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Hot water drilling and glaciological observations at the terminal part of Rhonegletscher, Switzerland in 2007

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Abstract

After the retreat of Rhonegletscher over a bedrock ridge, a proglacial lake has been forming at the glacier forefront since 2005. The lake and the glacier draw glaciological attention because the retreat may be accelerated by calving into the lake. As an initial investigation into studying the impact of the lake formation on the glacier, hot water drilling and preliminary observations were carried out at the terminal part of Rhonegletscher in the summer of 2007. Eight boreholes were drilled down to the bed and accurate ice thickness was determined from the borehole depth. The ice was 135 m thick at a point 700 m from the terminus and it gradually decreased downglacier. This observation revealed that the ice in this region was significantly thinner than previous estimation by an ice-radar survey. The water level in the 135-m borehole showed diurnal variations. The daily minima were steady during the study period at about 10 m higher than the surface elevation of the proglacial lake. After injecting a water jet into the bottom of the borehole, fine sediment was observed in the upwelling water. At some of the other drilling sites, however, scratches on the drilling nozzle suggested that the ice was underlain by solid rock. Thus, it is likely that the glacier bed conditions are inhomogeneous. The rate of change in ice thickness from 2000 to 2007 was determined to be $-2.8\,\mathrm{m\,a^{-1}}$, which indicates that glacier thinning has accelerated in the 21st century.

1. Introduction

Rhonegletscher in the Swiss Alps is one of the most well-documented glaciers in the world. The changes in the terminus position have been recorded in photographs and maps since the 18th century, from which a drastic retreat can be seen over the last 150 years. The changes in glacier length and ice volume from 1874 to 2000 are reported as −1800 m and −0.6 $\mathrm{km^3}$, respectively (Cryospheric Commission of the Swiss Academy of Sciences, 1881–2008; Zhano, 2004; Bauder *et al.,* 2007). Despite the recent warming trend, the retreat rate has decreased in the late 20th century because the glacier retreated over a changing bed slope. The terminus retreated over a steep slope in the 20th century, and then became nearly stagnant on a transverse rock ridge.

Although the changes in glacier length have been well recorded, only a few comprehensive glaciological observations have been carried out in Rhonegletscher. In the late 19th century, Mercanton (1916) conducted various field observations, including mass balance and ice flow speed measurements. Mass balance distribution over the glacier was studied in detail during the period of 1979–1987 (Funk, 1985; Chen and Funk, 1990) and the mass balance was parameterized to the regional climate. A brief summary of the field observations of the past was given by Carlen (2005). These observational data have been used for numerical modelling to reconstruct mass balance history (Huss *et al.,* 2008) and observed changes in the length and surface elevation of the glacier (Stroeven *et al.,* 1989; Wallinga and van de Wal, 1998; Sugiyama *et al.,* 2007).

The ice thickness was measured in detail with an ice radar along 12 profiles across the glacier and a bed rock elevation map was constructed by interpolating the profiles (Zahno, 2004). One of the interesting features in the bedrock topography is an over deepening beneath the terminal part of the glacier. There is a bedrock ridge in front of the current terminus, and behind this point the bed elevation decreases upglac-

ier, suggesting formation of a proglacial lake once the glacier retreats further. In fact, the terminus detached from the bedrock ridge in 2005, forming a lake between the glacier front and the ridge. The lake formation draws glaciological interest because the ice calving process may accelerate glacier retreat as was observed at the nearby Triftgletscher (Müller, 2004).

To investigate the response of Rhonegletscher to the formation of the proglacial lake, a research project was initiated with the collaboration of Hokkaido University and the Swiss Federal Institute of Technology. This report describes the preliminary results obtained in the 2007 summer field study.

2. Methods

2.1 Study site

Rhonegletscher is a temperate valley glacier in the Swiss Alps with a length of 7.85 km and a surface area of 15.9 km^2 (Cryospheric Commission of the Swiss Academy of Sciences, 1881–2008; Bauder *et al.,* 2007) (Fig. 1a). The glacier snout currently lies at an elevation of 2200 m a.s.l. (Fig. 1b). Because of the interest in the influence of the lake formation on the terminal part of the glacier, the field activity in summer 2007 was focused on the region within 1.5 km from the terminus. According to the bedrock elevation map constructed by Zahno (2004), the maximum ice thickness in the study area was about 260 m at approximately 1 km from the terminus.

