreat from 1990-2020, with the acceleration trend being particularly evident in the last decade. The glacier area decreased from 1248.70 $km^2$ in 1990 to 1068.10 $km^2$ in 2020, with a total retreat of 180.60 $km^2$ and an average annual retreat rate of 1.52 $\% \cdot a^{-1}$.

2) Glacier distribution area in the Pumqu Basin increased with altitude up to a certain height then gradually decreased, primarily due to the influence of topography and climatic conditions. The maximum glacier distribution area occurred in the 5900-6100 m elevation range.

3) All slope aspects in the Pumqu Basin showed retreat trends from 1990-2020. South-facing slopes had the largest retreat rate, while north-facing slopes had the smallest. North-facing slopes had the largest glacier distribution area, though the proportion of total glacier area showed an increasing then decreasing trend. Southwest-facing slopes had the smallest glacier distribution area, with both area and proportion showing decreasing trends.

4) Glaciers in the Pumqu Basin are mostly distributed in gentle terrain (5°-25°). All slope categories showed retreat trends, with retreat rates first increasing then decreasing with slope gradient. Glacier retreat was mainly concentrated in the 15°-45° range, with the maximum retreat rate in the 30°-35° range. Retreat rates were smaller in extremely gentle or extremely steep areas.

5) Using a 5-10 year lag period to analyze the impact of climate on glacier retreat, the results indicate that rising temperatures and decreasing precipitation may be the main causes of accelerated glacier retreat, with temperature having a greater impact than precipitation. It can be predicted that glaciers in the Pumqu Basin will likely continue to retreat in the coming decades, with the annual retreat rate potentially continuing to increase. Compared with large glaciers, small glaciers are more susceptible to climate influences.

