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Outline of 2002 - research activities on glaciers and glacier lakes in Lunana region, Bhutan Himalayas

Tomomi YAMADA[1], Nozomu NAITO[2], Shiro KOHSHIMA[3], Hiroji FUSHIMI[4], Fumio NAKAZAWA[5], Takahiro SEGAWA[3], Jun UETAKE[3], Ryohei SUZUKI[6], Nariyuki SATO[7], KARMA[8], Indra K. CHHETRI[8], Lobzang GYENDEN[8], Hironori YABUKI[9] and Kazuhisa CHIKITA[10]

1 Institute of Low Temperature Science, Hokkaido University, Sapporo 060-0819 Japan
2 Department of Environmental Information, Hiroshima Institute of Technology, Hiroshima 731-5193 Japan
3 Graduate School of Bioscience and Biotechnology, Tokyo Institute of Technology, Tokyo 152-8551 Japan
4 School of Environmental Science, University of Shiga Prefecture, Hikone 522-8533 Japan
5 Graduate School of Science, Nagoya University, Nagoya 464-8601 Japan
6 Graduate School of Environmental Studies, Nagoya University, Nagoya 464-8601 Japan
7 Graduate School of Environmental Earth Science, Hokkaido University, Sapporo 060-1810 Japan
8 Geological Survey of Bhutan, P. O. Box 173, Thimpu, Bhutan
9 Frontier Observational Research System for Global Change, Yokohama 236-0001 Japan
10 Graduate School of Science, Hokkaido University, Sapporo 060-0810 Japan

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Abstract

For the purpose to investigate formation and expansion mechanism of a moraine-dammed glacier lake in connection with shrinkage process and mechanism of a glacier, field observations were carried out on Lugge Tsho (Lugge glacier lake), debris-covered Lugge and Thorthormi Glaciers, and debris-free Ganju La Glacier in the Lunana region, Bhutan Himalayas in the late September to the early October 2002 as the first year's activity of the three-year-joint research project between Japan and Bhutan.

Surveys were performed on the lake-basin mapping of Lugge Tsho and on position of shorelines of the down- and up- lake ends, which are expansion fronts of the lake, for assessing expansion process and rate. The deepest lake depth was revealed to be 126 m, the mean depth to be 49.9 m, and the stored water to be 58.3 million m^3. The thermal and density structure of Lugge Tsho were also revealed using a TTD Profiler. The discharge and daily runoff from the lake watershed of 54.2 km^2 were clarified to vary from 2.5 to 5 $m^3 s^{-1}$ and from 4.3 to 6.8 mm, respectively.

The surface topographies of Lugge and Thorthormi Glaciers were surveyed, too, in each ablation area for detecting surface lowering, which could control formation of glacier lake. The total of 31 stakes were embedded in the areas to measure surface mass balance and flow.

A 50 cm depth pit observation and a 614 cm depth core drilling were performed on Ganju La Glacier. The samples are being analyzed by various dating methods to clarify annual net accumulation.

The outline of the field activities carried out in 2002 is reported with the preliminary results obtained also by the other observations.

1. Introduction

Glaciers in the world tend to shrink under the influence of the recent global warming. The trend is especially clear and has accelerated in a recent few decades in the Great Himalayas (Yamada *et al.*, 1992; Ageta *et al.*, 2001) because the Himalayan glaciers are summer accumulation type (Ageta and Kadota, 1992). It is conceivable that glacier shrinkage in Bhutan would be especially large in the Himalayas due to suffering the strong influence of the summer monsoon (Karma *et al.*, 2003).

The glaciers mainly consist of small debris-free glaciers and large debris-covered glaciers in the Himalayas. As the debris-covered glaciers are shrunk, many moraine-dammed glacier lakes have appeared on their debris-covered ablation areas. The newly born lakes have frequently caused glacier lake outburst floods (GLOFs) in this half century in the Himalayan countries of Bhutan, Nepal, India and

China (Yamada, 1998). GLOF inflicted serious damages not only to human losses, the valuable infrastructure and foundation of villagers, but also to the fragile nature along the river. In Bhutan, GLOFs have happened at least four times since 1950, most recently in 1994, the Lugge Tsho burst in the eastern Lunana region. GLOF mitigation is now urgent issue in these countries for their economical development, and also for villagers and fragile Himalayan natures.

To find adequate measures of GLOF mitigation must be difficult without enough knowledge on mechanisms of the lake formation, and of astonishing lake expansion, and characteristics of GLOF itself. To investigate behaviors of the past GLOF events and risk assessment of each moraine-dammed lake are also important for evaluating a future GLOF possibility and damages along a GLOF running river. Monitoring of variations of glacier lakes is also necessary. In addition, a mass balance study should be made as the essential background of glacier lake formation, because glacier lakes are born on the shrinking processes of debris-covered glaciers. Since it is too difficult to perform such studies on debris-covered glaciers due to their large size and difficulty in approaching their accumulation areas, small debris-free glacier should be studied for understanding the trend of glacier mass balance. It is also advantage for the mass balance study that a small glacier would quickly respond to climate changes.

In this connection, the joint research project between Japan and Bhutan (Geological Survey of Bhutan, GSB) was conducted in 1998 (Ageta and Iwata, 1999) and 1999 to investigate above mentioned issues. For continuing the study intensively, three-year-joint research project during 2002-2004 was planed and launched in the autumn of 2002.

This report describes the outline and some preliminary results of the field activities performed on the first year of the 2002-2004 project.

2. Research areas, members and schedule

The research project was carried out in the Lunana region of Bhutan Himalayas by 10 Japanese and 3 Bhutanese members from September to October, 2002. The trekking route and the research areas are shown in Fig. 1. A moraine-dammed glacier lake, Lugge Tsho (Lugge Lake), and two debris-covered glaciers, Lugge Glacier and Thorthormi Glacier were investigated in the eastern Lunana near Thanza village. Six debris-covered glaciers and two well-developed glacier lakes are distributed in this area (Fig. 2). A debris-free glacier was investigated on Ganju La Glacier (tentative name) located in the Ganju La (Ganju pass) near Woche village, the southwestern Lunana (Fig. 1).

The research members were divided into two teams. The first team, consisting of 7 Japanese (Yamada, Naito, Nakazawa, Segawa, Uetake, Suzuki, and Sato), and 3 Bhutanese, Karma, Chhetri, and Gyenden, left Thimpu on 26 August and arrived at the research site in Lugge Tsho area, the eastern Lunana on 14 September. The second team consisting of Kohshima, Fushimi and Ushida (Kyoto Prefectual University) left Thimpu on 6 September and joined the first team on 23 September.

Due to unfortunate transportation problems, the proposed 2002 research plan was forced to change completely, and the start of full research activities was delayed to 21 September. In addition, the Nika Chhu route, which had been planned to use as a relatively short return route from Thanza to Thimpu, was closed due to spread of foot and mouth disease of Yaks. The relatively long Snowman Trek Route, on which we came to Lunana, should be again employed as the return route. Accordingly, the duration of research activities in the Lugge area were limited for only two weeks from 21 September to 5 October, shortening about two weeks from the proposed research plan.

