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Expansion of glacier lakes in recent decades in the Bhutan Himalayas

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Abstract An inventory of glacier lakes was compiled based on observations carried out for 30 glacier lakes in the northern and northwestern parts of Bhutan in autumn 1998. Risk assessments for glacier lake outburst floods were made for these glacier lakes. Historical variations of glacier lakes and glacier termini were examined using photographs, satellite images, maps and published observations. In the northern region of Bhutan, supraglacial ponds on some debris-covered glaciers in the 1950s have subsequently grown into moraine-dammed lakes. Also, proglacial lakes have expanded substantially as a result of retreat of glacier termini.

INTRODUCTION

Glaciers in the Himalayas are shrinking more rapidly than glaciers in other regions of the world (Fujita *et al.*, 1997). In the Himalayas, precipitation on the glaciers is intense in summer during the summer monsoon. Winter is a dry season. A rise in summer air temperature on these summer-accumulation type glaciers in the Himalayas has an especially strong negative effect on mass balance (Ageta & Kadota, 1992). The proportion of rain is increased by the temperature rise and snow accumulation decreases; surface albedo is decreased by the snowfall decrease and ablation increases. The monsoon precipitation in Bhutan in the eastern Himalayas is much higher than that in Nepal and the western Himalayas (Eguchi, 1997). Therefore, a decrease in the

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glacier mass balance and associated glacier retreat with similar summer warming is likely to be more pronounced in Bhutan. However, no study has been published on glacier variations in Bhutan after exploratory work in the 1960s by Gansser (1970).

Since the rapid change of glaciers impacts geo-hazards such as glacier lake outburst floods (GLOF), combined monitoring of the variations of glacier lakes and the surrounding glaciers is needed for assessment of the future risk potential. A joint project between the Geological Survey of Bhutan and Japanese glaciologists and geomorphologists was initiated in 1998 for preparation of the updated inventory of major glacier lakes and assessment of the danger of GLOF. Field research was executed in northern and northwestern parts of Bhutan along the route shown in Fig. 1 during the period from 11 September to 19 October 1998. On the basis of this research and other available information, 30 glacier lakes were identified and GLOF risk assessments were made (Ageta & Iwata, 1999). Related observations were also carried

