EXPANSION OF THE IMJA GLACIER LAKE IN THE EAST NEPAL HIMALAYAS

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Abstract

I*n order to evaluate its expansion rate since 1992, the basin of the Imja Glacial Lake was resurveyed in 2002. Results showed that the expanded portion of the lake was concentrated near the glacier terminus, and that the lake had expanded due to the retreat of glacier ice. A survey around the ice cliff at the glacier terminus was also carried out to clarify the process of calving there. The result showed that the glacier ice was grounding. The ice cliff at the terminus was in continual contact with lake water, and had drifted due to valley winds passing over the lake. Therefore, submerged ice at the glacier terminus would melt efficiently, and the subaerial glacier ice remaining over the water surface would collapse of its own weight. The calculated melt rate of the submerged ice was approximately equal to the calving rate at the glacier terminus. It can, therefore, be concluded that the calving occurred due to submerged ice melting at the foot of the glacier termini in Imja Glacial Lake.*

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Повторное исследование приледникового озеро Imja было выполнено в 2002 г для определения порядка его изменений с 1992. Результаты показали, что расширенная часть озера была наибольшей около оконечности ледника, озеро расширилось из-за отступления ледника. Было выполнено обследование краевой части ледника на предмет возможного отела айсбергов. Оказалось, что ледник лежит на основании. Обломок льда у ледникового края был в непрерывном контакте с озером, и дрейфовал под действием долинных ветров. Поэтому, погруженный краевой ледниковый лед таял бы эффективно, и ледниковый край, остающийся под водной поверхностью разрушится под действием собственного веса. Расчетная норма таяния, погруженного льда, была приблизительно равна размерам образующихся айсбергов. Из этого можно заключить, что образование айсбергов произошло из-за таяния льда в основании краевой части ледника, погруженного в ледниковое озеро Imja.

Introduction

In the Himalayas, glaciers can be divided into two types; one is the non-debris covered glacier (clean type glacier), which is usually small, and the other is the debris-covered glacier (Moribayashi and Higuchi, 1977). Fujita *et al*., (1997) indicated that non-debris covered glaciers are shrinking more rapidly than glaciers in the other regions of the world, in relation to their mass balance amplitude. Debris-covered glaciers are also shrinking by declining the surface level (Naito *et al*., 2002). Some debris-covered glaciers have supraglacial lakes at their termini, which are surrounded and dammed by the moraine formed during the Little Ice Age. Those glacial lakes emerged during recent decades, and are now also expanding by calving at their termini.

Such moraine-dammed glacial lakes have sometimes produced the so-called Glacial Lake Outburst Flood (GLOF) due to the moraine collapse. GLOFs have occurred at least 13 times since the 1960s in the Arun and Sun River basins in the Nepal Himalayas (LIGG / WECS / NEA, 1988). At least 5 GLOFs were reported in the Bhutan Himalayas (Iwata *et al*., 2002). Mitigation and/or prevention of GLOF hazards is one of the more urgent issues to be addressed for water resource development and conservation in the Himalayas.

Inventories of glacial lakes in the Nepal and Bhutan Himalayas have been created by Mool (2001). The horizontal area expansion rates of glacier lakes in the Himalayas have been examined by many researchers using photographs, maps and satellite images (Yamada, 1998; Ageta *et al*., 2000; Yabuki, 2003; Kirkbride, 1993; Watanabe *et al*., 1994; Haeberli *et al*., 2001). Benn *et al*., (2001) have investigated bathymetric changes in the supraglacial ponds in the East Nepal Himalayas. However, little is known about the expansion process of moraine-dammed glacial lakes. It is important to examine such bathymetric changes in order to better understand the mechanism of glacial lake expansion. This paper aims to elucidate the process of glacier lake expansion. Our study compared the depth distributions between 1992 and 2002, and discussed the expansion process of the glacial lake from a survey around the ice cliff at the glacier terminus.

Study sites and methods

The investigation was carried out at Imja Glacier Lake in the Khumbu region of East Nepal. This lake is located at the termini of the Imja Glacier (27°59′N, 86°56′E; altitude 5010 m a.s.l.), which has a branch glacier, Lhotse Shar Glacier, as shown in Fig. 1. There is also another branch glacier, the Ambulapcha, which has the same drainage area as Imja Glacier Lake.

