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Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalayas

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Abstract

Himalayan Range extends more than 2,000 km from east to northwest; influence of summer monsoon on glaciers differs regionally. Glacier distribution in the whole Himalayas and terminal/areal variations of debris-free glaciers in the recent 30 years in Bhutan are analyzed from newly published inventories of India, east Nepal and Bhutan, topographic maps and satellite images.

Lowest elevations and estimated equilibrium line altitudes (ELAs) of glaciers in the eastern half of the Himalayas located at the similar latitudes descend toward east from Nepal via Sikkim-Bhutan to Arunachal. The estimated ELAs in the eastern Himalayas at the lower latitudes are not so much different from those in Himachal-Gharwal in the western Himalayas at the higher latitudes, though those descend from Himachal-Gharwal to Kashmir toward north (west). These tendencies of glacier distribution appear, since monsoon precipitation increases toward eastern/southern part from western/northern part in the Range, and the higher precipitation increases accumulation and accompanied cloudy weather decreases ablation.

Almost all glaciers measured in the whole Himalayas have been retreating in the recent decades. Averaged annual terminal retreat of glaciers in Bhutan is higher than that in Nepal. An increasing trend of glacier retreat is found in Nepal from west to east, in Nepal and Bhutan from north to south. These tendencies of glacier variation are explained, since glaciers vary more in places with the higher precipitation and the warmer temperature due to mass balance characteristics of the summer-accumulation type glaciers.

1. Introduction

The Himalayan Range extends more than 2,000 km along the direction of east-northwest and many glaciers in the range are shrinking recently. Since most of annual precipitation falls in summer due to the Indian summer monsoon, the summer precipitation is the main source of annual accumulation on the glaciers and characterizes the glacier regime in the Himalayas. The monsoon contributes not only to the accumulation, but also to the decrease of ablation due to accompanied cloudy weather during the melting season which provides the conditions with low air temperature and low insolation with additional effect of high albedo by new snow. Such glaciers were classified as the "summer-accumulation type" by Ageta and Higuchi (1984). Since the monsoon precipitation is much more in the eastern part than the western part and in the southern part than the northern part in the Himalayan Range (*e.g.* Eguchi, 1994, Fig. 1), distribution and variation of the glaciers depend on their locations in the Himalayas.

For the comparative study on glaciers in the eastern and western Himalayas, information on the glaciers in the easternmost Himalayas was specially scarce. In Bhutan, the first glacier observation was briefly made in the 1960s by Gansser (1970). In 1996 after the blank for many years, Phuntso Norbu, Division of Geology and Mines, Bhutan prepared an inventory of glaciers and glacier lakes in the northern part of Bhutan using satellite images of 1989 and 1990 and toposheets of 1962/63. The inventory was published with additional data and edition by the Geological Survey of Bhutan (1999). On the basis of these studies, expansion of proglacial lakes and retreat of glaciers in recent decades in Bhutan were reported by the present authors (Ageta *et al.*, 2000) with their field data. Most recently, an inventory of the glaciers and glacier lakes in Bhutan was published by ICIMOD (International Center for Integrated Mountain Devel-

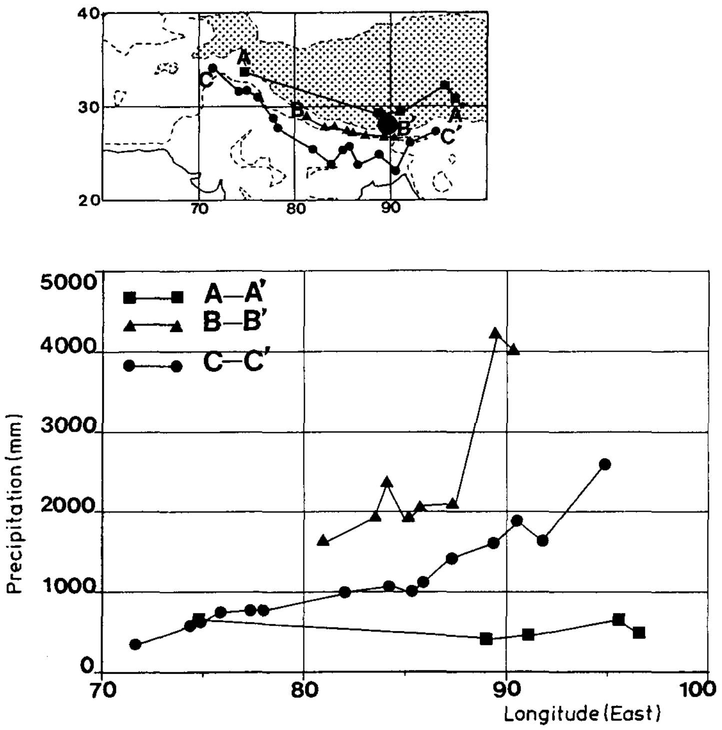

Fig. 1 Distribution of mean annual precipitation around the Himalayan Range (after Eguchi, 1994).
The main range is located between the line A-A' and the western part of the line C-C' to the line B-B'.
Averaged years are 1975-1980 for Bhutan, 1976-1980 for Nepal and 1951-1980 for others.

opment, 2001) as part of their work in Hindu Kush -Himalayan region.

With the background of increasing data of the eastern Himalayas mentioned above and those of the whole Himalayas introduced in the next chapter, the present study has been made. Purposes of the study are to clarify the characteristic tendency of glacier distribution in the whole Himalayas under different monsoon climates, and to clarify the glacier variation in recent decades in Bhutan where the monsoon precipitation is much more, comparing with glaciers in Nepal.

2. Data and method

Data bases used for the present study and the method are as follows:

1) Data for the glaciers in the Indian Himalayas are taken from the inventory by Geological Survey of India (1999). Here detailed data on location (latitude and longitude), orientation, the highest and lowest elevations, mean elevation of accumulation area and that of ablation area, length, mean width, surface area, the accumulation area ratio (AAR), mean depth, volume and the 6 digit morphological classification of the glaciers (UNESCO/IASH, 1970) are given for 1205 glaciers among total 5243 glaciers in India. In the present study, only the detailed glacier data tabulated in this inventory are used.

