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Changing features of the climate and glaciers in China's monsoonal temperate glacier region

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[1] Climatic data, ice core records, the tree ring index, and recorded glacier variations have been used to reconstruct a history of climatic and glacial changes in the monsoonal temperate glacier region of southwestern China during the last 400 years. The region's temperature has increased in a fluctuating manner during the twentieth century after two cold stages of the Little Ice Age (seventeenth to nineteenth centuries), with a corresponding retreat of most of the glaciers, against a background of global warming. Retreat rates accelerated after the 1980s. The few advancing glaciers that did exist have started to retreat in recent years. The amount, trend, and amplitude of variation of precipitation have differed in different parts of the region. The Dasuopu ice core, from the western part of the region, shows a decreasing trend in precipitation, the converse of the trend in temperature. In the eastern part of the region, however, a rising trend of rainfall has accompanied increasing temperatures as a result of the variable atmospheric circulations from different sources. The southwest monsoon, the principal controlling factor in the Chinese monsoonal temperate glacier region, can be classified into the Indian monsoon and the Bengal monsoon. The former passes across the Indian Peninsula from the Arabian Sea and transports vapor for precipitation in the western part of the monsoonal temperate glacier region. The Bengal monsoon, originating in the Bay of Bengal, is the major source of precipitation in the eastern part of the region. The eastern part is also influenced by the southeast monsoon arriving from the western Pacific, and the western part is affected in winter by the southern branch of the westerly circulation. This complex atmospheric situation results in differing patterns of precipitation in the western and eastern zones. Although it is clear that both temperature and precipitation affect the glaciers, further work is needed to confirm which of these is the major factor influencing present glacier change. *INDEX TERMS:* 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 1699 Global Change: General or miscellaneous; 1630 Global Change: Impact phenomena; 1827 Hydrology: Glaciology (1863); 3309 Meteorology and Atmospheric Dynamics: Climatology (1620)

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1. Introduction

[2] The monsoonal temperate glaciers in China are located in the region of the southeastern Plateau of Tibet, including the Hengduan and Daxue Mountains, the eastern part of the Himalayas, and the middle and eastern segments of the Nyainqêntanglha Range (Figure 1). This region is characterized by high precipitation (1000–3000 mm) in the glacier-covered area, a low snow line (4200–5200 m, which is ~800–1200 m lower than that of the polar glaciers in the western Plateau of Tibet), and relatively high temperatures (equilibrium line mean annual value −6°C, summer value 1°–5°C) [*Shi et al.*, 1988; *Li and Su*, 1996]. The most pronounced characteristic of monsoonal temperate glaciers is that they are very sensitive to climate; this means that a small increase or decrease of temperature can cause large-scale glacier retreat or advance [*Su and Shi*, 2000; *He et al.*, 2000]. Thus the glaciers are a very direct, clear indicator of climatic change.

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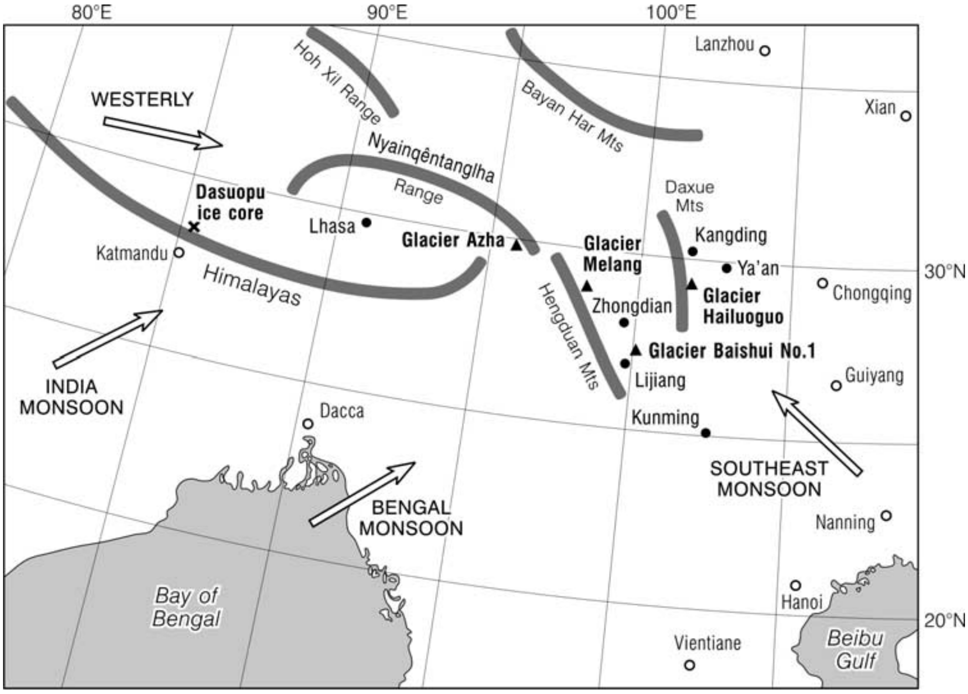