Debris-free glacier research party (Kohshima, Nakazawa, Segawa, Karma and Lobzang) left BC for Ganju La area on 30 September and arrived at Ganju La Glacier on 3 October. The other 8 members continued research activities in the Lugge area. In the proposal plan, debris-free glaciers in Jichu Dramo area on the way to Nika Chhu were planned to be investigated. However, as no transportation was available to approach there, the research area for debris-free glaciers had to be changed to the Ganju La area. The research period for the debris-free glacier was also forced to be shorten to 3 days only, from 4 to 6 October. The Lugge party left BC on 6 October and joined the Ganju La party at Woche on the way to Thimpu on 8 October. All members were back at Thimpu on 17 October.

3. Meteorological observation

An Automatic Weather Station (Lugge AWS) was installed in the dead ice area, lying between Lugge Tsho and the end moraine of Lugge Glacier (● in Fig. 2).

Its altitude is 4566 m, referred to the BC benchmark altitude of 4550 m a. s. l. The total of 9 meteorological components were started to record automatically at 12:00 on 17 September, 2002; air temperature, relative humidity, precipitation, wind speed, wind direction, downward and upward shortwave radiation, and net radiation are recorded every 30 minutes, and ground surface temperature is recorded every 1 hour. In addition, the maximum snow depth gauge was installed to obtain the maximum snow depth in the winter 2002/2003.

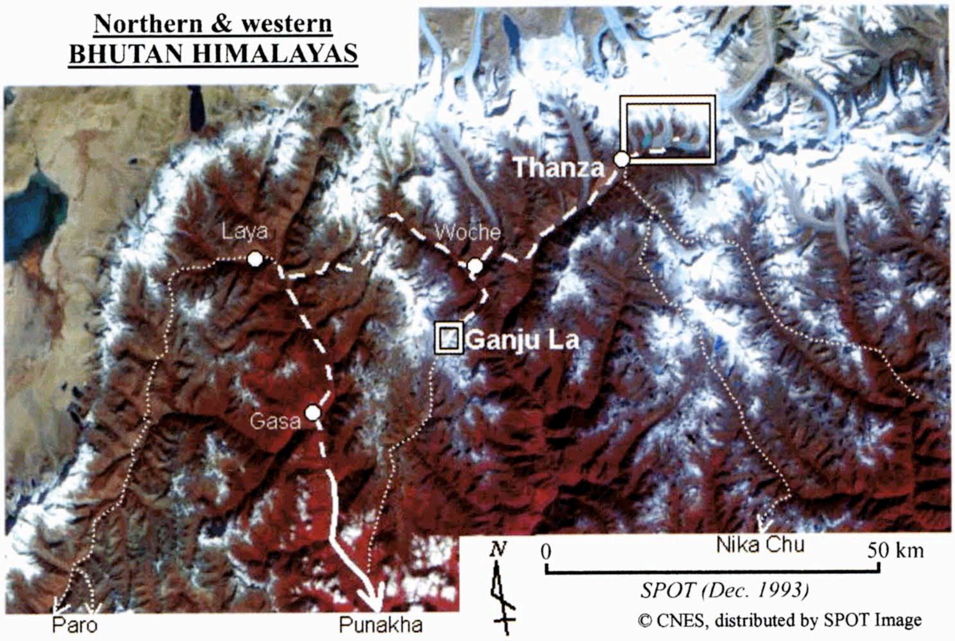

Fig. 1. Trekking route (thick dashed line) and research areas (squared areas). Thin dotted lines are other existing trekking routes.

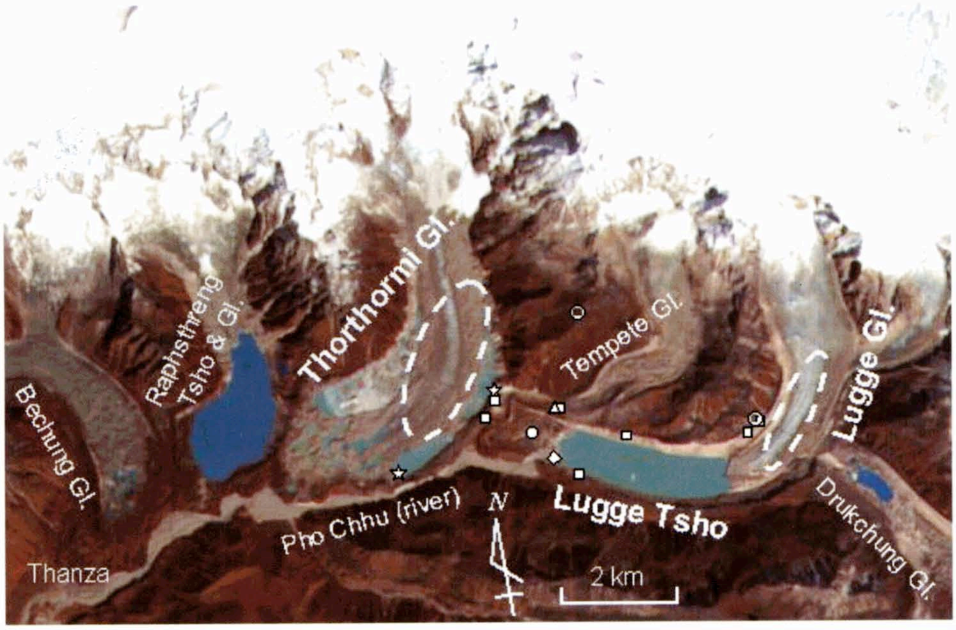

Fig 2. Distribution of glaciers and glacier lakes in the eastern Lunana, Bhutan Himalayas. (The based satellite image was taken on 20 Nov., 2001, by ASTER sensor.) The symbols indicate as following;▲: BC, ●: Lugge AWS, ◎: Precipitation gauges, ◆: Hydrological Station, ★: Water level surveyed points of supra-glacial ponds on Thorthormi Glacier, ■: Benchmark for topographical survey. Stakes were installed in the enclosed areas by thick dashed lines on Lugge and Thorthormi Glaciers, and surface topographies of the glaciers were also surveyed in the areas. On the surface of debris-covered ablation area of Thorthormi Glacier, there exist many supra- glacial ponds. The above-mentioned water level surveyed points (★) are at edges of two well-developed ponds, which are slenderly located along the left lateral moraine.

The temporal variations of the meteorological components during our stay in the field until 11:00 on 6 October are shown in Fig. 3. Total precipitation during the 19 days was 42.6 mm. Weather was bad in the former period, as it can be seen in the variations of precipitation (Fig. 3 (b)), air and ground surface temperature (Fig. 3 (a)), and shortwave radiation (Fig. 3 (d)). The relative humidity was generally high (Fig. 3 (b)). The variations of wind speed and direction in Fig. 3 (c) indicate existence of mountain and valley winds system in this area; relatively strong wind in direction of NW, which coincides with the valley axis, (valley wind) in daytime and weak wind (mountain wind) in night. Such wind system is typical in monsoon season in the Himalayan regions (Inoue, 1976). The radiation components in Fig.3 (d) are shown as positive when those heat flow toward the ground surface. The albedo was evaluated to be 0.17 on average at this Lugge AWS site, where the surface is covered by sand. Longwave radiations are not directly measured. The upward longwave radiation can be calculated with the ground surface temperature, and the downward one could be estimated as the residual term in radiation budget.

