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Climate change on the southern slope of Mt. Qomolangma (Everest) Region in Nepal since 1971

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Abstract: Based on monthly mean, maximum, and minimum air temperature and monthly mean precipitation data from 10 meteorological stations on the southern slope of the Mt. Qomolangma region in Nepal between 1971 and 2009, the spatial and temporal characteristics of climatic change in this region were analyzed using climatic linear trend, Sen's Slope Estimates and Mann-Kendall Test analysis methods. This paper focuses only on the southern slope and attempts to compare the results with those from the northern slope to clarify the characteristics and trends of climatic change in the Mt. Qomolangma region. The results showed that: (1) between 1971 and 2009, the annual mean temperature in the study area was 20.0℃, the rising rate of annual mean temperature was 0.25℃/10a, and the temperature increases were highly influenced by the maximum temperature in this region. On the other hand, the temperature increases on the northern slope of Mt. Qomolangma region were highly influenced by the minimum temperature. In 1974 and 1992, the temperature rose noticeably in February and September in the southern region when the increment passed 0.9℃. (2) Precipitation had an asymmetric distribution; between 1971 and 2009, the annual precipitation was 1729.01 mm. In this region, precipitation showed an increasing trend of 4.27 mm/a, but this was not statistically significant. In addition, the increase in rainfall was mainly concentrated in the period from April to October, including the entire monsoon period (from June to September) when precipitation accounts for about 78.9% of the annual total. (3) The influence of altitude on climate warming was not clear in the southern region, whereas the trend of climate warming was obvious on the northern slope of Mt. Qomolangma. The annual mean precipitation in the southern region was much higher than that of the northern slope of the Mt. Qomolangma region. This shows the barrier effect of the Himalayas as a whole and Mt. Qomolangma in particular.

Keywords: climate change; Mann-Kendall analysis; Mt. Qomolangma region; Koshi River; Nepal

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1 Introduction

Changes in the global environment, in particular, climate variation have become the center of attention from scientists and policy makers (Cai *et al*., 2009). As human activity has increased, there is still scientific uncertainty about future climate change under the influence of human activities (Houghton *et al*., 2001; Kabat, 2004; Steffen, 2005), even though it has become the main driving force in causing global climate change.

In the last one hundred years, the global average surface temperature has maintained an upward momentum of about 0.74℃ according to the prevailing views in the Intergovernmental Panel on Climate Change (IPCC) (Metz *et al*., 2007; Steffen, 2005). However, a conflicting NIPCC report was put forward by 24 scientists, including Singer (2008), the former director of the National Advisory Committee on Oceans and Atmosphere (NACOA). At the present time, there are still strongly divergent arguments on global climate change, especially on global warming issues.

The Tibetan Plateau is considered to be not only a sensitive and initiation region for climate change (Feng *et al*., 1998), but also a driving force and amplifier for it (Pan and Li, 1996). Mt. Qomolangma – the highest mountain peak in the world, located in the central Himalayas – has become the most sensitive area because of its unique physiographic conditions, matchless height and fragile environment (Yang *et al*., 2012).

The Himalayas have been a natural barrier obstructing warm and wet air flow from the Indian Ocean from coming to the north (TSET, 1975), so the arid and cold climate there has led to a marked regional differentiation between the northern and southern slopes (Tao and Ding, 1981; Ye, 1979). Only a few scholars (Yang *et al*., 2012; Yang *et al*., 2006) have studied the climate change conditions on the northern hillsides there as a result of harsh weather conditions, scarce meteorological stations and a lack of meteorological data over a long period. In addition, only a few studies have looked at the climate conditions on the southern hillside of Mt. Qomolangma, despite the fact that Shrestha *et al.* (1999, 2000) engaged in systematic research into the climate conditions of Nepal in the last century.

This paper focuses on the following. (i) The analysis of temperature and precipitation change between 1971 and 2009 on the basis of related data from 10 weather stations in the central southern Koshi Basin. The stations are located in Nepal on the southern hillside of Mt. Qomolangma in the central Himalayas, one of the most sensitive regions of global climate change. (ii) The examination of the similarities and differences when compared with the northern hillside of Mt. Qomolangma. (iii) The analysis of the climate change characteristics and trends in the region of Mt. Qomolangma.

Understanding the climate changing trend is essential to develop strategies for climate change adaptation. There is no doubt that this research could provide the scientific foundation for climate change prediction, water resource allocation, agricultural production management and ecological protection in this region.

2 Study area

The Kosi River, known for its seven Himalayan tributaries, is a trans-boundary river flowing through Nepal and India. Some of the rivers of the Koshi system, such as the Arun, the Sun Kosi and the Bhote Koshi, originate in the Tibet Autonomous Region of China. The Kosi

River is one of the largest tributaries of the Ganges. Along with its tributaries, the river drains 5.9×10^4 km^2 and has a total length of 255 km (Zhang *et al*., 2011).

The study area is located in the Koshi Basin on the southern hillside of Mt. Qomolangma in Nepal with its geographical location between 83°55'–88°13'E and 26°20'–28°21'N (Zhang *et al*., 2010) (Figure 1). It covers an area of 55,340.71 km^2, including Bagmati, Narayani, Janakpur, Sagamatha, Koshi and Mechi zones. The study area contains five of the world's highest mountain peaks, namely Qomolangma, Kanchenjunga, Lhotse, Makalu and Cho Oyu, the altitudes of which are above 8000 m. As the study area is on the southern margin of "the third pole", the change in altitude going from the Himalayas to the south falls from 8844.43 m to dozens of meters, passing through Trans-Himalayan, Himalayan, Middle Mountain, Siwalik, and Terai geo-ecological regions in sequence (Shrestha *et al*., 1999). As a result, vertical climate change there is very significant with natural vertical zones including the Himalayan transitional zone (above 5000 m), alpine zone (4000–5000 m), subalpine zone (3000–4000 m), temperate zone (2100–3000 m), subtropics (1000–2100 m), and tropics (less than 1000 m). Furthermore, land-cover types have been affected to show peak distributions mostly with increasing elevation for the significant vertical differentiation characteristics, varying successively from forest to shrub, grassland, meadow, sparse vegetation, bare rock and glacier.

