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CHAPTER 26

Remote sensing of rapidly diminishing tropical glaciers in the northern Andes

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ABSTRACT

This chapter presents an overview of some of the changes recently observed on glaciated areas in the tropical Andes of South America. Tropical glaciers are exceptional indicators of shifts in tropical climate, and the Andes are home to almost 99% of the world's tropical ice cover (Kaser et al. 1996). Many of the glaciated cordilleras in the northern Andes are mere remnants of what existed 50 years ago. Here we present a history of deglaciation of the Quelccaya Ice Cap in Peru, the largest body of ice in the tropics, which has lost approximately 30% of its total area in the last 35 years; the Cordillera Blanca, a glaciated range in Peru, which has lost over 20% of its area in the same period; glaciers in Colombia that have lost between 20–50% or more of their area in the last few decades; Tres Cruces, a glaciated area in Bolivia, which has lost over half of its area; and one glacier in Venezuela that has lost over 90% of its area. These changes are quite representative of overall glacier retreat throughout the tropical Andes.

26.1 INTRODUCTION

In studying Earth's changing climate, it is often difficult or impossible to decipher a signal from the noise of weather and the climate system's inherent chaotic and cyclic nature. It is therefore sometimes preferable to focus climate studies on the tropical regions, which are less affected by traveling synoptic patterns than are the higher latitudes, and more directly reflect the mean state of the climate. This is due, in part, to generally homogeneous thermal conditions that exist in the tropics because of the lack of influence of the Coriolis effect (Pierrehumbert 1995, Sobel et al. 2001). Additionally, much of the climatic activity that greatly affects humans, such as the El Niño–Southern Oscillation (ENSO), the Inter-Tropical Convergence Zone (ITCZ), and the Asian monsoon, are centered in the tropics (Thompson 2000). Tropical glaciers are exceptional indicators of environmental changes, including changes in the annual mean state of the climate, and the effects of these changes on natural systems (Thompson 2000, Kaser et al. 2010).

Careful monitoring of these ice fields and glaciers may help reveal small climatic changes that may otherwise go undetected. Accordingly, climate change signals are more readily observed in the tropics than elsewhere, and fluctuations on tropical glaciers are an ideal focus for climate reconstructions and for studies of contemporary climate change (Kaser 1999). At present, the tropics appear to be warming rapidly and are unequivocally responding to a change in the climate (Kaser et al. 1996, Thompson 2000, Thompson et al. 2000, Vuille et al. 2008).

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Tropical glaciers cover an estimated area of 2.5×10^3 km^2 or 0.016% of the total world ice cover (WGMS 1989). Of this total, Mexico hosts 11.4 km^2 of glaciers (White 2002), Africa 7.0 km^2 (Kaser and Osmaston 2002), and Indonesia 2.2 km^2 (Klein and Kincaid 2006). The remainder, nearly 99% of the total area of tropical glaciers, is in the Andes. While significantly more ice exists at higher latitudes, tropical glaciers are temperate, generally existing closer to melt threshold conditions and, accordingly, relatively small climate changes may significantly affect their mass balance. Furthermore, because tropical Andean glaciers tend to exist on steep slopes, occur in high-precipitation regions, and are mostly small ice bodies, they respond to climate changes rapidly, unlike the sluggish responses of more massive high-latitude valley glaciers (Jóhannesson et al. 1987, 1989).

The glaciers of the Andean cordilleras play a significant role as freshwater resources during the dry season ($\sim$6 months per year), in both the lowlands and altiplanos, for agriculture, drinking water, hydropower production, or mining activities (Williams and Ferrigno 1998, Carey 2005). Moreover, these glaciers have been associated with many natural disasters, which have caused material damage and thousands of casualties in several regions of these countries (Lliboutry et al. 1997, Huggel et al. 2007, Carey 2005, Kargel et al. 2011).

26.2 REGIONAL CONTEXT

Glaciers in the Andes, and elsewhere in the tropics, are generally very small. The largest tropical ice body, the Quelccaya Ice Cap, presently covers less than 45 km^2. These glaciers respond rapidly to climate forcings as they already exist right at the edges of the equilibrium line, and may exhibit an immediate response to small climate perturbations, such as can be induced by volcanic eruptions, which is clearly observable in the field.

A significant and accelerating deglaciation trend has been reported for recent decades from the high Andes and elsewhere in the tropics (Dyurgerov and, Vuille et al. 2008Meier 2000, Francou et al. 2000, Ramirez et al. 2001, Thompson et al. 2002, Paul et al. 2004, Ceballos et al. 2006, Vuille et al. 2008, Fujita and Nuimura 2011, Rabatel et al. 2013). Generally, late 20th century glacier recession has been attributed to global warming (Brecher and Thompson 1993, Thompson 2000, Vuille et al. 2000, Thompson et al. 2003). Detailed monitoring of some glaciers has led to the realization that interannual variability in mass balance is strongly modulated by ENSO through its influence on moisture variability (Wagnon et al. 2001, Francou et al. 2003, 2004). This pattern may not apply universally, however, since the influence of ENSO on mass balance is less coherent in other parts of the Andes (Kaser et al. 1990) where its influence on atmospheric moisture content is weaker (Aceituno 1988). Furthermore, in Chapter 33 of this book (“A world of changing glaciers: Summary and climatic context”), Kargel et al. show that there is a strong latitude gradient and commonly opposing signs of climate anomalies related to ENSO in the northern and southern parts of the tropical Andes.

Global temperatures and ENSO are not independent. Trenberth et al. (2002) found that ENSO indices tend to become more positive, favoring El Niño conditions, given warmer surface temperatures. Tsonis et al. (2005) suggest that it is the trend in global temperature that drives ENSO, favoring El Niño conditions when temperatures are rising, and favoring La Niña conditions when global surface temperatures are falling.

According to Vuille et al. (2008), tropical Andean glaciers are responding to a strengthening of tropical atmospheric circulation as well as warming; this strengthened circulation is having the effect of increasing precipitation at the lowest tropical latitudes, and drying the climate in the subtropics. Climate change projected this century includes accelerated warming and increased seasonality of precipitation (Christensen et al. 2007). Not surprisingly, the implications for glaciers are that they should continue to retreat.

In this chapter, we investigate several glaciated tropical areas of the northern Andes, organized into seven case studies: the Quelccaya Ice Cap, the Cordillera Vilcanota as a whole, Nevado Coropuna, the Cordillera Blanca, Colombian glaciers, Tres Cruces in Bolivia, and Venezuelan glaciers. A map of the northern Andes highlighting each of these areas is provided in Fig. 26.1.

26.3 SPECIAL TOPICS AND CASE STUDIES

26.3.1 Quelccaya, Peru

The largest single ice cap in the tropics, the Quelccaya Ice Cap (13°56′S, 70°50′W, 5,670 m asl), sits in a remote area 120 km north of Lake

Figure 26.1. Map of the study areas referred to in this chapter. Courtesy of Jefferson S. Rogers.

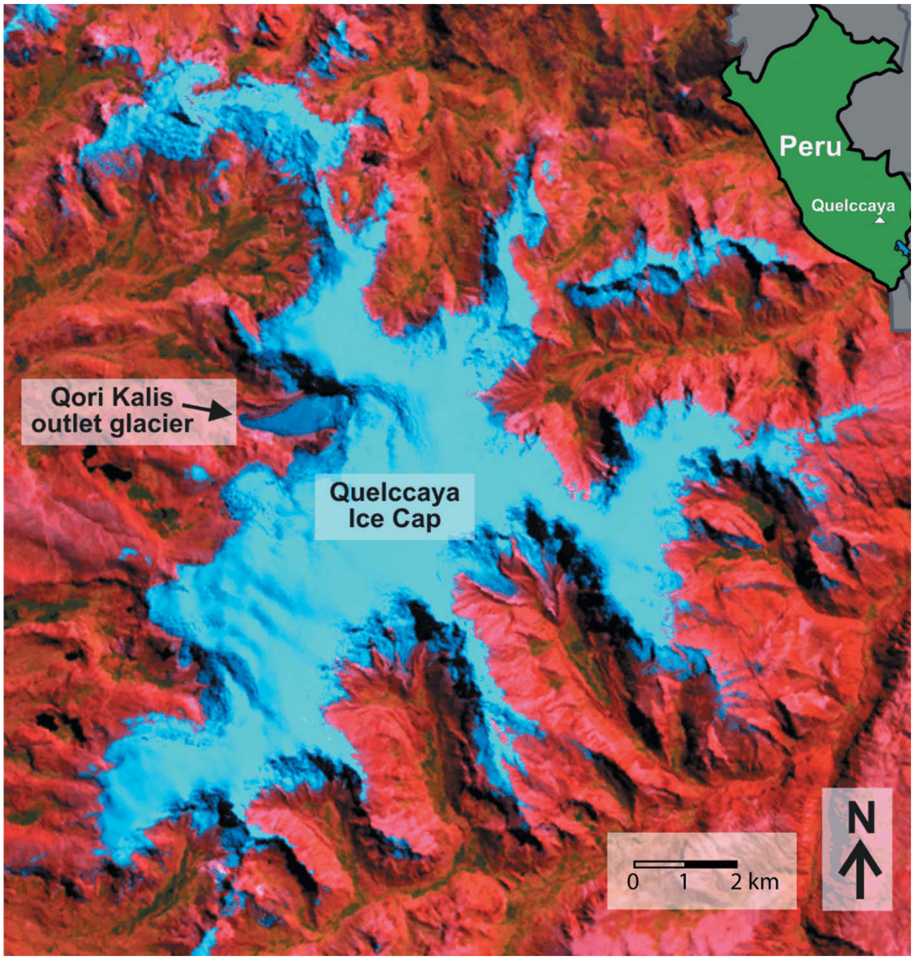

Figure 26.2. Satellite image of the Quelccaya Ice Cap from June 25, 1985. The location of the Qori Kalis outlet glacier is indicated.

Titicaca and only 40 km from the Amazon rainforest (see Fig. 26.1). From the summit of the ice cap, one can nearly distinguish the great Amazon rainforest just off to the east. In 1983 the ice cap had a measured thickness of 166 m.

Quelccaya is located in a tropical region that has a small annual temperature range yet pronounced seasonal precipitation differences (Vuille et al. 2003). Ice core data indicate that average annual accumulation on Quelccaya is 1.15 m yr^{-1} (water equivalent depth; Thompson et al. 1985). Over 80% of annual precipitation falls in the summer (November through March) when solar radiation reaching the Altiplano is most intense, contributing to the development of convective showers. Due to its dome shape, Quelccaya is very sensitive to changes in the height of the 0°C isotherm (Diaz et al. 2003).

Quelccaya's largest outlet glacier, Qori Kalis (Fig. 26.2), is a valley glacier on the west side of the ice cap. Terrestrial photogrammetry analyses since 1978 have identified accelerating rates of retreat for Qori Kalis, and have shown that it responds rapidly to climate forcings (Brecher and Thompson 1993; Thompson 2000; Thompson et al. 2000, 2003, 2006, Thompson pers. commun. 2006). These results, however, are difficult to generalize for the entire ice cap. Glaciers of varying aspects, slopes, and elevation ranges should be collectively evaluated to obtain a representative signal in the behavior of glaciers to climate forcing. Qori Kalis Glacier presents a single west-facing outlet-type glacier, which extends below the mean ice margin elevation by over 300 m, and thus experiences considerably warmer mean conditions and a different ablation regime at its terminus than most other parts of the Quelccaya ice margin.

If considered in its entirety, however, the Quelccaya Ice Cap presents an especially desirable target for studies of glacier–climate interaction. The margins of Quelccaya incorporate a broad range of topographic gradients, slopes, and aspects, so any changes in ice area that depend on these gradients will be dampened when aggregated for the entire ice perimeter. Furthermore, Quelccaya experiences high precipitation (>1,000 mm yr^{-1}), and compensating ablation primarily by melt occurs near its margins on most days throughout the year. These characteristics suggest that despite considerable inertial stability related to its large volume, the ice cap should be highly responsive to climatic variations.

Using techniques established by Albert (2002, 2007), a set of images of the Quelccaya Ice Cap spanning four decades was analyzed for ice extent area to create a history of ice extent. All known satellite images of the ice cap of appropriate spatial and spectral resolution were carefully analyzed for the presence of cloud cover or excess ephemeral snow cover, as each one is capable of obscuring the true ice extent. A total of 44 cloud-free images were collected from 1975 to 2009 and were analyzed to construct a history of ice area changes of the Quelccaya Ice Cap. Note that most images were chosen in the dry season, May through November, when there is less ephemeral snow cover to obscure actual ice cap margins. When possible, imagery was selected from the height of the dry season, June through August, when seasonal snow cover has usually ablated away to reveal the true ice extent, and snowstorms are extremely infrequent. Data include Landsat TM and ETM+, and ASTER multispectral imagery

Albert (2002) compared a series of techniques for accuracy and processing time in delineating the extent of the Quelccaya Ice Cap. The most accurate methods with the lowest costs in terms of user processing time included the widely used visible to near-infrared (VNIR) to shortwave infrared (SWIR) ratio such as TM4/TM5. These results are now widely accepted and utilized (e.g., Paul et al. 2002, 2004; see also Chapter 4 of this book entitled ''Glacier mapping and monitoring using multispectral data'' by Kääb et al.). Manual digitization was used when there was difficulty in using automated techniques (i.e., 1975) or when manual digitization had already been done for a previous study (i.e., 1985). Typically, the errors in area were small and confined to a few edge pixels of the glacier that were not consistently classified by the methods tested; they are described in detail in Albert (2002, 2008).