The meteorological data during 1 full year will be obtained in 2003 autumn. They could contribute to mass balance study of glaciers and also the study of an expansion mechanism of glacier lakes in this region. This Lugge AWS system is planned to maintain for a long term in cooperation with GSB.

Precipitation is one of the most important meteorological components for the studies abovementioned; it is known to depend strongly on altitude and local topography. Therefore, additional two tipping-bucket precipitation gauges were installed in different altitudes around Lugge Tsho area as shown by ○ in Fig. 2. One is beside a benchmark for topographical survey on the ridge of right lateral moraine of Lugge Glacier, altitude of which is about 4660 m according to a handy GPS; the other is on a peak at northward of BC, altitude of which is 5043 m as described on the topographical map of 1/50,000. At the two sites, the maximum snow depth gauge and the total precipitation gauge are also installed. In fact, the precipitation has been automatically observed also at Thanza by the joint team of Austrian and GSB. After obtaining one year data in 2003 autumn, distribution of precipitation will be revealed on altitude and along Pho Chhu river valley by utilizing all the available data.

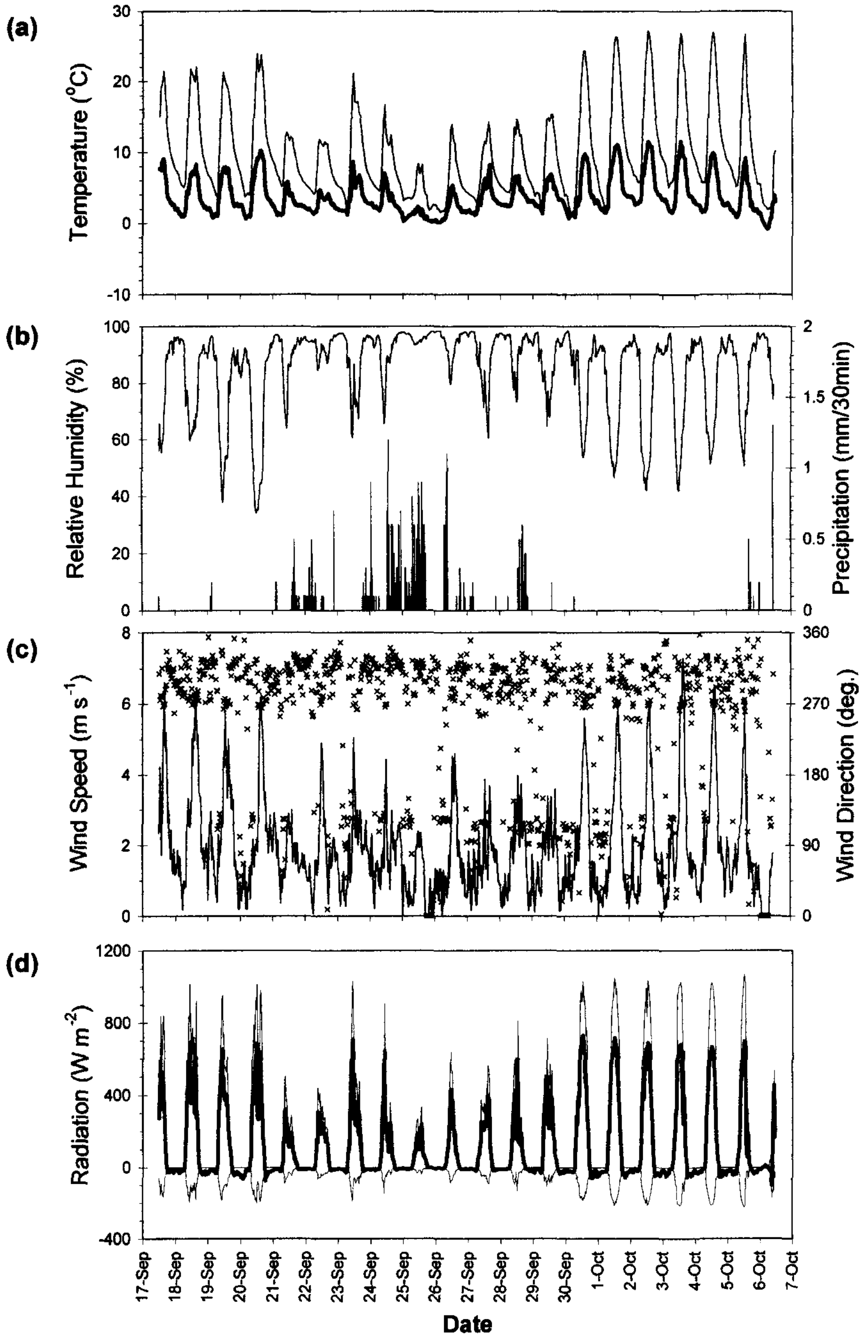

Fig. 3. Temporal variation of each meteorological element recorded at Lugge AWS during 19 days in 2002 autumn. Recording interval is 30 minutes for all elements except ground temperature, the interval of which is 1 hour. (a) Air temperature (thick line) and ground surface temperature (thin line). (b) Relative humidity (line for left axis) and precipitation (bar for right axis). (c) Wind speed (line for left axis) and wind direction (cross symbol, × for right axis). (d) Net radiation (thick line), downward (upper thin line) and upward (lower thin line) shortwave radiation. Sign is positive when heat flows toward the ground surface.

4. Observation of Lugge Tsho

Lugge Tsho is one of the typical moraine-dammed glacier lakes in the Bhutan Himalayas. Though the lake once released quantities of lake water in 1994, the risk of future GLOF remains high since the lake still stored enough amount of water, and the moraine dam was not yet completely collapsed.

As the basic information for the risk assessment of future GLOF, the characteristics of the Lugge Tsho were investigated.

4.1. Configuration of the lake basin

To understand the configuration of the Lugge Tsho basin, the depths of the lake were measured by a measure tape with a weight from a hand-rowing rubber boat. The measurement was made at 70 points during 4 days from 25 to 28 September. The measurement points were surveyed using a differential GPS system and a laser distance meter as an auxiliary.

The bathymetric map of the Lugge Tsho is shown in Fig. 4. The positions of the down-lake shore and the up-lake shore are surveyed by using a digital theodolite and a laser distance meter which will be mentioned later. Both lateral sides of the lake were determined by the distance between the boat position and the shore of the left and right lateral moraines, with the help of a topographical map (1:50,000) and a satellite imagery taken on 19 September 2002. The boat position was measured by the differential GPS system and the distance between the boat and both the shores of the moraines was measured by the laser distance meter with accuracy of 1 m.

The deepest depth of 126 m appears near the terminus of the Lugge Glacier and the average depth is 49.9 m. The lake area and the stored water is roughly estimated to be 117 ha and 58.3 million m^3, respectively. Thus, although the Lugge Tsho has already generated a GLOF in 1994, the lake still stores abundant water enough to generate another GLOF again. A continuous attention should be paid on monitoring changes of moraine-dam around the outlet of Lugge Tsho.

