Glaciers of Asia—

GLACIERS OF BHUTAN—An Overview

By Shuji Iwata

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

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By Shuji Iwata[1]

Introduction

The Kingdom of Bhutan is a little-known mountainous and heavily forested country located in the eastern Himalaya. Having a total area of 46,500 km^2, it extends about 300 km east to west, and 170 km north to south. The total area covered by glaciers in Bhutan is 1,317 km^2 (Mool and others, 2001).

Officials, explorers, and naturalists who traveled to Bhutan in the past provided no descriptions of glaciers in the Bhutan Himalaya; therefore, not much historical information is available. The first modern descriptions of the glaciers of Bhutan were undertaken in the 1970s by Augusto Gansser, who carried out intensive geological surveys and developed a chronology of past glaciations in northern Bhutan (Gansser, 1970, 1983). In addition, Gansser (1970) warned of the potential for glacier lake outburst floods [GLOFs (or jökulhlaups)] in the Lunana area and documented his report with excellent photographs of glaciers and glacial lakes.

The report by Gansser (1970) prompted interest in the glaciers and glacial lakes of Bhutan, and in 1984 and 1986, the Geological Surveys of Bhutan and India carried out joint surveys of glaciers and glacial lakes for an assessment of the hazard potential in the Lunana area (Sharma and others, 1986). Their report concluded that there was no danger of outburst floods from *Raphsthreng Tsho* (called Lunana Lake in the report). Unfortunately, on 7 October 1994, a GLOF from *Lugge Tsho* glacial lake killed more than 20 people in the town of Punākha in the lower reaches of the drainage basin (Watanabe and Rothacher, 1996; Geological Survey of Bhutan, 1999).

After the GLOF disaster, several field studies focused on glaciers and glacial lakes in the Lunana area (Indo-Bhutan Expedition, 1995; Royal Government of Bhutan (RGOB) Expedition, 1995; Water and Power Consultancy Services (WAPCOS), 1997; Haeusler and Leber, 1998, Ageta and Iwata, 1999). At the same time, some of the field teams visited areas outside Lunana to observe glaciers and glacial lakes, conducting GLOF-hazard assessments (RGOB Expedition, 1995, Ageta and Iwata, 1999; Karma and Tamang, 1999; Karma and others, 1999, 2004; Ageta and others, 2000; Iwata, Ageta, and others, 2002; Iwata, Narama, and Karma, 2001), and compiling inventories of glaciers and glacial lakes (Division of Geology and Mines, 1996; Geological Survey of Bhutan, 1999; Mool and others, 2001). Bhutan and Japan initiated cooperative glaciological studies of large debris-mantled glaciers and small debris-free glaciers (Yamada and Naito, 2003; Ageta and Kohshima, 2004).

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Intensive hazard-assessment and mitigation efforts have continued in Lunana (Leber and others, 2000, 2002, 2003). Based on the findings of these studies, this paper provides brief descriptions of glaciers and related phenomena in the Bhutan Himalaya.

Glacier Distribution and Types of Glaciers

Glacier distribution in a region, including exact numbers and areas of glaciers, is shown by a glacier inventory. The first glacier inventory in Bhutan was compiled in 1996 by the Geological Survey of Bhutan (Division of Geology and Mines, 1996), and was subsequently published in a revised form with 83 pages of text and 13 map sheets (Geological Survey of Bhutan, 1999). A more complete inventory was published by the International Center for Integrated Mountain Development (ICIMOD) in Katmandu, Nepal (Mool and others, 2001). These inventories were compiled from analysis of 1993 Satellite Pour l'Observation de la Terre (SPOT) imagery, and 1:50,000-scale topographic maps made by the Geological Survey of India from vertical aerial photographs taken in the 1960s. Mool and others (2001) counted 677 glaciers in Bhutan covering a total area of 1,317 km^2. [Editors' note: An inventory of glacier resources by Qin (1999), compiled from analysis of 1975–1978 Landsat MSS band 7 and false-color infrared images and some aerial photographs, documented 649 glaciers in Bhutan, covering a total area of 1,304 km^2, and including a total volume of 150 km^3.]

Glaciers are common on peaks and mountain flanks along the main topographic divide of the Bhutan Himalaya, and on plateaus and ridges that stretch to the south from the main Himalayan divide (fig. 1). Most glaciers are located in river basins, where the rivers flow from north to south. However, Bhutan also includes the north flank of the main divide in the northernmost part of the country, an area called the *Northern Basin,*[2] where rivers flow from Bhutan northward, toward the Autonomous Region of Tibet, China.

The total number, area, estimated volume, and average thickness of each glacier type in Bhutan is listed in table 1. Valley glaciers on the southern side of the main divide have narrow and steep upper basins, whereas glaciers in the *Northern Basin* have large, gently sloping accumulation areas. The longest glacier in Bhutan is 20.1 km — *Wachey Glacier* in Pho Chhu (river) basin (Mool and others, 2001). The largest single glacier basin, with a total area of 99.7 km^2, is located on the north slope of *Table Mountain* in the *Northern Basin*, northeast of Lunana (Mool and others, 2001). The accumulation areas of glaciers in the *Northern Basin* form an ice field that constitutes the north slopes of *Table Mountain*.

Large glaciers within valleys are characterized by debris-mantled snouts. On the south flank of the Bhutan Himalaya, slopes are steeper than those on the north slopes because topography on the south is formed by headward erosion of the rivers. As a result, rock cliffs occupy the heads of glacierized valleys. Headwalls of glacierized basins have ice and/or snow avalanches and rockfalls, processes enhanced by high precipitation from the summer monsoon.

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[2]U.S. Government publications require that official geographic place-names for foreign countries be used to the greatest extent possible. In the Glaciers of Bhutan section, the use of geographic place-names is based on the U.S. Board on Geographic Names as listed on the GEOnet Names Server (GNS) website: *http://earth-info.nga.mil/gns/html/index.html*. Names not listed in the BGN website are shown in italics.