The ice extents derived are presented in Fig. 26.3. A consistent trend of retreat is shown for the entire period. Note that changing satellite sensors and platforms have no discernible influence on the retreat trend or on overall extent where satellite records overlap. The map presented in Fig. 26.4 illustrates changes between 1990 and 2009. Although the 2009 image contains a small number of low cumulus clouds that lead to a slightly lower classification of ice area in that image, the general trend of retreat and spatial distribution of retreat is relatively consistent for any image pairs. Retreat occurs along all margins around the ice cap. Comparison with aerial photos taken in the 1960s suggests that this retreat began around the mid-1970s.

Overall, the ice cap has retreated from 58.9 km^2 in 1975 to 40.8 km^2 in 2010, a loss of 31% or 0.88% yr^{-1}, assuming a constant loss of ice annually of 1.04% computed as ''compound interest'' losses (see Chapter 1 of this book by Zemp et al. for a description of the compound interest approach). This is one of the fastest retreat rates found throughout the tropics. This rate has not been consistent through time, though. Assuming constant areal loss for each of the studied time periods, the retreat rate varied over time from 0.39% yr^{-1} from 1975 to 1985, 1.14% yr^{-1} from 1985 to 1990, 1.76% yr^{-1} from 1990 to 1996, 0.93% yr^{-1} from 1996 to 2000, 0.17% yr^{-1} from 2000 to 2005, and 1.94% yr^{-1} from 2005 to 2010.

Perhaps the most consistent way of measuring the retreat of the Quelccaya Ice Cap, based on the linear nature of the ice area over time (shown in Fig. 26.3) is the loss in area per year. In 35 years, the ice cap has retreated by 18.1 km^2, or approximately 0.5 km^2 yr^{-1}. At this rate the ice cap would be gone in approximately 80 years or by 2090.

Variability in ice extent shown as scatter about the trend line may be attributed to several factors. First, several satellite sensors were used, including MSS, which have varying spatial and spectral resolutions. Sensors with lower spatial and/or spectral resolution produce coarser maps of ice extent and therefore higher degrees of uncertainty. Second, while images in which the ice margins were completely obscured by seasonal snows were not included in this study, some amount of ephemeral snow is unavoidable, especially along steep slopes that are not well illuminated. Excess snow around the ice edges may account for some of the variability in ice extent. Illumination problems also become an issue in steep or shaded areas. Ratio

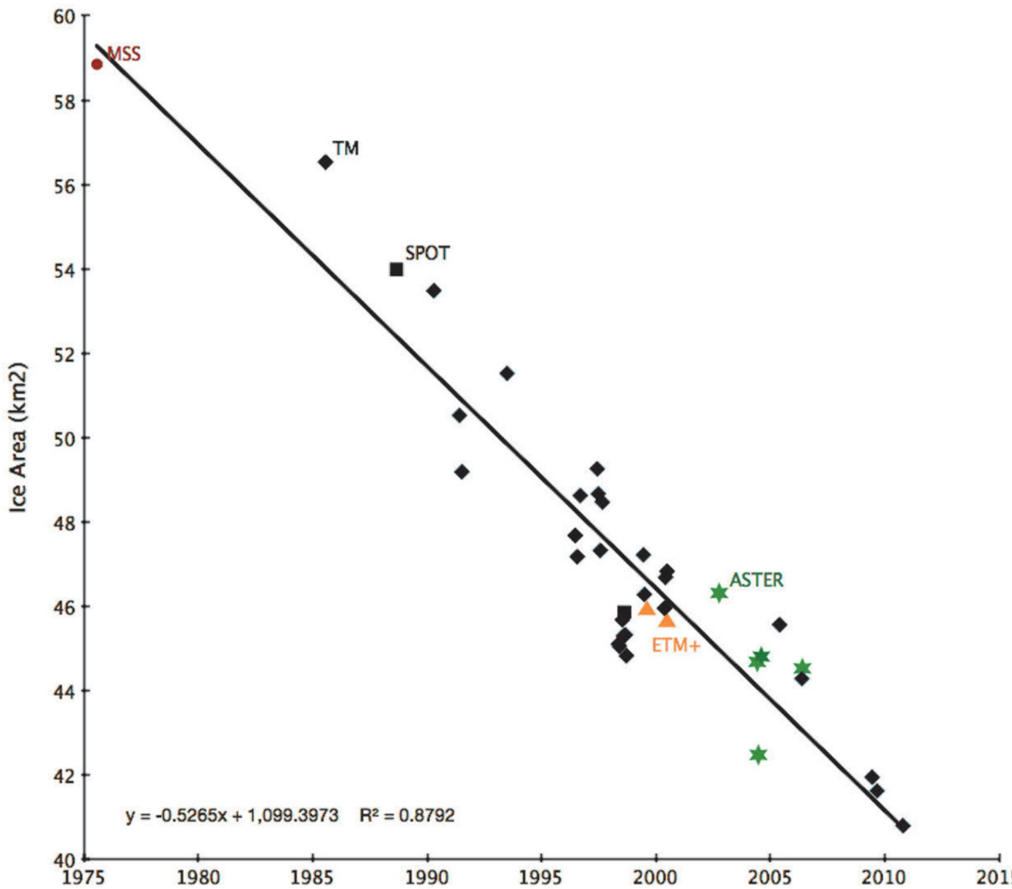

Figure 26.3. Ice extent history of the Quelccaya Ice Cap derived from satellite imagery. Satellite sensor sources are indicated by different symbols: Landsat MSS imagery in red circles, Landsat TM imagery in blue diamonds, SPOT imagery in black squares, Landsat ETM+ imagery in orange triangles, and ASTER imagery in green stars. Figure can also be viewed as Online Supplement 26.1.

images tend to reduce the effects of shading, but depressed spectral signatures are still more difficult to analyze accurately. Finally, some of the glaciers and ice margins are debris covered, leading to difficulties in separating them from the surrounding soil (arising again from variable sensor-dependent capabilities).

Overall, this ice extent history matches what has been observed in the field by Lonnie Thompson and Henry Brecher since the mid-1970s, including the two periods of limited retreat in 1992–1993 and 1999–2001.

26.3.2 Cordillera Vilcanota, Peru

The last two decades in Peru have been characterized by demographic growth and rising water demand for agriculture and domestic and economic activities, which have generated increasing pressure on water resources and conflicts within and among several provinces. During this period, glacier retreat in conjunction with climate change has decreased the hydrologic reserves provided by glaciers.

In 1970, Peruvian glaciers covered an area of some 2,041.85 km^2; the entire Cordillera Vilcanota had a surface of 418 km^2 (20.5% of Peruvian cordilleras), representing the largest freshwater reserve in the country. Coropuna (see next section) had a surface area of 82.7 km^2 (4%; Ames et al. 1988). Since then, glaciers have retreated considerably due to global climate change.

Within the framework of the Program on Climatic Change Adaptation in Peru (PACC; *Programa de Adaptación al Cambio Climático en el Perú*), supported by the Swiss Agency for Development and Cooperation (SDC), the study in the Cordillera Vilcanota (Cusco region) aims at mapping multitemporal hydrologic reserves according to watershed area. The aim is to support Peruvian institutions to establish a sustainable water man-

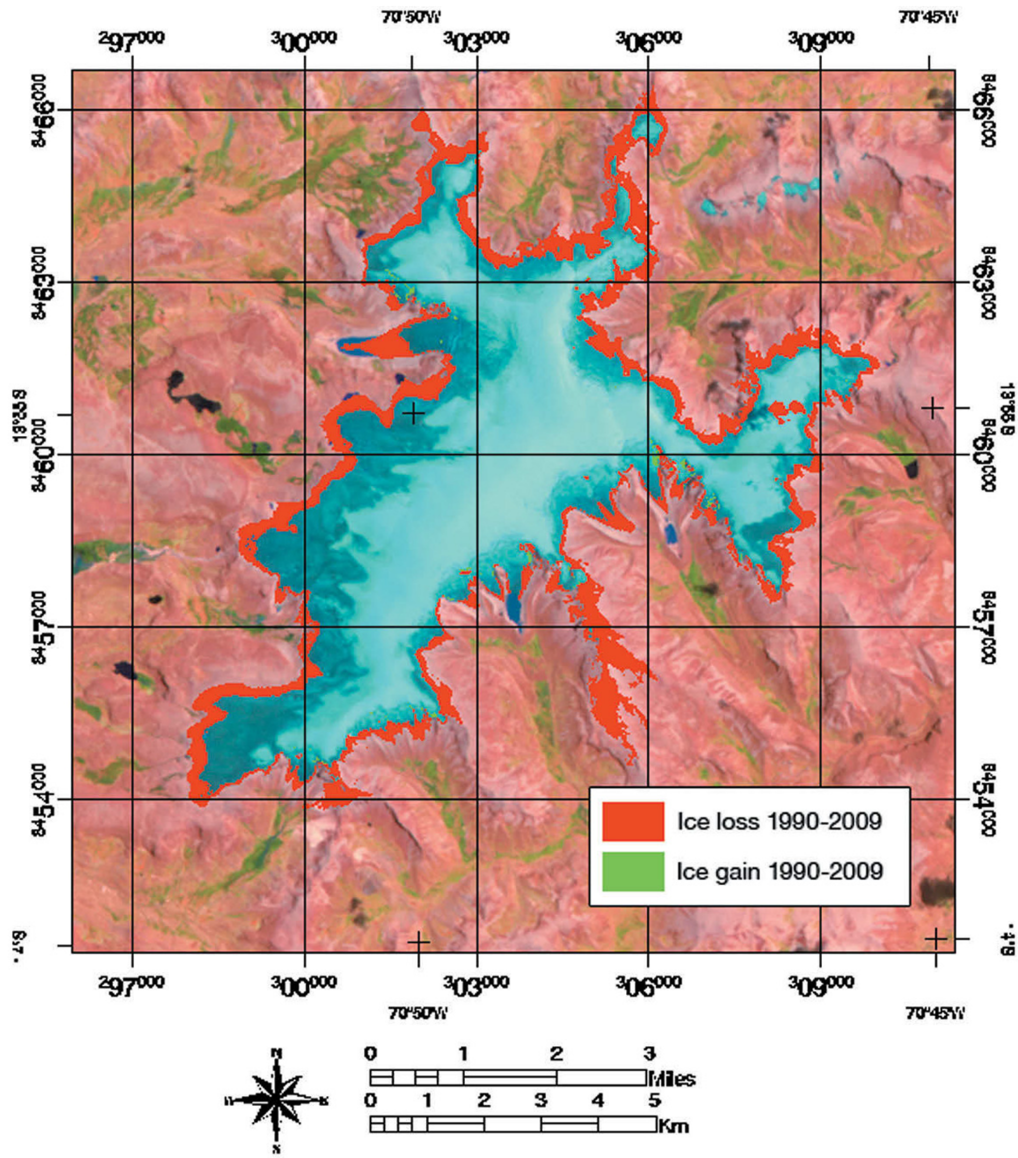

Figure 26.4. Map of Quelccaya Ice Cap, showing also its ice loss derived from a 1990 Landsat TM image and a 2009 TM image. Red areas represent ice loss or, more specifically, areas that were classified as ice in 1990 but not in 2009. Green areas represent ice gain, or areas that were classified as ice in 2009 but not in 1990. Figure can also be viewed as Online Supplement 26.2.

agement policy, which is one of their policies on climatic change adaptation.

The Cordillera Vilcanota is located between 13°26′–14°13′S and 70°37′–71°38′W, between the Andean Departments of Cusco and Puno (Fig. 26.1). According to Ames et al. (1988), based on 1962 aerial photos, Cordillera Vilcanota had 469 glaciers and its glaciated area represented 418.43 km^2. Drainage is eastward to the Atlantic Ocean via Río Vilcanota, Río Paucartambo, Río Inambari, and Río Madre de Dios. The highest mountain is Nevado Ausangate at 6,384 m asl (Williams and Ferrigno 1998).

The glacial cover of the Cordillera Vilcanota was assessed using Landsat 5 TM images of July 25, 1985, July 23, 1996, and August 4, 2006. Results showed that in 1985, 1996, and 2006, Vilcanota had a glacial surface of 443.6 km^2, 343.7 km^2, and 296.6 km^2, respectively (Fig. 26.5).

According to Fig. 26.5, between 1985 and 1996 the loss was 99.9 km^2 (with a mean retreat of 9 km^2 yr^{-1} or a compound interest percentage loss of

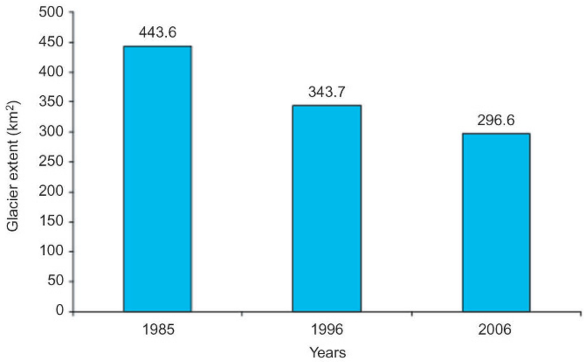

Figure 26.5. Glacial cover of the Cordillera Vilcanota between 1985 and 2006.

