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Distribution of mass input on glaciers in the Langtang Valley, Nepal Himalayas

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Abstract

Distribution of glacier mass input is investigated by means of meteorological observations and snow surveys in the Langtang Valley. Amount of surface mass balance during the monsoon season is lower in the upper part than the middle part of the valley due to less precipitation and higher air temperature. The distribution of the balance during the non-monsoonal periods is almost uniform in the winter of 1990−1991, while it is not uniform in the winter of 1989−1990 due to less accumulation in the upper reaches of the valley. The southward decline of the equilibrium line altitudes in the Langtang Valley can be explained by the distribution of the mass input shown in this study.

1. Introduction

Distribution of glaciers in a drainage basin is closely related to a variation of local climates through the process of surface mass input and output. A significant spatial variation of local climate can be expected to make a spatial difference of mass balance regime of glaciers in a drainage basin if the sampling area is enough large such as valleys in the Himalayas. Because most of the valleys in the Himalayas consist of U-shaped deep valleys surrounded by over 6000 meters mountain ridges, altitudinal and horizontal variations of the large scale mountain-valley systems induce strong local circulations of wind in the monsoon period to make a significant variation of the small climate (Yasunari and Inoue, 1978).

Distribution of mass balance components in the Himalayan valleys has, however, not been fully observed in spite of intensive observations of specific glaciers such as the AX010 (Ageta *et al.*, 1980) and Yala (Iida *et al*, 1987 ; Ozawa, 1991). In order to clarify the effects of local climate on the mass balance of glaciers, snow surveys and meteorological observations have been conducted in the Langtang Valley, Nepal Himalayas, since 1989. In this paper, results of the recent observations are shown, and seasonal characteristics of the spatial distribution of the mass input on the glaciers are discussed.

2. Study area

Langtang Valley is located at the central part of the Nepal Himalayas (Fig. 1). The valley is surrounded by high mountain ranges which partly exceed 7000 m in altitude. The valley opens southward in its upper reaches, and turns to south-west at the altitude of 4100 m. Configuration of the valley is the typical U-shaped trough having wide floor delineated by precipitous trough walls.

Glaciers develop at the heads of every tributaries, and they occupy about 138 km^2 in area (Shiraiwa and Yamada, in press). There are two types of glacier in this area ; the clean type glacier and the debris-covered type glacier (Moribayashi and Higuchi, 1977). The clean type glaciers are relatively small, and they are mainly located at the altitudinal belt between 6000 m and 5100 m in which hypsographical peak appeared. The debris-covered type glaciers are, on the contrary, large valley glaciers extending from summits of prominent peaks down to lower valley bottoms. The equilibrium line altitude (ELA) in the valley is reported to decline from the valley head in the north-west to the mouth in the west (Zheng *et al.*, 1984).

From the analysis of the meteorological data taken at the bottom of the Langtang Valley (3920 m a.s.l.), it is found that 55% of the annual precipitation is rain during the monsoon season, while the rest is by the synoptic disturbance which brings snow in winter and snow/rain in spring (Takahashi *et al.*, 1987 ; Seko, 1987). In addition to the seasonal change, barrier effects of mountains and local circulations largely modify the precipitation systems to make diurnal and regional variations, and induce altitudinal differences of the precipitation as reported by Seko (1987).

The diurnal variation of the precipitation with altitude was initially discussed in the Langtang Valley by Ueno and Yamada (1990), however, the spatial distribution of precipitation was not clarified because of the difficulty of simultaneous observations in the high-altitudinal sites.

3. Observations

The distribution of mass input on the glaciers were investigated by means of the air temperature, precipitation, maximum snow depth, and the data of snow surveys on three glaciers. In the following discussions, Nepal Standard Time, which is GMT plus 5 hours 45 minutes, is used.

The air temperature was measured at the Glacier Camp (GC, 5090 m), Gangja La (GA, 5090 m) and Kyungka Ri (KY, 5180 m) from June 1989 to March 1991. The measurement sites were located at wind-blown morainic fields, where a possible influence of snow on the thermistor sensors is minimum. The thermistor sensors were installed at 180 cm above ground surface after shaded with white pipes, with natural ventilation. Data were recorded automatically every 30 minutes, and daily average values were

