3.1 INTRODUCTION

The Carstensz area (4°S) is one of the few present day glacierized equatorial areas. Other tropical glaciers exist in Africa, on Mt. Kenya (Charlery 1935; Hastenrath 1975), Mt. Kilimanjaro (Humphries 1959) and the Rwenzori (Whittow et al. 1963), and in the South American Andes (e.g. Sierra Nevada de Cocuy, Nevada del Tolima and Nevada de Huila of Colombia and Paramo de Almorzadero and Quito in Ecuador). The extensive Qelccaya ice cap in Peru (19°S) is the subject of current investigation (Mercer et al. 1975).

The present upsurge of interest in the nature and direction of climatic change, and the effect of such change on social and economic factors (e.g. Bryson 1975) has led to an enquiry into the stability of climate in the past. Studies of the fluctuations of ice fronts have been a major source of data. The tropics are important because of their role in the world radiation balance, but meteorological records for most tropical areas (especially at high altitudes) cover only short periods and are very scarce.

Small tropical glaciers might be expected to respond sensitively, although complexly, to climatic changes, and thus a record of the ice fluctuations in Irian Jaya can help to extend our knowledge of climatic trends in this region.

3.1.1 The present ice areas

The total area covered by perennial ice and snow in the Carstensz area at the end of 1972 was about 6,9 km². The ice and snow covered area can be divided into five ice masses: the eastern and western portions of the Northwall Firm, the Meren Glacier, the Carstensz Glacier system, and the hanging glaciers of the Southwall (Photo 3.1).

The Northwall Firm, a continuous firm field at the time of Colijn's 1936 expedition (Dozy 1938), divided into two separate ice masses some time between 1942 and 1962, so that the area known as New Zealand Pass became ice free. The western portion of the Northwall Firm is a small ice-
field, draped along the gentle southwest facing slope atop the Northwall anticline. The icefield, with an area of about 2.5 km², extends for a distance of 3.5 km along the wall with a mean width of about 0.7 km. Its highest elevation is approximately 4,750 m and the lowest elevation is about 4,510 m. The edge of the icefield is lobed and there is visible evidence of minor flow in the field in a generally south-westerly direction.

The eastern portion of the Northwall Firn, a continuation of the western portion but now separated from it by New Zealand Pass, is in conjunction with the Meren Glacier (Photo 3.2). In this book, the eastern portion of the Northwall Firn is considered as being only that part of the icefield which does not feed the Meren Glacier. The area of this icefield is about 1.1 km², covering an altitude range of from 4,810 to 4,520 m. There is considerable crevassing around the lobed fringe of the ice.

The Meren Glacier (Photo 3.2) is a valley of glacier of Type 1 in Ahlmann's classification (Ahlmann 1948). The tongue of the glacier, which extends into the Meren Valley (Lembah Danau), has retreated substantially this century and is now only 400 m long, with a minimum elevation of 4,260 m. The firn field of the Meren Glacier includes both the upper reaches of the Meren Valley (called the Midden Firn by Dozy) and the eastern end of the Northwall Firn field around Ngga Pulu (4,862 m). The total area of the Meren Glacier is 1.95 km². The mean width of the tongue is 0.4 km and the maximum flowline length (from the summit of Ngga Pulu to the snout) is 2.0 km.

The Meren Glacier is characterized by, and takes its name from, the large number of englacial lakes which occur in the ablation zone (Photo 3.3 and Chapters 6 and 7). The lakes reach diameters of up to 10 m with water depths of up to 5 m. Some of the lakes are interconnected and melt streams drain the surface of the ablation zone, particularly on the southern side where the ice is least disturbed and almost stagnant. Extensive growths of cryovegetation are present on the Meren Glacier and black algae colonies are concentrated in the lakes (Chapters 6 and 7).

A very minor lobe of ice (the "Harrer" Glacier) descends from the Midden Firn over the east wall (Photo 3.4). The area of this lobe is less than 0.05 km².

