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Characteristics of precipitation during the monsoon season in high-mountain areas of the Nepal Himalaya*

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ABSTRACT Precipitation phenomena during some summer monsoon seasons were observed in high-mountain areas of the Nepal Himalaya. The main results obtained from these observations are as follows. (a) Precipitation along the main valley of Dudh Kosi decreases with altitude in the range from 2800 m to 4500 m a.m.s.l. (b) The total amount of precipitation around peaks and ridges is 4 or 5 times larger than that around valley bottoms. (c) The frequency and amount of precipitation around peaks and ridges are concentrated during the day-time when cumulus convection is predominant, while those around valley bottoms are concentrated during the evening up to midnight. (d) A linear relation between the surface air temperature and the percentage of occurrences of snowfall to all the cases of precipitation was obtained from the observations at the station (4958 m) near Glacier AX010 in Shorong Himal.

INTRODUCTION

Precipitation during the monsoon season plays a dominant role in the hydrological regimen, including the glacier mass budget, in Nepal. However, the precipitation phenomena differ greatly from place to place because of the highly rugged topography of the Himalayan mountains. It is important, therefore, to study the difference between mountain ridges and valley bottoms, and also the phase of precipitation, namely snowfall or rainfall.

Investigations on precipitation phenomena during the monsoon season were made in Khumbu and Shorong Himal (1974, 1976, 1978) in east Nepal and in Mukut Himal (1974) in central Nepal as a part of the Glaciological Expedition to Nepal. Some main results are reported in this paper.

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METHOD OF OBSERVATIONS

Continuous data for precipitation were obtained at Lhajung station (4420 m) and at the terminus of Glacier EB050 (E9, 5160 m) in Khumbu Himal, Shorong station (4850 m) in Shorong Himal and Hidden Valley station (5055 m) in Mukut Himal by using tipping-bucket raingauges. At all the other points along valleys and slopes, around ridges and on the glaciers, accumulated precipitation for continuous periods of up to ten days were observed by using simple raingauges with a funnel of diameter 20 cm. Since the periods during which precipitation was accumulated were not the same, it is not possible to compare the actual values with each other, but only via the ratio of each value to that during the corresponding period observed at the main station. Therefore, the area distribution of precipitation will be described by such ratios in this paper. Approximate distances between the main stations from Lhajung to Shorong and Hidden Valley are 30 km southwest and 300 km west, respectively; the locations of these stations were shown in the previous papers (Higuchi, 1976, 1980). Additionally, rainfall data of weather stations of the Meteorological Service, His Majesty's Government of Nepal were used.

DISTRIBUTIONS OF PRECIPITATION

Precipitation in the drainage basin of the Imja Khola

Ratios of the precipitation at the observation points in the drainage basin of the Imja Khola to that at Lhajung using available data from June to September 1974 are shown in Fig.1. The total precipitation at Lhajung during this period was 428 mm. The drainage of the Imja Khola is divided from the junction into two drainage basins, called the "Lobuche-Tshola drainage" and the "upper Imja drainage" (Fig.1).

Dhar & Narayanan (1965) studied precipitation in this area, but the data used in their work were only at Lukla and Namche Bazaar in an area much further down the Dhud Kosi. As regards the results of observations in Imja Kola, the following tendencies can be seen in Fig.1. (a) Precipitation in the Lobuche-Tshola drainage is more than that in the upper Imja drainage. (b) Along the main valley of Dudh Kosi and the lower Imja Khola, precipitation decreases with altitude in the range from 2800 m to 4500 m a.m.s.l. (c) Along large valley glaciers in these drainages, precipitation varies little among the observation points at the lower part of a glacier (KH: Khumbu Glacier, NP: Nuptse Glacier, LH: Lhotse Shar Glacier). (d) Along mountain slopes and some tributaries in these drainages, precipitation increases with height, especially in the neighbourhoods of small glaciers near ridges (TA: east slope of Mt Tauche, TS: Tshola Khola, KM: Kongma Valley). This phenomenon is described in more detail in the next subsection.

Additionally, it was found that the amount of precipitation over each drainage area varied under the influence of the direction of the prevailing upper wind.