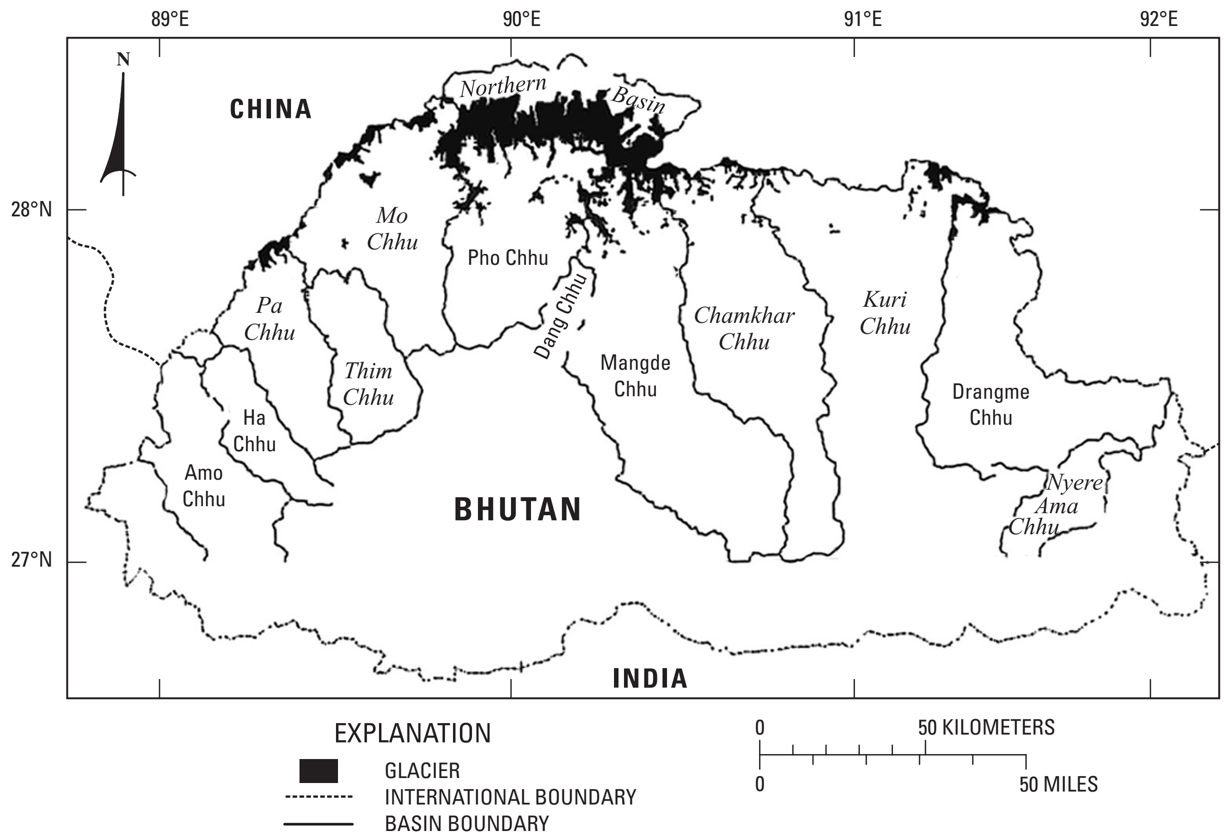

Figure 1.*—River basins and glacier distribution of the Bhutan Himalaya. After Mool and others (2001).*

TABLE 1.—*Total number, area, volume, and average thickness of each glacier type in Bhutan*

[Data sources: Mool and others (2001), and Karma and others (2003). Units: km, kilometer; m, meter]

Glacier type[1]	Number	Area (km^2)	Estimated volume (km^3)	Average thickness (m)
Valley glacier	51	691.76	90.222	130
Mountain glacier	453	579.02	35.510	61
Ice apron	94	33.40	1.197	36
Ice cap	16	5.19	0.182	35
Niche glacier	51	5.57	0.105	19
Cirque glacier	12	1.79	0.035	20
Total	677	1,316.73	127.251	97

[1]Glacier types are adapted from Müller and others (1997). Mountain glaciers are the most common, and their profile shows a hanging type.

***Figure 2.**—Small debris-free plateau glacier with glacial lakes at the* Gangrinchemzoe La *(pass is at 5,200 m) in 1998. The lake started to form around the mid-1980s.*

The large amount of supraglacial debris in accumulation areas produces extensive debris-mantles in ablation areas downglacier. Large debris-mantled glaciers develop in Lunana, the upper part of the Pho Chhu basin, and in the *Northern Basin,* where there are many steep, high mountains.

Numerous mountain glaciers, especially small hanging-type glaciers, occur on steep slopes of high peaks and on back walls of valley glaciers. Cirque glaciers, small ice caps, ice aprons, and niche glaciers are common on plateaus and ridges that stretch to the south from the main Himalayan divide (fig. 2). These small glaciers are virtually debris-free.

According to Mool and others (2001), the highest elevation of glacier basins is at about 7,500 m, near *Gankerphuensum* (7,570 m) in the Mangde Chhu basin, and the second highest is at about 7,300 m, near Chomo Lhāri (7,314 m) in the *Pa Chhu* basin. Although no measurements were conducted for the ICIMOD inventory, glacier basins at higher elevations may exist on Kula Kangri (*Kunla Khari*, 7,538 m). Values in Mool and others (2001) show that the lowest elevations of glacier termini are found slightly above 4,000 m. Glacier termini between longitudes 90.2°E. and 90.9°E. (the Mangde Chhu and *Chamkhar Chhu* basins) are somewhat higher, above 4,300 m. Glaciers in this area cannot flow down to lower elevations because of plateau-like landforms and high valley floors. A group of small mountain glaciers in the *Kuri Chhu* basin, located east of long 90.9°E., and the Drangme Chhu basin farther east, have very low maximum (below 5,000 m) and minimum (nearly 4,000 m) elevations.

The Geological Survey of Bhutan inventory (1999) lists a smaller number of glaciers than do Mool and others (2001), but glaciers on the list can be classified into debris-mantled and debris-free from the associated maps. Karma and others (2003) plotted frontal elevations of both debris-mantled and debris-free glaciers (fig. 3). The graph clearly shows that the termini of debris-mantled glaciers extend to lower elevations (4,200 m) than those of debris-free ones (4,700 m).

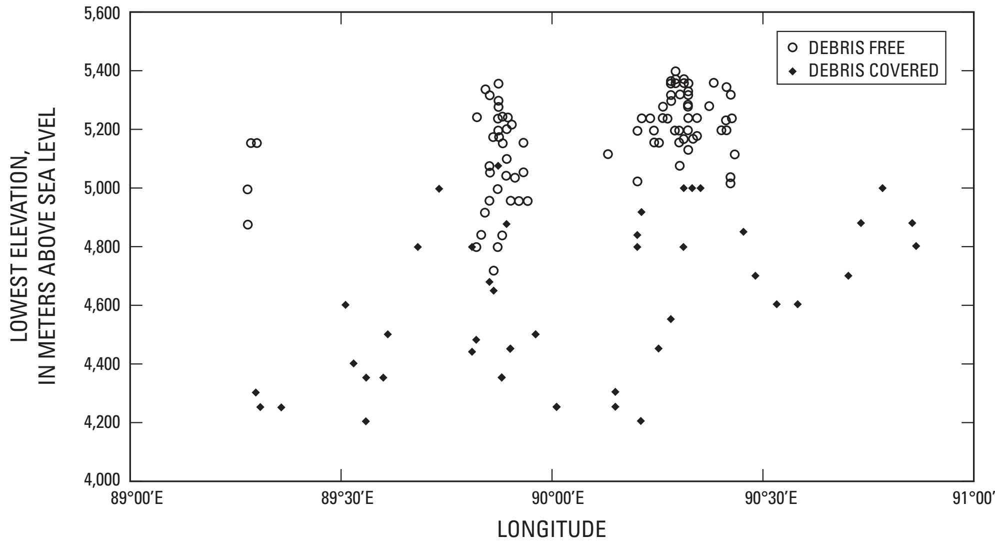

Figure 3.—*Distribution of the lowest elevations (glacier termini) of debris-free glaciers (open circles) and debris-mantled glaciers (solid diamonds) in the Bhutan Himalaya. Karma and others (2003).*