The Carstensz Glacier, which lies in the Yellow Valley (Lembah Kuning), parallel to and separated from the Meren Valley by a dividing ridge (the Midden Kam or Celah-tengah), is a valley glacier of Type 1 (Ahlmann 1948) (Photo 3.5). In 1936, a snow bridge connected the Carstensz Firn with the lower Meren Firn (Colijn 1937:164, 165) but this has since disappeared. The Carstensz Firn, which covers the south-western slopes of the East Carstensz Top (ca. 4,810 m) has a maximum elevation of 4,800 m and the glacier tongue descends to 4,380 m. The ablation zone
Photo 3.2 The eastern portion of the Northwall Firn and the Meren Glacier. New Zealand Pass is on the far left; East Carstensz Top, the Carstensz Glacier, and Middenspits on the right. The base camp was situated to the right of the lakes on the flat below the Meren snout.

Photo 3.3 Englacial lakes on the Meren Glacier below survey station FB. The lakes are typically 5 m in diameter.

Photo 3.4 The 'Harrer' Glacier (left foreground) and the east wall of Mt. Jaya (foreground). The foremost peak of the Northwall Firn is Ngga Pulu, and the snow covered peak in the distant background is Idenburg.

Photo 3.5 The Carstensz Glacier with Middenspits (left) and survey station CT on the top of the rock outcrop (right background).
Photo 3.6 The snout of the Wollaston Glacier on the south wall of Mt. Jaya. Survey station CT on the rock outcrop, left), Middenspits (centre) and Ngga Pulu (right background).
Photo 3.7 The Van de Water Glacier and East Carstensz Top (centre foreground) with the Carstensz Pyramid behind.
Photo 3.8 The Southwall Hanging Glaciers and the south face of the Carstensz Pyramid (4,884 m).
Photo 3.9 Part of a LANDSAT 1 (ERTSI) satellite image (MSS Band 7) of the Mt. Jaya region taken on 27 April 1974. Ice covered areas on Mt. Jaya and Mt. Idenburg are clearly delineated and continued retreat is evident. Lakes in the glacial valleys and north of Mt. Jaya, river systems, the northern moraines (Map 1 and Fig. 9.1) and many other features are identifiable. The continuing improvement of such technology provides the key to future remote monitoring of glacier variations.
Photo 3.10 The Carstensz glaciers in 1972 (top) and 1936 (bottom), looking towards the east. Clockwise from left to right: Northwall Firn, Meren Glacier and Meren Valley, Midden Kam (or Celah-Tengah), Carstensz Glacier and Yellow Valley, Carstensz Pyramid.

Photo 3.11 Well developed grikes and karren, together with undisturbed alpine humus soil and vegetation, contrast with the ground covered by the neoglacial advances. The paired moraines in the middle ground mark the neoglacial limit on the floor of the Yellow Valley.

Photo 3.12 Lower Meren Valley taken from above the neoglacial limit on the Midden Kam. The northern arms of the paired moraines that mark the snout positions of the maximum neoglacial advances can be seen in the centre middleground, immediately beyond Lake Hijau. Lake Ketel lower centre, Grasberg background left.
of the Carstensz Glacier is heavily crevassed; the crevasses running transversely near the firm line and becoming more longitudinally oriented towards the snout. Like the Meren Glacier, the Carstensz ablation zone supports extensive cryovegetation growths, but, as the surface is broken, there are few melt streams and only one englacial lake was present in 1972. The area of the Carstensz Glacier is 0.89 km², the maximum flow line length is 1.0 km and the mean width is 0.5 km.

There is little rock debris on the surface of either the Meren or Carstensz Glaciers. The only sizeable lateral moraine is along the south side of the tongue of the Meren Glacier, beneath the scree slopes around survey station FB. A small area of the south-east corner of the snout of the Meren Glacier is covered by debris carried downstream from these scree slopes.

Meltwater from the Northwall Firn, the Meren Glacier and the Carstensz Glacier drain into the basin of the Otonoma River.

Two other small glaciers, the Wollaston Glacier and the Van de Water Glacier (Photos 3.6 and 3.7), are fed from the firmfields on the side of the East Carstensz Top. Both can be classified as mountain glaciers. They descend over the south wall of the Carstensz fold, with highly broken snouts hanging on very steep slopes. The Wollaston Glacier (ca. 0.17 km²) extends over an elevation range of from 4,730 to 4,370 m and has a maximum length of 0.7 km. The Van de Water Glacier (ca. 0.14 km²) extends over an elevation range of 4,810 m to 4,390 m and has a maximum length of 0.6 km.

