Retreat of Tropical Glaciers in Colombia and Venezuela from 1984 to 2004 as Measured from ASTER and Landsat Images

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ABSTRACT

Like glaciers throughout the world, tropical glaciers in the northern Andes have retreated during the last century. In this study, the retreat of Andean glaciers in Colombian and Venezuela has been mapped from Landsat and ASTER images acquired between 1984 and 2004. Glacier retreat has been mapped for three glaciated regions in Columbia, the Sierra Nevada de Santa Marta, the Sierra Nevada del Cocuy, and the Ruiz-Tolima Massif as has the retreat of the single remaining glacier on the Pico Bonpland Massif in Venezuela. From the Landsat archives, several satellite images spanning the Landsat record were selected based on cloud cover over the glaciers and which provided adequate temporal coverage. All selected satellite images of the study sites were co-registered to each other with a root mean square (RMS) error for the ground control points of less than 20 meters. Snow and ice extent in each image was classified using the Normalized Difference Snow Index (NDSI) method and a density slice was used to create a binary snow/ice map. The total glaciated area on each individual peak was then determined from the classified snow and ice areas. This approach was found to be effective in determining glacier area. Incorporating historical data, a time series of glacier retreat from the early 1950s to 2003 was established. All four studied regions studied showed glacier retreat over this period. In the 1950s, the overall area of glaciers studied in Colombia and Venezuela glaciers was 91.36 km^2 in the 1950s. By 2003, the glaciers had retreated to approximately 62.07 km^2 which represents a total ice loss of 32%.

Keywords: Remote Sensing, Colombia, Venezuela, Tropical Glaciers

INTRODUCTION

As one indicator of global change, glaciers around the world have been studied. Topical glaciers are of particular interest to study because the distinct characteristics of tropical climates make glacier-climate interactions different from the mid- and high-latitudes (Kaser 1999). However, not all tropical glaciers have been comprehensively studied because their remoteness can limit accessibility and extensive cloud cover can preclude extended temporal studies from remote sensing. The recent increase in availability of satellite images over glacier regions has increased the likelihood of studies throughout these regions.

The tropical glaciers of Colombia and Venezuela, the focus of this study, were at a recent maximum extent during the Little Ice Age and have receded since this time (Kaser 1999).

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Utilizing historical data and satellite observations, glacier retreat in Columbia and Venezuela is measured over the past four decades.

The objective of this study is to quantify changes in the area of glaciers in several areas of Colombia and Venezuela using both historical data and measurements from satellite images to construct a time series starting in the early 1950's and ending in 2004. Glaciers in the following four regions have been studied: the Pico Bonplad Massif in Venezuela, the Sierra Nevada de Santa Marta, the Sierra Nevada de Cocuy and the Ruiz-Tolima Massif in Columbia. The study locations are illustrated in Figure 1. Glacier retreat on the Nevado del Huila, the only other glaciated region in Colombia, was not studied.

Figure 1: Map of Study Area

STUDY SITES AND THEIR GLACIAL HISTORY

The glaciers of the northern tropical Andes Mountains studied are located in Venezuela and Colombia along the western edge of South America and can be broken into four distinct glacial regions (Figure 1).

The Pico Bonpland Massif, of Venezuela, was formally the site of numerous glaciers extending around the peak with an elevation of 4,983 meters; now it is site of the last measurable Venezuelan glacier, Sinigüis located at 8º32′ N and 72º00′ W.

The Sierra Nevada de Santa Marta in northwestern Colombia is part of the Cordillera Central branch of the Andes Mountains extending into Colombia. Located near the Pacific coast, the Sierra Nevada de Santa Marta is the site of numerous glaciers located on a single peak at 10º34´N and 73º43´W.

The Sierra Nevada del Cocuy region of the Cordillera Oriental in the Columbian Andes is located in north-central Colombia, south of the Venezuelan border. The glaciated range trends north–south, and is located at 6º27′ N and 72º18′ W.