Glacier Equilibrium Line Altitude (ELA) and Climate

Bhutan has a monsoonal climate and most precipitation occurs in summer. Because monsoonal precipitation is much greater in the eastern and southern parts of the Himalaya than in the western and northern parts (Eguchi, 1991; fig. 4), glaciers have the characteristics of "summer-accumulation types." Glaciers receive most of their annual accumulation in the summer when ablation occurs simultaneously. The higher summer air temperature provides the following negative effects on mass balance of the summer-accumulation type glaciers (Ageta and Higuchi, 1984; Ageta and Kadota, 1992): (1) increased percentage of total precipitation in the form of rainfall reduces accumulation by snowfall, (2) decreased albedo due to less snowfall enhances ablation by insolation, (3) higher temperatures increase ablation. As a result, the variations of monsoon-type glaciers are very sensitive to the summer air temperature.

The equilibrium line altitude (ELA) is the most important parameter used to analyze glacier response to climate. Unfortunately, ELA information on glaciers in Bhutan is not available from the existing inventories. The ELA obtained from the author's observation in the field in September and October 1998 was 5,200–5,300 m on glaciers on the south side of the Himalaya in the northwestern and northern parts of Bhutan (Iwata, Naito, and others, 2003). This value is the lowest elevation of the ELA throughout the central and eastern Himalaya (Matsuoka, 2003). The intensity of the monsoon apparently produces the low ELA.

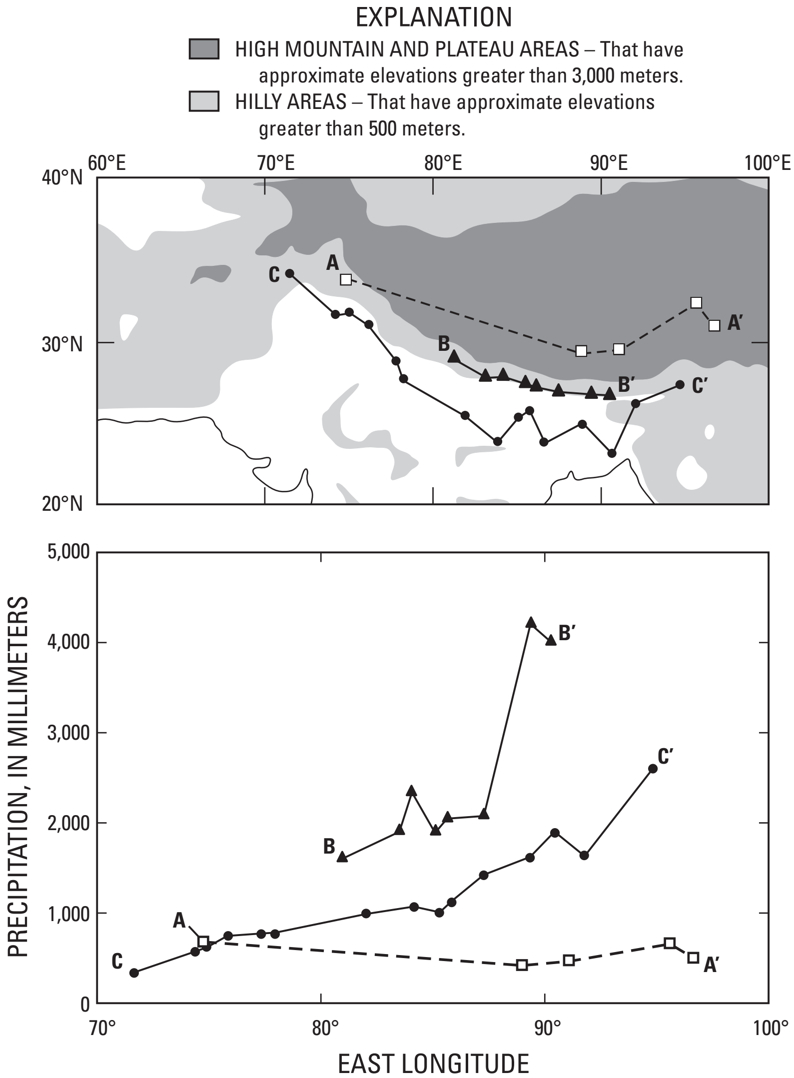

Figure 4.*—Variation of annual precipitation along the Himalaya.* **A**, *North of the Himalaya,* **B**, *Southern slopes of the Himalaya,* **C**, *Indian plain. From Eguchi (1991).*

Rock glaciers exist in many places along the *Snowman Trekking Route* in northwestern and northern Bhutan. Iwata, Gurung, and Komori (2003) reported on the lower limit of permafrost based on the distribution of active periglacial rock glaciers. The lower limit of discontinuous permafrost is at 4,800 m on north-facing slopes and at 5,000 m on south- and east-facing slopes. Results of automatic weather-station measurements between 1998 and 1999 suggest that mean annual air temperatures at the lower limits of the permafrost zone are −1.1 °C at 5,000 m and +0.1 °C at 4,800 m. These values mean that the relative height difference between the ELA and the lower limit of permafrost in the Bhutan Himalaya is the smallest in the Asian Continent (Matsuoka, 2003).

Isacks and others (1995) discussed the ELA depression during the Last Glacial Maximum (LGM) based on a determination of the maximum extent of glaciation using satellite imagery. Although their attempt was noteworthy, their conclusions are not supported by any field observations, and no glacial landforms have been dated using morphostratigraphic or cosmogenic-isotope dating methods.