There are two ice-marginal lakes in the terminal part of Rhonegletscher (Figs. 1b and 2), one at the western margin (Lake A) and another one in front (south) of the terminus (Lake B). Lake A has existed

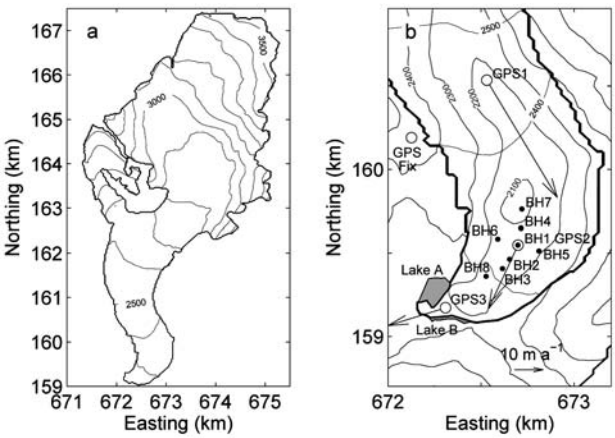

Fig. 1. (a) Map of Rhonegletscher with surface contour lines with intervals of 100 m. (b) Map of the study site showing the borehole locations (●), GPS survey sites (○) and flow velocity vectors. The contour lines indicate surface (black) and bed (grey) elevations with intervals of 100 m. The surface and bed elevations are based on the DEM in 2000 and the ice-radar survey by Zahno (2004), respectively.

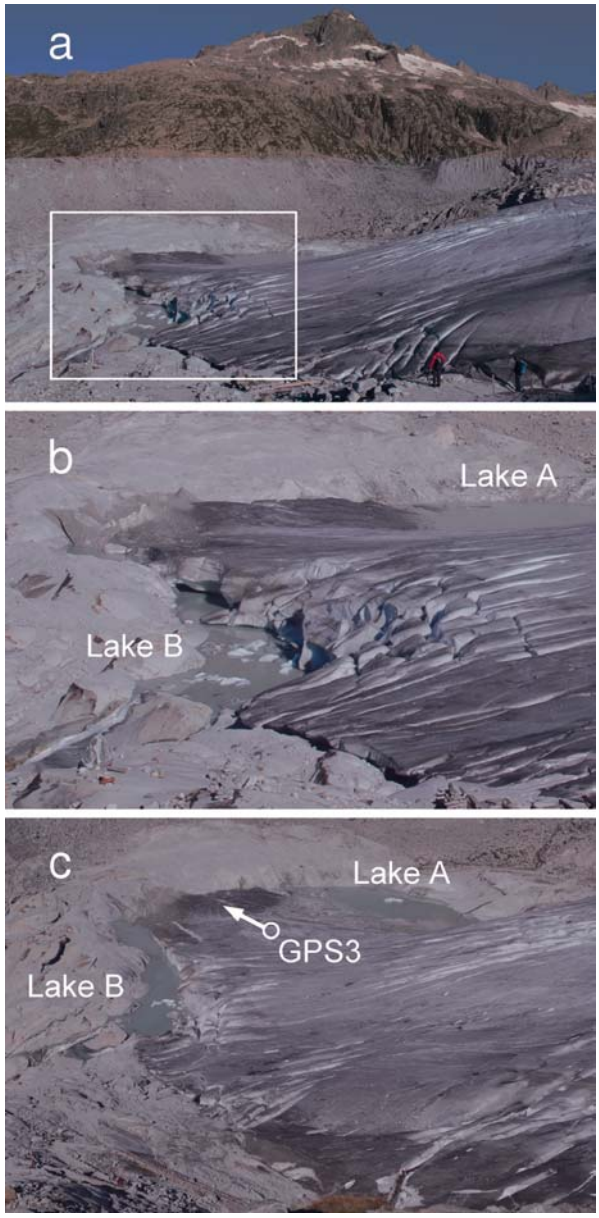

Fig. 2. (a) The terminal part of Rhonegletscher and (b) the ice-marginal lakes viewed from the southeast. (c) The same part of the glacier looking down from the east. Approximate location and flow direction of GPS3 are indicated. The photographs (a) and (b) were taken on 14 July and (c) on 9 September 2007.