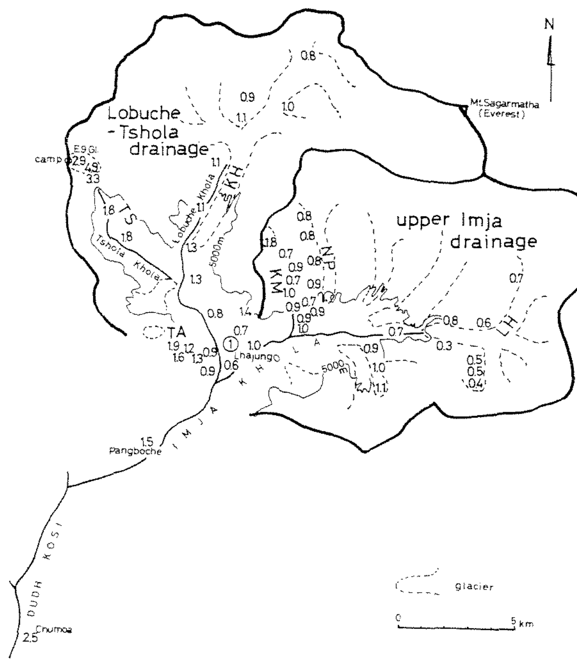

FIG.1 Distribution map of precipitation ratios in the drainage basin of Imja Khola, Khumbu Himal from June to September 1974 (after Ageta 1976).

Precipitation along the slopes leading up to the glaciers in Khumbu and Shorong Himal

The precipitation along the slopes leading up to Glacier EB050 in Tshola Khola in the west part of the Lobuche-Tshola drainage was measured through the whole monsoon period (from June to September) in the area higher than the temporary summer village named Dzonghla (4830 m). In Shorong Himal, also, it was measured during the monsoon season along the slope to one small glacier (Glacier AX030) in the area higher than the temporary village named Tamba (about 4000 m). The distributions of the daily mean precipitation during the observation period for these two slope lines are shown in Fig.2. In Shorong Himal, the slope below about 4500 m is coincident with the side-moraine ridge along the lower part of Dudh Kund Glacier.

Along the slope to Glacier EB050, the precipitation gradually increases as the altitude increases and reaches its maximum near the terminus of Glacier EB050 where the daily mean precipitation is 11.6 mm and the ratio of the total precipitation to that at Lhajung is 4.8. The decreasing rate of precipitation from point E9-5 towards higher altitudes seems to be small, as will be mentioned later. Along the slope leading up to the Glacier AX030 in Shorong Himal, on the contrary, the daily mean precipitation at each point is almost uniformly distributed from point SH-5 (4310 m) to point SH-10 (5210 m) at the terminus of the glacier (the value is nearly 12.5 mm per day), and no significant features related to the altitude have been observed.

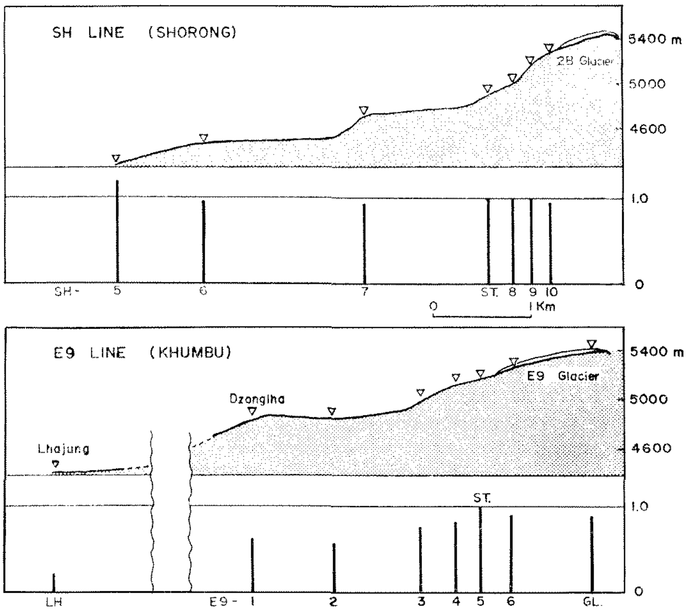

FIG.2 Cross sections of topography along SH (Shorong) and Glacier EB050 (E9) (Khumbu) lines and daily mean precipitation during the observation period along the two slope lines. Observation points are indicated by inverted triangles, and ST. and GL. mean our temporary meteorological stations in Shorong Himal and on Glacier EB050 (E9), respectively (after Yasunari and Inoue (1978)).