4.2 Water temperature and turbidity profile

In order to investigate the thermal and density structures of Lugge Tsho, the vertical profiles of water temperature (T, °C) and turbidity (ppm) were measured on 29 September by a TTD Profiler (Model: ATU200) at 4 points shown by ● in Fig. 4. The water temperature profiles are also allowed to estimate the change of stored heat in the lake, which is one of the important terms for assessing heat budget of the lake. Vertical profiles of water temperature, suspended sediment concentration (*SSC*), and calculated bulk density σ are shown in Fig. 5. The *SSC* is converted from measured value by using a relationship, which is described in Fig. 4 of Chikita *et al.* (1999).

Since lake water includes fine suspended particles, density of which (*SD*) is assumed to be 2730 kg m^{-3}, and its bulk density (*BD*) is higher than that of pure water (*WD*) as calculated by the following equations:

$$BD = (1 - SSC/SD) \times WD + SSC, \qquad (1)$$

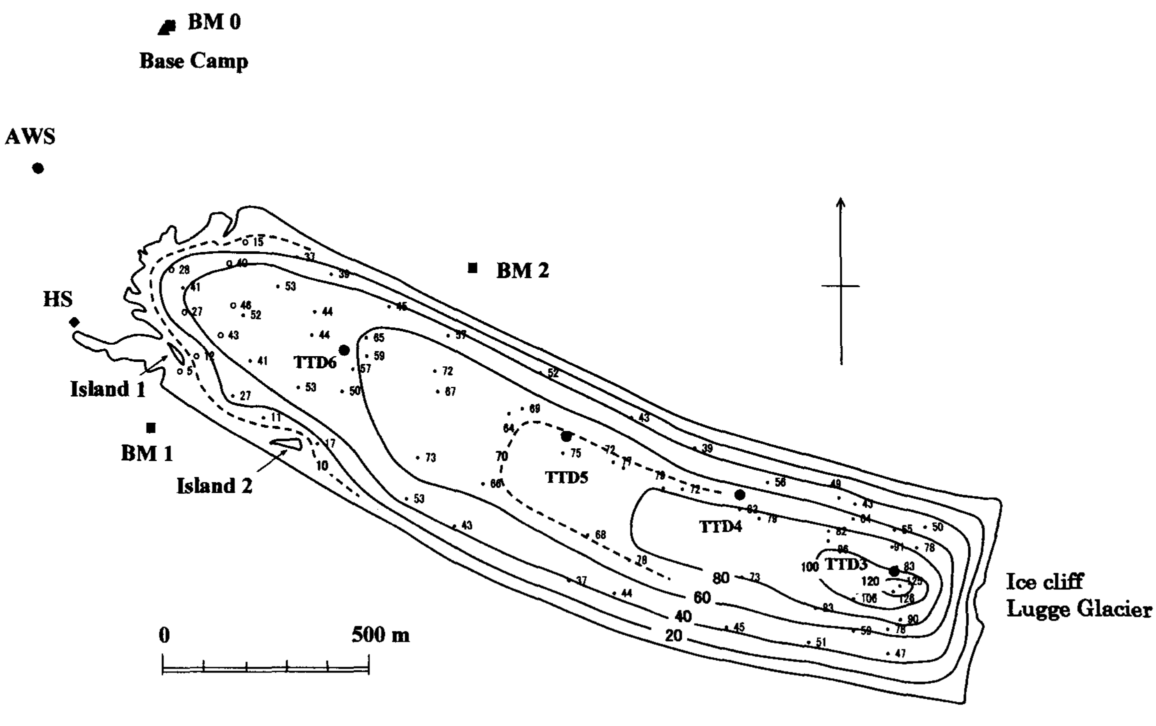

Fig. 4. Bathymetric map of Lugge Tsho. Small figures in the map represent depths of the lake measured at their surveyed points, the unit of which is meter.

$$WD = 1000 \times \{1 - (T + 288.9414) \times (T - 3.9863)^2 / (508929.2 / (T + 68.12963))\}, \quad (2)$$

where T is water temperature (°C). The Eq. 2 is an empirical equation called as the Thiesen-Scheel-Diesselhorst equation (Maidment, 1993). Since BD is nearly equal to 1000 kg m^{-3}, the density is represented by the deviation, σ, defined by $\sigma = (BD - 1000) \times 10$.

The lake water is characterized by extremely rich suspended sediment more than 0.3 g L^{-1} in concentration. The concentration profile of site TTD3 shows