for at least 10 years (since the late 1990s); whereas, Lake B formed in 2005. As it is observed in Fig. 2, ice blocks were breaking into Lake B during the summer 2007. Although the primary interest focuses on Lake B, Lake A is also important for the study because these will probably merge to form one lake in the future. The surface level of Lake B is expected to be nearly constant as the water spills over the rock ridge, which serves as a dam (Fig. 2b).

2.2 Hot water drilling

We used a hot water drilling system consisting

of a commercially available pump and heater unit (Kärcher HDS1000), a 3000-liter water basin, 0.5-inch diameter drilling hoses, water jet nozzles with diameters of 1.6–2.5 mm, a tripod, and a pulley equipped with a hose-length gauge. From 13 to 29 July, 2007, eight boreholes were drilled within 1 km of the glacier terminus, six along the central flow line and two closer to the side margins (Fig. 1b). Drilling speed was in the range of 30–50 m h^{-1} for the upper 100 m. Drilling was continued until the nozzle reached the glacier bed, which was recognized by a change in the hose tension. The borehole depth was determined by the length of the hose used for drilling. Because the hose stretched during the drilling, measured borehole depth (or ice thickness) may have an error of $+(1-2)$ m depending on the drilling depth and water level in the borehole.

2.3 *Water pressure measurement*

A vibrating wire pressure sensor (Geokon Model 4500) was installed at the bottom of a 138-m deep borehole (BH1 in Fig. 1b) to measure the subglacial water pressure. The pressure was recorded every 10 minutes using a data logger (Campbell CR1000) with an accuracy equivalent to a water level of ± 0.35 m. The pressure sensor data were periodically calibrated by measuring the water level in the borehole with a measuring tape and a float sensor.

2.4 *GPS survey*

A pair of GPS (Global Positioning System) receivers and antennae (Leica System 1200) was used to measure ice flow velocity and to survey glacier and lake surface elevation. One of the GPS antennae was fixed on solid rock at the western flank of the glacier (Fig. 1b), which served as a reference station for the static and RTK (Real Time Kinematic) measurements.

The flow velocity was measured at three locations (GPS1–3 in Fig. 1b) by surveying 4-m long aluminum stakes drilled into the ice. The other GPS antenna was mounted on the top of the stakes to record the L1 and L2 phase GPS satellite signals for 50 min. We used three-dimensional coordinates surveyed on 15 and 31 July to calculate the velocities. The accuracy of the static GPS measurement is within several millimeters in the horizontal direction (Sugiyama and Gudmundsson, 2004), which is less than 1% of the total displacement of the stakes during the survey interval.

The ice surface elevation was measured along two profiles on 31 July by using the RTK technique. One of the profiles follows along the central flow line (longitudinal profile) and the other one was across the glacier passing through the boreholes BH6, BH1 and BH5 (transverse profile) (Fig. 3a). The accuracy of the RTK measurements was monitored during the survey, which was less than 3 mm for the majority of the time. However, due to the roughness of the ice surface and tilt of the survey pole, positioning error was expected to be several centimeters. The surface elevation was used to obtain recent ice thickness changes by comparing it to the Digital Elevation Model (DEM) of 2000. The DEM was generated by photogrammetric analyses of aerial photographs with an accuracy in elevation of <0.3 m. (Zahno, 2004; Bauder *et al.*, 2007). We employed the same RTK technique to measure the lake surface elevation on 31 July and 8 September. The surface of Lake A was also measured by the static technique on 14 July.

