

Glacier shrinkages and climate conditions around Jichu Dramo Glacier in the Bhutan Himalayas from 1998 to 2003

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Abstract

Variations of Jichu Dramo Glacier and some other debris-free glaciers as well as the surrounding climate were observed through Japan-Bhutan joint field activities in the autumns of 1998, 1999, and 2003. The annual precipitation around the Jichu Dramo Glacier was estimated to be greater than 1500 mm, based on the record over 340 days in 1998–1999. The surface level of the glacier, which is located in an area strongly influenced by the summer monsoon, was estimated to be rapidly lowering at an approximate rate of 2–3 m a⁻¹ in 1998–2003. This estimate is the first example of surface lowering rates for glaciers in the Bhutan Himalayas. Further, its terminal retreat rate was estimated to be approximately 8 m a⁻¹ in 1998–2003. The terminal retreats of some other debris-free glaciers around Jichu Dramo since the mid-1980s have also been confirmed by comparing them with photos taken previously. Further monitoring of the remarkable glacier shrinkage in Bhutan is essential to assess the general trend of glacier shrinkage in the entire Himalayas.

1. Introduction

The variations of mountain glaciers worldwide have recently attracted considerable attention due to their significance in the rising sea levels. Summer-accumulation type glaciers in the Asian highland regions including the Himalayas are considered to be particularly vulnerable to global warming (Ageta, 1983; Fujita and Ageta, 2000; Naito *et al.*, 2001). This is because snowfall during summer can easily transform into rainfall, and the decrease in fresh snow can reduce the surface albedo of glacier, which would lead to lesser accumulation and greater ablation on the glaciers. In reality, relatively rapid glacier shrinkages have been reported in the Nepal Himalayas (e.g., Fujita *et al.*, 1997; Naito *et al.*, 2002). On the other hand, Bhutan, which is located near the eastern edge of the Himalayan range, receives heavier precipitation than Nepal (Eguchi, 1994) due to a stronger influence of the Asian summer monsoon. The glaciated area in the Bhutan Himalayas is spread over an area of 1,317 km² (Mool *et al.*, 2001). Karma *et al.* (2003) reported that the recent retreat rates of glacier termini in Bhutan are

almost twice larger than those of glacier termini in east Nepal obtained by Asahi (1999); further, they suggested that these rates may have resulted due to the stronger influence of the summer monsoon in Bhutan. However, thus far, no practical information has been reported with regard to the volumetric glacier shrinkage in Bhutan, because its evaluation requires the knowledge of the magnitude of not only the retreating area but also lowering surface level. The present paper reports the observational results on the surface lowering of a debris-free glacier, terminal retreats of some debris-free glaciers in the Bhutan Himalayas, as well as surrounding local climate.

In addition to the global issue of sea level rise, Glacier Lake Outburst Flood (GLOF) is another crucial problem faced by regional countries and people in the Himalayas (Yamada, 1998; Ageta *et al.*, 2000). Potentially dangerous glacier lakes usually grow on the terminal part of debris-covered glaciers, while the glaciers themselves shrink and moraines dam up the melt water. In order to assess the GLOF risk in Bhutan, Japan-Bhutan joint research was initiated in 1998 (Ageta and Iwata, 1999). Its primary targets have been glacier lakes and their corresponding debris-covered

glaciers; however, debris-free glaciers have also been a topic of research interests because in comparison to debris-covered glaciers, their variations could more simply be related to the local climate. In other words, the clarification of the relation between the local climate and the variations of debris-free glaciers could partly contribute to the studies on the growth of glacier lakes in the region. The present paper is based on the three field activities of the Japan-Bhutan joint research in the autumns of 1998, 1999, and 2003.

2. Study area and observation methods

The study area in the present paper is a high plateau with an altitude of over 5000 m located around the southeastern periphery of the so-called "Lunana" region in the northern part of Bhutan (Fig. 1). Many debris-free glaciers exist on this plateau. The main target of this study is a debris-free glacier located southward of the Jichu Dramo camping site, which is marked "G1" in Fig. 1. In the glacier inventory compiled by Mool *et al.* (2001), this glacier is represented by the code name "Pho_gr 131," and its total area, based on satellite images captured in the 1990s, is estimated to be 3.2 km². In the present paper, this glacier is termed the Jichu Dramo Glacier based on hearing from native villagers. The terminal positions and surface topography of the lower part of the glacier were repeatedly surveyed on Oct. 11, 1998; Oct. 17, 1999; and Oct. 14, 2003, using a digital theodolite and a laser distance meter ("SOKKIA SET 2000 series"). In addition, terrestrial photogrammetry was attempted on Oct. 11, 1998 for the lower part of the glacier.

The topographical survey of glacier extent was also executed for a small glacier near Jaze La, which is marked "G2" in Fig. 1, on Oct. 2, 1999 using the "SOKKIA SET 2000 series" for future evaluation of its variation. (This glacier "G2" was approached not from Jaze La but from the eastern valley.) Moreover, simpler observations of terminal fluctuations in comparison with photos taken previously were also carried out for some other debris-free glaciers on the plateau; distinct examples are marked as "G3"–"G5" in Fig. 1. The compared photos were taken in 1983–1984 by Mr. Toshihiro Tsukihara, who belonged to the Kyoto University Bhutan Expedition team. In the inventory compiled by Mool *et al.* (2001), glaciers "G3" and "G4" are denoted by the code names "Pho_gr 129" and "Mangd_gr 6," respectively; their total areas are evaluated to be 5.1 and 0.5 km², respectively. On the other hand, "G2" and "G5" may be recognized as parts of neighboring glaciers, and neither has been described in the inventory compiled by Mool *et al.* (2001).

