Climate and glacier change in southwestern China during the past several decades

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Abstract
Glaciers are distributed in the Nyainqentanglha Mountains, Himalayas, Tanggula Mountains, Gangdise Mountains and Hengduan Mountains in Southwestern China. Daily temperature and precipitation data from 111 stations, together with the records of glacier changes, indicate that temperature patterns during 1961–2008 were consistent with warming at a statistically significant level. Seasonal warming was greatest in autumn and winter. Temperature rise showed a significant relationship with sea surface temperature in the Western Pacific, net longwave radiation flux, altitude, sunshine hours, strengthening anticyclonic circulations in summer and anomalous cyclonic circulation in winter. The increase was more apparent in higher altitude areas than in lower ones. Precipitation variations were less marked than those of temperature, generally showing weak decreasing trends during 1961–2008. Increasing trends were apparent only in spring and winter, when regional trends of precipitation increases with altitude also were evident. The strengthening Western Pacific Subtropical Highs were related to precipitation variation. Against the background of increasing temperature, especially the increasing warming with altitude, the fronts of 32 glaciers and areas of 13 glacial basins have retreated, mass losses of 10 glaciers have been considerable, glacial lakes in six regions have expanded and melt water discharge of four basins has also increased, but these glaciers and basins in our study are only a fraction of the retreating glaciers over southwestern China.

Keywords: southwestern China, climate change, glacier change

1. Introduction and objectives
Global climate warming has accelerated since 1910 (IPCC 2007) and annual mean temperature increased by 0.4–0.5°C from 1860 to 2005 in China (China Meteorological Administration 2006). On the whole, precipitation has increased by 2%, whereas the frequency of rainy days in China decreased by 10% from 1960 to 2000 (Liu et al 2005a, 2005b). The increasing trend is more remarkable in western China, especially in the northwest (Ye et al...
Climate research has concentrated mainly on sub-regions or single districts over the study region. Temperature and precipitation have been studied in Yunnan province (Tao and He 2008, You et al 2006, Wan et al 2009), Tibetan Plateau (Liu et al 2006a, 2006b, 2009a, 2009b, Wu et al 2005), Sichuan Basin (Shao et al 2005, Chen et al 2008, Hu et al 2009), Hengduan Mountains (Li et al 2010d) and Guizhou province (Yan et al 2004, 2005). These studies have shown that significant widespread changes in temperature are associated with warming. Changes in precipitation exhibit much more spatial differences than do those of temperature, making it difficult to detect regional trends. However, there has been little systematic analysis of precipitation and temperature variations and its causes in the whole region, primarily owing to the lack of easily available data.

Here, annual and seasonal trends of temperature and precipitation in southwestern China during 1961–2008 have been analyzed, based on meteorological data from 111 stations (detailed information about data sources, quality control and methods is provided in the appendix) and the record of glacier changes from previous studies. The causes of temporal and spatial changes of temperature and precipitation have been examined, and glacier change and its relationship with climate change have also been discussed. The objectives of this study are to investigate the changes in temperature and precipitation during 1961–2008 and to outline the glacier fluctuations. This should lead to a better understanding of the frequency, intensity and duration of climate variability and glacier behavior over all of southwestern China.

2. Results and discussion

2.1. Climate change

2.1.1. Temporal trends. The annual temperature in southwestern China displayed a significant increase during 1961–2008, and seasonal variation also showed the same pattern (table 1). As figure 2(a) shows, the warming has accelerated since the mid-1980s over the study region, which may be caused by the increasing net longwave radiation flux at the surface from 1961–1985 to 1986–2008 and, what is more, the significance influencing areas were the Xizang plateau, Guizhou plateau, the eastern Sichuan basin and Yunnan plateau (figure 3(a)). In addition, the strengthening sea thermodynamic process under climate warming has also contributed to temperature rise especially after 1985, reflected by the more statistically significant correlation between annual temperature in southwestern China and sea surface temperature in the Western Pacific during 1986–2008 compared to that in 1961–1985 (figure 4). Spring temperatures increased in the 1960s, decreased slowly between 1970 and 1985, and then
Figure 2. Inter-annual variation of temperature and precipitation during 1961–2008. The dotted line is the linear trend and $R$ is the correlation coefficient for the linear trend. The smoother line is the nine-year smoothing average.
increased again (figure 2(b)). Autumn and winter temperatures increased consistently (figures 2(d) and (e)), whereas summer temperatures showed a slow rise after the 1960s’ decrease (figure 2(c)). The greatest warming occurred in autumn and then in winter, which may have been caused by the greater net radiation under the smaller snow cover in autumn, whereas winter has less net radiation owing to the higher albedo under the extensive snow cover. Warming was less than in northeastern China and the Xinjiang Autonomous region, but greater than in other regions. As in the Qilian Mountains and the Xinjiang Autonomous region, seasonal warming mainly occurred in autumn and winter over the study region (appendix). Through the study period, the annual precipitation in southwestern China showed a weak decreasing trend with fluctuations, and changed from stability in 1961–1980 to a slow decrease in the 1980s, an increase in the 1990s and another decrease in the 2000s (figure 2(f)). For seasonal precipitation, the decrease in autumn was statistically significant at the 0.05 level (figure 2(i)), whereas the increase in winter was significant (figure 2(j)). The summer precipitation fluctuated from a decrease to an increase at 10 year intervals (figure 2(h)), and the spring precipitation increased after fluctuating before the 1980s (figure 2(g)). Compared with other regions of China, the precipitation variations during 1961–2008 were inconspicuous (see the appendix).

2.1.2. Regional differences. As figure 5 shows, during 1961–2008, the annual and seasonal temperatures showed significant and consistent increases in the Xizang Plateau–Hengduan Mountains (hereafter XPHM) area. Except for winter with consistent warming in the Yunnan-Guizhou plateau (hereafter YGP), annual, summer and autumn temperatures experienced a decrease in the 1960s and then an increase, but it decreased before the end of the 1980s and then increased after 1990 in spring (figure 5). In the Sichuan Basin (hereafter SB) spring temperatures decreased prior to 1985, and then subsequently increased. The total trend is not significant, but autumn and winter displayed consistent increases (figure 5). Except for autumn, warming was greatest on the XPHM, where it exceeded the overall regional change, followed by the YGP and SB, linked to the increase of net longwave radiation flux from 1961–1985 to 1986–2008 in the study region with the exception of the SB (figure 3(a)). In terms of the seasons, the trend was greatest in summer and winter on the XPHM, but in autumn and winter on the YGP and SB. The difference in regional trends not only reflects the remarkable warming at higher altitudes but also indicates the influence of topography. In order to further evaluate the causes of regional differences, the correlation between temperature and sunshine hours has been analyzed in three sub-regions (table 1). The results indicated the crucial influence on the SB temperature because there are more clouds and fogs owing to the basin topography which can weaken sunshine duration. This can be also indicated by the similar variation of these two series (figure 6). However, this influence was mainly effective in winter at the XPHM and YGP.

