Glaciers of Asia—

GLACIERS OF INDIA

By Chander P. Vohra

SATELLITE IMAGE ATLAS OF GLACIERS OF THE WORLD

Edited by RICHARD S. WILLIAMS, JR., *and* JANE G. FERRIGNO

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GLACIERS OF INDIA—A Brief Overview of the State of Glaciers in the Indian Himalaya in the 1970s and at the End of the 20th Century

By Chander P. Vohra[1]

Abstract

Himalaya, "the abode of snow," has many glaciers distributed throughout its higher elevations. The glaciers are commonly clustered in large numbers in areas where many high peaks are located and sufficient precipitation occurs. The first estimate of total ice cover was probably made by von Wissman (1959) who stated that 33,200 km^2 or 17 percent of the Himalaya was ice covered. Few ice-cover estimates for individual river basins were made in the initial years of glacier studies. More recent work by Qin (1999) increased the glacierized area of the Himalaya to about 35,110 km^2. Based on the preliminary inventory by the Geological Survey of India (Kaul, 1999), about 8,500 km^2 of this ice cover is located in the Indian Himalaya.

Introduction

The study of glaciers in India is very important both from scientific and economical perspectives. The Himalaya contains one of the largest reservoirs of snow and ice outside the Polar Regions. The glaciers are a major source of fresh water, and all the rivers in northern India are nourished by meltwaters of the Himalaya glaciers, thereby affecting the quality of life of millions of people.

As in most parts of the Himalaya, the study of glaciers is handicapped by the remoteness of the area, altitude, topography, and debris cover on the glaciers, as well as the limited availability of large-scale maps, optimum aerial photographs, and high-resolution satellite images.

In 2001, Ravi Shanker, Director General of the Geological Survey of India (GSI), stated that glaciology, the study of snow, ice, and glaciers, is in its nascent stage in India (Srivastava, 2001); however, glacier observations in India actually began in the middle 1800s, and considerable work has been done in the last three decades.

[Editors' note: This manuscript was originally written in 1982 to describe the glaciers of India during the late 1970s and early 1980s, the "benchmark" time period (1972–1981) for the Satellite Image Atlas of Glaciers of the World, U.S. Geological Survey Professional Paper 1386-A–K. Because there were delays in publishing this chapter, the editors updated the manuscript slightly in 2006, using material from the Geological Survey of India, and a supplemental section — A Study of Selected Glaciers under the Changing Climate Regime, by Hasnain and others — was added to provide more current information.]

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[1] Former Director-General, Geological Survey of India.

Early Studies

Snow and glaciers in the Himalaya attracted the attention of early observers and much was written around 1840–50 about the "line of perpetual snows," beginning with Jack (1844) and von Humbolt (1845). Very few glaciers were visited at that time, but one of the popular ones was Pindari Glacier[2] in the State of Uttar Pradesh (Madden, 1847). Many of the early observations of glaciers were made by geographers and cartographers who were engaged in triangulation and map making of the Himalaya during the 19th century. Godwin-Austin (1862), for example, wrote about the glaciers of Mustakh Range and the upper Indus River basin. Many observers, including geologists, were satisfied with recording the positions of glacier termini and the evidence they observed of more extensive past glaciation. One of the earliest Indian geologists to write about glaciers in the Himalaya was P.N. Bose (1891), who visited *Kabru* and *Pandim Glaciers* in the State of Sikkim. Between 1907 and 1910, the Geological Survey of India initiated a coordinated effort to systematize observations of glacier fluctuations, as part of an international program to study glaciers (Cotter and Brown, 1907; Bridges, 1908–09).

Kanwar Sain (1946) was the first scientist to investigate the role of snow, ice, and glaciers in a comprehensive assessment of the surface water resources of the Himalaya. J.E. Church (1947), a celebrated expert in this field, visited the Himalaya in 1947 to organize a program of snow surveys for hydrological purposes. This program, however, did not flourish (Basu, 1947). In the years between 1910 and 1957, individual studies and observations on some of the glaciers continued (Grinlinton, 1912; Auden, 1937). A second effort at glacier observations was organized during the International Geophysical Year (1957–58), when many glaciers were revisited and a great deal of information regarding glacier fluctuations and their history was gathered (Jangpangi, 1958).

This was followed by further glacier studies during the International Hydrologic Decade (IHD), 1965–74, and the International Hydrologic Programme in 1975. Some results from those observations are listed in table 1. Mercer (1975a, b) prepared a very good review of the status of glaciology in India up to 1975, including references and maps.

TABLE 1.—*Recession of glaciers in the Indian Himalaya*

[Data source: Vohra (1981). Unit: m, meter]

Glacier name	Observational period	Recession (m)
Milam	1849–1957	-1,350
Pindari	1845–1966	-2,840
Shankalpa	1881–1957	-518
Poting	1906–1957	-262
No. 3 in the *Arwa* valley	1932–1956	-24
Gangotri	1935–1976	-600
Zemu	1909–1965	-440
Barashigri	1940–1963	-1,019
Sonapani	1906–1929	-905

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[2] The geographic place-names used in this section conform to the usage authorized for foreign names by 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*. The names not listed on the website are shown in italics.

Studies in the Late 20th Century

Studies begun in the 1970s embraced many aspects of snow and glacier phenomena and included glacier mass balance, the pattern of glacier movement, glacier recession/advance, meltwater discharge, ice thickness in glaciers, crystal fabrics of ice, the radiation balance of snow and ice surfaces, dating of ice by isotopic studies, detailed cartography of glaciers, the study of paleoglaciation, and compilation of glacier inventories. The studies are described by Tewari (1971) and Vohra (1981) and included in unpublished reports of GSI.

The Geological Survey of India organized a glaciology program under the direction of the author, and on 4 January 1974, a Glaciology Division was established at Lucknow. Other national agencies, such as the Survey of India, the Meteorological Department, the Physical Research Laboratory, Indian Space Research Organization, and the Bhakra Beas Management Board collaborated in this program. Some of the early results were as follows:

1. Mass balance on Gara Glacier in the Sutlej River basin was positive from 1974 to 1976, causing previous recession to stop in 1976. [The balance years from 1976 to 1980 were negative, but from 1982 to 1983 were positive (Srivastava, 2001)]. Gangotri Glacier receded between the 1930s and the late 1970s, but the rate of recession kept decreasing. [Between 1977 and 1991, the recession rate increased considerably (Srivastava, 2001)]. Nehnor Glacier in the State of Jammu and Kashmir receded in the 1970s and had only negative mass-balance years. [The negative mass-balance measurements continued from 1976 to 1984 (Srivastava, 2001)].

2. The Himalaya can be divided into four distinct areas on the basis of precipitation patterns: (a) dominant monsoon precipitation (the Mount Everest region and Sikkim), (b) dominant winter (westerly) precipitation (Ladākh and Spiti areas), (c) equal/sub-equal monsoon and winter precipitation (the Ganga basin (equal) and Beas basin (subequal)), and (d) rain-shadow areas (Vohra, 1981). The amount of meltwater produced and mass-balance characteristics of each glacier vary according to the area in which the glacier is found.

3. The ice at the terminus of Nehnor Glacier is less than 400 years old; however, ice at the terminus of Chaugme Khampa Glacier is only 100 years old.

4. Debris cover on the ablation zone of glaciers is ubiquitous throughout the Himalaya. As a consequence, the production of meltwater decreases, instead of increasing, with the decrease in elevation.

5. There are many ice-cored moraines in proglacial areas, and these play significant roles in the water balance of the glacierized basins of the Himalaya.

6. Precipitation in certain basins increases with elevation *within the glaciated* (sic, glacierized) *region* — even during the monsoon season.

Results of later glacier studies from 1974 to 2000 are found in the following description of individual glacier areas, in published and unpublished reports of the Geological Survey of India, and in Kaul (1999), Geological Survey of India (2001), and Srivastava (2001).

Total Number of Glaciers

In the 1980s, the author estimated that about 15,000 glaciers occur in the Himalaya. Considered high, this estimate was based on the average size of glaciers derived from glacier inventories from parts of the Himalaya, and from von Wissman's (1959) estimate of total ice cover. More recent glacier-inventory work by Qin (1999), however, determined that there were 18,065 glaciers in the five drainage basins of the Himalaya, covering 35,110 km^2; this number was based on analysis of 1975–78 Landsat MSS band 7 and false-color (bands 4, 5, 7) images, as well as some aerial photographs. So the author's 1980s estimate was actually 20 percent too low. A composite inventory of the glaciers of the Himalaya by Kaul (1999), based on a combination of detailed and regional assessments, yielded a total of only 5,243 glaciers covering an area of about 38,000 km^2. Kaul (1999) also reported that about 8,500 km^2 of the glaciers are located in the Indian Himalaya.

Glacier Distribution

Glaciers are found in all geographic areas of the Himalaya which lie above the elevation required to maintain ice. In some areas, they occur in large numbers and attain great lengths — measurable in tens of kilometers. Such mountain areas in India are the *Nun-Barashigri*, Gangotri-*Chaukhamba*, Kāmet group, Nanda Devi group, and Kānchenjunga (fig. 1). The principal glaciers of the Indian Himalaya, including their lengths, are: Gangotri, 30 km; Zemu (Sikkim Himalaya), 28 km; Mīlam (Nanda Devi area), 19 km; and *Kedārnāth* (Gangotri-*Chaukhamba* area), 14.5 km (fig. 1).

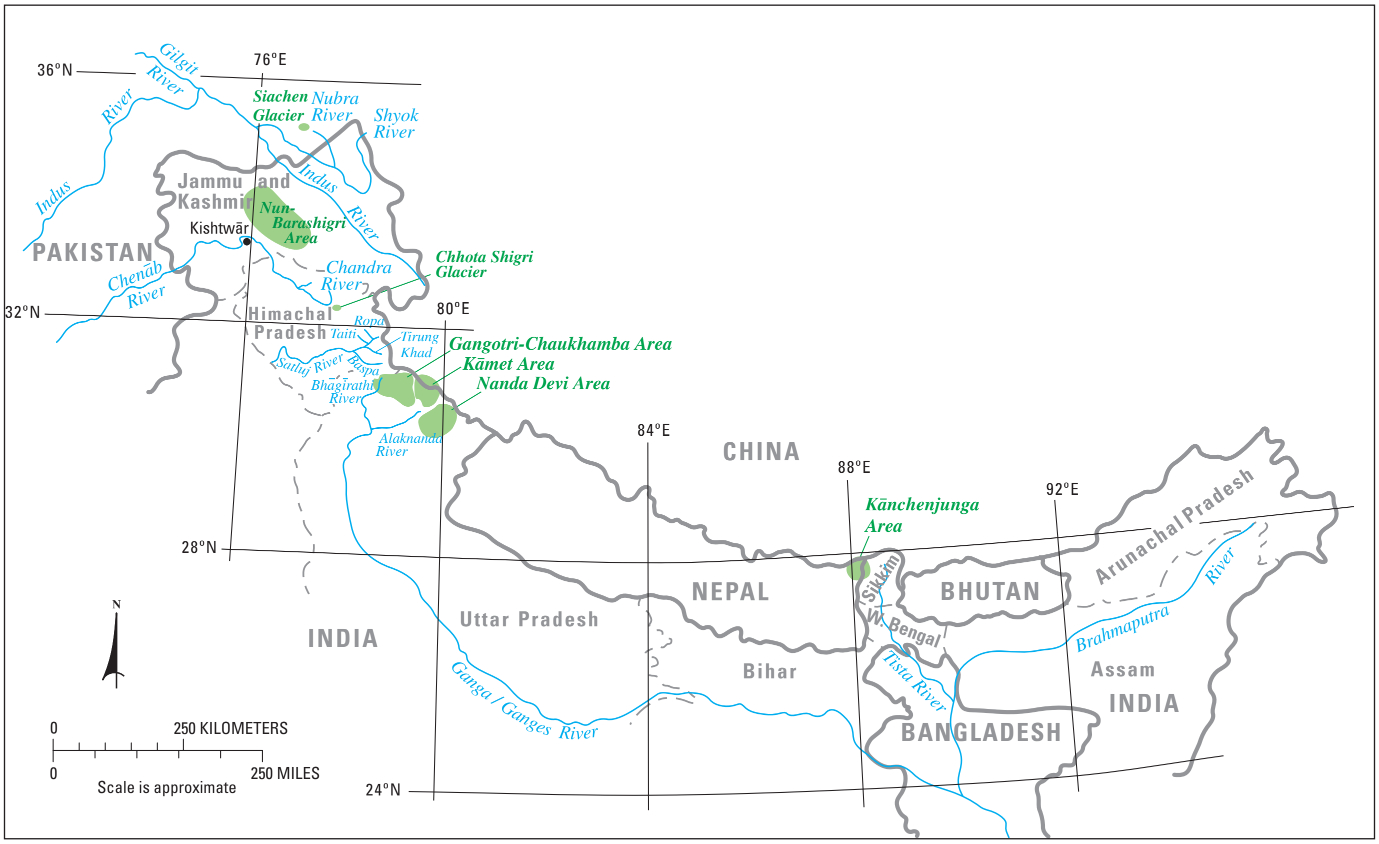

Figure 1.—*Sketch map showing the location of glacierized areas of India discussed in the text.*

Nun-Barashigri

The southern flank of the *Nun-Barashigri* range forms the northern portion of the Chenab River basin, north and east of Kishtwār; it is one of the most highly glacierized areas of the Indian Himalaya (figs. 2, 3). Nearly 1,000 large and small glaciers drain into the Chenab River. The northern flank of the *Nun-Barashigri* range also supports many glaciers, which drain north into tributaries of the Indus River. Several glaciers are greater than 10 km in length; two exceed 20 km, and a third is a little less than 20 km. Several ice fields, drained by outlet glaciers, occur in the general area around Nunkun peak (fig. 2) and also on the mountain itself. Ice fields are formed on mountain summits, or slightly lower down, and the highest summits protrude through the ice. This geomorphic characteristic is unique to this area, and perhaps indicates an earlier erosional surface. The glaciers are fed by both summer (monsoon) and winter (westerly) precipitation. Presently, many cirques and small glacier valleys, especially in the eastern part of the range, are ice free, indicating a post-glacierization phase. Landsat 1 MSS images of the area (Path 158–Rows 37 and 38), acquired on 4 September 1972, show the transient snow line at its highest elevation of the year. Landsat 2 MSS images were acquired on 10 and 11 September 1976 (Path 158, and 159–Rows 36 and 37), following a fresh snowfall (fig. 2). This late monsoon snow covered the highest points of the main Himalaya Range, and was not restricted to a particular elevation as is sometimes thought to occur. Figure 3 shows a map of that area, prepared for the preliminary Inventory of Himalayan Glaciers (Kaul, 1999). Based on the preliminary inventory, it is estimated that there are 989 glaciers covering 2,280 km^2 in the Chenab basin.

