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Zongxing Li

Study on Climate Change in Southwestern China

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Zongxing Li

Study on Climate Change in Southwestern China

Doctoral Thesis accepted by
Cold and Arid Region Environment
and Engineering Research Institute,
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2. ***Li, Z.X.,** He, Y.Q., An, W.L., Song, L.L., Zhang, W., Norm, C., Wang, Y., Wang, S.J., Liu, H.C., Cao, W.H., Theakstone, W.H., Wang, S.X., Du, J.K. (2011): Climate and glacier change in Southwestern China during the past several decades. Environmental Research Letters, 6 (2011) 045404. (Reproduced with Permission)
3. ***Li, Z.X.,** Feng, Q., Zhang, W., He, Y.Q., Wang, X.F., Norm, C., An, W.L., Du, J.K., Chen, A.F., Liu, L., Hu, M. (2012): Decreasing trend of sunshine hours and related driving forces in Southwestern China. Theoretical and Applied Climatology, 109(2012):305–321. (Reproduced with Permission)
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5. Yang, X.M., **Li, Z.X. (corresponding author)**, Feng, Q., He, Y.Q., An, W.L., Zhang, W., Cao, W.H., Yu, T.F., Wang, Y.M., Theakstone, W.H. (2012): The decreasing wind speed in Southwestern China during 1969–2008, and possible causes. Quaternary International, 263(2012):71–84.
6. **Li, Z.X.**, He, Y.Q., Pu, T., Jia, W.X., He, X.Z., Pang, H.X., Zhang, N.N., Liu, Q., Wang, S.J., Zhu, G.F., Wang, S.X., Chang, L., Du, J.K., Xin, H.J. (2010): Changes of climate, glaciers and runoff in China's monsoonal temperate glacier region during the last several decades. Quaternary International, 218 (2010):13–28. (Reproduced with Permission)
7. **Li, Z.X.**, He, Y.Q., Yang, X.M., Theakstone, W.H., Jia, W.X., Pu, T., Liu, Q., He, X.Z., Song, B., Zhang, N.N., Wang, S.J., Du, J.K. (2010): Changes of the Hailuogou glacier, Mt. Gongga, China, against the background of climate change since the Holocene.Quaternary International, 218(2010):166–175. (Reproduced with Permission)

Supervisor's Foreword

This study mainly explores the response of climate change in the cold regions of China to the global changes against the background of the monsoon climate. Based on the observation data, this paper systemically researches the spatiotemporal characteristics of climate in Southwestern China in nearly 50 years, and reveals the driving mechanism of climate change. On this basis, this study also delves into the response of the glacier system to climate changes. The main findings in this study are as follows:

(1) Through analysis of the records of field observations and previous studies, some changes are found in Southwestern China, including sharp temperature rises, slight interannual variability of the precipitation, obvious extreme climate events, significant decrease in sunshine duration and wind speed. Meanwhile, a close relation between spatial variation of climate and elevation has been confirmed. The research constructs the temporal and spatial patterns of climate change in Southwestern China, which makes up for the deficiency of research on the climate change in the study region, and provides a scientific basis for the establishment of countermeasures about slowing down and adapting to climate change.
(2) Aiming at the complexity and uncertainty of climate change in Southwestern China, this study systemically explores the action mechanism between the large-scale atmospheric circulation system, the complicated topography, human activities, and regional climate changes. At the same time, this study reveals the temporal and spatial correlation mechanism between circulation systems and the regional climate changes, confirms the significant influence of the micro-climate effect caused by the topography change to the regional climate change, and evaluates the effects of human activities to climate change, especially the fast urbanization process. These results provide important information for accurate assessment on warming climate and predictions of climate change, and provide a favorable basis for a precipitation in flood season and a forecast of extreme weather. In addition, they improve the level of research on climate change in the cold regions of China, enriching and developing the scientific

theory of global climate change. In 2012, the results were published in a magazine called "Global and Planetary Change". It is particularly pleasing that the results attracted considerable attention compared with others of the same scope, and were included in ESI in 2013.

(3) On the basis of the analyses of observation data on glaciers in Southwestern China, this study analyzes the response of glaciers to climate change from three aspects (the morphology of the glacier, glacial mass balance, and the process of hydrology) so that on one hand, it is clear about the responding relationship between glacier morphologic changes such as area, length and ice surface microrelief, and climate changes; and on the other hand, the mechanism of the action of climate warming to balance between energy and matter is uncovered in order to illustrate the effects of acceleration of glacial ablation to climate change and investigate the influence of meltwater on the hydrologic system. These findings show the response of glaciers in Southwestern China to climate change for the first time, deepen and expand the theoretical research of glacier response, which can provide decision-making basis for the assessment of meltwater change and the specific countermeasures against the disaster from snow and glaciers against the background of global warming. This finding was published in Environmental Research Letters in 2011 and received extensive concern of the international academia. Teppei J. Yasunari, a researcher in NASA invited by the periodical editor, wrote a review article entitled "What influences climate and glacier change in Southwestern China?" Likewise, this finding also was included in ESI in 2013.

In theory, the achievements of this study are important to innovation and development, which have made a significant contribution to research on the response of climate in cold regions, glaciers, and human activities to a global change against the background of the typical monsoon climate, and have provided some scientific bases for predictions, countermeasures against disasters due to extreme weather, utilization of water, and the establishment of counterplans to slow and adapt to climate change. With the intensifying of China's western development, it is believed that these results will play a more important role in our country's sustainable development and ecological construction in Southwestern China.

Lanzhou, June 2014 Prof. Yuanqing He

Abstract

Southwestern China includes the Sichuan, Yunnan, and Guizhou Provinces, the Xizang Autonomous Region, and Chongqing Municipality, with an area of 2.333×10^6 km^2 accounting for 24.5 % of the total land area of China. The topography declines from west to east and from north to south. There are four geomorphic units: the Xizang Plateau, the Hengduan Mountains, the Sichuan basin, and the Yunnan–Guizhou plateau. Southwestern China is a typical monsoonal climate region, controlled by the South Asia monsoon but also influenced by the East Asia monsoon. In addition, it is influenced by the Xizangan Plateau monsoon and the westerlies. According to the Chinese Glacier Inventory, there were 23,221 glaciers in southwestern China, covering an area of 29,523 km^2, which is 50.16 % of the total glacier number and 49.69 % of the total glacier area in China. Climate research has concentrated mainly on sub-regions or single districts over the study region, however, there has been little systematic analysis of climate change in the whole region. Here, the temporal-spatial variation and its causes of climate change and the glaciers' response in southwestern China during 1961–2008 have been analyzed based on meteorological data from 110 stations, NCEP/NCAR reanalysis data, and the records of glacier changes from field observations and previous studies. The main conclusions of the paper are as follows:

(1) Annual and seasonal warming trends in southwestern China during 1961–2008 were significant. About 77 % of the 110 stations displayed statistically significant increases in annual temperature. The increase was more apparent in higher altitude areas than in lower ones. Warm–dry flow in summer affected the study region, and the southern extent of the winter monsoon has also been weakened, which in part accounts for some of the climate warming experienced, especially in the warmest years in southwestern China. Sunshine hours have a crucial influence on the SB temperature, especially during spring and summer, whereas this influence mainly is effective in winter at the Xizang Plateau-Hengduna Mountains and Yunnan-Guizhou Plateau. In addition, the increased net longwave radiation flux over most areas in the study region and

sea surface temperature in Western Pacific may have also made some contributions to temperature rise. Precipitation variations were less marked than those of temperature, generally showing weak decreasing trends during 1961–2008. About 53 % of the stations experienced a trend of increasing annual precipitation. Stations with precipitation increases were also mainly at higher altitudes mainly owing to the more water vapor flux, but the significance level was low. Northward penetration of the summer monsoon is limited by an increasing northeasterly air flow over the region, and northwesterly winds in the north prevent southward transportation of water vapor from the ocean in summer. In addition, the water vapor flux showed weak variation from the most precipitation years to the least years. These characteristics suggest a weakened monsoonal flow and vapor transportation in recent years, and also partly explain the inconspicuous precipitation variations over southwestern China. In addition, the strengthening Western Pacific Subtropical High also has had some influence on precipitation variations.

(2) Analysis of changes in 12 indices of extreme temperature and 11 of extreme precipitation at 110 meteorological stations in southwestern China during 1961–2008 revealed statistically significant increases in the temperature of the warmest and coldest nights, in the frequencies of extreme warm days and nights, and in the growing season length. Decreases in the diurnal temperature range and the number of frost days were statistically significant, but a decreasing trend of ice days was not significant. In a large proportion of the stations, patterns of temperature extremes were consistent with warming since 1961. Warming trends in minimum temperature indices were greater than those relating to maximum temperature. Warming magnitudes were greater on the Xizang Plateau and the Hengduan Mountains than on the Yunnan-Guizhou plateau and in the Sichuan basin, as confirmed by the decrease of the regional trend from west to east. Changes in precipitation extremes were relatively small, and only the regional trends in consecutive wet days, extremely wet day precipitation, and maximum 1-day precipitation were significant. These trends are difficult to detect against the larger interannual and decadal-scale variability of precipitation. On the whole, the number of rainy days increased on the Xizang Plateau and in the Hengduan Mountains, but the rainy strength has also increased at lower altitude areas. Analysis of large-scale atmospheric circulation changes reveals that a strengthening anticyclonic circulation, increasing geopotential height, weakening monsoonal flow, and vapor transportation over the Eurasian continent have contributed to the changes in climate extremes in southwestern China. The spatial distribution of temporal changes of all climate extreme indices in southwestern China reflects the obvious altitude dependence. Trend magnitudes of temperature extremes are significantly higher for flat stations, followed by summit, intermountain basin, and valley stations. It is obvious that the larger decreasing trend is in summit station, followed by flat

stations, whereas the greater increasing trend mainly occurred in valley stations in southwestern China, and the intermountain stations also showed lower decrease or increase. In addition, the mean contribution of the UHI effect on regional trends of urban stations for cold extremes and warm extremes were 16.0 % and 7.9 %, respectively, based on the preliminary evaluation.

(3) Sunshine-hours is one of the most important factors affecting climate and environment. Trends of temporal and spatial patterns in sunshine hours and associated climatic factors over southwestern China are evaluated for the period 1961–2008 based on data from 110 meteorological stations. The results show that southwestern China is experiencing statistically decreasing sunshine hours with a rate of 31.9 h/10a during 1961–2008, and the statistically significant decrease in sunshine hours mainly occurred in lower altitude regions, especially in Sichuan basin and Guizhou plateau. It showed the close temporal and spatial correlation between wind speed and sunshine hours, and the larger decreasing trend displayed declining trend on non-windy days than that on windy days. This is strongly suggestive of the fact that stronger winds lead to longer sunshine hours, further validating that wind speed directly and strongly influences sunshine hours in southwestern China. The relative humidity also has great influence on sunshine hours reflected by the significant correlation and the similar trend between the two variables. Sunshine hours also have high correlation with precipitation and surface downwards solar radiation flux, whereas the effect from urbanization on regional-scales trend was inconspicuous. The increased total cloud cover and cloud water content from the 1960s to 1970s, and the decreased relative humidity and increased surface downwards solar radiation flux between the 1980s and 1990s have also influenced the variation in sunshine hours. In addition, the clear local influence of topography can be reflected by the decreasing magnitudes increased from summit to flat stations.

(4) Daily wind speed data from 110 stations in southwestern China were analyzed to determine trends, spatial differences, and possible causes. There was a statistically significant decrease of 0.24 m/s/10a in the annual mean wind speed during the period 1969–2008. The decreasing trend was faster (0.37 m/s/10a) during 1969–2000. Between 2001 and 2008, there was a significant increase. The pattern of seasonal changes was similar. Stations with stronger, significant decreasing trends were mainly on the Xizang Plateau, the Hengduan Mountains, and the Yunnan Plateau, and stations with significant increasing trends were mainly in the Sichuan basin, indicating the influence of altitude on wind speed. Surface wind speeds in southwestern China have been affected in recent years by both the changed large-scale atmospheric circulation and the regional and global warming. The analysis has confirmed that the decreasing wind speed during 1969–2000 was caused mainly by the decreasing monsoonal circulation and Westerlies, and the strengthening latitudinal wind speed has made some contributions to the increasing wind speed after 2000. And what is more, the

strengthening Xizangan monsoon has also made some contributions to wind change, which indicates lower wind speeds were related to increased temperatures, particularly to a rise in the minimum temperature in recent years. The weak wind speed may also be caused by the asymmetric decreasing latitudinal gradients of surface temperature and pressure gradient during 1969–2008. The data indicated a positive correlation between wind speed and sunshine hours suggesting another possible influencing factor. Topographical influences are evident in the higher annual and seasonal trends at summit and intermontane basin stations and the lower trends at valley stations. In addition, a minor influence from urban effect on wind speed has also been found.

(5) Glaciers are distributed in Nyainqntanglha Mountains, Himalayas, Tanggula Mountains, Gangdise Mountains, and Hengduan Mountains in southwestern China. Under temperature rise, especially the increasing warming with altitude recorded by 110 stations, ice cores, and tree rings in southwestern China, four characteristics of glacier variations occurred during the recent decades: the fronts of 32 glaciers and areas of 13 glacial basins have retreated, mass losses of ten glaciers have been considerable, glacial lakes in six regions have expanded and meltwater discharge of four basins has also increased; the typical glacier shows the accelerative ablation. The remarkable regional differences in glacier change in southwestern China may be caused by the following two factors: differences in temperature and precipitation; and differences in glacier location, scale, and frontal altitude. As response to climate change, eight monsoonal temperate glaciers were in stationary or advancing between the 1900s–1930s and the 1960s–1980s, and were in retreat from the 1930s to the 1960s and from the 1980s to the present. In other words, it is evident that the glacier retreat stages are in the warm and wet phases, and vice versa. The accumulated mass balance in Hailuogou basin is −10.83 m water equivalent in the past 45 years, an annual mean value of −0.24 m water equivalent, and 29 years are negative mass balance year, showing that it suffered a sustained mass loss of snow and ice in the period 1959/1960–2003/2004. And what is more, the warming climate has had an impact on the hydrological cycle at glacial area. As the glacier area subject to melting has increased and the ablation season has become longer, the contribution of meltwater to annual river discharge has increased, which can be reflected by the increased runoff in the downstream region of the glacial area of the Yanggongjiang basin during 1979–2003 and Hailuogou basin during 1999–2004, and the mean contribution of the runoff in the downstream region of the glacial area to the whole basin are 35.8 % and 54.7 %, respectively. The earlier onset of ablation at higher elevation glaciers has resulted in the period of minimum discharge occurring earlier in the year, and seasonal runoff variations are dominated by snow and glacier melt. The increased amplitude of runoff in the downstream region of the glacial area is much stronger than that of precipitation, resulting from the prominent increase

of meltwater from glacial region in two basins. As the acceleration of ablation velocity, the lengthening of ablation period and the extension of ablation area, changes of internal and upper surface morphology also occurred characterized by many ice-clefts, glacier collapses, decrease in thickness, enlargement of glacial caves, and reduction in the size of seracs, providing evidence of the response to climatic warming in recent years. However, it is difficult to discuss the quantitative relationship between climate change and glacier behavior in southwestern China owing to the limited observation in the glacial accumulation areas and the complexity of climate change and glacier dynamic response.

Keywords Climate change · Glaciers · Southwestern China

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Contents

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8. 2010.1–2011.12, Project for Incubation of Specialists in Glaciology and Geocryology of the National Natural Science Foundation of China (11J0930003): study on climate change and glaciers response in Southwestern China, 40,000 RMB, project director.

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Honors and Awards (only in postgraduate stage)

Outstanding post doctor of Cold and Arid Region Environment and Engineering Research Institute, Chinese Academy of Sciences, 2013;
Outstanding doctoral dissertations of Chinese Academy of Sciences, 2013; Outstanding graduates of Graduate University of Chinese Academy of Sciences, 2012; Chinese Academy of Science (CAS) president special award, 2012;
The BHPB Scholarship of Graduate University of Chinese Academy of Sciences, 2011;
Excellent League member of Chinese Academy of Sciences, 2011;
Young Researcher New Star Scientist Award in the "2010 SCOPUS Young Researcher Award Scheme for Climate Change", 2010;
The "Lu Jiaxi Scholarship for Excellent doctoral student", 2010;
The "Zhu Li Yue Hua Scholarship for Excellent doctoral student", 2010;
The Tri-excellent student of Chinese Academy of Science, 2010;
Second-Class of Physical Science Prize in Gansu Province, 2009;
The Chinese Academy of Science (CAS) president award of excellence", 2009;
The "Liu Tungsheng Scholarship for Earth Sciences", 2009;
Second-Class Scholarship of the Third "ORGANO PRIZE", 2009;
Third-Class Scholarship of the second "ORGANO PRIZE", 2008;
"Excellence Award" paper in the doctoral consortium, 2008.

Social Service

As the reviewer for Climate Dynamics, International Journal of Climatology, Quaternary International, Journal of Earth Sciences, Journal of Geographical sciences, Mountain Research and Development, Fresenius Environmental Bulletin, Acta Geographica Sinica and Scientia Geographica Sinica.

Chapter 1
Introduction

1.1 Background and Significance of Topics

> "Climate Change is not only an environmental issue, but also a development issue, in the final analysis it is the development problem." Climate Change Research, a hot spot in today's international scientific research field, is related to national survival and development space. Thus, a thorough study on climate change in southwest China is helpful to have a comprehensive understanding of the process of the the climate change in this region and the response of the global change. It will raise the level of the climate change research in the area and provide a scientific basis for the establishment of countermeasures to slow and adapt to climate change.

According to the IPCC's fourth assessment report (2007), the observed results including rising global mean temperatures and SST, a wide range of ice and snow melt, and the global mean sea level rise in the recent hundred of years, etc., showed that the tendency of climate warming has becoming more and more obvious. Its concrete manifestation are presented as follow:

(1) In the last 100 years, global mean temperatures increased 0.74 °C, and there are 11 years in top 12 warm years between 1995 and 2006. (2) Sea level rise is echoed by the trends of the climate warming. The global mean rate of sea-level rise is 1.8 mm/a; since 1993, the mean rate has increased to 3.1 mm/a. Reasons of resulting in such status are complicated. Thereinto, the thermal expansion and the melting of glacier, ice cap and polar ice sheets is deep prime matter. (3) The snow and the see ice area significantly reduced. It is showed by the satellite data that since 1978, the arctic sea ice sheets has been shrinking at a rate of 2.7 %/10 a. Indeed, the rates of retreat is more significant, 7.4 %/10 a, and mountain glaciers and snow cover area of both the Northern and Southern hemisphere also show a trend of shrinking. (4) From 1900 to 2005, the precipitation in the east area of North and South America, Northern Europe, Northern Asia and Central Asia increased significantly, but in Sahel, Mediterranean, South Africa and parts of South Asia, precipitation is reducing year by year. It's on the cards that since 1970s, the affected area of the global area have expanded. (5) Over the past 50 years, the frequency of cold day, cold night and frost in the most of the land had reduced. Whereas, warm day and warm night had

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become more frequent, followed by more severe precipitation events, regional floods, and strong storm. (6) The observed data confirmed that since around 1970, tropical cyclone activity of the North Atlantic has been increasing. (7) The observations of the land and the most of ocean demonstrate that a lot of natural systems are affected by regional climate change, especially the rising temperature. Along with the change of the snow, glaciers and permafrosts, the size and number of glaciers and lakes continue to go up, and the instability of the mountain and the permafrost is increasing, even some changes in ecosystems of both North and South pole emerge. The obvious augment of river runoff appeared in the rivers supplied by glaciers and snow and the preact of maximum flow in spring have made an impact on some hydrological systems. In addition, the warming of rivers and lakes also affect their thermal structure and water quality. (8) In the terrestrial ecosystems, with the earlier arrival of spring events, the growing range of the plants and the animals goes toward the poles and high altitude area. These changes are related to the recent warming. Similarly, in some marine and freshwater systems, the migration and changes of breeding ranges of the algae, plankton and fish are related to the warmer water and the related changes of ice caps, oxygen content and circulation (IPCC 2007). Moreover, in the 20th century, the temperature under 200–1,000 m deep ascended 0.5 °C, and about 80 % of the borehole temperature is rising (Huang et al. 1997; Pollack et al. 1998). According to the analysis of the sounding data, it was found that since 1958, the general warming trend of the underlying level of the troposphere are nearly similar to that of the strata, warming approximately 0.1 °C/10 a (Gaffen et al. 2000). The results got through the satellite microwave verified that the warming trend of the underlying level in troposphere is 0.05 °C/10 a (Brown et al. 2000). Over half a century, the tropospheric atmospheric temperature in the southern hemisphere showed a trend of growing, with temperatures range rising from low to high gradually. Thereinto, the heating rate of the 1,000 hPa in the ground floor is 0.013 °C/a, the heating rate of the 500 hPa in the middle of troposphere is 0.019 °C/a, the warming rate of 300 hpa in the upper troposphere is 0.036 °C/a.

In the recent hundred of years, as the main characteristics of climate changes, warming have taken place in many sections of China: (1) From 1905 to 2001, China's annual mean temperature appeared to be on the rise. It increases by 0.79 °C in 1997; the 1940s and after the middle of 1980s are two special periods, in which the temperature obviously is on the rise. (2) From 1905 to 2001, the change in China's mean annual precipitation is not very significant. It decreases by 8.6 mm in 1997; more precipitation occur in the 1910s, 1930s–1940s and 1980s–1990s, whereas less precipitation occur in other periods (Country Assessment of Climate Changes 2007). (3) In the recent 50 years, the frequency and intensity of China's main extreme weather and climate events emerge significant changes, mainly showing as the worsening drought conditions in north and northeast of China and the aggravating flood over the middle and lower reaches of the Yangtze River and China's southeast area. Since 1990, the annual precipitation is more than ordinary year, which resulted in 'southern flood and northern drought' and frequent drought and flood damage (Country Assessment of Climate Changes 2007). (4) During the period of 1950s–1990s, the mean rate of sea-level rise of china's coastal area is

2.5 mm/a, which is higher that the global mean from 1993 to 2001, the rate of sea-level rise of Yellow Sea and East China Sea is 5–8.6 mm/a, which is slightly higher than the global mean. In the book "The Evolution of China's Climate and Environment" published in 2005, it was showed that there have experienced 19 consecutive warm winters in China from 1986/1987. Among them, the temperature in 1951 increased significantly. From the change of the precipitation, although the national mean precipitation in nearly 50 years did not show obvious tendency, there are significant regional differences. The rainfall in the middle and lower reaches of the Yangtze river and west parts of Northwest China increased significantly. On the contrary, the rainfall in the southeastern Northeast China, North China and eastern parts of Northwest China decreased significantly. Obviously, it means that precipitation intensity is likely to increase along with the reduce of precipitation days all over the country. Ge et al. (2011) analyze the rate of the temperature variation over the past 2000 years by the comparison of every hundred years and every 30 years and that of the past 500 years by the comparison of every 10 years. The results indicate that from the national mean, the heating rate is (0.6 + 1.6) °C/100 a on the hundred scale during the 20th century; in the past 500 years, the maximum heating rate happened in the he process of transformation from the Little Ice Age to the warm period of 20th century is (1.1 + 1.2) °C/100 a, which may be the maximum in the past 2000 years. On the 30 scale, although the national mean temperature rises significantly during the 20th century, the maximum heating rate is still less than that of the historic time, which occurred at the end of Little Ice Age and 270–320 A.D., respectively. On the 10 scale, the warming at the end of the 20th century is very obvious, but it is not unprecedented in the past 500 years, and its time, length and range exist regional differences. During the 20th century, the fastest temperature reduction of the national mean on the 10 scale occurred in 1940–1950, the rate of which is (0.3 + 0.6) °C/10 a and is similar to that 20th century ago. The maximum cooling rate of each district during the 20th century does not exceed the maximum one of historical periods. Under the background of global climate changes, what changes have the climate of Southwest China experienced in recent years? What are the characteristics? Which factors will influence it? The inquiry of above questions will be helpful to have a comprehensive understanding of the process of regional climate change and the response on the global change, to further improve the area's climate change research, to raise the level of the climate change research and to provide scientific basis for the establishment of countermeasures to adapt to and slow climate change.

Glacier is the main component of the cryosphere, is the key link of water cycle, is the amplifier and indicator of climate change and is the important resource to support regional development. So systematacially exploring the response characteristics of glacier to climate change in Southwestern China contributes to have a comprehensive understanding of the influence of climate on the glacier system, to deepen and extend the theoretical study of the glacier response, and to provide theoretical basis for assessing the ice-snow change, the prevention and control of ice-snow damage as well as the rational development of ice and snow tourism resources and so on in the context of global climate change.

Under the background of climate warming, most mountain glaciers have been in the shrinking state, particularly from the end of 1980s, which shows obvious response to global warming and has a significant influence on the runoff, water resources use, ecological environment evolution, rising sea levels and so on (Dyurgerov 2003). According to the IPCC's fourth assessment report (2007), from 1960/1961 to 2003/2004, net material flat of global mountain glaciers and ice caps loss $1,550 \times 10^8$ t every year. In 1993–2003, the sea level rises 7.7 mm, as a result of widespread melting of glaciers and ice caps. The monitoring results from World Glacier Monitoring Service (WGMS) indicate that between 1980 and 2005, the global ice thickness reduced by an mean of about 10.56 m, and the shrinking trend is accelerating. The glacier in China also presents signs of accelerating melting. In the past 40 years, the glacier area retreat by a mean of 7 %, 3,790 km^2. The glaciers reserves are equivalent that the annual ice thickness thin 0.2 m (Qin et al. 2005). The related studies show that under the background of global climate change, the trend is more and more apparent since 1980s, which is showed by the accelerating reduction of glacier area and volume, the quite sharp material loss and the quickening water cycle due to the glaciers melting (Chiew and McMahon 1994; He et al. 2003). Dyurgerov's study (2003) on material balance of about 300 mountain glaciers all over the world, the altitude of equilibrium line, the accumulation ratio of area and the change of volume melt in 1961–1998 shows that since 1980s, the area and volume of glacier is sharply decreasing.

The glacier area in Alpine shrank 35 % in 1850–1975. By 2000, this proportion had risen to 50 %, and the shrinking rate of the area is about five times as many as 1850–1975 and 117 times as many as 1975–2000. It is clear that the retreating rate is significantly accelerated, which is likely to lead to the change of natural hazards, such as the landscape pattern of historical period, the slope stability, the water cycle, the river sediment loads and so on (Mitchell 2006). The glacier area in South America has shrank from 2,700 to 2,800 km^2 in 1950–1980 to less than 2,500 km^2 at the end of 20th century (Katz and Brown 1992). The glacier retreat of Andes has posed a threat to the supply of drinking water, irrigation and power generation. It is also likely to form a river flood and lake dam, then trigger more serious disasters (Katz and Brown 1992). Based on the climate prediction results, the ice reserves in the northern hemisphere will reduce by an mean of 50 % by 2050. Robinson (1999) demonstrates that since 1966 the annual mean snow cover area in the northern hemisphere shows a trend of decrease and reduces about 10 % since the middle of 1980s. Parkinson et al. (1999) by the satellite observations find that since 1973 the Arctic sea ice area also showed a trend of decline, and may reduce 2.8 % since 1978. During 1968–2002, Antarctic sea ice has a decreasing trend, the north bound of which retreat 0.1/10 a to south. Ma et al. (2004), Haeberli et al. (1998) said, according to the data from the World Glacier Monitoring Service (WGMS), the shrink rate is slow before the 20th century, but the shrink rate begin to accelerate after 20th century. Up to the end of 20th century, many glacier retreat 1–3 km. In the recent 20 years, the tropical snow-line rise about 100 m, which is equivalent that temperature increased 0.5 °C (Haeberli et al. 1998). The data analysis of ice clouds of National Aeronautics and Space Administration (NASA) and ICESat think that the sensitivity of the glacier change is underestimated by scientific community under the background of the warming. The melting speed of glacier in Greenland and Antarctica is faster than expectation, and the range of thinning is expanding greatly, particularly on the edge of the sea, where the glacier is rapidly melting. The thickness of some glaciers in the Antarctic fall 30 ft. (9.1 m) every year since 2003, even the decline rate in 2003–2007 is 50 % faster than in 1995–2003. Among 111 glaciers in Greenland, there 81 glaciers be melting quickly. The mean thinning speed of glacier is 0.84 m/a, the shrinking rate of which exceed 100 m/a. The thinning speed of some glaciers in the Antarctic Amundsen bay have exceeded 9.0 m/a (IPCC 2007).

Since the beginning of the 20th century, the glaciers in China gradually transfer to the shrinking state, and step into full retreat stage. From the beginning of the 1900s to 1920s–1930s, most glacier of the Qinghai-Xizang Plateau are in a relatively stable state, even forward phase; in 1940s–1960s, the glaciers are in severe recession period; during 1970s to 1980s, they stabilize or appear to a small forward; in the late 1980s–1990s, the strong retreat phenomenon of plateau glaciers is widespread greatly, and the retreat rate shows a trend of increasing in recent year (Pu et al. 2004). Since 1966 when the records began, most glacier in the middle section of Himalayan mountain have been in a severe shrinking state (Ren et al. 2003). The glaciers in the Tarim River Basin is as a whole the shrinking state in 1963–1999, while there are also a few one appearing forward phenomenon. When the changes led by the ice retreat offset, the area of glacier basin and reserves reduce 1,307.2 km^2 and 87.1 km^3 respectively, which accounting for 6.6 and 3.8 % of the total in 1963. The ice reduction equal to 783.5×10^8 m^3 water equivalent, and it decrease by an mean of 21.8×10^8 m^3. The results of measuring the scope of glacier in Xizang mountains since 1915 interpret that all the glaciers are in the shrinking state, the area of which have reduced 4719 km^2, the reserves of which have reduced 6,195 km^3, and the length of which have shortened 1,095 m with the sea level of end rising 158 m. In this period, the reduction of the area and reserves account for 4.3 and 4.4 % of the total in 1915 (Liu et al. 2005a, b).

By analyzing the distribution of the glacier of western Nianqingtanggoulashan Mountains interpreted by Landsat ETM^+ (2000), the finds are that there are 870 glaciers in this mountain; the area and the reserves have reduced 5.7 and 7 % in recent 30 years. Among them, the glacier whose area is 1–5 km^2 is the fastest, which account for 56.7 % of total areas. There are a little differences between the southeast and the northwest of Nianqingtanggoulashan Mountains. The area of glaciers in the southeastern mountains decreases 5.2 %, but the area of glaciers in the northwestern mountains decreases 6.9 %. The length in northwest slope reduces 305 ± 36 m, and the shrinking rate is 10.2 ± 1.2 m/a and the area has retreated 2.6 % (Shangguan et al. 2004). The majority of glacier in the Yulongkashi River are as a whole in a stable state in 1970–2001, while the minority have a severe shrinking trend. To be specific, during 1970–1989 glaciers showed a trend of expanding, and the area and reservers increase respectively 1.4 km^2 and 0.4781 km^3, which may account for 0.12 and 0.19 % of the amount in 1970 in study area. However, compared with 1970, the area and reservers during 1989–2001 reduce 0.5 and 0.4 %, respectively. But this region has the minimum glacier change in the arid region of northwest china

(Shangguan et al. 2008). The mean annual water material balance of Wu River No.1 glacier is −188.6 mm (about $-34.6 \times 10^4 m^3$), and the cumulative amount of material balance achieve −7,925 mm, which means the thickness of ice thins more than 8 m. Cumulative loss reach 1452×10^4 m^3. The glacier areas decrease 0.22 km^2 in 1962–2000 and present a accelerating decrease trend. From 1962 to now, the eastern end of Wu River No.1 glacier has retreated 168.95 m, western end shrinks 185.23 m (Li et al. 2003a, b, c). The number, area and reservers of glaciers in Xizangan PumQu Basin have decreased 10, 9 and 8.4 % from 1970 to 2000 (Jin et al. 2004). In 1969, the area in Gradando is 5.2 % less than that in peak of Little Ice Age, and 1.7 % more than that in 2000. From 1969 to 2000, the maximum shrink rate is 41.5 m/a and the maximum forward speed is 21.9 m/a, which means that the glaciers in this area basically in a stable state; the shrink rate is not very sharp with the exist of forward (Lu et al. 2002). In the 30 years from 1970 to 2000, the retreat amount of glaciers in Malan Shan 30–50 m, and the mean annual retreat amount is 1–1.7 m (Pu et al. 2001). The glacier end of Naimona'nyi Feng shrinks at the rate of about 5 m/a from 1976 to 2006; the backward speed reach 7.8 m/a in 2004–2006, which perform accelerating back tendency recently (Yao et al. 2007). The study of Li et al. (2008) on the glacier change in China indicates that the area of 18 of 19 glaciers basin come to appear shrink. Among them, the atrophy range of 9 basins located in Marine glacier valley are biggest. What is the response characters of glacier in Southwestern China in the context of climate change? How do the ice length, material balance and ice-snow runoff response to climate change? The answers to above questions have a significant meaning to access the changes of the regional ice-snow resources under the background of global warming and the influences on regional development, and will contribute to the reasonable development and protection of ice and snow resources.

The total area of Southwestern China accounts for a quarter of total land area, which located in the transition zone between the first ladder and the second ladder. The topography of Southwestern China is varied and complicated where has typical monsoon climate and is the main distribution area of glacier. A systemic study on the climate change in Southwestern China will contribute to providing evidence for the regional ecological construction, sustainable development, and resource development.

Southwestern China includes the Sichuan, Yunnan, and Guizhou Provinces, the Xizang Autonomous Region and Chongqing Municipality (directly under the central government), with an area of 2.333×106 km^2, accounting for 24.5 % of the total land area of China (Fig. 1.1). It located in the transition zone between the first ladder and the second ladder, and is the one of most complicated terrain sections, including plateaus, mountains, hills, basins and plains. The topography declines from west to east and from north to south. There are four geomorphic units: the Xizang plateau, with an mean elevation of 4,500 m and many higher mountains; the Sichuan basin, with an elevation range of 300–700 m; the Hengduan Mountains, consisting of a series of north–south-oriented mountain ranges with altitudes of 4,000–5,000 m and major rivers; and the Yunnan–Guizhou plateau with altitudes of 1,800–1,900 m (Zhao and Chen 1999). Southwestern China is a typical monsoonal climate region, controlled by the South Asia monsoon but also influenced by the

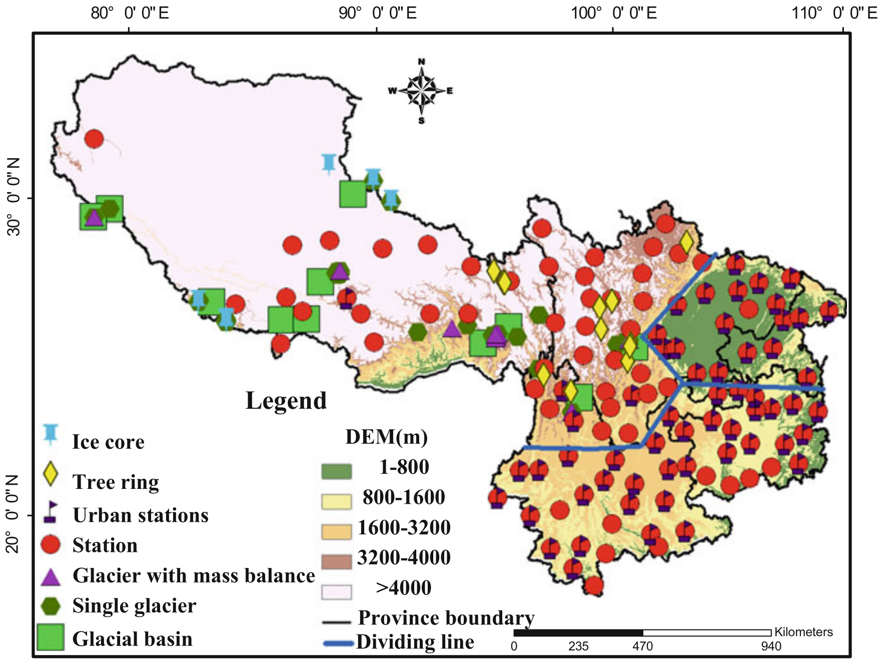

Fig. 1.1 The Southwestern China

East Asia monsoon in summer. It is also influenced by the Xizangan Plateau monsoon and the westerlies.

There are various types of climate in this area mainly with subtropical and temperate climate, so a variety of natural vegetation and ecological landscape can be found here. The climate of Xizang Plateau is alpine plateau climate; There is subtropical and tropical monsoon climate in Yunnan-Guizhou Plateau, where many places have four seasons of spring; Sichuan Badin has a subtropical monsoon climate and Hengduan Mountains have the temperate and subtropical monsoon climate with significant vertical zonality. Southwestern China is one of the major glacier area due to the towering terrain and the typical monsoon climate. According to the Chinese Glacier Inventory, there are the most glacier of China in the Xizang Autonomous Region, 22,468 glaciers, the area of which account for 49.02 % of the total glacier area in China. In addition, there are 684 glaciers in Sichuan (1.48 % of total area in China) and 69 glaciers in Yunnan (only 0.15 % of total area in China). It is worth mentioning that the distribution area of glaciers, the numbers and the volumes in Southwestern China all account for half of total amounts in China (Shi et al. 2000). Southwestern China is rich in the water resource. Its hydropower resources reserves is first all over the country, and the minable potential accounts of 68 % of China. At the same time, there are enough rainfall, the annual precipitation of which is treble as much as the national mean. Additionally, Southwestern China is a region where several minorities live together and produce special customs and culture. Therefore, a systemic study on the climate change in Southwestern China will contribute to providing evidence for the regional ecological construction, sustainable development, and resource development.

Current climate change researches mainly concentrated on some province or some geomorphic unit, and most researches are wanting in further exploration of influencing factors of climate changes. So, further exploring the climate change and its influencing factors will the shortage of these researches in this area and further enrich the related theory of the researches.

During 1961–2006, precipitation in winter and spring increased, while the annual precipitation and other seasonal rainfall reduced (Tao and He 2008). A rise in temperature and an increase in precipitation have produced important influences on river runoff of Southwestern area, even there is more evident difference in the climate and runoff between the monsoon and non monsoon period (You et al. 2005). Wan et al. (2008, 2009) analyze at length the spatial and temporal distribution of temperature in Longitudinal Range Gorge Region (LRGR) of Yunnan and the change of precipitation n LRGR of Southwestern China. The study of Fan et al. (2010) on the climate change of Yunnan Plateau in 1961–2004 shows that the annual mean temperature increased at the rate of 0.3 °C/10 a, and the rising rate of temperature between in winter and summer are 0.33 and 0.26 °C/10 a. The analysis proves that the diurnal range of temperature significantly reduced. The magnitude of warming of minimum temperature is significantly greater than that of maximum temperature and the most magnitude of warming mainly occur in south and northwest of study area. The air temperature and precipitation in 1960–2008 in Hengduan Mountains increase at the rate of 0.15 °C/10 a and 9.09 mm/10 a, respectively (Li et al. 2010b).

The precipitation of the Sichuan Basins is relatively stable in 1958–2000, and in recent 40 years, the trend of long-term precipitation variations significantly reduce in the west part of basin (Shao et al. 2005). Chen et al. (2008) confirmed that the air temperature and precipitation of the Sichuan Basins show a trend of falling down, and the magnitude of falling in temperature is 0.029 °C/10 a. The high incidence area of extreme high temperature event (EHTE) in 1961–2006 in Sichuan-Chongqi area is located in the east of 103 °E. In the long run, the frequency of EHTE has a sharp growth in northwestern Sichuan Basins; a downtrend will occur in the southeast of Sichuan Basins; a slight uptrend will occur in the southwest of the West Sichuan Plateau and southern mountains (Hu et al. 2008). In 1961–2007, the temperature of Sichuan Basins is a uptrend, and the magnitude of minimum temperature is higher than that of the mean temperature and the maximum of temperature. The temperature of Sichuan Basins begin to rise from about 1995 and the precipitation begin to reduce from 1990. It is clear that the reduction of precipitation from July to October is the main reason of reduction of annual precipitation (Chen et al. 2010a, b, c). There is a great discrepancy between the frequency of extreme precipitation events and the precipitation distribution of Sichuan Basins. In the long term, the frequency of extreme precipitation events in the west of Sichuan Basins has a slight downtrend and a uptrend in the east part of Chongqing, the linear trend of others area is quite obvious expect them (Hu et al. 2009).

Tang et al. (2009) preliminarily analysis and research the change trend of total cloud cover in the Xizangan areas. The results indicate that total cloud cover was significantly reduced over the most of Xizangan regions, among which the loss of the western Naquzhong is maximum, up to 2.32 %/10 a. There is a positive correlation with total cloud cover, precipitation and relative humidity (RH); while there is a negative correlation with total cloud cover, sunshine hours, mean temperature and the diurnal temperature range. Hurst index demonstrate that the total cloud cover decrease over the most of Xizangan regions, and this trend will not change in a short period. The annual mean temperature rise at the rate of 0.26 °C/10 a, which is sharply higher than rising rate of China and world. And the diurnal temperature range sharply decrease expect summer (Du 2001). In 1971–2000, the change of annual precipitation presents a positive trend. The inclination rate of precipitation is 1.44–66.6 mm/10 a. Annual changes of the number of precipitation days have a negative trend in Ngari Prefecture and Nyingchi Prefecture, whereas it is a positive trend in the midwest of Nagqu prefecture and the north of Chamdo Prefecture (Du and Ma 2004). During 1971–2005, the maximum potential evapotranspiration in Xizang Plateau reduce, which is −24.0 mm/10 a. The seasonal trend also present reduce, especially winter. However, surface moisture index sharply increase, which is 0.04/10 a. Particularly in recent 25 years, the uptrend is greatly enlarging. So after study, a conclusion can be given that the increase of precipitation and relative humidity and the decrease of the diurnal temperature range is the main reason of making humid index increase (Du et al. 2009).

Wang et al. (2010) points out that the distribution of threshold value of the precipitation and extreme rainfall in Yunnan-Guizhou Plateau has a great difference during flood season in 1961–2007. The threshold value has little relationship with amount of precipitation during flood season, but has a negative relationship with altitude.of stations. The chang trend in rainfall is not obvious, but the rainy days reduce sharply. In 1961–2006, 84.2 % of stations appeared a trend of reduced visibility. The maximum amount of reduction is −11 km/10 a and the minimum is −1 km/10 a. The reducing mean inclination rate of climate was 0.96 km/10 a in 1961–1979 and 1.6 km/10 a in 1980–2006. The mean visibility of plateau reduce to 27 km from about 34 km in 1960s. It is proved that the reason of the decrease of visibility and the increase of extinction have a close relationship with the pollutants concentration discharge by human (Zheng et al. 2010a, b). The sunshine days of 85 % of stations reduce in 1961–2005 in Yunnan-Guizhou Plateau. The reduction range is between 12.2 and 173.7 h/10 a. It is showed that the increase of plateau tropospheric aerosols and the pollutant concentration is the main reason of the decrease of sunshine days (Zheng et al. 2010a, b; Yan et al. 2004, 2005).

Ma et al. (2006) confirmed that a series of changes appeared after 1940s in Qinghai-Xizang Pleteau, Western Sichuan Plateau and Yunnan-Guizhou Plateau, for example, temperature rise, precipitation and humidity increase. While the temperature in the southwest and northeast of Sichuan Basin has an obvious downtrend, which indicate that the climate change of Southwestern China is out of sync with the global warming. Studies have shown that the precipitation resource of the plateau area in Southwestern China excluding Xizang Plateau increase in recent

40 years, whereas, that of the Eastern China decrease, expect Chongqing (Liu et al. 2007). Some researches indicate that the minimum temperature in general was heating up, and in January the minimum temperature warm faster than in July. The warm period happened in Winter of the 1980s rather than in summer of the 1950s (Ban et al. 2006). According to annual precipitation data of Southwestern China in 1951–1999, the summer precipitation present an interannual cycle of 3–4 years and an interdecadal cycle of 10–16 years, and the summer rainfall and the distribution of drought and flood have a good correlation with South Asia High (SAH) (Du et al. 2002). The researches show that the cloud cover change of 85 stations in Southwestern China (excluding Xizang province) has a obvious seasonal characteristic: the distribution of total cloud cover and low cloud cover appears on a diminishing scale from east to the west in spring, autumn and winter, which is opposite to that in summer. The annual mean total cloud cover and summer total cloud cover are yearly to decrease over the most of regions, and winter total cloud cover decrease in the north of Western Sichuan Plateau and south and east of Yunnan province. The low cloud cover change is stable in most areas but decrease in Sichuan Basin. There is a significant negative correlativity with temperature field and total cloud cover in Southwestern China, but there is not an obvious correlativity with temperature field and low cloud cover (Zheng et al. 2010a, b). In addition, some studies have proved that the main reason of the drought event is the reduction of water vapour transport resulted from the atmospheric circulation anomalies (Wang and Li 2010; Zheng et al. 2010a, b). In conclusion, current climate change researches mainly concentrated on some province or some geomorphic unit, and most researches are wanting in further exploration of influencing factors of climate changes.

1.2 Advances in Climate Change Research

1.2.1 The Fact of Climate Change

The main direction of climate change research is always reconstructing canonical sequence of climate change in a long time scale. In 17th and 18th centuries, with the meteorological observation instruments invented one by one, the meteorological observation is fundamentally transferred from qualitative description to quantitative measurement, which marked the beginning of the modern meteorology. China's meteorological observation stations have had one hundred years of history, which will contribute to provide authentic observation data for climate change in nearly one century (Wu 2005). Based on the meteorological observation data, a large number of scholars have carried out the research on sequence of climate change in a long time scale. In 1960s, Mitchell (2006) constructed a reliable mean temperature series. After 1980s, some researchers constructed a lot of mean temperature series by sorting and interpolating temperature data from different places. The temperature series constructed by Jones (1988, 1994), Jones and Moberg (2003) and Vinnikov et al. (1990), as the most iconic one among them, was revises and added more than once to improve the land and sea surface temperature data and finally was used by IPCC. The temperature variation sequences of century in China was constructed by Wang et al. (1990, 1994, 1998), Wang and Ye (1995), Shi et al. (2004), Tang and Ren (2005). The scale of the precipitation in time and space is very small. There need a lot of observation stations to estimate the mean global precipitation, but in fact, precipitation observations data is much less than temperature observation data and it is more difficult to establish global mean precipitation sequence. Bradley et al. (1987) set up mean land precipitation sequence of the Northern Hemisphere during 1850–1980 by the rainfall observation records of near 1,500 stations in the Northern Hemisphere. On the basis of Bradley's study, Diaz et al. (1989) analyzed the precipitation in the Southern Hemisphere, and emerged them to analyze the global mean precipitation index in 1890–1986. Hulme (1995) sorted global precipitation observations data into the grid mean precipitation and calculated the global mean land precipitation in 1900–1988. In recent years, Chinese scholars have conducted a comprehensive and systematic research on the global precipitation variation by using the latest and the most complete global land precipitation data (Shi et al. 2004; Yang and Shi 2003; Liu et al. 2006a, b). Chen et al. (2004) also have analyzed Chinese long precipitation sequence change.

The important direction of climate change research is always the systemic understanding of climate change trend in the long time scale. Jones and Moberg (2003) found that the global temperature variation did not fluctuate in 1881–2003. The temperature variations of South and North Hemisphere are very close to global temperature variation, but the varied range of the North Hemisphere is bigger than global one and the varied range of the South Hemisphere is smallest. Hulme indicates that global mean precipitation has a slight uptrend in 1900–1988, approximately add 1.6 %. Precipitation is much less except in 1950s–1960s and 1970s–1980s. Shi et al. (2004) showed that the global precipitation variation increases in winter, besides, there is not obvious change in other seasons.

Tang and Ren (2005) pointed out that the annual mean temperature increased 0.79 °C in 1905–2001. The temperature remarkable rise in 1930s–1940s and the mid of 1980s, but the temperature is quite low in other periods. Compared with the global mean and the mean of North Hemisphere, the warming in the early and mid part of 20th century is more significant and the low temperature is also obvious. In the recent hundreds of years, warming mainly occurred in winter and spring. Over the past years, some scholars began to study the climate change for past 50 years in most areas of China and confirmed the significant rising trend of temperature (Liu et al. 2007; Ban et al. 2006; Dong and Wu 2008; Yu et al. 2003; Wang et al. 2008; Cai et al. 2003). Chen et al. (2004) showed that the pluvial age of the areas in east of 100 °E are 1920, 1930–1940, 1950, 1973, the early of 1980 and 1990. Among them, the precipitation in 1920s and 1950s is most. For the areas in east of 100 °E, the precipitation in China began to decline after 1950s. In addition, there is a large number of researches of regional precipitation variation (Tang et al. 2005; Cai et al. 2008; Zhang and Feng 2010), which reveal the temporal and spatial variation characteristics of the regional precipitation in China.

In recent years, the attribution of climate warming has gradually become the hotspot and difficulty of climate change research. The conclusion of IPCC's first assessment report in 1990 was that the climate change in recent year is resulted from natural fluctuations or human activity or the common action of both together. In 1996, the IPCC's second assessment report pointed out that although it is limited to display the influence of human activity on global climate and there is some uncertainty in the main factor, more and more fact show that the influence of human activities on the climate has been detected. In 2001, by latest and authoritative example the IPCC's third assessment report indicated that the 66 % of global warming in the past 50 years may be caused by human activities. In 2007, according to the IPCC's fourth assessment report, the conclusion was gave that the main reason of global warming is probably the human activities, and the probability is more than 90 %. It is also controversial whether the global climate is resulted from the human activity or natural process, which also is a focus issue of the global climate change research for now and for quite a long time to come. Dai et al. (2010) think, after summarizing some studies published by Nature in 2009, that more researches on the climate change exist in the carbon cycle, cryosphere, marine and palaeoclimate reconstruction area. There also are some existing in the mechanism research of climate change and aerosol. It's worth noting that the research achievements in the greenhouse gases reduce while the researches on carbon turning white hot. Among the achievements, the study on climate changes is most, while the studies on the impact and policy responses are quite few as well as the study on estimates of climate change. It reflects the research status quo of global climate change that the mechanism study of climate change urgently need to strengthen. Comparing seasonal change of global surface temperature between 1954–2007 and 1990–1954, it is found that the phase of annual cycle of land surface temperature in the tropics brings forward 1.7 d during 1954–2007. This is obviously inconsistent with early change rate. The research workers hold the idea that the early change rate is dominated by the natural change, but the changes of recent 54 years may be caused by human activities. They also combine the satellite data and the temperature data in long time scale of 42 weather stations at the South Pole, and reconstruct the surface temperature sequence at the South Pole. Then a conclusion could be made that over the past 50 years, the warming rate of western South pole has exceeded 0.1 °C/10 a. Particularly in winter and spring, the rate is sharply remarkable. The modeling result of global circulation patterns indicates that the spatial distribution and the long-term change trends of antarctic temperature variation are not directly related to the enhancement of the antarctic westerlies.

In recent years, the extreme temperature and rainfall events have been more sensitive than the response of mean sequence to climate change and have received the widespread attention (Kunkel et al. 1999; Easterling et al. 2000). The researches of extreme weather have been carried out in some place all over the world, for example, the Asia-Pacific Region, Central and South Asia, South America and so on. These studies suggest that the extreme temperature index sharply warm, even the magnitude of warmth index is more than that of coldness index and night index is more than day index. The change trend of extreme precipitation index is very stable because of regional differences, so it is difficult to judge the general trend change. The studies have also shown that the index relevant with temperature presents obvious changes in the past 50 years, while the index relevant with the precipitation presents regional differences. The analysis of global climate extreme change shows that the extreme temperature index rise significantly in the 20th century, especially coldness index. This trend will become more obvious in future 20 years, while the precipitation index will show a wetting trend (Frich et al. 2002; Alexander et al. 2006).

The researches of climate extreme change in China show that the extreme temperature index also present a significant warming trend, particularly the coldness index. In terms of seasons, the change in winter is the most significant; in terms of the regional difference, the magnitude of warming in Northern China are biggest. The changes of regional extreme precipitation in China has certain regional features. For example, the extreme precipitation in the Yangtze river basin mainly occur in southeast and southwest part. since the mid of 1980s, the crest value of extreme precipitation events in the upstream of the Yangtze river brought forward to June, nearly synchronizing with that in the middle and lower reaches of the Yangtze river, which will inevitably increase the risk of floods. Since 1990s, the frequent occurrence of flood is closely related to the changes of time and space distribution of extreme precipitation in the Yangtze river basin. However, in the past 20–30 years, the extreme precipitation in Western China increased more obviously. In recent 40–50 years, the climate of Xinjiang has been warming and the precipitation has been increasing, particularly since 1987. Accordingly, the runoff rise sharply. It is found that the precipitation increasing is mainly because the rainfall intensity increase (Li et al. 2011a, b; Zhai et al. 1999, 2003; 2005). In terms of the national mean precipitation, the trend of precipitation change is not obvious in the past 50 years, but its spatial distribution is very uneven. The aridification is very serious in North China in the past 50 years. The change trend of strong precipitation and regional distribution of precipitation is very consistent, displayed by the reduced days of the heavy rain. Therefore, the change trend of extreme precipitation reflected by the regional historical climate records in China at least is in line with global trend, the main characteristic of which is still regional (Zhai et al. 2005). To sum up, over the past decades, China's widespread precipitation trend is mainly in the western region, especially in the northwest region. And there are the big regional differences of the precipitation variation trend in the eastern monsoon region. The recent study further support that more extreme precipitation events will happen in China and the mean intensity and magnitude has different degrees of increase, especially in the 1990s (Jiang et al. 2007). Qinghai-Xizang Plateau is always the key area of climate extreme research in China. Liu et al. (2006) think that daily maximum and minimum temperature and the length of growing season in the central and east of Qinghai-Xizang Plateau all significantly warm in 1961–2003. The most remarkable warming occur in winter and summer. In addition, this change present a bigger magnitude of warming at high altitudes than in low altitudes (Liu et al. 2009). The study of You et al. (2008) also prove that the extreme temperature index rose significantly in 1961–2005 in the central and east of Qinghai-Xizang Plateau, but the change trend of extreme precipitation is not significant.

The radiation or sunshine duration is one of the important driving force that impact on climate change, the planet ecosystem and human activities. For example, it can directly or indirectly affect the soil moisture through photosynthesis and water evaporation, and will be paid more attention in the climate change research. Most studies have found that the global solar radiation reduce one by one year in recent years, and this phenomenon is called "global dimming" (Stanhill and Cohen 2001; Liepert 2002; Alpert et al. 2005; Wild et al. 2005). In addition, this result also can be proved by most studies on the radiation or sunshine duration of areas all over the world, such as America, Western Europe and the most regions of Central Europe and India (Liepert 2002; Power 2003; Norris and Wild 2007; Sanchez-Lorenzo et al. 2007; Kumari et al. 2007). These studies make "global dimming" become a hot spot in the field of global change research. As it is the case in most areas of the world, it has also been widely reported that the radiation or sunshine duration of most areas in China is yearly to reduce, such as Northwestern China, Qinghai-Xizang Plateau, Northern China, Eastern China, and so on (Chen et al. 2010a, b, c; Yang et al. 2004; Zhang et al. 2004; Yang et al. 2008a, b; Xu and Zhao 2005). Moreover, a large number of studies on the change of the sunshine duration at the national level also confirm that the reduction of the sunshine duration is common in China (Kaiser and Qian 2002; Ren et al. 2005a, b; Liang and Xia 2005; Che et al. 2005).

Generally speaking, the main factors impacting on the change of solar radiation and sunshine hours are astronomy, geography, geometry (surface azimuth, dig angle, solar azimuth and solar altitude, etc.) physics (water-vapor absorption, scattering of air molecules, dust and scattering of atmospheric components such as O_2, N_2, CO_2, O_3) and meteorology (reflection of clouds and environmental elements etc.) etc (Ertekin and Yaldiz 1999). In addition, a large number of studies on the reduction of the sunshine duration at global level pointed out that the reasons of global dimming are also include the increase of atmospheric aerosol and other air pollutants caused by the human activities, the effect of the atmosphere, the cloud's optics property and the aerosol and the increase of cloud cover (Nazarenko and Menon 2005; Cutforth and Judiesch 2007). Grimenes and Thue-Hansen (2006) thought that "global dimming" may be caused by the back donation of global warming. Pinker et al. (2005) attributed the "global dimming" to the change of cloud cover, the increase of human activities, the aerosols and the low atmospheric transparency along with the volcanic eruptions. Qian et al. thought the fog or haze resulted from the discharges of a large number of air pollutants reflect or absorb the radiation from the sun to reduce the solar radiation to land surface, although sunny days are on the rise. Furthermore, many subsequent researches also consider that the increase of atmospheric aerosol is the main driving force resulting in the decrease of solar radiation and sunshine duration (Ren et al. 2005a, b; Chen et al. 2006; Guo and Ren 2006; Shi et al. 2007; Qian et al. 2007). Pinker et al. (2005) also found that the magnitude of global dimming has been reducing since 1990s and they attribute it to the lowering of pollution levels. Wild et al. (2005) further found that the lowering concentration of atmospheric aerosol in the most regions of the world can be attributed to drastic and effective measures in recent years. Alpert et al. also believe that the impact of human activities on climate change is at the regional level rather than at the global level. In other words, the phenomenon of the reduction of sunshine hours should be considered as regional dimming rather than global dimming.

The change of wind speed is an important symbol of changes of the atmospheric circulation system. The change of ground wind has received more attention from the public and academic field because the lowering wind speed in most parts of the world in recent years has posed a great challenge to the development and utilization of wind energy resources (Pryor et al. 2005). There many studies found the wind speed is also an important reason of less evaporation of pan (Roderick et al. 2007, 2008; Rayner 2007). Robert et al. (2010) carried on a research into the wind change at mid-northern latitudes for 1979–2008 by the data of 882 surface observation stations, and made it clear that the wind speed in most parts of study area reduce 5–15 %. Pirazzoli and Tomasin (2003) from the observation data of 17 stations in the coastal area of Italian, found that wind speed decreased significantly in the mid of 1950–1970, but it decreased slightly even appear to increase from 1980. Brazdil et al. (2008) also reported the wind speed in most regions of the Czech republic reduced. From the late 1940s to the mid of 1990s, both the annual mean wind speed and the mean wind speed in winter in the west coast of Canada decreased (Tuller 2004). And from 1973 to 2005, the wind change in the United States is characterized by downtrend (Pryor and Ledolter 2010). The wind speed in Australia significantly reduced by rate of −0.009 m/s/a over 1975–2006, and about 88 % of the all weather stations showed the wind speed reduced (McVicar et al. 2008). In 1962–2002, the medium winds events (mean 10 times in a year) and strong winds events (mean 2 times in a year) in New Zealand also showed a decrease trend. (Smits et al. 2005) The wind speed from the majority of seven weather stations in Minnesota in the United States showed a downtrend in recent 22–35 years expect one which appeared slight rise (Klink 2002). However, in the Baltic region, the annual mean wind speed increased from 1953 to 1999 and the wind speed of more than 75 % of the area increased significantly (Pryor and Barthelmie 2003).

Wang and Li (2004) made a study on the wind speed in 1951–2000 in China and indicated that the reducing trend is common, and the biggest reduction occurred in the northwestern region and in winter (Xu et al. 2006a, b). conducted a further study on the wind speed change in 1969–2000 in China, and found that the annual mean wind speed decreased about 28 %, the mean minimum rate was −0.021 m/s/a and the largest reduction mainly occurred in winter and summer. On the basis of the latest observation data from 652 weather stations, Gao et al. (2010) found that the annual and seasonal wind speed of most stations in China showed a significant decrease in 1969–2005, but there is a slight increase after 1991. In the upper, middle and lower of the troposphere, the annual mean wind speed decreased at the rate of −0.10–0.17 ms^{-1}/10 a. The further analysis confirmed that the lowering surface wind speed is not only caused by the atmospheric circulation change, but also the environment change around weather observation stations resulted from the urbanization. The accelerating urban construction and tall buildings has caused an obvious block to wind speed observation of stations in urban areas (Li et al. 2010a, b). From 1961 to 2004, the wind speed of Heilongjiang province appeared downtrend due to the significant temperature rise and massive changes in the land use caused by the urbanization (Zou et al. 2010). In 1961–2007, the wind speed change of Chongqing was in a reducing situation and the magnitude of lowering had become more and more obvious since 1974 (Li et al. 2010a, b). The annual mean wind speed in most stations of Northern China reduced at the rate of −0.2 to −0.5 m/s/10 a in 1957–2006 (Rong and Lang 2008). Through the analysis of the observation data of 104 stations, the wind speed decreased significantly at 1951–2006 in the North China Plane and the magnitude is −0.16 m/s/10 a (Yang et al. 2008a, b). In Jiangsu province, the annual mean maximum wind speed fluctuated in 1975–2008 and its general trend is to reduce (Chen et al. 2010a, b, c). A large number of studies have also shown that the reduction of wind speed is not only the main reason of surface evaporation drop in the Qinghai-Xizang plateau and all over the country, but also the key reason of causing sandstorm reduce (Qian et al. 2002; Wang et al. 2004; Huang et al. 2006).

There are some reasons causing the reduction of surface wind speed, which displayed by as follows: (1) the change of circulation system at large scale or the microscale weakening of synoptic system in the context of climate change (Lu et al. 2007; Seidel et al. 2008) (2) the increasing surface roughness of weather observation stations or the structural change of boundary layer (Lynch et al. 2004) (3) the instrument error or the observation error (DeGaetano 1998; McKee et al. 2000). Robert et al. (2010) found that the other reason of wind speed reducing 10–50 % in the Northern Hemisphere is the change of surface roughness, especially the land cover change in Eurasian continents, based on the reanalysis data. In China, the winter warming in the northern regions is likely to be the main reason of the reduction of winter monsoon. While, the temperature decrease in summer occurred in the central parts of Southern China and the significant rising temperature occurred in South China Sea and the northwestern Pacific may be associated with the weakening of the summer monsoon (Xu et al. 2006a, b). Gao et al. (2010) further analyzed and confirmed that reduction of the pressure gradient force in the lower of the troposphere is the other key reason, and pointed out that the wind speed change is caused by climate change. The change of surface wind speed has important environmental and social economic meanings. Zhou et al. (2006) had confirmed that the lowering wind speed has caused the reduction of wind power in the Pearl River Delta region. Liu et al. (2005a, b) held an idea that the reducing wind speed and the changing wind direction had brought great challenge for the development of regional wind energy resources in the broad arid zone centered by the Erdos Plateau in Inner Mongolia. So the study on the change of wind speed is helpful to have a comprehensive understanding of climate change and its influence to environment, ecological system and social economy.

1.2.2 The Mechanism of Climate Change

Hay et al. (2002) thought the factors of affecting climate change can boil down eleven ones. Combining theirs with others results, Zhang et al. (2005a, b) reduced these factors into 16 ones, which are the solar radiation, the cosmic dust concentration, the earth's orbit, the continental drift, the influence of mountain uplift to atmospheric circulation and environment, the ocean currents, the sea ice, the discharge of greenhouse gases, the atmospheric aerosol concentration, the polar stratospheric cloud cover, the polar vegetation, the "iron hypothesis" associated with dust aerosol, the transformation from C_3 to C_4 of plants, the celestial body collision, the volcanic eruptions and the circulation in core. For the reasons of global warming in the 20th century, it is generally believed that they are related to the increase of concentrations of greenhouse gases (IPCC 2007), although this idea is still controversial. Ren et al. (2005a) gave the key factors that may impact on the change of the surface temperature in nearly 50 or 100 years in China, including natural factors and human factors. The natural factors mainly consist of the natural events dominated by solar activity and volcanic activity and the changes dominated by the changes of vegetation, ice and snow and atmospheric circulation. The human factors contain the changes of greenhouse gas, land cover and atmospheric aerosols.

The results of the studies are generally believed that the vegetation coverage change eventually lead to the changes of regional precipitation, circulation situation, atmospheric temperature and humidity by changing the surface albedo, roughness and soil moisture and impacting on radiation balance and water balance. Li and Ding (2004) summarized the domestic and foreign related researches in recent 10 years, especially the influence of vegetation changes on Chinese regional climate, and found that the most studies thought a wide range of vegetation degradation could result in surface temperature rise, weakness of East Asian summer monsoon, decrease of precipitation and worsening drought. There was some controversy to the effects of urbanization to warming. Some researches suggest that the influence of the changes of the urbanization and land use to the temperature record after 1950 can be ignored in hemispheric and continental scale. The study of Jones et al. (1990) have shown that the magnitude of the influence of urbanization in hemispheric or global scale is significantly smaller than that in interdecadal or longer time scale. Recently, Parker found that the warming trend of minimum night temperature in the conditions of calm does not strengthen by using records of the global observatory, while it is most likely to be affected by the urban heat island during this period. Therefore, the long-term warming trend upon all land global wide is unlikely to be influenced by the enhanced urbanization. In the United States, it is almost impossible to separate the change trend of the temperature in the countryside from that in the city (Peterson and Owen 2005). But there are also some researches point out that the climate in the city is general warmer than that in the suburbs and the urban heat island has a significant effect on the temperature rise. For example, in 1973–1996 the urban heat island made the temperature of Seoul in South Korea rise 0.56 °C (Kim and Baik 2002). Other researches also confirmed that the urban heat island made temperature of South Korea in 1968–1999 increase 0.40 °C (Choi et al. 2003). Some studies also have shown that the urban heat island has significant contributions to temperature rise of Southeastern China (Zhou et al. 2004).

At present, it is common that the global warming is considered as the worsening greenhouse effect caused by the increase of greenhouse gas. Actually, this conclusion has certain basis to some extent. However, in terms of the scientific theory, the impact of increasing greenhouse gases caused by human activities is not the only reason (Li et al. 2003a, b, c). Based on some existing researches, the solar activity may also be another important cause of global warming in the 20th century. The influences of solar activities mainly includes the direct influence of solar radiation and the indirect influence of triggering geomagnetic field changes. The changes of earth magnetic field can impact on the atmospheric circulation and climate change through the dynamic process and thermal process (Li et al. 2003a, b, c). Zhou et al. (2007) summarized a large number of studies and made a conclusion that the weather and the climate are remarkably affected by solar activity in any scale. In recent years, the relationships between climatic elements, such as global cloud cover, the winter cyclone of the North Atlantic and so on, and the space weather events, such as the change of cosmic-ray flux, Solar Energetic Particle and so on, are discovered one by one. On this basis, Zhou et al. (2007) proposed the mechanism that the solar activities drives climate change. Its basic ideas are the space weather events affect weather and climate by changing the physical characteristics of cloud. The core is the relationship between the solar activities caused by space weather events and the microphysical process of cloud. At present, the theory of space weather can be divided into ion-induced nucleation mechanism and Tinsley mechanism. Zhong et al. (2004) found that the profiles in the south edge of Tarim Basin recorded the climate change since nearly 4 ka, especially the mean particle size of sediments. The fluctuations in decade and hundred scale are consistent with Greenland GISP2 temperature indicators of oxygen isotope in cores from ice and the atmospheric ^{14}C curve. And the most of cycles summarized by analyzing the red noise spectral have consistency with the cycle of the solar radiation changes, such as 196, 121, 97, 121, 45 and 33–30 years. Combined with a wide range of regional correlation, it is further proved that the sun radiation may be an important driver force of regional and global climate changes in ten to hundred scale. What the most important is that the surface temperature variations in the Northern Hemisphere have a remarkable consistency and the positive correlation with the sunspot cycles since 1940. This seemed to confirm the important role of the solar activity to the evolution of the earth's climate system.

The interannual variability of large-scale atmospheric circulation is one of the main drivers of climate change. Huang (2010) thought the variation of East Asia monsoon climate systems is not only related to the variation of ocean, land surface process and snow and ice, but also the dynamic process of this system. To a large extent, the interdecadal change of East Asia monsoon under this relationship is associated with major drought and flood disaster in China. The study shows that East Asia monsoon system has a obvious temporal and spatial variation. Among, the summer monsoon system has a quasi two-yearly oscillation in interdecadal scale, and appears a marked decresase in interannual change from the late of 1970s to now. This change is particularly significant in North China. While East Asian winter monsoon has a quasi four-yearly oscillation in interdecadal scale and also appears a marked decreases in interannual change since the late of 1980s, which cause the continuous warm winter in China (Huang et al. 2008). By analyzing the evolution of interface between east wind and west wind, it is confirmed that the shift from east wind in winter to southwest wind in summer happened in the lower of troposphere of the Asian monsoon region first occurred in the eastern bay of Bengal due to the spring warming of the Xizangan plateau, along with the intense convective precipitation. Therefore, the eastern bay of Bengal and the western indochina are the first region where the Asian monsoon occurs. At the same time, it is also pointed out that the circulation aroused by the summer warming of the Iranian Plateau and the Qinghai-Xizang plateau is nested in the thermal circulation of Eurasia, which strengthen the summer monsoon of the East Asian and aggravated the drought in Central Asia and West Asia. Moreover, the fluctuations aroused by the summer warming of the Iranian Plateau and the Qinghai-Xizang plateau exercises a great influence on climate pattern of East Asian in summer (Wu et al. 2004). The relationship of the processes of terrestrial carbon cycle and greenhouse gases has become a concern of climate changes. Which role the China's terrestrial ecosystems plays in global carbon cycle is a major environmental issues commonly concerned by the domestic and international scientists. Piao et al. (2009) comprehensively study the terrestrial carbon in China, and the results showed that the mean growth per year of carbon in China's terrestrial ecosystem is 0.19–0.26 Pg C from 1980s to 1990s. The carbon sequestration of China's terrestrial ecosystem is equivalent to 28–37 % of CO_2 discharges in China, which is much more than that of Europe (7–12 %), close to the United States (20–40 %). Northeastern China is the net discharge source of CO_2, mainly resulted from the excessive deforestation and the degradation of forest. And more than 65 % of carbon sequestration is in Southern China because of regional climate change, planting and the recovery of shrubs.

The mechanism and the reason of climate change research has always been the difficulties and focus of the climate change research, and the uncertainty of research also has attracted much attention. Ge et al. (2010a, b) analyzed the uncertainty of the result of the existing climate change researches, including the states of climate change in past two thousands years; for example, is there the medieval warm period and little ice age? Is the 20th century the warmest period in the past thousand years? Did the warming trend stop? Greenhouse effect (the different understanding about the greenhouse effect mechanism, the relationship between greenhouse gas discharges and the temperature variation, the effect of water vapor to the greenhouse effect and warming); climate model simulation (the comparison of simulation and measured results, the defects of the model) and 2 °C threshold and so on (its source and physical significance; the different understandings of 2 °C threshold). Finally, it is confirmed that the divergence and heated debate about climate change is inevitable due to the complexity of the climate changes. Many current studies on the climate changes are not conclusive and many problems need to be further studied. Zhao (2006) also believes that the difficulties of the projection of climate events in future one hundred years are how to estimate the reliability and the uncertainty of the global climate changes, how to consider the combined effect of both nature and human and how to reduce the uncertainty of projection. Fang (2011) thinks that it is a reality that the climate is changing and the earth is warming, but the reasons of climate change are quite complex and have not yet been determined at present.

1.2.3 The Impact of Climate Change

Climate change has brought some consequences to nature and economic society, such as, more and more extreme weather and climate events, increasing production instability, worsening problem of the water resources, significant retreat of glacier, the greater risk of major engineering security, the threat of sea level rise to the developed coastal areas, the destruction of biodiversity and so on. In addition, climate change will produce more effects on human health, industry, tourism, politics, economy and diplomacy. Li et al. (2003a, b, c) thought the impacts of climate change mainly reflect on the change of climatic zone, the impact on water resources, the change of natural belt, sea level rise, increasing natural disasters, the impact on agriculture, the influence on engineering and construction and the increase of plant diseases and insect pests. The observational studies confirmed that the northern boundary between subtropics and temperate zone in Eastern China move towards north and the phenological period has been moved up. In the past few decades, the forest area in Qilian Mountain reduced 16.5 %; the lower tree line rose from 1,900 to 2,300 m and the coverage decreased 10 %. Since 1980s, degradation of grassland ecosystem in the riverhead areas occurred, and the wetland in Sanjiang Plain reduced. The northern boundaries of each climatic zone will continue to move towards north along with the global warming. The extent of drought may be expanded, but the wetness area may be narrowed, and the Northern China tends to aridification. With the The vegetation zones of forest moving towards north, the productivity and production of the forest will have different degrees of increase, but the frequency of fire disaster increases and the spread scope of the forest diseases and insect pests will expand and aggravate. The alpine grassland areas of Qinghai-Xizang plateau will reduce significantly and the desert in plateau mountain will increase. The output and quality of grassland in Sichuan province drop slightly and the wetland areas in Southwestern China reduce, even the wetland function of Sanjiang Plain and Qinghai declines (Country Assessment of Climate Changes 2007).

Since 1950s, the measured runoff of some rivers is on the decline,such as the Yangtze River, the Yellow River, the Pearl River, the Songhua River, the Haihe River, Huaihe River and so on. From 1990s, the drought in the north and floods in the south are frequent, which cause a lot of property losses. Since the 20th century, China’s mountain glaciers retreat generally and the glacier area in the western mountain decreased 21 %. In the next 50–100 years, the mean annual runoff depth in some provinces of Northern China will decrease 2–10 %, but the mean magnitude of runoff reaches 24 %, which results in the water shortages of the north areas and further aggravation of flood in south areas. By 2050, the glacier area in the western areas is 27.2 % less than the middle of the 20th century, among the reduction of oceanic glacier is most significant. The great reduction of ice reserves in Western China and the mountainous areas make the seasonal adjustment of the runoff reduce (Zhang et al. 2008a, b). The influences of climate change to water cycle in cold areas are displayed by precipitation, evaporation, runoff, snow area, glacier and permafrost. The evaporation of the Northern Hemisphere has been gradually reducing and the runoff and its space-time distribution have taken place great changes. The snow cover area is smaller and smaller and the glacier is shrinking quickly. Along withe the global warming, permafrost melt leads to the thickness of the active layer increase. The above changes bring the acceleration of the global water cycle to a great extent (Shao et al. 2008). Climate warming will cause sea level rise and the inundation area of coastal lowland will expand in China. These areas will be threatened seriously, including the Yellow River delta, the Yangtze river delta and the Pearl River Delta. If sea level rise 30 cm, the inundation area would be 0.81 and 0.23 % of China in the context of non-fortification or current fortification. It was studied that according to the future climate situation, the drought in the upper reaches of Yangtze River will be mitigated; the frequency of flooding will increase in flood seasons, which increase the possibility of debris flow and landslide (Zhang et al. 2000). As the temperatures rise, the permafrost in the Qinghai-Xizang Plateau is gradually degrading. Up to 2050, 80–90 % of the patchy permafrost would have degraded; the seasonally thawed depth would increase; and permafrost area in the surface would reduce 10–15 %. The rise of lower boundary of permafrost will affect the stability of Qinghai-Xizang railway roadbed. In addition, for the climate changes, there is a great influence to the water quality of the eastline of project, rather than South to North Water Transfer Project (Country Assessment of Climate Changes 2007).

With the frequency of extreme weather increasing, all kinds of weather system activities will be more intense and frequent. For example, the frequency of meteorological disasters will increase, such as, drought, floods, high temperature, chilling damage and so on, which will add to the volatility of the agricultural production and the agricultural losses. Temperature increase has certain positive effect to the crop yields in some areas but the significant negative effects on the whole, meanwhile, the yield and quality of the main crop decline further. As the temperature rise, destructive insects will grow up in advance and too much breeding in a year, leading to the much hazard of crops. The burst size of available nitrogen is to increase with the climate warming. If it is supposed to keep the soil fertile as it was, the fertilizer rate must be increased resulting in the more production cost and more hazard of soil and environment. By 2030, China's total grain production will decrease 5–10 %, for example, the three main crops including wheat, rice and corn (Ning and Shen 2009). Additionally, Easterling et al. (2000) summed up that frequent extreme weather events add the probability of various kinds of natural disasters causing serious losses to the development of social economy, especially the frequent occurrence of extreme weather events. For example, the economic losses of the United States has reached to 6 billions dollars in 1990s from 100 millions dollars in 1960s because of the storms, and the number of times has increased by 35 times in 1990s from 10 times in 1960s. Besides, the loss caused by hurricane has risen from 5 billions dollars in the 1940s to 40 billions dollars in 1990s (Chapman and Walsh 1993).

The impacts of climate change on desertification are reflected in the scope, the outstretched velocity, the intensity and the potential risk of the desertification, as well as the structure, the function and the productivity of the arid ecosystem. Meanwhile, as the important storage of carbon in the world, the change of arid zone, to some extent, affects the increase and decrease of CO_2 in the atmosphere. It was estimated that the amount of carbon loss resulted from global desertification will totaled 18–28 Pg C (Ci and Yang 2004). Over the past 50 years, the significant warming occurred in the Northern China and the thermal resources increased in the growing season. The available water and sunshine showed reducing trends in different degrees and were distributed unevenly in time and space. The agrometeorological disasters like frost damage, chilling injury, cold wave, floods, hail and some decreased followed by the increasing drought. The climate change of the northeastern areas generally benefit the agriculture, displayed by the extended growth period of crops, the accelerated development process and the shortened growth period. The accumulated temperature increase obviously, at the same time, it move northward and enlarge eastward, which make the planting area expanded (Zhao 2010). Based on the study of climate change, there are some advantages and disadvantages to the southwestern tourism resources. The advantages can be shown that the period of tourism will lengthen in order to promote the economic development of tourism in this district due to the rise of the comfort degree of temperature. As we all know, the Southern China is known as a “gene pool of natural plants” and “kingdom of animals”. However, the threat of climate changes is fatal to the species diversity in Southern China. The loss of species diversity will bring the environmental degradation and have a negative impact on tourism image, thus the tourism income also will reduce in a certain extent. This is the disadvantages of climate change to the southwestern tourism resources (Yang et al. 2006). Under the background of the temperature rise, the spring phenology of woody plants in China before and after 1980s has obvious changes, which is consistent with the trend of temperature variation in spring. The movement of the phenological period change smaller because the magnitude of spring warming in northern areas is quite big rather than the smaller magnitude in southern areas (Zheng et al. 2003). However, just as the thought of Fang (2011), the impacts of climate change on the natural and social system are still disputed by scholars and need to objectively and rationally be known because the impacts have both advantages and disadvantages. The research of human civilization indicates that the great progresses have always been made in the warm period of earth, but the decline of a civilization was accompanied by the coldness all the time. In recent 70 years, human social productive forces has a remarkable increase and the material civilization also makes an unprecedented. Although, it is likely to be a historical coincidence, it is the material basis of the development of human civilization and also an undeniable fact that the warming climate is helpful to increase the crop yield.

