Correspondence

Early onset of rainy season suppresses glacier melt: a case study on Zhadang glacier, Tibetan Plateau

Alpine glaciers have retreated dramatically during the last few decades as global warming has impacted the Tibetan Plateau (e.g. Shi and Liu, 2000; Yao and others, 2004; Sakai and others, 2006; Ye and others, 2006; Kang and others, 2007). Glacier shrinkage over the Tibetan Plateau is mostly caused by a continuous deficit in mass balance of glaciers (Yao and others, 2004; Ye and others, 2005; Pu and others, 2008). Both temperature and precipitation affect glacier mass balance, and much research has focused on the temperature effect on glacier change (e.g. Oerlemans and Fortuin, 1992; Liu and others, 1998; Ye and others, 2005; Sakai and others, 2006; Pu and others, 2008). Using a numerical approach, a recent study revealed that the effects of precipitation seasonality and its concentration on glacier mass balance are more important than those of the annual precipitation amount (Fujita, 2008a,b), especially for glaciers located in a summer-precipitation climate. Due to the difficulty of monitoring precipitation at high elevations, few studies have discussed the effect of precipitation seasonality on glacier mass balance using observed data in the Tibetan Plateau. We demonstrate the seasonal influence of precipitation on glacier mass balance for a Tibetan glacier that is mainly influenced by the Indian monsoon during the summer and westerlies during the winter (Bryson, 1986; Yanai and Wu, 2006).

Zhadang glacier (30°28.57′ N, 90°38.71′ E; area 2.0 km^2, length 2.5 km) is located on the northeastern slope of Nyainqêntanglha mountain, southern Tibetan Plateau. Mass-balance and glacier terminus variations have been recorded since September 2005, when the Nam Co Station for Multisphere Observation and Research (NAMOR: 30°46.44′ N, 90°59.31′ E; 4730 m a.s.l.) was set up by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. The glacier faces north-northwest and spans an elevation range of 5515–6090 m a.s.l. It is debris-free, with a fan-shaped terminus. Two automatic weather stations (AWSs) have operated, one at the pass (5800 m a.s.l.) and the other in the terminal area (5400 m a.s.l.) of the glacier, since September 2005. A rain gauge was set up beside the terminus AWS in May 2007, and a hydrological observation site has operated at 5400 m a.s.l. since May 2006, close to the terminus. Since the meteorological data (e.g. air temperature and precipitation) do not cover the whole of 2005, we only report data for 2006–08.

A large deficit mass balance occurred during the mass-balance years 2005/06 and 2006/07 (Table 1; Fig. 1), but in 2007/08 there was a surplus mass balance and retreat of the glacier terminus slowed in 2008 (Table 1). Furthermore, variations in the glacier runoff in July and August 2008 were quite different from those in 2007 (Table 2; Fig. 1). Since the mass balance had been continuously in deficit for the previous decade (e.g. Yao and others, 2004; Ye and others, 2005; Pu and others, 2008), we investigated the reason for the mass-balance switch in 2007/08.

Meteorological data from NAMOR (located 50 km from Zhadang glacier) show that around 90% of the precipitation is deposited between May and September (You and others, 2007). Daily temperatures above 0°C commence in late May in the Zhadang glacier area as recorded by the AWSs (Fig. 1). Thus the accumulation and ablation seasons on the glacier overlap during the summer season (May–September). Mean air temperature during summer was 0.62°C higher in 2007 than in 2008 (Table 1), while precipitation was 57.5 mm lower in 2007 than in 2008. Monthly temperatures were lower in 2008 than in 2007 (Table 2). Monthly cumulative temperature above 0°C, a parameter associated mostly with glacier melt (e.g. Liu and others, 1998; Ohmura, 2001), was less in 2008 than in 2007. We suggest that low summer temperature is a major cause of weak glacier melt in 2008 and the associated surplus mass balance (223 mm) for the balance year 2007/08. However, when monthly and daily temperature and precipitation as shown in Table 2 and Figure 1 are investigated, differences in summer precipitation between 2007 and 2008 are clearly seen. Precipitation in May and June of 2008 was more than twice that of 2007 (Table 2). Roughly equal or less monthly precipitation occurred during the other months of 2008 compared with those in 2007. Similar monthly precipitation patterns appeared at NAMOR (Fig. 2), where precipitation in June 2008 was ~8 times that in June 2007, and precipitation in July 2008 was 1.5 times that in July 2007. Large precipitation differences in the early stages of the ablation season (May and June) between 2007 and 2008 imply that precipitation might be an important factor for the surplus mass balance in 2008.

