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Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by *in situ* surveys and multi-temporal ASTER imagery

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Abstract
Changes in the area and bathymetry of Imja Glacial Lake and in the elevation of its damming moraine, Khumbu region, Nepal Himalaya are investigated. Previously reported changes in the lake area have been updated by multi-temporal ASTER images, which revealed a decreased expansion rate after 2000. A provisional expansion of the lake observed in 2004, from which some studies concluded an accelerated lake expansion due to global warming, has, from 2005, subsided to the glacier surface. Bathymetric changes for the period 1992–2002 that were first obtained for Himalayan glacial lakes suggest that the melting of debris-covered ice beneath the lake is insignificant in terms of the increase in lake volume, and that the retreat of a glacier in contact with the lake by calving is essential for the lake's expansion. Changes in the height of a damming moraine for the period 2001–2007 suggest a continuous surface lowering near the lake, though the lowering rates are smaller than those for the period 1989–1994.

Keywords: Himalaya, glacial lake, ASTER

1. Introduction

Recent glacier recessions have been observed to lead to the development and expansion of glacial lakes in the Himalayas. Collapses of the lake dams can cause outburst floods that present serious hazards in populated regions (Bajracharya *et al* 2007b). Imja Glacial Lake is situated in the eastern Khumbu region, Nepal, below which the most frequently used trekking route for reaching the Mt Everest base camp is located (27°54′N, 86°55′E, figure 1). Because of its location and relatively easy accessibility even in the remote Himalayas, this lake has been thoroughly investigated by both *in situ* observational and remote sensing approaches (Watanabe *et al* 1994, 1995, Chikita *et al* 2000b, Bajracharya *et al* 2007b, 2007a, Quincey *et al* 2007, Sakai *et al* 2007, Bolch *et al* 2008, Hambrey *et al* 2008). The expansion history of the lake was first reported by Watanabe *et al* (1994) and was updated by Komori *et al* (2004) and Bajracharya *et al* (2007b). Despite the report of an accelerated expansion rate since 2001 (Bajracharya *et al* 2007b), it remains unclear just how the lake's length was measured. An automatic detection method of the lake surface using a normalized difference water index (NDWI) was recently attempted on Imja Glacial Lake by Bolch *et al* (2008); however, no detailed discussion of the expansion rate has emerged so far. Although some studies have asserted the expansion rate as posing a risk of a glacial lake outburst flood (GLOF) (Quincey *et al* 2007), determining the trigger and proof strength of the damming moraine is more important

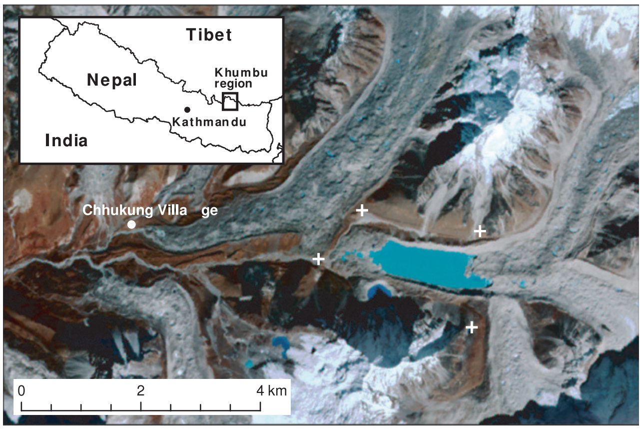

Figure 1. ASTER-VNIR image of Imja Glacial Lake in Khumbu region, Nepal Himalaya on 10 Nov. 2004. A base station for the October 2007 DGPS survey was established at Chhukung village. The other images are affine-transformed by referring to four obvious tie-points around the glacial lake (white crosses).

than whether or not the lake is expanding (Richardson and Reynolds 2000, Bolch *et al* 2008, Hambrey *et al* 2008). Regarding the damming moraine, the lake is thought to be relatively safe because of its enormous damming mass, while a significant lowering has been observed for the period 1989–1994 (Watanabe *et al* 1995). In this study, we attempt to describe year-to-year changes in the area of Imja Glacial Lake using recent satellite images that have become available for the Khumbu region since 2000. In addition, we also reveal changes in the bathymetries and update lowering rates of the damming moraine via *in situ* surveys, both of which are unobservable even with the latest remote sensing techniques.