The Ruiz-Tolima Massif is located in the Colombian Parque Nacional de los Nevados on the Cordillera Central chain of the Andes Mountains at 4º50´N and 75º20´W. In 1959, the Parque Nacional de los Nevados contained 53 glaciers when the glaciers were measured by aerial photography (Hoyas-Patiño 1998).

Work by Thouret *et al*. (1996) suggests that the glacier extent of the Ruiz-Tolima Massif, Sierra Nevada de Santa Marta, and Sierra Nevada del Cocuy of Colombia were approximately 1500 km^2, 1500 km^2, and 2000 km^2, respectively, during the last glacial maximum which occurred approximately 27,000–24,000 years BP.

A later major glaciation occurred before 13,000–12,400 years BP at which time the glaciers of the Ruiz-Tolima Massif had an approximate area of 800 km^2. During the late neoglacial period, during the Little Ice Age which occurred from the 1600's to the 1900's, the glacierized area was reduced to 100 km^2. The Sierra Nevada de Santa Marta had an approximate glacier area of 850 km^2 around 13,000–12,400 years BP, and 107 km^2 during the late neoglacial period. Glaciers in the Sierra Nevada del Cocuy showed similar retreat with an approximate glacier size of 1000 km^2 around 13,000–12,400 years BP and 150 km^2 during the Little Ice Age.

Similar to the Colombian glacier regions and other glaciers in the tropical and temperate zones, Venezuelan glaciers were affected by Quaternary glaciations. Between 20,000–13,000 years BP, glaciers in the area advanced. This period is denoted as the Mérida Glaciation. The Cordillera de Mérida branch of the northern Andes Mountains is the site to high peaks tall enough to support glacier conditions. At the end of the Merida Glaciation period, the Cordillera de Mérida chain had an approximate glacier area of 600 km^2. Since 13,000 years BP, significant decreases in glacial size are apparent (Schubert and Clapperton 1990).

DATA AND METHODS

Satellite Images

ASTER and Landsat TM and ETM+ images from 1984 to 2004 were used in this study. Images, listed in Table 1, were selected based on minimum amounts of snow and cloud cover and on which produced the best time series for each region. All images available for each region were reviewed and critiqued based on the following criteria: seasonal precipitation, cloud cover, extent of snow cover, and image acquisition date. Selection of images was limited by seasonal patterns in precipitation and temperature, causing increased cloud cover in the area. Following visual analysis of the initially screened images, only those images with minimal snow and cloud cover were selected for further analysis.

ASTER (Advanced Space-borne Thermal Emission and Reflection Radiometer) is an imaging instrument aboard NASA's Terra satellite which was launched in 1999 as a part of the Earth Observing System (EOS). Each ASTER scene covers an approximate area of 60 km by 60 km with 15 spectral bands at 3 spatial resolutions. The visual near infrared (VNIR) bands, short-wave infrared (SWIR) bands, and thermal infrared (TIR) bands of ASTER have 15, 30, and 90 meter resolution, respectively (Abrams 2000).

Each Landsat scene covers a larger area, approximately 185 km by 185 km. The Landsat Thematic Mapper (TM) on Landsat 4 and 5 has seven bands; six bands in the visible to short-wave infrared have a spatial resolution of 30 meters while the remaining thermal bands have 120 meter spatial resolution. The Enhanced Thematic Mapper Plus (ETM+), carried on the Landsat 7 satellite, has eight multispectral bands with six bands at 30 meter spatial resolution, two bands with 60 meter resolution, and one panchromatic band at 15 meter resolution (Landsat Project Science Office 2006).