Figure 1. The scope of the monsoonal temperate glacier region in China, locations of selected meteorological stations and representative glaciers, and the atmospheric circulations affecting the region.

[3] According to the glacier inventory [*Pu*, 1994, 2001], there are 8607 monsoonal temperate glaciers in China covering an area of 13,203 km^2, which is 18.6% of the total glacier number and 22.2% of the total glacier area in China. The climate of the region is controlled by three major atmospheric circulations: the Northern Hemispheric westerly wind system, which carries little vapor in winter; the southwestern monsoon, which includes the main sources of precipitation to the region in summer from May to October from the Indian Ocean; and in the eastern part of the region, the southeastern monsoon from the Pacific Ocean [*Hahn and Manabe*, 1975; *Lin and Wu*, 1990; *Ruddiman and Kutzbach*, 1989; *Parthasarathy et al.*, 1992; *Kripalani and Singh*, 1993; *Araguas-Araguas et al.*, 1998; *Duan et al.*, 2000; *He et al.*, 2000, 2002a, 2002b].

[4] *Ward* [1924] and *Wissmann* [1937] described the Chinese monsoonal temperate glaciers in the 1920s and 1930s. Since the 1990s, researchers have studied the region from a variety of viewpoints [*Wu*, 1995; *Xie and Kotlyakov*, 1994; *Aizen and Aizen*, 1994; *Aizen et al.*, 1996; *Li and Su*, 1996; *Su and Shi*, 2000; *He et al.*, 2000, 2001, 2002a, 2002b]. However, there are very few accounts that comprehensively report the rapidly changing features of climate and of glaciers in this region using multiple sources of evidence. Here information from the region, including climatic data, glacier change data, ice core records, and tree ring data, is examined against the background of global warming and the general retreat of the glaciers since the Little Ice Age. This is of value in relation to wider studies of global change.

2. Data and Methodology

[5] The basic objective of this paper is to analyze comprehensively and quantitatively recent changes of the climate and of glaciers in the study region. Multiple types of evidence, including climatic data from different parts of the region, tree ring data from the Hengduan Mountains, ice core records from the Himalayas, and the documented response of the glaciers have been used in the comparison and correlation of various indices. Daily observations of temperature and precipitation at the six selected stations in the study region (Figure 1) started between 1951 and 1958. The longest instrumental temperature and precipitation series is provided by the National Meteorological Data Center. Annual mean temperature and annual total precipitation are the basis for calculating a continuous trend of variation during a period of $\sim$50 years. In 1997, three ice cores were recovered from the Dusuopu Glacier in the Himalayas (Figure 1), the western part of the study region, with an electromechanical drill in dry holes. The first core (C1), 159.9 m long, was drilled at 7000 m above sea level (asl) on the flow line down from the top of the glacier col. Two cores (C2 and C3), 149.2 and 167.7 m long, respectively, were drilled to bedrock, 100 m apart, on the col at 7200 m. C2 was taken (in a frozen state) to the Laboratory of Ice Core and Cold Region Environment (LICCRE), Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences. C3 was taken (also frozen) to the Byrd Polar Research Center (BPRC), Ohio State University, USA. All samples were cut at intervals between 3 and 5 cm, and all cores were analyzed over their entire length for the oxygen isotopic ratio ($\delta^{18}O$) at BPRC and LICCRE using Finnigan Mat-252 spectrometers (accuracy 0.05‰). The results make it possible to reconstruct temperature changes during the last 560 years from the upper 87% of C3 [*Thompson et al.*, 2000]. In addition, the dust concentration (particles with diameters >0.63 μm) was determined in C3 for an indication of climatic variations (wet/drought) from 1440 A.D. [*Thompson et al.*, 2000]. The