Glacier Variations

Karma and others (2003) identified termini variations of debris-free glaciers in the 30-year period between 1963 and 1993 by analyzing published inventories (Geological Survey of Bhutan, 1999; Mool and others, 2001), topographic maps (1:50,000 scale, showing the early 1960s positions), and satellite images (1993 SPOT images). A total of 103 debris-free glaciers were selected for measurement, because these types of glaciers are sensitive to climatic change, and most debris-mantled glaciers show no changes of their frontal positions. The debris-free glaciers selected for analysis were small and had similar lengths. Karma and others (2003) determined that 90 glaciers (87.3 percent) are retreating, 13 (12.7 percent) are stationary, and no glacier was advancing. The horizontal distance of the frontal retreat of each glacier was plotted versus its latitude (fig. 5). Results indicate that the magnitude of glacier retreat is larger in the south and smaller in the north because of the higher sensitivity of glacier mass balance to the warmer temperature and greater precipitation in the south. Karma and others (2003) concluded that the average retreat rates of glacier termini in Bhutan are higher than those in Nepal.

Areal shrinkage of 66 glaciers selected from the 103 debris-free glaciers was measured on the maps with a planimeter (Karma and others, 2003). The 66 glaciers had a total area of 146.9 km^2 in 1963, and the area decreased to 134.9 km^2 in 1993 — an 8.1 percent shrinkage in 30 years. The smaller glaciers show higher shrinkage rates than larger glaciers, and three small glaciers with areas of 0.1, 0.15, and 0.2 km^2 in 1963 had completely disappeared by 1993 (Karma and others, 2003).

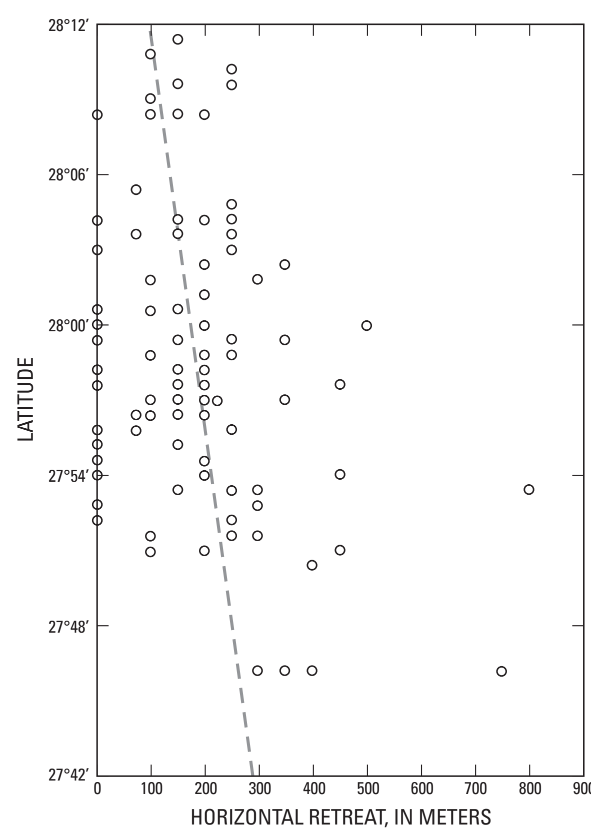

Figure 5.*—Horizontal distance of glacier-front retreat in the Bhutan Himalaya compared with latitude between 1963 and 1993. Dashed line shows the linear regression. From Karma and others (2003).*

Frontal variations of several debris-free glaciers on *Gangrinchemzoe-Gophu La Plateau* were observed in the field by Dr. Nozomu Naito in 1999 and compared with photographs taken in 1983–1984 by the Kyoto University Expedition (Yamada and Naito, 2003). *Gangrinchemzoe-Gophu La Plateau*, located to the southeast of Lunana, is 5,000–5,500 m in elevation, with many small glaciers and small glacial lakes (fig. 6). Observed glaciers have been shrinking markedly in recent decades as Karma and others (2003) reported.

Glacier variations since the late Pleistocene were mapped by Gansser (1983). He classified moraines and erosional landforms into six glacial stages in the entire area of northwestern and northern Bhutan. Gansser's glacial stages, however, were illustrated on the map but without explanation, and, in some cases, landforms with similar morphostratigraphic characteristics were assigned to two or more glacial stages.