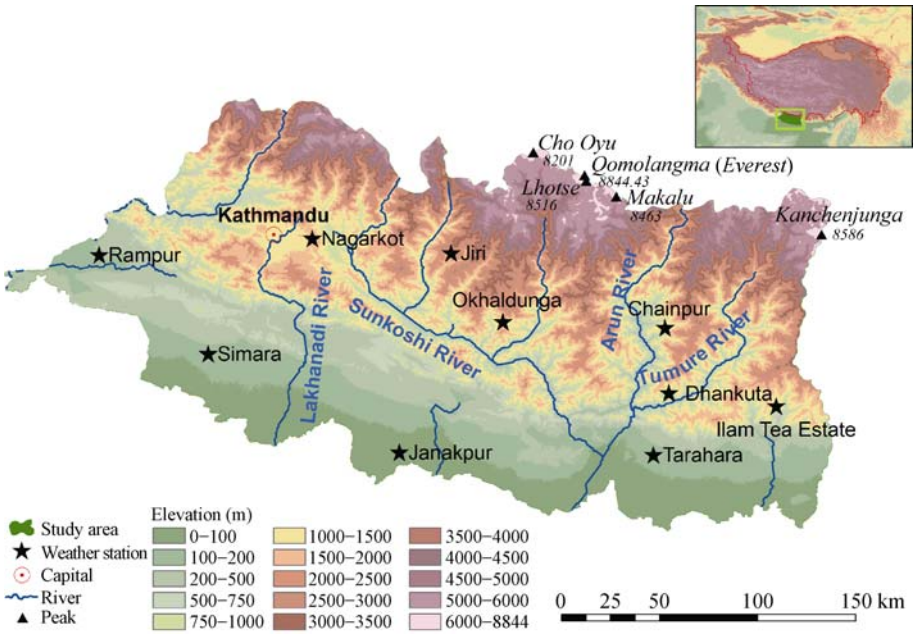

Figure 1 Location of the study area and the 10 meteorological stations

3 Data and data processing

Considering that the starting time of climate records did not coincide with each other, and there was removal or relocation of meteorological stations, we selected 10 meteorological stations (Figure 1 and Table 1) to collect the monthly mean temperature, the monthly mean maximum temperature, the monthly mean minimum temperature and monthly precipitation data between 1971 and 2009, establishing a unified and stable climate record series, and

maintaining the accuracy and uniformity of the climate data, to represent the climate conditions on the southern hillside of Mt. Qomolangma throughout the period. The data from 1971 to 2000 came from the observation data of the meteorological stations issued by the Department of Hydrology and Meteorology (DHM), which is an organization under the Ministry of Environment, Government of Nepal; the data from 2001 to 2009 came from the daily temperature and precipitation data of the meteorological stations offered by the International Centre for Integrated Mountain Development (ICIMOD), which had been processed using the same statistical methods as used by the DHM so as to maintain the uniformity of the climate data.

Table 1 Descriptions of the 10 meteorological stations included in this study

Station no.[a]	Station name	Elevation (m)	Latitude (°N)	Longitude (°E)	Physiographic region
0902	Rampur	256	27.62	84.42	Dun/Siwalik
0909	Simara	130	27.17	84.98	Terai
1043	Nagarkot[b]	2150	27.72	85.52	Middle Mountain
1103	Jiri	2003	27.63	86.23	Himalaya
1111	Janakpur	90	26.72	85.97	Terai
1206	Okhaldunga	1720	27.32	86.50	Middle Mountain
1303	Chainpur	1329	27.28	87.33	Middle Mountain
1307	Dhankuta	1160	26.98	87.35	Middle Mountain
1320	Tarahara	200	26.70	87.27	Terai/Siwalik
1407	Ilam Tea Estate[c]	1300	26.92	87.90	Middle Mountain

[a] Station numbers according to the Department of Hydrology and Meteorology station index numbers. Numbers increase from west to east, and north to south.
[b] Temperature data from 1971 to 1975 missing.
[c] Temperature data from 1971 missing.

The data have been rigidly revised. The missing temperature data have been interpolated using the method of Wang (1984) and Yu *et al*. (2003). Besides, owing to the enormous drop in altitude in the study area and the complicated topography, the correlation coefficient of precipitation at the different weather stations barely reached 0.67 at most. In other words, the deviation in the method of spatial interpolation processing of precipitation in this area is large (Hormann, 1994). Therefore, we adopted the method of time interpolation processing (the average monthly rainfall was taken as the average of that month in the previous two years, and the following two years) (Shrestha *et al*., 2000) to interpolate the data. In addition, we selected 1971–2000 to be the average time segment according to the new climate standard introduced by World Meteorological Organization (WMO).

The climate changing trend analysis mainly adopted the linear trend method (Wei, 1999) and Sen's Slope Estimates method (Kahya and Kalayci, 2004; Tabari and Talaee, 2011) to analyze the change in sequence of meteorological elements; the analysis of abrupt changes in climate was mainly carried out using the Mann-Kendall method (Wei, 1999).

In the Mann-Kendall test of abrupt change, on the premise of the positive sequence curve UF_k crossing the critical ratio reliability line, if the positive sequence and the inverse sequence have only one obvious crossing point located between the reliability lines, this is the catastrophe point and is statistically significant (Yin *et al*., 2009); on the other hand, if the

crossing point is located outside the reliability line or there are several obvious crossing points between the lines, we could not establish a definite catastrophe point. In that case, we used the Mann-Kendall method on different lengths of sequence separately on the basis of a moving *t*-test technique. In the different sequences, if there was still a point shown to be the catastrophe point, we could confirm that this point was the definite catastrophe point.

4 Results

4.1 Temperature characteristics of inter-annual variation

The annual mean temperature of the 10 meteorological stations in the study area during the period 1971–2009 ranged from 13.2 to 25.5℃; the temperatures of both Terai and Siwalik were above 20℃, but the temperatures of both Middle Mountain and Himalaya were clearly lower than 20℃ (Table 2 and Figure 2). The annual mean temperature in the study area was 20.0℃ (Table 2), about 15℃ higher than that on the northern slope of Mt. Qomolangma during the same period (1971–2004) (Yang *et al*., 2006).