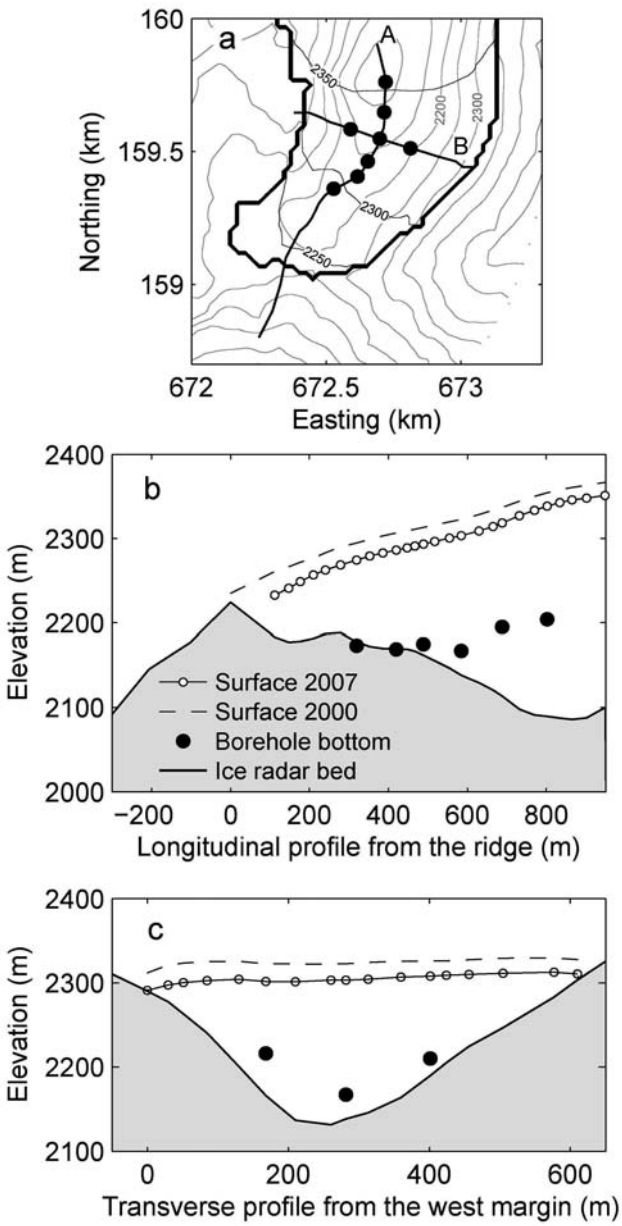

Fig. 3. (a) The GPS survey profiles (thick lines) and the borehole locations (●). The contour lines indicate surface (black) and bed (grey) elevations (Zahno, 2004) with intervals of 50 m. (b) Longitudinal and (c) transverse cross sections along the GPS survey profiles with surface elevations surveyed on 31 July 2007 (○) and based on the DEM in 2000 (dashed line), the bed elevation after Zahno (2004) and the borehole bottoms (●).

3. Results

3.1 Ice thickness

The ice thicknesses obtained by the borehole drilling were significantly different than those expected from the ice radar data (Table 1, Figs. 3b and c). The borehole depth of BH1 was 138 m, which was 29 m less than the ice thickness calculated from the bedrock map. The discrepancy increases upglacier and it is more than 100 m at the upper-most borehole, BH7. In the lower reaches, at the boreholes BH3 and BH8, the borehole depth agrees with the ice thickness from the ice-radar data within 5 m. Accordingly, the longitudinal bedrock profile is nearly parallel to the ice surface in the studied region and the bedrock depression expected beneath the boreholes BH1, BH4 and BH7 does not exist. The overestimation of the ice thickness in the ice radar data is also found in the transverse profile (Fig. 3c). The discrepancy is slightly greater on the western side of the glacier.

3.2 Bed condition

When the drilling at BH1 was completed to the bed, water continued running out of the borehole even after the water jet was stopped, which indicated very high subglacial water pressure. Interestingly, the upwelling water was turbid with fine white particles, which were most likely subglacial sediments raised by the hot water injection. After the drilling, the surface of the brass drilling nozzle was scratched as if it had been sand blasted (compare Figs. 4a and b). From these observations, it is evident that an unconsolidated sediment layer exists beneath the drilling site.