Table 1. Optimum images of the glaciers of Venezuela and Colombia

	Glacier Series	Date	Sensor Type	Path	Row
Colombia	Ruiz-Tolima Massif	01/01/1959 *	Aerial	—	—
		02/01/1976 *	Landsat 1	9	57
		10/24/1997	Landsat 5	9	57
		01/28/2001	Landsat 7	9	57
	Sierra Nevada de Santa Marta	01/01/1957 *	Aerial	—	—
		01/01/1973 *	Landsat 1	8	53
		12/16/1984	Landsat 5	8	53
		01/18/1991	Landsat 4	8	53
		12/20/2000	ASTER	8	53
		01/14/2004	ASTER	8	53
	Sierra Nevada del Cocuy	01/01/1959 *	Aerial	—	—
		01/18/1973 *	Landsat 1	7	56
		01/13/1986	Landsat 5	7	56
		12/23/1992	Landsat 4	7	56
		05/25/1999	Landsat 5	7	56
		01/14/2001	ASTER	7	56
		01/30/2001	ASTER	7	56
		03/06/2002	ASTER	7	56
		03/02/2003	ASTER	7	56
Venezuela	Pico Bonpland Massif (Siniguis)	01/01/1952 *	Aerial	—	—
		03/24/1985	Landsat 5	6	54
		01/20/1988	Landsat 4	6	54
		01/29/2000	Landsat 5	6	54
		02/11/2002	ASTER	6	54
		03/02/2003	ASTER	6	54
		02/01/2004	ASTER	6	54

** Measurements taken from Hoyos-Patiño (1998) and Schubert (1998)I*

Image Preprocessing

For ASTER scenes, the six SWIR bands were spatially oversampled to 15 meter resolution to match the VNIR bands using nearest neighbor resampling. For the Landsat images, all bands were oversampled from 28.5 meter to 15 meter resolution. Resizing all images to 15 meters allowed for better comparisons of snow and ice classification between the ASTER and Landsat platforms and facilitated visual interpretation of glacier area and comparisons of the classified glacier extent between platforms.

The images for each glacier region were coregistered using ground control points (GCPs) spaced throughout each scene. A minimum of 9 GCPs were used with all images. Images for each glacier area were coregistered to a master image (Table 2) selected for each glacier series. All images were projected into Universal Transverse Mercator, Zone 19N with a WGS-84 datum. Once the images in a glacial series were coregistered, they were overlaid to visualize glacial retreat over time for each area.

Table 2. Master Images for Image Coregistration

	Glacier Series	Date	Sensor Type	Landsat WRS Path	Landsat WRS Row
Colombia	Ruiz-Tolima Massif	01/28/2001	Landsat 7	9	57
	Sierra Nevada de Santa Marta	01/14/2004	ASTER	8	53
	Sierra Nevada del Cocuy	03/06/2002	ASTER	7	56
Venezuela	Pico Bonpland Massif (Sinigüis)	02/11/2002	ASTER	6	54

Snow and Ice Classification

Many image processing techniques could have been used in this study including manual digitization methods, band ratios and normalized difference ratios. Because this study focuses on digital area assessments, manual techniques were not considered. Further analysis of the band ratio method and normalized difference method were completed before selecting the best technique to use for all satellite images.

The Normalized Difference Snow Index (NDSI) and Band Math Ratio were both considered and computed for all ASTER images for comparison. The NDSI (equation 1) is a commonly employed snow detection method that helps to differentiate between cloud cover and snow/ice (Hall *et al.* 1995). The Band Math Ratio (equation 2) is a simple ratio between two bands, a and b

$$\text{NDSI} = \frac{(\text{NIR} - \text{Red})}{(\text{NIR} + \text{Red})} \tag{1}$$

$$\text{Band Math Ratio} = \frac{\text{Band a}}{\text{Band b}} \tag{2}$$

Both methods were analyzed for accuracy using several ASTER band combinations: one and five, two and five, and three and five. After visually assessing both methods and all band combinations, the NDSI method using ASTER band two (0.63–0.69 µm) and five (2.145–2.185 µm) was selected as best for determining glacial area for these study areas. The NDSI method was then applied to the Landsat scenes using the Landsat band combination, three (0.63–0.69 µm) and five (1.55–1.75 µm), that best approximated the ASTER bands.