For annual precipitation, only the XPHM showed a slow increase. A decrease occurred in the SB, whereas it decreased before 1990 and then increased on the YGP (figure 7). In the XPHM, seasonal precipitation displayed an increase (not including summer), and positive trends in spring and winter are significant (figure 7). Except for the slow increase in spring and winter, seasonal precipitation decreased during 1961–2008 on the YGP (figure 7). For the SB, summer and winter precipitation increased (figure 7). In contrast with temperature, the precipitation variations in three sub-regions were of low significance. The increases of spring and winter precipitation were greater on the XPHM than throughout southwestern China as a whole, whereas the decreases of both annual and autumn precipitation were larger on the YGP and in the SB, which may also reflect the influence of topography. These characteristics may be caused by the weakened monsoonal flow and vapor transportation in recent years. Dash et al (2009) have noted the decreased trend of the Indian monsoon in
Recent years, becoming unreliable and unstable. Many previous studies have confirmed the decreased East Asian monsoon, as reflected by the decreased mean surface wind speed of the East Asian monsoon over China (Xu et al. 2006) and the similar decline of the wind anomaly at 850 hPa averaged over east China and the coastal ocean (Xue 2001). As Table 2 shows, the increased winter precipitation in the XPHM and the decreased annual precipitation in the YGP may be related to the strengthening Western Pacific Subtropical High, and the influence from it on the SB mainly characterized by the statistically decreased autumn precipitation.

2.1.3. Spatial patterns. As figure 8 shows, about 92%, 85%, 82%, 94% and 95% of 111 stations showed an increasing trend for annual, spring, summer, autumn and winter temperature, statistically significant at 77%, 45%, 54%, 66% and 59%, respectively. The great influence of topography on the regional pattern of temperature in southwestern China is reflected by the location of stations with significant trends, which mainly are on the Xizang Plateau, the Hengduan Mountains and the Yunnan Plateau. Stations with non-significant trends are in the SB and on the Guizhou Plateau. The regional trends in temperature displayed a decrease from west to east. In autumn, the number of stations with significant trends was the highest, followed by winter. This indicates that the seasonal structure of temperature variations differs from the global and overall Chinese patterns, which show the greatest warming in winter and spring.

Compared with temperature, the significance of precipitation changes during 1961–2008 was low, but displayed complex spatial patterns. Although about 52%, 70%, 50%, 35% and 77% of the stations showed increasing trends for
Table 2. Correlation coefficients between precipitation and Western Pacific Subtropical High index ($n = 48$, when $r = \pm 0.29$, $P = 0.05$). (Note: values for trends significant at the 5% level are set in bold.)

| Sub-regions       | Index   | Annual | Spring | Summer | Autumn | Winter |
|-------------------|---------|--------|--------|--------|--------|--------|
| Southwestern China| Strength| 0.09   | 0.12   | 0.03   | 0.07   | 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   |

Figure 5. Inter-annual variation of temperature in the XPHM, YGP and SB during 1961–2008. The dotted line is the linear trend and R is the correlation coefficient for the linear trend. The smoother line is the nine-year smoothing average.

annual, spring, summer, autumn and winter precipitation, they were significant at only 5%, 21%, 0.9%, 1.8% and 11%, respectively (figure 9). Geographically, the increase of annual precipitation was mainly at stations on the Xizang Plateau, the Hengduan Mountains and the middle and northwestern YGP. In spring, decreasing trends mainly occurred in the SB and Guizhou Plateau. Stations with decreased summer precipitation were mainly located in the southwestern Hengduan Mountains, the western SB, the southwestern and eastern Xizang Plateau and the Yunnan Plateau. Compared with that of other seasons, the spatial distribution of autumn precipitation was characterized by a remarkable expansion of the area which
Figure 5. (Continued.)
Figure 6. Variations of annual temperature and sunshine hours in the SB during 1961–2008.

precipitation increases mainly occurred in higher altitude areas, but decreases were noticed at many lower ones.

2.1.4. Changes in the large scale atmospheric circulation. To examine the changes in circulation patterns associated with the temperature variation, the correlation fields between the overall temperature series in southwestern China and sea level pressure in summer and winter during 1961–2008 are shown in figure 10. In summer, there is a statistically positive correlation with the SLP in Mongolia (near Lake Baikal) and Tibetan Plateau. This indicates that increases in SLP correspond with those over most of southwestern China. However, there is not the statistically significant relationship between temperature series and SLP in winter with the exception of the significant negative correlations between winter temperature series and the SLP in the south China sea. Based on this correlation, circulation composite maps from NCEP/NCAR reanalysis in summer and winter were created over the domain of 0°–70° N and 30°–170° E at 500 and 300 hPa in order to investigate the role of circulation change in the trends discussed above.

Figure 7. Inter-annual variation of precipitation in the XPHM, YGP and SB during 1961–2008. The dotted line is the linear trend and \( R \) is the correlation coefficient for the linear trend. The smoother line is the nine-year smoothing average.
Figure 7. (Continued.)
As figure 11 shows, the geopotential height composite, with the largest differences (approximately $-25$ g pm) occurring near Lake Baikal (focused near 50°N, 45°E), indicates the cyclonic circulation that has developed over the Eurasian continent and the strengthening of northwesterly winds. However, an anomalous anticyclonic circulation, consistent with increased geopotential heights, has also developed over China (focused near 35°N, 80°E and 40°N, 125°E) at 500 hPa (figure 11(a)) and has a significant relationship with temperatures in warm summers. These atmospheric circulations are consistent with composites for 300 hPa (figure 11(b)). Thus, the northeasterly wind over southwestern China and a northwesterly flow over the northern part of southwestern China have strengthened, in turn weakening the northward penetration of the Indian monsoon and any southeasterly flow from the Pacific and Indian Oceans. This brings warm and dry flow to the study region, which explains the higher temperature in strongly positive trend years.

In winter, one enhanced anticyclonic circulation has developed over the Eurasian continent (centered near 40°N, 120°E), and an anomalous cyclonic circulation near 65°N, 80°E is also shown on the geopotential height composite at 500 (figure 12(a)) and 300 hPa (figure 12(b)) which had a significant relationship with temperatures in warm winters. The differences between anticyclonic circulation and cyclonic circulation have weakened the northwesterly wind in the north of China and have intensified the development of anomalous southerly winds over much of southwestern China. In turn, this has weakened the southerly extent of the winter monsoon and has decreased incursions of colder air, in part explaining the consistent increase of winter temperatures, especially the higher temperature in strongly positive trend years.