1.2.4 The Current Characteristics of the Climate Change Research

(1) Fundamantality. The study on the change process of the climate system is still the main direction of climate change research and is also the fundamantality of comprehensively and systematically recognizing the climate change. The confirmation of the climate change mechanism is still the theme of current climate change. Because of the complexity of the process of climate change, there are some lacks on the understanding of the driving mechanism in climate change on different time scales. The uncertainty evaluation of process, mechanism and prediction of climate change is still a difficulty of climate change research. Now there are lots of scientific uncertainty on understanding of the mechanism of climate change, particularly in thousand years scales. So There is still a long way to systematically aware many key mechanisms and processes. The forecast of future climate change has been the difficulty of climate change research, and there is a big challenge on the error analysis and uncertain assessment of the fruit. The climatic and environmental effects of cryosphere changes have drawn more attention and have gradually been a new concern because of its sensitive response and feedback to climate changes, but the awareness of its climatic, hydrological and ecological effects is still very superficial. Although the assessment of the effects of climate change has become increasingly mature, there are some shortcomings on the study of mitigation and adaptation strategies.

(2) Spanning. The climate change research has shifted from the single research of the air temperature and precipitation to the comprehensive analysis of changes in the climate system, such as extreme weather events, wind speed, sunshine, cloud cover, the potential evaporation and so on. This comprehensive study on the climate system is not only helpful to systematically understand the matter of climate change, but also to further aware the mechanism of climate change, which will lay the physical foundation for the predictions for the future climate change. The analysis of the fact and process of climate changes has transferred to the cognition of the mechanism and driving force. Generally speaking, the dominant cause of the climate change is the change of the global radiation balance and the oscillation of the climate system itself. In other words, the climate change has its physical basis. So based on the physical basis, the research on the mechanism of climate change become an important aspect of the climate change research. Although there are much controversy on the understanding of mechanism of climate change in hundred years scales, the complexity, comprehensiveness and non homogeneity of mechanism of the climate change are confirmed once again, which lay the foundation for the breakthrough research of the new mechanism and point out the direction. The prediction research of current climate change lays stress on the coupled process of the multiple forcing factors, which requires more explorations to coupled mechanism. For example, taking the change of land use, vegetation

cover changes and atmospheric aerosol into consideration. While, the future forecasts research need a comprehensive consideration by putting a positive force and a negative force into the same environment. The researches have transferred from know climate change to adapt to it. The climate change is an eternal theme. At present, scholars have paid more attention to the coping strategies after climate change, namely how to slow down and eventually adapt to the various effects brought by the climate change in order to realize the sustainable development of human society. Currently, one of the most controversial issues focus on whether the drive of climate change is natural or human, which will raise awareness of climate change to a large extent and provide a new train of thought for a more comprehensive understanding of the mechanism of climate change. This understanding will further promote a major breakthrough in the mechanism of climate change research.

(3) Comprehensiveness. The current research of climate change highlights the comprehensive utilization of various means, which provides a better technical means for the development of the climate change research. At present, the record of climate change research has converted from single to multiple in order to find out the similarity of changes. This conversion improves the scientific level and credibility of the climate change research to a large extent. The cooperation and communion of more different researches can also make the reliability and credibility of the climate change research gradually increase. Mechanism research is a comprehensive analysis of earth giant system, therefore, the cross with other natural sciences is the key basis of this research. In addition, the cross with social science outstands the study on countermeasures research. In the final analysis, the adaptation of climate change is what scientific and reasonable measures should be taken when the giant society as the main body of human being face the problem of climate change. So in the context of this, on the one hand, it is necessary to reduce the impact of climate change to us; on the other hand, we should finally adapt to the new climate through the scientific and rational response.

(4) Sensitivity. Climate change is not only an environmental issues, but also a development issue, in the final analysis it is the development issue. Climate change research is related to national survival and development, and is the hot field of today's international scientific research. Especially in the 15th conference of "United Nations Framework Convention on Climate Change" (UNFCCC) in 2009 in Copenhagen, the developed countries again taking use of the shift from the understanding of climate change into a political consensus write the knowledge, "global temperature rise should be limited within 2 °C" with a great controversy in science into the "Copenhagen Agreement" in order to lay a vital foundation for the implementation of a series of strategies, the purpose of which is to limit the development of developing countries. Under the background of this, the study on the carbon cycle and the influence of natural and human factors to the temperature rise have been a new hotspot in the researches of the climate change. At the same time, the concepts, such as low carbon economy, green economy, environmental protection, mitigation

and adaptation of climate change, carbon reduction and some gradually become the new consciousness of social development. While, the developed countries combine carbon discharges and the right of development through their political influence, and bring a lot of pressure to the developing countries or the emerging industrialized countries by various means, for example, the international climate negotiations. Zheng (2010), the director of the China Meteorological Administration, thought that China's response on climate change after the Copenhagen climate conference should focus on the following aspects: The coping works should be put into the legal system; It is necessary to develop and promote the environment-friendly technologies and to develop the low carbon economy, green economy and circular economy; It should be done to strengthen the infrastructure of the weak areas and to improve the comprehensive ability of adapting to climate change; We should actively explore the market system and mechanism conformed to China's national conditions; We should strengthen the scientific research and technological development of climate change and improve the soft power of science and technology; We should enhance the consciousness of responding climate change in the whole society; We also should strengthen the knowledge popularization of climate change and enhance society's awareness of the importance and urgency to tackle climate change.

1.3 The Main Contents

On the basis of existing research, by collecting and sorting the meteorological data, NCEP/NCAR reanalysis data and the glacier change data from the surface-based observing stations this study focuses the analysis on the characteristics of the spatial and temporal variations of climate factors in Southwestern China, explores the possible influencing factors and analyzes the response of the glacier system to climate change. The main contents of this study can be displayed as follows:

(1) This study utilizes a variety of data to analyze the spatiotemporal characteristics of annual and seasonal mean temperature and precipitation. Based on the analysis of sea level pressure, geopotential height and wind field etc., this study probes into the atmospheric circulation mechanism of researched areas and further analyzes the influences of elevation on air temperature and precipitation variations, the differences of change trends between the urban and the rural, the relationship of air temperature variations with radiation, sea surface temperature (SST) and sunshine duration and so on, and the effects of the water vapor flux and the western Pacific subtropical high on the precipitation variation.

(2) By using the latest international definition of extreme temperature and rainfall events, statistical method and the standard of extreme threshold value, we conduct the research on the spatial and temporal variations and the influences of

elevation on extreme temperature and rainfall events in Southwestern China, do deep analysis on the background of atmospheric circulation of the extreme temperature and rainfall events in the study areas, hold a pilot study on the influence of the urbanization process on air temperature variation and make a comparison with the trend of climate extreme events in the rest of the world.

(3) The sunshine duration has important influences on the mean temperature variation in the southwest of China. So based on the ground observation Stations and reanalysis data, we study the spatiotemporal characteristics of the sunshine hours in 1961–2008 in Southwestern China, further analyze the influence of wind speed, relative humidity, altitude and topography, the urbanization process, precipitation and water content of clouds etc. on the spatiotemporal characteristics of the sunshine hours and finally create awareness of the trend, the magnitude and the possible causes of sunshine hours change.

(4) The wind speed is one of the major indications of atmospheric circulation change, and also is the important influence of the changes of the sunshine hours in the study area. This study explores the spatiotemporal characteristics of wind speed in Southwestern China by the data of wind speed from the observation stations and the reanalysis data, then reveals its internal mechanism from the meridional wind, zonal wind, plateau monsoon, regional climate warming, horizontal baric gradient and so on.

(5) The glacier is a sensitive indicator of climate change. By the sorting and the analysis of the existing observation data this study summarizes the response of glacial changes in Southwestern China to climate change under the background of climate warming, and discusses the relationship of glacier length, material balance, output water in ice and snow area, the glacier surface morphology and so on with climate change.

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Chapter 2
Data and Methods

2.1 Data

2.1.1 The Observation Data

2.1.1.1 The Observation Data of Southwestern Areas from China Meteorological Administration

The observation data of ground stations is the main data source of this study. The data about the daily mean temperature, daily minimum temperature, daily precipitation, daily wind speed and daily sunshine hours are from the meteorological observation database of national meteorological information center in China Meteorological Administration (http://www.nmic.gov.cn/). The time span of meteorological data is mainly set from January 1st, 1961 to December 31st, 2008 in order to ensure the length of all data uniform and stable. It's important to note that the wind speed data exist discontinuity in the record because of the replacement of the monitoring device in 1960s (Liu et al. 2004). For the sake of avoiding this problem, this study select the period from January 1st, 1969 to December 31st, 2008 to study base on the selection of Xu et al. (2006) about the study period of the wind speed change research in China. We gathered all ground observation data in the administrative range of five provinces in Southwestern China. There 27 stations are eliminated due to some reasons, such as, new stations, a longer break during observation, the problem in data records and quality and so on. The rest of the meteorological stations space distribute unevenly, especially there are few stations in the west of the Xizangan Plateau. We wipe one more off (Shiquan river station) in order to reduce the impact of sparse stations to climate change in the whole area. Finally, 110 meteorological stations are remained, which have the data of good quality, relatively even distribution and relatively continuous records and which are built earlier than 1961 (Fig. 1.1). The world meteorological organization (WMO) number, the name, longitude, latitude, altitude, etc. of stations selected in this

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chapter can be seem in Table 2.1. The elevation range of this 110 stations is between 285.7 and 4,700 m. Among them, there are 9 stations are above 4,000 m; the elevation range of 17 stations is between 3,000 and 4,000 m; the elevation range of 16 stations is between 2,000 and 3,000 m; there are 32 stations located in 1,000–2,000 m and there are 36 stations located in 1,000 m below. The related data of the East Asian monsoon index and South Asia monsoon index in 1961–2001 uses the research achievements of Guo et al. (2004) for references, and the data of plateau monsoon index is provided by China Meteorological Administration National Climate Center (http://ncc.cma.gov.cn/cn/). In addition, the population and energy consumption data in China are from the provincial statistical yearbook.

2.1.1.2 The Data Quality Control of Stations

Most stations in China was established in the 1950s, and the station observation data is more steady after 1960s. However, stations' move, environment change around stations, the types of observation instrument and the change of observation time all will directly affect the comparativeness and continuity of the observation records, and have the different degrees of influence on the uniformity of annual climate data sequence (Wu 2005). In addition, there about 70 % of China's 731 standard ground observation stations have experienced relocation, of which about 31 % move once and about 41 % move more than two times, especially the stations located in the city, for example, the stations in Beijing, Shanghai and other major cities have moved to the district between suburbs and cities (Li et al. 2004a, b). So it is necessary to select qualified observation data by the data quality control before analysis in order to ensure the accuracy of the results of the study. The quality control of meteorological observation data in this study is to examine the date of the daily mean temperature, daily minimum temperature, daily maximum temperature and daily precipitation by using the international test method and software non-uniformity: RclimDex and RHtest, and to find out the station having data quality problems, then to delete them from the original data, finally to select the qualified observation stations and to make a statistics and analysis on the basis of this data. The control and inspection of data quality mainly includes three aspects: whether the recording date of data is consistent with reality; whether the daily precipitation is less than zero and whether the daily minimum temperature is greater than the maximum temperature; whether the relocation and the local environment changes caused the of the observation data records.

Data quality control mainly use RClimDex software and the text of data non-uniformity use RHtest software. The softwares above and their documentation can be downloaded in this website (http://cccma.seos.uvic.ca/ETCCDI/software.shtml) the reading file and writing file of softwares above have their specific formats. It is the first step of texting the quality control to prepare the data format as required. There are five requirements in the input of softwares above. Firstly, the data files should be ASCII text files. Secondly, the data sequence may be the annual, monthly and daily precipitation, the minimum temperature, the maximum temperature (the

Table 2.1 The selected weather stations in Southwestern China

WMO number	Name	Latitude	Longitude	Altitude (m)
55279	Bangor	31°23′	90°01′	4,700
55299	Naqu	31°29′	92°04′	4,507
55472	Xainza	30°57′	88°38′	4,672
55578	Shigatse	29°15′	88°53′	3,836
55591	Lhasa	29°40′	91°08′	3,648.9
55598	Tsetang	29°15′	91°46′	3,551.7
55664	Dingri	28°38′	87°05′	4,300
55680	Jiangzi	28°55′	89°36′	4,040
55696	Longzi	28°25′	92°28′	3,860
55773	Parry	27°44′	89°05′	4,300
56312	Nyingchi	29°40′	94°20′ 2	991.8
56106	Suoxian	31°53′	93°47′	4,022.8
56116	Dingqing	31°25′	95°36′	3,873.1
56137	Chamdo	31°09′	97°10′	3,306
56227	Bowo	29°52′	95°46′	2,736
56038	Shiqu	32°59′	98°06′	4,200
56079	Ruoergai	33°35′	102°58′	3,439.6
56144	Derge	31°48′	98°35′	3,184
56146	Ganzi	31°37′	100°00′	3,393.5
56152	Sertar	32°17′	100°20′	3,893.9
56167	Daohu	30°59′	101°07′	2,957.2
56172	Barkam	31°54′	102°14′	2,664.4
56173	Hongyuan	32°48′	102°33′	3,491.6
56178	Xiaojin	31°00′	102°21′	2,369.2
56182	Songpan	32°39′	103°34′	2,850.7
56187	Gaoping	30°49′	106°15′	300
56188	Dujiangyan	31°00′	103°40′	698.5
56193	Pingwu	32°25′	104°31′	893.2
56196	Mianyang	31°27′	104°44′	522.7
56247	Batang	30°00′	99°06′	2,589.2
56251	Xinlong	30°56′	100°19′	3,000
56257	Litang	30°00′	100°16′	3,948.9
56287	Ya'an	29°59′	103°00′	627.6
56357	Daocheng	29°03′	100°18′	3,727.7
56374	Kangting	30°03′	101°58′	2,615.7
56385	Emeishan	29°31′	103°20′	3,047.4
56386	Leshan	29°34′	103°45′	424.2
56441	Derong	28°43′	99°17′	2,422.9
56459	Muli	27°56′	101°16′	2,426.5
56462	Jiulong	29°00′	101°30′	2,987.3

(continued)

Table 2.1 (continued)

WMO number	Name	Latitude	Longitude	Altitude (m)
56475	Yuexi	28°39′	102°31′	1,659.5
56479	Zhaojue	28°00′	102°51′	2,132.4
56485	Leibo	28°16′	103°35′	1,255.8
56492	Yibin	28°48′	104°36′	340.8
56671	Huili	26°39′	102°15′	1,787.3
57206	Guangyuan	32°26′	105°51′	513.8
57237	Wanyuan	32°04′	108°02′	674
57306	LangZhong	31°35′	105°58′	382.6
57313	Bazhong	31°52′	106°46′	417.7
57328	Daxian	31°12′	107°30′	344.9
56565	YanYuan	27°26′	101°31′	2,545
57405	Suining	30°30′	105°33′	355
57608	XuYong	28°10′	105°26′	377.5
56571	Xichang	27°54′	102°16′	1,590.9
56586	Zhaotong	27°21′	103°43′	1,949.5
56651	Lijing	26°52′	100°13′	2,392.4
56664	Huaping	26°38′	101°16′	1,244.8
56444	Deqin	28°29′	98°55′	3,319
56684	Huize	26°25′	103°17′	2,110.5
56739	Tengchong	25°01′	98°30′	1,654.6
56748	Baoshan	25°07′	99°11′	1,652.2
56751	Dali	25°42′	100°11′	1,990.5
56763	Yuanmou	25°44′	101°52′	1,120.6
56533	Gongshan	27°45′	98°40′	1,583.3
56543	Zhongdian	27°50′	99°42′	3,276.7
56548	Weixi	27°10′	99°17′	2,326.1
56768	Chuxiong	25°02′	101°33′	1,824.1
56778	Kunming	25°00′	102°39′	1,886.5
56786	Zhanyi	25°35′	103°50′	1,898.7
56838	Ruili	24°01′	97°51′	776.6
56856	Jingdong	24°28′	100°52′	1,162.3
56875	Yuxi	24°20′	102°33′	1,716.9
56880	Yiliang	24°55′	103°10′	1,532.1
56886	Luxi	24°32′	103°46′	1,704.3
56951	Lincang	23°53′	100°05′	1,502.4
56954	Lancang	2°34′	99°56′	1,054.8
56959	Jinghong	22°00′	100°47′	582
56964	Simao	22°47′	100°58′	1,302.1
56966	Yuanjiang	23°36′	101°59′	400.9
56969	Mengla	21°29′	101°34′	631.9

(continued)

Table 2.1 (continued)

WMO number	Name	Latitude	Longitude	Altitude (m)
56977	Jiangcheng	22°35′	101°51′	1,120.5
56985	Mengzi	23°23′	103°23′	1,300.7
56986	Pingbian	22°59′	103°41′	1,414.1
56994	Wenshan	23°23′	104°15′	1,271.6
59007	Guangnan	23°29′	104°31′	1,227.5
57348	Fengjie	31°01′	109°32′	299.8
57633	Qiuyang	28°50′	108°46′	664.1
57426	Liangping	30°41′	107°48′	454.5
57432	Wanxian	30°46′	108°24′	186.7
57516	Shapingba	29°35′	106°28′	259.1
57522	Fuling	29°45′	107°25′	273.5
57606	Tongzi	28°08′	106°50′	972
56691	Xianning	26°52′	104°17′	2,237.5
56793	Panxian	25°43′	104°28′	1,800
57614	Xishui	28°20′	106°13′	1,180.2
57707	Bijie	27°18′	105°17′	1,510.6
57713	Zunyi	27°42′	106°53′	843.9
57722	Meitan	27°46′	107°28′	792.2
57731	Sinan	27°57′	108°15′	416.3
57741	Tongren	27°43′	109°11′	279.7
57803	Qianxi	27°02′	106°01′	1,231.4
57806	Anshun	26°15′	105°54′	1,431.1
57816	Guiyang	26°35′	106°44′	1,223.8
57825	Kaili	26°36′	107°59′	720.3
57832	Sanhui	26°58′	108°40′	626.9
57902	Xingren	25°26′	105°11′	1,378.5
57906	Wangmo	25°11′	106°05′	566.8
57916	Luodian	25°26′	106°46′	440.3
57922	Dushan	25°50′	107°33′	1,013.3
57932	Rongjiang	25°58′	108°32′	285.7

unit of precipitation is mm, and the unit of temperature is °C). Thirdly, there should have spaces between the data columns. For example, each element is separated by one or more space. Fourthly, the lost or missing data in the records must be taken place by −99.9 coding. Fifthly, the data records must be ordered as the calendar date.

RClimDex software mainly includes three steps to do the quality control: (1) to modify all the missing values to the format which can be identified by software, for example, −99.9, after automatically identifying the error of the raw data and to replace all unreasonable value to NA (not available), for example, negative rainfall or less daily maximum temperature value than the daily minimum temperature. (2) To examine the potential outliers in the data sequence so that the researchers make a test, calibration and delete according to the actual data. The outliers refers to the values that the daily data records are more than user custom range. Meanwhile, the researchers themselves can set the threshold of outliers according to the actual situation of the selected data. Generally, the record range of the data is defined as a daily mean value pluses or minuses the n times standard deviation, that is (mean − n * std, mean + n * std). Among them, std presents the intraday standard deviation; n is the threshold of outliers inputted by users, for example, the daily maximum temperature is 30 °C. In this study, the threshold of outliers is set as the daily highest temperature is not more than 45 °C, the daily minimum temperature is no less than −35 °C, and the daily rainfall is not more than 180 mm. In this case of this, the study set three standard deviation to test the threshold of abnormal data so as to better determine the quality of the raw data. (3) The software will automatically generate time series diagrams rainfall and temperature in order to check whether there is any quality problem in the interannual and in-year change of data (Aguilar et al. 2005; New et al. 2006). For example, Fig. 2.1 is an example of quality control of precipitation data. Whether there is any quality problem in the precipitation data by the generating histogram and the Kernel filtering isodense, which is a kind of nonparametric test method (Aguilar et al. 2005). The precipitation data quality showed by this figure is good. Figure 2.2 is the trend diagram of in-year change of precipitation and temperature automatically generated by RClimDex. Through this figure the outliers of temperature or precipitation from a certain station can be monitored. Figure 2.3 is the inter-annual variation of DTR recorded by RClimDex, which is used to test the abnormal situation in its changing trend.

The uniformity test of data is relatively complicated and usually need to do with the aid of the detailed records of inspected stations and the records of the nearby

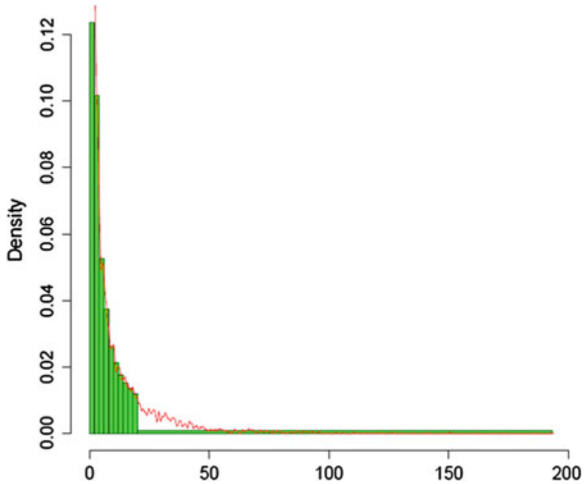

Fig. 2.1 Example of daily precipitation successful quality control procedures using. RClimDex (Histogram (*vertical bars*) and Kernel-filtered density (*line*) showing the high density)

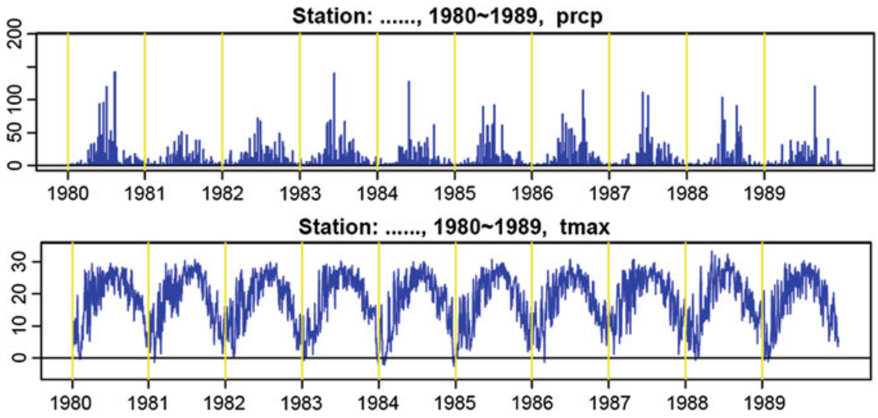

Fig. 2.2 Annual variation of daily precipitation and the maximum temperature recorded by RclimDex during 1980–1989

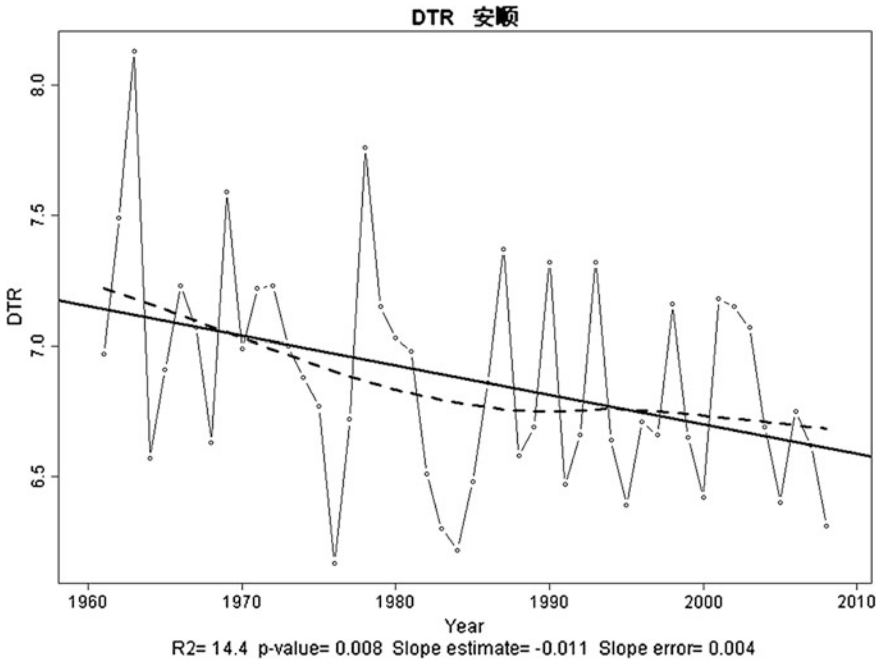

Fig. 2.3 Inter-annual variation of DTRin Anshun station recorded by RClimDex

stations (Dyurgerov 2003). At present in China, there are non uniformity in the climate data sequence due to the historical evolution of the meteorological stations, especially relocation of the site. And the inspection work of non uniformity is still not enough. Many researchers lack enough awareness to the importance and application value of the information about historical evolution, and most of the research work by using the data of stations all lake the analysis and test of the annual data sequence (Wu 2005). In this study, we choose RHtest to evaluate the uniformity of observation data from meteorological stations, which estimate the multiple step change existing in the time series of data based on the two phase regression model (Wang 2001; Wang and Zhou 2005).

For the first time, Easterling and Peterson (1995) used RHtest to examine the non uniformity of the time series of data in the study of Canadian climate extreme. Lund and Reeves (2002), Wang (2003) made the further revision through their own researches. Zhang et al. (2004) examined the daily maximum temperature, daily minimum temperature and annual change trend of daily range by using the revised two phase regression model, identified the potential non uniformity of data and obtained good study effect. Thereafter, this method gets a great academic recognition as one of the important methods of testing non uniformity of data sequence, has eventually become a visualization software available for users and has brought great convenience for scientific research workers. The first step of this method is to test the annual sequence changes of the data by the analysis of regression model. The second step is to use regression model to find out the discontinuity in annual sequence changes. The third step is to apply F test to determine the statistical meaning of the regression model. Only when test results of the regression model in the first step would have reached the confidence level of 95 %, the results of the regression model in the second step was believed to be reliable. The fourth step is to identify whether the discontinuous points have statistical meaning and to finalize the uniformity of the data sequence. The data set selected in this study have eight stations existing potential discontinuity in the sequence of daily maximum temperature and four stations in a sequence of daily minimum temperature (Fig. 2.4).

Through seeking the original records of data and the historical documents of stations, we found that only one appears discontinuity of data because of site relocation among the 12 stations, the discontinuous data of the rest is caused by outliers. Hereby, we eliminate these outliers and remove a station with data non uniformity, in which the daily mean temperature, daily maximum temperature and daily minimum temperatures has the discontinuity around 1983 and the temperature variation characteristics is significantly consistent with that around the stations. We found the station site relocated in 1983 after checking the data records. Through a series of procedures, we finally select 110 eligible stations to be used in this study (Table 2.1).

2.1.2 The Data on Glacier Change

The data about the terminus fluctuation of glaciers, the change in areas and ice lake, material balance and so forth are mainly from previous works, the details of which can be shown in Chap. 7. Here we will focus on the source of data on the terminus fluctuation of eight glaciers, such as Hailuogou Glacier, Hailuogou No. 2 Glacier, Big

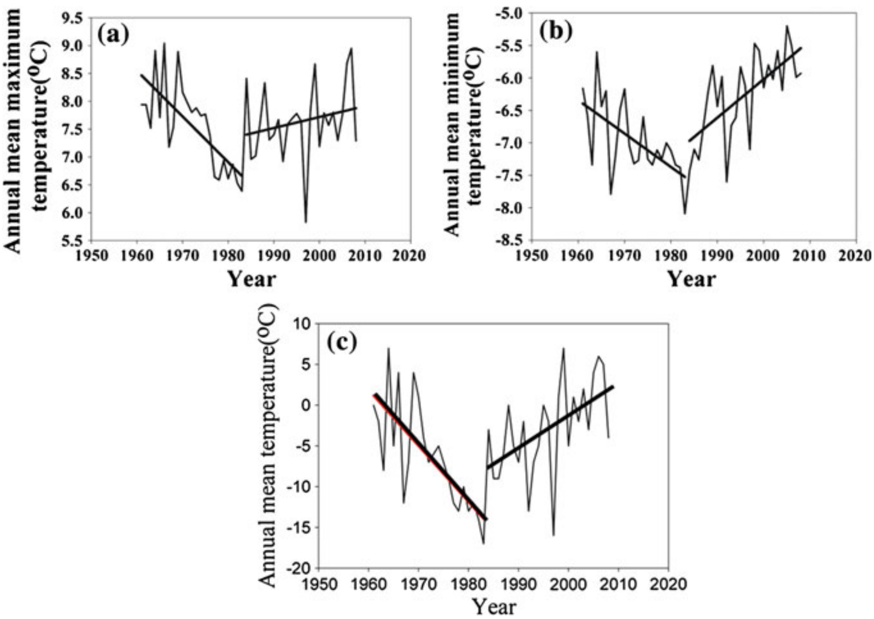

Fig. 2.4 Homogeneity test of annual mean daily maximum temperature (**a**), minimum temperature (**b**), and mean temperature (**c**) for station Jiali (30°40′N, 93°17′E, 4,488.8 m a.s.l.). (The largest, statistically significant discontinuity around 1983 is verified by the original station data, which indicate that the station relocated in 1983)

Gongba Glacier, Small Gongba Glacier, Mingyong Glacier, Aza Glacier, Yanzigou Glacier and Baishui No. 1 Glacier. Before 1997, the data about the terminus fluctuation of these glaciers were from previous studies (Heim 1936; Su et al. 2002; Zhang et al. 2001; Pu 1994; Liu 2005; Li et al. 2008, 2009a, b, 2010a, b). The data of Hailuogou Glacier in 2006 and the data of Big Gongba Glacier and Small Gongba Glacier in 2007 are from author's on-the-spot investigation in 2006 and 2007; and since 1997, the data of Baishui No. 1 Glacier are from the field observations of Mount Yulong glacier and the environmental research station. The melting data of Hailuogou Glacier, Big Gongba Glacier and Baishui No. 1 Glacier in 1982 and 1983 come from a book named by "Glacier in Hengduan Mountains", while in 1990–1998 the melting data of Hailuogou Glacier is provided by Zhang wenjing in the Chengdu Mountain Office of Chinese Academy of Sciences. The meteorological and hydrological data of Hailuogou Glacier are offered by the observation station focusing on the alpine ecosystem of Mount Gongga. This station was built in 1988 and affiliated with the Chengdu Mountain Office of Chinese Academy of Sciences. The data on temperature variation in China and in Northern Hemisphere use the study of Wang et al. (1998) for reference. The data on material balance of Hailuogou Glacier from 1959/1960 to 1992/1993 are from the research result of water-material balance in the book named by "Chinese glacier and environment", and the data on material balance during 1993/1994–2003/2004 is calculated by author with water balance method based on the climate data and hydrological data in 1994–2004 from the observation station focusing on the alpine ecosystem of Mount Gongga. The hydrological data in 1979–2003 of Mujiaqiao hydrological station in Yanggongjiang valley are taken from Lijiang's hydrological bureau, and the climate data of Lijiang Basin are provided by Lijiang's Bureau of Meteorology.

2.1.3 The Reanalyzed Data

The atmospheric reanalysis data of National Center of Aatmospheric Research (NCAR) or National Centers for Environmental Prediction (NCEP) has two versions: the NCEP/NCAR global reanalysis products (NCEP-R1) and NCEP/DOE second set of reanalysis products (NCEP-R2). NCEP-R1 product has two main characteristics. One is the cover period of data is longer, from 1948 to now. The other is it integrate in a wide range of the observed data. NCEP-R2 is an upgrade or update version of NCEP-R1. It changes the known system error of NCEP-R1, and introduces the latest physical process. That is to say, it is the recalculation in the context of improving the system of NCEP-R1, therefore, they have the same input field, vertical and horizontal resolution. The improved reanalysis system correct the problems in using remote sensing technology to get snow parameters, for example, the area and the thickness of snow, and improve the forecast of winter precipitation, ground surface temperature and surface flux in high latitudes region (Kistler et al. 2001; Ma et al. 2008).

The reanalysis data sets of NCEP/NCAR-R1 contains the data from January 1948 to now, and its spatial resolution is 2.5° × 2.5° (Kalnay et al. 1996). It cover the whole earth (0–360°E; 90°S–90°N); the 17 isobaric surfaces in vertical direction from the ground are respectively 1,000, 925, 850, 700, 600, 500, 600, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 hPa. In addition, there also is the surface mean sequence values. This study determines the impact of changes in atmospheric circulation system to climate change of Southwestern China by using the reanalysis data of NCEP/NCAR-R1 on monthly mean geopotential height, meridional and zonal wind, and relative humidity. Moreover, this study also make use of the reanalysis data on the net surface long-wave radiation, the net surface shortwave radiation, sea surface temperature, sea level pressure and others. The reanalysis data of the NCEP/NCAR on monthly mean temperature and air pressure also be used in this study to understand the change of the surface pressure gradient force and the change of wind speed (Kalnay et al. 1996). And in order to analyze the cause of sunshine time changes, the reanalysis data of the NCEP/NCAR on mean downward solar radiation flux, total area of cloud cover and water content of the cloud and so forth has been used.

2.2 Methods

2.2.1 The Linear Trend

A reasonable linear denotes the relations between climate variables and time; x_i denotes a contain climate variables; t_i denotes corresponding time of x_i. Then unary linear regression equation is developed between x_i and t_i.

$$\hat{x}_i = a + bt_i \tag{2.1}$$

In this formula, a is the regression constant; b is the regression coefficient. a and b can be estimated by the least squares.

The symbol of the regression coefficient b refers to the inclination of climate variables x. When $b > 0$, it indicates that x is on the rise with the increase of time t; when $b < 0$, it indicates that x is on the decline with the increase of time t. The numerical size of b reflects the rate of rise or fall, that is, the tendency of rising or falling. Generally, b is called the tendency rate of climate (that is the change range).

$$\begin{cases} a = \bar{x} - b\bar{t} \\ b = \frac{\sum_{i=1}^{n} x_i t_i - \frac{1}{n}\left(\sum_{i=1}^{n} x_i\right)\left(\sum_{i=1}^{n} t_i\right)}{\sum_{i=1}^{n} t_i^2 - \frac{1}{n}\left(\sum_{i=1}^{n} t_i\right)^2} \end{cases} \tag{2.2}$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i;\ \bar{t} = \frac{1}{n}\sum_{i=1}^{n} t_i \tag{2.3}$$

It is necessary to calculate the correlation coefficient r in order to reflect the close degree of the linear relationship between the climate variables x and time t. Generally, r is called the climate trend coefficient.

$$r_{xt} = \frac{\sum_{i=1}^{n} (x_i - \bar{x})(t - \bar{t})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \sum_{i=1}^{n} (t - \bar{t})^2}} \tag{2.4}$$

When the absolute value r is the greater, it indicates the relation between climate variables x and time t is closer. If we want to judge whether the climate change trend is significant or not, significance text of the correlation coefficient r is still necessary. α can be determined as the level of significance, if the absolute value $r > r_\alpha$, it indicates that climate variables x change significantly with the change of time t, or it was not significant. The paper use ρ to text. when $\alpha = 0.05$, if $r > 0.2818$, it suggests that the change trend is obvious; when $\alpha = 0.01$, if $r > 0.3649$, it means that the change trend is significant; When $\alpha = 0.001$, if $r > 0.4562$, it says that the trend is very significant. In this study, the linear correlation is 0.05 degree of confidence, and the straight line presents the linear trend.

2.2.2 Moving Mean

Moving mean is a basic method of trend fitting, which is equivalent to a low-pass filter used to determine the change trend of mean of the time sequence. For climate change sequence x of the sample size n, the moving mean sequence is:

$$\hat{x}_i = \frac{1}{k}\sum_{i=1}^{k} x_{i+j-1} \tag{2.5}$$

In this formula, k is for the sliding length, which is determined according to the specific matters and the size of the sample. Generally, k take an odd number so that the mean can be added to each time coordinates in the time sequence; $j = 1, 2, \ldots, n - k + 1$.

The observed value is calculated with moving mean, and n data can get $(n - k + 1)$ smoothed values. After smoothing, the great weakening of cycle which is shorter than the sliding length shows the change trend. Based on previous researches, the climate change sequence in study areas has the short cycle of 2, 2.5, 4, 7, 9, 11, 28 years. After considering again, the length of time sequence is 48 years. The sliding length take a value as 9, that means that the change of climate sequence is a sliding trend of 9 years, which has been marked with thicker curve in this paper.

2.2.3 The Calculation of Regional Trend

In order to avoid the effect of abnormally high or low values from individual stations or in individual years to emperature and precipitation sequence of the entire area, first of all, we make the mean value of climate data of stations, then calculate the change sequence of climate elements in the study area. Next the sequence of climate elements of stations in different periods, such as the monsoon and non-monsoon, are made as the period from December to following February is winter; the period from March to May is spring; the period from Jull to August is summer; the period from September to November is autumn; the period from May to October is monsoon and the period from November to following April is non-monsoon. Then we will calculate the annual, seasonal, monsoon and non-monsoon sequence of climate elements in different regions. The division between monsoon and non-monsoon use the conclusion of "Hengduan Mountain Glacier" written by Li and Su (1996). The calculation results of data in this study take the significance level of 0.05, if the statistical value is less than the significance level, the trend is thought significant. Finally, the spatial distribution diagram of tendency rate change of climate elements is drawn under the situation of ArcGIS to analyze the spatial variation.

The climate sequence in study area and the sub regional areas are calculated as the following formula:

$$x_{r,t} = \sum_{i=1}^{n_t} (x_{i,t} - \overline{x}_i)/n_t \tag{2.6}$$

In this formula, $x_{r,t}$ is the annual or seasonal means of the climate parameters of a region (e.g., temperature) in t years; $x_{i,t}$ is the value of a certain climate parameter of i staion in t year; x_i is the mean value of a certain climate parameter of i station in 1961–2008; n_t is the number of eligible station of a certain climate parameter. $x_{i,t}$ and x are standardized before calculation to avoid the influence of the abnormally high value.

2.2.4 The Definition of Urban Station and Rural Station and the Basis of Classification

Generally, the method to study the urban heat island effect is to compare the observations of meteorological stations in large cities with that in surrounding areas (the rural), and the difference between them will be defined as the contribution of city heat island (Jones et al. 2008; Ren et al. 2008). Due to the limitation of data, this study mainly analyzes the difference of change magnitude of each climate element between the rural station and the city station. A large number of climate researches defined population as an important basis of classifying urban stations and rural stations. This study use the research result of Easterling et al. (1997) as reference to define the meteorological station, of which administrative area has a population of more than 50,000 as urban station, otherwise, it is rural station. Based on this method, 110 stations in Southernwestern China are divided into 58 rural stations and 52 urban stations.

In order to determine whether the regional terrain where observation stations are located is influential to the observations, we set a specific distance as the radius to calculate the altitude difference between the observation stations (the center of a circle) and the surrounding eight directions with the use of GTOPO30 digital elevation model (http://eros.usgs.gov). Among at least five of eight directions, the elevation difference between them less than 100 m is defined as the plain station; less than 0 m is defined as peak stations; that in 100–300 m is defined as inter-mountain basin station; more than 300 m station is defined as the valley station. Then the geographic coordinates of meteorological stations are input in the digital terrain map to check the above calculation results and ultimately to determine terrain types of stations.

2.2.5 The Division of Sub-regions

In order to more systematically know the differences of regional climate change, this study make a factor analysis to the change trend of the annual mean temperature (standard value) of 110 stations and separate the areas with the same temperature trends. Factor analysis is a statistical method which can sort out several variables of which the correlation is quite close, and look each kind as a factor so as to distinguish factors with different changing trend, finally reach the purpose of classification. Southwestern China can be divides into three sub-regions by using the analysis results of changes factor of the annual mean temperature, that is to determine stations with the consistent temperature variation trends, and combining the latitude location and altitude. The first factor accounts for 42 % of the total variance and is Xizang Phateau and Hengduan Mountains. It includes: Shiquan River, Bangor, Naqu, Xainza, Shigatse, Lhasa, Zetang, Dingri, Jiangzi, Linzhi, Parry, Suoxian, Bowo, Longzi, Changdu, Dingqing, Shiqu, Ruoergai, sertar, Hongyuan, Dege, Ganzi, Barkam, Daofu, Xiaojin, Batang, Xinlong, Litang, Daocheng, Kangding, Muli, Jiulong, Yuexi, Songpan, Yanyuan, Xichang, Deqin, Gongshan, Shangri-la, Weixi, Lijiang, Huaping and Dali. The second factor accounts for the 33 % of the total variance and is Yunnan-Guizhou Plateau. It contains: Huize, Tengchong, Zhaotong, Baoshan, Yuanmou, Chuxiong, Kunming, Zhanyi, Ruili, Jingdong, Yuxi, Luxi, Wenshan, Yiliang, Lincang, Jinghong, Simao, Yuanjiang, Mongla, Jiangcheng, Mengzi, Pingbian, Guangnan, Xianning, Xishui, Panxian, Tongzi, Bijie, Zunyi,Meitan, Sinan, Tongren, Qianxi, Anshun, Guiyang, Kaili, Sanhui, Xingren, Wangmo, Luodian, Dushan, and Rongjiang. The third factor accounts for 9 % and is Sichuan Basin. It includes: Dujiangyan, Pingwu, Mianyang, Ya-an, Emeishan, Leshan, Zhaojue, Leibo, Yibin, Huili, Guangyuan, Wanyuan, Yanzhong, Bazhong, Daxian, Suining, Gaopingqu, Luzhou, Xuyong, Liangping, Wanxian, Peiling, Shapingba, Qiuyang and Fengjie.

2.2.6 The Changes of Atmospheric Circulation System in a Large Scale

On the basis of the reanalysis data on monthly mean meridional wind field, monthly zonal wind field, relative humidity, and geopotential height of 300 and 500 hPa in 1961–2008, this study analyzes the correlation between annual mean temperature and sea level pressure (SLP) of the studies areas in 1961–2008 by using the software of Grads. Based on this point, this study synthesizes the composite graph of atmospheric circulation of isobaric surface of 300 and 500 hPa in four seasons between 1961–1985 and 1986–2008. The variation can be got through former period minus latter one. Moreover, the study also analyzes the relationship between variation and temperature variations at the same period. In the same way, the composite graph of atmospheric circulation of extreme minimum and maximum temperatures in the isobaric surface of 300 and 500 hPa in summer (June–August) and winter (December–February) of 1961–2008 is synthesized, and the circulation of two periods is presented by that former minus the latter. The extreme high temperature in summer in Southwestern China occurred in 1961 and 2006, whereas, the extreme low temperature in summer happened in 1965, 1968,1974 and 1976; the extreme high temperature in winter occurred in 1987, 1999, 1987, 2003 and 2007, while the extreme low temperature in winter happened in 1968, 1976 and 1983.

Water vapor transport is the main factor of the atmospheric water cycle, and has an important influence on the regional climate change. In order to understand the change of water vapor transport in the study areas and its impact on regional precipitation variation under the background of climate change, this study makes use of the NCEP/NCAR reanalysis data on monthly mean meridional wind field, zonal wind field and relative humidity and the geopotential height to calculate the integral layer of atmospheric vapor transport flux, and analyzes the vapor flux change and its impact on regional precipitation variation under the background of climate warming in Southwestern China. The specific calculation formula is as follows:

$$Q = \frac{1}{g}\int_{p_t}^{p_0} (u, v)q dp \tag{2.7}$$

In this formula, u and v respectively is the east-west winds and south-north wind of air column per unit area in each layer of the atmosphere; q is the specific humidity of air column per unit area in each layer of the atmosphere; P_0 is the sea level pressure; P_t is pressure when it is assumed that there is no water vapour in the atmosphere. For simplicity sake, the study will take P_0 = 1,000 hPa and P_t = 300 and 500 hPa. According to the principle proposed above, we calculate the mean water vapor flux of 500 and 300 hPa isobaric surface in summer and winter of 1961–2008 and the annual mean water vapor flux of 1986–2008 and 1961–1985 in study areas. The variation is presented through former minuses the latter. In addition, we also calculate the difference of water vapor flux of between more precipitation and less precipitation, and the former minuses the latter to present variation. In summer, the years with more precipitation are 1980, 1998 and 1999; the years with less precipitation are 1972, 1975, 1992 and 2006. In winter, the years with more precipitation are 1967, 1983, 1992, 1983 and 2004; the years with less precipitation are 1963, 1970 and 1974. In addition, in order to further verify the influence of the circulation system change on the climate parameters change in the study area, this study analyzes the annual and seasonal changes of meridional and zonal wind in the two periods of 1986–2008 and 1961–2008, and calculate the change of solar radiation flux, water content in cloud, relative humidity and so on in the different periods.

2.2.7 The Definition and Calculation of Extreme Event Index

The standard method to define and calculate the climate extreme index in this study is "the detection and index of climate change" of World Meteorological Organization (http://cccma.seos.uvic.ca/ETCCDI). This method has been widely used to research extreme weather events by scholars both at home and abroad. The research team of "the detection and index of climate change" finally identified 27 indexes of the climate events which consist of 16 temperature indexes and 11 precipitation indexes. These indexes are calculated with daily maximum temperature, daily minimum temperature and daily precipitation. The meaning of index and the basis of calculation will be shown in following parts. The above index can be classified into five types: (1) relative index based on percentage threshold; (2) absolute indicator presenting maximum or minimum in a season or a year; (3) threshold indicator; (4) continuous indicator; (5) other indicators, such as the annual total rainfall of rainy season, the temperature daily range (maximum minuses minimum), mean precipitation intensity in rainy days (precipitation divides rainfall days) etc. (Alexander et al. 2006).

Now the most common in the climate extreme change research on the international is using a percentile value as the threshold of extremum. The value more than the threshold value is considered as extreme value, which is considered to be the extreme events. The climate extreme threshold is determined by Bonsal non parametric solutions and the calculation steps are as follows:

It is assumed that a meteorological element has N values which are arranged as the ascending order $x_1, x_2, \ldots, x_m, \ldots, x_n$. The probability of that a value is less than or equal to x_m:

$$\mathrm{P} = (\mathrm{m}\,0.31)/(\mathrm{n} + 0.38) \tag{2.8}$$

In this formula, m is serial number of x_m.

The statistics of extreme temperatures is to arrange the temperature data of a day in 1961–2008 as the ascending order and take the 10th and the 90th percentile value as the threshold of extreme temperature. When the temperature in a day is greater than the 90th percentile value, it is thought that the extreme high temperature event occurs in that day; when the lowest temperature is less than 10th percentile values, it is thought that the extreme low temperature event happens in that day. The statistics of the extreme precipitation events is to arrange the daily precipitation year by year from 1961 to 2008 as the ascending order and take the mean of 48 years of 99th percentile value as the threshold of extreme rainfall events. When rainfall in a day exceeds the threshold, it is thought that the extreme precipitation events occurs in that day. When the RClimDex software is calculating the index, not all index calculation base on the month due to the practical application. if the time of missing data is not more than three days of a month and not more than 15 days of a year, the monthly and annual extreme index will be calculated; if the data in a month is missing, extreme index of this years will calculate incorrectly. According to research needs, total 23 climate extreme indexes are chosen, of which calculation is completed with RclimDex. The calculation principle of the selected indexes is as follows:

1. The days of extreme low temperature during the day (TX10)
   Tx_{ij} is the daily maximum temperature on the *i*th day during *j*; $Tx^{in}10$ is the 10th percentile threshold. The relative proportion of the index is expressed in the following formula: $Tx_{ij} < Tx_{in}10$, the unit is *d*.
2. The days of extreme low temperature at night (TN10)
   Tn_{ij} is the daily minimum temperature on the *i*th day during *j*; $Tn_{in}10$ is the 10th percentile threshold. The relative proportion of the index is expressed in the following formula: $Tn_{ij} < Tn_{in}10$, the unit is *d*.
3. The low value of the daily maximum temperature (TXn)
   TX_{kj} is the daily maximum temperature on the *k*th month during *j*; the smallest value of daily maximum temperature is expressed in the following formula: $TXn_{kj} = \min(Tx_{kj})$, the unit is °C.
4. The low value of the daily minimum temperature (TNn)
   Tn_{kj} is the daily minimum temperature on the *k*th month during *j*; the smallest value of daily minimum temperature is expressed in the following formula: $TNn_{kj} = \min(Tn_{kj})$, the unit is °C.
5. The freezing days (ID)
   Tx_{ij} is the daily maximum temperature on the *k*th month during *j*; the number of days is counted with the following formula: $Tx_{ij} < 0$ °C, the unit is *d*.
6. The frost days (FD)
   Tn_{ij} is the daily minimum temperature on the *i*th day during *j*; the number of days is counted with the following formula: $Tn_{ij} < 0$ °C, the unit is *d*.
7. The daily range of temperature (DTR)
   Tx_{ij} and Tn_{ij} are the daily maximum and minimum temperature on the *i*th day during *j*; *I* is the total number of days during *j*, counted with the following formula:

$$DTR_j = \frac{\sum_{i=1}^{I} \left(Tx_{ij} - Tn_{ij}\right)}{I} \text{ the unit is } ^\circ\text{C}.$$

8. The days of extreme high temperature at night (TN90)
   Tn_{ij} is the daily minimum temperature on the *i*th day during *j*; $Tn_{in}90$ is the 90th percentile threshold. The relative proportion of the index is expressed in the following formula: $Tn_{ij} > Tn_{in}90$, the unit is *d*.
9. The days of extreme high temperature during the day (TX90)
   Tx_{ij} is the daily maximum temperature on the *i*th day during *j*; $Tx_{in}90$ is the 90th percentile threshold. The relative proportion of the index is expressed in the following formula: $Tx_{ij} > Tx_{in}90$, the unit is *d*.

10. The high value of daily maximum temperature in a year (TXx)
    TX_{kj} is the daily maximum temperature on the kth month during j; the maximum value of daily maximum temperature each month is counted with the following formula: $TX_{xkj} = \max(Tx_{kj})$, the unit is °C.
11. The high value of daily minimum temperature in a year (TNx)
    TN_{kj} is the daily minimum temperature on the kth month during j; the maximum value of daily minimum temperature each month is counted with the following formula: $TN_{xkj} = \max(Tn_{kj})$, the unit is °C.
12. The growth day length (GSL)
    T_{ij} is the daily mean temperature on the ith day during j; when the statistics firstly appear, there are at least six consecutive day meeting the following formula: $T_{ij} > 5$ °C; when the statistics firstly appear after July 1st (Northern Hemisphere), there are at least six consecutive days meeting the following formula $T_{ij} < 5$ °C, the unit is day.
13. The total precipitation in the rain day (PRCPTOT)
    RR_{ij} is the daily precipitation on the ith day during j; I is the number of days during j, which is counted with the following formula:

$$PRCPTOT_j = \sum_{i=1}^{I} RR_{ij}, \text{the unit is mm.}$$

14. The annual mean precipitation intensity in rainy days (SDII)
    RR_{wj} is the daily precipitation in rainy day w(RR ≥ 1 mm) during j; W is the number of rainy days during j, which is counted with the following formular:

$$SDII_j = \frac{\sum_{w=1}^{W} RR_{wj}}{W}, \text{ the unit is mm/d.}$$

15. Extreme precipitation (R95)
    RR_{wj} is the daily precipitation in rainy day w(RR ≥ 1 mm) during j; RR_{wn95} is the 95th percentile threshold of precipitation in rainy day during 1961–1990; W is the number of rainy days during j, which is counted with the following formular:

$$R_{95pj} = \sum_{\mathrm{w}=1}^{\mathrm{W}} RR_{wj} \text{ where } RR_{wj} > RR_{wn95} \text{ the unit is mm/d.}$$

16. Very extreme precipitation (R99)
    RR_{wj} is the daily precipitation in rainy day w(RR ≥ 1 mm) during j; RR_{wn99} is the 99th percentile threshold of precipitation in rainy day during 1961–1990; W is the number of rainy days during j, which is counted with the following formular:

$$R99_{pj} = \sum_{w=1}^{W} RR_{wj} \text{ where } RR_{wj} > RR_{wn99} \text{ the unit is mm/d.}$$

17. The maximum precipitation in odd days (RX1 day)
    RR_{ij} is the daily precipitation on the *i*th day during *j*; the maximum precipitation in one day during *j* is counted with the following formula: $Rx1day_j = \max(RR_{ij})$, the unit is mm.
18. Total precipitation in five consecutive days (R×5 day)
    RR_{kj} is the precipitation in five consecutive days and end in *k* day during *j*; the maximum precipitation in five day during *j* is counted with the following formula:

$$Rx5day_j = \max(RR_{kj}), \text{the unit is mm.}$$

19. The maximum consecutive drought days (CDD)
    RR^{ij} is the daily precipitation on the *i*th day during *j*; the maximum consecutive drought days is counted with the following formula: $RR_{ij} < 1$ mm, the unit is *d*.
20. The maximum consecutive rainy days (CWD)
    RR_{ij} is the daily precipitation on the *i*th day during *j*; the maximum consecutive rainy days is counted with the following formula: $RR_{ij} \geq 1$ mm, the unit is *d*.
21. The number of days when the daily precipitation is more than 10 mm (R10 mm)
    RR_{ij} is the daily precipitation on the *i*th day during *j*; the number of days is counted with the following formula: $RR_{ij} \geq 10$ mm, the unit is *d*.
22. The number of days when the daily precipitation is more than 20 mm (R20 mm)
    RR_{ij} is the daily precipitation on the *i*th day during *j*; the number of days is counted with the following formula: $RR_{ij} \geq 20$ mm, the unit is *d*.
23. The number of days when the daily precipitation is more than 25 mm (R25 mm)
    RR_{ij} is the daily precipitation on the *i*th day during *j*; *nn* take 25 in this study, the number of days is counted with the following formula: $RR_{ij} \geq$ nnmm, the unit is *d*.

2.2.8 The Calculation of Glacier Length and Material Balance

The data of terminus fluctuation of glaciers and the change in terminus elevation mainly are based on the previous researches (mostly before 2,000 year) and the observation of recent years (Table 2.2). Based on this point, the change in length of glacier is counted with the following formula:

$$L = L1 + D \tag{2.9}$$

In this formula, L is the glacier length; L1 is the glacier length in current year used as a reference, that is the length of 1982 or 1983 recorded; D is the fluctuating distance of glacier terminus. If the glacier advances prior to the current year, D is negative value; if the glacier advances after the current year, D is positive. The fluctuating speed of glacier terminus is the ratio of fluctuating distance to number of years.

The glacier mass balance is a combined action of result of climate factors like hydrotherm on the glacier, and is one of the most sensitive indicators reflecting climate change. Its dynamic change is the material basis of the change in the glacial scale and runoff. The observation and estimation of glacier material balance have received a wide of concern for a long time. In spite of the high precision, the traditional method given priority to with the measured still need to spend a lot of manpower, material resources and time, which limits to get observations of glacier mass balance in a larger scale. Within the scope of the river basin, the material balance changes have similar temporal and spatial variation characteristics. When Shen (2000) studied the distribution of Chinese glacial hydrology and climate, he found the precipitation and runoff distribution have a negative exponential relation with its area in the west plateau land. The region covered by glacier is the biggest distribution area of rainfall, runoff and runoff coefficient. Starting from the statistical mechanics and the maximum entropy principle, according to the characteristics of precipitation and runoff distribution, a set of equations used to calculate the glaciers mean material balance with hydrological and meteorological observation data have been deduced. On the basis of these formulas, we will be able to resume the year-to-year changing sequence of the mean material balance with the application of unoff and precipitation data recorded in hydrologic stations, which has a realistic meaning to systematically research the material balance of all the mountains and basins and to recover the understand the history of glacier mass balance and the influence of glacier change on runoff. This study calculates material balance of HaiLuoGou glacier during 1993/1994–2003/2004 with water balance method, and its principle is as follows:

$$Bn = (P - E - R)/K \tag{2.10}$$

In this formula, Bn is glacier mass balance, P is the basin rainfall, R is the runoff, E is evaporation, K is glacier coverage in the basin.

2.2.9 The Calculation of Water Output in Snow and Ice at High Altitudes

Mount Gongga (29°20′−30°20′N, 101°30′–102°15′E) and Mount Yulong (27°10′–27°40′N, 100°9′–100°20′E) are the typical Marine glacier areas. HaiLuoGou river basin is located in the east slope of Gongga mountain and finally falls into the Dadu River. There are eight glaciers with a total area of 29.66 km^2 (Pu 1994) in this basin, and the total area of HaiLuoGou river basin is 78.07 km^2. The whole river basin consists of mountains, of which minimum altitude is 2,920 m. The areas below 3,800 m are covered by vegetation, while the areas above 3,800 m are covered by ice and snow. The main water input in this river basin is from precipitation and ice and snow melting water. Gongga Mountain station in Chengdu land office began to observe the hydrological condition in 1994, which is located in the HaiLuoGou glacier terminus of 1 km. Yanggongjiang basin is located at the southern tip of Yulong snow mountain, within which the glacier area is 2.44 km^2 (Pu 1994). The melting water feeds into the Lijiang Basion and finally falls into Yanggongjiang. Lijiang-Yulong Snow Mountain region is mainly covered by limestones, and the rock dissolve physiognomy is relatively developed. So the precipitation and the melting water of Yanggongjiang basin can more easily infiltrate into underground and form underground water, then pour out surface in lower place of Lijiang basin forming many mouths to recharge the surface runoff. In 1979, hydrographic office of Lijiang county set up a hydrometric station in mainly controlling the Yangjiang river basin. The areas controlled is 436.8 km^2 and mainly is composed of Yulong snow mountain land and Lijiang Basin. Among these areas, snow and ice-snow region at high altitude which is more than 4,000 m is 13.8 km^2, and the other area is 423.0 km^2.

As calculating the water balance of rive basin, we just need to take the balance of non ice-snow region at low altitude into consideration, like Lijiang Basin, because there are not the observation data of precipitation and glacier melting water runoff at high altitude. At the same time, we approximately think ice-snow region at high altitude as one of input item of that region at low altitude, that is $P_{Glacier}$, without the distinction between the liquid precipitation and glacier melting water. In addition, the precipitation is another input item, that is P. And the output items include watershed runoff (D) and the actual evaporation (E). Therefore, the equation of water balance in the low altitude area can be presented as Eq. (2.11):

$$P_{Glacier} + P = D + E \tag{2.11}$$

Among them, the actual evaporation E can be calculated with potential evaporation E_0. According to the calculation of monthly evaporation E_0 in two river basins with Baney-Criddle model, Yang et al. (1994) showed that the actual evaporation calculated with this formula can present the actual evaporation of the entire basin.

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Chapter 3
Spatial and Temporal Variation of Temperature and Precipitation in Southwestern China

3.1 Temporal Variation of Temperature and Precipitation

3.1.1 Mean Temperature and Precipitation

The mean temperature in Southwestern China in 1961–2008 is 12.7 °C, and the mean temperature in spring, summer, autumn, winter, monsoon period and non monsoon period are 13.3, 19.9, 13.1, 4.5, 7.5 and 17.9 °C, respectively. The annual and seasonal maximum temperature are 23.8, 25.6, 28.3, 23.7, 17.6, 20.3 and 27.3 °C, respectively, which appear in Yuanjiang station, Yunnan Province at low latitude and altitude. The according minimum temperature are −1.3, −1, 7.5, −1.1, −11.5, −8.1 and 5.2 °C, respectively, which mainly occur in Shiqu, Naqu, Pali etc. at high altitude. The annual mean precipitation in 1961–2008 is 965 mm, and the mean precipitation in spring, summer, autumn, winter, monsoon period and non monsoon period are 188, 501.4, 218.9, 41.8, 157 and 796.7 mm, respectively. The precipitation in spring, autumn and monsoon period account for 82.6 % of annual mean precipitation. The annual and seasonal maximum precipitation are 2,251.7, 577.5, 1,273.6, 501.5, 224.2, 699.3 and 1,929.7 mm, respectively, which happen in the Jiangcheng station, Yunnan Province. The according minimum precipitation are 285.2, 9.17, 95.5, 22.2, 0.4, 3.0 and 63.14 mm, respectively, which occur in Dingri and Tsetang station, Xizang Autonomous Region. As shown in Fig. 3.1, the spatial distribution of the mean annual and seasonal temperature declines gradually from southwest to northeast. The maximum temperature is distributed in the Yungui Plateau and Sichuan Basin, while the minimum temperature is distributed in the Xizang Plateau and Hengduan mountain.

The spatial distribution of the mean annual and seasonal precipitation is same to the temperature (see Fig. 3.2), and reflects the significant influence of topography and elevation. The mean annual and seasonal temperature of Xizang Plateau and Hengduan mountain in 1961–2008 are 7.0, 7.5, 14.5, 7.4, −1.2, 1.7 and 12.4 °C, respectively, and the mean annual and seasonal precipitation are 674, 113.6, 372.8,

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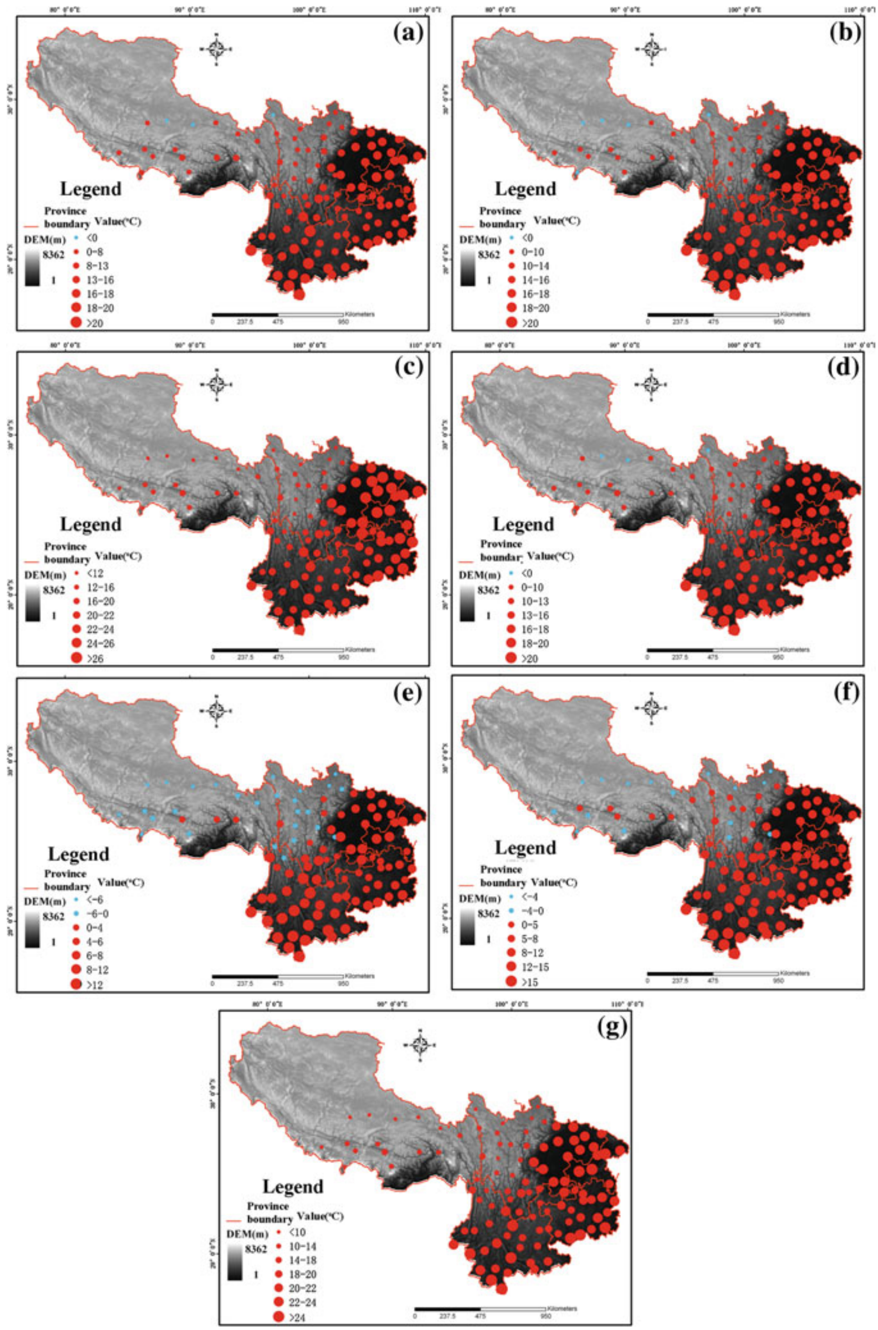

Fig. 3.1 Spatial distribution of the mean annual and seasonal temperature during 1961–2008 in Southwestern China, **a** annual, **b** spring, **c** summer, **d** autumn, **e** winter, **f** winter monsoon period, **g** summer monsoon period

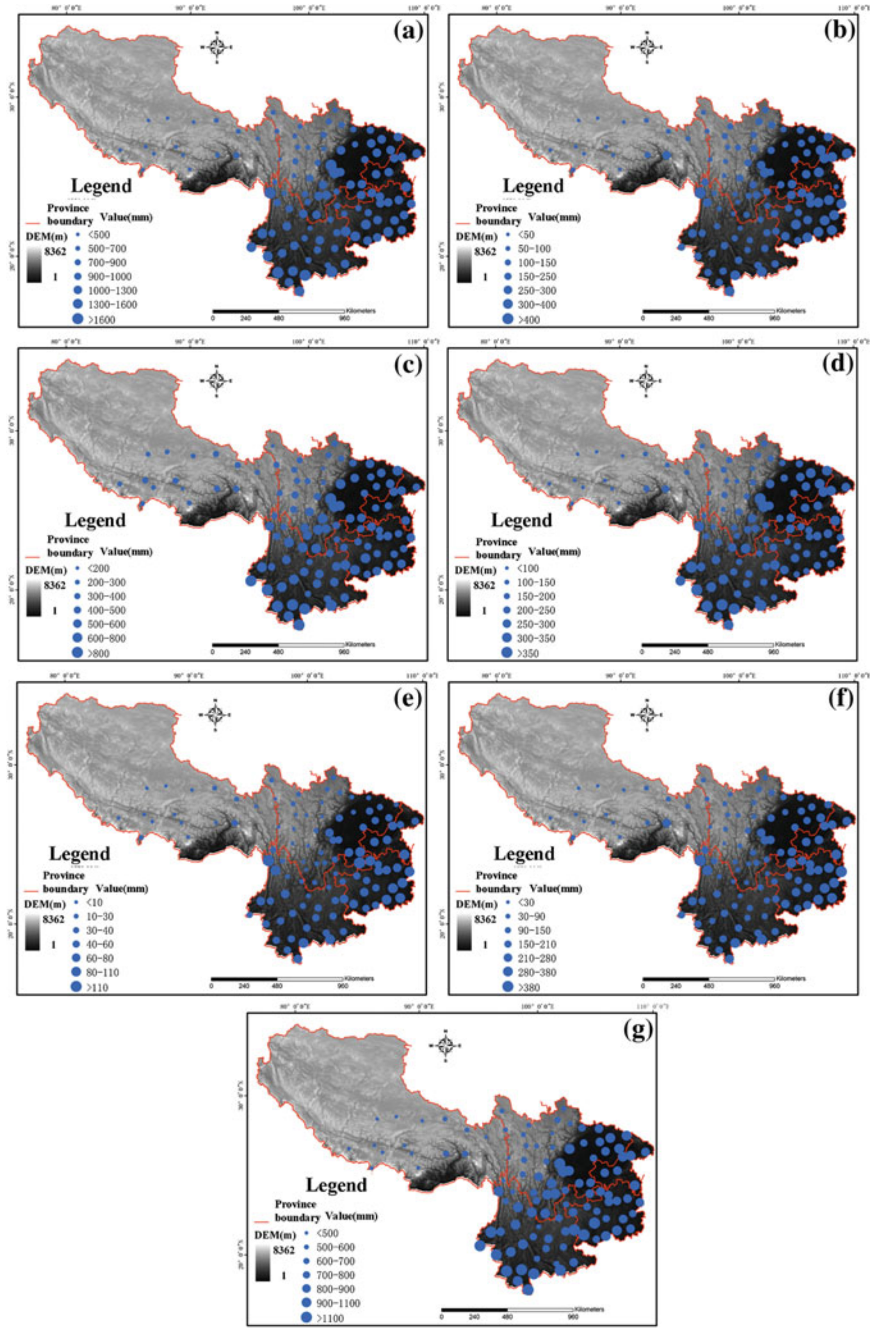

Fig. 3.2 Spatial distribution of the mean annual and seasonal precipitation during 1961–2008 in Southwestern China, **a** annual, **b** spring, **c** summer, **d** autumn, **e** winter, **f** winter monsoon period, **g** summer monsoon period

148.8, 19.7, 84.1 and 574.3 mm, respectively. Accordingly, the mean temperatures in Sichuan Basin are 16.0, 16.2, 24.7, 16.5, 6.7,10 and 22.0 °C, respectively, and the mean precipitation are 1,148.3, 233.7, 572.0, 276.7, 51.5, 209.0 and 937.0 mm, respectively. The difference between temperature and precipitation of sub-regions confirms again the influence of topography and elevation on the distribution of regional temperature and precipitation.

3.1.2 The Annual Change of Temperature

In the past 50 years, the temperature in Southwest China increase gradually, and the magnitude of warming is 0.33 °C/10 a. The magnitude of warming is smaller before the mid of 1980s, whereas the magnitude is relatively bigger after the mid of 1980s, which suggests the warming is accelerating gradually (Fig. 3.3). The significant warming trend can also be shown in the season variation. The magnitudes of temperature variation in spring, summer, autumn and winter are 0.18, 0.19, 0.26 and 0.24 °C/10 a. Since 1961, the mean temperature in winter continued to rise.

The summer mean showed a trend of fluctuating downward and kept a slow rise, but the magnitude of rising increased; the spring mean increase in 1960s followed by an accelerated rise in the mid of 1989s, then appear a slow decline from 1970s to the mid of 1980s (see Fig. 3.3). What the difference from other regions is that the sharp rising of temperature in Southwest China mainly occurs in autumn, but the big magnitude of warming in autumn and winter is similar to that of Qinglian mountains and Xinjiang Autonomous Region (Fig. 3.1).

In terms of the mean annual temperature, the magnitude of changing in Xizang Plateau–Hengduan mountains, Sichuan Basins and Yunnan-Guizhou Plateau are 0.36, continued to rise in 1961–2008; the temperature in Yunnan-Guizhou Plateau kept a table rise except for the fluctuating downtrend in 1960s; the temperature in Sichuan Basins showed a wavelike decrease change before 1985 followed by a significant rise (Fig. 3.3). The magnitude of temperature variation in spring in Xizang Plateau–Hengduan mountains, Sichuan Basins and Yunnan-Guizhou Plateau are 0.23, 0.13 and 0.13 °C/10 a. The Sichuan Basins failed to be estimated the significant level. The temperature in Sichuan Basins and Yunnan-Guizhou Plateau show a trend of fluctuating downward from the end of 1980s to beginning of 1990s. Among them, the magnitude of declining of latter is bigger. Thereafter, the temperature in these two areas keep a stable rise. While the temperature keep a sharp rise in Xizang Plateau–Hengduan mountains (Fig. 3.3). The summer temperature in Xizang Plateau–Hengduan mountains, Sichuan Basins and Yunnan-Guizhou Plateau increase at the rate of 0.29, 0.22 and 0.04 °C/10 a. The Sichuan Basins failed to be estimated the significant level. The temperature in Xizang Plateau–Hengduan mountains continued to rise in 1961–2008; the temperature in Yunnan-Guizhou Plateau showed a wavelike decrease change in 1960s, and rised from 1970s to the mid of 1980s, then was on a slow decline followed by a rise from 21st century. In Sichuan Basin, the mid of 1980s is a watershed. Before this time the temperature

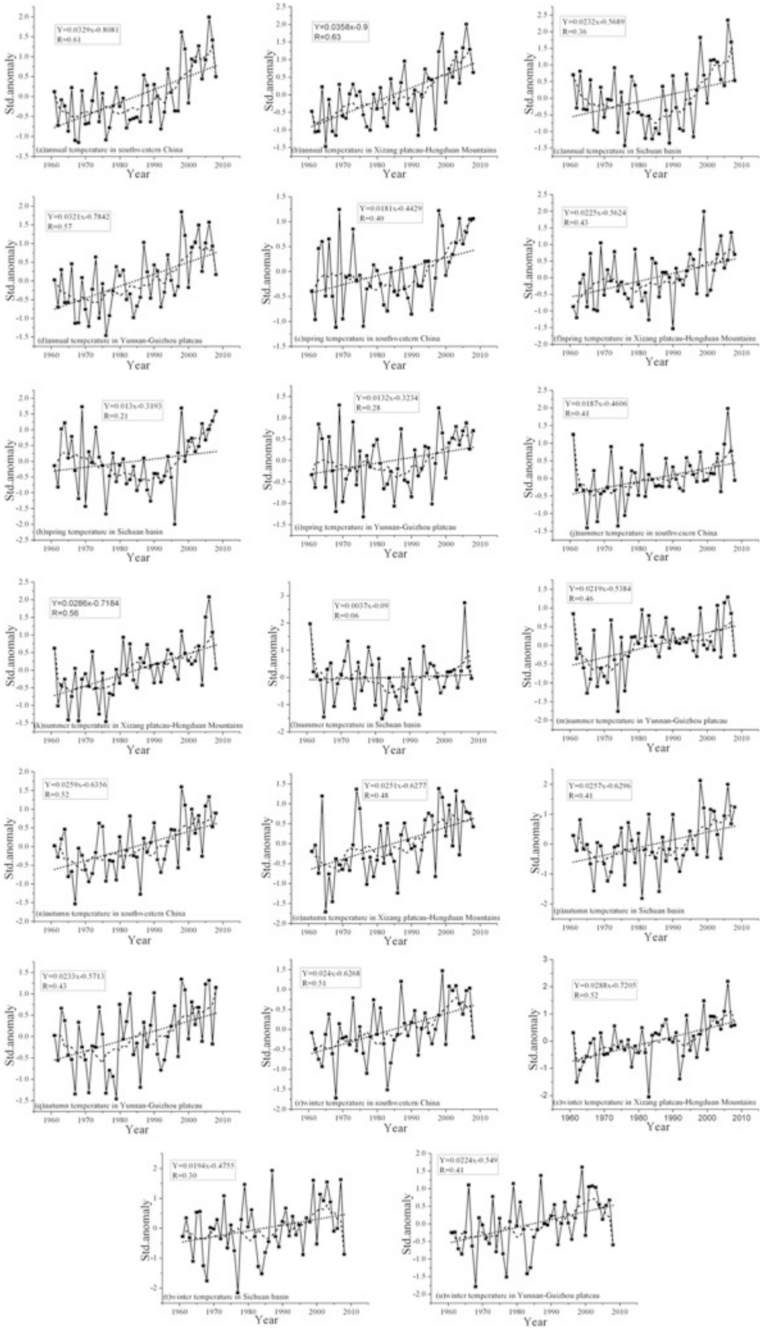

Fig. 3.3 Inter-annual variation of temperature during 1961–2008

showed a stepped decrease, whereas after this time it showed a stepped increase (Fig. 3.3).

The magnitude of temperature variation in autumn in these three regions are 0.25, 0.23 and 0.26 °C/10 a, respectively. What the difference from other seasons is that the magnitude of warming in Sichuan Basin is biggest followed by Xizang Plateau–Hengduan mountains. The temperature in Sichuan Basins and Yunnan-Guizhou Plateau decreased slowly before the mid of 1970s, then was on a continuous rise (Fig. 3.3). The magnitude of temperature variation in winter in these three regions are 0.29, 0.22 and 0.19 °C/10 a, respectively. All they showed a rise during the study (Fig. 3.3). Except for in autumn, the magnitude of temperature variation in Xizang Plateau–Hengduan mountains is biggest and more than that of whole Southwestern China. The difference of magnitude of temperature variation in the sub-regions reflects the influence of topography. The magnitude of warming in Xizang Plateau–Hengduan mountains is larger in winter and summer; the magnitude of warming in Sichuan Basins and Yunnan-Guizhou Plateau is larger in autumn and winter; while the temperature of Sichuan Basin is nonsignificant increase trend in spring and summer. Compared with other regions in China, the warming magnitude of mean annual temperature of Southwestern China is smaller than that of Northeastern China and Xinjiang Autonomous regions, but larger than that of Northwestern China, Qilian Mountain and Himalaya Mountains. In addition, the magnitude of warming in autumn is much larger than Hengduan Mountains, Northwestern China and Xinjiang Autonomous regions (Fig. 3.1).

3.1.3 The Annual Precipitation Variation

The precipitation of Southwestern China showed a non-statistically significant decrease in 1961–2008. The magnitude of changing was −0.006 mm/10 a and kept stable in 1961–1980, then had a slow decline. But it was rising significantly in the whole 1980s, while showed a wavelike decline trend after new century (Fig. 3.4). The magnitude of precipitation variation in four seasons were 0.061, 0.023, −0.077 and 0.093 mm/10 a, respectively in study areas. It showed a statistically significant decrease as a whole, although there was a slow increase trend in the mid of 1970s; the precipitation in summer had a fluctuating change from increase to decrease as a cycle of about 10 years; the precipitation in winter showed a slow increase in a statistical significance; while the precipitation had an obvious fluctuation before 1980s followed by a rising trend (Fig. 3.4).