Table 2 Decadal variation of annual mean temperature in the study area

Station name	Annual mean temperature 1971–2009 (℃)	Temperature anomaly (℃)				Number of days (temperature >30℃) anomaly (days)[a]			
		1970s	1980s	1990s	2000s	1970s	1980s	1990s	2000s
Rampur	24.1	–2.80	–0.13	0.51	0.51	–33.17	–1.57	11.63	12.43
Simara	24.1	–2.54	–0.02	0.17	0.22	–42.04	–8.74	6.66	0.26
Nagarkot	14.6	–10.28	–0.17	0.19	0.14	—	—	—	—
Jiri	14.2	–1.51	–0.06	0.13	0.30	—	—	—	—
Janakpur	24.8	–3.00	0.08	0.44	0.37	–47.88	–46.78	6.82	6.72
Okhaldunga	16.9	–1.96	–0.25	0.44	0.96	—	—	—	—
Chainpur	19.7	–1.99	0.37	–0.34	–1.42	–8.40	17.70	–10.30	–16.30
Dhankuta	18.8	–5.55	–0.67	0.58	1.56	0.83	–2.07	0.63	18.33
Tarahara	24.0	–2.49	–0.12	0.19	0.02	–26.57	–3.27	8.43	–8.57
Ilam Tea Estate	19.2	–3.92	–0.06	0.18	0.61	—	—	—	—
Average Value	20.0	–3.60	–0.10	0.25	0.33	—	—	—	—

[a] Stations with annual maximum temperature lower than 30°C are not listed.

Owing to the influence of tropical monsoons on South Asia and the warm and wet flow brought about by the Indian Ocean, in addition to the high Himalayas blocking the flow of cold wind moving southward from Mongolia–Siberia, the temperature in Terai and Siwalik is higher than that in regions influenced by subtropical monsoons with the same latitude in China. In addition, the annual mean temperature at Middle Mountain and Himalaya is at least 7℃ higher than the temperature at the five meteorological stations on the northern slope of Mt. Qomolangma (Yang *et al*., 2006). Even though we ignore the influence of altitude on temperature, this is still higher than the temperature in regions with the same latitude in China, which is in direct contrast to the situation on the northern slope (Yang *et al*., 2006).

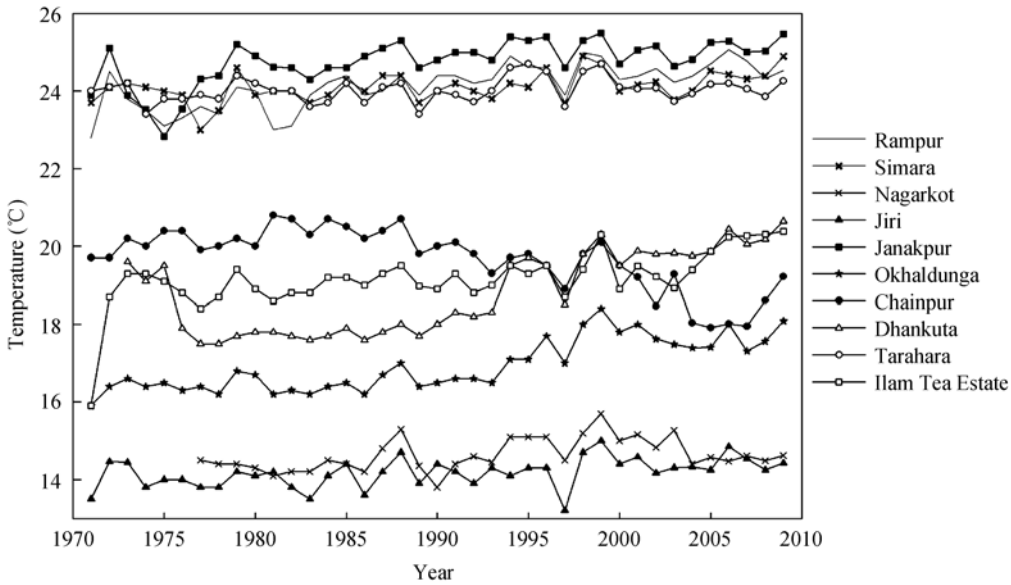

Figure 2 Annual mean temperature change at the 10 meteorological stations in the study area from 1971 to 2009

We can conclude from Figure 2 that the annual mean temperature in the early 1970s fluctuated highly from the low in 1971 to the culmination in 1972, and then back to the low in 1974 followed by wavelike rises. In the 1980s, the annual mean temperature continued to fluctuate upward with two culminations separately in 1984 and 1987 until 1989, when the temperature was declining. The temperature had a slight tendency to decline in 1992, and recovered to rise, then fell abruptly to a low with minimum or secondary minimum temperatures at several meteorological stations in 1997. However, in 1998, the temperature picked up to the average level of the 1990s. The fluctuation in this period might be related to the large-scale El Nino Event from 1997 to 1998. After 2000, the temperature maintained a wavelike rise with small peaks in 2005 and 2006 and a higher peak in 2009.

It is worth noting the trend at the stations of Chainpur and Dhankuta. Before 1990, the temperature at Chainpur was similar to the above; however, after 1990, the trend of temperature there has been fluctuating downward abruptly with the exception of 2009, when the temperature picked up slightly, but was still lower than the average temperature in the 1990s. As regards Dhankuta, the temperature had been in a slightly fluctuating upward trend and only increased markedly in the period 1992–1998, thus Dhankuta is the station with the most significant increase in temperature. Dhankuta is the headquarters of the eastern development regions, and the natural environment there was available for people to change the land use patterns on a large scale, so many infrastructures, including urban settlements, are expanding there. As a result, the underlying surface varied and affected the local climate so that the temperatures at these two stations changed with the trend as noted above; however, this interpretation has to be demonstrated through research in the future.

