Retreat of the Irian Jaya Glaciers from 2000 to 2002 as Measured from IKONOS Satellite Images

JONI L. KINCAID[1] and ANDREW G. KLEIN[1]

ABSTRACT

Using IKONOS images, retreat of the Mt. Jaya glaciers in Irian Jaya, Indonesia, from 2000 to 2002, has been measured. The total area of the Mt. Jaya ice masses was 2.326 km^2 and 2.152 km^2 in 2000 and 2002, respectively. Measured ice loss from 2000 to 2002 was 0.174 km^2, which represents 7.5% of the 2000 area. Comparing these glacier changes with previously published glacier areas indicates these glaciers have continued their observed retreat that began in the mid-19th century. Between 2000 and 2002 the E. Northwall Firn, the Carstensz, and the W. Northwall Firn lost 4.5%, 6.8%, and 19.4% of their respective 2000 areas. Sometime between 1994 and 2000 the Meren Glacier appears to have disappeared.

Keywords: remote sensing, Indonesia, tropical glacier

INTRODUCTION

Tropical glaciers have followed the same recessional trend as most glaciers over the past century, and are experiencing increasingly higher rates of recession (IPCC, 2001). Existing tropical glaciers are small and generally under 0.5 km^2 in size. This small size reduces their response time to climate change and therefore, changes in mass balance or areal extents are more likely representative of current, and not cumulative, climate trends (Francou et al., 2003). Temperature is thought to be the controlling factor for glacial change on Mt. Jaya as precipitation is not a limiting factor (Allison and Kruss, 1977). However, Francou et al. (2003) found that in the tropical Andes the physical processes of ablation were primarily controlled by albedo and incoming long-wave radiation; factors that were directly related to temperature. Whatever the causes, tropical glacier recession appears to be accelerating (IPCC, 2001).

However, a paucity of glacial observations in the tropics, due in part to their limited accessibility, limits our knowledge of tropical glacier recession rates, as well as our understanding of glacier-climate relationships in the tropics. Tropical glacial environments are generally remote, and harsh climate conditions offer only small windows of opportunities for investigation. This has resulted in significant data collection for only a small number of glaciers in the world and these data commonly cover only short time periods (Braithwaite and Zhang, 1999; Dyurgerov and Meier, 2000). Kaser and Osmaston (2002) note several excellent studies on tropical glaciers, but many more are needed. Stating that, at this time, tropical mountain glacier studies remain "alpine-centric" for lack of sufficient research.

[1]Department of Geography, Texas A&M University, 3147 TAMU, College Station, TX 77843-3147

Remote sensing technology enables large-scale collection of glacial data. Surface velocities, mass balance changes, glacier retreat, snow and ice densities, snow depth, surface temperatures, and snow and ice topography are a few of the characteristics of glaciers that can be remotely sensed (Konig et al., 2001). This technology is enabling collection of a more geographically extensive database of both spatial and temporal observations on glaciers.

The objective of this project is to quantify the changes in areal extent that have occurred on the Mt. Jaya glaciers utilizing IKONOS images acquired by the sensor on June 8, 2000 and June 11, 2002. The measured areal changes will then be compared to previously published estimates of glacier area.

IKONOS Images

On September 24, 1999, the IKONOS sensor was successfully launched and is currently acquiring very high spatial resolution images of 1 m and 4 m for panchromatic and visible/near-infrared multispectral bands, respectively (Space Imaging, 2004). This resolution permits easy detection of glacier boundaries and accurate mapping of many remote and inaccessible areas. The horizontal accuracy of the orthorectified images, with ground control points (GCPs), is 0.5 m and the height accuracy is 0.7 m (Fraser et al., 2002). However, these image products are not corrected for terrain displacement and therefore, mapping in areas of steep and varying relief may have more error (Grodecki and Dial, 2001).