The magnitude of annual precipitation variation in Xizang Plateau–Hengduan Mountains, Sichuan Basins and Yunnan-Guizhou Plateau were 0.085, −0.049 and −0.088 mm/10 a. Among them, only the precipitation of Xizang Plateau–Hengduan Mountains was slowly increase in fluctuation. The precipitation of Yunnan-Guizhou Plateau fluctuated to delince before 1990s and had a obvious rise in 1990s, but it fluctuated to delince again after 2000. The precipitation of Sichuan Basin kept the trend of fluctuating decline all the time in recent 50 years (Fig. 3.4). The magnitude

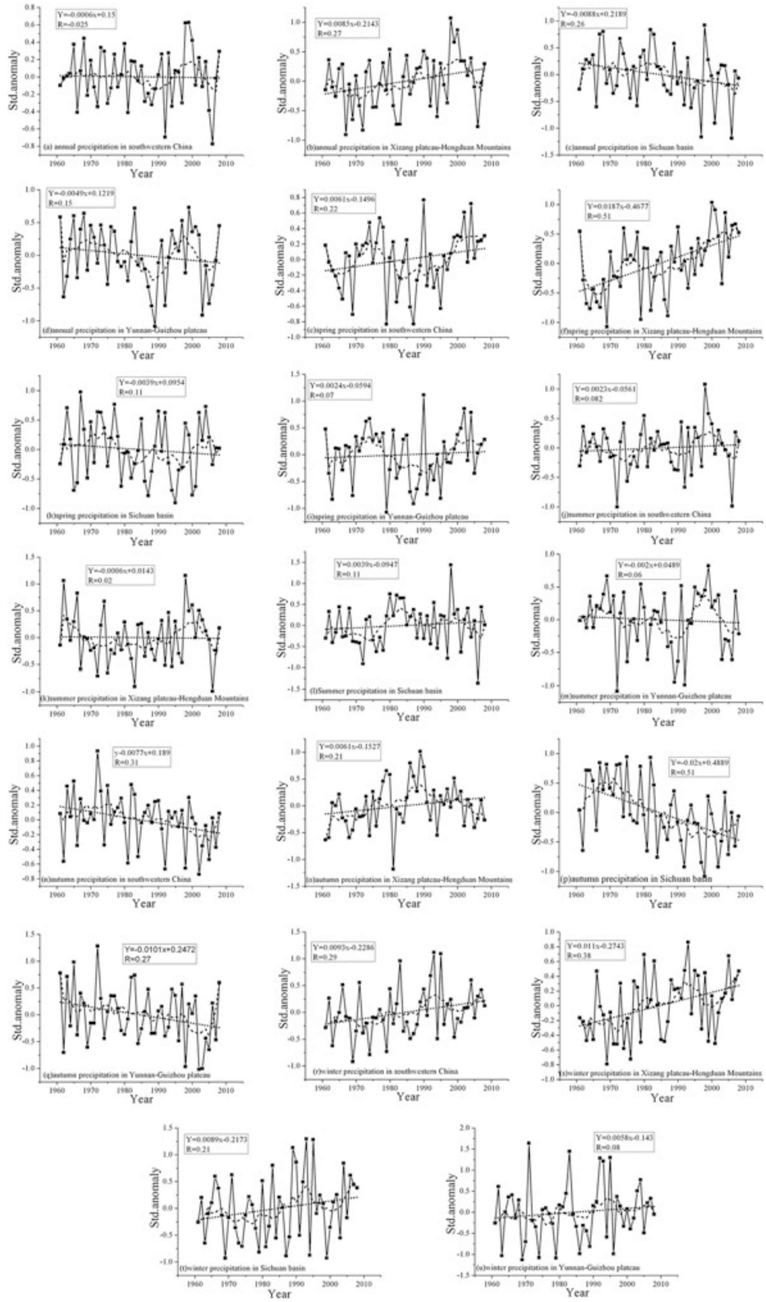

Fig. 3.4 Inter-annual variation of precipitation during 1961–2008

of spring precipitation variation in these three regions were 0.187, 0.024 and −0.039 mm/10 a. The precipitation of Xizang Plateau–Hengduan Mountains had a significant increase, whereas the precipitation of Sichuan Basin had a slow decrease. The precipitation of Yunnan-Guizhou Plateau was on a rise in 1961–1975, but it delinced in 1975–1990. Thereafter it rised again (Fig. 3.4). The magnitude of summer precipitation variation in these three regions were −0.006, −0.02 and 0.039 mm/10 a. The precipitation of Xizang Plateau–Hengduan Mountains slowly declined in 1970s, then kept a stable trend up to the mid of 1990s. In 1995–2005 it appeared a rise, but it declined after 2005. The precipitation of Yunnan-Guizhou Plateau fell in fluctuation before 1990s and rose in the whole 1990s, then it appeared a significant decline. Before the mid of 1980s the precipitation of Sichuan Basin showed a wavelike increase, then it slowly decreased. In general, it showed a rising trend (Fig. 3.4). The autumn precipitation of Xizang Plateau–Hengduan Mountains showed a trend of fluctuating increase before 1990s, thereafter it fluctuated to decrease. The magnitude of changing is 0.061 mm/10 a. The precipitation of Yunnan-Guizhou Plateau decreased at the rate of −0.101 mm/10 a in 1961–2008. The autumn precipitation of Sichuan Basin declined significantly at the rate of −0.2 mm/10 a in nearly 50 years (Fig. 3.4). The winter precipitation of Xizang Plateau–Hengduan Mountains had a obvious rise in fluctuation, of which magnitude is 0.11 mm/10 a; the winter precipitation of Yunnan-Guizhou Plateau slowly increased at the rate of 0.058 mm/10 a; that of Sichuan Basin had a wavelike decrease before 1980s, and it began to increase up to 1990s, but it declined in fluctuation again (Fig. 3.4).

As a whole, compared with the temperature variation, the magnitude of precipitation variation is smaller, but the annual fluctuation reflects the complexity and the difference in regions. The precipitation in winter and spring significantly increase, while it decreases sharply in autumn. The precipitation of Xizang Plateau–Hengduan Mountains in winter and spring much more than that of Southwestern China, and the annual and autumn precipitation of Sichuan Basins and Yunnan-Guizhou Plateau are more than that of Southwestern China as well. Compared with other regions, the magnitude of precipitation variation in Southwestern China is smallest in 1961–2008 and generally is in a stable state (Table 3.1).

3.1.4 Inter-annual Variation of Temperature and Precipitation in Monsoon Period and Non Monsoon Period

The annual mean temperature of Southwestern China in monsoon period and non monsoon period increased at the rate of 0.2 and 0.28 °C/10 a from 1961 to 2008, and the magnitude of rising obviously enlarged after the mid of 1980s (Fig. 3.5). In 1961–1961, the precipitation in monsoon period basically keep in a stable state and has been in a slow fluctuation. Thereafter, the fluctuating range enlarge obviously.

Table 3.1 Comparison of temperature (°C/a) and precipitation (mm/a) change in Southwestern China with other regions of China

Regions/period	Annual temperature	Spring temperature	Summer temperature	Autumn temperature	Winter temperature	Data sources
Central Tibet/ 1961–2000	0.24		0.16		0.26	Bian and Du (2006a)
Qilian/ 1960–2005	0.30	0.18	0.26	0.38	0.50	Jia et al. (2008)
Himalaya/ 1971–2004	0.23					Yang et al. (2006)
Xinjiang/ 1960–2005	0.33	0.74	0.94	1.94	2.07	Liu et al. (2009)
Gansu/ 1957–2006	0.21					Wu et al. (2008)
Northeastern China/ 1953–2001	0.36	0.4	0.13	0.2	0.6	Dong and Wu (2008)
Northwestern China/ 1951–2004	0.26					Yao et al. (2009)
Yunnan/ 1960–2007	0.15					Cheng and Xie (2008)
SB/1951–2000	−0.03					Chen et al. (2008)
Hengduan mountains/ 1960–2008	0.15	0.59	0.15	0.17	0.35	Li et al. (2010d)
Southwestern China/ 1961–2008	0.33	0.18	0.19	0.2	0.24	This study
Regions/period	Annual precipitation	Spring precipitation	Summer precipitation	Autumn precipitation	Winter precipitation	Data sources
Central Tibet/ 1961–2000	19.9					Bian and Du (2006a)
Qilian/ 1960–2005	11.8	3.2	3.63	0.667	0.967	Jia et al. (2008)
Xinjiang/ 1960–2005	8.5	4.54	17.14	6.63	7.29	Liu et al. (2009a, b)
Gansu/ 1957–2006	−3.17					Wu et al. (2008)
Northwestern China/ 1951–2004	−21.44					Yao et al. (2009)
SB/1951–2000	−22.56					Chen et al. (2008)
Hengduan mountains/ 1960–2008	9.09	8.62	−1.5	1.53	1.47	Li et al. (2010d)
Southwestern China/ 1961–2008	−0.006	0.061	0.023	−0.077	0.093	This study

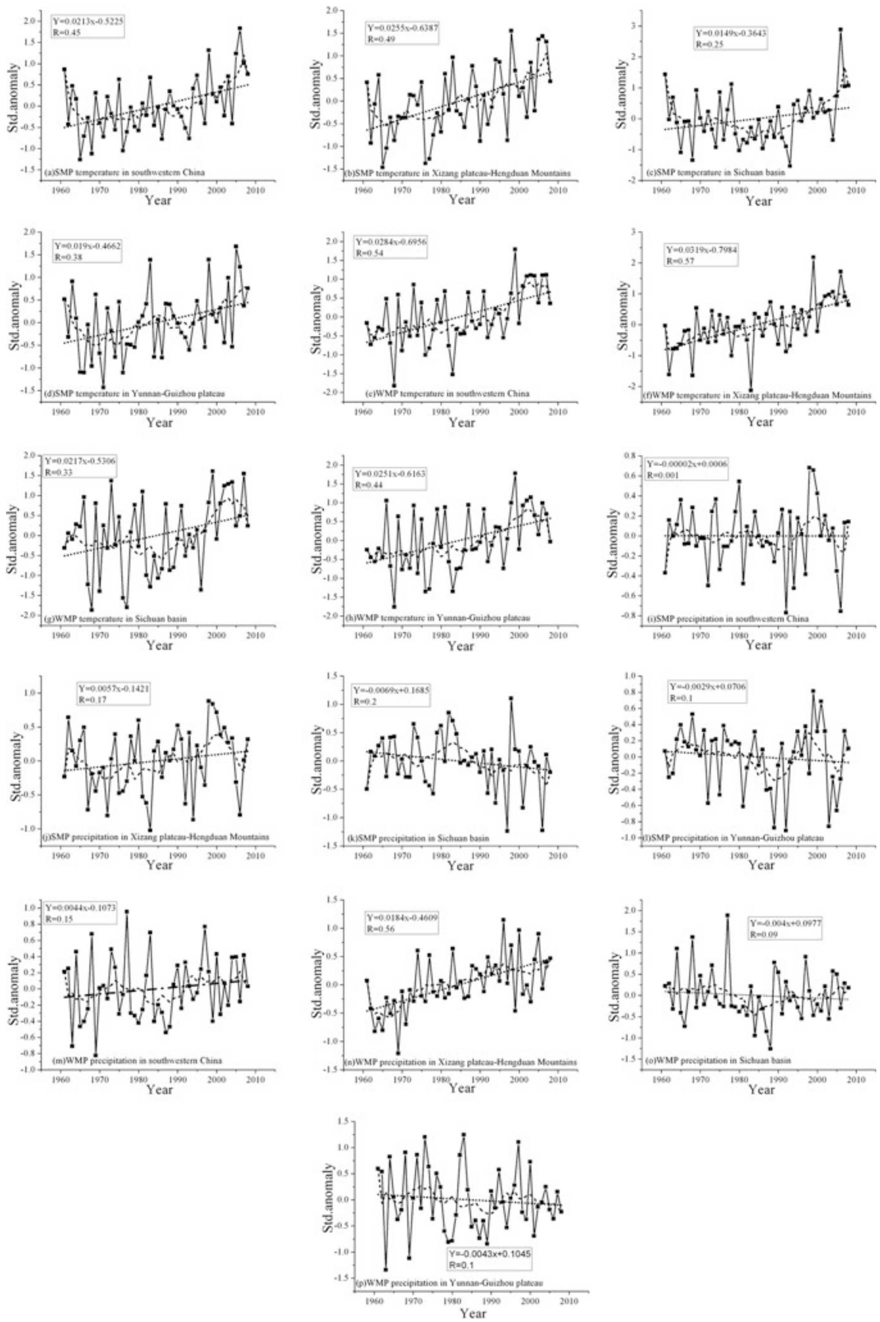

Fig. 3.5 Inter-annual variation of temperature and precipitation in summer monsoon period and winter monsoon period during 1961–2008

The precipitation in non monsoon period slowly increases at the rate of 0.044 mm/10 a. The inter-annual variation transfers from the rise of 1961–1975 to declination of 1976–1985, then slowly goes up after the mid of 1980s (Fig. 3.5). The magnitude of temperature variation in monsoon period in Xizang Plateau–Hengduan Mountains, Sichuan Basins and Yunnan-Guizhou Plateau are 0.26, 0.19 and 0.15 °C/10 a. All they show a statistically significant warming. The temperature of Sichuan Basin slowly declined before the mid of 1980s, then obviously rose. The temperature of Yunnan-Guizhou Plateau changed as the shape of W. In other words, it fell in 1960s and rose in 1970–1985, then slowly declined in 1985–1995. Thereafter, it showed a significant trend of rising (Fig. 3.5). The magnitude of temperature variation in non monsoon period in these three sub-regions in turn are 0.32, 0.25, and 0.22 °C/10 a, and all they have undergone significance test (Fig. 3.5). The temperature of Sichuan Basin in monsoon period had a slow decline before the mid of 1980s, however, the temperature of Yunnan-Guizhou Plateau and Xizang Plateau–Hengduan Mountains kept a significant rising trend all the time. The precipitation of Xizang Plateau–-Hengduan Mountains in monsoon period slowly increase in fluctuation at the rate of 0.057 mm/10 a, which showed a wavelike decline in 1960s, then had a wavelike rise. While the precipitation of Yunnan-Guizhou Plateau had a slow decrease in fluctuation at the rate of −0.029 mm/10 a. It had been in a dropping trend all the time except for the 1990s. In nearly 50 years, the precipitation of Sichuan Basin had a sustained downward trend by rate of −0.069 mm/10 a (Fig. 3.5). The precipitation of Sichuan Basin in non monsoon period showed a slight drop by rate of −0.04 mm/10 a, and its inter-annual variation presented a change as the shape of V with the 1980s being the divided point (Fig. 3.5). The precipitation of Yunnan-Guizhou Plateau in non monsoon period also slowly declined at the rate of −0.043 mm/10 a, and its inner-annual variation had a obvious fluctuation. Among these three sub-regions, there only precipitation of Xizang Plateau–Hengduan Mountains in non monsoon period significantly increase at the rate of 0.184 mm/10 a, which indicates the rising trend of precipitation at high altitude (Fig. 3.5).

3.1.5 The Temperature and Precipitation Variation Reflected by Ice Cores and Tree Rings

The ice core accumulation of Dasuopu located in the central part of Himalayas Mountain declined significantly since 1930, which may reflect the reduction of precipitation (Duan et al. 2002). The study on the ice core of Everest region suggested the accumulation sharply dropped in the 1950s and 1960s, then kept a slow declination. This phenomenon also reflects that one of the remarkable feature of climate change in the central part of Himalayas Mountain is precipitation decrease. However, the analysis of the ice core isotope in this region confirmed the significant warming trend. Based on this point, Ren et al. (2003) considered that temperature increase and temperature decrease as well as the warm and dry climate caused by the sharp increase of summer temperature are the main reason of glacier change in this region. These conclusion can be confirmed in this study. The analysis found that the annual, autumn and monsoon precipitation of the central part of Himalayas Mountain had a obvious decrease in recent 50 years. The study of Hou and Zhang (2003) on the ice core accumulation of East Rongbuk and far East Rongbuk indicated that in two periods of 1954–1963 and 1964–1997, the average accumulation of ice core in each period were 581.7 and 321.2 mm, 267.5 and 150.3 mm, which showed a sharp drop over the past 50 years. The study of Zhang et al. (2004) on the ice core records of East Rongbuk found that the precipitation variation at high altitude had a much sensitivity than at low altitude.

The study of Kang and Qin (2000) on the ice core records of far East Rongbuk in the north slope of Everest confirmed that the warming trend of this region and 1974–1986 was a remarked warming period. The research of Zhang et al. (2007a, b) on Geladandong ice core determined that the accumulation dramatically raised since 1960, and the annual mean accumulation in the period from the end of 1960s to the beginning of 1990 was about 1.5 times more than before 1960s. But the accumulation started to fall continuously after entering 1990s. This change is consistent the annual precipitation variation of nearby stations, such as Naqu, Lhasa and Bangor. In addition, the further study of the ice cores also confirmed the summer temperature significantly rose and annual temperature accelerated after 1970s. Yao et al. (2006) made a summary about the ice core records of Piruogangri and thought that the temperature in Qinghai–Xizang Plateau showed a significant warming over the past 100 years. Through the comprehensive analysis of ice core accumulation in Qinghai–Xizang Plateau, Hou et al. (2002) pointed out that the ice core accumulation of Dongkemadi located in north-central plateau had been on a rise in general since 1950. While several ice core accumulation in the southern plateau showed a obvious downward trend. The further analysis indicated that maybe there are two reasons resulted in accumulation reduction: less rainfall and dramatical melting caused by sharp rise of temperature. Moreover, the research on the snow and ice profile environment records of Baishui No. 1 confirmed that the main reason of accumulation reduction is dramatical melting caused by sharp rise of temperature.

According to the analysis of width data of tree ring, Song et al. (2007) found that mean minimum temperature of Jouzhaigou area in winter half year had been in the high-value duration and significantly rose from 1984 to now. Zhang et al. (2010) found that tree ring records could pointed out the autumn and winter mean minimum temperature in Changdu, Xizang rose significantly in the 1970s and 1980s, and the winter minimum temperature gradually rose since the end of 1960s. The study of Fan et al. (2008) thought it is a significant warm period since 1990 in the central part of Hengduan Mountains. Shao and Fan (1999) pointed out that the winter minimum temperature of western Sichuan heat up significantly since the 1960s by means of the width data of tree ring. Duan et al. (2010) reconstructed the temperature variation from August to September in the past 171 years in

Gongga mountain areas by means of tree ring chronology (RC). The results showed that the abnormal high temperature years of mean temperature of August and September have 22 years, and the abnormal low temperature years have 23 years. Among them, there are four obvious low temperature periods, including 1837–1842, 1884–1891, 1899–1905 and 1984–1989; and three obvious high temperature periods, including 1966–1973, 1916–1924 and 1876–1881.

The above records are mainly from the high altitude areas of Himalayas, Mount. Tunggula, Nyenchen Tanglha and Hengduan Mountain, where there are a few meteorological observation stations (Fig. 3.6). These research results show two points. In the one hand, they reflect the significant warming of high altitude areas and demonstrate the significant elevation effect of temperature; in the other hand, they also reflect the uncertainty of precipitation variation in high altitude area. The ice core accumulation shows an obvious decrease trend, especially after the mid of 1980s, which is likely to be caused by intensified melting and increasing liquid precipitation under the background of warming. Therefore, the warm and dry climate in some regions of Xizhang Plateau can be confirmed by the combination of stations records and ice cores records, for example, the central part of Himalayas.

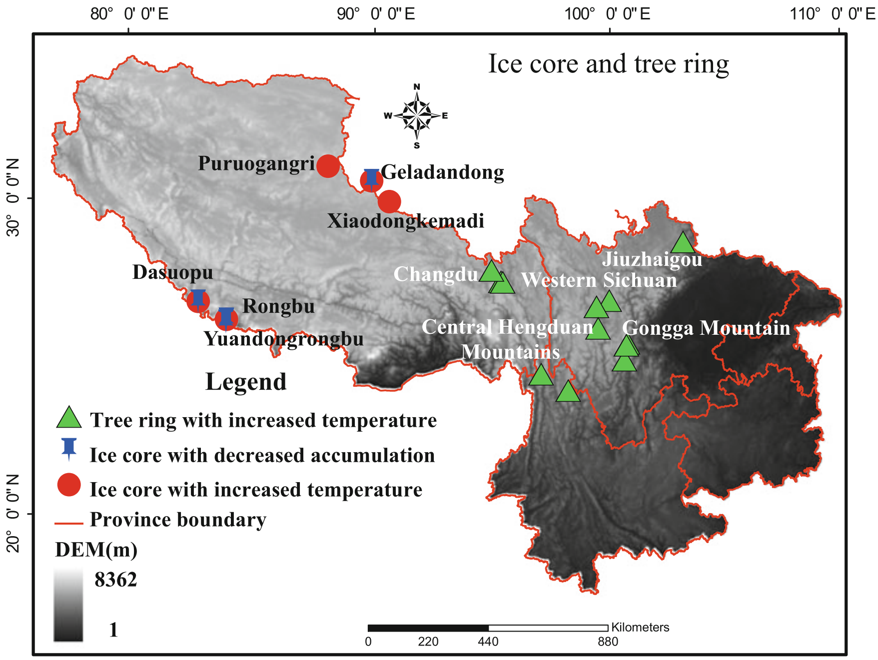

Fig. 3.6 Spatial distribution of 7 ice cores and 4 tree rings reflected temperature and precipitation variation in study area from the previous researches

3.2 Spatial Variation of Temperature and Precipitation

3.2.1 The Spatial Distribution of Temperature Variation

Except for a number of stations in Sichuan Basin, the southeastern region of Hengduan Mountain and Guizhou Plateau, there about 92 % of the stations in Southwestern China showed a warming trend from 1961 to 2008; the warming trend of 77 % had succeeded in the significance text. The magnitude of temperature variation in Xizang Plateau–Hengduan Mountain and Yunnan Plateau are much larger, and the stations with a significant warming are also mainly distributed in these regions. While the stations with non significant warming mainly are located in Sichuan Basin (Fig. 3.7). The spring temperature of about 85 % of the stations obviously increased, but only 45 % of the stations showed the significant increase. These stations are principally distributed in Xizang Plateau, the north and south of Hengduan Mountain and the west of Yunnan Plateau. The spring temperature of partial stations in southeast of Hengduan Mountain and the east of Yunnan Plateau declined significantly, the areas with non significant warming are chiefly in Sichuan Basin and Guizhou Plateau (Fig. 3.7). The magnitude of summer temperature variation of about 82 % of the stations was positive. About 54 % of the stations showed a significant warming trend, which mainly were distributed in Xizang Plateau–Hengduan Mountain and Yunnan Plateau. However, the spring temperatures of a large number of stations located in the Sichuan Basin decreased, and the stations with non significant warming are chiefly in the edge of Sichuan Basin and Guizhou Plateau (Fig. 3.7). Except for a number of stations in Yunnan–Guizhou Plateau with a declined temperature, the autumn temperature of about 92 % of the stations in Southwestern China showed a warming trend. Among them, the warming trend of 77 % had succeeded in the significance text. Compared with the spring and summer temperature, the autumn temperature in the edge of Sichuan Basin and the northern region of Guizhou Plateau was on the rise. Whereas, a number of stations located in the northern region of Hengduan Mountain and the east of Yunnan Plateau present a non significant warming trend (Fig. 3.7).

The winter temperature of about 95 % of the stations in the study area showed a warming trend, the number of which accounted for 59 % of total stations. These stations are mainly distributed in Xizang Plateau–Hengduan Mountain and Yunnan Plateau. More stations in Sichuan Basin and Guizhou Plateau had a non significant warming trend (Fig. 3.7). In general, the magnitude of temperature variation gradually reduced from west to east. The stations with significant warming and large magnitude of warming were primarily distributed in Xizang Plateau–-Hengduan Mountain and Yunnan Plateau, while the stations with non significant warming trend were located in Sichuan Basin and Guizhou Plateau. This distribution characteristic confirmed the wider margin of warming happened in high altitude areas. In addition, the most stations significantly warmed in autumn and winter, which reflected the special seasonal structure of the warming once again.

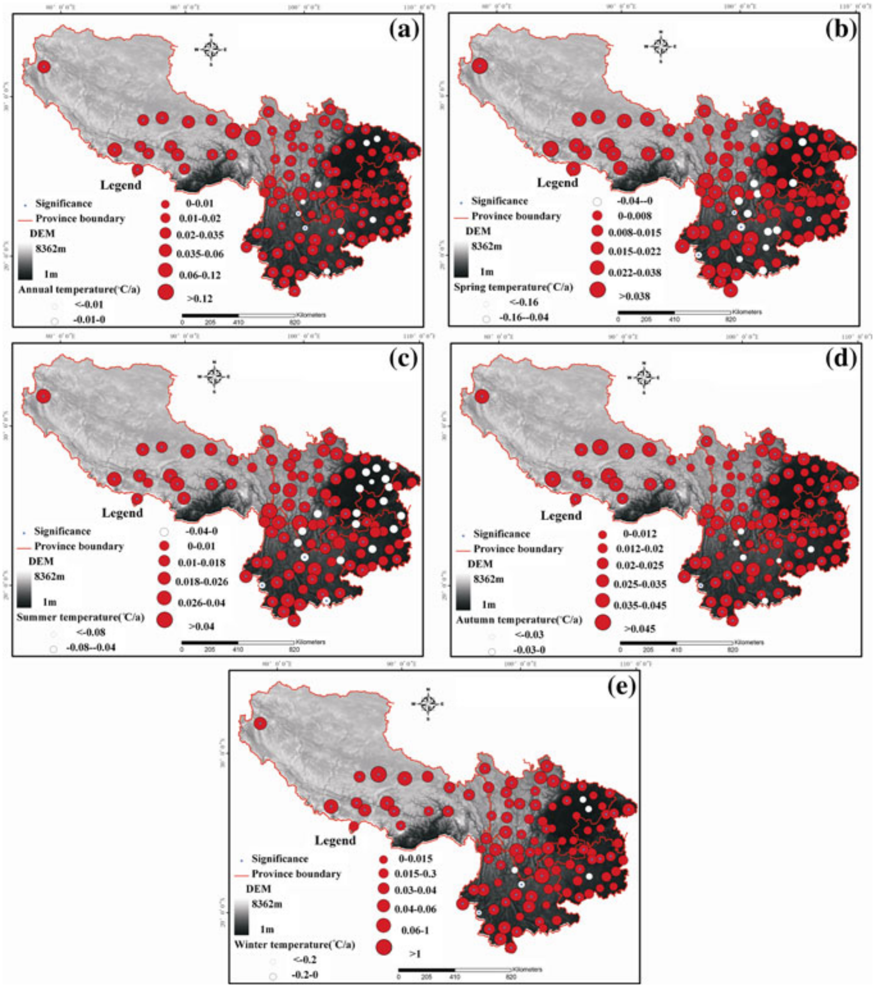

Fig. 3.7 Spatial distribution of temperature variation during 1961–2008. Reprinted by permission from IOP Publishing: Ref. (Li et al. 2011). Copyright (1993), **a** annual temperature, **b** spring temperature,**c** summer temperature, **d** autumn temperature, **e** winter temperature

3.2.2 The Spatial Distribution of Precipitation Variation

The annual precipitation of about 53 % of the stations in southwest China show an increase momentum, but only about 5 % of the stations increase significantly and mainly are located in Xizang Plateau. The stations with an increase trend also are mainly distributed in high altitude area. Among them, some stations in the central section of the Xizang Plateau–Hengduan Mountain have a larger magnitude, while the stations with reducing precipitation are mainly located in eastern Yunnan Plateau, Guizhou Plateau and Sichuan Basin. The stations, of which precipitation reduce by a wide margin are mainly distributed in regions around the Sichuan Basin (Fig. 3.8). The spring precipitation of about 70 % of the stations show an increase momentum, and the stations with a wider margin are located in Hengduan Mountain and Yunnan Plateau. The stations in the south of Xizang Plateau–Hengduan Mountain which account for about 20 % of total stations have a significant increase in precipitation. Almost all stations in Guizhou Plateau and Sichuan Basin show a downtrend, and the reducing magnitude of Guizhou Plateau is wider among them (Fig. 3.8). Only 50 %

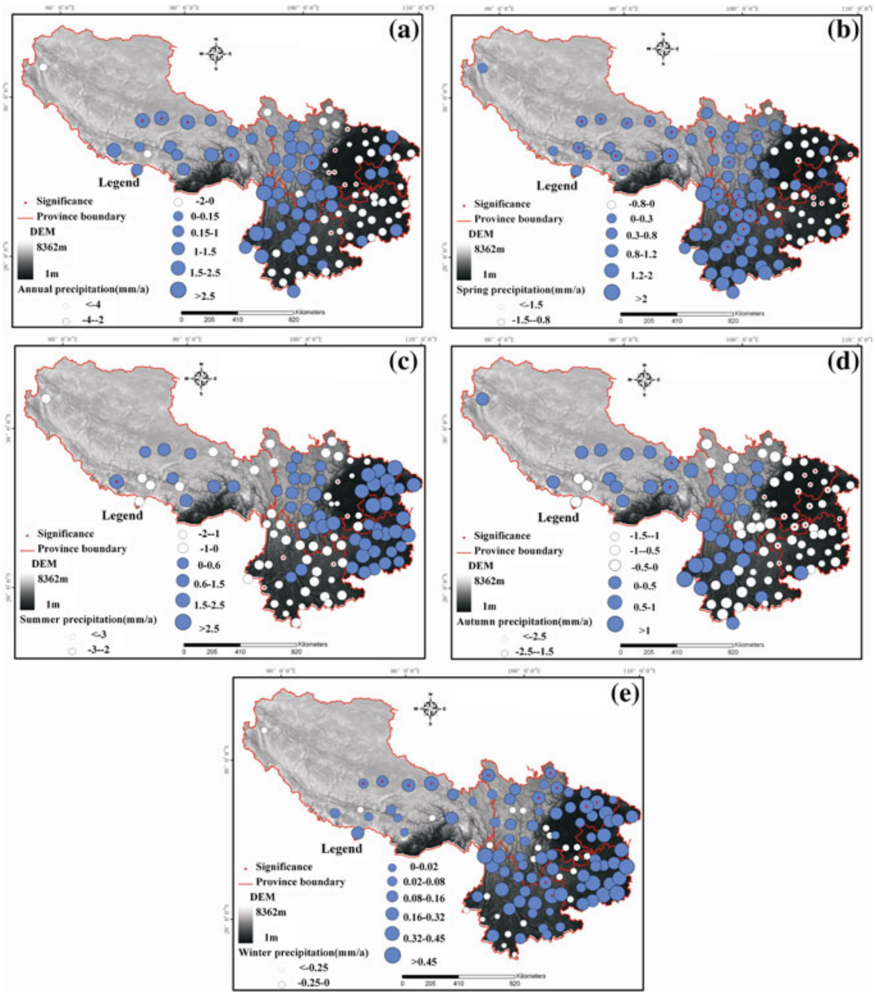

Fig. 3.8 Spatial distribution of precipitation variation during 1961–2008. Reprinted by permission from IOP Publishing: Ref. (Li et al. 2011). Copyright (1993), **a** annual percipitation, **b** spring percipitation, **c** summer percipitation, **d** autumn percipitaiton, **e** winter percipitation

of stations performance increase trend in summer precipitation, except for the Xizang Plateau–Hengduan Mountain. What the biggest difference with spring precipitation is that the summer precipitation of all stations in the eastern Sichuan Basin and Guizhou Plateau show an increasing trend. However, the precipitation of stations in western Sichuan Basin, the southwest and north of Hengduan Mountain, the east and southwest of Xizang Plateau and the whole Yunnan Plateau. Among them, a number of stations in the west of Yunnan Plateau and the west of Sichuan Basin present an opposite trend with spring precipitation, that is the summer precipitation have a wider magnitude of variation (Fig. 3.8).

Compared with other seasons, the most remarkable character of autumn is that the area of precipitation reduction significantly increase. These stations account for about 65 % of the total stations. Among them, there are about 12 % of stations distributed in Sichuan Basin and Guizhou Plateau. In addition, a large number of stations in northern and south central Hengduan Mountain, the east and southwest of Yunnan Plateau and the three stations in the central part of Himalaya show a downward trend, among which the magnitude of precipitation reduction is widest (Fig. 3.8). The region of precipitation increase in Southwestern China is widest in winter. There are about 77 % of the stations with the rising trend, among 11 % of the stations increase significantly, which are located in the north part of Xizang Plateau–Hengduan Mountain. Almost the winter precipitation of all stations in Sichuan Basin and Guizhou Plateau increase similar to the spatial distribution of summer precipitation. The increase magnitude in the east of Sichuan Basin, the south of Hengduan Mountain and the east of Guizhou Plateau is much wider, while the stations with precipitation decrease are distributed in the southwest edge of Sichuan Basin and the west of Yunnan Plateau (Fig. 3.8). On the whole, the regions of precipitation increase are mainly in high altitude area, while the summer and winter precipitation in Sichuan Basin and Guizhou Plateau also increased distinctly.

3.2.3 The Spatial Distribution of Temperature and Precipitation Variation in Summer Monsoon Period and Winter Monsoon Period

The temperatures of about 90 % of the stations in Southwestern China is on the rise in summer monsoon period, among them, there are about 53 % of the stations with significant warming which are mainly distributed in Xizang Plateau–Hengduan Mountain and Yunnan Plateau. However, the most stations in Sichuan Basin, Guizhou Plateau, the central part of Hengduan Mountain and the southeastern Yunnan Plateau show a non significant warming. Moreover, the four stations located in the southeast of Hengduan Mountain occur a significant temperature drop (Fig. 3.9). The temperature of about 94 % of the stations in winter monsoon period is on the rise, and the stations with significant warming account for about 68 % of total stations. Different from the summer monsoon period, the area with significant

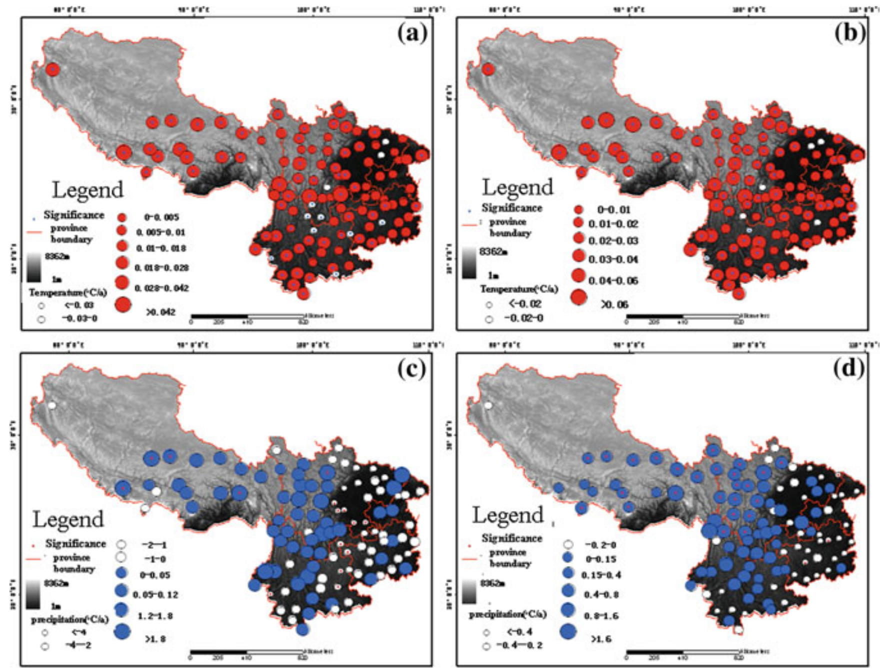

Fig. 3.9 Spatial distribution of temperature and precipitation variation in summer monsoon period and winter monsoon period during 1961–2008, **a** summer monsoon period, **b** winter monsoon period, **c** summer monsoon period, **d** winter monsoon period

warming sharply enlarge in winter monsoon period. The station with non significant temperature increase or decrease are mainly distributed in the central part of Sichuan Basin, the southern Guizhou Plateau and the southeast of Yunnan Plateau (Fig. 3.9).

The monsoon precipitation of about 50 % of the stations show an increasing trend which are mainly distributed in Xizang Plateau–Hengduan Mountain and the north of Yunnan Plateau, and among these stations, only 5 % of the stations succeed in the significance test. However, the most stations in Sichuan Basin, Guizhou Plateau, the east and west edge of Yunnan Plateau show a downward trend. Among them, the precipitation of some stations in the west of Sichuan Basin and the west of Guizhou Plateau significantly reduce. The precipitation increase mainly happens in high altitude area (Fig. 3.9). Compared with summer monsoon period, the area of precipitation increase in winter monsoon period expands. About 61 % of the stations have an apparent increase momentum, but only 23 % of the stations pass the significance test which are concentrated in Xizang Plateau and Hengduan Mountain. In addition, the precipitation of almost all the stations in Yunnan Plateau increases. On the contrary, almost all the stations in Guizhou Plateau, most stations in the Sichuan Basin and some stations in Yunnan Plateau show a decline trend in precipitation. Among them, the magnitude of reduction is widest in Guizhou Plateau (Fig. 3.9).

3.3 Driving Mechanism for Temperature and Precipitation

3.3.1 The Relationship of Temperature and Precipitation Variation with Elevation

Based on the analysis on monthly mean minimum temperature of Qinghai–Xizang Plateau and the areas around it in 1961–2006, a conclusion can be made that the warming magnitude of hight altitude areas is much wider (Liu et al. 2009), and this fact also is found during the research on the climate change in Swiss areas and Rocky Mountains (Beniston and Rebetez 1996; Fyfe and Flato 1999). As what the Fig. 3.10 shows, there are a great positive correlation between the magnitude of annual mean temperature changes of all stations in Southwestern China and the elevation, which suggests that the warming magnitude will increase as the rise of elevation. The correlation values between the magnitude of spring, summer, autumn and winter temperature change and the elevation are 0.25, 0.46, 0.36 and 0.33. The warming magnitude increases as the rise of elevation in summer, autumn and winter except for spring. Among these three seasons, the significance of the warming magnitude in summer is biggest followed by autumn (Fig. 3.9). The magnitude of temperature changes in summer monsoon and winter monsoon period of all stations in Southwestern China and the elevation also has a positive correlation with the elevation, and the correlation values are 0.43 and 0.50. Moreover, the elevation effect of warming is quite significant (Fig. 3.10). As shown by Table 3.2, in terms of the maximum warming magnitude in different altitudes, the annual, spring, summer, autumn, winter, summer monsoon and winter monsoon maximum warming magnitude respectively occur in the altitude of 3,500–4,000, 4,000–4,500, 3,500–4,000, 4,500–5,000, 2,000–2,500, 4,500–5,000 and 4,000–4,500 m. All happen in the altitude of above 3,500 m except for winter one. Accordingly, the minimum warming magnitude respectively occur in the altitude of 1,000–1,500, 1,000–1,500, 0–500, 2,500–3,000, 500–1,000, 0–500, and 0–500 m. Among them, all happen in the altitude of below 1,500 m except for autumn one.

The number of stations, of which the magnitude of temperature changes in different altitudes succeed in the significance test, also reflect the significant warming at high altitude. The three stations in the altitude of 4,500–5,000 m have a significant warming. The six stations in the altitude of 4,000–4,500 m also show a significant warming except for one station in summer and two stations in winter. The annual and each seasonal temperature of eight stations in the altitude of 3,500–4,000 m is on an obvious rise. In the elevation of 3,000–3,500 m, there only annual and winter temperature of nine stations significant rise, and the temperature of seven and eight stations change warmer in summer and winter monsoon period, while just four stations warm in spring. There are nine station in the altitude of 2,500–3,000 m showing significant warming trend in winter monsoon period, while all there are half of stations which fail to pass the significance test in spring, autumn and summer monsoon period. The six of seven stations located in an altitude of 2,000–2,500 m show a significant warming trend in autumn and the winter

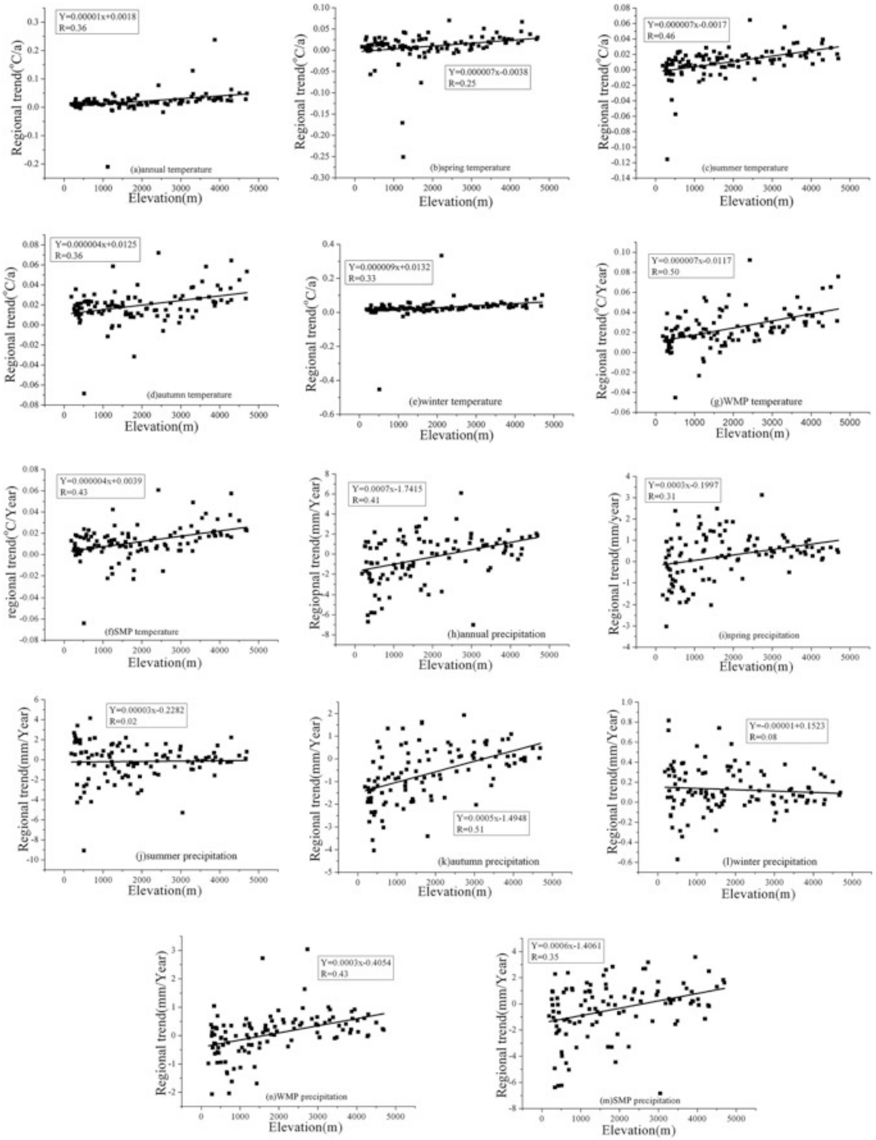

Fig. 3.10 The relationship of temperature and precipitation variation with elevation during 1961–2008

monsoon period, and there is only one in winter. There are only half of 16 stations located in an altitude of 1,500–2,000 m heating up in a year, winter and summer monsoon period, while there are only six station warming obviously. There are seven stations in an altitude of 1,000–1,500 m, of which the temperature rise significantly in spring, and the number of stations in an altitude of 1,000–1,500 m

Table 3.2 Trend magnitudes of temperature and precipitation variation in different altitudes rank (°C or mm/10 a)

Altitude (m)	Number	Annual (°C)	Spring (°C)	Summer (°C)	Autumn (°C)	Winter (°C)	Winter monsoon (°C)	Summer monsoon (°C)
4,500–5,000	3	0.42	0.31	0.21	0.42	0.74	30.00	0.26
4,000–4,500	6	0.34	0.33	0.23	0.35	0.43	0.39	0.28
3,500–4,000	8	0.58	0.27	0.24	0.32	0.41	0.38	0.25
3,000–3,500	9	0.38	0.18	0.21	0.22	0.37	0.28	0.18
2,500–3,000	9	0.14	0.09	0.12	0.13	0.27	0.21	0.09
2,000–2,500	7	0.24	0.16	0.20	0.24	0.78	0.35	0.16
1,500–2,000	16	0.16	0.06	0.11	0.15	0.25	0.23	0.07
1,000–1,500	16	0.01	−0.18	0.08	0.16	0.19	0.17	0.08
500–1,000	17	0.17	0.12	0.06	0.14	−0.04	0.19	0.08
0–500	19	0.09	0.05	−0.08	0.15	0.12	0.12	0.06
Altitude (m)	Number	Annual (mm/10 a)	Spring (mm/10 a)	Summer (mm/10 a)	Autumn (mm/10 a)	Winter (mm/10 a)	Winter (mm/10 a) monsoon	Summer (mm/10 a) monsoon
4,500–5,000	3	18.70	5.42	4.37	3.24	1.23	2.93	15.75
4,000–4,500	6	3.85	3.71	1.99	−0.18	1.46	3.29	2.15
3,500–4,000	8	9.88	6.30	1.18	3.45	0.65	4.50	9.98
3,000–3,500	9	−3.97	5.61	−7.86	−2.26	0.42	4.06	−7.80
2,500–3,000	9	17.35	8.20	5.43	2.67	1.05	9.10	12.79
2,000–2,500	7	−0.38	3.73	−2.91	−2.61	1.56	2.44	−2.78
1,500–2,000	16	1.91	9.31	−7.80	−4.84	1.84	3.40	−3.04
1,000–1,500	16	−4.82	4.25	−0.77	−7.90	1.38	−2.68	−1.10
500–1,000	17	−18.34	−2.91	−9.85	−9.21	0.42	−5.90	−17.22
0–500	19	−17.88	−5.47	6.74	−18.66	2.06	−2.24	−13.422

which show a sharp warming trend in a year, summer and summer monsoon period are 12. There more than ten stations present a warming trend in a year, autumn, winter, summer monsoon and winter monsoon period among 17 station in an altitude of 500–1,000 m. And there are 11 stations warming significantly in autumn among 19 stations in an altitude of 0–500 m.

The climate correlation analysis indicates that the regions with a wider magnitude of warming in Southwestern China are mainly located above an altitude of 3,500 m. Some existing researches believe that there are three possible reasons of significant warming in the high altitude areas of Qinghai–Xizang Plateau in China. (1) The variation of cloud cover is possible to have significant effects on the recent climate warming of Qinghai-Xizang Plateau. The reflection and scattering of the cloud abate along with the significant increase of low cloud cover at night, which will lead to more heat absorbed by ground surface and cause sharply warming. In addition, the total cloud cover and low cloud cover are yearly to decrease during the day, which also lead to more solar direct radiation absorbed by ground surface and thus accelerate the surface warming (Duan and Wu 2006). Moreover, the study of Tang et al. (2009) also confirms that the annual total cloud cover of most areas of Xizang Autonomous Region was on a significant decline trend in 1971–2008. Thereinto, the reducing magnitude of the central west part of Naqu, reaching 2.32 %/10 a, but the total cloud cover of southern edge of Xizang Autonomous Region has a non significant decrease trend. The total cloud cover is positively correlated with precipitation and relative humidity, and negatively correlated with sunshine hours, mean temperature and diurnal temperature range. These two correlations reflect the significant role of cloud cover to temperature changes. (2) The positive feedback of snow/ice albedo is also considered as one of the factors causing climate warming of the plateau because the plateau is one of the most sensitive snow feedback areas on the earth. With the climate warming of the plateau, seasonal snow and ice melting on the ground surface acts in advance, which will cause the reduction of surface albedo and more absorption of solar radiation, and then cause the further melting of surface snow. This positive feedback process of snow/ice albedo also accelerates the warming of plateau (Liu and Chen 2000). (3) The thickening of dirt on the surface of snow and ice or the increase of dust density in the high altitude area will make the snow and ice albedo reduce and then result in the increase of radiation and temperature, which also is one of the factors of significant warming in the high altitude area. The research of Qian et al. (2011) has proven that the black carbon aerosol has an obvious contribution on reducing the ice and snow albedo and increasing solar radiation.

As the Fig. 3.11 shows, there is a positive correlativity with the magnitude of annual precipitation change of all stations in Southwestern China and altitude. The correlation value is 0.41, which indicates that the magnitude of precipitation increase widen with the rise of altitude. The correlation values with the magnitude of four seasons precipitation and the altitude respectively are 0.31, 0.02, 0.51 and −0.08. Thereinto, the changing magnitude increases with the rise of altitude in spring and autumn, but the changing magnitude decreases with the rise of altitude in winter (Fig. 3.11). The magnitudes of precipitation change of all stations in summer

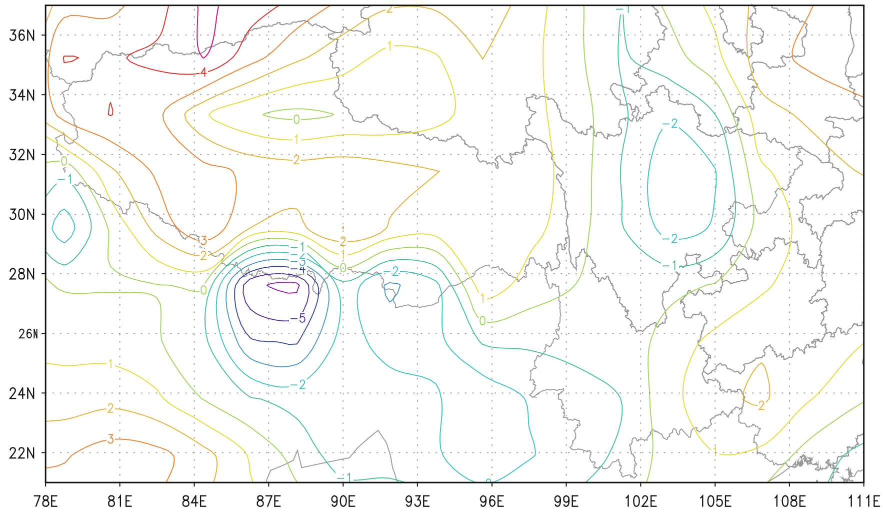

Fig. 3.11 Difference of annual net longwave radiation flux at surface between 1961–1985 and 1986–2008

monsoon and winter monsoon period have the positive correlation with the altitude, which reflects a significant altitude effect (Fig. 3.11). As shown by Table 3.3, the maximum magnitudes of precipitation change in a year, spring, summer, autumn, winter, summer monsoon and winter monsoon period occur in the altitude of 4,500–5,000, 1,500–2,000, 0–500, 3,500–4,000, 0–500, 2,500–3,000 and 4,500–5000 m. The minimum magnitudes of precipitation change in a year, summer, winter, summer monsoon and winter monsoon period occur in the altitude of 500–1,000 m, and the spring and autumn minimum magnitudes occur in the altitude of 0–500 m, which confirms that the precipitation decrease mainly happen in low altitude areas; more altitudes have the precipitation decrease in autumn and summer, but more altitudes have the precipitation increase in winter and spring. Compared with the temperature, the magnitude of precipitation change of less stations can pass the significance test in different altitudes. The magnitude of precipitation change of three stations located in 4,500–5,000 m is only not significant in summer and autumn, but significant to increase in other seasons. There are half of stations in altitude of 4,000–4,500 m showing a significant increase in winter and winter monsoon period. But in the altitude of 2,500–3,500 m, there are more than half of stations are on the rise in winter monsoon period. There are some stations located in the altitude of 500–2,500 m passing the significance test in spring. And there are eight of nineteen stations in 0–500 m showing a significant decrease. To sum up, compared with temperature, the altitude effect is smaller, but the fact also is confirmed that the precipitation at high altitude areas increase.

In order to further analyze the influence of topographical types where the meteorological stations are located in on the observation data of the annual mean temperature and precipitation, the 110 stations were classified into four topographic types: summit station, intermontane station, flat station and valley station. The air freedom of flat station is maximum; valley station has an unique valley wind system, where airflow movement is hampered larger; the wind speed of summit station is strongest. These features will have obvious influence on the variation magnitude of temperature and precipitation. As shown in Table 3.3, the variation magnitudes of annual and winter temperature of intermontane station are bigger than other types of stations. While, the variation magnitudes of flat stations in spring, summer, autumn, winter, summer monsoon and winter monsoon period are biggest. On the whole, the warming magnitude declines gradually as the order of flat station, intermontane station, valley station and summit station. On the contrary, the flat and openness of terrain decrease successively. In terms of precipitation, the maximum reduction magnitude of annual sequence stands in summit station, and the winter, summer, autumn and summer monsoon precipitation also show a same trend. The minimum increase magnitudes in spring and winter monsoon are in flat station, but the maximum increase magnitudes in a year, winter, spring, autumn, summer monsoon and winter monsoon stand in valley station. And the summer precipitation of intermontane station shows a increase trend. These characteristics also reflects the obvious impact of terrain on precipitation. All in all, the regional terrain has a obvious influence in the observation result of temperature and precipitation. Therefore, it is very necessary to consider the influence of terrain in the climate change research.

Table 3.3 Mean trend magnitudes of temperature and precipitation in differing topographical types (°C or mm/10 a)

Temperature	Number	Annual	Winter	Spring	Summer	Autumn	Winter monsoon	Summer monsoon
Summit station	2	0.17	0.27	0.09	0.11	0.19	0.22	0.10
Intermontane station	33	0.24	0.42	0.15	0.10	0.23	0.29	0.13
Flat station	40	0.23	0.36	0.17	0.16	0.27	0.33	0.18
Valley station	35	0.23	0.17	0.10	0.14	0.19	0.24	0.13
Precipitation	Number	Annual	Winter	Spring	Summer	Autumn	Winter monsoon	Summer monsoon
Summit station	2	−24.95	−1.44	4.51	−19.88	−8.87	1.46	25.88
Intermontane station	33	1.93	0.58	2.58	3.27	−4.82	0.64	1.70
Flat station	40	−7.73	1.51	1.08	2.02	−6.93	0.41	−6.03
Valley station	35	7.53	2.12	8.03	−3.05	−0.55	5.02	1.76

3.3.2 The Correlation with Temperature Variation, Radiation, Sea Surface Temperature and Sunshine Hours

As shown in Table 3.4, after the mid of 1980s, the annual and seasonal temperature in Southwestern China warmed acceleratedly, and annual, spring, summer monsoon and winter monsoon temperatures in 1961–1985 presented a weak decline trend. The annual and seasonal temperatures of Xizang Plateau–Hengduan Mountain in 1961–1985 was on the non-significant rise, but the warming magnitude in 1986–2008 enlarged obviously. In 1961–1985, the temperature of Yunnan–Guizhou Plateau in a year and other seasons decreased or increased slightly except that it increased sharply in summer. While it warmed by a large margin in every period. The temperature of Sichuan Basin in 1961–1985 had a downward trend, and the annual and spring temperature decrease significantly. But it had a significant warming in every period except for winter, and the warming magnitude was higher than that of whole Southwestern China, Yunnan–Guizhou Plateau and Xizang Plateau–Hengduan Mountain.

As shown in Fig. 3.11, compared with 1961–1985, net longwave radiation flux of Southwestern China except for Sichuan Basin increases remarkably from 1986 to 2008, which reflects that the strength of air or ground heating process gradually increased, and eventually causes temperature rise. Further analysis found that the correlation with annual mean temperature and sea surface temperature of the western Pacific Ocean in 1986–2008 is higher than 1961–1985, which suggests the obvious contribution of ocean thermal process strengthening gradually to significant region warming. But the specific mechanism of this contribution still need to further analyze (Fig. 3.12). The season of the maximum warming magnitude was

Table 3.4 Mean trend magnitudes of temperature during 1961–1985 and 1986–2008 in Southwestern China (°C/10 a)

	Years	Annual	Spring	Summer	Autumn	Winter	Winter monsoon	Summer monsoon
Southwestern China	1961–1985	−0.03	−0.11	0.07	0.07	0.03	−0.001	−0.003
	1986–2008	**0.72**	**0.67**	**0.35**	**0.61**	**0.30**	**0.56**	**0.59**
	1961–1985	0.23	0.14	0.20	0.15	0.15	0.19	0.13
XPHM	1986–2008	**0.66**	**0.55**	**0.34**	**0.49**	**0.47**	**0.61**	**0.48**
	1961–1985	−0.03	−0.16	0.30	0.05	−0.02	−0.07	0.09
YGP	1986–2008	**0.51**	**0.46**	0.21	**0.53**	0.13	**0.35**	**0.43**
	1961–1985	**−0.38**	**−0.37**	−0.31	−0.03	−0.13	−0.22	−0.28
SB	1986–2008	**0.96**	**1.00**	**0.52**	**0.80**	0.21	**0.70**	**0.86**

Values for trends significant at the 5 % level are set in bold

autumn in 1961–2008 in researched area followed by winter. The maximum in 1986–2008 happened in autumn and spring. While the greatest warming in China and all over the world mainly occurred in winter and spring, which reflects the effect of snow areas at high altitude. It is worth noting that the high altitude area in studied area is quite wide. Just Xizhang Plateau accounts for 54.6 % of whole studied area. The larger snow areas in winter and spring bring high albedo of ground surface and further result in the reduction of surface net radiation. However, the snow areas is minimum in autumn rather it is July that had been confirmed by field study. So the snow and ice albedo is low in this time, and the more solar radiation would be absorbed by ground surface.

As shown in Table 3.5, only spring temperature in 1961–2008 in the studied are had a positive correlation with sunshine hours. The correlation value of annual, spring and summer temperature with sunshine hours in 1961–1985 had passed the significance test, while only the positive correlation value of summer temperature in 1986–2008 with sunshine hours failed to pass the significance test. It states that the increasing sunshine hours has a obvious contribution on accelerated warming after the mid of 1980s. In terms of three sub-regions including Xizang Plateau–-Hengduan Mountain, Yunnan–Guizhou Plateau and Sichuan Basin, the effect of sunshine hours change to the temperature change of Sichuan Basin in 1961–2008 is most significant. This figure also can be proven by the similar change trend of temperature and sunshine hours in this area (Fig. 3.13). And the effect in Yunnan–Guizhou Plateau mainly happened in spring and winter; the effect in Xizang Plateau–Hengduan Mountain mainly occurred in winter (Table 3.5). In 1961–1985, there was a positive correlation with sunshine hours change and the annual and seasonal temperature change of these three sub-regions, which suggests the common influence of sunshine hours on temperature. The correlativity with sunshine hours change and temperature change of Yunnan–Guizhou Plateau and Sichuan Basin was relatively significant during 1986–2008. But there only winter temperature had a significant positive with sunshine hours change in Xizang Plateau–-Hengduan Mountain, and the autumn sunshine hours has a negative correlativity with the temperature of Yunnan–Guizhou Plateau and Xizang Plateau–Hengduan

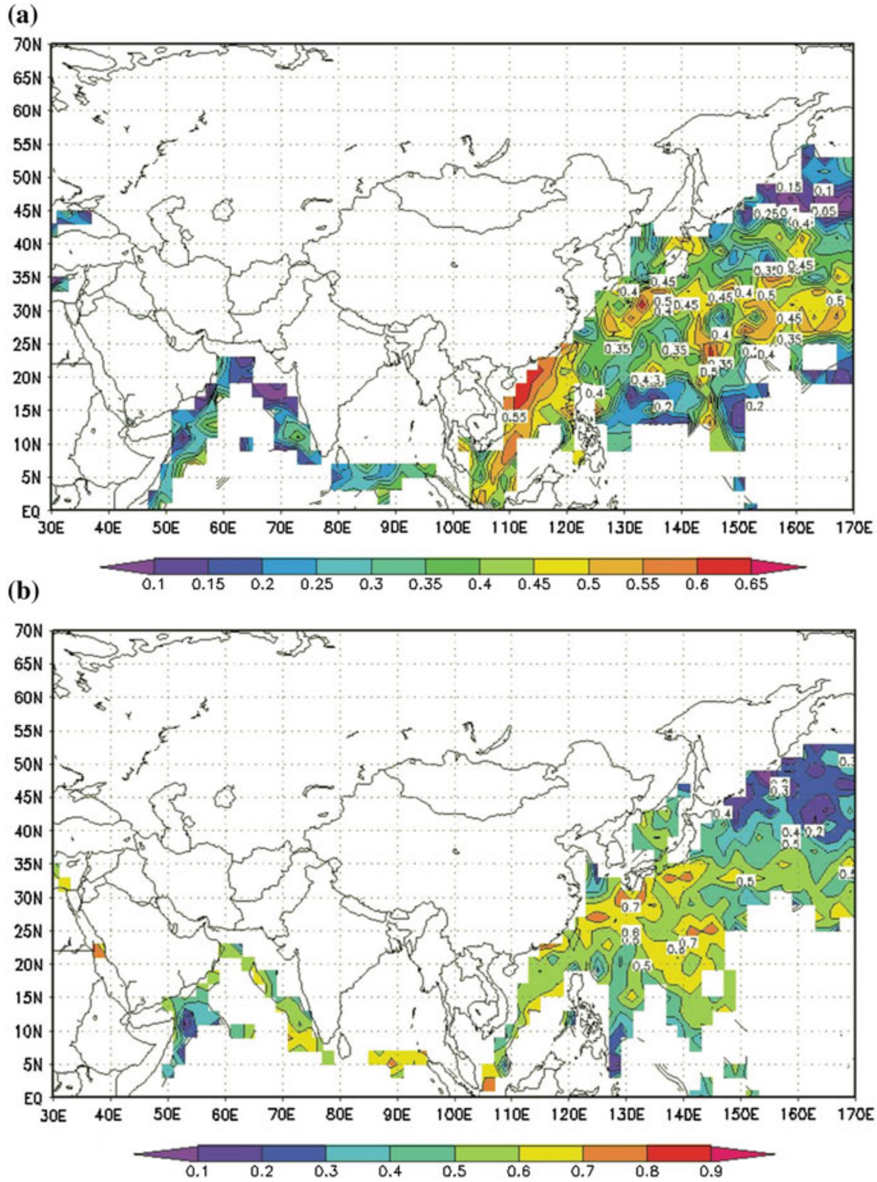

Fig. 3.12 Correlation field between annual temperature series in Southwestern China and annual sea surface temperature in 1961–1985 (**a**) and in 1986–2008 (**b**)

Mountain, which indicates the sunshine hours has more significant impact in the temperature change at low altitude, and reflects the regional difference of sunshine hours change in 1986–2008.

Table 3.5 Correlation coefficients between temperature and sunshine hours in three sub-regions of Southwestern China

	Years	Annual	Spring	Summer	Autumn	Winter
Southwestern China	1961–2008	−0.09	**0.44**	0.24	0.02	0.16
	1961–1985	**0.48**	**0.66**	**0.73**	0.024	0.27
	1986–2008	**0.35**	**0.52**	0.25	**0.32**	**0.56**
	1961–2008	**0.36**	**0.67**	**0.65**	**0.31**	0.14
SB	1961–1985	**0.77**	**0.66**	**0.86**	**0.32**	0.25
	1986–2008	**0.66**	**0.79**	**0.63**	**0.44**	**0.58**
	1961–2008	0.04	**0.50**	0.19	0.10	**0.38**
YGP	1961–1985	**0.45**	**0.65**	**0.65**	−0.07	**0.50**
	1986–2008	**0.49**	**0.54**	0.024	**0.44**	**0.49**
	1961–2008	−0.13	0.27	0.11	−0.14	**0.34**
XPHM	1961–1985	**0.37**	**0.61**	**0.54**	0.25	**0.44**
	1986–2008	0.1	0.17	0.20	−0.17	**0.47**

Values for trends significant at the 5 % level are set in bold

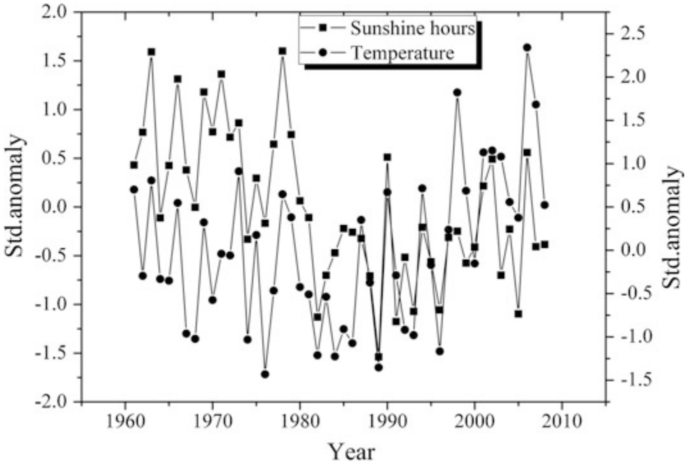

Fig. 3.13 Inter-annual variation between annual mean temperature and sunshine hours during 1961–2008 in Sichuan basin

3.3.3 The Correlation of Temperature and Precipitation Variation and Atmospheric Circulation

In order to examine the influence of atmospheric circulation variation on temperature change in studied area, this study analyze the correlation with spring and winter temperature and sea-level pressure of 0–70 and 30–170°N. As shown in Fig. 3.14, the summer temperature has a positive correlativity with the sea level

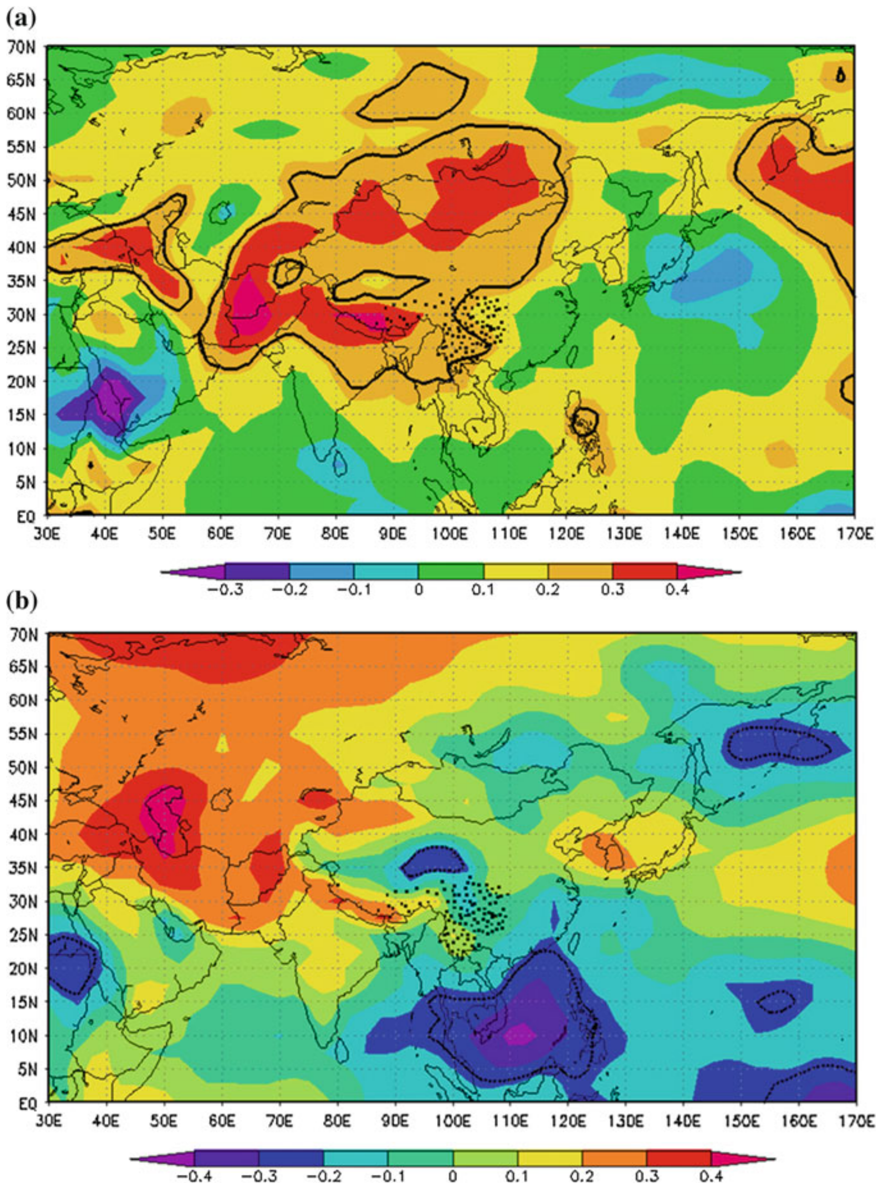

Fig. 3.14 Correlation fields between the overall temperature series in Southwestern China and sea level pressure in summer (**a**) and winter (**b**) during 1961–2007. Reprinted by permission from IOP Publishing: Ref. (Li et al. 2011). Copyright (1993)

pressure of Mongolia region (Lake Baikal), the south part of Qinghai–Xizang Plateau and the north part of southwest Asia, which suggests that the sea level pressure of above regions have an obvious impact on the summer temperature increase. The winter temperature of studied area shows a negative correlation with the sea level pressure of Mongolia region, Southeastern China, the north part of Qinghai–Xizang Plateau, and a significantly positive correlation with Central Asia, European regions and the south part of Qinghai–Xizang Plateau. Thereinto, a significant negative correlation with the sea level surface of the north part of Qinghai–Xizang Plateau has been shown. This indicates that the winter temperature rise is associated with the rise of sea level pressure of Mongolia region, Southeastern China, and the north part of Qinghai–Xizang Plateau as well as the reduction of Central Asia, European regions and the south part of Qinghai–Xizang Plateau. Based on this point, this study maps two circulation composite images of summer and winter or extreme high temperature year and extreme low temperature year by means of NCEP/NCAR reanalysis data, and arrives at the circulation changes in these two special periods through all extreme high temperature years minus all extreme low temperature years.

From the deviation photo of strongly positive and negative temperature in summer (Fig. 3.15), a strong cyclone circulation is formed in Northern China with centered by the Lake Baikal at 500 hpa and has been an important circulation system of Eurasia. The biggest difference of geopotential height (about −25 gpm) appears in around Lake Baikal which center is near 50°N and 110°E. The composite images of geopotential height at 300 hpa also shows similar features and the maximum difference of geopotential height is about −10 gpm. At the same time, there are two anticyclonic circulations formed on both sides of cyclone system, which centers respectively in 50°N and 40°E, 50°N and 160°E. In addition, two anomalous anticyclonic circulations also form in Western and Eastern China which centers respectively in 35°N and 80°E, 45°N and 120°E. The geopotential height difference is much larger in these two areas in China. On the one hand, this change of circulation reflects the weakening of Asian monsoon system and lead to the strengthening of northwest wind in the north and east of the Qinghai–Xizang Plateau. On the other hand, the anticyclone in Eastern China has not only hindered the moving of sea warm current towards north, also greatly compressed the influence range of sea warm current and eventually made the studied areas dominated by prevailing northeast wind. Thereby, the moving of Indian monsoon and any airflow from south of ocean are weakened towards north and the studied area is controlled by the anticyclone system. Therefore, the influence of two anomalous anticyclonic circulations on strongly positive temperature in summers in Southwestern China has resulted in xerothermic northwest wind formed in the north of Qinghai–Xizang Plateau. Moreover, the northeast airflow resulted from anticyclone in Eastern China moves towards south passes Hengduan Mountains, Sichuan Basin and Yunnan–-Guizhou Plateau and finally arrives at Xizang Plateau. This northerly air current blocks the transport of water vapor from the ocean to north and makes the studied area controlled by xerothermic air mass. To some extent, these circulation backgrounds explain why air temperature increases and the rainfall decreases in summer in the study area. As shown in Fig. 3.16a, there is an anomaly enhanced cyclone circulation at near 50°N and 45°E (central Asia and Europe), of which maximum deviations of geopotential height is about −80 gpm. It causes that the anticyclonic

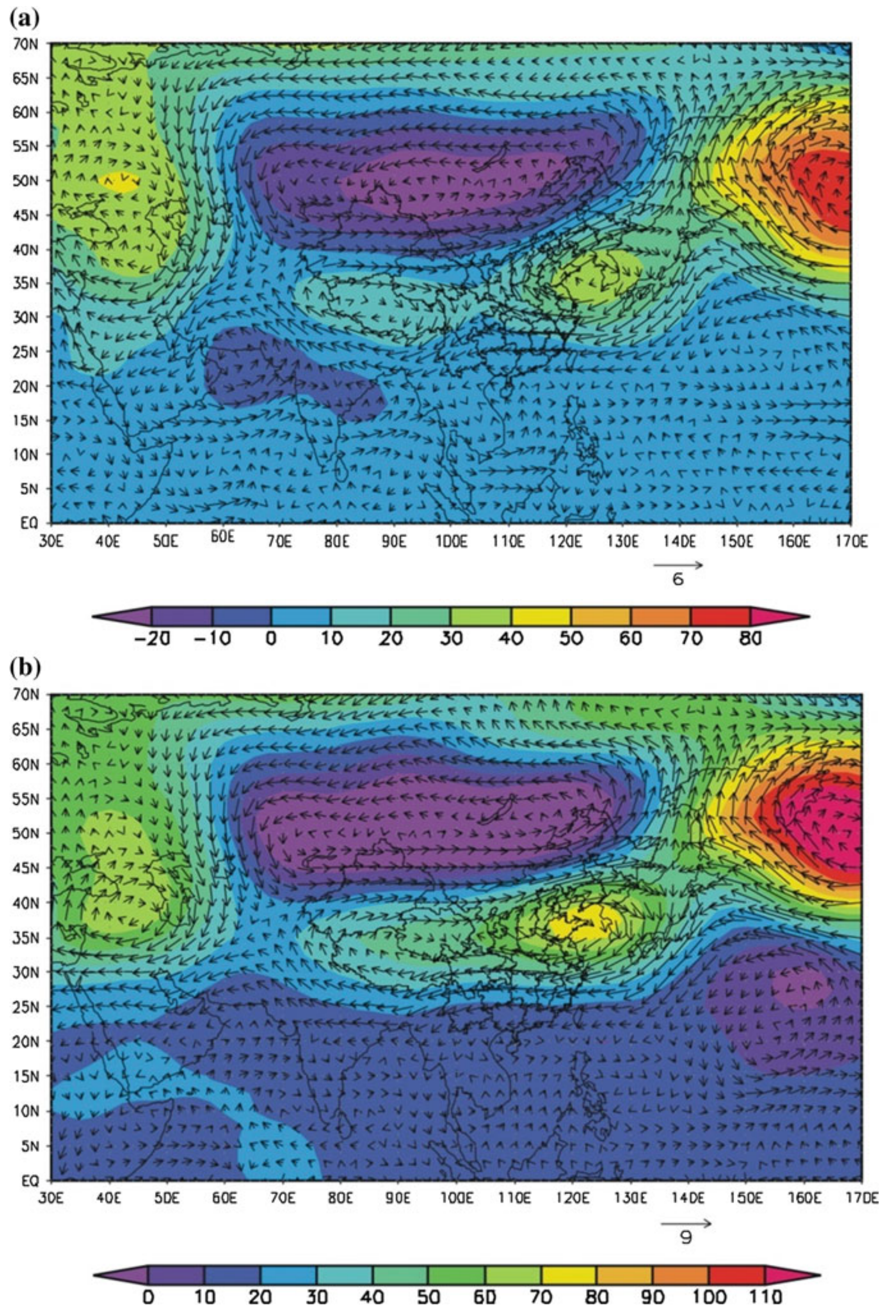

Fig. 3.15 Differences between mean geopotential height and wind field at the 500 hPa (**a**) and 300 hPa (**b**) in summers with strongly positive and negative temperature deviations exceeding ±1σ of the 1961–2008 mean

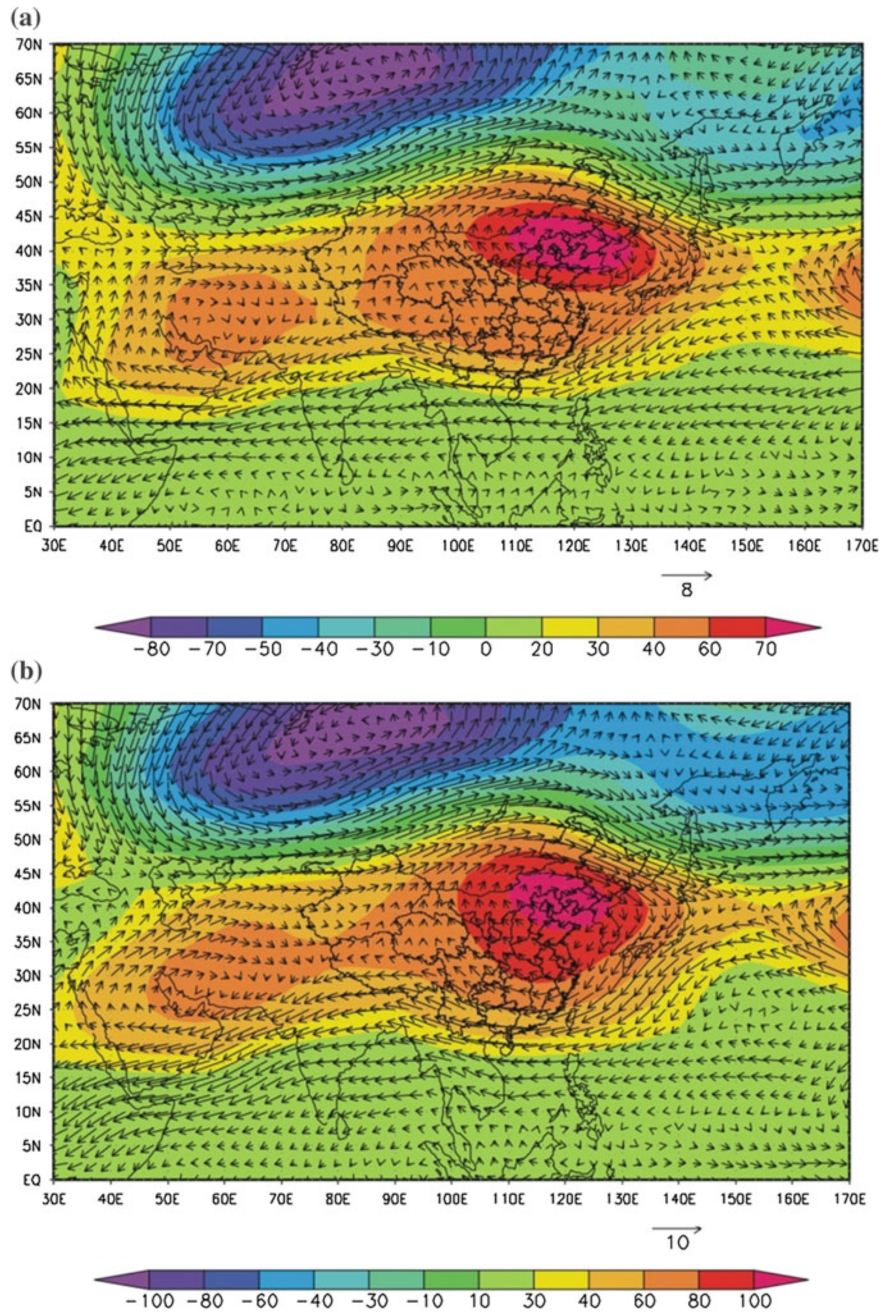

Fig. 3.16 Differences between mean geopotential height and wind field at the 500 hPa (**a**) and 300 hPa (**b**) in winters with strongly positive and negative temperature deviations exceeding ±1σ of the 1961–2008 mean

circulation of Eurasia centered by near 40°N and 120°E presents a weakening trend and make the center move towards south and arrive at North China. This circulation form is consistent with the composite image of geopotential height at 300 hPa (Fig. 3.16). On the one hand, the above circulation backgrounds show the strengthening of west wind circulation in summers with strongly positive temperature. On the other hand, the deviations between winter anticyclonic circulation and cyclonic circulation has been strengthened and developed southwest wind in Northern China, which weakens the strength of winter monsoon, limits its stretching to south and reduces the rate of winter cold wave. The studied areas also suffer the effect of southeast warm wet air current from the sea and these circulation backgrounds are helpful to the winter warming.