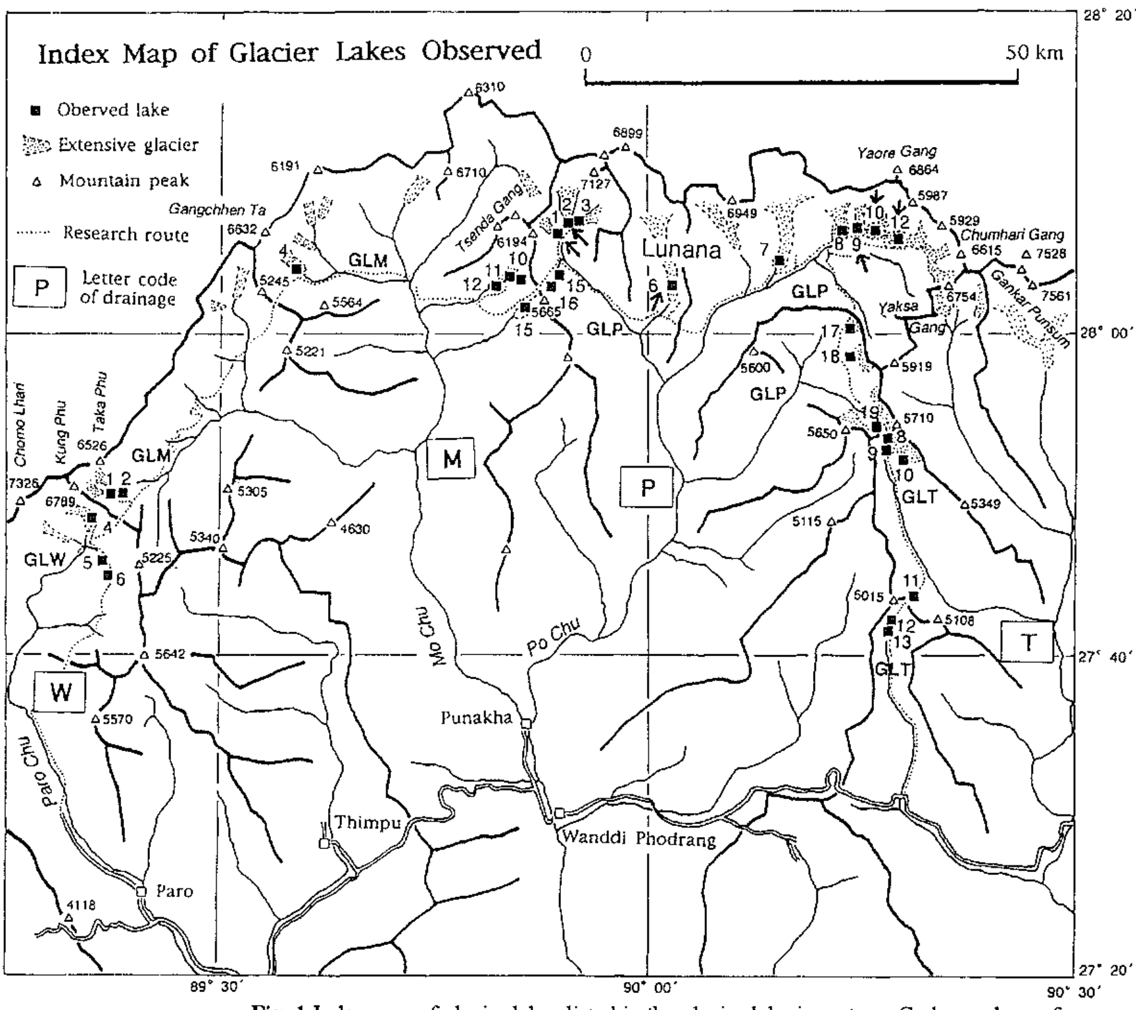

Fig. 1 Index map of glacier lakes listed in the glacier lake inventory. Code numbers of glacier lakes described in this paper are indicated by arrows.

out on glacier variations, climate and glacial geomorphology. Water temperature and lake depth distribution was measured at Raphsthreng Tsho (lake) in the Lunana region (GLP9), the upper stream of Po Chu (river) (Fig. 1).

Observations in 1998 aimed to obtain a broad view of conditions in a large area where ground observations have been scarce. In the present paper, brief results of the GLOF assessment are presented; the results on variations of selected glacier lakes and glacier termini are described as a basis for further study.

VARIATIONS OF GLACIER LAKES

Glacier lakes observed

An inventory of glaciers and glacier lakes in the headwaters of major river basins of Bhutan was published by the Division of Geology and Mines (1996); glaciers, glacier lakes and the first-order river basins were labelled and numbered in this inventory. Their code numbers are used here with some provisional additional numbers where required (Fig. 1).

Glacier lakes were classified into three types based on location, mode of formation and recent condition:

(a) *Supraglacial ice-melt ponds or lakes*: most of them are small and shallow in size, but they tend to connect to each other and grow into large contiguous lakes.

(b) *Moraine-dammed lakes*: some lakes store large quantities of water and have probability of GLOFs that could cause severe damage downstream.

(c) *Lakes located in basins far from glaciers or without glaciers*: they are located in cirques or glacial troughs which were scoured by Pleistocene glaciers. These lakes are stable because of solid rock spillways and no direct influence of glacier variation.

All of lakes of types (a) and (b) were associated with debris-cover on glacier ice that caused differential melting, and increased surface irregularities developed ponds or lakes.

Dimensions for the main glacier lakes of types (a) and (b) were measured on maps (1:50 000 toposheets made by the Survey of India using aerial photographs in 1956 and 1958), satellite images and literature. Examples are considered below. Code numbers of glacier lakes described in the next section are indicated by arrows in Fig. 1.

Expansion of glacier lakes and risk of GLOF

In Lunana region, several debris-covered glaciers extend their tongues into the flat valley floor of the eastern headwaters of Pho Chu; three glaciers form a contiguous chain of termini with large glacier lakes called Lugge Tsho (GLP12), Thorthomi Tsho (GLP10) and Raphsthreng Tsho (GLP9) (Fig. 2). This area appears to be the most vulnerable for GLOF along the observed route, since the lakes could interact with each other as described below.