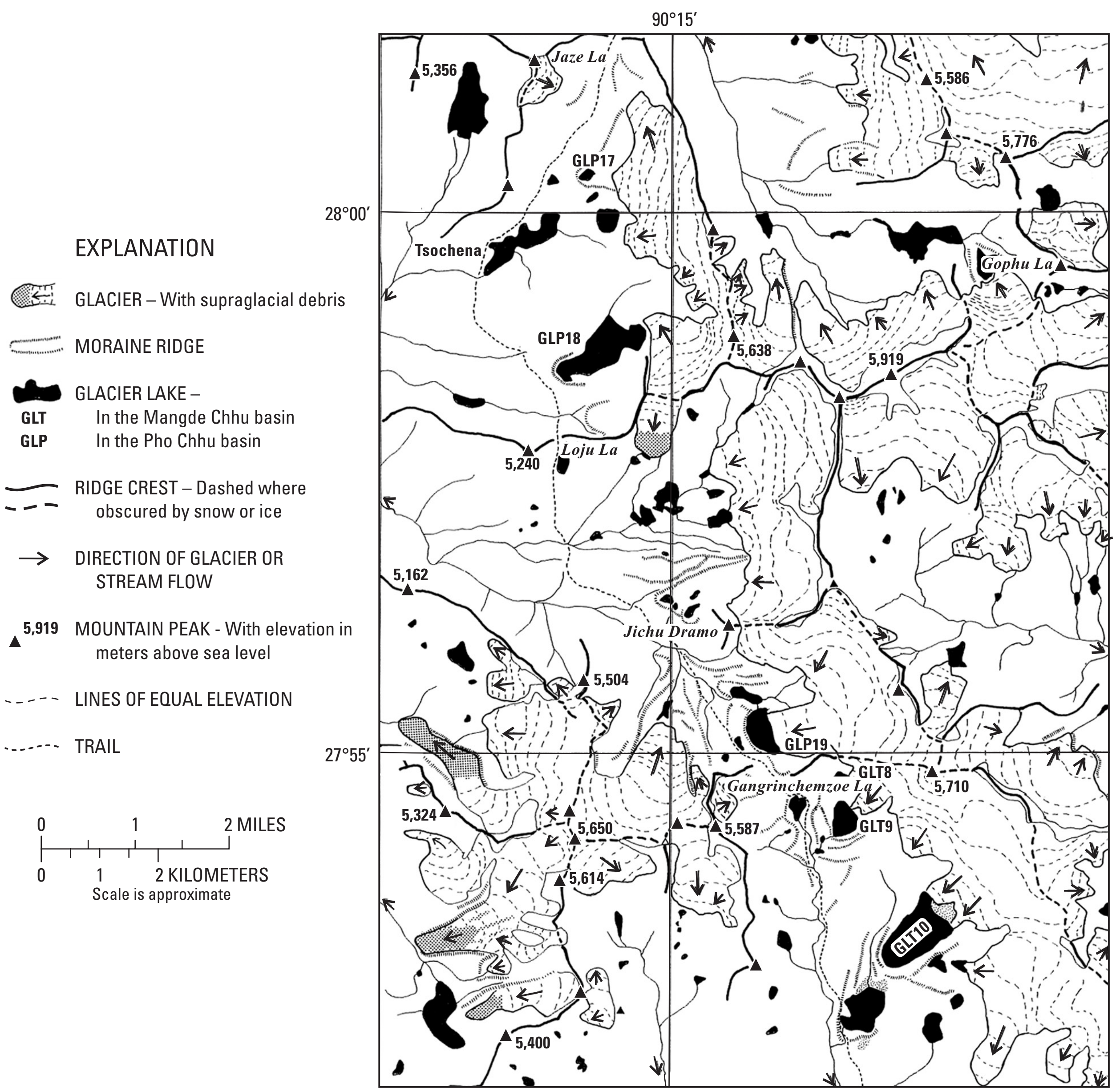

Figure 6.—Gangrinchemzoe-Gophu La Plateau *area showing debris-free and debris-covered glaciers and small glacial lakes. After Yamada and Naito (2003); revised from Ageta and Iwata (1999), based on interpretation of 1993 SPOT image.*

Iwata and his colleagues carried out geomorphological research in the Lingshi area, northwestern Bhutan, and Lunana in northern Bhutan (Iwata, Narama, and Karma, 2002). Moraines formed by valley glaciers in the Lingshi area constitute three distinct stages, with differences in spatial situations, volume of moraines, and surface features, such as clasts, soils, and vegetation. Moraines in the *Thanza* village area in Lunana also show three stages (fig. 7), with characteristics similar to those in the Lingshi area. Based on morphostratigraphic criteria (Iwata, 1976), these three stages correlate with some glacial stages in the Khumbu Himal, eastern Nepal. Dates of moraines in the Khumbu Himal (Richards and others, 2000) provide a tentative chronological sequence of these three stages. Valley glaciers in Bhutan expanded during the following periods: (1) the Takaphu and Raphsthreng Stages that may correlate to the "Little Ice Age" and late Holocene Epoch glacial advances, (2) the Jykhuje and Tenchey Stages that may represent the late Pleistocene Epoch and/or early Holocene glacial advances, and (3) the Lingshi Dzong and Lunana Stages that may coincide with the "Late glacial stage" of the Pleistocene Epoch.

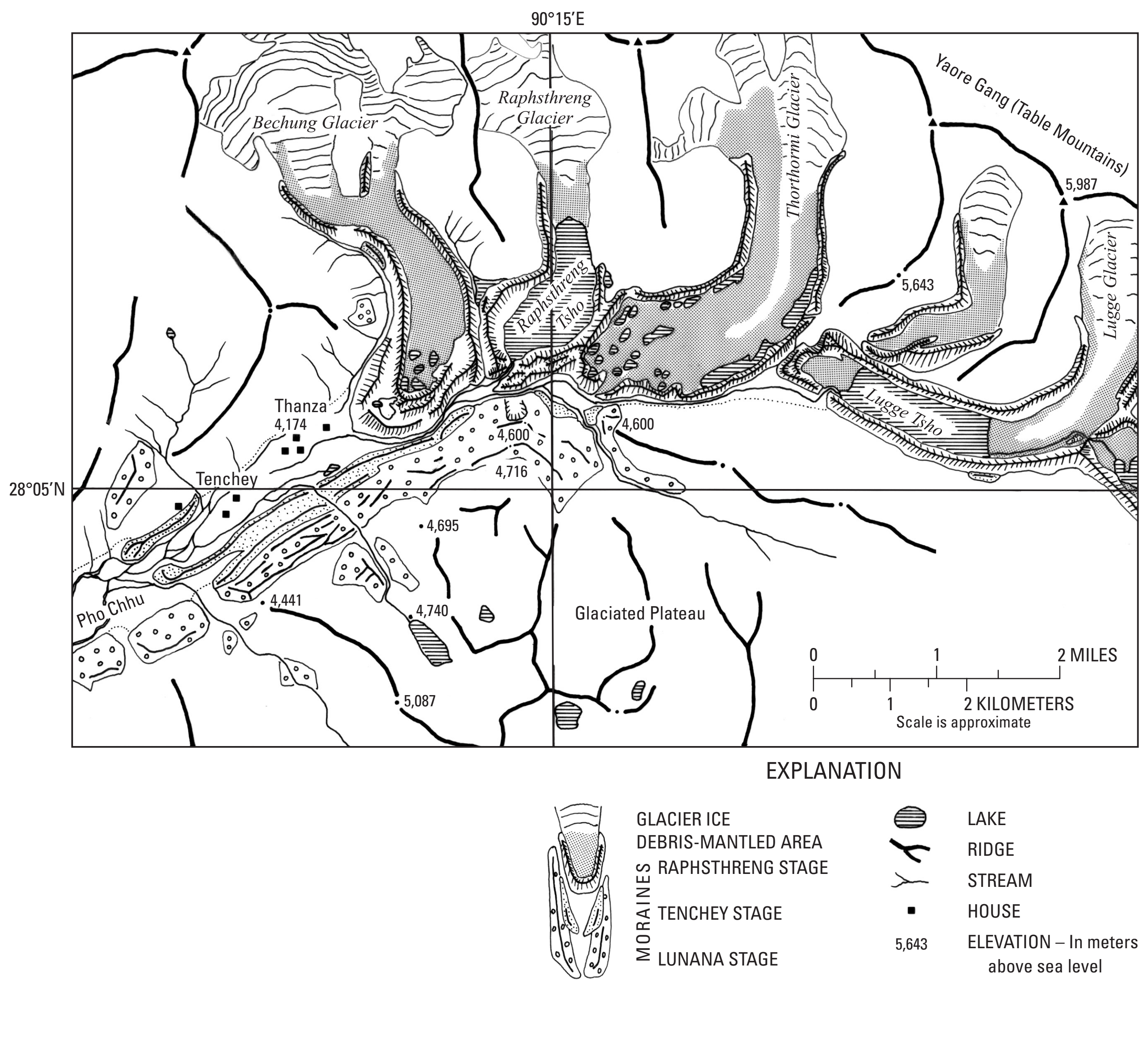

***Figure 7.**—Geomorphological map of the area around* Thanza *village (4,170 m) in the eastern part of Lunana, northern Bhutan, showing debris-mantled glaciers, glacial lakes, and moraines. From Iwata, Narama, and Karma (2002).*

Glacial Lakes

Glacial lake outburst flood (GLOF) events have occurred in the high-mountain areas of the Bhutan Himalaya during the past 50 years and have increased in recent years. After the 1994 GLOF from *Lugge Tsho* glacial lake (fig. 8), inventories of glacial lakes were compiled based on 1989 and 1990 SPOT images to identify potentially hazardous lakes (Division of Geology and Mines, 1996; revised version: Geological Survey of Bhutan, 1999). A total of 62 glacial lakes were listed with information, such as code name, types of lake, elevation, dimensions, geographic coordinates, and location. The remarks noted that 37 glacial lakes should be field checked and/or monitored.