This study calculates the average of water vapor flux in summer and winter of 1961–2008 by using the NCEP/NCAR reanalysis data and arrives at the difference of both the water vapor fluxes through dry years minus wet years so as to further understand the influence of circulation system on the precipitation change. As shown in Fig. 3.17, whether in winter or summer, the maximum mean water vapor flux from 1961 to 2008 in Southern China always is in the high altitude area centered by Xizang Plateau, which indicates the abundant water vapor transport in this region, and which may be one of reasons that the precipitation increase in the studied area are mainly in the high altitude area. The difference of water vapor flux of South China between in wet years and dry years is very small, which indicates the vapor flux slightly changes in these two periods. But the water vapor flux in wet years is slightly higher than in dry years in the east and west of Xizang Plateau, the south of Hengduan Mountain and Yunnan Plateau (Fig. 3.18). These characteristics prove that the water vapor transport of the studied area has no obvious interannual difference, indicate the difference of wet year and dry year is not caused by the changes of water vapor transport and make sure the non-significant change trend of rainfall in studied area. The change of the western Pacific subtropical high is regarded as one of the main factors impacting precipitation change in China, and the strength of the western Pacific subtropical high gradually increased in recent years. As shown in Table 3.6, the winter precipitation of Southwestern China, Xizang Plateau and Hengduan Mountain has a significant positive correlation with the strength and area index of the western Pacific subtropical high, and also shows a positive correlation with precipitation of Yunnan-Guizhou Plateau, which reflects the significant contribution of enhancement of the western Pacific subtropical high on winter precipitation increase. The possible mechanism is the enhancement of the western Pacific subtropical high in winter will contribute to the transport of ocean warm airflow to mainland, thus cause the precipitation event. The enhanced western Pacific subtropical high presents an obvious negative correlation with the annual and spring precipitation of Yunnan-Guizhou Plateau, as well as a significantly negative correlation with autumn precipitation of Sichuan Basin. Because the stretching of western Pacific subtropical high towards west after strengthening in summer and autumn will make the studied area controlled by dry air and eventually lead to temperature rise but precipitation reduction.

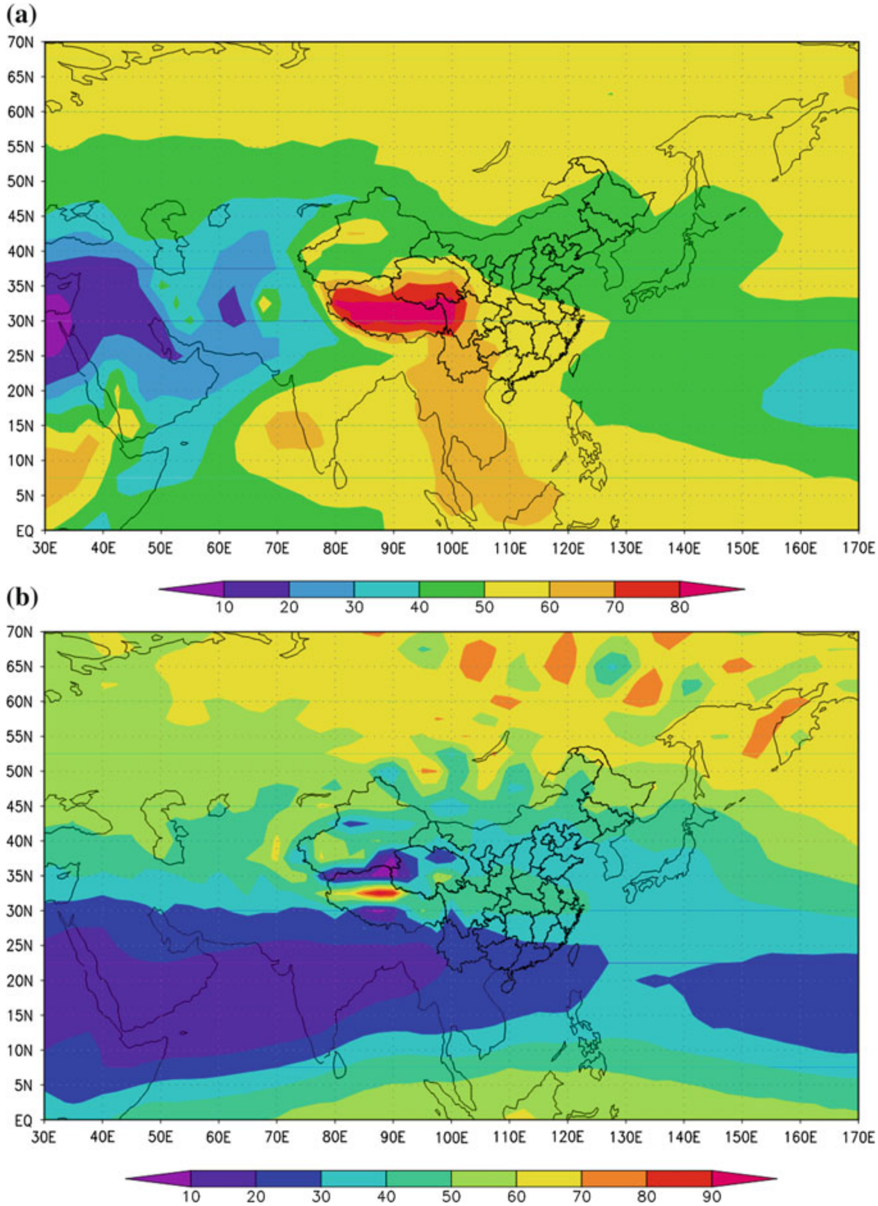

Fig. 3.17 The mean water vapor flux at 500 hPa in summers (**a**) and winters (**b**) during 1961–2008

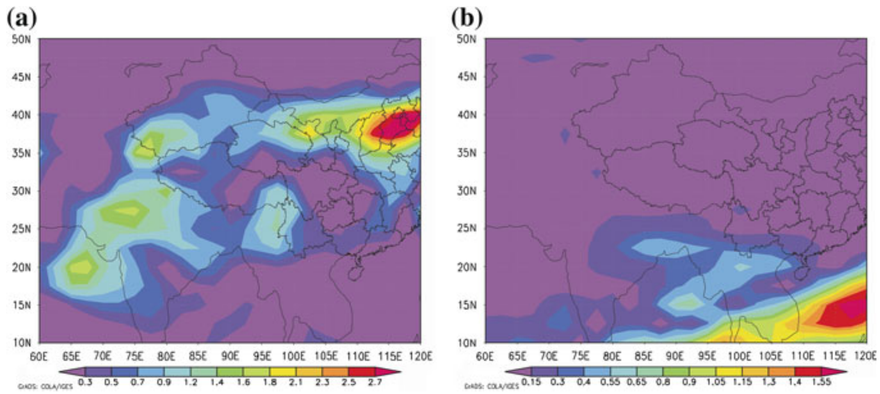

Fig. 3.18 Differences between mean water vapor flux at 500 hPa in summers (**a**) and winters (**b**) with strongly positive and negative temperature deviations exceeding ±0.5σ of the 1961–2008 mean

Table 3.6 The correlation between precipitation and Western Pacific subtropical high index

Regions	Index	Annual	Spring	Summer	Autumn	Winter
Southern China	Strength	0.13	0.09	0.08	0.09	**0.55**
	Area	0.13	0.12	0.03	0.07	**0.59**
XPHM	Strength	0.13	0.09	0.08	0.09	**0.55**
	Area	0.13	0.12	0.03	0.07	**0.59**
YGP	Strength	−0.26	−0.26	−0.03	0.02	0.26
	Area	**−0.31**	−0.21	0.06	−0.08	0.21
SB	Strength	−0.08	−0.2	0.24	**−0.33**	0.17
	Area	−0.16	−0.19	0.17	**−0.44**	0.13

Values for trends significant at the 5 % level are set in bold

3.3.4 The Comparison of Variation Magnitude of Temperature in Urban and Rural Stations

At present, most of the researches think that climate warming can be attributed to the increased concentrations of greenhouse gases (IPCC 2007). However, the long-term surface warming may also be associated with other climate factors, for example, the impact of urban heat island effect (Zhou et al. 2004). City heat island effect is one of the human factors which have important effects on climate change. The surface condition and circulation characteristics of the city are dramatically changed due to the land use change caused by urbanization, which results in the change of power balance, power balance and water balance, and eventual formation of the obvious city microclimate (Morris et al. 2001). In order to analyze the difference between urban and rural stations, the 110 meteorological observation stations have been divided 58 urban stations and 52 rural stations. The results indicate that the mean temperature of the rural stations of 83 % and the urban stations of 76 % present a increase trend; the temperature of the rural stations of 38, 47, 67, 52, 62, 52 % and the urban stations of 58, 67, 67, 67, 79 and 69 % all have been on the rise in spring, summer, autumn, winter, summer monsoon and winter monsoon period. There are more unban stations warming in autumn and there are more rural stations warming in winter. The more obvious thing is that the magnitudes of annual and seasonal temperature change in rural station are higher than the urban stations (Fig. 3.19).

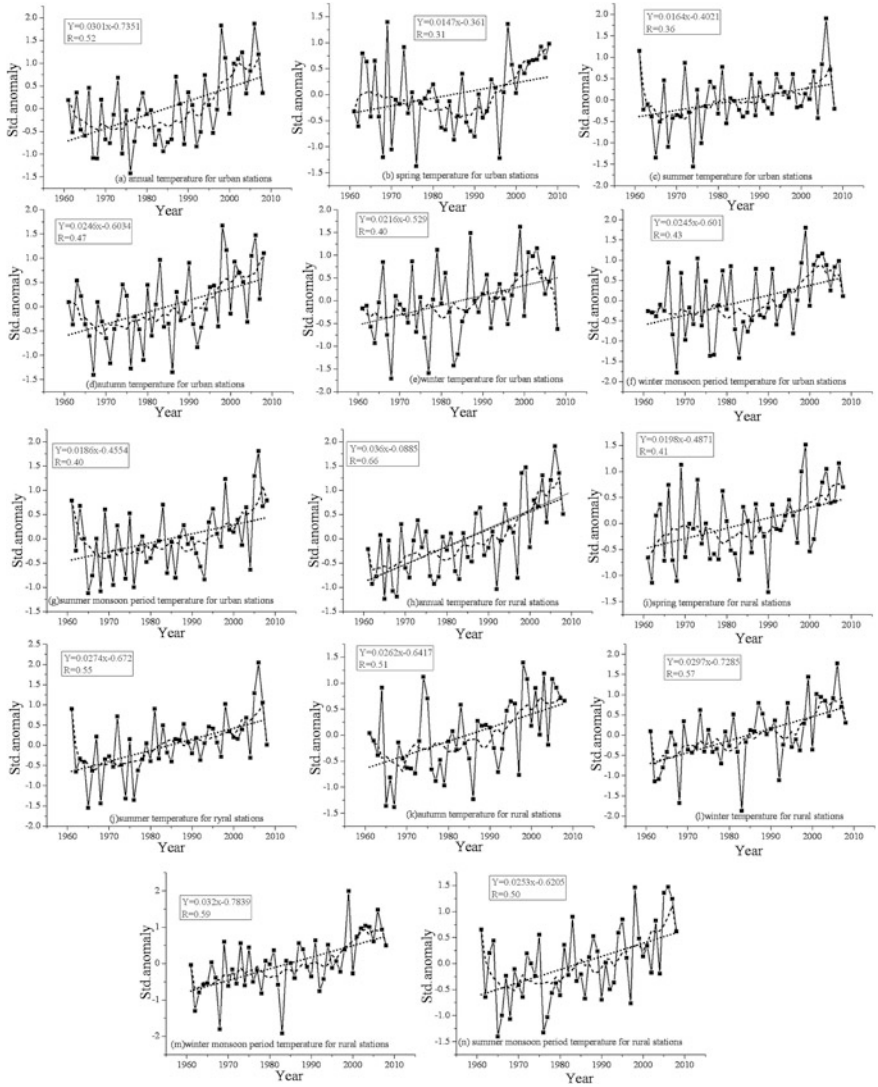

Fig. 3.19 Inter-annual variation of temperature in urban and rural stations during 1961–2008

As the Fig. 3.19 shows, the temperature of rural stations has a continuous increase, whereas the temperature of urban stations appeared a decrease in 1960s, then slowly rise during 1970–1985 and finally significantly rise during the following time. The temperature of rural stations is continuous to rise in spring, but the temperature of urban stations decline before 1985 and then rise. All in all, the obvious trend variation of urban stations is a larger temperature increase after the mid of 1980s, while the rural stations show a continuous temperature rise. In general, the deviations of magnitude of temperature change between urban stations and rural stations is defined as the contribution of urban heat island effect (Jones et al. 2008; Ren et al. 2008). If this could be looked as a basis, the urban heat island would not have a significant contribution to the mean temperature change of urban stations in studied area. This reasoning may be explained by following three aspects: (1) the effect of altitude explains the dramatical warming happened in rural stations, and the magnitude of temperature change in studied area shows a trend of increasing with the rise of altitude. The mean altitude of urban and rural station are 1,156 and 1,692 m, respectively. There is only one urban station in Xizang Plateau and two urban stations in Hengduan Mountain. The all rest of urban stations are located in Yunnan–Guizhou Plateau and Sichuan Basin. In addition, the change trend of the annual mean temperature in urban stations is similar to that of Yunnan–Guizhou Plateau and Sichuan Basin, which also confirmed the above reasoning (Fig. 3.20). (2) The urban heat island effect mainly influence extreme temperature, especially the extreme minimum temperature, which will be analyzed detailedly in Chap. 4. (3) As the studied area is lower in urbanization rate, there are only three stations in megacities where the population is more than millions among 58 selected urban stations. Additionally, there some researches have proven that in megacities, for example, Seoul, the capital of South Korea, the urban heat island effect resulted in that the annual mean temperature increase 0.56 °C during 1973–2006 (Kim and Baik 2002). The related researches in China also have confirmed that the significant affect of the urban heat island to annual mean temperature mainly occurs in megacities like Beijing, Shanghai etc. Moreover, the study of Tang et al. (2008) has demonstrated that the urban heat island effect has a slight influence on the

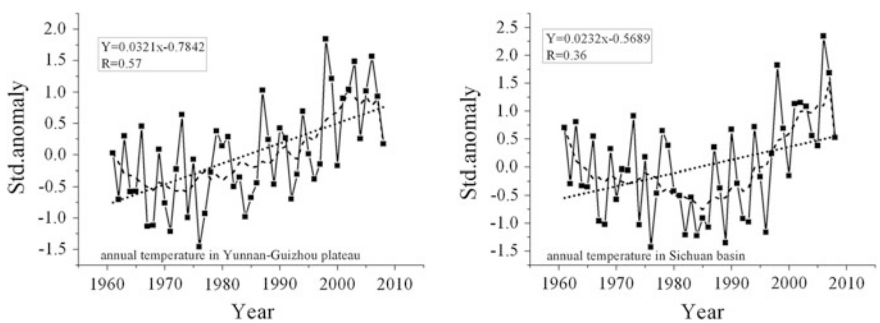

Fig. 3.20 Inter-annual variation of temperature in Yunnan-Guizhou plateau and Sichuan basin during 1961–2008

observation station in Sichuan, Yunnan, Guizhou and Chongqing because of the lower urbanization level. To sum up, the altitude is the main reason resulting in the difference in the magnitude of temperature change.

3.4 Summary

This chapter focuses on the analysis of partial and temporal variations of annual mean temperature and precipitation as well as its possible influencing factors by means of the meteorological data of 110 stations. The main finds of the chapter are as follows:

(1) The temperature significantly raised, and the precipitation showed a stable trend. In 1961–2008, the annual mean temperature was 12.7 °C and the annual mean precipitation was 965 mm. The spatial distribution of the temperature and precipitation showed a gradual decline trend from southwest to northeast. Nearly 50 years, annual average temperature significantly warmed and the magnitude was 0.33 °C/10 a. The magnitude of temperature rise enlarged obviously after 1980s rather than a small magnitude before 1980s. The seasonal temperature change also reflects the significant warming trend. The annual precipitation in the studied area showed a slight reduction non-statistics significance from 1961 to 2008 and the magnitude of change was −0.006 mm/10 a. The precipitation remained stable in 1961–1980, then it slowly declined in the whole 1980s and increased obviously in 1990s. But the precipitation showed a wavelike decrease change after stepping into new century, thereinto, the sping and winter precipitation increase obviously.

(2) The warming and precipitation increasing in the high altitude area was more apparent. The annual mean temperature of stations of about 77 % in studied area significantly increased. On the whole, the stations with significant and wider margin of warming were mainly distributed in Xizang Plateau, Hengduan Mountain and Yunnan Plateau, and the stations with non-significant increase and decrease were mainly distributed in Sichuan Basin and Guizhou Plateau, of which the magnitude of temperature increase rose significantly with the rising of elevation. In addition, the magnitude of warming fell successively in the order of flat station, intermontane station, valley station, and summit station. The significance level of precipitation change is extremely low and the annual precipitation stations of only 5 % increased significantly. The stations with precipitation increase are mainly distributed in Xizang Plateau, Hengduan Mountain and the central and northwest of Yunnan–Guizhou Plateau, while the stations with precipitation decrease are mainly located in the eastern part of Yunnan Plateau, Guizhou Plateau and Sichuan Basin. Moreover, the stations with wider margin of significant decrease are mainly distributed in surrounding Sichuan Basin. From this point, the characteristic of precipitation increase at

high altitude and precipitation decrease at low altitude has been presented. The maximum magnitude of decreasing occurred in summit stations and the maximum magnitude of increase happened in vally station.

(3) There are many causes of significant warming after the mid of 1980s. Compared with the 1961–1985, the net longwave radiation flux received by ground surface increased significantly from 1986 to 2008, which indicates that the strength of atmospheric heating process has been increased gradually. The correlation level with the annual average temperature of Southwestern China and the sea surface temperature of the western Pacific in 1986–2008 was significantly higher than in 1961–1985, which reflects the apparent contribution of gradual strengthening of ocean thermal process to significant warming in the latter period. The significantly positive correlation with the temperature change and sunshine hours during 1986–2008 in the studied area reflects its apparent contribution to the accelerated temperature rise after the mid of 1980s. In addition, the urban station is more than the rural station both in the magnitude of temperature variations and the percentage of stations showing significant warming, which is considered to be caused by the elevation difference of distribution of urban station and rural station.

(4) The regional warming is associated with the change of atmospheric circulation in the large scale. The studied area is under the influence of two anomalous anticyclonics in summers with strongly positive temperature, which causes that the northeast wind of Hengduan Mountain, Yunnan–Guizhou Plateau and Sichuan Basin would block the transport of the ocean water vapor toward north makes the studied area under the control of dry and hot air mass. The difference between winter anticyclonic circulation and cyclone circulation further strengthens and forms the southwest wind in Northern China. Then it weakens the strength of winter monsoon in turn, limits its stretch to south. In addition, it reduces the rate of the cold air like winter cold wave and further contributes to the temperature rise in winter. These circulation background partly explained the significant warming in the studied area.

(5) The correlation with precipitation changes and water vapor flux is weak. In 1961–2008, the maximums of the average water vapor flux in winter and summer were both in the high altitude area of Xizang Plateau, which partly explained the precipitation increase in this region. The difference of vapor flux in winter of dry years and wet years is very small, while in summer, the vapor fluxes of the east and west of Xizang Plateau, the south of Hengduan Mountain and Yunnan Plateau in wet years are slightly more than the dry years. This demonstrates that water vapor transport has no apparent interannual variation and confirms the weak correlation with the interannual variability of precipitation and water vapor flux. The western Pacific subtropical high has an obvious influence on the precipitation change of researched area. The enhancement of western Pacific subtropical high in winter is helpful to the transport of warm air current from oceans to the mainland resulting in

precipitation events. However, the stretch of western Pacific subtropical high in summer and autumn toward west to the mainland after strengthening will cause the studied area is controlled by dry and warm air mass and eventually lead to temperature increase and precipitation decrease.

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Chapter 4
Spatial and Temporal Variation of Climate Extremes in Southwestern China

4.1 Spatial and Temporal Variation of Climate Extremes

4.1.1 Spatial and Temporal Variation of Indices of Temperature Extremes

As shown in Fig. 4.1, the annual mean TX10, TN10, TXn, TNn and FD all showed an upwards trend in 1961–2008 in Southwestern China except for ID. The annual means of ID, TX10, TN10, TXn, TNn and FD are 9.8 d, 16.5 d, 16.3 d, 1.7 °C, −8.5 °C and 74.5 d, respectively (Table 4.1). The cold day frequency (TX10) reduced significantly at a rate of about 0.13 d/10 a. The interannual change showed a wavelike increase before the mid of 1980s and a decrease followed (Fig. 4.1). There were stations of about 79 % being on the decline among 110 stations selected. Among them, the magnitude of decline of 36 % had passed the significant test (Table 4.1). The magnitude of TX10 decrease of stations distributed in east of Xizang Plateau and Hengduan Mountain was large and obviously more than that of stations in Yunnan–Guizhou Plateau and Sichuan Basin. Additionally, TX10 of some stations in the east of Sichuan Basin and Yunnan Plateau increased (Fig. 4.2). The cold night frequency (TN10) of studied area significantly reduced at a rate of about 0.37 d/10 a in 1961–2008, during which the TN10 of stations of about 95 % reduced and the magnitude of decline of 91 % had passed the significant test. The spatial distribution shows a gradual reduction trend from high altitude area to low altitude area (Figs. 4.1 and 4.2) Overall, the spatial distribution of regional trends of above two indices shows a gradual decline trend of warming magnitude from west to east, reflects the significant effect of elevation, and also confirms that night index is warming by a wider margin than daytime index.

There the coldest day temperature (TXn) from 85 % of the stations and the coldest night temperature (TNn) from 97 % of the stations perform an increase trend during 1961–2008 in Southwestern China. In terms of TXn, the increase trend of only 24 % of the stations have passed the significance test, and the significantly increase of

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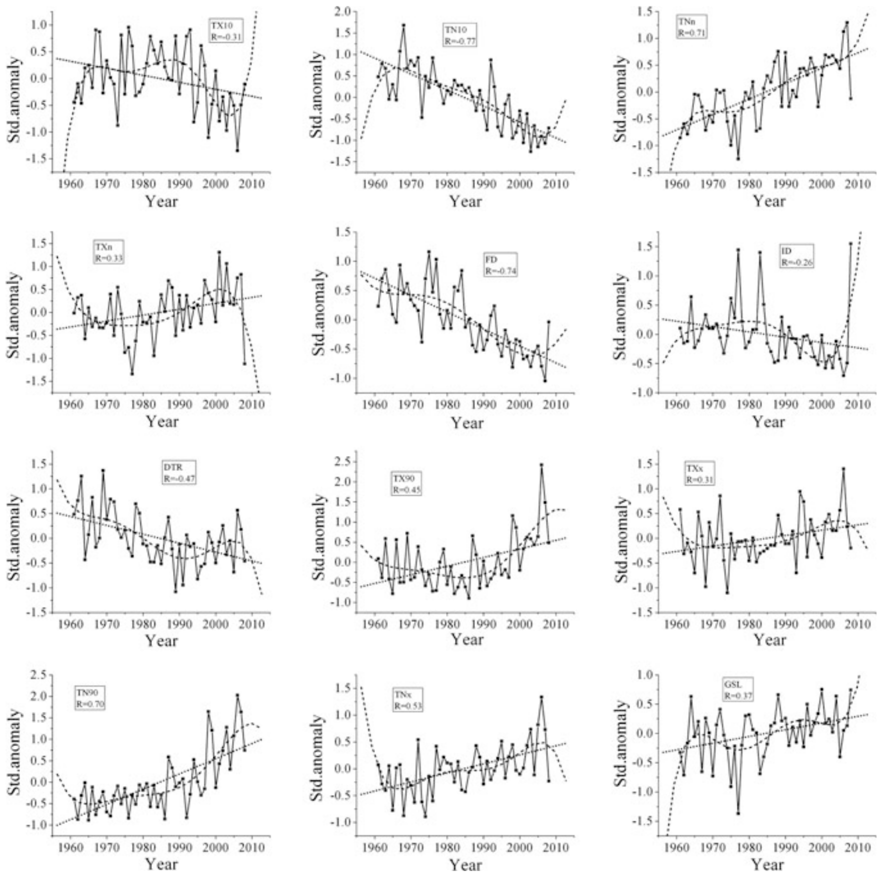

Fig. 4.1 Regional annual anomaly series, 1961–2008, for indices of temperature extremes

about 77 % of the stations in TNn confirms that the minimum temperature is warming by a widest margin (Table 4.1). TXn showed a reducing trend before 1980s and fluctuated to rise, then showed a wavelike decrease change after 2000. The magnitude of changing 0.13 °C/10 a. While TNn continued to warm at a rate of about 0.29 °C/10 a. Both magnitudes of changing are successful in significance test, but the latter one is two times more than the former one (Fig. 4.1). Except for a few stations in Sichuan Basin and the south of Hengduan Mountain where TXn shows a downward trend, TXn in the most stations shows a increasing trend. The stations with a significant decrease are mainly distributed in the east of Xizang Plateau and the central of Yunnan–Guizhou Plateau (Fig. 4.2). Compared with TXn, TNn warm universally in Southwestern China (Fig. 4.2). Due to the low latitude location of the study area, there 55 stations have no ice days (ID), and 6 stations have no frost days (FD). In 1961–2008, the ice days non-significantly reduced and the magnitude is very small (0.09 d/10 a). It slowly increased before 1980, then gradually reduced after 1980. There 15 stations decreased significantly which are mainly distributed in

Table 4.1 Trends per decade and percentage of stations with positive or negative trends for regional indices of temperature and precipitation extremes in Southwestern China during 1961–2008 (°C or mm or d/10 a)

Index	Averages	Regional trends	Range	Percentage of stations showing positive trend	Percentage of stations showing significant positive trend	Percentage of stations showing negative trend	Percentage of stations showing significant negative trend
TX10	16.5	**−0.13**	−11.3–1.3			79	36
TN10	16.3	**−0.37**	−4.6–2.6			95	91
TXn	1.7	**0.13**	−0.3–0.9	85	24		
TNn	−8.2	**0.29**	−0.1–2.0	97	77		
ID	9.8	−0.09	−5.7–0.4			86	27
FD	74.5	**−0.29**	−21.2–0			98	81
DTR	10.9	**−0.18**	−0.6–0.2			82	50
TN90	16.1	**0.36**	−3.6–10.4	95	88		
TX90	16.5	**0.22**	−4.0–8.8	88	62		
TXx	31.1	**0.11**	−0.4–0.8	81	29		
TNx	19.4	**0.17**	−0.5–0.7	80	67		
GSL	301.0	**0.12**	−2.2–14.0	96	38		
PRCPTOT	912.6	0.03	−69.0–12.2	57	25		
SDII	9.1	0.03	−0.3–0. 5	59	11		
RX1 day	66.8	**0.05**	−7.6–10.8	64	10		
R95	238.2	0.04	−37.3–39.1	63	10		
R99	74.0	**0.05**	−19.3–24.6	67	8		
RX5 day	116.6	0.03	−11.5–12.7	55	8		
CDD	58.9	−0.05	−57.5–4.5			74	28
CWD	8.4	**−0.08**	−1.7–1.0			76	19
R10 mm	27.4	0	−2.1–3.8	55	15		
R20 mm	10.7	0	−1.1–1.1	55	8		
R25 mm	7.9	0.02	−0.9–1.1	61	12		

Values for trends significant at the 5 % level are set in bold

Xizang Plateau. But the five stations in Yunnan–Guizhou Plateau showed a increasing trend (Figs. 4.1 and 4.2). Frost days continue to decrease significantly at a rate of about 0.29 d/10 a. There are 98 % of the stations performing a downward trend and around 81 % of the stations passed the significance test. The magnitude of decline of most stations in Xizang Plateau and Hengduan Mountain are more than the Yunnan–Guizhou Plateau and Sichuan Basin, while the stations with non-significant decrease are mainly distributed in the Yunnan–Guizhou Plateau (Figs. 4.1 and 4.2).

The diurnal temperature range is an important indicators of knowing climate extremes. Liu et al. (2006) found that both maximum temperature and minimum temperature were on the rise in recent decades, but the magnitude of warming of minimum temperature was more than that of the maximum temperature with resulting in the continuous decrease of the diurnal temperature range. The research of You et al. (2008a, b) also confirmed this change. In addition, the magnitude of

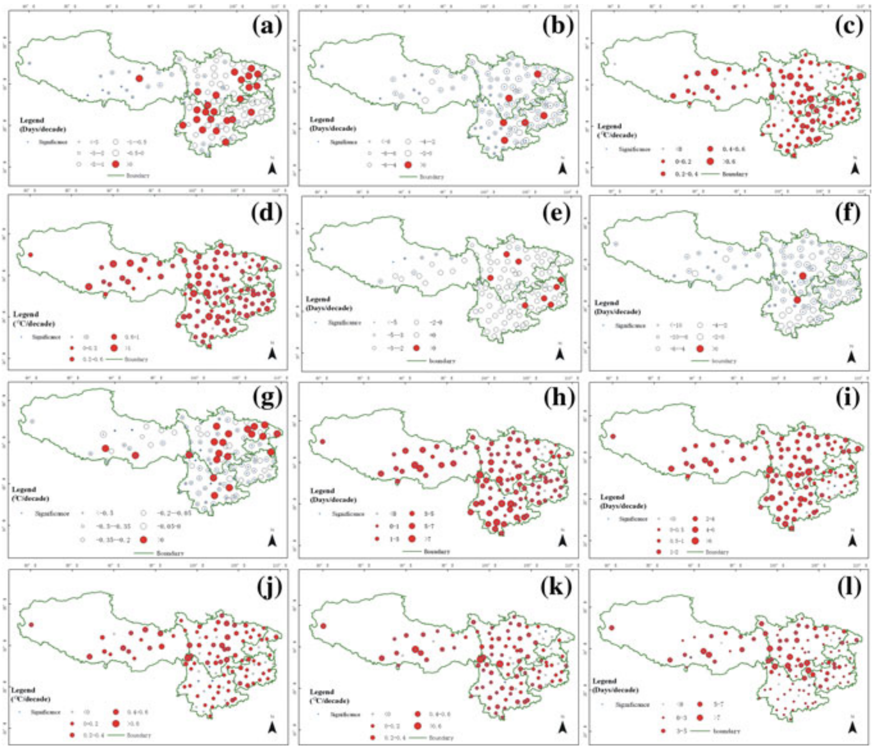

Fig. 4.2 Spatial distribution of trends per decade for TX10, TN10, TXn, TNn, ID, FD, DTR, TN90, TX90, TXx, TNx and GSL

global minimum temperature rise also more than the maximum temperature (Easterling et al. 2000). A conclusion can be made from Fig. 4.1, the average of diurnal temperature range of studied area from 1961 to 2008 was 10.9 °C, and the annual diurnal temperature range (DTR) significantly reduced at a rate of about 0.18 °C/10 a. It is interesting that the annual diurnal range continued to decrease before 1990 but fluctuated to increase afterwards (Fig. 4.1). Above change was caused by the variation gap between the widening and narrowing of regional trends of the maximum temperature in recent years. The further analysis indicated that the mean maximum temperature non-significantly reduced at a rate of about −0.12 °C/10 a in studied area from 1961 to 1989. The mean minimum temperature of the corresponding period significantly increased 0.20 °C every 10 years. In 1990–2008, the mean maximum temperature significantly increased at a rate of 0.9 °C/10 a, while the magnitude of average minimum temperature rise was 0.84 °C/10 a. There were about 82 % of the stations with the diurnal range showing a downtrend, among which only 50 % of the stations passed the significance test (Table 4.1).

The stations with significant decrease were mainly distributed in Yunnan–Guizhou Plateau and the south of Hengduan Mountains, which suggested that the magnitude of warming of minimum temperature in these regions was greater than the maximum temperature all the time. However, the temperature of most stations in Xizang Plateau and the north of Hengduan Mountain showed a non-significant decrease, and the temperature of most stations in Sichuan Basin had a non-significant decrease or increase. This spatial distribution reflected that the greater the magnitude of the minimum temperature rose, the more obviously diurnal range reduced and vice versa (Fig. 4.2). The variation of diurnal range was affected by the maximum and minimum temperature and was related to the seasonal structure of regional warming. Therefore, compared with others indexes, the spatial and temporal variation showed a certain complexity.

As shown in Table 4.1, the annual mean of TN90, TX90, TXx, TNx and GSL of studied area in 1961–2008 were 16.1 d, 16.5 d, 31.1 °C, 19.4 °C, and 301 d, respectively. As shown in Fig. 4.1, the warm night frequency (TN90) significantly increased at a rate of about 0.36 d/10 a, and the magnitude of increase was very significant after the mid of 1980s (Fig. 4.1). There are about 95 % showing a uptrend among the 110 stations selected. Thereinto, there 88 % of stations had a marked rise, which were mainly located in others regions except for the eastern Sichuan Basin, while there were several stations in Sichuan Basin showing a decline trend (Fig. 4.2). The warm day frequency (TX90) declined slowly before the mid of 1980s and markedly rose afterward. Its magnitude of changing was 0.22 d/10 a in 1961–2008. There were approximately 88 % being on the rise in 110 stations selected, and 62 % of the stations significantly increased. But the low magnitude of changing confirmed that it was much greater to warm at night than in the daytime once again (Fig. 4.1). In terms of spatial distribution, the stations with sharp warming were mainly located in Xizang Plateau, Yunnan Plateau and the south of Hengduan Mountain, whereas a number of stations in Guizhou Plateau and the north of Hengduan Mountain increased or decreased non-significantly (Fig. 4.2).

The warmest day temperature (TXx) in studied area remarkably increased at a rate of about 0.11 °C/10 a from 1961 to 2008. It increased slowly before the mid of 1980s and sharply afterward. Although there are 81 % of stations being on the rise among 110 stations selected, only 29 % of the stations passed the significance test which are mostly distributed in Xizang Plateau, the eastern Hendguan Mountain. The most stations in Yunnan–Guizhou Plateau and Sichuan Basin had a small magnitude of increasing, and TXx of several stations reduced (Figs. 4.1 and 4.2). The warmest night temperature (TNx) was continuous to rise at a rate of about 0.17 °C/10 a. About 80 % of stations showed a trend of increase in 110 stations selected, and 67 % of stations significantly warmed. The stations with greater magnitude of warming were located in the high altitude area, while the most stations in the eastern Sichuan Basin and several stations in Guizhou Plateau had a downtrend (Figs. 4.1 and 4.2).

From the overall average level of Southwestern China, the growing season length (GSL) increased significantly at a rate of 0.12 d/10 a, and the interannual change were significantly increased except for slight decrease in the 1970s (Fig. 4.1). The GSL of about 96 % of stations had a rising trend among 110 stations selected, but only 39 % of stations located in Xizang Plateau and Hendguan Mountain passed the significance test. Furthermore, the magnitude of GSL rise in above two areas was significantly greater than other areas. This spatial distribution reflected apparent effect of elevation (Fig. 4.2).

On the whole, the stations with temperature extremes index significantly warming are mainly distributed in Xizang Plateau and Hendguan Mountain, but the stations with non-significant rise or reduce are mainly distributed in Yunnan–-Guizhou Plateau and Sichuan Basin. This distribution reflects the apparent effects of the terrain and elevation and confirms the significant warming in high altitude area. The magnitude of temperature extremes index rise in Xizang Plateau and Hendguan Mountain is much greater than that in Yunnan–Guizhou Plateau and Sichuan Basin, which is similar to the spatial distribution of the regional trends of annual mean temperature. The study of Liu et al. (2009a, b) also confirmed that the magnitude of temperature rising in the east of Qinghai–Xizang Plateau and its surrounding regions is apparently more than that in low altitude regions. In addition, the station with a cooling trend for TXn, TX90, TX10, TNx, TN90 and TN10 are mainly located in the eastern Sichuan Basin.

4.1.2 Spatial and Temporal Variations of Precipitation Extremes

The annual averages of PRCPTOT, SDII, RX1 day, R95, R99, RX5 day, CDD, CWD, R10, R20 mm and R25 mm are 912.6 mm, 9.1 mm/d, 66.8 mm, 238.2 mm, 74 mm, 116.6 mm, 58.9 d, 8.4 d, 27.4 d, 10.7 d and 7.9 d, respectively in Southwestern China (Table 4.1). Compared with temperature extremes index, the significance of changes in precipitation extremes in southwest China is low and shows a more complex spatial and temporal difference. Only changing trends of maximum 1-day precipitation (RX1 day), consecutive wet days (CWD), extremely wet day precipitation (R99) have passed the significance test among 11 indexes. Therefore, the changing trend still has a big uncertainty in understanding regional precipitation extremes change in interannual and interdecadal scale (Table 4.1). As shown in Fig. 4.3, the wet day precipitation (PRCPTOT) in 1961–2008 fluctuated to change in 10 years period, but the general trend was rising and the regional trends was 0.03 mm/10 a. In addition, there are 57 % of the 110 stations showing a increasing trend (Table 4.1), which were mainly distributed in the high altitude region of Xizang Plateau, Hengduan Mountain, Yunnan Plateau and others. However, the most stations located in the Guizhou Plateau and Sichuan Basin had a wider margin of decrease, and the stations accounting for 25 % of all stations with a significant increase were primarily situated in Xizang Plateau. The above result also confirmed that the precipitation increase in this region mainly happened in high altitude area (Fig. 4.4). The annual average precipitation on wet days (SDII) had a slow decreasing trend with fluctuations before 1990s and increased afterwards.

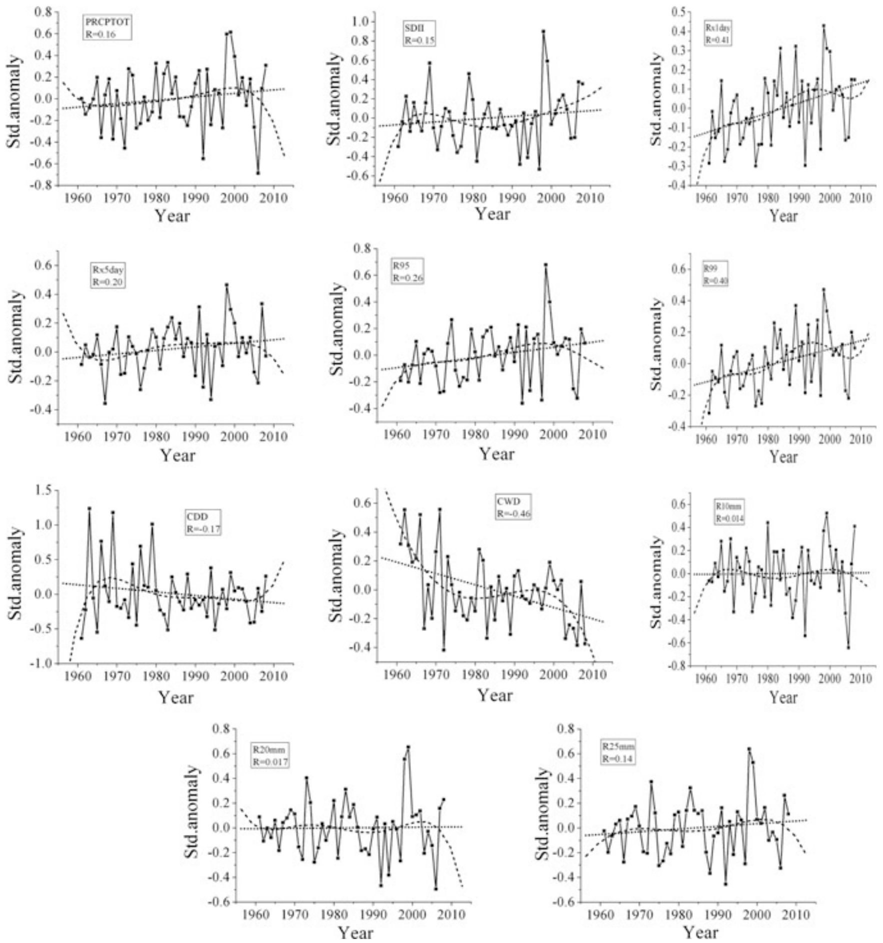

Fig. 4.3 Regional annual anomaly series, 1961–2008, for indices of precipitation extremes

The regional trends in 1961–2008 was 0.03 mm/d/10 a. There were 59 % of stations performing an increasing trend, but only 11 % of stations had passed the significance test. Most station having an increasing SDII lied in Guizhou Plateau and Sichuan Basin and a few stations were situated in Xizang Plateau–Hengduan Mountain where the wet day precipitation increased by a large margin (Figs. 4.3 and 4.4). The related research hold an idea that the spatial pattern of PRCPTOT demonstrates that its increase occurred principally in higher altitude areas, and the same was true of SDII (You et al. 2008a, b), which was just opposite to the distributed character of them in Southwestern China. This special distributed regularity indicated that the increase of wet day precipitation in Xizang Plateau–-Hengduan Mountain was really not the result of the precipitation increase on wet days but the contribution of the increasing precipitation days or duration extension

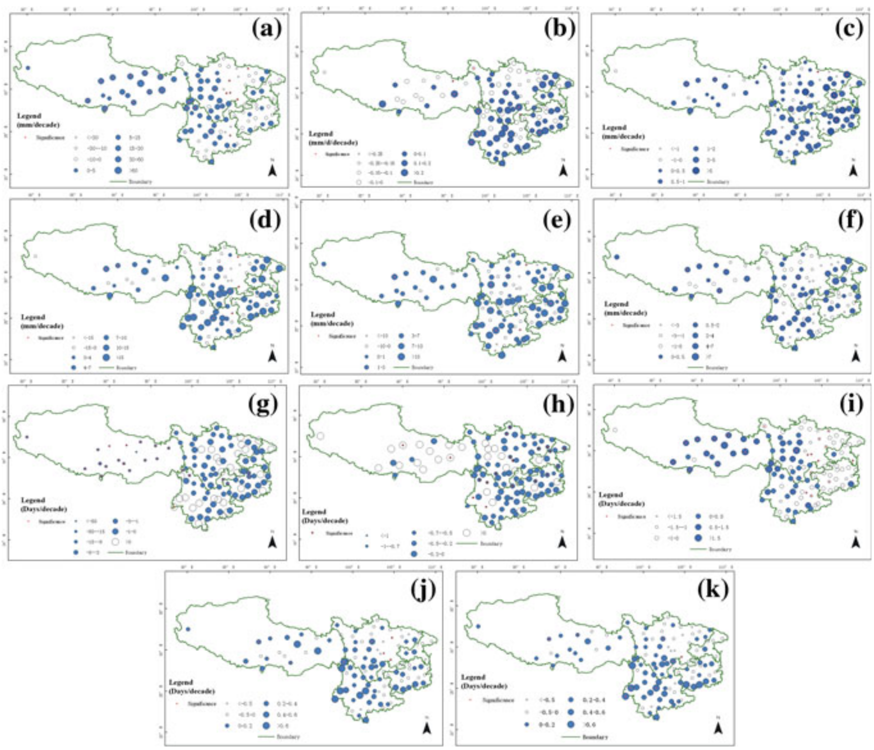

Fig. 4.4 Spatial distribution of trends per decade for PRCPTOT, SDII, RX1 day, R95, R99 and R5X day. **a** PRCPTOT. **b** SDII. **c** RX1 day. **d** R95. **e** R99. **f** RX5 day. **g** CDD. **h** CWD. **i** R10 mm. **j** R20 mm. **k** R25 mm

of precipitation every time. On the contrary, the precipitation intensity increased obviously in Guizhou Plateau, the most regions of Yunnan Plateau and the east of Sichuan Basin, but the less precipitation leaded to significant decrease of wet day precipitation. The spatial distribution of CWD also proved above feature.

The change trend of the maximum 1-day precipitation (RX1 day) and the maximum 5-day precipitation (RX5 day) is shown in Fig. 4.4, RX1 day continued to grow at a rate of about 0.05 mm/10 a during 1961–2008, and its regional trends had passed the significance test. There 64 % of the 110 stations exhibited the increasing trend, but only 11 % of stations passed the significance test. The stations with increasing or decreasing trend are evenly distributed in the studied area, but the magnitude of increase of stations located in the low altitude areas is relatively greater, which reflects that the extreme precipitation events has being increasing to some extent. The fluctuation of RX5 day was quite apparent. It had a weak decline in 1961–1975, and increased in 1976–1985. Then it showed a fluctuated change every 10 years. In general, RX5 day presented a slight increase and the magnitude is 0.03 mm/10 a (Fig. 4.3). Although approximately 55 % of stations had a rising trend, only 8 % of stations had passed the significance test, which were mainly distributed in Xizang Plateau, Hengduan Mountain, the east of Sichuan Basin and Yunnan Plateau. This distribution partially reflected the increase of rainfall days in the high altitude areas. The stations with a downward trend concentrated on the west of Sichuan Basin and Guizhou Plateau (Fig. 4.4).

The very wet day precipitation (R95) rose before 2000 in the studied area, and showed a falling trend. On the whole, R95 increased at the rate of 0.04 mm/d/10 a but failed to pass the significance test (Fig. 4.3). Approximately 63 % of the stations were on the rise but only 10 % of the stations passed the significance test, which were mainly distributed in Xizang Plateau, the south of Hengduan Mountain, Yunnan Plateau, Guizhou Plateau and the east of Sichuan Basin. While the stations with a decrease trend were primarily located in the north of Hengduan Mountain and the west of Sichuan Basin (Fig. 4.4). The variation of extremely wet day precipitation (R99) was similar to the very wet day precipitation (R95), but its increasing trend is more apparent. Overall, R99 increased at the rate of 0.05 mm/d/10 a and passed the significance test, which indicated the possibility of precipitation extremes events had been increasing year by year (Fig. 4.3). In terms of R99, although there were 67 % of the stations situated in low altitude areas and showing an increasing trend, only 8 % of stations had pass the significance test. Above analysis demonstrated that the significance level of change tendency in extreme precipitation index was relatively low in the studied area. But what need to be emphasized is that the precipitation increase in the high altitude area chiefly is a result of the increasing precipitation days or duration extension of precipitation every time. The numbers of precipitation and the rainy days had a remarkable increasing trend in the high areas and the rainfall intensity increased obviously in the low altitude.

The consecutive dry days (CDD) in studied area had a fluctuated decline change in other periods instead of a rising trend in 1990s. On the whole, CDD decreased at a rate of about 0.05 d/10 a (Fig. 4.3). There were 74 % of stations in the studied areas being on the decline, but only 28 % of stations passed the significance test. The stations with the significant falling trend are mainly located in Xizang Plateau, which proved the increase of rainy days. However, the stations showing a rising trend are mainly distributed in Yunnan Plateau and Sichuan Basin, which reflected the decrease of rainy days (Fig. 4.4). The consecutive wet days (CWD) in Southwestern China had a sharp decline in 1961–1961 followed by a slight increase. After 2000, it began to drastically reduce again. Generally, CWD showed a decreasing trend at a rate of 0.08 d/10 a and had passed the significance test (Fig. 4.3). CWD of about 76 % of the stations located in Guizhou Plateau and Sichuan Basin reduced in the studied area. Thereinto, 19 % of all station situated in Sichuan Basin had a remarkable decline. Furthermore, a number of station in Hengduan Mountain decreased apparently. However, the stations with a increasing trend were mainly distributed in Xizang Plateau and the central of Hengduan Mountain. This spatial distribution pattern confirmed again that the precipitation increase in the high altitude area was the result of the increase of rainy days. But the precipitation increase in the low altitude area was mainly caused by the decrease of rainy days and the increase of rainfall intensity (Fig. 4.4). Generally, CDD and CWD should had two approximate reverse changes, and only Xizang Plateau and the central of Hengduan Mountain showed the apparent opposite trend in Southwestern China. CDD and CWD in other regions exhibited a common decrease, which may be resulted in the seasonal structure of rainy day. From the analysis of Chap. 3, it could be found that the precipitation increase in winter monsoon period was quite apparent, which suggested that the increase of rainy days may be a reason of the decrease of CDD. While the reduction of CWD mainly is the result of the decrease of rainy days in summer monsoon period.

The number of heavy (R10 mm), heavier (R20 mm) and heaviest precipitation days (R25 mm) had a weak increasing trend with fluctuations (Fig. 4.3). More than half of the stations experienced an increase, but it was significant at a minority (Table 4.1). Spatially, Xizang Plateau and Hengduan Mountains stations displayed increasing trends for R10 mm (heavy precipitation days), and most of them had passed the significance test. According this point, it was confirmed that precipitation increase of the high altitude area was the result of the increase of rainy days. The stations having a decrease were distributed in Sichuan Basin and the central and east of Yunnan–Guizhou Plateau, and some station declined significantly (Fig. 4.4). For R20 mm and R25 mm, a number of stations in Xizang Plateau, Yunnan–Guizhou Plateau and Sichuan Basin displayed increasing trends, whereas there was a lot of stations exhibiting decrease trend in the north of Hengduan Mountain and Guizhou Plateau, and Sichuan Basin (Fig. 4.4). These results indicated that the increase of rainy days, especially R10 mm, is a main factor resulting in the precipitation increase in Xizang Plateau and Hengduan Mountain. R20 mm and R25 mm also presented a remarkable increase. Southwestern China is located in the transition zone between the first ladder and the second ladder and is the source region of numerous rivers. The landslide and debris flow also happen most frequently in this region. It is inevitable that the increase of rainy days will make the possibility of the outbreak of various geological disasters intensified, so it has an important practical significance to strengthen the monitoring, forecast and prevention research of meteorological disasters.

On the whole, the spatial and temporal variations of PRCPTOT, R10 mm, R20 mm and R25 mm indicate that the increase of rainy days in high altitude area is quite outstanding and it is an important contribution causing the precipitation increase. The variations of RX1 day, R95, R99, RX5 day and some suggest that although extreme precipitation events in the studied area has increased in recent years, the trend still failed to pass the significance test. The changes of CDD, SDII and CWD and others demonstrate that the primary character of extreme precipitation change in Southwestern China is that the rainy days at high altitude and the rainfall intensity at low altitude increase apparently, but their changing process and mechanism still need to verify by data recorded in long period.

4.2 Comparison Among Climate Extremes Indexes

4.2.1 The Consistency of Climate Extremes Indexes

As shown in Table 4.2, the first factor included almost all temperature extremes indexes except for DTR in the results of factor analysis, accounted for 52 % of the overall variance of the temperature data, and indicated the consistent and common warming trend of temperature extremes index. The above content could be proven by the significant correlation between indexes (Table 4.3). DTR, which reflects the relationship between maximum and minimum temperatures, dominated the second factor and accounted for 14 % of the overall variance of the temperature data. With the more obvious warming of maximum precipitation in recent years, the change of DTR had shifted from the leading factor of the maximum temperature warming to the common effect of both maximum and minimum temperature. Therefore, the difference between them decreased with the increase of the magnitude of maximum temperature rise (Fig. 4.1). TNx and ID dominated the third factor and accounted for 7 % of the overall variance of the temperature data, indicating the decline of ID was in relation to the rise of TNx. GSL dominated the fourth factor and accounted for 7 % of the overall variance of the temperature data. It was mainly affected by the change of coldest temperature. The relevance with ID, TN10, TNn and TX90 also confirmed the rise of minimum temperature was the main reason of the increase of growth days.

The results of factor analysis (Table 4.2) shows that all indexes dominated the first factor and accounted for 59 % of the overall variance of the temperature data, reflecting the consistency of the annual total precipitation and the changing trend of precipitation extremes and indicating that the contribution rate of precipitation extremes to annual precipitation increases gradually (Table 4.4). In addition, it also confirms the non-significance of the precipitation change trend in Southwestern China. R99 and RX1 day dominates the second factor and accounts for 59 % of the overall variance of the temperature data, indicating that RX1 day is the primary influencing factor of R99. The third factors accounts for 9 % of the overall variance of the temperature data and is dominated by CDD. CDD has a relativity with other indexes. Although it shows a decreasing trend, it presents a significantly regional difference. And its change is mainly decided by the seasonal structure of rainy days. CWD dominates the fourth factor and accounts for 8 % of the overall variance of the temperature data, because its change is mainly affected by the variation of rainy days in summer monsoon period. CDD and CWD are characterized by declining trend but for different causes, which reflects the complexity and particularity of regional precipitation change. This also can be shown in the weak correlation with other precipitation indexes (Table 4.4). There are remarkable correlations among PRCPTOT, R10 mm, R20 mm, R25 mm, R95, R99, between RX1 day and RX5 day. On the one hand, it is because the extreme precipitation events mainly occurred in summer monsoon period. On the other hand, it also reflects the increasing trend of extreme precipitation in the studied area (Table 4.4).

Table 4.2 Results of factor loadings perceptual explained variance in temperature and precipitation extremes

Temperature	Factors					Precipitation	Factors				
Index	1	2	3	4	5	Index	1	2	3	4	5
DTR	0.04	0.86	−0.43	0.2	0.02	Annual precipitation	0.89	−0.33	0.01	−0.06	0.21
FD	−0.88	0.36	0.08	−0.01	−0.04	CDD	−0.1	0.51	0.73	0.32	0.29
GSL	0.44	−0.39	−0.35	0.64	0.31	CWD	0.11	−0.48	−0.09	0.85	−0.13
ID	−0.67	−0.01	0.59	0.3	−0.03	Prcptot	0.91	−0.32	−0.03	−0.08	0.21
TN10	−0.81	0.3	−0.29	−0.02	0.31	R10	0.74	−0.57	0.1	−0.04	0.17
TN90	0.85	−0.01	0.32	0.17	−0.25	R20	0.87	−0.29	0.3	−0.07	−0.13
TNn	0.84	−0.3	−0.2	−0.08	0.18	Rnn	0.9	−0.12	0.26	−0.14	−0.16
TNx	0.69	0.12	0.56	−0.19	0.25	R95	0.9	0.28	−0.08	−0.01	−0.05
TX10	−0.79	−0.39	−0.04	−0.09	0.27	R99	0.76	0.51	−0.28	0.16	0.12
TX90	0.82	0.4	0.07	0.27	−0.07	RX1 day	0.79	0.48	−0.23	0.08	0.12
TXn	0.69	−0.02	−0.56	−0.35	−0.13	RX5 day	0.82	0.27	−0.3	0.12	−0.06
TXx	0.66	0.39	0.32	−0.17	0.45	SDII	0.75	0.32	0.32	−0.01	−0.38
Percentage of variance	52	14	13	7	5	Percentage of variance	59	16	9	8	4

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Table 4.3 The correlation coefficients of temperature extremes

	DTR	FD	GSL	ID	TN10	TN90	TNn	TNx	TX10	TX90	TXn	TXx
DTR	1.00											
FD	0.21	1.00										
GSL	−0.05	**−0.55**	1.00									
ID	−0.21	**0.62**	**−0.33**	1.00								
TN10	**0.34**	**0.78**	**−0.31**	**0.36**	1.00							
TN90	−0.09	**−0.70**	0.29	**−0.35**	**−0.81**	1.00						
TNn	−0.12	**−0.87**	**0.51**	**−0.65**	**−0.66**	**0.60**	1.00					
TNx	−0.13	**−0.51**	0.04	−0.24	**−0.58**	**0.70**	**0.48**	1.00				
TX10	**−0.35**	**0.56**	−0.19	**0.46**	**0.67**	**−0.69**	**−0.46**	**−0.50**	1.00			
TX90	**0.40**	**−0.55**	**0.31**	**−0.44**	**−0.55**	**0.84**	**0.55**	**0.60**	**−0.75**	1.00		
TXn	0.16	**−0.62**	0.27	**−0.84**	**−0.41**	**0.40**	**0.69**	0.20	**−0.50**	**0.44**	1.00	
TXx	0.17	**−0.44**	0.07	**−0.30**	**−0.41**	**0.48**	**0.45**	**0.75**	**−0.60**	**0.60**	0.28	1.00

Values for trends significant at the 5 % level are set in bold

Table 4.4 The correlation coefficients of precipitation extremes

Total precipitation		Prcp				RX1			RX5			
		CDD	CWD	tot	R10	R20	R25	r95p	r99	Day	Day	SDII
Precipitation	1.00											
CDD	−0.21	1.00										
CWD	0.18	−0.09	1.00									
Prcptot	**0.95**	−0.24	0.17	1.00								
R10	**0.87**	−0.26	0.29	**0.89**	1.00							
R20	**0.84**	−0.07	0.17	**0.85**	**0.79**	1.00						
R25	**0.80**	−0.04	0.05	**0.83**	**0.70**	**0.93**	1.00					
R95	**0.71**	−0.02	−0.02	**0.74**	**0.45**	**0.68**	**0.78**	1.00				
R99	**0.51**	0.06	−0.01	**0.55**	**0.26**	**0.41**	**0.51**	**0.84**	1.00			
RX1 day	**0.56**	0.05	−0.07	**0.59**	**0.34**	**0.46**	**0.56**	**0.81**	**0.93**	1.00		
RX5 day	**0.63**	−0.11	0.09	**0.63**	**0.41**	**0.56**	**0.63**	**0.82**	**0.79**	**0.82**	1.00	
SDII	**0.51**	0.19	−0.06	**0.49**	**0.41**	**0.66**	**0.72**	**0.73**	**0.60**	**0.66**	**0.59**	1.00

Values for trends significant at the 5 % level are set in bold

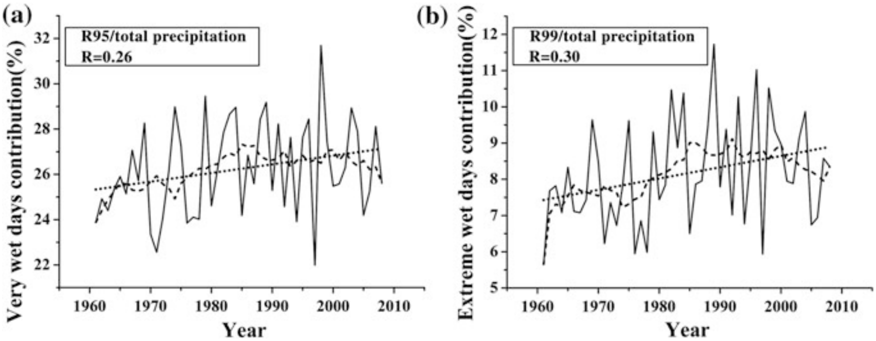

Fig. 4.5 Regional series for **a** the ratio of the index of precipitation on very wet days (R95) to total precipitation and **b** the ratio of the index of precipitation on extremely wet days (R99) to total precipitation

As shown in Fig. 4.5, in 1961–2008, the average contribution rate of very wet day precipitation (R95) to annual precipitation (0.38 %/10 a) in Southwestern China is 26 %. The minimum is 22 %, and the maximum is 32 % happening in 1998. On the whole, the ratio of R95 in annual precipitation continues to rise. The contribution rate of extremely wet day precipitation (R99) to annual precipitation increases at a rate of 0.31 %/10 a and passes the significance test. The average contribution rate was 8.2 % in 1961–2008, and the minimum and maximum were 5.7 and 11.7 %, respectively. The total contribution rate of R95 and R99 to annual precipitation was 34.2 %. The increasing trend of contribution rate suggested that the extreme precipitation events increased year by year in the studied area. The related researches also confirmed that 95 % of the net precipitation increase is mainly from R95 (You et al. 2010a, b, c, d). In terms of regional differences, the ratio of R95 in the annual total precipitation of Xizang Plateau–Hengduan Mountain, Yunnan–Guizhou Plateau and Sichuan Basin were 18, 26 and 31 %, respectively. The ratio of R99 were 5, 8 and 10 %. Obviously, R95 of Sichuan Basin make most contribution to the annual total precipitation, which reflects the significant increase of extreme precipitation events in the low altitude area.

4.2.2 The Regional Difference of Climate Extremes Indexes

As shown in Table 4.5, the averages of TX10, TN10, TN90 and TX90 in Xizang Plateau–Hengduan Mountain, Yunnan–Guizhou Plateau and Sichuan Basin were same for many years. From other indexes, it could be shown that the average of Xizang Plateau–Hengduan Mountain was maximum, Sichuan Basin followed and Yunnan–Guizhou Plateau is last one. The temperature extreme indexes of three subregions in 1961–2008 showed a clear warming trend. The temperature extreme of Xizang Plateau–Hengduan Mountain continued to warm, and the warming

Table 4.5 Trend per decade for regional indices of temperature and precipitation extremes in three sub-regions (°C or mm or d/10 a)

Index	XPHM		SB		YGP	
	Average	Regional trends	Average	Regional trends	Average	Regional trends
TX10	16.5	**−0.23**	16.5	−0.09	16.5	−0.08
TN10	16.3	**−0.44**	16.4	**−0.33**	16.3	**−0.35**
TXn	−2.1	**0.12**	2.6	0.12	5	**0.15**
TNn	−17.2	**0.3**	−3.5	**0.24**	−1.5	**0.33**
ID	21.1	**−0.15**	4.5	−0.09	1.2	−0.04
FD	165	**−0.34**	19.8	**−0.28**	11.4	**−0.26**
DTR	13.9	**−0.26**	7.6	0.01	9.5	**−0.29**
TN90	16.2	**0.45**	15.6	**0.25**	16.3	**0.36**
TX90	16.5	**0.28**	16.5	**0.22**	16.5	**0.15**
TXx	26.3	**0.16**	35.3	0.12	33.8	0.05
TNx	13	**0.27**	25.2	0.06	22.9	**0.18**
GSL	229.4	**0.24**	340	**0.2**	353.1	0.11
PRCPTOT	583.5	**0.2**	1,109.8	−0.09	1,143.1	−0.02
SDII	6.9	0	10.6	0.02	10.6	0.06
RX1 day	34.9	**0.07**	104.7	0.04	79.8	**0.05**
R95	120	**0.08**	358.9	−0.01	296	0.04
R99	33.5	**0.09**	117.4	0.04	93	**0.05**
RX5 day	73.0	0.05	166.4	0.06	135.4	0.006
CDD	92.7	−0.12	31.6	0	38.9	−0.05
CWD	8.9	0.018	7.1	**−0.15**	8.7	**−0.1**
R10 mm	18.5	**0.13**	29.2	**−0.13**	35.4	−0.06
R20 mm	3.2	**0.08**	14.3	**−0.09**	16.3	0.01
R25 mm	2.9	**0.08**	10.5	−0.06	11.8	0.05

Values for trends significant at the 5 % level are set in bold

magnitude was significantly greater than the other two areas. The regional trends of 12 indexes here all passed the significance level test, while there 8 and 6 indexes respectively in Yunnan–Guizhou Plateau and Sichuan Basin passed the significance level test. In terms of the absolute value of regional trends, Yunnan–Guizhou Plateau was slightly greater than Sichuan Basin. What the most apparent interannual variation is that the extreme temperature index had a slow rise or weak decline before the mid of 1980s and sharply warmed afterward. In addition, generally three sub-regions were characterized by that the warming range of coldness indexes and night indexes were greater than that of warmth indexes and daytime indexes. The difference of temperature extremes indexes between regions further confirmed that a wider margin of warming occured in the high altitude area.

In 1961–2008, the maximum average of PRCPTOT, SDII, CWD, R10 mm, R20 mm and R25 mm was in Yunnan–Guizhou Plateau, Sichuan Basin followed and the average of them in Xizang Plateau–Hengduan Mountain is minimum, which was consistent with the difference of annual total precipitation. RX1 day, RX5 day, R95 and R99 is greatest in Sichuan Basin, followed by Yunnan–Guizhou Plateau. The maximum CDD occurred in Xizang Plateau–Hengduan Mountain and Yunnan–Guizhou Plateau followed. It showed again that the precipitation extremes events mainly in low altitude area over the passed 50 years, especially in Sichuan Basin (Table 4.5). The precipitation extremes index in Xizang Plateau–Hengduan Mountain appeared an obvious increasing trend. Excepting the changing trend of RX5 day, SDII and CWD could not pass the significance test and the CDD was significantly reduced, other precipitation index were significantly increased. The significant increase of PRCPTOT also confirms the increase of rainfall in the area, the significant increase of other precipitation indexes showed that the increase of rainy days was a main factor resulting in the increase of regional precipitation. However, the non-significant change of RX5 day, SDII and CWD verified that the extreme precipitation events and precipitation intensity increased non-significantly. The significant reduction of R10 mm, R20 mm and CWD in Sichuan Basin revealed that the apparent feature of extreme precipitation variation and the main reason of total precipitation decrease in recent years was the reduction of rainy days which will certainly lead to the uneven distribution of rainy time and the increase of extreme precipitation events.

The regional trends of RX1 day, R99 and CWD in Yunnan-Guizhou Plateau had succeeded in the significance test, which revealed that the increase of extreme precipitation events and the rainfall intensity was apparent in this region was apparent, and indicated again that the increase of extreme precipitation in the studied area was mainly occurred in low altitude area. SDII identifying rainfall intensity kept a stable state in Xizang Pleteau–Hengduan Mountain, and showed a increasing trend in Yunnan–Guizhou Plateau and Sichuan Basin. Furthermore, CWD significantly reduced in latter two region, which affirmed precipitation intensity increased in low altitude area while rainy days reduced. All in all, the regional difference of extreme precipitation can be made a conclusion that the warming magnitude at high altitude area is greater than that of low altitude area; the significant increase appeared in rainy days at high altitude areas, and the rainy days reduced in low altitude but precipitation intensity increased; although the extreme precipitation events showed an increasing trend, but this trend just is significant in low elevation area.

4.2.3 The Comparison of Coldness and Warmth Indexes

In order to get more knowledge of changing in daily maximum temperature and daily minimum temperature, a comparison about the tendency of the extreme coldness and warmth index had been made in Table 4.6. In terms of warm day frequency (TX90) and cold day frequency (TX10), the regional trends of TX90 in about 83 % of the stations was 1.64 times greater than that of TX10. The regional

Table 4.6 Number and proportion of individual stations where the trend in one index is of greater magnitude than the trend in a second

Comparison	Basis	Qualified percentage of stations
TX90 > TX10	abs	83
TN90 > TN10	abs	48
TXx > TXn	rel	31
TNx > TNn	rel	12
TXx > TNx	rel	42
TXn > TNn	rel	18
TX90 > TN90	abs	21
TX90 > TN10	abs	24
TX10 > TN10	abs	5
TN90 > TX10	abs	95
ID > FD	abs	5

abs absolute value, *rel* real value

trends of warm night frequency (TN90) in about 48 % of the stations was wider than that of cold night frequency (TN10), but the absolute value of latter one was more than that of former one. The regional trends of coldest day temperature (TXn) was 0.021 °C more than that of warmest day temperature (TXx), and the former index was greater than latter index in about 69 % of stations. The regional trends of coldest night temperature (TNn) was 2.23 times more than that of coldest day temperature (TXn), and the former index was greater than latter index in about 82 % of stations. There were about 58 % of the stations where the regional trends of TXx was greater than that of TXn. There were 82 % of stations where the regional trends of TNn was greater than that of TXn. The regional trends of TN90 was 1.65 times greater than that of TX90 which existing in 79 % of stations. The regional trends of TNn was 2.85 times of TNx.

Above analysis indicates that the warming magnitude of coldness indexes (TN10, TXn, TNN) are significantly greater than part of warmth indexes (TN90, TXx, TNx). IPCC (2007) thinks that the main reason is the more warming magnitude of winter than summer. Its physical mechanism is the water vapor content in winter is less than in summer, so the radiation force of greenhouse gases strengthens in winter thus causing the much wider margin of warming (Aguilar et al. 2009). The warming magnitude of night indexes (TNx, TNn, TN10, TN90) is significantly greater than daytime indexes (TXx, TXn, TX90, TX10). The more obvious thing is that the stations with a warming trend in night indexes are distributed evenly. But only TX90 and TX10 in daytime indexes show similar characteristics, the rest indexes just increase remarkably in high altitude area. Numerous studies have confirmed the warming trend of extreme minimum temperature is greater than extreme maximum temperature, and the night indexes warm more sharply than daytime index (Easterling et al. 2000; Manton et al. 2001; Griffiths et al. 2005; Klein Tank et al. 2006; Vincent et al. 2005).

4.2.4 *The Comparison of This Study and Other Sources*

Although the climate extremes index in Southwestern China has a same trend to other regions in the world, there the apparent difference can be shown. As shown in Table 4.7, the research durations almost are in the latter 50 years of 20th century. It is found that the regional trends of temperature in the studied area is significantly lower than that of other areas probably caused by the different calculation methods in different areas or indicating the less warming magnitude in Southwestern China. Before, "Climate and Environmental Evolution in China" (Qin et al. 2005) reported that the magnitude of temperature changing in this region is least in China and the temperature of some regions showed a decrease trend. The most apparent thing is that the warming magnitudes of warmest and coldest day temperature as well as warmest and coldest night temperature are much less than that of other regions in the world. And the changing rate of ice days in Southwestern China is least and non-significant, but the decreasing magnitude of diurnal temperature range is much more than that of other regions in the world (excluding the central and east of Qinghai-Xizang Pleteau). The study of You et al. (2010a, b, c, d) on extreme temperatures in China indicates that the decreasing magnitudes of Northeastern China, Northern China and Northwestern China are remarkably more than the Southern China, which is caused by the wider warming magnitude of minimum temperature in Northern China (Zhai and Pan 2003). In addition, a number of studies also think that the urban heat island effect is a main contribution to the wider margin of decrease of diurnal temperature range (Griffiths et al. 2005; Jones et al. 2008; Ren et al. 2008). The meaning of comparison is not very important due to the complexity and regional difference of precipitation index variation as well as the significance of less magnitude of extreme precipitation index in the studied area. However, the most apparent thing is that the magnitude of extreme precipitation index is very small in the studied area. To sum up, for major regions in the world, the climate extremes indexes have a slight change.

4.3 Driving Mechanism for Climate Extremes

4.3.1 *The Correlation with Climate Extremes and Atmospheric Circulation*

The significant correlation with temperature change and sea level pressure in Southwestern China can be found from the analysis of last chapter. In order to further study the role of circulation variation in the change of climate extremes discussed above, this study draws the circulation composite figures at 500 and 300 hpa in spring, summer, autumn and winter between 1961–1985 and 1986–2008 by means of NCEP/NCAR reanalysis data, and selects 0°–70°N and 30°–170°E as the studied area through 1986–2008 minus 1961–1985 to get the circulation difference of both.

Table 4.7 Trends of temperature and precipitation extremes from this study and other sources (°C or mm or d/10 a)

Index	South western China	Eastern and central Tibetan Plateau	China	Global	Middle east	Central and southern Asia	Southern and west Africa	Central and northern south America	Western central Africa
	(1961–2008)	(1961–2005)	(1961–2005)	(1951–2003)	(1950–2003)	(1961–2000)	(1961–2000)	(1961–2003)	(1955–2006)
TN10	**−0.37**	**−2.38**	**−2.06**	**−1.26**	**−1.3**	**−5.7**	**−1.63**	**−2.4**	**−1.71**
TX10	**−0.13**	**−0.85**	−0.47	−0.62	−0.4	−2.6	1	**−2.2**	**−1.22**
TXn	**0.13**	**0.3**	**0.35**	0.37	0.2		**0.18**	**0.3**	**0.13**
TNn	**0.29**	**0.69**	**0.63**	**0.71**	**0.28**	**0.73**	**0.27**	**0.3**	**0.23**
ID	−0.09	**−2.46**							
FD	**−0.29**	**−4.32**	−3.73		−0.6				
DTR	**−0.18**	**−0.2**	−0.18	**−0.08**	**−0.12**	−0.12	−0.01	**0.1**	0
TX90	**0.22**	**1.26**	0.62	**0.89**	**0.66**	4.72	**2.24**	**2.5**	**2.87**
TN90	**0.36**	**1.58**	**1.75**	**1.58**	**1.2**	6.86	**2.35**	**1.7**	**3.24**
TXx	**0.11**	**0.28**	0.07	**0.21**	0.07	0.17	**0.16**	**0.3**	**0.25**
TNx	**0.17**	**0.25**	**0.21**	**0.3**	**0.23**		**0.19**	**0.2**	**0.21**
GSL	**0.12**	**4.25**	**3.04**						
PRCPTOT	0.03	6.66	3.21	**10.59**	−0.3	6.87	−0.05	8.7	**−31.13**
SDII	0.03	0.03	0.06	0.05	−0.006		**0.08**	**0.3**	0.06
RX1 day	**0.05**	0.27	1.37	**0.85**	**0**	1.02	0.05	**2.6**	−0.87
R95	0.04	1.28	**4.06**	**4.07**	−0.3	**6.46**	0.02	**18.1**	−12.19
R99	**0.05**	1.09							
RX5 day	0.03	−0.08	1.9	0.55	0	1.26	0.33	3.5	−1.54
CDD	−0.05	**−4.64**	−1.22	−0.55	−5		3.57	0.4	−0.06
CWD	**−0.08**	−0.07							
R10 mm	0.00	0.23							
R20 mm	0.00								
R25 mm	0.02								
Data sources	This study	You et al. (2008a)	You et al. (2010a)	Alexander et al. (2006)	Zhang et al. (2005a, b)	Klein Tank et al. (2006)	New et al. (2006)	Aguilar et al. (2005)	Aguilar et al.–

Values for trends significant at the 5 % level are set in bold

Table 4.8 Trend per decade for regional indices of temperature and precipitation extremes between 1961–1985 and 1986–2008 (°C or mm or d/10 a)

Temperature index	Regional trend	Regional trend	Precipitation index	Regional trend	Regional trend
TX10	0.2	**−0.49**	PRCPTOT	0.08	0.07
TN10	**−0.2**	**−0.53**	SDII	−0.01	**0.16**
TXn	−0.15	0.09	RX1 day	**0.08**	0.02
TNn	0.15	**0.22**	R95	**0.08**	0.01
ID	0.16	0.06	R99	**0.08**	−0.01
FD	−0.08	**−0.21**	RX5 day	**0.07**	0.003
DTR	**−0.39**	0.09	CDD	−0.03	0.01
TN90	0.09	**0.74**	CWD	**−0.19**	**−0.11**
TX90	**−0.2**	**0.73**	R10 mm	0.03	0.09
TXx	−0.11	0.19	R20 mm	0.05	0.08
TNx	0.07	**0.25**	R25 mm	0.06	0.08
GSL	−0.06	0.04			

Values for trends significant at the 5 % level are set in bold

The main reasons of selecting 1985 as the separation are as follows: (1) As shown in Table 4.8, the warming magnitudes of all the extreme temperature index in 1986–1986 are greater than in 1961–1985; TX10, TXn, TX90, TXx and GSL show the cooling trends, but warm significantly in 1986–2008; there are eight index changes in 1986–2008 passing the significance level test instead of three indexes in 1961–1985. (2) In terms of precipitation indexes, there are five index changes passing the significance test in 1961–1985 but only two indexes in 1986–2008; From 1961–1985 to 1985–2008, the increasing magnitude of PRCPTOT, RX1 day, RX5 day, R95, R99, R10 mm, R20 mm and R25 mm declined significantly, and the magnitude of SDII and CDD turned increase from decrease.

As shown in Fig. 4.6, the maximum difference of geopotential height at 500 hpa in summer between 1961–1985 and 1985–2008 occurred in surrounding 45°N and 100°E. The former period is nearly 40 gpm higher than the latter one. It confirms that the powerful anticyclone circulation develops in Eurasia and the center is located in Mongolia and Lake Baikal. In addition, there is a cyclonic circulation developing in the west Pacific Ocean near Japan and its center is 35°N and 155°E.

Under the control of high pressure system, most areas in China are affected by the dry and warm air, and the studied area also is controlled by dry and hot northerly winds. But the northerly winds hinders the northward moving of sea warm air current and causes the warm and dry circulation, which will cause the apparent temperature rise. Above circulation background suggests that the Asian monsoon system strength weakened in 1986–2008 and caused the precipitation decrease in the studied area, compared with 1961–1985. This kind of circulation pattern is similar to 300 hpa isobaric surface (Fig. 4.7).