Generally, the Indian monsoon onset is in mid-June (Chang and Chen, 1995; Wu and Zhang, 1998) and precipitation is concentrated in July and September in the southern Tibetan Plateau (Kang and others, 2000; You and others, 2007). For example, 85% of precipitation occurs between July and September at Bange and Dangxiong stations, which are about 50–100 km from the Nam Co basin. Precipitation amounts in June of 110.0 mm in the glacier area (Table 2) and 87.3 mm at NAMOR (Fig. 2) suggest that the rainy season onset was earlier by 1 month in 2008 than in 2007. The India Meteorological Department reported that the onset of the monsoon in 2008 was about a week ahead of its normal date in the Bay of Bengal, and the monsoon advanced relatively rapidly due to the interaction of monsoon circulation with the mid-latitude westerly system, resulting in higher monsoon rainfall in June (24% above the long-term averaged value) over all of India (India Meteorological Department, http://www.imd.ernet.in/section/nhac/dynamic/endseasonreport.pdf). Thus an early

Table 1. Air temperature and precipitation during the summer (May–September), and mass-balance and terminus variation for Zhadang glacier during 2006–08

	2006	2007	2008
Air temperature (°C)*	1.00	0.97	0.35
Precipitation (mm)	–	417.7	475.2
Mass balance (mm w.e.)[†]	–1099	–783	223
Terminus variation (m)[†]	–	–12.0	–5.9

*Average data from two AWSs.

[†] Data represent a mass-balance year (e.g. value in 2006 covers the year 2005/06).

–, not measured.