The Southwall Hanging Glaciers (Photo 3.8) are a number of small interconnected mountain glaciers, plastered as an ice apron on the south face of the Carstensz Pyramid (4,882 m). These glaciers have a total area of about 0.2 km², a maximum elevation of 4,820 m, and descend to about 4,600 m.

Meltwaters from the Wollaston, Van de Water, and Southwall Hanging Glaciers all drain eventually into the Teing River system.

The glaciological studies undertaken by the Carstensz Glaciers Expeditions were concentrated on the two present day valley glaciers, the Meren and Carstensz Glaciers. The results of these studies are reported in Chapter 4. Historical and other evidence for recent changes in the ice areas as a whole are discussed below.

3.2 THE RECENT HISTORY OF THE ICE AREAS

Retreat of glaciers on Mt. Jaya during the present century can be documented from aerial photographs, and the positions of dated cairns, as well as from records of expeditions, the earliest of which was made in 1912 (Wollaston 1914a, b). The most useful records are less than half that old, and so geomorphological and related evidence has been used to augment our knowledge of glacier fluctuation over the past few centuries. Mercer (1967) compiled a bibliography of literature published before 1963, which contains photographs of ice areas in Irian Jaya, and this has been brought up to date by Peterson et al. (1973).
3.2.1 Historically documented records

Map 3 (back pocket) is an overlay for Map 2, and shows ice front positions at the various dates for which information is available. The 1972 positions were surveyed by the CGE; the 1936 and 1962 positions were plotted from photographs and the surveyed positions of cairns left in those years, and most of the 1942 ice-fronts were included on the photogrammetric plot (Chapter 2). The remaining ice fronts were sketched in from photographs only. The positions of the Meren and Carstenz Glacier snouts were also surveyed by the CGE in 1973 but are not plotted on Map 3, being only 10 to 15 m from the 1972 fronts.

The Colijn expedition, in 1936, erected cairns in front of the Meren and Carstenz Glaciers (Dozy 1938): one at a distance of 65 m from the Meren ice front, and two more, 23 m and 105 m respectively, beyond the snout of the Carstenz Glacier. The Harrer expedition, in 1962, erected a cairn 30 m in front of the Meren ice front, and another two in front of the Carstenz ice front and roughly in line with those placed by Dozy. The innermost of Harrer's cairns is assumed to have been at the ice front (Harrer 1964, Plate 3.6). Photos 3.1 and 3.10 compare the ice extent at the time of Colijn's visit with the 1972 extent.

In addition to the cairns and photos of these two expeditions, photos are available from the Wollaston expedition of 1912/13 (Wollaston 1914a, b), the Rouffaer Military expedition of Lieut. Doorman of 1914 and the Roux expedition of 1926 and 1938 (Roux 1940-1950). There are also oblique aerial photographs taken from the passing aircraft of Kroondijk, missionary air services (such as AMI and MAF), and mining and exploration company charter flights. All available air and ground photographs were used to sketch ice front positions in the absence of more reliable data.

The oblique photographs of the USAF Trimetrogon series were used to plot the 1942 ice front position outside the area covered by the vertical photogrammetry. The 1942 Carstenz ice front, and parts of the northwestern Northwall Firn, were plotted in this way. Cloud obscured the ice over part of the trimetrogon coverage and in such cases, stereo plotting was not possible. However ice front positions could be seen on one photo of the photogrammetric model in most cases, and ice fronts appear on the machine plot with good approximation.

The solid line indicating the 1972 ice front, was determined by tachometric survey, the remaining outline for 1972 being derived from range finder observations from established survey control stations, or from uncontrolled photographs. The December 1974 position of the Meren glacier snout was plotted with the aid of measurements and photographs taken by R. Mitton (Newmont Pty. Ltd.).

Some annotated photographs of ice fronts, from various sources, together with selected CGE photographs, are lodged with the World Data Centre (Glaciology) United States Geological Survey, 1305 Tacoma Avenue, South Tacoma, Washington 98402 USA. The original CGE material (mainly negatives and colour positives) is lodged with the Department of Meteorology, University of Melbourne, Parkville, 3052, Australia.