The inventory of glacial lakes made by ICIMOD (Mool and others, 2001) was compiled from topographic maps made by the Survey of India (1960s), aerial photographs, and Landsat Thematic Mapper (TM) (1993–1999), Indian Remote Sensing (IRS) 1D Linear Self Scanning (LIS) S3 (1999), and SPOT (1994) satellite images. A total of 2,674 lakes were listed with a total area of 106,776 km^2. The number of lakes is very large, because it includes all lakes in glaciated and glacierized areas, including small tarns in empty cirques. Mool and others (2001) identified 24 potentially dangerous glacial lakes concentrated in the Pho Chhu (Lunana) and Mangde Chhu basins; lakes in the *Northern Basin* (north of the main divide) were excluded from the assessment. Potentially dangerous glacial lakes are mostly located in or adjacent to the ablation areas of large debris-mantled glaciers. Field observations and analyses of maps and satellite images indicate that most supraglacial lakes tend to connect with each other and can enlarge rapidly. Since the 1970s, some moraine-dammed lakes formed and have rapidly expanded in area, caused by retreating and/or melting of glaciers (Ageta and Iwata, 1999; Ageta and others, 2000; Iwata, Ageta, and others, 2002).

After the 1994 GLOF from the *Lugge Tsho* glacial lake, many research groups visited the Lunana area to carry out risk assessments, risk mitigation, and disaster prevention efforts (Indo-Bhutan Expedition, 1995; RGOB Expedition, 1995; WAPCOS, 1997; Haeusler and Leber, 1998; Leber and others, 2000, 2002, 2003). The Bhutan Government carried out hydraulic-engineering projects, and between 1996 and 1998, they excavated a drainage channel at the outlet of *Raphsthreng Tsho* (figs. 7 and 9) using hand labor. As a result, the water level of the lake was lowered by 4 m. [Editors' note: see figure 14 (p. I71) and the Glacier Hazards section (p. I68–I71) in Morales Arnao (1998) for a discussion of similar hazard-mitigation work in Perú.]

A Bhutan-Japan joint team, which included the author, visited and assessed the risk potential of glacial lakes in areas along *Snowman Trekking Route* through northwestern and northern Bhutan (Ageta and Iwata, 1999). Analysis of the occurrence of trigger mechanisms, impact on the lakes, and stability of moraine-dams suggests that there are at least five potentially dangerous glacial lakes of the 30 lakes studied in northwestern and northern Bhutan. Three of these in eastern Lunana, including *Lugge Tsho*, *Raphsthreng Tsho*, and *Thorthomi Tsho,* still contain a large volume of water, are connected to each other, and interact sensitively through water flux and erosion (Iwata, Ageta, and others, 2002).

The inventory by Mool and others (2001) identified a large and dangerous glacial lake called *Chubda Tsho* in the upper part of *Chamkhar Chhu* basin, Bumthang, central Bhutan. In 2002, this author carried out a short field study at the lake. The *Chubda Tsho* is not a moraine-dammed lake, but a large supraglacial lake (fig. 10). No definite terminal moraine dams the lake, but at the lower end of the lake there is only a gentle threshold composed of the debris-mantled glacier. The lake tends to expand more toward the upglacier end than the downglacier end. However, the expansion rate is not high, most

***Figure 8.**—Lugge Tsho lake from the western end. The ice cliff of Lugge Glacier is at the eastern end of the lake. A large volume of water still remains after the 1994 glacier lake outburst flood (GLOF) (1998 photograph by S. Iwata).*

***Figure 9.**—Raphsthreng Tsho lake and erosion on the toe of the lateral moraine caused by the 1994 glacier lake outburst flood (GLOF) from Lugge Tsho. The excavation made at the outlet of Raphsthreng Tsho lowered the water level 4 m. To the left is the debris-mantled Bechung Glacier (1998 photograph by S. Iwata).*

***Figure 10.**—Chubda Tsho supraglacial lake on the debris-mantled ablation area of Chubda Glacier, upstream in the Chamkhar Chhu basin, north-central Bhutan (2002 photograph by S. Iwata).*

likely because expansion toward the upglacier end may be counter balanced by glacier advance. Although this glacial lake does not pose an urgent danger of GLOF, the lake threshold itself may fail and so detailed inspections of the threshold by glaciologists with knowledge of debris-covered glaciers are necessary (Iwata, Gurung, and Komori, 2003; Komori and others, 2004).

The inventories of glacial lakes from satellite images indicate that many large and dangerous glacial lakes exist in headwater areas of *Kuri Chhu* in the Autonomous Region of Tibet, China. *Kuri Chhu* flows from the Autonomous Region of Tibet, China, to Bhutan, so that, if a GLOF from these lakes occurs, areas in the lower reaches of *Kuri Chhu* in Bhutan could sustain heavy losses.

In analyzing SPOT images, Dr. Jiro Komori found evidence of a recent GLOF and warned of the risk of future GLOFs in the region (Ageta and Kohshima, 2004). The Bhutanese Government is concerned about this danger, but cannot take preventative action because the lakes are located in China.

Constant and regular monitoring of glaciers and glacial lakes is urgently required to develop necessary hazard-mitigation strategies (Wangda, 2000). Monitoring of satellite imagery is the most effective tool for the purpose. Table 2 and figure 11 show optimum Landsat 1, 2, and 3 imagery for conducting historic studies of the glaciers of Bhutan.