Therefore, the northerly winds in Southwestern China blocks the northward moving of the oceans warm air current, leads to the sharp rise of temperatures in

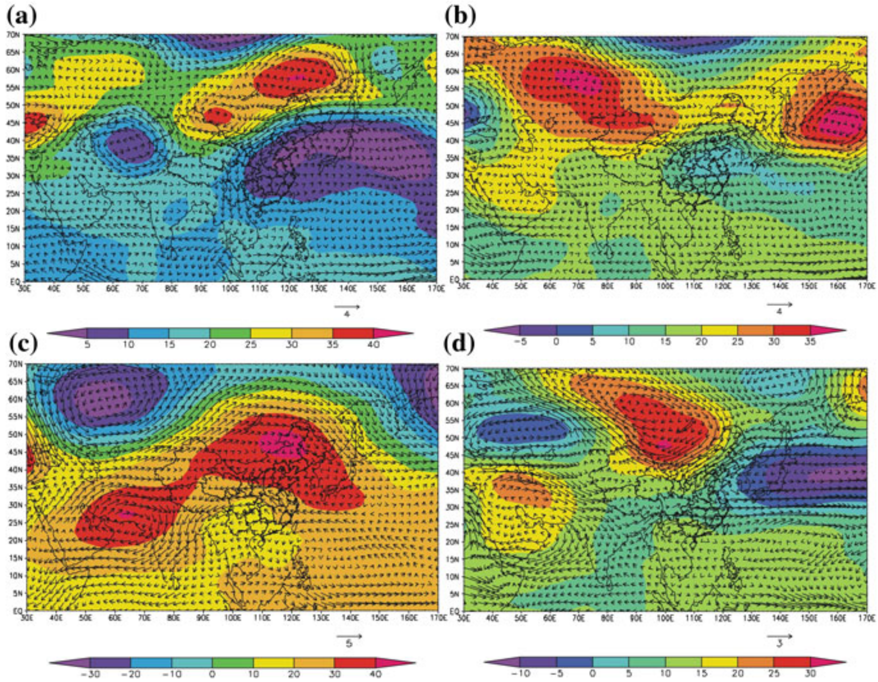

Fig. 4.6 Difference of wind speed and geopotential height at 500 hPa in summer (**a**), autumn (**b**), winter (**c**) and spring (**d**) between 1986–2008 and 1961–1985. Reprinted from the Lancet: Li et al. (2012a). Copyright (2012), with permission from Elsevier

summer and causes the decreasing frequency of precipitation. The study of Zhang et al. (2008a, b, c) also confirmed that the strengthening of geopotential height in Mongolia in summer is the key reason of the rapid warming in China, and the circulation field developed because of above reason will be inclined to block the northward moving of any oceans air current. An anticyclone system is developed in Eurasia in autumn and centered as Western Mongolia and Northwestern China, which is similar to summer. But the influenced range of anticyclone center in autumn is much wider than in summer, even Southwestern China is within the scope of the direct effect (Figs. 4.6 and 4.7). Under the background of this circulation, the studied area is controlled by hot and dry air mass and northerly winds prevails here. The circulation patterns also confirms that the weakening of the Asian monsoon system. The strengthening northerly winds blocks the ocean air mass resulting in the influence of hot and dry air on the studied area, which will lead to the significant increase of scorching weather and the decrease of rainfall. In winter of Eurasian, an anticyclone system develops in Mongolia and Lake Baikal region, at the same time, a abnormal cyclone system form in 500°N and 50°E. Their difference (−25 gpm) in geopotential height of centers also shows above conclusion. This circulation pattern reflects the increase of intensity of westerly winds

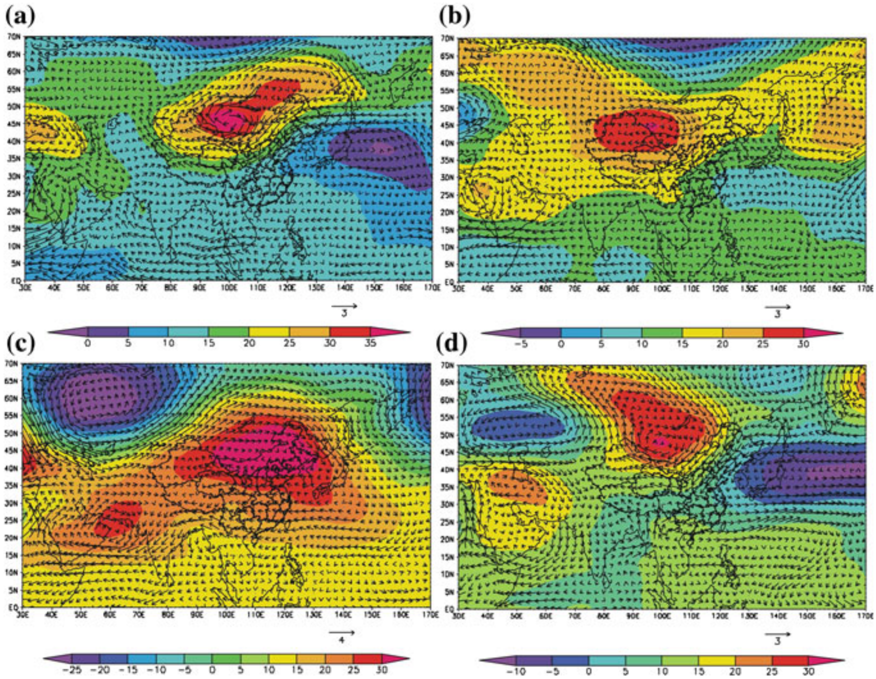

Fig. 4.7 Difference of wind speed and geopotential height at 300 hPa in summer (**a**), autumn (**b**), winter (**c**) and spring (**d**) between 1986–2008 and 1961–1985. Reprinted from The Lancet: Li et al. (2012a). Copyright (2012), with permission from Elsevier

from 1961–1985 to 1986–2008 (Figs. 4.6 and 4.7). Under the background of this, the southwest wind prevail in Northwestern China and the north of it, and Southwestern China is mainly controlled by the southwestly warm and wet air mass. This wind field structure will weaken the strength of the winter monsoon, what is worse, it will reduce the invading toward south of winter monsoon and cold air. In addition, this pattern will lead to a drop in extreme cold events in winter and temperatures rise, which partly explains the significant warming in winter. In the spring, a same circulation pattern to winter is shown, but its intensity and influenced scope of anticyclone and cyclone significantly reduce, compared with winter. It indicates that the strengthening of west wind and the formation of the east and southeast wind in winter monsoon creates a good circulation background.

Figure 4.8 demonstrates the difference of annual mean water vapor flux (a, b) and longitudinal wind speed (c, d) between 1986–2008 and 1961–1985. The most obvious information in this figure is that the water vapor flux of the major regions in Southwestern China kept stable except that of eastern Xizang Plateau and the northern Hengduan Mountain had a slight increase from former period to latter period. More importantly, the longitudinal wind speed of two isobaric surfaces exhibited apparent decline trend (Fig. 4.8). These two characteristics reflect the

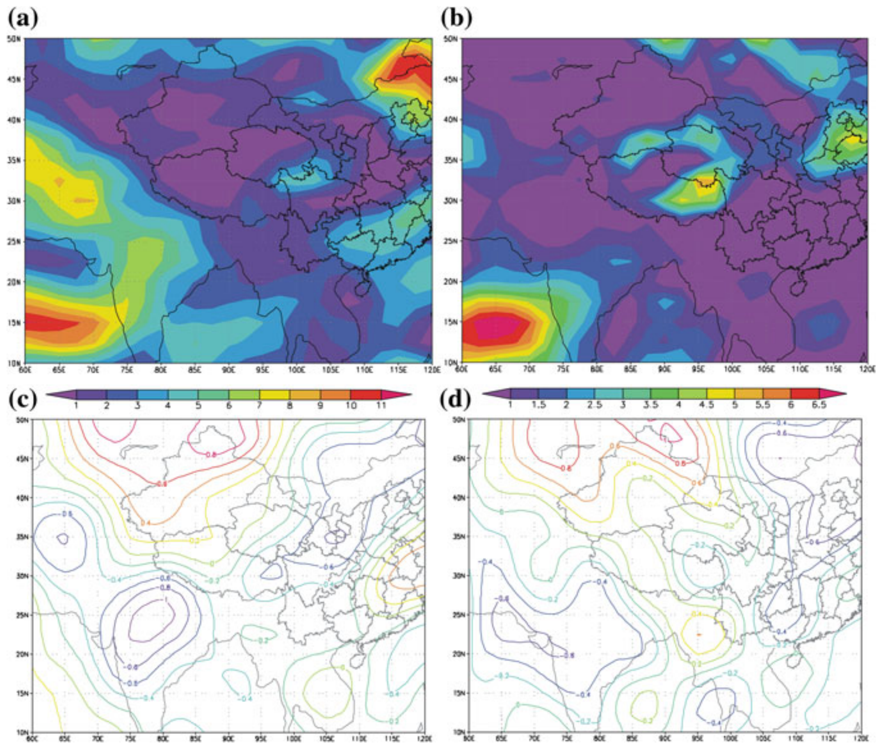

Fig. 4.8 Difference of annual mean water vapor flux (**a**, **b**) and longitudinal wind speed (**c**, **d**) between 1986–2008 and 1961–1985 (a and c is at 500 hPa; b and d is at 300 hPa). Reprinted from the Lancet: Li et al. (2012a). Copyright (2012), with permission from Elsevier

weakening of monsoon circulation and water vapor transport in recent years. According to Asian monsoon index calculated by Guo et al. (2003), it was found that the east Asian monsoon had drastically reduced since 1961, south Asian monsoon also had a fluctuated change characterized by strength reducing, (Fig. 4.9) which proved that the weakening of the Asian monsoon system once again. Wang (2001) thought that the weakened monsoon circulation system since the 1970s brought more precipitation for Southern China but weakened the water vapor transport toward north.

The studies of Dash et al. (2008) and Wu (2005) also confirmed that Indian monsoon system reduced in nearly decades and became more and more unstable. The researches of Ding et al. (2005), Gong and Wang (2000) and Xu et al. (2006a, b) also hold the idea that the weakened Asian monsoon system resulted in more extreme precipitation events in China and triggered floods in the south of China. The weakening of the monsoon circulation and water vapor transport had produced important influences on the change of extreme precipitation in Southwestern China, but its impact mechanism still needs more follow-up studies to identify.

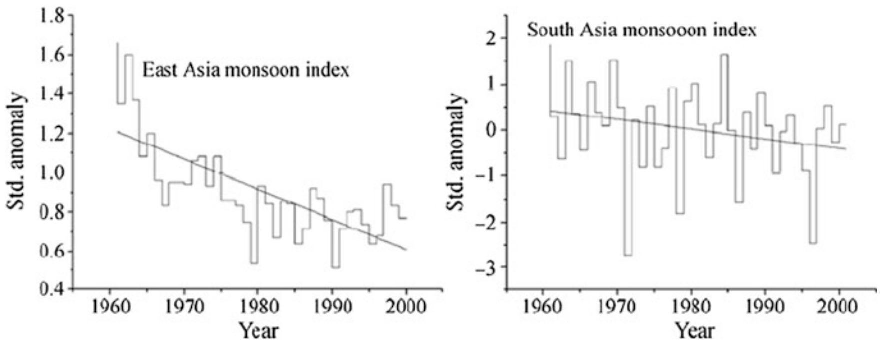

Fig. 4.9 Change of Eastern Asia monsoon index and Southern Asia monsoon index during 1961–2001

4.3.2 The Correlation with Climate Extremes and Elevation

A good statistical relationship between extreme temperature index and elevation in Southwestern China existed. The correlation coefficient of DTR, FD, ID, TN10 and TX10 and elevation had pass the significance test of 0.05, and the value (P) of FD, ID, TN10 and TX10 less than 0.0001, that is $P < 0.0001$. The five indexes showing decreasing trend all had a negative correlation with elevation, which reflect the regional trend increased with the rise of elevation. The warming magnitude of GSL, TN90, TNn and TNx showed a increasing trend along with the rise of elevation, but the magnitude of TXn, TX90 and TXx had not passed the significance test. All in all, the warming magnitude of the studied area in 1961–2008 became greater with the rise of elevation. In terms of the obvious degree of elevation, the coldness indexes (TN10, TX10 and TNn) is greater than the warmth indexes (TN90, TX90 and TNx) and night index (TNn, TNx, TN10 and TN90) is greater than the daytime index (TXn, TXx, TX90 and TX10). In addition, only the statistical relationship of TX10 with the altitude passed the significance test. As shown in Table 4.9, in terms of five indexes performing decline trend, the maximum warming magnitude of ID, TX10, TN10 and DTR occurred in 4,500–5,000 m of elevation, and only that of FD appeared in 2,000–2,500 m of elevation, reflecting the significant warming of high altitude areas. The maximum warming magnitude of GSL, TN90 and TNx occurred at 3,500–4,000 m, and that of TXn, TX90 and TXx respectively happened in 4,500–5,000, 3,500–4,000 and 3,000–3,500 m of elevation. The maximum warming magnitude of all coldness indexes occurred at 4,500–5,000 m except for FD, while that of the three warmth indexes appeared at 3,500–4,000 m. These features the wider warming magnitude of high altitude areas compared with low altitude areas (Figs. 4.10 and 4.11).

In terms of extreme precipitation index, the regional trends of only PRCPTOT, CWD and R10 mm showed a increasing trend with the rise of elevation, reflecting the increase of wet day precipitation and rainy days in the high altitude area. While the negative correlation of CDD with elevation indicated that the decrease of consecutive

Table 4.9 Mean trends per decade of temperature extremes in categorized elevation ranks (°C or d/10 a)

Altitude (m)	Stations	id	fd	gsl	txx	txn	tnx	tnn	tx10	tx90	tn10	tn90	dtr
0–500	18	0.00	−0.84	1.20	0.07	0.14	0.03	0.34	−0.21	1.00	−1.79	1.44	−0.06
500–1,000	16	−0.04	−2.12	2.35	0.15	0.2	0.14	0.47	−0.55	1.92	−2.62	3.04	−0.1
1,000–1,500	17	−0.18	−1.29	1.82	0.05	0.31	0.09	0.44	−0.48	1.17	−2.54	2.95	−0.11
1,500–2,000	17	−0.08	−3.25	1.13	0.04	0.22	0.1	0.47	−0.25	2.11	−3.08	3.55	−0.18
2,000–2,500	8	−0.29	**−6.80**	**5.44**	0.15	0.16	0.24	0.56	−0.72	2.31	−3.14	3.53	−0.15
2,500–3,000	10	−0.24	−4.52	4.73	0.18	0.29	0.18	0.56	−0.72	1.43	−3.44	3.18	−0.16
3,000–3,500	8	−1.13	−4.34	4.21	**0.24**	0.28	0.21	0.64	−1.11	2.27	−4.19	3.86	−0.18
3,500–4,000	8	−0.84	−4.71	6.36	0.21	0.19	**0.30**	0.71	−1.95	**2.59**	−4.69	**4.87**	−0.22
4,000–4,500	7	−2.68	−3.97	3.24	0.19	0.15	0.23	0.75	−1.88	2.29	−4.62	3.69	−0.21
4,500–5,000	3	**−4.97**	−5.80	3.04	0.18	**0.58**	0.24	**1.43**	**−2.22**	2.16	−5.64	4.78	**−0.40**

Values for the highest trends in categorized elevation ranks are set in bold

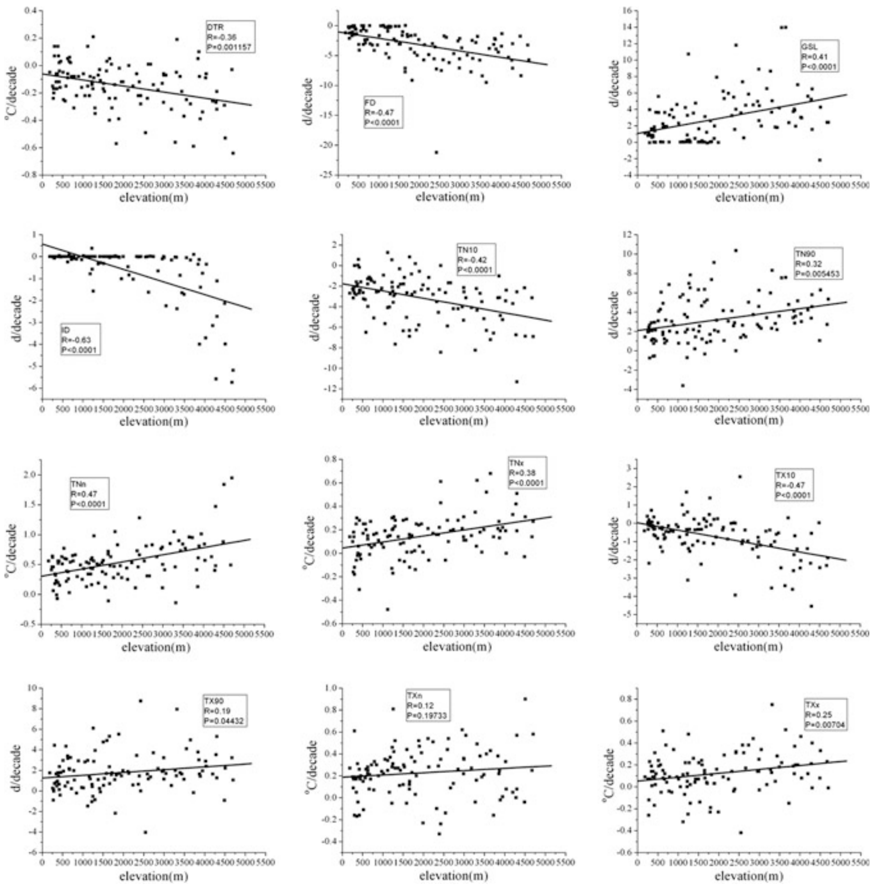

Fig. 4.10 Trend magnitudes of temperature extremes versus elevation. Reprinted from the Lancet: Li et al. (2012b). Copyright (2012), with permission from Elsevier

dry days mainly occurred in high altitude areas. The rest of the extreme precipitation index had more sharp change with the rise of elevation except for SDII and RX1 day, reflecting the increase of rainfall with altitude rising. The maximum declining magnitude of CDD appeared at 3,000–3,500 m, and the regional trends of R99, RX1 day and SDII occurred at an altitude of 3,000–3,500, 3,000–3,500 and 3,500–4,000 m, respectively. In addition, these three indexes all increased with altitude rising, reflecting the increase of CWD and PRCPTOT in high altitude area was the result of R10 mm increasing. The maximum increasing magnitude of SDII is in high altitude area, whereas the minimum occurred at an altitude of 1,000–1,500 m, suggesting again that the strengthening of precipitation intensity and extreme precipitation events resulted from above the mainly appeared in low altitude area (Table 4.10).

In terms of R95, R99 and RX5 day, the maximum increasing magnitude occurred at above 4,500 m, and the minimum occurred at 3,000–3,500 m. The maximum

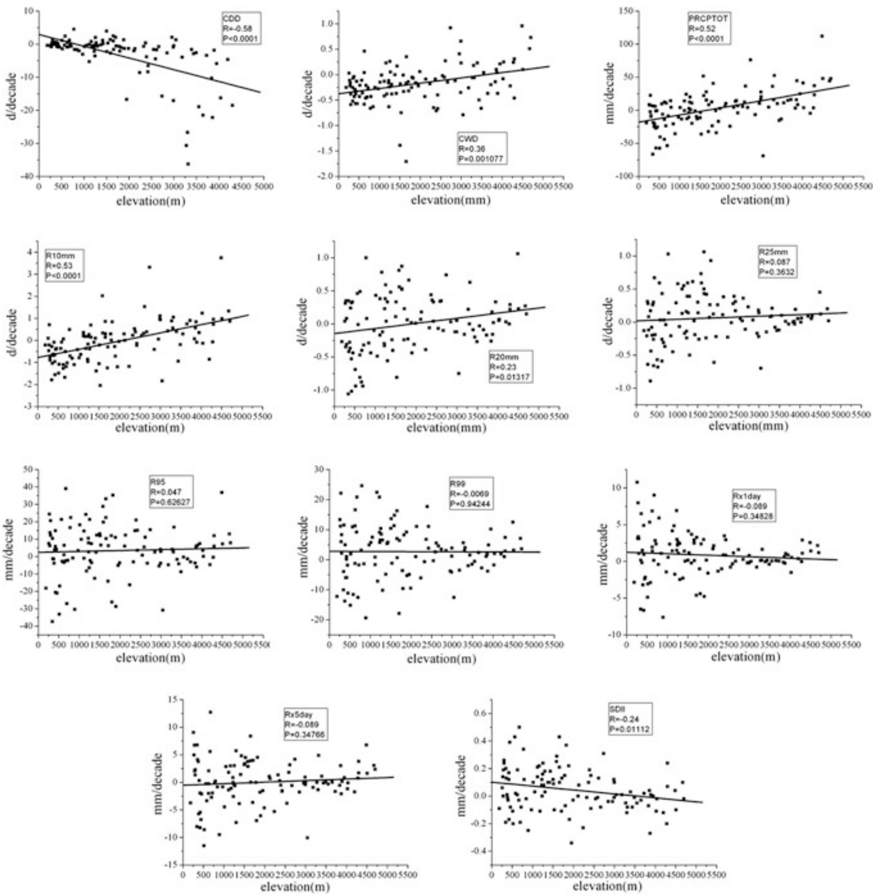

Fig. 4.11 Trend magnitudes of precipitation extremes versus elevation. Reprinted from the Lancet: Li et al. (2012b). Copyright (2012), with permission from Elsevier

increasing magnitude of R20 mm occurred at an altitude of 4,000–4,500 m, while the minimum was at low elevation area. On the whole, the significant increasing trend of eight indexes appeared in above 3,000 m, reflecting that the increase of rainy days mainly happened in high altitude area. While the increase of RX1 day, SDII, R95 and R99 in low altitude area proved that the extreme precipitation increase characterized by the strengthening of precipitation intensity mainly happened in the area. The increasing trend of RX1 day, RX5 day, SDII, R20 mm, R25 mm, R95, and R99 primarily concentrated in elevation of 1,000–3,000 m, maybe reflecting the apparent trend of extreme precipitation events increasing in this area.

As shown in Table 4.11, due to the high freedom of air, the warming magnitude of flat station is maximum, followed in turn by intermontane station, valley station and summit station. The assessment of Pepin and Seidel (2005) on the impact of

Table 4.10 Mean trends per decade of precipitation extremes in categorized elevation ranks (mm or d/10 a)

Altitude (m)	Stations	cdd	rx1 day	rx5 day	sdii	r10 mm	r20 mm	R25 mm	cwd	r95p	r99p	prcptot
0–500	18	−0.02	1.08	−0.03	0.07	−0.57	−0.17	−0.10	−0.29	1.1	0.87	−12.75
500–1,000	16	−0.14	1.03	−1.33	0.04	−0.77	−0.27	−0.06	−0.3	−0.57	2.52	−16.42
1,000–1,500	17	−0.63	**1.65**	0.11	**0.11**	−0.21	0.06	0.16	−0.15	5.72	5.38	0.30
1,500–2,000	17	−1.05	0.40	0.81	0.09	−0.14	0.16	**0.26**	−0.32	7.80	2.71	2.23
2,000–2,500	8	−3.87	1.20	−0.71	0.02	−0.01	0.12	0.18	−0.4	6.68	5.58	3.45
2,500–3,000	10	−4.32	0.21	0.33	0.05	0.84	0.12	0.05	0.18	2.91	1.61	20.26
3,000–3,500	8	**−12.91**	**0.10**	−0.81	−0.04	0.05	−0.08	−0.10	−0.24	−3.31	−0.67	2.76
3,500–4,000	8	−10.50	0.30	−0.07	−0.04	0.46	−0.02	0.04	−0.09	0.65	1.65	17.43
4,000–4,500	7	−5.63	0.85	1.44	−0.01	0.80	0.25	0.12	0.14	7.62	3.70	30.90
4,500–5,000	3	9.44	1.58	**2.35**	−0.01	**1.06**	0.22	0.11	**0.45**	**9.36**	**4.63**	46.70

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Values for the highest trends in categorized elevation ranks are set in bold

Table 4.11 Mean trends per decade of climate extremes in differing topographical types (°C or mm or d/10 a)

Temperature extremes	Number	tn10	tx10	txn	tnn	fd	id	tn90	tnx	tx90	txx	dtr	gsl
Summit station	2	−2.85	−1.11	**0.46**	0.46	−2.95	−0.01	2.41	0.11	1.42	0.16	−0.07	3.21
Intermontane station	35	−3.53	−0.82	0.24	0.63	−3.77	**−1.05**	3.18	0.12	1.48	0.08	−0.19	3.21
Flat station	39	**−3.93**	−0.99	0.27	**0.75**	**−4.06**	−0.66	**3.82**	**0.21**	1.84	**0.18**	**−0.24**	**3.84**
Valley station	35	−3.42	**−1.31**	0.19	0.44	−3.22	−0.91	3.79	0.19	**2.33**	0.15	−0.09	2.94
Precipitation extremes	Number	cdd	cwd	prcptot	r10 mm	r20 mm	R25 mm	r95	r99	rx1 day	rx5 day	sdii	
Summit station	2	0.45	**−0.28**	**−24.23**	**−0.45**	**−0.35**	**−0.28**	**−13.96**	**−4.34**	0.39	**−5.06**	0.06	
Intermontane station	35	−9.75	−0.07	8.64	0.07	0.07	0.15	5.29	2.52	0.46	−0.25	0.05	
Flat station	39	**−12.18**	−0.2	−1.07	−0.24	−0.09	−0.03	−1.24	1.74	0.67	−0.45	**−0.03**	
Valley station	35	−10.93	−0.11	16.83	0.46	0.16	0.14	8.52	4.62	0.95	1.43	0.08	

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Values for the highest trends in differing topographical types are set in bold

terrain types to temperature change also confirmed the more warming magnitude of summit station compared with other stations. In terms of precipitation index, the summit station showed a apparent decrease trend and the magnitude was much greater, the next one is flat station, major of which was on the decline. Excepting for the two of valley stations and three of intermontane stations, the rest of stations had a rising trend. But the increasing trend is remarkable greater, especially wet day precipitation (PRCPTOT), heavier precipitation days (R20 mm), very wet day precipitation (R95) and the maximum 5-day precipitation (RX5 day). This pattern indicated that the apparent influence of terrain to precipitation change, reflected the increase of extreme precipitation events was mainly occurred in valley station and demonstrated that the significant effect of orographic rainfall to regional precipitation. Therefore, it has a very important meaning to strengthen the monitoring research of the extreme precipitation events in valley in Southwestern China for the prevention and control of regional meteorological and its related geological disaster.

4.3.3 The Comparison of Temperature Extremes Between Urban and Rural Station

As shown in Table 4.2, for the TX10, TN10, FD and DTR showing decrease trend, the magnitude of rural station was greater than the urban station, but the urban station in percentage of stations showing significant decrease trend was greater than rural station. Except for TN90 and TNx, the extreme temperature index changes of urban stations is greater than the rural station. There are some number of stations having a significant warming trend in TN90 and TX90 of warmth indexes between urban and rural station, but the TNx and TXx of rural station is more greater. In addition, the stations showing a significant warming in GSL, TNn and TXn in rural stations are more than urban stations. The percentage of stations of coldness index (TN10, FD, TXn and TNn) in urban station showing remarkable warming are more than the rural station. And the stations where the three warmth indexes (GSL, TNx and TXx) performs apparent warming trend in rural station are more. The stations where the three night indexes (TNn and TN10) performs apparent warming trend in urban station are more. While he stations where the three daytime indexes (TXx and TX10) performs apparent warming trend in urban station are more (Table 4.12). The main reasons of this differences are the cold index events generally appear in the winter when the urban heat island effect is the most obvious; the warmth index events occur in the summer and the warming magnitude of rural stations at high altitude in summer is greater than the urban stations at low altitude. The result of above comparison indicates the regional trends of urban station is greater than the rural station in the studied area. If this difference is caused by the urban heat island effect, the influence is mainly reflected on the minimum temperature, which is consistent with the research result of Griffiths et al. (2005) on Asia–Pacific region.

Table 4.12 Trend per decade of urban (N = 58) and rural stations (N = 53), percentage of stations with significant warming trend and the contribution from UBI on the regional trends of urban stations for temperature extremes (°C or d/10 a)

Index	Urban station				Rural station				
	D (%)	SD (%)	SI (%)	Regional trends	Contribution rate (%)	D (%)	SD (%)	SI (%)	Regional trends
TX10	74	12	5	−0.15	26	85	47	2	−0.11
TN10	93	88	0	−0.40	30	96	85	0	−0.39
TXn	14	0	24	0.14	27	17	0	17	0.10
TNn	2	0	78	0.33	10	6	0	68	0.30
FD	98	83	2	−0.35	18	98	75	2	−0.29
DTR	81	62	5	−0.22	15	83	53	6	−0.19
TN90	7	2	83	0.36		6	0	83	0.38
TX90	14	5	55	0.26	27	11	2	55	0.19
TXx	24	3	10	0.14	16	13	2	34	0.11
TNx	22	3	50	0.20		17	0	62	0.21
GSL	3	0	24	0.22	14	6	0	53	0.19

D percentage of stations with decrease trend, *SD* percentage of stations with significant decrease trend, *SI* percentage of stations with significant increase trend
Systematical researches

Generally, the difference of temperature changes between urban and rural station is defined as the contribution of the urban heat island to temperature rising of city area (Jones et al. 2008; Ren et al. 2008). If based on this, the average contributions of the urban heat island in the studied area to cold index (TX10, TN10, TXn, TNn and FD) warm index (TNx, TNn, TN90 and TX90) were respectively 16.0 and 7.9 % in 1961–2008, and the contribution to daytime index was higher than night index. Obviously, it also had a greater contribution to cold index. The further analysis found that the urban heat island made the regional trend of diurnal temperature range (DTR) increased 0.16 °C in 1961–2008 and caused that warmest day temperature (TXx), coldest day temperature (TXn) and coldest night temperature (TNn) rised 0.11, 0.18 and 0.15 °C, respectively from 1961 to 2008. The sequence of contribution rate of urban heat island to extreme temperature indexes is TXn > TX90 = TXn > TX10 > FD > TXx > DTR > GSL > TNn. After comparison with the existing research result (Kim and Baik 2002; Choi et al. 2003; Jones et al. 2008; Ren et al. 2008) of some regions in the world, it is found that the urban heat island has a little contribution to the warming of urban stations in Southwestern China. The main reasons are: (1) a low level of urbanization in the studied area. There are only three cities where the population is more than one million; (2) the big altitude difference of terrain in the studied area and the greater warming magnitude of high altitude area. It indicates that the higher warming of urban stations may confirm the greater contributions of the urban heat island. However, the above analysis is just a simple comparison about warming magnitude between urban and rural stations based on target population. So its result has a big limitation. The specific impact of urbanization process to extreme temperature changes are still subject to follow-up.

4.4 Summary

This chapter analyzed detailedly the spatial and temporal variations and influencing factors of 12 temperature extremes indexes and 11 precipitation extremes indexes among 110 station in Southwestern China. The results are as following:

(1) The temperature extreme index warms significantly in studied area. Mean TX10, TN10, TXn, TNn, FD, DTR, TN90, TX90, TXx, TNx and GSL all in Southwestern China showed a statistically significant warming in 1961–2008 except for ID, and all indexes accelerated to warm agter the mid of 1980s. The warming magnitudes of coldness and night index are significantly greater than warmth and daytime index. The regional trends of studied area is apparently less than that of other regions in the world. The percentage of stations of TX10, TN10, TXn, TNn, ID, FD, DTR, TN90, TX90, TXx, TNx and GSL performing significant warming trend in 1961–2008 are 36, 91, 24, 77, 27, 81, 50, 88, 62, 88, 67 and 38 %. On the whole, the stations with extreme temperature index significantly warming are mainly distributed in Xizang Plateau and Hengduan Mountain, and the stations with non-significant warming trend or decreasing trend are located in Yunnan–Guizhou Plateau and Sichuan Basin. The warming magnitude of extreme temperature index also increases with the rise of altitude. In terms of the influence of terrain, the magnitude of flat stations is the maximum followed by intermontane station, valley stations and summit station in turn.

(2) The significance level of precipitation extremes index is quite low. There the changing trend of only the maximum 1-day precipitation (RX1 day), consecutive wet days (CWD) and extremely wet day precipitation (R99) have passed the significance test. The percentage of stations of PRCPTOT in 1961–2008, SDII, RX1 day, R95, R99, RX5 day, R10 mm, R20 mm and R25 mm with significant increasing trend are 25, 11, 10, 10 , 8, 8, 15, 8 and 12 %, respectively. The percentage of stations of CDD and CWD performing significant reduction are 8 and 19 %. The changes of RX1 day, R95, R99, RX5 day and others reflects that though the extreme precipitation events increased in recent years, this trend failed to pass the significance test. The spatial distribution of extreme precipitation index reveals that the significant increase of rainy days at high altitude and the strengthening of rainfall intensity year by year. From 1961 to 2008, the average contribution of the precipitation extremes in the studied area (R95 and R99) to annual precipitation is 34.2 % and keep rising trend, suggesting that the extreme precipitation has a more and more contribution to the annual precipitation. The highest frequency of precipitation events occurs in Sichuan Basin, and the contribution rate of extreme precipitation reaches to 41 % of to annual precipitation. The major extreme precipitation indexes in flat and summit stations have a downtrend, while the major indexes in valley and intermontane stations are on the rise.

(3) The large-scale atmospheric circulation is the main cause of the change of the climate extremes events. In summer and autumn, a anticyclonic circulation

develops in Eurasia and is centered by western Mongolia and Northwestern China, indicating the weakening of Asian monsoon system from 1961–1985 to 1986–2008. Because of this, the studied area is controlled by dry and hot air mass, and the northly wind binders the moving of ocean warm air current toward north resulting in a wider margin of warming and decreasing frequency of precipitation. In the winter and spring of Eurasia, an anticyclone system and an abnormal cyclone system develop simultaneously and are centered by Mongolia and Lake Baikal area, reflecting the strengthening of west wind intensity from 1961–1985 to 1986–2008. In the context of this, a southwest wind forms in Northwestern China and the north of it. This wind field pattern reduces the invasion of winter monsoon and cold air toward south and eventually lead to the decrease of extreme cold events and temperature rise. From 1961–1985 to 1986–2008, except for the eastern Xizang Plateau and the northern Hengduan Mountain with water vapor slightly increasing, the rest regions basically keep stable. More importantly, the apparent weakening of meridional wind from former period to latter period confirms weakening monsoon circulation and water vapor transport in recent years, and partly explains the non-significant change of precipitation extremes in the studied area.

(4) The contribution of urban heat island effect to the warming magnitude of temperature extremes index cannot be ignored. The urban stations in regional trend of temperature extremes index and percentage of stations with significant warming trend are more than the rural stations. The preliminary analysis found that the mean contribution rate of urban heat island to the warming magnitude of coldness index (TX10, TN10, TXn, TNn and FD) and warmth index (TNx, TNn, TN90 and TX90) of urban stations are 16.0 and 7.9 %, respectively. Its contribution to night index also more than that of daytime index. Urban heat island causes the regional trend of diurnal temperature range (DTR) increased 0.16 °C in 1961–2008 and the warmest day temperature (TXx), coldest day temperature (TXn) and coldest night temperature (TNn) rised 0.11, 0.18 and 0.15 °C, respectively. The sequence of contribution rate of urban heat island to extreme temperature indexes in the studies area is TXn > TX90 = TXn > TX10 > FD > TXx > DTR > GSL > TNn.

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Chapter 5
Spatial and Temporal Variation of Sunshine Hours in Southwestern China

5.1 Temporal Variation of Sunshine Hours

5.1.1 Mean Sunshine Hours

In 1961–2008, the annual mean sunshine hours in Southwestern China was 1894 h and the daily mean sunshine hours was 5.2 h. The maximum annual mean sunshine hours was 3,514 h occurred in Shiquanhe stations of Xizang Autonomous Region and the minimum was 930 h occurred in Dujiangyan station of Sichuan Province. The annual mean sunshine hours in summer and winter monsoon period were 531, 483, 438, 783, 956, and 949 h. That of spring and winter were significantly higher than that of summer and autumn. The according maximum of four seasons were 932, 957, 888, 2,250, 1,720, and 1,901 h, respectively and the minimum were 236, 279, 156, 90, 311 and 549 h. As shown in Fig. 5.1, the high value of annual mean sunshine hours in the studied area mainly occurred at high altitude areas, such as Xizang Plateau, Hengduan Mountain and Yunnan Plateau, while the low altitude areas like Guizhou Plateau and Sichuan Basin had less sunshine hours. A same distribution pattern of annual mean sunshine hours to yearly period was showed by spring, winter, autumn and winter monsoon period, whereas the lower value of sunshine hours in summer and summer period happened in the west of Sichuan Basin, the south of Hengduan Mountain and Yunnan Plateau. In terms of regional average, annual, spring, summer, autumn, winter, summer and winter monsoon sunshine hours in Xizang Plateau and Hengduan Mountain were 2,484, 671, 564, 614, 777, 1,302 and 1,188 h. The corresponding value in Yunnan-Guizhou Plateau were 1,678, 484, 433, 484, 968, 843, and 847 h, respectively, reflecting that the sunshine hours decrease with the decline of altitude; the sunshine hours in winter and spring of Xizang Plateau-Hengduan Mountain were more than in summer and autumn, while there was few difference between them in Yunnan-Guizhou Plateau; that in summer and autumn of Sichuan Basin was more than in winter and spring.

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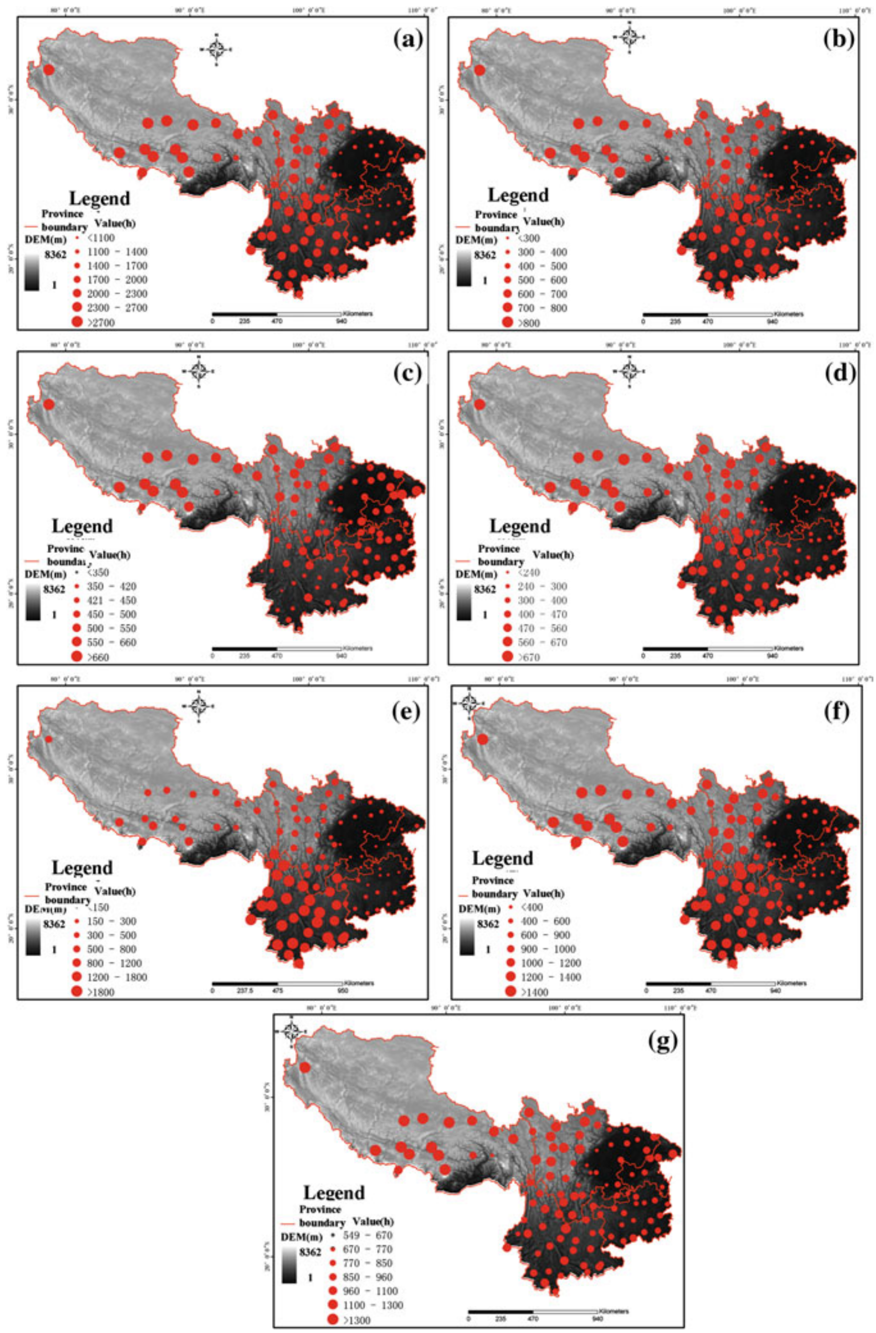

Fig. 5.1 Spatial distribution of the average sunshine hours during 1961–2008, **a** annual. **b** Spring. **c** Summer. **d** Autumn. **e** Winter. **f** Winter monsoon period. **g** Summer monson period

5.1.2 The Interannual Variation of Sunshine Hours

As shown in Fig. 5.2, the annual mean sunshine hours reduced at the rate of 31.9 h/10 a in 1961–2008. The interannual variation was represented through the increase of 1960s, the continuous decrease during 1970–1990 and the rise afterward. The decreasing magnitude in 1961–2008 was −35.7 h/10 a and had passed the significance test, but the increasing magnitude in 1991–2008 was 18.1 h/10 a which failed to pass the significance test. This change is consistent to the "darkening" and "brightening" of most parts of the world since 1960s concluded by observation data and satellite data, and also had a same decreasing tendency (−19.92 h/10 a) to sunshine hours of Northwestern China in 1961–2007. But its tendency is much different from that in the east and central of Qinghai-Xizang Plateau, where the sunshine hours increased at the rate of 49.8 h/10 a in 1961–1982 but decreased ar the rate of −65.1 h/10 a. It also was different from other regions in China which continued to decline over the passed several decades, reflecting the regional difference of sunshine hours variation (Table 5.1).

In 1961–2008, the decreasing magnitude of spring, summer, autumn, winter, summer and winter monsoon sunshine hours were −6.9, −18.2, −2.7, −4.9, −9.3 and −20.6 h/10 a, respectively. And the changing magnitude in 1961–1990 were

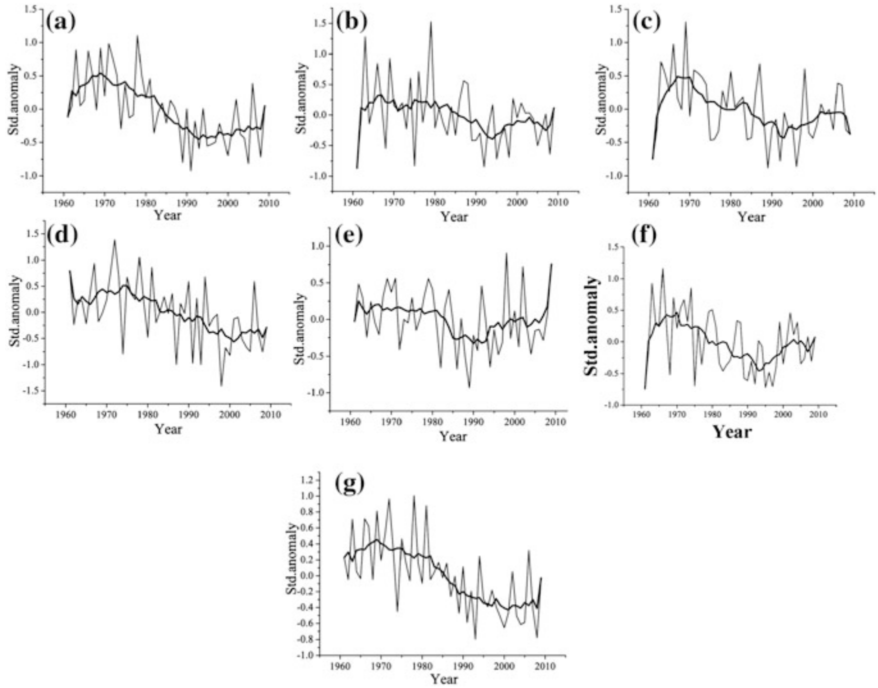

Fig. 5.2 Inter-annual variation of sunshine hours in Southwestern China during 1961–2008, **a** annual, **b** winter, **c** spring, **d** summer, **e** autumn, **f** WMP, **g** SMP

Table 5.1 Sunshine hour's trends in many parts of China (h/10 a)

	Period	Annual	Spring	Summer	Autumn	Winter	Sources
North China	1965–1999	**−82.9**	**−72.9**	**−75.7**	**−73.7**	**−28.3**	Yang et al.–
Liaoning Province	1956–2008	**−57.6**	**−14.3**	**−18.4**	**−10.4**	**−7.6**	Yang et al. (2010)
Hebei Province	1965–2005	**−96.7**	**−20**	**−28.9**	**−27.4**	**−23.1**	Guo et al. (2010)
Anhui Province	1955–2005	**−88.3**	**−6.6**	**−42.5**	**−16.9**	**−22.2**	He et al.–
Henai Province	1965–2006	**−110.4**	**−10**	**−53**	**−25**	**−26**	Jiao et al. (2008)
Jiangsu Province	1960–1999	**−66.4**					Shen et al. (2007)
Shanxi Province	1959–2008	**−65.4**	**−4.9**	**−28.1**	**−13.5**	**−23.6**	Fan et al. (2010a, b)
Guizhou Province	1961–2005	**−12.2–144.3**					Zhen et al.–
Tibet autonomous region	1971–2005	**−34.1**		**−24.7**			Du et al.–
The eastern and central Tibetan Plateau	1961–2005	**−20.6**	**−5.7**	**−7.4**	**−3.4**	**−3.1**	You et al. (2010a, b)
The northwestern China	1961–2007	**−19.9**					Chen et al. (2010a, b, c)
	1961–2008	**−31.9**	**−6.9**	**−18.2**	**−2.7**	**−9.3**	
Southwestern China	1961–1990	**−35.7**	−11.1	**−11**	**−11**	**−2.7**	This study
	1991–2008	**18.1**	**11.8**	−14.3	9.4	8.1	

Values for trends significant at the 5 % level are set in bold

−11.1, −11, −11, −2.7, −18.4 and −18.3 h/10 a, respectively. In addition, the corresponding change magnitude in 1991–2008 were 11.8, −14.3, 9.4, 8.1, 23.4, and 7.2 h/10 a. Winter, spring and winter monsoon sunshine hours increased in 1960s, then decreased for 1970–1995 and was on the rise afterward (Fig. 5.2). However, autumn sunshine hours represent a downtrend in 1961–1990, then continued to rise in 1991–2008 (Fig. 5.2). On the whole, the annual and seasonal sunshine hours showed a decline tendency before 1990, then had a apparent rise. The decreasing magnitude was most significant in summer and summer monsoon period, but the changing magnitude in winter and winter monsoon period had not passed the significance test. From 1961 to 1990, only the decreasing magnitude of spring could not pass the significance test and the changing magnitude of spring, summer and winter monsoon period was remarkably higher than in 1961–2008. While the increasing magnitude of only spring and winter monsoon period had passed the significance test (Table 5.1). As shown in Table 5.1, the sunshine hours in Southwestern China were less than that of other regions except for the Qinghai-Xizang Plateau and Northwestern China. Additionally, the reduction of sunshine hours mainly occurred in summer half year, and the decreasing magnitude of Eastern China was much more than that of Western China (Table 5.1).

The sunshine hours in Xizang Plateau-Hengduan Mountain had a downtrend at the rate of −21.3 h/10 a in 1961–2008. For its interannual variation, it was on a decline in 1960s, then had a fluctuated change and sharply decreased until 2000, but had a rising trend after 2000. The changing magnitude of 1961–1990 and 1991–2008 were positive, suggesting a obvious difference with the change of Southwestern China (Fig. 5.3). As the Table 5.2 showing, only the decrease magnitude of autumn and summer monsoon period had passed the significance test, and the difference of seasonal variation was very significant. Spring continued to increase after the decrease in 1960. In summer, the sunshine hours increased in 1961–1980 then decreased in 1981–2008. It fluctuated to decline in autumn and had a slow rise in winter before 1985, then showed a wavelike decrease change. While the changing trend is same to annual one (Fig. 5.3). In 1961–1990, the sunshine hours in other seasons all showed a rising trend except for summer monsoon period, but all the changing magnitude had not passed the significance test (Table 5.2).

In 1991–2008, the spring and summer sunshine hour significantly declined and the increasing magnitude in winter, summer and winter monsoon period had passed the significance test. On the whole, there was a big difference in the variation of sunshine hour between this region and Southwestern China; its changing magnitude is much smaller and the significance level was also lower. In addition, the decrease magnitude in winter and spring also remarkably less than that in summer and autumn.

In 1961–2008, the sunshine hour in Yunnan-Guizhou Plateau continued to decrease and increased afterward. The changing magnitude was −33.1 h/10 a. Its decreasing magnitude in 1961–1990 was bigger than that of the entire studied period, and it increased at the rate of 29.3 h/10 a in 1991–2008 with a same trend to Southwestern China (Fig. 5.4). In spring, the sunshine hours increased in 1960s then decrease continuously; in summer, it sustained to decline before 2000 and had a rising tendency afterward; the sunshine hours in autumn was on a decline before

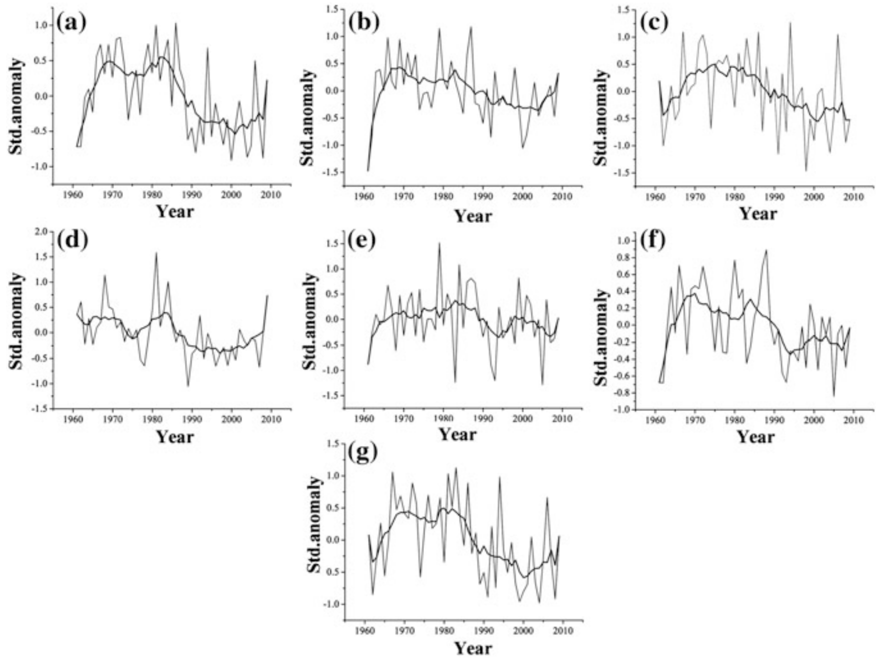

Fig. 5.3 Inter-annual variation of sunshine hours in Xizang plateau and Hengduan mountains during 1961–2008, **a** annual, **b** winter, **c** spring, **d** summer, **e** autumn, **f** WMP, **g** SMP

Table 5.2 Sunshine hour's trends in three parts of Southwestern China (h/10 a)

		Annual	Spring	Summer	Autumn	Winter	Winter monsoon	Summer monsoon
XPHM	1961–2008	**−21.3**	−4.6	−8.9	**−8.1**	−2.1	−7.2	**−18.9**
	1961–1990	14.7	4.3	9.6	−11.2	7.6	3.5	−4.6
	1991–2008	4.1	−0.3	**−6.8**	8.11	**2.8**	**2.8**	**7.6**
SB	1961–2008	**−52.6**	−6.0	**−29.3**	−2.0	**−13.1**	**−19.1**	**−31.1**
	1961–1990	**−93.1**	**−17.1**	**−36.3**	**−15.3**	**−19.3**	**−15.4**	**−41.6**
	1991–2008	**54.6**	**46.2**	−5.9	6.0	10.0	**42.5**	3.4
YGP	1961–2008	**−33.1**	**−10.6**	**−17.9**	1.9	−4.9	−7.4	**−27.8**
	1961–1990	**−51.3**	**−21.5**	−11.7	**−18**	2.3	−20.5	**−24.3**
	1991–2008	29.3	−7.4	4.6	19.8	1.5	14.8	4.6

Values for trends significant at the 5 % level are set in bold

1990, then increased and in winter it showed a slow rise and a wavelike decline afterward; in winter monsoon period, it increased in 1960s, then decreased, but it increased again after 1990. While the sunshine hour in summer monsoon period kept a downtrend (Fig. 5.4). The decreasing magnitude of spring, summer and summer monsoon period had succeeded in the significance test in 1961–2008, and

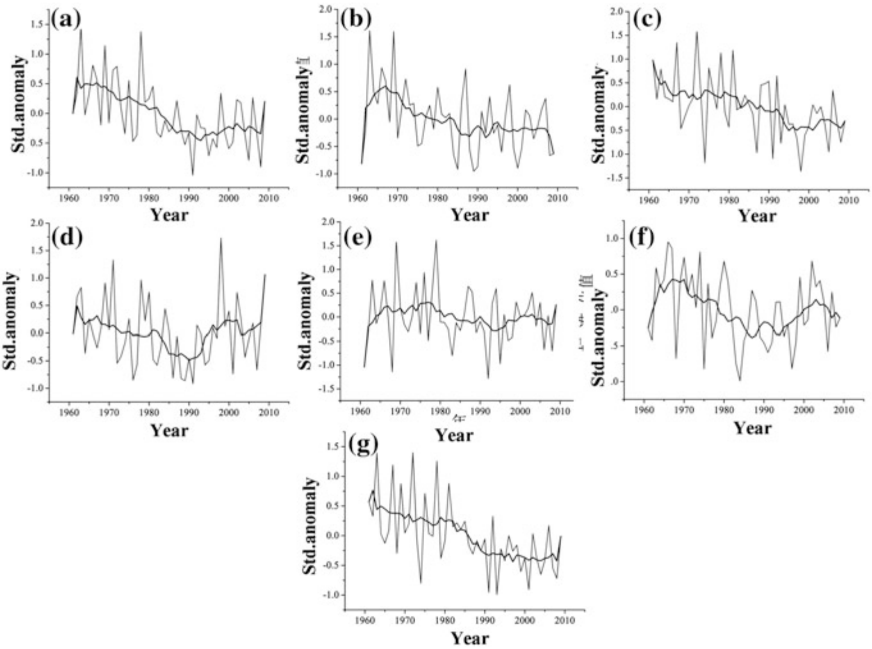

Fig. 5.4 Inter-annual variation of sunshine hours in Yunnan-Guizhou plateau during 1961–2008, **a** annual, **b** spring. **c** summer, **d** autumn, **e** winter, **f** WMP, **g** SMP

the decreasing magnitude in spring and summer were greater than that in autumn and winter, while the summer monsoon was greater than winter monsoon. In 1961–1990, the spring, autumn and summer monsoon sunshine hour had a sharp decline. Other seasons showed a increasing trend in 1991–2008 except for spring (Table 5.2).

As shown in Fig. 5.5, the annual mean sunshine hour decreased significantly before 1990 and increased afterward. Its decreasing magnitude in 1961–1990 was greater than that of entire studied area (Table 5.2). The changing trends in spring and winter monsoon period were same to that in a year. It continued to decline in summer, winter and summer monsoon period, while it slowly decreased in autumn before 1985 and showed a fluctuated increasing afterward (Fig. 5.5). In 1961–2008, the changing magnitude of only spring and autumn could not pass the significance test. All seasons in 1961–1990 showed a apparent decline, but just spring and winter monsoon perions in 1991–2008 had passed the significance test. The decline magnitude in spring and autumn in Sichuan Basin were much less than that in summer and winter, and the summer monsoon perions was greater than the winter monsoon period. But for increasing magnitude, the spring and winter were greater than summer and autumn (Table 5.2).

In conclusion, the changing trend of sunshine hour in Sichuan Basin and Yunnan-Guizhou Plateau are similar to that in Southwestern China, and both their changing magnitudes were higher than the regional level. However, the changing

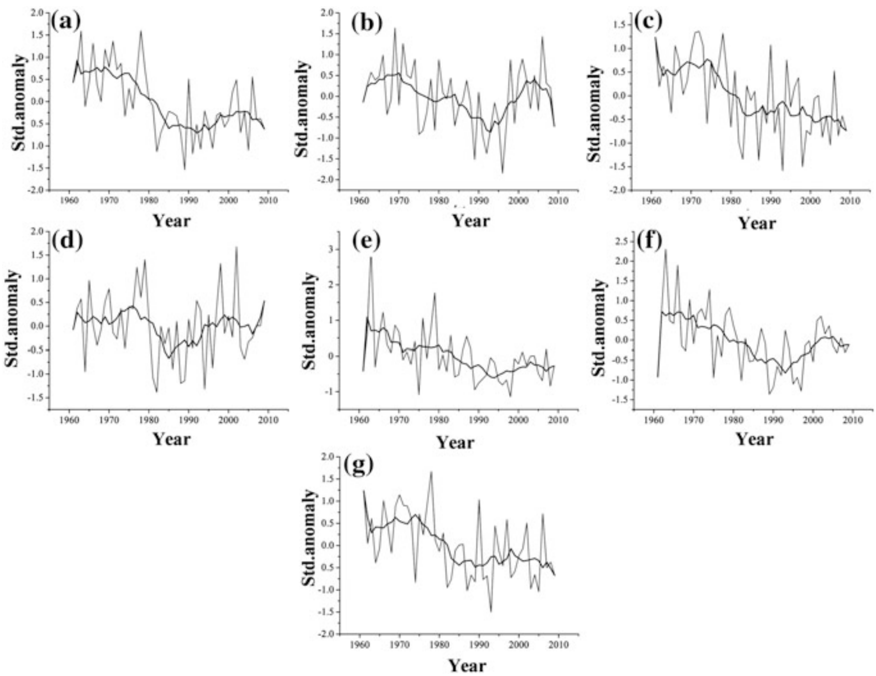

Fig. 5.5 Inter-annual variation of sunshine hours in Sichuan basin during 1961–2008, **a** annual, **b** spring, **c** summer, **d** autumn, **e** winter, **f** WMP, **g** SMP

magnitude in Xizang Plateau-Hengduan Mountain was much less. Among these three sub-regions, the changing magnitude in Sichuan Basin was greatest followed by Yunnan-Guizhou Plateau and Xizang Plateau-Hengduan Mountain in turn. A same feature also was shown in the significance level of changing magnitude. All they decreased more sharply in summer monsoon period than in winter monsoon period, and the increase magnitude was opposite.

5.2 Spatial Variation of Sunshine Hours

5.2.1 Spatial Distribution of Variation Trends in Sunshine Hours During 1961–2008

As shown in Fig. 5.6, there were 78 % of stations showing a decrease sunshine hour in 1961–2008 among 110 stations and the station passing the significance test in decrease magnitude accounted for 59 %. Except for several stations in the southeast of Hengduan Mountain and the southwest of Yunnan Plateau, the major station in studied area had a decline change. The stations with a wider margin of decrease were mainly distributed in Hengduan Mountain, Guizhou Plateau and Sichuan

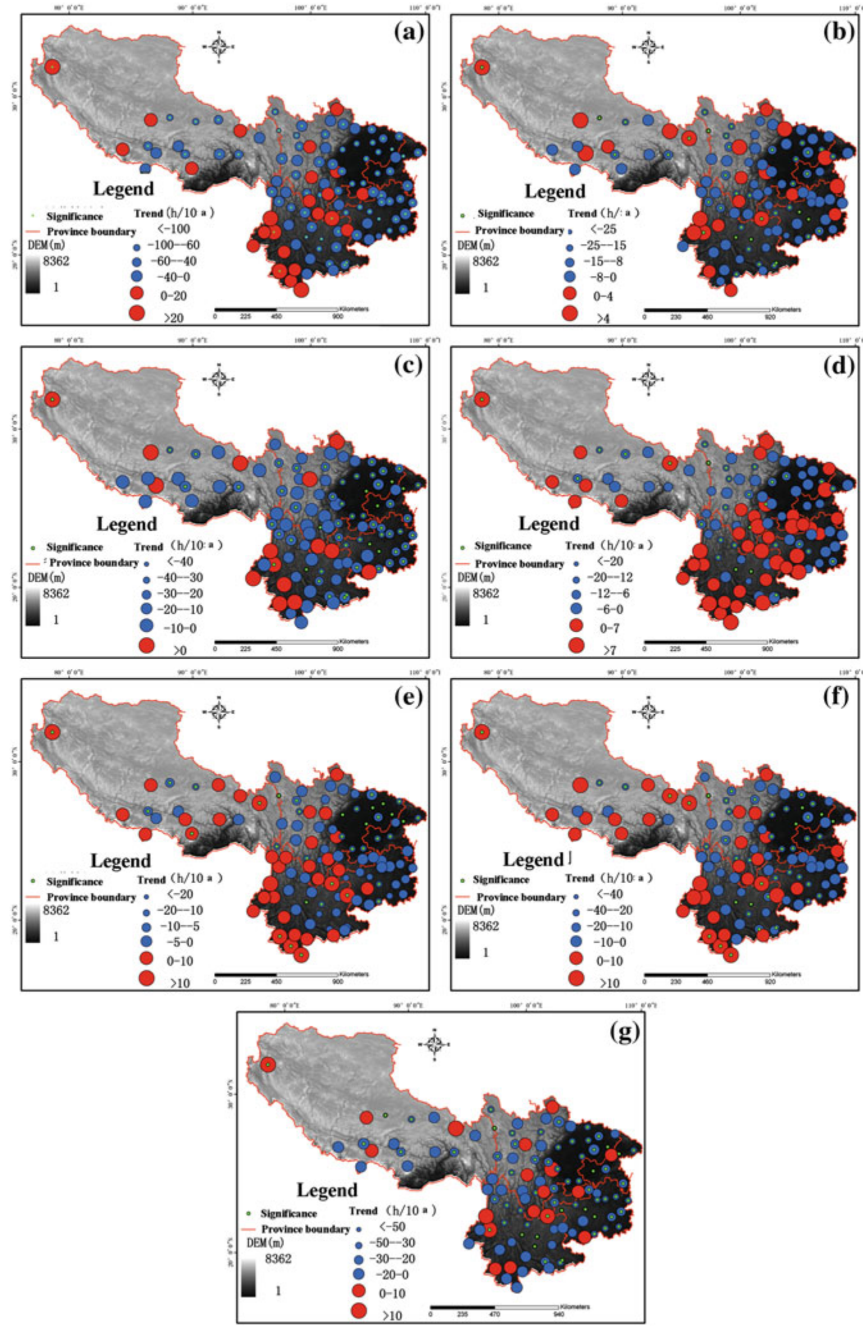

Fig. 5.6 Spatial distribution of variation trends in sunshine hours during 1961–2008, **a** annual, **b** spring, **c** summer, **d** autumn, **e** winter, **f** WMP, **g** SMP

Basin, while a drop or a remarked rise could be found in the stations situated in Xizang Plateau. During the researched period, abort 79 % of stations exhibited a decrease in spring sunshine hour, but significant drop was showed in 32 % of stations among 110 stations. The stations with non-significant drop chiefly were located in Xizang Plateau, Hengduan Mountain, and Guizhou Plateau, while the stations with a increasing trend were situated in Xizang Plateau and the west of Yunnan Plateau (Fig. 5.6). In summer, there were approximately 86 % of stations having a decreasing change in sunshine hour, but there were only a half among them declined sharply. Most obviously, the station with a sharp drop were mainly distributed in the low altitude area, like Guizhou Plateau and Sichuan Basin. Whereas, the stations in high altitude area had a non-significant decrease or increase (Fig. 5.6).

The sunshine hour in studied area appeared a little drop in autumn, just the stations in Hengduan Mountain showed a remarkable decline, accounting for 23 % of all stations. While the stations in southwestern Yunnan Plateau, southeastern Hengduan Mountain, and Xizang Plateau increased, accounting for 38 % of stations (Fig. 5.6). There were 68 % of stations reduced in winter sunshine hour, but only 28 % of the 110 stations had passed the significance test in apparent decline, which were mainly distributed in the low altitude ares, such as Guizhou Plateau and Sichuan Basin. However, the most stations in Xizang Plateau, the south of Hengduan Mountain and the southwest edge of Yunnan Plateau had a increase trend (Fig. 5.6).

Except for the some stations in Xizang Plateau and Hengduan Mountain, only 84 % of stations performed a reduce trend in summer monsoon sunshine hour, but only 53 % of them had passed the significance test in this factor, which were mainly situated in Guizhou Plateau and Sichuan Basin (Fig. 5.6). The winter monsoon sunshine hour of stations in Xizang Plateau, Hengduan Mountain and the southwest of Yunnan Plateau accounting for 30 % of all stations was on the rise, and about 30 % of stations located in Guizhou Plateau and Sichuan Basin decreased sharply (Fig. 5.6). As a whole, the decrease of sunshine hour in Southwestern China principally appeared in low altitude area, especially in Guizhou Plateau and Sichuan Basin. While most stations in high altitude area reduced slightly or had a rising trend.

5.2.2 Spatial Distribution of Variation Trends in Sunshine Hours Between 1961–1990 and 1991–2008

In order to further recognize the changing features of the sunshine hour in the studied area, this study analyzed the regional trend of all stations between 1961–1990 and 1991–2008. As shown in Fig. 5.7, the percentage of stations with a downtrend in annual mean sunshine hour was 68 %, but there were 37 % of them passing the significance test which were situated in Yunnan Plateau—Plateau and

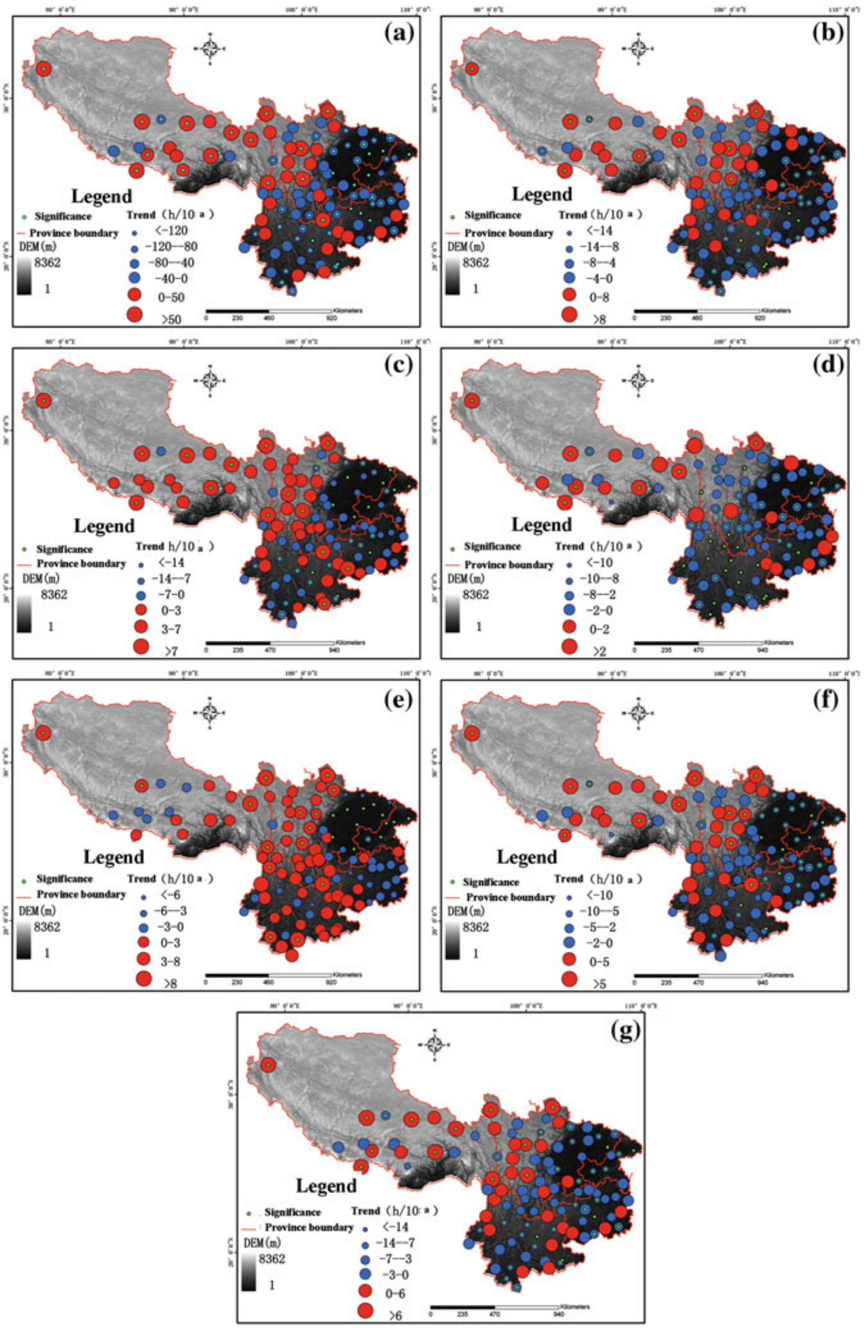

Fig. 5.7 Spatial distribution of variation trends in sunshine hours during 1961–1990, **a** annual, **b** spring, **c** summer, **d** autumn, **e** winter, **f** WMP, **g** SMP

Sichuan Basin. Whereas the stations with increasing trend were located in high altitude area. Except for some stations in Xizang Plateau and Hengduan Mountain, approximately 78 % of the stations reduced in spring sunshine time. The stations in Yunnan Plateau—Plateau and Sichuan Basin showed a remarkable decrease and accounted for 29 % of all stations. The percentage of stations with a decline trend in summer sunshine hour was 62 %, but only 25 % of them had passed the significance test. Moreover, the stations in izang Plateau and Hengduan Mountain appeared a rising tendency (Fig. 5.7).

In autumn, the stations showing decreasing sunshine hour were most in a year. Except for some stations in Xizang Plateau, about 80 % of the stations performing a reducing trend and the stations with a sharp rise were mainly distributed in low altitude area. Approximately 45 % of the stations in Guizhou Plateau and Sichuan Basin had a drop in winter sunshine hour, and 13 % of stations with a remarkable decrease were primarily situated in Sichuan Basin. In summer and winter monsoon period, the spatial distribution of variation trends in sunshine hours was similar to the yearly, and there were respectively 70 and 68 % of stations showing a downtrend. But there only 28 and 20 % of stations drop down sharply (Fig. 5.7). Overall, during 1961–1990, the stations exhibiting a decrease trend were mainly in low altitude area, while the stations with increase trend were located in high altitude area. The percentage of station showing a drop or sharp decrease was less than that of 1961–2008.

In 1991–2008, the annual mean sunshine hour of about 61 % of stations increased, but only 30 % increased significantly among them. Most stations in Guizhou Plateau showed a dropping trend, and the rest stations with a decreasing trend scattered in other regions except for Yunnan Plateau (Fig. 5.8).

In spring, about 58 % of stations showed a increasing trend, but only 23 % of them had passed the significance test which were mainly distributed in Guizhou Plateau and Sichuan Basin and a few stations were in Xizang Plateau and Hengduan Mountain. While almost all stations in Yunnan Province reduced significantly (Fig. 5.8). Summer sunshine hours of only 43 % of the stations increased, and the stations with significant increase just accounted for 11 % which located in Xizang Plateau and Yunnan Plateau, while the stations in Hengduan Mountain, Guizhou Plateau and Sichuan Basin decreased. The sunshine hour in the whole Yunnan Plateau increased, and the most stations in Xizang Plateau and Hengduan Mountain also showed a rising trend, accounting for 69 % of all stations. But there were only 27 % of stations having a remarkable rise (Fig. 5.8). In winter, the stations with decreasing trend were located in Guizhou Plateau and the south of Hengduan Mountain. While there about 63 % of the stations showed an increasing trend, a sharp rising just appeared in 19 % of stations. In summer and winter monsoon period, the spatial distribution of variation trends in sunshine hours was similar to the yearly, and there were respectively 67 and 53 % of stations showing a uptrend. But the stations passing the significance test only had 28 and 20 % (Fig. 5.8). In conclusion, the most apparent feature in this period was that the stations with a rising trend increased apparently in low altitude.

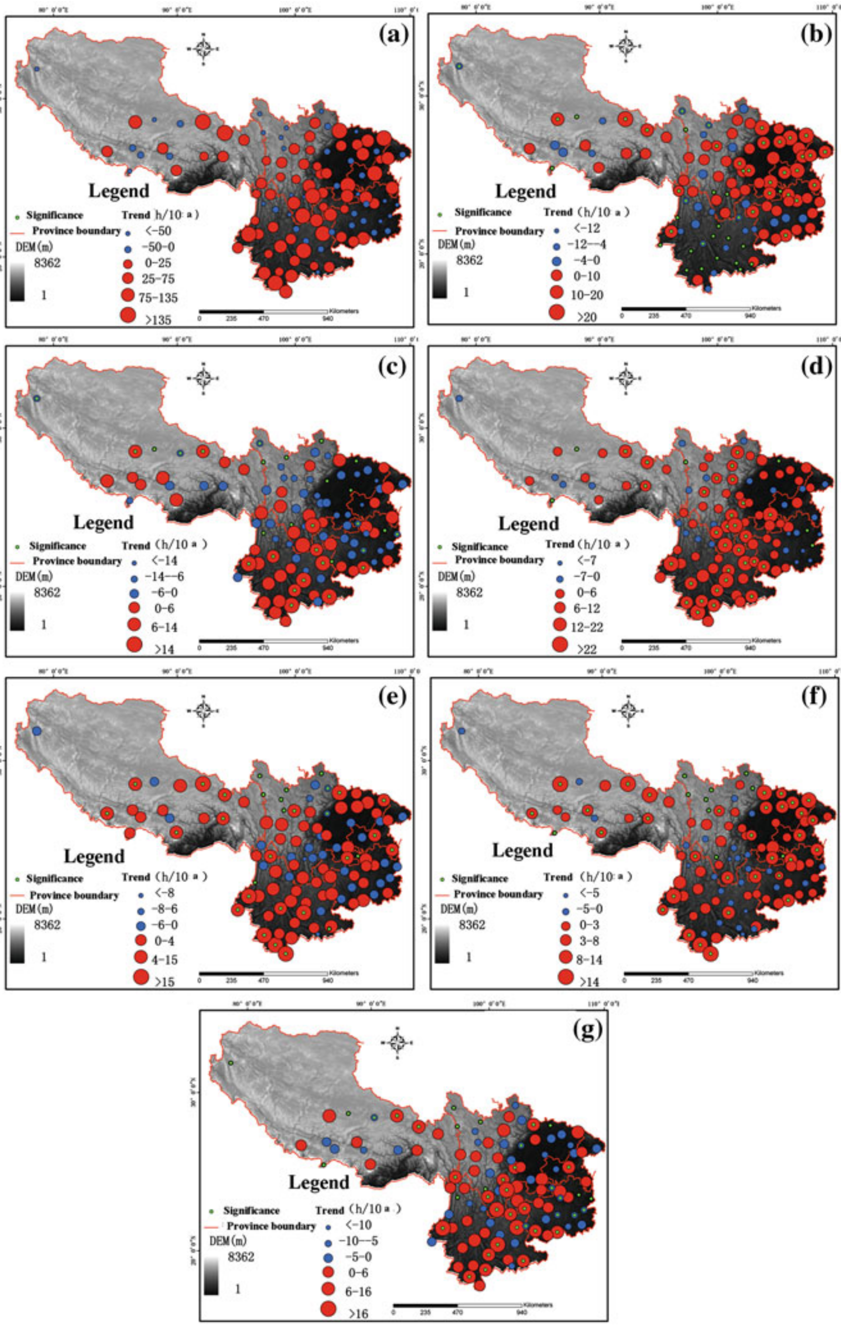

Fig. 5.8 Spatial distribution of variation trends in sunshine hours during 1991–2008, **a** annual, **b** spring, **c** summer, **d** autumn, **e** winter, **f** WMP, **g** SMP

5.3 Driving Mechanism for Sunshine Hours

5.3.1 Relationship Between Wind Speed and Sunshine Hours

Related researches thought that the wind speed is the major reason of sunshine hour changing (Roderick et al. 2007, 2008; Rayner 2007; Robert et al. 2010). Two characters of temporal and spatial variation in wind speed and sunshine hour in Southwestern China can be showed as follows: (1) a significant correlation and similar changing trend. In 1969–2008, there was a significant positive correlation between wind speed and sunshine hour in studied area except for in autumn, and the correlated level of them became higher in 1969–2000 (Table 5.3). In addition, a same changing trend of wind speed and sunshine hour indicated the close relationship between the weakening of speed wind and the decrease of sunshine hour (Fig. 5.9). The influence of wind speed to sunshine hour represented a regional difference. The wind speed and sunshine hour showed a significantly positive correlation in Xizang Plateau-Hengduan Mountain except for yearly and winter, because there were less precipitation and more sunny day, so wind speed had a little influence to sunshine hour. While annual, winter and winter monsoon wind speed

Table 5.3 Relationship between wind speed and sunshine hours during 1969–2008 (h/10 a)

	Annual	Spring	Summer	Autumn	Winter monsoon	Summer monsoon	Winter
Trend in 1969–2000 (h/10 a)	**−62.40**	**−15.90**	**−30.90**	**−6.60**	**−11.30**	**−26.00**	**−37.50**
Trend in 2001–2008 (h/10 a)	−4.80	−5.90	**−15.80**	**17.80**	**−22.60**	**−56.90**	**26.80**
Trend in non-windy days during 1969–2008 (h/10 a)	**−41.54**	**−7.38**	**−20.50**	−3.09	**−7.06**	**−12.96**	**−24.79**
Stations with decreasing trend in non-windy days	0.82	0.80	0.86	0.69	0.76	0.80	0.86
Trend in windy days during 1969–2008 (h/10 a)	**−29.90**	**−8.14**	**−12.99**	−3.41	−2.56	**−7.25**	**−20.61**
Stations with decreasing trend in windy days	0.76	0.79	0.87	0.56	0.61	0.63	0.82
Correlation coefficients with wind speed in 1969–2008	**0.58**	**0.41**	**0.53**	0.16	**0.28**	**0.46**	**0.52**
Correlation coefficients with wind speed in 1969–2000	**0.67**	**0.47**	**0.61**	0.20	**0.38**	**0.60**	**0.60**
Correlation coefficients with wind speed in 2001–2008	−0.27	**0.39**	−0.16	0.01	**−0.84**	**−0.67**	−0.13
Correlation coefficients with wind speed in XPHM in 2001–2008	**0.21**	**0.46**	**0.30**	**0.34**	**0.25**	**0.51**	**0.62**
Correlation coefficients with wind speed in YGP in 2001–2008	**0.29**	0.07	0.07	0.22	**0.36**	**0.31**	0.26
Correlation coefficients with wind speed in SB in 2001–2008	**0.31**	**0.31**	0.01	0.21	**0.39**	**0.34**	**0.49**

Values for trends significant at the 5 % level are set in bold

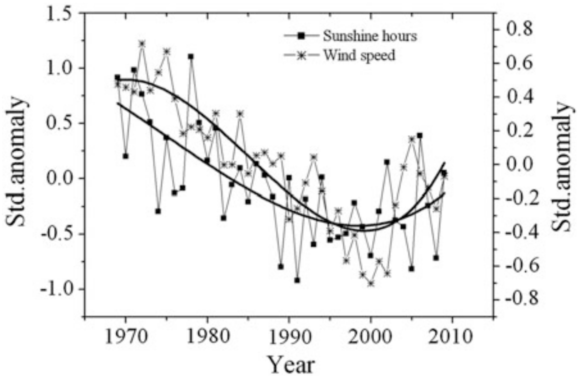

Fig. 5.9 Variation of annual mean sunshine hours and wind speed during 1969–2008. Reprinted from Li et al. (2012), with kind permission from Springer Science+Business Media

had a apparently positive correlation in Yunnan-Guizhou Plateau (Fig. 5.3). The wind speed in Sichuan Basin showed a significantly positive correlation with the sunshine hours except for summer and winter. These differences indicated that the effect of wind speed to sunshine hours in high altitude area mainly happened in summer half year, but to low altitude occurred in winter half year. In addition, both they did not show a apparently positive correlation in summer and autumn of Yunnan-Guizhou Plateau and Sichuan Basin from 1969 to 2008. In 2001–2008, the annual and seasonal variations of wind speed and sunshine hour revealed a negative correlation, and the sunshine hours accelerated to decrease in winter and winter monsoon period, which reflected the regional difference of influence of wind speed to sunshine hours. (2) A same regional trends of sunshine hours with wind speed had be shown by all stations. The sunshine hour in 1969–2000 decreased much more sharply than 2001–2008 when the sunshine hours showed a rising tendency in autumn and summer monsoon period (Fig. 5.3).