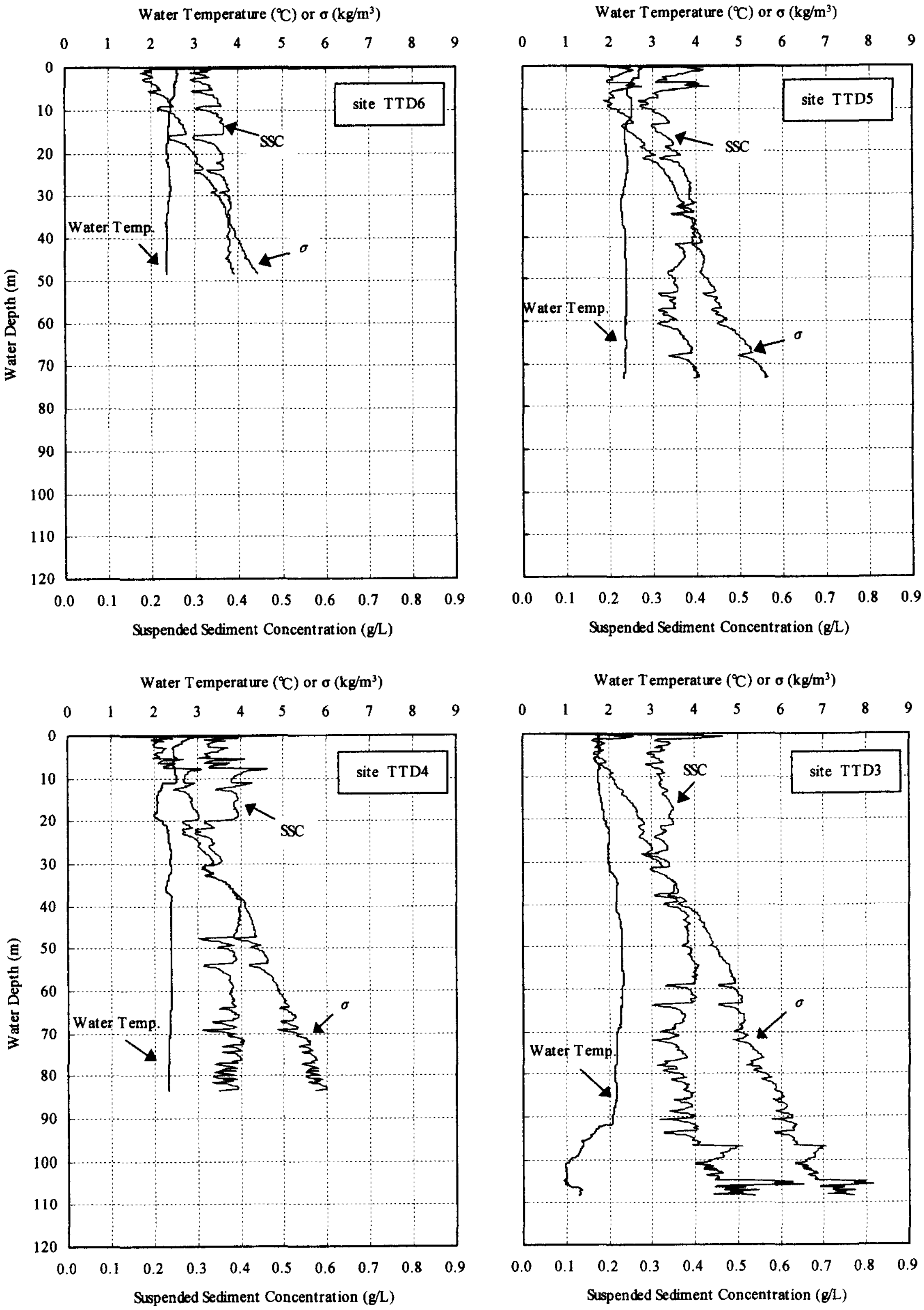

Fig. 5. Profiles of water temperature, suspended sediment concentration (SSC) and bulk density (σ).

relatively high *SSC* in the intermediate layer of 30 to 70 m in depth. The thickness of this intermediate layer gradually decreases from up-lake to down-lake as seen from site TTD4 to TTD6. This suggests the horizontal intrusion of "suspension interflow" from site TTD3 to TTD6. The bottom layer of the lake at site TTD3 near the glacier terminus is obviously occupied by the relatively cold and high turbid water at more than 95 m in depth. These characteristic *SSC* profiles are attributed to two main waters flowing into the lake. One is supra-glacial stream water from Drukchung Glacier via Lugge Glacier surface. The stream may mainly flow into the intermediate layer of Lugge Tsho. The other is water coming through the en-glacial drainage system of Lugge Glacier, which is characterized by relatively cold and sediment rich water. The water directly flows into the lake from the en-glacial channel or channels opening underwater on the lake-sided slope under the ice cliff. The water creates the cold and sediment rich layer seen just above the bottom of site TTD3. This indicates that the inflow water generated the sediment-laden underflow on the down-lake slope of the glacier.

Water temperature falls in relatively narrow range between 2 and 3°C throughout the depth, except for the bottom layer at site TTD3, and there is no warm water in the surface layer, suggesting no active warming by radiation in this season.

The density profiles indicate that the lake generally stands in the stable density stratification, though many unstable layers are seen in the intermediate layers due to horizontal intrusion of relatively turbid water at many depths.

4.3 *Discharge from Lugge Tsho watershed*

To investigate hydrological features of the Lugge watershed, water level and discharge were measured at the outlet of the lake and the relationship between them was obtained. The Hydrological Station is shown by ◆ (HS) in Fig. 4.

The relative water level was automatically measured with 1 hour interval from 14:00 on 23 September to 12:30 on 5 October by a hydrostatic pressure type water level gauge. The gauge is still operating and 1 year long data will obtained in the autumn of 2003. The relative water level measured by the gauge is converted into absolute water level by referring to a fixed point (Water Level Benchmark) on a big rock near the site. The fixed point consists of a steel bolt embedded into the rock. The temporal variation of the absolute water level is shown in Fig. 6. Water level slightly decreased with time during September and remarkably increased in October. A typical post monsoon climate began and fine days continued from 1 October. Water level only changed within 20 cm in the observation period of 12 days.

The discharge was calculated by the water depth and the 60% depth flow velocity measured each at 10 vertical sections along a transversal cross section, the surface width of which was 980 cm, at the outlet site. The relationship between the absolute water level (the vertical distance from the water surface to the water level Benchmark) and the discharge is shown in Fig. 7. Using the relationship, the automatically measured water level is converted into the discharge. Temporal variation of the resulted discharge is shown in Fig. 8. The amount of discharge is varied from 2.5 to 5 $m^3 s^{-1}$ in this season. In the fine weather beginning on 1 October, the discharge remarkably increases up to 5 $m^3 s^{-1}$. The daily discharge from the area of 54.2 km^2, derived from the 1/50,000 topographical map, is varied from 230,500 to 369,800 $m^3 day^{-1}$, which corresponds to daily runoff from 4.3 to 6.8 mm.

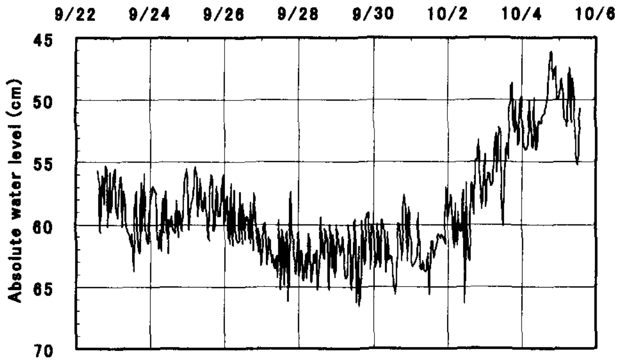

Fig. 6. Temporal variation of absolute water level.

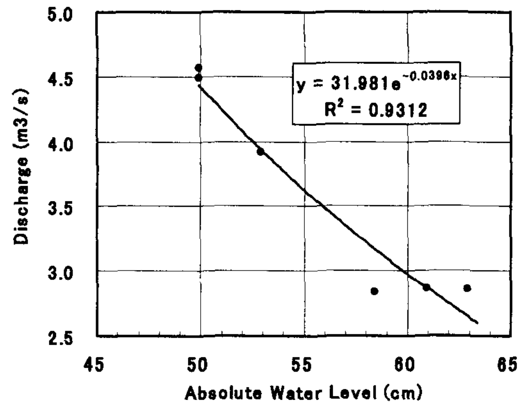

Fig. 7. Relationship between absolute water level and discharge.

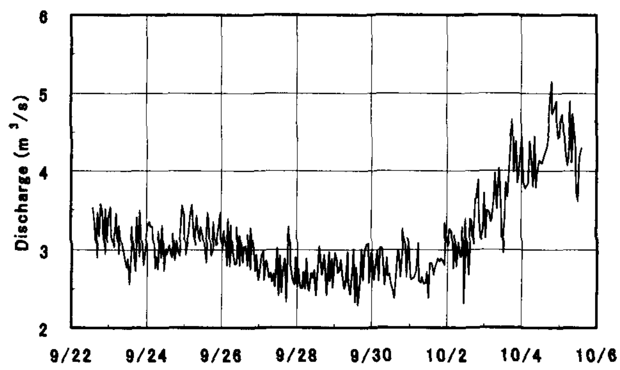

Fig. 8. Temporal variation of discharge.