3.2.2 Geomorphologically derived records

Map 3 also shows the limits of the last neoglacial readvance (Chapter 9). This is plotted from geomorphological evidence, which is in many places supported by vegetation patterns. It would be possible to map the limits of the last neoglacial advance from the distribution of plant communities alone, but because contrasts in the maturity of soils and the vegetation succession are closely related to the geomorphological limit, all three types of evidence can be used together.

3.2.2.1 Terminal moraines and the extent of the last neoglacial advance — If the present ice bodies were to greatly advance, valley glaciers would occupy most of the Meren and Yellow Valleys (Lembah Danau and Lembah Kunung) and small glaciers would form in the steep valleys around New Zealand Pass and below the "Harrer" Glacier. Around nearly all of the rest of the ice perimeter, the ice margin would advance over bare limestone slopes that end in steep cliffs. Only the valley glaciers, and, to a lesser extent, the Southwall Hanging Glaciers, are surrounded by rock faces, which would provide a source of debris for moraine building. Hence, it is only in the valleys that terminal moraines marking the limits of minor glacial advances are found.

The limit of the last neoglacial readvance has been plotted from the position of terminal moraines in the Yellow and Meren Valleys, around New Zealand Pass, and in the valley of the "Harrer" Glacier. The paired terminal moraines of the Yellow and Meren Valleys are indistinctly outlined by the contours on Map 2.

The remaining limits have been determined from photographs on which the zone of sparse vegetation, bare rock, and minimal soil and lichen cover is well marked. The positioning of this zone is aided by the much better development of minor solution sculpture (karren) outside the area affected by any of the four neoglacial advances of the last 3500 years (Chapter 9). The contrast between the zones is most marked at the major paired moraines of the Yellow and Meren Valleys (Photos 3.11 and 3.12).

Up-valley from the moraines, the valley floors and sides are plastered with boulder clay and drainage is on the surface. There is a good indication of past ice thickness and surface gradient in the well-marked lateral moraines, and in the limits of fresh till. Soil formation and plant colonisation are in an early stage (Chapter 8), the moraine crests are sharp, and the slopes are unstable. Depressions between valley wall and lateral moraine have not accumulated organic matter and, especially in the Yellow Valley, there is much bare ground.

Beyond the limits of the neoglacial advances the soils and the vegetation communities, even at elevations higher than the neoglacial moraines, are stable and mature. Many of the grikes (up to a metre or so deep) are occupied by a dark alpine humus soil, and the weathering forms on exposed rock exhibit a full range of minor solution sculpture. Many of these minor karren features are also found on limestone outcrops near the glacier front.
3.3 SUMMARY OF ICE RETREAT DATA

The most precise measurements of ice snout retreat are available for the Meren and Yellow Valleys. Retreat rates for mean snout positions are presented in Table 3.1, which has been extended from the data given by Allison (1975).

Changes in the total glaciated area and in ice volume are shown in Table 3.2. The estimates of total ice volume are approximate only, being derived from sketchy information on ice thicknesses. The 1972 ice volumes are derived from the CGE glaciology studies (Chapter 4), the 1942 volumes from a few photogrammetrically determined surface elevations (Map 2) and the volumes at the maximum neoglacial extent from the geomorphological evidence of ice thickness. The one elevation determined by the Colijn expedition that is inconsistent with CGE elevation, that for the summit of Ngga Pulu, would suggest that the top of the Meren Glacier accumulation zone had lowered by about 45 m between 1936 and 1973 (Chapter 2).

<table>
<thead>
<tr>
<th>Year</th>
<th>Source</th>
<th>Meren Glacier</th>
<th>Carstensz Glacier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Horizontal retreat since last observation (m)</td>
<td>Approximate mean elevation of terminus (m)</td>
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<tr>
<td>1850</td>
<td>see text</td>
<td>3950</td>
<td>3950</td>
</tr>
<tr>
<td>1926</td>
<td>Dozy (cairn)</td>
<td>2080 24.2</td>
<td>2080 258</td>
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<td>1942</td>
<td>USAF trimetrogon photos</td>
<td>3223 53.0</td>
<td>4221 13</td>
</tr>
<tr>
<td>1962</td>
<td>Harrew (cairn)</td>
<td>478 23.9</td>
<td>4240 19</td>
</tr>
<tr>
<td>1972</td>
<td>Feb, CGE survey</td>
<td>374 37.4</td>
<td>4300 50</td>
</tr>
<tr>
<td>1973</td>
<td>Feb, CGE survey</td>
<td>15 15.0</td>
<td>--</td>
</tr>
<tr>
<td>1974 (pers. com.)</td>
<td>Dec, R. Mitton</td>
<td>185 100.9</td>
<td>--</td>
</tr>
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</table>