Table 2.—*Optimum Landsat 1, 2, and 3 MSS images of the glaciers of Bhutan*

[Code column indicates usability for glacier studies; see figure 11 for explanation]

Path-Row	Nominal scene center latitude and longitude	Landsat identification number	Date	Code	Cloud cover (percent)
147–41	27°23′N. 91°49′E.	2147040007635190	16 Dec 76	●	5
148–40	28°49′N. 90°47′E.	2148040007635290	17 Dec 76	●	5
148–41	27°23′N. 90°23′E.	2148041007635290	17 Dec 76	◕	10
149–40	28°49′N. 89°21′E.	2149040007635390	18 Dec 76	◕	10
149–41	27°23′N. 88°57′E.	2149041007635390	18 Dec 76	◑	15

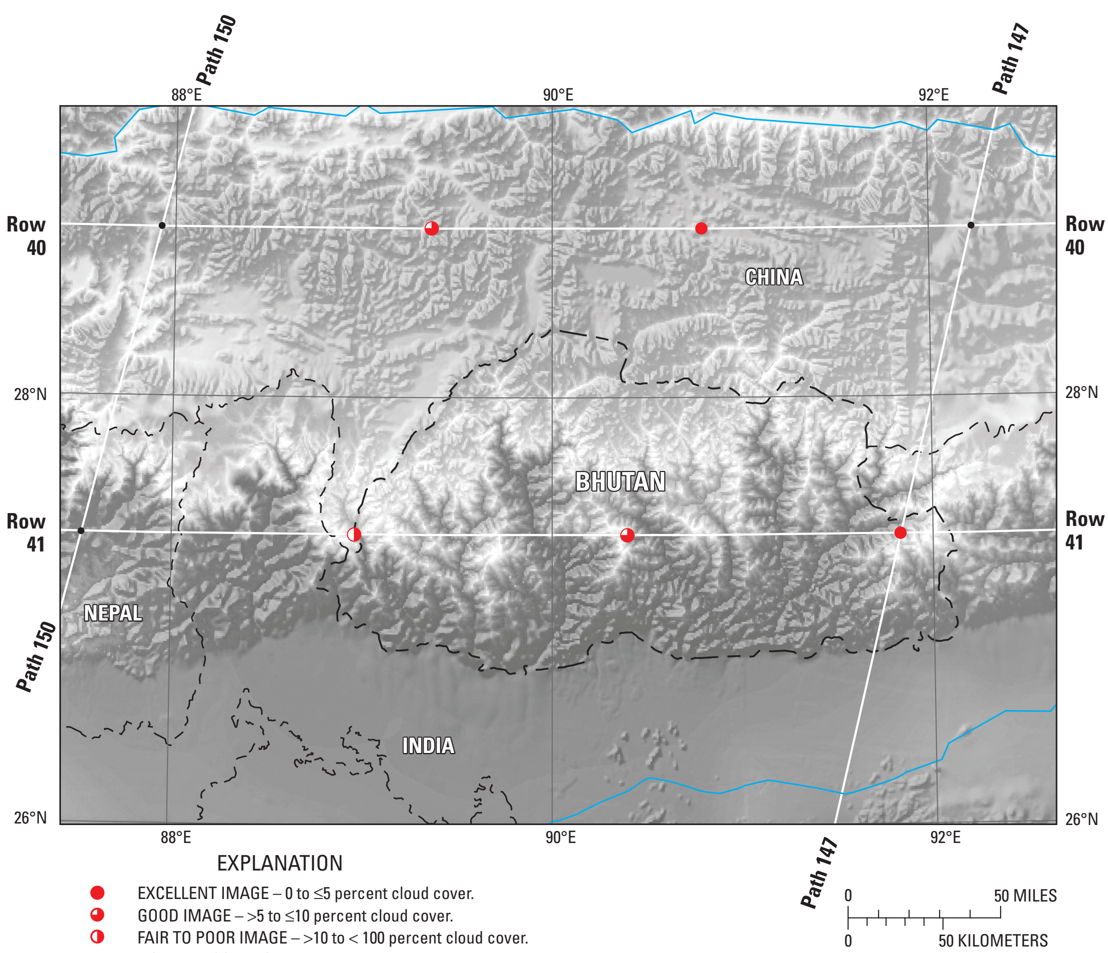

Figure 11.—*Map of the optimum Landsat 1, 2, and 3 MSS images of the glaciers of Bhutan. Compare with table 2.*

References Cited

Ageta, Y., and Higuchi, K., 1984, Estimation of mass balance components of a summer-accumulation type glacier in the Nepal Himalaya: Geografiska Annaler, v. 66A, no. 3, p. 249–255.

Ageta, Y., and Iwata, S., eds., 1999, Report of Japan-Bhutan joint research 1998 on the assessment of glacier lake outburst flood (GLOF) in Bhutan: Nagoya University, Institute for Hydrospheric-Atmospheric Science (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu), 161 p.

Ageta, Y., Iwata, S., Yabuki, H., Naito, N., Sakai, A., and others, 2000, Expansion of glacier lakes in recent decades in the Bhutan Himalayas, *in* Nakawo, M., Raymond, C.F., and Fountain, A., eds., Debris-covered glaciers, Proceedings of a workshop held at Seattle, Washington, USA, 13–15 September 2000: IAHS Publ. no. 264, p. 165–175.

Ageta, Y., and Kadota, T., 1992, Predictions of changes of glacier mass balance in the Nepal Himalaya and Tibetan Plateau — A case study of air temperature increase for three glaciers: Annals of Glaciology, v. 16, p. 89–94.

Ageta, Y., and Kohshima, S., eds., 2004, Report of Japan-Bhutan joint research 2003 on the assessment of glacier lake outburst flood (GLOF) in Bhutan: Nagoya University, Graduate School of Environmental Studies; Tokyo Institute of Technology, Graduate School of Bioscience and Biotechnology; Geological Survey of Bhutan, 64 p. (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Division of Geology and Mines, 1996, Glaciers and glacier lakes in the headwaters of major river basins of Bhutan: Thimphu, Ministry of Trade and Industry, 55 p. (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Eguchi, T., 1991, Regional and temporal variations in precipitation in the eastern part of the Himalayas: Kochi, Japan, Kochi University, Faculty of Humanities and Economics.

Gansser, A., 1970, Lunana: The peaks, glaciers and lakes of northern Bhutan: The Mountain World 1968/69, p. 117–131.

Gansser, A., 1983, Geology of the Bhutan Himalaya: Basel, Birkhauser Verlag, 181 p.

Geological Survey of Bhutan, 1999, Glaciers and glacier lakes in Bhutan: Thimphu, Ministry of Trade and Industry, Geological Survey of Bhutan, 2 vols., 83 p., and 13 map sheets.

Haeusler, H., and Leber, D., 1998, Final report of the Raphstreng Tsho outburst flood mitigation project: (Lunana, Northwestern Bhutan), Phase I: University of Vienna, Institute of Geology, 33 p. (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Indo-Bhutan Expedition, 1995, Geology, environmental hazards and remedial measures of the Lunana area, Gasa Dzongkha — Report of 1995 Indo-Bhutan Expedition: Geological Survey of India, 40 p., and maps (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Isacks, B.L., Duncan, C.C., and Klein, A.G., 1995, Modern and LGM glacial extents from satellite images and digital topography — Implications for LGM climate in the Bhutan Himalayas [abs.]: Abstracts-International Himalayan/Tibetan Plateau Paleoclimate Workshop, Kathmandu, p. 24.