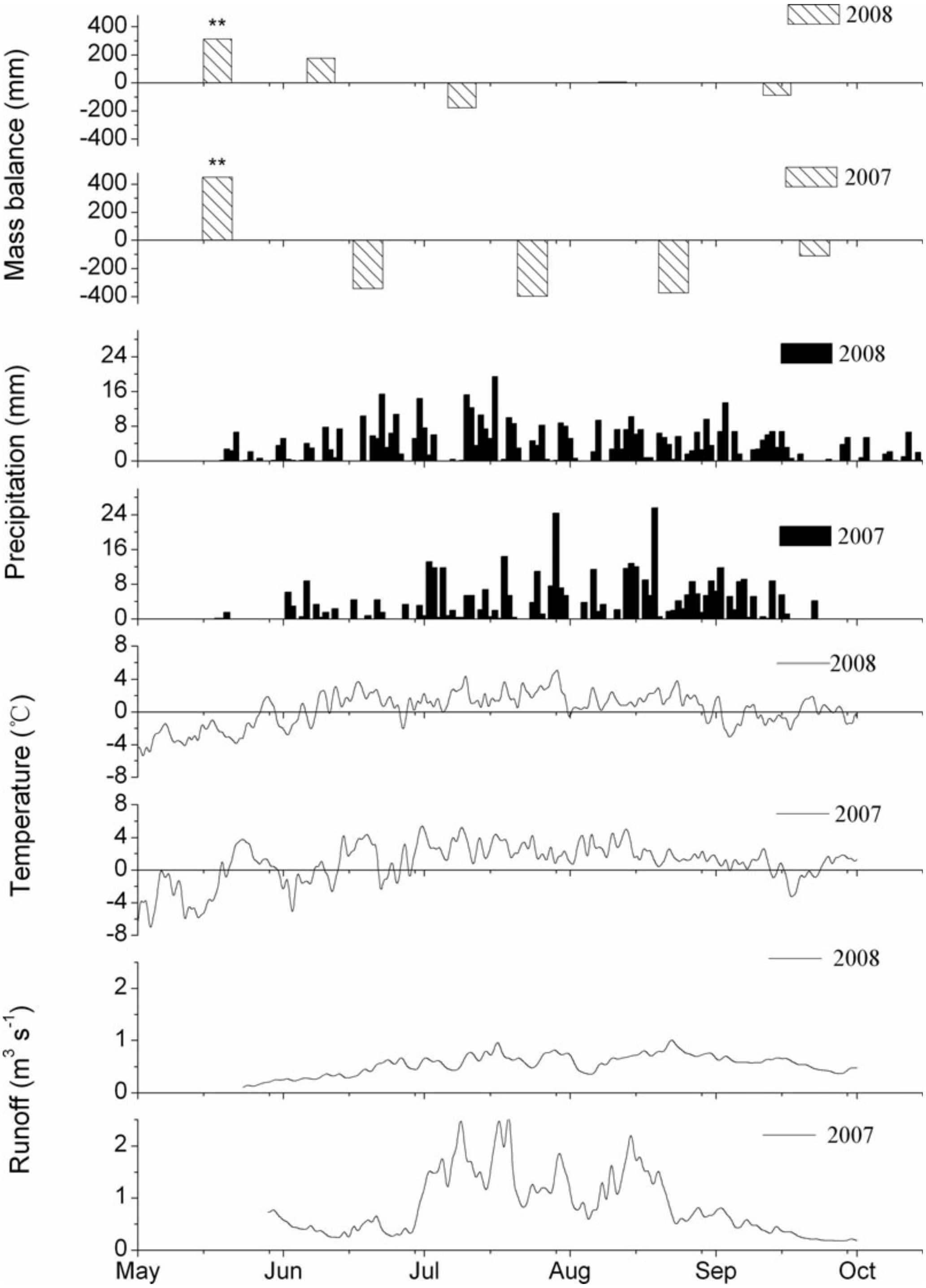

Fig. 1. Comparisons of daily air temperature, precipitation, runoff and monthly mass balance at Zhadang glacier between 2007 and 2008. ** represents winter mass balance (October–May).

Table 2. Comparisons of observed monthly data between 2007 and 2008

	May		June		July		August		September	
	2007	2008	2007	2008	2007	2008	2007	2008	2007	2008
Air temperature (°C)	–1.34	–2.35	0.73	0.87	2.70	2.21	2.29	1.36	0.42	–0.36
Cumulative temperature above 0°C (°C)*	21.66	3.95	41.17	36.99	83.82	68.63	71.05	43.44	22.88	10.31
Precipitation (mm)	13.1†	33.0†	44.2	110.0	145.0	145.0	145.8	110.6	69.6	76.6
Mass balance (mm)	449‡	312‡	–346	174	–399	–178	–375	5	–112	–90
Total runoff (10^6 m^3)	–	–	1.11	1.04	4.13	1.76	2.86	1.82	0.94	1.41

*Value calculated by adding all daily air temperatures above 0°C. †Data represent winter mass balance (October–May). ‡Data from NAMOR. –, not measured.

rainy season in the Nyainqêntanglha region is consistent with early onset of the Indian monsoon and its rapid progress over South Asia.

We suggest that this early rainy season also caused the lower temperatures observed in 2008 compared with 2007. As shown in Figure 2, the higher precipitation in October and November of 2006 than in 2007 coincided with lower October–February temperatures; while the much lower precipitation in May–July of 2007 than in 2008 coincided with a period of higher temperatures in 2007 than in 2008. This suggests that precipitation, which occurs as snowfall over the glacier as observed in the field, can strongly influence regional temperature. Given that snow has much higher albedo than soil or grassland, we suggest that more snowfall contributes to lower temperatures. In summary, the early rainy season in 2008 contributed to low summer temperature, causing reduced loss of glacier ice and a surplus mass balance in 2008. The early rainy season suppressed summer glacier melt.