3.2.2.2. Mode of retreat since the last neoglacial advance — The retreat of the Carstensz Glacier from the moraines in Photo 3.14 appears to have been relatively steady and uncomplicated. Below about 4,270 m, retreat took place across glacial deposits, and a regular series of small (~30 cm) retreat moraines occupy the central portion of the Yellow Valley between Dozy’s caisns and the incised section of the creek (Photo 3.15). Up-valley from these cairs the valley floor is mainly of limestone bedrock and no moraine ridges are found.

The central portion of the Meren Valley, between Lakes Ketel and Biru, is also occupied by small retreat moraines up to 1 m high. They display some irregularity in orientation and spacing, probably due to the breakdown of regular ice flow as the glacier thinned across the prominent bedrock step immediately up-valley from Lake Biru. Apart from the distinct terminal moraine edges, and associated lateral moraines, that indicate early stages of ice retreat, there are no well marked still stands in either the Meren or Yellow Valleys (Photo 3.12).

The only other place where the neoglacial advance terminated in proximity to a supply of detritus and on slopes gentle enough for moraine ridges to form, was north of New Zealand Pass. The moraine ridges here indicate a significant still stand, which was probably near the neoglacial limit, although ice might at one stage have tumbled over the cliff immediately below the moraines (Photo 3.16).

3.2.2.3 Age of the last neoglacial advance — There is no directly measured age for the initiation of retreat from the neoglacial limits. Neither the lakes and ponds, nor the closed depressions within the area, have accumulated organic matter suitable for dating. The vegetation patterns and lichen growth are unsuitable for judging age, and tree rings are absent in the few woody species that have colonised the moraines. The fresh nature of the moraine crests and of the lake and pond margins, and the lack of erosion, all indirectly indicate that retreat began within the last few centuries. The Yellow Valley sequence shows that the retreat post dates 1350 to 1500 BP (Chapter 9).

Extrapolation of retreat rates calculated for the period 1936–1974 suggests that retreat from the last neoglacial advance might have begun about 120–150 years BP. This date is confirmed by numerical modelling of the retreating glaciers (Sec. 3.4). Preliminary results from thermoluminescence, using a method devised after Zeller (1968), do not contradict this hypothesis.
Table 3.2 Approximate changes in glaciated area and ice volume

<table>
<thead>
<tr>
<th></th>
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<th>1942</th>
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<tr>
<td></td>
<td>(km$^2$)</td>
<td>(km$^2$)</td>
<td>(km$^2$)</td>
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<tr>
<td>Northwall Firm*</td>
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<td>8.3</td>
<td>5.5 (280)</td>
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<td>11.1</td>
<td>11.1 (410)</td>
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<td>Carstensz Glacier</td>
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<td>1.1 (55)</td>
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<td>Van de Water</td>
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<td>0.14</td>
<td>2</td>
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<tr>
<td>Glacier</td>
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<td>41</td>
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<td>13.0</td>
<td>13.0</td>
<td>6.9</td>
<td>254</td>
</tr>
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</table>

* The ice divide between the Meren Glacier drainage basin and the Northwall Farm shifts as the Meren snow retreats.
** Extent of the 1936 southern ice areas have been obtained from a plot of the Goljak Expedition aerial oblique photographs (kindly supplied by Dr J. J. Dozy) onto the C.G.E. base map. The estimated areas differ slightly from those given by Dozy (1938).