2) Data for the glaciers in eastern Nepal Himalayas (85.0°E-88.2°E) are taken from the inventory by Asahi (1999). Glaciers in western Nepal are not included in this inventory. Here the similar data of glaciers mentioned in the Indian inventory can be found except mean elevation of accumulation area and that of ablation area, length, mean width, surface area, AAR, mean depth, volume. In addition, the maximum altitude of debris-covered area, the estimated equilibrium line altitude (ELA) and others are given. Terminal variations of the glaciers since the Little Ice Age (LIA) and from 1959 to 1992 are also given. The ELA was determined on the basis of morphological characteristics of glaciers; the terminal positions in LIA, 1959 and 1992 were identified by the moraines, the toposheets and the aerial photographs, respectively (Asahi, 1999).

3) For the general analysis on the glaciers in the Bhutan Himalayas, data are taken from the inventory by ICIMOD (2001). Here almost all the information mentioned in the Indian inventory can be found except for mean elevation of accumulation area and that of ablation area, mean width and AAR.

4) For the analyzed glaciers in Bhutan, some of data are used from the inventory by Geological Survey of Bhutan (1999). Here the information is limited to the lowest elevation, orientation and geographical location of the glacier.

5) In addition, data for the variation of the glaciers in the Bhutan Himalayas are collected on the basis of the toposheets (1:50,000 scale published in the late 1960s by the Survey of India, ground verifications carried out in 1961-1963) and satellite images (SPOT, resolution of 20 m, taken in December, 1993). A base map of the glacier boundaries in 1963 was made from the toposheets. Glacier boundaries in 1993 were marked on the same base map from a corresponding set of satellite images. Finally these maps were used to measure the variations of termini and areas of the glaciers during the 30 years period (1963-1993). Each glacier area was measured with a planimeter (Planix 6, Tamaya Inc.). Since it is difficult to distinguish the active termini of debris-covered glaciers, only debris-free glaciers were selected for this analysis.

The ELA is the most important parameter to analyze glacier distribution from a viewpoint of glacier mass balance. However, the ELA is not given for the glaciers in the Indian Himalayas by Geological Survey of India (1999), and the altitude of the contour line which divides the accumulation area in half (*CE*) and that for the ablation area (*AE*) are given in the inventory without explanation on the determination method of those. Therefore, the ELA was estimated using the given *CE* and *AE* with the highest and lowest elevations of each glacier (*HE* and *LE*, respectively). Method to calculate the ELA for the Indian glaciers was taken as follows. Supposing

$$CE=(HE+ELAc)/2,$$
$$AE=(LE+ELAa)/2, \text{ and}$$
$$ELA=(ELAc+ELAa)/2,$$

then

$$ELA=CE+AE-(HE+LE)/2,$$

where *ELAc*: Approximated *ELA* from the relation with *CE* and *HE*, *ELAa*: Approximated *ELA* from the relation with *AE* and *LE*.

3. Glacier distribution in the Himalayas

For the analysis on the glacier distribution in the Himalayas, data of India, east Nepal and Bhutan are taken from the glacier inventories by Geological Survey of India (1999), by Asahi (1999) and ICIMOD (2001), respectively. The whole Himalayan Range is divided into 7 regions (from west to east: Kashmir 'K', Himachal Pradesh 'H', Gharwal 'G', Nepal 'N', Sikkim 'S', Bhutan 'B' and Arunachal Pradesh 'A') as shown in Fig. 2. The 5 regions except Nepal and Bhutan belong to India. Listed glaciers with morphological classifications of the glacierets and snowfields, and glaciers with hanging and interrupted in their longitudinal profile were excluded from this analysis. Rock glaciers are not listed in the Indian and Bhutanese inventories; those in the Nepalese inventory were excluded. Glaciers with AAR of 0 or 100 which are seen in the Indian inventory were also excluded from this analysis. Glaciers in Nepal whose length is shorter than 5 km were excluded for plotting in Figs. 3 and 4, since too many glaciers are listed in the inventory for plotting in the narrow space.

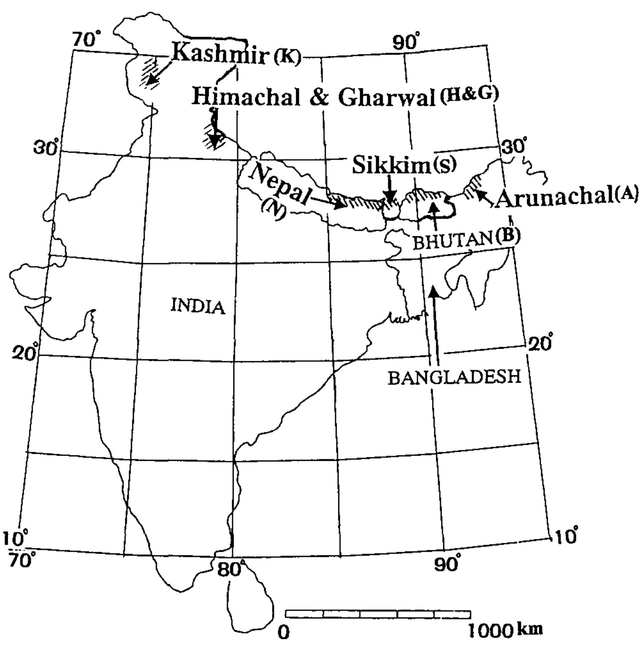

Fig. 2 Location of 7 glacierized regions in the Himalayas.

3.1. Highest and lowest elevations of the glaciers

Distribution of the highest and lowest elevations of the glaciers in the Himalayan Range along longitudes is shown in Fig. 3a to compare those among the regions from west to east. Since the highest elevation of a glacier is controlled by the elevation of the mountain range, only those in the westernmost part (Kashmir), where the mountains are relatively low among the Himalayas, are low. The highest elevations of glaciers in Nepal, where high mountains exist, are not so high, since those correspond to the highest elevations of main ice bodies which are usually lower than the tops of the catchment areas in the glacier inventory by Asahi (1999). The lowest elevations of glaciers (altitudes of the glacier termini) are found to be lower in the western and eastern parts of the range than the glaciers in the central part.

Since the lowest elevation of the glacier is rather representative for the glacier regime than the highest elevation, Fig. 3b shows distribution of the lowest elevations of the glaciers in the Himalayas along latitudes to compare those among regions from south to north. Generally, the lower latitude has the higher air temperature at a same altitude and also receives the higher solar radiation. Such climatic condition enables glaciers to distribute in the wider range of lowest elevations, increasing the higher termini at the lower latitude as seen in Fig. 3b. This latitudinal effect may allow the existence of glaciers with the lower termini at the higher latitude (Fig. 3b) which are the glaciers seen in the westernmost mountains with the low elevations (Fig. 3a).