Gangotri-*Chaukhamba*

Although the Gangotri-*Chaukhamba*, Kāmet, and Nanda Devi mountain groups are adjacent to each other, they are separated by major river valleys (figs. 4, 5). The Gangotri-*Chaukhamba* area is a cluster of many mountain peaks, 6 to 7 km in elevation, from which many large and small glaciers flow.

Only two glaciers have been studied in this area — the Gangotri and the *Chaurabari*. The most impressive is the Gangotri Glacier, the longest glacier in the Indian Himalaya. This is a “complex glacier” type with large tributaries. Its main trunk is 26 km long, and the overall ice surface of Gangotri Glacier and its tributaries covers an area of a little more than 200 km^2. It is estimated to contain about 20 km^3 of ice. Its meltwater stream becomes a high-volume river after emerging from a sub-glacier tunnel at the glacier terminus — the holy “*Gaumukh*” (cow’s mouth) of Hindu mythology. This glacier has been studied since 1817, though only documented since 1886. The glacier has been receding since 1935, but the greatest recession occurred from 1977 to 1990 (Srivastava, 2001). Since 1990, observations were made from 1992 to 1997, and the Gangotri Glacier was in continuous recession (Srivastava, 2001). The river coming from the Gangotri Glacier is called Bhāgīrathi River, and it is considered to be the primary source of the Ganga (Ganges River). All of the glaciers in the Gangotri-*Chaukhamba* area receive nourishment from the monsoon and westerly winter precipitation. Although detailed figures are not available, the total precipitation is only moderate.

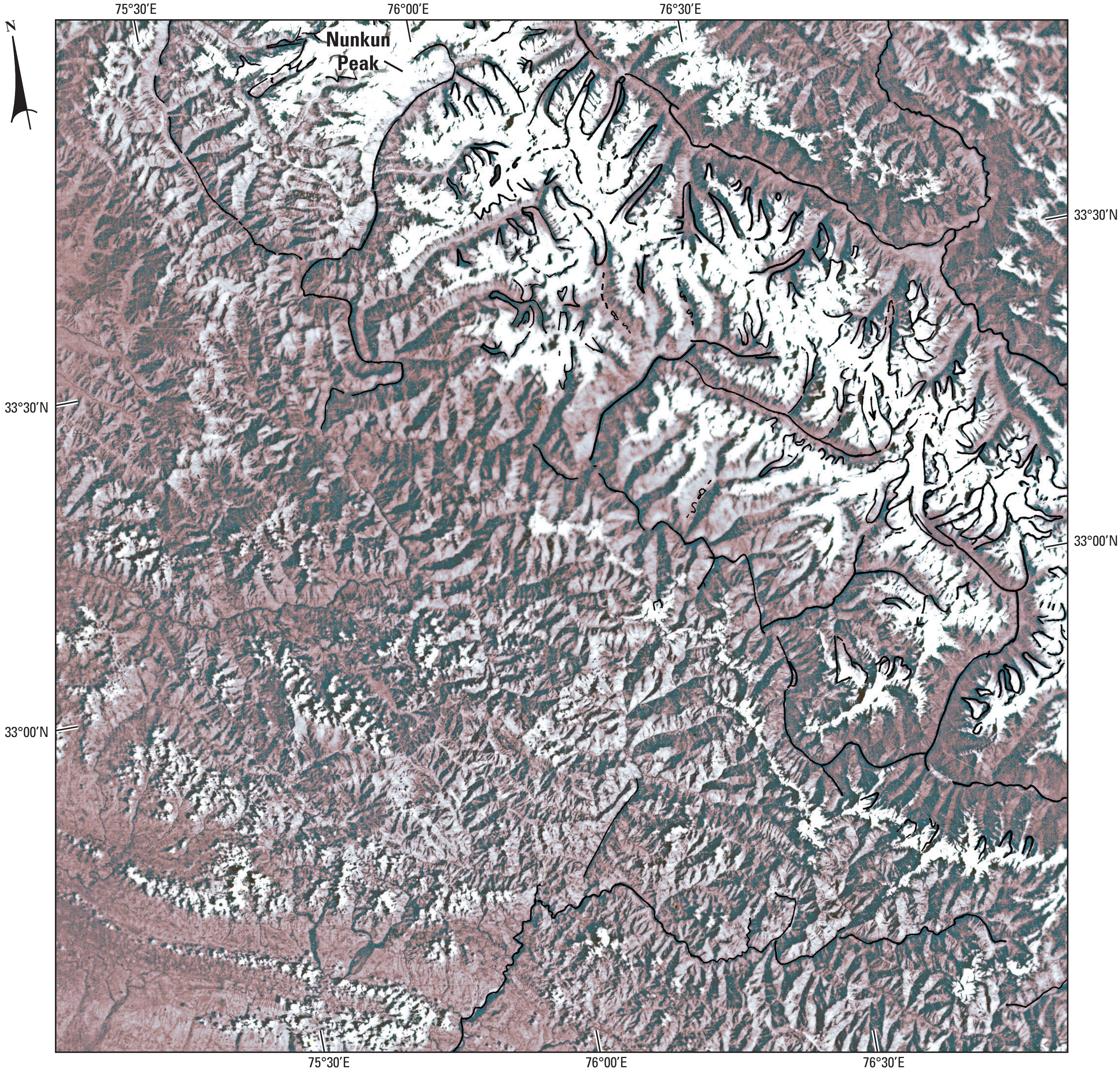

***Figure 2.**—Landsat 2 MSS image of the* Nun-Barashigri *area with some of the many glaciers outlined. The image was acquired after a fresh, late monsoon snowfall. The Landsat MSS image (2159037007625590, 11 September 1976; Path 159–Row 37) is from the U.S. Geological Survey EROS Data Center, Sioux Falls, South Dakota.*

The valley below the *Gaumukh* contains abundant evidence of past glacier advances. Seventeen kilometers downstream, at a place named Gangotri, a glacial pavement begins and extends further downstream; a narrow epigenetic gorge, deeply entrenched into the "pavement," also begins at this point. A temple is constructed here to mark the location of the glacier terminus when Bhagirathi Rishi first discovered this glacier. The date of the visit is lost in the maze of mythology, but this previous glacier position may date from the beginning of the Holocene Epoch.

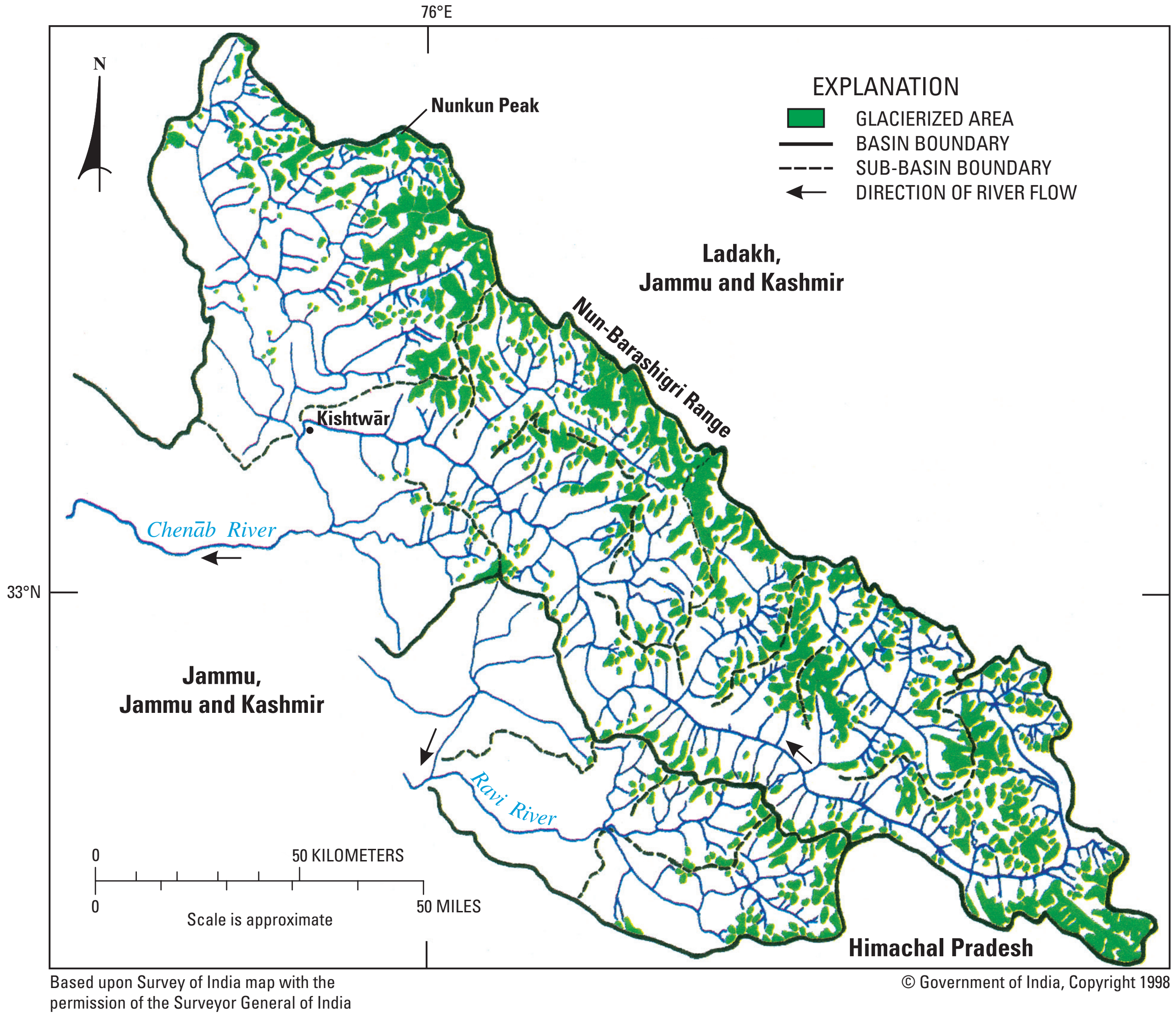

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Figure 3.*—Glacierized area of the Chenab and Ravi basins. From the preliminary "Inventory of the Himalayan Glaciers" by the Geological Survey of India (Kaul, 1999).*

Satluj River Basin

To the north and west of the Gangotri group of peaks flows the Satluj River, which originates in *Mansrovar Lake*. After the Glaciology Division was established as part of the Geological Survey of India in 1974, an initial glacier inventory was planned for the Baspa river basin, the largest glacier-fed tributary of the Satluj basin. The pilot inventory was conducted using the Guidelines of the World Glacier Inventory (Müller and others, 1977, 1978), and was followed by studies of other basins in the Satluj basin. Work was then extended to other parts of the Himalaya (Kaul, 1999). As a result, a thorough survey has been made of part of the Satluj basin and some of the early work and later results are described below.

The total ice cover for the Satluj River basin was estimated in the 1940s to be about 6,390 km^2 or approximately 11 percent of the basin area. The estimates were probably made from the generalized 1:1,000,000-scale maps. There are often major differences in the determination of the area of ice cover when using maps of different scales. When compared with figures from a later glacier inventory in the late 1970s using larger-scale maps, this estimate was found to be far too high. A comparison is given in table 2.

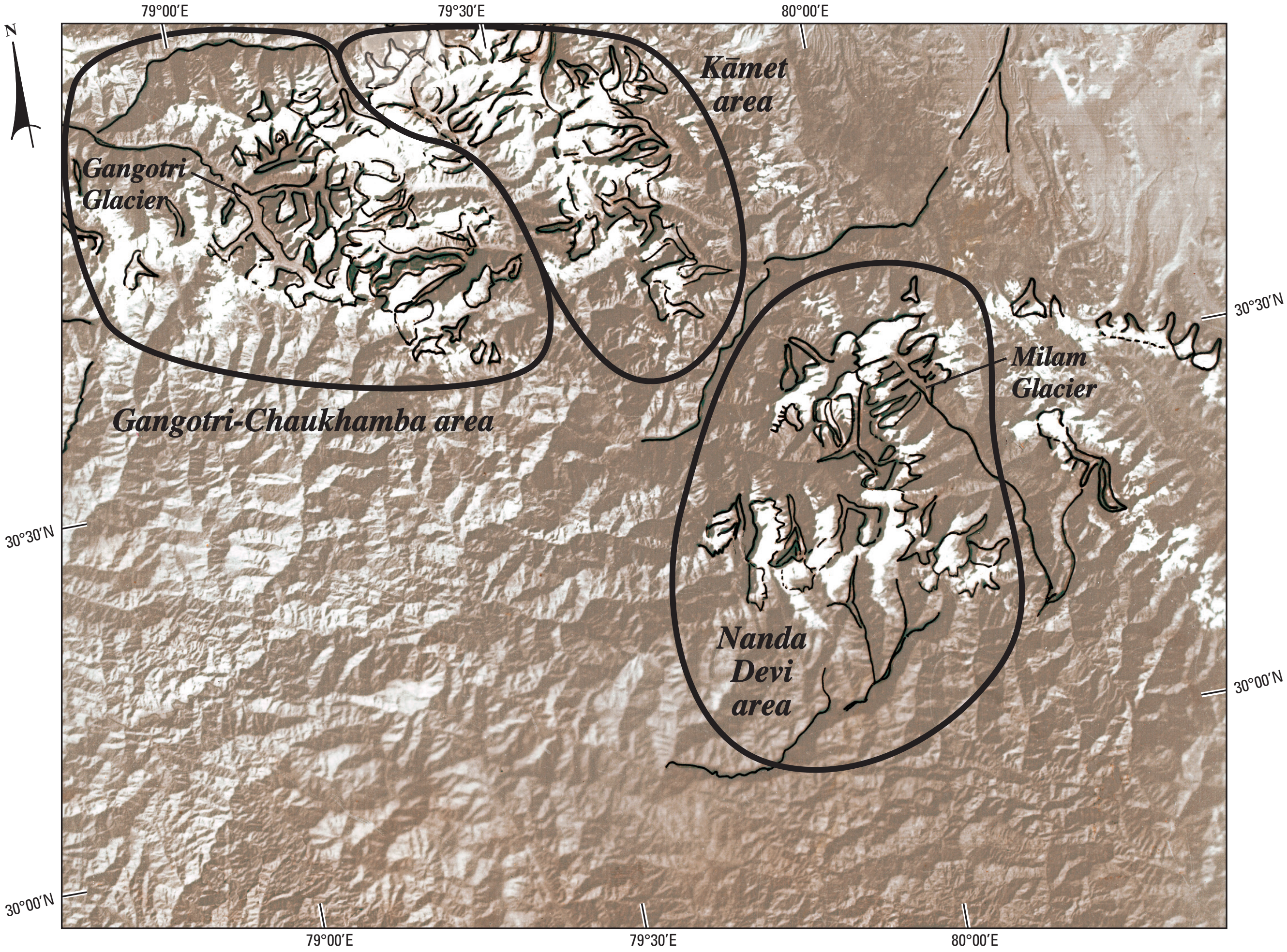

Figure 4.*—Landsat 2 MSS image of the Gangotri-Kāmet-Nanda Devi areas of the Indian Himalaya. The major glaciers are demarcated. This area includes the Gangotri Glacier, largest in India. Its meltwater stream, the Bhāgīrathi River, is considered to be the main source of the Ganga (Ganges River). The Landsat MSS image (2156039007632490, 19 November 1976; Path 156–Row 39) is from the U.S. Geological Survey EROS Data Center, Sioux Falls, South Dakota.*

The glacierization in the Indian part of Satluj River basin is similar to the Chinese part. The four percent figure for ice cover is representative of both parts of the basin. The more glacierized tributaries of the Satluj River (table 2) also indicate the same differences in ice-cover area determined from maps of different scales. Interestingly, the differences resulting from a comparison of ice cover on 1:250,000- and 1:50,000-scale maps are relatively minor, however. The major difference is in calculations based on the 1:1,000,000-scale maps.