Air temperature was measured automatically by using the "Optic StowAway" in a single solar shield with a time interval of one and half hours at three sites in the Lunana region from the autumn of 1998 to

that of 1999. One site was a flat site located in the lateral moraine near the left-bank periphery of the middle stream part of the Jichu Dramo Glacier ("Upper JD"). The second site was downstream of the glacier terminus ("Terminal JD"), as shown in Fig. 1, and the third site was in Thanza village, which is located at a distance of approximately 20 km in the direction of NNW from the Jichu Dramo Glacier. Hourly precipitation and the maximum snow depth were measured only at the "Upper JD" site. The precipitation measurement was performed using a tipping-bucket rain gauge and "HOBO Event" logger, and the maximum snow depth was recorded by soft metallic sticks attached horizontally with a vertical spacing of 5 cm to a vinyl chloride pole. The recording period of 340 days for the hourly precipitation was slightly shorter than an entire year because the recording was abruptly terminated possibly due to a battery problem.

The altitudes discussed in the present paper were originally measured using a "Thommen baro altimeter" during the field trips. On the other hand, standard altitudes were adopted at sites where they could be read on 1:50,000 toposheets published by the Survey of India. The original altitudes at all the field sites were then corrected with respect to relative altitudes measured by the baro altimeter at the nearby standard sites. For example, the standard altitude of Thanza is 4160 m and the altitudes of "Upper JD" and "Terminal JD" are corrected to be 5245 and 5115 m, respectively, with respect to the standard Thanza altitude. The accuracy of these corrected altitudes is not very good; it shows an approximate deviation of a few tens of meters.

Iwata *et al.* (2003) suggested that the lower limit of the permafrost in the Bhutan Himalayas was located at 4800–5000 m a.s.l., based on the distribution of active rock glaciers. On the other hand, Fujii and Higuchi (1976) explained that the altitudinal lapse rate in the ground temperature at a depth of 50 cm, where its diurnal variation can be considered to be negligible, should become considerably greater than that in air temperature above the lower limit of the mountain permafrost zone, based on observations in the Nepal Himalayas. In the present study, we attempted a similar observation to detect the lower limit of the mountain permafrost zone in the Lunana region from the view-point of the ground temperature. The ground temperature at a depth of 50 cm was measured manually at a total of 102 sites with various altitudes along the Snowman Trekking route, a part of which is indicated by the dotted line in Fig. 1. It was measured using a digital thermistor thermometer during the trekking periods in the autumns of 1998 and 1999. Several minutes were allowed to pass for the thermistor to acclimatize after its insertion into the ground. The manually-measured ground temperature was



Fig. 1. Location of the study area. The lower figure is a distribution map depicting glaciers and glacier lakes in the area revised from that provided by Ageta and Iwata (1999) by using a SPOT satellite image taken on Dec. 11, 1993 and the 1: 50,000 scale toposheets published by the Survey of India. "G1" indicates the Jichu Dramo Glacier and "G2"–"G5" indicate the other glaciers described in this paper. "U" and "T" indicate locations of the "Upper JD" and "Terminal JD" sites, respectively. The dotted line indicates the trekking route.

Table 1. Summary of the main results of the meteorological measurements in 1998–1999.

Location		Thanza	Terminal JD	Upper JD		
Altitude		4160 m	5115 m	5245 m		
Meteorol. element		Air Temperature	Air Temperature	Air Temperature	Precipitation	Max. Snow Depth
Data logger		Optic StowAway	Optic StowAway	Optic StowAway	HOBO Event	(handmade)
Starting date and time		Oct. 2, 1998 13 : 30	Oct. 11, 1998 15 : 00	Oct. 12, 1998 12 : 00	Oct. 12, 1998 12 : 00	Oct. 12, 1998
Ending date and time		Sep. 28, 1999 10 : 30	Oct. 6, 1999 15 : 00	Oct. 8, 1999 10 : 30	Sep. 17, 1999 14 : 00	Oct. 8, 1999
Results	Mean Temp.	3.9°C	-2.9°C	-2.5°C	Total amount: 1349 mm	550–600 mm
	Max.Temp.	24.3°C	19.1°C	21.1°C		
	Min. Temp.	-15.4°C	-25.0°C	-24.2°C		

subtracted with the temperature recorded simultaneously at the meteorological station (2380 m.a.s.l.) in Thimphu, the capital of Bhutan, to cancel its seasonal variation.

3. Results and discussion

3.1. Air temperature and precipitation in 1998–1999

The main results recorded at the three sites in 1998–1999 are summarized in Table 1. The nearly annual precipitation in this area is 1349 mm at the “Upper JD” site during the 340 days. The total annual precipitation around the Jichu Dramo Glacier should be considered to be greater than 1500 mm because of the following two reasons: 1) the recording period did not consider late September and early October, when monsoon precipitation was still expected in the Bhutan Himalayas, and 2) some amount of solid precipitation could not be captured by the rain gauge. By ignoring these problems, a simple comparison shows that the annual precipitation at the Jichu Dramo Glacier was more than one and a half times greater than that at Shangboche AWS in the Khumbu region, east Nepal, which was reported to have received a precipitation of 907 mm from October 1998 to September 1999 (Ueno *et al.*, 2001). Figure 2 shows the temporal variations in daily precipitation recorded at “Upper JD” and air temperatures at the three sites. The daily mean air temperature is generally below 0°C from October to April at “Upper JD.” Almost all the precipitation during the season was recorded in daytime when the air temperature was above 0°C. During winter, the recorded precipitation may be due to the water from the melting of the snow packed on the rain gauge; in such a case, the recording time would be of no significance. This fact partly supports the reason 2) mentioned above and the possibility of an annual precipitation greater than 1500 mm at the site. On the other hand, heavy precipitation was concentrated in the summer monsoon season from late May to September. This implies that glaciers in this region are