3.2. Equilibrium line altitudes of the glaciers

The equilibrium line altitude (ELA) is an important parameter for mass balance of a glacier. It represents regional climatic condition in the glacier regime, while the highest and lowest elevations of glaciers are affected additionally by topographic condition of each glacier. Therefore, ELA is considered to reflect representatively the regional difference of the monsoon effect on the glacier regime over the Himalayan Range. The ELAs of glaciers in India and Nepal were decided as mentioned in Section 2, and those of Bhutan are excluded due to limited data in the present analysis.

Distribution of the estimated ELAs of the glaciers in the Himalayan Range along longitudes is shown in Fig. 4a. As same in the case of the lowest elevation, glaciers show the lower ELAs in the eastern and western part of the Himalayas than the central part. Moreover glaciers in the westernmost part (Kashmir) with the southern aspect show the higher ELAs than those with the northern aspect.

Figure 4b shows distribution of the estimated ELAs in the Himalayas along latitudes. Glaciers at the lower latitudes show the higher ELAs than those located at the higher latitudes. In general, rising of the ELAs from north to south is seen, but a rise of ELAs is not so much from the regions 'H & G' to 'N, S, A' in comparison with a rise from the region 'K' to 'H & G' in Fig. 4b. This tendency can be attributed to the positive effect of the monsoon on mass balance in the eastern Himalayas as seen in Fig. 4a and the latitude effect on the region 'K' as mentioned in the section 3.1.

3.3. Variation of the glacier terminus

The glaciers in the Nepal Himalayas have been shrinking considerably in length (terminus retreat), area and thickness during the recent few decades (Higuchi *et al.*, 1980; Fushimi and Ohata, 1980; Yamada *et al.*, 1992; Kadota *et al.*, 1993; Fujita *et al.*, 1997; Fujita *et al.*, 2001; Kadota *et al.*, 2002; Naito *et al.*, 2002). Variations of the glacier termini (advancing, retreating or stationary) in the Himalayas are shown in order from west to east in Table 1. For the glaciers in the 5 regions in India and in Nepal, data are taken from Geological Survey of India (1999) and Asahi (1999), respectively. All types of glaciers are included except glaciers with uncertain tongue activity. Since the tongue activity is not given for the glaciers in Bhutan by the ICIMOD (2001), data of Bhutan in Table 1 represent only 103 debris-free glaciers on which the glacier variation is measured by the present study. The period for judging the tongue activity differs from region to region. For the glaciers in Nepal and Bhutan, those are from 1959 to 1992 and from 1963 to 1993, respectively. The exact period for the glaciers in India cannot be confirmed, as it is not stated clearly in the inventory.

As seen in Table 1, almost all glaciers in India and Bhutan and most in Nepal have been retreating and advanced glaciers occupy none or small ratios in each region in the Himalayan Range, though the observed period and criteria of the judgment are different among countries.

4. Glacier distribution and variation in the Bhutan Himalayas

4.1. Numbers and areas of the glaciers

The International Center for Integrated Mountain Development published the most detailed inventory of glaciers and glacial lakes in the Bhutan Himalayas (ICIMOD, 2001). This inventory listed 677 glaciers and 2674 glacial lakes in total numbers occupying 1316.7 km^2 and 106.8 km^2 in total areas, respectively. Glaciers in the Bhutan Himalayas exist along the northern border adjoining with the Tibetan Plateau (Fig. 5). The ice reserve in Bhutan was calculated to be 127.25 km^3 in total of each glacier volume (ICIMOD, 2001) estimated from the empirical relation between the area and the thickness of glaciers in Tianshan Mountains by Liu and Ding (1986).