Since 1971, apart from Chainpur, the annual mean temperatures of the 10 stations have shown an obvious rising trend (Table 3). To be specific, the linear rate of temperature increase has passed 0.3℃/10a in Rampur (0.36℃/10a, α=0.01), Janakpur (0.33℃/10a, α=0.01), Okhaldunga (0.48℃/10a, α=0.01), and Dhankuta (0.70℃/10a, α=0.01); however,

Nagarkot (0.17℃/10a, α=0.01) and Jiri (0.14℃/10a, α=0.01) with higher altitudes have not seen the influence of altitude in climate warming (Aizen *et al*., 1997; Beniston *et al*., 1997; Diaz and Bradley, 1997; Giorgi *et al*., 1997; Liu and Hou, 1998; Yao *et al*., 2000). Besides, after comparison of the years when the temperature clearly started to rise at these stations using the Mann-Kendall abrupt change test, there is still no reflection of this influence; therefore, we believe that the study area might be influenced more by warm, wet flow from the Indian Ocean, which has weakened the sensitivity to global climate change at high altitudes.

Table 3 Rising rate of annual mean temperature, annual mean maximum temperature, and annual mean minimum temperature in the study area

Station name	Rising rate of annual mean temperature (℃/10a)	Rising rate of annual mean maximum temperature (℃/10a)	Rising rate of annual mean minimum temperature (℃/10a)
Rampur	0.363	0.358	0.417
Simara	0.151	0.069	0.202
Nagarkot	0.177	0.250	0.066
Jiri	0.147	0.504	–0.288
Janakpur	0.333	0.097	0.333
Okhaldunga	0.480	0.828	0.128
Chainpur	–0.511	–0.258	–0.765
Dhankuta	0.696	1.038	0.068
Tarahara	0.071	–0.036	0.166
Ilam Tea Estate	0.301	0.528	0.271
Average Value	0.250	0.415	0.070

We can conclude from the decadal variation of annual mean temperature in Table 2 that the temperature on the southern slope of Mt. Qomolangma, apart from Chainpur, has clearly risen since the 1970s and from the temperature anomaly in 1971–2000 that the temperature has picked up remarkably after the 1990s and increased at a significant speed after 2000, even about 0.57℃ higher than the average temperature in the 1970s. In addition, we can also determine from the temperature anomaly in days when the temperature was higher than 30℃ that the number of days when the temperature was above 30℃ within a year tends to increase year by year. It is clear that a warming trend is present.

The Mann-Kendall trend test on the temperature data in the period 1976–2009 revealed the obvious rising tendency of the annual mean temperature and the annual average maximum temperature in the inter-annual fluctuations in the study area, in addition to a slight low-key upward tendency of the annual average minimum temperature (Figure 3 and Table 3). The linear rate of rising mean, maximum and minimum temperature was 0.25℃/10a, 0.42℃/10a, and 0.07℃/10a, and all of them passed the significance level α=0.05. From the linear rate of rising temperature, we determined that the contribution of annual average maximum temperature to the rising temperature was much higher than that of annual mean temperature and annual average minimum temperature in six of the 10 metrological stations (Table 3). Hence, the rising temperature in this area where the upward tendency kept increasing is obviously much more significantly influenced by the rising maximum temperature. In contrast, on the northern side of the slope, the upward tendency (the average linear

