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New Zealand glacier snowline survey, 2000

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Abstract

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New Zealand glaciers have experienced significant changes as a result of recent weather patterns. An extensive and detailed survey of direct, undelayed changes in annual glacier mass balance, which uses the altitude of end-of-summer glacier snowline as a surrogate for balance change, has shown that the recent trend of positive balances has reversed since 1998. Although all balances measured were negative, the change has yet to pass through some glacier systems and a few are still continuing to advance. The survey was carried out by photographing the position of the snowline on 49 selected index glaciers from a light aircraft. The altitudes of some of the snowlines recorded were near the highest levels measured since surveys began in 1977.

Introduction

The results presented here continue an annual glacier/climate monitoring programme, begun in 1977 for the New Zealand glacier inventory, in which the position (altitude) of the end-of-summer snowline of 49 selected glaciers arranged in transects across the Southern Alps is photographed (Figure 1).

New Zealand's 3144 glaciers extend from Mount Ruapehu in the North Island at 39° 15' S to southern Fiordland at 45° 57' S. Three North Island volcanic cones reach close to the permanent snowline, but only Mount Ruapehu, with a summit at 2752 m, supports glaciers. Because of the distances involved, these glaciers are not included in this survey. In the South Island, average peak summits range from 1850 m in Fiordland to 3000 m in the central Southern Alps and descend to 2000 m in the north-central Southern Alps. To the northeast, the Kaikoura Ranges reach to over 2700 m, where active rock glaciers have developed under the dry climate.

New Zealand has a humid maritime climate, with the Southern Alps lying across the path of prevailing westerly winds. Mean annual precipitation rises rapidly from 3000 mm along the narrow western coastal plains to a maximum of 15 000 mm or more in the western part of the Alps close to the Main Divide. From this maximum, precipitation diminishes exponentially to about 1000 mm in the eastern ranges. This creates steep eastward precipitation gradients and the mean altitudes of the glaciers closely follow these gradients (Chinn & Whitehouse 1980).

Glaciers and climate change

Glacier fluctuations are amongst the clearest signals of climate change, because glaciers are highly sensitive, large-scale indicators of the energy balance at the Earth's surface. They give convincing signals of past climate change from decades to millennia. Atmospheric changes are signalled by direct, undelayed changes in annual mass balance, which are filtered, smoothed, and enhanced before they become apparent at the glacier front. Glacier snowline altitudes give a direct value for annual glacier health and balance, whereas the climate signal indicated by glacier frontal positions is severely modified by glacier response times and dynamics.

The Equilibrium Line Altitude (ELA)

The winter snowpack normally covers the entire glacier in a wedge, with the greatest snow depths near the highest altitudes, tapering to zero at the lower edge. This lower margin, or transient snowline, of the snowpack rises as summer melt progresses until it reaches a maximum altitude for the year at the end of summer (in April). Located somewhere near the middle of the glacier, this end-of-summer snowline indicates an equilibrium line where snow fall exactly equals snow loss over the past glacial year. This line, normally visible as the contrast between the discoloured concentration of dust on firn and the clean snow of the previous winter, is the glacier snowline for that year. It is the *altitude of this glacier snowline* (defined as the Equilibrium Line Altitude (ELA) by Meier & Post (1962)) that is measured by these snowline surveys. For any individual glacier in equilibrium with the climate, the altitude of the annual glacier snowline, averaged over many years, defines the steady-state Equilibrium Line Altitude (steady-state ELA). A snowline of this altitude will indicate zero change to the balance of the glacier, and, if continued over many years, there will be no change in glacier size.

A climate change will change the glacier mass balance and shift the altitude of the annual ELA. Thus the annual snowline position with respect to the long-term or steady-state ELA is used as a surrogate for annual balance changes at each glacier (Chinn 1995). It is the *departure* of the glacier snowline from the steady-state ELA that is reported here. The trend surface of this difference is *not* a measure of absolute snowline altitude: it is a measure of the *change from the average climate* at each glacier.