Inventory from Landsat Imagery

Landsat Multispectral Scanner (MSS) images from the late 1970s/early 1980s were used for compiling a glacier inventory for a part of the Satluj River basin and for making a glacier map of some parts of this basin. The results were compared with the existing late 1970s inventory for the Baspa Gād and *Tirung Khad*, two tributaries of Satluj River (table 3).

The ice-cover areas match relatively well, the difference being less than 5 percent. The snowline was easy to delineate on the Landsat images, as were the ice margins, except in the case of small ice bodies. Some glaciers, marked as tributaries of larger glaciers on the maps, were easily distinguished on the images as having independent termini.

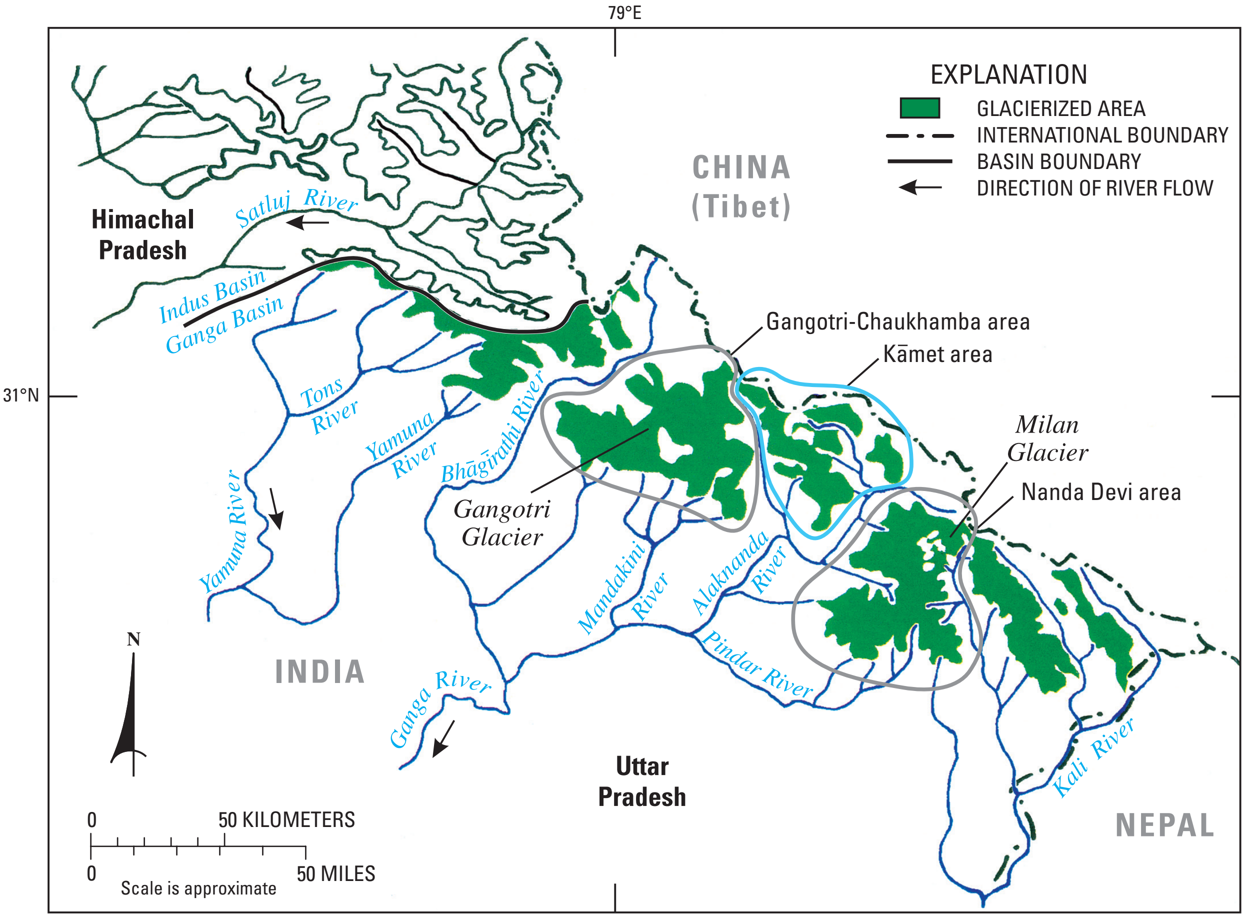

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Figure 5.*—Glacierized area of the Ganga basin showing the Gangotri-*Chaukhamba*, Kāmet, and Nanda Devi glacierized areas based on the preliminary "Inventory of the Himalayan Glaciers" by the Geological Survey of India. Modified from Kaul (1999).*

TABLE 2.—*Ice cover determined in the late 1970s from maps of different scales as a percentage of the basin*

[—, no data]

Basin name	Percent ice cover		
	1:1,000,000-scale map	1:250,000-scale map	1:50,000-scale map
Satluj River	11 (Total basin)	4 (Indian part of basin)	—
Satluj River tributaries:			
Ropa Gād	32	9.3	—
Taiti Gād	37.7	9.7	—
Baspa Gād	—	19.3	22.2
Tirung Khad	—	13.1	14.7

Table 3.—*Comparison of glacier inventories from maps and Landsat images in the glacierized drainage basins, prepared in the late 1970s/early 1980s*

[Unit: km², square kilometer]

Basin	Total ice cover delineated from maps (km²)	Total ice cover delineated from Landsat images (km²)	Percentage difference, as seen on the Landsat images
Baspa Gād	186.97	178.46	4.5
Tirung Khad	69.98	67.08	4.1

The snowline on a Landsat 2 MSS image acquired on 17 August 1977 (Path 157–Row 38) was used to delineate the boundary between ablation and accumulation areas. Because this was lower in elevation than the computed equilibrium lines used for the existing late 1970s inventory, some differences in the respective glacier ablation and accumulation areas calculated from the two sources were inevitable. A comparison is given in table 4; only glaciers on which the snowline was well marked are included.

Table 4.—*Percentage reduction or increase in the ablation, accumulation, and total area of glaciers, determined by comparing late 1970s Landsat 2 MSS images with the already existing late 1970s inventory*

[Abbreviations: MSS, multispectral scanner; km², square kilometer; %, percent reduction or increase]

River basin	Ablation area, in km²	Accumulation area, in km²	Total area, in km²
Baspa Gād	-15.59 (32.1%)	+13.43 (16.8%)	-2.16 (1.7%)
Tirung Khad	-16.69 (53.4%)	+11.27 (49.4%)	-5.42 (10%)

The difference in respective accumulation and ablation areas because of the lower snowline on the 17 August 1977 Landsat image is obvious. The reduction in the delineation of the ablation area using Landsat imagery is marginal in the case of Baspa Gād basin, but it is significant in the case of *Tirung Khad* basin. In all probability, it is a reflection of the erroneous inclusion of proglacial moraines within the ablation area of the glaciers in the existing late 1970s inventory which was compiled primarily from maps.

Another example from the *Tirung Khad* glacier No. 49 where field work was done is given in table 5. The results from Landsat images and field work are similar, except for some differences due to the lower snowline on the Landsat

Table 5.—*Comparison of calculation of ablation, accumulation, and total area of the* Tirung Khad *glacier No. 49 between maps (existing late 1970s glacier inventory), Landsat images (late 1970s/early 1980s), and field work*

[Unit: km², square kilometer]

Source	Ablation area (km²)	Accumulation area (km²)	Total (km²)
Existing glacier inventory	[1]4.91	3.00	[1]7.91
Landsat images	1.63	4.31	5.94
Actual field work	2.42	3.09	5.50

[1] These figures are probably too high, because proglacial moraines could not be separated from the debris-covered termini when topographic maps were prepared.

images. Modern maps were not available when the inventory was compiled for the Spiti River basin. Therefore, the information derived from the Landsat images considerably improved the inventory in that area.

In conclusion, Landsat imagery (fig. 6, table 6) and other higher resolution satellite images are very useful for the Himalayan region where modern maps are not available, and where aerial photography acquired at the end of the ablation season is sparse. Also, it is less time consuming to make an inventory from Landsat images, although the imagery does not provide elevation information.

More recent results from the intensive glacier studies in the Satluj River basin can be seen in figure 7, taken from Kaul (1999). Other recent unpublished and published glacier reports covering this basin were prepared by GSI (Geological Survey of India, 2001; and Srivastava, 2001).

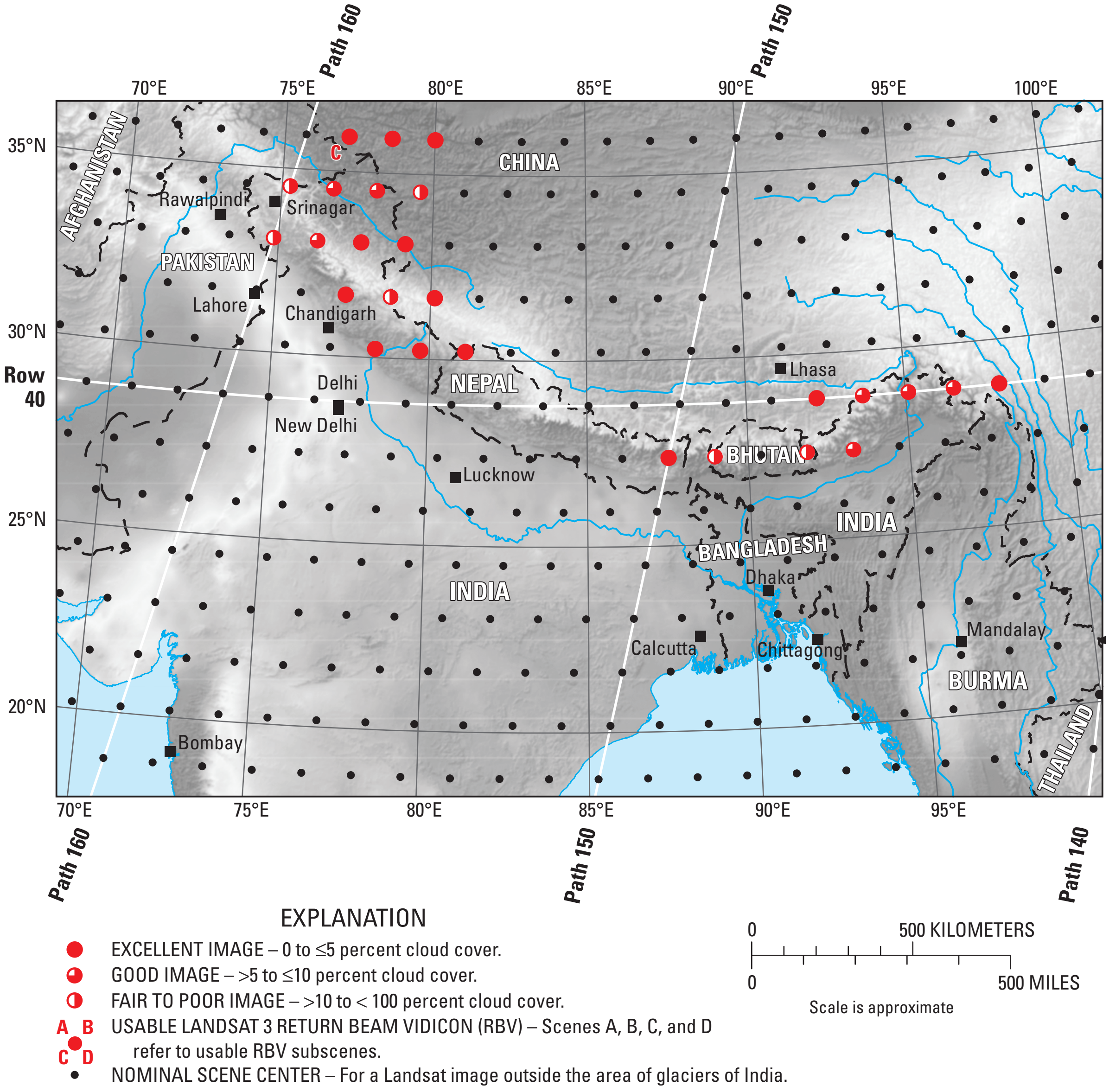

Figure 6.—Optimum Landsat 1, 2, and 3 images of the glaciers of India. Compare with table 6.