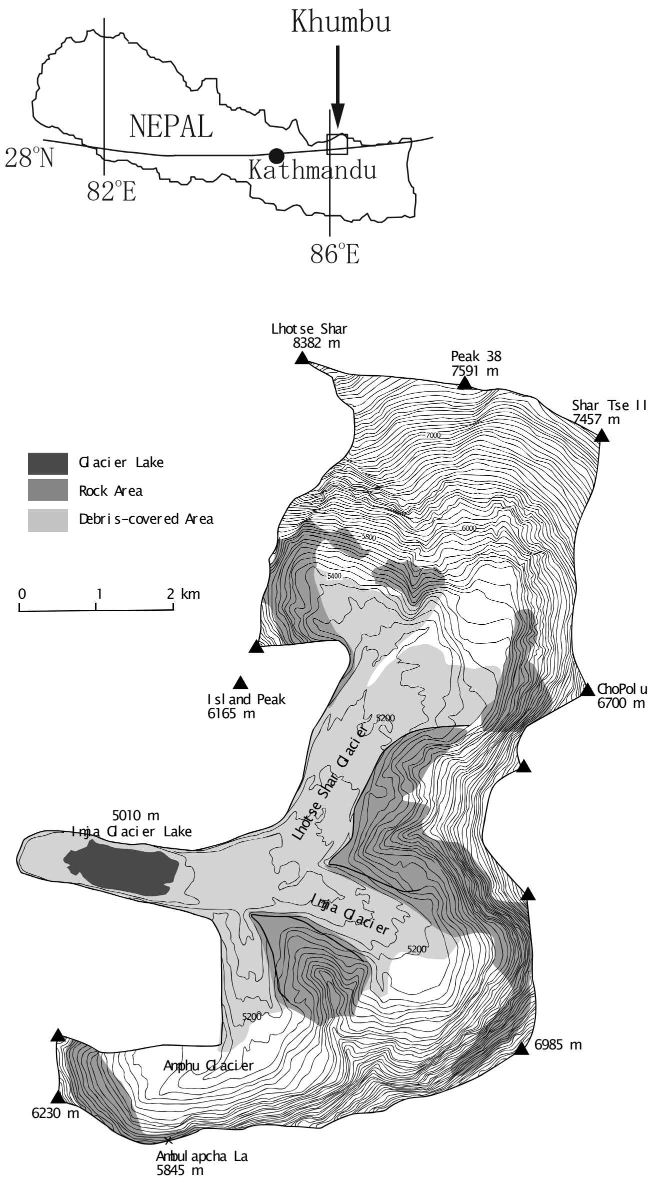


Fig. 1. Location of Khumbu area in Nepal, and topographical map of drainage area of Imja Glacial Lake

However, its glacier ice did not connect with the Imja Glacier in 2002. A bathymetric map of the Imja Glacier Lake was made in April 1992 by Yamada and Sharma (1993). There were a few small lakes near the end-moraine in the 1960's, and the lake area had expanded to 0.6 km^2 by 1992, extending upstream of the Imja Glacier (Yamada, 1998).

Observations at the Imja Glacial Lake were carried out from 4 to 7 April 2002 during the ice-covered period. The depth was confirmed at 80 uniformly dispersed points by a tape measure through boreholes opened by a fisherman's drill. Depth measurement points along one longitudinal line (from site A to site B in Fig. 2) were surveyed by GPS. Using a compass and tape, directions and distances of the depth measurement points along a cross line were measured from points along the longitudinal line from site A to site B.

A survey of the ice cliff at the glacier terminus was also carried out. It was too dangerous to set a mirror directly at the top edge of the ice cliff and moraine because the shoreline and the ice cliffs include steep slopes of moraines and ice. The shoreline of the lake and the top edge of the ice cliff at the glacier terminus were then measured by a compass and a laser distance meter from each depth measurement point near the shoreline. The accuracy of the distance meter was ±1 m. Relative heights of the ice cliff from the lake ice surface to the top edge of the ice cliff were also measured by the same means.