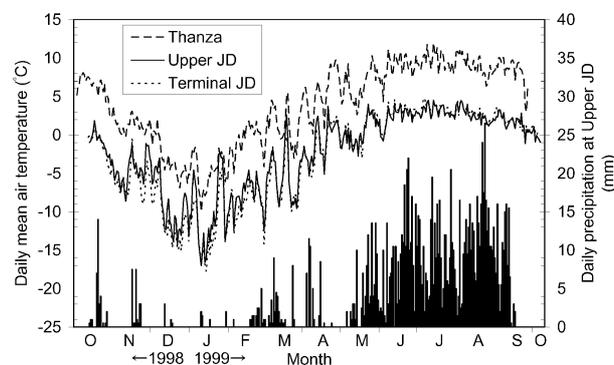


Fig. 2. Temporal variations in daily precipitation at “Upper JD” (bar for right axis) and daily mean air temperature at the three sites.

strongly characterized by summer-accumulation.

In Fig. 2, the air temperature at “Terminal JD” appears to be lower than that at “Upper JD” in winter, despite the altitude of the former being lower by 130 m. This apparent inverse relation of the air temperature in the two sites is clearly shown in Fig. 3, where two types of altitudinal lapse rates in air temperature are also displayed. It is implied in Fig. 3 that the air temperature at “Terminal JD” drops severely in winter, and then, the lapse rate between “Terminal JD” and Thanza becomes significantly high. This was probably because cold air mass moved down the glacier surface and reached the “Terminal JD” site, i.e., the effect of katabatic winds was enhanced in winter. Thus, the temperature recorded at “Terminal JD” in winter could not be considered to be representative of the air temperature at its altitude. On the other hand, “Upper JD” was located laterally outside the glacier; therefore, the katabatic winds could hardly affect its air temperature. The annual average altitudinal lapse rate in air temperature between “Upper JD” and Thanza is $5.9^{\circ}\text{C km}^{-1}$. Incidentally, the lapse rate of $6.5^{\circ}\text{C km}^{-1}$ between “Terminal JD” and Thanza is averaged only in the summer from May to September. Even if an error in the altitude is considered, its effect on the

lapse rate would be less than 5%. Therefore, the latter lapse rate in the summer may be slightly influenced by the katabatic winds at "Terminal JD." Finally, it is concluded that the lapse rate in this region is approximately $6^{\circ}\text{C km}^{-1}$.

3.2. *Altitudinal distribution of ground temperature*

Around one-third of the 102 sites where the ground temperature was measured in the Lunana region were located on relatively steep slopes. Therefore, only the data measured at 67 flat sites have been analyzed in order to dampen the effects of differential solar radiation. Consequently, the differences in the ground temperature at a depth of 50 cm between Lunana region and Thimphu are plotted against the altitude in Lunana in Fig. 4. The altitudinal lapse rate in the ground temperature shown in Fig. 4 appears similar to that in air temperature. It is difficult to recognize a clear change in the lapse rate of the ground temperature above a certain altitude, such as described by Fujii and Higuchi (1976). Unfortunately, the present data should be concluded insufficient for detecting the lower limit of the mountain permafrost zone.

3.3. *Variation of Jichu Dramo Glacier*

The Jichu Dramo Glacier was selected in 1998 as a target for monitoring the variation of debris-free glaciers. Its surface topography is fairly wavy in its lower part, as seen in Fig. 5. Figure 6 is a map of the Jichu Dramo Glacier obtained from terrestrial photogrammetry performed in 1998. Based on repeated topographical surveys conducted in 1998, 1999, and 2003, the locations of the glacier terminus and some surface bumps on the lower part of the glacier are depicted in Fig. 7. At first, the retreat of the glacier terminus is clearly identifiable. By dividing the area between the surveyed termini by the surveyed glacier width, the average terminal retreat rates are evaluated to be approximately 11 and 7 m a^{-1} in 1998–1999 and 1999–2003, respectively. Then, the average retreat rate during the period 1998–2003 is 8 m a^{-1} .

Among the surface bumps surveyed, a total of 12 bumps were surveyed more than twice. These are indicated in Fig. 7 as solid symbols with tentative names. From their horizontal displacements, their horizontal velocities were calculated, as listed in Table 2. Generally, the horizontal speed decreases upstream to downstream, as usually seen in the ablation area of a

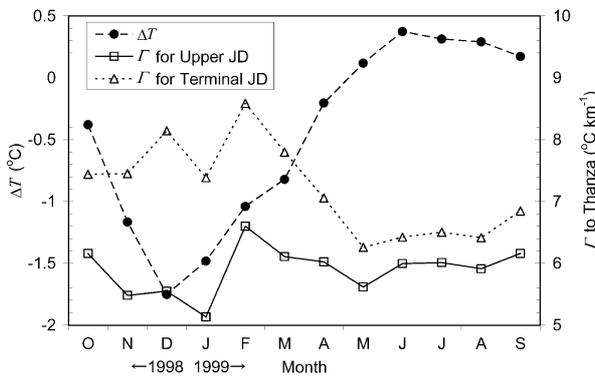


Fig. 3. Seasonal variations in monthly averaged air temperature difference at "Terminal JD" to "Upper JD," ΔT ; and altitudinal lapse rates in air temperature, Γ , for the two sites with respect to Thanza (on right axis).