The distinctly different features of the areal distribution of precipitation between Khumbu and Shorong Himal may be explained as follows; in Shorong Himal, the role of the orography of the Numbur-Karyolung range as a barrier may be great. It is well known that over northern India moist static instability is large below about the 600 mbar level throughout the monsoon period. Thus, precipitation of a broader scale in Shorong Himal may be caused by the convective instability released by forced uplift of the conditionally unstable air of the lower troposphere from the Indian Plain along the southern slope of this mountain range. On account of this "barrier effect" of Shorong Himal and also Hinku Himal on the moisture supply, a semi-arid climate may appear in the Khumbu region, which is located on the lee side of Shorong and Hinku Himals. However, around the rocky peaks and ridges of 5000-6000 m in the Khumbu region, the relatively large amount of precipitation may be provided by cumulus convection induced by the heating of the rocky ground by strong solar radiation. Similar features have been confirmed not only around Glacier EB050 but also around small glaciers in this region, as shown in Fig.1.

Finally, taking into account the rainfall data of some meteorological stations, the distribution of precipitation along the Himalayan slope around Shorong and Khumbu Himal is schematically illustrated in Fig.3. In this figure, three areas of maximum precipitation can be seen over Mahabharat Lekh, at the large frontal slope area of Shorong and Hinku Himals, and around minor peaks and ridges (5000-6000 m) in Khumbu region.

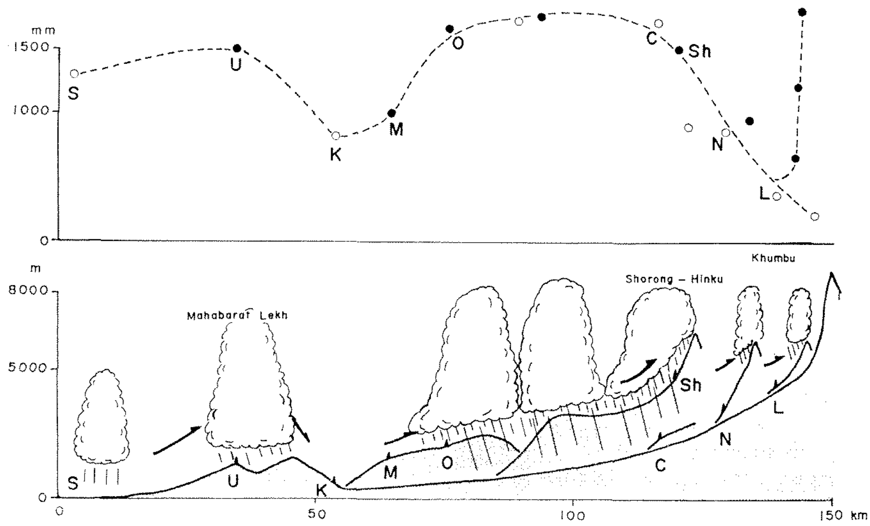

FIG.3 Distribution of precipitation (upper) and schematic diagram of principal areas of precipitation (lower) along the Himalayan slope around Shorong and Khumbu Himal. Black circles in the upper figure show the observation points around peaks, ridges and plateaux, and open circles are those around valleys. Station names are shown by initials as follows: S:Sirawa, U:Udayapur Gadhi, K:Kurule Ghat, M:Mane Bhanjyang, O:Okhaldhunga, Sh:Shorong, C:Chaurikharka, N:Namche Bazaar, L:Lhajung (after Yasunari & Inoue, 1978).

Precipitation on glaciers

Distributions of precipitation on glaciers were observed in Shorong and Khumbu Himal, and also Mukut Himal, in combination with mass balance studies on the glaciers, though those along large valley glaciers were observed only at the lower part than the altitude of 5400 m in Imja Khola basin, Khumbu Himal.

As mentioned in the former subsection (refer to Fig.1), precipitation on the large valley glaciers varies little along the valley, but there is a possibility of increase of precipitation at the upper part, for example, the maximum at an altitude of 6500-7000 m on the north slope of Mt Chomolangma (Everest) as reported by Gao & Shen (1979).

Results for the other glaciers, of which locations are lower than the altitude of 6000 m, are as follows, as shown in Fig.4.

(a) Glacier AX010 in Shorong Himal: Precipitation was observed at eight points along the centre line of the glacier and nine points along the rock ridge just beside the glacier during the period from 10 June to 24 September 1978. Precipitation was not very different among the points, although the highest observation point on the glacier and the top of the ridge had slightly smaller amounts than others (Ageta *et al.*,1980).