Results

The average ice thickness of the lake surface in 2002 was about 70 cm, which was thicker than that in 1992 (about 50 cm). Figure 3 shows a bathymetric map drawn from the depth distribution data. The measured maximum depth was 90.5 m. Figure 4 shows the ice cliff height distribution along a cross section (average height, around 30 m).

Table 1
Summary of dimensions of Imja Glacier Lake in 1992 and 2002

Measurement/year	April 1992	April 2002
Average depth (m)	47.0	41.6
Maximum depth (m)	99	90.5
Area ($\times 10^6$ m^2)	0.60	0.86
Stored water ($\times 10^9$ m^3)	28.0	35.8

A summary of the changes from 1992 to 2002 is shown in Table 1. The surface area of the glacier lake in 2002 had increased by 40% over that in 1992. Stored water volume had risen by 28% compared to that in 1992, although the average depth had decreased.

Discussion

The depth profile in front of the glacier was rather complicated in 2002 as shown in Fig. 3. There was a peninsula at the glacier terminus, which was not there in 1992. It might have developed from a middle moraine between the Imja and Lhote Shar Glaciers, which was left after the glacier ice melted. Glacier ice might have been left under the debris at the peninsula.

The expansion rate on the right bank looks different from that on the left bank at the glacier terminus during recent years, possibly because of the difference in flow dynamics between the Imja and Lhote Shar Glaciers. The shoreline near the outlet showed no great change since in 1991 (Yabuki, 2003). The bathymetric map shown in Fig. 3 was then superimposed on the map made in 1992 seen in Fig. 5 on the assumption that the shoreline near the outlet was substantially unchanged.

The longitudinal cross section in Fig. 6 shows a change (from A to B in Fig. 2) in the lake depth from 1992 to 2002, assuming that the water level in 1992 was equal to that in 2002. The cross section revealed no great difference from the outlet to the glacier termini as it was in 1992. The depth in 2002 was shallower (maximum 15 m) than that in 1992 in some portions. There are two possible reasons for this. One is that the abundant sediment produced at the base of the glacier was carried away by glacier meltwater and deposited in the lake basin. The other is a possible locational error.

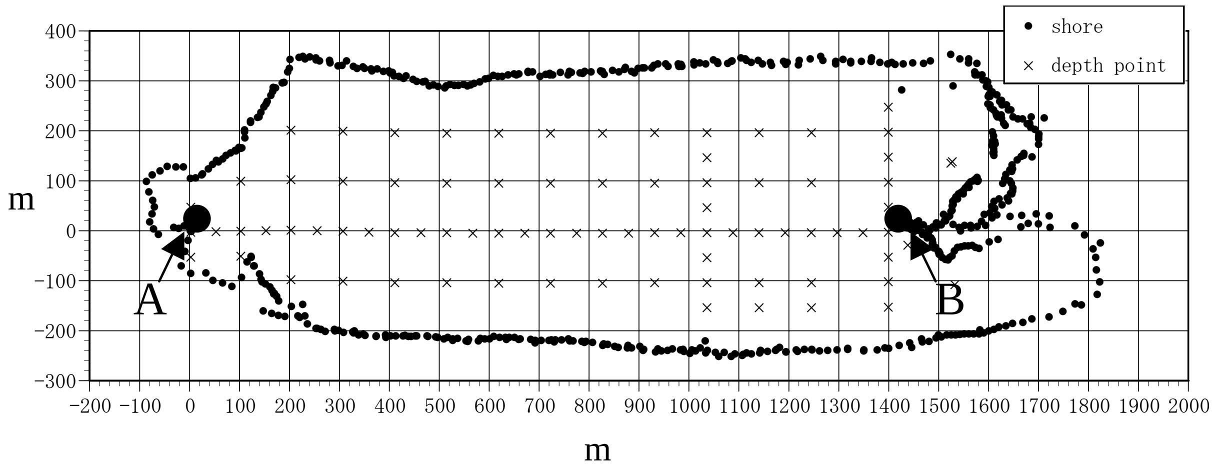


Fig. 2. Depth measured point (×) in 2002 and observed shoreline (•) of Imja Glacial Lake. Location of depth measurement points from A to B along a longitudinal line were measured by GPS