annual accumulation rate in C2 was determined from seasonal variations of $\delta^{18}O$ values, from the thickness and density of annual ice layers, and from an ice flow model [*Yao et al.*, 2000] to record the historic variation of precipitation during the last 400 years. More than 100 years of climate data from India are also used in order to improve the understanding of recent climatic and glacial changes in China's monsoonal temperate glacier region. Owing to high spatial variability in rainfall over the entire country, *Sontakke and Singh* [1996] have divided the whole of India into six zones by averaging summer (June–September) rainfall values observed at 116 rain gauge stations. The mean summer rainfall data from 15 stations in one of the six zones, northeastern India (NEI), between 1848 and 1995 are used in the paper to compare with data from the adjacent Dasuopu ice core.

[6] Tree ring sampling has been undertaken recently at between 3500 and 3750 m asl on Mount Yulong near Lijiang (Figure 1), the southernmost glacier-covered area in Eurasia. Samples for analysis were collected in 16 cores from 8 trees in the fir belt, which has an upper limit close to the glacier tongues. These are the only up-to-date tree ring data from this region. Cross-dating was carried out after the samples were dried, fixed, and polished. Ring widths were measured with a precision of 0.01 mm. Using the method of *Fritts* [1976], the measured ring widths (W_t) were standardized and converted to ring width indexes (I_i) by dividing the width for year t by the expected growth (Y_t):

$$I_i = W_t / Y_t.$$

[7] Division by the expected growth both removes the trend in growth and scales the variance so that it is approximately the same throughout the entire length of the time series. Glacier change data from the study region (retreat and advance) are based on the location of "new" moraines and other glacial landforms, recent observations at some typical temperate glaciers, and the Chinese glacier inventories for the Yangtze River, Lancangjiang River, and Nujiang River drainage basins [*Pu*, 1994, 2001].

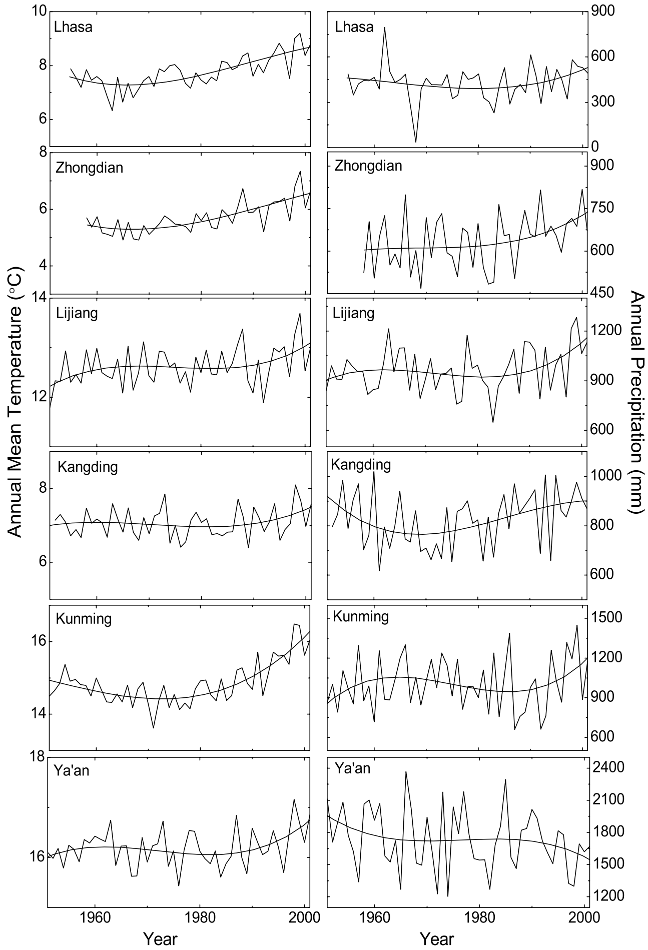

Figure 2. Variations of mean annual temperature and annual precipitation at Lhasa, Zhongdian, Lijiang, Kangding, Kunming, and Ya'an in the different parts of China's monsoonal temperate glacier region during the last 50 years. Trend lines fitted to the data are fifth-order polynomials.