2.1.5. Altitude dependences. Increasing attention is being given to climate change in high altitude areas: it has been suggested that surface air temperatures are increasing more rapidly at higher altitudes (Giorgi 1997, Yang et al 2006, Tian et al 2006, Liu et al 2009a, 2009b). In general, the regional trend of annual temperatures exhibited a statistically significant increase with altitude (table 3), and variations of seasonal temperature also showed the same trend with the
Figure 9. Spatial distribution of precipitation variation during 1961–2008. Stations with a significant regional trend are indicated by a red dot.

There is some disagreement about precipitation variations with altitude on the Tibetan Plateau (Wu et al. 2005), but the positive correlation between regional trends of annual precipitation and altitude reported here is significant (table 3). For seasonal precipitation, the only statistically significant increases with altitude were in spring and autumn, with a decreasing trend in winter (table 3). The largest negative trends were in the 500–1000 m altitudinal zone (in summer, winter and annual values), and at 0–500 m (spring and autumn) (figure 13). Decreasing trends of summer and autumn precipitation, but increasing trends in winter and spring, characterized many altitudinal zones. As a whole, increases
of precipitation were mainly in higher altitude zones, while lower zones exhibited decreases: regional trends of annual and seasonal precipitation, other than that of winter, were negative in the three altitudinal zones below 1500 m. These characteristics indicated that orographic rainfall has a great influence on precipitation increase at higher altitude regions.

2.2. Glacier change under increasing temperature

Glaciers are remarkable indicators of climate change, and their changes often reflect temperature fluctuations. Increased temperatures in southwestern China may result in negative mass balances, glacier retreat, the enlargement of glacial lakes, and increased meltwater discharge (figure 14).

2.2.1. Drastic glaciers retreat in southwestern China. In the Nyainqentanglha Mountains, between 1970 and 2007, the Lalun, Zhadang, Palu and 50270C0049 glaciers retreated by 12.9, 10, 9.9 and 4.6 m/a in response to increasing temperatures since the 1980s, and the Xibu glacier retreated by 37.7 m/a between 1970 and 1999 (Kang et al. 2007). Between 1915 and 1980, the overall area of 102 glaciers in the Gangrigabu Mountains was reduced at a rate of 0.63 km²/a, and from 1980 until 2001, as temperature increased in weather stations near the glacial region, 52 glaciers suffered an average loss of 0.39 km²/a with a retreat of 7.4 m/a (Liu et al. 2005a, 2005b). The Gurenhekou glacier retreated by 8.1 m/a during 1970–2003 (Pu et al. 2006). In the Ranwuwu basin, the glacier area had experienced a 1.14 km² reduction per year in 1980–2005 as temperatures increased at Bomi, Chayu and Linzhi weather stations (Xin et al. 2009). The Yalong glacier retreated by 47.9 m/a during 1980–2001, as its area declined by 0.073 km²/a (Liu et al. 2005a, 2005b). The Ruoguo glacier, located in the headwaters of the Yigongzangbu river basin,
retreated at a rate of 70.6 m/a in 1959–1975 (Shi 2008). In the Palongzangbu basin, the Azha glacier retreated by 62.6 m/a during 1980–2006, No. 4 glacier retreated by 14.6 m/a during 1980–2008, and glaciers No. 10, No. 94 and No. 390 retreated 10.2, 13.7 and 5.5 m yr\(^{-1}\), respectively during 2006–2008 (Yang et al 2010). During 1970–2007, the area of the glaciers in the Nam Co basin was reduced by 0.98 km\(^2\)/a (Chen et al 2009). In an area where winter temperatures at four weather stations near the glacial region increased at rates of 0.34–0.68 °C/10 a, the Zhadang glacier contracted by 0.4 km\(^2\) with a 10 m retreat per year during 1970–2007 (Chen et al 2009).

In the Geladandong area, the glacier size between 1969 and 2000 had a 0.47 km\(^2\)/a decrease (Lu et al 2002). The Jianggudiru glacier in the Selincuo area showed a retreat of 38.4 m/a during 1969–1999 (Lu et al 2005). The Dongkemadi and Xiaodongkemadi glaciers in the Tanggula Mountains

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**Figure 11.** Differences between mean geopotential height and wind field at the 500 hPa (top panel) and 300 hPa (bottom panel) in summers with strongly positive and negative temperature deviations exceeding \(\pm 1 \sigma\) of the 1961–2008 mean. Warm summers were 1961, 2006 and cold summers occurred in 1965, 1968, 1974, 1976. (The statistically significant areas \((P < 0.05)\) are identified by the white contours.)
Figure 12. Differences between mean geopotential height and wind field at 500 hPa (top panel) and 300 hPa (bottom panel) in winters with strongly positive and negative temperature deviations exceeding ±1σ of the 1961–2008 mean. Warm winters are 1987, 1999, 2001, 2003, 2007 and cold winters occurred in 1968, 1976, 1983 (The statistically significant areas (P < 0.05) identified by the white contours.)

retreated by 3.4 m and 3 m yr⁻¹, respectively, between 1994 and 1999 (Pu and Yao 2004).

The Mapangyongcuo basin in the Himalaya region experienced a glacier reduction of −0.25 km²/a during 1974–2003, mainly the consequence of temperature increase measured at Pulan station near the glacial region (Ye et al 2008). The Namulani glacier had a 4.8 m/a retreat during 1976–2006 (Yao et al 2007). Nie et al (2010) found that the Dongrongbu glacier, Zhongrongbu glacier, Yuandrongbu glacier and Rejiang glacier showed retreats of 9.4, 14.6, 14 and 65.7 m/a during 1976–2006, and Ren et al (2003) considered these retreats were mainly caused by temperature increase and precipitation decrease based on values from the Dingri and Nielamu stations. Che et al (2005) thought the Jicunpu glacier retreated by 52.3 m/a during 1976–2003, and Li et al (1999) have found glaciers had a 66.5 m/a retreat in the northern slope and an 81.5 m/a advance in the southern slope of the Bukatage Mount during 1973–1994. In the Pengqu basin, the glacier area

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and volume decreased at 4.1 km²/a and 0.375 km³/a during 1970–2001, and 99 glaciers disappeared as temperatures rose and precipitation increased (Jin et al. 2004).