2. Data used, observations and analyses

2.1. ASTER data

Orthorectified VNIR images of the advanced spaceborne thermal emission and reflection radiometer (ASTER) on Terra satellite with a spatial resolution of 15 m are used for this analysis. The images are generated and distributed as Level 3A01 products by the ASTER Ground Data System (ASTER GDS) at the Earth Remote Sensing Data Analysis Center (ERSDAC) in Japan (ERSDAC 2002, Fujisada *et al* 2005). The images used in the analysis are listed in table 1. The location of each image was affine-transformed by referring to four obvious tie-points on a reference image captured in 2004 (figure 1). The analyzed domain is so restricted around the lake that the four tie-points will work well. The root mean square errors (RMSEs) of the affine transformation are within 3 m (table 1). The lake areas were identified using NDWI following the procedure of Bolch *et al* (2008). Visual checking and editing were also performed to rectify errors due to ice areas and shadows on the lake.

2.2. Bathymetric survey

Observations to obtain the bathymetry of Imja Glacial Lake were carried out in early April of 1992 and 2002 when the lake was ice-covered. The depth measurements were made by a tape measure lowered through boreholes made with a fisherman's drill at 61 points in 1992 (Yamada and Sharma 1993) and at 80 uniformly dispersed points on the lake in 2002. The position of each point in both years was determined using a compass and tape measure. Measurement points only along a longitudinal line were surveyed by a differential Global Positioning System (GPS) in 2002. Shorelines of the lake were measured during both observations 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.

Table 1. Acquisition dates of ASTER data and RMSEs due to affine transformation and areas of Imja Glacial Lake. Area uncertainties are obtained by assuming that the shoreline crosses at the center of all grid cells. They are therefore obtained with a shoreline length multiplied by 7.5 m, a half of cell resolution.

Acquisition date	RMSE of affine transformation (m)	Area (km^2)
14 Oct. 2000	1.14	0.844 ± 0.036
20 Dec. 2001	0.78	0.827 ± 0.040
21 Nov. 2002	1.14	0.868 ± 0.037
23 Oct. 2003	1.80	0.889 ± 0.039
10 Nov. 2004	Reference	0.928 ± 0.041
29 Nov. 2005	0.30	0.896 ± 0.042
01 Feb. 2006	3.07	0.897 ± 0.041
06 Jan. 2008	1.98	0.920 ± 0.036

2.3. Surveys around end-moraine

Surveys around the end-moraine were carried out in Nov. 2001 using a digital theodolite with a laser-distance meter (SOKKIA SET2100). Relative locations of 1348 points were surveyed from nine benchmarks installed on/around the end-moraine area. A prism mirror was placed on noteworthy topographical features such as peaks, cols, ridges, bottom lines of trenches, pond edges and edges of spillways. The measurement error, taking into account the mirror setting, was evaluated as ±0.1 m (Fujita *et al* 2008). A topographical map of the end-moraine was obtained by this survey (Sakai *et al* 2007).

Surveys by a carrier-phase differential GPS (DGPS, CMC All Star receivers) were carried out on/around the end-moraine in April 2002 and October 2007. One GPS was installed as a base station at a base camp near the lake in 2002 and at Chhukung Village, 3 km from the survey area in 2007. Data post-processing of DGPS measurements was performed using Waypoint GrafNav/GrafNet software (NovAtel Inc.) to obtain the relative positions and altitudes of all points on a common Universal Transverse Mercator projection (UTM, zone 45N, WGS-84 reference system). Data showing horizontal and vertical errors of more than ±5 m in position and ±1 m in altitude, which are the output of the software, were excluded from the subsequent analysis (13% for 2002 and 8% for 2007, of the total measured points in each year).