Water continued running out after the drilling at BH2 as well. However, sediments were not observed in the water. In the case of BH4, the edge of the nozzle used for the drilling was scraped (Fig. 4c), suggesting that the nozzle had hit on solid rock at the bottom of the borehole. Similar indications on the nozzle were found after the drilling at BH5. It was not possible to judge the bed condition at every drilling site, because water did not flow out of other boreholes and the nozzles were not always replaced before the next drilling. Nevertheless, these observations indicate that the glacier is underlain by patches of sediment and bedrock in this region.

3.3 Borehole water level

During the period from 13 to 31 July, the water level in BH1 showed diurnal variations (Fig. 5). The

Table 1. Locations and depths of the boreholes and ice thicknesses estimated for the drilling sites from the bedrock map (Zahno, 2004).

Borehole	Easting	Northing	Surface elevation	Borehole depth	(Zahno, 2004)
	m	m	m a.s.l.	m	m
BH1	672698.03	159548.24	2304.63	138	167
BH2	672654.68	159463.21	2294.86	120	134
BH3	672616.75	159407.00	2287.72	119	119
BH4	672715.89	159648.79	2319.45	124	206
BH5	672812.51	159512.29	2309.42	99	120
BH6	672590.60	159584.72	2302.64	87	137
BH7	672720.24	159762.90	2339.46	135	250
BH8	672527.93	159360.07	2275.77	103	99

Fig. 4. Water jet nozzles (a) before the drilling and (b) after the drilling of BH1 and (c) BH4.

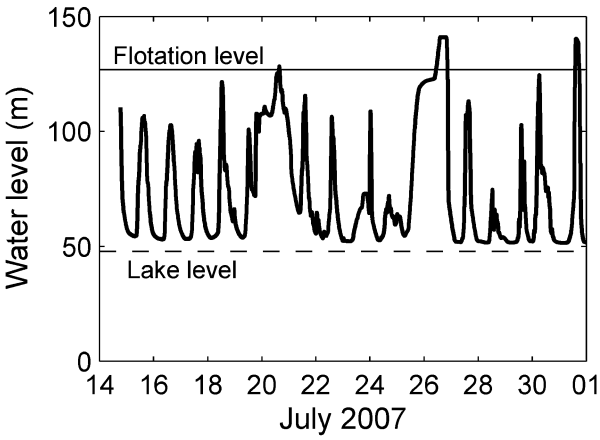

Fig. 5. Water level in borehole BH1. The solid and dashed lines correspond to the ice overburden pressure level and the surface elevation of Lake B, respectively.

level began to rise in the morning at 0900–1000 hr and peaked in the afternoon at 1400–1600 hr. It dropped during the night at a rate slower than that of the rising. The water level exceeded the flotation level several times, including the events on 26 and 31 July that the borehole was overflowing. In contrast to the variable peak water levels, the daily minima in the early morning were nearly constant during the period. The minimum levels were approximately 10 m higher than the surface level of the lakes.

3.4 *Lake surface level*

According to visual observations in July, the water level of Lake A varied diurnally with an amplitude of several decimeters and reached peak levels in the late afternoon. Since the level of Lake B is nearly constant, as described in the previous section, the two lakes were not completely connected in July. Given a constant surface level from July to September for Lake B, the level of Lake A in July was 23–25 cm higher than that of Lake B (Table 2). Because the measurements at Lake A were carried out in the late afternoon, it is likely that the surfaces of the two lakes were at a similar level during the night. On 8 September in the afternoon, the surface level of Lake A was 10 cm lower than that of Lake B.

3.5 *Ice flow speed*

The horizontal ice flow speed decreases downglacier as it is usually observed near the terminus of a valley glacier (Fig. 1b and Table 3). However, the flow speed of 21.2 m a^{-1} at GPS3 is a fairly large value for ice motion observed within 100 m from the terminus. At this site, ice flows west approximately to the point where the glacier reaches the upglacier side of the bedrock ridge, forming an ice barrier between the two lakes (Fig. 2c). Thus, this relatively fast ice motion prevents the connection of the two lakes. The vertical flow speeds are negative (downward ice motion) at the three GPS survey sites.