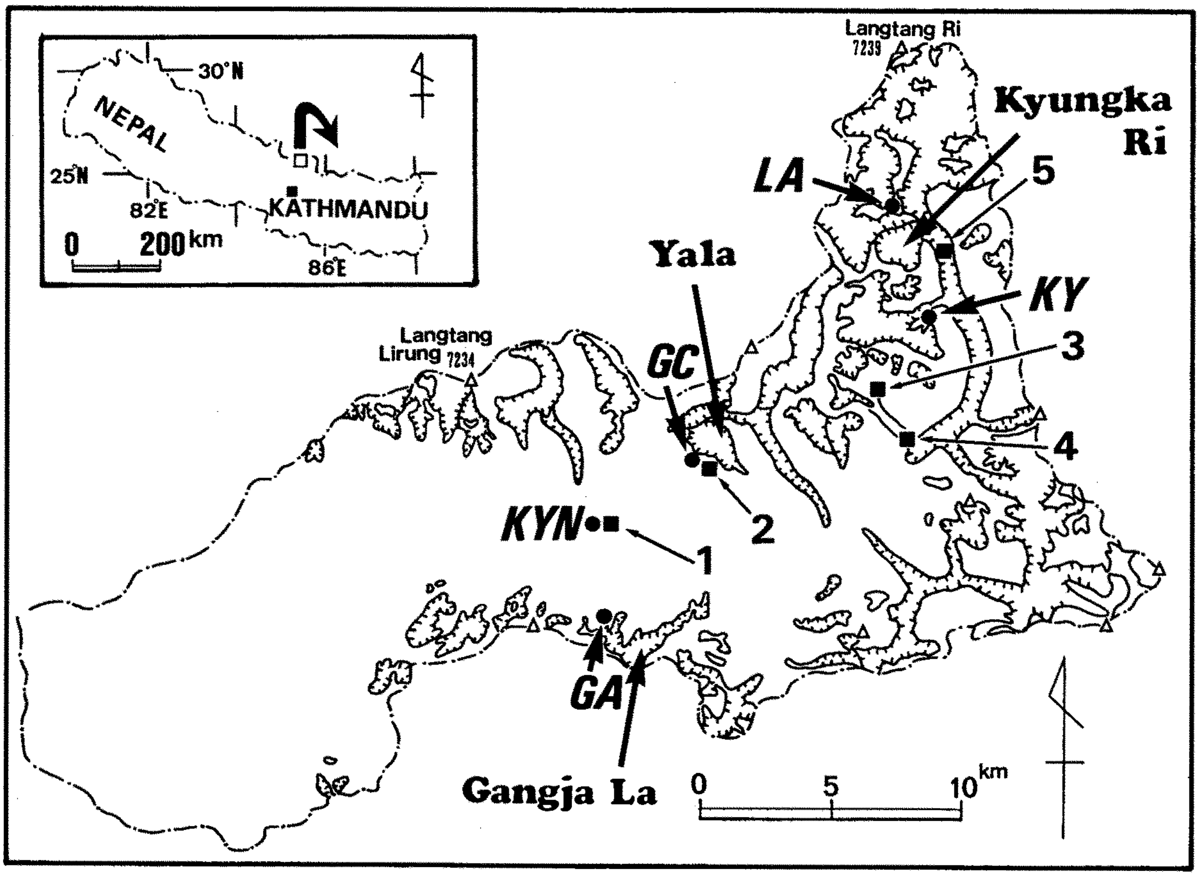

Fig. 1. Langtang Valley and the observation sites. Solid circles and solid squares indicate the meteorological observation sites and the sites where maximum snow depth was measured, respectively. 1 : Kyangchen (3920 m), 2 : Glacier Camp (5090 m), 3 : Pemdang Glacier (5013 m), 4 : Pemdang Kalkha (4677 m), 5 : Langtang Ri Base Camp (4942 m).

Fig. 2. Maximum snow depth meter at the Langtang Ri Base Camp (4942 m). Upper most bent bar denoted by the arrows indicates the level of maximum snow surface.

used for analysis.

Precipitation was measured from June 1990 to April 1991 by tipping-bucket gauge at Kyangchen (KYN, 3920 m), GC, GA and the Langtang Glacier (LA, 5300 m). Hourly data were obtained from the automatic data-logger system. Daily accumulated data during the monsoon season, June to September, were used for the analysis. Periods for probable snow falls are excluded.

Maximum snow depth in winter was estimated at five locations in the valley using maximum snow depth meters (Fig. 2). The meters were installed at KYN, GC, the Pemdang Glacier (5013 m), the Pemdang Kalkha (4677 m) and the Langtang Ri Base Camp (4942 m) on December 1989 (Fig. 1), and were withdrawn on June 1990.

Snow surveys were conducted on three small glaciers, the Yala, Gangja La and Kyungka Ri NW Glaciers (Figs. 1 and 3). They are clean type glaciers, having the almost same dimensions (Yala, 2.49 km^2 ; Gangja La, 3.54 km^2 ; Kyungka Ri NW, 1.6 km^2, respectively), and extending at almost same altitudinal belt. They are mainly nourished by snow falls rather than avalanches, since they are not surrounded by precipitous walls. Furthermore, they represent three geographical conditions of the valley ; south and north-facing slopes in the middle reaches, and uppermost reaches of the valley. The equilibrium lines on each glacier are considered to pass at the altitudes of approximately 5200 m, 5200 m and 5350 m, respectively.

The snow profiles were observed on May 1991, when the annual balance most likely closes to the maximum in the Himalayas (Ageta, 1983). Snow pits were excavated down to the depth of the previous dirt layer at several altitudes on the glaciers from May 5 to 22, 1991. Snow structure, thickness, density and temperature were measured at each profile.

