Study of the Mass Balance of Small Glaciers in Khumbu Himal during the Summer Monsoon Season*

Yutaka Ageta** and Kazuhide Satow***

Abstract

Glaciological observations were made for the study of the glacier mass balance in the Nepal Himalayas, which is characterized by the simultaneous occurrence of considerable accumulation and ablation during the summer monsoon season. The upward change of the glacier surface level and the considerable amount of deposited snow due to the summer snowfall were observed at the end of summer over the whole area of the glaciers by means of stake measurements and stratigraphic observations respectively. On the other hand, the mass balance from July to September is calculated in consideration of the ice amount to be superimposed on the glacier ice of sub-zero temperature. The growth of the superimposed ice contributed to the positive mass balance in the upper-middle part of the glacier, while the mass balance during the same period was negative in the lower part. The total of the summer balance for the whole area of each observed glacier is concluded to have been positive. Such a positive summer balance is attributed mainly to the accumulation in late summer.

1. Introduction

It is an important characteristic of the glaciers in the Nepal Himalayas that the mass exchange of the glaciers is very active only during one season, namely, the summer monsoon season when much of the annual accumulation and ablation occur simultaneously. For the study of the mass balance of the glaciers under the complex circumstance mentioned above, stake measurements and stratigraphic observations, including measurements of the thermal conditions of the ice, were made during the monsoon season from June to September, 1976 in Khumbu Himal, east Nepal. These observational results concerning the mass balance are presented and the mass balance is discussed on the basis of these results in this paper.

2. Observed glaciers

Glacier EB 050**** (E09), Gyajo Glacier namely Glacier CB 480**** and Glacier DX 080**** (D07) were observed. The locations of these glaciers are shown in Fig. 1. All of them are small glaciers located near ridges and not covered with thick superficial moraines.

The locations of observed points on these glaciers are shown in the maps of Fig. 2. The map of Glacier EB 050 (Fig. 2a) was made on the basis of the glacier inventory by the Glaciological Expedition of Nepal. The index number by Muller (1970) is shown in parentheses.

* Glaciological Expedition of Nepal, Contribution No. 43  
** Faculty of Education, Yamaguchi University, Yamaguchi 753  
*** Nagaoka Technical College, Nagaoka, Niigata 940  
**** name quoted from the index number of the glacier inventory by the Glaciological Expedition of Nepal. The index number by Muller (1970) is shown in parentheses.
of the results of a triangular survey by the authors and ground photogrammetry around the terminus area by Iwata and Yokoyama. The area indicated with a dashed line in Fig. 2a is the steep slope of snow, ice and rock with a mean inclination of about 45°. This slope was not taken into account throughout the descriptions in the present study for lack of data, though the debris of avalanches from this slope was seen at its foot. The map of Gyajo Glacier (Fig. 2b) was made on the basis of a contour map by Tanaka (1972), with slight modification in the terminus area. The area and the elevation of the terminus of each glacier are as follows;

- Glacier EB 050: 0.42 km² 5160 m
- Gyajo Glacier: 1.08 km² 5270 m
- Glacier DX 080: 1.15 km² 5140 m

3. Results

3.1. Stake measurements

Stake measurements were made on Glacier EB 050 from June to September and on Gyajo Glacier from July to September. The bottom of each stake was buried into the glacier ice under the snow cover using an ice drill except for the stakes in the upper part of Glacier EB 050, where the thickness of the snow cover was more than 2 m. According to the stake measurements, the change of snow or ice thickness ($4s$) relative to the snow or ice surface on the date of the previous measurement can be observed. In the case of the present study, the surface at all stake points was covered with snow on the all dates of the measurements.

Fig. 3a shows $4s$ relative to the snow surface on June 17 or 20 as the zero level on Glacier EB 050 and Fig. 3b shows that on July 15 or 16 as the zero level on Gyajo Glacier. In these figures, the stake numbers in Fig. 2 are indicated for each curve.

It can be seen in Fig. 3a that $4s$ on Glacier EB 050 from the middle of June to the end of July was negative at some stakes in the middle plateau (5360 m-5300 m) and the lower part (5300 m+) of the glacier, while that during the latter half of
the monsoon season was high positive at all stakes. Since stakes L3, P2, P6, P8 and P11, of which heights above the snow surface on July 23 were about 100 cm, could not be found on September 23, $\Delta S$ during this period at these points is assumed to be more than 100 cm. As a whole, $\Delta S$ during the monsoon season was positive all over the glacier. On Gyajo Glacier, $\Delta S$ from the middle of July to the middle of September was positive at all stakes on the glacier as seen in Fig. 3b.