3.3.1 Local significance of the ice retreat

The changes of the ice extent on Mt. Jaya have both local and regional significance. The regional implications, basically climatic, require an assessment of evidence from other high mountains of Irian Jaya, but many local effects are immediately obvious. These effects include:
- up-slope and up-valley movement of vegetation patterns,
- formation of new lakes, and their colonisation by lacustrine flora and fauna (Chapter 7),
- reopening of trade routes over the Northwall between the Kemabu Plateau and the southern valleys (Chapter 11),
- upward migration of cryovegetation (Chapter 6),
- gradual coincidence of the climatic and orographic snowlines. The rising snowline would progressively eliminate areas relying on topographic effects for their accumulation. This effect is important in assessing present day New Guinea snowlines.

3.3.2 Ice fluctuations in other parts of Irian Jaya

The recent pattern of ice retreat for the other ice fields of Irian Jaya seems to have been similar to that observed on Mt. Jaya. The recession of ice and snow in the area is detailed by Peterson et al. (1973). Two of the three small ice domes on Mt. Idenbarg (4,717 m) in 1908 had disappeared by 1943, and the remaining dome has receded markedly since then. Similar retreats are documented for Mt. Tikora (4,730 m), where the ice had disappeared by 1962, and for Mt. Mandala (4,640 m).

3.4 POSSIBLE CAUSES OF THE ICE RETREAT

Ice masses can retreat either because they have a mass budget deficit or, in the case of periodically surging glaciers, as part of a cycle of rapid advance and slow retreat. Although the total mass budget for the Meren and Carstensz Glaciers was negative in 1972 (Chapter 4), this does not necessarily imply that there has been a budget deficit for the last 100 years or so, and the possibility that the glaciers have surged must be considered.

Basal sliding is the major velocity component of a glacier during a surge. For some glaciers, a critical stage can be reached, where positive feedback between basal lubrication due to frictionally generated melt and the sliding velocity, causes a surge. Budd (1975) suggests that surging glaciers can be separated from ordinary glaciers on the basis of the mass flux rate (ρ) and surface slope (s), with glacial velocities being those with values of ρs > 0.08 greater than about 500 m a$^{-1}$ (ρ is a shape factor dependent on the glacier cross-section). The mass flux rate at the equilibrium line can be expressed as:

$$\Phi = \frac{Q}{W \cdot s_1 \cdot s_2}$$

where Q is the total net accumulation for the accumulation zone,
W is the surface width near the equilibrium line, and
s1 and s2 are shape factors (s1 = 0.5).

From the results of Chapter 4, the value of ρs > 0.08 for the Carstensz Glacier is estimated to be about 200 m$^2$ a$^{-1}$ (Q > 400 m$^2$ a$^{-1}$ × 10$^6$, W = 700 m, s = 20 per cent, s = 0.9). For the Carstensz Glacier surging: ρs > 250 m$^2$ a$^{-1}$ (Q > 500 m$^2$ a$^{-1}$ × 10$^7$, W = 1,500 m, s = 25 per cent, s = 0.8). On this basis it appears unlikely that either the Meren or Carstensz Glacier surged.

It is possible to model glacier surges for a certain class of glaciers by including a simplified theory of sliding, with constant lubrication factor (ρ) and viscosity (η), in the two-dimensional steady state glacier model of Budd & Jansen (1975) (v. Budd 1975). Both the Meren and Carstensz Glacier steady states have been modelled (Allison 1975) and their likelihood of surging was tested by introducing the basal sliding equations into the model. The sliding velocity of both glaciers was very low (~1 m sec$^{-1}$) and neither showed any indication of surging for values of ρ and η comparable to those used for other temperate glaciers.

Additional evidence discounting surging of the Carstensz glaciers can be found in the apparently synchronous retreat of the Meren Glacier and the
Carstensz Glacier, in the lowering of the surface of the Meren accumulation zone during retreat of the snout (Chapter 2) and in the explanation of the observed neoglacial ice profiles by a steady state glacier model without basal sliding (Allison & Kruss, in press).

Given that the Carstensz Glaciers are highly unlikely to experience regular surges, then the retreats must be due to a mass budget deficit. The mass budget of a glacier is controlled, through the processes of accumulation and ablation, by climatic elements, and hence the retreat of the glaciers implies a climatic shift since the time of the last neoglacial advance.