5. Observation of debris-covered glaciers

Though six debris-covered glaciers are concentrated in the Lugge area, only Lugge and Raphsthreng Glaciers have well developed moraine-dammed glacier lakes on their ablation areas (see Fig. 2). As mentioned in the introduction, Lugge Tsho had once burst in 1994. It is still evaluated as very dangerous (Ageta and Iwata, 1999) because the lake still stored abundant volume of water behind the moraine. Among the other glaciers with no big lake, Thorthormi Glacier has many supra-glacial ponds on its ablation area. Since those ponds are growing according to the inspection of satellite imaginaries taken in different years (Ageta *et al.*, 2000) the supra-glacial ponds are considered to be developing into one moraine-dammed glacier lake by means of enlargement of ponds and connecting to each other. A moraine-dammed glacier lake is now gradually forming on Thorthormi Glacier. Therefore, Lugge Glacier and Thorthormi Glacier are chosen as the typical glaciers, already having a lake and under the process of lake formation, respectively. Once a lake has formed, it expands in unbelievably high rate (Yamada, 1998). Lugge Glacier is investigated as a typical sample in this stage. Meanwhile, the formation of a glacier lake essentially depends on the rate of surface lowering, which depends on the surface mass balance and the emergence velocity, i.e., thickening rate of a glacier due to compressive flow usually realized in the ablation area (Yamada *et al.*, 2003). These observations were planed to carry out on Thorthormi Glacier.

5.1. Stake setting

In order to measure distributions of surface mass balance and flow velocity, 21 stakes (about 3.5 m long bamboo poles) and 10 stakes were installed on the debris-covered ablation areas of Thorthormi and Lugge Glaciers, respectively. The stakes were located along a longitudinal line and a transversal line on each glacier. Their positions were all surveyed using a digital theodolite and a laser distance meter from the network of benchmarks, and they will be re-surveyed in 2003 autumn.

5.2. Topographical survey of glacier surface

The surface topographies of Lugge and Thorthormi Glaciers were surveyed, in addition to the stake points, in the areas enclosed by thick dashed lines in Fig. 2. Their cross-sectional profiles along a longitudinal line are shown in Fig. 9 (a) and (b), respectively. After re-survey in 2003, the annual surface lowering will be revealed.

The positions of the ice cliff, which will be described later, are also shown by + in Fig. 9 (a). Since approaching near the ice cliff is dangerous, the most downstream surveyed point on the Lugge Glacier is located at distance of about 500 m from the ice cliff. Similarly it is very risky to approach to downstream part of the ablation area of Thorthormi Glacier because of many ponds developing there.

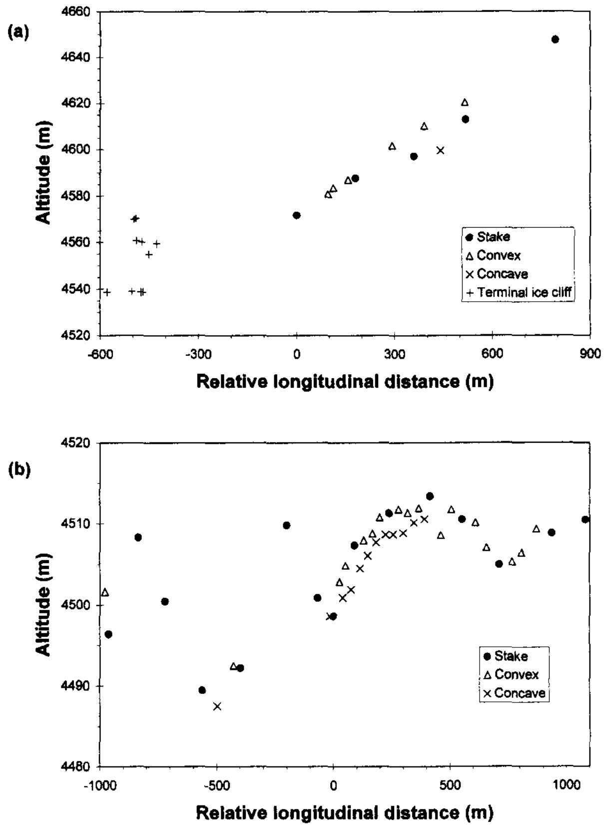

Fig. 9. Surface topography along the longitudinal line of (a) Lugge Glacier and (b) Thorthormi Glacier. The relative longitudinal distance refers to the cross point with the transversal survey line as positive to upstream.

Ogives are well developed on upper part of the ablation area below an icefall of Thorthormi Glacier. Densely surveyed points around 0 to 400 m in relative longitudinal distance in Fig. 9 (b) were surveyed tops (△) and bottoms (×) of the ogive waves. The height of each ogive and the horizontal interval of the ogive waves are about 2–3 m and 40 m, respectively. Since the ogives are formed due to a seasonal fluctuation of glacier flow, their horizontal intervals suggest annual flow speeds, assuming steady state of glacier flow. Surface flow speed of Thorthormi Glacier would be roughly 40 $\mathrm{m\,a^{-1}}$ in the upper ablation area, exact value of which will be obtained after re-survey of the stakes in 2003 autumn.

The surface flow speed (U_s) should consist of plastic deformation (U_d) and basal flow (U_b). The U_d depends on ice thickness, surface slope, ice temperature, and transversal cross-sectional shape as represented by a following equation:

$$U_d = \frac{A}{2}(f\rho g \sin\alpha)^3 H^4, \quad (3)$$

where A is a function of ice temperature, f is a factor depending on a ratio of glacier width to ice thickness in a simple sense, ρ is ice density, g is a gravitational acceleration, α is a surface slope, and H is ice thickness. If ignoring U_b, H is calculated to be about 490 m by using Eq. 3 under giving $U_d \approx U_s \approx 40$ m a^{-1}, $A = 6.8 \times 10^{-24}$ s^{-1} Pa^{-3} for ice temperature of 0 °C, $\alpha = 12$ m/400 m $= 0.03$ (see Fig. 9 (b)), and assuming $f = 0.7$. However, because U_b is probably not negligible in Thorthormi Glacier, the calculated value of 490 m might be a very weak referential value as the maximum estimate of ice thickness. Ice thickness is basically important information to consider glacier dynamics by means of any kind of glacier flow models. Its measurement is necessarily desired in near future to reveal the formation mechanism of a glacier lake.

5.3. *Survey of the shorelines at the down-lake end and at the up-lake end of Lugge Tsho*

The shoreline of the down-lake end was surveyed at 68 points. The up-lake end, where is the ice cliff of the Lugge Glacier terminus contacting with Lugge Tsho, was surveyed at ten points, consisting of 6 points at tops of the cliff and 4 points at the shoreline of the cliff, by using the digital theodolite and the laser distance meter. The results are shown in Fig. 4 and Fig. 9 (a). Re-survey in 2003 will reveal how much Lugge Tsho would expand (maybe impossible to retreat).

The altitude differences between the top and the shoreline of the ice cliff in Fig. 9 (a) indicate heights of the cliff from the lake surface. The minimum height was 16.2 m, the maximum was 31.7 m, and the average was in between 20-30 m. The altitude of the lake level was surveyed to be 4538.7 m in average in the reference to the altitude of BC benchmark, 4550 m.