Changes in runoff observed close to the glacier terminus provide evidence of weak glacier melt during summer 2008 (Fig. 1). In 2007, elevated runoff occurred in July and August (Fig. 1), and monthly total runoff during these two months was more than double that in the other months (Table 2). This suggests the typical glacier melt-flow behavior that high runoff occurs during the glacier melt season (Fujita and others, 2007; Gao and others, in press). In contrast to 2007, runoff was relatively constant (Fig. 1), and monthly total values were similar (Table 2) from May to September 2008, reflecting weak glacier melt and a low contribution to river flow.

Given the relatively short and limited data series available from Zhadang glacier, we cannot fully quantify the effect of temperature and precipitation on glacier mass balance. The model calculations by Fujita and Ageta (2000) demonstrate that glaciers (e.g Xiao Dongkemadi glacier on the central Tibetan Plateau) can maintain their mass since the monsoon provides precipitation (mostly snowfall) during the melt season, keeping surface albedo high and largely restraining ablation. The calculations also show that glaciers on the plateau are more vulnerable than those of other regions because of summer accumulation (Fujita and Ageta, 2000). A more detailed quantitative evaluation of Dongkemadi glacier reveals that a change in air temperature will cause not only an increase in melt by sensible heat, but also a drastic increase in melt due to lowering of the albedo, since some of the snowfall changes to rainfall. Meanwhile, a significant amount of precipitation as snow in summer presents excessive melting and a loss of glacier mass due to high albedo on the glacier surface (Fujita and Ageta, 2000; Fujita and others, 2007). Therefore, both lower temperature and increased precipitation in summer 2008 contributed to the surplus mass balance at Zhadang glacier. Our observed results support these quantitative evaluations.

On the global scale, numerical calculations with a warming test also show higher sensitivities for glaciers located within a summer accumulation pattern than for those within a winter accumulation pattern (Fujita, 2008a,b). These studies show the importance of precipitation seasonality on the climatic sensitivity of glacier mass balance, which in previous studies has been linked only with annual precipitation. In the Dongkemadi glacier basin, by changing the dates given for a meteorological perturbation for a period of only 5 days, a seasonal sensitivity test of glacier runoff shows that an increase in precipitation will cause a decrease in glacier runoff through a year (Fujita and others, 2007). Precipitation in the early melt season (May–June) is most effective in decreasing glacier runoff since a high-albedo snow cover will effectively prevent surface melting. These findings imply that glacier surface conditions altered by a perturbation of only 5 days will greatly affect the heat/mass balance of the glacier and glacier runoff for the next melt period, though such a perturbation only slightly altered the annual averages (Fujita and others, 2007). Our observations confirm these simulation results for the global and regional scales which indicate the parameterization of mass balance with annual precipitation amount is insufficient to describe the response of glaciers to climate change. We suggest that the onset of the rainy season should be considered when applying glacier change studies to issues such as global warming, especially in monsoon regions with summer-precipitation climate.

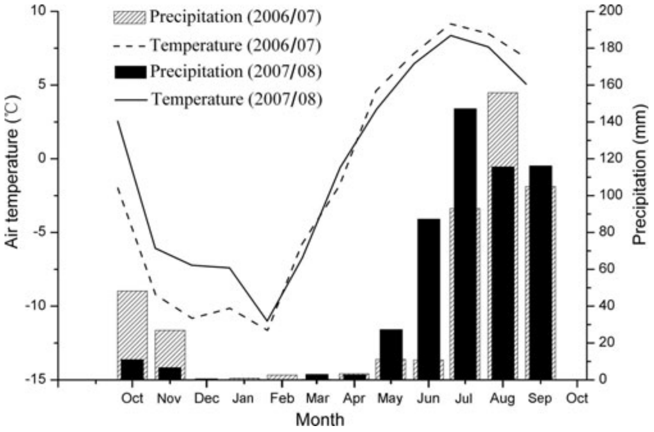

Fig. 2. Comparisons of monthly air temperature and precipitation at NAMOR between 2006/07 and 2007/08.

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