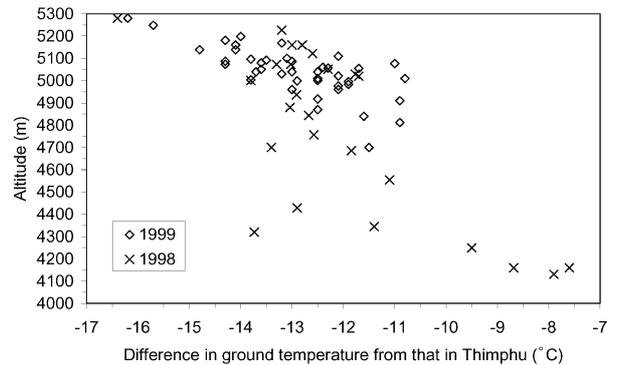


Fig. 4. Altitudinal distribution of ground temperature at 50 cm depth in Lunana region. The ground temperature is subtracted with that at Thimphu to cancel its seasonal variation.



Fig. 5. Photo of the lower part of the Jichu Dramo Glacier taken near the "Upper JD" site in the left-bank lateral moraine on Oct. 11, 1998. The main stream of the glacier runs from right to left in this photo.

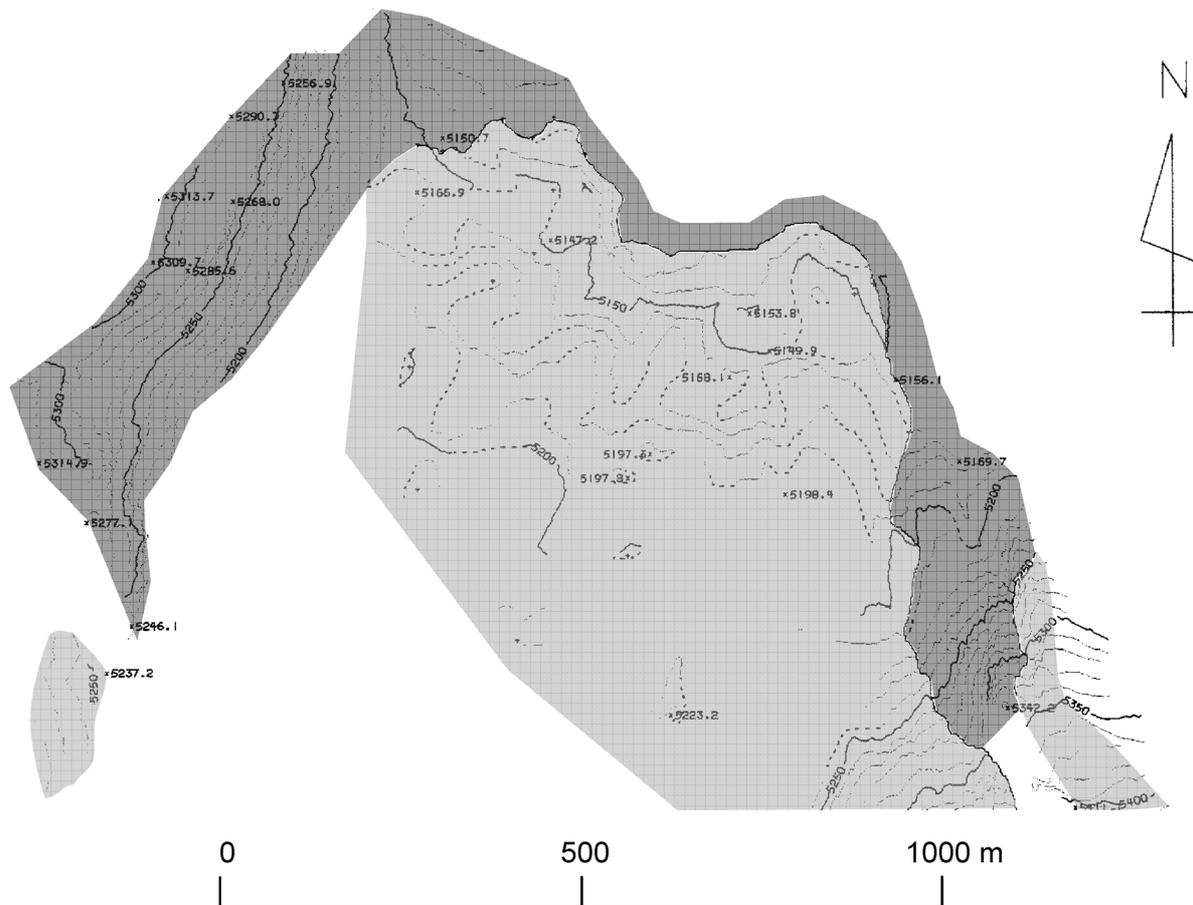


Fig. 6. Map of the lower part of the Jichu Dramo Glacier compiled from terrestrial photogrammetry performed on Oct. 11, 1998. Light and dark shaded parts are glaciated and non-glaciated (bedrock and moraines) areas, respectively. The blank part is invisible from the benchmarks.