To determine the glacial area in each image using the NDSI ratio, a density slice was performed to classify pixels containing snow and ice. For both ASTER and Landsat, pixels with NDSI values ranging between 0.4 and 1.0 were classified as snow and ice. To compute the total glaciated area for each area, a region of interest (ROI) was drawn around glaciated area to determine the number of pixels with NDSI values in the selected range. This ROI approach helped eliminate clouds and other features misclassified as snow/ice. In some instances, transient snow cover still may be misinterpreted as glacier.

RESULTS

Glacier changes between the 1950s and 2003 for the study areas in Columbia and Venezuela were determined using historical information and satellite images. In the 1950s, the total glacier area for three study regions in Colombia was 89.33 km^2. By 2003 the total glacier area had been reduced to 45.77 km^2. From the 1950s to 2003 the calculated total ice loss in Colombia was 43.56 km^2. The Sierra Nevada del Cocuy contributed 52% of the total ice lost, the Ruiz-Tolima Massif contributed 42% of this loss and the Sierra Nevada de Santa Marta contributed 6%. These ice loss percentages are directly related to the total glacier area of each region.

Out of the 10 Venezuela glaciers mapped in 1952 with a total area of 2.91 km^2 (Schubert 1998), only one glacier is still visible from ASTER and Landsat images as of 1985. In 2004 the last remaining glacier on the Pico Bonpland Massif-Sinigüis, decreased from 2.03 km^2 in 1952 to 0.29 km^2 or 86% of its 1952 area. Unfortunately, several images analyzed of this glaciated region had to be eliminated due to seasonal snow cover in the area.

Table 3. Glacier Areas

	Glacier Series	Date	Area (km^2)
Colombia	Ruiz-Tolima Massif	1959 Historic *	33.95
		10/24/1997	17.47
		01/28/2001	15.81
	Sierra Nevada de Santa Marta	1957 Historic *	16.26
		1973 Historic *	14.10
		12/20/2000	13.66
	Sierra Nevada del Cocuy	1959 Historic *	39.12
		1973 Historic *	28.00
		05/25/1999	20.39
		03/06/2002	16.30
		03/02/2003	16.30
Venezuela	Pico Bonpland Massif Sinigüis	1952 Historic *	2.03
		03/24/1985	0.66
		01/20/1988	0.58
		01/29/2000	0.38
		02/11/2002	0.33
		03/02/2003	0.29

* *Measurements taken from Hoyos-Patiño (1998) and Schubert (1998)*

Ruiz-Tolima Massif

In 1959, five peaks with glaciers existed in the Parque Nacional de los Nevados, but as of 1976 only three glaciated peaks are still visible, Ruiz, Tolima, and Santa Isabel (Hoyas-Patiño, 1998). In 1959, glacier area on the Ruiz-Tolima Massif was 33.95 km^2 and was reduced to 15.81 km^2 by 2001 (Figure 2). This represents a 53% loss in ice over a 42-year time span. Individually, glaciers on the Nevado del Ruiz decreased from 21.4 km^2 to 10.92 km^2, a total loss of 49%. The Nevado del Santa Isabel glaciers decreased from 9.78 km^2 to 3.61 km^2, losing 63% of their area. The Nevado del Tolima glaciers declined from 2.22 km^2 in 1959 to 1.26 km^2 in 2001, a total ice loss of 43% (Tables 3 and 4).

Table 4. Glacier Areas of the Ruiz-Tolima Massif

Glacier	Date	Area (km^2)
Nevado de Santa Isabel	1959 Historic *	9.78
	10/24/1997	4.19
	01/28/2001	3.61
Nevado del Ruiz	1959 Historic *	21.40
	10/24/1997	12.13
	01/28/2001	10.92
Nevado del Tolima	1959 Historic *	2.22
	10/24/1997	1.15
	01/28/2001	1.26