4. Results

4.1. Air temperature

Seasonal variations of monthly mean air temperature at GC, GA and KY from June 1989 to March 1991 are shown in Fig. 4. Pre-monsoon season, from March to mid-June, is characterized by gradual increase of air temperature. Monsoon season, from mid-June to the end of September, is dominated by positive value of air temperature. In this season, diurnal variation of the air temperature is generally very small due to a thick cloud cover. The monsoon season suddenly ends at the end of September and is followed by the post-monsoon season, from October to December, which is characterized by fine weather. The air temperature decreases in this period, and the winter season begins in January. The winter is dominated by the monthly mean air temperature of approximately -10 ℃, although a relatively warm period is observed in the winter of 1989–1990.

Although the annual variations of the air temperature showed a similar pattern among the individual sites, variations of anomalies from the average values of three stations showed seasonal characteristics (Fig. 5). In this figure, 9-days running mean is performed to exclude the day to day variations. From November to January, three curves are almost close to each other. On the contrary, during rest of the period, KY

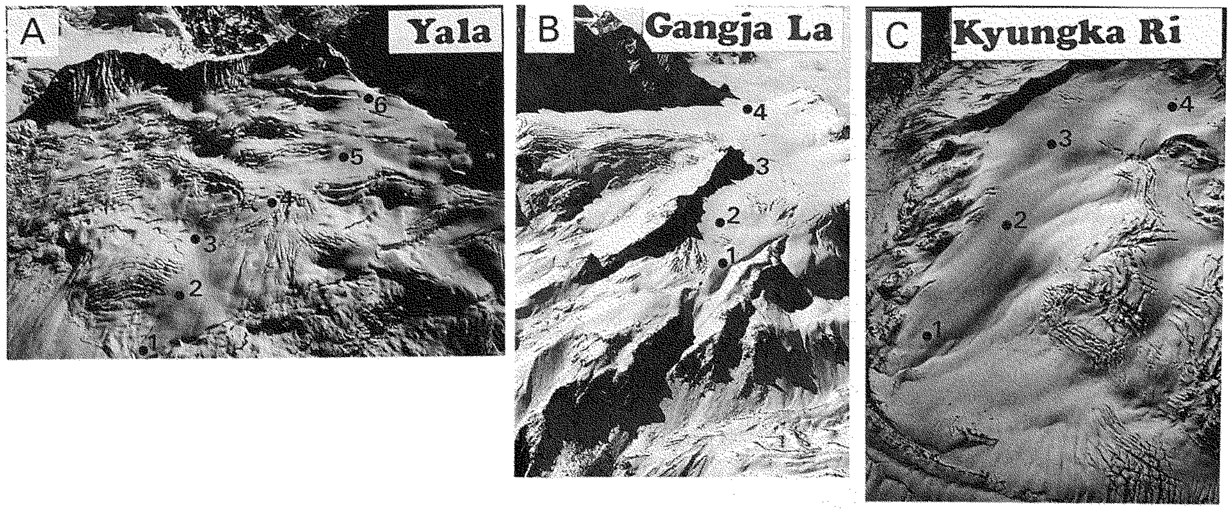

Fig. 3. Glaciers where snow surveys were conducted. Solid circles indicate the sites where snow pits were excavated. A : Yala, B : Gangja La, and C : Kyungka Ri NW Glaciers.

has relatively higher values and GC has lower ones comparing to the three stations' average. Particularly from the pre-monsoon to monsoon seasons, KY shows almost + 1 ℃ warmer conditions than that of GC. GA shows almost average values throughout the year except from February to April, 1990. Regional characteristics of the cloud amount and related sensible heating from the ground surface contribute to these characteristics.

4.2. Precipitation during the monsoon season of 1990

Precipitation is considered to be liquid during the monsoon season in Kyangchen, while it is supplied both as liquid or solid in other sites considering from the empirical relationship between mean surface air temperature and the percentage of solid precipitation (Ageta *et al.*, 1980). The percentage of solid precipitation, however, does not affect the amount of daily precipitation, since its contribution is recorded as liquid water in the gauge due to the melting in the day time.

Daily precipitation changes during the monsoon season in 1990 are shown in Fig. 6. Monsoon season in 1990, defined on the time series of precipitation, ambiguously started on 15 June and suddenly ended on 28 September. The four time-series change in the relatively same phase with cyclic fluctuations of 10 to 20 days, while absolute amount of precipitation varies considerably from station to station. Total amount of the precipitation during the observation period was as follows ; 541.5 mm in Kyangchen, 818.5 mm in the Glacier Camp, 959.0 mm in Gangja La and 556.0 mm in the Langtang Glacier. Total amount of precipitation at KYN (3920 m) is almost two third of that at GC and GA. Station KYN is located at the bottom of the valley where less precipitation from the cumulus clouds is brought comparing to the stations along the mountain slopes, as reported by Seko (1987) and Ueno and Yamada (1990). On the other hand, the precipitation at LA and KYN is nearly the same although the LA is located at almost the same altitude as GC and GA. This is because less moist air is conveyed to the upper part of the valley by monsoonal circulations prevailing from the south. Mountain barrier running west-east in the southern side of the valley prevents the moisture at low level from penetrating into the uppermost reaches of the valley. Meanwhile, the small difference of precipitation amount between GC and GA indicates the nearly the same precipitation condition between the south- and north-facing slopes at the middle reaches of the valley.