It can be said from Fig. 3a and 3b that $\Delta S$ at the end of the monsoon season relative to the zero level increased with increase of elevation on each glacier, although $\Delta S$ during the latter two months of the monsoon season on Glacier EB 050 was higher than that on Gyajo Glacier at the same elevation.

Stake measurements are convenient for the observation of the change of the surface level. However, without stratigraphic observations, $\Delta S$ cannot show the effects of the densification of snow and the refreezing of percolated water, the amounts of which are necessary for the exact assessment of the mass balance.

### 3.2. Stratigraphic observations

Stratigraphic observations were made on Glacier EB 050 in June and September, on Gyajo Glacier in July and September and on Glacier DX 080 in September. The results in September are shown in Fig. 4. Wet granular snow with a grain size of 1-4 mm and a density around 0.5 g/cm$^3$ was dominant over the glaciers during the monsoon season. The dirt layer was found in granular snow above the glacier ice except the lower part of each glacier where the dirt covered the glacier ice directly as shown in Fig. 4.

If the balance year of glaciers in the Nepal Himalayas is divided into two seasons, namely the 'summer season (wet season)' and the 'winter season (dry season)', it can be said that dirt layers are formed in the dry season as reported on Gyajo Glacier by Fushimi (1978). Therefore, the snow thickness above the dirt layers is a useful index concerned with the mass balance.

Since the snow above the dirt layer in Fig. 4 was deposited until the middle or the end of September after the formation of the dirt layer in the dry season, it represents the snow deposited during the summer season in the year of the observations, 1976. The amounts of it in water equivalent ($D_S$) against elevation on Glacier EB 050 and Gyajo Glacier are shown in Fig. 5 with the area in each elevation interval. The deposited snow in volume for the same elevation intervals as shown also in Fig. 5 was calculated on the assumption that $D_S$ had a linear relation with the elevation, which was different between the upper part (>5360 m), the middle plateau (5360 m-5300 m) and the lower part (<5300 m) of Glacier EB 050 (Fig. 5a) but was uniform over Gyajo Glacier (Fig. 5b). The amount of snow deposited during the summer season in 1976 in water equivalent for the whole area of each glacier and its average for a unit area are calculated as follows;

- **Glacier EB 050**: $2.4 \times 10^5$ m$^3$ 56 cm
- **Gyajo Glacier**: $3.8 \times 10^5$ m$^3$ 35 cm

It can be said from Fig. 5 that $D_S$ at a higher place was more than that at a lower place on each glacier, although Gyajo Glacier had a smaller value of $D_S$ at an equivalent elevation in comparison with those of other two glaciers as seen in the results of the depth at dirt layers in Fig. 4.
It was observed in September that the current summer snow covered even the termini of the three glaciers. These tendencies are similar to the results of the stake measurements described in Section 3.1. Stratigraphic observations of the dirt layer are useful for the evaluation of the amount of the snow deposited during the current summer. This can be obtained with only one visit to a glacier at the end of summer. However, $D_s$ cannot show the effect of the refreeze of melt water which percolates down to the glacier ice surface below the dirt layer as mentioned also in the case of the stake measurements in Section 3.1.

Therefore, the depth of the glacier ice surface below the snow surface was measured by means of pit observations as shown in Fig. 4. At some of observed points, such a depth was measured from the bottom of the pit by the use of a sounding stick which could pierce through thin ice layers, as shown with dashed lines in Fig. 4. Ice which could not be broken by the sounding stick was supposed to be the glacier ice, considering results which were confirmed by pit observations at neighbouring points. These results will be discussed in Chapter 4.

3.3. Thermal conditions in Glacier EB 050
The refreeze of melt water is controlled by the thermal conditions in the glacier. Therefore, the ice temperature was measured in a bored hole at P4 located in the middle plateau of Glacier EB 050 at 5330 m elevation, as shown in Fig. 2a. The zone of the middle plateau is in the category of 'soaked facies' (Benson, 1962) which is dominant in small glaciers with a small elevation span in Khumbu Himal.

An ice hole with a diameter of 10 cm was bored on June 22 to an ice depth of 369 cm from the bottom of the snow pit, which was dug down to the glacier ice surface at a snow depth of 146 cm from the snow surface. The total depth from the snow surface to the bottom of the ice hole was thus 515 cm. The ice hole was filled with water, due to soaked snow at the melting point, to the top of the hole until the next morning. Since freezing of water started from the bottom of the hole, the depth at the freezing front of the water which filled the hole was used as an indication of the freezing speed. Three resistance thermometers were set in the ice hole on June 24 at ice depths of 110 cm, 210 cm and 310 cm from the glacier ice surface.
The results are shown in Table 1.