**Measurements taken from Hoyos-Patiño(1998)*

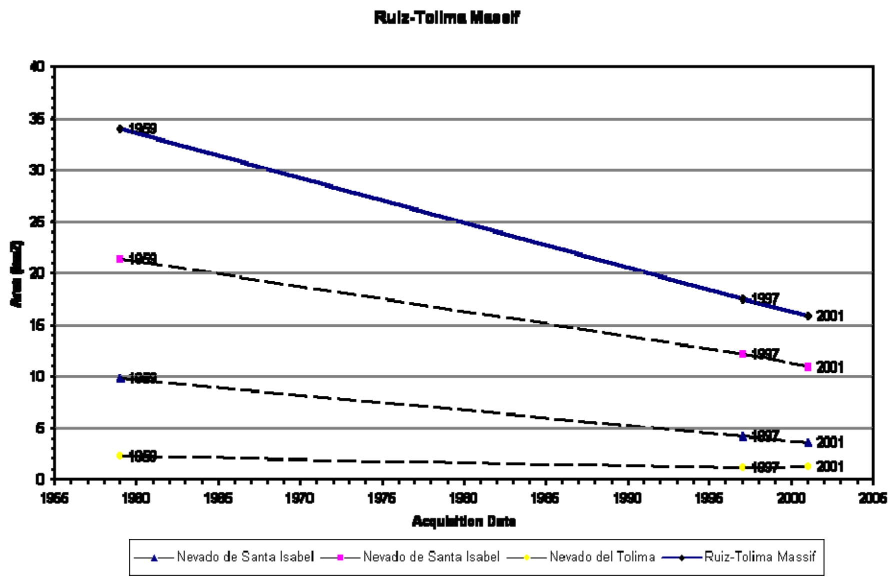

Figure 2. Time Series for Ruiz-Tolima Massif Glaciers

Sierra Nevada de Santa Marta

The Sierra Nevada de Santa Marta was the second Colombian Glacier region studied (10º34′ N and 73º43′ W). As determined from aerial photography, the region had 88 glaciers in 1957 with a total glacial area of 16.26 km^2 (Hoyas-Patiño 1998). Based on the 2000 ASTER image the total glaciated area was 13.66 km^2. Using the 2000 ASTER image, the most recent available snow free image, the total ice loss for the Sierra Nevada de Santa Marta is 2.86 km^2 or 16% (Table 3 and Figure 3). However, the 2000 estimate of glacier area still may be impacted by some transient snow cover.

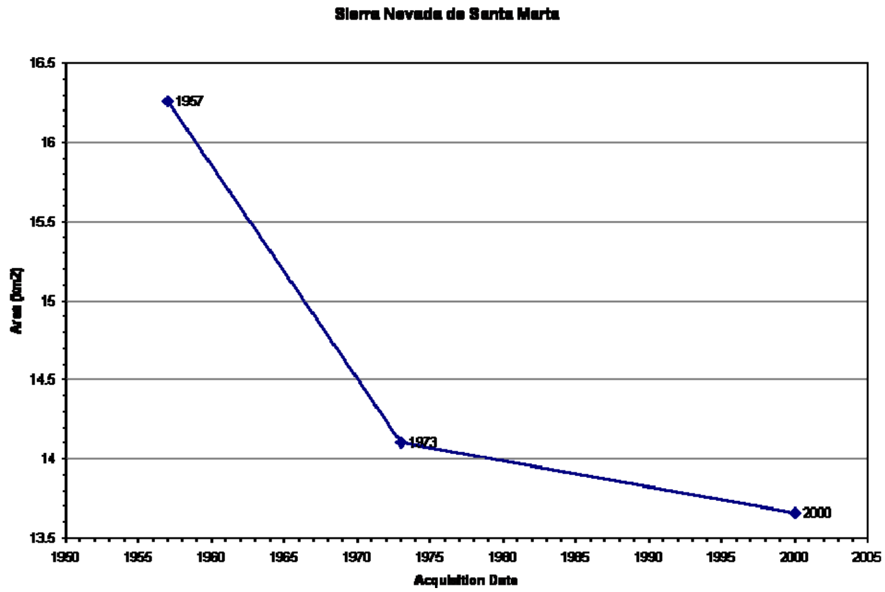

Figure 3. Time Series for Sierra Nevada de Santa Marta

Sierra Nevada del Cocuy

The Sierra Nevada del Cocuy is also a glaciated area in Colombia (6º27′ N and 72º18′ W). The total glaciated area in 1959 was 39.12 km^2 (Hoyas-Patiño 1998) and had retreated to 16.3 km^2 in 2003. In 44 years the area had a total ice loss of 58% (Table 3 and Figure 4).