The points surveyed in 2001 were transformed to the UTM coordinates relative to three benchmarks around the end-moraine (white crosses in figure 5(a)). This was accomplished not by affine transformation but by rotating and shifting to obtain the minimum measurement errors. Standard deviations of differences between the repeatedly measured and averaged

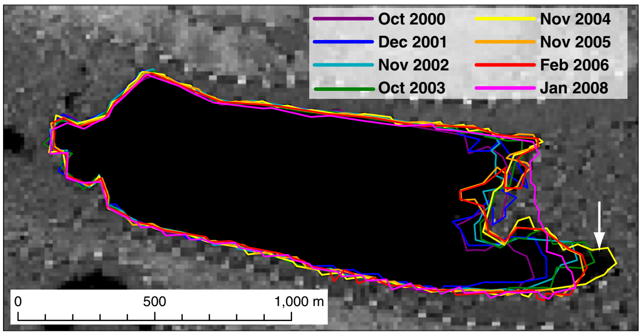

Figure 2. Change in shoreline of Imja Glacial Lake derived by the ASTER-NDWI method from 2000 to 2008. The background image is of ASTER-NDWI in Nov. 2004. The arrow denotes a hollow, discussed in the text.

positions of the three benchmarks (seven measurements in total) were determined to be measurement errors of 0.40 m in position and 0.86 m in altitude.

All surveyed points (38 571 in 2002 and 113 577 in 2007) were converted to 1 m resolution digital elevation models (DEMs) by the inverse distance weighing (IDW) method, in which the reference points to obtain the altitude of grid cells were limited to within a circle with a radius of half of the diagonal of the targeted grid cells (0.7 m). Any grid cell without measured points was excluded from the subsequent analysis. Since measured points in 2001 were too scarce to generate DEM by the IDW method, the altitude of a given grid cell was obtained by averaging the measurement points included in each cell. In many cases, only one measurement point was available for a cell. Ultimately, 1293 cells for 2001, 19 213 cells for 2002 and 42 507 cells for 2007 were obtained.

3. Results and discussion

3.1. Changes in lake area

Figure 2 shows changes in the shoreline of Imja Glacial Lake since 2000 as revealed by the ASTER-NDWI method. The reliability of the ASTER-NDWI method was confirmed by the shoreline in Nov. 2002 (0.868 km^2) which was consistent with the survey in Apr. 2002 (0.864 km^2, figure 4(b)). Lake areas, which are the averages of manual delineations by two of the authors, are also plotted in figure 3. It suggests that the manual delineation tends to estimate the lake area as smaller than that by the NDWI method. Bajracharya *et al* (2007b) have asserted that the expansion rate accelerated between 2001 and 2006 due to a change in the length of the glacial lake. Their assertion is too arbitrary to be acceptable, however, since their longitudinal distance was measured at a hollow expanded area of the left bank; that area had reached its maximum in 2004 but then shrank again as shown in figure 2. The 2004 hollow area remains as a debris-covered surface in the latest image of early 2008, whereas the main part of the contacting line between lake and glacier has expanded (figure 2). Therefore, the lake area showed a transient maximum in 2004 (figure 3, table 1). For the restoration of the glacier surface in 2005, a rapid advance of the upstream glacier (a possible reason behind the shrinkage of the lake area) can be ruled out since no significant movement was detected by checking ponds and cliff shadows on the upstream glacier surface with ASTER visible images. A lowering of the lake level, on the other hand, provides an alternative possibility. Watanabe *et al* (1995) and Watanabe (2008) have reported a continuous lowering of the lake level since the 1980s. Insignificant changes in the downstream shorelines during the 2000s, however, do not support an obvious lowering of the lake level (figure 2). Ground surveys in 2001 and 2007 also showed an unchanged lake level (within 0.2 m in height) during that period. An uplift of the glacier tongue is another plausible possibility under the circumstances given the unchanged lake level and no glacier advance, though no significant evidence has emerged since no direct measurement of the upstream glacier surface was made, and the accuracy of the ASTER DEM was insufficient to detect such a change (Fujita *et al* 2008). The expansion rate of Imja Glacial Lake obviously decreased after 2000 (figure 3), ruling