5.4. *Water level survey of supra-glacial ponds on Thorthormi Glacier*

Though a big glacier lake has never been formed on Thorthormi Glacier, many supra-glacial ponds are distributed (Fig. 2). Among them, the three ponds are relatively well developed. The most developed pond is located along the right lateral moraine, and many icebergs are floating on the pond. The other two developed ponds are slenderly located along the left lateral moraine. The left lateral moraine ridge is eroded from both sides; by water of the two ponds at the inner side and by the river stream of Pho Chhu, including a GLOF event happened in 1994, at the outer side. Because this ridge is very sharp, there has been a doubt that some water might leak from the inner ponds through the moraine and it could weaken strength of the moraine. This topic is discussed in the following section.

On the other hand, if an en-glacial conduit connects supra-glacial ponds, it will accelerate the shrinkage of the glacier as Sakai *et al.* (2000) was suggested. Therefore, it is important for study of glacier shrinkage to inspect how many en-glacial conduits exist and which ponds are connected each other. For this purpose, water levels were surveyed on the two well developed ponds along the left lateral moraine. The surveyed points are shown by ★ in Fig. 2. As the result, the water level of the downstream pond was 3 cm lower than that of the upstream pond. Because the difference of 3 cm is too small considering surveying accuracy, the water levels of these two ponds should be rather concluded to have no significant difference. In other words, there must be an en-glacial conduit connecting the two ponds, and the two ponds might join together in near future.

In addition to above mentioned research works, microorganisms affecting the surface albedo of the glacier were sampled at many points on the ablation areas of Lugge and Thorthormi Glaciers.

6. Origin inspection of water sprang out from the left lateral moraine of Thorthormi Glacier

Waters sprang out at many places in the outside of the left lateral moraine of Thorthormi Glacier to the right bank of the river Pho Chhu. Are the waters originated from the pond waters scattered on the ablation area of Thorthormi Glacier? If the waters are leakage from the ponds, the left moraine will be deteriorated and tend to collapse easily in future. For inspecting an origin of these waters, electric conductivity (EC) and water temperature (T_w) were measured at 12 points along the right bank of Pho Chhu. The EC value was automatically converted to the value at temperature of 25 °C by the EC meter.

The waters possibly originate from three sources such as the leakage-water from a pond-water on Thorthormi Glacier, underflow of the river-water of Pho Chhu and a groundwater. The values of EC and T_w of the pond-water on Thorthormi Glacier directly contacting with the left lateral moraine were measured, obtaining 5.05 μs m^{-1} and 0.7 °C. Those of the outlet-water from Thorthormi Glacier was 5.15 μs m^{-1} and 3.4 °C. Pho Chhu water was measured at many points along the river, obtaining 3.80～3.95 μs m^{-1} and 3.3～3.6 °C. Since the value of EC is distinctly different between waters from the Thorthormi Glacier and from the Pho Chhu, the origin of waters sprang would be inspected by measuring EC. The value of T_w also can be used as a reference.

The data suggest that the waters sprang out at 10 points except that at 2 points near the outlet of Thorthormi Glacier are originated from the underflows of Pho Chhu, because their values of EC and T_w are clearly fallen within those ranges of the river-water of Pho Chhu. Even if possible change of EC

from that of the pond-water during leakage through moraine is taken into consideration, the *EC* should have naturally increased in this case, but our measurement results at the 10 points were lower enough than that of the pond-water. On the other hand, water at a point sprang out near the outlet is obviously identified as seepages of the outlet water, because the value of *EC* is the same as that of the pond-water and the outlet-water. Then, water at the other point near the outlet is identified as a groundwater due to extremely high *EC* value of 12.7 $\mu s\,m^{-1}$ in comparison with those of the river-water, the pond-water and the outlet-water.

As a result, no leakage was fortunately found from the Thorthormi Glacier through the left lateral moraine. Thus, there is no apprehension of moraine deterioration due to leakage.

7. Ground temperature observation

7.1. Experiment of diurnal change of rock surface temperature

According to the GLOFs of Mingbo Glacier in 1977 (Fushimi *et al.*, 1985) and Langmoche Glacier in 1985, debris falls as well as avalanches are possible triggers to cause GLOF in case that there is a steep rock wall just behind a glacier lake. If diurnal temperature change in the rock wall surface is large, erosion process at the wall would be enhanced due to active freeze-thaw process, and larger debris falling could be happened (Gardner, 1992). In this viewpoint, it may be important to examine the diurnal change of rock surface temperature. At higher altitude in the Himalayas, black lichens often cover rocky surface around accumulation areas of large glaciers in the Himalayas. It would absorb the solar radiation effectively, causing the upward air mass, and forming the cumulus cloud along the southern slope. In short, the diurnal change of the rock surface temperature could play an important role both to the local climate and the weathering process.

A preliminary experiment of the rock surface temperature was carried out at BC from 26 September to 3 October by using temperature sensors wrapped with black and white vinyl tapes, each. The former period of the experiment was rainy from 26 to 30 September and the later was fine from 1 to 4 October. Figure 10 is the result, showing that the maximum surface temperature with black tape exceeded more than 30 °C, but that with white tape was around 20 °C. On the other hand, there is no signifcant difference in the minimum temperatures around 0 °C. As this experimental result suggests, the black lichens will make the rock surface temperature warmer during day time and will influence the active weathering at the higher altitude by accelerating the freeze-thaw process. Consequently, the accelerated weathering will produce a large amount of debris, which forms debris-covered glaciers, and moreover, there would be a possibility that the falling of huge debris could trigger GLOFs.

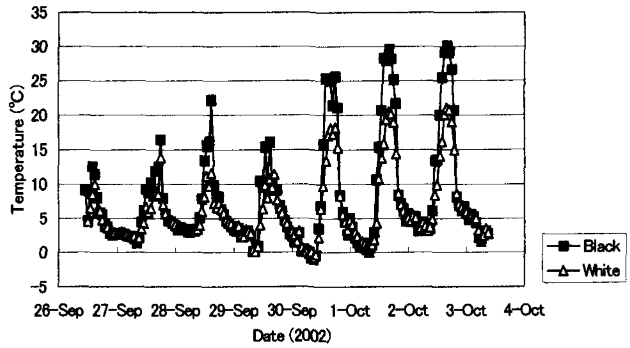

Fig. 10. Experiment of surface ground temperature by using black and white vinyl tapes at BC from 26 September to 3 October.