Between 1974 and 2007, the Kangwure glacier on Mount Xixiangbangma retreated by 8.9 m/a, with area and volume losses of 0.03 km²/a and 0.001 km³/a, as temperatures recorded at the Dingri and Nielamu stations increased (Ma et al. 2010). The Dasuopu glacier on Mount Xixiangbangma also retreated by 4 m/a during 1968–1997 (Pu and Yao 2004). The glacier area on Mount Namulani reduced by 0.27 km²/a during 1976–2003, while the adjacent Pulan weather station exhibited a temperature rise and precipitation decrease (Ye et al. 2007). With increasing temperature and decreasing precipitation of five weather stations near the glacial region, the glacier area in the Mount Qomolangma National Nature Preserve was reduced by 17.93 km²/a during 1976–2006 (Nie et al. 2010). In the upstream Manla area of the Nianchu river basin, the glacier area contracted by 0.52 km²/a during 1980–2005, mainly as a consequence of a remarkable temperature rise noted at Jiangzi and Rikaze stations (Li et al. 2010). In the last three decades of the 20th century, the glacier area in the Poqu and Rongxer basins decreased by 2.2% and 3.1%, respectively (Wu et al. 2004).

Retreating glaciers in the Hengduan Mountains included the Hailuogou glacier (23.6 m/a, 1930–2006), the Hailuogou glacier No. 2 (17.6 m/a, 1930–90), the Yanzigou glacier (46.7 m/a, 1930–90) and the Dagongba glacier (5.8 m/a, 1930–2007). The Mingyong glacier on Mount Meli retreated by 13.4 m/a between 1932 and 2002. The glacier area on Mount Yulong was reduced by 0.07 km²/a between 1957 and 1999, and four glaciers disappeared. From 1900 until 2008, Baishui glacier No. 1 had a retreat of 7.6 m/a. On Mount Gongga, the glacier area decreased by 0.41 km²/a during 1966–2002 (Zhang et al. 2010a, 2010b). The influence of temperature on accumulation and ablation of these monsoonal temperate glaciers is greater than that of precipitation, and glacier retreat stages coincided with warm and wet phases (Li et al. 2010).

Although summer temperature had increased by 0.3–0.5 °C during 1960–2002 at Chayu and Bomi stations near the glacial region of the Gangrigabu Mountains, the area of 36 glaciers increased by 10.4 km² with an average frontal advance of 389 m during 1980–2001. Among these, 50282B0136 glacier and 50282B0123 glacier had an 1117 and 1762 m advance (Liu et al. 2005a, 2005b). However, the maximum annual precipitation in Bomi and Chayu stations is 1.9 and 2.1 times more than the minimum value during 1960–2002. Shi et al. (2006) deduced this increase may have caused glacial advances. In addition, Wang and Dong (2002) also confirmed precipitation had increased by 10% during 1951–1999 in this region.

2.2.2. Significant glacier mass loss. In the Palongzangbu basin, the mean annual mass balance during 2005/06–2007/08 for glaciers No. 94, No. 12 and No. 10 was −0.75 m, −1.30 m and −0.52 m water equivalent/a, respectively. For No. 4 glacier during 2005/06–2006/07, it was −0.37 m water equivalent. For the Demula glacier during 2006/07–2007/08, it was −1.42 m water equivalent/a, and for the 24 K glacier in 2007/08, it was −1.22 m/a (Yao et al. 2010). The thickness of glaciers No. 4, No. 10 and No. 12 decreased by 5.2 m, 4.5 m and 2.9 m/a, respectively during 2006/07; analysis indicated their mass loss may have been related to increased temperature and severe melting (Yang et al. 2008). The thickness of the Zhadang glacier in the Nam Co basin decreased by 0.29 m/a in 1970–2007, and the mean annual mass balance during 2005/06–2007/08 was −0.59 m water equivalent/a (Kang et al. 2007). For the Namulani glacier during 2004–6, the mean annual mass balance was −0.69 m water equivalent (Yao et al. 2007). Wang et al. (2010a, 2010b) reported that the glacier volume in the Mount Naimonanyi region decreased by 0.12 km³/a during 1976–2001. In the source regions of the Yangtze River, glacier volume contracted by 0.07 km³/a during 1969–2000 (Yang et al. 2003). In the Gangrigabu Mountains, glacier volume of 102 glaciers contracted by 0.11 km³/a during 1915–80, and the value for 52 glaciers in 1980–2001 is 0.05 km³/a (Liu et al. 2005a, 2005b). Glaciers volume in the Pengqu basin, the upstream area of Manla reservoir in the Nianchu river basin and Mount Namulani also contracted by 0.38 km³/a during 1970–2001 (Jin et al. 2004), by 0.23 km³/a during 1980–2005 (Li et al. 2010) and by 0.12 km³/a during 1976–2001 (Wang et al. 2010a, 2010b). In the period 1974–2007, the Kangwure glacier also had a 0.0481 km³ volume reduction (Ma et al. 2010).

The mean annual mass balance of Baishui glacier No. 1 was −2.19 m water equivalent/a during 1952–2003, and the thickness of the tongue decreased by 15 m between 2000 and

Figure 13. Variation of temperature and precipitation with elevation.
2004 (Li et al. 2010b). The accumulated mass balance of the Hailuogou glacier during 1959/60–2003/04 was $-10.83 \text{ m water equivalent/a}$, with the annual mean value changing from $-1.80 \text{ m a}^{-1}$ in 1959/60–1970/71 to 1.10 m a$^{-1}$ in 1971/72–1984/85, and to $-5.40 \text{ m equivalent/a}$ in 1985/86–2003/04 (Li et al. 2010a). The trend of significant ablation has continued, with an annual ablation of 6.16 m water equivalent/a at the Hailuogou glacier tongue during 1990/91–1997/98 (Li et al. 2010b).

2.2.3. Expansion of glacier lakes and increasing meltwater. The runoff of the Rongbu River at Mount Qomolangma in June, July and August 2005 was 69%, 35% and 14% higher than the 1959 values, respectively (Liu et al. 2006a, 2006b). Meltwater accounted for 54.6% of the annual mean runoff from the Hailuogou in the period 1994–2004, and the contribution of meltwater from higher altitudes to increased runoff in recent years has been substantial (Li et al. 2010c). A temperature increase of 0.1$^{\circ}$C would result in a runoff rise of 2.6 m$^{3}$ s$^{-1}$ in the Hailuogou basin (Li et al. 2010a). Within the Yanggong basin, the increase of snow and glacier meltwater from 1979–1988 to 1994–2003 was 90.9%, far exceeding the increases of precipitation (1.1%) and river discharge (78.7%) (Li et al. 2010b). Glacier retreat in the Himalayas has greatly contributed to the increase of runoff in recent decades (Zhang et al. 2009). In the source regions of the Yangtze river, glacier volume declined by 0.07 km$^{3}$ a$^{-1}$ from 1969 to 2000, equivalent to a $0.63 \times 10^8 \text{ m }^3$ loss of glacial water resources (Yang et al. 2003). In the upper and lower reaches of the Qugaqie River in the Nam Co Basin, the increase of runoff during the ablation season is largely controlled by air temperature (Gao et al. 2009). The runoff depth of the Dongkemadi river basin increased by 5.61 mm a$^{-1}$ during 1955–2008, and about 66% of the increased runoff contributed by the glacial melting under temperature rise (Gao et al. 2011).