3. Results

3.1. Temperature and Precipitation Variations in the Last 50 Years

[8] Fifty years of annual average precipitation and temperature data from Lijiang, Zhongdian, Kangding, and Ya'an, located at the southern, central, northern, and western sides of the Hengduan Mountains, respectively, from Lhasa in the far west, and from Kunming in the far east of the region (Figure 1) are shown in Figure 2. The mean annual temperature at all of the stations has increased since the 1970s, and the rate of change has accelerated since the 1990s, with a fluctuating cycle of 2–3 years. The annual precipitation at most of the stations has increased but in a less marked fashion than temperature. In contrast, the mean annual precipitation at Ya'an has been decreasing since the mid-1980s, and the change has been much larger than that at the other stations.

[9] The data indicate that the climate in the Chinese monsoonal temperate glacier region started warming gradually in the 1970s and that the warming trend intensified during the 1990s. Influenced by the southwest monsoon, precipitation in the Hengduan Mountains in the western part of the region started to increase in the 1980s, accompanying the global warming trend. At Ya'an the annual rainfall is higher, its variability is greater, and the trends of change are different from those in the west. In part, this is because the site has a different altitude (850 m) and topography (at a lower plain area) than those of other stations (at plateau areas between 2000 and 4000 m) and is influenced both by the southwest and southeast monsoons.

3.2. Dasuopu Ice Core Records and Indian Precipitation

[10] The record in the Dasuopu ice core (Figures 3 and 4) indicates changes of climate, including changes in the intensity of the southwest monsoon [*Yao et al.*, 2000; *Thompson et al.*, 2000; *Duan et al.*, 2000]. The $\delta^{18}O$ values in the ice core show that temperature was relatively stable between 1600 A.D. and 1750 A.D., while there was a cooling trend in the eighteenth century. The climate started to become warmer from 1880 A.D., and this trend intensified after the middle of the twentieth century. The variability of the accumulation rate in the core documents variations of

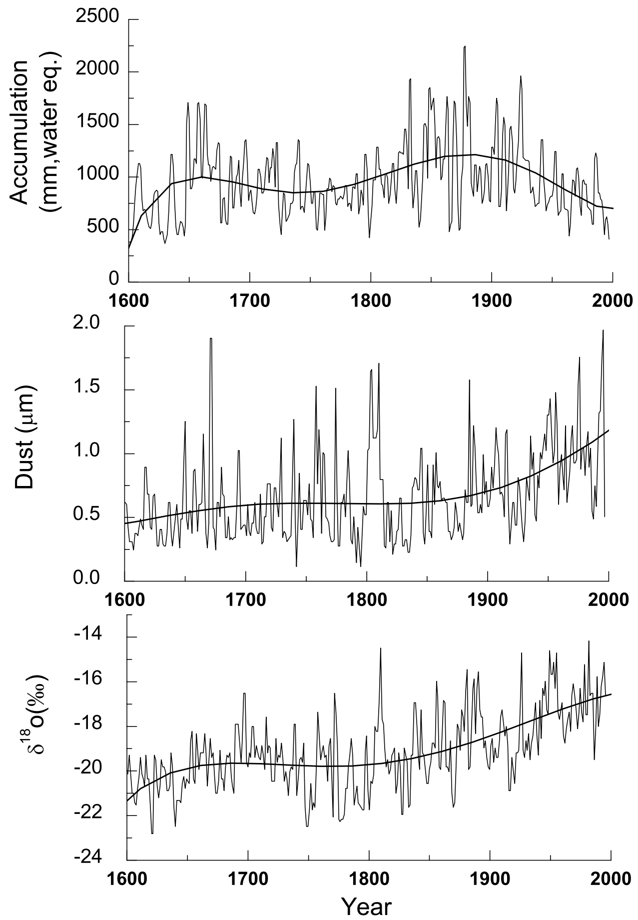

Figure 3. Variations of δ^{18}O values, the annual accumulation rate, and dust content in the Dasuopu ice core, 1600 A.D. to present. Trend lines fitted to the data are fifth-order polynomials.

precipitation and monsoonal activity at the site since 1600 A.D. There were two cold, arid stages during the early half of the seventeenth century and during the later half of the eighteenth century, during the period of the Little Ice Age. A negative relation between accumulation rate and dust content in the last 400 years suggests that higher precipitation corresponds to a lower dust content and that the dust content is higher in arid climate conditions [*Thompson et al.*, 2000]. The increase of dust content throughout the twentieth century reflects the fact that the climate in the western part of the study region (the southern Plateau of Tibet) has developed gradually into a warm, arid type.