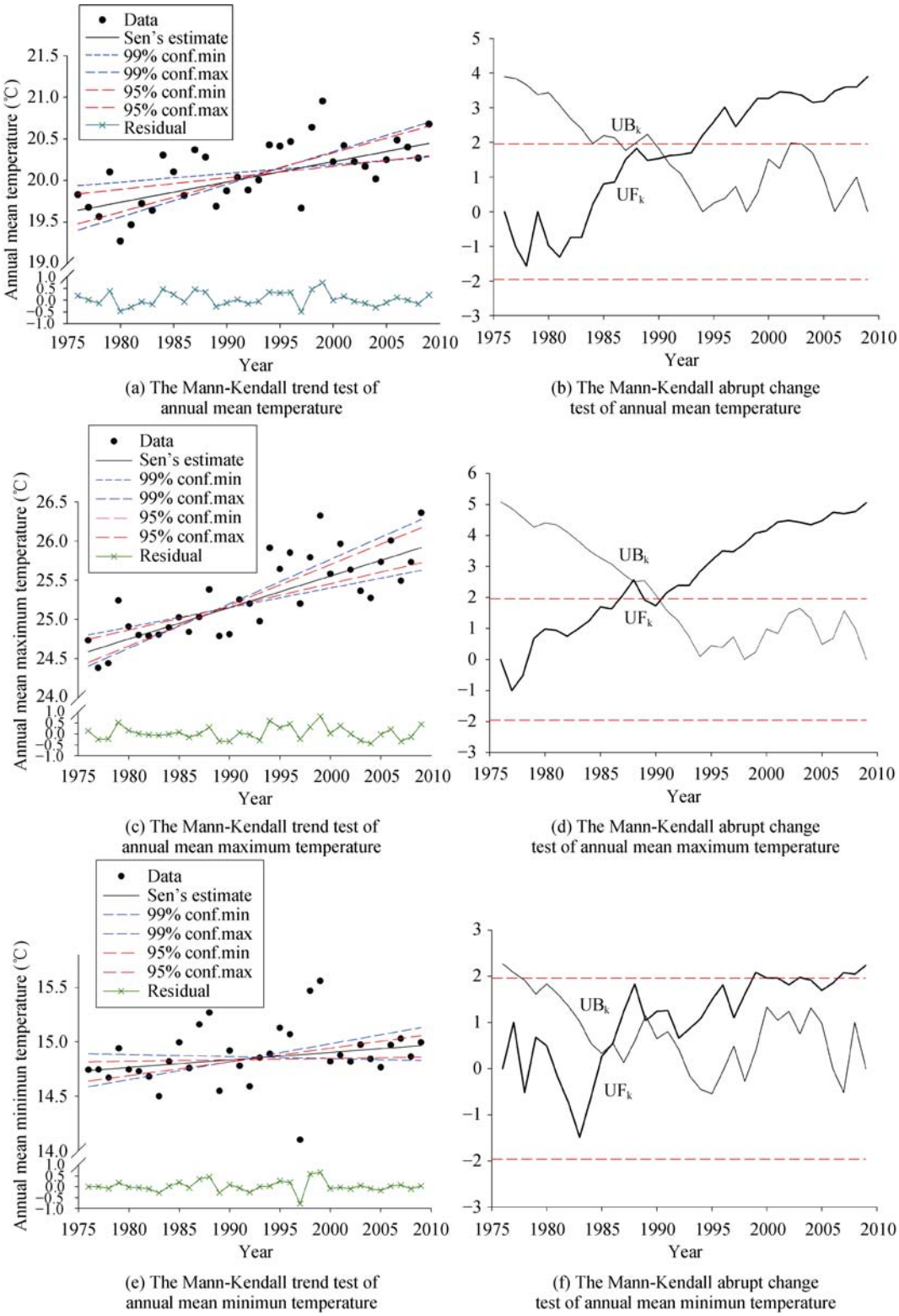

Figure 3 The Mann-Kendall trend test and abrupt change test of annual mean temperature, annual mean maximum temperature, and annual mean minimum temperature in the study area

rate of rising temperature is 0.23℃/10a) basically corresponds to that in the south, but the rising temperature there is mainly influenced by the average minimum temperature (Yang *et al*., 2006). As a result, the warming tendency on the southern and northern slopes of Mt. Qomolangma has a certain regional character, but there are several factors that have effects on the temperature variation which require further steps to analyze the rising temperature mechanism.

After analyzing the data from 49 metrological stations in Nepal during the period 1971–1994, Shrestha *et al.* (1999) found that the temperature in Nepal has been successively rising since the 1970s. The temperature variation we found has the same tendency as concluded by Shrestha and colleagues. However, the linear rates of rising temperature in these two reports differed enormously because the research conclusions of Shrestha and colleagues were based on annual average maximum temperature; in addition, the research areas in the two reports were different.

Moreover, with reference to Figure 3, according to the Mann-Kendall abrupt change test, we can see that the annual mean temperature rose abruptly after 1990, and passed the critical line in 1993. The annual average maximum temperature also changed abruptly, tending to increase markedly in 1990. There are two visible crossing points within the confidence interval for annual average minimum temperature, thus, we could not confirm if this was the catastrophe point. Even if it was the catastrophe point, the warming tendency is still unclear as the UF_k curve has rarely passed the critical line.

Study of the climate change at Mt. Qomolangma is a pointer to future trends of climate change in other regions of the Chinese mainland by virtue of the earlier temperature rise at Mt. Qomolangma (Feng *et al*., 1998; Lin and Zhao, 1996; Liu and Chen, 2000). After comparing our research results with the annual mean temperatures in the study area during the period 1971–2009 based on the results of a high creditability, high-resolution study by the Climate Research Unit (CRU) of East Anglia University in the UK (Yang *et al*., 2009), we concluded that the inter-annual climate variation trends in both studies basically concurred ($R=0.753$, $\alpha=0.01$), although the temperature of the CRU study is a little lower than that of the observed station data (Figure 4).

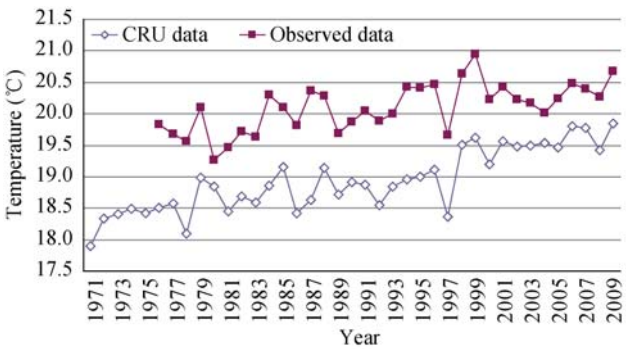

Figure 4 Contrast of annual mean temperature trend between the CRU data and the observed data from 1971 to 2009

We performed the Mann-Kendall abrupt change test on the annual mean temperature data of the CRU during the periods 1971–2009 and 1976–2009 to minimize the influence of partially lacking data for Nagarkot station on the analysis of the temperature tendency in the

period 1971–2009. It is seen in Figure 5 that there is a crossing point in the 1990s in both studies (Mann-Kendall abrupt change test on the annual mean temperature data of the CRU in the period 1976–2009 and the observed station data), which we cannot confirm to be the catastrophe point, as the location of the crossing point in the CRU data is beyond the critical line. Likewise, there is a crossing point in 1992–1993 beyond the critical line in the abrupt change test of the CRU data in 1971–2009, which we could not confirm either. In addition, the temperature has an upward tendency because we can see that the UF_k and UB_k figures are above 0, and the UF_k has passed the critical line since 1974, the initial year to present an obvious upward tendency. We could not confirm the catastrophe point. We took sequences of different lengths for the Mann-Kendall test and found a crossing point in the 1990s so that, subsequently, we could conclude that the crossing point in 1992 was the catastrophe point.

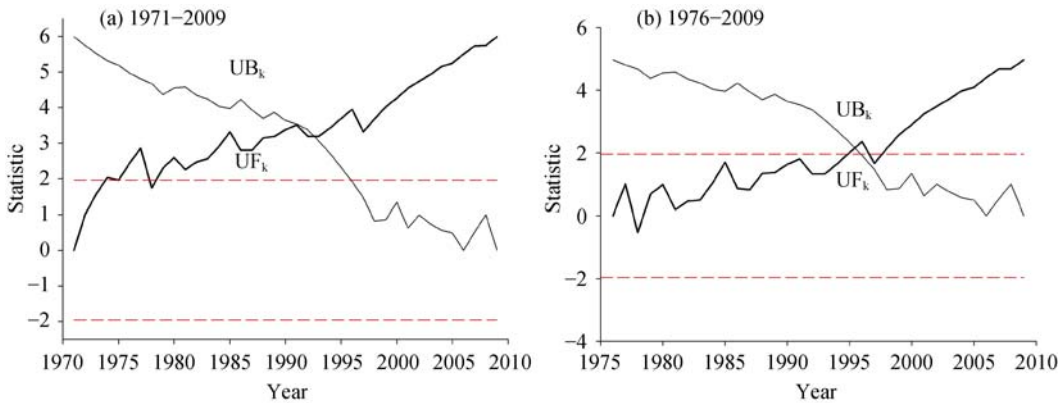

Figure 5 Mann-Kendall abrupt change test of annual mean temperature in the study area