Between 1980 and 2005, the area of Ranwu lake expanded by 0.13 km$^2$/a, mainly as a consequence of the increase of meltwater from glaciers (Xin et al. 2009). Meltwater contributes a little over half the supply to the lake, which grew by 1.91 km$^2$/a during 1970–2007 (Kang et al. 2007). Zhu et al. (2010) concluded that an increase of precipitation and meltwater, and a decrease of evaporation caused by a rise of temperature, accounted for the expansion of Nam Co lake. The area of glacial lakes in the Selincuo region expanded by 7.39 km$^2$/a from 1969 until 1999, mainly caused by increased meltwater and precipitation (Lu et al. 2005). Climate warming, precipitation increase, accelerating ablation and glacier retreat have resulted in a 29% increase of the area of glacial lakes in the Himalayas during the past 30 years (Wang et al. 2010a, 2010b). The areas of Galuncuo and Kangxicuo lakes also increased by 104% and 118% from 1987 to 2001, respectively, and Lumuchimi lake enlarged by 118% from 1977 to 2003 (Chen et al. 2005). Lakes near Highway S301 in Tibet have increased by 12.77 km$^2$ yr$^{-1}$.
from 1970 to 2000 with a warming climate, glacier melting and permafrost degradation (Wang et al. 2008). The areas of Bamucuo, Pengcuo, Dongcuo and Nailirungcuo lakes have increased during the last 30 years: the main factors directly related to lake water level are rainfall, ice-snow ablation and permafrost recession (Bian et al. 2006). In the upstream area of Manla reservoir in the Nianchu river basin, the lake areas increased by 0.1 km²/a during 1980–2005 (Li et al. 2010). The area of glacier lakes in the Mount Qomolangma National Nature Preserve has expanded by 1.64 km²/a during 1976–2006, which accounts for 64.73% of the area in 1976 owing to glacial ablation (Nie et al. 2010). Yao et al. (2010) concluded that the expansion of glacial lakes in western China was mainly caused by the substantial loss of glacial mass during recent decades.

2.2.4. Relationship between climate change and glacier variation. Temperature rise, especially the increasing warming with altitude, is remarkable in southwestern China, as confirmed by the records of Dongrongbu, Yuandongrongbu and Dasuopu ice cores located in the Himalayas and Xiaoqiongkemadi, Puruogangri and Geladandong ice cores in the Tanggula Mountains (Duan et al. 2002, Yao et al. 2006, Zhang et al. 2007, Hou and Zhang 2003) and tree ring records in the Hengduan and Nyainqentanglha Mountains (Song et al. 2007, Zhang et al. 2010a, 2010b, Fan et al. 2008, Shao and Fan 1999, Duan et al. 2010). These results further demonstrate climate warming with greater magnitudes at higher altitude areas in southwestern China, which must be one of the most crucial factors causing glacier retreat. In addition, net accumulation of Dongrongbu, Yuandongrongbu, Dasuopu and Geladandong ice cores showed decreasing trends, especially after 1980. Improved understanding of the influence of precipitation on glacier change requires further observations in the accumulation areas.

Regional differences of glacier variation in southwestern China are evident. These may be caused by differences in temperature and precipitation at different glacial regions. For example, precipitation and annual temperature were 801 mm and 1.7 °C more at the Hailuogou glacier front (3000 m) in the eastern slope than at the Dagongba glacier front (3700 m) during 1982/83 in the western slope of Mount Gongga. Precipitation in the accumulation area is 1000 mm greater at the Hailuogou glacier than at the Dagongba glacier (Li and Su 1986). Retreat velocity is faster on the eastern slope than on the western slope in Mount Gongga. In addition, glaciers had a 66.5 m/a retreat in the northern slope, but an 81.5 m/a advance in the southern slope of Mount Bukatage during 1973–1994. The other factor is the differences in glacier location, size and terminus altitude. For example, No. 94 glacier had a faster retreat during 2006–2008 than No. 390 glacier in the Palongzangbu basin because the frontal altitude of the former is 160 m higher than the latter, and Yuandongrongbu glacier with a relatively smaller glacial area also retreated by a higher rate than the Dongrongbu glacier during 1976–2006 to the east of Qomolangma, because the greater/higher the glacial scale/frontal altitude is, the later is the response to climate change.

Xu et al. (2009) noted increasing absorption of visible radiation caused by black carbon (hereafter BC) of deep fresh snow, which would be a significant contributing factor to the observed rapid glacier retreat on the Tibetan Plateau. Yasunari et al. (2010) found the albedo reductions caused by increasing concentration of BC in snow would lead to runoff increases of 70–204 mm of water. This runoff is the equivalent of 11.6–33.9% of the annual discharge of a typical Tibetan glacier. Qian et al. (2011) also thought that a ~1.0 °C average increase of the surface air temperature has been caused by the increasing BC over the Tibetan Plateau (also see Flanner et al. 2007). In addition, Takeuchi et al. (2001) have also noted the effect of snow algea on snow albedo reduction. Scherler et al. (2011) confirmed that more than 65% of the monsoon-influenced glaciers that have been observed are retreating, but debris-covered glaciers with stagnant flow-gradient terminus regions typically have stable fronts, which highlights the importance of debris cover for understanding glacier retreat. Although these influences are crucial on glacier melting, evaluating their contribution to glacier change in southwestern China needs future work.

At present, the limited observations in glacial accumulation areas do not yet allow discussion of the qualitative relationship between climate change and glacier behavior in southwestern China. And what is more, the complexity of climate change and glacier dynamic response to it require long-term observation, which can be supported by two peculiar phenomena in southwestern China: (1) the temperature had an increase of about 0.74 °C with an 44.5 mm precipitation rise in the Hengduan Mountains during 1960–2008 (Li et al. 2010d), combined with significant glacial ablation and retreat; (2) a considerable number of glaciers advanced in the Gangrigabu Mountains with increased precipitation and temperature during 1980–2001 (Shi et al. 2006). Different glaciers behave in different ways and timescales, so it is important to monitor change of glaciers over the long-term.

3. Conclusion

Annual and seasonal warming trends in southwestern China during 1961–2008 were significant. About 77% of the 111 stations displayed statistically significant increases of annual temperature. At the seasonal level, the percentage of stations with significant increasing trends ranged from 45% in spring to 59% in winter. The warming trend was greater on the XPHM than in the SB and YGP, reflecting altitude dependence. Seasonal warming occurred in summer and winter on the XPHM, but in autumn and winter over the SB and YGP. In general, the greatest warming occurred above 3500 m, whereas the lowest mean trends were at stations below 1500 m. The increased net longwave radiation flux over most areas in the study region and sea surface temperature in the Western Pacific may have made some contributions to temperature rise. 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 XPHM and YGP. In addition, the warming with altitude may be caused by the changed cloud cover, the positive feedback from snow/ice albedo and the increased BC in snow.