7.2. Ground temperature in moraines

The Himalayan glaciers are rapidly melting possibly by the global warming (Fushimi and Ohata, 1980; Yamada *et al.*, 1992; Ageta *et al.*, 2001). Similarly, melting of a permafrost layer enfeebles hardness or strength of the glacial moraine structure, and would cause GLOFs. So, it is important to measure the ground temperature in the moraines in order to check existence of the permafrost layer and to monitor its change. The preliminary results of the ground temperature measurement at 5 points around Tempete, Lugge and Thorthormi Glaciers are shown in Fig. 11. The measurements were carried out on 29 September, 1 and 2 October. From the temperature gradient, it could be guessed that there would be permafrost layer in deeper part at the altitude of 5239m in the upper part of Tempete Glacier, but the temperature gradients in the other 4 cases become smaller with depth and it is difficult to judge existence of permafrost there. The temperature profile at the altitude of 4570 m in the moraine of Thorthormi Glacier (⑤) is, how-

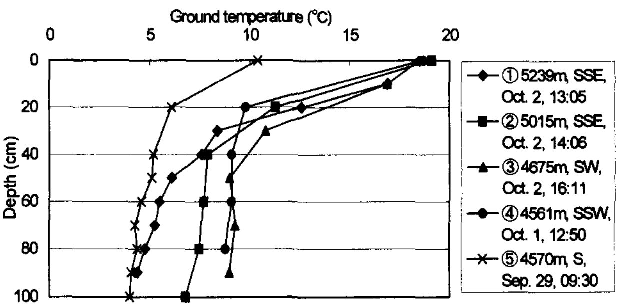

Fig. 11. Ground temperature profiles in moraines. Altitude, direction of ground surface, measured date and time at each site are described in the legend. Each location is; ①: upper, ②: middle, ③: lower parts of Tempete Glacier, ④: left lateral moraine near the outlet of Lugge Glacier, and ⑤: left lateral moraine of Thorthormi Glacier.

ever, quite lower than the other three cases, although the site is one of the two lowest measurement sites. Diurnal variation of the ground temperature is considered to be negligible below 50 cm depth (Fujii and Higuchi, 1976). Then, as seen in Fig. 3 (a) and Fig. 10, no large change in daily mean temperature during these 3 days can be recognized. Moreover, all the other measurement sites have similar ground directions from SSE to SW as S of the case ⑤. Although data and information are limited and not enough to judge still, this difference in the temperature profile might be attributed to existence of permafrost in the moraine of Thorthormi Glacier. If the permafrost actually exists there and it is gradually melting away, strength of the moraine structure would be weakened against GLOF, which is worried in future at the Thorthormi Glacier when a big glacier lake would be formed from the present many supra-glacial ponds. Further investigation on the moraine structure and monitoring of its change are expected for the risk assessment of future GLOF.

8. Observation of a debris-free glacier

A debris-free glacier was investigated on Ganju La Glacier on the north slant of Ganju La (Ganju pass, see Fig. 1). A 50 cm depth pit observation and a 614 cm depth core drilling were performed at the same site on the upper part of the glacier to obtain annual net accumulation and algal biomass concentration in the glacier body. Chemical samplings were also carried out at both the pit and cores. Microorganisms on the glacier surface affecting the surface albedo were sampled at three altitudes on the glacier at 5000 m, 4850 m and 4750 m a.s.l. for the purpose to clarify altitudinal change in biomass and species-composition of the microorganisms. The location of the glacier terminus was surveyed for detecting glacier fluctuation in future.

The observed stratigraphy is shown in Fig. 12. Snow layers were occupied only upper 46 cm, consisting of 2 cm new snow on the surface and granular snow of 2 to 46 cm in depth. Below this depth, all the parts were constituted of superimposed ice. Three distinct black dirt layers were detected at 46 to 50, 151 to157 and 252 to 256 cm in depths and also several brown semi-dirt layers are found in the cores. According to the preliminary algae analysis, these dirt and semi-dirt layers consist of algal biomass. These algae are assumed to be bred at surface during summer season and create visible dirt layers. Therefore, algal biomass profile could be applied to core dating, because peaks in the profile would indicate summer surfaces (Yoshimura *et al.*, 2000). The uppermost dirt layer could be assumed to be created in the summer of 2002, suggesting the net accumulation in the late summer of 2002 to be 22.1 cm in water equivalent. Further analysis of the algal biomass is expected to reveal the annual net accumulation in this glacier.

Structures of algal community in the ice cores are being analyzed in laboratory, because those would provide useful information to judge whether the drilling site was in accumulation area or in ablation area. Analysis of the pollen in the cores is also planned in future. Pollen scattering is concentrated in a short season, and the season depends on the species of the pollen. Therefore, analysis of pollen concentrations in the cores with identification of their species could give good markers for core dating, too, as Ambach *et al.* (1966) tried it for pit samples. Further studies with these multiple methods are expected in near future for accurate core dating and determining the annual net accumulation in this glacier.

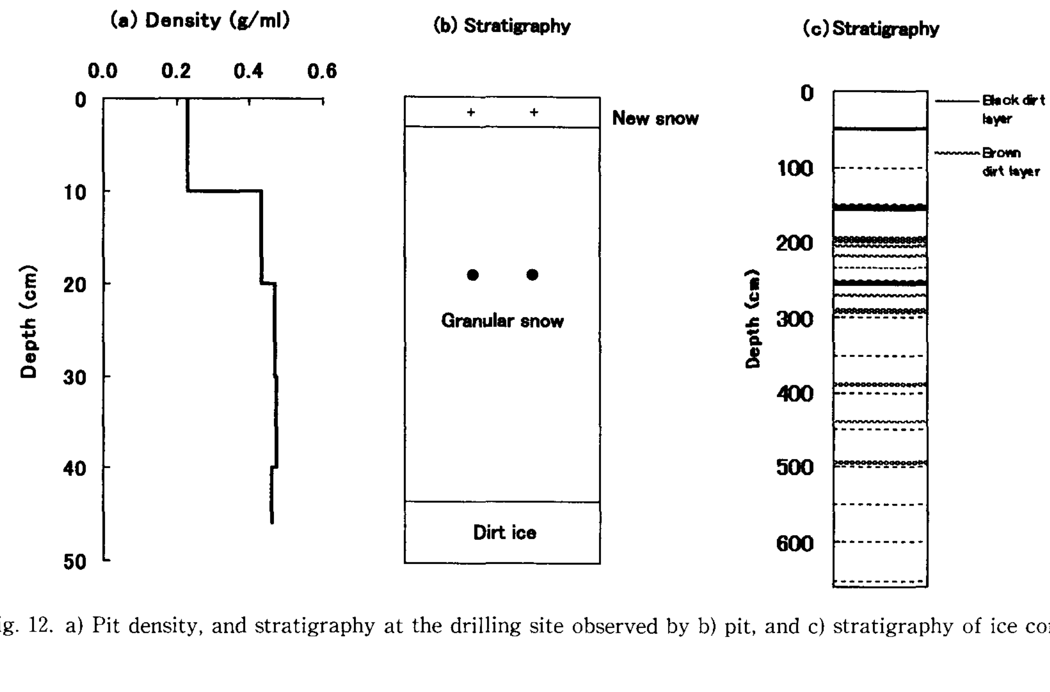

Fig. 12. a) Pit density, and stratigraphy at the drilling site observed by b) pit, and c) stratigraphy of ice cores.

The field works in the autumn of 2002 was carried out in the basis of preliminary investigation as the first year activity of the three-year-joint research project between Japan and Bhutan. Re-surveys and data collections from the instruments installed in 2002 are planned in the autumn of 2003. The re-surveys will reveal accurate expansion rate/process of Lugge Tsho, and annual mass balance, surface lowering and flow velocity of Lugge, Thorthormi and Ganju La Glaciers, and terminal retreat of Ganju La Glacier. Annual conditions of hydrology and meteorology will be also obtained by means of the automatic data loggers installed in 2002. These studies are still on-going. After harvesting above mentioned data, detailed discussions will be expected for the glaciers and the glacier lakes in Lunana region, Bhutan Himalayas.

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