Research shows that the global temperature rose dramatically twice in the period 1971–2004: the first time from 1976, and the second time from 1993 (Yang *et al*., 2006). Thus, we learned that the evident temperature rise in the study area was observed 1–2 years earlier than that which occurred on a global scale, while Yang et al. (2006) pointed out that the evident temperature rise on the northern slope of Mt. Qomolangma was observed 6 years earlier at least than the occurrence on a global scale. The difference above might be due to the fact that regions with low altitude were influenced by monsoons that weakened the dependence of climate warming on altitude and delayed the warming time.

In conclusion, it has been demonstrated that the temperature on the southern slope of Mt. Qomolangma has an obvious upward tendency in the last 40 years, and there was an enormous upward tendency in 1974 and 1992, no matter from which perspective the data were analyzed.

4.2 Characteristics of seasonal change of temperature

Due to the dominance of the Indian Ocean summer monsoon and the winter westerlies, in the Himalayas, it is cold and dry in winter while it tends to be warm and wet in summer. On the other hand, dominated mostly by the Indian Ocean monsoon without the influence of the winter westerlies, the average annual temperature on the southern slope of Mt. Qomolangma is 20.0℃ (Table 2), and the average temperature in January is 12℃, much higher than that on the northern slope (Yang *et al*., 2006).

Comparison of the inter-annual variation of monthly average temperature on the southern slope of Mt. Qomolangma between the 1970s and the 2000s revealed that a significant temperature rise was observed in February and September (Figure 6), when the increment passed 0.9℃. In addition, increments from June to December passed 0.5℃. We performed the Mann-Kendall test on this, and found that the temperature had been rising in every month, apart from March and April, since 1971 (Table 4). Even though we ignored the influence of lack of data for Nagarkot station in 1971–1975 on this whole tendency, we found that temperature had an upward tendency since 1976, even in September, when the increment passed 0.9℃, and the linear rate of rising temperature had already passed the significance level (α=0.01). In addition, the rising temperature tendency showed a lack of significant effect in February, but much more effect with higher warming amplitude from June to December when the increment passed 0.5℃. Figure 4 shows that the warming trend in 1976–2009 is more evident than that in 1971–2009, and there might be some connection with drastic fluctuations in the early 1970s, regardless of the lack of data for Nagarkot (Figure 2).

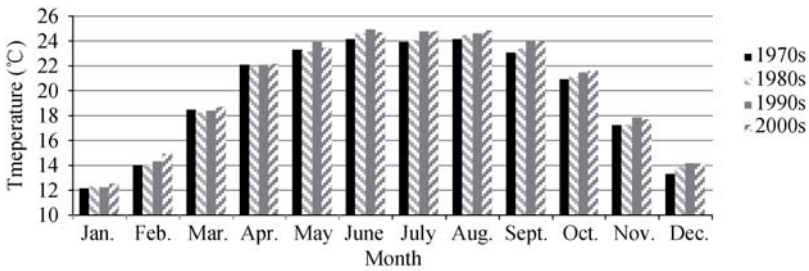

Figure 6 Decadal variation of monthly mean temperature in the study area from 1971 to 2009

Table 4 Mann-Kendall trend test of monthly mean temperature in the study area[a]

Month	1971–2009				1976–2009			
	Z_{mk}	Q_{median}	Significance	Trend	Z_{mk}	Q_{median}	Significance	Trend
Jan.	0.02	0.001		↑	1.25	0.019		↑
Feb.	0.59	0.013		↑	1.53	0.035		↑
Mar.	–0.36	–0.007		↓	0.98	0.020		↑
Apr.	–0.29	–0.007		↓	0.95	0.022		↑
May.	0.30	0.004		↑	1.29	0.018		↑
Jun.	0.64	0.003		↑	1.47	0.013		↑
Jul.	2.87	0.022	**	↑	3.65	0.033	***	↑
Aug.	1.29	0.011		↑	2.39	0.019	*	↑
Sep.	3.15	0.029	**	↑	3.97	0.041	***	↑
Oct.	0.96	0.014		↑	2.58	0.039	**	↑
Nov.	1.54	0.014		↑	2.33	0.023	*	↑
Dec.	1.84	0.019	+	↑	2.05	0.024	*	↑
Mean Temperature	2.03	0.014	*	↑	3.88	0.024	***	↑

[a] f(year) = Q × (year-firstDataYear) + B, B is not listed.

"***" represents α=0.001, "**" represents α=0.01, "*" represents α=0.05, "+" represents α=0.1, blank cells represent α>0.1.

4.3 Variation of inter-annual precipitation

The Tibetan Plateau has unique climate features by virtue of its unique geographical conditions (Zheng and Li, 1999). Research has shown that water vapor on the Tibetan Plateau comes from the Indian Ocean in summer and the Atlantic and Mediterranean by the prevailing westerly winds in winter (Sun, 1996).

As one of the regions with the maximum elevation range in the world, the southern slope of Mt. Qomolangma is a complex terrain vulnerable to the convection system of local weather. Therefore, the spatial variability of precipitation is huge, and the distribution of precipitation is also uneven there. There is no denying that precipitation varies from south to north. The Himalayas block water vapor from the Indian Ocean and Bay of Bengal from reaching the northern slope. Even though water vapor is derived from this source and arrives there, the amount of precipitation has already been severely depleted (TSET, 1975). The annual mean precipitation in this study area is 1729.01 mm, much higher than that on the northern side of Mt. Qomolangma. Among the stations, the highest precipitation in the study area is 2044.86 mm in Rampur, and the lowest precipitation is 999.46 mm in Dhankuta.