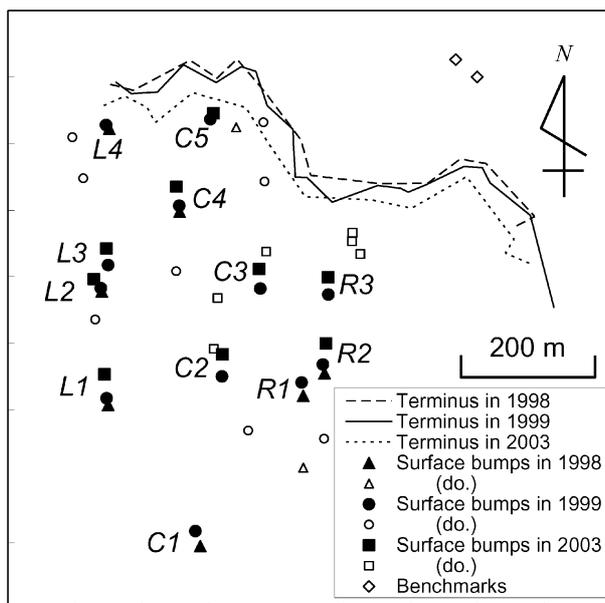


Fig. 7. Horizontal location of the terminus and surface bumps of the Jichu Dramo Glacier surveyed on Oct. 11, 1998; Oct. 17, 1999; and Oct. 14, 2003. Solid symbols indicate the surface bumps surveyed more than twice, the names of which are same as those in Table 2. Geographical coordinates of the two benchmarks were measured with GPS as $(27^{\circ}55'6.9''N, 90^{\circ}14'48.7''E)$ and $(27^{\circ}55'8.0''N, 90^{\circ}14'47.6''E)$, according to personal communication from Dr. Koji Fujita who visited the site in 2004.

glacier. The horizontal direction of the velocity distributes from NW to NNE, that is, it has an average northward direction. The surveyed altitudes of the 12 bumps are then projected on the northward distance

relative to bump "C1" in 1998, as shown in Fig. 8. Two pairs of regression lines in Fig. 8 are obtained for the same bumps. Both the pairs indicate that the average surface level of the bumps has lowered. The lowering

surface levels in 1998–1999 and 1999–2003 are obtained as 2.3–3.9 and 7.4–12.2 m, respectively. Their average surface lowering rates in 1998–1999 and 1999–2003 are 3.2 and 2.4 m a⁻¹, respectively. Therefore, by assuming no change in the surface undulation, the surface lowering rate in the lower part of the Jichu Dramo Glacier can be estimated as approximately 2–3 m a⁻¹.

Table 2. Horizontal velocities of resurveyed surface bumps on the Jichu Dramo Glacier. The names of bumps are same to those displayed in Fig. 7. The velocity is expressed as horizontal speed *U* and azimuth from the north *HA*.

Name of bump	In 1998–1999		In 1999–2003	
	<i>U</i>	<i>HA</i>	<i>U</i>	<i>HA</i>
	(m a ⁻¹)	(deg.)	(m a ⁻¹)	(deg.)
C1	24.0	342.5	<i>(no survey in 2003)</i>	
C2	<i>(no survey in 1998)</i>		8.3	0.5
C3	<i>(no survey in 1998)</i>		7.3	356.6
C4	9.1	355.8	7.2	351.5
C5	<i>(no survey in 1998)</i>		2.5	27.0
R1	20.5	353.2	<i>(no survey in 2003)</i>	
R2	13.9	350.8	7.9	7.5
R3	<i>(no survey in 1998)</i>		6.5	359.4
L1	10.6	348.5	9.0	355.0
L2	5.2	346.9	4.2	321.5
L3	<i>(no survey in 1998)</i>		6.2	353.9
L4	7.5	321.3	<i>(no survey in 2003)</i>	

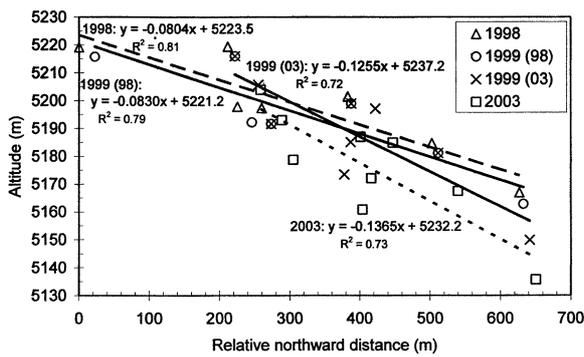


Fig. 8. Vertical profile of the resurveyed 12 bumps along the northward direction. The bumps in 1999 are indicated in two categories; “1999 (98)” for 7 bumps which were surveyed both in 1998 and 1999, and “1999 (03)” for 9 bumps which were done both in 1999 and 2003. (The 4 bumps that were surveyed for all three times belong to both the categories.) Two solid regression lines are obtained for each categorized bumps in 1999. The dashed and dotted regression lines are obtained for the bumps in 1998 and 2003, respectively.

This estimate is the first example of surface lowering rates for glaciers in the Bhutan Himalayas. Naito *et al.* (2002) tabulated the average surface lowering rates of entire areas of three debris-free glaciers (Fujita *et al.*, 1997, 1998, 2001) and the ablation areas of two debris-covered glaciers (Kadota *et al.*, 2002; Naito *et al.*, 2002) observed in the Nepal Himalayas; their rates ranged up to approximately 2 m a⁻¹. The present estimate of 2–3 m a⁻¹ for the surface lowering rate in the lower part of the Jichu Dramo Glacier is, in a simple comparison, greater than the rates observed in Nepal. However, the difference in the estimated area of each glacier complicates this simple comparison. Nevertheless, the fairly rapid glacier shrinkage might be due to the stronger influence of the summer monsoon in the Bhutan Himalayas because the strongly characterized summer-accumulation type glaciers would be considerably vulnerable to global warming. Further studies on glacier shrinkage in the Bhutan Himalayas are strongly desired to confirm its general trend.