In general, the images are acquired in five spectral bands ranging from 0.45 to 0.90 mm: one panchromatic band, three visible infrared (VIR) bands, and one near-infrared (NIR) band. The radiometric resolution is eight bits for the multispectral bands and 11 bits for the panchromatic band. This enables more detail to be discerned within the image in areas of shadows and low contrast (Grodecki and Dial, 2001). Good results for automated classifications and change detection have been demonstrated utilizing all five bands available with IKONOS images. This is attributed to the high geometric and radiometric accuracy of IKONOS, as well as the spectral resolution of the images (Haverkamp and Poulsen, 2003).

One of the main concerns in studying glaciers using visible and near-infrared images is whether or not cloud-free images are available at the required temporal scale for the study. Although visibility and clouds are a negative factor in selecting IKONOS images, the frequency at which the sensor acquires images is good. It collects images of the same geographical space once approximately every three days at 40° latitude, more frequently at higher latitudes, and less frequently near the equator (Grodecki and Dial, 2001). Despite the lack of middle and thermal infrared bands, the high spatial, radiometric, and temporal resolutions of the IKONOS sensor enables data to be more easily analyzed than many of the other current sensor systems.

STUDY SITE AND ITS GLACIAL HISTORY

The Mt. Jaya glaciers are located in Irian Jaya, Indonesia at latitude 4º05′S and longitude 137º10′E. (Figure 1). In 1972 it was determined by trigonometrical survey that the peaks of Mt. Jaya reach 4884 m (Peterson et al., 1973) and are part of a west-northwest to east-southeast trending mountain range that extends across the island of New Guinea (Wollaston, 1914). The site was first visited in 1912 by A. Wollaston (Wollaston, 1914), A.H. Colijn and J.J. Dozy in 1936 (Dozy, 1938 as cited by Allison, 1974), H. Harrer in 1962 (Harrer, 1963 as cited by Peterson et al., 1973), and by the Australian Universities' Expeditions in the early 1970s (Peterson et al., 1973). Rock cairns were erected at the ice fronts during the Dozy and Harrer site visits. Field reports and photos from the expeditions, aerial photos taken by the United States Army Air Force in 1942 and the Indonesian and Australian militaries from 1976 to 1981 (Allison and Peterson, 1989), as well as more recent analysis of Landsat (Allison and Peterson, 1989) and SPOT (Peterson and Peterson, 1994) images help make the Mt. Jaya glaciers some of the most-well-studied glacier areas in the tropics.

Loffler (1982), focusing on the last major glaciation, reports that glacier recession initiated around 15,000 yrs BP and the Mt. Jaya glaciers disappeared by approximately 7,000 yrs BP. The glaciers then began to regenerate about 5,000 yrs BP. Average retreat rates, from 1936 to 1972, were calculated at 33 m yr^{-1} and 16 m yr^{-1} for the Meren and Carstensz Glaciers, respectively. Extrapolation of these rates suggests that a recession may have begun about 1820–1850 A.D (Peterson et al., 1973). Since circa 1850 total ice loss for these glaciers has been estimated at 16.4 km^2 (Loffler, 1982).