TABLE 6.—*Optimum Landsat 1, 2, and 3 images of the glaciers of India*

[EROS, Earth Resources Observation and Science.. Code column indicates usability for glacier studies; see figure 6 for explanation]

Path-Row	Nominal scene center latitude and longitude		Entity number (USGS EROS data center)	Date	Code	Cloud cover (percent)	Remarks
143–40	28°49′N.	97°57′E.	2143040007631190	06 Nov 76	●	0	
144–40	28°49′N.	96°31′E.	2144040007631290	07 Nov 76	◕	10	State of Arunachal, Pradesh, eastern Himalaya. Line drops
145–40	28°49′N.	95°05′E.	1145040007335590	21 Dec 73	◕	10	State of Arunachal, Pradesh, eastern Himalaya
146–40	28°49′N.	93°39′E.	2146040007635090	15 Dec 76	◕	10	State of Arunachal, Pradesh, eastern Himalaya
146–41	27°23′N.	93°15′E.	2146041007635090	15 Dec 76	◑	20	State of Arunachal, Pradesh, eastern Himalaya
147–40	28°49′N.	92°13′E.	2147040007635190	16 Dec 76	●	5	
147–41	27°23′N.	91°49′E.	2147041007700390	03 Jan 77	◑	20	
149–41	27°23′N.	88°57′E.	2149041007635390	18 Dec 76	◑	15	Sikkim Himalaya glacier area. Image used for figure 8
150–41	27°23′N.	87°31′E.	2150041007635490	19 Dec 76	●	5	Sikkim Himalaya glacier area. Image used for figure 8
155–39	30°15′N.	81°09′E.	2155039007634190	06 Dec 76	●	5	
156–38	31°41′N.	80°09′E.	2156038007632490	19 Nov 76	●	0	
156–39	30°15′N.	79°43′E.	2156039007632490	19 Nov 76	●	0	Gangotri-Kemet-Nanda-Devi glacier areas; image used for figure 4
157–35	35°58′N.	80°00′E.	2157035007632590	20 Nov 76	●	5	
157–36	34°32′N.	79°34′E.	2157036007726590	22 Sep 77	◑	40	Line drops
157–37	33°07′N.	79°08′E.	2157037007632590	20 Nov 76	●	5	
157–38	31°41′N.	78°42′E.	2157038007632590	20 Nov 76	◑	25	
157–39	30°15′N.	78°17′E.	2157039007630790	02 Nov 76	●	0	A few line drops
158–35	35°58′N.	78°34′E.	2158035007630890	03 Nov 76	●	5	A few line drops
158–36	34°32′N.	78°08′E.	2158036007630890	03 Nov 76	◕	10	Eastern Karakoram Range. A few line drops
158–37	33°07′N.	77°42′E.	2158037007630890	03 Nov 76	●	5	Eastern *Nun-Barashagri* Range
158–38	31°41′N.	77°16′E.	2158038007630890	03 Nov 76	●	5	A few line drops
159–35	35°58′N.	77°08′E.	2159035007630990	04 Nov 76	●	5	
159–36	34°32′N.	76°42′E.	2159036007630990	04 Nov 76	◕	10	A few line drops
159–37	33°07′N.	76°16′E.	2159037007630990	04 Nov 76	◑	20	*Nun-Barashagri* glacier area. Line drops
159–37	33°07′N.	76°16′E.	2159037007625590	11 Sep 76	◕	10	*Nun-Barashagri* glacier area; image used for figure 2
160–36	34°32′N.	75°16′E.	2160036007631090	05 Nov 76	◑	20	A few line drops
160–37	33°07′N.	74°49′E.	2160037007631090	05 Nov 76	◑	50	

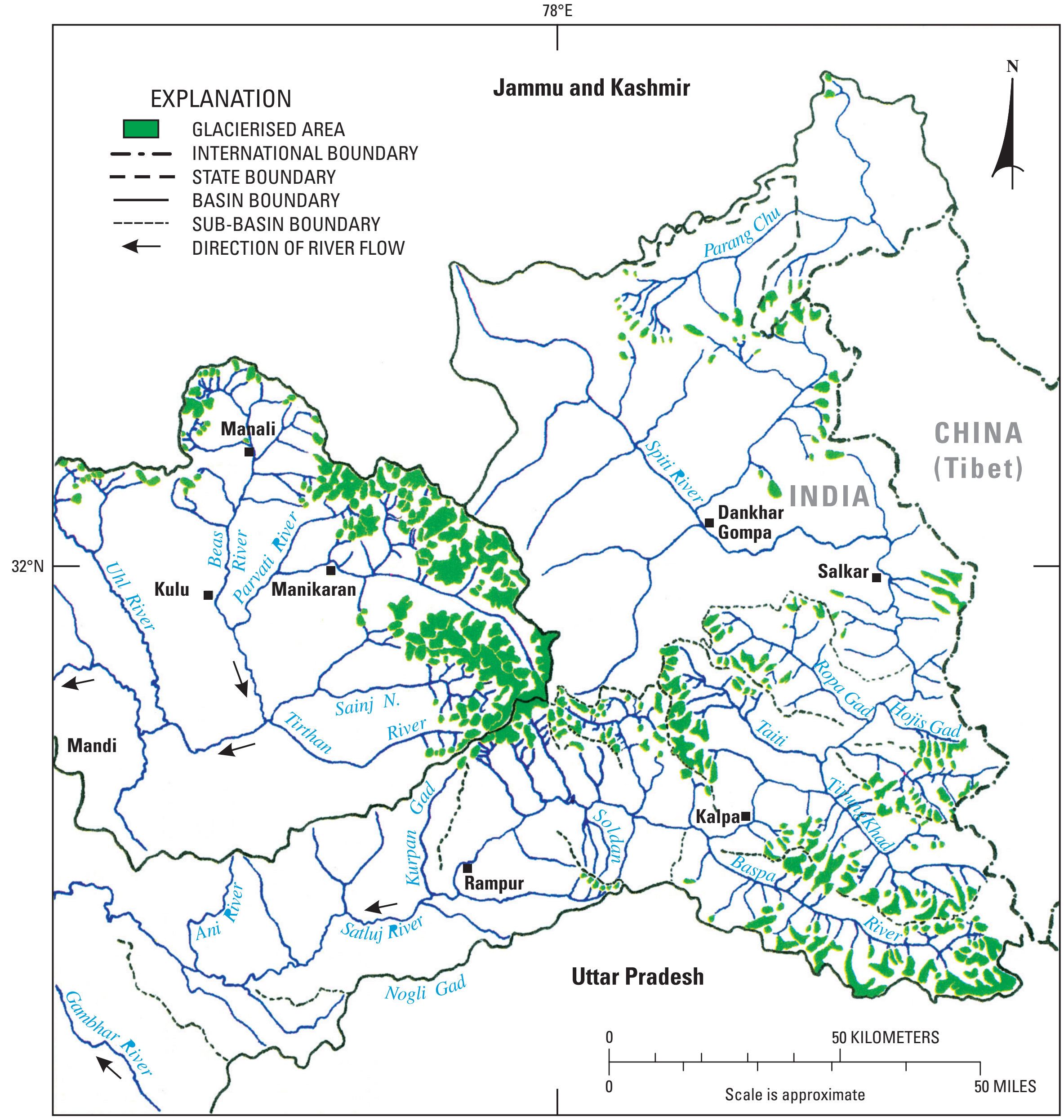

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Figure 7.*—Glacierized area of the Satluj River basin. From the preliminary "Inventory of the Himalayan Glaciers" by the Geological Survey of India (Kaul, 1999).*

Kāmet

Kāmet peak is the highest (7,759 m) of the Kāmet group. It supports dozens of major glaciers and many smaller ones (figs. 4, 5). All of the glaciers drain into the Alaknanda River or other tributaries of the Ganga.

Nanda Devi

The Nanda Devi group is dominated by Nanda Devi peak (7,820 m). Several high mountain peaks here form a rim of a large amphitheater — the fabled "sanctuary" of the Himalayan mountaineers — drained by *Rishi Ganga* through an almost impassable gorge. There are large glaciers within the "sanctuary," and the Milam Glacier drains outward from the northeast part into Dhaulīganga River (figs. 4, 5). In this area, Milam, *Poting* and *Shankalpa*

Glaciers (*Shankalpa* is east of Dhaulīganga) have been visited and observed by scientists of the Geological Survey of India since the 1970s. The most recent findings of GSI are published in Kaul (1999), Geological Survey of India (2001), and Srivistava (2001).

Sikkim Himalaya

Sikkim Himalaya, to the east of Nepal, is dominated by the massif of Kānchenjunga (8,591 m), the third highest peak in the Himalaya (fig. 8). It is located in the northwestern part of the State of Sikkim, along the border with Nepal. Zemu Glacier, 28 km long and 41.2 km^2 in total surface area (Kaul, 1999), is the main glacier descending from the massif (fig. 9). The massif is highly glacierized, and many other major and minor glaciers are located on it.

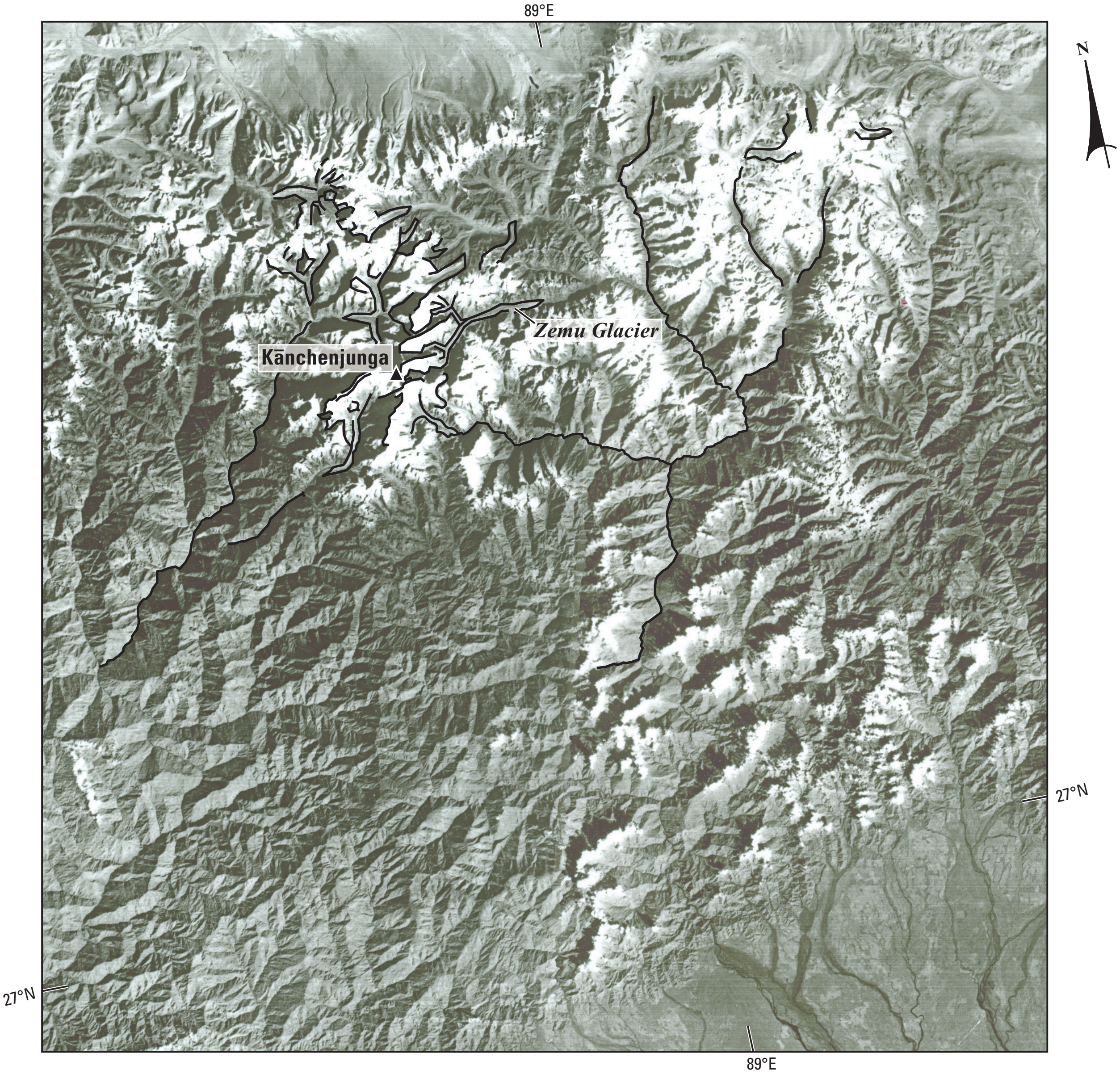
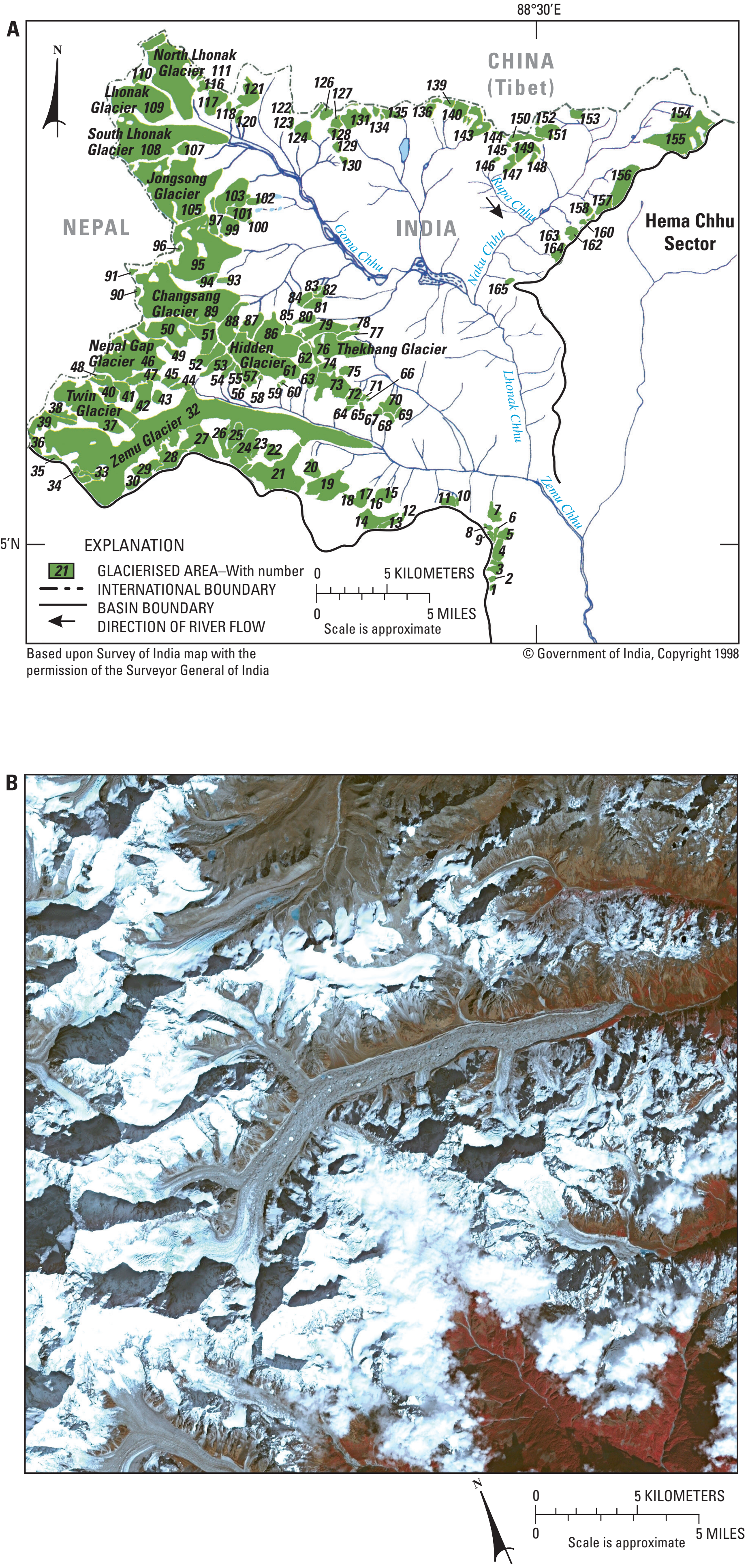


***Figure 8.**—Landsat 2 MSS image mosaic of the Sikkim Himalaya dominated by the Kānchenjunga massif, the third highest peak in the Himalaya. Many large glaciers are located here, including the 28 km-long Zemu Glacier. The Landsat MSS images (2149041007635390, 18 December 1976; Path 149–Row 41 (right); and 2150041007635490, 19 December 1976; Path 150–Row 41 (left)) are from the U.S. Geological Survey EROS Data Center, Sioux Falls, South Dakota.*



Based upon Survey of India map with the permission of the Surveyor General of India

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Figure 9.—*Map and ASTER image of the Zemu Glacier area.* **A**, *Glacier map of the Zemu Basin of the Sikkim Himalaya. From the preliminary "Inventory of the Himalayan Glaciers" by the Geological Survey of India (Kaul, 1999). Zemu Glacier is in the lower left. The numbers on the glaciers relate to the glacier inventory data in Kaul (1999, p. 149).* **B**, *27 November 2001 ASTER image of Zemu Glacier (lat 27°45′N., long 88°16′E.). The image (AST_L1B_00311272001045729_20060817160447_7392 hdf) is courtesy of Adina Racoviteanu, Department of Geography and Institute of Arctic and Alpine Research, University of Colorado at Boulder.*

This area apparently receives more precipitation than the adjacent Mount Everest region to the west, whose glaciers are smaller. The northern and northeastern mountains in the State of Sikkim support relatively few major glaciers, although small glaciers do exist. Zemu Glacier and a small glacier in northern Sikkim have been studied by the Geological Survey of India and other Indian agencies.