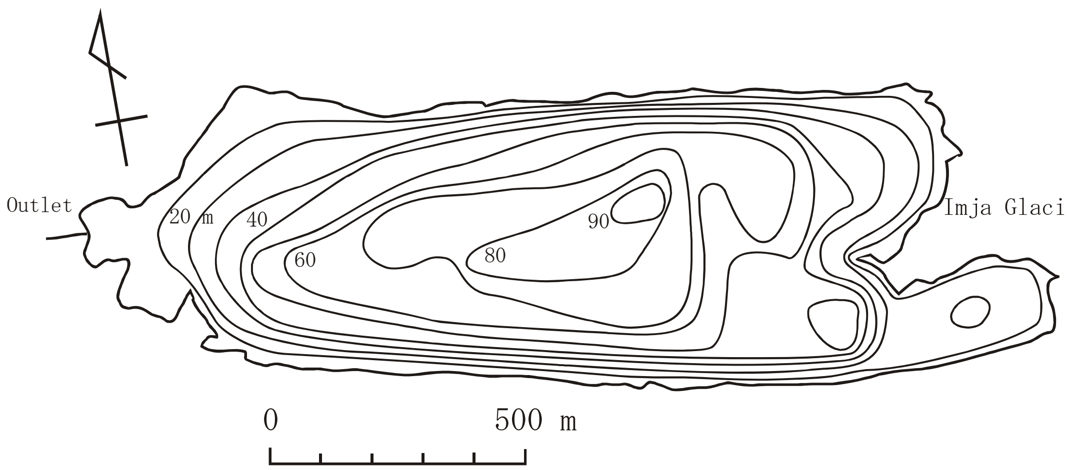


Fig. 3. Bathymetric map of Imja Glacier Lake drawn from depth distribution data in Fig. 2

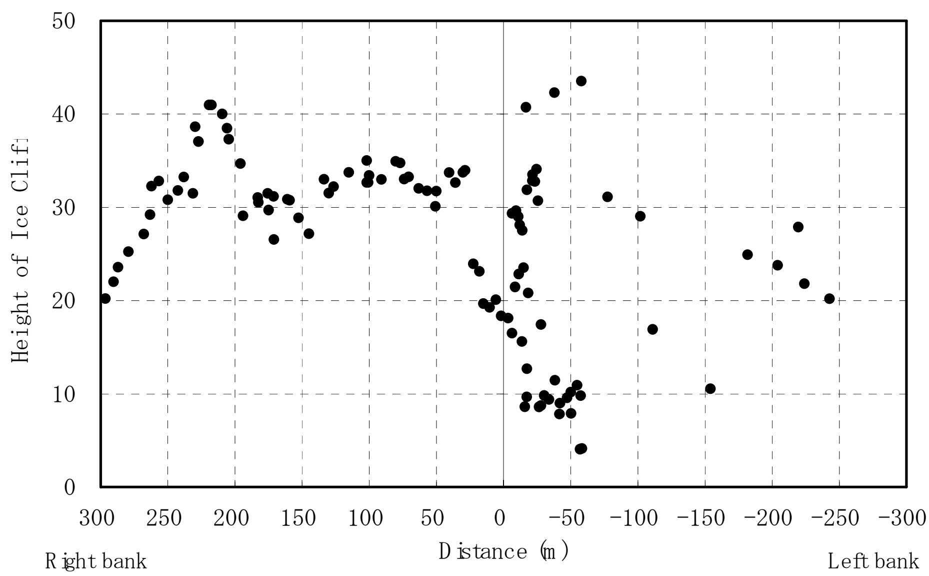


Fig. 4. Distribution of ice cliff height at the glacier terminus from left bank to right bank