[11] δ^{18}O values in the Dasuopu ice core started to rise in the 1930s, indicating an apparent warming period, during which there was a decreasing trend of precipitation. From 1850 A.D., variations in precipitation in the NEI region were consistent with those of the accumulation rate in the Dasuopu ice core (Figure 4). The relationship is statistically significant (r = 0.67, σ = 0.99). However, there is no marked correlation between accumulation/precipitation and the temperature in India (Figure 4).

3.3. Tree Ring Data From Mounts Yulong and Tianbao

[12] The sampling locations of tree rings and present climatic conditions confirm that the annual tree rings mainly represent variations of local temperature. The results of the ring width index from Mount Yulong (Figure 5a) were lower in the last part of the seventeenth century and in the early half of the eighteenth century and for much of the time between the midnineteenth century and the 1930s. This reflects the colder conditions during the first and second stages of the Little Ice Age and in the early twentieth century. The tree ring data indicate that temperature has been rising progressively since the 1930s, except for two periods between 1950 and 2000, consistent with local glacier change. Variations of the tree ring index since the seventeenth century in Mount Tianbao near Zhongdian (Figure 5b), reported by *Wu and Lin* [1983], and data from the Hengduan Mountains, reported by *Wu* [1995], resemble the results from Mount Yulong (r = 0.24; σ = 0.99), although the increasing amplitude in the Mount Tianbao profile for the period 1700–1750 exceeded that of Mount Yulong.

3.4. Recent Changes of Some Typical Temperate Glaciers

[13] Data showing the advancing and retreating status of some typical temperate glaciers (Figure 1) are presented in

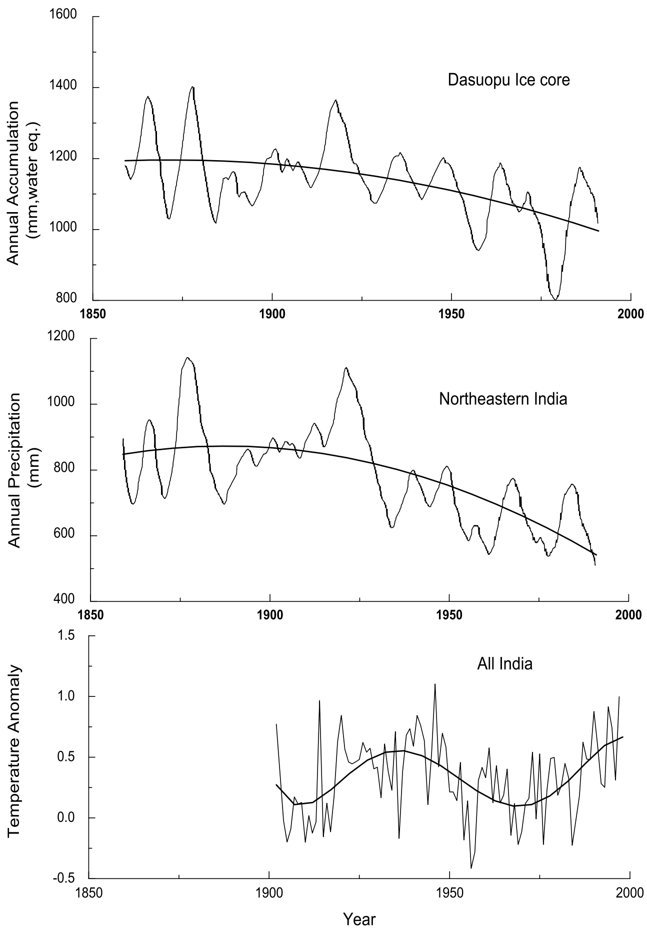

Figure 4. Variation of the annual accumulation rate in the Dasuopu ice core, the mean annual precipitation in northeastern India, and the Indian mean temperature anomaly since 1850 A.D. The curves are plotted using 5-year mean running values, and trend lines fitted to the data are second-order polynomials.