4.3. Maximum snow depth in the winter 1989 – 1990

Figure 7 shows the maximum snow depth during the winter of 1989–1990 at five stations shown in Fig. 1. It shows the altitudinal dependence of the maximum snow depth; the maximum snow depth increased with increasing altitude. But the station 5, which is located at the upper part of the valley, shows less snow comparing to that of the middle reaches of the

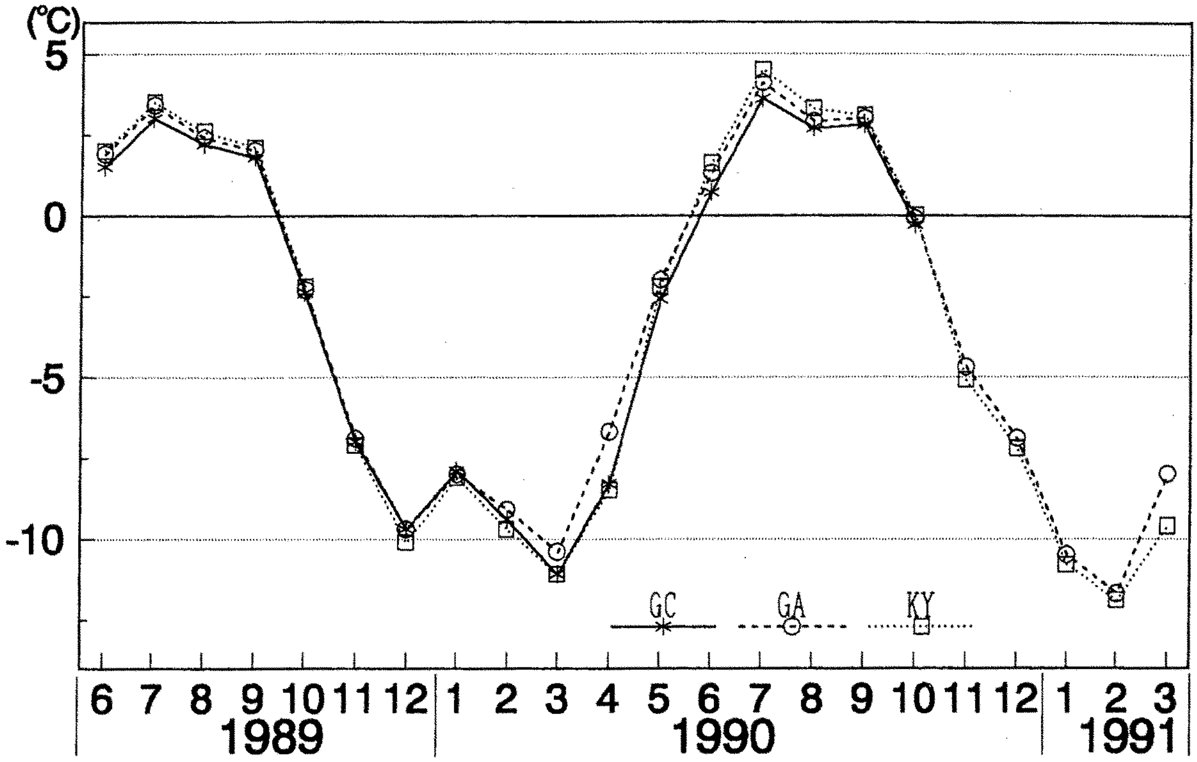

Fig. 4. Monthly mean air temperature at three observation sites from June 1989 to March 1991.