As we have stated above, the spatial variability of precipitation in this area is large because the water vapor source is closely linked to monsoon intensity rather than variation of terrain or altitude (Yao *et al*., 1995). For instance, from the perspective of inter-annual variation, we can see that the annual mean precipitation on the southern slope has increased slightly by 4.27 mm/a (Table 5 and Figure 7), among which the annual mean precipitation of the Jiri and Janakpur stations has increased clearly by 10.05 mm/a and 16.28 mm/a, respectively. Both of these passed the significance level test (α=0.01). For stations such as Chainpur, Dhakuta and Ilam Tea Estate, the annual mean precipitation has shown a slight decreasing tendency. It is worth noting that we performed the Mann-Kendall trend test on the data from Nagarkot, and found that the value of Sen's Slope Estimates, Q_{median}, is positive; thus, the variation trend is upward, but the linear trend is downward.

From the perspective of average precipitation in the decadal station and the inter-annual variation precipitation anomaly, precipitation in 1972 reached its lowest point in the 40 year

Table 5 Mann-Kendall trend test of annual average precipitation for the 10 meteorological stations in the study area[a]

Station name	Z_{mk}	Q_{median}	Significance	Trend	Linear increase rate (mm)
Rampur	0.97	4.570		↑	4.94
Simara	1.02	7.717		↑	9.30
Nagarkot	0.46	1.667		↑	–1.67
Jiri	2.73	13.205	**	↑	10.05
Janakpur	2.88	16.125	**	↑	16.28
Okhaldunga	0.52	1.794		↑	2.44
Chainpur	–0.16	–0.818		↓	–0.03
Dhankuta	–0.62	–1.400		↓	–1.40
Tarahara	1.48	7.347		↑	6.86
Ilam Tea Estate	–0.80	–3.400		↓	–4.11
Annual Average precipitation	1.33	5.199		↑	4.27

[a] f(year) = Q × (year-firstDataYear) + B, B is not listed.
"**" represents α=0.01, blank cells represent α>0.1.

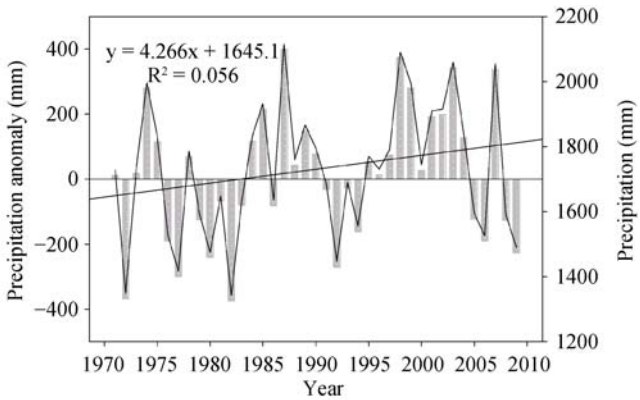

Figure 7 Annual average precipitation and the precipitation anomaly in the study area from 1971 to 2009

period and remained low in the period from the mid-1970s to the early 1980s. After that, it was abundant from 1984 to 1990 and reached a peak in 1987. There was a sharp decline in 1992, consistent not only with the trend of precipitation at Nyalam Station in China (Yang *et al*., 2006) but also with the conclusion that precipitation had shown an obvious downward tendency since 1990 (Shrestha and Kostaschuk, 2005). Then, precipitation started to increase from 1995 and only decreased in the periods 2005–2006 and 2008–2009.

On the basis of the Mann-Kendall abrupt change test of annual mean precipitation in 1971–2009, we can see that UF_k in 1971–1972 and 1976–1984 showed a period of declining precipitation in accordance with the trend of annual mean precipitation. There are three crossing points within the critical lines, but we cannot say that the precipitation variation is as obvious as the temperature variation in the long term as the UF_k and UB_k values near the crossing points basically do not cross the critical line (Figure 8). Shrestha *et al.* (2000) pointed out that the precipitation variation in this area might be linked to some extreme phenomena such as an El Nino Event (Southern Oscillation), sea surface temperature change or the eruption of a volcano.

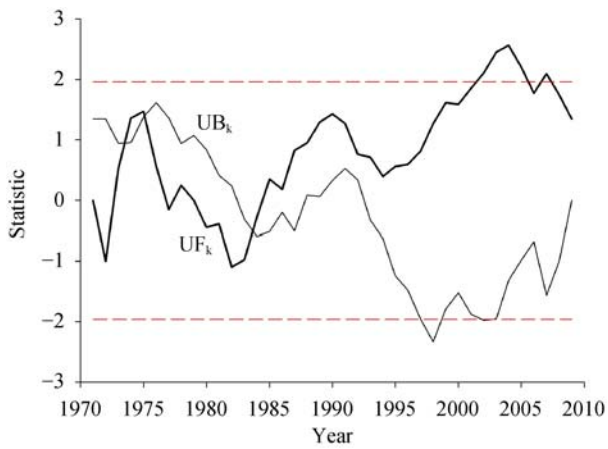

Figure 8 Mann-Kendall abrupt change test of average precipitation in the study area from 1971 to 2009

4.4 Characteristics of seasonal precipitation variation

The southern slope of Mt. Qomolangma, located at low latitude, has an obvious variation of

precipitation with season, where the climate is a monsoonal climate including a rainy season and a dry season obviously influenced by the Indian Ocean monsoons. Shrestha *et al.* (1999) divided the four seasons in this region into winter (from December of the previous year to February), premonsoon (from March to May), monsoon (from June to September), and postmonsoon (from October to November).

After performing the Mann-Kendall trend test on the monthly mean precipitation (Table 6), we determined that the monthly mean precipitation from March to August appeared to be upward, and it showed an opposite tendency in other months. Only in September had it passed the significance level test (α=0.05). This indicates that the feature of monthly mean precipitation variation is unclear. Furthermore, we performed the Mann-Kendall trend test on the seasonal variation according to the division of seasons made by Shrestha and found that the seasonal mean precipitation has a downward tendency only in the postmonsoon season. As regards the other seasons, it appeared to have an indistinct upward tendency. This indicates that the feature of seasonal variation in this area is unclear.