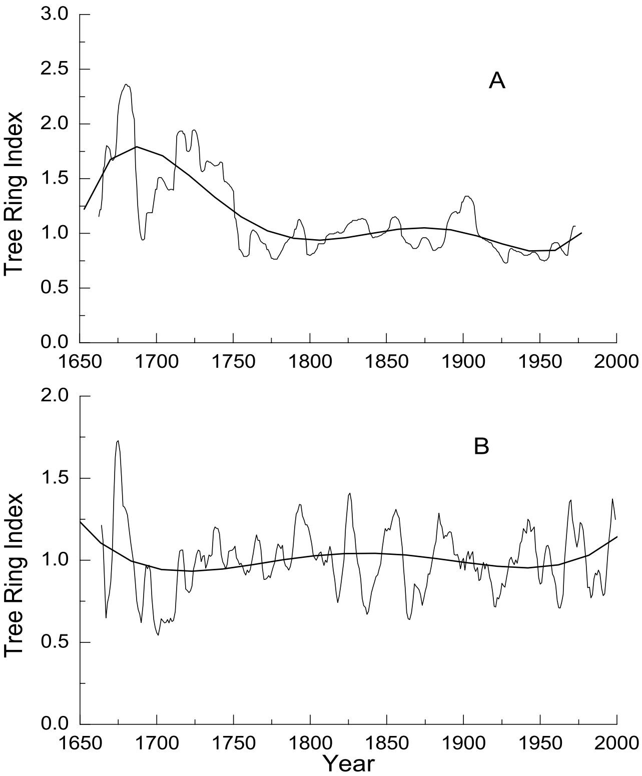

Figure 5. Variation of the tree ring index from 1650 A.D to the present in samples from (a) Mount Yulong, near Lijiang, and (b) Mount Tianbao, near Zhongdian. Trend lines fitted to the data are fifth-order polynomials.

Tables 1 and 2. Table 1 shows the rates of area reduction between the Little Ice Age and the present for glaciers of different sizes in different parts of the study region [*Pu*, 1994, 2001; *Su and Shi*, 2000]. Since the Little Ice Age of the seventeenth to nineteenth centuries, the total glacier area in the region has been reduced on average by 30%, ~3921 km^2. The glacier retreat rate differs as a function of the size of the glacier: the smaller the glacier, the larger its rate of decrease; the larger the glacier, the lower its rate of decrease.

[14] There are regional differences of glacier change, as shown in Table 2 [*He et al.*, 2000; *Zheng et al.*, 1997]. For instance, the Baishui Glacier Number 1 on Mount Yulong (Figure 1), the southernmost glacier of Eurasia and with a small area, is most sensitive to climate, and its area has decreased by 60% from the Little Ice Age to the present. It retreated ~1250 m between the Little Ice Age and the middle of the twentieth century, and it has retreated again since the 1980s (Table 2). The retreat rate has increased in the last few years in response to rapid climatic warming; the observed retreat from 1982 to 1997 was 150 m, and from 1998 to 2002 it was ~100 m. The Hailuogou and Azha Glaciers, located to the north and west, respectively (Figure 1), have also retreated very quickly since the 1980s. Although the Melang Glacier on Mount Mainri was advancing before 1998, it began to retreat gradually after 1998, indicating that it, too, has responded to post-1980s climatic warming. However, the mean rate of decrease of some large valley glaciers on Mount Gongga between the Little Ice Age and the present has been only 27%. It is clear that the different geographical locations and scales of the glaciers and their sensitivities to climate have resulted in differences in the time and amplitude of their variations.

4. Discussion

[15] A variety of indices have been used to reconstruct the climatic and glacial changes in China's monsoonal temperate glacier region in different timescales during the last 400 years. Instrumental climatic data, tree ring data, and glacier variations provide a comprehensive picture of changes in different parts of the study region during that period. The ice core record and the tree ring index clearly show the two cold stages of the Little Ice Age between the seventeenth and the nineteenth centuries, evidence of which is also provided by the advancing glaciers present at that time.