Lugge Tsho (GLP12) and Drukchung Tsho (GLP13) Lugge Tsho (28°06'N, 90°18'E, 4520 m a.m.s.l.) is located at the eastern end of Lunana valley at the head of

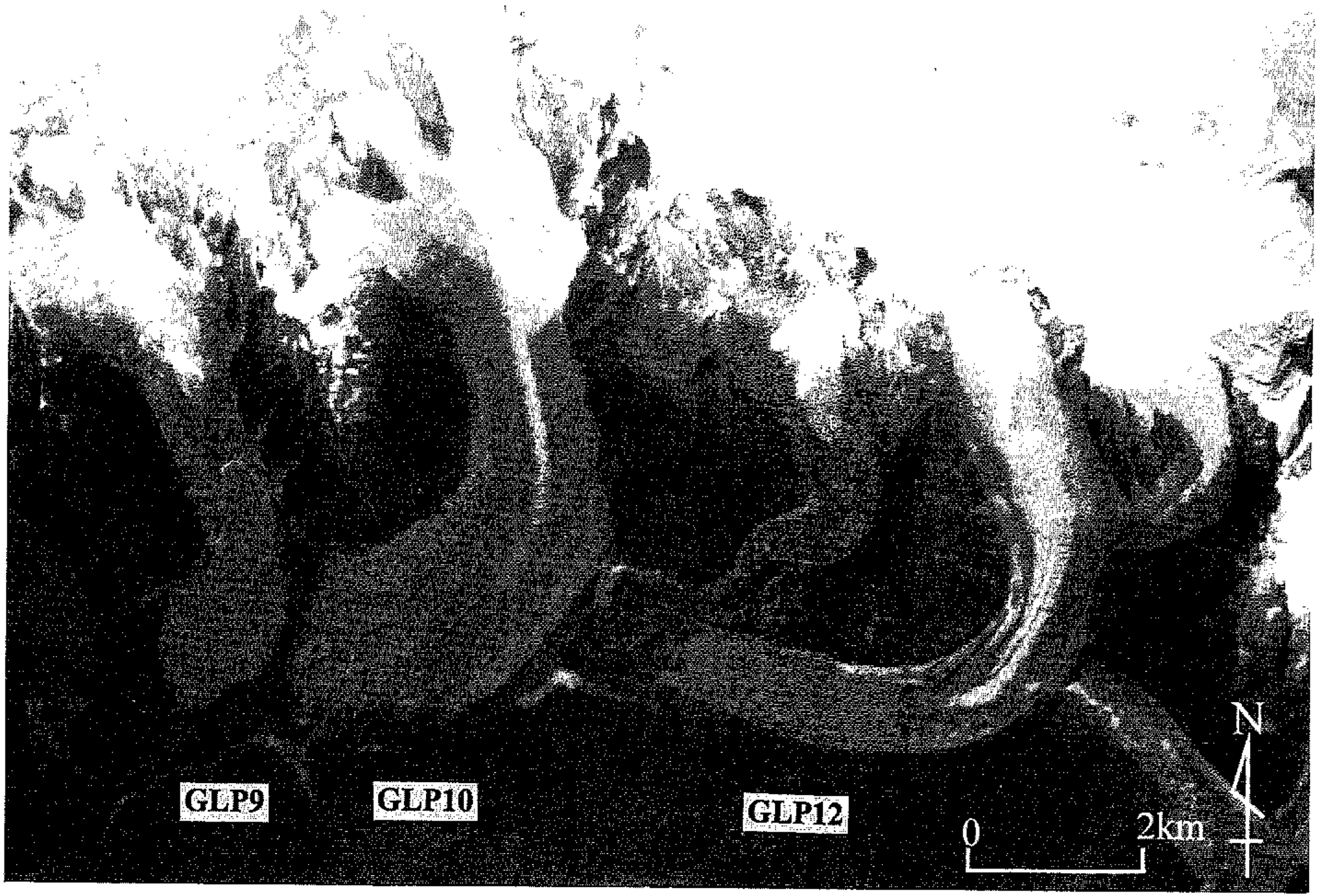

Fig. 2 Glacier lakes in Lunana on contiguous debris-covered glaciers. Lugge Tsho (GLP12), Thorthomi Tsho (GLP10) and Raphsthreng Tsho (GLP9) from east in a SPOT-XS satellite image taken on 11 December 1993 (copyright: CNES).

Po Chu. On 6–7 October 1994, GLOF from Lugge Tsho killed 21 persons and damaged many facilities. The outburst occurred by the sudden expansion of a small cleft at the lower end of the left lateral moraine of Lugge Glacier. Ice was observed in the cut through the moraine a week after the outburst, and failure of the moraine was probably induced by melting of its ice core (Division of Geology and Mines, 1996). Expansion of the outlet channel is easily recognized on the satellite images of SPOT taken before and just after the GLOF as illustrated in Fig. 3.