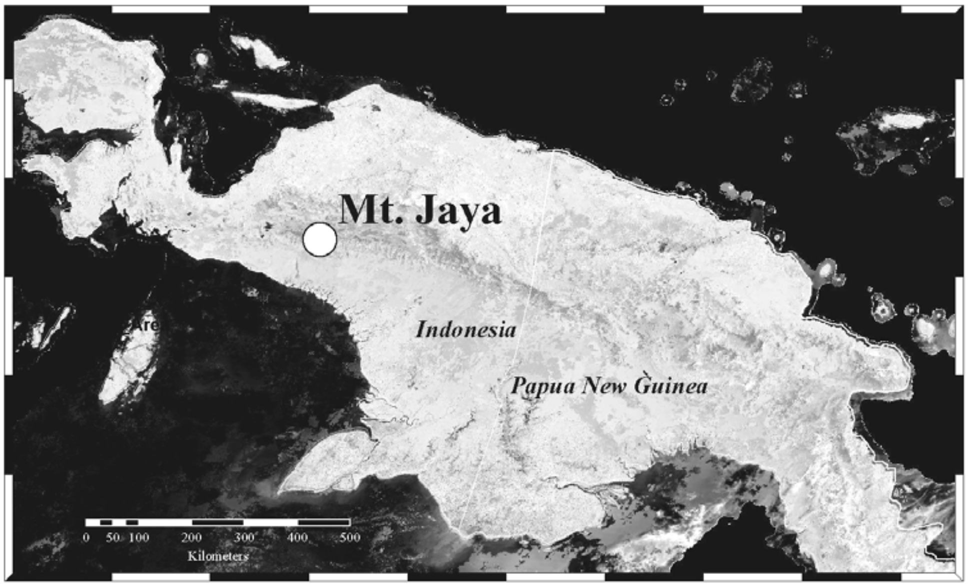


Figure 1. Site map for the Mt. Jaya glaciers.

METHODS

IKONOS images from June 8, 2000, and June 11, 2002, were obtained from SpaceImaging Corporation in a Universal Transverse Mercator projection and a WGS84 datum (Figure 2). The 1-m resolution of these multispectral images enables visual image analysis to be used to precisely map the glacier margins. To map glacial change over the two-year period, a precise image-to-image coregistration was performed. Initial attempts using visual selection of ground control points (GCPs) in both images and applying a global third-order polynomial transformation proved unsuccessful at adequately aligning the images with local relief displacements, the major cause of the poor alignment. This is frequently the case in mountain terrain and poor alignment is not surprising, as lack of an adequate digital elevation model meant the IKONOS images could not be terrain corrected.

To overcome this limitation, a subset of the original image covering the glaciated area was extracted. An automated image correlation technique was used to identify GCPs in both images, with the June 11, 2002 image used as the base image. An automated correlation routine attempted to identify GCPs on a grid with a 20-pixel interval in X and Y. Over 25,000 high-quality points were identified in both images. The June 8, 2000 image was then coregistered using these GCPs and a localized Delaunay Triangulation. Visual analysis determined the registration approach provided good registration over most of the image. In a couple of locations, localized offsets of 8 m were visible. However, across most of the image the offsets were less than 1 m.

Once the images were coregistered, all the ice masses within the three main glacier areas were manually digitized through visual analysis of the IKONOS images. Identification of the glacial margin at the 1-m pixel level could be accomplished at scales of 1:1000 or better using the visible IKONOS bands for distinguishing between snow and the surrounding limestone bedrock. In some locations, the ice margins and surrounding bedrock had quite similar reflectances in the visible