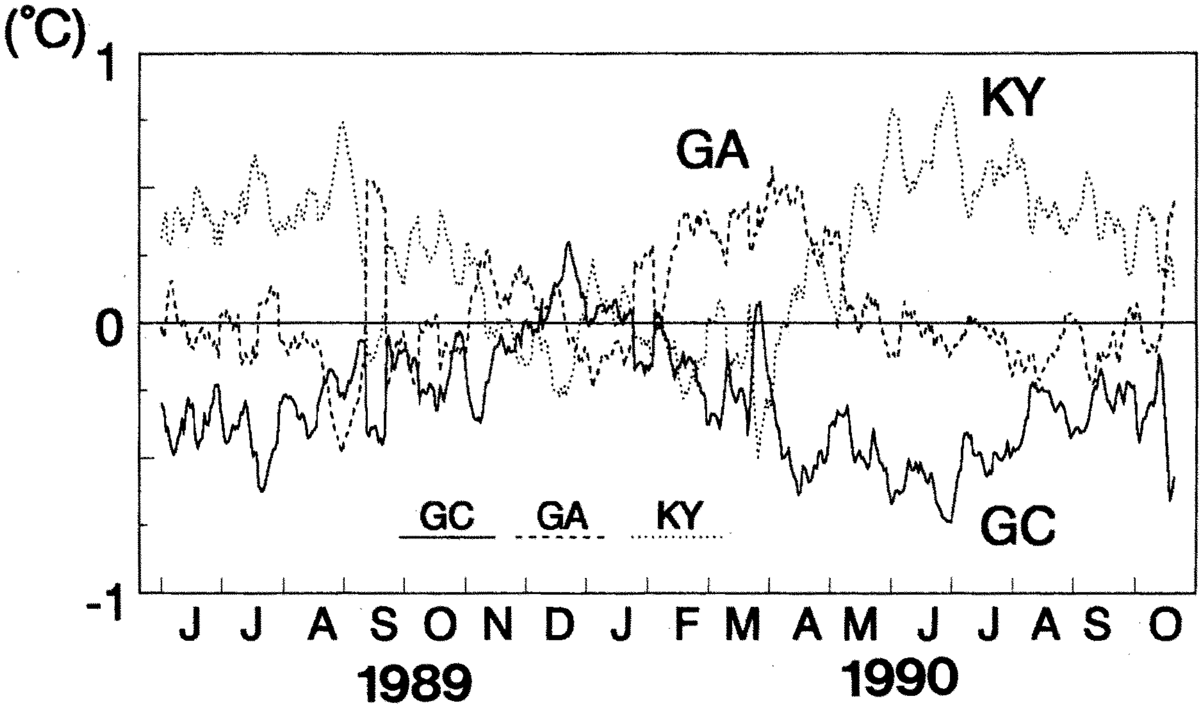

Fig. 5. Time-series of the 9 days running mean values of the air temperature anomalies from the average values of three stations. The air temperature at the Station KY (5140 m) was calibrated to the air temperature at the altitude of 5090 m, using a air temperature lapse rate of 6 ℃/km.

valley (Stations 2,3,4), although both are at the same altitude. The result suggests that the precipitation in winter is also less in the upper part of the valley like the summer of 1990.

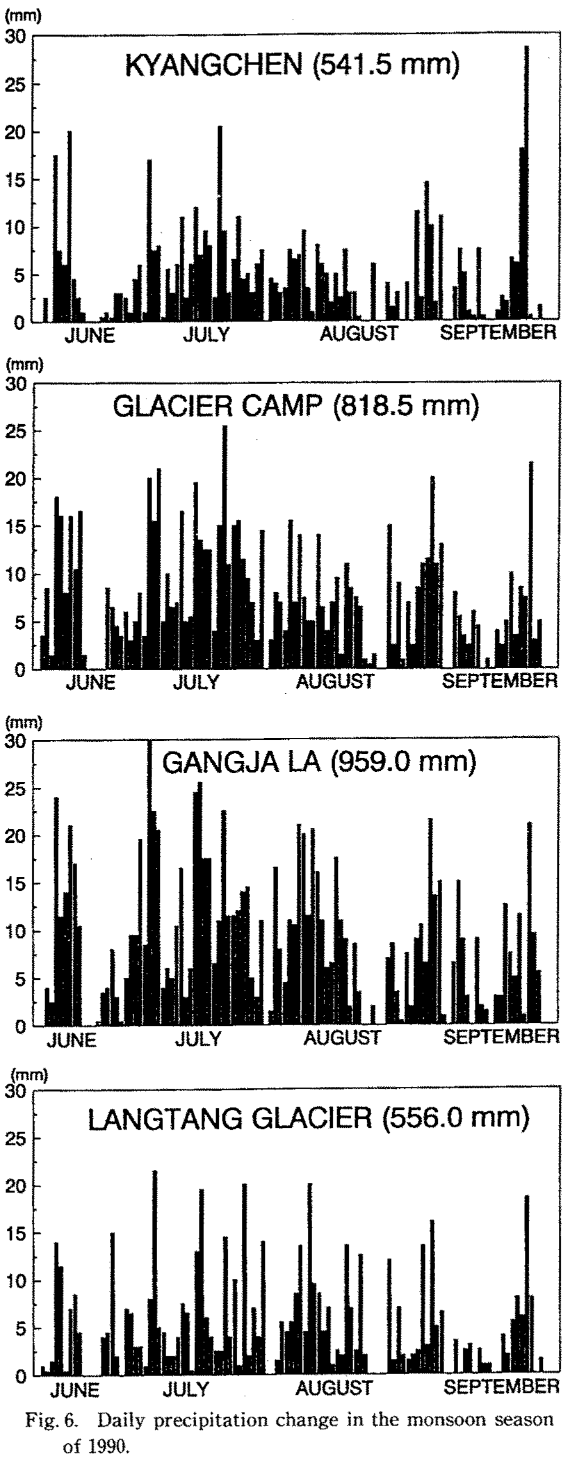

Fig. 6. Daily precipitation change in the monsoon season of 1990.

4.4. Snow profiles on the glaciers

Figure 8 shows the snow profiles in May 1991, obtained at the several altitudes on the three glaciers. Iida *et al.* (1987) and Kohshima (1987) clarified that a distinct dirt layer is initially formed in spring and is developed by biological activities through the monsoon season. Therefore, one lower most ice layer and one major dirt layer, which are depicted at the bottoms of each profile, are considered to represent the glacier surface at the beginning of monsoon season in 1990. Namely, the profiles shown in Fig. 8 represent the surface mass balance between the beginning of monsoon in 1990 to May 1991.