The rest stations showed a decreasing trend in 1969–2000 except for 11 stations in Xizang Plateau and Yunnan-Guizhou Plateau, and 65 % of stations declined significantly. In 2001–2001, nearly half of stations increased in sunshine hour and about 32 % of the station had passed the significance test. Furthermore, the decreasing magnitude of 10 % of the stations were less than of 1969–2000. The stations with a increasing trend are mainly distributed in Xizang Plateau, the central of Hengduan Mountain, the central of Yunnan Plateau and Guizhou Plateau (Fig. 5.10). In conclusion, wind speed and sunshine hour showed significant spatial and temporal correlation, proving the influence of wind speed to sunshine hour.

In order to further analyze the impact of wind speed to sunshine hour, this study divided 110 stations into two types based on whether annual mean daily wind speed is greater than 1.5 m/s and makes an analysis. They are 62 stations where the daily mean wind speed is greater than 1.5 m/s (winded days) and 48 stations where the daily mean wind speed is less than 1.5 m/s (windless days). As Table 5.3 showing, in 1969–2008, the decreasing magnitude of sunshine hours in annual, spring,

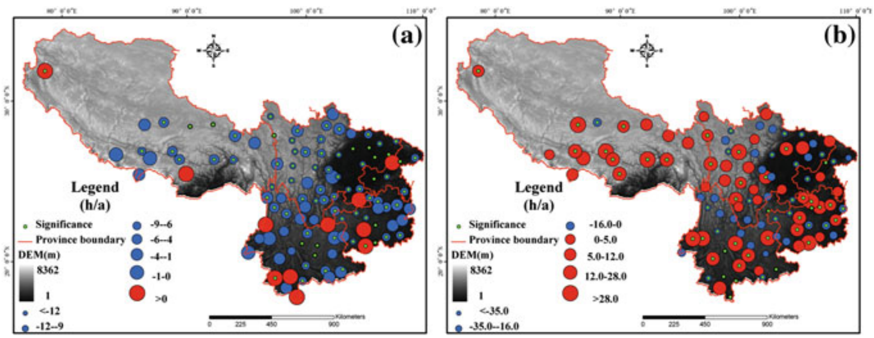

Fig. 5.10 Spatial distribution of sunshine hours' variation trends during **a** 1969–2000 and **b** 2001–2009

summer, autumn, winter, summer and winter monsoon were respectively −41.54, −7.38, −20.50, −3.09, −7.06, −24.79 and −12.96 h/10 a in the stations of studied area where the daily mean wind speed were less than 1.5 m/s. While the corresponding values of annual and seasonal wind speed were respectively −29.90, −8.14, −12.99, −3.41, −2.56, −20.61 and −7.25 h/10 a in the stations where the daily mean wind speed were greater than 1.5 m/s. Most apparently, the sunshine hour of stations where the wind speed was less than 1.5 m/s decreased much more sharply than the stations where the wind speed was greater than 1.5 m/s, and the percentage of stations having a decreasing annual and seasonal sunshine hours also showed a same characteristic. This conclusion confirmed again that wind speed is one of main driving forces of sunshine time changes and also suggested that the weakening of wind speed really is the direct and strong influence factor of the reduction of sunshine hour in Southwestern China. In fact, it is impossible that the weak wind speed blows away clouds, aerosols, and other air pollution in the air. So the relationship between wind speed and the possible materials in the air which may influence the radiation, like clouds cover and atmospheric aerosols is one of the major physical processes of sunshine hour change in the studied area. Moreover, related studies have confirmed that the wind speed in the air plays an important role on cleaning. The study of Fu et al. (2008) found that Yangtze river Delta region occurred severe pollution due to the abnormal stagnation of air, when the daily mean wind speed is less than 1.0 m/s. Satheesh and Moorthy (2005) also thought that the wind speed is a most influential factor of the change of regional atmospheric aerosol concentration. The study of Yang et al. (2008a, b, c) also confirmed that weakening wind speed is the main reason of the reduction of sunshine hour.

5.3.2 The Relationship Between Relative Humidity and Sunshine Hour

As shown in Fig. 5.15, the humidity had a fluctuating decrease from 1961 to 2008 in Southwestern China. Thereinto, it kept a stable state, then increased until 2000 and appeared a sharp drop after 2001. The decreasing magnitude was −2.24 %/10 a and had passed the significance test (Table 5.4). The annual mean humidity and sunshine hour showed a obviously opposite trends during the researched period (Fig. 5.11) which also be shown from their significantly negative correlation. In addition, the humidity and sunshine time changes had a significantly negative correlation between 1961–1990 and 1991–2008 (Table 5.4), suggesting that the humidity is another influencing factor of sunshine hour change, because the water vapor in the air can strongly weaken the solar radiation by absorbing, scattering and reflection, etc. A same trend is also displayed between seasonal and annual humidity change. They all decreased significantly in 2001–2008, and the decrease magnitude is maximum in winter and minimum in spring. The seasonal change also had a apparently negative correlation with sunshine hours, especially in winter and spring the correlation coefficient is greatest (Fig. 5.4), which confirmed again the important effect of humidity to regional sunshine hours.

The annual mean humidity slightly increased in 1961–2008 in Xizang Plateau-Hengduan Mountain, and sharply increased in summer, winter and winter monsoon period, but reduced in spring, autumn and summer monsoon period (Table 5.4). As shown in Fig. 5.11, the annual mean humidity and sunshine hour had reverse changes in Xizang Plateau-Hengduan Mountain, and the annual and seasonal sunshine hour had a significantly negative correlation with humidity, which indicated the apparent weakening of humidity to sunshine hour at the high altitude area (Table 5.4).

The annual mean humidity in Yunnan-Guizhou Plateau continued to decrease, same to seasonal change (Fig. 5.11). The humidity had a significantly negative correlation with sunshine hour, and the correlation coefficient suggested that the effect of humidity to winter and spring was greater than summer and autumn., because there were little cloud cover in winter and spring. But the sharp warming, especially night warming, leaded to the strengthening of evaporation and the weakening of condensation of water vapor and further resulted in the relative increase of humidity during the daytime, even ultimately enhance its ability to weaken the solar radiation. The annual and seasonal humidity in Sichuan Basin slowly rose before 1990 and declined afterward. Its change had a significantly negative correlation with the sunshine hour, because due to the special terrain, more air relative humidity and foggy days of this regions would greatly weaken the solar radiation, thereby reducing the sunshine hours (Table 5.4). In conclusion, the reverse trend and significantly negative correlation between humidity and sunshine hour in the studied area verified that humidity is another influencing factor of sunshine hour changes, and the sharp reduction after 1990s undoubtedly is the key reason of the increasing of sunshine hour at the same period.

Table 5.4 The relationship between annual mean sunshine hours and relative humidity during 1961–2008 in Southwestern China and its three sub-regions

	Period	Annual	Spring	Summer	Autumn	Winter	Winter monsoon	Summer monsoon
Trends (%/10 a)								
Southwest	1961–2008	−0.20	−0.03	−0.35	−0.47	0.20	0.01	−0.40
China	1961–1990	−0.01	0.17	−0.36	−0.17	0.36	0.3	−0.25
XPHM	1991–2008	**−2.24**	**−1.67**	**−2.24**	**−2.19**	**−2.45**	**−2.04**	**−2.14**
	1961–2008	0.07	0.34	**−0.51**	−0.15	**0.63**	**0.54**	−0.32
YGP	1961–2008	**−0.60**	**−0.47**	**−0.56**	**−0.87**	**−0.43**	**−0.49**	**−0.63**
SB	1961–2008	−0.14	−0.33	−0.01	−0.41	0.20	0.03	−0.29
Correlation coefficient								
Southwestern	1961–2008	**−0.32**	**−0.65**	**−0.51**	**0.42**	**−0.58**	**−0.62**	−0.20
China	1961–1990	**−0.63**	**−0.71**	**−0.77**	**−0.42**	**−0.62**	**−0.64**	**−0.62**
	1991–2008	**−0.45**	**−0.63**	**−0.66**	**−0.56**	**−0.43**	**−0.60**	**−0.52**
XPHM	1961–2008	**−0.53**	**−0.76**	**−0.60**	**−0.71**	**−0.56**	**−0.42**	**−0.59**
YGP	1961–2008	−0.12	**−0.48**	**−0.30**	**−0.44**	**−0.70**	**−0.39**	−0.05
SB	1961–2008	**−0.50**	**−0.72**	**−0.65**	**−0.63**	**−0.55**	**−0.74**	**−0.53**

Values for trends significant at the 5 % level are set in bold

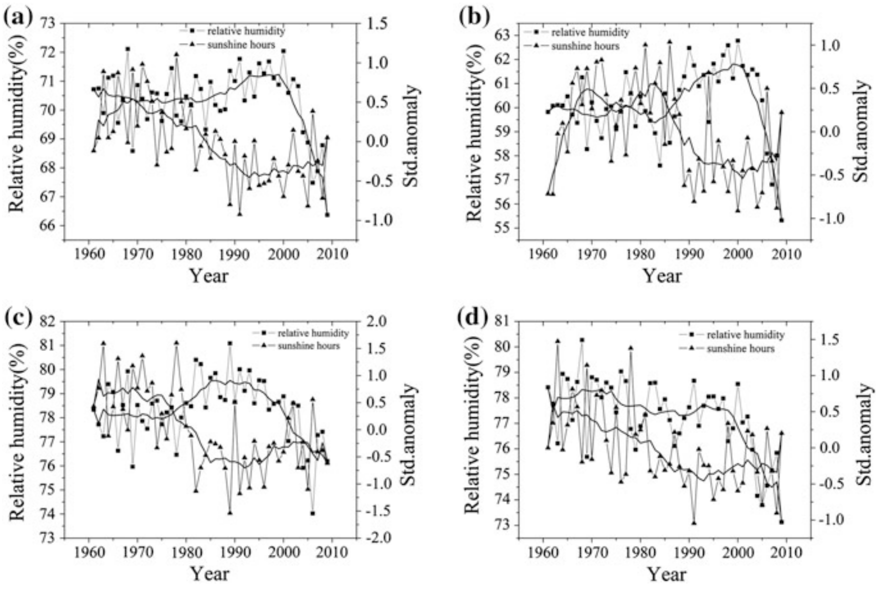

Fig. 5.11 Variation of annual mean sunshine hours and relative humidity during 1961–2008 in Southwestern China and its three sub-regions. **a** Southwestern Asia. **b** Xizang plateau-hengduan mountains. **c** Sichuan basin. **d** Yunnan-Guizhou plateay

5.3.3 The Comparison of Sunshine Hours Between Urban and Rural Stations

A number of researches at home and abroad attributed the decrease of sunshine hours to the serious atmosphere pollution caused by rapid urbanization process and increasing concentration of atmospheric aerosols (Xu et al. 2006a, b; Qian et al. 2002; Wang et al. 2004; Huang et al. 2006; Lu et al. 2007). In order to analyze the impact of urbanization process, this study compares the regional trends between the rural and urban stations. As shown in Table 5.5, the changing trends of annual and seasonal sunshine hours in urban stations were greater than in rural stations in 1961–2008, and the autumn, winter and the winter monsoon trends had not passed the significance test. The annual spring, summer, winter and winter monsoon sunshine hours in urban stations increased more sharply than in rural stations in 1991–2008, and the summer trends also was greater than that of rural stations. Moreover, the sunshine hour in urban stations showed a decreased tendency while the rural station was on the rise. Obviously, a apparent difference can be shown from the changing trends of urban and rural stations (Fig. 5.12). The annual sunshine hours of urban stations in 1961–2008 continued to reduce, while the rural stations successively appeared an increase in 1960s, a stable state in 1970–1985, a decrease in 1985–2000 and a slow rise afterward. The seasonal change in sunshine hour of urban stations also showed a continuous drop, whereas, in rural stations the

Table 5.5 Trends, correlation coefficients and percentage of stations with negative or positive trends for sunshine hours in urban and rural stations of Southwestern China (h/10 a)

	Urban station					Rural station				
	Trends (1961–2008)	D	SD	Correlation coefficient	Trends (1991–2008)	Trends (1961–2008)	D	SD	Correlation coefficient	Trends (1991–2008)
Annual	−3.37	50	41	0.65	2.35	−2.18	38	25	0.6	1.6
Spring	−0.67	49	20	0.47	1.78	−0.74	40	16	0.57	0.31
Summer	−1.97	55	39	0.33	−1.43	−0.98	42	16	0.55	−0.63
Autumn	−0.36	39	14	0.2	0.86	−0.19	30	12	0.33	1.45
Winter	−0.78	47	19	0.32	0.85	−0.22	28	9	0.29	0.23
Winter monsoon	−1.25	48	25	0.52	2.78	−0.57	30	12	0.38	0.73
Summer monsoon	−2.67	53	39	0.4	−0.65	−1.6	41	20	0.63	0.45

D is percentage of station with decrease trend, *SD* is the percentage of station with significant decrease trend

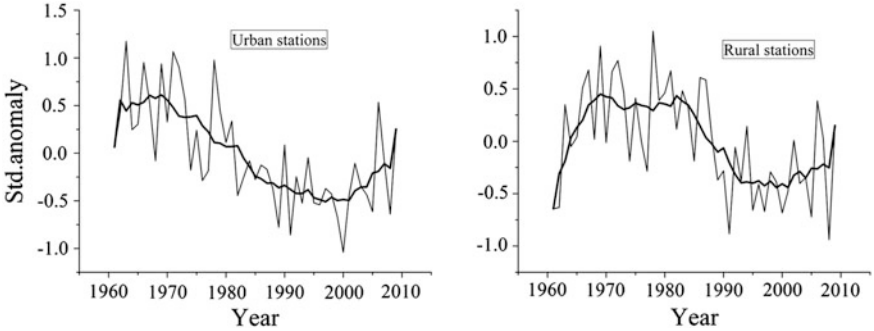

Fig. 5.12 Inter-annual variation of annual mean sunshine hours in urban stations and rural stations during 1961–2008

winter, spring and winter monsoon sunshine hour had a slight increase in 1960s followed by a decrease. And before 1980 the summer, autumn and summer monsoon sunshine hour exhibited a slight rise or a stable state, but decreased from 1980 to 2000 and was on the rise afterward. On the whole, the change trend of urban stations was similar to that of Yunnan-Guizhou Plateau and Sichuan Basin, while the change trend of rural stations was similar to that of Xizang Plateau-Hengduan Mountain because the rural stations were mainly situated in this region. There were more urban stations showing a decreasing trend in annual and seasonal sunshine hours in 1961–2008 compared with the rural stations, and the majority of stations with significant decrease were urban stations. In addition, no matter where the urban or rural stations, both annual and seasonal sunshine hour had a significantly positive correlation, which suggested again that wind speed is a important influencing factor of sunshine hour in Southwestern China.

In general, the influence of urbanization on sunshine time mainly was shown by environmental effects resulted from the increase of atmospheric aerosol concentration including direct effect and indirect effect. The direct effect refers that the atmospheric aerosol not only scattered solar radiation but also enhanced the reflectivity of shortwave radiation, eventually reduced the radiation or sunshine hour. Indirect effect refers that as cloud condensation nuclei, the aerosol change features like cloud cover, eventually lead to the wider margin of cloud albedo so as to reduce the surface solar radiation (Quaas et al. 2004). Therefore, the most direct expression of the impact of urbanization on sunshine hour is that increasing aerosol concentration will lead to the reduction of sunshine hour. The study of Guo and Ren (2006) on sunshine hour in Southeastern China and Tianjin Province demonstrated that the continuous increase of atmospheric aerosol is the main reason of the reduction of sunshine hours in above regions. A large number of researches also confirmed that the atmospheric pollution worsened and eventually leaded to the apparent increase of atmospheric aerosol concentration in the context of rapid economic development during 1961–2000, especially since 1980s (Fan et al. 2005). Since 1961, the energy consumption also show a significant increase in the trend in Southwestern China.

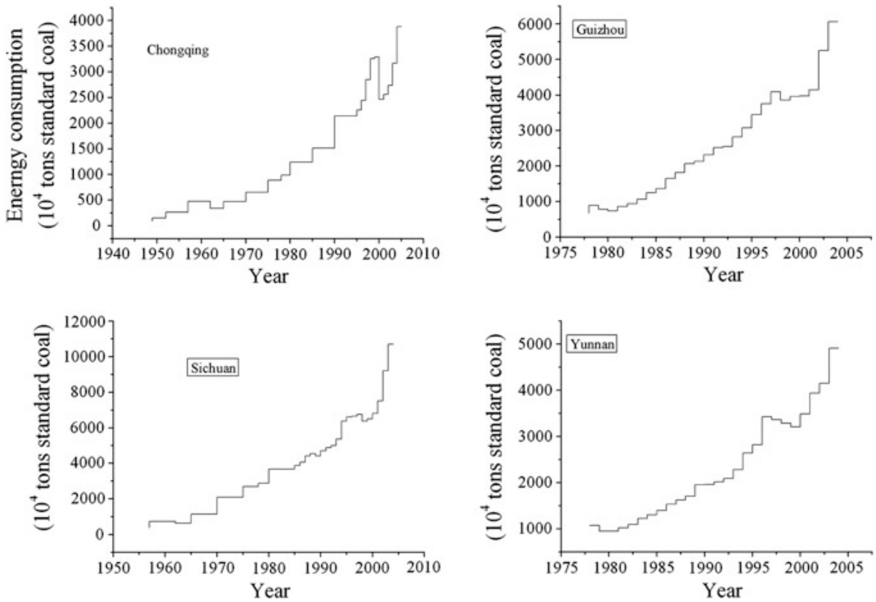

Fig. 5.13 The variation of energy consumption in Southwestern China. Reprinted from Li et al. (2012), with kind permission from Springer Science+Business Media

According to the statistical yearbook, the energy consumption in Chongqing of 1949–2004, Sichuan of 1957–2004, Yunnan and Guizhou of 1978–2004, especially in the 1980s increased significantly. And the energy consumption of above provinces before 2004 were 42.6, 28.3, 9 and 4.6 times as much as that of 1949, 1957, and 1978, respectively (Fig. 5.13). Under this background, the discharges of industrial waste gas, industrial sulfur dioxide and industrial soot all significantly increased in Southwestern China (Table 5.6), which reflected the deterioration of the air pollution in the studied area and the increase of concentration of atmospheric aerosol to some extent. What need to be stressed is that the discharges of atmospheric pollutants in studied area appeared a reduce trend in recent years under the strict air pollution control (Table 5.6), which is beneficial to reduce the concentration of atmospheric aerosol. However, the sunshine hour in studied area had shown a increasing trend from 1990s instead of an opposite trend to energy consumption.

The coal-fired heating of most areas in China generated the concentration of atmospheric aerosol in winter was significantly higher than the summer, in other words, the influence of aerosol concentration on the sunshine hour in winter was usually greater than in summer (An et al. 2000; Ma et al. 2005; Niu et al. 2006; Wu et al. 1999; Yu et al. 2002). As shown in Table 5.5, the decreasing magnitude was maximum in summers of 1961–2008 either in urban station or in rural station. From 1991 to 2008, the sunshine hour in summer in both urban and rural station showed a decline trend. Although the winter sunshine also had a decreasing trend, the magnitude was apparently less than summer and autumn. In addition, a common

Table 5.6 Atmosphere pollution discharge and controlling industrial waste gas in Southwestern China during 1990–2008

Year	1990	1995	1998	1999	2000	2002	2003	2004	2005	2006	2007	2008	2009
Total volume of industrial waste gas discharge (10^8 m^3)	1×10^4	1.3×10^4	1.1×10^4	1.3×10^4	1.33×10^4	1.6×10^4	1.7×10^4	2×10^4	2.1×10^4	3×10^4	4.9×10^4	3.6×10^4	4.3×10^4
Total amount of industrial sulfur dioxide discharge (10^4 tons)	222	154			262		260	273	291	333	307	276	163
Total amount of industrial fumes discharge (10^4 tons)	100	117	107	133	150	122	123	121	114	94	79	62	55
Area of soot control zones (km^2)					1548		2,220	2,558	2,438	2,779	821	799	
The investment costs on controlling industrial waste gas (10^4 Yuan)			2.7×10^4	4.1×10^4	8.7×10^4	6×10^4	7.6×10^4	16.3×10^4	19.4×10^4	25.8×10^4	30×10^4	24×10^4	17×10^4

Reprinted from Li et al. (2012), with kind permission from Springer Science+Business Media pattern was that the aerosol concentration of urban region was significantly higher than that of suburbs, and that of big cities was higher than medium and small cities. The big cities of Southwestern China, such as Guiyang and Kunming had the higher decreasing magnitude of sunshine hour in 1961–2008. Guiyang was −120.9 h/10 a and Kunming was −108.4 h/10 a. While the sunshine hour of Kunming in 1991–2008 increased at the rate of 16.5 h/10 a, and the decreasing magnitude of sunshine hour in Guiyang reduced 65.9 h/10 a compared with 1961–1900. The phenomenon that sunshine hour did not decrease with the acceleration of urbanization process may suggested the faint influence of urbanization process. More importantly, since 1990s, the remarkable achievements in the control of atmospheric pollution had been made in the two cities, and the discharge of industrial fumes, industrial dust and industrial sulfur dioxide decreased year by year (Fig. 5.14). At the same time, the removal of industrial fumes, industrial dust and industrial sulfur dioxide increased year by year (Table 5.7). Based on this, it was deduced that the prominent achievements of atmospheric pollution control had a

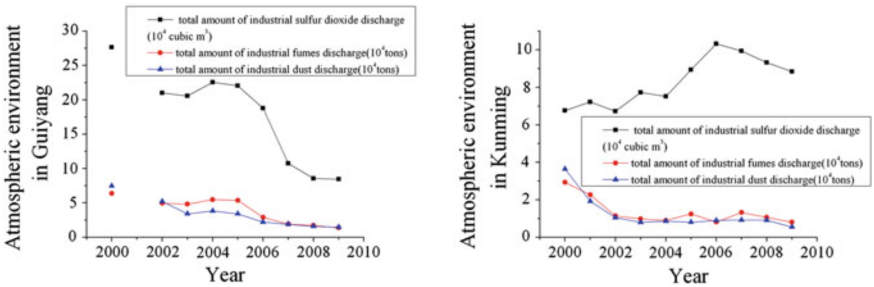

Fig. 5.14 The discharging atmospheric pollutes in Guiyang and Kunming during 2000–2008

Table 5.7 Controlling on atmosphere pollution discharge in Kunming and Guiyang during 2003–2008

		2003	2004	2005	2006	2007	2008	2008
Kunming	Total amount of industrial sulfur dioxide discharge (104 tons)	32.6	36.3	42.5	42.0	55.0	63.2	59.3
	Total amount of industrial fumes discharge (104 tons)	62.5	62.7	86.5	105.6	125.1	125.2	130.7
	Total amount of industrial dust discharge (104 tons)			78.2	68.7	65.7	41.0	42.8
Guiyang	Total amount of industrial sulfur dioxide discharge (104 tons)	8.2	8.2	9.1	15.0	14.6	24.1	18.8
	Total amount of industrial fumes discharge (104 tons)	12.7	13.5	13.6	84.9	99.5	95.5	110.9
	Total amount of industrial dust discharge (104 tons)			30.4	33.3	33.6	32.2	41.4

positive effect on the increase of the sunshine hour in recent years. A conclusion can be made from the above analysis that the rapid urbanization process is not the main influencing factor of differences between urban and rural station in changing magnitude of sunshine hour. And the basic reason is that the urban stations are mainly located in Yunnan-Guizhou Plateau and Sichuan Basin where are the wider margin of decrease occurred in 1961–2008. Furthermore, the stations at low altitude also had a significant increase in 1991–2008 (Figs. 5.6, 5.7 and 5.8).

5.3.4 Correlation with Sunshine Hour and Other Meteorological Factors

In order to further understand the influence of meteorological factors to sunshine hours, this study analyzed the correlation in 1961–2008 with annual downward solar radiation flux absorbed by ground surface, total area of the cloud, water content of the clouds and sunshine hour by using the reanalysis data. As shown in Fig. 5.15, the annual mean downward solar radiation flux absorbed by ground surface decreased in 1980s and continued to increase after 1990. This trend was same to that of sunshine hour. In addition, their statistically significant positive correlation level also supported it (Table 5.8), and evidenced again the increasing

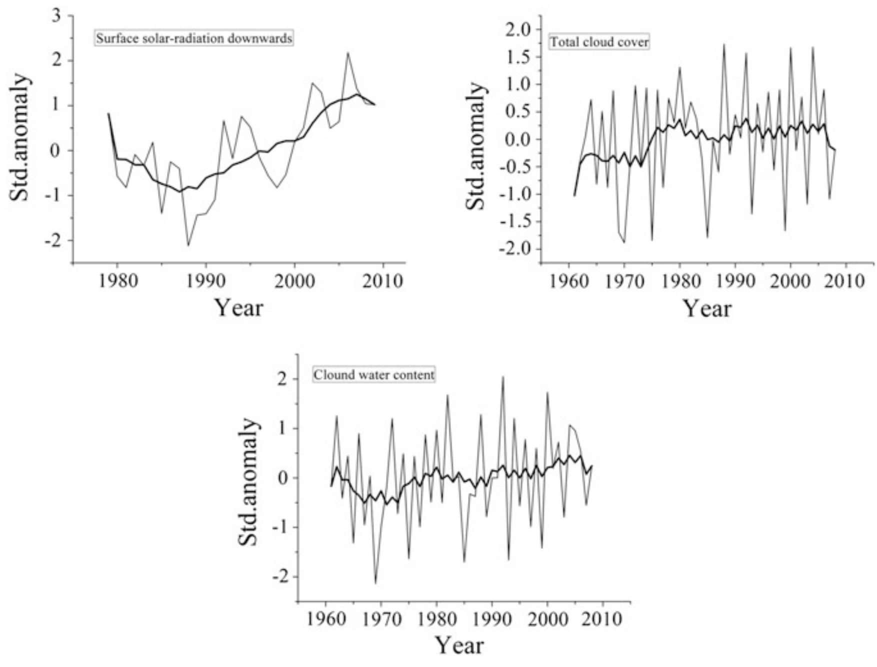

Fig. 5.15 Variations of other meteorological factors in Southwestern China

Table 5.8 Correlation coefficients between sunshine hours and precipitation, downwards solar radiation flux and relative humidity on the annual and seasonal basis in Southwestern China during 1961–2008

	Period	Annual	Winter	Spring	Summer	Autumn monsoon	Winter monsoon	Summer
Precipitation	1961–2008	**−0.29**	**−0.52**	**−0.29**	**−0.73**	**−0.31**	**−0.48**	**−0.4**
Downwards solar radiation flux	1979–2008	**0.77**	**0.75**	0.27	**0.46**	**0.62**	**0.55**	0.25

Values for correlation coefficients significant at the 5 % level are set in bold

trend of sunshine hour since 1990s in Southwestern China. In terms of total area of cloud, it showed a slightly wavelike change in 1961–2008, and became stable after 1980 (Fig. 5.15). The maximum area of clouds is 72 %, and the minimum is 66 %. This faint change had a big difference from the changing trend of sunshine hour in the studied area. However, a large number of studies thought the increase of cloud cove will lead to the less sunshine hour. For example, the increase of cloud cove caused that the sunshine hours in the central and east of Qinghai-Xizang Plateau decreased year by year since 1983 (You et al. 2010a, b). Kaiser (1998, 2000) analyzed the change of cloud cover of 196 stations in 1954–1996 and found that most stations showed a decreasing trend. Qian et al. (2007) analyzed the total cloud cove and low cloud cover of China from 1954 to 2001 by using the observation data of 537 stations and got a same conclusion. The existing researches on cloud cover also pointed out that the total cloud cover in most areas of Tibetan autonomous region showed a trend of significant reduction in 1971–2008 (Tang and Li 2003). The total cloud cove and low cloud cover of 85 stations in Southwestern China excluding Xizang Province exhibited a decreasing trend in 1960–2005 (Zhang et al. 2011a, b). Based on this, it is possible that the reduction of cloud cover has beneficial effects to the sunshine hour in studied area in recent years, but the detailed influence mechanism needs to be analyzed by means of observation data. The cloud water content increased continuously after declining in 1960s, which is just opposite to the change of sunshine hour (Figs. 5.16 and 5.17). More importantly, a significantly negative correlation with annual and seasonal sunshine hour

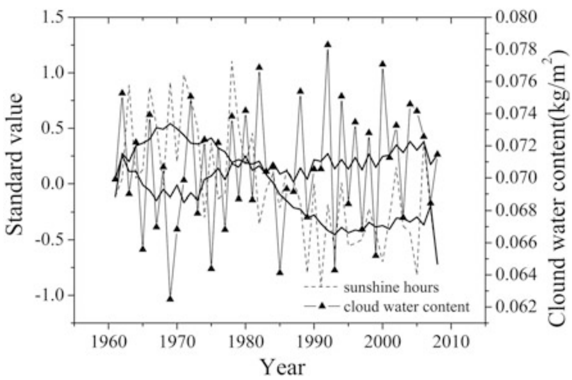

Fig. 5.16 Variation of annual mean sunshine hours and cloud water content during 1961–2008 in Southwestern China

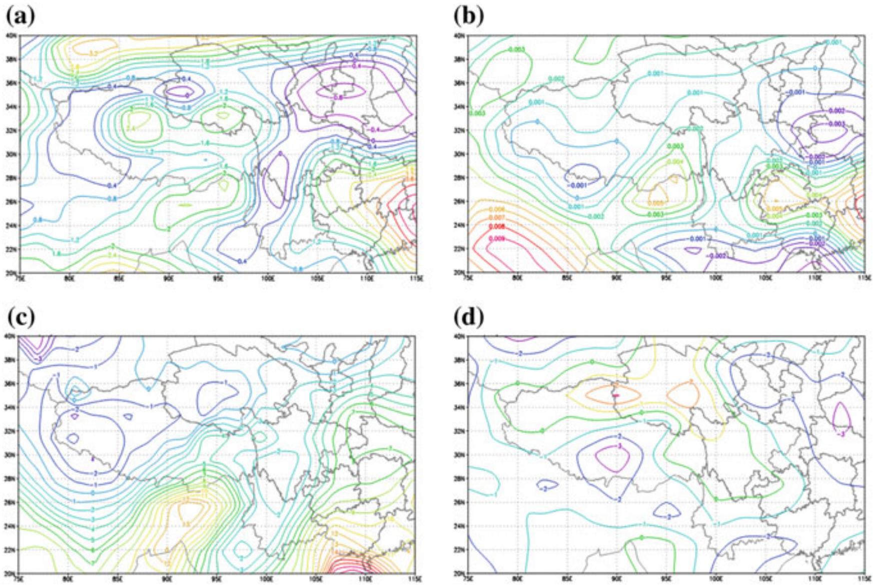

Fig. 5.17 Difference of total cloud cover (**a**) and cloud water content (**b**) between 1961–1970 and 1971–1980, and differences of the downwards solar-radiation flux (**c**) and relative humidity (**d**) from 1981–1990 to 1991–2000 at 300 hPa in Southwestern China

and precipitation was shown, especially in summer (Table 5.8), indicating again the impact of precipitation and water vapor content in the air on the sunshine hour. Because this region is a monsoon climate zone, the precipitation and cloudy days mainly concentrated in summer and autumn, which also partly explains the wider margin of reduction of sunshine hours in these two seasons, particularly the summer sunshine hour in 1991–2008 significantly reduced. In addition, the analysis of the reanalysis data revealed that annual cloud area showed a increasing trend from 1961–1970 to 1971–1980 and the cloud water content also increased. These features may partly explained the increase of sunshine hour in 1960s and the decrease in 1970s (Fig. 5.17). Downward solar radiation flux had been on the rise from 1981–1990 to 1991–2000, and the relative humidity in Southwestern China excluding Hengduan Mountain deceased, which was same to the observation data from ground stations and may partly explained the increase of sunshine hours after 1990 (Fig. 5.17).

5.3.5 Correlation with Sunshine Hour and Altitude

As above analysis mentioned, in 1961–2008, the stations with a wider margin of decrease in sunshine hour were mainly distributed in low altitude are, reflected from the decrease of sunshine hour along with the rise of altitude (Fig. 5.18). Except for

Table 5.9 The relationship between trends in sunshine hours and altitude or topography during 1961–2008

		Number	Annual	Winter	Spring	Summer	Autumn monsoon	Winter monsoon	Summer
	Correlation coefficient with altitude		0.2	0.28	0.12	0.46	0.02	0.23	0.29
Trends	Summit	2	−19.357	−7.6134	−4.4285	−7.3897	−0.2995	−12.431	−6.9495
	Valley	35	−32.2346	−3.13704	−6.22503	−13.5846	−4.23708	−7.05624	−20.1829
	Intermountain	34	−20.5165	−1.41086	−4.85116	−11.4071	−0.49509	−3.68912	−15.1043
	Flat	40	−50.6249	−8.29636	−11.8654	−23.2995	−4.93283	−17.1948	−31.4615
Percent with decreasing stations	Summit		50 % (50 %)	50 % (50 %)	50 % (50 %)	50 % (0 %)	50 % (50 %)	50 % (50 %)	50 % (50 %)
	Valley		86 % (60 %)	57 % (23 %)	80 % (23 %)	94 % (43 %)	74 % (23 %)	66 % (20 %)	91 % (46 %)
	Intermountain		62 % (44 %)	62 % (12 %)	71 % (26 %)	74 % (41 %)	41 % (21 %)	59 % (24 %)	71 % (44 %)
	Flat		88 % (73 %)	83 % (38 %)	88 % (45 %)	90 % (65 %)	70 % (25 %)	85 % (53 %)	90 % (68 %)

Values in braces is the percentage of stations with significant decreasing trend the summer and monsoon, the sunshine hour did not have a significantly statistical relationship with the altitude, which suggested that there was no obvious altitude dependence in sunshine hour of studied area (Table 5.9). In terms of terrain influence, flat station had the widest margin of decrease in sunshine hour, in turn followed by valley station, intermontane station and summit station. The spring, summer, autumn and summer monsoon sunshine hour also had similar features. And the magnitude of decrease in summit station during winter and winter monsoon period was apparently greater than in valley and intermontane station but less than in flat station (Table 5.9). The percentage of stations with significant decrease trend also showed a same change that it declined from flat station to summit station in turn during the annual, spring and winter monsoon period and it declined from valley, flat, intermontane and summit station in turn during summer, autumn and summer period (Table 5.9). On the whole, the maximum margin of decrease occurred in fault station, and the minimum occurred in summit stations, which may be related to wind speed because generally the wind speed in summit station was stronger than other types of stations.

5.4 Summary

This chapter focuses on the analysis of the temporal and spatial variation as well as the influencing factors of sunshine hours in Southwestern China in 1961–2008. The results can be showed as following:

(1) It is very obvious that the sunshine hours changes in different stages. The annual mean sunshine hour was 1894 h in 1961–2008. The larger values of annual mean sunshine hours were mainly distributed in the high altitude areas, such as Xizang Plateau, Hengduan Mountain and Yunnan Plateau, while the lower values were in the low altitude area, such as Guizhou Plateau and Sichuan. The annual mean sunshine hour sharply decreased at the rate of 31.9 h/10 a in 1961–2008, and the interannual changes were performed by the increase of 1960s, the continuous decrease during 1970–1990 and the rise afterward. The seasonal sunshine hours also had a drop before 1990, then grew up apparently, and the decline trend is remarkable in summer and summer monsoon period. The decreasing magnitude of sunshine hour in 1961–1990 was greater than that of entire studied period, while the sunshine hour was on a significant rise in 1991–2008 except for in spring.

(2) The sunshine hours change is more significant in low altitude area. The sunshine hour of about 59 % of stations in the studied stations decreased significantly in 1961–2008 which were mainly distributed in low altitude area, especially in Guizhou Plateau and Sichuan Basin. Whereas most stations in high altitude areas showed a slight decreasing or increasing trend. The stations with a decline were mainly distributed in low altitude area from 1961 to 1990, while the station showing a increasing trend were located in high altitude

areas. There were about 61 % of the stations showing a rising stations in sunshine hour from 1991 to 2008 which were primarily situated in low altitude area. Different from the temperature and precipitation, the sunshine hours changes in the studied area did not represent a obvious correlation with altitude yet. In terms of the influence of terrain, the widest margin of decrease occurred in flat stations, and the next two were valley and intermountain station. The least magnitude appeared in summit stations.

(3) The wind speed and humidity are the main influencing factors of sunshine hours in the studied areas. Except for in autumn, the wind speed had a significant correlation with sunshine hours change in 1969–2008, and they had same changing trend. The magnitude of decrease of sunshine hour in 1969–2000 was apparently greater than in 2001–2008, and the spatial distribution pattern of them were similar to that of wind speed during a same period. In addition to the spring and autumn, the sunshine hours of stations where the wind speed was less than 1.5 m/s decreased much more sharply than that of stations where the wind speed was more than 1.5 m/s, and the percentage of former stations was greater than the latter ones. The humidity was the other influencing factor of sunshine hour changes. The opposite changing trend to sunshine hour was showed by humidity in 1961–2008, and the annual and seasonal changes had a significant correlation with sunshine hours because the water vapor in the air could weaken the solar radiation by absorbing, scattering and reflecting etc. In addition, the sunshine hours changes also had a apparent correlation with the change of downward solar radiation flux, cloud water content, area of cloud cover and precipitation.

(4) There is little correlation between accelerated urbanization process and sunshine hours. The changing magnitude and percentage of urban stations with a dropping trend were much greater than rural stations in 1961–2008, and the increase magnitudes of annual, spring, autumn, winter and winter monsoon sunshine hours in urban stations were greater than rural stations. However, the sunshine hour change did not show a reverse trend to accelerated urbanization process. There was not reverse trend between sunshine hour and the increase of aerosol concentration caused by energy consumption. The influence of aerosol concentration on sunshine hour in winter is generally greater than in summer. Either in urban or rural stations, the summer sunshine hour decreased most sharply in 1961–2008, and only the changing magnitude of sunshine hours in summer was negative during 1991–2008. The decreasing magnitude of sunshine hour in Guiyang and Kunming were maximum in their province. While the sunshine hour in Kunming increased in 1991–2008, and obviously, the decreasing magnitude in Guiyang was less than 1961–1990. Further analysis found that the root cause of differences between urban and rural stations in sunshine hours is that the urban stations are mainly located in low altitude areas, such as Guizhou Plateau and Sichuan Basin where the decreasing magnitude of sunshine hour was maximum in 1961–2008 and the increasing magnitude was more significant in 1991–2008.

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Chapter 6
Spatial and Temporal Variation of Wind Speed in Southwestern China

6.1 Temporal Variation of Wind Speed

6.1.1 The Mean Wind Speed

The annual mean wind speed in Southwestern China was 1.75 m/s in 1969–2008. The annual mean maximum wind speed was 4.26 m/s occurred in Bange of Tibet Autonomous Region, and the minimum wind speed was 0.54 m/s occurred in Wanxian of Sichuan Province. The seasonal mean wind speed was greatest in spring (2.15 m/s) followed by winter (1.78 m/s), summer (1.61 m/s) and autumn (1.47 m/s) in turn. The minimum wind speed in spring, summer, autumn and winter were respectively 0.69, 0.59, 0.35 and 0.35 m/s, and the maximum wind speed in turn were 4.80, 3.96, 3.71 and 5.00 m/s. The annual, maximum and minimum wind speed in summer and winter monsoon period were 1.80, 0.55, 3.61 and 1.51, 0.59, 2.87 m/s. West wind circulation is a key one to influence the climate change in winter monsoon in Southwestern China, so the high value of wind speed in studied area primarily appeared in winter half year. As shown in Fig. 6.1, the station with the annual mean maximum wind speed were mainly distributed in Xizang Plateau, Hengduan Mountain and the central of Yunnan–Guizhou Plateau. While the wind speed of most stations in the east and west of Yunnan–Guizhou Plateau and Sichuan Basin was weaker. The seasonal mean wind speed also had a same distribution pattern. Overall, annual mean wind speed weakened from west to east, which reflecting the influence of terrain. The annual mean wind speed of Xizang Plateau–Hengduan Mountain was 2.15 m/s, which obviously greater than the mean of Southwestern China and other two regions. Its means in spring, summer, autumn, winter, summer monsoon and winter monsoon were respectively 2.67, 1.91, 1.78, 2.2, 2.32, and 1.97 m/s, which all more than the corresponding values in the studied area. The annual mean wind speed was 1.66 m/s, and the means in spring, summer, autumn, winter, summer monsoon and winter monsoon were respectively 2.01, 1.5, 1.37, 1.73, 1.8 and 1.51 m/s, which lower than that of Xizang Plateau–Hengduan

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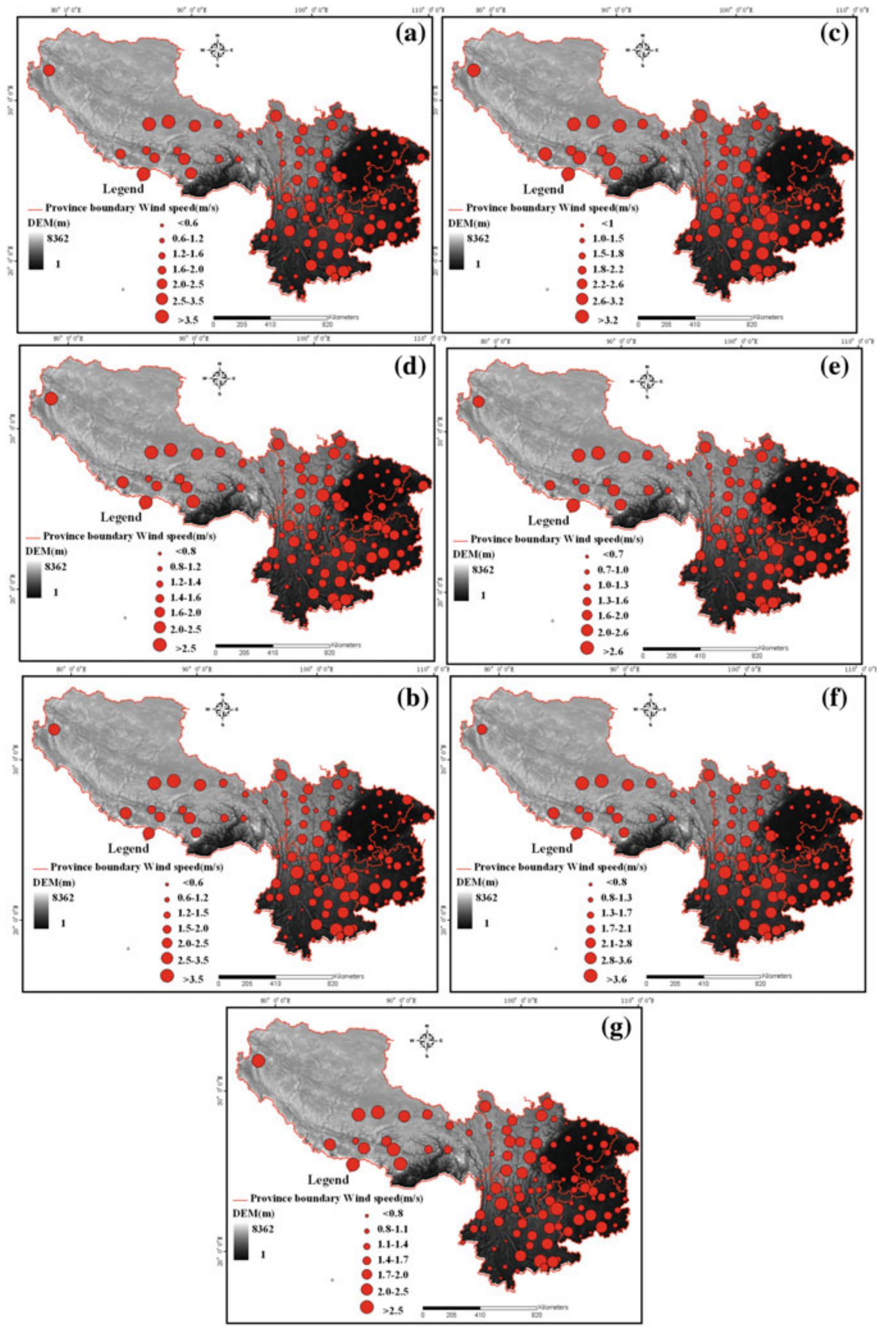

Fig. 6.1 Spatial distribution of annual mean wind speed during 1969–2008, **a** annual wind speed, **b** winter wind speed, **c** spring wind speed, **d** summer wind speed, **e** autumn wind speed, **f** WMP wind speed, **g** SMP wind speed

Mountain, but greater than that of Sichuan Basin. The annual and seasonal mean, maximum and minimum wind speed all were the smallest among these three regions. These differences reflected again the influence of the terrain and altitude on annual mean wind speed.

6.1.2 The Interannual Variation of Wind Speed

The annual mean wind speed of studied area significantly decreased at the rate of 0.24 m/s/10 a in 1969–2008, and the decreasing rate (0.37 m/s/10 a) in 1969–2000 was remarkably greater than that in 1969–2008, furthermore the wind speed increased apparently at the rate of 0.55 m/s/10 a in 2001–2008 (Fig. 6.2). In 1969–1990, the annual mean wind speed in China had a significant drop at the rate of −0.25 m/s/10 a and decreased drastically to −0.06 m/s/10 a, which was similar to the change trend of Southwestern China (Gao et al. 2010). From the results of comparison in Table 6.2, the decreasing magnitude of studied area in wind speed was greater than the mean level of China and other regions, and the changing trend in spring, summer, autumn, winter, summer monsoon and winter monsoon were similar to the annual trend in 1969–2008 (Fig. 6.2), corresponding change trends in every season were −0.28, −0.16, −0.14, −0.22, −0.26 and −0.18 m/s/10 a. The changing magnitude in wind speed respectively were −0.35, −0.26, −0.30, −0.38, −0.39 and −0.29 m/s/10 a in 1969–2000, which all were greater than the decreasing magnitude in the whole studied area. In 2001–2008, the seasonal variation trends in wind speed were 0.13, 0.13, 0.13, 0.82, 0.33 and 0.74 m/s/10 a, among which only spring had not passed the significance test (Table 6.1). The maximum decrease in studied area happened in winter and spring, while the maximum occurred in autumn, moreover, the increasing magnitude in summer was the maximum since 2001. The seasonal decrease in Southwestern China was apparently greater than in China and Northern China, but less than Northeastern China and Qinghai-Xizang Plateau (Table 6.2). In short, the annual and seasonal wind speed in 1969–2008 displayed an evidently decrease in studied area, but a sharp rise turned up after 2000. This change meaned that the increase of wind speed also needed to be verified in further observation data.

As shown in Table 6.1, although the annual mean wind speed of three sub-regions during 1969–2008 showed a decline trend, there were some differences in the changing trends. In 1960s, the wind speed in Xizang Plateau–Hengduan Mountain increased and had a significant drop in 1970–2000, then displayed an rising trend. While the wind speed in Yunnan–Guizhou Plateau and Sichuan Basin continued to decrease before 2000 and fluctuated to increase afterward. The annual and seasonal decrease magnitude in wind speed of Xizang Plateau–Hengduan Mountain succeeded in passing the significance test in 1969–2008 and apparently greater than that of Yunnan–Guizhou Plateau and Sichuan Basin. The dropping magnitude of Sichuan Basin in summer and autumn was really small and had not passed the significance test. In addition, the wind speed of Yunnan–Guizhou

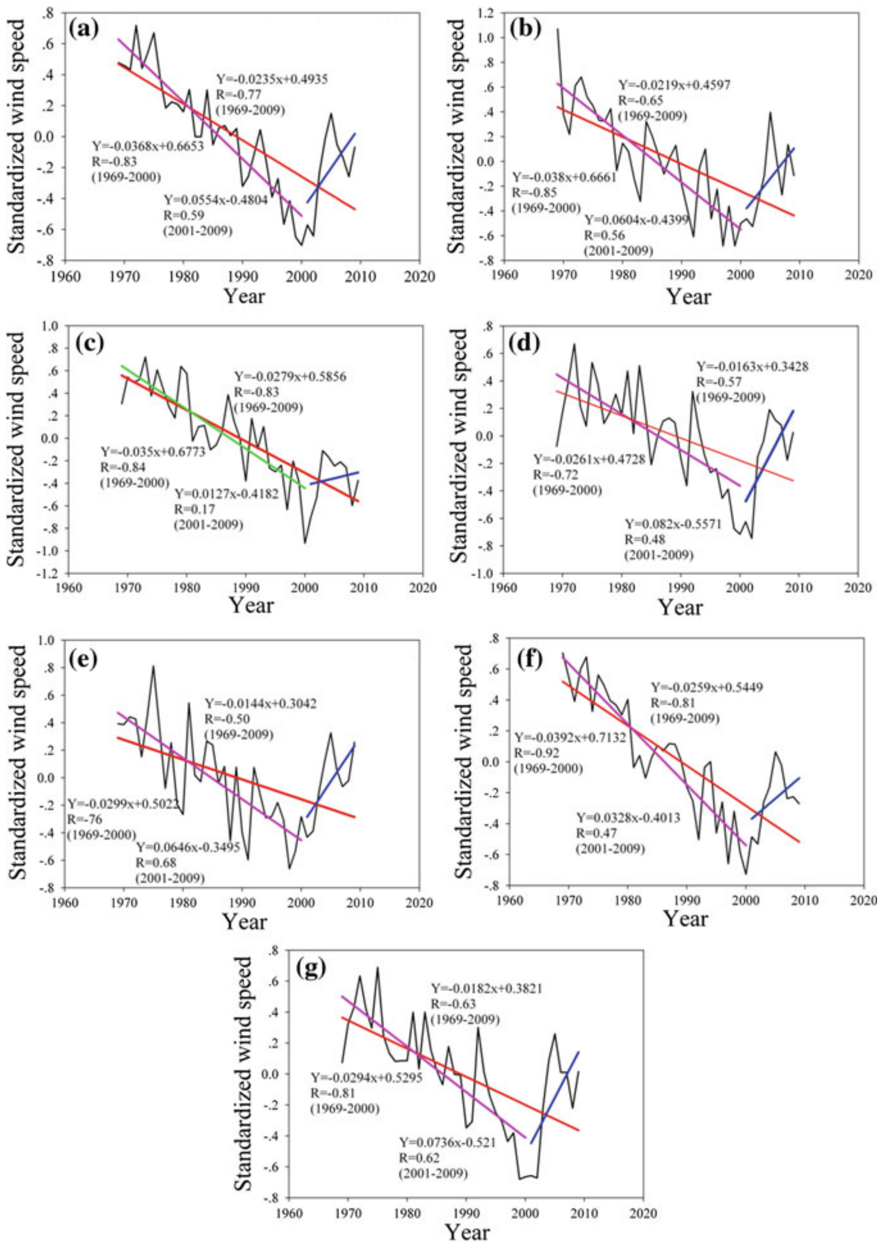

Fig. 6.2 Annual and seasonal variations of wind speed in Southwestern China. Reprinted by permission from Macmillan Publishers Ltd: Yang et al. (2012). Copyright (2012), **a** annual, **b** winter, **c** spring, **d** summer, **e** autumn, **f** winter monsoon period, **g** winter monsoon period

Table 6.1 Annual mean wind speed (m/s) and regional trends (m/s/10 a) in three sub-regions of Southwestern China

Sub-region	Mean wind speed	Annual	Spring	Summer	Autumn	Winter	Winter monsoon	Summer monsoon
XPHM	Mean	2.15	2.67	1.91	1.78	2.2	2.32	1.97
	Maximum	0.76	0.88	0.89	0.61	0.64	0.69	0.82
	Minimum	4.26	4.8	3.96	3.72	5.01	4.89	3.84
SB	Mean	1.27	1.49	1.29	1.12	1.16	1.26	1.26
	Maximum	0.54	0.64	0.59	0.35	0.35	0.45	0.57
	Minimum	3.05	3.14	2.79	2.84	3.41	3.3	2.79
YGP	Mean	1.66	2.01	1.5	1.37	1.73	1.8	1.51
	Maximum	0.63	0.76	0.59	0.45	0.5	0.55	0.59
	Minimum	3.09	3.99	2.79	2.81	3.57	3.61	2.87
	Regional trend	Annual	Spring	Summer	Autumn	Winter	Winter monsoon	Summer monsoon
XPHM	1969–2008	**−0.43**	**−0.5**	**−0.42**	**−0.39**	**−0.4**	**−0.46**	**−0.45**
	1969–2000	**−0.51**	**−0.47**	**−0.49**	**−0.53**	**−0.51**	**−0.54**	**−0.53**
	2001–2008	**0.89**	**0.45**	**1.14**	**1.02**	**0.94**	**0.77**	**1.04**
SB	1969–2008	**−0.16**	**−0.22**	**−0.11**	**−0.07**	**−0.15**	**−0.2**	**−0.11**
	1969–2000	**−0.4**	**−0.39**	**−0.31**	**−0.31**	**−0.42**	**−0.46**	**−0.32**
	2001–2008	**0.94**	**0.42**	**1**	**0.82**	**1.21**	**0.87**	**0.92**
YGP	1969–2008	**−0.13**	**−0.2**	−0.006	0.008	**−0.14**	**−0.15**	−0.04
	1969–2000	**−0.27**	**−0.31**	−0.11	**−0.17**	**−0.31**	**−0.31**	**−0.17**
	2001–2008	**0.38**	−0.09	**0.77**	**0.68**	**0.29**	0.02	**0.75**

Values for trends significant at the 5 % level are set in bold

Table 6.2 Wind speed trends in China and its regions (m/s/10 a)

	Period	Annual	Spring	Summer	Autumn	Winter	Sources
Heilongjiang	1961–2004	−0.31	−0.40	−0.23	−0.30	−0.32	Zhou et al.–
Chongqing	1961–2007	−0.04					Li et al. (2010)
Tibetan Plateau	1980–2005	−0.24	−0.29	−0.24	−0.19	−0.23	You et al. (2010)
North China Plain	1951–2006	−0.16	−0.19	−0.10	−0.15	−0.22	Liu et al. (2009a, b)
Northeastern China	1961–2000	−0.23	−0.33	−0.16	−0.18	−0.24	Yang
China	1969–2005	−0.18	−0.21	−0.15		−0.19	Guo et al. (2010)

Plateau had weaker changes in above seasons. Except that the decreasing magnitude of Yunnan–Guizhou Plateau in summer failed to pass the significance test, the remarkable increasing magnitude in these three regions had passed the significance test compared with that of 1969–2000. As the whole, the dropping magnitude of Xizang Plateau–Hengduan Mountain was greatest and the Sichuan Basin followed. In 2001–2008, in addition to a faint declines in spring and winter monsoon wind speed of Yunnan–Guizhou Plateau, others all exhibited a significant increase, and among them, the increasing magnitude in summer and autumn were maximum. The rising magnitude of Sichuan Basin in annual, winter and winter monsoon period became wider. In other seasons, the increasing magnitude of Xizang Plateau–Hengduan Mountain was greatest and that of Yunnan–Guizhou Plateau was least (Table 6.1). In conclusion, the increasing and decreasing magnitude of wind speed in Xizang Plateau–Hengduan Mountain were maximum; the increasing magnitude in Sichuan Basin was greater but the decreasing magnitude was less; wind speed in Yunnan–Guizhou Plateau had a slight change and high stability.

6.2 Spatial Variation of Wind Speed

6.2.1 The Spatial Distribution of the Wind Speed Variation Between 1969–2008 and 1969–2000

The annual mean wind speed of about 77 % of the 110 stations in 1969–2008 displayed a decreasing trend, and the stations with significant decrease trend accounted for 66 %. Excluding some stations with an increasing wind speed in the west of Yunnan Plateau, Guizhou Plateau and Sichuan Basin, several of which were characterized by a significant increase, most stations with a wider margin of decrease and having passed the significance test were mainly distributed in Xizang Plateau, Hengduan Mountain and Yunnan Plateau (Fig. 6.3). In 1969–2000, about

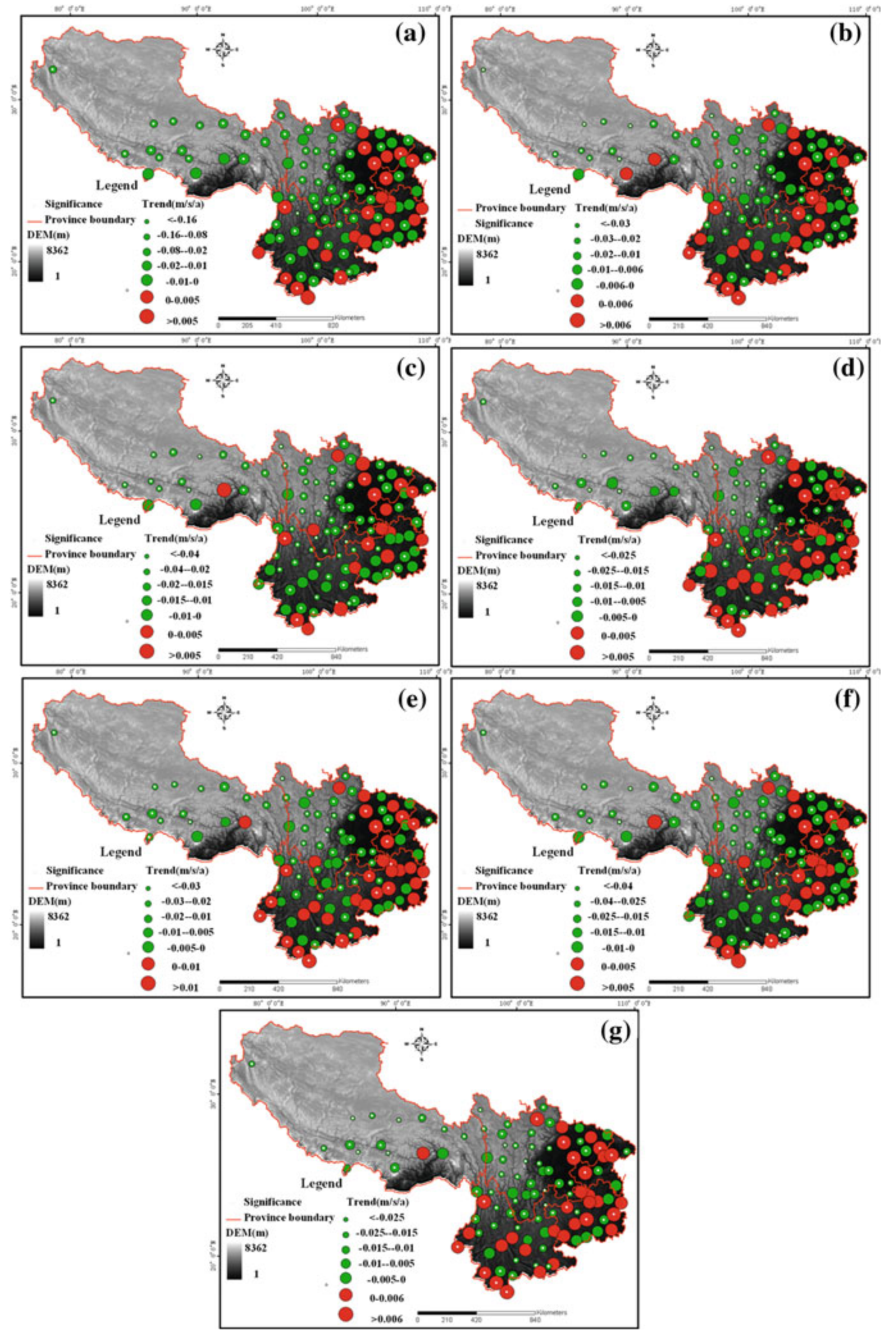

Fig. 6.3 Spatial distribution of variational trends in wind speed during 1969–2008. Reprinted from The Lancet: Yang et al. (2012). Copyright (2012), with permission from Elsevier, **a** annual, **b** winter, **c** spring, **d** summer, **e** autumn, **f** winter monsoon period, **g** summer monsoon period

82 % of the stations showed a dropping trend in wind speed and about 69 % of the stations significantly reduced. They were Xizang Plateau, Hengduan Mountain, Yunnan Plateau, the west of Guizhou Plateau and the east of Sichuan Basin, while a few stations in the southwest edge of Yunnan Plateau, the central of Guizhou Plateau and Sichuan Basin revealed a up toward trend (Fig. 6.4).

And the station passing the significance test accounted for 67 %. In addition to a few stations in Yunnan–Guizhou Plateau and Sichuan Basin, the stations with a wider margin of significant decrease were located in Xizang Plateau and Hengduan Mountain, whereas the stations at low altitude had a less drop (Fig. 6.3). There were 95 stations displaying a downtrend from 1969 to 2000 and 69 stations had passed the significance test. Among them, the stations with the significant decline trend were situated in Xizang Plateau, Hengduan Mountain and Yunnan Plateau, while the most stations in Guizhou Plateau and Sichuan Basin exhibited a non-significant decreasing trend and some stations had a increasing trend (Fig. 6.4). The autumn wind speed reduced in about 70 % of stations during 1969–2008, but the decreasing magnitude of just 48 % of stations located in the eastern Xizang Plateau and Hengduan Mountain had passed the significance test. While the most stations in Yunnan–Guizhou Plateau and Sichuan Basin had an increase or non-significant decrease (Fig. 6.3). From 1969 to 2000, there were about 78 % of 110 stations selected displaying a decrease, but just 59 % of stations declined significantly which were mainly distributed in Xizang Plateau, Hengduan Mountain and Yunnan Plateau. The stations with non-significant decrease or increase were primarily in the edge of Yunnan Plateau, Guizhou Plateau and Sichuan (Fig. 6.4). There were about 76 % of stations exhibiting a dropping wind speed in winter during 1969–2008, while just 57 % of stations located in Xizang Plateau–Hengduan Mountain declined significantly. The majority of stations in Yunnan–Guizhou Plateau and Sichuan Basin revealed a non-significant decrease or increase (Fig. 6.3). The wind speed of approximately 86 % of 110 stations was on the declined in 1969–2000 and 73 % of stations showed a significant decrease which were distributed in Xizang Plateau, Hengduan Mountain and Yunnan Plateau, while the non-significant decline or rise was displayed in some stations of Guizhou Plateau and Sichuan Basin (Fig. 6.4).

In springs of 1969–2008, approximately 84 % of the stations reduced in wind speed.

In winter monsoon period of 1969–2008, about 80 % of the stations dropped in wind speed and the decreasing magnitude of 65 % of stations which were situated in high altitude areas, such as Xizang Plateau, Hengduan Mountain and Yunnan Plateau had passed the significance test. Whereas the wind speed of a few stations in the southwest edge of Yunnan Plateau, Guizhou Plateau and the central of Sichuan had a rise. This distribution pattern reflected the significant influence of terrain (Fig. 6.3). About 87 % of the stations in Xizang Plateau, Hengduan Mountain and Yunnan Plateau showed a reducing trend from 1969 to 2000, among them, there were 76 % of stations significantly reducing. While the stations showing non-significant decrease were distributed in Guizhou Plateau and Sichuan Basin (Fig. 6.4). In the summer monsoon period of 1969–2008, the percentage of stations having a downtrend in the annual mean wind speed was 71 % which were mainly

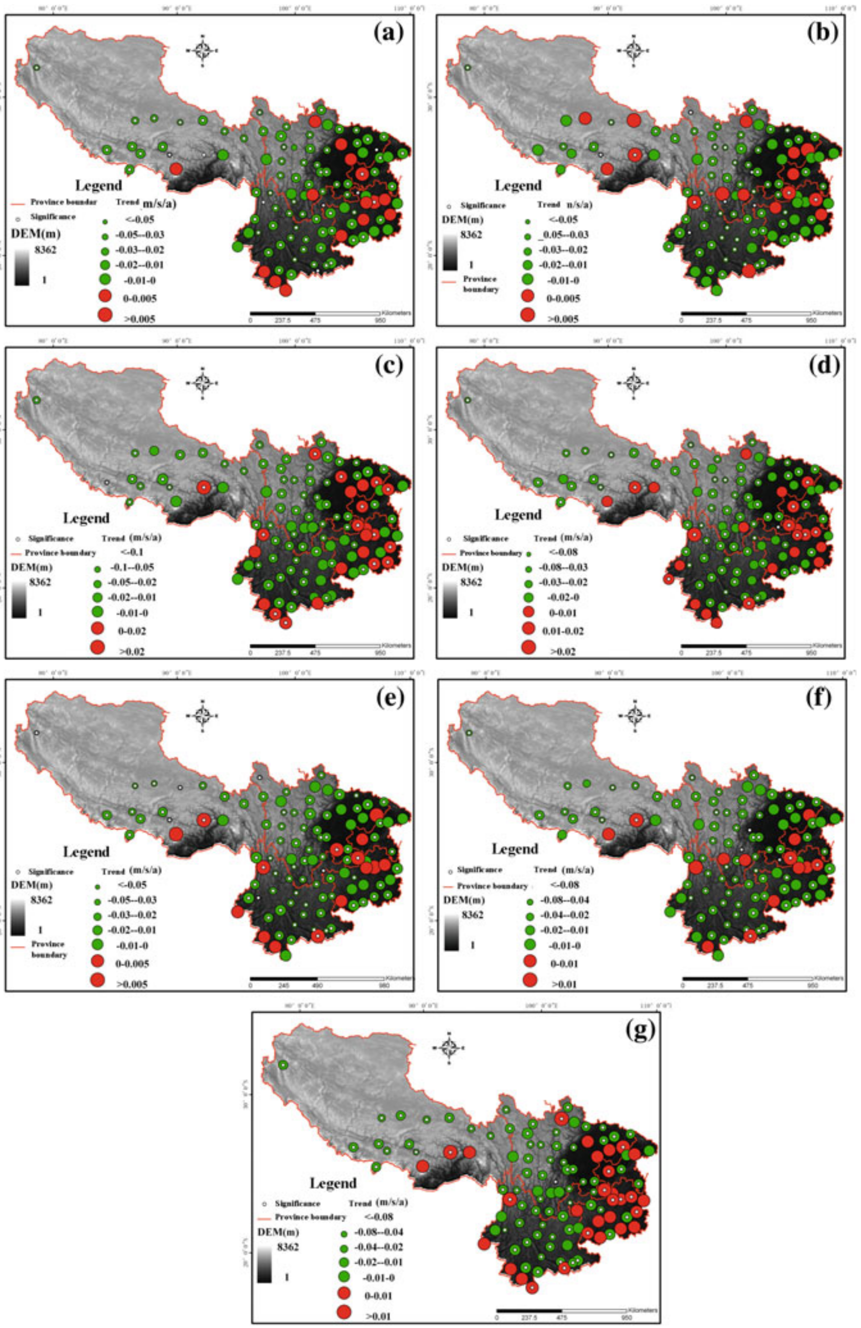

Fig. 6.4 Spatial distribution of variational trends in wind speed during 1969–2000, **a** annual, **b** winter, **c** spring, **d** summer, **e** autumn, **f** winter monsoon peroid, **g** summer monsoon period

located in Xizang Plateau–Hengduan Mountain and 56 % of them had passed the significance test, while the stations in Yunnan Plateau, Guizhou Plateau and Sichuan Basin increased and accounted for 29 % of all stations selected (Fig. 6.3). In 1969–2000, 73 % of all stations in Xizang Plateau, Hengduan Mountain and Yunnan Plateau had a dropping wind speed and the stations where the decreasing magnitude passed the significance test accounted for about 65 %. Thereinto, the increasing trend in Guizhou Plateau was most remarkable (Fig. 6.4). On the whole, the stations where the wind speed declined in 1969–2008 and 1969–2000 were mainly distributed in high altitude area, and in latter period there were more stations showing a significant decrease. In addition, the decreasing magnitude exhibited a reducing law from west to east, reflecting the impact of terrain.

6.2.2 Spatial Distribution of Wind Speed Variation

During 2001–2008 the annual mean wind speed reduced in the stations accounting for 35 % of all stations and located in Xizang Plateau and Guizhou Plateau. The stations with a wider margin of increase were mainly located in Hengduan Mountain, Yunnan Plateau and the western Sichuan Basin (Fig. 6.5). About 59 % of the stations in spring wind speed increased and a significant increase occurred in the stations accounting for 42 % of all stations in Hengduan Mountain, Yunnan Plateau and Sichuan Basin, while several stations in Xizang Plateau, the central of Hengduan Mountain and Guizhou Plateau revealed a decreasing trend, among them there were most stations declined significantly (Fig. 6.5). In 2001–2008, the summer wind speed in about 67 % of the stations in the studied area was on the rise and there were 55 % of the stations increased significantly which were mainly distribution in Hengduan Mountain, Yunnan Plateau and the western Sichuan Basin, while the several stations in the east of Xizang Plateau, Guizhou Plateau and the east of Sichuan Basin decreased significantly (Fig. 6.5). The autumn wind speed increase happened in the stations accounting for 66 % of 110 stations selected and the 56 % of the stations passed the significance test which were mainly distributed in Yunnan Plateau, Hengduan Mountain and the western Sichuan Basin. However, the most stations in Guizhou Plateau and the east of Xizang Plateau still showed a significant decrease tendency (Fig. 6.5). The wind speed increases appeared in about 65 % of the stations, and 51 % of the stations increase significantly. These stations were distributed in Hengduan Mountain, Yunnan Plateau and Sichuan Basin, while a number of stations in Xizang Plateau and Guizhou Plateau were on the decline (Fig. 6.5). About 63 % of the stations in winter monsoon wind speed increased, and 51 % of stations increased significantly, these stations are mainly located in Hengduan Mountain, Yunnan Plateau and Sichuan Basin, while a decreasing trend still appeared in the stations in the eastern Xizang Plateau, the southeastern Hengduan Mountain and southeastern Yunnan Plateau (Fig. 6.5). About 67 % of stations increased in summer wind speed during 2001–2008 and the dramatical increase in 58 % of the stations had pass the significance test.

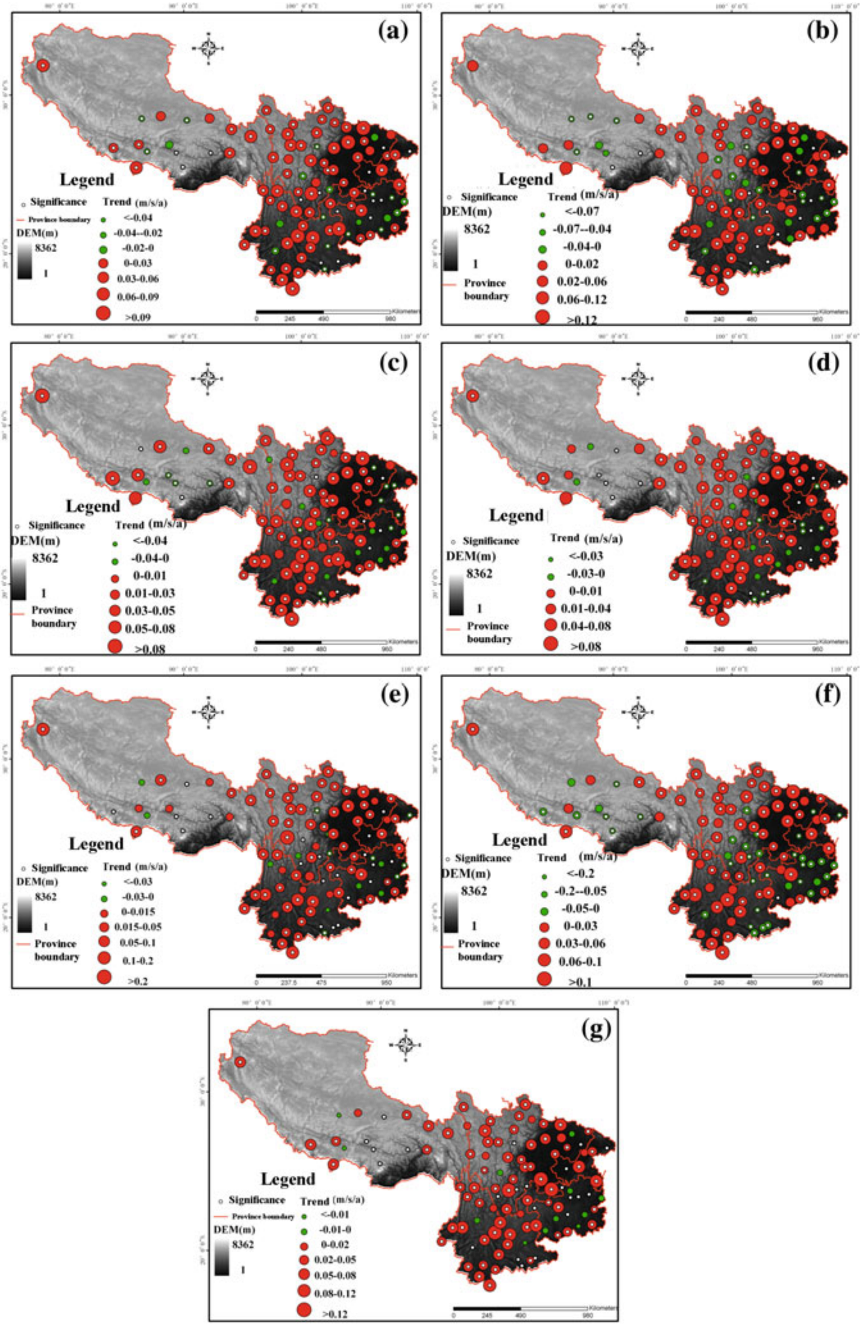

Fig. 6.5 Spatial distribution of variational trends in wind speed during 2001–2008, **a** annual, **b** winter, **c** spring, **d** summer, **e** autumn, **f** winter monsoon peroid, **g** summer monsoon period

These stations were mainly in other regions except for the east of Xizang Plateau and Guizhou Plateau (Fig. 6.5). All in all, in 2001–2008, the wind speed performing a increasing trend mostly were distributed in Yunnan Plateau, Hengduan Mountain and Sichuan Basin. And the stations with a decreasing wind speed were located in Xizang Plateau and Guizhou Plateau.