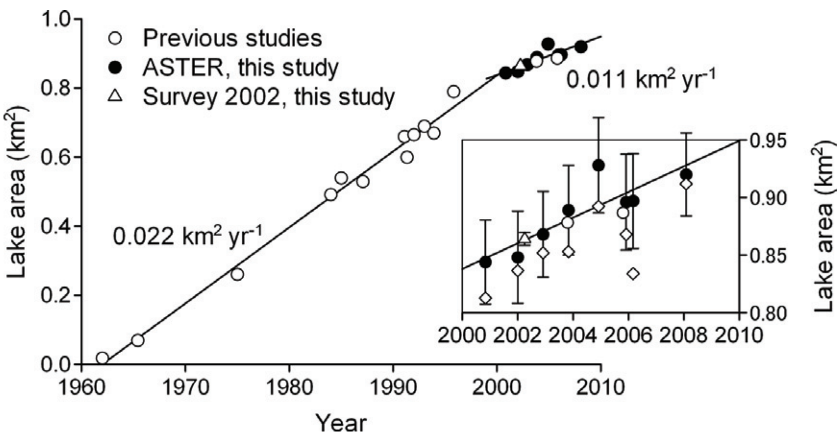

Figure 3. Change in area of Imja Glacial Lake derived by the ASTER-NDWI method from 2000 to 2008. Open and solid circles denote remote-sensed lake areas cited from previous studies (Watanabe *et al* 1995, Komori *et al* 2004, Bolch *et al* 2008) and those in this study, respectively. Open triangle denotes an area surveyed in 2002. The inset graph details 2000–2010. Open rhombuses in the inset graph denote areas derived manually. Error bars in the inset graph are obtained by assuming that the shoreline crosses at the cell center for ASTER-NDWI, and by assuming 1 m uncertainty of the distance meter for the 2002 survey. Linear regression lines are individually depicted for the data before and after 2000. Areas in 2003 and 2005 from Bolch *et al* (2008), manually traced areas and survey data are excluded from the regression lines.