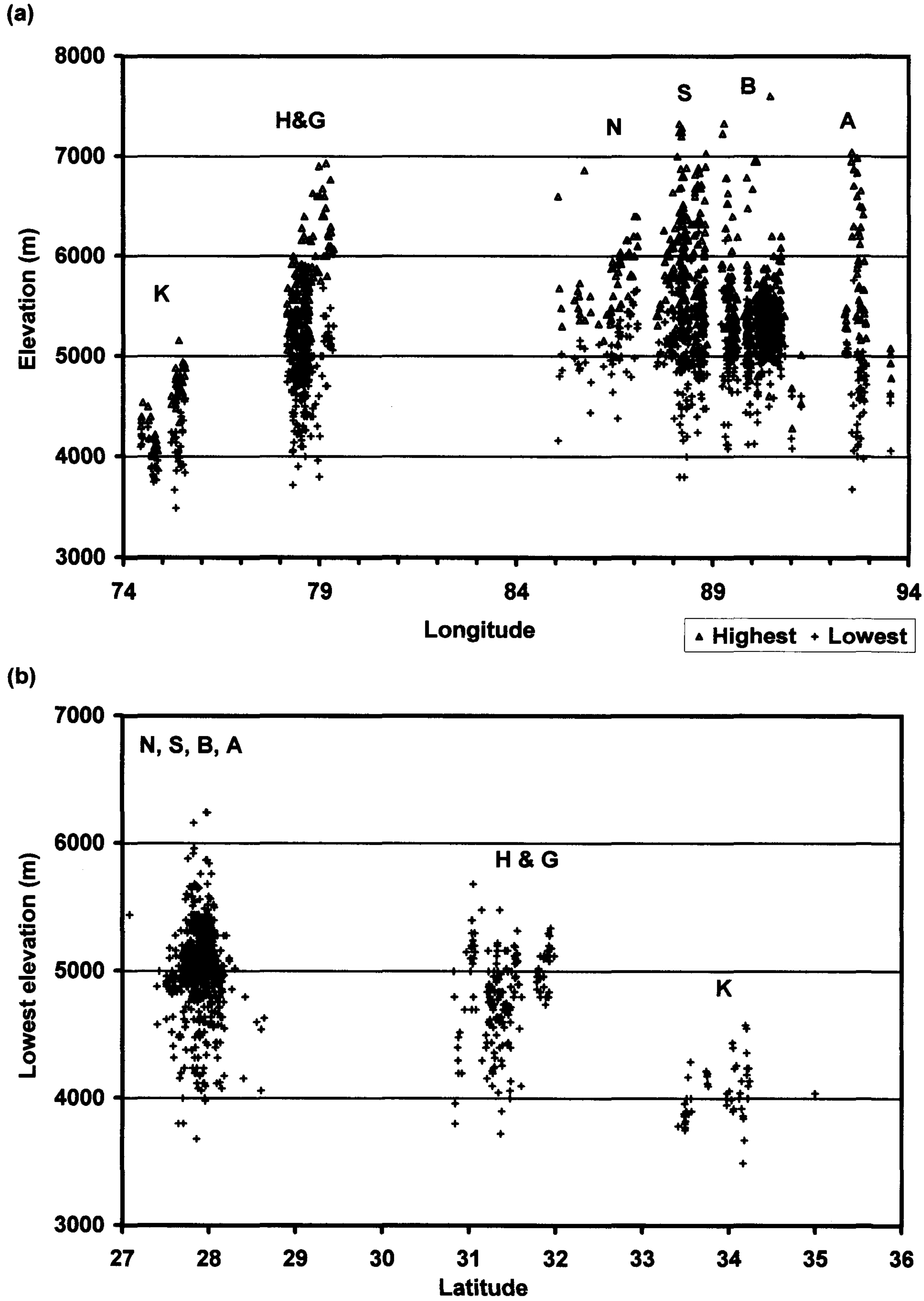

Fig. 3 Distribution of the highest and lowest elevations of glaciers along longitudes (a) and the lowest elevations of glaciers along latitudes (b) in the Himalayas. Notation of the regions is given as shown in Fig. 2.

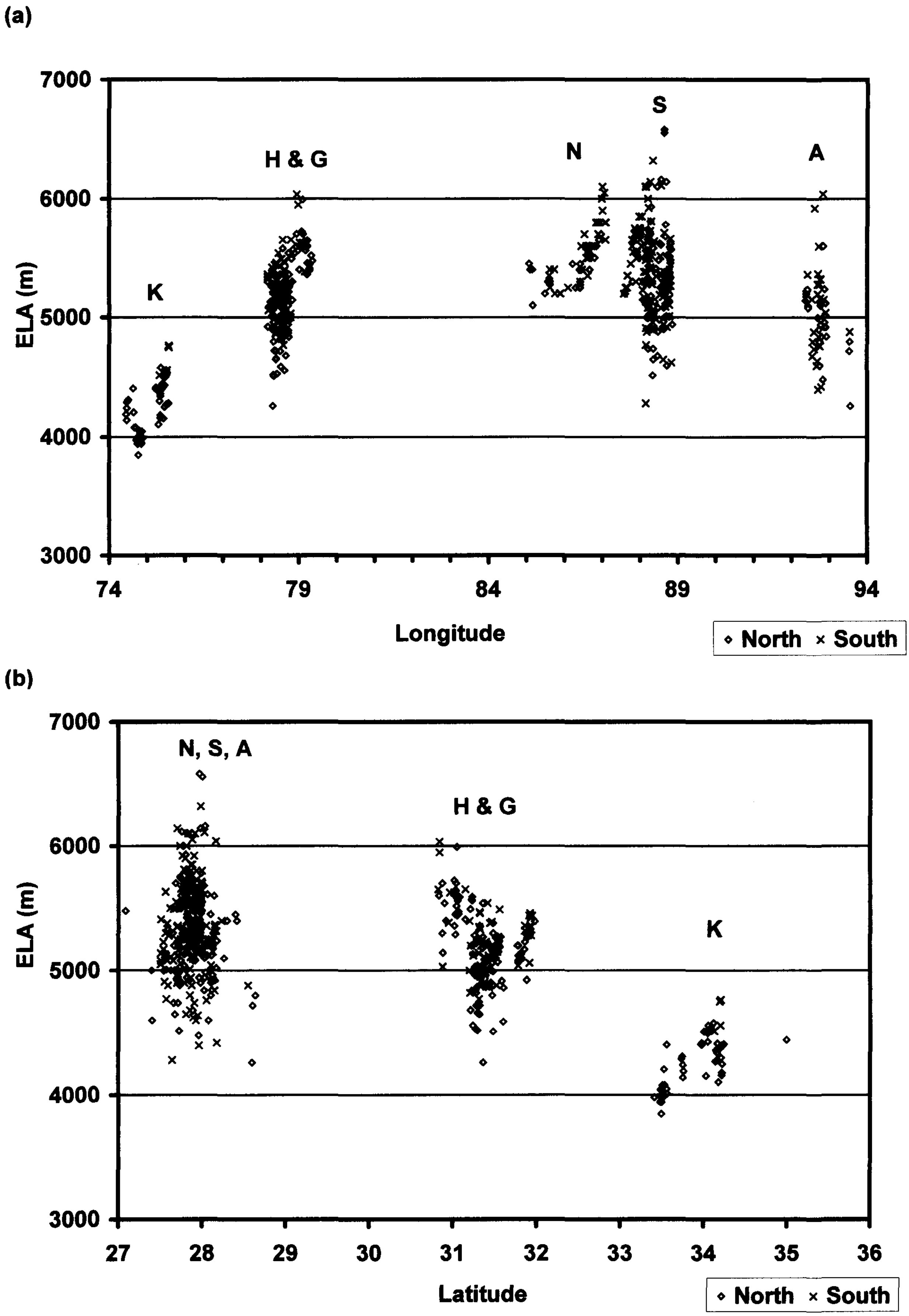

Fig. 4 Distribution of the estimated equilibrium line altitudes (ELAs) of glaciers in the Himalayas along longitudes (a) and latitudes (b).
Notation of the regions is given as shown in Fig. 2.
Flowing orientations of glaciers are divided into north and south.

Table 1. Tongue activity of the glaciers in the Himalayas.

Region	Number of glaciers	Retreat (%)	Stationary (%)	Advance (%)
Kashmir	17	100.0	0	0
Himachal	52	96.2	1.9	1.9
Gharwal	177	97.7	2.3	0
East Nepal	485	57.3	34.9	7.8
Sikkim	255	99.6	0.4	0
Bhutan	103	87.3	12.7	0
Arunachal	62	96.8	3.2	0