2.29% yr^{-1}), and between 1996 and 2006 it was a loss of 47.1 km^2 (-4.7 km^2 yr^{-1} or -1.46% yr^{-1}). The results indicate that the maximum rate of retreat occurred during the 1980s and 1990s; the same maximum rate periods are also observed in Nevado Coropuna (Silverio and Jacquet 2012). Fig. 26.6 shows the changing extent of Japujapu Glacier (13°45.77′S latitude, 71°5.40′W longitude) and Osjollo Anante Glacier (13°44.61′S latitude, 71°4.4′W longitude), between 1985 and 2006. This is an example of general glacier retreat in the Cordillera Vilcanota during the two decades.

26.3.3 Nevado Coropuna, Peru

Nevado Coropuna is located between 15°26′–15°39′S latitude and 72°30′–72°46′W longitude in the Cordillera Ampato in the Peruvian State of Arequipa (Fig. 26.7). The mountain range is approximately 15 km (east–west) long and 8 km (north–south) wide (Silverio and Jaquet 2012). It includes several summits higher than 6,000 m, its highest peak reaching 6,425 m. Coropuna drains entirely into the Pacific Ocean.

According to Ames et al. (1988), based on June 1962 aerial photos, Coropuna had 17 glaciers and its glaciated area was 82.6 km^2. Based on an ASTER image of October 14, 2000, the glacier surface was estimated to be 60.8 km^2 (Racoviteanu et al. 2007).

Based on a Peruvian topographic map (1:100,000 scale), in 1955, the glacial cover of Coropuna was 122.7 km^2. As measured from a Landsat 2 MSS image of July 30, 1975, this surface had reduced to 104.7 km^2, and by August 1, 1985, Landsat 5 MSS images indicate it was further reduced to 96.4 km^2. Based on Landsat 5 TM images of August 31, 1996 and September 4, 2003, the glacier surface of Coropuna was estimated to be 63.5 and 56.4 km^2, respectively (Silverio and Jaquet 2012).

Between 1955 and 2003, Coropuna lost 66.3 km^2 of its glacial cover, which represents a mean retreat of 1.4 km^2 yr^{-1}, or a loss of 54% in 48 years or averaging 1.61% yr^{-1} according to the compound interest formulation (Fig. 26.7). However, nominal data suggest that the loss rate was neither a steady area loss per year nor a steady percentage loss. Rather, a maximum rate of retreat may have occurred during the 1980s and 1990s, a phenomenon probably linked to precipitation deficit during El Niño 1983 and 1992 events (Silverio and Jaquet, 2012). The satellite record of retreat (1975–2003) shows a marked retreat averaging 1.72 km^2 yr^{-1} or about 2.19% yr^{-1} (Fig. 26.7).

26.3.4 Cordillera Blanca, Peru

There is urgency in using new remote-sensing tools to derive glacier datasets in a cost-effective and timely manner for remote glacierized areas with limited field measurements, such as the Cordillera Blanca of Peru. Tropical glaciers in the Cordillera Blanca are of interest because of rapid melting reported in the last two decades (Kaser et al. 1990). A glacier inventory for the Cordillera Blanca was compiled on the basis of 1962 and 1970 aerial photos (Ames et al. 1989). Subsequently, more recent Landsat and SPOT satellite images were used to estimate the change in glacier extent in the Cordillera Blanca at different scale and time steps (Georges 2004, Kaser et al. 1996, Silverio and Jaquet 2005). However, there remains a paucity of information on glacier parameters such as hypsometry, size distribution, and termini elevations, due to lack of reliable elevation data from which these parameters can be extracted. Updated glacier parameters are needed to assess the spatial patterns of glacier change for the Cordillera Blanca, and are the focus of this study.

Racoviteanu et al. (2008) present glacier changes from 1970 to 2003 in the Cordillera Blanca of Peru (8°30′S, 77°W) estimated from 2003 SPOT-5 satellite data and 1970 aerial photos. New glacier outlines were constructed for 2003 and compared with an older inventory constructed from 1970 aerial photos. Geographic information system (GIS) methods were used to perform spatial analyses at different scales, and to update the glacier statistics for the entire Cordillera Blanca. Based on classification of two SPOT-5 satellite images, the glacierized area of the whole Cordillera Blanca

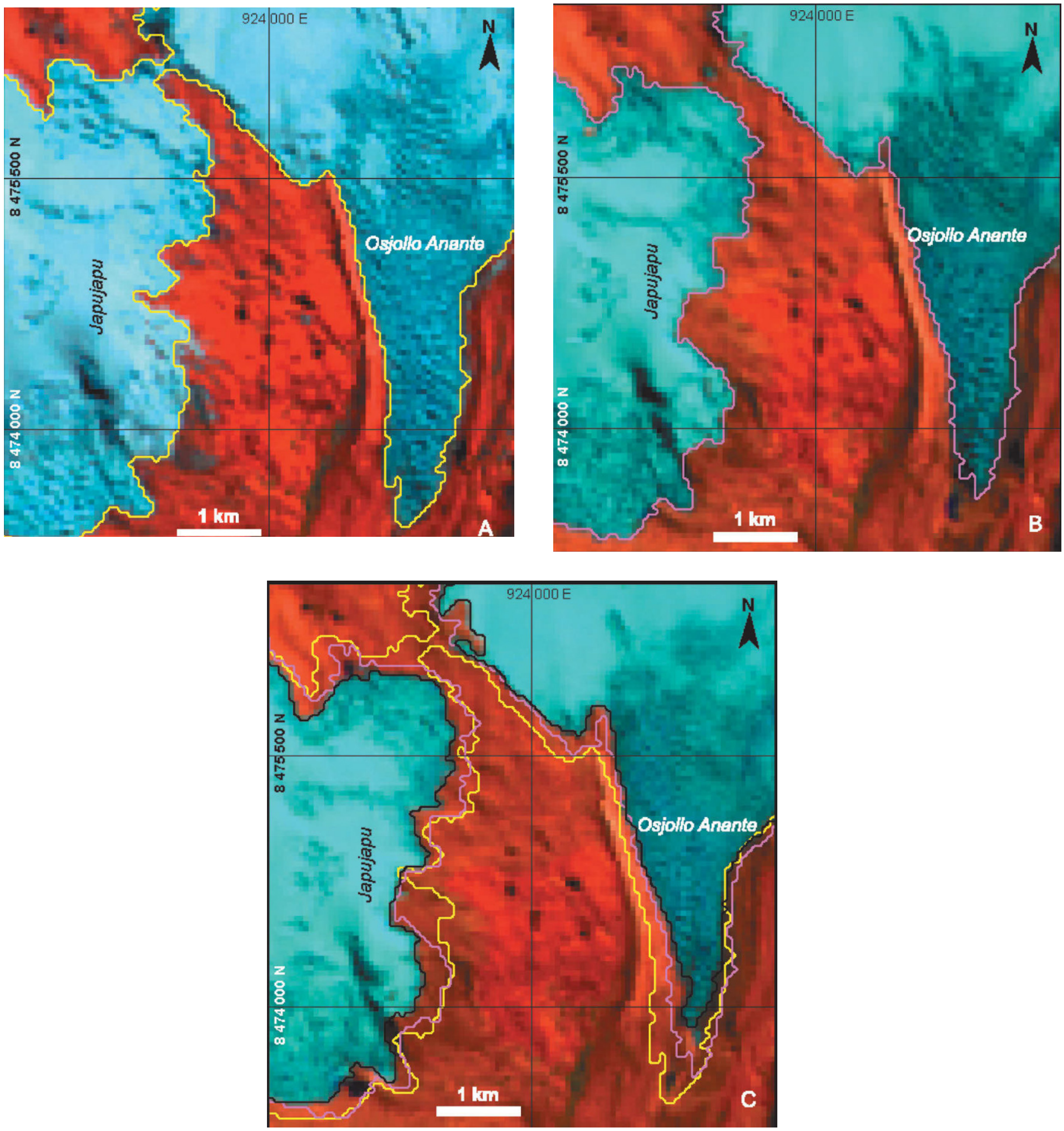

Figure 26.6. Situation of Japujapu Glacier and Osjollo Anante Glacier in (A) 1985, (B) 1996, and (C) 2006. Extent changes between 1985 (yellow outline), 1996 (purple), and 2006 (black) are shown in panel (C). Images are georeferenced to the Universal Transverse Mercator, zone 18 south.

was estimated to be 568 km^2 in 2003. This indicates a loss in glacier area of -22.4% from 1970 to 2003, which averages to a rate of area loss of 0.67% yr^{-1} in the last three decades. The number of glaciers increased due to disintegration of ice into smaller parts. For the suite of glaciers analyzed since 1970, glacier termini elevations rose by a mean of +113 m while median elevation rose by +65 m, showing a shift of glacier ice to higher elevations, with bigger shifts for glaciers on the eastern side of the Cordillera. Annual air temperature has shown a significant rising trend in the last 30 years, with larger temperature increases at lower elevations, along with a slight decrease in precipitation. Geospatial inventory datasets derived from SPOT-5 are in the public domain in the Global Land and Ice Measure-

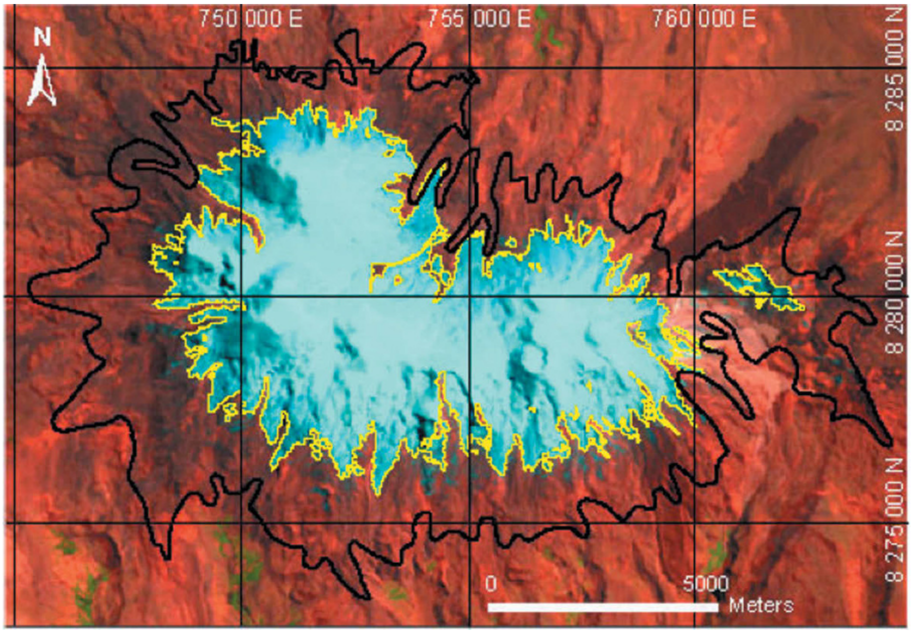

Figure 26.7. Nevado Coropuna glacial cover between 1955 (black contour) and 2003 (yellow contour; georeferenced to the Universal Transverse Mercator, zone 18 south).

ments from Space (GLIMS) Glacier Database (*www.glims.org*) maintained at the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado (Racoviteanu and Arnaud 2005).

This research combines data from SPOT and older aerial photos with GIS analyses to understand the spatial patterns of glacier fluctuations in the Cordillera Blanca at the decadal scale (Racoviteanu et al. 2008). The Cordillera Blanca (Fig. 26.8) is the largest glacierized area in the tropics, stretching 180 km north–south between 8°30′ and 10°S latitude (Kaser et al. 1990). The glacierized area was estimated to be 723.37 km^2 based on 1962/1970 aerial photos (Ames et al. 1989). Elevation ranges from ~3,500 to ~6,800 m, and some glaciers have debris-covered tongues. There is an absence of thermal seasonality, although there is a wet season from October through May and a dry season from May to September. Accumulation occurs mostly during the wet season, and there is ablation all year round (Kaser and Osmaston 2002). Southeasterly winds bring precipitation from the Amazon, making the windward (east side of the cordillera) much wetter than the leeward (west) side.

Data sources for this study included: (1) two 1:100,000 topographic maps constructed from 1962/1970 aerial photos; (2) a digital elevation model (DEM) with 30 m postings created from contour lines based on the topographic maps; (3) two SPOT-5 scenes (10 m VNIR spatial resolution) acquired at the end of the ablation season in August 2003, which covered more than 90% of the Cordillera Blanca; (4) a DEM derived from the SRTM for 2000; and (5) 54 GCPs acquired with a differential GPS on nonglacierized terrain. The vertical accuracy (root mean square error in the vertical coordinate, $RMSE_Z$, with respect to the GCPs) of the DEM was 18 m. Four mountain groups (Pongos and Caulliraju in the south and Roscos and Pelegatos in the north) were outside the SPOT scenes.

We used the Normalized Difference Snow Index (NDSI; Hall et al. 1995) with SPOT channels 1 (visible) and 4 (mid-infrared) and applied a segmentation threshold of 0.5 to extract the ice-covered area. Debris-covered glaciers were digitized manually using a slope map and color composite maps (SPOT 234). We derived glacier parameters (glacier area, minimum, maximum and median elevations, mean slope angle, and mean aspect) using grid-based modeling and zonal functions in ArcInfo. Total accuracy of glacier outlines (including geolocation and glacier delineation errors) was estimated at ±15 m. We selected 367 glaciers whose ice divides in 2003 matched closely with those from the 1970 inventory, and investigated the changes in area and glacier size, orientation, slope, and location using regression analysis and GIS.

Classification of the two SPOT-5 scenes yielded 480 glaciers, covering an area of 516.1 km^2.