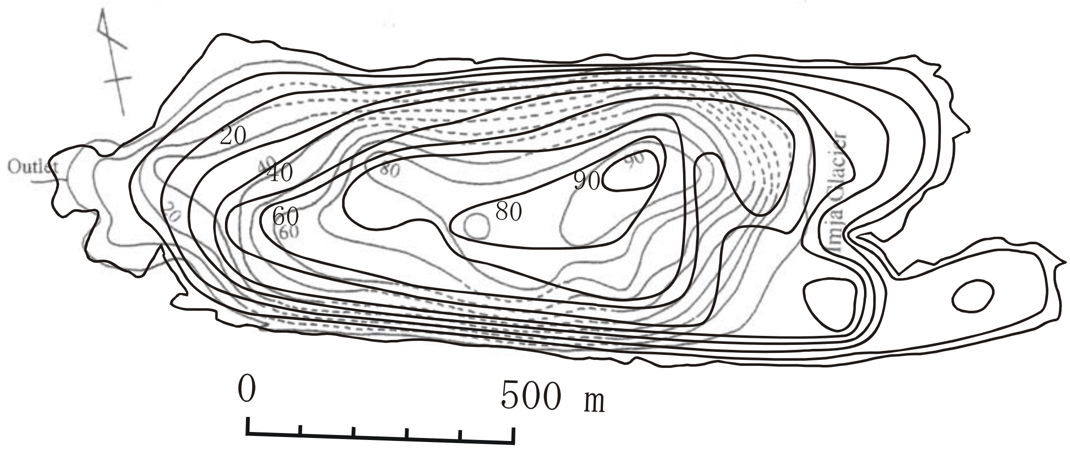
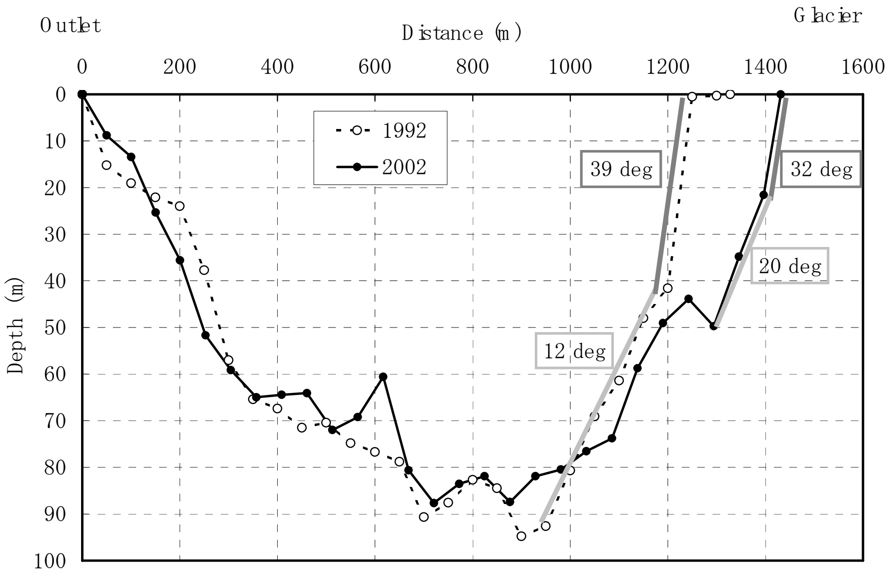


Fig. 5. Bathymetric map shown in Fig. 3 was superimposed on that of 1992



by assuming that the shoreline near the outlet had not changed

Fig. 6. Longitudinal depth distribution from point A to B (Fig. 2) in 2002 (black line) and in 1992 (dotted line). Numbers in rectangles show inclination of the lake basin

Figure 6 indicates that the bathymetric expansions were mainly the result of glacier retreat, not melting of the lake basin. We observed ice calving at the ice cliff of the glacier terminus during the open-water period.

Here, we consider the process of calving. Glacier frontal change (S) can be expressed by a simple mass-balance calculation, following Powell and Molnia (1989):

$$S = S_G - S_C - S_M \qquad (1),$$

where, S_C – calving speed (m yr^{-1})
S – subaerial frontal change (m yr^{-1})
S_G – ice velocity (m yr^{-1})
S_M – melting rate at subaerial ice cliff (m yr^{-1})

The observed velocity of a glacier near the terminus of a debris-covered glacier in the Nepal Himalayas was 1 to 2 meters a year (Kodama and Mae, 1976; Naito and others, 2002). Therefore, the ice velocity of the glacier terminus, S_G, is negligible compared to other elements.