Eastern Himalaya

In the Eastern Himalaya, a few large glaciers could be delineated on the Landsat 2 MSS image acquired on 3 January 1977 (table 6). The area covers the northern part of the State of Arunachal Pradesh. Smaller glaciers are also present in this area, although only scant information is available about them. Perhaps the strong monsoon, prevalent in the State of Assam, penetrates to this area and provides the requisite nourishment for glacier presence.

Surge-Type Glaciers

Surge-type glaciers are easy to identify on aerial photographs and on Landsat images. Glacier surges often leave their characteristic imprint on glaciers; contorted medial moraines are the most impressive and useful of such characteristics. A search through the Landsat MSS images indicates that surge-type glaciers are rare in the Himalaya, but common in the Karakoram Range. Some Landsat images of the Indian Karakoram show a concentration of surge-type glaciers, including glaciers that have surged in the past. The mountains between the Shyok River (up to Saser) and Gilgit River include many surge-type glaciers.

Glaciers in the Shyok valley (for example, *Chong Kumdan* and *Kichik-Kumdan Glaciers*) are well-known for repeated surge events in this region. During their advances, the Shyok River becomes dammed, causing a large amount of water to accumulate behind the ephemeral dam, which, in time, bursts through the ice dam, producing an outburst flood. The ensuing floods ravage the areas downstream. A huge flood occurred in 1929. More recently, in a Landsat 2 MSS image of July 1978, two glaciers appear to have advanced into the Shyok River valley but have not yet blocked it. Two large glaciers at the head of the river also show surge-type features. Many of the glaciers descending from the northwestern part of the high divide between Shyok and Nubra drainage basins, including those draining into *Kole-Ching Ha* (in China), also seem to exhibit surge-type characteristics.

Conclusions

The study of glaciers is important in India, both scientifically and economically. The meltwater of Indian glaciers affects the quality of life of millions of people. The observation of glaciers in India started in the middle 1800s, and gradually became more prevalent. In the last 25 to 30 years, many intensive glacier studies have been completed.

A Study of Selected Glaciers under the Changing Climate Regime

By Syed Iqbal Hasnain,[3] Rajesh Kumar,[4] Safaraz Ahmad,[5]
and Shresth Tayal[3]

Introduction

Low-latitude mountain environments are highly sensitive indicators of climate change (Thompson and others, 1995; Broecker, 1997; Beniston and Fox, 1996). The retreat of glaciers corresponding to global trends has been significant since the middle of the 19th century (Hastenrath, 1995; Kaser, 1999); therefore, glaciers have more recently become the subject of intensive observation. Several studies in the Himalayan region found that the glaciers have retreated considerably during the last two decades (Fujita and others, 1997, 2001; Kadota and others, 1997, 2000; Ageta and others, 2001; Naithani and others, 2001). Several analyses have shown that it is not only increased temperature and/or decreased precipitation that are responsible for recession of glaciers in lower latitudes, but also changes in humidity (Kaser and Noggler, 1991; Hastenrath and Kruss, 1992; Kaser, Georges, and Ames, 1996; Kaser and Georges, 1997; Kaser, 1999; Wagnon and others, 1999).

The glaciers of the high mountains which are located in low latitudes cover a total area estimated at about 2.5×10^3 km^2, which corresponds to 0.16 percent of the total glacier-ice cover of the world (Haeberli and others, 1989). Although negligible in area (if all of these glaciers melted tomorrow, eustatic sea level would not rise more than about 1 cm), they are nevertheless known to be very sensitive components of the environment and deserve attention in the context of both global climate change (Kaser, Hastenrath, and Ames, 1996) and local and regional water supply.

Mass-balance data are useful in glacier-climate interaction studies. The conventional method for mass-balance measurement is normally applied to benchmark glaciers having International Commission on Snow and Ice (ICSI)-approved attributes (Kaser and others, 2002). However, in rugged terrain in remote areas like the Himalaya, remote-sensing techniques are useful for understanding regional climate change and its impact on glaciers because more areal coverage is available with less effort on the ground. A rough estimate of the glacier mass balance can be derived from the accumulation area ratio (AAR) (Kulkarni, 1992; Sapiano and others, 1998; Ramussen and others, 1999). The AAR of a glacier is defined as the ratio between the accumulation area and the area of the entire glacier, and is determined by using the equilibrium line altitude (ELA) that separates the ablation and accumulation areas on a glacier surface.

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The demand for global fresh water has increased four-fold since 1940, due to a growing population, expansion of irrigation of croplands, increasing urbanization, and industrialization. In the Indian subcontinent, snow and glacier ice of the Hindu-Kush Himalaya provide a very large percentage of the low-land, dry-season flow of the Indus, Ganges (Ganga), and Brahmaputra Rivers. The discharge from glaciers helps to maintain year-round continuity in water availability to surrounding ecosystems and living habitats. Considering Himalayan glaciers as water reserves and effectively managing these mountain water resources could help avoid a future water crisis in coming decades. The glacierized basins in the Himalaya are the primary source of freshwater and perennial river flow in the Indian subcontinent.

Recent Glacier Studies

In recent years, new technologies have been applied to the study of glaciers in India, in addition to continued field investigations. The studies described in this section have provided valuable information about the effects of changing climate on the glaciers.

Gangotri Glacier

The Gangotri Glacier originates at an elevation of 7,143 m ASL in the *Chaukhamba* group of peaks and extends between 30°42′N. and 31°01′N. latitude and between 78°54′E. and 79°18′E. longitude (fig. 10). It terminates in a snout about 25 km below at *Gaumukh* at an elevation of about 4,000 m. The area of ice cover of the Gangotri Glacier is about 250 km^2. Gangotri Glacier feeds the Bhāgīrathi River and is situated at the transitional zone between the eastern and western Himalaya, reflecting the properties of both. But this glacier is also vulnerable to the threats posed by climate change and associated phenomena.

A detailed field observation of the Gangotri Glacier, carried out during 2002 and 2003, revealed that huge amounts of debris were being deposited on the glacier surface from adjacent mountains because of an increase in glacier erosion. Near the snout, numerous transverse crevasses had developed in the glacier due to the steep slope and unloading of stresses. Material was deposited near the snout because of rapid, continuous deglaciation during the past few decades. A few ice-dammed lakes were located on the supraglacial surface (figs. 11, 12), about 9 km upglacier, near the junction with the tributary glacier, *Kirti Bamak*. The lakes ranged in size from 50 m^2 to 150 m^2 (estimated during the field excursion in July 2002, led by Dr. Rajesh Kumar). The existence of ice-dammed lakes may be due to the low gradient (8–9°) in front of *Kirti Bamak*.

The Terra satellite's Advanced Spaceborne Thermal Emission Reflectance Radiometer (ASTER) composite image (fig. 13), produced by Jesse Allen and available on the U.S. National Air and Space Administration's (NASA) Earth Observatory website [*http://earthobservatory.nasa.gov*], shows how the Gangotri Glacier terminus has receded since 1780. The lines showing the location of the terminus are approximate. This satellite image reflects a much enhanced increase in recession of the terminus of the Gangotri Glacier during the last 30 years. Calculations show a recession rate of 3.77 m a^{-1} for the period 1780 to 1849, 6.53 m a^{-1} for the period 1849 to1900, 9.38 m a^{-1} for the period 1900 to 1971, and 27.66 m a^{-1} for the period 1971 to 2001.

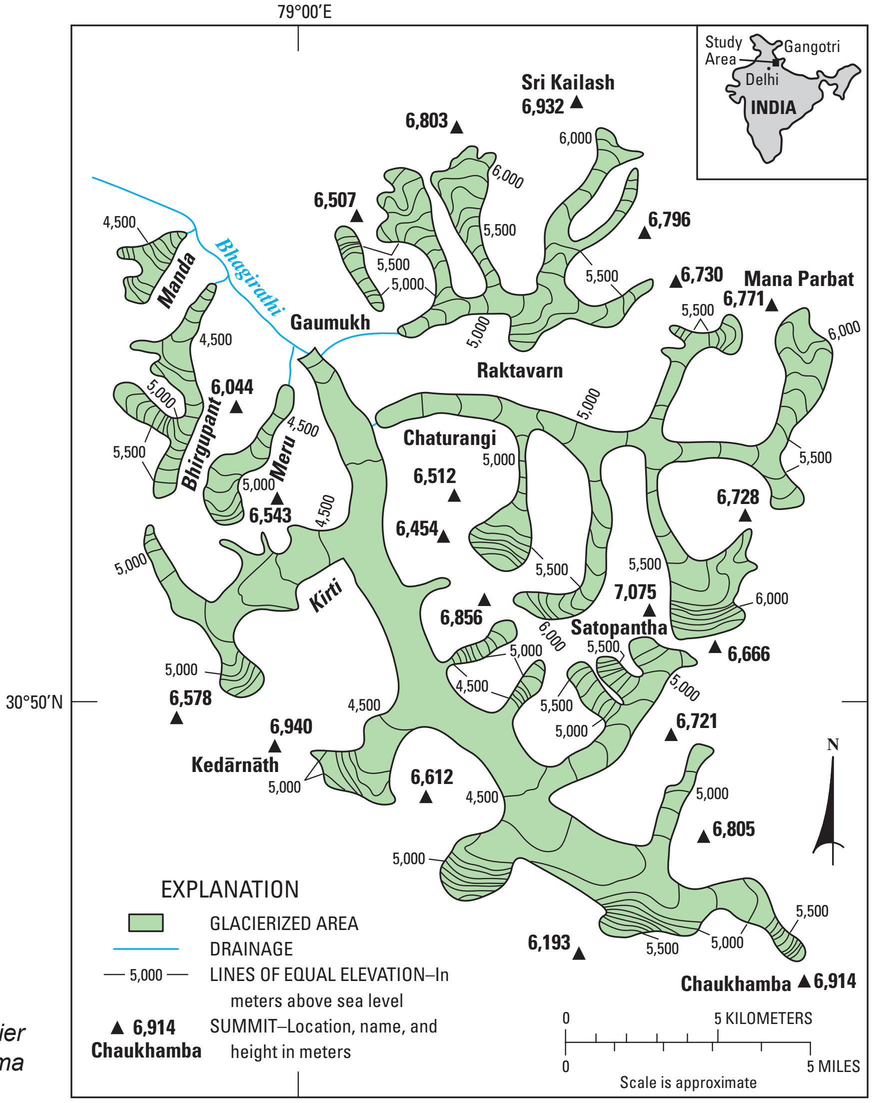


Figure 10.—Location map of Gangotri Glacier and associated glaciers. Modified from Sharma and Owen (1996).

Figure 11.—Lake formed on Gangotri Glacier (approximate lat 31°N., long 79°E.) near the junction with Kirti Bamak Glacier. The background peak is Kedārnāth. Photograph by Dr. Rajesh Kumar, July 2002.

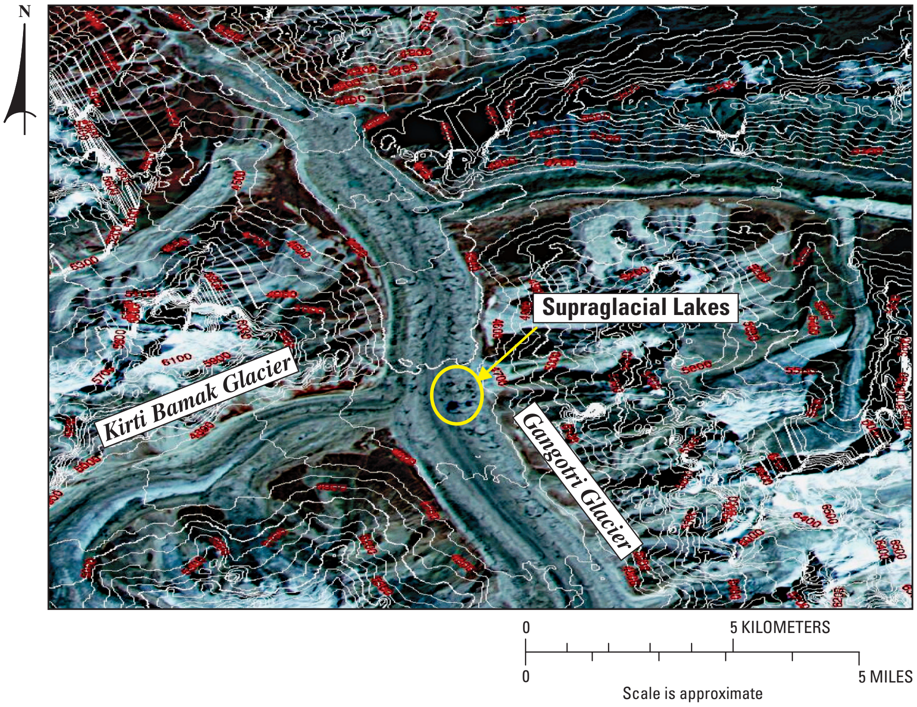


Figure 12.— *Enlargement of 9 September 2001 ASTER image showing supraglacial lakes on the Gangotri Glacier (approximate lat 31°N., long 79°E.). Image I.D. AST_LIA:2004126903.*