Snow profiles, especially obtained in the higher part of the glaciers, are divided roughly into two major snow layers ; the Upper Layer composed of a series of thin stratified snow layers intercalated by ambiguous dirt layer or ice lenses, and the Lower Layer recognized as relatively homogeneous-grained snow type.

The Upper Layer consists of the stratified thin layers. Each layer is composed mainly of compacted snow partly intercalated both by ice lenses and thin dirt layers. During this study it was observed that the compacted snow was metamorphosed into granular snow in the profiles excavated in the ablation area in the beginning of May and in the higher region in the late May. But the grain size of the Upper Layer is

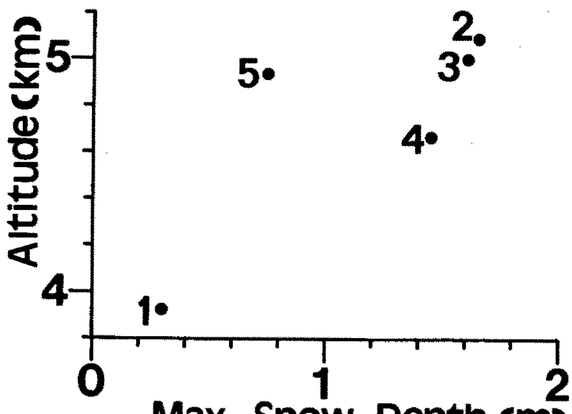

Fig. 7. Relations between the maximum snow depth and the altitude in the winter 1989–1990. 1 : Kyangchen (3920 m), 2 : Glacier Camp (5090 m), 3 : Pemdang Glacier (5013 m), 4 : Pemdang Kalkha (4677 m), 5 : Langtang Ri Base Camp (4942 m).

generally smaller than that of the Lower Layer, while the temperature is higher.

The Lower Layer is composed of a homogeneous -grained snow. A depth hoar layer was observed in the upper part of the Lower Layer, while it was absent in the Upper Layer. The grain size up to 6 mm was found in skeleton-type depth hoar which was underlain by a solid-type depth hoar layer. The temperature of the Lower Layer was slightly lower than the Upper Layer. The boundary between the Upper Layer and the depth hoar layer was often marked by a thin dirt layer (profiles 5305 m of the Yala, 5130 m of the Gangja La, 5160 m, 5260 m, 5420 m of the Kyungka Ri Glaciers).

A depth hoar layer can be formed by vapor transfer under the strong temperature gradient field in snow (Akitaya, 1974). Such a condition is most likely occurred in the study area in the beginning of post -monsoon season; continuation of the clear day causes radiative cooling on the snow surface, while the snow is still wet and warm in this period. A thin dirt layer, which is formed by the dry-fall out in the post-monsoon season as reported by Iida *et al.* (1987), also support that the top of the depth hoar layer indicate the end of monsoon season. On the basis of these observed evidences, we speculate that the Upper and Lower Layers represent the summer balance, and the balance between the beginning of the post-monsoon season of 1990 and May 1991, respectively.

5. Discussions

5.1. Regional characteristics of the climate in the Langtang Valley

The upper parts of the valley has lower precipitation and higher air temperature during monsoon season than in the middle reaches of the valley. This may be ascribed to the differences of precipitation conditions along the valley. Less moisture transport to the upper part of the valley due to the barrier and inland effects induce weaker convections and less precipitation around the upper reaches. Sensible heating from the ground due to the lesser cloud amount induces the relatively high temperature comparing to that at the same altitude. This heating effect is fundamentally the same as the mechanism of producing the Thermal Low over the Tibetan Plateau.

On the contrary, relatively small differences were found in the climate of the south- and the north-facing slopes in the middle reaches of the valley during the monsoon season. This shows that monsoon winds initially supply moisture along the valley and then this moisture reaches to the higher altitude on both slopes by convection. A slightly higher air temperature at GA during pre-monsoon and monsoon seasons may be ascribed due to the less cloud amount in the north-facing slope.

5.2. Altitudinal and spatial variation of the mass balance

The balance or mass balance (b) at any time is the algebraic sum of the accumulation and ablation (Paterson, 1981). The surface balance was obtained between the beginning of the monsoon season in 1990 and May 1991 at several points on the three glaciers, assuming that the lowermost dirt or ice layers of the snow profiles (Fig. 8) represent the beginning of the monsoon season, and that the boundary between the Lower and Upper Layers represent the beginning of the post-monsoon season in 1990.

Figure 9 shows the altitudinal changes of the water equivalent values of the surface mass balances which are divided into the balance during the monsoon season of 1990 (b_1 : open symbols) and the balance from the beginning of the post-monsoon in 1990 to May 1991 (b_2 : semi-open symbols). The term b_1 is sum of the accumulation and ablation during monsoon season, while the term b_2 represents only accumulation during rest of the observation period because the ablation during this period is considered to be very small due to the cold air temperature (Fig. 4) and negligible geothermal heat flux. Therefore, the summation of these two does not necessarily coincide with the annual net balance b_n, due to lack of information for a month of June, 1991.