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## Figures

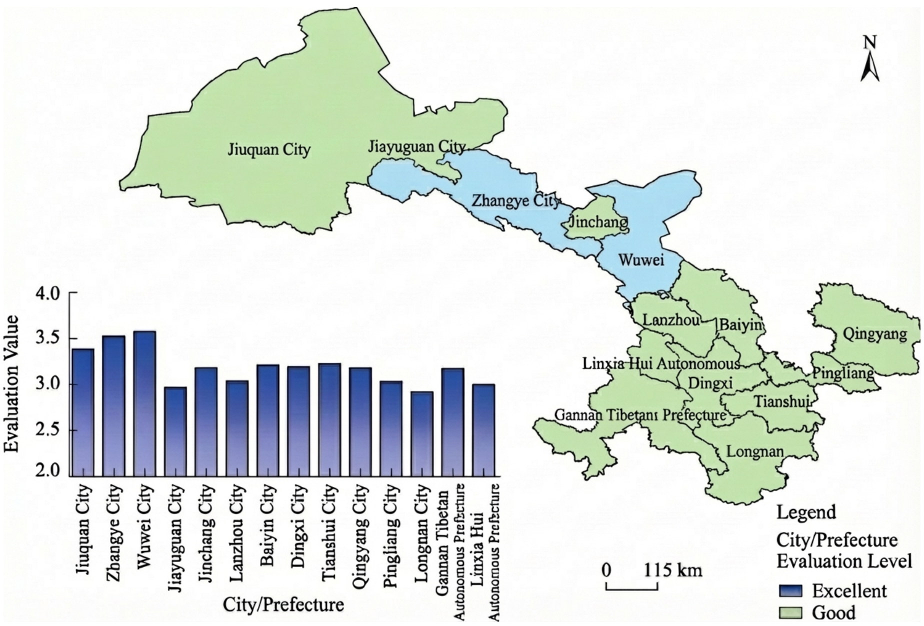


Figure 1: Figure 3

*Source: ChinaXiv —Machine translation. Verify with original.*

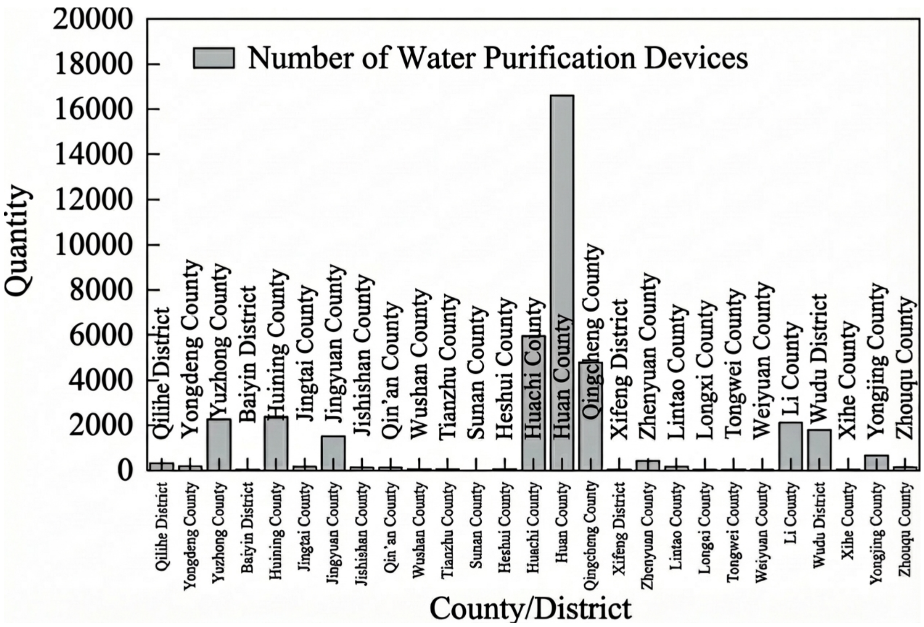


Figure 2: Figure 7

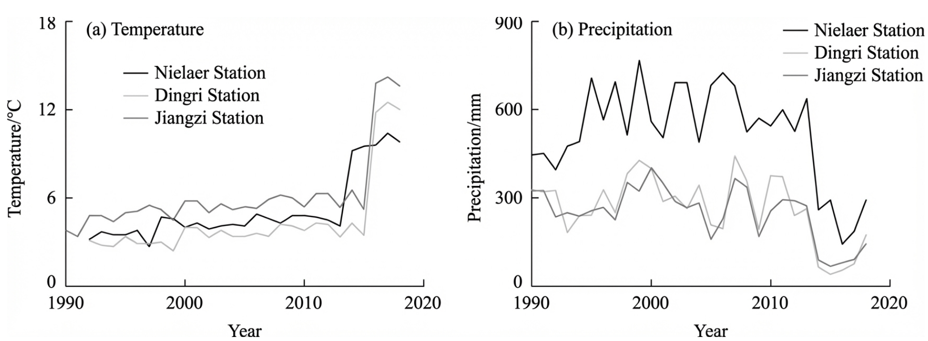


Figure 3: Figure 8

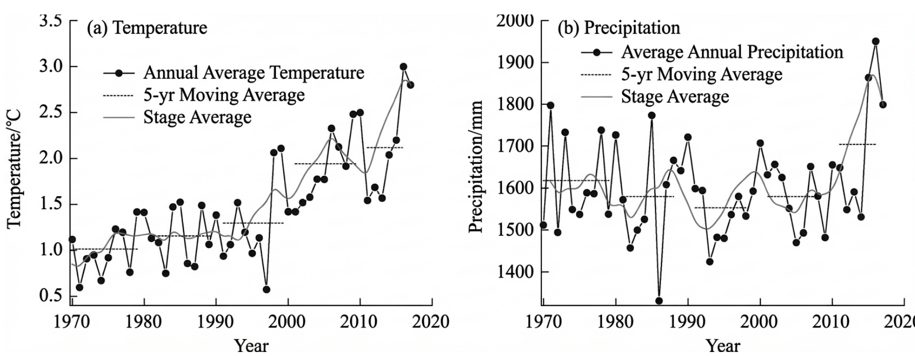


Figure 4: Figure 9