About 53% of the stations experienced a trend of increasing annual precipitation. Seasonally, such a trend was evident at between 50% (summer) and 77% (winter) of the 111 stations. Stations with precipitation increases were also mainly at higher altitudes, but the significance level was low. Elsewhere, and mainly below 1500 m, a weak and fluctuating decreasing trend of annual precipitation included marked regional differences. A statistically significant decrease of autumn precipitation was common. Northward penetration of the summer monsoon is limited by an increasing northeasterly air flow over the region, and northwesterly winds in the north are preventing southward transportation of water vapor from the ocean in summer. These characteristics suggest a weakened monsoonal flow and vapor transportation in recent years, and also partly explain the inconspicuous precipitation variations over southwestern China. The strengthening Western Pacific Subtropical High also has had some influence on the increased winter precipitation in the XPHM, the decreasing annual precipitation in the YGP, and the statistically decreased autumn precipitation on the SB. In addition, the increased orographic rainfall may be causing the precipitation increase with altitude.

Under temperature rise, especially the increasing warming with altitude recorded by 111 weather stations, ice cores and tree rings in southwestern China, three characteristics of glacier variations occurred during recent decades: drastic retreat, large mass loss and an increase of the area of glacial lakes or lakes supplied by meltwater. Precipitation decrease also had some influence on glaciers’ retreat in some areas, such as the central Himalayas. The remarkable regional differences of glacier change in southwestern China may be caused by the two following factors: differences in temperature and precipitation; and differences of glacier location, scale, and frontal altitude. However, it is difficult to discuss the qualitative 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.

Future studies will include an assessment of the influence of climate variations on regional sustainable development in southwestern China, and the relationship between climate change and glacier variation, especially the influence from precipitation fluctuation. This is vital because the consequences of glacier retreat and associated floods, mud flows and rock falls caused by meltwater and storms affect traffic, tourism and wider economic development. Relationships between changes in temperature and attendant changes in precipitation are likely to have a major impact on the hydrological cycle, especially in the glacial basins, under possible future warmer conditions.

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Appendix

A.1. Data and methods

A.1.1. Data sources. Daily precipitation, temperature and sunshine hours data were provided by the National Climate Center, China Meteorological Administration (CMA) (http://cdc.cma.gov.cn/). Against a background of rapid development of meteorological observations, the modern nationwide network of weather stations in mainland China began operation in the 1950s. After data quality control and homogeneity assessment, the selected 111 stations all have data available since the end of the 1950s or the early 1960s and are located at altitudes between 285.7 and 4700 m. Accordingly, the period from 1 January 1961 to 31 December 2008 was analyzed in this work. Records of glacier changes were based principally on previous studies, and detailed information is provided in section 2.2.

Monthly mean geopotential height and wind field data at 500 and 300 hPa, sea level pressure (SLP), net shortwave and longwave radiation flux at the surface were obtained from the National Oceanic and Atmospheric Administration–Cooperative Institute for Research in Environmental Sciences (NOAA–CIRES) Climate Diagnostics Center reanalysis R1 dataset (www.cdc.noaa.gov/). This gives continuous global coverage from January 1948 to the present with a spatial resolution of 2.5° x 2.5° (Kalnay et al 1996, Kistler et al 2001). The data of sea surface temperature (SST) during 1800–2007 with a spatial resolution of 2.5° x 2.5° are from the European Climate Assessment and Dataset (http://eca.knmi.nl/). The data of Western Pacific Subtropical High index are from the National Climate Center (http://ncc.cma.gov.cn/en/).

A.1.2. Quality control. Data quality control is a necessary step prior to analysis of variations of temperature and precipitation, because erroneous outliers can seriously impact their trends. Data quality control was performed using the computer program RClimDex, developed and maintained by Xuebin Zhang and Feng Yang at the Climate Research Branch of the Meteorological Service of Canada. Software and documentation are available online for downloading (http://cccma.seos.uvic.ca/ETCCDI/). The software identifies on first run erroneous temperature and precipitation data, such as precipitation values below 0 mm. Additional execution involves identification of potential outliers, which have to be manually checked, validated, corrected or removed. Here, 3 standard deviations was chosen as the threshold for a finer
Table A.1. Comparison of temperature (°C/a) and precipitation (mm/a) change in southwestern China with other regions of China. (Note: values for trends significant at the 5% level are set in bold.)

| Regions/period              | Annual temperature | Spring temperature | Summer temperature | Autumn temperature | Winter temperature | Data sources           |
|-----------------------------|--------------------|--------------------|--------------------|-------------------|-------------------|-----------------------|
| Central Tibet/1961–2000     | 0.024              |                    | 0.016              | 0.026             |                   | Bian and Du (2006)    |
| Qilian/1960–2005            | 0.030              | 0.018              | 0.026              | 0.038             | 0.050             | Jia et al (2008)      |
| Himalaya/1971–2004          | 0.023              |                    | 0.094              | 0.194             | 0.207             | Yang et al (2006)     |
| Xinjiang/1960–2005          | 0.033              | 0.074              | 0.094              | 0.194             | 0.207             | Liu et al (2009a, 2009b) |
| Gansu/1957–2006             | 0.021              |                    |                    |                   |                   | Wu et al (2008)       |
| Northeastern China/1953–2001| 0.036              | 0.04               | 0.013              | 0.02              | 0.06              | Dong and Wu (2008)    |
| Northwestern China/1951–2004| 0.026              |                    |                    |                   |                   | Yao et al (2009)      |
| Yunnan/1960–2007            | 0.015              |                    |                    |                   |                   | Cheng and Xie (2008)  |
| SB/1951–2000                | −0.0029            |                    |                    |                   |                   | Chen et al (2008)     |
| Hengduan mountains/1960–2008| 0.015              | 0.059              | 0.015              | 0.017             | 0.035             | Li et al (2010d)      |
| Southwestern China/1961–2008| 0.031              | 0.018              | 0.019              | 0.026             | 0.024             | This study            |

| Regions/period              | Annual precipitation | Spring precipitation | Summer precipitation | Autumn precipitation | Winter precipitation | Data sources           |
|-----------------------------|-----------------------|-----------------------|----------------------|----------------------|----------------------|-----------------------|
| Central Tibet/1961–2000     | 1.99                  |                       |                      |                      |                     | Bian and Du (2006)    |
| Qilian/1960–2005            | 1.18                  | 0.32                  | 0.363                | 0.067                | 0.097                | Jia et al (2008)      |
| Xinjiang/1960–2005          | 0.85                  | 0.454                 | 1.714                | 0.663                | 0.729                | Liu et al (2009a, 2009b) |
| Gansu/1957–2006             | −0.317                |                       |                      | −0.417               | 0.024                | Wu et al (2008)       |
| Northwestern China/1951–2004| −2.144                |                       |                      |                      |                     | Yao et al (2009)      |
| SB/1951–2000                | −2.256                |                       |                      |                      |                     | Chen et al (2008)     |
| Hengduan mountains/1960–2008| 0.909                 | 0.862                 | −0.15                | 0.153                | 0.147                | Li et al (2010d)      |
| Southwestern China/1961–2008| −0.00                 | 0.006                 | 0.002                | −0.008               | 0.009                | This study            |