3.4. Variations of the nearby debris-free glaciers

The map in Fig. 9 shows surface topography and extent of a small debris-free glacier near Jaze La (“G2” in Fig. 1) surveyed in 1999. This map will be useful for future evaluations of the glacier variation.

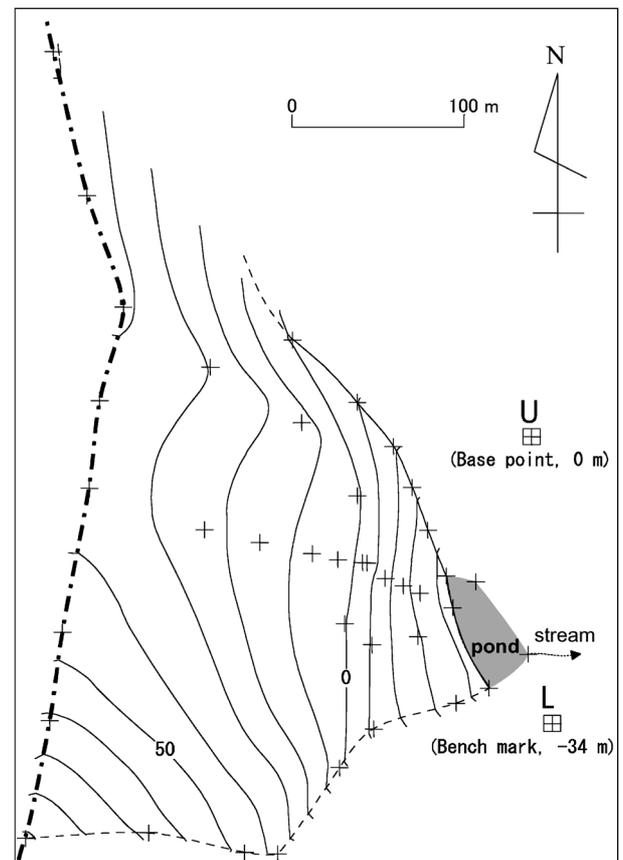


Fig. 9. Map of a small glacier near Jaze La (“G2” in Fig. 1) surveyed on Oct. 2, 1999.

Photographs of many other debris-free glaciers in the study area were taken during the trekking periods, particularly of those glaciers that were previously photographed in 1983 and 1984. Figures 10–12 are three photo sets of glaciers; these figures distinctly show their variations. The terminus of a glacier northward of Gangrinchemzoe La (Fig. 10 and “G3” in Fig. 1) retreated remarkably and a proglacial lake was formed during the period 1984–1998. Manual projection of the terminal locations on the 1:50,000 topographic map published by the Survey of India revealed an approximate retreating distance of 300–400 m in the 14 years. The average retreat rate of $20\text{--}30\text{ m a}^{-1}$ is significantly greater than those observed in the Nepal Himalayas, which were tabulated by Naito (2001); this is probably because this rapid retreat has been enhanced by calving into the proglacial lake. This glacier has continued to retreat at a relatively moderate

rate after 1998. Apparent terminal retreats were also found for the glaciers southwestward of Gangrinchemzoe La (Fig. 11 and “G4” in Fig. 1) and northwestward of Gopu La (Fig. 12 and “G5” in Fig. 1). In the future, the execution of terrestrial photogrammetry for such inaccessible glaciers is desired in order to accumulate quantitative information on glacier variation.

4. Concluding remarks

The present paper partly supports the idea that the glaciers in the Bhutan Himalayas are located in an area that is strongly influenced by the summer monsoon, and they are considerably vulnerable to global warming. The annual precipitation around the Jichu Dramo Glacier was estimated to be greater than 1500 mm, based on the record over 340 days in 1998–1999.