It can be seen in Table 1 that the ice temperature was below the freezing point even in summer, though it was warmed up a little, as seen in the result of September 22, due to the summer temperature of air and snow. Ice temperature at a deeper point was lower than that near the glacier ice surface, so the freezing speed at the deeper part was higher in the first week, then decreased corresponding to the ascent of the freezing front to the shallower part. Then the freezing front reached the top of the ice hole. On the other hand, ice with a thickness of about 7 cm was superimposed on the glacier ice surface at P4 during the period from June 22 to September 22.

It can be said in view of ice temperature that the middle plateau of Glacier EB 050 has the characteristics of a 'polar glacier' in Ahlmann's geophysical classification (Ahlmann, 1948). Mae et al. (1975) obtained a similar result in Khumbu Glacier, Khumbu Himal (Fig. 1). The combination of soaked snow and cold ice, as described in this section, produces a suitable condition for the formation of the superimposed ice, since melt water at the freezing point in soaked snow can percolate down to the glacier ice surface; then its latent heat can be absorbed by the cold ice.

4. Discussions

4.1. Level changes of the surface, the dirt layer and the glacier ice

The change of the surface level ($ds$), the change of snow thickness above the dirt layer ($dd$) and the change of snow thickness above the glacier ice ($di$) during the period from July 15 to September 15 in 1976 obtained from the stake measurements and the stratigraphic observations on Gyajo Glacier.

<table>
<thead>
<tr>
<th>Point name with elevation</th>
<th>G1 5470m</th>
<th>G3 5440m</th>
<th>G5 5430m</th>
<th>G7 5415m</th>
<th>G9 5385m</th>
<th>G10 5360m</th>
<th>G11 5330m</th>
<th>G12 5325m</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ds$</td>
<td>+83</td>
<td>+75</td>
<td>+77</td>
<td>+59</td>
<td>+44</td>
<td>+25</td>
<td>+32</td>
<td>+22</td>
</tr>
<tr>
<td>$dd$</td>
<td>+86</td>
<td>+84</td>
<td>+86</td>
<td>+61</td>
<td>+55</td>
<td>+58</td>
<td>+61</td>
<td>+63</td>
</tr>
<tr>
<td>$di$</td>
<td>+72</td>
<td>+58</td>
<td>+72</td>
<td>+43</td>
<td>+44</td>
<td>+52</td>
<td>+54</td>
<td>+57</td>
</tr>
<tr>
<td>$ds-\Delta d$</td>
<td>- 3</td>
<td>- 9</td>
<td>- 9</td>
<td>- 2</td>
<td>- 11</td>
<td>- 33</td>
<td>- 29</td>
<td>- 41</td>
</tr>
<tr>
<td>$ds-\Delta i$</td>
<td>+11</td>
<td>+17</td>
<td>+ 5</td>
<td>+16</td>
<td>0</td>
<td>-27</td>
<td>-22</td>
<td>-35</td>
</tr>
</tbody>
</table>

* $I_s = 0.85(ds-\Delta i)-I_t$ : Change of mass in water equivalent (cm)  
* $I_s = 0.85(ds-\Delta i)$ : Water equivalent of $i_s(ds) - i_t(ds)$

$d$ : Change of snow thickness (cm)  
$ds = s_d - s_s$  $s_s(3x)$ : Stake height above the surface in September (July)  
$dd = d_s - d_d$  $d_s(d_d)$ : Snow thickness above the dirt layer in September (July)  
$di = i_s - i_d$  $i_s(d_i)$ : Snow thickness above the glacier ice in September (July)  
$D_s(d_d)$ : Water equivalent of $d_s(ds)$

Table 1. Freezing speed of melt water and ice temperature in the bored hole at P4, Glacier EB 050.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>1230</td>
<td>815</td>
<td>1145</td>
<td>1735</td>
<td>845</td>
<td>1315</td>
<td>930</td>
<td>1645</td>
<td>1155</td>
<td>1600</td>
</tr>
<tr>
<td>Depth of freezing front from ice surface (cm)</td>
<td>369</td>
<td>362</td>
<td>314</td>
<td>310</td>
<td>211</td>
<td>163</td>
<td>117</td>
<td>84</td>
<td>80</td>
<td>0*</td>
</tr>
<tr>
<td>Freezing speed (mm/hour)</td>
<td>3.5</td>
<td>17.5</td>
<td>7.0</td>
<td>15.7</td>
<td>16.8</td>
<td>6.7</td>
<td>3.1</td>
<td>2.4</td>
<td>&gt; 0.4</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ice temperature at the depth from ice surface (°C)</th>
<th>110 cm</th>
<th>210 cm</th>
<th>310 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.0</td>
<td>-1.2</td>
<td>-1.8</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>-1.2</td>
<td>-1.8</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
<td>-1.2</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