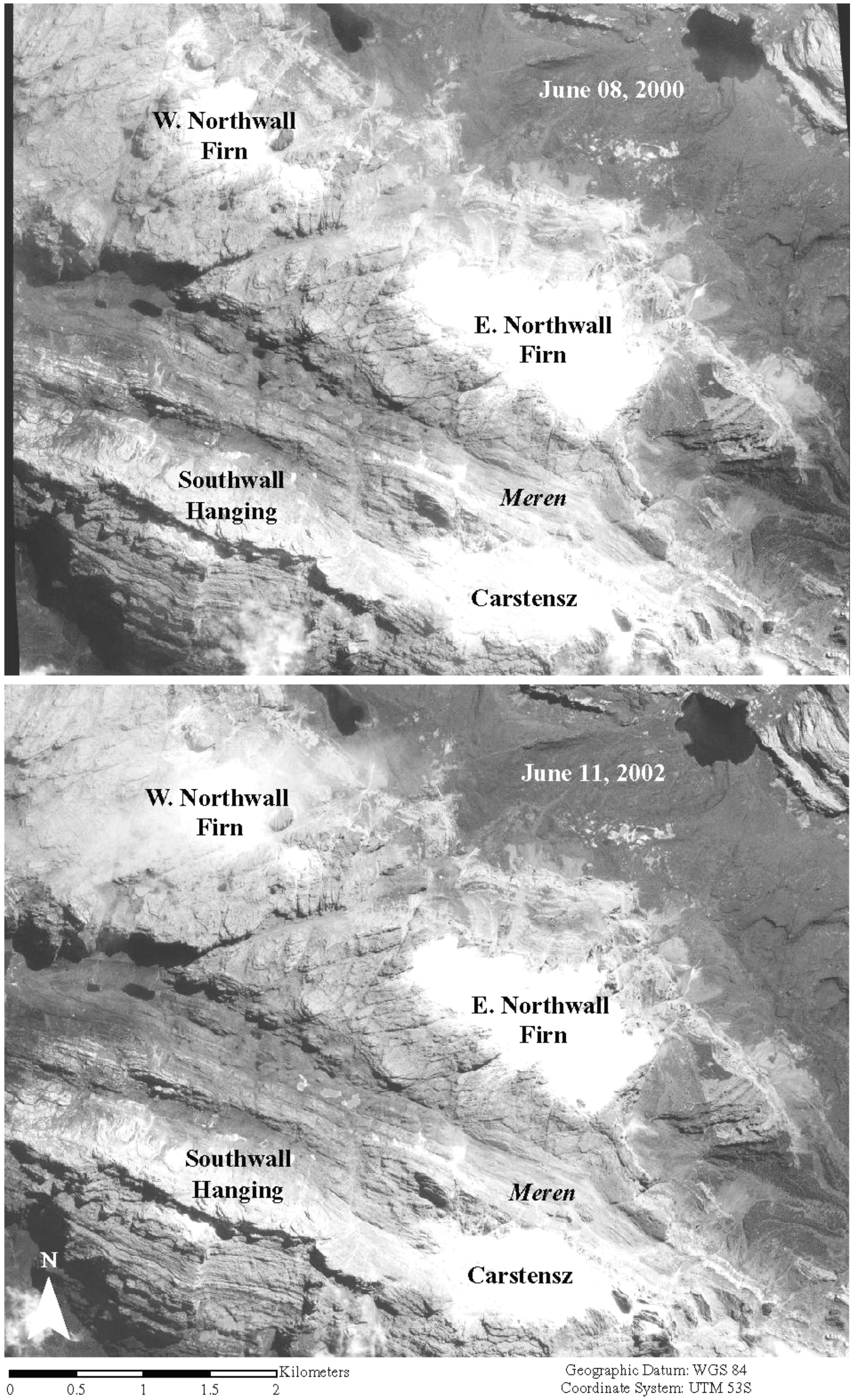
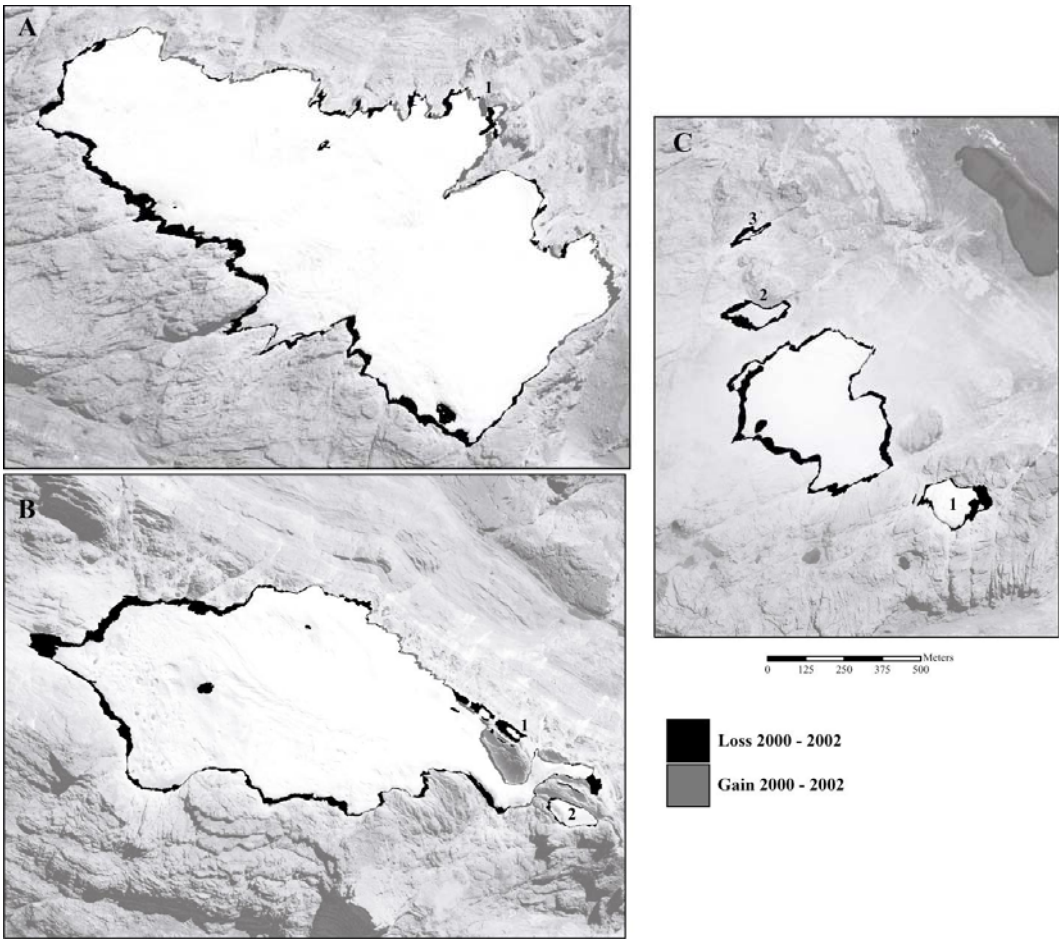