Figure A.1. Example of precipitation successful quality control procedures using Rclimdex (histogram (vertical bars) and Kernel-filtered density (line)).

quality control of the data, that having been found to be the best method for data quality control in previous studies (Zhang et al 2005, Aguilar et al 2005, New et al 2006). Figure 1 is an example of the plots used for quality control of precipitation data. It explains the data density in two different ways: a histogram (bars) and a Kernel-filtered plot (line), a nonparametric approach to density fitting (Aguilar et al 2005). Both show that precipitation data from the station are fine.

Homogeneity assessment can be quite complex, often requiring close neighboring stations, detailed station history and a long time series (Vincent et al 2005). Data homogeneity was assessed with the Rhtest software (http://ccma.seos.uvic.ca/ETCCDI/), which uses a two-phase regression model to check for multiple step change points that could exist in a time series (Wang and Zhou 2005). The model was first proposed to test the homogeneity of a climatological series by Easterling and Peterson (1995) and was used by Vincent (1998). The model and statistical test were revised by Lund and Reeves (2002), Wang (2003) and Zhang et al (2005), in order to identify potential inhomogeneities in the data. The first model describes an overall trend in the tested series. The second model describes an overall trend divided by a potential step at an estimated date. The models are compared using an F test to determine whether the step substantially improves the fit of the model. When the F statistic is greater than the 95th percentile, the second model is accepted and it is concluded that there is a step in the tested series (Wang 2003). Once a possible

Figure A.2. Homogeneity assessment results for annual mean temperature for Jiali station, the station was relocated in 1983 (30.67°, 93.28°, 4488.8 m).
### Table A.2. Glacier changes in southwestern China.

| Area                        | Glacier name | Period       | Glacier number | Length change (m/a) | Area change (km²/a) | Volume change (km³/a) | Source                        |
|-----------------------------|--------------|--------------|----------------|---------------------|----------------------|------------------------|--------------------------------|
| Nyainqntanglha mountains    | Gangrigabu   | 1915–1980    | 102            | −14.4               | −0.63                | −0.091                 | Liu et al (2005a, 2005b)    |
|                             |              | 1980–2001    | 52             | −7.4                | −0.39                | −0.054                 |                                |
|                             |              | 1980–2001    | 36             | 12.125              | 0.33                 | 0.044                  |                                |
|                             | Yalong       | 1980–2001    | 1              | −47.9               | −0.07                |                        |                                |
|                             | 50282B0136   | 1980–2001    | 1              | 34.9                | 0.02                 |                        |                                |
|                             | 50282B0123   | 1980–2001    | 1              | 55.1                | 0.02                 |                        |                                |
| Nam Co basin                |              | 1980–2001    | 52             | −7.4                | −0.39                | −0.054                 | Chen et al (2009)            |
| Rangwuhu basin              |              | 1980–2001    | 36             | 12.125              | 0.33                 | 0.044                  |                                |
| Palongzangbu basin          | Azha         | 1980–2006    | 1              | −62.6               | −1.14                |                        | Yang et al (2010)            |
|                             |              | 1980–2006    | 1              | −14.6               |                      |                        |                                |
|                             | No. 4        | 1980–2008    | 1              | −10.2               |                      |                        |                                |
|                             | No. 10       | 2006–2008    | 1              | −13.7               |                      |                        |                                |
|                             | No. 94       | 2006–2008    | 1              | −5.47               |                      |                        |                                |
|                             | No. 390      | 2006–2008    | 1              | −12.9               |                      |                        |                                |
| Nyainqntanglha mount        |              | 1970–2007    | 1              | −10                 |                      |                        | Kang et al (2007)            |
|                             | Zhadang      | 1970–2007    | 1              | −9.9                |                      |                        |                                |
|                             | Palu         | 1970–2007    | 1              | −37.7               |                      |                        |                                |
|                             | Xibu         | 1970–1999    | 1              | −4.6                |                      |                        |                                |
|                             | 50270C0049   | 1970–2007    | 1              | −8.1                |                      |                        | Pu et al (2006)              |
| Duilongqu basin             | Gurenhekou   | 1970–2006    | 1              | −70.6               |                      |                        | Shi (2008)                   |
| Yigongzangbu river basin    | Ruoguo       | 1959–1975    | 1              | −37.7               |                      |                        |                                |
|                             |              | 1970–2000    | −0.47          |                      | 0.02                 | 0.375                  | Jin et al (2004)             |
|                             | 1969–2000    | −0.47        | 0.02           | 0.375               | Jie et al (2010)      |                            |                                |
|                             | Jaygodirunace| 1969–2000    | 1              | −38.4               |                      |                        |                                |
|                             | 5K451F12     | 1969–2001    | 1              | 21.3                |                      |                        |                                |
|                             | Selincuo basin| 1994–1999    | 1              | −3.4                |                      |                        | Pu and Yao (2004)            |
|                             | Dongkmadi    | 1994–1999    | 1              | −3                  |                      |                        |                                |
|                             | Xiaodongkmadi| 1994–1999    | 1              | −3                  |                      |                        |                                |
| Tanggula mountains          |              |              |                |                     |                      |                        |                                |
|                             | Geladandong area| 1994–2000   | −0.47          |                      | 0.02                 | 0.375                  | Jin et al (2004)             |
|                             | Selincuo basin| 1994–1999    | −3.4           |                      | 0.02                 | 0.375                  | Jie et al (2010)             |
|                             | Dongkmadi    | 1994–1999    | −3             |                      |                     |                        |                                |
|                             | Xiaodongkmadi| 1994–1999    | −3             |                      |                     |                        |                                |
|                             |              |              |                |                     |                      |                        |                                |
| Himalayas                   |              |              |                |                     |                      |                        |                                |
|                             | Pengequ basin | 1970–2001    | 999            | −4.10               | −0.375               |                        |                                  |
|                             | The upstream | 1980–2005    | −0.52          | −0.232              |                      |                        | Li et al (2010)              |
|                             | Mount Namulani| 1976–2001    | −0.118         |                      | 0.02                 | 0.375                  | Wang et al (2010a, 2010b)    |
|                             | Namunani     | 1976–2006    | −4.8           |                      | 0.02                 | 0.375                  | Ye et al (2007)              |
|                             | 1974–2003    | −4.8         | 0.02           | 0.375               | Ye et al (2008)       |                            |                                |
|                             | Mapangyongcuo| 1974–2003    | −0.25          |                      | 0.02                 | 0.375                  | Ye et al (2008)              |
|                             | Kangwure     | 1974–2007    | −8.9           |                      | 0.03                 | −0.001                 | Ma et al (2010)              |
|                             | Dasipu       | 1968–1997    | −4             |                      | 0.02                 | 0.375                  | Pu and Yao (2004)            |
|                             | Jcunpu       | 1976–2003    | −52.3          |                      | 0.02                 | 0.375                  | Nie et al (2010)             |
|                             | 1976–2006    | −17.93       | 0.02           | 0.375               | Nie et al (2010)      |                            |                                |
|                             | 1976–2006    | −14.6        | 0.02           | 0.375               | Nie et al (2010)      |                            |                                |
|                             | Zongrongbu   | 1976–2006    | 14.0           |                      | 0.02                 | 0.375                  | Nie et al (2010)             |
|                             | Yuanongrongbu| 1976–2006    | 14.0           |                      | 0.02                 | 0.375                  | Nie et al (2010)             |
|                             | Dongrongbu   | 1976–2006    | −9.1           |                      | 0.02                 | 0.375                  | Nie et al (2010)             |
|                             | Reqiang      | 1976–2006    | −65.7          |                      | 0.02                 | 0.375                  | Nie et al (2010)             |
|                             | Glaciers in northern slope| 1973–1994| −66.5          |                      | 0.02                 | 0.375                  | Li et al (1999)              |
|                             | Glaciers in southern slope| 1973–1994| 81.5           |                      | 0.02                 | 0.375                  | Li et al (1999)              |
step change was identified in the annual series, it was checked against the station history. 15 stations ceased operation during the 1980s and 1990s, 12 stations had a potential step in the annual mean temperature. Historical explanations for the cause of the step, such as relocation, were found for only one station. Therefore, the stations were removed from the final data set. Figure 2 shows an example from the Tibet Autonomous Region for which a step change was detected. The station shows a statistically significant discontinuity around 1983, verified by the original station data, which indicated that the station was relocated in that year.