Table 6 The Mann-Kendall trend test of monthly average precipitation in the study area[a]

Period	Zmk	Qmedian	Significance	Trend
Jan.	–0.64	–0.090		↓
Feb.	–0.53	–0.088		↓
Mar.	0.35	0.093		↑
Apr.	0.46	0.252		↑
May.	1.11	0.893		↑
Jun.	0.07	0.112		↑
Jul.	0.36	0.747		↑
Aug.	2.40	3.147		↑
Sep.	–0.41	–0.362	*	↓
Oct.	–0.60	–0.425		↓
Nov.	–1.84	–0.201		↓
Dec.	–0.06	0.000	+	↓
Winter	0.00	0.001		↑
Premonsoon	1.60	1.052		↑
Monsoon	1.50	4.660		↑
Postmonsoon	–0.75	–0.564		↓

[a] f(year) = Q × (year-firstDataYear) + B, B is not listed.
"*" represents α=0.05, "+" represents α=0.1, blank cells represent α>0.1.

From the perspective of the decadal variation of monthly average precipitation (Figure 9), the variation was so complex that the precipitation in June can reach its maximum in the 1970s; the precipitation in July and September can reach its maximum in the 1980s; the precipitation in August can reach its maximum in the 1990s; and the fluctuation of precipitation in the remaining months is slight, contributing a small proportion to the annual precipitation. The precipitation increased markedly from 1984 to 1990 by virtue of the precipitation in July and September in the 1980s.

Figure 9 reveals that the study area is more influenced by the wet, warm flow from the Indian Ocean and the Bay of Bengal without an even distribution of precipitation in the seasons. The rainfall is mainly concentrated in April to October, especially in the monsoon

season (from June to September), when precipitation is about 78.9% of the whole year's total. Table 7 indicates that the precipitation variation of the premonsoon and monsoon period in this area within the past 40 years is relatively small and that of the postmonsoon and winter season is relatively large, as the C_v value of the premonsoon and monsoon period is obviously lower than that of the postmonsoon and winter season.

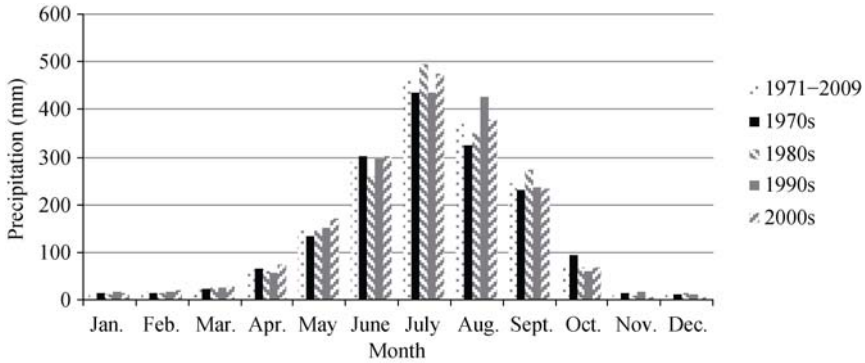

Figure 9 Decadal variation of monthly average precipitation in the study area from 1971 to 2009

Table 7 Variation characteristics of precipitation in the study area from 1971 to 2009

Eigen value	Period				
	Whole year	Winter	Premonsoon	Monsoon	Postmonsoon
Climatological normal (mm)	1729.01	41.06	240.62	1364.73	82.61
Percentage (%)	–	2.40	13.90	78.90	4.80
Coefficient of variation (C_v)	0.12	0.62	0.24	0.13	0.59
Maximum (mm)	2116.24	104.29	370.50	1722.90	211.00
Minimum (mm)	1342.00	4.53	100.90	964.90	10.00

The precipitation in the study area is relatively concentrated in the premonsoon and monsoon period, about 92.8% of the whole year's total. At the same time, the rainstorms could increase the risk of landslip, fulminant flood, debris flow and other significant damage owing to localized high precipitation. Thus, how to deal with the crisis and damage is worth considering.

5 Conclusions

Based on the analysis of temperature and precipitation data from 10 stations on the southern slope of Mt. Qomolangma in Nepal in the past 40 years, the results show the following.

(1) The annual mean temperature in this region from 1971 to 2009 is 20.0℃, the rising rate of annual mean temperature is 0.25℃/10a, and the temperature increase is more influenced by the maximum temperature in this region. On the other hand, the temperature increase on the northern slope of Mt. Qomolangma region is more influenced by the minimum temperature. In 1974 and 1992, the temperature here clearly rises 1–2 years earlier than the temperature rise on a global scale.

(2) Precipitation has an asymmetric distribution, and the annual mean precipitation is 1729.01 mm from 1971 to 2009. In this region, it shows an increasing trend by 4.27 mm/a, but this is not statistically significant.

(3) From the perspective of monthly temperature and precipitation, the temperature rises markedly in February and September, when the increment passes 0.9℃. The rainfall is mainly concentrated in the period from April to October, especially in the monsoon season (from June to September) when the precipitation is about 78.9% of the whole year's total.

(4) The dependence of climate warming on altitude is not clear in this region, whereas the trend of climate warming is obvious on the northern slope of Mt. Qomolangma. The annual mean precipitation in this region is much higher than that on the northern slope of Mt. Qomolangma region as a result of the dual influences of warm, wet flow and the Mt. Qomolangma barrier.

It is worth noting that there might be some errors in temperature and precipitation comparisons on the northern and southern slopes of Mt. Qomolangma due to the different observation methods used in Nepal and China, which we cannot evaluate quantitatively. However, the results represent the basic climate change tendency in the study area, which shows an upward rising temperature trend with an unclear change in precipitation, as the 10 meteorological stations were properly chosen with consideration for their geographical location and elevation.

By virtue of the indication of Mt. Qomolangma's climate change on future trends, we suggest building several new meteorological stations in the region with an elevation of above 4000 m in the range of Mt. Qomolangma, so as to understand the mechanism of climate change. The new stations will provide first-hand information on global climate change so that we can mitigate hazards such as regional flooding and glacier lake outbursts induced by climate change.

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