Table 2. Lake surface elevation and the time of measurements.

	14 July	31 July	8 September
		m a.s.l (hh:mm)	
Lake A	2211.75 (17:35)	2211.73 (18:47)	2211.40 (13:51)
Lake B	–	–	2211.50 (15:45)

Table 3. Components of the flow velocity to the east (u_x), to the north (u_y) and upward (u_z), and the horizontal flow speed (u_h).

Site	u_x	u_y	u_z	$\lvert u_h \rvert$
	m a^{-1}	m a^{-1}	m a^{-1}	m a^{-1}
GPS1	24.65	-45.77	-6.24	51.99
GPS2	-10.26	-24.71	-1.40	26.76
GPS3	-20.07	-6.96	-1.58	21.24

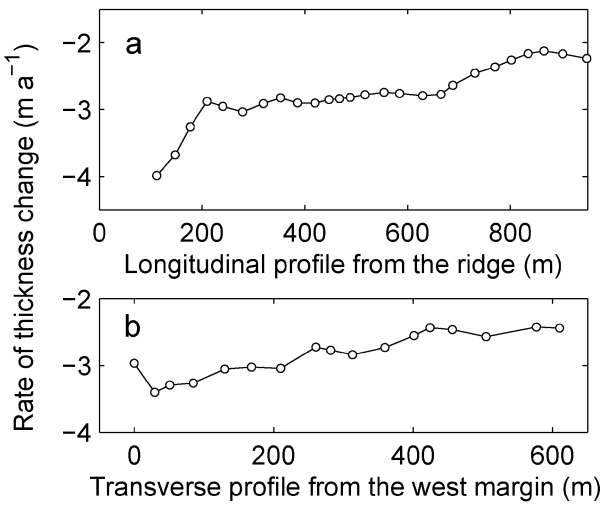

Fig. 6. Rates of ice thickness change from 2000 to 2007 (a) along the longitudinal profile and (b) transverse profile.

3.6 *Surface elevation*

The surface elevations measured by GPS along the longitudinal and transverse profiles are shown with those obtained from the DEM in 2000 (Figs. 3b and c). The elevation changes since 2000 indicate that the ice has thinned by approximately 20 m. The magnitude of the ice thickness change increases down glacier in the longitudinal profile (Fig. 6a) and towards the west margin in the transverse profile (Fig. 6b). The thickness changes averaged over the profiles are −19.2 m (−2.75 m a^{-1}) and −19.6 m (−2.81 m a^{-1}) for the longitudinal and transverse profiles, respectively.

4. Discussion

4.1 Implications of the bedrock elevation profile

The borehole depth disagreed with the previously reported ice thickness, probably because of an error in the bedrock elevation map introduced by interpolation of the ice radar data (Zahno, 2004). Since most of our boreholes were located in between the cross glacier radar profiles, uncertainty in the bedrock map may be significant. The agreement is better in the lower reaches (BH3 and BH8) where one of the radar profiles exists. It is not likely that the drilling nozzle hit a rock in the ice before it reached the glacier bed as the borehole depth was systematically less than the ice thickness from the ice radar.

The longitudinal bedrock profile revealed in this study (Fig. 3b) is of great importance in predicting the future development of the proglacial lake. Since bedrock depression does not exist at >500 m from the terminus, the maximum area and depth of the lake after glacier retreat would be less than predicted based on the ice-radar data. The lake depth along the valley center will reach approximately 50 m; the glacier will be separated from the lake when the terminus retreats 800 m upglacier from the present position. Thus, the influence of the lake on the glacier is limited.

The new bedrock profile is also important to predict the retreat of Rhonegletscher during the next few decades. Due to the lack of bedrock depression, ice flux into the terminal part is less than expected. Accordingly, the retreat rate of the glacier would be greater than previous prediction by numerical modelling based on the ice-radar data (Sugiyama *et al.,* 2007). Further field measurements for a more complete bedrock elevation map and numerical investigations using the new information are required.

