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 mainly 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 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 stream, 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

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

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)*</td>
<td>1.00</td>
<td>0.97</td>
<td>0.35</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>–</td>
<td>417.7</td>
<td>475.2</td>
</tr>
<tr>
<td>Mass balance (mm w.e.)</td>
<td>−1099</td>
<td>−783</td>
<td>223</td>
</tr>
<tr>
<td>Terminus variation (m)</td>
<td>–</td>
<td>−12.0</td>
<td>−5.9</td>
</tr>
</tbody>
</table>

*Average data from two AWSs.
†Data represent a mass-balance year (e.g. value in 2006 covers the year 2005/06).
–, not measured.
Table 2. Comparisons of observed monthly data between 2007 and 2008

<table>
<thead>
<tr>
<th></th>
<th>May</th>
<th>June</th>
<th>July</th>
<th>August</th>
<th>September</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature (°C)</td>
<td>-1.34</td>
<td>-2.35</td>
<td>0.73</td>
<td>0.87</td>
<td>2.70</td>
</tr>
<tr>
<td>Cumulative temperature above 0°C (°C)*</td>
<td>21.66</td>
<td>3.95</td>
<td>41.17</td>
<td>36.99</td>
<td>83.82</td>
</tr>
<tr>
<td>Precipitation (mm)</td>
<td>449†</td>
<td>312‡</td>
<td>-346</td>
<td>174</td>
<td>-399</td>
</tr>
<tr>
<td>Mass balance (mm)</td>
<td>-4.13</td>
<td>1.04</td>
<td>1.11</td>
<td>1.76</td>
<td>-112</td>
</tr>
<tr>
<td>Total runoff (10^6 m³)</td>
<td>--</td>
<td>--</td>
<td>1.11</td>
<td>1.04</td>
<td>4.13</td>
</tr>
</tbody>
</table>

*Value calculated by adding all daily air temperatures above 0°C. †Data represent winter mass balance (October–May). ‡Data from NAMOR. –, 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).
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 perturb-

![Fig. 2. Comparisons of monthly air temperature and precipitation at NAMOR between 2006/07 and 2007/08.](image)

ACKNOWLEDGEMENTS

This study was supported by the National Basic Research Program of China (2005CB422004), the Chinese Academy of Sciences (KZCX2-YW-145), the Ministry of Sciences and Technology (2006FY110200) and Sixth Framework Programme Priority (036952). We acknowledge the staff at NAMOR for help in the field.

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6 May 2009
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