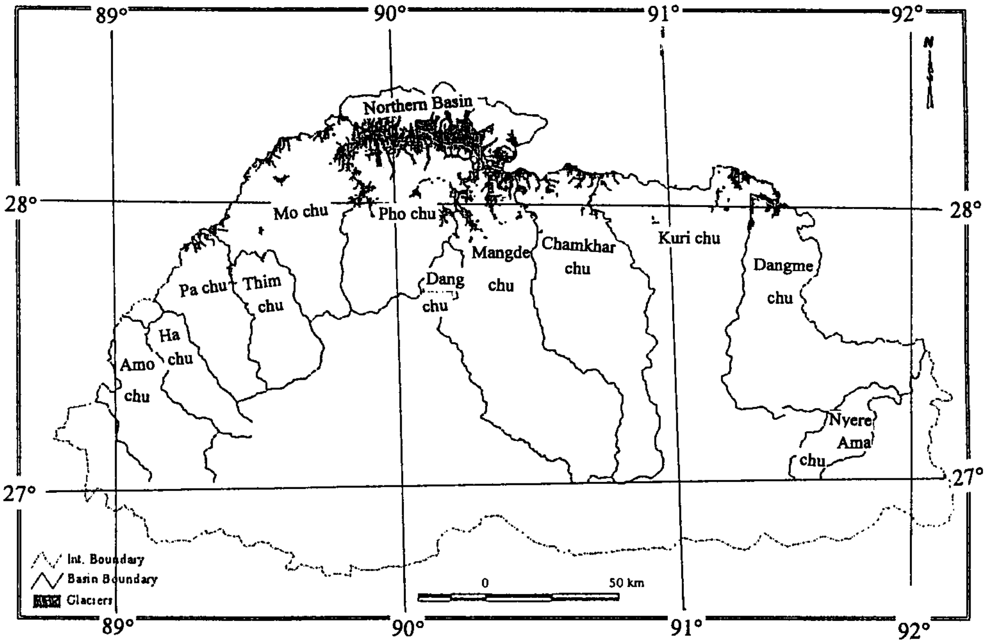

Fig. 5 Glacier distribution map of the Bhutan Himalayas (from ICIMOD, 2001).

Table 2. Total number, area and volume with average thickness of each glacier type in Bhutan. (compiled from ICIMOD, 2001)

Type	Number	Area (km^2)	Volume (km^3)	Thickness (m)
Valley glacier	51	691.76	90.222	130
Mountain gl.	453	579.02	35.510	61
Ice apron	94	33.40	1.197	36
Ice cap	16	5.19	0.182	35
Niche	51	5.57	0.105	19
Cirque glacier	12	1.79	0.035	20
Total	**677**	**1316.73**	**127.251**	**97**

This inventory grouped glaciers in Bhutan into 6 types and listed their numbers, areas and ice reserves (volumes) in each of glacierized 4 basins consisted of 9 sub-basins. Their totals in Bhutan for each glacier type with the averaged glacier thickness that is obtained from each total volume divided by each total area are compiled in Table 2. It can be seen that the valley glacier has the highest values of the total area and the average thickness, though its number is only 8% of the 677 glaciers in Bhutan and the majority of glaciers in Bhutan belong to the mountain glacier.

4.2. *Highest and lowest elevations of the glaciers*

The highest and lowest elevations of glaciers in Bhutan are analyzed in the same manner with the glaciers in the whole Himalayan Range. Like in the previous case, listed glaciers in ICIMOD (2001) with morphological classifications of the glacieret and snowfield, and glaciers with hanging and interrupted in their longitudinal profile were excluded from this analysis.

Distribution of the highest and lowest elevations of glaciers along longitudes is shown in Fig. 6. The lowest elevations of all glaciers in the Bhutan Himalayas are located above 4000m. Since the mountains are higher in the western part (from 90.13°E), the highest elevations of glaciers distribute up to the higher altitudes. Glaciers in the region between 90.23°

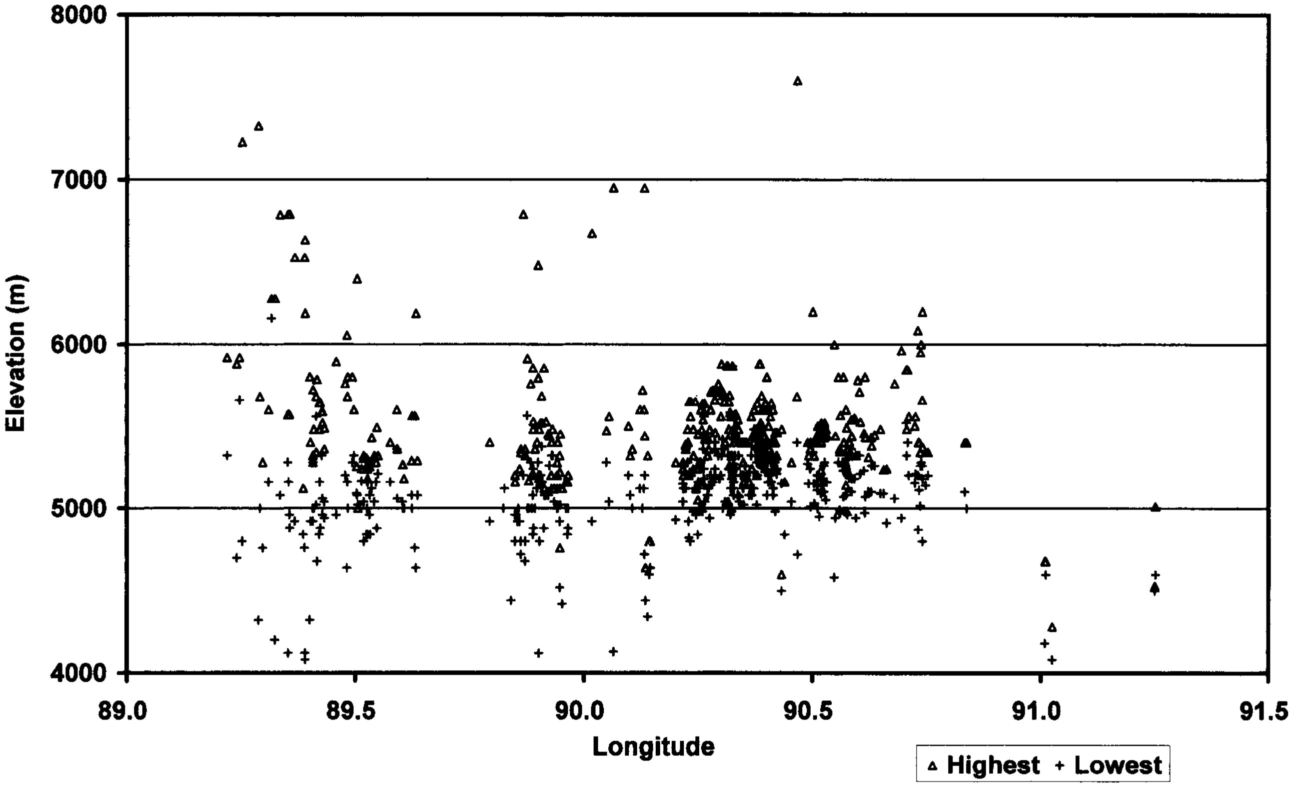

Fig. 6 Distribution of the highest and lowest elevations of glaciers in the Bhutan Himalayas along longitudes.