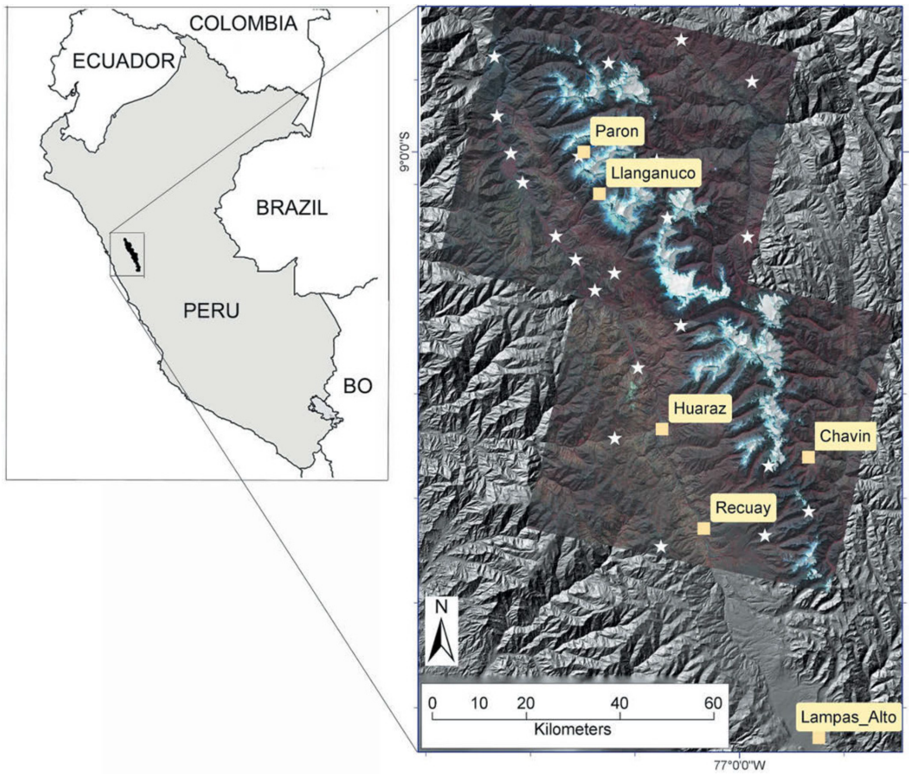

Figure 26.8. The Cordillera Blanca study area showing the two orthorectified SPOT scenes from August, 2003. The images are shown as color composites using bands 1, 2, and 3 on shaded (SRTM) topography. Also shown are the 24 ground control points (GCPs) acquired with a differential GPS (white stars). Figure can also be viewed as Online Supplement 26.3.

Descriptive statistics of the 480 glaciers derived from SPOT imagery and from the digital version of the 1970 inventory are presented in Table 26.1. Debris-covered glaciers covered an area of 14.9 km^2 (2.9% of the total glacierized area). On the area covered by the satellite image, we calculated an overall factor of recession of 516.1 km^2/665.1 km^2= 0.77. Using this recession factor, we estimate the glacier area for omitted mountain groups to be 53.8 km^2. After adding these glaciers to the area covered by SPOT imagery, the glacier area for the entire Cordillera Blanca is estimated to be 569.6 km^2 in 2003. Compared with 723.37 km^2 reported by Ames et al. (1989) for 1970, this indicates a retreat of ~21.3% in 33 years, averaging 4.7 km^2 per year assuming a constant annual loss. If only those parts of the range mapped in both inventories are included, ice loss over the same period is 22.4% (Table 26.1). If, instead, ice loss is computed using a compound interest formulation, the mean loss rate compounded over the 33-year period is 0.72% yr^{-1}.

In 2003, the elevation of glacier termini ranged from 4,204 to 5,369 m, with a mean of 4,881 m. On average, glacier termini are 102 m higher on the western slope of the Cordillera (4,914 m) than on the eastern slope (4,812 m). This is because glaciers on the eastern side of the Cordillera Blanca extend to lower elevations, under the influence of moisture from the Amazon. Glaciers in this area typically have a southwest aspect (193°), reflecting the preferential growth of glaciers in areas with south and west orientations, which are more shaded during the wet (accumulation) season (Mark and Seltzer 2005). Average glacier size in 2003 is 1.07 km^2.

An example of glacier change from 1970 to 2003 in the Huascarán–Chopicalqui massif is shown in Fig. 26.9. Comparison of glacier statistics in 1970 and 2003 shows that the number of glaciers increased from 445 to 480 due to the disintegration of ice bodies and downwasting of glaciers (Table 26.1). Similar trends have been observed in other glacierized areas (e.g., Paul et al. 2004). The decrease in glacier area and the shift of glacier ice to higher elevations is evident when 1970 hypsography is compared with 2003 hypsography (Fig. 26.10).

Table 26.1. Comparison of IGN 1970 and SPOT 2003 glacier inventories. Glacier elevations were extracted from the DEM for both the IGN 1970 and SPOT 2003 inventories.

	Minimum	*Maximum*	*Average*	*Total*
IGN 1970				
Minimum Z (m)	4,127	5,370	4,750	
Medium Z (m)	4,328	5,557	5,086	
Slope	13	48	31	
Aspect (deg)	0	359	187	
Area (km^2)	0.03	18.44	1.48	
Number of glaciers				445
1970 area (km^2) (excluding Pongos, Caulliraju, Roscos, and Pelegatos)				665.1
1970 area (km^2) (including Pongos, Caulliraju, Roscos, and Pelegatos)				723.37
SPOT 2003				
Minimum Z (m)	4,204	5,369	4,881	
Medium Z (m)	4,420	5,695	5,150	
Area (km^2)	0.006	16.17	1.07	
Slope	12	52	32	
Aspect (deg)	0	359	193	
Number of glaciers				480
2003 area (km^2) (excluding Pongos, Caulliraju, Roscos, and Pelegatos)				516.1
2003 area (km^2) (including Pongos, Caulliraju, Roscos, and Pelegatos)				569.6
Percent area change 1970–2003				22.4

For the subset of 367 glaciers selected for detailed analysis, we found that, on average, glacier termini shifted upwards by 113.4 m, with a rise of 38% more (+136.7 m) on the eastern side of the divide than on the western side (+99.4 m). Median elevations increased by 65.6 m on average, with 10% more on the eastern side (+69.3 m) than on the western side (+63.2 m; Table 26.2). This indicates that glaciers reaching lower altitudes on the wetter eastern side are showing more pronounced shifts to higher elevations. However, there was no significant difference in the loss in glacier area from 1970 to 2003 between the eastern and the western side of the Cordillera Blanca (Table 26.2).

The linear rate of glacier change of $-0.68\%\ \mathrm{yr}^{-1}$ (1970–2003) derived in this study is consistent with trends noted in previous studies in the Cordillera Blanca (Table 26.3), as well as with the behavior of other tropical glaciers including Nevado Coropuna ($0.7\%\ \mathrm{yr}^{-1}$ from 1962 to 2000; Racoviteanu et al. 2007) and Qori Kalis Glacier ($0.6\%\ \mathrm{yr}^{-1}$; Thompson et al. 2006) in the southern Peruvian Andes; Mt. Kilimanjaro ($1.15\%\ \mathrm{yr}^{-1}$ from 1970 to 1990) and Mt. Kenya in the East African mountains (0.8%

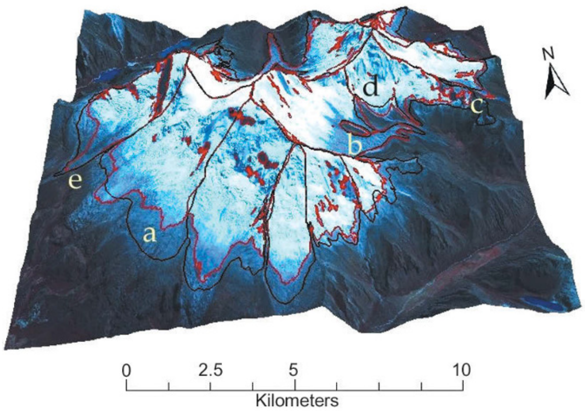

Figure 26.9. Glacier change in the Huascarán–Chopicalqui massif estimated from the 1970 digital inventory and 2003 SPOT-5 imagery. Assuming constant area loss each year, glaciers in this area have retreated at a rate of 0.45% yr^{-1} in the last three decades. The number of glaciers has increased from 18 to 26, indicating that some glaciers split to make smaller ones. Figure can also be viewed as Online Supplement 26.4.

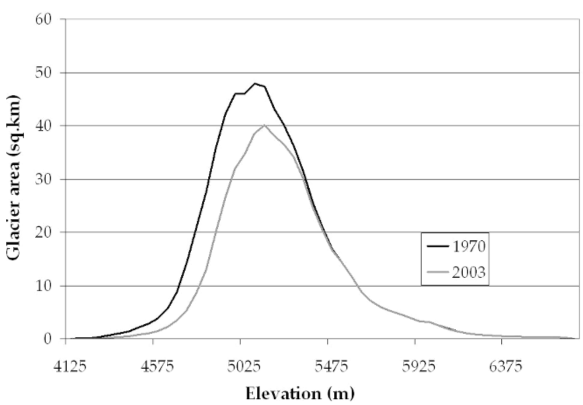

Figure 26.10. Histogram of elevation differences over the Cordillera Blanca derived from SRTM elevation data and 1970 and 2003 glacier outlines. The decrease in glacier area and the shift of glacier ice to higher elevations is evident.

yr^{-1} from 1963 to 1993; Kaser 1999). In addition, our results point to the rate of ice loss accelerating by a factor of +2.5 times in the last decade compared with the 1970s through the 1990s (Table 26.3). This is consistent with trends reported from other areas (Khromova et al. 2006, Thompson et al. 2006). Francou et al. (2000) found that the ablation rates of low-latitude glaciers have increased fivefold in the last decade with respect to former decades, suggesting that low-latitude glaciers experience faster changes in area.

Table 26.2. Glacier elevation and area changes from 1970 (IGN digital inventory) to 2003 (SPOT-derived glacier outlines) for 367 selected glaciers with the same ice divides in both inventories

	Number of glaciers	*Area change* (%)	*Median elevation change* (m)	*Termini elevation change* (m)
Eastern CB	135	−21.9	+60.4	+136.76
Western CB	232	−22.2	+63.2	+99.4
All glaciers	367	−22.1	+65.6	+113.4

CB = Cordillera Blanca.

The sources of uncertainty in glacier change analysis arise from: (1) image classification errors; (2) geolocation errors; (3) the quality of the baseline data used; (4) inconsistencies in how glacier boundaries and ice divides were delineated in the various datasets; and (5) the quality of elevation data used for the analysis. The main problems we encountered were:

- The processing methods used to derive glacier outlines from multitemporal data were not standardized, leading to inconsistencies in the various datasets compared.
- Any estimate of glacier change is highly sensitive to the accuracy of the baseline used. Georges (2004) revised 1970 glacier extents and derived a glacier area of 658.6 km^2 instead of 723.3 km^2 reported in Ames et al. (1989). If we compare our results with the reanalysis done by Georges (2004), we obtain a change in area from 1970 to 2003 of only 14%.
- Ice divides have been defined differently in the various datasets. For example, there were discrepancies in the 1970 glacier areas reported in the published version of the IGN inventory (Ames et al. 1989), the digital version used in this study, and a reanalysis done by Georges (2004). Previous inventories (Georges, 2004) excluded inactive parts at the heads of glaciers, whereas our study included them. Our SPOT ice divides, derived by semiautomatic methods, did not match ice divides from the 1970 inventory perfectly, which made area comparison difficult.
- Additional uncertainties could arise because 1970 extents were derived from aerial photos acquired in 1962 and 1970.

Table 26.3. Estimates of ice extent for the entire Cordillera Blanca from previous studies based on aerial photos and satellite images. The rate of change is given with respect to 1970 IGN baseline data published in Ames et al. 1989.

Year	*Study*	*Area* (km^2)	*Data source*	*Rate of loss since 1962/1970* (% yr^{-1})	*Compound interest loss* (% yr^{-1})
1970	Ames et al. (1989)	723.37	1962/1970 aerial photos	—	
1970	Georges (2004)	658.6	Reevaluation of 1962/1970 aerial photos	—	
1986	Silverio and Jaquet (2005)	643	1986 Landsat	0.69	0.73
ca. 1990	Georges (2004)	618.8	1987/1991 SPOT XS	0.72	0.79
ca. 1997	Morales Arnao (1998)	611	1995/1997 Landsat	0.58	0.62
1997	Silverio and Jaquet (2005)	600	1997 Landsat	0.67	0.69
2003	This study	569.6	2003 SPOT-5	0.68	0.72

Remote-sensing data combined with GIS techniques were useful in assessing changes in glacier parameters (size, slope, orientation, glacier termini, and median elevation). We estimate that glaciers in the Cordillera Blanca lost ~22.4% of their area from 1970 to 2003, with an upward shift of glacier ice to higher elevations and an acceleration in glacier loss in the last decade. Inconsistencies among previous datasets made the one-on-one comparison of glacier change difficult, and they highlight the need for standardized processing methods as well as careful field verification. Remotely sensed data must be used with care in mountain areas, since topographic effects play an important role, and introduce difficulties in image interpretation. The classification method based on the NDSI reduces the problems induced by solar illumination and slope effects, but shadows still remain problematic. Further steps are needed to minimize the large differences between comparisons of glacier areas derived from diverse satellite data and those from old aerial photos or field surveys. These steps include using the same assumptions and definitions of the makeup of a glacier, establishing methods for debris cover delineation, and using automatic methods for ice divides. Once these procedures are in place, further work can be undertaken toward using multitemporal glacier datasets for glacier change detection at higher time resolution as well as for mass balance applications.