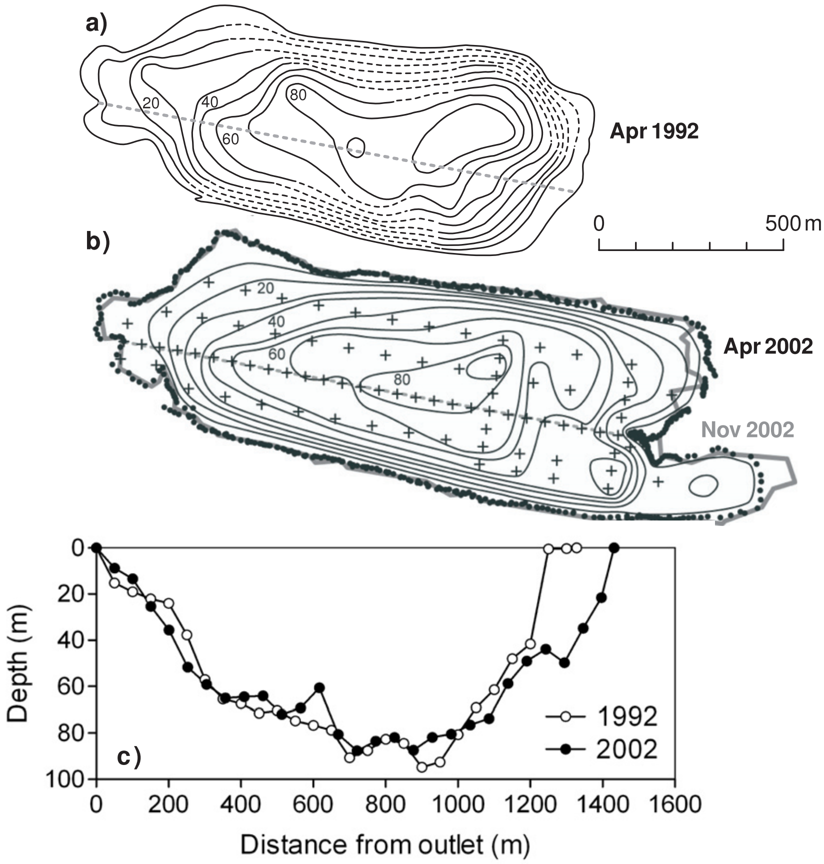

Figure 4. Bathymetries of Imja Glacial Lake measured in (a) Mar. 1992 (Yamada 1998) and (b) April 2002. Profiles along center lines, shown as dotted lines in (a) and (b), are compared (c). Crosses in (b) denote depth measurement points. The thick gray line in (b) denotes a shoreline derived from ASTER-NDWI in Nov. 2002. Small numbers in the lake denote depth in meters.

out the accelerated expansion in length asserted by Bajracharya *et al* (2007b).

3.2. Change in bathymetry

Figure 4 shows two bathymetries measured in 1992 and 2002. Although bathymetric maps have been measured in several glacial lakes along the Himalayas (Yamada 1998), the first volume change in a Himalayan glacial lake was calculated in this study (table 2). Satellite images in 1992 (Landsat5 TM) and in 2001 (ASTER) indicated that no significant change has occurred in the downstream shoreline of the lake. It became possible to superimpose two bathymetries and thus to obtain longitudinal depth profiles from 1992 and 2002 (figure 4(c)). The profiles show no significant lowering of the lake bottom at the downstream side, but do confirm an obvious expansion in front of the glacier terminus. An insignificant lowering of the lake bottom might be due to the insulation effect of thick debris on the ice beneath the lake and a continuous supply of debris (Chikita *et al* 2000a). A drastic expansion of the lake, on the other hand, was caused by a retreat of the upstream glacier. Many Himalayan glacial lakes have expanded by this mechanism (Yamada 1998, Komori *et al* 2004, Bajracharya *et al* 2007b). It is implausible that the debris-covered ice over the lake level has melted out for one decade only by heat exchange between ice and atmosphere through a debris mantle even though drastic glacier melts have been observed in the Himalayas (Fujita *et al* 1997, 1998, 2001). It has been suggested that the glacier melt of ice contacting the lake water enhanced the calving and thus the rapid glacier retreat by observational studies (Kirkbride 1993, Röhl 2006) and numerical (Sakai *et al* 2009). A significant change in depth at the expanded portion observed in this study also suggests that the lake expansion was caused by calving rather than by melting of debris-covered ice on the glacier surface.

Table 2. Changes in area and volume of Imja Glacial Lake in 1992 (Yamada 1998) and 2002 (this study). Area uncertainty in 2002 is obtained with a shoreline length multiplied by 1 m, an uncertainty of the distance meter. Volume uncertainty is calculated by assuming measurement error in depth by 0.5 m.