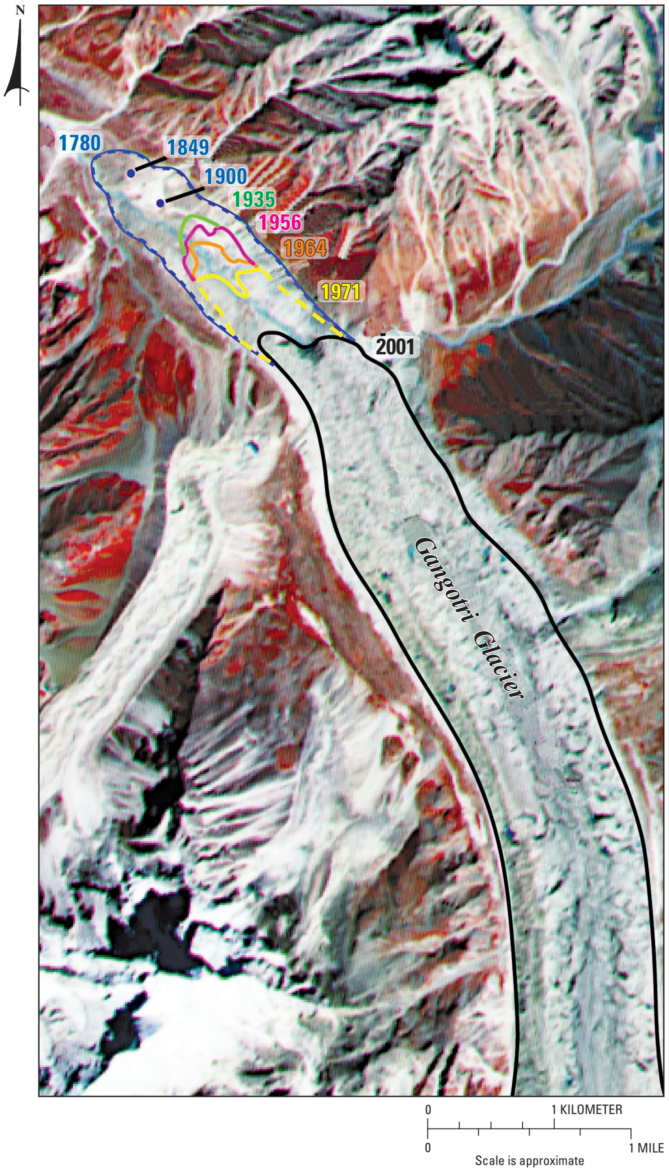


Figure 13.—*Enlargement of 9 September 2001 ASTER image showing position of the terminus of Gangotri Glacier between 1780 and 2001 (approximate lat 31°N., long 79°E.). Image from Jesse Allen, NASA's Earth Observatory, based on data provided by the ASTER Science Team. Glacier-retreat boundaries courtesy of the U.S. Land Processes Distributed Active Archive Center (LP DAAC). Image I.D AST_LIA:2004126903.*

Shrinkage of the glaciers is linked to climate change due to decrease in winter precipitation, increase in summer precipitation, and atmospheric temperature change. Investigations carried out by the Intergovernmental Panel on Climate Change (IPCC) (Watson and others, 1998) concluded that the Earth's average temperature has increased by 0.6 ± 0.2°C during the 20th century. The increase in air temperature is projected to be about +1.4°C to +5.8°C by the end of 21st century. The projected increase will impact hydrometeorological processes more vigorously than during the 20th century. The impact of increased temperature and liquid precipitation on glaciers and snowfields in the Himalaya is likely to be profound. Recession of snowfields and glaciers will impact the long-term, seasonal pattern and the annual availability of freshwater and the hydropower capacity (Jóhannesson, 1997; Benn and others, 2000). Under the projected scenarios of IPCC, the change in ELA of the Gangotri Glacier has been computed by Hasnain and others (2004) (fig. 14). With an increase in temperature of +3°C the ELA will rise and the AAR will decrease from 0.40 to 0.15, indicating a more negative mass balance of the Gangotri Glacier during the 21st century.

Using an Indian Remote Sensing (IRS) panchromatic satellite 1D image acquired in September 2001, the area of the Gangotri Glacier at the headwaters of the main source of the Ganges river main stem was measured to be about 77 km^2. This area was 87 km^2 on the 1:150,000-scale topographic map published by the Survey of India in 1985, implying that the glacier lost about 12 percent of its area during the intervening 16 years. The average rate of the snout recession at *Gaumukh* was also computed by comparing the snout position on the 1985 topographic map and the 2001 panchromatic image. The average rate of recession for this period in this location was about 23 m a^{-1} (Hasnain and others, 2004).

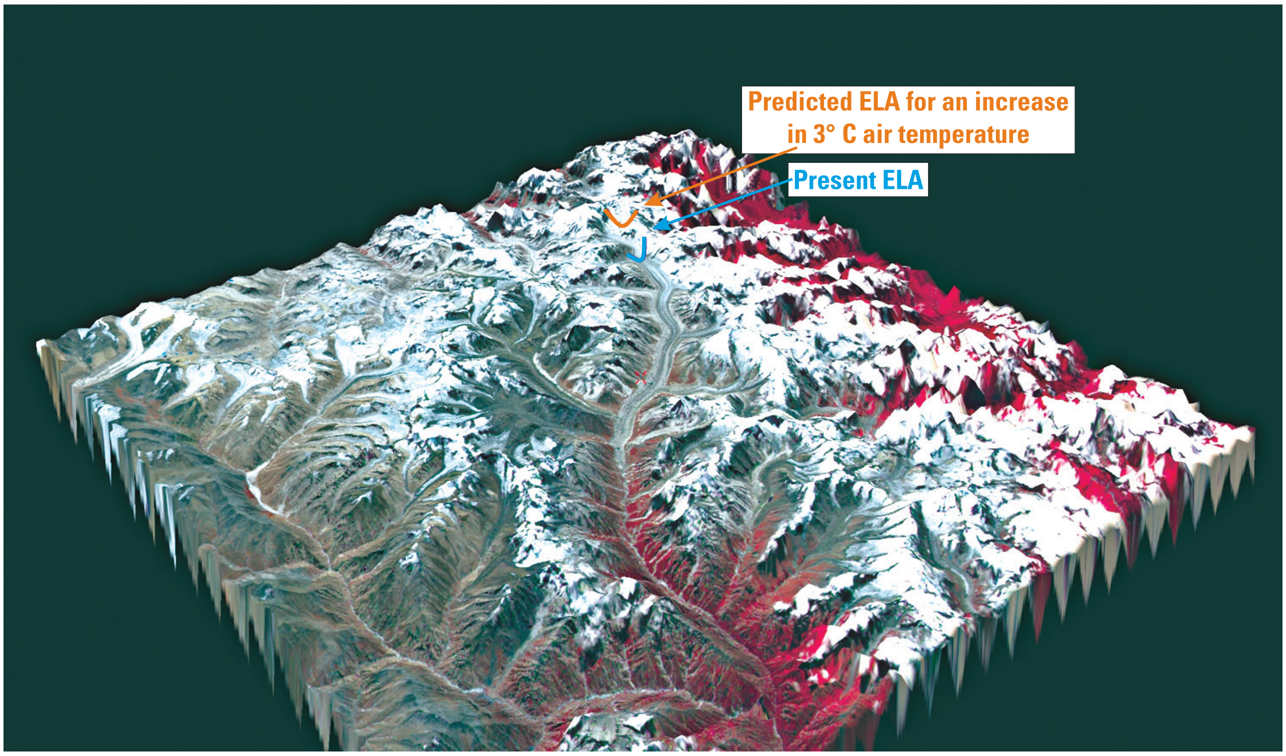


Figure 14.*—Predicted change in location of the equilibrium line altitude (ELA) for an increase of 3 °C air temperature in the Gangotri Glacier region.*

Chhota Shigri Glacier and Mass-Balance Measurements

Chhota Shigri Glacier, located between 32°11′–32°17′N. and 77°30′–77°32′E., extends from 4,000 m ASL to more than 5,600 m ASL (fig. 15). It is a valley-type glacier, debris covered in the lower ablation zone and lies in the Chandra-Bhāga river basin on the northern ridge of Pir Panjāl Range in the Lāhul-Spiti valley of Himachal Pradesh. The snout was located at 32°17′N., 77°32′E. in 2003. The glacier is in the monsoon-arid transition zone; therefore, it is considered to be a potential indicator of the northern limits of the intensity of the monsoon. It is influenced by both the Asian monsoon in the summer and the westerlies in the winter. From its snout to the accumulation zone near

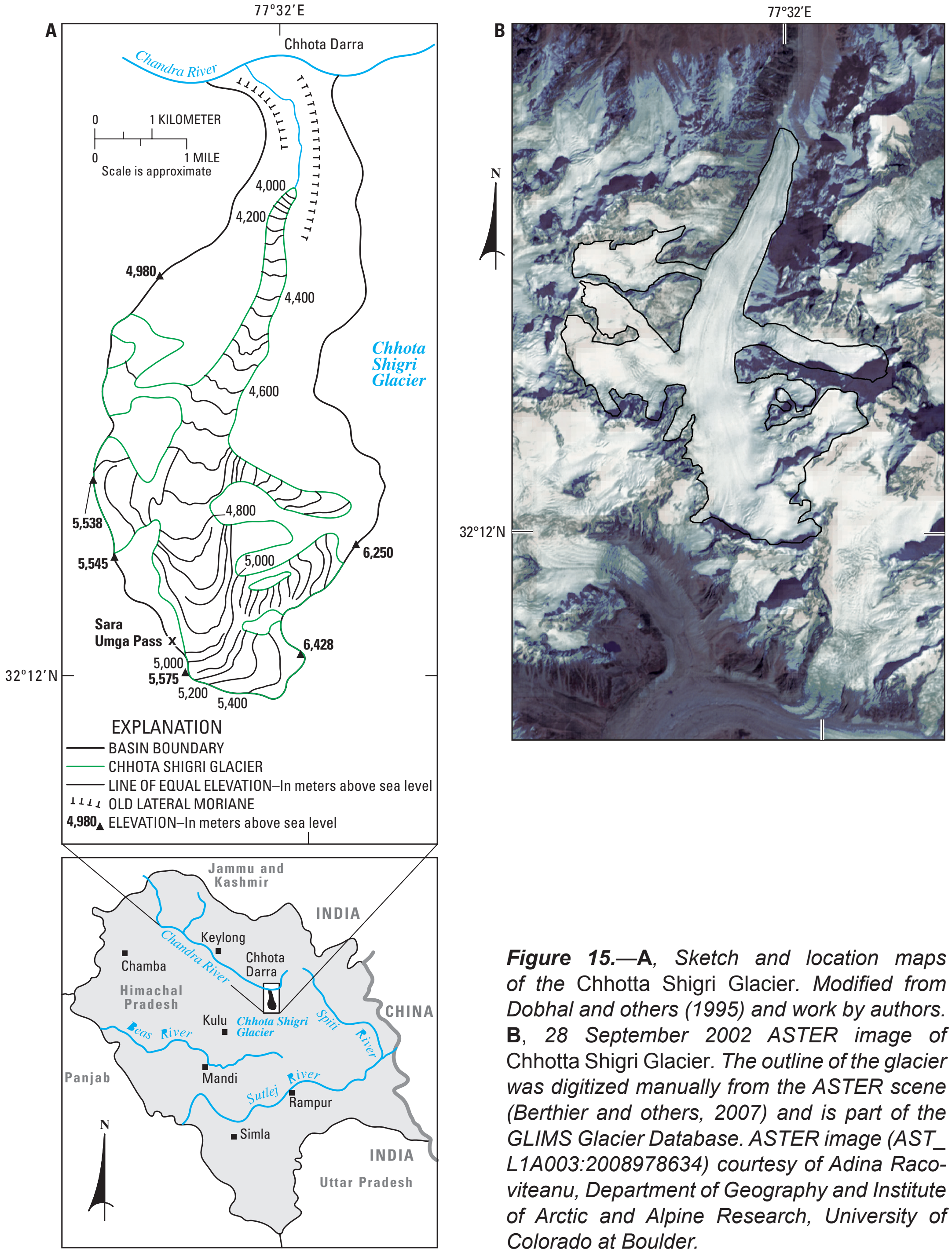


***Figure 15.*—A**, *Sketch and location maps* of the Chhotta Shigri Glacier. *Modified from Dobhal and others (1995) and work by authors.* **B**, *28 September 2002 ASTER image of* Chhotta Shigri Glacier. *The outline of the glacier was digitized manually from the ASTER scene (Berthier and others, 2007) and is part of the GLIMS Glacier Database. ASTER image (AST_L1A003:2008978634) courtesy of Adina Racoviteanu, Department of Geography and Institute of Arctic and Alpine Research, University of Colorado at Boulder.*

Sara Umga Pass (4,900 m ASL), *Chhota Shigri Glacier* is 9 km long and its width varies from 0.5 to 1.5 km in the ablation zone to about 4.5 km above the equilibrium line (Kumar, 1988). Field studies determined that the equilibrium line was at 5,170 m ASL in 2002–03 and in 2003–04 (Wagnon and others, 2007) — an upward shift since the 1987–89 ELAs, when the equilibrium line was at 4,650–4,840 m (Dobhal and others, 1995). Fluctuations in the width of the ablation zone are between 0.3 and 1.5 km, and are between 1.5 and 3 km in the accumulation zone (Hasnain and others, 1989). The *Chhota Shigri Glacier* drains into the Chandra River. The total drainage area of the *Chhota Shigri Glacier* basin is about 45 km^2, and the glacier occupies about 20 percent of the drainage area (Dobhal and others, 1995). Several supraglacial streams have formed in the ablation zone; most of them terminate in moulins or crevasses.

The *Chhota Shigri Glacier* snout has been retreating (fig. 16). The average rate of the *Chhota Shigri Glacier* snout recession was calculated by Kumar and Dobhal (1994) to be -7.5 m a^{-1} from 1970 to 1989. However, this rate has increased to -27 m a^{-1} during the period 1989 to 2000.

The areal coverage of the *Chhota Shigri Glacier* has been compared on various satellite images (Landsat 5 TM (1989), Satellite Pour l'Observation de la Terre (SPOT) (1994), Landsat 7 ETM+ (2000)), and on 1:50,000-scale

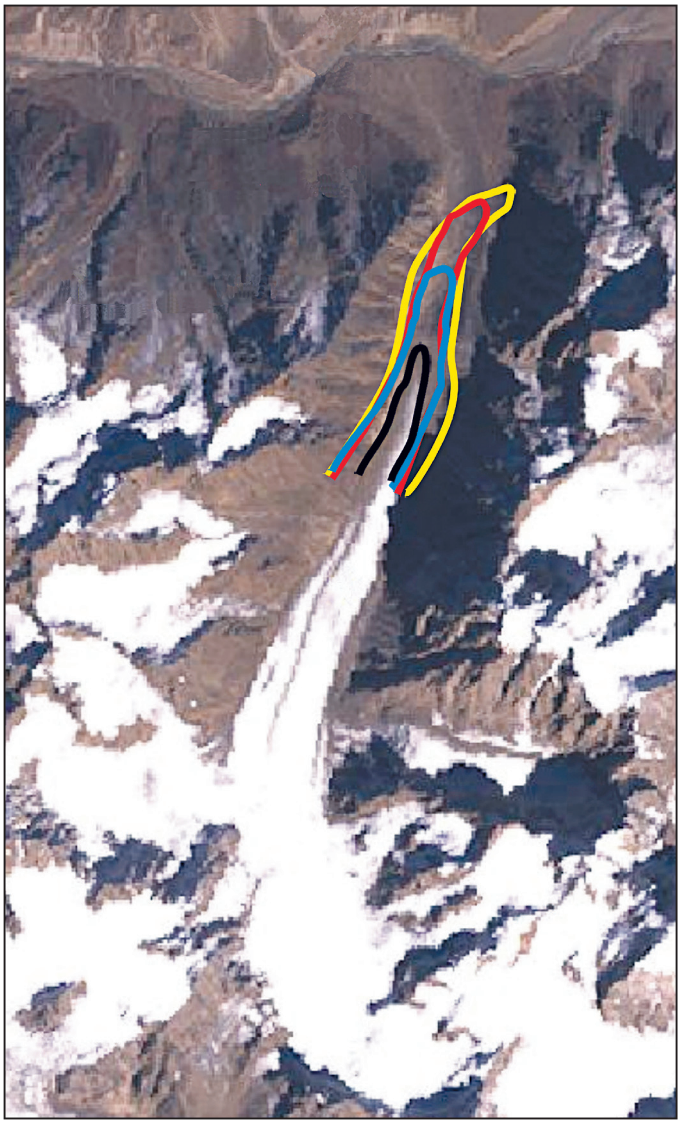


***Figure 16.**—Retreat of* Chhota Shigri Glacier *snout (approximate lat 32°15′N., long 77°30′E.) in the last 40 years mapped from topographic maps and satellite images. The 1960 and 1987 terminus positions are from topographic maps, the 1994 position from a SPOT image, and the 2000 position from a Landsat 7 ETM+ image.*

topographic maps published in 1960 and 1988. A digital elevation model (DEM) of the *Chhota Shigri Glacier* was prepared with the contour value derived from the topographic map of 1988. A comparative analysis of the planimetric cover of the *Chhota Shigri Glacier* on the geomorphological map of 1988 (surveyed in 1987) and the 2000 Landsat image shows that the areal glacier coverage decreased about 12 percent in the 13-year interval (fig. 17).