* It was not observed when the freezing front reached the top of the hole.
(0.0) means the temperature of melt water filled in the hole.
(đi) in Gyajo Glacier during the period from July 15, 16 to September 15 are shown in the upper lines of Table 2. The relations of  \( \Delta d > \Delta s > \Delta i \) at G1-G7 and of  \( \Delta d > \Delta i > \Delta s \) at G10-G12 can be seen in Table 2. In view of these relations, Gyajo Glacier can be divided into two parts by the boundary around G9, namely an upper-middle part and a lower part.

To explain the relations of these index values, representative models of the upper-middle part (G3) and the lower part (G11) are shown in Fig. 6. It can be seen in Fig. 6 that in both parts the level changes of the surface (\( \Delta s \)) were upward (positive) though those of the dirt layers (\( \Delta s - \Delta d \)) were downward (negative), while that of the glacier ice (\( \Delta s - \Delta i \)) was upward (positive) in the upper-middle part but downward (negative) in the lower part, with values as shown in the middle lines of Table 2.

The level changes as shown in Fig. 6 are explained as follows:
1) Upward changes of the surface level (\( \Delta s > 0 \)) even in the lower part were caused by considerable accumulation due to monsoonal snowfalls.
2) Downward changes of the dirt layer level (\( \Delta s - \Delta d < 0 \)) could be caused by the densification and the ablation of old snow which was seen below the dirt layer in July, and the ablation of the glacier ice in the lower part as will be described in 3). It is supposed that the ablation of the old snow covered with the dirt occurred when the current summer snow above the dirt layer happened to disappear temporarily during the period from July to September. It may also occur under strong radiation when the thickness of the current summer snow happened to be thin, according to the study on the internal melting of snow by Yosida (1960).

Anyway, the ablation mentioned above could occur easily at the lower part G10, G11 and G12, where the old snow with the thickness around 6 cm in July (\( i_s - d_i \) in Fig. 6) disappeared.
3) Upward change of the glacier ice level (\( \Delta s - \Delta i > 0 \)) in the upper-middle part of the glacier was caused by the growth of superimposed ice due to the refreezing of percolated water. The downward change (\( \Delta s - \Delta i < 0 \)) in the lower part was due to the ablation of the glacier ice under such conditions as the temporary disappearance or thinning of snow cover above it in connection with the ablation of the old snow mentioned in 2).

As explained above, two parts of the glacier were characterized respectively by the occurrences of the growth and the ablation of superimposed ice in summer. Since the ablation of the superimposed ice occurred under the condition described in 3), the upper limit of the area where the glacier ice was covered with the dirt directly till the end of summer (\( d_s = i_s \) in Fig. 6) due to the disappearance of the old snow, is considered to correspond with the boundary between them. These limits were observed at elevations of 5360 m on Gyajo Glacier, 5250 m on Glacier EB 050 and 5220 m on Glacier DX 080 in September, as shown in Fig. 4.

The higher elevation of this limit on Gyazo Glacier in comparison with those of other two glaciers corresponds to the tendency of Gyazo Glacier to have smaller values of \( \Delta s \) (as reported in Section 3.1), \( D_s \) (as reported in Section 3.2) and also \( i_s \) (in Fig. 4), at an equivalent elevation. However, the heights of the limits above the terminus of each glacier were similar to each other, namely around 90 m. The percentage of the area below the elevation of this limit to the whole area of each glacier was about 20% on Gyazo Glacier and Glacier DX 080, and 7% on Glacier EB 050.

4.2. Mass balance

The mass balance during the period from July to September in water equivalent can be obtained from the following formula, assuming 0.85 g/cm³ as the density of the superimposed ice.

\[
I_s + 0.85(\Delta s - \Delta i) - I_J
\]  (1)

Here \( I_s (I_J) \) is the water equivalent of snow above the glacier ice in September (July) with a snow thickness of \( i_s (i_J) \). This formula shows the mass change during the period above the level of the glacier ice, in July in the upper-middle part and in
September in the lower part, as seen in Fig. 6. The mass change below this level is negligible in both parts.