Evolution of Lugge Tsho since the 1950s is illustrated in Fig. 3. In the 1950s, there were no significant lakes on either Lugge Glacier or Drukchung Glacier which joins Lugge Glacier from the southeast. According to Gansser's observation in 1967, many supraglacial ponds had formed on both glaciers; he found clear signs of recent drainage of ponds on Drukchung Glacier (Gansser, 1970). From 1967 to 1988, these ponds joined together to form two large moraine-dammed lakes, Lugge Tsho and Drukchung Tsho. Drukchung Tsho reached a maximum area in 1988 (Fig. 3) and probably drained through a supraglacial channel of Lugge Glacier to Lugge Tsho. Lugge Tsho had a maximum area in 1993. It shrank after a 1994 outburst, when the western end of the lake receded by nearly 500 m.

If the outlet channel of Lugge Tsho were to become blocked in the future, a rise of the water level over its wide area would increase the risk of another GLOF. Possible causes of a blockage could be: (a) a landslide from the steep inner slope of the lateral moraine, (b) the large-scale failure of the inner slope caused by melting of the ice core in the lateral moraine. If GLOF from Lugge Tsho were to occur again, there might be a high risk of Thorthomi Tsho further downstream adding to the flood due to erosion of

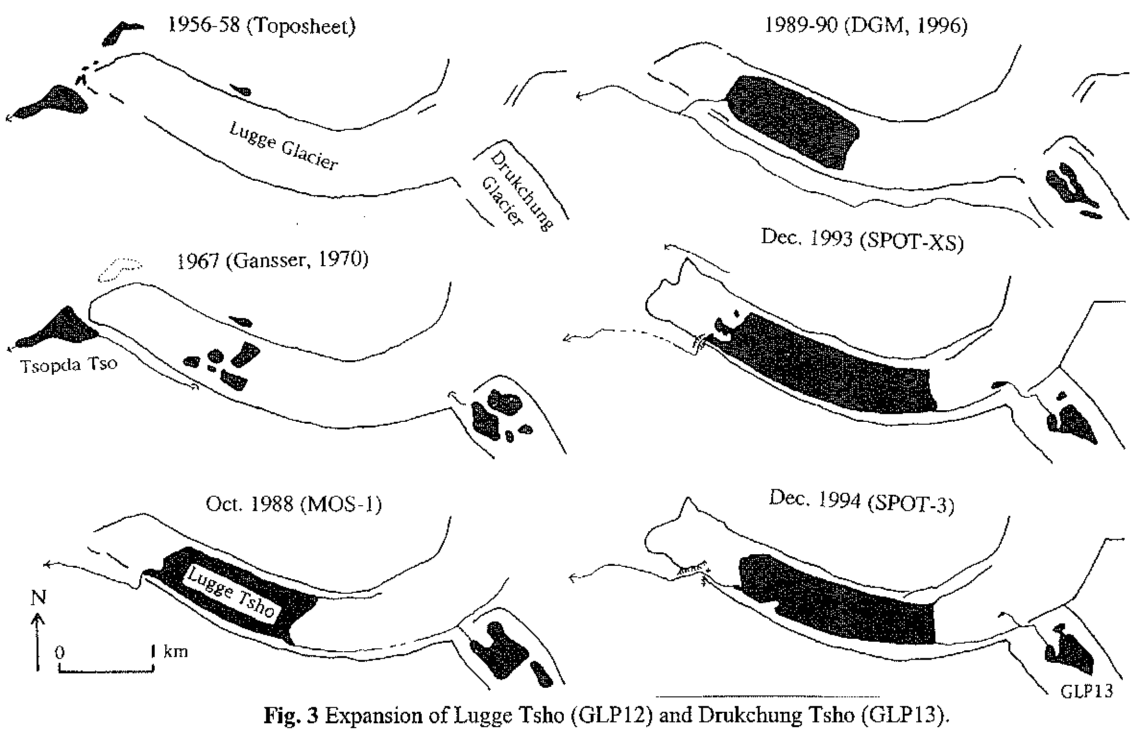

Fig. 3 Expansion of Lugge Tsho (GLP12) and Drukchung Tsho (GLP13).