(b) Glacier EB050 in Khumbu Himal: Precipitation was observed near the terminus of the glacier during the period from 10 June to 30 September 1976. Observations were also made at two higher points near and on the glacier (as shown in Fig.2) for about 20 days from the middle of June to the beginning of July 1976. Difference of precipitation among these three points was small (Yasunari & Inoue, 1978).

(c) Rikha Samba Glacier in Mukut Himal: Precipitation was observed at four points along the lateral moraine of the glacier during the period from 8 July to 31 August 1974. Difference of precipitation was small (Fujii *et al.*, 1976).

The above results are shown in Fig.4 using the ratios of precipitation at different altitudes to that at the lowest observation point of each glacier. Mean daily precipitation during the observation periods at such points in Glacier AX010, Glacier EB050 and Rikha Samba Glacier is 12.1 mm, 12.5 mm and 4.1 mm, respectively. Precipitation at the uppermost part in Glacier EB050 and Rikha Samba Glacier was not measured. Precipitation at the uppermost part of glaciers, where wind is usually strong, is not clear, since errors of measurements are supposed to increase due to the wind effect. However, it can be said that precipitation is not so very different in the one glacier which is small.

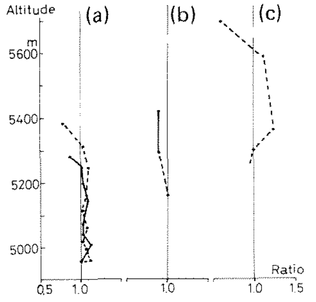

FIG.4 Ratios of precipitation along the glacier to that at the lowest observation point of each glacier (a)Glacier AX010, (b)Glacier EB050, (c)Rikha Samba Glacier; solid line: results on the glacier; dashed line: results beside the glacier.

DIURNAL VARIATIONS OF PRECIPITATION

Diurnal variations of precipitation were investigated by using three-hourly amounts of precipitation for the stations at Lhajung, Glacier EB050 and Shorong. Histograms of the frequency and the cumulative amount of precipitation at these three stations are shown in Fig.5.

At Shorong Station, although the data are only available for 16 days, both the frequency and the amount of the precipitation are concentrated during the day-time, especially from 0900 h to 1500 h. At Glacier EB050 Station (47 days), they are also concentrated during day-time, but a little later in the day (from 1200 h to 1800 h) as compared to those at Shorong Station. At Lhajung Station, on the

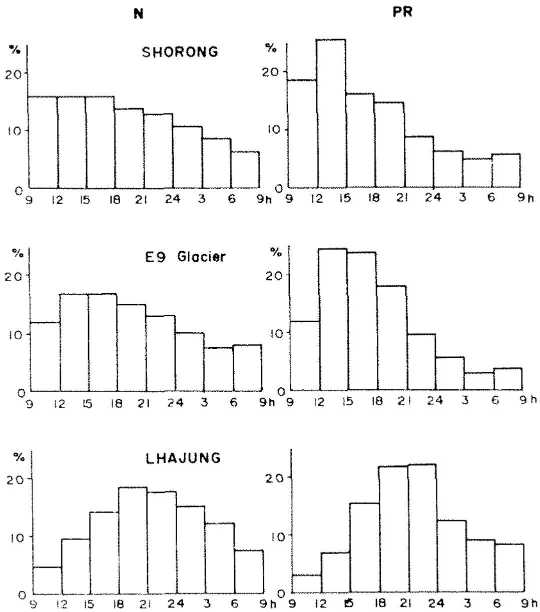

FIG.5 Histograms of frequency (N) and cumulative amounts of three-hourly precipitation (PR) for the three stations (after Yasunari & Inoue, 1978).

other hand, they are concentrated during the evening up to midnight (from 1800 h to 2400 h).

The results at Shorong and Glacier EB050 stations suggest that cumulus convection during day-time provides most of the precipitation. At Lhajung the precipitation during the night-time is concentrated in the evening until midnight (1800 h to 2400 h). In this period, the valley wind coming up along the Imja valley still remains, though the wind speed becomes fairly weak (Inoue, 1976). On the other hand, a weak downward motion may occur from around ridges and along the slopes caused by radiative cooling. Therefore it is suggested that the nocturnal precipitation at Lhajung results from convergence of air by this weak sinking motion along the slopes and the weak valley wind. A simplified pattern of diurnal variation of local circulation and related cloud formation is shown in Fig.6.