E and 90.84°E show higher termini altitudes. This is due to the plateau like topography in this region where the glaciers cannot flow down to the lower altitudes. A group of small mountain glaciers with very low highest (below 5000m) and lowest elevations are found to exist in the easternmost part. A similar set of glaciers is also seen in the Bhramaputra basin (Arunachal) in the Indian Himalayas, the easternmost part of the Himalayan Range (Fig. 3a). It can be thought that much monsoon precipitation in these easternmost regions favors such small glaciers to distribute in these lower mountain regions.

Large valley glaciers flowing from very high peaks in the Himalayas are usually covered with thick debris in their lower part. Figure 7 shows the lowest elevations of debris-covered glaciers obtained from Geological Survey of Bhutan (1999) and those of debris-free glaciers obtained from the present study in the Bhutan Himalayas. Clearly it can be seen that the lowest elevation of the debris-covered glaciers are

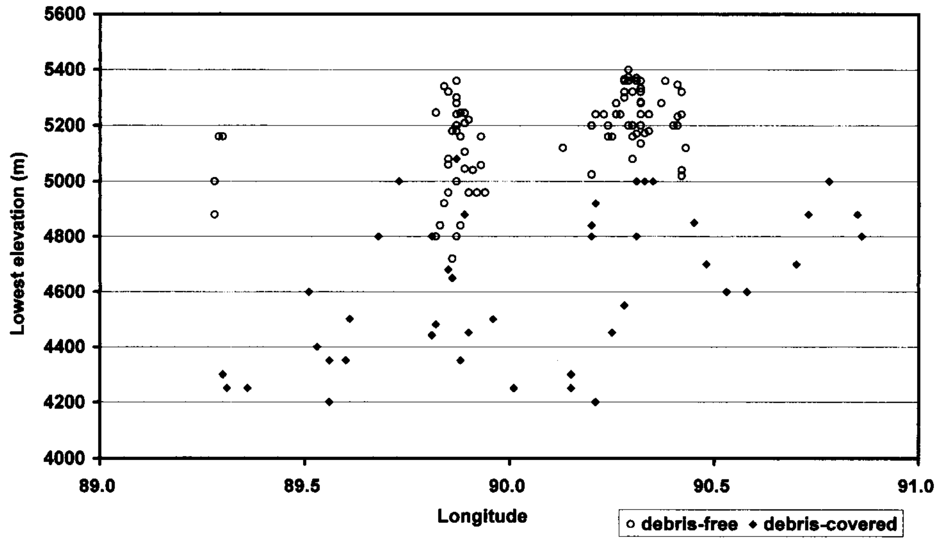

Fig. 7 Distribution of the lowest elevations of debris-free glaciers and debris-covered glaciers in the Bhutan Himalayas.

lower than those of the debris-free glaciers. It can be attributed to rich ice supply from the large upper stream and insulating effect of ablation by thick debris of the debris-covered glaciers.

4.3. *Glacier terminus variation from 1963 to 1993*

Ageta *et al.* (2000) examined the retreat rate of selected four glaciers which have glacier lakes at their termini by comparing photographs, satellite images and maps in different years. The mean annual retreats of the three glaciers among them in recent decades were in a range of 30-35 m in the horizontal distance. However, the rates were variable with time, probably due to irregular calving of the glacier tongues to their lakes. In the present study, termini variations of debris-free glaciers are examined for a period of 30 years (1963-93), since the debris-free glaciers are more sensitive to the climate change. For this analysis, the various materials are used as described in Section 2. A total of 103 glaciers are included for this analysis from different parts of the Bhutan Himalayas (Fig. 5). Debris-covered glaciers are excluded, since it is difficult to locate their active terminus position under the thick debris-cover.

Since the distance of terminal variation is considered to be controlled by the size of each glacier (Ageta, 1995; Ageta *et al.*, 2000) as well as climate change, comparison of the terminal variations among different glaciers should be made carefully. The comparisons are made hereafter in this paper for the only debris-free glaciers. Since this glacier group is smaller in size (with the length within several kilometers), comparing to the debris-covered glacier group, the above problem is thought to be reduced.

In Fig. 8, terminal variations of the glaciers in the Bhutan Himalayas are shown in horizontal and vertical retreat along latitudes. There are no advancing glaciers found within the data collected for this analysis. Since glacier boundaries in 1993 in the satellite image were marked on the base map in 1963 as described in Section 2 and the terminal altitudes in 1993 were read at the contour lines of the glacier surfaces in 1963, the vertical retreats are overestimated by the former glacier thickness at the terminal positions in 1993. A decreasing trend of glacier retreat from south to north can be roughly seen in Fig. 8.

Figure 9 shows the relation of annual retreat rates averaged for 1963-1993 in horizontal and vertical distances with the lowest elevation of the glaciers in the Bhutan Himalayas. Annual rates of glacier variations in averages for these 30 years distributed in a range between a stationary state and a horizontal retreat of 27 m yr^{-1} (8 m yr^{-1} in a vertical retreat).

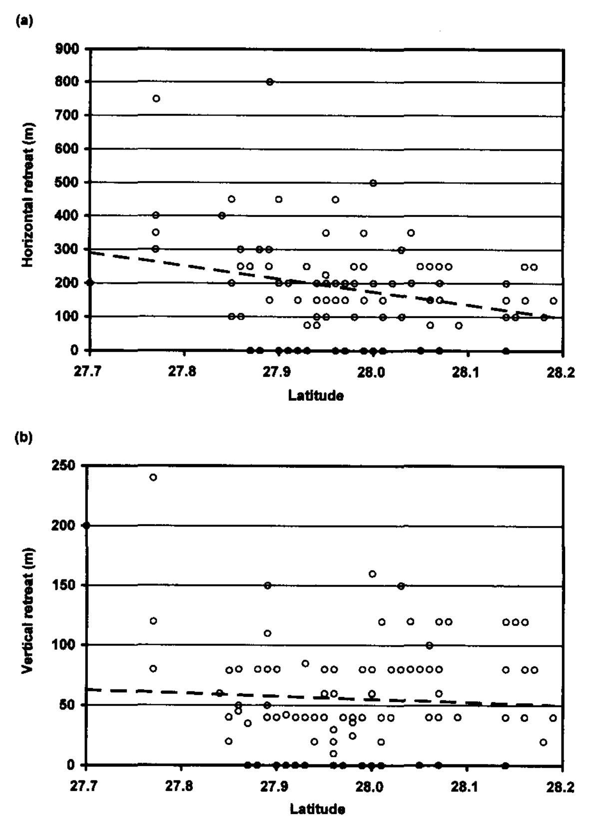

Fig. 8 Horizontal and vertical retreats of the debris-free glacier termini in the Bhutan Himalayas along latitudes for 1963-1993.
Dashed lines are the linear regression lines.