26.3.5 Colombia

Most Colombian glaciers extend along a north–south transect from Sierra Nevada de Santa Marta on the Caribbean coast to the south of the Cordillera Central (Fig. 26.11). Further to the east, the Sierra Nevada de El Cocuy also hosts several glaciers. In general, glaciers in Colombia can be found at altitudes higher than about 4,700 m asl, but their occurrence is dependent on local meteorological and topographic conditions. Glacierized mountain peaks reach an altitude between 5,100 and 5,700 m asl. Colombian glaciers are usually inventoried according to the mountains or mountain ranges where they exist: Sierra Nevada de Santa Marta, Sierra Nevada de El Cocuy, Nevado del Ruíz, Nevado de Santa Isabel, Nevado del Tolima, and Nevado del Huila. Glacierized areas in these mountains currently range from about 1 to 20 km^2 (Ceballos et al. 2006).

Although the total current glacierized area is small (45.3 km^2, IDEAM 2012), glaciers in Colombia are important for the local high-mountain ecosystem, for local water consumption, and for use as landmarks and tourism. Glaciers are furthermore highly relevant with respect to natural hazards. The fact that several glaciers in Colombia are located on top of active volcanoes represents large potential hazards due to possible interaction of volcanic activity with ice which may lead to devastating mass

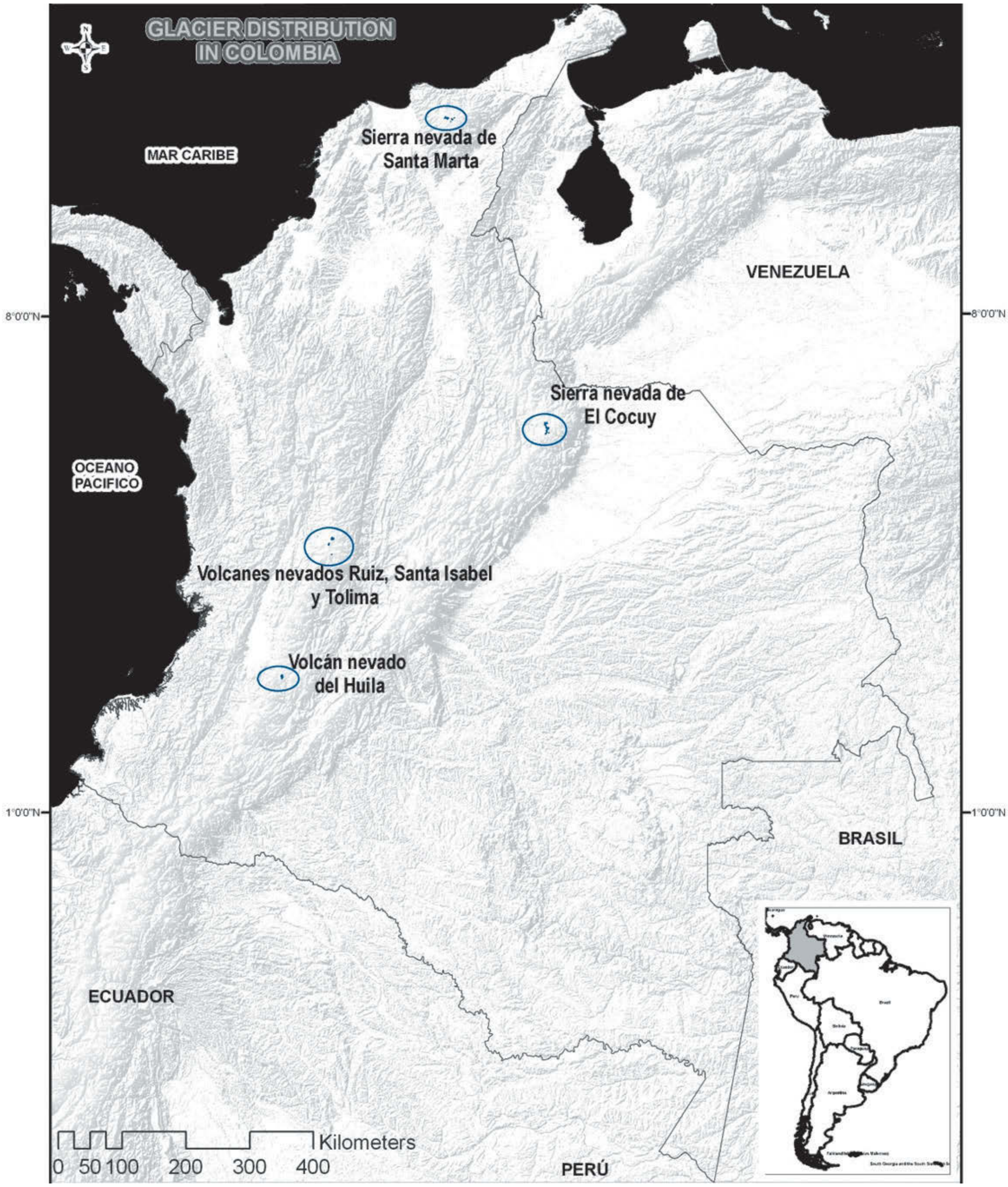

Figure 26.11. Map illustrating the location of glaciers in Colombia.

flows (Huggel et al. 2007). One of the most severe volcanic and glacier disasters occurred on Nevado del Ruíz in 1985 when a moderate-sized eruption of the volcano melted glacier ice and snow and produced lahars (volcanic mudflows) which destroyed the town of Armero and killed more than 20,000 people (Thouret 1990).

In accordance with observations in other tropical regions, glaciers in Colombia have undergone significant retreat in the past several decades. The low elevation of mountain summits relative to the elevation of the 0°C isotherm, coupled with consequently small accumulation areas, makes glaciers in Colombia particularly vulnerable to climate

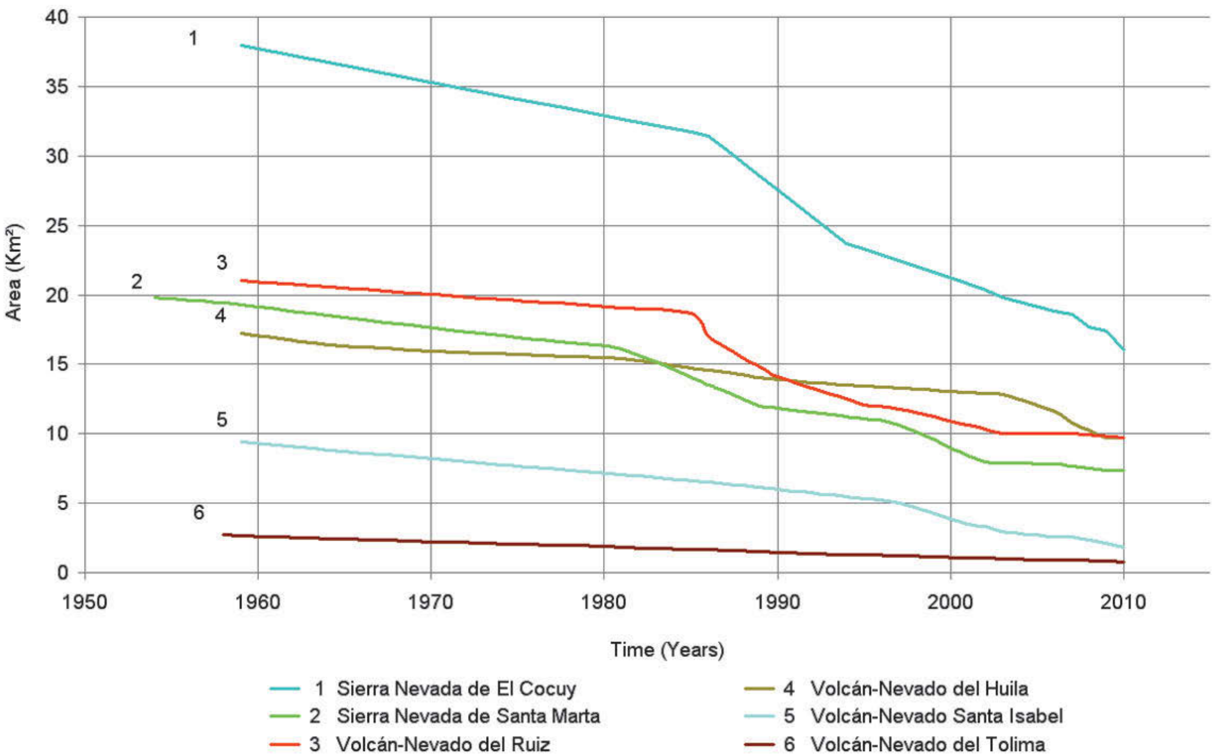

Figure 26.12. Glacier area change over recent decades of ice-capped volcanoes in Colombia.

change. Since the Little Ice Age maximum around 1850 to 1880 when glaciers occupied a total area of ca. 374 km^2, eight glacierized areas have been doomed to extinction (Flórez 1992). For the 20th century, measurements show dramatic glacier recession, in particular from the mid-1980s up to the present (Fig. 26.12 and Table 26.4). The regions most affected by glacier shrinkage are the Sierra Nevada de Santa Marta and Nevado de Santa Isabel. In the first area, a loss of area of 50% has been observed over the last 20 years, while the latter area showed a 50% loss over an even shorter period (15 years). The Sierra Nevada de El Cocuy, Nevado de Tolima, and Nevado del Ruíz lost considerable glacier area (35–45%) over the last 15 to 17 years of the 20th century. The ice masses on Nevado del Ruíz were additionally affected by the 1985 volcanic eruption noted above. Glaciers on Nevado del Huila showed comparable moderate glacier shrinkage with about a 20% loss in the last 20 years up to 2007. However, volcanic eruptions that started in February 2007 significantly affected the glaciers and caused an additional loss of glacier ice. In the last $\sim$20 years the average shrinkage rate of Colombian glaciers has been between 2 and 4.5% yr^{-1} with total area loss of between 40 and 60%. Precipitation, and hence accumulation, in this region is also affected by ENSO, as illustrated in Fig. 23.13 for the 1997–1998 El Niño event.

Glacier length change measurements conducted since the 1980s reveal a similar trend of rapid glacier retreat. On Nevado de Santa Isabel, glacier termini retreated between 170 and 250 m over 15 years (1988 to 2003), which results in a mean annual retreat rate of 12 to 16 m respectively (Fig. 26.14). In the Sierra Nevada de El Cocuy which contains a total glacier area approximately six times larger than Nevado de Santa Isabel, longitudinal retreat at some glacier tongues has reached close to 500 m over the last 18 years (Fig. 26.15).

Ice thickness measurements were occasionally performed on the Ruíz, Tolima, and Santa Isabel volcanoes as part of volcanic monitoring. The most extensive ground-penetrating radar (GPR) measurements were carried out on Nevado del Ruiz in 1999 and showed a maximum and average ice thickness of 190 and 47 m, respectively. Similar studies were conducted on Nevado de Santa Isabel and Nevado del Tolima in 2000 and 1998, respectively, with reported ice thickness of 60 m (maximum thickness 103 m) for Santa Isabel and 70 m (maximum thickness 170 m) for Tolima (Huggel et al. 2007). New measurements on Nevado de Santa Isabel in 2008 indicated reduced mean thickness of about 48 m. We will make some final remarks about the negative balance of Santa Isabel Glacier in the Discussion.

The main agencies involved in glacier monitoring in Colombia are the Institute for Hydrology, Meteorology and Environmental Studies (IDEAM) and the Servicio Geológico Colombiano (formerly INGEOMINAS). In recent years, major efforts have been made to better integrate Colombia's glaciers into international monitoring programs. Cooperation between Colombia and Switzerland, involving the World Glacier Monitoring Service (WGMS), has prompted the initiation of glacier mass balance measurements on Santa Isabel. The small ice cap on this inactive volcano has several outlet glaciers, and one of them, Conejeras, was selected for mass balance studies (Fig. 26.14). Results of the first four years of measurements corroborate considerable glacier shrinkage as measured in length and area changes.

In accordance with international programs, glacier monitoring in Colombia follows a strict procedure that involves: (1) glacier inventory studies for all glacierized areas with repeat rates of 5–10 years (in some areas reduced to 2–5 years); (2) glacier length observations on selected glaciers (e.g., Sierra Nevada de El Cocuy, Nevado de Santa Isabel, and Nevado del Ruíz); and (3) mass balance studies on a defined catchment (Conejeras on Nevado de Santa Isabel). Satellite remote sensing is a fundamental component of inventory studies with imagery typically acquired from sensors on board ASTER, Landsat TM and ETM+, SPOT, and ALOS since 2008. A repeat period of 2–5 years should normally not pose any difficulties for obtaining feasible satellite images. In an equatorial region such as Colombia, however, cloud cover is a persistent feature and may well entail several years without appropriate satellite cover. This is particularly true for the glaciers in the Cordillera Central (Ruíz, Santa Isabel, Tolima, and Huila).