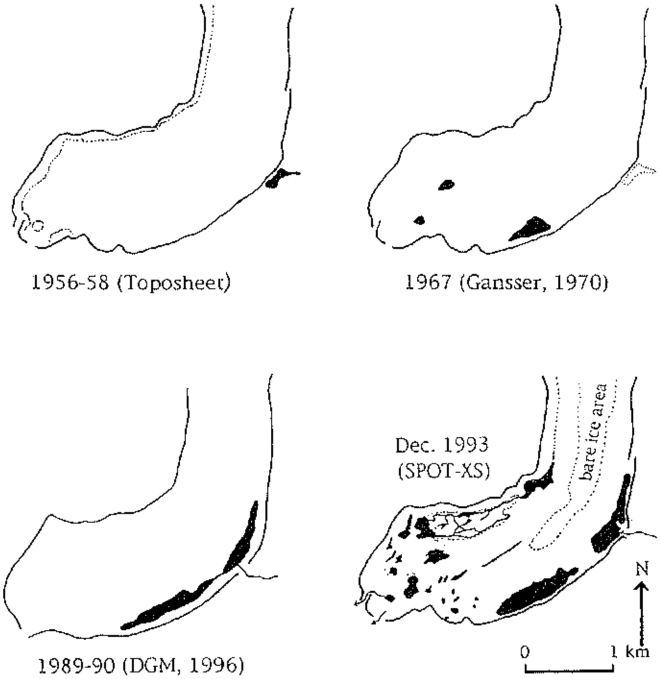

Fig. 4 Expansion of Thorthomi Tsho (GLP10).

the outer slope of its vulnerable left lateral moraine by the flood water as described below.

Thorthomi Tsho (GLP10) Expansion of supraglacial ice-melt lakes (28°06′N, 90°17′E, 4440–4480 m a.m.s.l.) on Thorthomi Glacier has accelerated in the 1990s as shown in Fig. 4. A continuing expansion of the lakes was documented by 1998 observations. The thin debris cover on the glacier surface, which accelerates ice melting, and the very gentle gradient of the snout may lead to the formation a large lake in the near future.

The left (southeast) lateral moraine is being eroded from both sides and the moraine ridge is becoming sharp and narrow; the inner slope is retreating because of expansion of the long lakes along the base. The outer slope is eroding its base by lateral and downward cutting of the river which discharges from Lugge Tsho (GLP12). In addition, a considerable amount of water is leaking from the left lateral moraine to the river channel from Lugge Tsho. There is therefore a potential for collapse of this moraine and associated release of water in the near future.

Raphsthreng Tsho (GLP9) Raphsthreng Tsho (28°07′N, 90°15′E, 4400 m a.m.s.l.) rapidly expanded between the 1950s and the 1980s from supraglacial lakes to a moraine-dammed lake, while in the 1990s the lake maintained almost the same state (Fig. 5). Lake expansion has halted, probably because the glacial bed steeply rises just upstream from the present terminus position.

The lake level of Raphsthreng Tsho is about 50 m lower than the levels of supraglacial lakes on Thorthomi Glacier to the east (Fig. 2). The moraine between

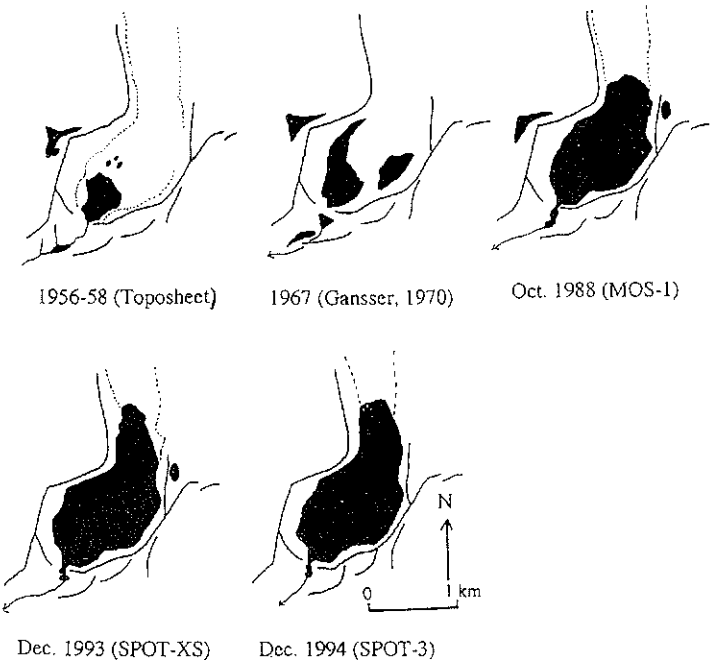

Fig. 5 Expansion of Raphsthreng Tsho (GLP9).

them is damming water flow from Thorthomi lakes to Raphsthreng Tsho. If this moraine dam were to break, the outburst from Thorthomi lakes could initiate a catastrophic outburst of Raphsthreng Tsho. Although the moraine looks stable at present, vulnerability of this moraine to failure could increase, if seepage from Thorthomi Glacier to Raphsthreng Tsho weakens this moraine. The probability of failure of the terminal moraine dam of Raphsthreng Tsho has been mitigated by artificial excavation of the outlet channel in 1996–1998. But the risk is still high because the lake contains a large volume of water (maximum depth about 100 m) with the additional danger from Thorthomi Glacier.