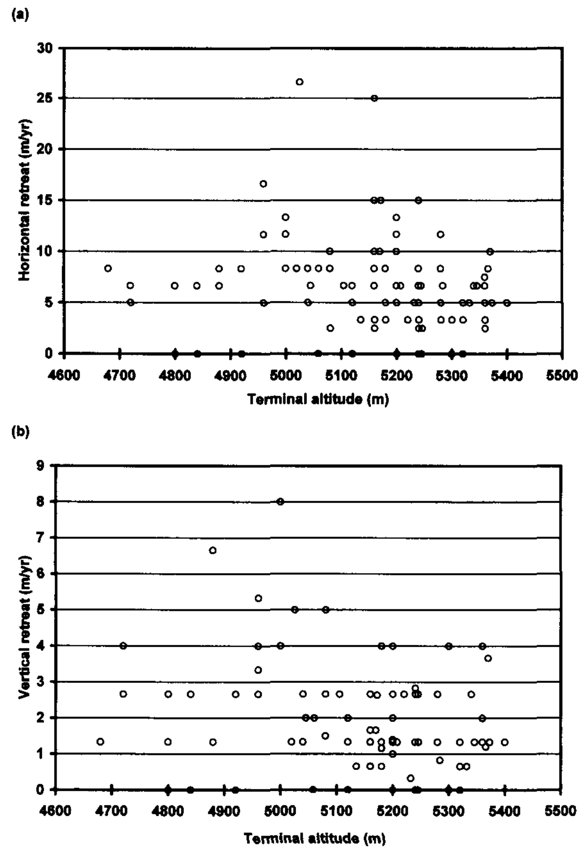

Fig. 9 Relation of annual retreat rates averaged for 1963-1993 in horizontal and vertical distances with the lowest elevation of the debris-free glaciers in the Bhutan Himalayas.

4.4. *Comparison with glacier terminus variation in Nepal from late 1950s to early 1990s*

Variations of the debris-free glacier termini in the Bhutan Himalayas are compared with those in the east Nepal where detailed data are available from Asahi (1999). For this analysis, the glacierets and snowfields, and glaciers with hanging and interrupted in their longitudinal profile were excluded as same as the former analyses. Here, data of 100 debris-free glaciers in Nepal for the period from 1959 to 1992 are used.

Horizontal and vertical retreats of glacier termini in annual rates in the east Nepal and Bhutan Himalayas are shown along longitudes and latitudes in Figs. 10 and 11, respectively. Since there are no advancing glaciers in Bhutan, the advancing glaciers in the east Nepal (12% of the glacier number) are not included for the comparison purpose. Periods of the average rates for the glaciers in east Nepal and Bhutan are 33 years (1959-1992) and 30 years (1963-93), respectively. A general increasing trend of the retreat rates from west to east can be roughly seen in the east Nepal (Fig. 10). Glaciers in both countries show a decreasing trend of the retreat rates from south to north (Fig. 11).

Average variation rates of the glacier termini in the east Nepal and Bhutan in the recent decades are tabulated in Table 3. The calculations were made from the rates of glaciers for different types of variations *i.e.* for all types of variations (advancing, stationary and retreating), for stationary and retreating only and for retreating glaciers only; the rates were averaged from totals of each glacier group as advancing to be negative and retreating to be positive. In all cases, average variation rates are higher for the glaciers in the Bhutan Himalayas.

4.5. *Areal variation of the glacier extent in the Bhutan Himalayas from 1963 to 1993*

Areal shrinkage of glaciers in the Bhutan Himalayas is evaluated by the method as described in Section 2. Out of the 103 debris-free glaciers on which the termini variations were analyzed, glaciers with unclear lateral boundaries were excluded and the areal variation was measured on 66 glaciers for the 30 years as shown in Table 4. The glaciers had a total area of 146.87 km^2 in 1963 and the area decreased to 134.94 km^2 in 1993; that is 8.1% shrinkage from the total area in 1963. The percentage of shrinkage at each range of the glacier area has a tendency that the smaller glaciers have the higher shrinking rate more than the lager glaciers as seen in Table 4. Three small glaciers (0.2, 0.15, 0.1 km^2 in 1963) completely disappeared by 1993.

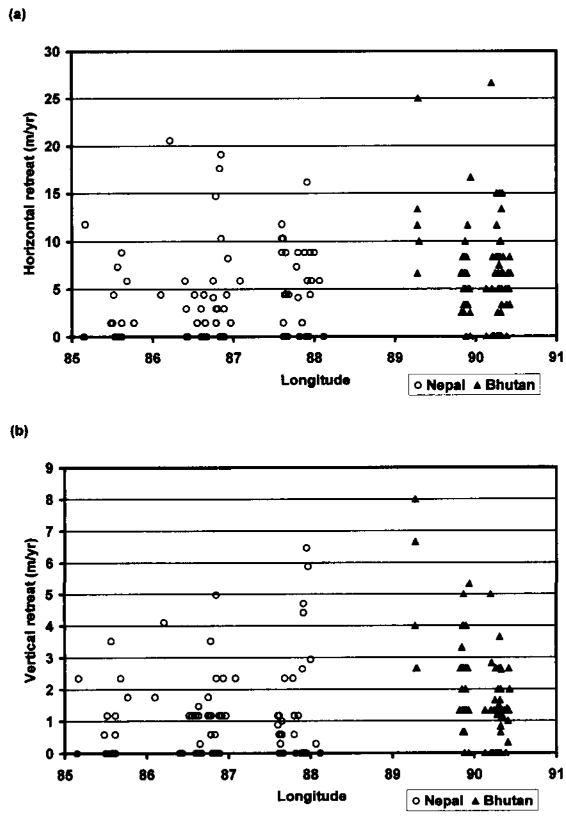

Fig. 10 Horizontal and vertical retreats of debris-free glacier termini in averaged annual rates in the east Nepal (1959-1992) and Bhutan Himalayas (1963-1993) along longitudes.