The altitudinal dependence of b_1 is obvious in these three glaciers, as the values of b_1 are increasing with altitude. The term b_2 seems to be independent from altitude. This is because the snow deposited from the beginning of the post-monsoon in 1990 to May 1991 did not experience any intensive ablation. The altitudinal dependence of solid precipitation amount (Seko, 1987 ; Ohta *et al.*, 1990 ; Motoyama *et al.*, 1990) is not very significant in this case, because the altitudinal belt of only 400 meters is concerned here.

The spatial distribution of the surface mass balance was found by comparing the values of the surface mass balance at almost the same altitude in different glaciers. In the monsoon season, the Gangja La

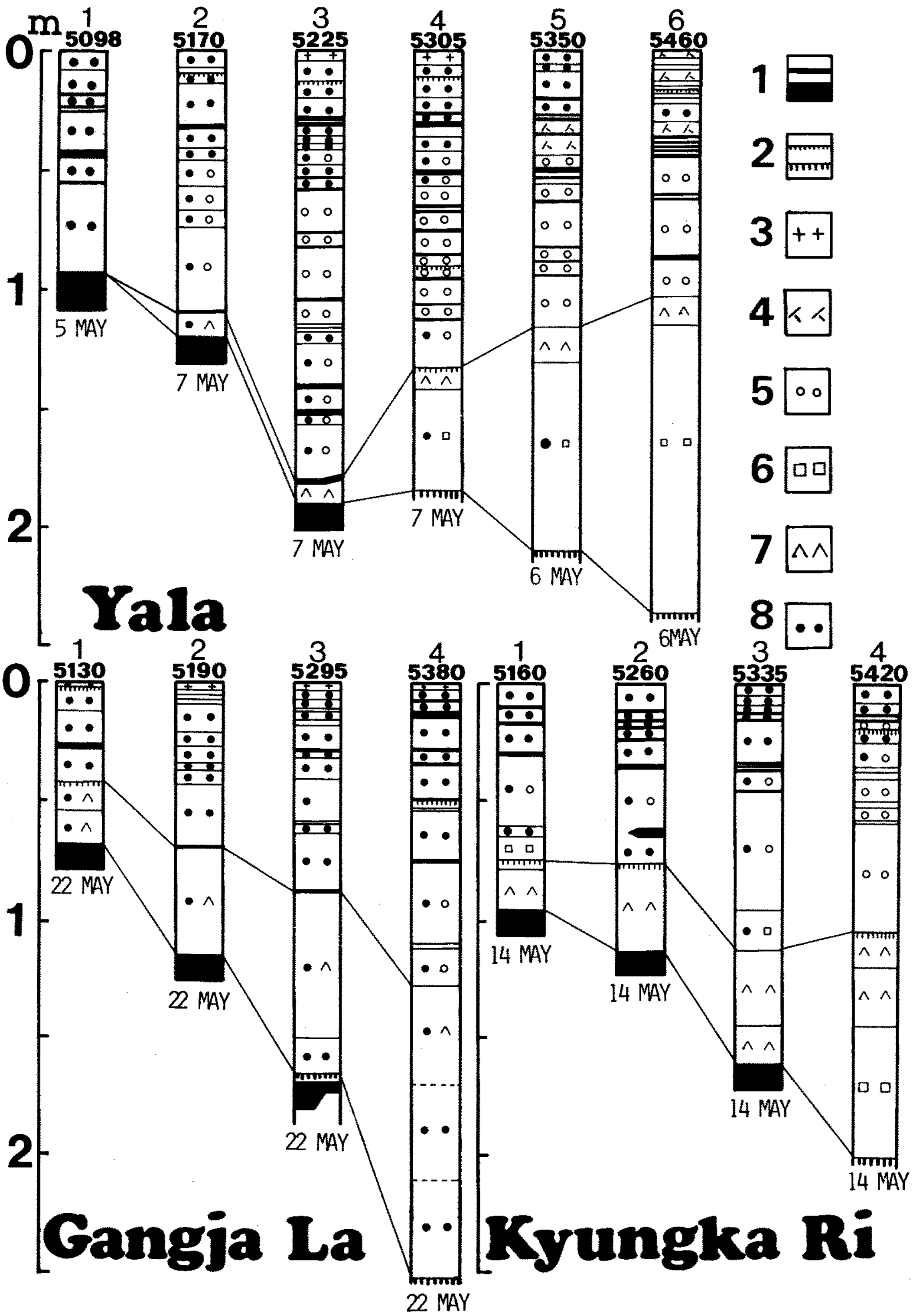

Fig. 8. Snow profiles excavated at each glacier on May, 1991. 1 : ice lens and ice layer, 2 : thin and thick dirt layers, 3 : new snow, 4 : lightly compacted snow, 5 : compacted snow, 6 : solid-type depth hoar, 7 : skeleton-type depth hoar, and 8 : granular snow.