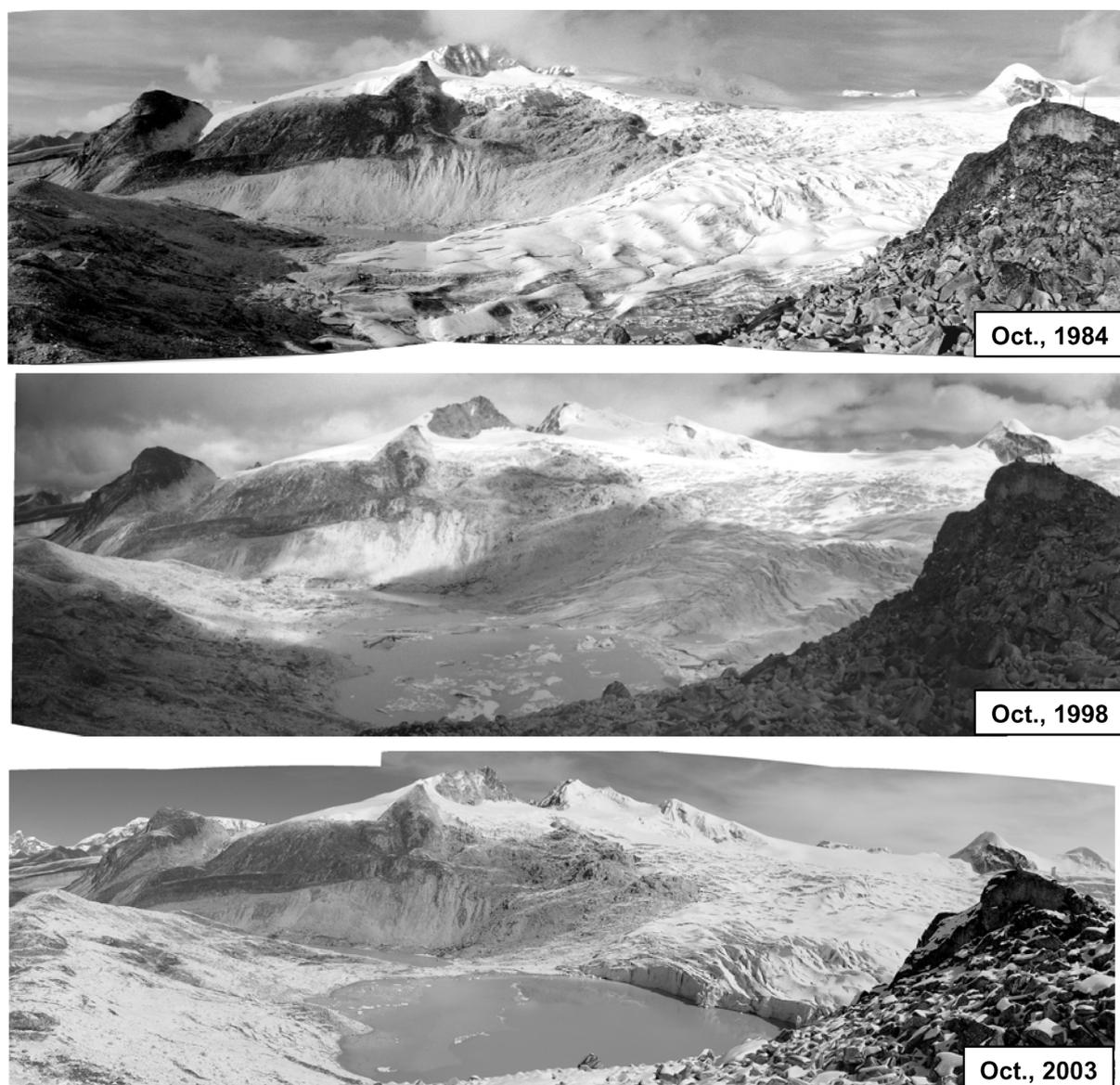


Fig. 10. Photos of the glacier “G3” in Fig. 1 taken at Gangrinchemzoe La on Oct. 2, 1984 (top; provided by Mr. Toshihiro Tsukihara); Oct. 13, 1998 (middle); and Oct. 15, 2003 (bottom).