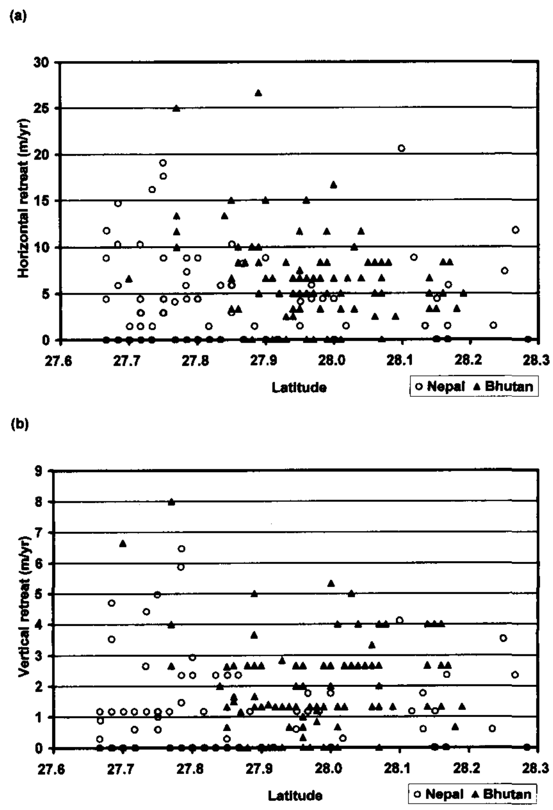

Fig. 11 Horizontal and vertical retreats of debris-free glacier termini in averaged annual rates in the east Nepal (1959-1992) and Bhutan Himalayas (1963-1993) along latitudes.

Table 3. Average variation rates of glacier termini in east Nepal and Bhutan in the recent decades.

For retreating (positive rate), **stationary and advancing** (negative rate) **glaciers**

Region	Period (years)	Variation rate (m/yr)		No. of glaciers
		Vertical	Horizontal	
Nepal	33 (1959-92)	0.59	3.14	100
Bhutan	30 (1963-93)	1.9	6.27	103

For retreating and stationary glaciers only

Nepal	33 (1959-92)	1.13	4.36	88
Bhutan	30 (1963-93)	1.9	6.27	103

For retreating glaciers only

Nepal	33 (1959-92)	1.72	6.61	58
Bhutan	30 (1963-93)	2.23	7.36	86

Table 4. Areal shrinkage from 1963 to 1993 for the different size of glaciers in the Bhutan Himalayas.

Area in 1963 (km^2)	Number of glaciers	Total area in 1963 (km^2)	Total area in 1993 (km^2)	Total area shrank (km^2)	Shrinkage (%)
0-1	22	11.11	8.64	2.47	22.2
1-2	14	19.36	16.61	2.75	14.2
2-3	12	28.68	25.98	2.7	9.4
3-4	9	27.98	26.27	1.71	6.1
4-5	3	12.62	11.89	0.73	5.8
5-6	3	16.32	15.43	0.89	5.5
8-12	3	30.8	30.12	0.68	2.2
TOTAL	**66**	**146.87**	**134.94**	**11.93**	**8.1**

No glacier in the area of 6-8 km^2 in 1963.

5. Discussions and conclusions

5.1. Glacier distribution in the Himalayas

Monsoon precipitation increases toward the eastern (southern) part from the western (northern) part in the Himalayan Range (*e.g.* Eguchi, 1994, Fig. 1). The higher precipitation increases glacier accumulation and decreases ablation due to accompanied cloudy weather. In relation with the above, the following tendencies of glacier distribution were found in the present study.

- The lowest elevations (Fig. 3a) and the ELAs (Fig. 4a) of the glaciers in the eastern half of the Himalayas descend toward east from Nepal via Sikkim-Bhutan to Arunachal) which are located at the similar latitudes.
- The ELAs in Fig. 4b in Nepal-Sikkim-Bhutan-Arunachal (south) are not so much different from those in Himachal & Gharwal at the higher latitudes, though those in the western higher latitudes descend from Himachal & Gharwal to Kashmir toward north due to the latitude effect.
- Groups of small mountain glaciers with very low highest and lowest elevations were found in the easternmost parts of Bhutan and Arunachal (Figs. 3a and 6).

These tendencies of glacier distribution are attributed to the monsoon effect due to the characteristic distribution of precipitation mentioned above.

5.2. Glacier variation in the Himalayas

The glaciers in the Himalayas and the surrounding areas have characteristics of being a "summer-accumulation type". The glaciers receive most of annual accumulation in summer when ablation occurs simultaneously. The higher summer air temperature provides the following negative effects on mass balance of summer-accumulation type glaciers (Ageta and Highuchi, 1984; Ageta and Kadota, 1992).

1) Increased proportion of rain in the total precipitation reduces accumulation by snowfall.

2) Decreased albedo due to less snowfall enhances ablation by insolation.

3) Higher temperature increases ablation.

As a result, glacier variation in the monsoon area depends sensitively on the summer air temperature as shown with empirical relations of accumulation and ablation with precipitation and air temperature by the above references. The above characteristics are also shown with the simulation model by Fujita and Ageta (2000) which consists of the detailed energy balance model including albedo effect and others, and with the simulation model by Naito *et al.* (2001) which includes glacier dynamics. On the basis of the empirical equation in Ageta and Kadota (1992), mass balance variation of a glacier in case of same temperature increase and constant precipitation is expected as follows.

1) Decrease of accumulation is more in an area with higher precipitation (east/south), since accumulation

is proportional to precipitation under the same temperature condition.

2) Increase of ablation is much more at the warmer place (lower latitudes, lower altitudes), since ablation is a power function of air temperature.

Almost all glaciers measured in the whole Himalayas have been retreating in the recent decades (Table 1). In Bhutan, total areal shrinkage from 1963 to 1993 for 66 debris-free glaciers is 8% of the initial total (147 km^2) and the shrinkage rates of smaller glaciers are higher than those of the larger glaciers (Table 4). And the following differences in variation of debris-free glaciers were found.

- Regional differences of glacier retreat were found between Nepal and Bhutan; the average retreat rate in Bhutan (east from Nepal) is higher than Nepal in the recent about 30 years (Table 3).
- Some zonal differences were roughly seen such as increasing trend of glacier retreat from west to east in Nepal (Fig. 10), from north to south in Nepal (Fig. 11) and in Bhutan (Figs. 8 and 11).

These regional and zonal tendencies of glacier variation can be attributed to the mass balance effect mentioned above.

As the result described above, characteristics in the distribution and variation of Himalayan glaciers have been understood in term of local difference of monsoon activity and the mass balance feature of summer-accumulation type glaciers.

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