Under the projected scenarios of Watson and others (1998), the ELA of the *Chhota Shigri Glacier* has been computed for a temperature increase of +3 °C in the region. The projected AAR of the glacier has also been computed, and shows a decrease from 0.40 to 0.10 for a temperature increase of +3 °C. This implies that the glacier will be about 80 to 90 percent more vulnerable to melting with an increase in temperature of +3 °C.

The International Commission on Snow and Ice (ICSI) selected *Chhota Shigri Glacier* as a benchmark glacier in the Himalayan region in 2002. An international training course on glacier mass balance was held from 24 September

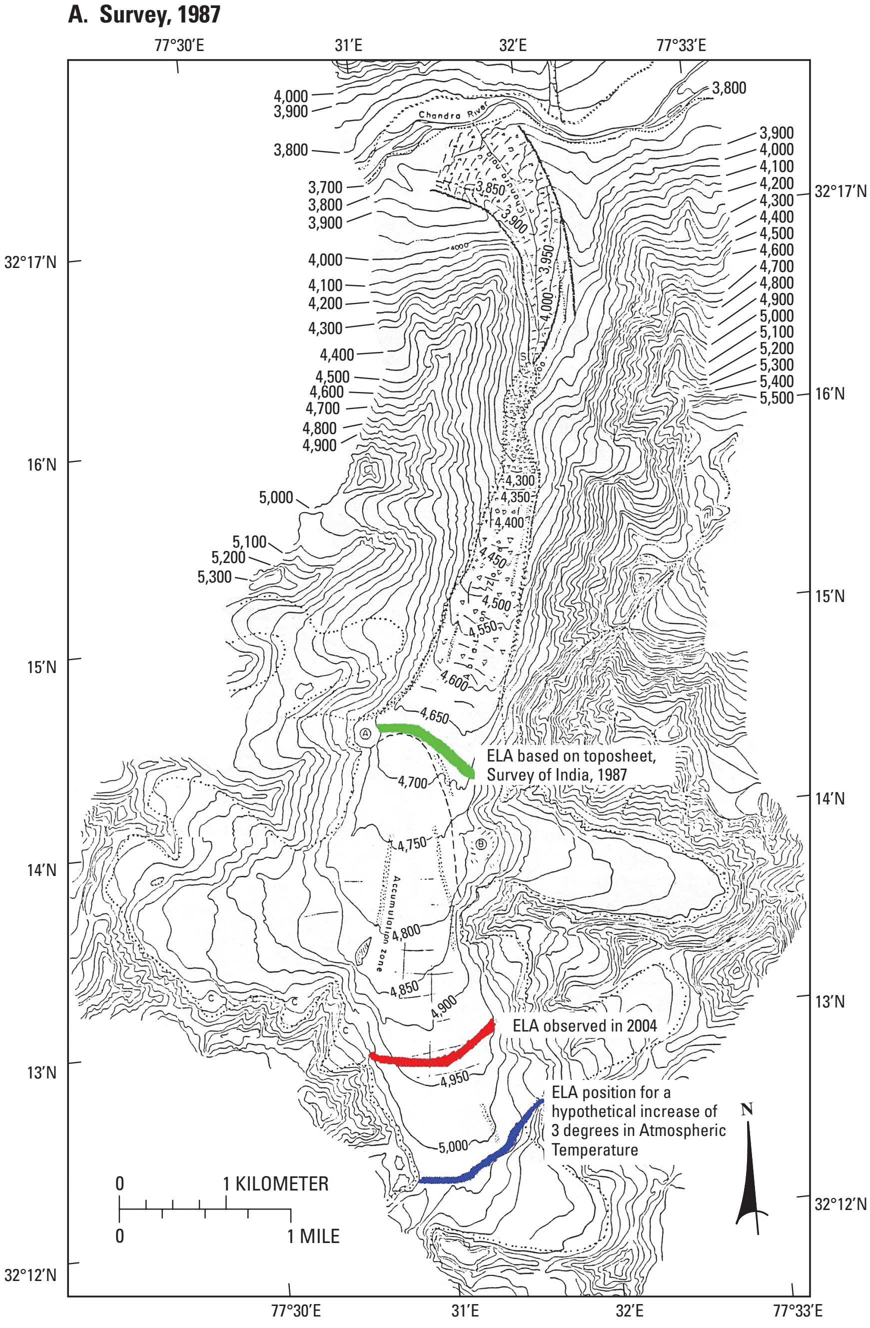
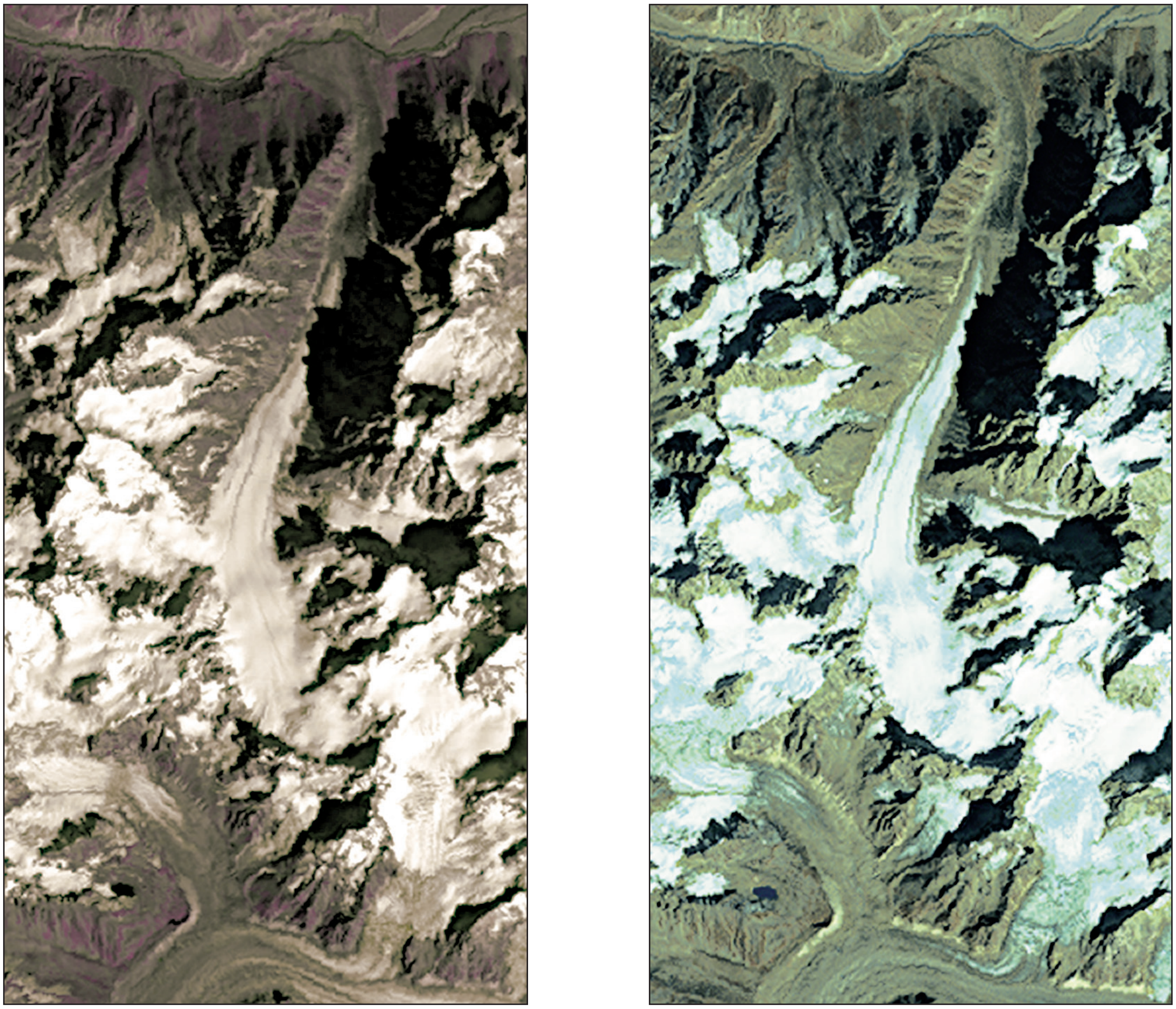


Figure 17.—(at left and at right) *In the process of deglaciation, the surface area of the* Chhota Shigri Glacier *(approximate lat 32°15′N., long 77°30′E.) has been reduced about 12 percent in the 13 years from 1987 to 2000. The area in 1987 was taken from a 1988 topographic map of the Survey of India, surveyed in 1987 (***A***). A 9 October 1989 Landsat 5 TM image (***B***), shows the glacier near the time of the 1987 survey. In 2000, the area is shown on a 15 October Landsat 7 ETM+ image (***C***).*



B. Landsat, 1989

C. Landsat, 2000

to 10 October 2002. It was organized by ICSI, with the Glacier Research Group, Jawaharlal Nehru University (JNU), as local organizers, and technical support from Institut de Recherche pour le Développement (IRD) (France), Institute of Geography (Austria), Geological Survey of Denmark and Greenland (Denmark), Department of Physical Geography and Quaternary Geology and Glaciology (Sweden), and Nagoya University (Japan). As part of the training course, stakes were emplaced in the glacier with a steam drill (fig. 18). The glacier was revisited in 2003 and 2004 and measurements were carried out on the glacier using the stakes as reference points. Also, snow/firn pits were dug in the accumulation area of *Chhota Shigri Glacier* to obtain information on the yearly accumulation of snow. The only recognizable changes in the snow stratigraphy between 2002 and 2004 were a few slight differences in the size of the firn grains and the addition of a few thin ice layers. The ice layers were clear in some places, but contained dirt at other places. Very little change in the density profile has been observed at two pits located at elevations of 5,200 and 5,405 m ASL. A third pit, at an elevation of 5,500 m ASL, showed a large variation in the density profile; density increased with depth and reached 0.86 g cm^{-3} (glacier ice) at a depth of 300–338 cm (Kumar and others, 2005).

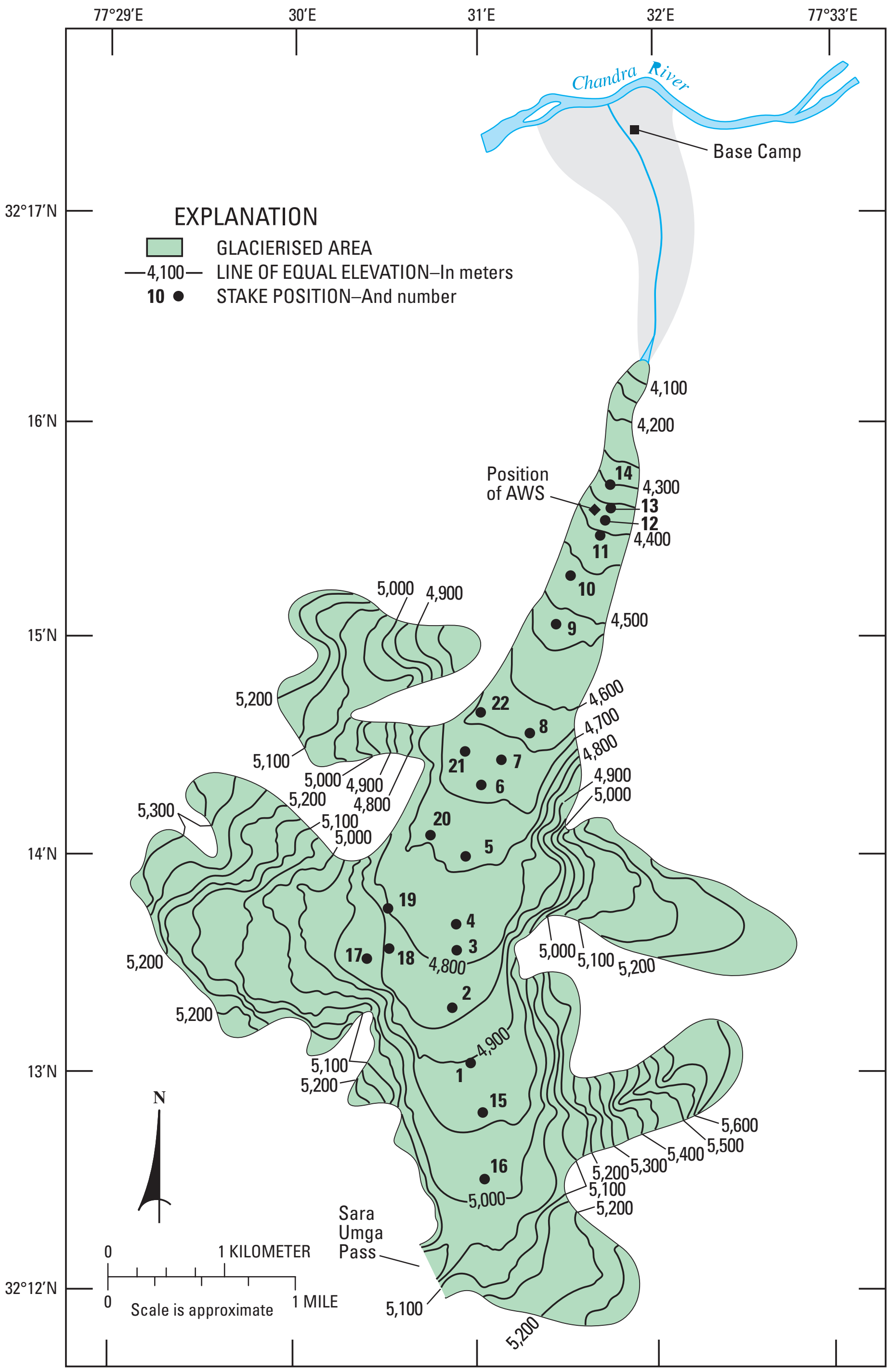


***Figure 18.**—Map of the* Chhota Shigri Glacier *showing location of stakes installed in 2002 and the automatic weather station (AWS) installed during September–October 2003. Modified from Kumar and others (2004).*

The various positions of the terminus between 1984 and 1986 (campaign of Department of Science and Technology, New Delhi) were indicative of the annual climatic variation on the glacier, and showed three main episodes of advance and retreat. Fluctuations of the equilibrium line, observed during the same period, support the above observations. The snout of the glacier continued to recede at a rate of 18.7 m a^{-1} during 1986–88. This retreat was accompanied by a negative mass balance of 1.55×10^{6} m^{3} a^{-1}, observed during 1987–88 (Nijampurkar and Rao, 1992).