Tarina Lakes (Tarina Tsho GLP1 and Mouzom Tsho GLP2) These glacier lakes are located at the western headwaters of Pho Chu (Figs 1 and 6). The evolution of the Tarina Lakes is illustrated in Fig. 7. Comparison of 1998 observations with a photograph taken in 1967 by Gansser (1970) shows that the area of the upper lake (GLP2: 28°07'N, 89°55'E, 4340 m a.m.s.l.) expanded upstream due to retreat of the debris-covered tongue of the glacier. A satellite image in 1988 shows that the present condition with the terminus on the top of a rock cliff in the valley was already established 10 years ago (Fig. 7). Since upper ends of both of the glacier lakes GLP1 and GLP2 have been located at the foot of high rock cliffs, upvalley expansion of the lakes has been blocked. A fall of ice from the hanging ice masses of the glaciers terminating on the cliffs could displace water very rapidly causing overflow and downstream flooding.

Supraglacial ponds (GLP6) of Wachey Glacier Wachey Glacier is located about 15 km downstream of Tarina Lakes along the western branch of Pho Chu (Fig. 6). As

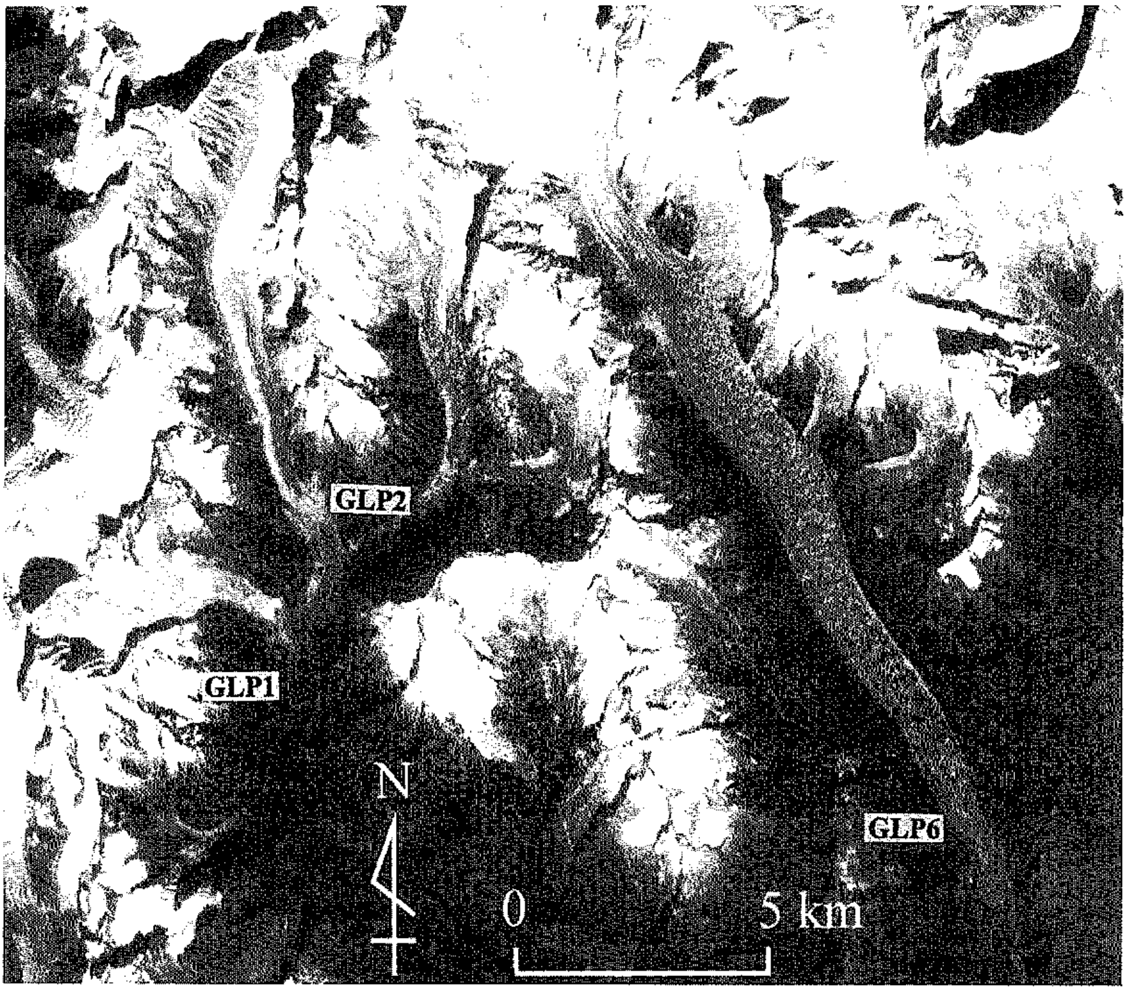

Fig. 6 Glacier lakes along the western branch of Pho Chu. Tarina Lakes (GLP1 and GLP2) and supraglacial ponds (GLP6) of Wachey Glacier in a SPOT-XS satellite image taken on 3 December 1993 (copyright: CNES).

shown in Fig. 8, only a few ponds were found in the map of Wachey Glacier in the 1950s. In 1967, Gansser (1970) found nine supraglacial ponds on the debris-covered area of this glacier. These ponds (28°03'N, 90°02'E, 4360–4440 m a.m.s.l.) more than doubled in area in December 1993 as seen in Fig. 8.

EXPANSION RATES OF PROGLACIAL LAKES UPVALLEY

Variations of glacier lakes and glacier termini can be detected from comparison of photographs, satellite images and maps in different years. For some glaciers, the variation can be measured from photographs taken in 1984 by T. Tsukihara and in 1998 by the authors. Between 1988 and 1993 Lugge Tsho expanded about 0.8 km (Fig. 3) in association with the glacier retreat. Raphsthreng Tsho expanded about 0.5

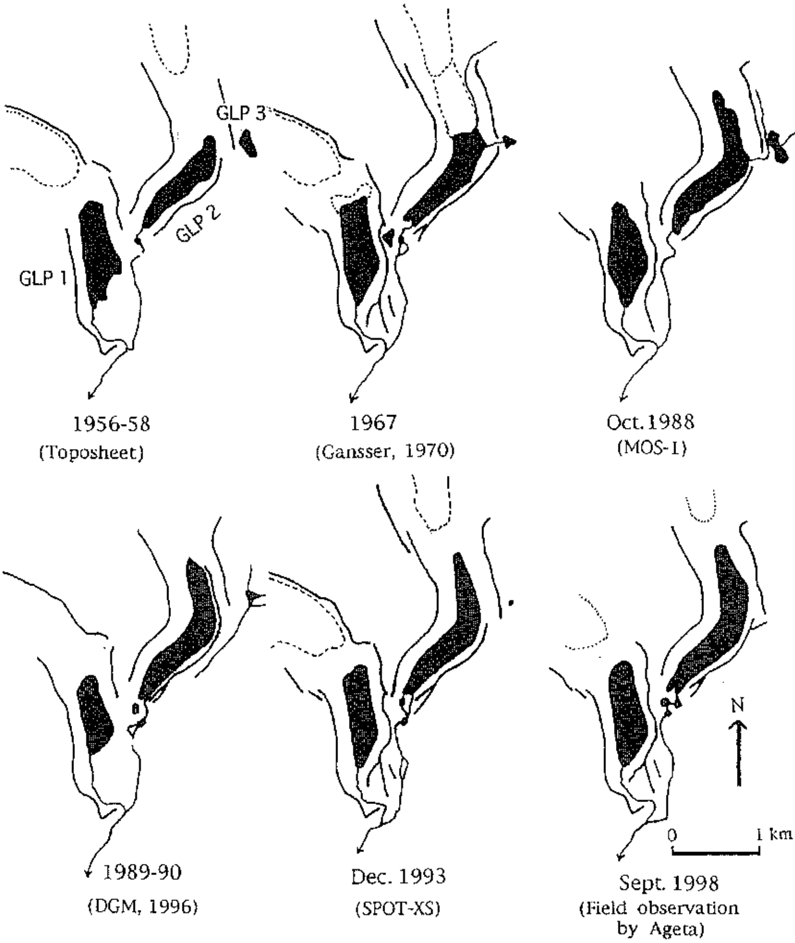

Fig. 7 Expansion of Tarina Lakes (GLP1, GLP2).