Figure 2. Subsets of the original IKONOS images of the Mt. Jaya glaciers.

wavelengths. Therefore, the glacierized areas were first delineated at a lower spatial resolution (1:4000) to facilitate mapping at the higher 1:1000 map scales. Once the general glacier margin had been mapped at a lower map scale, distinguishing between ice and the surrounding limestone was more easily completed at a scale of 1:000. In a few extremely difficult cases, mapping was restricted to the 1:4000 scale. Overall, for most of the glacier, it was possible to identify the margin within +/– 1 m.

Only ice masses that were at least 500 m^2 were analyzed due to difficulties in assessing the boundaries of smaller ice masses. Once the glacier margins were mapped, glacier areas were calculated within a Geographic Information System (GIS).



Figures 3A, B, and C represent the digitizing results for the E. Northwall Firn, the Carstensz Glacier, and the W. Northwall Firn, respectively.

RESULTS

In the 2000 and 2002 IKONOS images, seven ice masses were observed on Mt. Jaya. These were identified as the E. Northwall Firn, the W. Northwall Firn, and the Carstensz and Southwall Hanging Glaciers (Figure 3). The total ice was calculated to be 2.326 km^2 and 2.152 km^2 in 2000 and 2002, respectively. Total ice loss on Mt. Jaya during this period amounted to 0.174 km^2 representing 7.48% of the ice totals for 2000. Of all the glacial ice lost on Mt. Jaya from 2000 to 2002, the Carstensz Glacier contributed 29.3%, the E. Northwall Firn contributed 31.6%, and the

W. Northwall Firn contributed 39.1%. The calculated areas and losses for the Mt. Jaya glaciers from 2000 to 2002 are shown in Table 1.

Table 1. Areas and losses as determined by analysis of IKONOS images. All areas and losses are given in km^2.

Glacier	2000	2002	Ice Loss	% Ice Loss
Total for Mt. Jaya Glaciers	2.326	2.152	0.174	7.48
Carstensz Glacier	0.747	0.696	0.051	6.83
Main Area	0.734	0.686	0.048	6.54
Ice Mass 1	0.003	0.001	0.002	66.67
Ice Mass 2	0.01	0.009	0.001	10
E. Northwall Firn	1.228	1.173	0.055	4.48
Main Area	1.228	1.17		
Ice Mass 1	0	0.003		
W. Northwall Firn	0.351	0.283	0.068	19.37
Main Area	0.287	0.245	0.042	14.63
Ice Mass 1	0.037	0.026	0.011	29.73
Ice Mass 2	0.022	0.011	0.011	50
Ice Mass 3	0.005	0.001	0.004	80

The E. Northwall Firn

The total ice mass representing the E. Northwall Firn was calculated to be 1.228 km^2 in 2000 and 1.173 km^2 in 2002, resulting in a loss of 0.055 km^2 (Figure 3A), a 4.5% loss from the 2000 area. In 2000, the E. Northwall Firn was a single ice mass, but by 2002 a small portion had separated to the northeast and another to the southwest. The area of the northeast mass was calculated to be 0.003 km^2 in area, but the southwest portion was too small to be accurately measured. This left the main E. Northwall Firn to be 1.17 km^2.