Our study, based on two years of observations (2002–03 and 2003–04), shows a negative mass balance of 5.03×10^6 m^3 a^{-1} during 2002–03, and 10.37×10^6 m^3 a^{-1} during 2003–04 (figs. 19*A*, *B*) (Kumar and others, 2005). The negative mass balance nearly doubled in two years and increased more than 3- to 6- fold compared with the value in 1987–88, only 15 years before. The glacier is becoming considerably thinner at lower altitudes, based on the increasing negative net mass balance.

Siachen Glacier

Siachen Glacier (approximately 35°11′N., 77°12′E.), is 78 km long and lies in the area claimed by both Pakistan and India, between the Saltoro ridgeline to the west and the main Karakoram Range to the east. The Saltoro ridge originates from the Sia Kangri peak, in the Karakoram Range, and the elevation ranges from 5,500 m to 7,350 m ASL. The major passes on this ridge are Sia La at 6,000 m and Bilafond La at 5,800 m ASL. The Siachen Glacier occupies the great Himalayan watershed that demarcates central Asia from the Indian subcontinent and that separates Pakistan from China in this region.

A comparative analysis of Landsat images of the Siachen glacier for the years 1978, 1989, and 2001 (fig. 20) clearly reflects a retreat in the terminus of the glacier. But a complete determination of the rate of retreat of the glacier with proper field validation is still to be carried out. Although a field study should be done because of the importance of the glacier and its known retreat, the area is under security restrictions and field work is prohibited.

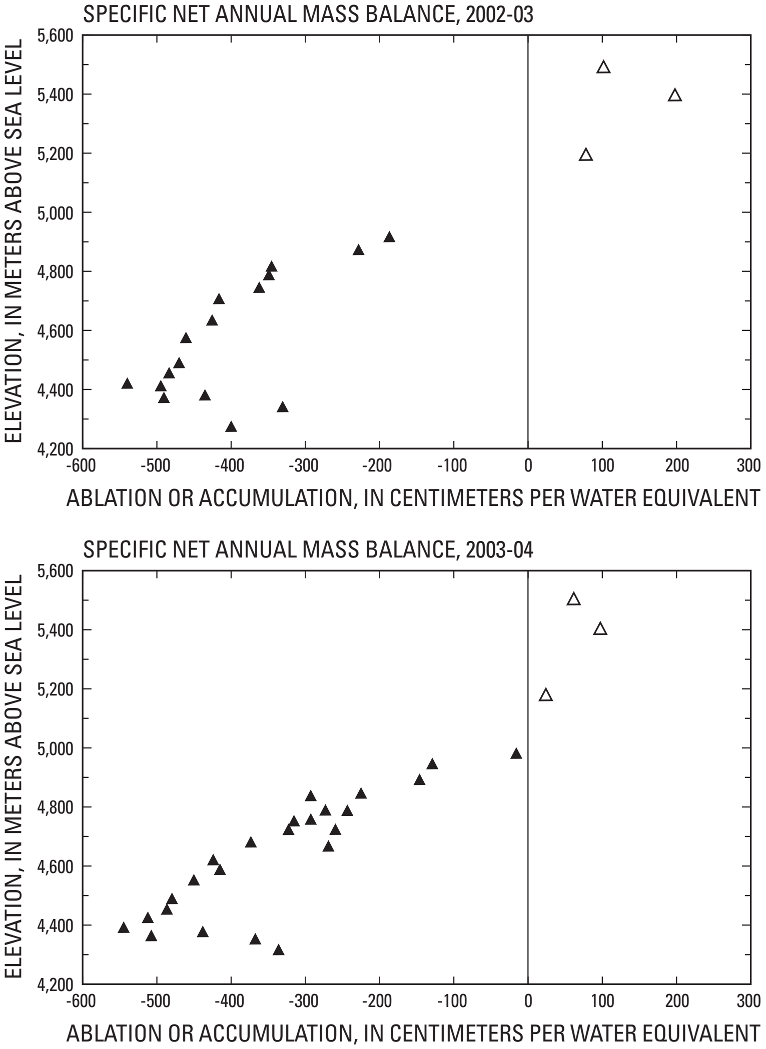


Figure 19.**—A**, *Specific net annual mass-balance (2002–03) near measurement points averaged against the elevation on* Chhota Shigri Glacier*;* **B**, *Specific net annual mass-balance (2003–04) near measurement points averaged against the elevation on* Chhota Shigri Glacier*. we = water equivalent.*

Figure 20.—*Retreat of the terminus of Siachen Glacier (approximate lat 35°11′N., long 77°12′E.) from 1978 to 2001. The 1978, 1989, and 2001 terminus positions are shown on Landsat images: 18 July 1978 Landsat 3 MSS image (Path 159–Row 35), 9 October 1989 Landsat 5 TM image (Path 147–Row 36), and the 31 October 2001 Landsat 7 ETM+ image (Path 147–Row 36).*

Glacier Lakes

Glacier movement and interaction with debris cover on glacier surfaces results in various glacier-surface features. With high rates of melting, these surface features form glacier lakes, both supraglacial and ice-marginal. The formation and disappearance of new supraglacial lakes is a natural phenomenon. But an increase in the number and area of supraglacial lakes on the glacier surface can be linked with high rates of ice melting or excess downwasting of the glaciers. The coalescing of the small lakes results in large glacier lakes that store huge quantities of water and sediment. These glacier lakes can be bounded by the terminal moraine of the glacier, forming moraine-dammed or ice-margin lakes.

The glacial moraine boundary consists of soft and loose material. Steep lateral moraines with highly unstable slopes lie against the steep glacier tongues. Even minor seismic activity, a landslide, ice calving, or snow and rock avalanches can result in the sudden release of huge amounts of water, which cause flash floods downstream. These glacier lake outburst floods (GLOFs) (jökulhlaups) can cause major damage to inhabitants and their infrastructure, and to the ecosystem and environment throughout the Himalayan region

Many glacier lakes have developed during the last half century in the Himalaya, and their numbers have increased in recent years, likely visual evidence of global warming. If the current glacier downwasting trend continues, more potentially dangerous moraine-dammed lakes can be expected to develop. Therefore, it is important to identify the potential GLOF sites in the Himalaya so that necessary preventative action can be taken. For this purpose, an inventory of the glaciers and glacier lakes of Nepal and Bhutan was prepared by the International Centre for Integrated Mountain Development (ICIMOD) (Mool, Bajracharya, and Joshi, 2001; Mool, Wangda, and others, 2001). Aerial photographs and other remote-sensing data were used to identify these sites, and the temporal change in area of these lakes was studied using sequential images. In 1998, engineering construction was begun to reduce the water level in Tso Rolpa, one of the potentially dangerous lakes (see also Morales Arnao, 1998, p. I67–I71, for mitigation of hazards from moraine-dammed lakes in the Cordillera Blanca, Perú).

Similarly, a number of glacier lake studies have been conducted in the Indian part of the Himalaya. The results showed GLOF-potential sites in the Dhaulīganga River in the Ganga headwaters. The area of the largest glacial lake in 1989 was about 0.15 m^2; the dimensions of the other small glacier lakes ranged from 0.025 to 0.075 km^2. Recently, a new assessment of two glacier lakes in the Ganga headwater area was conducted using Landsat 1978, Landsat 1990, and Landsat 2001 images. The results showed that, since 1978, the big glacier lake area in Ganga headwaters has increased by about 40 percent, while the area of the smaller lakes has increased by only about 13 percent. The study indicates that both hydrodynamics and calving are major processes that control the glacier-lake expansion (Chikita and others, 1999). In the Chandra River basin, the area of a glacier lake was 0.359 m^2 in 1972 and increased to 1.156 m^2 in 1996 (Kulkarni, 2003). The remapping of this lake, using Landsat 1990 and 2001 images, indicated that the area of the lake has increased about 22 percent since 1990. Evolution of the glacier lakes in the Tista River headwaters are shown in Landsat 1976, Landsat 1990, and ASTER 2001 images (fig. 21). These images clearly show an increase in the number and area of the lakes.

All of the above pilot studies suggest the number and areal cover of the glacier lakes increased in the last 30–40 years. This is a clear sign of global warming and of its impact on glacier lakes. Routine monitoring of the areal coverage of potential GLOF lakes is necessary to prevent the destruction of downstream property and population. Remotely-sensed data, particularly ASTER, can be utilized to monitor these lakes regularly.

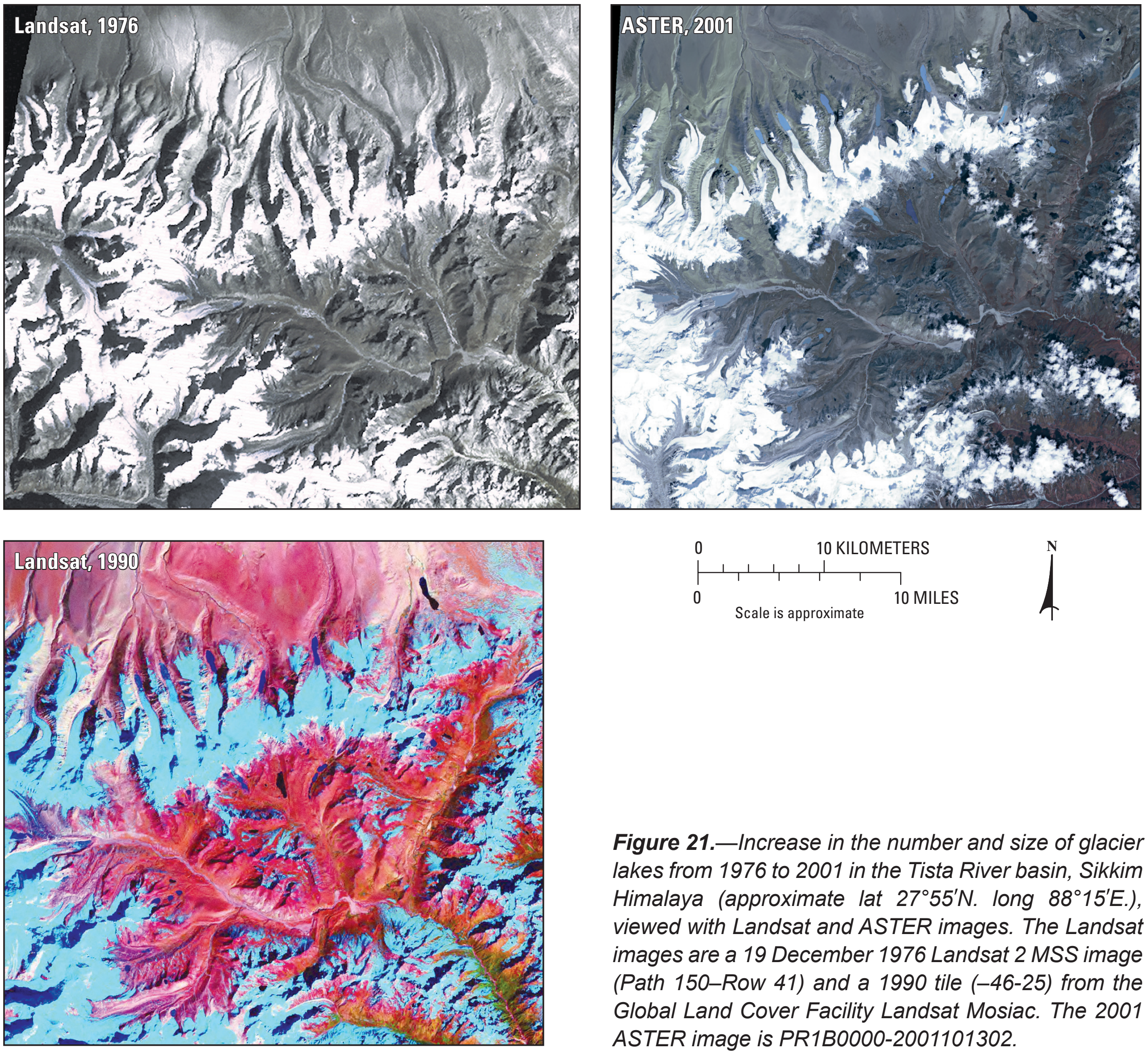


Figure 21.*—Increase in the number and size of glacier lakes from 1976 to 2001 in the Tista River basin, Sikkim Himalaya (approximate lat 27°55′N. long 88°15′E.), viewed with Landsat and ASTER images. The Landsat images are a 19 December 1976 Landsat 2 MSS image (Path 150–Row 41) and a 1990 tile (–46-25) from the Global Land Cover Facility Landsat Mosiac. The 2001 ASTER image is PR1B0000-2001101302.*

Conclusions

Remote-sensing techniques are very useful for cataloguing changes in glaciers and understanding climate change phenomena. Time-series analysis suggests that the summer temperature at an elevation of 4,000 m ASL has increased in the last forty years in headwaters of the Chenab and Ganga Rivers. Increased air temperatures have resulted in the shrinkage of the *Chhota Shigri Glacier* by about 12 percent in the last 13 years. In addition, 12 percent shrinkage of the main stem of the Gangotri Glacier has occurred in the last 16 years. This implies a rapid rate of shrinkage of many of the glaciers in the Himalaya in recent years. From model results, it was determined that, for an increase of +3 °C air temperature, the ELA will move upward about 400 m, and the AAR of the *Chhota Shigri* and Gangotri Glaciers will decrease from 0.4 to about 0.10 and 0.15, respectively. The model thus suggests that, if there is an increase of +3 °C air temperature during the summer, 80 to 90 percent of the surface area of *Chhota Shigri* and Gangotri Glaciers will be in the ablation area and therefore in the process of melting. This will further increase the meltwater discharges, rapid shrinkage, and rapid snout recession already seen at the end of the last century. Increases in the size and number of glacier lakes in the Himalaya clearly reflect the increasing influence of global climatic changes in the region.

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