Glacier studies worldwide have demonstrated that the ELA lies at an altitude where the ratio of the accumulation area to the total glacier area (AAR) has an average value close to 0.6. For glaciers in balance, the steady-state ELA would be the mean of many years' readings, but, as the New Zealand glaciers have been dominated by positive balances since this programme began, a mean value of observed snowlines is not appropriate. In past reports, the AAR and thus the annual ELA altitude has been estimated from glacier maps. With the recent completion of the NZMS 260 maps at a scale of 1:50 000, more appropriate and accurate ELA values have been derived by the laborious process of digitising area curves for each glacier. The long-term ELAs are read off the glacier area curves at 0.4 of the area up from the glacier terminus.

Field methods

Collection of field data involves flying over the glaciers in a light aircraft to take simple oblique photographs of the position of the end-of-summer glacier snowlines. The snowlines visible on the photographs are sketched on to a map of each glacier and the resulting accumulation areas are mapped and measured by digitiser. The "snowline altitude" is then accurately read from the glacier area-altitude curve.

Survey flights

On the flights, a folder of photographs of each glacier is held by the "navigator" seated beside the pilot. These photographs are used to closely duplicate the position from which previous photographs were taken. The photographer operates from the back seat, shooting from both sides of the aircraft. These surveys also provide the opportunity to record geomorphic features and events, other glaciers, and selected glacier termini in addition to the index glaciers. The flights are made mainly between 9000 ft (2700 m) and 10 000 ft. (3000 m). An altitude of at least 10 000 ft gives the best angle on the glacier snowlines, but civil aviation regulations do not permit normal flights to remain above this altitude for prolonged periods.

The flight should be made on the elusive "last perfect day before the first winter snowfall", after the end of significant summer melt. Significant melt continues throughout February and March, but by April there is a high probability that a snowfall will have occurred. Experience has shown that although successful surveys have been made in April, there is about a 1 in 4 probability of snow before this time. A light fall of fresh snow will conceal the position of the snowline, so the surveys are planned for the first suitable weather from the beginning of March. Suitable weather to fly the entire Southern Alps demands particularly settled conditions. A successful survey cannot be guaranteed as there is also a 1 in 10 probability that there will be no suitable flying weather in March before a fresh snowfall occurs.

The flights were made in a Cessna Cardinal 177 chartered from Wanaka Flightseeing at Wanaka airfield. This high-wing aircraft is eminently suitable as it has no obstructing wing struts and a relatively high cruising speed. The detailed mountain knowledge of the pilot permitted direct "front window" navigation without any flying time lost to searching for the index glaciers.

The 1999–2000 glacial climate

After an unremarkable 1999 winter, the 2000 ablation season opened with a spectacular northwest storm in December which brought a 100 to 150 year return-period precipitation to the Otago mountains with associated flooding. This event would have enhanced ablation losses on the glaciers. January was one of the coldest on record for Queenstown and the wettest for Dunedin. Southeasterlies with rain with snow to the foothills at the beginning of February brought an end to a prolonged drought in north Otago (the December storm did not extend into Central Otago).

Itinerary

March began with a stationary anticyclone in the central Tasman Sea which brought intermittent strong westerly winds to southern Fiordland (Figure 2). The position of this disturbed westerly was difficult to predict, and, on a forecast of showers in Fiordland, the flight was postponed from 1 March. (In reality, the weather over Fiordland was perfect on 1 and 2 March.) On a favourable forecast, the first leg of the snowlines flight was made by Trevor Chinn and Gareth Clare, piloted by Andy Woods, on 7 March, to complete the Fiordland section while cloud remained over the northern South Island and before another westerly encroached on to Fiordland (Figure 3). However, cloud banks were encountered south of the Darran Mountains, and some difficulty was encountered gaining a suitable view of the Mt. Irene glacier which lay just beneath a complete cloud cover. Here the survey leg was terminated and Merrie Range and Mt. Caroline were not visited.

On 8 March, while cloud remained to the west (Figure 4), leg 2 covered the eastern Alps. An isolated skiff of fresh snow camouflaged the snowlines on Ridge and Langdale Glaciers and Retreat Glacier was cloud covered. After refuelling at Hokitika, leg 3 to the Kaikoura Range was completed. On the return, another unsuccessful attempt was made to photograph Retreat Glacier.