Carstensz Glacier System

The total ice mass representing the Carstensz Glacier System was calculated to be 0.747 km^2 in 2000 and 0.696 km^2 in 2002, resulting in a loss of 0.051 km^2, a 6.83% loss from the 2000 area (Figure 3B). (The Carstensz Glacier system consists of the Carstensz, Wollaston, and Van de Water Glaciers. The Carstensz Glacier is the main area and shares a firn field with the smaller Wollaston and Van de Water Glaciers [Allison and Peterson, 1976].) The Wollaston Glacier appears to have disappeared by 2000. This observation is supported by the 1994 report (Peterson and Peterson) that the Wollaston Glacier was nearly gone. However, exact determination of whether the Wollaston Glacier has disappeared and calculations for the area of the Van de Water Glacier could not be measured because the divide between these small ice masses and the main Carstensz cannot be determined in either the 2000 or 2002 image. Although the Carstensz Glacier has largely remained contiguous, approximately six smaller ice masses were observed in the 2000 image appearing to have separated from its eastern edge. By 2002, only three of these smaller ice masses remained, of which only the size of two could be accurately determined by visual analysis. Ice Mass 1 was calculated to be 0.01 km^2 and 0.009 km^2 in 2000 and 2002, respectively, and Ice Mass 2 to be 0.003 km^2 and 0.001 km^2. The Carstensz, excluding the smaller portions, was calculated to be 0.734 km^2 in 2000 and 0.686 km^2 in 2002.

The W. Northwall Firn

In 2000 and 2002, the W. Northwall Firn consisted of four remaining ice masses. This indicates further separation of the Northwall Firn since before 1981 when aerial photos showed the W.

Northwall Firn as three separate firn fields. The three separate firn fields were confirmed in 1983 Landsat images and reported by Allison and Peterson (1989). The total ice mass representing the W. Northwall Firn was calculated to be 0.351 km^2 in 2000 and 0.283 km^2 in 2002 resulting in a loss of 0.068 km^2; a 19.4% loss from the 2000 value (Figure 3C).

The Southwall Hanging Glacier

In 2002, the Southwall Hanging Glacier was identified as a small ice mass. However, shadows in the image affected the accuracy with which this ice mass could be digitized, and thus no areas could be accurately measured.

The Meren Glacier

Sometime between 1994 and 2000 the Meren Glacier appears to have entirely disappeared as it is not visible on the 2000 image. This finding is consistent with the 1994 report that the Meren Glacier had separated from its accumulation area, had become dead ice, and would soon disappear (Peterson and Peterson, 1994).

DISCUSSION

The Australian Universities' Expeditions in the early 1970s mapped five ice masses (1) the Meren Glacier, (2) the Southwall Hanging Glacier, (3) the east and (4) west Northwall Firn areas, and (5) the Carstensz Glacier system, which included the Wollaston and Van de Water Glaciers (Allison and Peterson, 1976). With the exception of the Meren Glacier, and possibly the Wollaston Glacier, all of these ice masses were identified in the 2000 and 2002 images. A summary of the published glacier areas (Allison, 1974; Allison and Peterson, 1976; Allison and Peterson, 1989; Peterson and Peterson, 1994), as well as the results from the analysis of the IKONOS images for 2000 and 2002, are given in Table 2 and are shown visually in Figure 4. Comparing the mapped area in 2000/2002 with glacier areas from previous studies indicates that, overall, the glaciers are continuing a recessional trend that began in the mid 1800s.