4.2 Hydrological conditions

The diurnal variations in the borehole water level in BH1 indicate that the subglacial water pressure was controlled by the water supply from the surface and subglacial drainage. Due to the snow and ice melt during the daytime, the bed was highly pressurized in the afternoon. The pressure immediately dropped when the melt rate decreased in the evening, suggesting that a subglacial drainage system had already developed.

A well-established drainage system was also implied by the fact that the daily minimum water levels did not change during the period. The hydraulic gradient between the borehole and the lake was nearly constant because the conduit had already developed and reached a steady size. It is important that the borehole level was relatively high, even at night, under the influence of the lake water. Since the pressure head in the studied region never drops below the lake surface, subglacial water pressure was maintained at a high level. This effect is more significant near the terminus, where the ice surface level is closer to the lake level. The high water pressure is the likely reason for the relatively fast ice flow at GPS3.

The difference in lake level between Lakes A and B provides information on the hydraulic connection between the two lakes. In July, the water level was higher in Lake A, probably because water inflow into Lake A was not efficiently drained into Lake B. The levels were nearly the same in September, suggesting that the two lakes had become more connected. Decrease in the melt water runoff may have reduced the lake level difference, but some difference should have been observed if the connection of the two lakes had not changed. The slightly higher level in Lake B may be due to more inflow from upper reaches into Lake B through a subglacial drainage conduit.

4.3 Ice thickness change from 2000 to 2007

The ice thickness change in Rhonegletscher from 1874 to 2000 was studied by Zahno (2004) by comparing DEMs generated from old maps and photogrammetric analyses of aerial photographs. According to the results, the rates of thickness change at the elevation of 2250–2350 m for the periods 1874–1929, 1929–1959, 1959–1980, 1980–1991 and 1991–2000 are -0.49, -0.92, -0.12, -0.92 and -1.87 m a^{-1}, respectively. Therefore, the changing rates from 2000 to 2007 observed in this study (-2.75 m a^{-1} and -2.81 m a^{-1} along the longitudinal and transverse profiles) indicate that glacier thinning has accelerated during the last decade.

The recent increase in the thinning rate is consistent with mass balance changes in Swiss glaciers. Huss *et al.* (2008) computed seasonal mass balances of four glaciers in the Swiss Alps including Rhonegletscher for the period of 1865–2006. The rate of mass loss averaged over the four glaciers has progressively increased after the period of mass gain from 1974 to 1981. The period 1998–2006 was characterized by strongly negative mass balances as the result of high summer temperatures.

If a constant thinning rate of -2.8 m a^{-1} is assumed, the lake will expand upglacier to the location of BH1 and BH7 in 2040 and 2052, respectively. Nevertheless, formation and development of the lake may accelerate the thinning and retreat of Rhonegletscher. The sharp increase in the thinning rate near the terminus (<200 m in Fig. 6a) suggests that the effects of the lake on the glacier terminus, e.g., calving and ice flow acceleration, are already influencing the glacier. The reason for the thinning rate variation across the glacier (Fig. 6b) is unclear. It may be the result of the curving valley shape which affects ice flow regime and solar radiation. To predict the change of Rhonegletscher under the influence of lake development, detailed field observations of the ice flow and surface melt distributions

in addition to the calving process are required.

5. Conclusion

Hot water drilling and preliminary observations were conducted in Rhonegletscher with focus on the effects of the newly formed proglacial lake on the terminal part of the glacier. Important information obtained by this field research includes:

1. In the region 500–800 m from the terminus, the ice is up to 100 m thinner than the previous estimation. The development of the proglacial lake in the future is limited to 800 m upglacier from the current terminus.
2. Subglacial sediment exists in at least a part of the studied region. The glacier bed probably consists of patches of sediment and bedrock.
3. Subglacial water pressure varied diurnally. The borehole water level drops at night to about 10 m higher than the lake surface level.
4. Horizontal flow speed near the terminus is relatively fast (21 m a^{-1}), suggesting that basal motion is enhanced by the lake.
5. The glacier is thinning at a rate of 2.8 m a^{-1} in the studied region. The thinning rate has increased in the 21 century.

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