The terminus of the Imja Glacier is pointing west. The mean melt rate of the ice cliff facing west was 8 cm during the melting season at the Lirung Glacier (Sakai *et al*., 1998). The melting season lasts about 5 months from May to September in the Nepal Himalaya. Therefore, the melting rate at the subaerial ice cliff would be approximately 12 m yr^{-1}.

Subaerial frontal changes have differed between the right and left side in recent years. The average subaerial frontal change; S was 43 m yr^{-1} (Yabuki, 2003). The average calving speed, S_C, is therefore, calculated to be 31 m yr^{-1} from the equation (1).

The calving process would differ from the condition of the glacier terminus floating/grounded (Warren *et al*., 1995, 2001; Kirkbride, 1997). According to Krimmel and Vaughn (1987), flotation of the terminus of the Columbia Glacier would occur when less than 12-14% of the ice thickness is unsupported by buoyancy, and calving appears to commence when that critical value is reached. The maximum potential of buoyancy glacier ice can be evaluated from the maximum depth of the lake. The observed maximum depth and ice cliff height at the Imja Glacial Lake were 90 m and 30 m, respectively. At that time, 25% of the ice thickness was unsupported by buoyancy. Those results prove that Imja's maximum lake depth lacked enough buoyancy to float the glacier ice terminus. Calving of temperate/grounded glaciers has been relatively well investigated in tidewater glaciers. Lacustrine calving, however, has received relatively little attention (Warren *et al*., 2001).

During the day, strong valley winds blow in the longitudinal direction toward Imja's terminal cliff which is in direct contact with the lake water. This wind would produce wind-driven currents in the surface layer. Shortwave radiation proved to be the most effective absorbed heat at the lake surface (Sakai and others, 2000). Surface water, therefore, will absorb strong solar radiation during the day, and the warmed surface water can then accelerate the subaqueous glacier-melt (Chikita *et al*., 1997; 1999). Kirkbride and Warren (1997) also concluded that calving rates are controlled by waterline melting at the Maud Glacier in New Zealand's Southern Alps.

The ice melt rate under the thick debris layer is almost negligible (Sakai *et al*., 2000). Therefore, it is necessary to expose the ice surface to melt and to hollow out the foot of the ice cliff. The slope of the lake bottom near the glacier terminus was calculated as shown in Fig. 6. The smallest slope angle of exposed ice cliff was approximately 30°, and gentler slopes were covered with debris (Sakai and others, 1998). The result of the calculation of the sloping face of the glacier terminus indicates that the submerged exposed ice cliff height had declined from about 40 m in 1992 and about 20 m in 2002.

The melt rate at the foot of the glacier ice (*S*) can be estimated as follows using an equation for the melt rates of towed polar icebergs (Weeks and Cambell, 1973), first modified and adapted for use by Powell (1983) for calving temperature ice cliffs;

$$S = 7.14 \times 10^{-6} v^{0.8} \Delta T / l_i^{\,0.2} \qquad (2),$$

where, $v =$ vertical boundary layer velocity (m sec^{-1})
$\Delta T =$ ice/water temperature difference (°C)
$l_i =$ mean water depth at calving front (m)

The constant number, 7.14×10^{-6}, which depends on the dynamic and kinematic viscosities of water, was altered to adapt the equation to pure water. The ice temperature must be 0°C, since the ice in contact with the lake water which was higher in temperature. The observed lake surface water temperature was about 6°C in June 1997 at Imja Glacier Lake (Chikita *et al*., 2000). Therefore, it was supposed that the ice/water temperature difference was 6°C during the monsoon season (5 months from mid-May to mid-September).

Surface water velocity was observed to be 2 to 3% of the wind velocity at Lake Biwa in Japan by Iwasa (1990). At the Tsho Rolpa Glacier Lake in East Nepal, Himalayas, the surface water velocity should be 0.04-0.07 m sec^{-1}, since the average wind velocity is about 2.2 m sec^{-1}. It might be supposed that the water velocity in front of the glacier is equal to the surface water velocity, since the lake surface water flows from the outlet to the ice cliff of the glacier, and furthermore, it flows down the face of the ice cliff of the glacier terminus. As a result, the melt amount during the monsoon period (5 months) should be 23 to 36 meters. The range of the calculated submerged melt rate corresponded to the calving rate of 31 m yr^{-1} deduced from observation data, suggesting that the calving at the Imja Glacial Lake was caused by submerged ice melting. But, since the water velocity was a relatively rough estimation, further observations of the lake water velocity in front of the glacier terminus should be carried out.