	Area (km^2)	Volume ($\times 10^6$ m^3)
Apr. 1992	0.60	28.0
Mar. 2002	0.864 ± 0.006	35.8 ± 0.7

3.3. Lowering of end-moraine

We obtained changes in height on/around the end-moraine of Imja Glacial Lake by comparing the 1 m resolution DEMs in 2001, 2002 and 2007 (figure 5). Elevation differences were calculated at a point where both elevations were available in

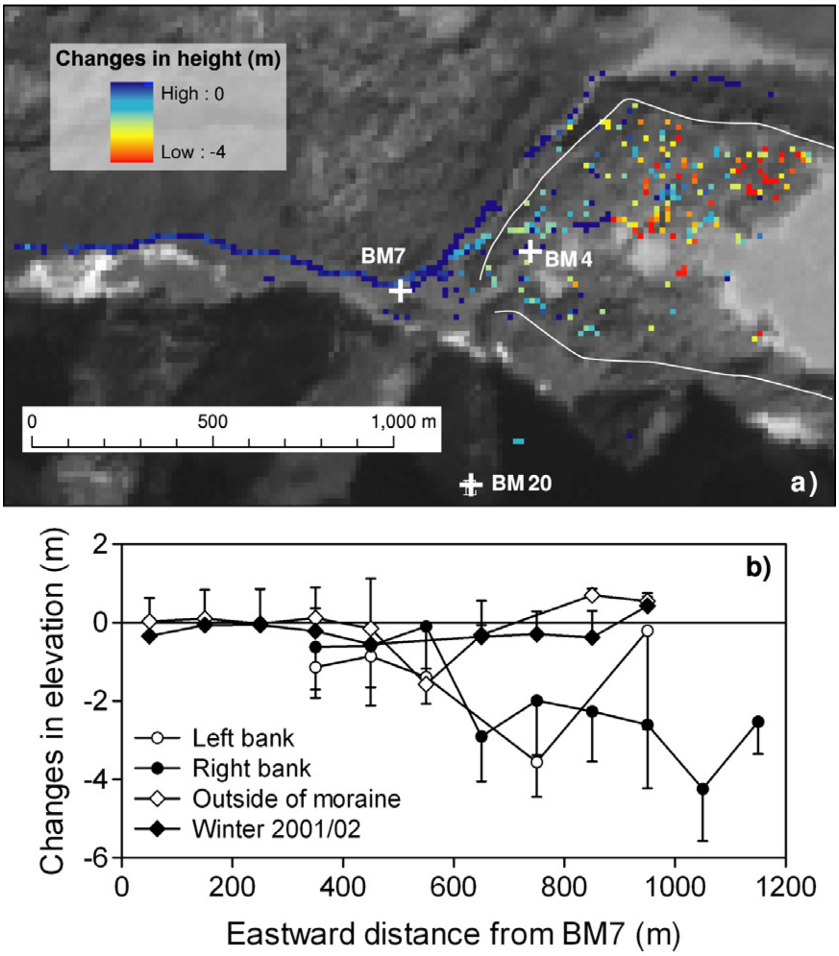

Figure 5. Map (a) and graph (b) of height changes around Imja Glacial Lake between 2001/02 and 2007. The elevation changes with 1 m resolution have been averaged on 15 m resolution for better visibility. White crosses and lines in (a) denote benchmarks installed during the survey in 2001 and the manually traced moraine ridge. The background image of (a) is of ASTER-VNIR band 2 taken in Nov. 2008. Lowerings are averaged at an interval of 100 m along an eastward line from the benchmark BM7 (b). Standard deviations of the elevation changes within each elevation bin are depicted on one side for visibility.

Table 3. Changes in elevation on/around the end-moraine of Imja Glacial Lake.

Region and period	Number of cells	Average (m)	Standard deviation (m)
Outside: Apr. 2002–Oct. 2007	1537	−0.06	0.67
Nov. 2001–Apr. 2002	40	−0.22	0.49
Left bank: Nov. 2001–Oct. 2007	43	−1.63	1.71
Right bank: Apr. 2002–Oct. 2007	395	−1.97	1.67