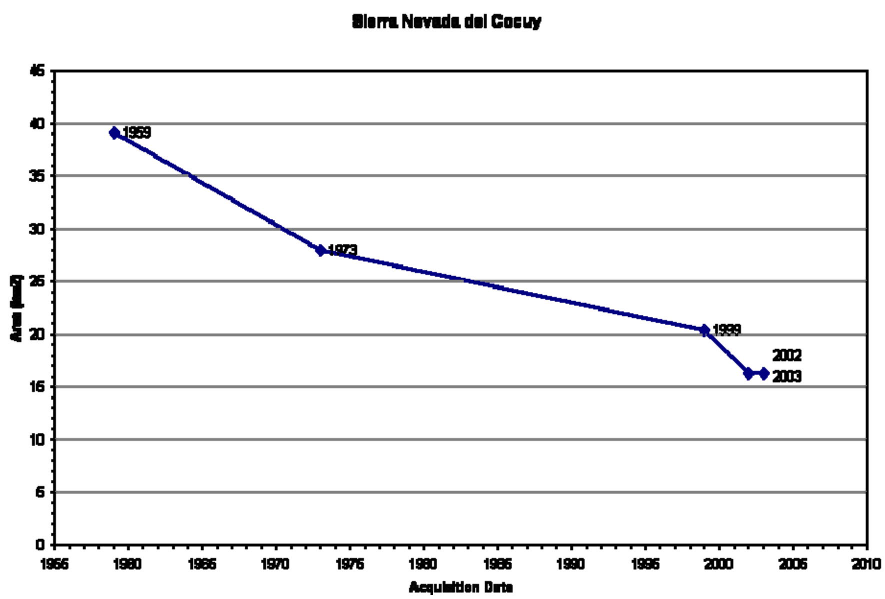

Figure 4. Time Series for Sierra Nevada del Cocuy Glaciers

Pico Bonpland Massif–Sinigüis Glacier

The Pico Bonpland Massif glacier region is located in Venezuela at 8º32′ N and 71º00′ W. In 1952 two glaciers, Siniguis and Nuestra Senora, existed on Pico Bonpland/Humbolt. In a Landsat 5 image acquired for the Pico Bonpland Massif, on March, 24, 1985, the only visible glacier was the Sinigüis glacier. The total glacier area assessment in 1952 was 2.03 km^2 and by 2003 the glacier area had decreased to 0.29 km^2. This is a total area loss of 1.77 km^2 or 87% of the 1952 area (Table 3 and Figure 5).