The maximum water temperature was about 2°C during an ice–covered period in April 2002. Thus, there must have been some melting of the submerged ice during that period. However, the velocity of lake water must be much less in summer than in winter when the lake is covered with ice.

In the Nepal Himalayas, the horizontal expansion rate of each glacier lake varied (Yamada, 1998). Those rates do not necessarily depend on individual altitudes. The reason for these differences might become clear by observing the surface lake water temperature and velocity of the lake water.

Ice cliffs surrounding supraglacial ponds retreat by melting. Calving used to start when supraglacial ponds expanded to reach a diameter of hundreds of meters; and the growth rate of the water surface area would increase when calving starts at the ice cliff, as indicated by Kirkbride (1993). The above calculation indicates that the water temperature and wind blowing over the water surface might be a key to intergrading the expansion process from melting to calving at the ice cliff.

Conclusions

A bathymetric map was made in 2002 for comparison to one from 1992. The comparison confirmed that the Imja glacial lake was enlarged by the retreat of the glacier. A survey around the ice cliff revealed that the terminus of the glacier ice was not floating but grounded. Therefore, it was clear that the calving did not occur not due to buoyancy. Valley winds blow in the daytime during the monsoon season in the Himalayas. These winds could well carry warm surface water to the glacier face. Therefore, the calving would have occurred from submerged ice melting at the foot of the glacier terminus. Estimations of the melt rate of the submerged ice showed enough range to confirm that the calving occurred due to submerged ice melting.

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References

Ageta Y., Iwata S., Yabuki H., Naito N., Sakai A., Narama C., Karma (2000). Expansion of glacier lakes in recent decades in the Bhutan Himalayas. *International Association of Hydrological Sciences* Pub. 264 (Symposium at Seattle 2000 «Debris-covered glacier»), 165-175.

Benn D.I., Wiseman S., Hands K.A. (2001). Growth and drainage of supraglacial lakes on debris-mantled Ngozumpa Glacier, Khumbu Himal, Nepal. *J. Glaciol.*, 47(159), 626-638.

Chikita K., Yamada T., Sakai A., Ghimire R.P. (1997) Hydrodynamic effects on the basin expansion of Tsho Rolpa Glacier Lake in the Nepal Himalaya. *Bulletin of Glacier Research*, 15, 59-69.

Chikita K., Jha J., Yamada T. (1999) Hydrodynamics of a supraglacial lake and its effect on the basin expansion: Tsho Rolpa, Rolwaling Nepal Himalaya. *Arctic, Antarctic and Alpine Research*, 31(1), 58-70.

Chikita K., Joshi S.P., Jha J., Hasegawa H. (2000) Hydrological and thermal regimes in a supraglacial lake: Imja, Khumbu, Nepal Himalaya. *Hydrological Sciences*, 45(4), 507-521.

Fujita K., Nakawo M., Fujii Y., Paudyal P. (1997) Changes in glaciers in Hidden Valley, Mukut Himal, Nepal Himalayas, from 1974 to 1994. *J. Glaciol.*, 42, 583-588.

Iwasa Y. (1990) *Engineering Limnology*. 1st ed. 504 p. Sankai-do Press, Tokyo.

Iwata S., Ageta Y., Naito N., Sakai A., Narama C., Karma (2002) Glacial lakes and their outburst flood assessment in the Bhutan Himalaya. *Global Environmental Research*, 6(1), 3-17.

Haeberli W., Kääb A., Mühll D.V., Teysseire P. (2001) Prevention of outburst floods from periglacial lakes at Grubengletscher, Valais, Swiss Alps. *J. Glaciol*., 47(156), 111-122.