In 1936 the Northwall Firn was reported as a single, contiguous firn field (Dozy, 1938, as cited by Allison, 1974). By 1972, the Northwall Firn had split into two ice masses separated by the New Zealand Pass. This separation is thought to have occurred some time between 1942 and 1962 (Allison and Peterson, 1976). Disintegration of the Northwall Firn into four independent firn fields was noted by Landsat mapping of the glaciers in 1982 and 1983 and confirmed by aerial photographs (Allison and Peterson, 1989). In the 2000 IKONOS images five ice masses were identified as the Northwall Firn: four within the W. Northwall Firn area and one large E. Northwall Firn mass. For the periods of 1972–2000 and 2000–2002, the ice loss for the W. Northwall Firn was calculated at 2.15 km^2 and 0.07 km^2, respectively. For the same time periods, the E. Northwall Firn lost –0.005 km^2 and 0.06 km^2. The gain in area for the 1972–2000 period may represent a portion of the E. Northwall Firn that was previously included in the area measurements of the Meren Glacier. Previous measurements of the E. Northwall Firn considered only the portion of the ice mass that was not feeding the Meren Glacier. As the tongue of the Meren receded, this boundary shifted (Allison, 1974). With the separation of the Meren Glacier from its accumulation area and its disappearance, a portion of the E. Northwall Firn area mapped from the 2000 IKONOS image could have, at one time, represented part of the Meren Glacier.

Table 2. Summary of published glacier areas. Areas for 1850 to 1972 obtained from summary provided by Allison (1974) and Allison and Peterson (1976). Areas for 1972 (corrected) and 1974 obtained from Allison and Peterson (1989) and areas for 1987 from Peterson and Peterson (1994).

	Neoglacial (ca. 1850)	1913	1936	1942	1962	1972
Entire Mt. Jaya area	18.8		13			6.95
Total Northwall Firn	9.1		8.3	5.5		
E. Northwall Firn						1.1
W. Northwall Firn						2.5
Meren Glacier	5.1		2.8	2.6	2.1	1.95
Total Carstensz System	3.6		1.6			1.2
Carstensz Glacier	2.5		1.25	1.1	0.95	0.89
Wollaston Glacier	0.5	0.3	0.2			0.17
Van de Water Glacier	0.6	0.2	0.15			0.14
Southwall Hanging Glacier	1.0	0.4	0.3			0.2

	1972 (Corrected)	1974	1987	2000	2002
Entire Mt. Jaya area	7.3	6.4 (6.6)	3.0	2.33	2.15
Total Northwall Firn	3.6	2.8 (3.0)		1.58	1.45
E. Northwall Firn				1.23	1.17
W. Northwall Firn				0.35	0.28
Meren Glacier	2.2	2.1		0	
Total Carstensz System	1.4	1.4		0.75	0.7
Carstensz Glacier				0.75	0.7
Wollaston Glacier					
Van de Water Glacier					
Southwall Hanging Glacier	0.1	0.1			

The 2000 and 2002 areas are the results from this study. Ice loss rates for the Mt. Jaya Glaciers were calculated and are given in Table 3. The overall trend for the area is an increasing rate from 1936 to 1974, decreasing from 1974 to 2000, and then again increasing from 2000 to 2002. However, the greatly accelerated rate during the 1972 to 1974 period and the rate increase for 2000 to 2002 may not necessarily be representative of anomalies in the record, since the other rates are averaged over longer periods. For example, if the 1972–1974 areas are averaged into the 1974–1987 areas, then the trend of increasing rates of loss continues until 1987. Also, the 1972–1974 rates are based partly on Landsat image analysis. The coarse resolution of these images limits the accuracy with which areal changes in glacier extent over a two-year period can be made.