The mass increase due to the refreezing of melt water percolated into the old snow during this period can be evaluated as follows, if the density of the old snow is 0.50 g/cm³:

\[(0.85 - 0.50)(d_s - d_i)\]  \hspace{1cm} (2)

The mass change of the current summer snow during the period from July to September in water equivalent is given as follows:

\[D_S - D_J\]  \hspace{1cm} (3)

Here \(D_S(D_J)\) is the water equivalent of snow above the dirt layer in September (July) with a snow thickness of \(d_s(d_J)\). The results of formulas (1), (2) and (3) for Gyajo Glacier are shown in the lower lines of Table 2 and in Fig. 7 which also shows \(D_S\) (Fig. 5b).

It can be seen from these values that the refreezing of melt water made a contribution of 10-20% to the positive mass balance during the period from July to September in the upper-middle part. This contribution cannot be disregarded in a mass balance study. It also can be seen that the mass change of the current summer snow was not much different from the mass balance during the same period in the upper-middle part, but considerable difference can be seen in the lower part where the mass balance was negative in spite of an upward change of the surface level.

Consequently, the amount of snow deposited during the current summer \((D_S)\) reported in Section 3.2 is considered to be similar to the current ‘summer balance’ for the upper-middle part only. The results of the stake measurements \((\Delta s)\) reported in Section 3.1 are also supposed to be able to show the variation tendency of the mass balance for the upper-middle part only. However, the area of the part for which the above does not hold, namely the lower part, was a small percent of the whole area of each glacier, as mentioned in Section 4.1. Therefore, it can be inferred that the total of the summer balance for the whole area of each small glacier observed in the present study was positive.

Since \(D_S - D_J\) occupied 70-90% of \(D_S\) at each point on Gyajo Glacier (Fig. 7) and Glacier EB 050, it can be said that the positive summer balance is attributed mainly to the accumulation during the late summer, as also seen in the results of the stake measurements on Glacier EB 050 (Fig. 3a) and in the results on Gyajo Glacier in 1970 by Fushimi (1978). The precipitation at the terminus of Gyajo Glacier was about 80 cm in water equivalent during the period from July 15 to September 14, 1976. This value is thought to suggest that the amount of accumulation was more than two times the mass balance during the same period in the upper-middle part on Gyajo Glacier in Table 2.

In any case, for the exact measurements of the mass balance during the period of interest, the snow thickness above the glacier ice, the snow density and the level of the surface must be measured at the beginning and the end of the period over the whole area of the glacier, as seen in formula (1). Since some places in the upper part have thick snow cover above the glacier ice, as seen in the examples at U4 and U6 on Glacier EB 050 (Fig. 4a), it may be necessary to use substitute methods in the upper parts of some glaciers. On the other hand, in the lower part, if the glacier ice is always exposed to the surface in the ablation area, the stake measurements only are enough for the mass balance study, as seen in formula (1) \((I_S, I_J\) and \(\Delta i = 0)\). However, those only are not enough in the lower part of the small glaciers in the Nepal Himalayas where the considerable accumulation and ablation occur simultaneously during the summer. Therefore, full observations of the above items are required even at the terminus area.

5. Concluding remarks

The observational results concerned with the mass balance of the small glaciers during the summer monsoon season can be summarized as follows:

1) The level change of the glacier surface was upward over the whole area of the glaciers due to the summer snowfall, as shown by \(\Delta s\) obtained from the stake measurements.
2) The amount of snow deposited during the summer season was considerable over the whole area of the glaciers, as shown by $D_s$ obtained from the stratigraphic observations.

On the other hand, the mass balance from July to September, $I_s + 0.85(D_s - d_t) - I_t$, was calculated in consideration of the ice amount to be superimposed on the glacier ice of sub-zero temperature. The growth of the superimposed ice contributed to a positive mass balance in the upper-middle part of the glacier, while the mass balance during the same period was negative in the lower part. The general method was mentioned for the mass balance measurements on the glaciers where much of the annual accumulation and ablation occur simultaneously during the summer season.

The total of the summer balance for the whole area of each observed glacier was concluded to be positive. Such a positive summer balance was attributed mainly to the accumulation in late summer. It is now necessary to show how the mass balance of glaciers in the Nepal Himalayas varies through the year. It was reported by Ikegami and Inoue (1978) using the results of stake measurements that Kongma Glacier in Khumbu Himal had a negative balance mainly during the pre-monsoon season and a positive balance during the summer monsoon season. However, more intensive observations throughout the year are necessary.

References