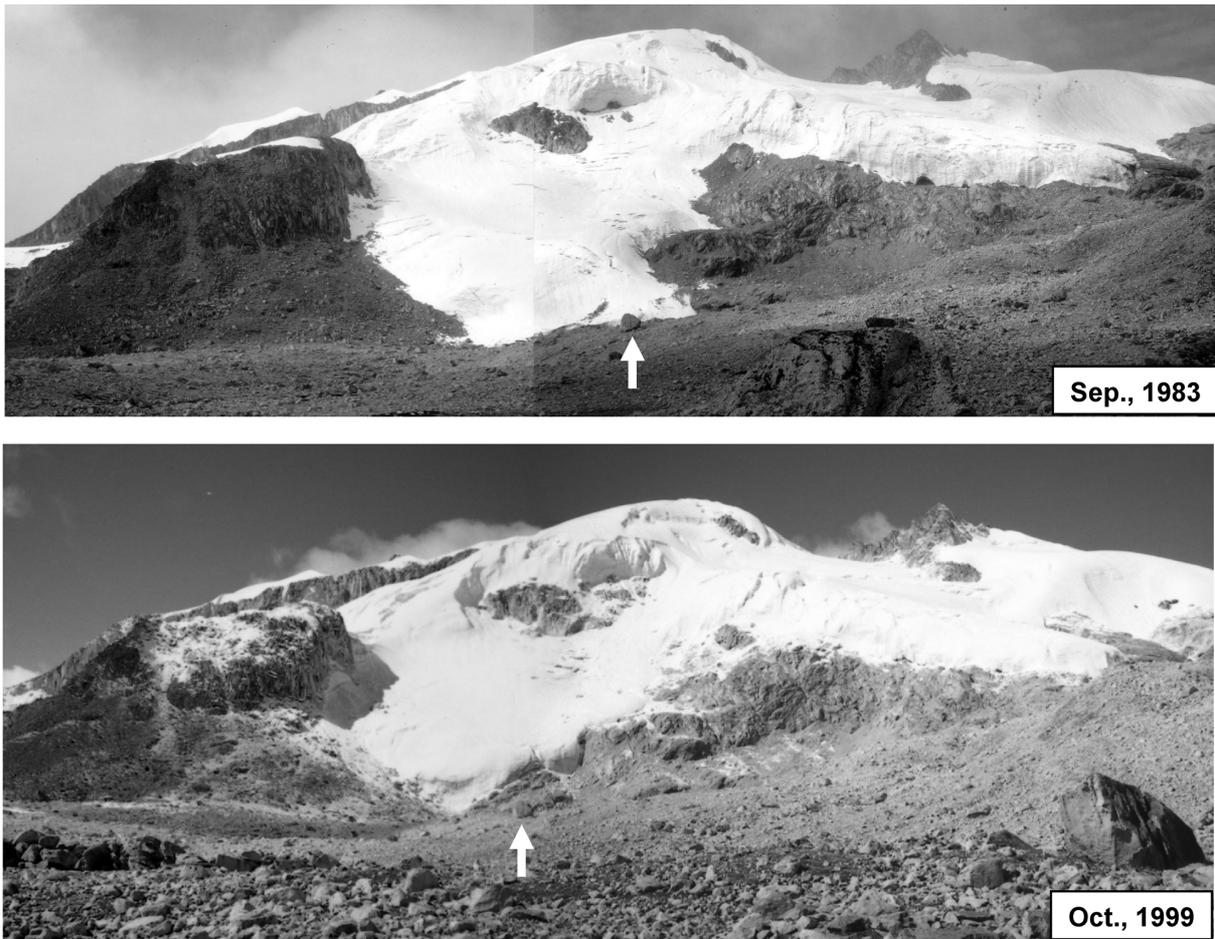


Fig. 11. Photos of the glacier “G4” in Fig. 1 taken on Sep. 25, 1983 (upper; provided by Mr. Toshihiro Tsukihara) and Oct. 9, 1999 (lower). The arrow indicates the same rock in each photo.

Surface lowering rate of approximately $2\text{--}3\text{ m a}^{-1}$ for the Jichu Dramo Glacier during 1998–2003 is the first attempted estimate for glaciers in Bhutan. The terminal retreat rate of the glacier during the same period was calculated as approximately 8 m a^{-1} . Glacier retreats have been also observed on some other debris-free glaciers in adjacent locations since the mid-1980s. On the basis of a simple comparison, these remarkable glacier shrinkages/retreats appear to be quicker than those observed in the Nepal Himalayas. This implies that the extrapolation of the glacier shrinking volume to the general trend in the entire Himalayas based on the limited information obtained in Nepal could be an underestimate. Finally, the information on glacier shrinkage in Bhutan should be concluded as essential for the assessment of the general trend in the Himalayas; therefore, further investigations are strongly desired.

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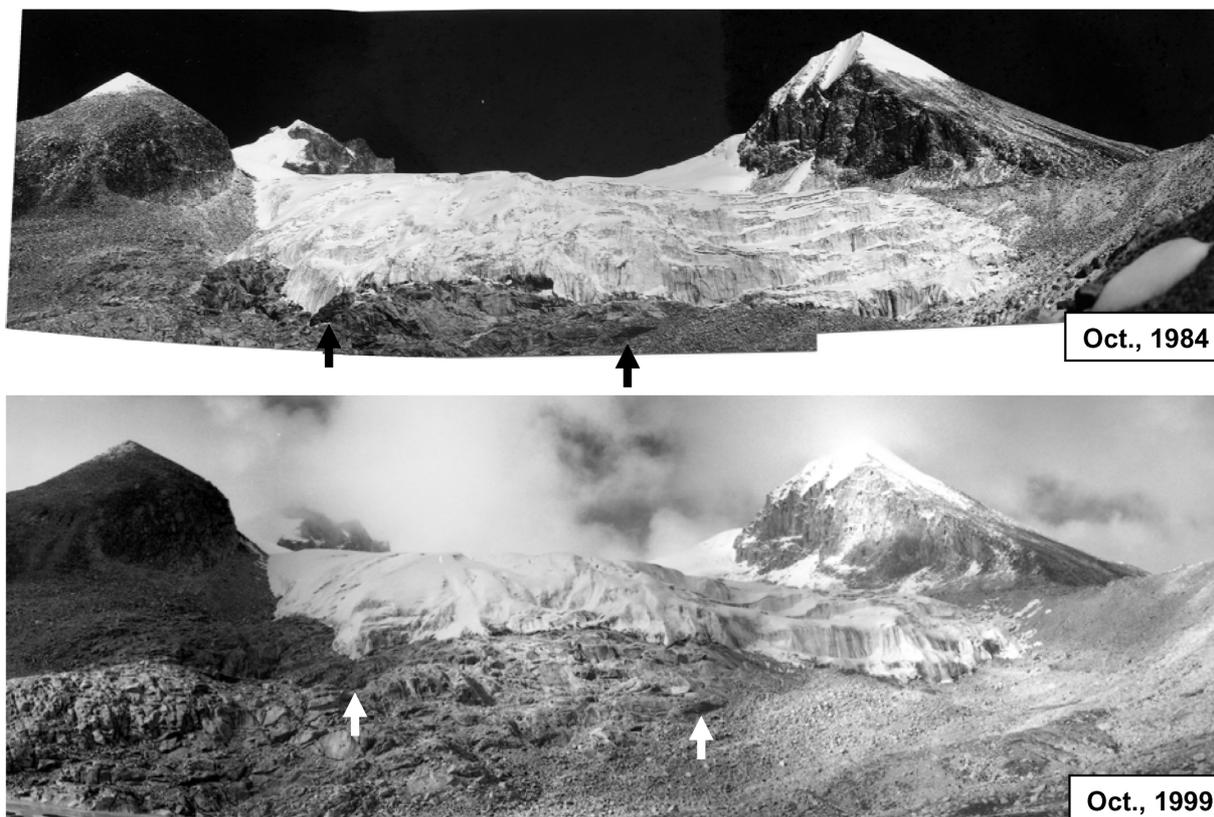


Fig. 12. Photos of the glacier "G5" in Fig. 1 taken on Oct. 17, 1984 (upper: provided by Mr. Toshihiro Tsukihara) and Oct. 3, 1999 (lower). Arrows indicate the same rocks in each photo.

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