A.1.3. Methods. In order to learn more about the spatial changes in temperature and precipitation, it is necessary to divide the study region into sub-regions. Cluster analysis is used to partition a data set into clusters so that between-cluster data are similar and within-cluster data are dissimilar. Different clustering methods use different similarity definitions and techniques. Several clustering algorithms were analyzed from three different viewpoints: clustering criteria, cluster representation, and algorithm framework. The analysis showed that southwestern China can be divided into three sub-regions: the Xizang Plateau-Hengduan Mountains (hereafter XPHM), the Yunnan-Guizhou plateau (hereafter YGP) and the Sichuan Basin (hereafter SB) (figure 1).

After data quality control and homogeneity assessment, the annual average value and anomalies of temperature and precipitation in different seasons were calculated. Seasons were winter (December–February), spring (March–May), summer (June–August) and autumn (September–November). In order to avoid average series being dominated by those stations with higher values, the simple anomalies were standardized by dividing them by the station standard deviation during the study period.

Linear trends of temperature and precipitation were calculated using a nonparametric approach. Sen’s robust slope estimator, based on Kendall’s τ (Sen 1968), which does not assume a specific distribution for the data, and is not sensitive to outliers, was applied in studies of annual temperature and precipitation change in Canada (Zhang et al 2000) and of extreme wave heights over Northern Hemisphere oceans (Wang and Swail 2001). After removing the influence of possible auto-correlation based on the methods used by Pryor and Ledolter (2010), the regional temperature and precipitation series were converted into trends per decade. A linear trend was considered to be statistically credible if it was significant at the 0.05 level. In addition, the nine-year smoothing average was used to show the inter-annual variation of temperature and precipitation.

Regionally averaged anomaly series (including the whole of southwestern China and the three sub-regions) for temperature and precipitation were calculated using formula (1):

$$x_{r,t} = \frac{\sum_{i=1}^{n_t} (x_{i,t} - \bar{x}_i)}{n_t}$$

where \(x_{r,t}\) is the regionally averaged value of temperature and precipitation in the annual and seasonal series in year \(t\); \(x_{i,t}\) is the value for station \(i\) in year \(t\); \(\bar{x}_i\) is the 1961–2008 mean value at station \(I\) and \(n_t\) is the number of stations with data in year \(t\). To avoid the average series being dominated by those stations with a high value, \(x_{i,t}\) and \(\bar{x}\) were standardized by dividing them by the station standard deviation (New et al 2006). ArcGIS was employed to study the spatial distribution of temporal changes in temperature and precipitation.

To quantify changes in large scale atmospheric circulation, separate mean circulation composites for summer (JJA) and winter (DJF) were derived with both strongly positive and negative temperature anomalies, using monthly mean geopotential height and wind field data at 500 and 300 hPa. We derived separate mean circulation composites for summer (JJA) and winter (DJF) with both strongly positive and negative temperature anomalies. We then subtracted the latter from the former (warm minus cold) to represent the changes in circulation between warm and cold years, and the effect of warming. To be defined as strongly positive/negative, individual temperature anomalies had to exceed ±1.0. In addition, we have also subtracted the latter from the former (new minus old) to represent the changes in net longwave and shortwave radiation flux between 1961–85 and 1986–2008 because these variations showed a significant relationship with regional temperature series.

### Table A.2.

| Area                        | Glacier name | Period   | Length change (m/a) | Area change (km²/a) | Volume change (km³/a) | Source          |
|-----------------------------|--------------|----------|--------------------|--------------------|-----------------------|-----------------|
| Yulong mountain             | Baishui No. 1| 1900–2008| 7.6                | −0.07              |                       | Li et al (2010b) |
| Hengduan mountains          | Dagongba     | 1930–2007| −5.78              |                    | −0.41                 | Zhang et al (2010a, 2010b) |
|                             | Xiaogongba   | 1930–1990| −2.5               |                    |                      | Li et al (2010b) |
|                             | Yanzigou     | 1930–1990| −46.7              |                    |                      |                 |
|                             | Hailuogou    | 1930–2006| −23.6              |                    |                      |                 |
|                             | Hailuogou No.2| 1930–1990| −17.6              |                    |                      |                 |
| Meli mountain               | Mingyong     | 1932–2002| −13.4              |                    |                      |                 |

A.2. Comparison of temperature and precipitation change in southwestern China with other regions of China (table A.1)

A.3. Glacier changes in southwestern China (table A.2)
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