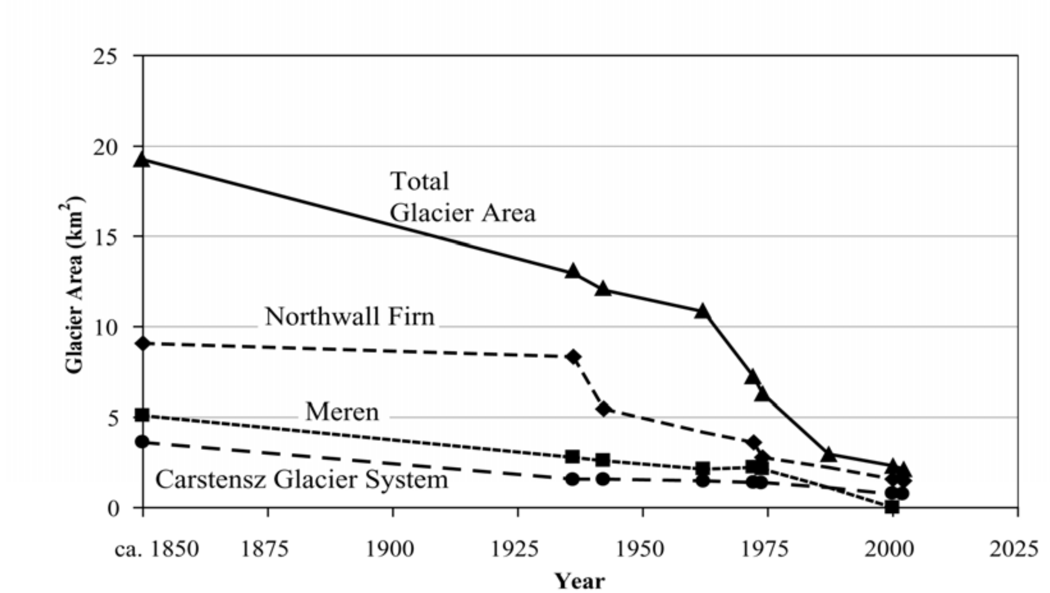


Figure 4. Receding glacier areas in the Mt. Jaya region from ca.1850 to 2002.
Symbols represent data points.

Analysis of the rates of ice loss for each of the main glacial areas indicates that the Carstensz and Meren (until its separation from its accumulation area) glaciers have experienced fairly steady rates of loss over the past century. However, the rate for the Northwall Firn has fluctuated greatly. This is most likely due to topographic differences between the small valley glaciers and the firn field, which lies atop a ridge. Peterson and Peterson (1994) also report that the lower recessional rate of the Carstensz Glacier is partly due to a higher percentage of its accumulation area being situated at higher altitudes. The physical processes of glaciers are complicated and lack of more frequent, detailed studies of these glaciers does not permit a precise explanation of the causal factors.

Table 3. Rates of ice loss from ca. 1850 to 2002. All rates are given in km^2 yr^{-1}.

Glacier	1850–1936	1936–1942	1942–1962	1962–1972	1972–1974	1974–1987	1987–2000	2000–2002
Mt. Jaya*	0.07	0.16			0.35–0.45	0.26–0.28	0.05	0.09
Northwall Firn	0.01	0.47	0.06		0.3–0.4	0.05		0.065
Carstensz Glacier	0.02	0.01			0	0.025		0.025
Meren Glacier	0.03	0.03	0.025	–0.01	0.05	>0.08		—

*Includes the Harrer and Southwall Hanging Glaciers.

CONCLUSIONS

Changes in the areal extent of glaciers currently existing in the Mt. Jaya region of Irian Jaya, Indonesia, were determined using IKONOS images. The recession of Mt. Jaya glaciers, which began in the mid-19th century, has continued through 2002. Over the past century, the Harrer, Meren, and possibly the Wollaston Glaciers have disappeared. Between 1974 and 2000 the overall recession rate for the Mt. Jaya glaciers decreased. This contrasts with the IPCC (2001) assessment that retreat of tropical glaciers, including in Irian Jaya, has accelerated. However, this decreased rate appears to stem primarily from the 1972–1974 retreat rate of the Northwall Firn. Although this rate seems unusually high, it is not without precedent. A similarly high retreat rate was calculated for the Northwall Firn area from 1936 to 1942.

More frequent studies are required to better determine and understand the retreat of the Irian Jaya glaciers. Remote sensing technology, such as high-resolution IKONOS images, makes more frequent glacier observations possible. With IKONOS, glacier mapping was confidently completed with glacier boundaries identified at the meter scale in many instances. In addition, IKONOS images can be used as a ground truthing source in combination with other technologies, such as ASTER, that can provide additional information by which the understanding of glacier-climate dynamics can be improved.

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