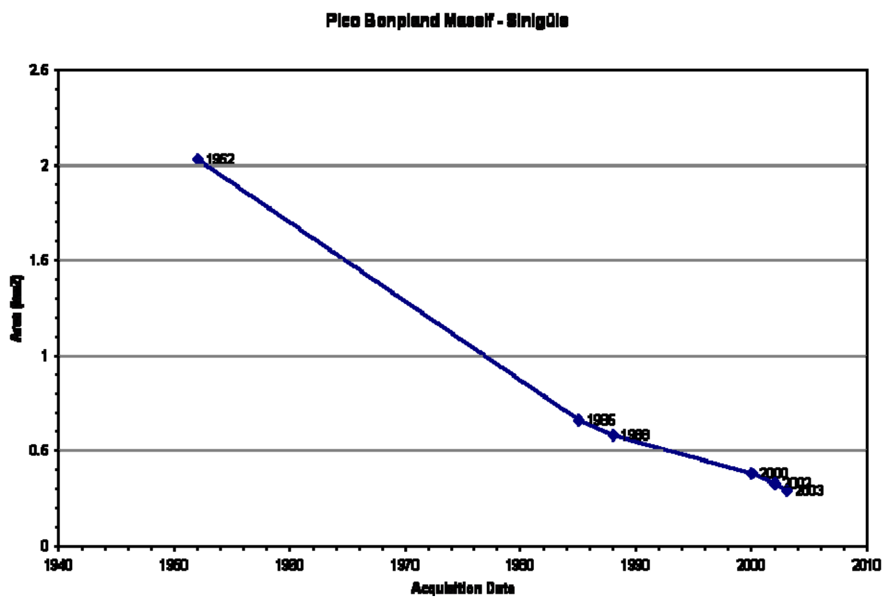

Figure 5. Time Series for Pico Bonpland Massif – Sinigüis Glacier

DISCUSSION

Aerial photography and Landsat Multispectral Scanner (MSS) images provide historical measurements of the Colombian and Venezuelan glaciers. Although these measurements help to expand the time span used in this study, it is unknown exactly how the areas were calculated. In this study, the Normalized Difference Snow Index (NDSI) provided a strong foundation for estimating the areas of the glacier regions by discriminating the snow/ice in the images through the use of a 0.4 threshold. By providing a uniform criterion to delineate snow and ice, it is possible to construct a glacier retreat time series. Examining the trend for each glacier area, it is evident that each region has experienced a decrease in glacier area over the past fifty years.

The glaciated region of the Sierra Nevada de Santa Marta illustrates the commission errors caused by increases in seasonal snow cover as several images could not be used due to transient snowfall obscuring glacier boundaries. Nevertheless, the overall trend on this glacier series confirms a general decrease in glacier area from 1957 through 2004.

In the case of the glacier area Ruiz-Tolima Massif, volcanic activity in the area is a partial cause for the decline in glacial area. As part of a series of stratovolcanoes, extending along the Andes from the southern tip of Chile to the northern portion of Venezuela, Nevado del Ruiz is currently in an active eruptive state. Recent eruptions in the mid-1980s affected temperatures in the glacier area enough to trigger snow and ice melt, which is supported by the decline in areal extent of the Ruiz-Tolima Massif glaciers between the mid-1980's and 2001 (Linder and Jordan 1991, Linder *et al.* 1994).

On November 13, 1985, an eruption on Nevado del Ruiz caused South America's deadliest eruption, a result of devastating lahars. The last known eruption of Nevado Del Ruiz occurred in

1991. Unlike Ruiz, Nevado del Tolima and Nevado de Santa Isabel, the other stratovolcanoes in the Ruiz-Tolima Massif, are not currently in an eruptive state at this time (Hoyas-Patiño 1998). Figure 4 illustrates the time series of area measurements, and shows a general decline in glacier size from 1959 to 2001.

The series of images from the glaciers of Sierra Nevada del Cocuy make up the largest time series in this study, 9 images over 44 years. Originally consisting of numerous distinct glaciers, Sierra Nevada del Cocuy has continually shown a significant loss in glacier size over the study period, resulting in steep general decrease in glacial area. The observed retreat of the Sierra Nevada del Cocuy glaciers confirm notions of tropical glacier loss in this region.

Finally, the glaciers of Venezuela are also disappearing. The sole remaining glacier, Sinigüis, showed a steady reduction in size between 1988 and 2003 after a dramatic decrease in size from 1952 to 1985. The computed loss rate from 1952 to 1985 and from 1988 to 2003 is 41515 m^2/year and 19333 m^2/year, respectively. Overall, a general decrease in glacier size is shown in Figure 5 during the 51-year period.

CONCLUSION

Overall a decline in glacial area can be seen throughout all four studied glacier regions of the tropical Colombian and Venezuelan Andes. Steady to extreme decreases in area are captured by the Normalized Difference Snow Index (NDSI) calculations completed in this study. From the 1950's to present, significant snow and ice loss over the area portray proof of a regional glacier recession. Broadening the scale, glaciers throughout the tropics are showing similar retreating characteristics (Kaser 1999, Kincaid and Klein 2004), and globally, glaciers around the world, from different regions, climates, and human interferences, confirm the results of this survey (IPCC 2001).

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