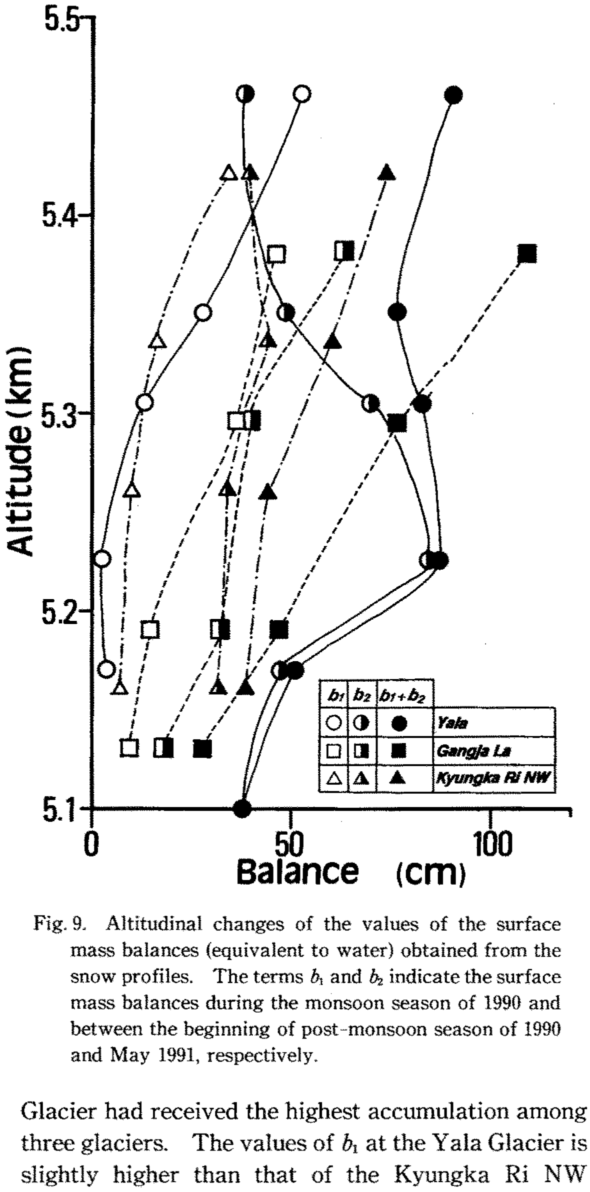

Fig. 9. Altitudinal changes of the values of the surface mass balances (equivalent to water) obtained from the snow profiles. The terms b_1 and b_2 indicate the surface mass balances during the monsoon season of 1990 and between the beginning of post-monsoon season of 1990 and May 1991, respectively.

Glacier had received the highest accumulation among three glaciers. The values of b_1 at the Yala Glacier is slightly higher than that of the Kyungka Ri NW Glacier. On the contrary, the values of b_2 does not significantly differ from one glacier to another, except for the altitudinal belt between 5200 m and 5300 m of the Yala Glacier, where the values are locally higher than the others. The uniformity of b_2 may be related to the source of winter precipitation which is considered to be as synoptic scale atmospheric disturbance (Seko, 1987).

The spatially uniform distribution of b_2 in the winter of 1990–1991 contradicts the result obtained by the observation of maximum snow depth in the winter of 1989–1990, which indicates that the upper part receives less snow accumulation than the middle part of the valley. Although the methods used for the observation are different, it can be said that the spatial distribution of the snow in winter differs from one year to the another.

Concluding remarks

The meteorological observations and the snow surveys have shown the seasonal characteristics of the spatial distribution of glacier mass input in the Langtang Valley. During the monsoon season, the glacier in the upper reaches of the valley was less accumulated than the glaciers in the middle reaches. This is mainly explained by the spatial distribution of precipitation; the upper part of the valley receives the precipitation approximately two third of that in the middle reaches. The slightly higher air temperature, ascribed to the less cloud amount in the upper part of the valley, also contributes to the small values of b_1.

The mass input in the winter of 1990–1991, represented by b_2, was almost uniform throughout the valley, while it was not uniform in the winter of 1989–1990 ; the upper part had received less snow than the middle part of the valley. This interannual variation should be studied in the future.

The southward decline of the ELAs in the Langtang Valley (Zheng *et al.*, 1984) can be explained by the drier environment of the upper reaches of the valley during the monsoon season as shown by our observations. In addition, the drier climate observed in the winter of 1989–1990 in the upper part of the valley also contribute to amplify the ELA's southward decline. However, in order to confirm this phenomenon, it is highly necessary to observe the distribution of mass input during the non-monsoonal as well as the monsoonal periods at least for a few more years.

The amount of mass input during the non-monsoonal period is also important to consider the glacier mass balance in the valley as noted by Seko (1987) and Seko and Takahashi (1991). On the basis of our two-years observation of snow in winter, we also support their idea. Also from this study, it is found that the summer balance b_1 can be distinguished from the rest of the balance using snow profiles. Hence, in order to clarify the amount of snow accumulation during the non-monsoonal periods, the results obtained from previous studies at the Yala Glacier (Watanabe *et al.*, 1984 ; Ozawa, 1990) should be compared with the present result.

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