Table 1. Percentage Area Reduction of Glaciers in Different Size Classes in China's Monsoonal Temperate Glacier Region Since the Little Ice Age

	Area		
	Little Ice Age, km^2	Present, km^2	Percent
	Glacier Size = <1 km^2		
Mount Najiabawa	155.8	91.1	71
Mount Palongzangbu	154.1	90.3	70
Mount Chayuhe	134.9	80.8	67
Mount Yulong	12.1	7.0	73
Mount Gongga	66.0	38.3	72
Mount Queer	26.2	16.7	57
Sum	549.1	324.2	69
	Glacier Size = 1.01–5 km^2		
Mount Najiabawa	214.1	154.5	39
Mount Palongzangbu	114.1	79.5	43
Mount Chayuhe	270.1	198.3	36
Mount Yulong	6.5	4.6	41
Mount Gongga	107.9	77.7	39
Mount Queer	26.0	20.7	26
Sum	738.7	535.3	38
	Glacier Size = 5.01–10 km^2		
Mount Najiabawa	61.6	51.3	20
Mount Palongzangbu	68.3	57.9	18
Mount Chayuhe	99.7	82.4	21
Mount Yulong[a]			
Mount Gongga	50.2	42.8	17
Mount Queer	18.2	16.0	14
Sum	298.0	250.4	19
	Glacier Size = 10.01–100 km^2		
Mount Najiabawa	242.5	218.5	11
Mount Palongzangbu	291.1	259.0	12
Mount Chayuhe	137.1	125.6	9
Mount Yulong[a]			
Mount Gongga	145.9	132.0	10.5
Mount Queer	18.2	17.0	7
Sum	834.8	752.1	11
	All Glaciers		
Mount Najiabawa	674.0	515.4	31
Mount Palongzangbu	627.6	486.7	29
Mount Chayuhe	641.8	487.1	32
Mount Yulong	18.6	11.6	60
Mount Gongga	370.0	290.8	27
Mount Queer	88.6	70.4	26
Sum	2420.6	1862.0	30

[a]The glacier's size on Mount Yulong is smaller than the classified glacier's scale in the first line.

Table 2. Variation of Some Typical Glaciers in the Chinese Monsoonal Temperate Glacier Region Since the Little Ice Age

Time Period	Altitude of the Glacier End, m	Advance and Retreat, m
Baishui Number 1 Glacier, Mount Yulong (*Area, 1.7 km^2; Length, 2.5 km*)		
Little Ice Age (17th–19th centuries)	3800	+
19th century to 1957	4353 (1957)	−1250
1957–1982	4100(1982)	+800
1982–1997	4200(1997)	−150
1998–2002	4250 (2002)	−100
Melang Glacier, Mount Mainri (*Area, 13 km^2; Length, 11.7 km*)		
1932–1959	2100	−2000
1959–1971	2740 (1971)	+800
1971–1982	2700 (1982)	+70
1982–1997	2660 (1997)	+40
1998–2002	2670 (2002)	−30
Hailuogou Glacier, Mount Gongga (*Area, 23.7 km^2; Length, 13.6 km*)		
Early 20th century to the 1930s	2850(1930)	±
1930–1966	2880~2900 (1996)	−1150
1966–1981	2920 (1982)	−177.8
1981–1989	2940 (1989)	−170
1990–1998	2980(1994)	−200
Azha Glacier, Southeastern Tibet (*Area, 29.5 km^2; Length, 20 km*)		
1920–1930	2000	+
1933–1973	2400 (1973)	−700
1973–1976	2600 (1976)	−200
1976–1980	2700 (1980)	−100

There was another short cold stage in the early twentieth century. All observed and proxy climatic indices indicate a rising trend of temperature in the whole region from the 1950s that has been intensified since the 1980s, during which period most glaciers have been retreating. However, there has been an irregular change of precipitation in the region. Dasuopu ice core signals and precipitation data from India indicate that the western part of the region was wetter from the middle of the nineteenth century until the 1930s and that annual precipitation decreased gradually from the midtwentieth century to the present. Precipitation at Ya'an, at a different altitude (850 m) than other stations (2000–4000 m) in the northeastern margin of the region, has been decreasing in the last 50 years, and the pattern of change has differed from that of temperature. In contrast, 50-year records from Lijiang, Zhongdian, Kangding, and Kunming indicate a gradual rising trend of precipitation in the Hengduan Mountains and adjacent areas in the eastern part of this region, especially in recent years. Since the early twentieth century, especially from the 1930s, most of the glaciers have been retreating gradually in response to warming conditions.

[16] These similarities and contrasts of climatic and glacial changes in China's monsoonal temperate glacier region, which have taken place against a global background, are determined by the varied regional atmospheric circulation and precipitation sources. The highly developed industries in the world economy have resulted in a rapid increase of greenhouse gases in the atmosphere, which has caused global warming [*Meehl and Washington*, 1993]. The data cited in this paper are evidence of a rising trend of temperatures in the whole study region and indicate that monsoonal activity has intensified since the 1950s [*Wang et al.*, 2002].