Iwata, S., 1976, Late Pleistocene and Holocene moraines in the Sagarmatha (Everest) region, Khumbu Himal: Seppyō (Japanese Journal of Snow and Ice) v. 38, special iss., p. 109–114.

Iwata, S., Ageta, Y., Naito, N., Sakai, A., Narama, C., and Karma, 2002, Glacial lakes and their outburst flood assessment in the Bhutan Himalaya: Global Environmental Research [Tokyo], v. 6, no. 1, p. 3–17.

Iwata, S., Gurung, Deo Raj, and Komori, J., 2003, Report of Chubda Tsho in the head waters of Chamkar Chhu, Bumthang, 2002, *in* Yamada, T., and Naito, N., eds., Report of Japanese - Bhutan joint research 2002 on the assessment of glacier lake outburst flood (GLOF) in Bhutan: Hokkaido University, p. 54–66.

Iwata, S., Naito, N., Narama, C., and Karma, 2003, Rock glaciers and the lower limit of mountain permafrost in the Bhutan Himalayas: Zeitschrift für Geomorphologie, N.F. Supplementband 130, p. 129–143.

Iwata, S., Narama, C., and Karma, 2002, Three Holocene and late Pleistocene glacial stages inferred from moraines in the Lingshi and Thanza village areas, Bhutan: Quaternary International v. 97/98, p. 69–78.

Karma, Ageta, Y., Naito, N., Iwata, S., and Yabuki, H., 2003, Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalayas: Bulletin of Glaciological Research v. 20, p. 29–40.

Karma, and Tamang, K.B., 1999, Preliminary report on Tsokar Tsho in the head waters of Chamkhar Chhu, Bhumthang: Geological Survey of Bhutan, (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Karma, Thapa, T., and Ghalley, K.S., 1999, Preliminary report on Chubda Tsho in the headwaters of Chamkhar Chhu, Bhumthang: Geological Survey of Bhutan, 11 p., and tables, figures, and maps (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Komori, J., Gurung, D.R., Iwata, S., and Yabuki, H., 2004, Variation and lake expansion of Chubda Glacier, Bhutan Himalayas, during the last 35 years: Bulletin of Glaciological Research, v. 21, p. 49–55.

Leber, D., Haeusler, H., Brauner, M., Payer, T., and Wangda, D., 2003, Final report of the glacier lake outburst flood (GLOF) mitigation project (2002–2003) — Pho Chhu-Western branch (Tarina and Tang Chhu Watershed), Bhutan: University of Vienna, Department of Geological Sciences; Thimpu, Bhutan, Ministry of Trade and Industry, Department of Geology and Mines, 97 p., and maps (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Leber, D., Haeusler, H., Brauner, M., and Skuk, S., 2000, Technical Report — Luggye Mitigation Project, Lunana, Bhutan: University of Vienna, Institute of Geology, 71 p. (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Leber, D., Haeusler, H., Brauner, M., and Wangda, D., 2002, Final report of the glacier lake outburst flood (GLOF) mitigation project — Pho Chhu-Eastern branch (Thanza-Lhedi; 2000–2002), Lunana, Bhutan: University of Vienna, Institute of Geology; Thimpu, Bhutan, Ministry of Trade and Industry, Department of Geology and Mines, 189 p., and maps (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Matsuoka, N., 2003, Contemporary permafrost and periglaciation in Asian high mountains — An overview: Zeitschrift für Geomorphologie, N.F. Supplement Bd. 130, p. 145–166.

Mool, P.K., Wangda, D., Bajracharya, S.R., Kunzang, K., Gurung, D.R., and Joshi, S.P., 2001, Inventory of glaciers, glacial lakes and glacial lake ouburst floods — Monitoring and early warning systems in the Hindu Kush-Himalayan region, Bhutan: Kathmandu, International Centre for Integrated Mountain Development (ICIMOD), 227 p.

Morales Arnao, B., 1998, Glaciers of Perú (I–4), with a section on Quelccaya Ice Cap, by Hasternrath, S., *in* Williams, R.S., Jr., and Ferrigno, J.G., eds, Satellite image atlas of glaciers of the world: U.S. Geological Survey Profesional Paper 1386–I (South America), p. I51–I79. [*http://pubs.usgs.gov/prof/p1386i/*]

Müller, F., Caflish, T., and Müller, G., 1977, Instruction for compilation and assemblage of data for a World Glacier Inventory: Zürich, Temporary Technical Secretariat for World Glacier Inventory, Swiss Federal Institute of Technology; International Commission on Snow and Ice, International Association of Hydrological Sciences, United Nations Environment Programme, United Nations Educational, Scientific and Cultural Organization, 28 p.

Qin Dahe, chief ed., 1999, Map of glacier resources in the Himalayas; 1st ed.: Beijing, Science Press, scale 1:500,000, 7 sheets. [Compilation of map based on analysis of 1975–1978 Landsat MSS 7 and false-color images and some aerial photographs]

Richards, B.W.M., Benn, D.I., Owen, L.A., Rhodes, E.J., Spencer, J.Q., 2000, Timing of late Quaternary glaciations south of Mount Everest in the Khumbu Himal, Nepal: Geological Society of America, Bulletin, v. 112, no. 10, p. 1621–1632.

Royal Government of Bhutan (RGOB) Expedition, 1995, Preliminary report on the investigation of glacial lakes at Pho Chhu source and the assessment of flood affected areas in Lunana: Royal Government of Bhutan Expedition (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu).

Sharma, A.R., Ghosh, D.K., and Norbu, P., 1986, Report on Lunana Lake expedition —1986: Geological Survey of India (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu, Bhutan).

Wangda, D., 2000, The need to monitor glaciers and glacier lakes in the headwaters of major river basins of Bhutan: Bhutan Geology News Letter SL No. 2, p. 17–19.

Watanabe, T., and Rothacher, D., 1996, The 1994 Lugge Tsho glacial lake outburst flood, Bhutan Himalaya: Mountain Research and Development, v. 16, no. 1, p. 77–81.

Water and Power Consultancy Services (WAPCOS), 1997, Raphstreng Lake, Lunana (Bhutan) — Report on flood mitigatory measures (Phase 1—1996): Water and Power Consultancy Services (India) Limited.

Yamada, T., and Naito, N., eds., 2003, Report of Japan-Bhutan joint research 2002 on the assessment of glacier lake outburst flood (GLOF) in Bhutan: Hokkaido University, Institute of Low Temperature Science; Nagoya University, Graduate School of Environmental Studies; Geological Survey of Bhutan, 106 p. (not officially published; available for inspection in the Geological Survey of Bhutan, Thimphu, Bhutan).