RELATIONS BETWEEN THE PHASES OF PRECIPITATION AND SURFACE AIR TEMPERATURE

The phase of precipitation at the ground depends on the melting process of precipitation elements during their fall from the clouds. Therefore, air temperature at the ground is related to whether precipitation occurs in the form of snow or rain. In the glacier area in the Nepal Himalaya, the critical temperature for the change of phase of precipitation is in the range of the summer temperature.

The relations between the probability of occurrence of solid precipitation and surface air temperature were observed during the monsoon season (June-September) at the station (4958 m) near the

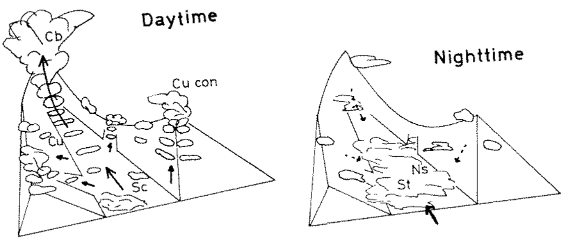

FIG.6 Simplified pattern of diurnal variation of local circulation and related cloud formation (modified from Ageta, 1976).

terminus of Glacier AX010 in Shorong Himal. Ageta *et al.*,(1980) reported the results separately for the day-time and the night-time as shown in Fig.7, since the vertical profile of air temperature was supposed to be fairly different between them. The number of all cases of precipitation was 691 in the day-time and 287 in the night-time.

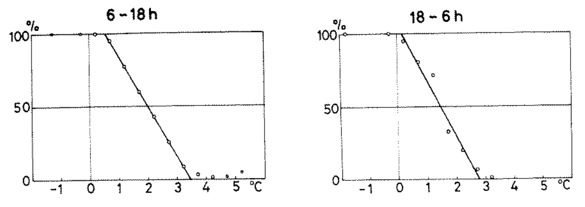

FIG.7 The relations between the probability of occurrence of solid precipitation and surface air temperature in the day-time and the night-time during the summer monsoon season in Shorong Himal (after Ageta et al., 1980).

It can be seen from Fig.7 that the probability of occurrence of solid precipitation in the day-time is more than that in the night-time at the same surface temperature. Ageta *et al.*,(1980) explained this difference by the daily change of vertical profile of air temperature near the surface due to radiation.

Linear relations between the surface air temperature and the probability of solid precipitation can be seen from Fig.7. Ageta *et al.*, (1980) obtained the following relations.

day-time (0600-1800 h): $S = -34T + 118 \quad (0.5 < T < 3.5)$

night-time (1800-0600 h): $S = -38T + 106 \quad (0.2 \leqslant T < 2.8)$

Here, S is the percentage of occurrence of solid precipitation to all cases of precipitation, and T is the surface air temperature (°C) at the time of precipitation. In this case, S of 50% is given at T of 2.0°C in the day-time and 1.5°C in the night-time. Higuchi (1977) also reported the frequency distribution of the critical temperature for change between snow and rain in July and August at the station (5055 m) in Mukut Himal. The result is similar to the case in

Shorong Himal in that the range of 2.0 to 2.5°C has the highest frequency for the change of precipitation phase.

Linear relations between T and S were obtained in Japan by Itō (1944) and in the area near Tashkent by Glazyrin (1970). However in the case in Shorong Himal, T at S of 50% is lower and the change of T accompanies a larger change of S than in their cases. Though such differences are caused by complex factors, it is thought that one of the reasons is that the time of suspension of precipitation elements in air with its temperature above the melting point is longer in day-time due to the convective valley wind, and air temperature near the surface is colder in night-time due to the radiative cooling, as seen from Fig.6 in the case in Shorong Himal.

In the whole area of Glacier AX010, it was estimated that about 55% of total precipitation during the period from June to September was in solid form. At the snowline on the maritime glaciers in the periphery of the Tibetan Plateau in China, 70% of annual precipitation is solid (Li, 1980). Rain on glaciers is discharged at once, just after the rainfall. On the contrary, water discharge from glaciers decreases in the case of solid precipitation, because deposited new snow on the glacier surface decreases the melting of glaciers due to the effect of its high albedo. This role of new snow is specially effective in summer when radiation is strong. Therefore, the phase of summer precipitation is very important for the hydrological system in the glacier area where much of the precipitation is in summer.

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