[17] Changes of precipitation and temperature have differed, with variations of precipitation being much more complex than those of temperature. Many factors may be responsible for this [*Su and Shi*, 2000, *Shi et al.*, 2002]. Differences in regional precipitation have many causes [*Lin and Wu*, 1990; *Thompson et al.*, 2000; *Duan et al.*, 2002]. First, there are different sources and different patterns of atmospheric circulation. The southwest monsoon has two trajectories, one from the Bay of Bengal, by way of Bengal and Burma to the Hengduan Mountains and then northward, and the other from the Arabian Sea/Indian Ocean, crossing the Indian Peninsula and the Himalayas to influence the southern part of the Plateau of Tibet [*Dey and Kumar*, 1983; *Lin and Wu*, 1990; *Zheng et al.*, 1997; *Tian et al.*, 2001]. As the distance between the sources and precipitation sites varies, the intensity and influence of the two water vapor sources differs. Accordingly, the southwest monsoon can be divided into the Indian monsoon and the Bengal monsoon (Figure 1). The Indian monsoon has had a principal effect on the Dasuopu ice core (from the eastern Himalayas) and on the western part of China's monsoonal temperate glacier region. The Bengal monsoon prevails in Mount Hengduan and adjacent areas in the eastern part of the region. The southeast monsoon coming from the North Pacific crosses most of southeastern China and carries precipitation vapor to the study region. Both the southeast monsoon and the Bengal monsoon influence the precipitation at Mount Hengduan and adjacent areas. The westerly circulation in the Northern Hemisphere mainly influences the winter precipitation of the region, and of course, its influence is stronger in the west than in the east.

[18] Second, other factors such as differences in altitude, topography conditions, glacier sizes, and the orientation of climatic observation stations or ice core/tree ring drilling sites may play an important role and cause varied regional climatic features; these factors may then result in nonuniform patterns of precipitation and glacier variations in the study region. There is a positive correlation between precipitation and temperature in the east and a negative correlation in the west. Since both temperature and precipitation influence glacier changes, further work is needed to clarify which of these is the major factor affecting glaciers.

5. Conclusions

[19] 1. Instrumental climatic data, ice core signals, tree ring indices, and recorded glacier variations indicate that the temperature in China's monsoonal temperate glacier region has increased in a variable manner during the twentieth century, resulting in the retreat of most of the glaciers, and that there were two cold stages in the Little Ice Age of the seventeenth to nineteenth centuries.

[20] 2. The amount, variability, and trend of precipitation have varied in different parts of the region. The climatic records in the Dasuopu ice core indicate a decreasing trend of precipitation in the area of the Himalayas and in the western part of the region since the 1920s, with an inverse relationship with temperature. In the Hengduan and Daxue Mountains and adjacent areas, there has been a rising trend of precipitation since the 1980s, synchronous with temperature change with the exception of a lower-altitude station.

These may be attributed to variable atmospheric circulations, altitudes, and topography.

[21] 3. The southwestern monsoon, which is the prevailing airflow in the Chinese monsoonal temperate glacier region, consists of two parts: The Indian monsoon from the Arabian Sea passes across the Indian Peninsula and transports most of the vapor for precipitation in the Himalayas, the western part of the region, and the other, the Bengal monsoon from the Bay of Bengal, crosses Bengal and Burma and is the major source of precipitation in the Hengduan Mountains and in other areas of the eastern part of the region.

[22] 4. The eastern part of the region is also influenced by the southeast monsoon from the western Pacific and by the westerly circulation in winter. The complex atmospheric situation and other regional geographical factors results in differences in the patterns of the climate in the west and the east.

[23] 5. The temperate glaciers in the region have been very sensitive to climate warming since the Little Ice Age, and most have been retreating continuously throughout the twentieth century. The rate of retreat increased after the 1980s in response to rapid global warming.

[24] **Acknowledgments.** This work was supported by the Hundred Talents Project (CAS2002-43), by Special Funds to Famous Young Scientists from the Chinese Natural Science Foundation (40071023), by the Knowledge-Innovation Programs (210506, 210019, and KZCX2-301), and by the Cold and Arid Regions Environmental and Engineering Institute, Chinese Academy of Sciences.

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