The retreat of the glaciers of Irian Jaya is not unique, but appears to coincide with a general retreat of alpine glaciers on a global scale (e. g., Kasser 1973; Kasser 1967). In particular, other tropical glaciers show a general pattern of steady monotonic retreat (e.g., Hastenrath 1975 (East Africa); Schubert 1972 (Venezuela); Wood 1970 (Colombia)) and the prima facie explanation for such widespread retreat is that of a zonal climatic shift in tropical regions.

The link between the glacier mass budget and the climate is complex. A deficit in a temperate glacier mass budget can be caused by increased air temperature, decreased solid precipitation, increased radiation absorption (due to changes in surface albedo, cloudiness, or solar radiation), increased evaporation (due to changes in humidity or windspeed), or by a combination of any or all of these factors. However, given the reported increase of temperature in the tropical zone between 1870 and 1940 (Mitchell 1961), a general warming is the most attractive explanation of the widespread tropical glacier retreats.

The observed retreat of the Carstensz glaciers from their present day extent, can be well matched by the numerical model of the glaciers if a steady warming rate of 0.6°C per century is simulated by an increase in the model equilibrium line altitude (0.7°C/100 m) (Allison & Kruss, in press). The model of the retreating glaciers matches both the observed retreat rates and the intermediate ice profiles inferred from the geomorphology and aerial photographs. The applied warming rate of 0.6°C per century is in excellent agreement with the warming rate calculated from tropical temperature data (Mitchell 1961). The model suggests that for Mt. Jaya, the warming would need to have commenced around 1830-1850 and that there would have been a phase lag of about 30 years before the glaciers started to retreat significantly.

Although an increase in temperature is suggested as a very likely cause of the retreat of the glaciers of Mt. Jaya, other factors, or combinations of factors, remain as possible causes. A decrease in precipitation alone is unlikely as the cause, requiring a mean annual precipitation decrease of over 1 m per century to give the observed retreat, but small decreases in the glacier surface albedo would have led to extensive retreat. Possible mechanisms for decreased albedo exist in either increased cryovegetation colonization of the ice or in decreased fresh snowfall on the accumulation zones.

3.5 REFERENCES

Allison, J. & Kruss, F., in press, Estimation of recent climate change in Irian Jaya by numerical modelling of tropical glacier systems. (Australian Conference on Climate and Climatic Change, Melbourne, December 1975), Arctic and Alpine Environments 9(1).
Colijn, A. H., 1937, Naar de eeuwige sneeuw van tropisch Nederland. Amsterdam, Schelte & Giltay.
4.1 The Meren and Carstensz Glaciers

The Meren Glacier and the Carstensz Glacier, the major valley glaciers, account for about 40 per cent of the total present day ice covered area. Both glaciers have retreated considerably from their recent maximum extent (Chapter 3) but are still the most dynamic ice masses in the region. The detailed glaciological observations undertaken by the Carstensz Glaciers Expeditions were confined to these two glaciers.

The surface topography of the Meren Glacier and the Carstensz Glacier is shown in Fig. 4.2. The ice boundary of the ablation zone of both glaciers was determined by tacheometric survey from a primary network of control stations on rock (see Chapter 2). The northern ice boundary of the Northwall Firm was determined with reference to photogrammetry from the 1942 trimetrogon air photographs and from ground photography of the Carstensz Glaciers Expeditions. Eastern and southern ice boundaries have been estimated from ground and aerial oblique photographs of the CGE.

Surface elevation contours have been drawn from the tacheometric data and from the spot elevations of a network of canes on both glaciers (Fig. 4.1). The cane elevations were found by triangulation from the control stations.

The average surface slope of the Meren Glacier, along a central flow line, is 25 per cent and that of the Carstensz Glacier is 20 per cent, but the distribution of surface slope is markedly different for the two glaciers. The maximum slope on the central flowline of the Meren glacier occurs where the Northwall Firm flows into the Midden Firm, and the accumulation zone (average surface slope $\bar{a}$ of 30 per cent) is steeper than the ablation zone ($\bar{a} = 22$ per cent) where the englacial lakes occur. In contrast, the Carstensz Glacier has a relatively flat accumulation zone ($\bar{a} = 15$ per cent) and a broken ablation zone that increases in slope towards the snout ($\bar{a} = 26$ per cent).