Kirkbride M.P. (1993) The temporal significance of transitions from melting to calving termini at glaciers in the central Southern Alps of New Zealand. *The Holocene*, **3**(3), 232-240.

Kirkbride M.P., Warren C.R. (1997) Calving processes at grounded ice cliff. *Annals of Glaciology*, 24, 116-121.

Kodama H., Mae S. (1976) The flow of glaciers in the Khumbu Region. *Seppyo*. (Special issue) 38, 31-36.

Krimmel R.M., Vaughn B.H. (1987) Columbia Glacier, Alaska: Changes in velocity 1977-1986. *J. Geophysical Research*, 92(B9), 8961-8968.

LIGG/WECS/NEA (1988) *Report on first expedition to glaciers and glacier lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun Koshi) river basins, Xizang (Tibet), China*. 192 p. Science Press, Beijing, China. Sino-Nepalese Joint Investigation of Glacier Lake Outburst Flood in Himalayas in 1987, Lanzhou Institute of Glaciology and Geocryology, Academia Sinica, and Water and Energy Commission Secretariat of Nepal, Science Press, Beijing, China.

Moribayashi S., Higuchi K. (1977) Characteristics of glaciers in the Khumbu region and their recent variations. *Seppyo*, 39 (Special Issue), 3-6.

Naito N., Kadota T., Fujita K., Sakai A., Nakawo M. (2002) Surface lowering over the ablation area of Lirung Glacier, Nepal Himalayas. *Bulletin of Glaciological Research*, 19, 41-46.

Powell R.D. (1983) Glacial-marine sedimentation processes and lithofacies of temperate tidewater glaciers, Glacierbay, Alaska. *Glacial-marine sedimentation*. Ed. B.F. Molnia, 185-232. Plenum Press, New York and London.

Powell R.D., Molnia B.F. (1989) Glacial-marine sedimentary processes, facies and morphology of the south-southeast Alaska Shelf and fjords. *Mar. Geol*., 85, 359-390.

Sakai A., Nakawo M., Fujita K. (1998) Melt rate of ice cliffs on the Lirung Glacier, Nepal Himalayas, 1996. *Bulletin of Glacier Research*, 16, 57-66.

Sakai A., Takeuchi N., Fujita K., Nakawo M. (2000) Role of supraglacial ponds in the ablation process of a debris-covered glacier in the Nepal Himalayas. International *Association of Hydrological Sciences* Pub. 264 (Symposium at Seattle 2000 «Debris-covered glacier»). 119-130.

Warren C., Glasser N.F., Harrison S., Winchester V., Kerr A.R., Rivera A. (1995) Characteristics of tide-water calving at Glacier San Rafael, Chile. *J. Glaciol.*, 41(138), 273-289.

Warren C., Benn D., Winchester V., Harrison S. (2001) Buoyancy-driven lacustrine calving, Glacier Nef, Chilean Patagonia. *J. Glaciol.*, 47(156), 135-146.

Watanabe T., Ives J.D., Hammond J.E. (1994) Rapid growth of a glacial lake in Khumbu Himal, Himalaya: prospects for a catastrophic flood. *Mountain Research and Development*, 14(4), 329-340.

Weeks W.F., Cambell W.J. (1973) Icebergs as a fresh-water source: an appraisal. *J. Glaciol*., 12(65), 207-233.

Yabuki H. (2003) Monitoring of Imja Glacier Lake in the East Nepal using the satellite image. (submitted)

Yamada T., Sharma C.K. (1993) Glacier lake and its outburst flood in Nepal Himalayas. Proceedings of International Symposium on Snow and Glacier. Hydrology (Kathmandu, Nepal), *IAHS-AISH* Pub. 218, 319-330.

Yamada T. (1998) *Glacier lake and its outburst flood in the Nepal Himalaya*, Monograph 1, 96 p. Data Center for Glacier Research, Japanese Society of Snow and Ice.

Sakai A., Fujita K., Yamada T. (2005) Expansion of the Imja Glacier Lake in the East Nepal Himalayas. *Glacier Caves and Glacial Karst in High Mountains and Polar Regions*. Ed. B.R. Mavlyudov, 74-79. Institute of geography of the Russian Academy of Sciences, Moscow.