km between 1984 and 1998, and 0.3 km between 1988 and 1993 (Fig. 5). Tarina Lake (GLP2) expanded about 0.7 km from 1967 to 1988 (Fig. 7) and successive expansion was blocked by a cliff. The unnamed debris-free glacier, north of Gangrinchemzoe Pass (between GLP19 and GLT8 in Fig. 1), retreated about 0.4 km from 1984 to 1998; as a result, a small pond grew into a proglacial lake (GLP19: 27°55'N, 90°16'E, 5100 m a.m.s.l.). The above are examples of upvalley expansions of proglacial lakes accompanied by the corresponding retreat of glacier termini.

Mean annual expansion distances of proglacial lakes during recent years and glacier lengths in Bhutan are compared with available data from the Nepal Himalayas (Tsho Rolpa: 27°50'N, 86°28'E, 4580 m a.m.s.l.; Imja Lake: 27°59'N, 86°56'E, 5010 m a.m.s.l.) in Table 1. Since the expansion of Lugge Tsho can be measured only for the period from 1988 to 1993, available data of other lakes for the same period are shown in a different column. The mean annual expansions of three lakes (GLP9 and GLP19 for 1984–1998, GLP2 for 1967–1988) in Bhutan converge in a range of 30–35 m year^{-1}. However, the rates are variable with time as found for GLP9 and Tsho Rolpa (Table 1). Irregular calving of the glacier tongues is probably a major contribution to such variations.

Table 1 Mean annual expansion of proglacial lakes upvalley.

Glacier name (Lake code/name)	Expansion distance: m year^{-1}	period	m year^{-1} during 1988–1993	Glacier length (km)
Bhutan				
Lugge (GLP12)			160	5
Raphsthreng (GLP9)	35	1984–1998	60	3
Tarina (GLP2)	35	1967–1988	blocked by a cliff	8
unnamed* (GLP19)	30	1984–1998		3
Nepal				
Trambau (Tsho Rolpa)[a]	60	1983/84–1997	80	20
Imja (Imja)[b]	40	1984–1992		9

* The unnamed glacier, which is the only debris-free in the above glaciers, is located north of Gangrinchemzoe Pass.

[a, b] Based on figures in Yamada (1998) and Watanabe *et al.* (1995), respectively.

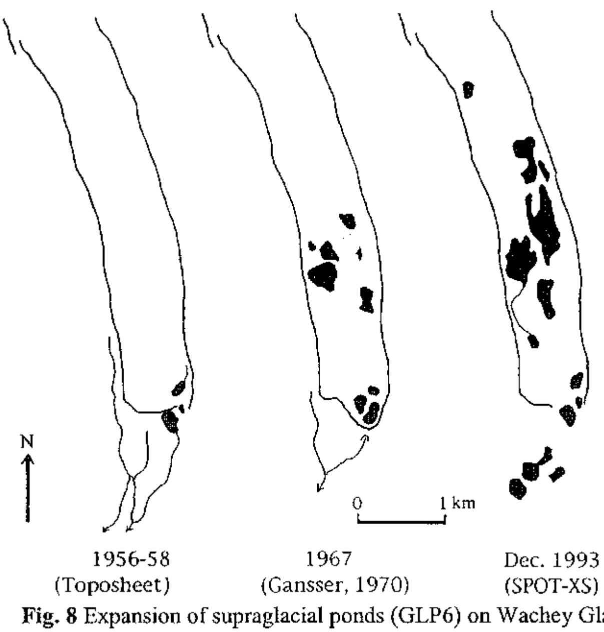

Fig. 8 Expansion of supraglacial ponds (GLP6) on Wachey Glacier.

Comparison of the rates between Bhutan and Nepal from Table 1 is difficult. Absolute rates appear smaller in Bhutan than Nepal, but rates relative to the glacier lengths are larger. The retreat rate of the unnamed glacier, which is the only debris-free glacier in Table 1, is very large in comparison with those of small debris-free glaciers in Nepal, most of which are retreating at only several m year^{-1} (Kadota, 1997).

For the further analyses of variations of proglacial lakes and glaciers, the interaction between them should be studied, such as calving and ice melting of glacier tongues by lake water. Proper criteria and methods to standardize the variation of debris-covered and debris-free glaciers with different scales are required for comparison of the glacier variations in different regions.

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