6.3 Driving Mechanism for Wind Speed

6.3.1 Correlation with Wind Speed and Large-Scale Atmospheric Circulation

In order to explore the influence of atmospheric circulation on wind speed, this study made an analysis on the variations of meridional and zonal wind through two periods. The 2000 year was the divide between them. This study also drew the difference figure of meridional and zonal wind between 1986–2000 and 1969–1985 at 500 hPa. The variation was revealed through latter period minus the former period. And the region range selected was 20°N–40°N and 75°E–115°E. More apparently, in addition to the western Xizang Plateau, the meridional wind had been showing a down toward trend from 1969–1985 to 1986–2000 in studied area and the zonal wind had a wider margin of decrease in latter period, suggesting that the weakening of wind speed of west wind circulation and monsoon circulation could be the main reason of the reduction of wind speed in studied area before 2000 (Fig. 6.6). The researches results of Dash et al. (2008) and Wu (2005) also confirmed that the Indian monsoon was in an unstable state and performed a decreasing trend in recent year. With the purpose of further analysis on the correlation with the variation of circulation system and the increasing of wind speed in 2001–2008, this study drew the difference figure of meridional and zonal wind between 1991–2000 and 2001–2008 at 500 hPa. The variation was revealed through latter period minus the former period. As shown in Fig. 6.7, overall, the meridional wind in Southwestern China exhibited a apparent reduce from 1991–2000 to 2001–2008, particularly in Xizang Plateau the decreasing magnitude was greatest. While the wind speed in Guizhou Plateau and Sichuan Basin had a upward tendency. Excepting for Yunnan Plateau, the zonal wind in studied area was on the obvious rise. Above results indicated that the strengthening of zonal wind might play an important role on the increasing of wind speed in Southwestern China since 2000. And the IPCC's fourth assessment report (2007) also confirmed the apparent strengthening trend in the west wind circulation of the northern hemisphere.

From the analysis of seasonal variation of meridional and zonal wind in 1969–1985 and 1986–2000 (Fig. 6.8), it was found that the spring wind speed of meridional and zonal wind in studied area was stronger in latter period than in former period, which demonstrated the faint increase. While the wind speed also declined significantly in former period. The summer and autumn zonal wind in 1986–2000 was greater than in 1969–1985, and the meridional wind strengthened

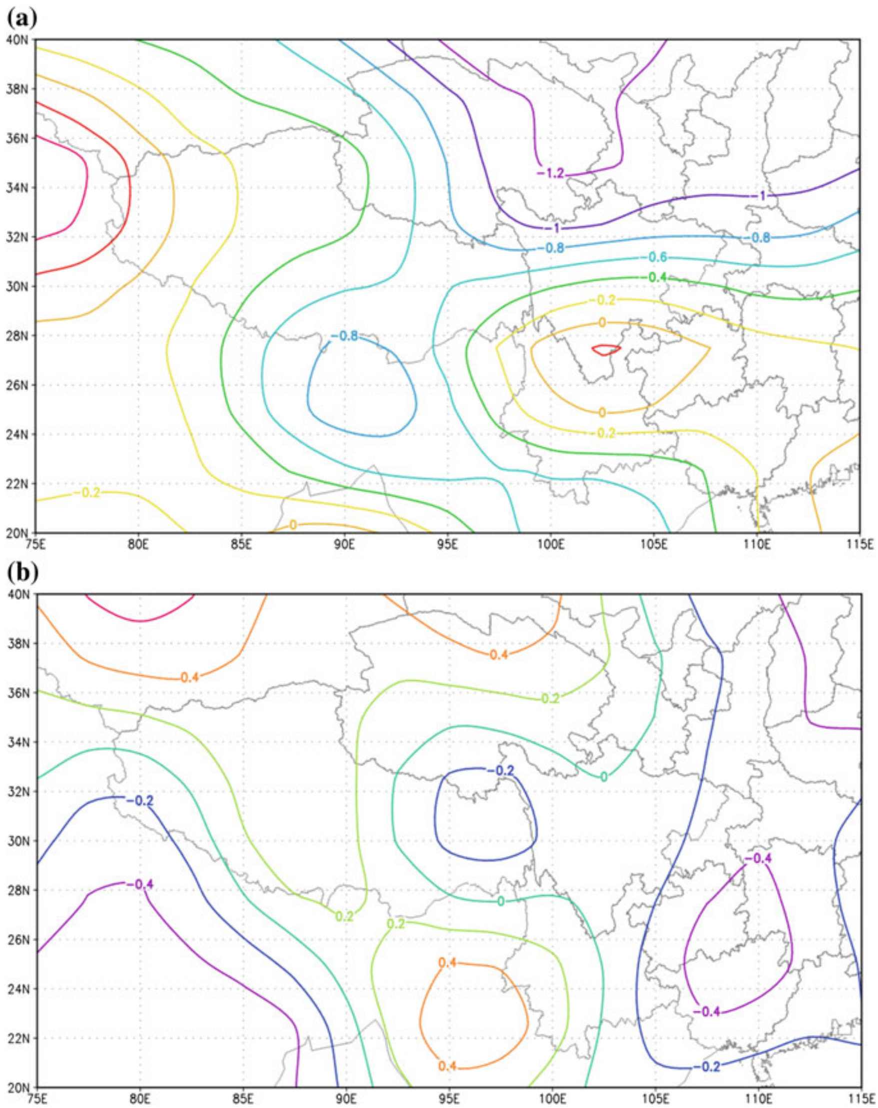

Fig. 6.6 Difference of the altitudinal wind speed (**a**) and the longitudinal wind speed (**b**) at 500 hPa between 1986–2000 and 1969–1985

in Xizang Plateau but weakened in other regions. The winter zonal wind changed weaker by a large margin in latter period, which suggested the weakening of circulation system.

These results indicated that from 1969–1985 to 1986–2000, the wind speed in other seasons had a slight correlation with the weakening of meridional and zonal wind except for in spring and also verified that the common impact of the variation

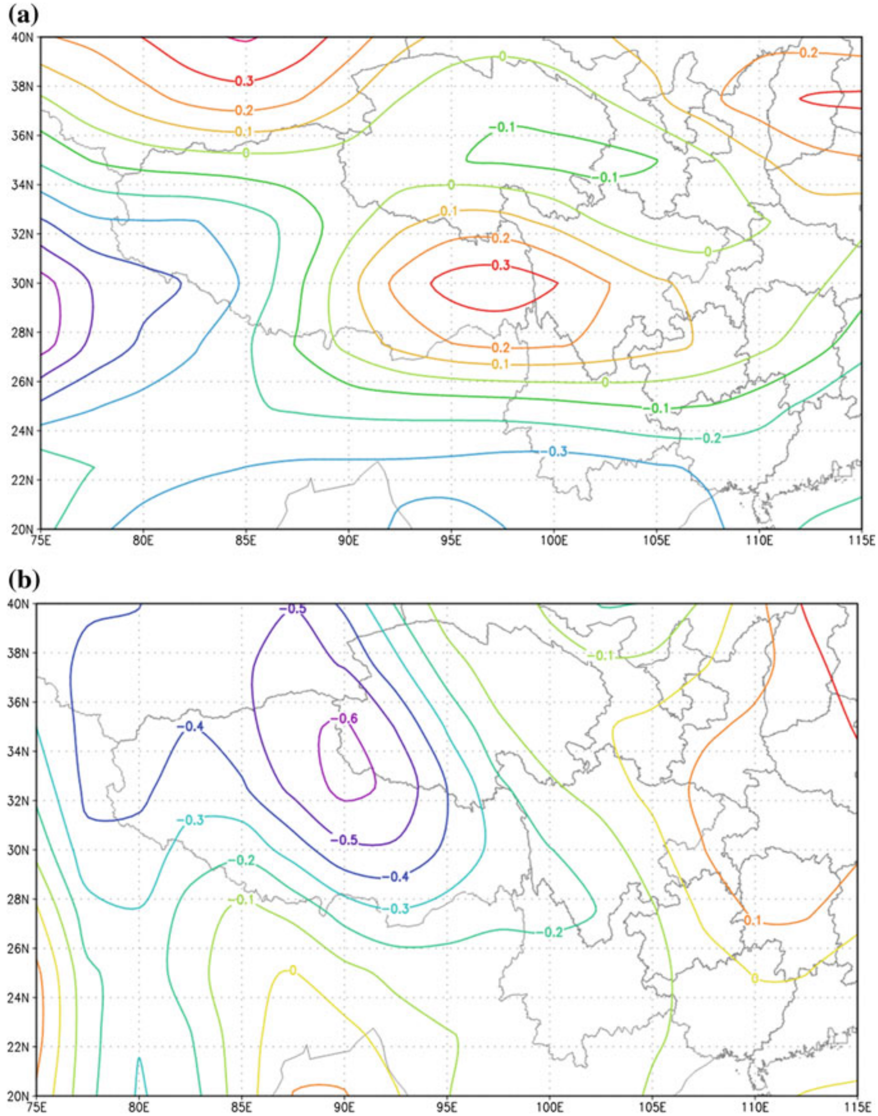

Fig. 6.7 Difference of the altitudinal wind speed (**a**) and the longitudinal wind speed (**b**) at 500 hPa between 2001–2008 and 1991–2000

of atmospheric circulation system on the change of wind speed. From 1991–2000 to 2000–1991, the zonal wind in spring in the whole studied area had an obvious decreasing trend and the decreasing magnitude was wider at high altitude area where the meridional wind also weakened apparently except for Yunnan Plateau and Guizhou Plateau. It may be partly explained the relatively weak growth in the spring wind speed. The summer zonal wind speed reduced slightly in latter period,

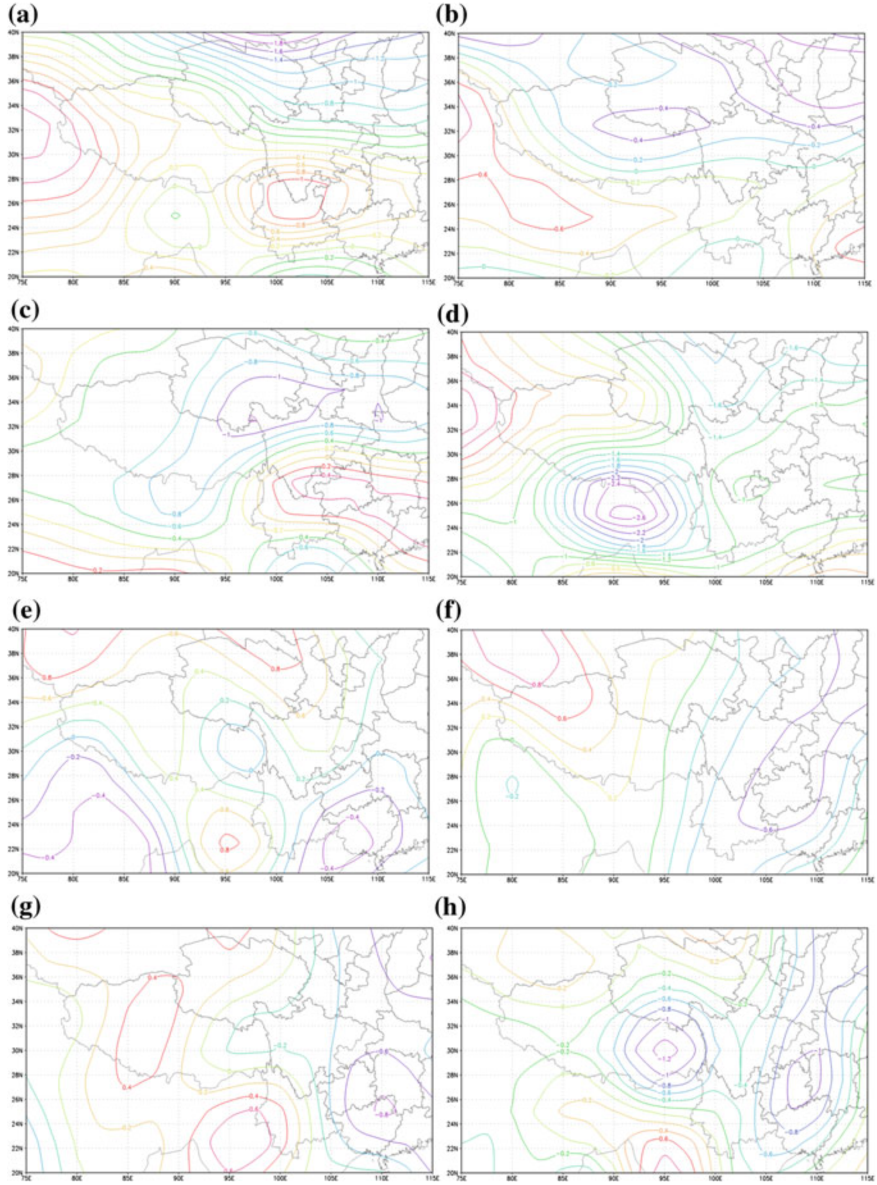

Fig. 6.8 Difference of the seasonal altitudinal wind speed (**a**–**d**) and the seasonal longitudinal wind speed (**e**–**h**) at 500 hPa between 1986–2000 and 1969–1985 from spring to winter

while the meridional wind had a rising trend in most regions in addition to the west areas of Xizang Plateau, which reflected that the increasing of meridional wind was one of possible reasons of strengthening of wind speed. Through the comparison of these two periods, it was revealed that the zonal wind speed of studied area in

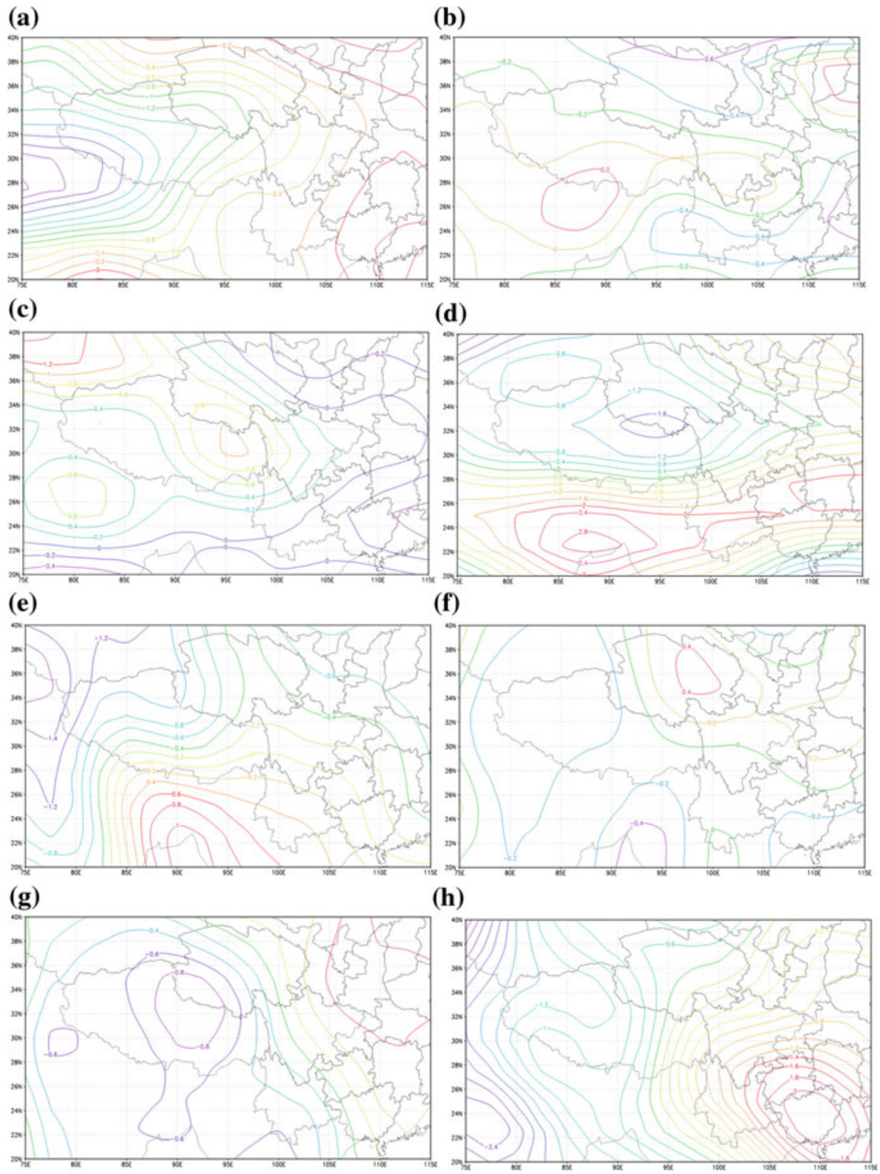

Fig. 6.9 Difference of the seasonal altitudinal wind speed (**a–d**) and the seasonal longitudinal wind speed (**e–h**) at 500 hPa between 2001–2008 and 1991–2000 from spring to winter

autumn strengthened by a wider margin in latter period than in former period, and showed a increasing trend in other regions except that a downtrend was exhibited in Xizang Plateau, which suggested that the influence of the strengthening of autumn zonal wind on the wind speed variation. The winter zonal wind declined significantly in Xizang Plateau and the northern Sichuan Basin, while a wider margin of increase appeared in the south part of studied area, especially in Yunnan–Guizhou Plateau. Furthermore, the meridional wind also showed a similar changing feature. It partly explained the increase of the winter wind speed (Fig. 6.9).

In recent years, a large number of studies had confirmed that the weakening of monsoon circulation made a significant contribution to the reduce of wind speed in China. The research of Xu et al. (2006a, b) found that the weakening east Asian monsoons was the important reason of the decrease of average surface wind speed over the passed 30 years, and in Eastern China and its adjacent sea area at 850 hPa the annual mean wind speed also was characterized by a downward trend, reflecting the abating of east Asian monsoon (Xue 2001). In addition, the lower pressure difference between land and sea also confirmed the weakening of the monsoon circulation system in recent years (Guo et al. 2003). This kind of evidences also included the lowering average wind speed of north-south direction in Central and Eastern China at 850 and 850 hPa (Yu et al. 2004) and the rising geopotential height of isobaric surface at 500 hPa (Huang and Yan 1999). Moreover, there were similar changing trend in geopotential height of isobaric surface at 850 and 500 hPa in Eurasia and western Pacific in 1961–2001 (Weng et al. 2004), implying the correlation with the weakening intensity of the east Asian monsoon and factors related of influencing the large-scale climate changes in the Asia–Pacific region. In addition to global warming which was the most obvious factor, other factors included the frequency of increasing positive index at the annular modal of northern hemisphere (Wallace and Thompson 2001) and the mechanism change of climate in decadal-scale appeared in northern Pacific nearly 1976 (Wang and Li 2004). The study results of Zhang et al. (2008a, b, c) suggested that the annual mean wind speed at upper, middle and lower tropospheric were characterized by the decline trend from 1980 to 2006 in China. These facts indicated again that the large-scale atmospheric circulation system featuring weakening monsoon circulation was one of the important factors resulting in the decrease of surface wind speed in Southwestern China.

In addition to the west wind and monsoon circulation, Southwestern China was affected by plateau monsoon too. So this study also analyzed the influence of plateau monsoon in wind speed variation. Plateau monsoon change was generally measured by the index of Qinghai-Xizang Plateau, and referred to the accumulative total value after that the height values at each lattice point minus the potential at 500 m within the specific area. There were two indexes, the calculation area of one index A was 25–35°N and 80–100°E; the other was 30–40°N and 75–105°E. This research adopts the index B of Qinghai-Xizang Plateau. As shown in Table 6.3, the annual and seasonal Qinghai-Xizang Plateau index increased from 1969 to 2008, and the margin of increase in winter was widest, up to 7.38 hPa/10 a which passed the significance test. More importantly, the annual average wind speed and the plateau index had a significantly negative correlation and the correlation coefficient was 0.56 ($P < 0.0001$). The seasonal variation also showed a significantly negative correlation (Table 6.3), especially the autumn correlation coefficient reached −0.67 ($P < 0.05$). Thus it was proved that the strengthening Qinghai-Xizang Plateau index

Table 6.3 Variation of Tibetan monsoon and its correlation with wind speed (hPa/10 a)

Period		Annual	Spring	Summer	Autumn	Winter	WMP	SMP
1969–2008	Trends (°C/a)	**4.28**	**2.77**	**2.82**	**4.16**	**7.38**	**5.23**	**3.24**
	Correlation coefficients	**−0.56**	**−0.32**	**−0.49**	**−0.67**	**−0.55**	**−0.4**	**−0.62**
1969–2000	Correlation coefficients	**−0.51**	−0.15	**−0.48**	**−0.7**	**−0.53**	**−30**	**−0.66**
2001–2008	Correlation coefficients			**−0.37**	**−0.5**	**−0.57**	**−0.29**	

Values for trends significant at the 5 % level are set in bold

had significant influence on the decrease of wind speed in Southwestern China, because it affected the wind speed on the ground by changing the regional atmospheric circulation mode. As is known to all, Qinghai-Xizang Plateau affected the global and regional atmospheric circulation system by the strong heat and dynamic action, such as the strength of west wind and Asian monsoon. And the remarkable increase of plateau index had an impact on regional monsoon circulation and west wind circulation, then caused the change of ground wind speed. But the specific mechanism of action still needed be studied further.

6.3.2 Correlation with Wind Speed and Regional Warming

A number of studies (Liu et al. 2009a, b; Yan 2002; Gadgil 2007; Trenberth et al. 2007) had affirmed that the reducing of wind speed in recent decades in China was influenced by the continental scale climate change, especially the Eurasian temperature rise in recent years. For example, the higher the ground temperature in winter might reduce the surface pressure, thus weakened the temperature and the pressure gradient between the land and the adjacent sea, eventually reduced pressure gradient force and led to the decrease of the wind speed (Xu et al. 2006a, b). The study of Xu et al. also thought that the weakening of winter monsoon mainly was relative with the wider margin of warming in Northern China, while the weakening of summer monsoon was related to the slight cooling of the central and south of China and the significant warming in the south China sea and west of north pacific, verifying the significant influence of the change in pressure gradient caused by the asymmetric variation of temperature on the wind speed. As shown in Table 6.4, generally in 1969–2008, the annual and seasonal mean temperature, mean maximum and minimum temperatures showed significant warming trend, and the magnitude of minimum temperature was widest. More importantly, the annual mean wind speed had a negative correlation with the annual mean temperature and mean maximum and minimum temperatures, but the correlation with maximum temperature failed in the significance test (Table 6.5). In seasonal scale, the annual mean wind speed just had a significantly negative correlation with the mean temperature in autumn and winter monsoon period, but had no obvious correlation with

Table 6.4 Variation of temperature during 1969–2008 in Southwestern China (°C/10 a)

		Annual	Spring	Summer	Autumn	Winter	WMP	SMP
Trends (°C/a)	Mean temperature	**0.41**	**0.24**	**0.23**	**0.34**	**0.25**	**0.32**	**0.28**
	Maximum temperature	**0.28**	0.09	**0.16**	**0.28**	**0.14**	**0.19**	**0.19**
	Minimum temperature	**0.49**	**0.35**	**0.4**	**0.37**	**0.36**	**0.41**	**0.41**

Values for trends significant at the 5 % level are set in bold

Table 6.5 Temperature trends and their correlation with wind speed in Southwestern China

Region	Temperature	Annual	Spring	Summer	Autumn	Winter	WMP	SMP
Southern	Mean temperature	**−0.4**	−0.22	0.03	**−0.33**	−0.26	**−0.3**	−0.15
China	Maximum temperature	−0.22	0.06	0.2	−0.22	−0.03	−0.07	0.03
	Minimum temperature	**−0.54**	**−0.45**	−0.28	**−0.33**	**−0.41**	**−0.53**	**−0.32**
XPHM	Mean temperature	**−0.49**	**−0.31**	**−0.32**	**−0.37**	−0.22	**−0.4**	**−0.33**
SB	Mean temperature	0.09	0.18	**0.47**	0.03	−0.08	0.05	0.27
YGP	Mean temperature	−0.17	0.2	**0.44**	−0.002	−0.001	0.03	**0.32**

Values for trends significant at the 5 % level are set in bold

the mean temperature in summer. While the negative correlation with other seasons could not pass the significance test. There was a significantly negative correlation between wind speed and mean minimum temperature and there was no apparent correlation between wind speed and mean maximum temperature in addition to autumn. It verified that the climate warming, especially the rising of minimum temperature was another key factor leading to the marked decrease of wind speed in the studied area, and the reverse changing trends between wind speed and temperature also supported this conclusion.

Horizontal pressure gradient force is the direct cause and the power of air horizontal movement, while the change of horizontal temperature gradient is the main factor of change of horizontal pressure gradient. For example, the asymmetric rise of temperature led to the decrease of temperature gradient in the regional level, then resulted in the abating of horizontal pressure gradient force and eventually made regional wind speed reduce. The study of Zhang et al. (2008a, b, c) found that the reduction of the meridional thermal gradient in the middle and high altitude area made the magnitude of warming in high altitude area wider than in low altitude area since 1980s, resulting in the decrease of wind speed. The study of Klink (1999) also considered that the change in wind speed caused by thermal difference was related to the change of surface pressure gradient resulted from ground temperature gradient, especially in high altitude area. In order to verify whether there is decrease in zonal temperature gradient, three regions were selected with the longitude range of 80°E–110°E: low latitudes (15°N–25°N), middle-latitude (45°N–35°N) and high latitudes (55°N–65°N).

This study calculate the differences of surface temperature and pressure gradient among low, medium and high latitudes by using the NCEP/NCAR reanalysis data on monthly mean air temperature and air pressure. As shown in Fig. 6.10, in 1969–2008, the temperatures in three regions of low, medium and high latitudes significantly warmed, and the magnitude were respectively 0.13 °C/10 a, 0.24 °C/10

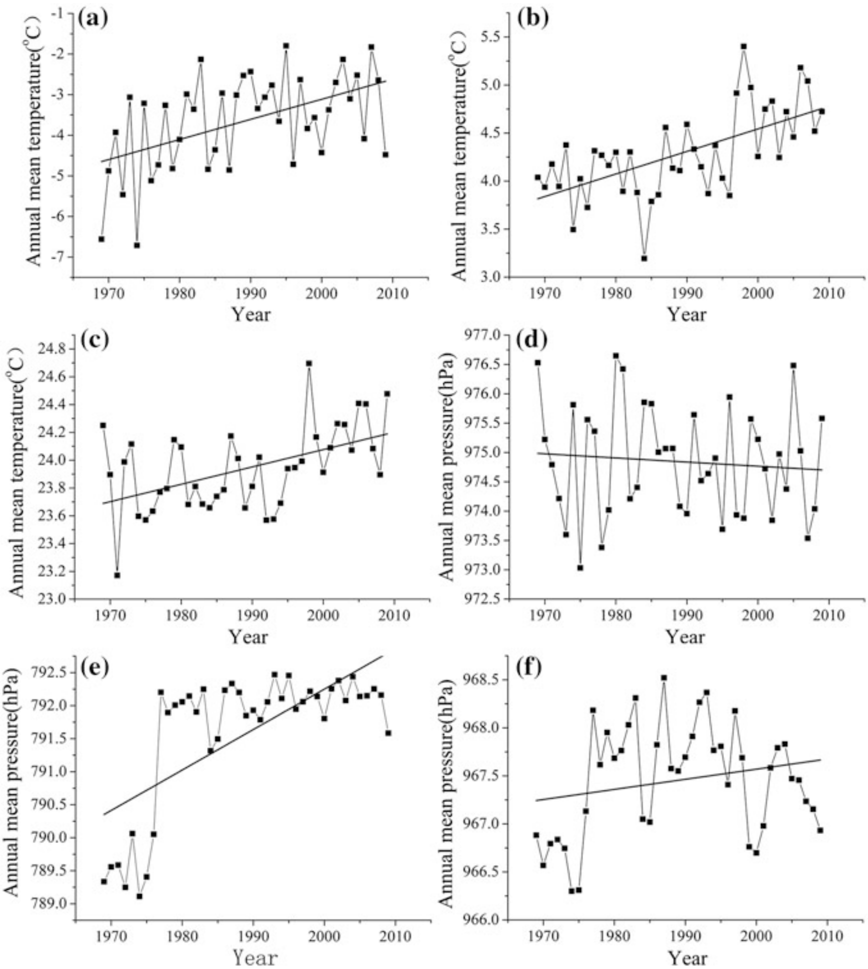

Fig. 6.10 Variation of surface temperature (**a**–**c**) and pressure (**d**–**f**) in lower, middle and higher altitude areas during 1969–2008. Reprinted from The Lancet: Yang et al. (2012). Copyright (2012), with permission from Elsevier **a** high latitude regions, **b** middle latitude regions, **c** low latitude regions, **d** high latitude regions, **e** middle latitude regions, **f** low latitude regions

a and 0.50 °C/10 a, which all passed the significance test. Obviously, the magnitude of warming in high latitudes was greatest. The asymmetric warming in different latitudes would reduce the differences of zonal temperature and lead to the decline of latitudinal temperature gradients. In terms of pressure change, although the surface pressures of three latitudes were on the increase, the magnitude of air pressure rise in middle latitude was maximum and that in high latitudes was minimum. It also showed an asymmetric change (Fig. 6.10). More importantly, under the background of asymmetric warming, the annual mean pressure gradient in low–middle latitudes area and middle–high latitudes region presented a downtrend in 1961–2008 (Fig. 6.11), which would result in the decrease of wind speed. Therefore, the weakening of pressure gradient between different latitudes is an important reason of decrease of wind speed under the background of warming.

The influence of temperature on wind speed change also showed obvious regional differences. As shown in Table 6.5, the annual and seasonal wind speed change in Xizang Plateau–Hengduan Mountain had significantly negative correlations with the temperature change except for the winter, while the wind speed in Yunnan–Guizhou Plateau and Sichuan Basin showed a positive correlation with the temperature in summer and summer monsoon period. The other seasonal and annual temperature had lower correlation with the wind speed wind change, reflecting the more significant influence of warming on wind speed in high altitude area. This confirmed again that the wind speed change caused by thermal difference mainly appeared in high altitude area (Klink 1999). In addition, the further analysis found that the correlation coefficients of annual wind speed and the maximum and minimum temperature in Xizang Plateau–Hengduan Mountain were −0.65 and −0.40, respectively and had passed the significance test. The corresponding values in the Sichuan Basin were –0.04 and 0.19 and in Yunnan–Guizhou Plateau were –0.34 and 0.06, reflecting that the warming of minimum temperature had a most influence on reduction of wind speed because the rising magnitude and the warming trend of minimum temperature were greatest. From the analysis, it was suggested that the changing trends of minimum temperature in Xizang Plateau–Hengduan Mountain, Yunnan–Guizhou Plateau and Sichuan Basin in 1969–2008 were

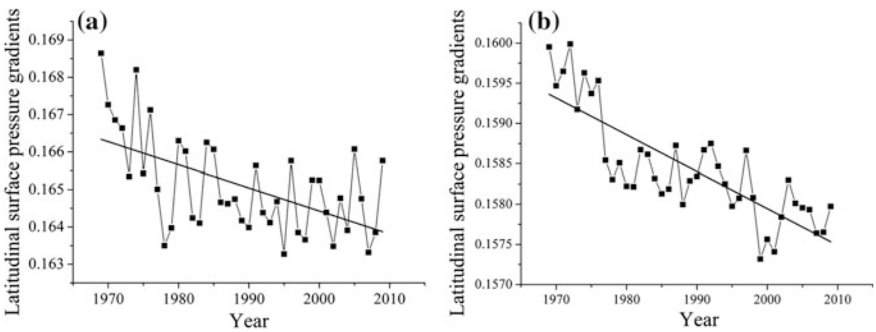

Fig. 6.11 Annual mean pressure gradient in low–middle latitudes (**a**) area and middle–high latitudes (**b**) region presented a downtrend in 1961–2008

respectively 0.52, 0.51, and 0.45/10 a, and the maximum temperature were 0.31, 0.31, and 0.22/10 a in 1969–2008.

6.3.3 Correlation with Wind Speed and Sunshine Hour

The annual mean sunshine hour in Southwestern China performed a decreasing trend in 1969–2008, and the seasonal sunshine hour declined significantly in addition to autumn. The similar changing trend was shown by sunshine hour and wind speed (Fig. 5.9), and other season had a significantly positive correlation with the wind speed except for autumn and winter (Table 6.6), suggesting the interaction of sunshine hour and wind speed. Because the heating effect of a longer sunshine hour to atmosphere became stronger, thus accelerated the atmospheric movement and formed a faster wind speed, and vice versa. The previous analysis also confirmed that the sunshine hour is one of influencing factors of wind speed change, indicating the interaction and impact between them. The effect of sunshine hour change on wind speed also showed a certain regional difference. In addition to winter, the annual and seasonal change of wind speed revealed the significantly positive correlation with sunshine hour in Xizang Plateau–Hengduan Mountain, while in Sichuan Basin, the significantly positive correlation was shown in other seasons except autumn. And the positive correlation was shown only in summer and autumn in Yunnan–Guizhou Plateau (Table 6.6), suggesting the common influence of sunshine hour on wind speed change in studied area and the significant impact on high altitude areas. While the influence of sunshine hour on low altitude area like Yunnan–Guizhou Plateau and Sichuan Basin mainly appeared in winter half year. In addition, there was a little influence of winter sunshine hours change on the wind speed at high altitude because the sunshine hour was longer in winter and its change was relatively stable. However, due to the enlargement of snow area in high altitude area, the albedo decreased, eventually caused that the ground net radiation reduced and made the heating effect to atmosphere subdue. In the autumn, the sunshine hour change had a little influence on Yunnan–Guizhou Plateau and Sichuan Basin because the autumn precipitation was relatively concentrated and cloud cover was large, so the wind speed might be influenced by the intensity of monsoon.

Table 6.6 Correlation between solar duration and wind speed in Southwestern China

Region	Annual	Spring	Summer	Autumn	Winter	WMP	SMP
Southwestern China	**0.46**	**0.4**	**0.53**	0.14	0.28	**0.47**	**0.52**
XPHM	**0.6**	**0.51**	**0.58**	**0.48**	0.14	**0.35**	**0.63**
SB	**0.54**	**0.44**	**0.56**	0.11	**0.37**	**0.61**	**0.43**
YGP	**0.5**	**0.57**	0.26	**0.18**	**0.45**	**0.43**	0.26

Values for trends significant at the 5 % level are set in bold

6.3.4 Correlation with Wind Speed and Altitude

The previous analysis found that the mean wind speed and its variation trend showed an apparent dropping trend from west to east, which was confirmed by the change of annual and seasonal mean wind speed in different altitudes (Fig. 6.12). As shown in Fig. 6.13, the changing trends of both the annual and seasonal wind speed had the negative correlation with altitude, in other words, the decreasing magnitude widened with the rise of altitude, verifying that the decrease of wind speed main occurred in high altitude area. In order to further understand the influence of the terrain, the terrain of 110 observation stations was divided into four types: summit station, flat station, intermountain station and valley station. As shown in Table 6.7, the decreasing magnitude of wind speed reduced from summit station, intermountain station, flat station and valley station in turn during 1969–2008. The minimal reduction appeared in valley station and the seasonal wind speed also showed a same changing pattern. The annual wind speed in about 100 % of summit station, 82 % of intermountain station, 63 % of flat station and 65 % of valley stations displayed a remarkable decrease. About 65 % of intermountain stations stranded at above 1,500 m and only 35 % of falt stations were located in above 1,500 m. The decrease of wind speed mainly occurred in high altitude area, so the intermountain stations showing the downtrend were more than flat stations. The decreasing magnitude was least because of the hindering effect of valley terrain to airflow movement. These features demonstrated again that the decrease of wind speed mainly occurred in high altitude area and also suggested the influence of terrain types on wind speed change.

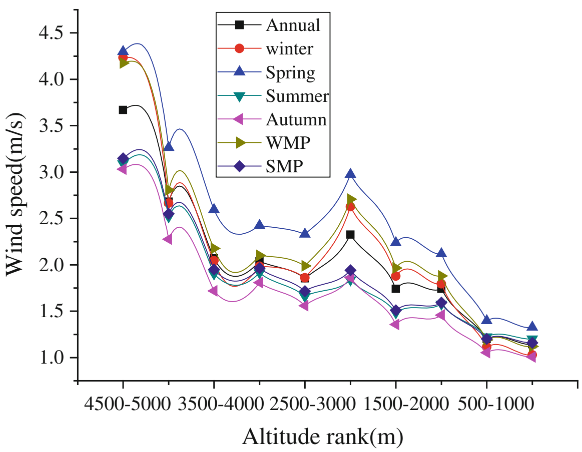

Fig. 6.12 The variation of annual mean wind speed with altitude during 1969–2008

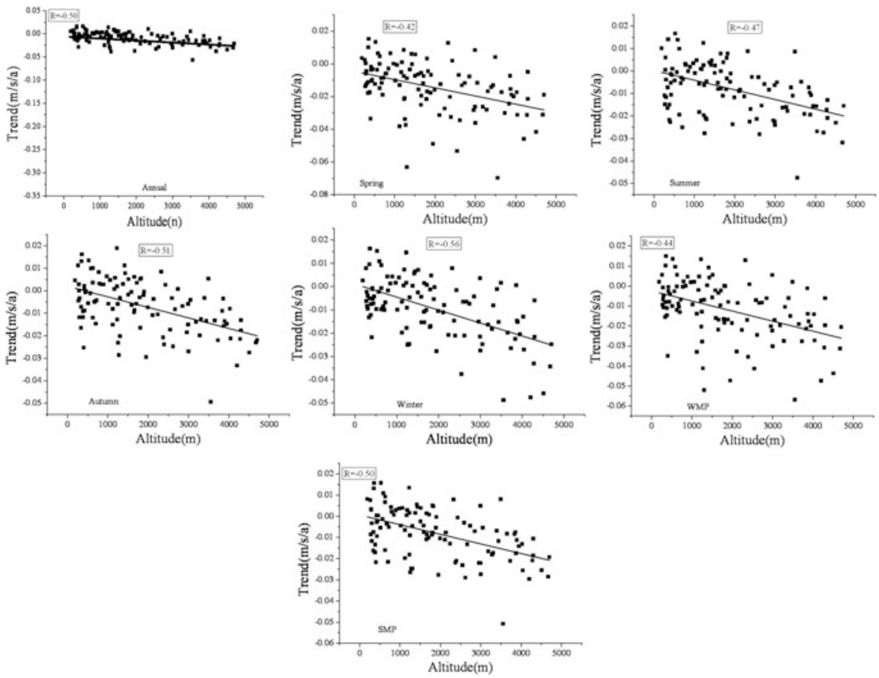

Fig. 6.13 The correlation between regional trends of wind speed and altitude

Table 6.7 Mean trends of wind speed at different topographical sites (m/s/10 a)

Terrain types	Number	Annual	Spring	Summer	Autumn	Winter	WMP	SMP
Summit station	2	−0.2	−0.24	−0.15	−0.16	−0.26	−0.24	−0.16
Intermountain station	34	−0.18	−0.24	−0.14	−0.13	−0.18	−0.21	−0.15
Flat station	40	−0.16	−0.18	−0.09	−0.01	−0.16	−0.17	−0.01
Valley station	34	−0.007	−0.009	−0.007	−0.005	−0.06	−0.007	−0.007

6.3.5 Comparison of Wind Speed Between Urban and Rural Stations

In addition, numerous studies also found that in recent years, the accelerated urbanization is one of the influence factors of the decrease of wind speed, because a large number of urban construction changed the surrounding environment of the urban meteorological stations, particularly the block resulted from this to atmospheric movement would reduce the ground wind speed, thus bring bigger error to observation results. The study of Klink confirmed that a smaller margin of changes in ground surface structure would cause the decrease of observed wind speed, for example, urbanization, air pollution, land use and cover change. In order to analyze the effect, 110 stations could be divided into two types: urban station and rural stations, and the differences of changing trend were contrastively analyzed. As shown in Table 6.8, in 1969–2008, the annual and seasonal mean, maximum and minimum wind speed of urban stations in studied area were greater than that of rural station because the urban stations were mainly located in low altitude area like Yunnan–Guizhou Plateau and Sichuan Basin. In 1969–2008, the decreasing trend of annual and seasonal wind speed between urban and rural station had passed the significance test, but the decreasing magnitude in rural station was greater than in urban station and the percentage of stations with significant decrease was more than that of urban station, verifying the influence of altitudes because the stations with significant decrease were mainly located in the high altitude area (Table 6.9). In addition, although the percentage of stations with decrease and significant decrease in rural stations were greater than in urban stations in 1969–2000 (Table 6.9). During 2001–2008, the increasing magnitude of annual, spring, autumn, summer monsoon and winter monsoon period in rural stations were greater than in urban stations. The increasing magnitude of urban stations in autumn and winter were greater, and more stations with increasing trend were distributed in rural region, but the urban stations showing significant increasing trend were more than rural stations (Table 6.9). The above analysis indicated that the difference in altitude between urban and rural stations was the main reason leading to the difference of changing trend in wind speed.

Table 6.8 Annual mean wind speed (m/s) and trends (m/s/10 a) in urban and rural stations in Southwestern China

	Wind speed (m/s)	Annual	Spring	Summer	Autumn	Winter	WMP	SMP
Urban station	Mean	1.6	1.94	1.5	1.35	1.62	1.7	1.5
	Maximum	0.54	0.64	0.59	0.45	0.45	0.51	0.57
	Minimum	3.28	4.17	2.79	2.84	4.01	4.02	2.87
Rural station	Mean	1.92	2.38	1.74	1.61	1.96	2.07	1.77
	Maximum	0.56	0.74	0.59	0.35	0.35	0.45	0.59
	Minimum	4.26	4.8	3.96	3.72	5.01	4.89	3.84
	Trend (m/s/10 a)							
Urban station	1969–2008	**−0.25**	**−0.31**	**−0.1**	**−0.14**	**−0.25**	**−0.29**	**−0.15**
	1969–2000	**−0.43**	**−0.41**	**−0.26**	**−0.35**	**−0.42**	**−0.44**	**−0.32**
	2001–2008	**0.42**	**0.13**	**0.54**	**0.3**	**0.67**	**0.34**	**0.45**
Rural station	1969–2008	**−0.29**	**−0.32**	**−0.23**	**−0.21**	**−0.26**	**−0.29**	**−0.26**
	1969–2000	**−0.38**	**−0.34**	**−0.27**	**−0.34**	**−0.38**	**−0.38**	**−0.33**
	2001–2008	**0.7**	**0.23**	**0.11**	**0.77**	**0.6**	**0.37**	**0.97**

Values for trends significant at the 5 % level are set in bold

Table 6.9 Percentage of stations with negative or positive trends of wind speed in urban and rural stations, Southwestern China

	Period	Urban station		Rural station		Urban station		Rural station	
		D (%)	SD (%)	D (%)	SD (%)	I (%)	SI (%)	I (%)	SI (%)
Annual	1969–2008	67	48	87	71				
	1969–2000	79	66	85	73				
	2001–2008					60	59	69	60
Spring	1969–2008	79	59	87	77				
	1969–2000	90	64	81	62				
	2001–2008					60	48	58	35
Summer	1969–2008	60	40	88	67				
	1969–2000	74	50	85	73				
	2001–2008					66	52	69	60
Autumn	1969–2008	55	40	85	63				
	1969–2000	74	52	83	67				
	2001–2008					64	59	69	54
Winter	1969–2008	67	48	85	69				
	1969–2000	83	67	90	79				
	2001–2008					66	53	65	52
WMP	1969–2008	74	57	85	73				
	1969–2000	88	67	87	71				
	2001–2008					62	53	63	48
SMP	1969–2008	55	45	87	71				
	1969–2000	67	57	79	73				
	2001–2008					66	60	69	56

Abbreviations are as follows: *D* is the percentage of stations with decreasing trend, and *SD* is the percentage of stations with significant decreasing trend; *I* is the percentage of stations with increasing trend, and *SI* is the percentage of stations with significant increasing trend

6.4 Summary

This chapter focuses on the analysis on the spatial and temporal variations of wind speed as well as its influencing factors from 1969 to 2008 in Southwestern China by using daily wind speed observation data of 110 stations. The results indicated as following:

(1) The wind speed decreased significantly, especially in high altitude area. The mean wind speed was 1.75 m/s in 1969–2008, and the higher values of annual and seasonal wind speed are mainly distributed in Xizang Plateau, Hengduan Mountain and the central of Yunnan–Guizhou Plateau, while the wind speed of most stations in the east and west of Yunnan–Guizhou Plateau and Sichuan Basin was weaker. In 1969–2008, the annual average wind speed significantly reduced at the rate of 0.24 m/s/a. The changing trend of wind speed in 1969–2000 was −0.37 m/s/10 a, and the wind speed strengthened apparently

in 2001–2008 and the changing tendency of seasonal wind speed was similar to the annual one. The decreasing magnitude of wind speed in 1969–2000 were higher than the corresponding values of the entire studied period. About 66 % of the stations in 1969–2008 showed a significant reduce in annual average wind speed, and more stations displayed a decreasing trend from 1969 to 2000, while the wind speed of almost more than half of stations incresed sharply in 2001–2008. On the whole, the stations with a decreasing wind speed were situated in high altitude area and the changing magnitude exhibited a decline trend from west to east. In 2001–2008, the stations with increasing trend were mainly located in Hengduan Mountain, Yunnan Plateau and Sichuan Basin, and the stations with a weakening wind speed were distributed in Xizang Plateau, and Guizhou Plateau.

(2) The atmospheric circulation is the main influencing factor of the wind speed changes in the studied area. The meridional winds showed a lower trend from 1969–1985 to 1985–2000 in studied area except for the west of Xizang Plateau, and the decreasing trend of zonal wind in latter period was greater than in former period, suggesting that the weakening of wind speed of west wind circulation and monsoon circulation might be the main cause of reduce in win speed before 2000. From 1991–2000 to 2000–2008, in addition to the Yunnan Plateau, the significant increase of zonal wind indicated that the strengthening of zonal wind might play an important role in the increase of wind speed since 2000. The remarkable influence of atmospheric circulation on wind speed also be confirmed by the seasonal changes of meridional and zonal winds. In 1969–2008, Qinghai-Xizang Plateau index displayed an uptrend, and there was a significantly negative correlation between annual and seasonal wind speed and plateau index, reflecting the apparent effect of the strengthening of Qinghai-Xizang Plateau monsoon on the decreasing wind speed in studied area.

(3) The regional climate warming is another reason of decreasing wind speed. Annual mean temperature and mean minimum temperature showed a significantly negative correlation with annual mean wind speed. In seasonal scale, the wind speed just had a significant negative correlation with the mean temperature and mean minimum temperature in autumn and winter monsoon period, reflecting that the temperature rise, especially the wider margin of warming in minimum temperatures was a key factor of weakening of wind speed. Further analysis found that in 1969–2008, the warming magnitude of high latitudes area was greatest; the increasing magnitude of air pressure in middle altitude area was greatest and the increasing magnitude of air pressure in high altitude area was least. In the context of this, the annual mean pressure gradient in the low-middle altitude areas and the middle-high altitude areas reduced year by year, indicating that the reduction of pressure gradient force was the main reason of the weakening of wind speed.

(4) The sunshine hour and altitude etc. Also have some effect on the wind speed changes. In addition to the autumn and winter, wind speed showed a significantly positive correlation with sunshine hour. The significantly negative correlation with annual and seasonal wind speed changes and the altitudes

affirmed the elecation effect of wind speed. The decreasing magnitude of wind speed reduced from summit station, intermountain station, flat station and valley station in turn during 1969–2008. The decreasing magnitude of wind speed in rural station was greater than in urban station in 1969–2008 and 1969–2000, and the percentage of rural stations performing significant decreasing trend was greater. In 2001–2008, the increasing magnitude of wind speed in annual, spring, autumn, summer monsoon and winter monsoon period was greater than in urban station, and the rural stations with increasing tendency were more than urban stations. Further analysis found that the different altitudes of two types of stations were the main reason of these differences.

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Chapter 7
Glaciers Response to Climate Change in Southwestern China

7.1 Characteristics of Glaciers Change

There are 23,221 glaciers in Southwestern China which cover an area of 29,523 km^2, accounting for 50.16 % of total areas and 49.69 % of total numbers in China (Shi et al. 2000). Through the sorting of existing research results on glacier change in the studied area in recent years, under the background of warming, some phenomena had been found, such as significant glacial retreat, drastical mass losses, increasing glacial runoff and the expanding areas of lakes supplied by ices or glaciers, reflecting the obvious response to climate warming.

7.1.1 The Glacier Retreat and Shrinking Areas

On average, the 102 glaciers in Gangrigabu Mountain retreated by 1,095 m in the end of 1915–1980, and the mean area reduced by 47.9 km^2, even the ice reserves decreased by 6.95 km^3. 52 glaciers retreated by 237.2 m in the end of 1980–2001, and the areas reduced by 12.42 km^2. Meanwhile, the climate change was characterized by temperature rise and precipitation increase (Liu et al. 2005a, b). Lanong glacier, zhadang glacier, panu glacier and 50270C0049 glacier in Nyainqntanglha Mountains retreated by respectively 381.8, 489.5, 377.2, and 176.1 m during 1970–2007. Xibu glacier retreated by 1,130.2 m (Kang et al. 2007) in 1970–1999 period and Gurenkekou glacier retreated by 293 m (Pu et al. 2006) in 1970–2003 (Fig. 7.1). The glacier area of Ranwuhu basin in southwestern Tibet reduced by 29.7 km^2 from 1980 to 2005, thereinto, the Yanong glacier basin went back 1,534 m and its area shrank by 2.33 km^2. In the same period, the changing trend of annual man temperature was 1.34 °C in Bomi stations in this region, and its warming rate was 1.36 °C/10 a. The changing trend of annual man temperature was 1.34 °C in Chayu stations, and its warming rate was 0.20 °C/10 a. The changing trend of annual

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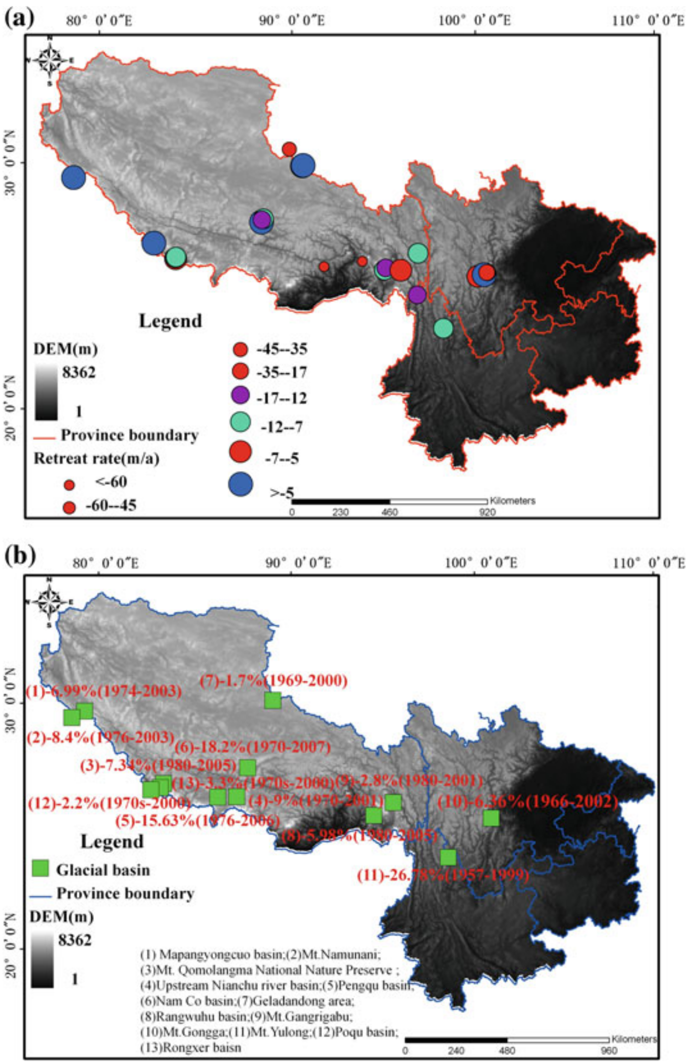

Fig. 7.1 Distribution of the observed glaciers **a** and glacial basins **b** with retreating trend in Southwestern China

man temperature was 1.54 °C in Linzhi stations, and its warming rate was 0.38 °C/10 a. While the rainfall of three stations basically kept stable. The glacier area and ice reserves of Pengqu basin in Xizang shrank by 131.24 km^2 and 12.01 km^3, respectively. There were 99 glaciers having disappeared. The temperature was on a significant rise and the wider margin of precipitation change occurred in adjacent Dingri station in 1961–2000 where the precipitation had a slight increase (Jin et al. 2004). Ruoguo glacier in the upstream of Yigongcangbu River retreated by 1,200 m during 1959–1975 (Shi et al. 2000). Azha glacier in Palongzangbu River basin retreated by

1,690 m in 1980–2006, and Palong No. 4 glacier retreated by 423 m during 1980–2008. Palong No. 10, No. 94 and No. 390 retreated by 30.5, 41.2, and 16.4 m, respectively in 2006–2008 (Yang et al. 2008a, b, c, 2010a, b) (Fig. 7.1). Since 1970, the temperature rose significantly in Namtso basin, and the warming magnitude in winter was greater than in summer, but the summer precipitation increased significantly. Under the background of this, the glacier area shrank by 37.1 km^2 in 1970–2007. Thereinto, the area of Zhadang glacier reduced 0.4 km^2 (Chen et al. 2009). The glacier in the south of Rivergudiru in Siling Co retreated by 1,228 m in 1969–2000 (Lu et al. 2005). The reduced glacier area in Geladandong region was 14.91 km^2 in 1969–2000, at the same time, the temperature rose sharply (Lu et al. 2002) (Fig. 7.1). The Dongkemadi and little Dongkemadi in Mount tunggula retreated by 20.4 and 18 m in 1994–1999 (Pu et al. 2006).

The Mapangyongcuo basin in the Himalaya region experienced a glacier reduction of 7.53 km^2 during 1974–2003 (Ye et al. 2008). Namunani glacier had a retreat of 150 m during 1976–2006 (Yao et al. 2007a, b), and its mean temperature in the summer half year and the annual mean temperature rose by 0.17 and 0.18 °C. The East Rongbu glacier and Central Rongbu glacier in Everest region retreated by 198 and 315.5 m, respectively in 1966–2001, and the Far East Rongbu glacier had a retreat of 230 m in 1966–1997. At the same time, the climate in this region presented a dry climate characteristic (Ren et al. 2003) (Fig. 7.1). The glacier area of protection zone in Everest shrank by 501.91 km^2 in 1976–2006, the key cause of which was thought a marked increase in the temperature and decrease in rainfall by analyzing (Nie et al. 2010). The Kangwure glacial of Xixiabangma Peak region retreated by 303 m from 1974 to 2007, and its area and ice reserves reduced by respectively 1.02 km^2 and 0.0481 km^3 (Ma et al. 2010). Dapusuo glacier retreated 120 m during 1968–1997 (Pu et al. 2006). Namunani Peak in the Himalaya region experienced a glacier reduction of 7.12 km^2 during 1976–2003, mainly the consequence of temperature increase and precipitation decrease was measured at Pulan station near the glacial region (Ye et al. 2007). The glacier area in the upstream of Manla reservoir in the Himalaya region had a decrease of 17.41 km^2 in 1980–2005. While over the past 50 years, the annual mean temperature rose by 1.4 °C, and the precipitation did not show a long-term trend (Li et al. 2010a, c, d, e). From 1970s to 2000, the glacier area in Boqu basin and Ruoge basin reduced by 5.2 and 10.2 km^2, respectively (Wu 2004) (Fig. 7.1).

Compared with 1966, the glacier area of Gongga Mountain reduced by 6.36 % in 2002. Since the observation records existing in adjacent Hailuogou, Jiulong and Xinduqiao, the analysis on the annual precipitation and annual mean temperature revealed that the annual man temperature had been on the rise in these three stations in line with the background of global warming. The temperatures in the east slope of Gongga Mountain measured by Hailuogou station had increased about 0.42 °C in the past 20 years, and the temperatures in the west slope of Gongga Mountain measured by Jiulong and Xinduqiao station had increased about 0.67 °C in the past 50 years, while the annual precipitation had a slight change in both slopes (Zhang et al. 2010a, b). Hailuogou glacier retreated 1,816.8 m during 1930–2006, and the Hailuogou No. 2 and Yanzigou glaciers in Gongga Mountain had a retreat of 1,075 and 2,850 m, respectively. While the Dagongba glacier retreated 450 m from 1930 to 2007. Mingyong glacier in Meri Snow Mountain had retreated by 950 m in 1932–2002. The total glacier area in Yulong Snow Mountain reduced by 3.11 km^2 in 1957–1999, and there were four glacier having disappeared. The Baishui No. 1 glacier retreated 830 m in 1900–2008 and the annual mean temperature and precipitation in nearby Lijiang station displayed a decreasing trend at the rate of 0.15 °C/10 a and 14.2 mm/10 a, respectively (Li et al. 2008a, b, 2009a, 2010a, b). In addition, the surface morphology of glaciers had changed significantly under the background of accelerating melting. For example, the ice-shelf collapse of Yanggong River in Yulong Snow Mountain in 2005 (Zhang et al. 2007a, b, c, d), the changes of ice tongue in Azha glacier (Yang et al. 2008a, b, c), the increase of the subglacial water in Hailuogou glacier (Liu and Liu 2009) etc. all were the typical facts of severe changes in glacier surface morphology.

However, not all glaciers were in a retreat. There were also a part of the glacier advancing in recent years. The summer temperature of Bomi and Chayu station nearby Gangrigabu Mountain increased by 0.3–0.5 °C in 1960–2002, during which the maximum total precipitation in Bomi and Chayu station were 1.9 and 2.1 times of the minimum precipitation. The glacier area in this region enlarged by 10.4 km^2 in 1980–2001 and advanced by 389 m. Furthermore, the 5O282B0136 glacier and 5O282B0123 glacier advanced respectively by 1,117 and 1,762 m (Liu et al. 2005a, b). Accordingly, Shi et al. (2006) deduced that if the precipitation in the high altitude area had increased as same multiples, the main reason of the advance of glacier were precipitation increase. Moreover, 5K451F12 glacier in Geladandong region also moved forward 680 m in 1969–2000 (Lu et al. 2002).

7.1.2 Severe Mass Loss of Glacier

The mass loss of glacier was another significant feature of glacial changes in the studied area. As shown in Fig. 7.2, Baishui had a apparent mass loss in 1952–2003, its annual mean mass balance value was the water equivalent of −218.8 mm in past 52 years, and the thickness of ice tongue thinned by 15 m in 2000–2004 (Li et al. 2009a, b). From 1959/1960 to 2003/2004, the value of water mass balance in Hailuogou was −10825.5 mm (water equivalent), and the annual mean value of mass balance was −240.6 mm (water equivalent). During 1990/1991–1997/1998, the height of melting ice tongue was 6.84 m, which was equivalent to water equivalent of 6,157 and 876 mm more than that of 1982/1983 (Li et al. 2008a, b, 2009b, c, 2010a, b).

The annual mean thickness of No. 4, No. 10 and No. 12 glaciers had thinned by 5.2, 4.5, and 2.9 m, respectively during 2006/2005–2007/2005 (Yang et al. 2008a, b, c) and the annual mean mass balance of No. 94, No. 12 and No. 10 glaciers in this basin were water equivalent of −748.7, −1,303 and −517 mm during 2005/2006–2007/2008, while the annual mean mass balance of No. 4 was −370 mm during 2005/2006–2006/2007. The annual mean mass balance of Demula glacier

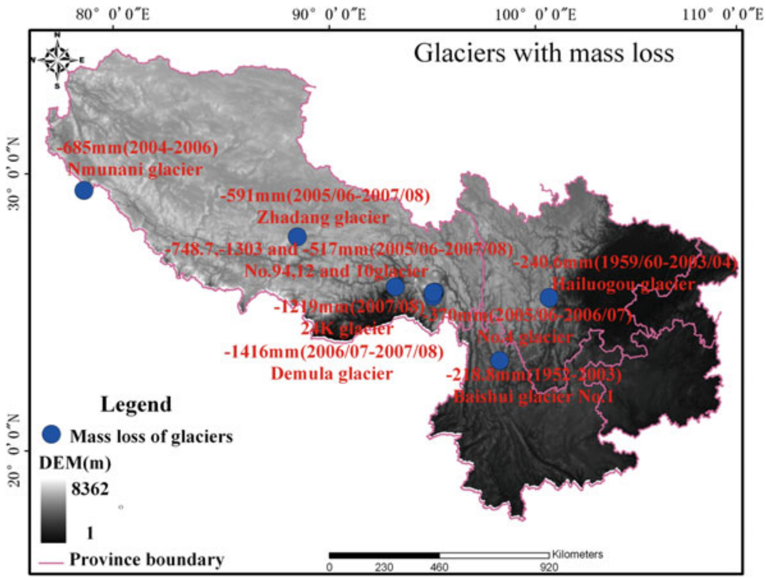

Fig. 7.2 Distribution of the observed glaciers with mass loss in Southwestern China

was water equivalent of −1,416 mm during 2006/2007–2007/2008 and the value of mass balance of 24 k glaciers was water equivalent of −1219 mm (Yang et al. 2010a, b). The thickness of Zhadang glacier in Namucuo basin thinned by 11.2 m in 1970–2007 (Kang et al. 2007), and the annual mean mass balance during 2005/2006–2007/2008 was water equivalent of −591 mm (Yao et al. 2007a, b).

The the annual mean mass balance of Namunani glacier in the western Himalayas was −685 mm during 2004–2006. The ice reserves of Namunani Peak had reduced 3.06 km^3 in 1976–2001 (Wang et al. 2010a, b, c).

7.1.3 *Expansion of Ice Lakes or Lakes Supplied by Ices*

As shown in Fig. 7.3, the areas of ice lakes in Ranwu Lake basin of southwestern Tibet increased by 3.48 km^2 from 1980 to 2005 (Xin et al. 2009). The area of Namucuo Lake expanded 72.6 km^2 in 1970–2007 (Kang et al. 2007). Zhu et al. thought that the main reasons of expansion of Namucuo Lake were regional precipitation increase, severe melting and decreased evaporation under the background of climate warming, and the contribution of melt water reached 50.6 %. The area of ice lake in Selincuo region expanded by 221.72 km^2 in 1969–1999, (Lu et al. 2005) which was caused by the increase of precipitation and melt water. The areas of ice lakes had expanded by 29 % in 2008 than in 1970, and the areas of ice lakes in different height showed a expanding trend. The peak of net increasing area appeared in 5,000–5,300 m, confirming the significant warming of high altitude areas.

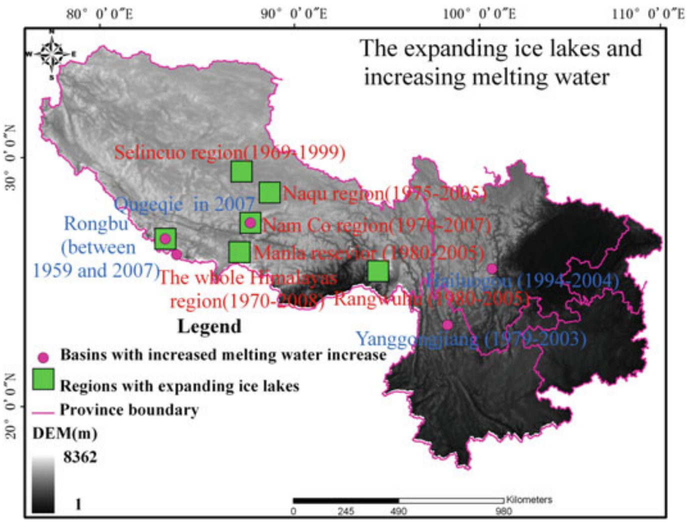

Fig. 7.3 Distribution of the enlarged glacial lakes and basins with the increased melting water in Southwestern China based on the observation

The further analysis hold a idea that temperatures rise, glaciers retreat, increasing glacier melt water were the main causes of the expansion of ice lakes in areas (Wang et al. 2010a, b, c, 2011a, b).

The areas of Galuncuo and Kangxicuo in the Himalayas region increased by 104 and 118 %, respectively in 2001 than in 1987 (Chen et al. 2005). The area of Lumuchimi increased by 118 % in 2003 than in 1977 (Che et al. 2005a, b). Compared with in 1975, the areas of water level of four lakes, such as Bamucuo, Pengcuo, Dongcuo and Nairipingcuo expanded by 48.2, 38.2, 19.8 and 26.0 km^2 in 2005. Its primary reasons were analyzed as the warm and wet climate, such as rising temperatures, increasing precipitation, decreasing vaporization and permafrost degradation (Bian et al. 2006). The lake area in the upstream of Manla reservoir had increased to 10.89 km^2 in 2005 from 8.33 km^2 in 1980, meanwhile, the total area of lakes expanded by 30.8 % (Li et al. 2010a, c, d, e). Under the background of global climate warming, glaciers melting, glaciers retreat and permafrost degradation, the lake area along S301 highway had expanded 408.76 km^2 in 2000 than in 1970 (Wang et al. 2008a, b). The comprehensive study of Yao et al. (2010) verified that the severe retreat of glaciers was one of reasons leading to the expansion of regional lake areas.

Studies confirmed that the contribution rate of ice and snow melt water in Hailuogou basin is 54.7 % from 1999 to 2004. The analysis found that the runoff will increase 2.6 m^3/s when the temperatures rise by 0.1 °C in this region (Li et al. 2008a, b). Compared with in 1979–1988, the runoff increased 78.7 % and the melt water increased by 90.9 %, but precipitation increased by only 15.1 % in 1994–2003 in Yanggong River basin of Yulong Snow Mountain (Li et al. 2009a). Through the contrast of hydrology observation data between 1959 and 2005 in Rongbu basin of Everest, there was a wider margin of increase in total runoff in

2005 than in 1959, and the monthly mean runoff from June to August in 2005 increased by 69, 35 and 14 % than in 1959 (Liu et al. 2006a, b, c). The analysis on multiple regression of runoff with temperature and precipitation suggested that the temperature played a leading role in the change of runoff in upstream or downstream of Qugaqie basin in Namucuo, and the leading role was more pronounced in upstream due to more proportion of glacier area (Gao et al. 2009). Zhang et al. (2009) considered that the main characteristic and consequences of changes in climate and glacier were common temperature rise, severe glacier retreat and the expanding ice lakes in the Himalayas region. Furthermore, the glaciers retreat will lead to the increased risk of glacier disasters and had a long-term influence on river runoff and water resources in this region.

7.1.4 The Significant Glacier Melt

Since 1999, the observational studies of Yulong Snow Mountain where the monitored glaciers was Baishui No. 1 showed a significantly accelerated glacier melt which was mainly embodied in: (1) The glacier area severely atrophied. Du (2011) found that the glaciers in Yulong Snow Mountain apparently continued to shrink in recent years. From 1957 to 2001, the total areas of glaciers had reduced to 5.30 km^2 from 11.6 km^2, decreasing by 54.31 %, and the annual mean decrease was about 0.138 km^2. By 2009, the total glacier areas reduced to 4.42 km^2 and shrank by 61.90 % than in 1957. Its annual mean decrease was about 0.138 km^2. The analysis confirmed that the contraction rate of glacier area had been accelerating. (2) The glacier mass showed a negative balance. By calculating the data measured, Du (2011) found that the mass balance value of Baishui No. 1 in 2008/2009 was −1,047 mm and in 2009/2010 was −1,467 mm. Compared with the same period in 1982, the daily mean melt in 2009 increased from 7.4 to 9.2 cm, and the daily water layer thickness increased to 75 mm from 37. (3) The glacier fronts had a obvious retreat. The altitude of Baishui No. 1 glacier fronts retreated to 4,365 m in July 2010, which rose by 155 m compared with the same period in 1997. The annual mean retreating speed of Baishui No. 1 glacier fronts in 1998–2008 was 3.75 m more than in 1982–1998, and the annual mean retreating distance of fronts increased by 7 m compared with in 1982–1998. Moreover, the width at an altitude of 4,680 m of Baishui No. 1 glacier reduced by 20 m in 2004–2010. (4) A significant warming appeared in glacier area. The analysis on the gradient meteorological observation data and the observation results of ice temperature indicated that the glacier area had a significant rise in temperature. The measured results in 2009 showed that the annual mean temperatures at altitude of 4,300 m and near balance line (elevation of 4,800–5,000 m) were 2.1 and 1.5–2.5 °C higher than in 1982 (Xin 2011). In 2008, the ice temperature at 5 m deep in an altitude of 4,600 m rose by 0.41 °C compared with the observation values at the same period in 1982 (Wang et al. 2011a, b). The significant warming in the glacier area will lead to the sharp decrease in cold storage of ice, then result in the faster glacier melt.

7.2 Shortening of Glaciers Length

7.2.1 Characteristics of Stage in Glaciers Length

As shown in Fig. 7.4, eight marine glacier present a step change mainly characterized by retreat in recent 100 years. From the beginning of the 20th century to 1930s, in addition to Baishui No. 1, the remaining 7 glaciers were in stable or forward state. In the 1930s–1960s, the glaciers were in a shrinking state. Hailuogou glacier, Hailuogou No. 2 glacier, Yanzigou glacier, Big Gongba glacier, Little Gongba glacier, Mingyong glacier, Azha glacier and Baishui glacier retreated by 1,150, 800, 2,350, 175, 200 m or so, 2,000, 700 and 1,250 m, respectively. From 1960s to early 1980s, the glaciers were in a stable or slowing down. Big and Little

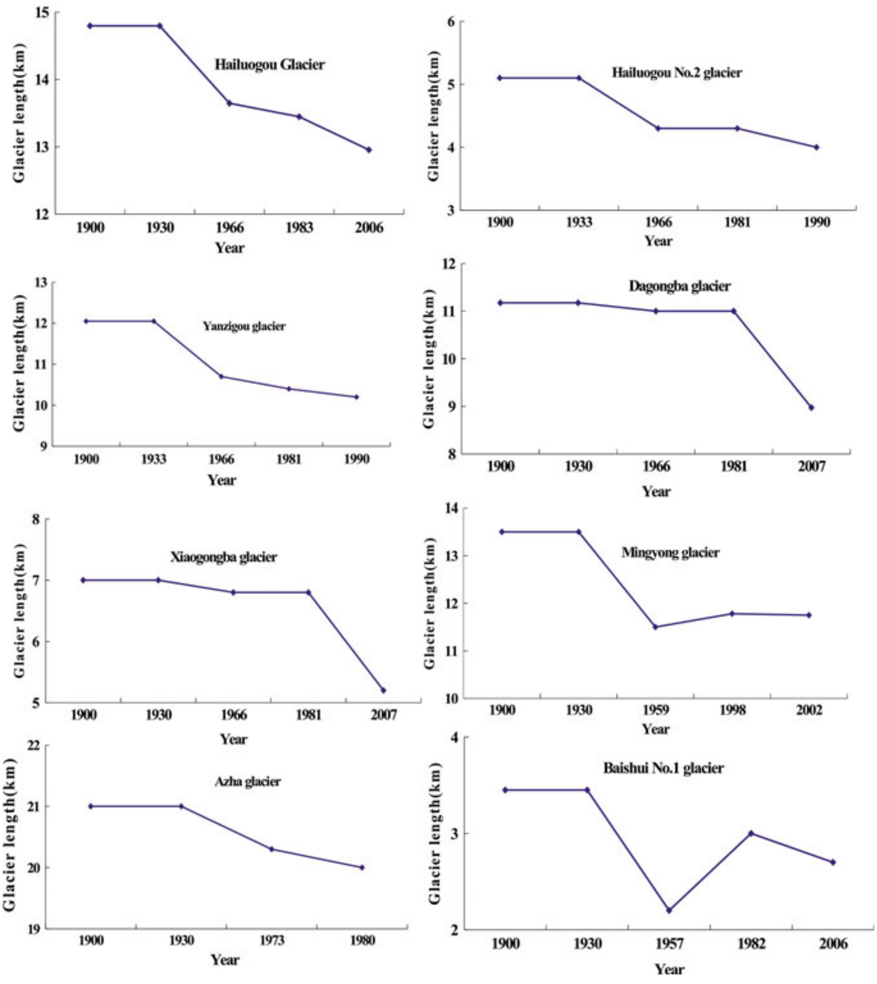

Fig. 7.4 Variation of the length of 8 glaciers in southwestern China. Reprinted from the Lancet: Li et al. (2010c). Copyright (2010), with permission from Elsevier

Gongba glaciers and Hailuogou No. 2 glacier were in a stable state. Yongming glacier and Baishui No. 1 glacier moved forward 1,080 and 800 m, respectively. It was easy to determine the retreating speed of other glaciers slowed down apparently from the smaller tilt of broken line than former stage. From 1980s to now, all the glaciers were in retreating state. Hailuogou glacier retreated by 491 m in 1983–2006. Hailuogou No. 2 glacier and Yanzigou glacier retreated by 300 and 200 m, respectively in 1981–1990. Big and Little Gongba glaciers had a retreat of 25 m and 12.5 m in 1981–1990. Baishui No. 1 glacier went back 380 m in 1982–2008, and the Mingyong glacier had retreated by 30 m in 1998–2002.

7.2.2 The Spatial Difference of Glacier Retreat

As shown in Fig. 7.5, there were difference in changing trends of each glacier because of the differences in latitude location, local climate change, local environment and glacier itself characteristics (glacier length, area and gradient). They were mainly displayed in the following aspects:

(1) The changing trend of glacier in the east slope of Gongga Mountain was wider than in the west slope in the same period, and the retreating speed in former period was remarkably faster than in the latter period. In 1970s–1980s, the Hailuogou and Yanzigou glacier in the east slope of Gongga Mountain showed a slow retreat, while the Big and Little Gongba glaciers were in a stable state. The melting of ice tongue in east slope also was more than in the west slope. Likewise, the Gongba glacier in the west slope also had a slight retreat since 1980s. The investigation in 1982/1983 confirmed that the annual mean temperature and precipitation of Big Gongba glacier fronts (3,700 m) in the west slope were 22 °C and 1137.7 mm, whereas the annual mean temperature and precipitation of Hailuogou glacier in east slope at an altitude of 3,000 m were 3.9 °C and 1,938 mm. Furthermore, the precipitation in glacier accumulation area located in the east slope was around 1,000 mm greater than in the west slope (Li and Su 1996).

(2) Among three glaciers in the east slope of Gongga Mountain, because of the differences in location and scale of glacier, the changing trend of Yanzigou glacier with a shorter length was slightly greater than that of Hailuogou glacier, while the retreating speed of Hailuogou glacier was significantly greater than the Hailuogou No. 2 glacier located in same basin but had a higher altitude of front.

(3) When the influence of the glacier itself characteristics were ignored, the reflection of glacier at low altitude to climate fluctuations was stronger than that of glacier at high altitude. During 1930–1966, the Mingyong glacier in lower latitude retreat most fastly, and the retreating speed of Baishui No. 1 glacier which was located at lower latitude but had a higher altitude of front was similar to that of Hailuogou No. 2 located in higher latitude. In addition, in the cooling phase of 1970s–1980s, Mingyong glacier and Baishui No. 1 glacier showed a significant advance, while the glaciers at high altitude displayed a slow or stable state.

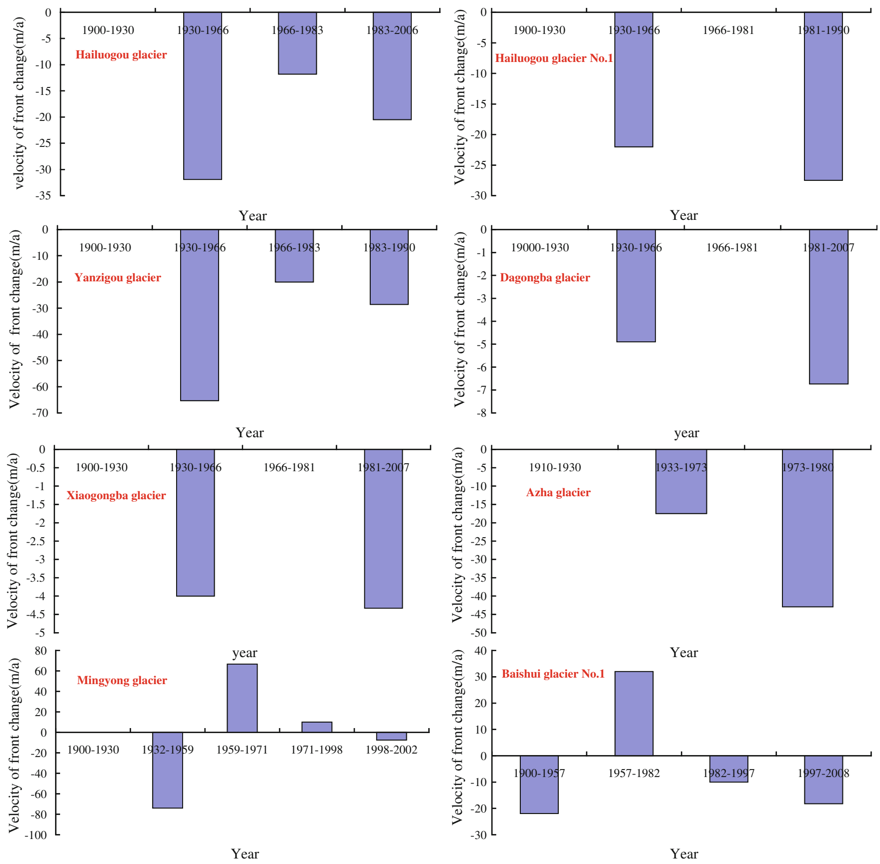

Fig. 7.5 Variation velocity of 8 glaciers during the past 100 years. Reprinted from the Lancet: Li et al. (2010c). Copyright (2010), with permission from Elsevier

7.2.3 The Relationship of Glacier Length and Climate Change

The temperature changing trend of China was basically consistent with the northern hemisphere over the past century that both showed a fluctuation change mainly characterized by warming trend. The period from the end of the 19th century to the beginning of the 20th century was the continuous low temperature stage, while the period from 1930s to 1960s was the continuous high temperature stage. The period from 1970s to the middle of 1980s was the low temperature stage, and they were in a intense heating state from 1980s to now (Qin et al. 2005). The studies have shown that marine glacier area entered into a short cold stage, that is the beginning of 20th century. The temperature rose back from 1930s to 1960s but declined again in 1970s, while both temperature and precipitation showed a sharp increasing after

1980s (He et al. 2003a, b). Li et al. (2010b) confirmed that the temperature of Hengduan Mountain presented the statistical significance of warming trend, and the warming magnitude was 0.15 °C/10 a. Thereinto, the temperature was relatively low in 1960s and 1980s, and that in others were higher. In 2000–2008, the annual mean temperature was 0.46 °C higher than the average for many years. The annual precipitation of Hengduan Mountain was lower in 1960s and 1970s and relatively higher after 1980s, especially that in 1990s was 29.84 mm more than the average for many years. After entering 2,000, the precipitation declined apparently compared with that in 1990s. The annual precipitation increased at a rate of about 9.09 mm/10 a in 1961–2008. The analysis of Chaps. 3 and 4 also confirmed that the temperature continued to warm since 1961 in Southwestern China and accelerated to rise after the middle of 1980s. While the precipitation remained stable.