Satellite remote sensing is an important tool for monitoring the ice-capped volcanoes of Colombia. The 1985 Nevado del Ruíz catastrophe attracted a lot of scientific and public interest in volcano–glacier hazards. The glaciers of Nevado del Ruíz have also been monitored more recently (e.g., the ASTER images of March 2003 and 2005; Thouret et al. 2007). An international project to give early warning of hazards from Nevado del Tolima provided ground-based and satellite measurements that enable determination of volcanic activity and glacier changes. Of particular interest is Nevado del Huila, the southernmost ice-capped volcano of the Cordillera Central. This volcano has been dormant for several hundred years without any historically documented eruption activity, but began to erupt on February 19, 2007, with subsequent eruptions in April 2007 and November 2008. Due to its extensive glacier area, Huila represents a severe threat to population centers along its main drainage basins. In fact, the early-2007 and late-2008 eruptions were accompanied by floods and debris flows along the Paéz river, probably resulting from a mixture of pyroclastic debris, melting snow and ice, and additional water from hydrothermal reservoirs. Difficult access and the presence of guerrilla forces in this region make satellite images the primary monitoring tool. In the course of the February 2007 eruption the ASTER sensor was programmed to capture Nevado del Huila. A QuickBird image from the same period allowed detailed investigation of its glaciers.

26.3.6 Tres Cruces, Bolivia

Bolivia is second only to Peru in its areal coverage of tropical glaciers. Recent estimates (Kaser and Osmaston 2002) indicate Bolivia hosted approximately 572 km^2 of ice ca. 1980. With the exception of approximately 10 km^2 of glaciers in the Cordillera Occidental (Jordan 1998), the vast majority of the total glacier area was found in the Cordillera Oriental (eastern Cordillera). The Cordillera Oriental comprises two large cordilleras—Apolobamba and Real—and the smaller cordillera of Tres Cruces (Quizma Cruz) which includes two adjacent small massifs: the Cordillera Choquetanga and Nevado Santa Vera Cruz (Fig. 26.16), which are of interest here.

The glaciers on Tres Cruces and the two smaller massifs represent the southernmost tropical glaciers found along the eastern margin of the Andes. In the mid-1980s, these areas hosted approximately 35 km^2, or 6% of Bolivia's glacier cover as determined from Landsat TM images. While glaciers in the area are not extensive, the area's geographic location at the southernmost margin of tropical glaciers in the eastern Andes makes it of interest. In addition to the satellite-based estimates of glacial changes presented here, other recent studies have also employed remote sensing to examine the area's glaciers (Ribeiro et al. 2005, 2007). These studies also demonstrate a reduction in glacier area, although the exact geographic extent covered in the analyses is unclear.

Table 26.4. Change in glacier extent for selected glacier areas in Colombia.

Glacier mountain range	*Year*	*Area* (km^2)	*Loss between periods* (km^2)	*Annual loss* (km^2)	*Retreat rate compound interest* (% yr^{-1})
Sierra Nevada de Santa Marta	1850	82.6			
			61.2	0.687	−1.50
	1939	21.4			
			2	0.133	−0.65
	1954	19.4			
			3.3	0.122	−0.69
	1981	16.1			
			4.1	0.512	−3.61
	1989	12			
			0.9	0.15	−1.29
	1995	11.1			
			2.72	0.39	−3.94
	2002	8.38			
			0.68	0.17	−1.68
	2007	7.7			
			0.3	0.15	−1.97
	2009	7.4			
			—	—	—
	2010	7.4			
			—	—	—
Sierra Nevada de El Cocuy	1850	148.7			
			109.8	1.046	−1.27
	1955	38.9			
			7.45	0.24	−0.68
	1986	31.45			
			7.75	0.97	−3.47
	1994	23.7			
			3.9	0.43	−1.98
	2003	19.8			
			1.2	0.3	−1.55
	2007	18.60			
			0.9	0.9	−4.84
	2008	17.70			
			0.3	0.3	−1.69
	2009	17.40			
			1.4	1.4	−8.0
	2010	16.00			

Glacier mountain range	*Year*	*Area* (km^2)	*Loss between periods* (km^2)	*Annual loss* (km^2)	*Retreat rate compound interest* (% yr^{-1})
Volcán Nevado del Ruiz	1850	47.5			
			26.5	0.243	−0.75
	1959	21			
			1.4	0.087	−0.43
	1975	19.6			
			0.9	0.09	−0.47
	1985	18.7			
			1.7	1.7	−9.09
	1986	17			
			2.9	0.725	−4.57
	1990	14.1			
			2.83	0.4	−2.56
	1997	11.76			
			1.44	0.28	−2.58
	2002	10.32			
			0.28	0.06	−0.5
	2007	10.04			
			0.34	0.07	−1.1
	2010	9.7			
Volcán Nevado Santa Isabel	1850	27.8			
			17	0.177	−0.98
	1946	10.8			
			1.4	0.108	−1.06
	1959	9.4			
			3	0.107	−1.36
	1987	6.4			
			1.1	0.122	−2.07
	1996	5.3			
			1.97	0.29	−7.45
	2002	3.33			
			0.73	0.18	−4.83
	2007	2.6			
			0.8	0.2	−11.5
	2010	1.8			

(*continued*)

Table 26.4 (*cont.*)

Glacier mountain range	*Year*	*Area* (km^2)	*Loss between periods* (km^2)	*Annual loss* (km^2)	*Retreat rate compound interest* (% yr^{-1})
Volcán Nevado del Tolima	1850	8.6			
			5.5	0.057	−1.06
	1946	3.1			
			0.4	0.033	−1.14
	1958	2.7			
			1.1	0.038	−1.79
	1987	1.6			
			0.42	0.042	−3.00
	1997	1.18			
			0.14	0.027	−2.53
	2002	1.038			
			0.108	0.0216	−2.17
	2007	0.93			
			0.19	0.06	−7.3
	2010	0.74			
Volcán Nevado del Huila	1850	33.7			
			16.2	0.148	−0.60
	1959	17.5			
			1.2	0.2	−1.18
	1965	16.3			
			0.9	0.056	−0.35
	1981	15.4			
			1.5	0.167	−1.13
	1990	13.9			
			0.6	0.1	−0.73
	1996	13.3			
			0.35	0.06	−0.53
	2001	12.95			
			2.15	0.39	−2.98
	2007	10.8			
			1.1		−5.23
	2009	9.7			
			0	0	0
	2010	9.7			

Total area in 2007: 49.43 km^2.

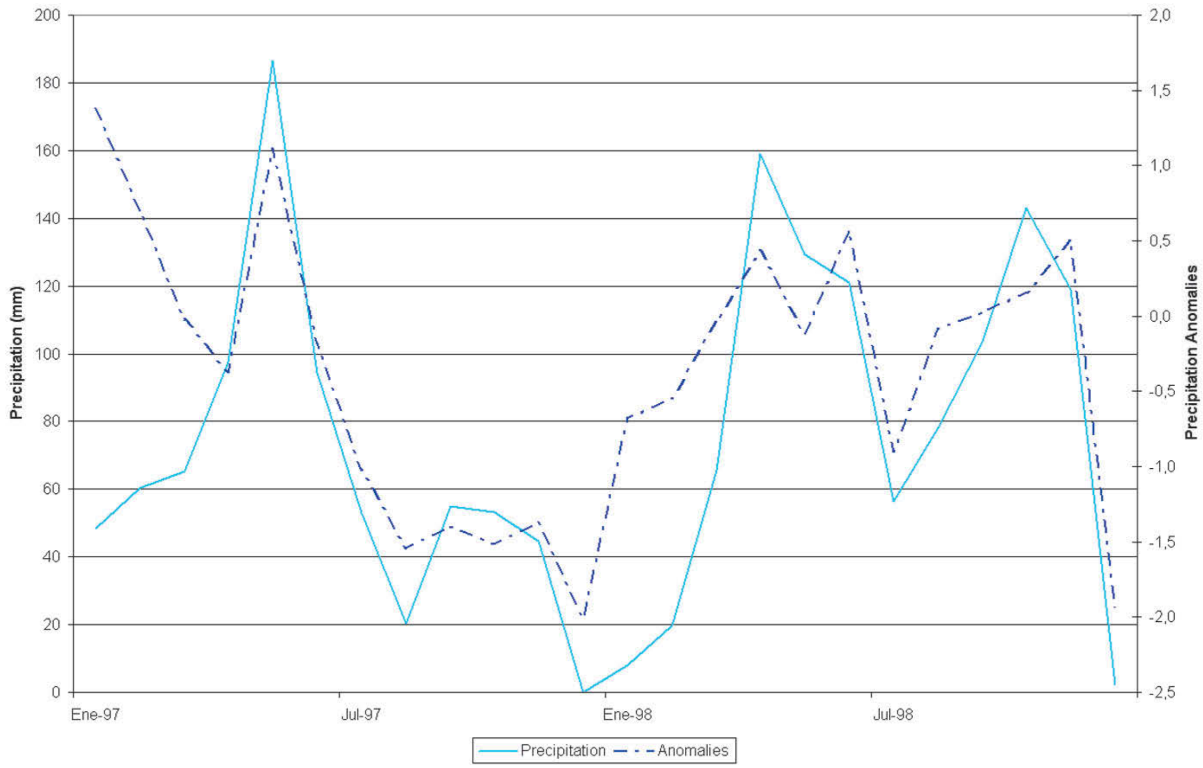

Figure 26.13. Precipitation and standardized anomalies registered at the El Cocuy meteorological station (06°26′N, 72°23′W, 3,716 m asl) between 1997 and 1998 demonstrating the precipitation deficit that resulted from the corresponding El Niño.

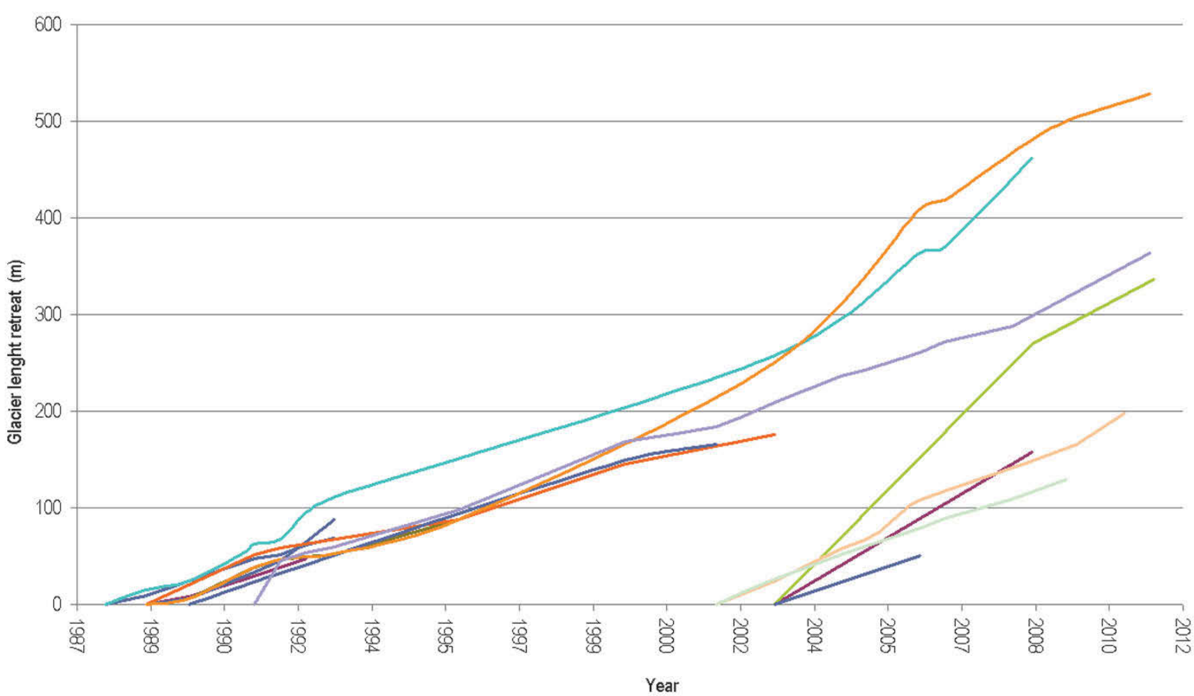

Figure 26.14. Cumulative glacier length change in different glacier tongues of Nevado de Santa Isabel.

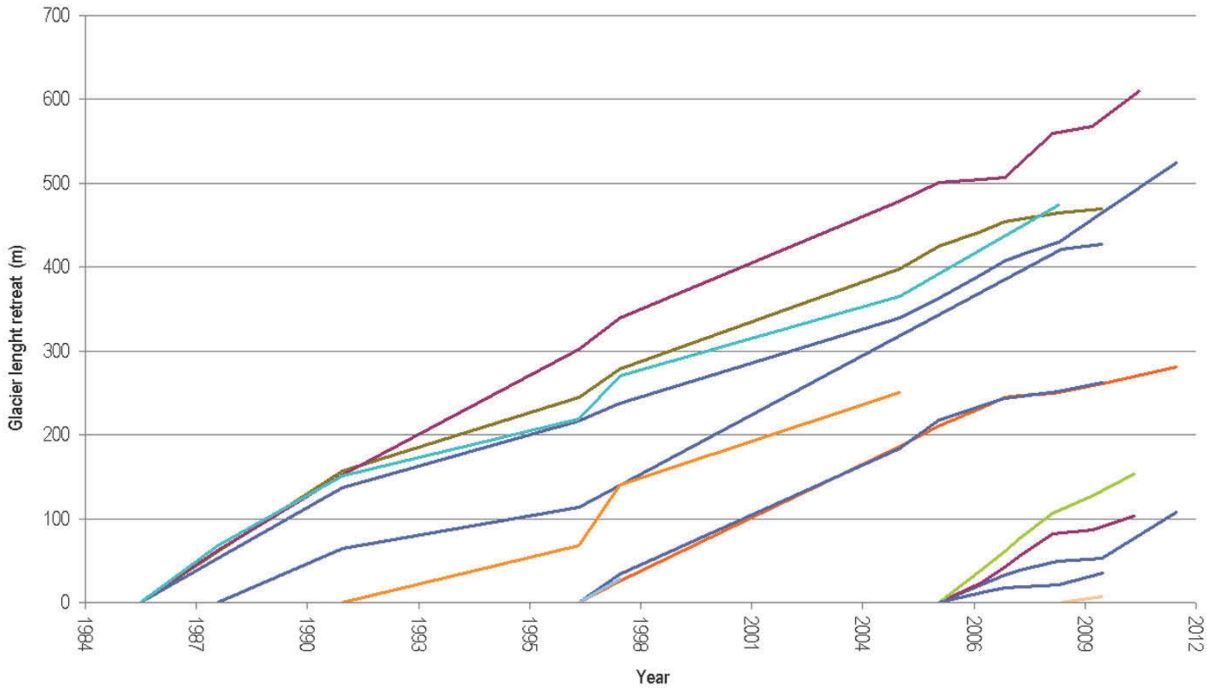

Figure 26.15. Cumulative glacier length change in different glacier tongues of the Sierra Nevada de El Cocuy.