the targeted years. Elevations outside the end-moraine are considered to be unchanged for six years since 2001, and therefore serve as a validation of the surveys. Summarized changes in elevation show little change outside the end-moraine except for minor variability (table 3). Changes in elevation during a short period (5 months) also show little change with only minor variability. These small changes serve to guarantee accurate surveys and position fittings. Changes in elevation on the end-moraine, on the other hand, show a significant lowering for six years since 2001 (table 3). The distribution of changes in elevation shows a more obvious lowering of the damming moraine near the lake (figure 5(a)). An insignificant horizontal shift (less than 1 m) of several painted stones surveyed in 2001 and 2007 suggests that the lowering was caused not by ice flow, but rather by ice melt. The distribution of the lowering is clearly consistent with an ice distribution under the debris mantle, which was surveyed by electrical resistivity tomography and ground-penetrating radar (Hambrey *et al* 2008). This supports the concept that the lowering was caused by melt of the debris-covered ice. We also confirmed the presence of a rugged topography with many ice cliffs and a few ponds near the lake (eastern part) in contrast to a rather smooth topography around the downstream area (western part) during the survey of 2007. Less lowering and minor variability of changes in elevation at the downstream side (figure 5(b)) suggest an ice melt suppressed by thicker debris, which provided an insulating effect. A more significant lowering and a larger variability of changes in elevations near the lake (figure 5(b)), on the other hand, suggest a heterogeneous melting of ice, which might have been caused by concentrated heat absorption by the ice exposed on the face of the ice cliff and by the pond surface (Sakai *et al* 1998, 2000, 2002).

Watanabe *et al* (1995) showed lowering rates of the damming moraine ranging from -0.1 to -2.7 m yr^{-1} for the period 1989–1994 while our surveys show those ranging from -0.06 to -1.03 m yr^{-1} for the period 2001–2007. Such a change in melt rates suggests that the debris-covered damming moraine of the lake has become stable with respect to topographical morphology.

3.4. Change in lake level

Lowering of the lake surface has also been previously reported by Watanabe *et al* (1995), though no direct survey was performed (10.3 m for the period 1989–1994). Our surveys suggest no significant change in the lake level (within 0.2 m in height) between 2001 and 2007. Lowering of the lake level by 10 m is equivalent to a 62 m retreat of the shoreline along the centerline as deduced from the bathymetries (figure 4(c)). Multi-temporal satellite images showed no significant change in the downstream shoreline of the lake (figure 2). During the early stage of lake formation in the late 1980s, a significant melting of the damming moraine was observed together with changes in lake level and downstream shoreline (Watanabe *et al* 1995). After the 1992 surveys, however, the lake level and the downstream shoreline seemed to be stable. Expansion of the lake is occurring only at the upstream shoreline due to glacier retreat.

4. Conclusions

As shown in this study, changes in Himalayan glacial lakes have been observable from repeated high-resolution remotely sensed images since 2000. In particular, frequent multi-temporal imaging will be valuable for understanding the underlying expansion mechanisms of glacial lakes in detail. Changes in the height of the damming moraine and the lake level, on the other hand, still require *in situ* surveys due to the insufficient accuracy of satellite-based remotely sensed DEMs (Fujita *et al* 2008). Despite the stable downstream shoreline of Imja Glacial Lake over the last two decades, continued lowering will in turn cause the downstream expansion of the lake, though the lowering rate of the damming moraine seems to be settling compared with that in the late 1980s. This downstream expansion could increase the risk of GLOF. Repeated measurements of the bathymetry of Imja Glacial Lake, which are also unobservable with current remote sensing techniques, show an insignificant deepening of the lake bottom. Our result shows that the expansion of a glacial lake in terms of volume has occurred not by the melting of bottom ice under deposited debris, but by the calving of a glacier terminus. Repeat measurements of bathymetries would provide further information, such as which part of the glacial lake were stable, melting or calving. Despite the currently safer condition of Imja Glacial Lake with respect to its GLOF potential (Watanabe 2008), this glacial lake still threatens the safety of local people as well as the many trekkers visiting the most famous trekking route in the Himalayas. Monitoring of the lake area using multi-temporal satellite images as well as intermittent *in situ* surveys will be required to forestall the GLOF risk.

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