As shown in Table 7.1, by contrasting the changes of 8 glaciers fronts in recent years with the temperature changes of China and Northern Hemisphere, ice core records of Dapusuo, records of tree rings in Hengduan Mountain and the climate changes of Southwestern China and Hengduan Mountain in nearly 50 years, there was obvious correspondences between them. The cooling period from the end of 19th century to the beginning of 20th century which was the cool and dry period of Hengduan Mountain in summer corresponded to the stability or relatively advancing phase. The warming period from 1930s to 1960s which was the warm and wet period of Hengduan Mountain in summer corresponded to the shrinking phase. The cooling period from 1970s to the middle of 1980s which was the cool and dry period of Hengduan Mountain in summer corresponded to the relatively stable or slowly retreat stage. The warming period from 1980s to now which the warm and wet period of Hengduan Mountain in summer corresponded to the retreat stage since the middle of 1980s. These reflected that the glaciers advanced or kept stable in cold and dry climate and retreated or got losses in warm and wet climate. It fully showed that the the influence of temperature on matter accumulation and ablation of glacier was greater than the influence of precipitation. However, this deduction still remained to be seen in further observational studies. He et al. (2003a, b) and Pang et al. (2007) indicated that the global warming was the main cause of the glacier retreat in Yulong Snow Mountain. Above each glacier showed an obvious response to climate change, fully reflected the high sensitivity of changes in glacier fronts to climate changes, and the above glaciers all were the marine glaciers with high sensitivity to climate changes. Strictly speaking, the changes in front retreat did not fully show the synchrony with climate change. On the one hand, it was because the changes in front retreat had a response lag to climate changes which formed because the drop of ice thickness and the sharp decrease of reserve were first, next was the retreat of whole fronts. On the other hand, it was because the data of eight glacier changes was not continuous, so it was very difficult to reflect the process of glacier retreat and its specific lag. In addition, the environment of glacier (slope, altitude etc.) and the glacial features (length, area etc.) had the important influences on the change of glacier fronts.

Lijiang station with an average elevation of 2,400 m was located in 25 km south of Yulong Snow Mountain which was situated at the north edge of Lijiang Basin. The retreat speed of Baishui No. 1 glacier in 1998–2006 increased by 7 m than in

Table 7.1 Relationship between climate fluctuation and eight glaciers change

Period	Climate variation in China and the Northern Hemisphere	Climate variation in central Mt. Hengduan and Mt. Yulongr recorded by tree rings	Climate variation ecorded by Dasuopu ice core	Climate variation recorded by 16 climate stations	Glacier change	Mass balance change of Hailuogou glacier
1900–1920s	Cold period	Cold and dry period	Temperature decrease; steady glacier accumulation		Steady or advancing	
1930–1960s	Warm period	Warm and wet period	Temperature increase; decreased glacier accumulation		Retreating	Annual average mass balance is −178.8 mm during 1959/1960–1970/1971
1970–middle 1980s	Relatively cold period	Cold and dry period	Relative temperature decrease; glacier accumulation	Relative temperature decrease; precipitation decreased from 1960s–middle 1970s	Steady or advancing or retreating with relatively slower velocity	Annual average mass balance is 109.4 mm during 1971/1972–1984/1985
Middle 1980s–today	Accelerative climate warm	Warm and wet period	Fast temperature rise; severe accumulation decline	Accelerating warming and decreased precipitation after 1990s	Retreating	Annual average mass balance is −537.5 mm during 1985/1986–2003/2004

Table 7.2 Relationship between change of Baishui glacier No. 1 and climate in Lijiang

	Temperature (°C)	Precipitation (mm)	Retreat velocity (m/a)
1982–1997	12.67	947.38	9.4
1998–2006	13.31	1,062.76	16.4

1982–1997. However, the temperature and precipitation in latter period were 0.64 °C and 115.4 mm greater in former period. Moreover, the temperature of Lijiang in 1997–2004 was 0.54 °C higher than in 1982/1983, and the water equivalent of melting ice tongue increased 113 mm (Table 7.2). It also indicated that the retreat period of marine glacier was in the warm and wet weather stage. On the one hand, the cold storage of ice dropped sharply along with the rising of temperature. On the other hand, the increasing of non-solid precipitation frequency and total amount would further accelerate the disappearance of glaciers because when the temperature changes ΔT ≤ 0.5 °C, the precipitation changes could play a great role on the glacier changes; when ΔT > 0.5 °C, the glacier changes were mainly decided by temperature rather than precipitation changes (Gao et al. 2000). Since 1998, the fronts changes in altitude performed a same or opposite trend with the changes of temperature and precipitation, and the distance of fronts retreat also showed a similar change with precipitation and temperature (Fig. 7.6), reflecting that the sharp warming was the main cause of severe retreat of glacier.

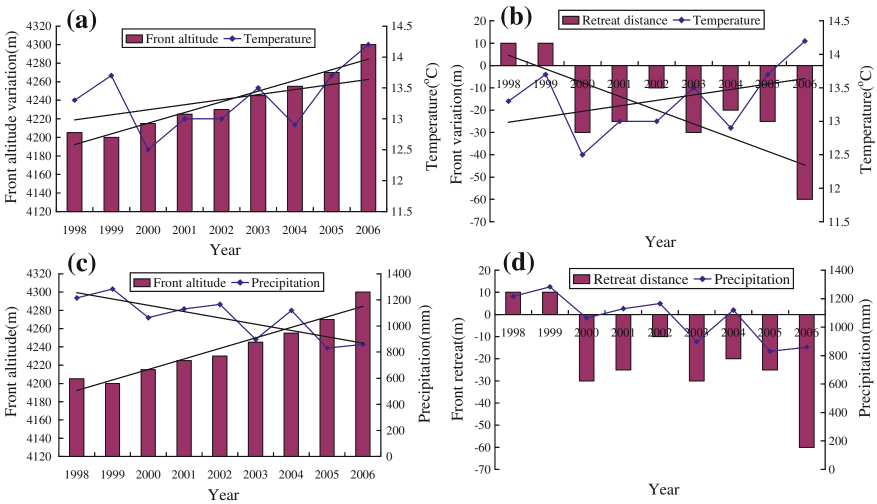

Fig. 7.6 Relationship between front altitude of Baishui glacier No. 1 and climate in Lijiang during 1998–2006 (**a** and **b**); Relationship between front retreat of Baishui glacier No. 1 and climate in Lijiang during 1998–2006 (**c** and **d**). Reprinted from the Lancet: Li et al. (2010c). Copyright (2010), with permission from Elsevier

7.3 Negative Balance of Glacier Mass

7.3.1 Balance of Glacier Mass in Hailuogou Glacier

As shown in Fig. 7.7, from 1959/1960 to 2003/2004, the mass balance value of accumulated water of Hailuogou glacier was −1,0825.5 mm (water equivalent) and the annual mean balance value was −240.6 mm (water equivalent), indicating that the Hailuogou glacier was given priority to lose for 45 years, during which there were 16 years showing a positive balance and 29 years showing a negative balance. Two turning point existed in mass balance changes: 1970/1971 and 1984/1985. On the basis of this, the mass balance was divided into three stages: negative balance (1959/1960–1970/1971), positive balance (1971/1972–1984/1985) and severely negative balance (1985/1986–2003/2004). The analysis found that the warming period at the beginning of 1950s–1960s was corresponding to the negative balance stage (warm and wet period of Hengduan Mountain in summer) when the the mass balance value of accumulated water of Hailuogou glacier was −2,145.6 mm (water equivalent) and the annual mean balance value was −178.8 mm (water equivalent). In addition, there were five balance years during this period. The cooling period in the middle of 1970s–1980s was corresponding to the positive balance stage (cold and dry period of Hengduan Mountain in summer) when the the mass balance value of accumulated water of Hailuogou glacier was 1,532.2 mm (water equivalent) and the annual mean balance value was 109.4 mm (water equivalent). Furthermore, Hailuogou glacier presented a positive balance and there were eight balance years during this period. The strong warming period in middle 1980s was corresponding

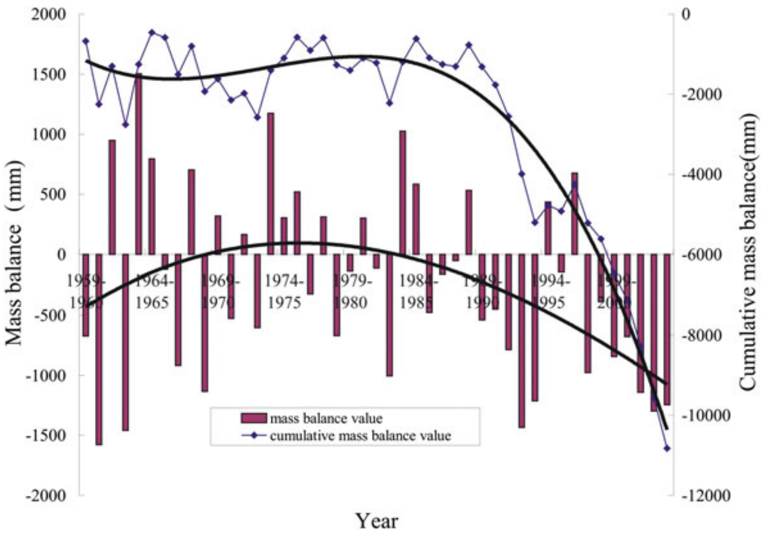

Fig. 7.7 Variation of mass balance in Hailuogou glacier during 1959/1960–2003/2004

to the severely negative balance stage (warm and wet period of Hengduan Mountain in summer) when the the mass balance value of accumulated water of Hailuogou glacier was −10,212 mm (water equivalent) and the annual mean balance value was −537.5 mm (water equivalent). This period was the most severely negative balance stage and had only three positive balance years (Fig. 7.3). In short, the mass lossed was the main characteristic of Hailuogou glacier changes for 45 years because the mass losses caused by the strong warming always was more than the slow increase of mass accumulation. In addition, the temperature rise would lead to the increase of the frequency and amount of liquid precipitation. And then, on the one hand, it could reduce the material recharge of ice; on the other hand, the latent heat released by changes in precipitation form would accelerate the melting of glaciers. Furthermore, the appearance of shortly positive balance mainly was the result of temperature decrease in this period.

7.3.2 The Relationship Between Mass Balance Changes in Hailuogou Glacier and Climate Changes

As shown in Fig. 7.8, the mass balance in Hailuogou glacier performed a opposite change to the accumulated temperature of Northern Hemisphere, fully suggested

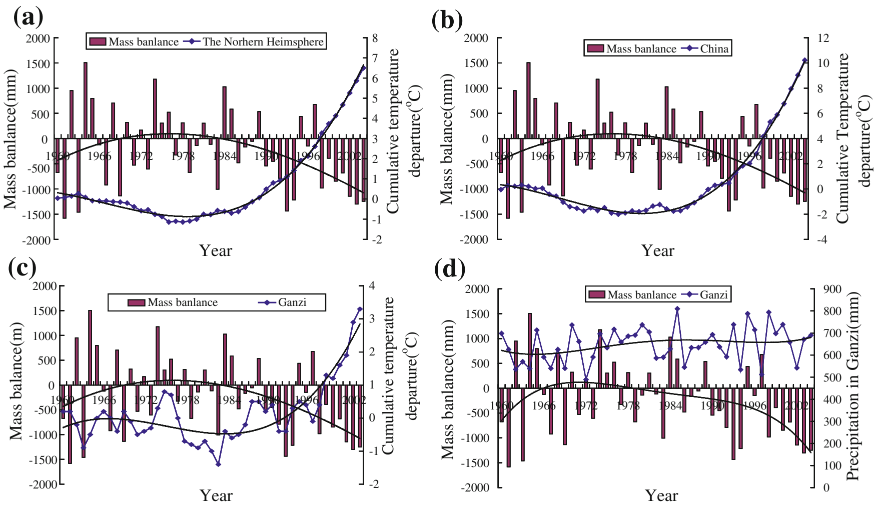

Fig. 7.8 **a** The relationship between mass balance and the annual mean temperature of the Northern Heimsphere. **b** The relationship between mass balance and the annual mean temperature of China. **c** The relationship between mass balance and the annual mean temperature of Ganzi. **d** The relationship between mass balance and the annual mean precipitation of Ganzi station. Reprinted from the Lancet: Li et al. (2010d). Copyright (2010), with permission from Elsevier

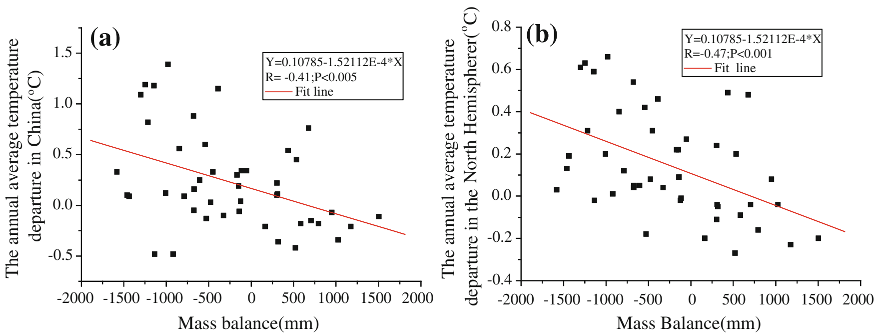

Fig. 7.9 **a** The statistical significance between mass balance and the annual mean temperature of China. **b** The statistical significance between mass balance and the annual mean temperature of the Northern Hemisphere. Reprinted from the Lancet: Li et al. (2010d). Copyright (2010), with permission from Elsevier

that the climate warming was the main reason of mass losses of glaciers. In addition, the interannual variation of mass balance also showed a significantly negative correlation with those of China and Northern Hemisphere, and the correlation coefficients were −0.47 and −0.41, respectively (Fig. 7.9). It once again showed that the changes in glaciers mass balance with the general trend of a negative balance resulted from global warming. In the severely negative balance stage, the rising of temperature cause the accelerated melting of glaciers and made glaciers in the state of losses. While in the positive balance stage, the decrease of temperature lowered the melting and shortened the melting period. Conversely, the accumulation increased and accumulation period lengthened, then the glaciers were in a state of income. By contrasting the mass balance changes of Hailuogou with the changes in temperature and precipitation of Ganzi Station which was located in the north slope of Gongga Mountain and 80 km away from Hailuogou (Fig. 7.8), it could be found that the temperature also presented an obvious rise and the changes of mass balance and temperature showed the opposite trends. In addition, the precipitation showed a slow increase trend and there was no an obvious relationship between mass balance and precipitation, verifying that the temperature rise was the main reason of glaciers losses and the slight increase did not far recharge the mass losses cause by temperatures rise. More important is the precipitation change in low altitude is not necessarily same to that in glacier area at high altitude. As shown in Table 7.3, in nearly half a century, the mass balance and climate change displayed an apparent correspondence. The mass got severe losses in warm and wet period, while the mass had an obvious accumulation in cold and dry period but the accumulation was a little less. The corresponding relation with temperature and mass balance in the changing stages and the significantly negative correlation with mass balance and temperature demonstrated that the mass losses of Hailuogou glacier mainly was the result of climate warming.

Table 7.3 Relationship between climate fluctuation and mass balance

Climate changes of China and Northern Hemisphere since the end of 19th century (Shi et al. 2000)	Climate changes of Hengduan Mountain since 1900 (Fan et al. 2008a, b, c)	The mass balance changes of Hailuogou glacier
Warm period in 1930s–1960s	Warm period in 1930–1950s; Wet period in 1930–1960	The mean mass balance was −178.8 mm in 1959/1960–1970/1971
Relatively cold period in 1970s–-middle 1980s	Cold period in 1960–1985 dry period in 1960–1990	The mean mass balance was 109.4 mm in 1971/1972–1984/1985
Obviously warm period from 1980s to today	warm and wet period from 1990 to today	The mean mass balance was 109.4 mm in 1985/1986–2003/2004

7.4 Increasing of Glacial Runoff

7.4.1 Process of Runoff Changes in Yanggong River

As shown in Fig. 7.10, in 1979–2003, the precipitation of Lijiang and the runoff of Mujiaqiao which was general control station increased significantly, which indicated that under the background of climate warming, the recharges and discharges in Lijiang Basin had the significant increases. Meanwhile, the increasing trend of minimum runoff in Mujiangqiao revealed that the recharge of groundwater to surface runoff in Lijiang Basin remarkably increased along with the climate warming. In order to analyze the response of runoff in Lijiang Basin to the climate warming in different seasons, this study considered the period of 1979–1988 as the earlier stage of warming when the annual mean temperature was 12.8 °C and the period of 1994–2003 as the later stage of warming when the annual mean temperature was 13.03 °C, then calculated the percentage of increase on the average of runoff in every month in the earlier stage of warming to in the later stage of warming (Fig. 7.11).

The analysis found that the runoff of Mujiaqiao in every month significantly increased. Thereinto, it increased most significantly in spring (from March to May), during which the percentage of increase in runoff was more than 100 %, while the percentages of increase in runoff in other seasons were less than 100 % (Fig. 7.11). The related studies have shown that under the background of global warming, the most significant warming appeared in winter and spring (Bultot 1988; Miller and Brock 1989; Dyurgerov and Meier 2000). Therefore, the significant temperature rise in spring will increase the melt water in the snow and ice areas at high altitude in Yanggong River basin so that the spring increasing of runoff was the maximum in Mujiaqiao where the spring mean temperature in former period was 0.17 higher than in latter period, (Fig. 7.11). In terms of changes within the year, the runoff was mainly recharged by underwater because of the less rainfall during the dry period

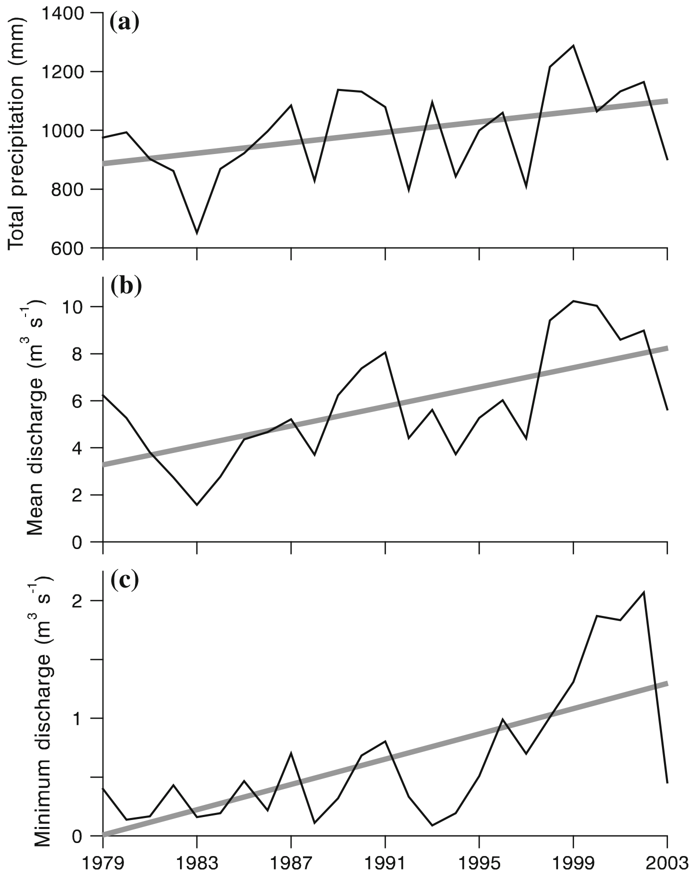

Fig. 7.10 Annual total precipitation variation during 1979–2003 in Lijiang (**a**); annual average discharge variation during 1979–2003 in Yanggongjiang basin (**b**); annual minimum discharge variation during 1979–2003 in Yanggongjiang basin (**c**)

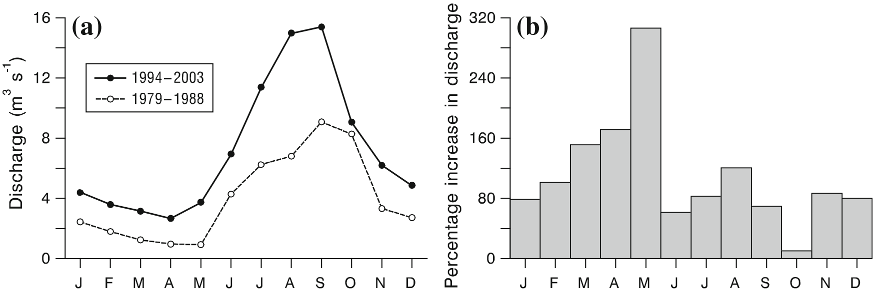

Fig. 7.11 The increased percent of monthly discharge between 1994–2003 and 1979–1998 (**a**); The seasonal variation of monthly average discharge between 1994–2003 and 1979–1998 (**b**). Reprinted from the Lancet: Li et al. (2010c). Copyright (2010), with permission from Elsevier

(from October to next May). The runoff gradually reduced from winter to spring and reached the minimum in late spring because the recharge of underwater will gradually reduce as the time going (Fig. 7.11).

From the Fig. 7.11, it can be seen that the runoff decreased gradually for the earlier stage or later stage of warming period. But it gradually increased from May and reached the peak in September, which was the embodiment of changes in recharge form according to the seasons in Yanggong River basin because it was monsoon period from May, and the precipitation would increase sharply. Most obviously, the monthly minimum runoff was in May in the earlier stage of warming period, while the monthly minimum runoff appeared 1 month in advance, that is April, which suggested that the warming in winter and spring made the ice and snow melt in Yanggong River basin have a significant influence on the time of runoff, in a word, the preact of melting period brought forward the recharging period of ice and snow melt and made the runoff in May increase (Fig. 7.11). Under the background of global warming, the interannual and seasonal runoff exhibited an increasing trend, but the increase in spring, summer and winter all were more than in autumn, reflecting the influence of climate warming in above seasons were more apparent than in summer. On the one hand, it suggested that the seasonal pattern of regional warming was one of the important factors of changes in the seasonal pattern of water cycle in marine glacier areas in the context of warming. On the other hand, the summer and autumn runoff were recharged by precipitation in Yanggong River basin and the precipitation increase was not very obvious in the same period, so the increase of runoff was relatively small.

In order to further know the response of the changes in the ice and snow melt water at high altitude to climate changes under the background of warming, we calculated the input of water $P_{Glacier}$ of ice and snow region in Yanggong River basin (altitude >4,000 m) to Lijiang Basin every year by using the water balance formula in Chap. 2, and found that the $P_{Glacier}$ in 1979–2003 showed an obvious rising trend (Fig. 7.12). Apparently, the contribution of ice and snow area at high altitude in Yanggong River basin to the runoff of Lijiang Basin increased year by year with the climate warming and the severe melting. The average of contribution for many years was water equivalent of 154.4 mm. however, as the glaciers reserves decreased year by year, the amount of contribution would begin to fall back when it reached a peak, which would decrease the security of regional water resources. In 1979–2003, average $P_{Glacier}$ accounted for 35.8 % of annual mean runoff in Yanggong River basin which might be a higher value. Buried river channels were complex due to the carbonate landscape in this basin, so more runoff became the groundwater and probably discharged researched area by underground river, which made the surface runoff less within the basin. The average of runoff for many years in Mujiaqiao stations was 429 mm which was significantly less than the precipitation in same period. So if we want to accurately understand the contribution of water resources in the ice and snow area at high altitude, it is very necessary to strengthen the researches on groundwater circulation and the condition of water resources in recharging basin in the follow-up work.

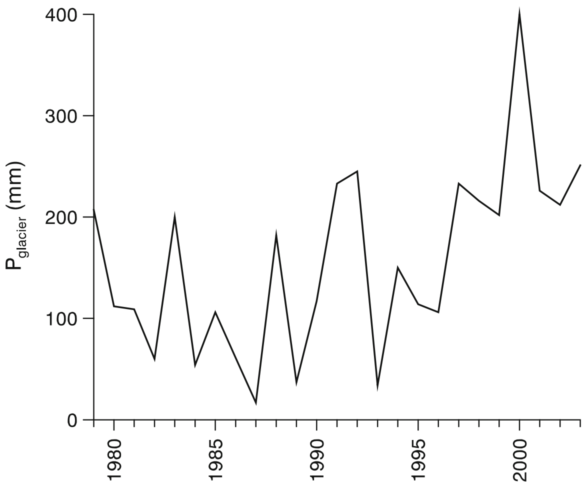

Fig. 7.12 Annual output discharge variation during 1979–2003 in snow-glacier covered area of Yanggongjiang basin

Table 7.4 The increased percent of precipitation, discharge and $P_{glacier}$ between 1994–2003 and 1979–1988

	Precipitation (mm)	Discharge (mm)	$P_{glacier}$ (mm)
1979–1988	908	300	110
1994–2003	1,045	536	210
% Increase	15.1	78.7	90.9

As shown in Table 7.4, the increasing trend of discharge in Yanggong River during the earlier stage was greater than during the latter stage of warming. The reasons were as following. Firstly, the growth of precipitation in high altitude area was more than in low altitude area under the background of global warming (Dyurgerov and Meier 2000). The observations confirmed that the annual mean temperature at an altitude of 4,300 and 4,800–5,000 m (balance line) in Baishui No. 1 had rose by 2.1 and 1.5–2.5 °C than in 1982 (Xin 2011). The annual mean temperature of Lijiang meteorological station (2,400 m) in 2009 was 1.4 °C higher than in 1982. Secondly, the severe melting in Yanggong River basin due to warming led to the significant increase in melt water. The temperature in latter period increased by 0.23 °C than in the former period, but the runoff of Mu-jiangqiao had a more remarkable increase than the precipitation of Lijiang. The mean precipitation (1,045 mm) in latter stage of warming period (1994–2003) increased by 15.1 % than that (908 mm) in former stage of warming period (1979–1988), and the mean runoff depth (536 mm) of Mujiaqiao in latter stage of warming period had an increase of 78.7 % than that (300 mm) in former stage of warming period. Chiew and McMahon (1994) thought that the precipitation changes always were expanded in the response on runoff and the percentage of runoff change was about 2 times of precipitation after analyzing the impacts of climate change on the 28 representative basins runoff in Australia. Obviously, the significant increase of runoff in Mujiaqiao cannot be entirely resulted in the precipitation increase in Lijiang. The response of glacier on temperature fluctuations was more sensitive because of the smaller area of glcaciers in Yanggong River basin, therefore, the discharge of water in high altitude area during the latter stage had risen by 90.9 % than the former stage. Moreover, the sharp warming in latter stage (1994–2003) made the snowline height significantly rise and the melting area expand but the accumulation area narrow, which caused that the solid precipitation at the high altitude areas turned into liquid precipitation (Higuchi and Ohata 1996). It increased the liquid precipitation in glacier areas and the melt water. So, the temperature rise of Yanggong River was the main reason causing the significant increase of recharge (namely $P_{Glacier}$) in Lijiang Basin.

7.4.2 *Process of Runoff Change in Hailuogou*

As shown in Fig. 7.13, the runoff of Hailuogou in 1999–2004 increased significantly, and the annual mean runoff in 2004 increased 3.33 m^3/s than in 1999. The temperature also showed an obvious rise, while the precipitation and vaporation howed a trend of decline but reduction of the evaporation was far less than the increase of runoff. From the contrast between 1999 and 2004, the vaporation reduced by 103 mm and the precipitation decreased by 55 mm, while the runoff depth with a increasing trend was 1,334 mm. It indicated that under the background

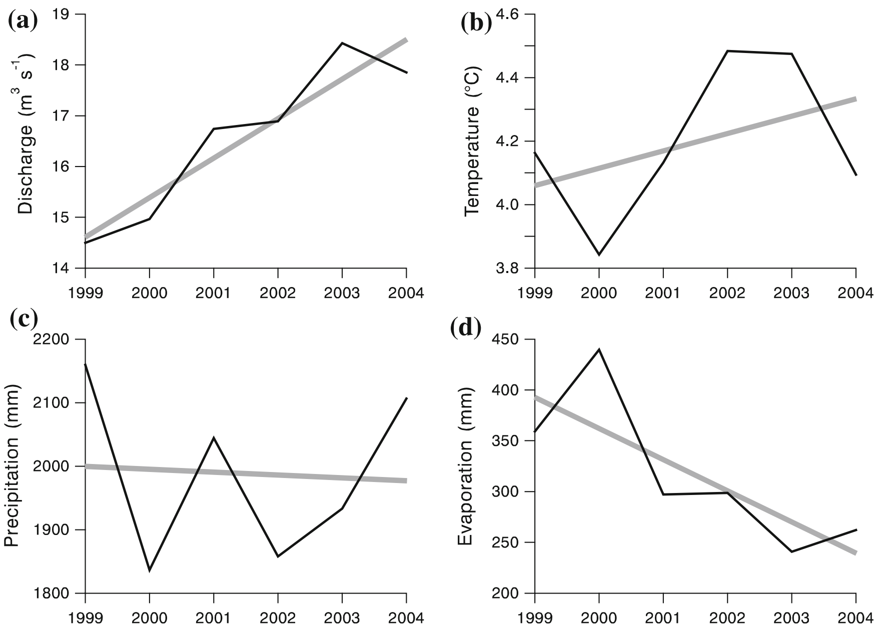

Fig. 7.13 The variation of discharge (**a**), temperature (**b**), precipitation (**c**) and evaporation (**d**) during 1999–2004 in Hailuogou basin

of climate warming, the accelerating melting, expanding melting area, lengthening melting period and larger cover area of glaciers which accounted for 37.7 % of total areas resulted in more and more recharge of ice and snow melting water to rivers. Because the marine glaciers were located in monsoon region at low latitude and had a stronger sensitivity to climate, the weak warming would lead to a nonlinear increase of melting, which accelerated the glacier losses and the speed of water cycle to a certain degree. Furthermore, recharge of glaciers to the basins ($P_{glacier}$) in 1999–2004 showed a trend of obvious rise (Fig. 7.14). The average was water equivalent of 2,024.6 mm for many years, demonstrating the important contribution of glaciers to runoff increase. The temperature of Hailuogou in 2003 increased by 0.31 °C than in 1999, but the precipitation in 2003 was 237.5 mm less than in 1999. The runoff depth in 2003 had an increase of 681.44 mm compared with 1999, at the same time, $P_{glacier}$ also was water equivalent of 790.81 mm more than in 1999, which suggested that the increase of discharge in glacier area resulted from temperature rise played an important role on the increase of runoff within the basin (Tables 7.4 and 7.5).

In addition, the seasonal change of precipitation and runoff depth in Hailuogou (Fig. 7.15) showed that the peaks of precipitation and runoff depth occurred in June and August. And the precipitations in October and April were quite similar but the runoff depth in October was 162 mm more than in April. The basin area is lesser and there were most bedrock mountains here. The hydrological station was located in 1 km away from the Hailuogou glacier front. These conditions determined that the confluence of precipitation within the basin could not be 2 month later than the surface runoff because the recharge of ice and snow melting water in the high

Fig. 7.14 Annual output discharge variation during 1999–2004 in snow-glacier covered area of Hailuogou basin

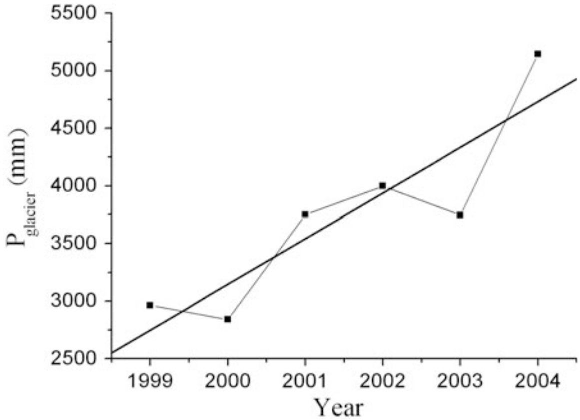

Table 7.5 Mean annual precipitation, runoff and PGlacier in the Hailuogou basin in 1999 and 2003, all values are in mm equivalent

Year	Precipitation (mm)	Runoff depth (mm)	Mean $P_{glacier}$ (mm)
1999	2,160	3,418.7	1,617.6
2003	1,932.5	4,100.1	2,408.41

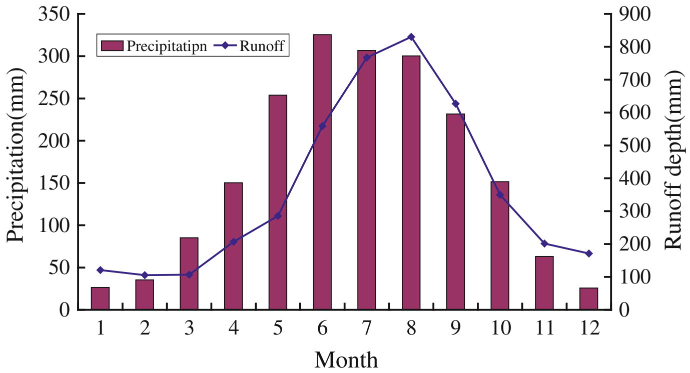

Fig. 7.15 The seasonal variation between precipitation and runoff in Hailuogou basin

mountain to downstream surface runoff had a lag to a certain degree. It was because he confluence of melt water in glacier areas was relatively slow due to itself water cycle system. The previous researches had proven that the Hailuogou glacier had a complex underground water circulation system indicating that the change of the glacier melting water determines the change of water quantity in the whole basin to a large extent. Additionally, the mean $P_{glacier}$ of Hailuogou basin in 1999–2004 accounted for 54.7 % of the average runoff depth for many years, showed again that the ice and snow melting water in Hailuogou had a primary role on the recharge of River.

7.4.3 Possibale Effects of Increasing Discharge at High Altitude

Hailuogou basin and Yanggong River basin were recharged by marine glaciers, but their geographical locations, areas, altitudes, internal features, etc. had great differences. For example, the glacier area in Hailuogou basin was significantly more than that in Yanggong River basin. However, under the background of climate warming, their contribution values of glacier region to water quantity are at a significant increasing state in the interannual scale, which can indicate that the increase of ice and snow melting water caused by climate warming had been shown in different marine glacier regions. Therefore, to strengthen the observation of water cycle in marine glacier region can not understand the mechanism of water cycle in the context of climate warming, but also reveal the interaction of climate and hydrology in marine glacier region from the observational studies for a long time as so to provide a scientific basis for global change and regional development. Due to the hydrology observation for a short time and the lack of observation data on the elements in some glacier areas, the equation of water balance made in this study still had some limitations. The researches on the mechanism of water cycle and the response on climate warming in marine glacier basin still need to measured for a longer time.

If temperatures continue to rise, ice and snow melting water in marine glacier basin will continue to increase in the short term, and a series of disasters, such as floods, landslides and ice rock collapse will occur in great quantities, combined with the heavy rain and under the condition of steep mountains so that a major inconvenience will be brought to regional transportation, tourism and development of production. And the global warming will accelerate the hydrologic cycle in marine glacier area, aggravate water loss and soil erosion and generate a great threat for soil in mountainous area and ecological environment. Since 1980s, in order to develop the regional economy, the ice-snow tourism resources get the sufficient development in marine glacier area and a series of famous tourist area were built, such as Yulong Snow Mountain, Hailuogou in Gongga Mountains, Merry Snow Mountain etc. However, under the background of global warming, the safety of large tourist facilities like ropeway need to be further argued. And the sustainable development and protection of ice-snow tourism resources is particularly important, so it is very necessary to rationally utilize and protect the ice-snow tourism resources and strengthen comprehensive monitoring and scientific research work of the glacier areas in typical basins.

7.5 Fragmentation of Glacier Microtopography

The change of glacier surface morphology was the embody of the accumulation and loss of mass, energy conversion and mechanism changes caused by climate change on glacial appearance characteristics. It was refer in particular to the change of external characteristics, of which essence were the glacial shrinkage and mass losses caused by climate warming. And the change of external characteristics were displayed by thickness decrease, widening and increasing ice-cranny, ice collapses, runoff increase, channel expansion, the formation and break of glacial drifts and some. The adaptive mechanisms of glaciers referred to itself feedback system of resisting external forces like erosion and destruction by its own integrity, cold storage, material feedback mechanism, energy exchange, rheological structure, material exchange and surrounding environment factors. The surface morphology change mainly characterized by mass losses destroyed the integrity of the glacier, expanded the areas accepting external force, increased the strength and depth of outside influence and accelerated the melting.

7.5.1 Surface Morphology Change of Baishui No. 1

The recent investigation found that the surface morphology change of Baishui No. 1 in Yulong Snow Mountain presented three characteristics due to climate warming (Fig. 7.16). (1) The ice surface was broken seriously in the ablation area and there were a lot of ice-cranny. The ice surface occurred obvious differences in melting because of the effects of ice structure, slope, debris cover, glaciers movement and

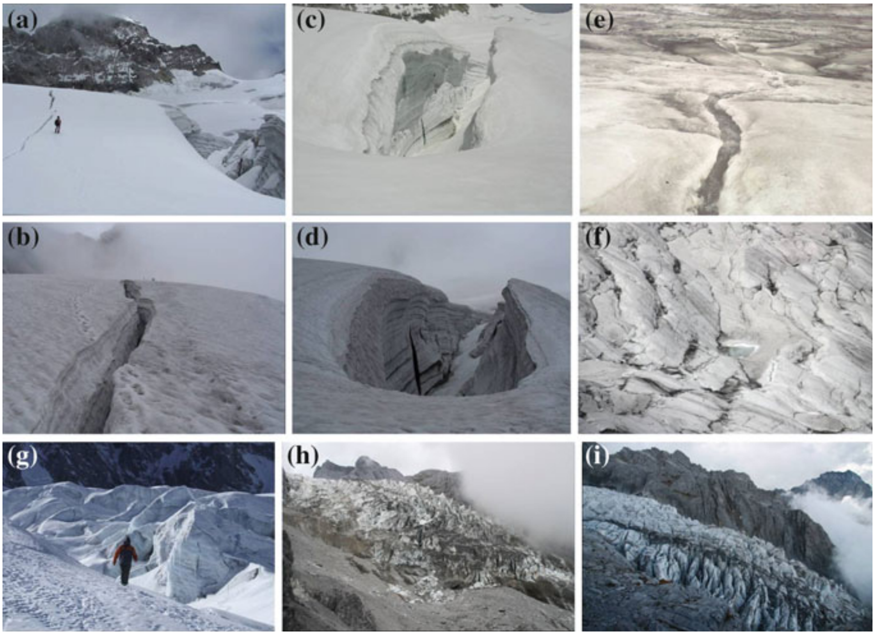

Fig. 7.16 Changes of ice-cranny in accumulation area of Baishui glacier No. 1 (**a**, **b**); Changes of ice-groove in accumulation area of Baishui glacier No. 1 (**c**, **d**); ice-lake in Baishui glacier No. 1 (**e**); ice-rivers grown in accumulation area of Baishui glacier No. 1 (**f**); Crashing in ablation area (**g**, **h**, **i**)

others. Plus, the surface runoff poured downward along ice-cranny and resulted in drastical broken ice which brought a great difficulty to glacier observation. (2) The melting was severe in accumulation area and the deep ice-cranny increased year by year, which showed a trend of gradual breaking. There appeared several deep ice-crannies which were 30 m deep and 1–3 m wide and profile of about 20 m deep and 10 m wide in the accumulation area of Baishui No. 1 glacier. The formation of ice-cranny and profile was the apparent sign of changing internal structure and severe melting. Especially, the cranny and profile had the tendency of deepening and widening in a short period (Fig. 7.16). In addition, the exploration in 2008 discovered that some small lakes and rivers appeared in the ice surface in accumulation area (Fig. 7.16). (3) The ice shelf collapsed frequently. It can be often seen that the collapsing ices fell down because of the rapid melting, movement and abrupt slope. The most serious collapse happened in Yanggong River No. 5 of Yulong Snow Mountain in 2003 and 2005. Zhang et al. (2007a, b, c, d) analyzed and found that the drastical melting and accelerating movement were the main reason of collapse under the background of climate warming, and the inducements were the hot and dry year appeared suddenly as well as the favorable terrain.

7.5.2 Surface Morphology Change of Hailuogou Glacier

Figure 7.17 referred to the variations of Hailuogou glacier front in 1994, 2004, 2006 and 2007. In 1994, there was white ice surface, less debris cover and thicker glacier. But in 2004, due to the severe melting, the thickness of glacier became thinner obviously, and the debris cover became thicker and appeared in the whole ice surface. Up to 2006 and 2007, just some accumulated debris cover could be discovered in the glacier front and a little glacier ice was be found in the end of melt water. Furthermore, the land where the glacier ever existed in was covered by rich plants, so the debris cover was. Because of the severe glacier melting, there was the obvious runoff in the ice surface covered by little debris (Fig. 7.17). Under the effect of scouring of ice surface runoff, the ice hole formed and connected the glacier tongue to subglacial river so that the effective link was formed between ice surface runoff and subglacier runoff (Fig. 7.17). In 2006, a ice-cranny of 1 m wide and 30 m deep had hindered the investigation of accumulation area in Hailuogou No. 2. The thickness of Hailuogou glacier front had reduced by 12 m for 12 years from 1993 to 2004. A glacier cave had appeared in the great glacier waterfall since 1990s. And a big ice-cranny of 300 m long and 20 wide was in the middle of glacier tongue. Because the severe melting result in the decreasing thickness of glacier and the subglacier river caused the collapse, big and small caves and cranny could be discovered in the surface of glacier tongue, which resulted in the unevenness of ice surface covered by debris. The severe melting caused many crannies appearing in the arch area of glaciers and eventually make the glacial arch disappear. The continuous retreat and thinning led to the disappearance of the famous hole which was the entrance of subglacier river in tourism area of Hailuogou.

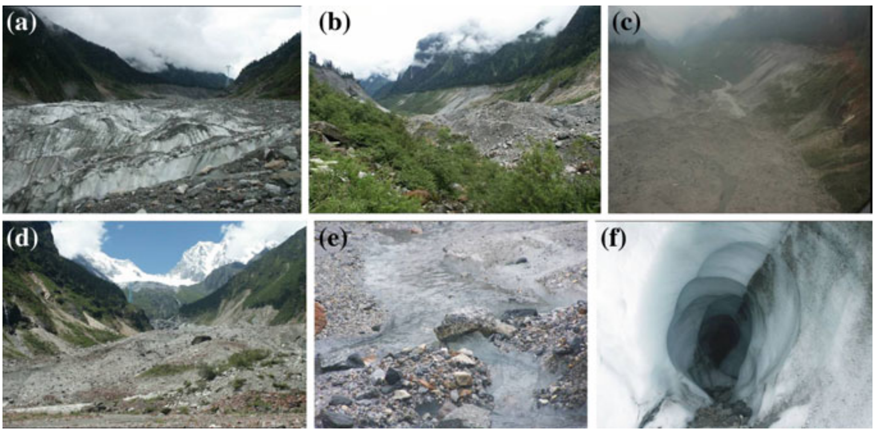

Fig. 7.17 The variations of Hailuogou glacier front in 1994 (**a**), 2004 (**b**), 2006 (**c**) and 2007 (**d**); ice-rivers in Hailuogou glacier tongue (**e**); the entry of subglacial rivers of Hailuogou glacier (**f**)

7.5.3 The Changes of Gongba Glacier

The Gongba glacier in the west slope of Gongga Mountain was explored in June 2007. As shown in Fig. 7.18, the surface morphology change has three characteristics: (1) The entire glacier tongue almost was covered by debris and the glacier front covered by debris appeared many crannies with the sever melting of glaciers, so the collapses and caves were found here and there. (2) There was a ice-lake of about 150 m wide in the cross of big and small Gongba glaciers. This lake formed because the glacier melt water was blocked by the accumulation of debris. When its water level reached a certain height, the outburst was most possible under the condition of special weather. Due to the severe melting and thick debris cover, there were many small moraine lakes and ice-lakes distributed in the whole glacier tongue and called "Haizi" by local residents. (3) The glacier waterfall collapsed frequently which was the component of most marine glaciers. Under the background of climate warming, the rapid melting caused the accelerating movement in the bottom of glaciers and finally resulted in the collapse, which indicated that the reducing of recharge resource and the increasing of material circulation. Generally, the glacier tongue was recharged through the snow slide in the accumulation area of

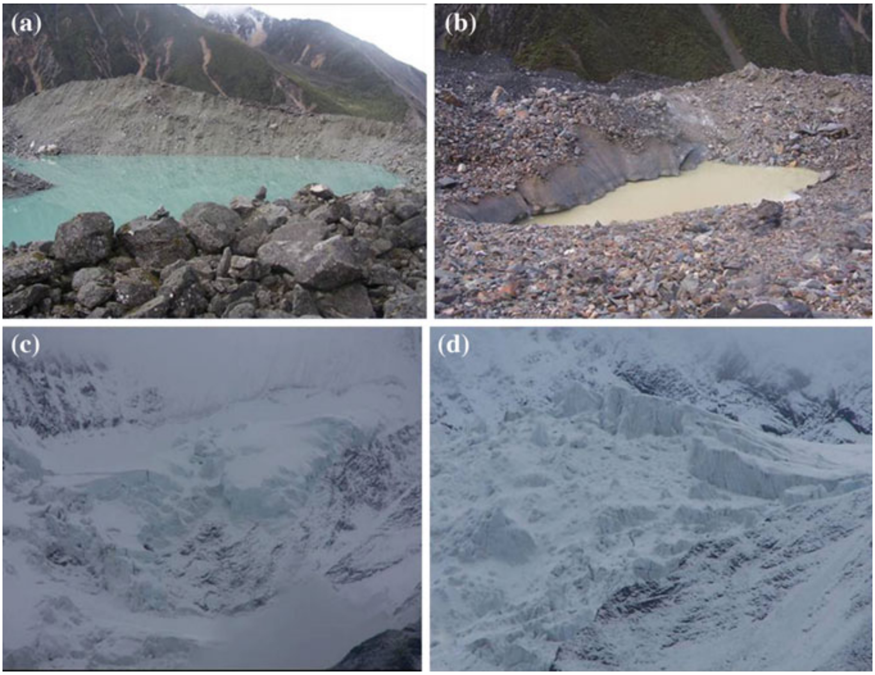

Fig. 7.18 A big ice-lake in the front of Dagongba and Xiaogongba glacier (**a**); a small lake in Dagongba glacier tongue (**b**); ice-fall happened in Xiaogongba glacier (**c**); ice-fall in Dagongba glacier (**d**)

most marine glaciers so that the glacier tongue kept in low altitude. But now it was recharged by glacier collapse and snow slide, which was another obvious signal of reducing mass accumulation and severe ablation.

7.5.4 The Response of Glacier Surface Morphology Changes to Climate Change

The continuous warming led to the sharp drop of cold storage. On the one hand, it speeded up the melting. On the other hand, it made melting area expand, melting period lengthen and ablation rate accelerate along with the changes of internal mechanism and glacier surface morphology. The changes of glacier surface morphology also were strong evidence of glacier change in the context of global warming because the glacier change was solid and comprehensive which was not displayed by the decrease of length, width and depth, but also by the external morphological changes resulting from the changes of physical mechanism. In addition, the location of glacier surface morphology changes moved toward upstream of glacier as the rising of snow line, which made some surface characteristics gradually move to glacier accumulation area. The many collapses and the ice-crannies in some marine glaciers were the prime examples. These changes would further undermine glaciers adaptive system and accelerate melting, because the occurrence of big crannies did not destroy the integrity of the glacier but increased the area and depth of the outside influences. More importantly, it would lead to the infiltration of melt water into crannies and further accelerate the retreat and fragmentation of glaciers which was very obvious in Yuong Snow Mountain. Moreover, the collapse of big ice waterfall in marine glacier area was one of signals of rapid melting. The big ice waterfall was an important link between accumulation area and glacier tongue and was an important channel of material supply of glacier tongue. In recent years, the exposed rocks caused by the collapse of ice waterfall reflected that the accumulation of marine glaciers could not balance the mass losses resulted in severe melting of glacier tongue at low altitude under the background of sharp melting. It would lead to the gradual disappearance of glacier tongue and make the glacier change. For example, the valley glaciers could become cirque glaciers or hanging cirque glaciers. The ice-shelf collapse was another performance of rapid ablation of marine glacier. The drastical melting would result in the accelerating movement in the bottom of glacier and the collapse occurred under the condition of steep slope and terrain. When the glacier tongue moved to a certain location, the possible collapse was possible for some big glaciers, which did not cause the rapid retreat but the natural disasters like flood and landslides.

7.6 Summary

By sorting and analyzing glacier observation data and previous studies, the response of glaciers in Southwestern China to climate change are mainly displayed as following:

(1) Under the background of temperature rise, especially the further warming in high altitude area, the glacier changes in Southwestern China showed four characteristics. The first is sharp retreat and shrinking area. 32 glaciers in Nyainqntanglha Mountains, Himalayas, Tanggula Mountains and Hengduan Mountains had obvious retreat, and the areas of 13 glaciers shrank significantly. The second is mass losses of glaciers. The mass of No. 94 glacier, No. 12 glacier, No. 4 glacier and No. 10 glacier in Nyainqntanglha Mountains, Demula glacier, Zhadang glacier in Tanggula Mountains, Namunani glacier in Himalayas, Hailuogou glacier and Baishui No. 1 in Hengduan Mountains showed a negative balance in recent years. The third is the significant increase of lake area and ice runoff recharged by glaciers. The ice area of Selincuo, Naqu, Namucuo, Himalayas Mountain, the upstream of Manla reservoir and Ranwuhu basin had a increasing trend. The recharge of snow-ice melting water in Hailuogou basin, Yangjiang River basin, Rongbu River basin and Qugaqie basin to runoff increased year by year. The last one is significantly accelerated ablation of typical glaciers monitored. Its main characters were severely shrinking area, accelerated retreat of glacier front, drastical losses of ice storage and the significant warming of glacier area. The studies suggested that the temperature rise is a major cause of regional glacier retreat, and precipitation decrease in some regions also has played an important role in the glacial retreat, such as the Himalayas.

(2) The change in length is the most direct response of glacier to climate change. Under the background of climate change, eight marine glaciers fronts in Hengduan Mountains changed in different stages and the changes presented a general trend of retreat. The period from the beginning of 20th century to 1930s was the stable or forward stage. The period of 1930s–960s was the retreat stage. The period from 1970s to the mid of 1980s was the stable or forward stage. And since 1980s, the glaciers retreated significantly, but there was a certain difference in changing magnitude of glaciers due to the differences of its own characteristics (length, area, altitude, slope direction, etc.), environment, latitude location and some. The studies suggested that the change in length of eight glaciers obviously corresponds to the climate changes in China, Northern Hemisphere, Southwestern China and Hengduan Mountain, and presents a forward trend in cold and dry period and backward trend in warm and wet period.

(3) The material balance reflects the direct influence of climate change on glaciers from amount of mass. During 1959/1960–2003/2004, the accumulated water-material balance value of Hailuogou for 45 years was −1,0825.5 mm (water equivalent), and the annual mean balance value was −240.6 mm (water equivalent), indicating that it was given priority to with losses for 45 years.

During 45 years, there are 16 years showing positive balance and 29 years showing negative balance. The staged change of mass balance in Hailuogou was opposite to that of China, Northern Hemisphere and Hengduan Mountain, demonstrating that the climate warming is the main cause of mass losses.

(4) The glacier hydrological system is a sensitive indicator of climate change. In 1979–2003, the precipitation, mean runoff and minimum runoff increased significantly. Under the background of warming, the recharging water of snow and ice area at high altitude to Lijiang Basin increased year by year, verifying that the increase of ice-snow melting water was the main contribution to the increase of runoff. And the average for many years was water equivalent of 154.4 mm. The temperatures rose by 0.23 °C in 1994–2003 compared with 1979–1988. The precipitation increased by 15.1 % in the same period, but the mean runoff depth was 78.7 % in latter period more than in former period. The discharging water in the snow and ice area at high altitude in Yanggong River increased by 90.9 %. The monthly minimum runoff in +Mujiaqiao appeared in May in the earlier stage of warming period, while it occurred 1 month in advance in the latter stage of warming period. It indicated that the warming in spring and winter made the ice-snow melt in Yanggong River basin play an important role on the time of runoff. The runoff of Hailuogou increased significantly from 1999 to 2004 and the temperature rose remarkably. But the precipitation and vaporation showed a downtrend in the same period. However, the recharging water of high altitude to basin had a apparent rise, and the average for many years was 2,024.6 mm. The temperature of Hailuogou in 2003 was 0.31 °C higher than in 1999, but the precipitation was 237.5 mm less than in 1999, and the runoff depth in 2003 was 681.44 mm higher than in 1999. At the same time, the discharging water of snow and ice area at high altitude was 790.81 mm higher than in 1999. The peaks of precipitation and runoff depth in Hailuogou occurred in June and August. These facts showed that under the background of climate warming, the severe melting led to more and more recharge of melt water to runoff.

(5) The changes in glacier surface morphology are also respond to climate change. The continuous rise of temperature led to the sharp drop of cold storage, on the one hand, it speeded up the melting of glaciers. On the other hand, it made the melting area expand, melting period lengthen and ablation rate accelerate along with the significant changes of internal mechanism and glacier surface morphology. The glacier change is solid and comprehensive, which was displayed not only by the decrease of length, width and thickness and the mass losses, but also by the external morphological changes caused by the changes of physical mechanism. In addition, the location of glacier surface morphology changes moved toward upstream of glacier as the rising of snow line. The recent observation had confirmed that the changes in glacier surface morphology were mainly displayed by the thinning thickness of glaciers, more and bigger ice-crannies, the collapse of ice-shelf, increasing ice surface runoff, the changes in debris cover, the formation and break of ice-lakes and others. These changes will further accelerate the melting, retreat and fragmentation of glaciers.

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Chapter 8
The Main Conclusion and Prospect

8.1 Conclusions

Based on the observation data of 110 meteorological stations and the NCEP/NCAR reanalysis data, this study systematically researched the spatial and temporal variations of annual mean temperature and precipitation in Southwestern China and its influencing factors and further analyzed the interannual variation, spatial distribution of extreme temperature and precipitation as well as the correlation with atmospheric circulation, altitude, urban heat island and some by combining some research materials and using a variety of analysis methods. This study also explored the characteristics and reasons of spatial and temporal variations of sunshine hours from wind speed, relative humidity, urbanization process, cloud water content, local terrain and so on, and revealed the influences of the large-scale atmospheric circulation, regional climate warming, horizontal pressure gradient and plateau monsoon on the temporal and spatial variation of wind speed. On the basis of this, this study analyzed and summarized the response characteristics of glaciers in studied area to climate changes and the correlation with glacier length, material balance, glacier runoff, surface morphology change and the climate change. Some conclusions can be made as following.

(1) The annual mean temperature and precipitation respectively were 12.7 °C and 965 mm in 1961–2008. The temporal and spatial distribution of the annual and seasonal temperature and precipitation gradually reduced from southwest to northeast. In recent 50 years, the annual mean temperatures had a significant rising at the rate of 0.33 °C/10 a. The temperature increased sharply before the mid of 1980s but showed a slight rise after the mid of 1980s. The seasonal temperature change also reflected the significant increasing trend. In 1961–2008, the annual precipitation in the studied area exhibited a non-statistically faint reduce, and the interannual changes kept stable in 1961–1980, slowly fall down during the whole 1980s, then increased apparently in 1990s and had a wavelike decrease in new century. The precipitation performed an

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increasing trend in winter and spring. The station with a significant warming and a wider margin of warming were distributed in Xizang Plateau, Hengduan Mountain and Yunnan Plateau, while the stations with a non-significant warming or cooling were mainly located in Guizhou Plateau and Sichuan Basin. In addition, the magnitude of warming increased with the rise of altitude, verifying the wider margin of warming in the height altitude area. The changing trend of temperature declined in turn from flat station, intermountain station, valley station and summit station. The urban station was greater than the rural stations in the changing trend of temperature and the percentage of station with a significant warming, which resulted from the differences in altitudes of two types of stations. The station having an increasing trend in annual mean precipitation were primarily situated in Xizang Plateau, Hengduan Mountain, the central and northwestern Yunnan–Guizhou Plateau. And the stations with a significant decrease were located around Sichuan Basin. The maximum magnitude of increase and decrease in precipitation occurred in Valley Station and summit station, respectively.

Regional warming is closely associated with changes in large-scale atmospheric circulation. The extremely high temperature in summers in the studied area was controlled by two anomalous anticyclonism which caused that the strengthening northwest wind in northern and eastern Qinghai-Xizang Plateau weakened the power of summer monsoon moving northward. And the northeast wind of Hengduan Mountain, Yunnan–Guizhou Plateau and Sichuan Basin also hindered the northward transport of sea water vapor, which made the studied area controlled by hot and dry air mass. The differences of atmospheric circulation between extremely high and low temperature in winters indicated that the cyclone circulation further strengthened and developed into southwest wind in Northern China which in turn weakened the intensity of winter monsoon, limited the movement southward and is beneficial to the temperature rise with the help of sea warm and wet current. The higher mean water vapor flux in winter and summer during 1961–2008 explained the increase of the precipitation in the studied area. There was a small difference between water vapor fluxes in wet years and dry years. In summer, only the water vapor fluxes in the east and west of Xizang Plateau, the south of Hengduan Mountain and Yunnan Plateau in wet years were slightly greater than in dry years. These circulation characteristics partly explained the faint change of precipitation. In addition, some studies found that the net long wave radiation flux, sea surface temperature of western Pacific and sunshine duration had played an obvious role in the accelerating warming after the mid of 1980s. The precipitation is also significantly associated with the subtropical high pressure of western Pacific.

(2) In addition to ID (0.09 d/10 a), mean TX10 (0.13 d/10 a), TN10 (0.37 d/10 a), TXn (0.13 °C/10 a), TNn (0.29 °C/10 a), FD (0.29 d/10 a), DTR (0.18 °C/10 a), TN90 (0.36 d/10 a), TX90 (0.22 d/10 a), TXx (0.11 °C/10 a), TNx (0.17 °C/10 a) and the GSL (0.12 d/10 a) showed statistically significant warming trend, and the warming trend increased after the mid of 1980s. After constricting, it was found that the warming trend of coldness index and night

index were greater than that of warmth index and daytime index. The changing trend of extreme temperature index in studied area was significantly greater than that in other regions of world. Like annual mean temperature, the stations with a significant warming in extreme temperature index were mainly distributed in hight altitude area, and the stations with a non-statistical warming or decreasing trend were located in Yunnan–Guizhou Plateau and Sichuan Basin. Furthermore, the warming trend of extreme temperature index increased with the rise of altitude. The maximum of warming trend occurred in flat station followed by intermountain station, valley station and summit station in turn. Compared with the index of extreme temperature, the significance level of changes of extreme precipitation index was lower. Only the changing trends of maximum 1-day precipitation (RX1 day), consecutive wet days (CWD) and extremely wet day precipitation (R99) had passed the significance test among 11 indexes. The increasing rainy days at high altitude and the increasing rain intensity at low altitude can be verified not only by the spatial distribution of extreme precipitation index but also by that its changing trend increased with the rise of altitude. In 1961–2008, very wet day precipitation and extremely wet day precipitation (R95 and R99) had the contribution rate of 34.2 % to annual precipitation. The highest frequency of extreme precipitation event occurred in Sichuan Basin where the contribution rate was 41 %. The precipitation index of summit station showed a decline trend and the most indexes of flat station also were on the decrease, but the precipitation index of valley station and intermountain station had increased.

Large-scale atmospheric circulation is the main cause of the change of the extreme weather events. From 1961–1985 to 1986–2008, Asian summer monsoon system showed a trend of weakening. Due to this, the summer and autumn in studied area were mainly controlled by hot and dry air mass, leading to a wider margin of warming. Furthermore, the prevailing northly wind hindered the northward movement of the sea warm current and resulted in lower frequency of the precipitation. The changes of the circulation system in winter and spring reflected the increasing intensity of west wind. Under this background, the southwest wind formed within Northwestern China and its north regions, and the east wind or southeast wind formed in Southern China. This wind filed pattern will weaken the intensity of winter monsoon in reverse, and eventually cause the decrease of extreme cold events. Compared with in 1961–1985, in addition to the eastern Xizang plateau and northern Hengduan Mountain where the water vapor flux had a weak increase in 1986–2008, other regions basically was a stable state. And the meridional also displayed a apparent decline from 1961–1985 to 1986–2008, indicating that the weakening of monsoon circulation and water vapor transport and partly explained the extreme precipitation index with a non-significant changes. The contribution of urban heat island effect to warming trend of extreme temperature index cannot be ignored. The changing trend and the percentage of urban station with a significant warming were greater than that of rural station. This study confirmed preliminarily that the contribution rate of urban heat island to the warming trend of coldness indexes (TX10, TN10, TXn, TNn and FD) and warmth indexes (TNx, TNn, TN90 and TX90) in researched area were 16.0 and 7.9 %, respectively.

(3) The annual mean sunshine hour was 1894 h in Southwestern China. The maximum occurred in Xizang Plateau, Hengduan Mountain and Yunnan Plateau, and the sunshine hours in Guizhou Plateau and Sichuan Basin were fewer. The annual and seasonal sunshine hours in studied area decreased before 1990 but increased significantly afterward. In 1991–2008 and 1961–1990, the stations with decreasing sunshine hours were mainly distributed in low altitude area, especially in Guizhou Plateau and Sichuan Basin, while the most stations had a slight decrease or apparent increase in high altitude areas. However, the majority of station in the low altitude area increased sharply in 1991–2008. The decreasing trend was maximum in flat station followed by valley station, intermountain station and summit station successively. The increasing magnitude of annual, spring, autumn, winter and winter monsoon sunshine hours in urban station were greater than in rural stations during 1991–2008, of which fundamental reasons was that the urban stations were mainly situated in low altitude area like Yunnan–Guizhou Plateau and Sichuan Basin where the decreasing magnitude of sunshine hour in 1961–2008 was greatest and the increasing magnitude in 1991–2008 was more significant.

Wind speed is the main cause of the change of the sunshine hour in the studied area. The changes in wind speed and sunshine hours showed the significantly positive correlation during 1969–2008 in the studied area in addition to the autumn, and both them had the same change tendency. In 1969–2000, the decreasing magnitude of sunshine hours was apparently greater than in 2001–2008. During these two periods, the change tendency of sunshine hour had a similar spatial distribution to the changes of wind speed. In 1969–2008, the decrease tendency of sunshine hours of stations where the wind speed was less than 1.5 m/s was apparently greater than the that of stations where the wind speed was more than 1.5 m/s in studied area except for the spring and autumn. Furthermore the percentage of stations with a decrease tendency in annual and seasonal sunshine hour was similar to the sunshine hours. The humidity was another factor influencing the change of sunshine hours. The changes of humidity and sunshine hours showed two opposite tendencies during 1961–2008, and the changes of annual and seasonal sunshine hours had the significantly negative correlation. Additionally, solar radiation flux received by ground surface, cloud cover, water amount in cloud and precipitation had remarkable influences on sunshine hour, particularly the changes of sunshine hour in 1970 and 1990.

(4) The annual mean wind speed was 1.75 m/s in the studied area, and the station with a stronger wind speed were located in Xizang Plateau, Hengduan Mountain, the central of Yunnan–Guizhou Plateau, while the annual mean wind speed in most stations of the east and west of Yunnan–Guizhou Plateau

and Sichuan Basin was weaker. The mean wind speed reduced significantly at the rate of 0.24 m/s/a in 1969–2008. The decrease rate (0.37 m/s/a) of wind speed in 1969–2000 was significantly higher than in 1969–2008, while the wind speed increased at the rate of 0.55 m/s/10 a in 2001–2008. The seasonal wind speed showed a similar change tendency to annual wind speed. From 1969 to 2008, the decrease magnitude of wind speed declined from summit station, intermountain station, and flat station to valley station successively. There were more stations showing a decreasing wind speed in 1969–2000 than in 1969–2008. These stations were located in high altitude area. The decrease magnitude declined from west to east in spatial distribution. In 2001–2008, the stations performing increase tendency were distributed in Hengduan Mountain, Yunnan Plateau and Sichuan Basin, and the stations exhibiting decrease tendency were situated in Xizang Plateau and Guizhou Plateau. In addition, the root cause of differences in changes of wind speed between urban station and rural station was that these two types of stations were distributed in different altitudes. The average elevation of all rural stations was 2,692 m, and the average one of all urban stations was 1,156 m. The stations with a significant change were in high altitude area.

The changes in atmospheric circulation are the main cause of the change of the wind speed in the studied area. The analysis found that in addition to the west of Xizang Plateau, the meridional wind decreased from 1969–1985 to 1986–2000 in studied area, and the zonal wind decreased more sharply in latter period than in former period. It demonstrated that the weakening of west wind and monsoon circulation may be the main reason of the decrease of wind speed before 2000. Compared with 1991–2000, the zonal increased significantly during 2001–2008 in addition to Yunnan Plateau, indicating that the strengthening of zonal wind may be the important contributors to the increases of wind speed. In 1969–2008, Qinghai-Xizang Plateau index increased obviously, and annual and seasonal wind speed had the significantly negative correlation with the plateau index, reflecting the apparent effect of the strengthening of plateau monsoon on the decrease of wind speed in the studied area. The regional warming was another reason of decrease of wind speed in the studied area. The changes in wind speed were opposite to that of temperature and had a significantly negative correlation with the temperature, especially the minimum temperature. Further analysis found that under the background of asymmetric warming, the annual mean pressure gradient of low-central latitude area and central-high latitude area performed a decline trend, suggesting that the weakening of pressure gradient was the key incentives of the decrease of wind speed. In addition, sunshine hours, altitude and so on also had some effect on the wind speed changes.

(5) Under the background of temperature rise, especially the further warming in high altitude area, the glacier changes in Southwestern China showed four characteristics. The first is sharp retreat and shrinking area. 32 glaciers in Nyainqntanglha Mountains, Himalayas, Tanggula Mountains and Hengduan Mountains had obvious retreat, and the areas of 13 glaciers shrank

significantly. The second is mass losses of glaciers. The mass of No. 94 glacier, No. 12 glacier, No. 4 glacier and No. 10 glacier in Nyainqntanglha Mountains, Demula glacier, Zhadang glacier in Tanggula Mountains, Namunani glacier in Himalayas, Hailuogou glacier and Baishui No. 1 in Hengduan Mountains showed a negative balance in recent years. The third is the significant increase of lake area and ice runoff recharged by glaciers. The ice area of Selincuo, Naqu, Namucuo, Himalayas Mountain, the upstream of Manla reservoir and Ranwuhu basin had a increasing trend. The recharge of snow-ice melting water in Hailuogou basin, Yangjiang River basin, Rongbu River basin and Qugaqie basin to runoff increased year by year. The last one is significantly accelerated ablation of typical glaciers monitored. Its main characters were severely shrinking area, accelerated retreat of glacier front, drastical losses of ice storage and the significant warming of glacier area. The studies suggested that the temperature rise is a major cause of regional glacier retreat, and precipitation decrease in some regions also has played an important role in the glacial retreat, such as the Himalayas.

The changes of front were the most apparent reflection of glacier on climate changes. Eight marine glaciers fronts in the studied area changed in different stages and the changes presented a general trend of retreat. They present a forward trend in cold and dry period and backward trend in warm and wet period. The material balance reflects the direct influence of climate change on glaciers from amount of mass. During 1959/60–2003/04, the accumulated water–material balance value of Hailuogou for 45 years was –10825.5 mm (water equivalent), and the annual mean balance value was –240.6 mm (water equivalent), indicating that it was given priority to with losses for 45 years. During 45 years, there are 16 years showing positive balance and 29 years showing negative balance. The staged change of mass balance in Hailuogou was opposite to that of China, Northern Hemisphere and Hengduan Mountain, demonstrating that the climate warming is the main cause of mass losses. The glacier hydrological system is a sensitive indicator of climate change. As the climate became warmer and warmer, the recharging water of snow and ice area at high altitude of Yanggong River basin in 1979–2003 and Hailuogou basin in 1999–2004 increased remarkably, verifying that the increase of ice-snow melting water was the main contribution to the increase of runoff. And under the background of warming, the seasonal structure of glacier hydrological system was changing significantly. For example, compared with 1979–1988, the minimum runoff in Yanggong River basin during 1994–2003 occurred one month in advance and the peak value of runoff depth in Hailuogou basin lagged two months behind that of precipitation. The changes in glacier surface morphology are also respond to climate change. The recent observation had confirmed that the changes in glacier surface morphology were mainly displayed by the thinning thickness of glaciers, more and bigger ice-crannies, the collapse of ice-shelf, increasing ice surface runoff, the changes in debris cover, the formation and break of ice-lakes and others. These changes will further accelerate the melting, retreat and fragmentation of glaciers.

8.2 Prospect

(1) The comprehensive utilization of all kinds of material is beneficial to understand overall process and regular of climate changes. The distribution of meteorological stations in Southwestern China is uneven, especially in the west of Xizang Plateau where there are few observation station existing for many years. And the meteorological observation system in the high altitude (above 5,000 m) is still weak, which restricts to thoroughly understand the whole process of the temperature and precipitation changes in the studied area. Although the records of ice cores and tree ring at high altitude can be considered as the important basis of research on climate change, the great difficulty in obtaining restrict the widespread use of them within the whole studied area. Therefore, a series of measures, such as systematically analyzing the applicability of various reanalysis data and material in Southwestern China, understanding the difference between various data sources, sorting and comparing the different data sets, applying the observation data, reanalysis data, satellite remote sensing data and climate model output into the researches on climate change contribute to the integrated cognition of process and regular of climate changes.

(2) A breakthrough of the follow-up work is to deeply analyze the causes of climate change. The reasons of climate change are complex as well as various. Due to the limitations of data, information, and personal ability, this study explores the reasons of climate change in Southwestern China from a few aspects. Although some meaningful conclusions are made, there are a lot of unanswered questions. For example, what is the sunshine hour and SST of western Pacific related to the accelerating warming after the mid of 1980s? What is the relationship between cloud cover and the decrease of sunshine hour? How do the changes of atmospheric circulation and surface condition (vegetation, urban architecture) influence the wind speed? the solution of these problems needs to accumulate more observation data for a longer time and information and to use more reasonable methods, especially the model simulation.

(3) It is meanful to assess the influence of climate changes on regional development. From the conclusion of Easterling et al. (2000) about the changes in global extreme climate, it is revealed that the probability of extreme climate events around the world increases year by year over the past few decades, resulting in more losses in different factors. Southwestern China is the transition zone of the first and second ladder and become the area of frequent occurrence of geological disaster like mud-rock flow due to the high altitude, special geology and hydrology. Under the background of the increasing extreme climate events, particularly the extreme precipitation, all kinds of geological disasters will be more likely to occur. So it is of great significance to strengthen the monitoring and forecast of extreme climate events for regional disaster prevention and mitigation and reducing losses resulted from

meteorological disasters. In addition, with the changes of wind speed and direction as well as sunshine hour, which challenges and opportunities the development of wind energy and solar energy resources will face also need to be explored in future work.

(4) It is of significance to systematically assess the effect of urbanization process on the climate change. In terms of the effects of urban heat island, this study just focuses on the contrast of warming between urban station and rural station on basis of population. But it does not strictly define the urban heat island from population index. Although this index has been widely used in lots of researches at home and abroad, it is still needs to comprehensively analyze the changes and the influence of urbanization process from land use, thermal condition of building material, urban landscape lamp at night and others. Additionally, the altitude factor needs to be deducted in evaluating the contribution of regional urban heat island. By comparing the analysis of sunshine hours between urban and rural station, there two points need to be emphasized: Firstly, if with the increase of aerosol concentration, urbanization process had a huge impact on sunshine hour, the sunshine hours in Reban station would reduce sharply after 1990. However, the sunshine hours in Southwestern China presented a slight increase or stable state from 1990s and did not fall with the quickening pace of urbanization. Secondly, the great treatment of atmospheric pollution in recent years is important for the increase of the sunshine time, therefore, for not all regions, the decrease in sunshine hour attributes to the influences of human activities, such as atmospheric aerosol. Analysis found that the wind speed does not weaken due to the rapid urbanization process, which also has been performed in the research in wind speed of China. If the urbanization process had significant influence on wind speed, the wind speed would reduce by a wider margin after 1990 because the urban expansion in China began in the end of 1980s and earlier 1990s. However, the wind speed showed a stable or increasing trend after this period (Xu et al. 2006; Gao et al. 2010). Moreover, this phenomenon also occurred in the southeast of Queensland and the northeast of New South Wales, Australia where are of high urbanization McVicar et al. (2008). This inconsistent phenomenon between wind speed in urban station and the urbanization process may reflect another influence of urbanization development on wind speed. For example, when the urbanization process has developed to a certain degree, it will strengthen the urban atmospheric circulation and result in the increase of wind speed. Certainly, these speculations still need to be verified in observation data and model simulation for a longer time.

(5) The research on response mechanism of glacier to climate change is short of more observation data. Temperature and precipitation are two key factors resulting in the change of glaciers. It is generally believed that precipitation plays a great role on glacier change when temperature change $\Delta T \le 0.5$ °C; when $\Delta T > 0.5$ °C, glacier change is mainly decided by temperature, and the precipitation does not play a leading role (Gao et al. 2000). The rising magnitude in temperature of 11 stations at more than 4,000 m of altitude was 0.036

°C/a in 1961–2008, and the temperature rose by 1.73 °C for 48 years. According to above law, the glacier retreat was mainly affected by the temperature rise in recent years. The meteorological observation of Baishui No. 1 glacier in 2009 also found that the magnitude of warming in the high altitude area was greater than in the low altitude. In addition, the occurrence of peak of increased net area of glacier lake at 5,000–5,300 m of altitude in Himalayas Mountains suggests the wider margin of warming in the high altitude area (Wang et al. 2011). Temperature rise causes not only the decrease in cold storage but the increase in frequency and amount of solid rainfall, and further accelerates the melting. However, the temperature is not the only climate factors affecting the glacier change. But because of the less observation data on precipitation at high altitude and the complexity of precipitation system in the mountainous area, there a large amount of observation data still need to be accumulated to know its effects.

The local position, glacier size, the altitude of glacier fronts, local climate and so on also are the influencing factors of glacier changes. For example, the temperature and precipitation of Hailuogou glacier in the east slope of Gongga Mountain were higher than those of Gongba glacier in the west slope. So glaciers in the east slope retreat faster than those in west slope. The retreat speed of glaciers in the north slope of Everest in Himalayas mountains was 50–83 m/a in 1973–1994, while the glaciers in the south slope advanced by the rate of 58–105 m/a, because the precitation of south slope is greater than that of north slope. Palongzangbu No. 94 glacier retreated faster than No. 390 glacier in 2006–2008, and the altitude of No. 94 glacier fronts was 160 m higher than No. 390 glacier fronts. The area of Far East Rongbu glacier was a little smaller and its retreat speed was faster than that of East Rongbu glacier, because larger the area of glacier was or higher the altitude of fronts was, the slower the response on climate changes. In addition, Xu et al. (2009) discovered that the black carbon aerosol on the surface of snow and ice has significant contribution to the acceleration of glacier melt. Yasunari et al. (2010) found that the glacier melt caused by increased black carbon aerosol concentration on the surface of snow and ice will increase 70–204 mm of melt water runoff which will account for 11.6–11.6 % of annual runoff of a typical glacier in Qinghai-Xizang Plateau. The assessment of Qian et al. (2011) showed that the increased black carbon aerosol in the whole Qinghai-Xizang Plateau will make the ground surface temperatures rise by 1.0 °C and result in sharp melting. Undoubtedly, the effect of this factor on melting of glaciers is huge. The studies of Takeuchi et al. (2011) and Flanner et al. (2007) also confirmed the above conclusion. Scherler et al. (2011) confirmed that about 65 % of marine glaciers in the south slope of Himalaya had a retreat trend, but the fronts of glaciers covered by thick debris were on a stability, reflecting the important effect of debris cover on protecting glaciers. Above analysis shows that the influencing factors of glaciers have diversity and complexity, and the effects of them on glacier change in Southwestern China still need to be explored in the follow-up work.

Currently, on the one hand, the limited observation data especially in glacier area is not allowed to explore the relationship between glaciers and climate change from quantification. On the other hand, the dynamics of response of glaciers to climate change still need to be constantly improve, because it changes based on the different type, size and location. This can be proven by two special facts in marine glaciers change of China in the context of same climate. The temperature and precipitation in Hengduan Mountain increased by 0.74 °C and 44.5 mm, respectively from 1960 to 2008, and the glaciers had a severe retreat and mass losses. There are 36 glaciers advancing in Gangrigabu Mountain located in the east part of Nyainqntanglha Mountains, and the temperature and precipitation of adjacent Bomi station increased by 0.29 °C and 70.8 mm in the same period. Basically speaking, if we want to know the response mechanism of the glacier to climate change, we have to make a deep exploration from glacier dynamics and energy balance. Although these works has made great progress in some glaciers of Northwestern China, such as Tianshan No. 1 glacier and Qilian Mountain No. 71 glacier, there is no obvious progress up to now due to the shortage of observation data and the great difficulty in obtaining data.

Due to the sharp melting, the recharging water of ice and snow area to basin increases year by year, resulting in the apparent increase in surface runoff of same glaciers in Southwestern China and the acceleration of water circulation. This is a comprehensive response of the system of "precipitation–glacier–groundwater–surface runoff" to global warming. But the concrete mechanism of its response remains to be validated by more observation data. We in particular need to develop and strengthen hydrological models research of ice and snow relying on observation data. More importantly, a series of changes of glacier system characterized by mass losses will impact on the economy development, water cycle, disaster prevention, water resources and ecological environment of glacier area influenced in Southwestern China. Therefore, it is of great significance to strengthen the monitoring of runoff change in glacier area. Moreover, it is a new direction to intensively study glaciers morphology changes from physics under the background of warming.

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