Jordan (1991) presents an extensive and pioneering glacier inventory of Bolivia based on aerial photos acquired from multiple sources from 1948 through 1983 and serves as a valuable baseline from which to compare satellite-derived estimates of Bolivian glacier extents. This inventory, along with a discussion of more recent Landsat satellite images of Bolivian glaciers is presented in Jordan (1998). Digitization of published glacier maps of the Tres Cruces region produced from aerial photos acquired in 1975 (including the lower elevation glaciers of the main peaks) indicate that the area covered by glaciers for the region shown in Figure 26.16 in 1975 was approximately 55.4 km^2.

The digitized inventory enables direct comparison with glacier extents derived for the period 1986–2000 from Landsat TM images (WRS-2 path 233/row 72). Images acquired in 1986, 1992, and 2000 were deemed suitable for preliminary estimate of glacier extent as they are cloud free. All images were georegistered and surface reflectances computed from satellite radiances using standard techniques. NDSI images (Dozier 1989, Hall et al. 1995) were computed and thresholded to create binary maps of snow and glacier-covered pixels. Because transient snow in nonglaciated areas was an issue in some images, only those pixels identified as containing glaciers in 1975 were considered as possibly glacier covered in subsequent years.

The resulting glacier retreat time series is illustrated in Fig. 26.17 and indicates that the greater Tres Cruces region lost substantial glacier mass between 1975 and the present day. Of the 55.4 km^2 area identified as being glacier covered in 1975, only 27.4 km^2 (49%) were identified as containing snow and ice in Landsat images from 2000. As is evident in Figure 26.16, much of the early ice loss appears to have come from glaciers found outside the three main glaciated regions. Relatively persistent snowfields could easily be mistaken for glaciers and thus contribute to incorrect measurements of glacier area change; this remains a problem for some areas. While perhaps not surprising, it does highlight the need to verify sources of historical glacier extents when comparing them with more recent satellite images. Multiple ASTER images are currently the principal means of projecting the area covered by glaciers well into the 21st century.

26.3.7 Venezuela

The northernmost tropical glaciers in the Andes are found in Venezuela and today are confined to the Sierra Nevada de Mérida. Since their extent was first mapped in 1910, these glaciers have undergone considerable retreat. Today, small ice masses can be identified from satellite images on only three peaks:

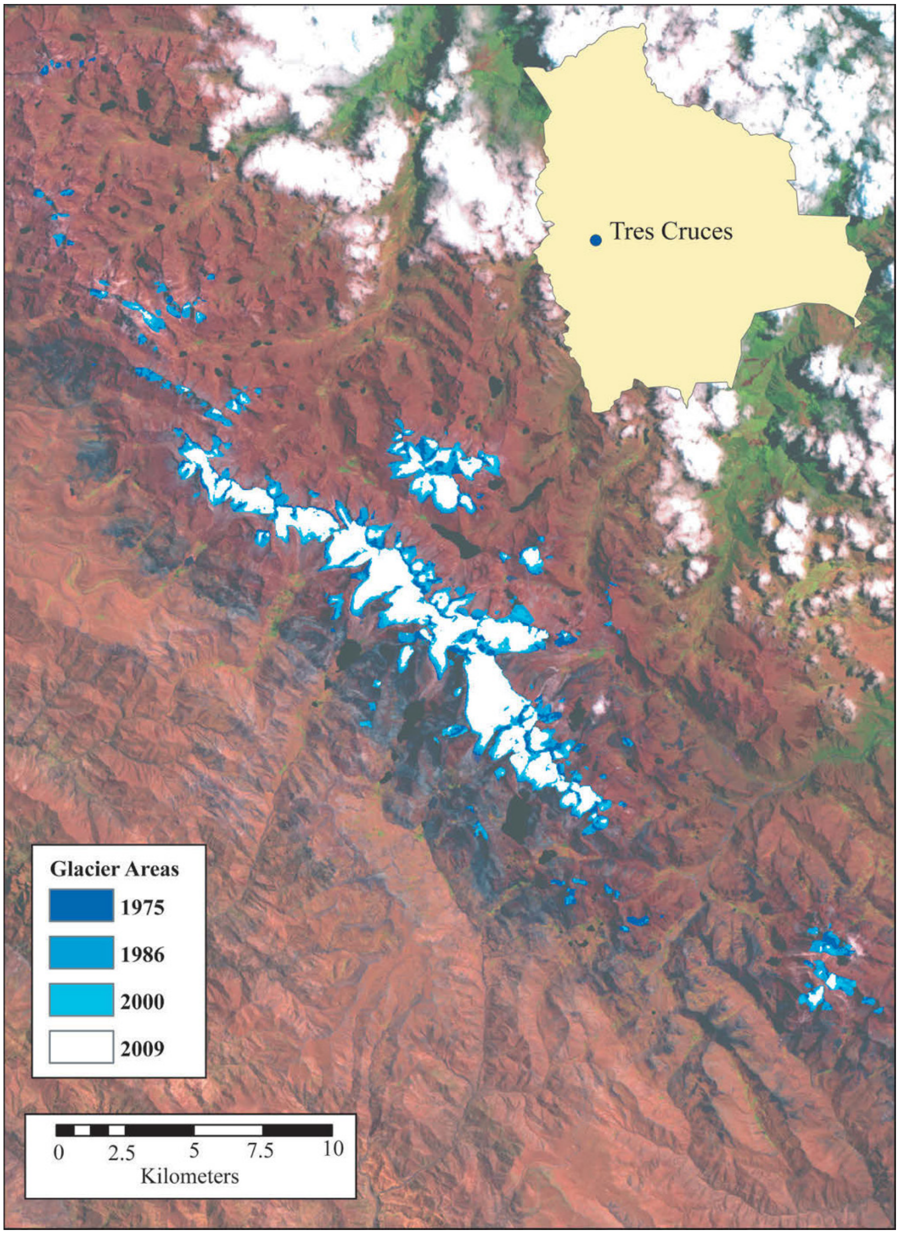

Figure 26.16. Areal extent of glaciers in the Tres Cruces region, Bolivia, from 1975 to 2000. The inset map indicates the location of the region within Bolivia. Map coordinates are eastings/northings in UTM zone 19S. Figure can also be viewed as Online Supplement 26.5.

Pico Bolívar (5,002 m), Pico Humboldt (4,942 m), and Pico Bonpland (4,893 m). Unfortunately, the small size of the remaining ice masses on Pico Bolívar makes them difficult to accurately map from historical satellite archives, thus the discussion here highlights the recent retreat of remaining ice on Pico Humboldt and Pico Bonpland (8°32′N, 71°00′W; Fig. 26.18).

The glacier retreat documented here builds on the region's first glacier maps created in 1910 (Jahn 1925), as well as the considerable work carried out on the region's glaciers by Carlos Schubert who used aerial photos acquired in 1952 (Schubert 1972, 1980, 1984, 1992, 1998, Schubert et al. 1993). While the early glacier mapping of Jahn (1925) is not amenable to quantitative determination of glacier area (Schubert 1998), it is clear that glacier retreat in the Sierra Nevada de Mérida was first observed in the first decade of the 20th century, and substantial retreat of these glaciers has con-

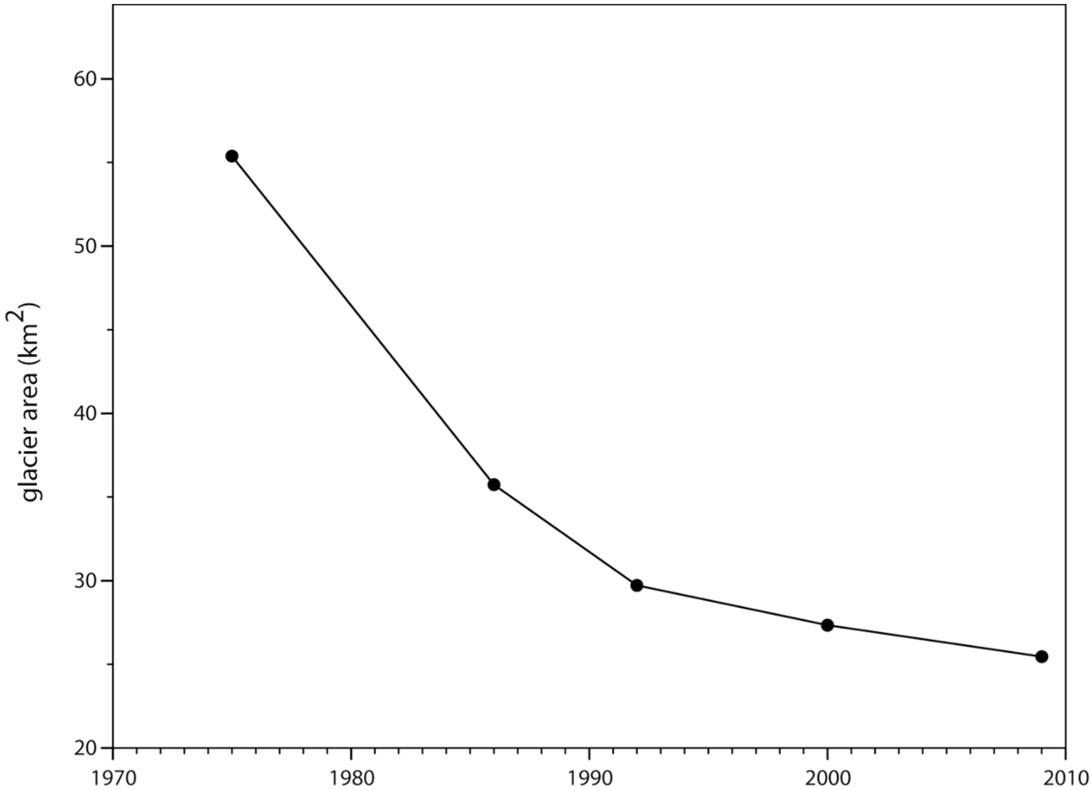

Figure 26.17. Observed retreat of glaciers in the Tres Cruces region from 1975 to 2009.

tinued to be observed since 1952. This retreat continues as of today.

Although Schubert (1998) qualitatively assessed glacier change from Landsat MSS images, no attempt was made to quantitatively measure glacier area from these images. However, the retreat of the remaining ice masses on Pico Humboldt and Pico Bonpland since the early 1980s can be measured by combining 10 cloud-free images from both ASTER as well as Landsat MSS and TM.

All images were georegistered and their digital numbers (DNs) converted into surface reflectances using standard instrument-specified approaches and a simple atmospheric correction using the modified blackbody atmospheric correction procedure of Chavez (1988). Glacier extents in 1981 were manually mapped from visual analysis of Landsat 3 MSS images. Glacier extents from 1985 to 2001 were determined from Landsat TM images, and glacier extents from 2002 to 2007 were determined from ASTER images. For both TM and ASTER, pixels containing snow and ice were identified by thresholding an NDSI image. This approach has a long history in snow mapping and works adequately for small ice masses (Dozier 1989, Hall et al. 1995). In some cases, pixels that could unambiguously be identified as containing transient snow cover were manually removed from analysis.

Since 1952 the areal extent of the remaining ice masses on Pico Humboldt and Pico Bonpland has decreased considerably from 2.03 km^2 at that time (Schubert 1992, 1998) to 0.17 km^2 in 2007 (when the first draft of this chapter was written). This loss represents a 92% reduction in area over this 55-year period (Fig. 26.19). The figure shows an almost constant area retreat rate averaging 0.034 km^2 per year from 1952 to 2007. If the average rate of retreat continues, these ice masses will have disappeared by 2012 or 2013, shortly before this book's publication. However, if the retreat rate slows slightly, the last remnants could persist a few years longer. Assuming constant area loss each year, the average rate of ice loss over the period has been 1.67% yr^{-1} or, if computed following a compound interest approach, the rates are 4.41% yr^{-1}.

26.4 REGIONAL SYNTHESIS

Regardless of the cause, glaciers are retreating rapidly throughout the northern Andes. In the Cordillera Blanca, glaciers are retreating at an average

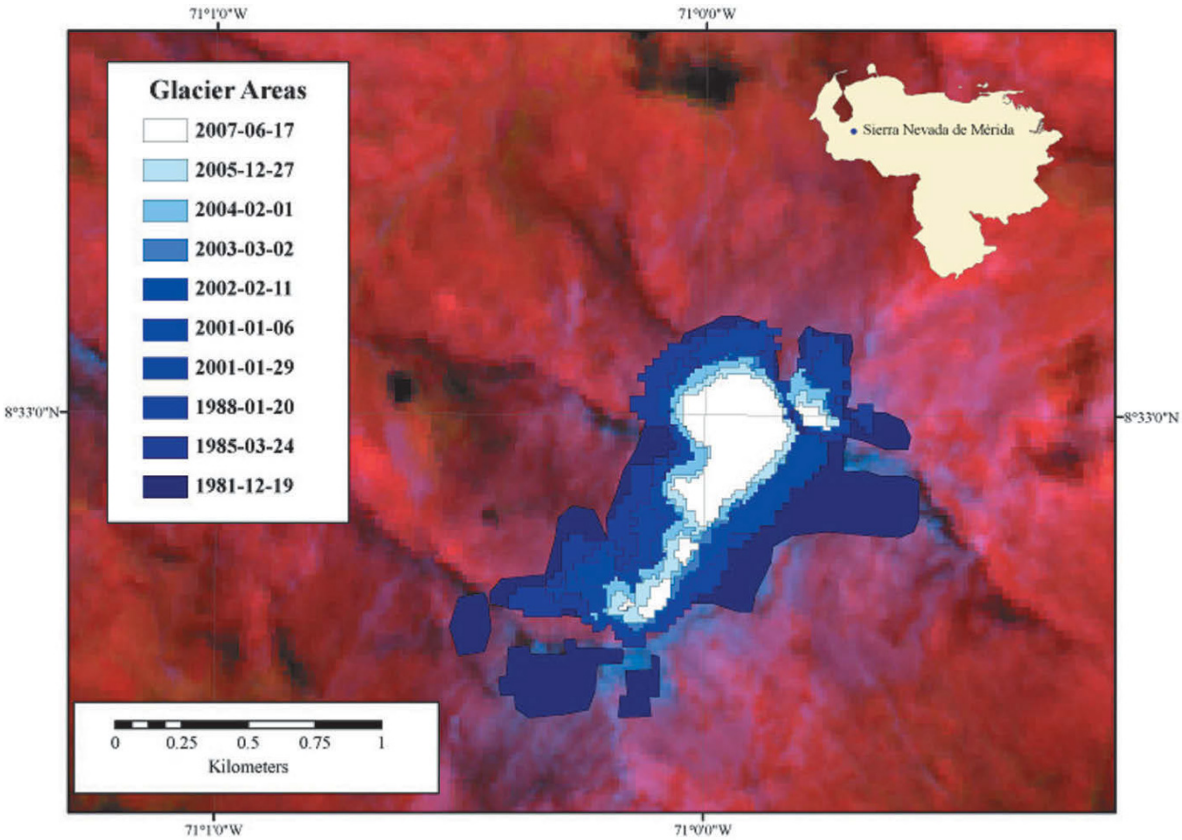

Figure 26.18. Areal extent of the ice on Pico Humboldt and Pico Bonpland, Venezuela, from 1981 to 2007. The inset map indicates the location of the Sierra Nevada de Mérida within Venezuela.

rate of 0.72% yr^{-1} (1970–2003). Qori Kalis Glacier in southern Peru is retreating at a linear rate of 0.6% yr^{-1} (Thompson et al. 2006), while the larger Quelccaya Ice Cap is retreating at a rate of 1.04% yr^{-1} (1975–2010), and the Cordillera Vilcanota as a whole lost glacier area at the rate of 1.90% yr^{-1} (1985–2006). While the results for Vilcanota may suggest that larger areas are more susceptible to retreat, the opposite is actually true; smaller glaciers are more susceptible to retreat. Qori Kalis is fed by a larger and higher lying ice cap, and therefore is dependent on change in the ice cap as a whole. When scaling up to the entire cordillera, faster retreat than the ice cap alone occurs because the cordillera contains over 400 individual glaciers, all of which are smaller than the ice cap, and thus more vulnerable to retreat.

In Peru, Nevado Coropuna retreated 1.61% yr^{-1} between 1955 and 2003 and 2.19% yr^{-1} between 1975 and 2003. For the small ice cap on Nevado de Santa Isabel, Colombia, retreat rates as high as 7.5% yr^{-1} (1996–2002) were found. In Tres Cruces, Bolivia, glaciers retreated at an average of 2% yr^{-1} (1975–2000). The smaller glaciers in Venezuela are retreating at a rate of 4.41% yr^{-1} (1952–2007).

Similar retreat rates are found throughout the tropics—Kilimanjaro is retreating at 1.15% yr^{-1} (1970–1990) and glaciers on Mt. Kenya are retreating at 0.8% yr^{-1} (1963–1993; Kaser 1999). In addition, our results for the Cordillera Blanca point to a two to threefold acceleration of the rate of ice loss in the last decade compared with 1970–1990 decades. This is consistent with trends reported from other areas (Khromova et al. 2006, Thompson et al. 2006). Francou et al. (2000) found a fivefold increase in the rate of ablation of a low-latitude glacier in the last decade with respect to former decades, suggesting that low-latitude glaciers may experience more rapid changes in area than middle and high-latitude glaciers.

26.5 DISCUSSION

Colombia's different climatic factors and their influence on glacier shrinkage are not understood

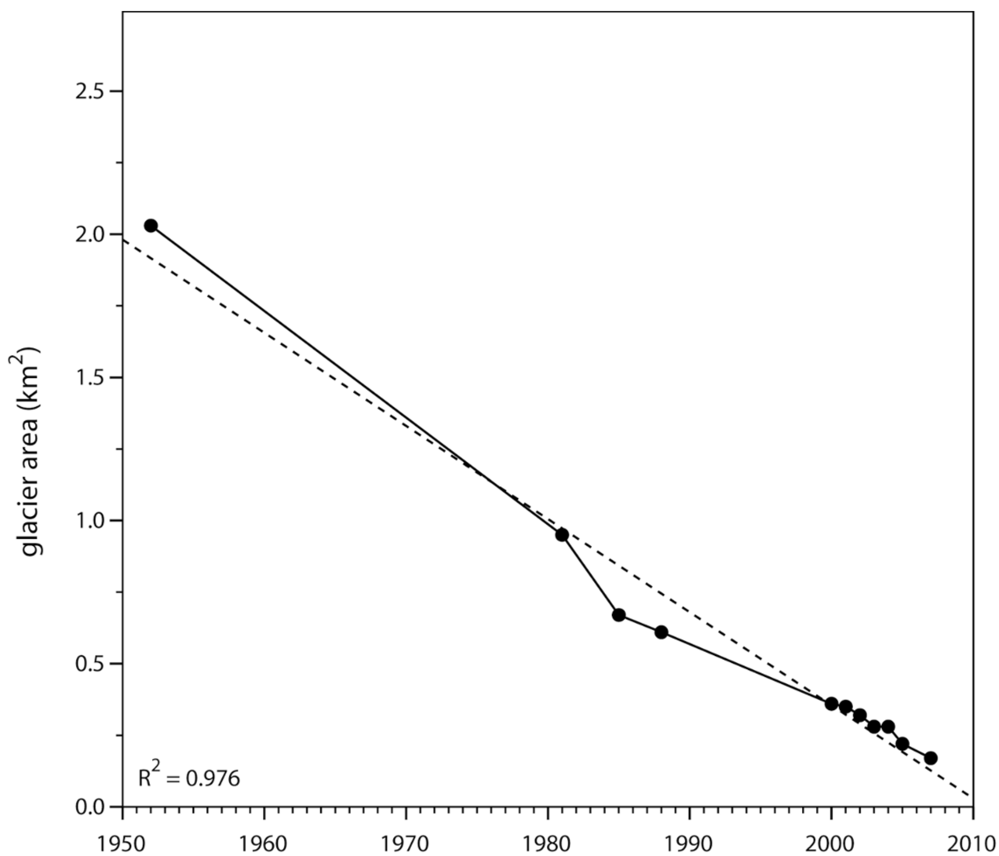

Figure 26.19. Observed retreat of the Pico Humboldt and Pico Bonpland ice masses from 1952 to 2007. The dashed line represents the best-fit linear retreat trend over this period.

in detail. The rise in air temperature is certainly a decisive factor in glacier retreat but it is unlikely to be the only factor. Data from the El Cocuy Meteorological Station document a rise in mean annual air temperature of roughly 1°C during the 25 years leading up to 2000 (Ceballos et al. 2006). A rise in temperature implies a corresponding rise in the equilibrium line altitude (ELA), which often provokes an immediate reaction from glacier tongues under tropical conditions (Kaser and Georges 1997). Comparative studies of meteorological data from a nearby station and glacier length change at Nevado de Santa Isabel suggest a remarkably direct reaction of glacier tongue extent to increases in air temperature (Ceballos et al. 2006), although another factor influencing the particularly rapid glacier retreat at Santa Marta and Santa Isabel may be related to the small size of glaciers in this area. Scale and edge effects become increasingly effective for accelerated glacier retreat when glaciers reach a critical size. This effect has been generally recognized for midlatitude glaciers (Paul et al. 2004), but it is particularly so for tropical glaciers (Francou et al. 2003). For the small ice cap on Nevado de Santa Isabel, it is suggested that the critical glacier size was reached in the 1990s. Additionally, heating of rocks surrounding the glacier as a result of solar radiation can induce local advection of warm air and thus increase sensible heat fluxes. The extraordinary loss of area of almost 40% in only 6 years (1996–2002) supports this hypothesis and makes further rapid shrinkage likely.

Precipitation is a major factor in that it both directly and indirectly influences the mass balance of tropical glaciers. In addition to thermal homogeneity, the inner tropics are characterized by relatively constant humid conditions in terms of hygrometric seasonality, even though intraannual variability can be quite high. Seasonality is caused by oscillation of the ITCZ which results in the peak precipitation seasons being March to May and September to November in Colombia. In El Niño years, such as that of 1997–1998, less precipitation

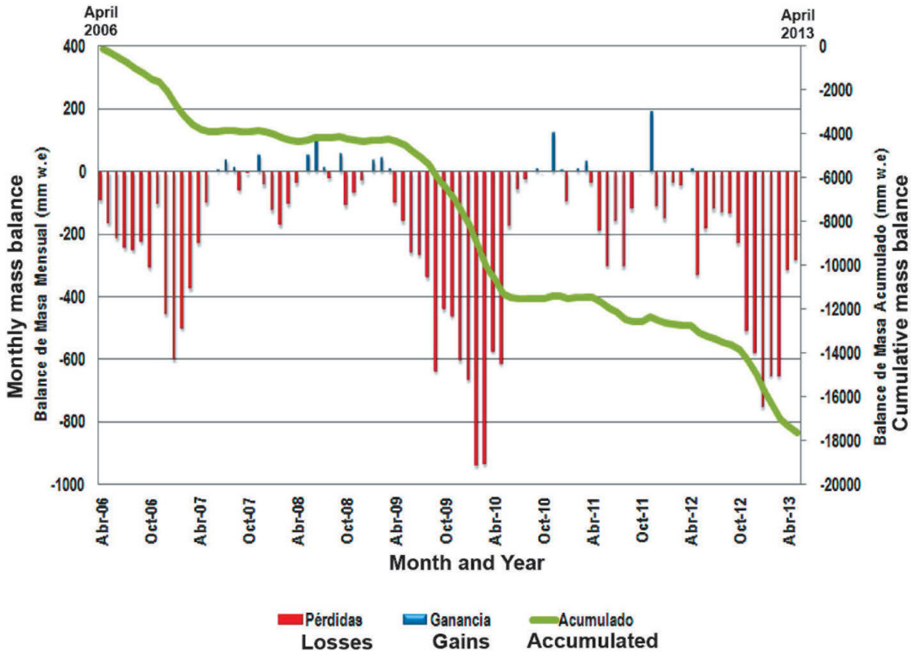

Figure 26.20. Monthly and accumulative mass balance of the iconic Santa Isabel Glacier (Colombia).

is observed. The indirect effects of precipitation variability on glacier mass balance act through feedback mechanisms on albedo. Wagnon et al. (2001) claim that albedo feedback is actually far more efficient at explaining variability in annual mass balance than annual variability in accumulation. The effect of changes in precipitation and related albedo on glacier length variation in the El Cocuy region is clearly shown for the 1997–1998 period in Fig. 26.15. Using aerial photos and satellite images, Arnaud et al. (2001) studied the ENSO influence on Sajama Volcano (Bolivia) which highlighted greater snowline sensitivity to precipitation than to temperature.

Humid conditions in La Niña years, such as occurred in 1999 when greater-than-normal precipitation was recorded, have slowed glacier retreat. Lower temperatures, increased snow accumulation on the glacier, and reduced direct radiation during the 1999 La Niña further contributed to a lower-than-normal glacier length retreat of 7 to 8 m in El Cocuy during that year.

The recent (last two to three decades) rate of glacier loss is about 3% per year. If this trend continues glaciers in Colombia could disappear within three to four decades, or be reduced to small patches of ice on the highest summits. Regional climate phenomena such as ENSO will continue to have an important influence on glacier loss in the future.

As our final remarks, the reader should consider Fig. 26.20 (and see also IDEAM 2012), which shows monthly resolved balances and accumulative balance for Santa Isabel Glacier (Colombia) over a 7-year period. Glacier responses to climate change are varied across the tropical Andes, as we have shown. However, the inability of this glacier to accumulate significantly even during the most favorable months has been widespread in much of the region. Santa Isabel Glacier is an icon of glacier state and dynamics in the northern Andes.

26.6 ACKNOWLEDGMENTS

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