Leg 4 was flown on 9 March (Figure 5) and all the western glaciers were recorded before the next front was observed approaching south of Haast Pass.

It was gratifying to have completed the survey flights (Figure 6) as on 13 March a very cold southerly brought snow to the Alps and the eastern foothills.

Glacier length fluctuations

This project supplies data to the World Glacier Monitoring Service (WGMS) based in Zurich, Switzerland, which publishes a 5-yearly record of fluctuations of glaciers from around the world (IAHS(ICSI)/UNEP/UNESCO 1998). This year, in addition to the index glaciers, data were collected on glacier termini fluctuations for analysis of changes that have occurred between 1995 and 2000. The termini positions of 97 glaciers in addition to the index glaciers were photographed (Table 1). This work involved a small addition to the flight time required for the index glaciers. The photographs have yet to be analysed to determine frontal fluctuations.

A second flight

On 10 April some of the index glacier sites were revisited on a glaciological flight with Dr W. Haeberli, a Swiss glaciologist who was on a visit to New Zealand. The flight covered an area from

Mt. Aspiring to the Godley Glaciers, but many of the glacier snowlines were obscured by fresh snow. This visit provided valuable data on the magnitude of the changes that occur late in the ablation season after the survey flight, and, in particular, how much the snowline is likely to rise after the survey has been completed (Table 2).

Methods

Derivation of the glacier snowline

The procedures of Chinn & Salinger (1999) were used to derive the snowline elevations by mapping and digitising the annual accumulation area for each glacier, and reading the snowline elevation from a plotted area-altitude curve.

On the detailed base map of each glacier, the snowline positions were carefully sketched from the photographs and the resulting mapped accumulation areas were digitised to measure the areas. From the total accumulation area for each glacier, the snowline elevation is then read off the area-altitude curve constructed for each glacier. This snowline elevation provides a single figure for the glacier for the year. This figure, the departure from the long-term ELA, indicates the annual mass balance of the glacier. Positive values or high snowline elevation signifies less snow and therefore a negative balance.

Glacier terminus fluctuations

Glacier front fluctuations (e.g., Haeberli et al. 1998) are normally recorded as the change in the distance between a fixed point and the nearest ice of the glacier. However, the fluctuations recorded on this programme have been subjective assessments of the difference between two sequential photographs which are presented simply as A (advance), S (stationary), or R (retreat). As a trial, the terminus positions of the Siege Glacier were carefully sketched on to the glacier map and the positions digitised. The distance to the mapped glacier front from an arbitrary point was then measured using the line-length facility of the digitiser. These measurements have a very high degree of precision, but a low accuracy of about ± 10 m. Because the absolute value of the glacier front change is of little climatic importance, it is the trend that is best related to climate, so this result is very acceptable. The accuracy of the method may easily be increased by taking the average of a number of length measurements. It is proposed to apply this method to the fluctuations of the set of glaciers to be supplied to the WGMS.

Results

Average snow accumulation over winter followed by presumed lowered ablation rates over a cool summer suggested that the glaciers should end the year with near equilibrium mass balances. Yet despite the presumed cool summer, snowlines at all glaciers were among the highest recorded, indicating another year of strong negative balance. The results emphasise the importance of ablation losses under La Niña summer circulation and include the effects of a short period of high ablation losses during the December storm. The amount of bare ice exposed, and the obvious reduction in size of the smaller glaciers, revealed that the mass gains to the glaciers made over the past two decades of dominantly positive balances has all been lost during the past three years of negative balances.

Variable cloud cover again prevented a complete coverage of the index glaciers. Merrie Range and Mt. Caroline were not visited because of cloud, and there are no values for Jaspur Glacier and Browning Range where the snowline had risen above both the glacier and mountain top. Fresh snow obscured the snowlines on Ridge and Langdale Glaciers, and cloud cover gave poor quality views of Mt. Irene, Barrier Peak, Mt. Gendarme, and Rolleston Glacier.

The 1999 survey did not record snowline elevations for Mt. Ella and Kaikoura Range because the former had partial cloud cover and the latter a cover of fresh snow. However, the photographs of these two sites taken in 2000 showed snowline elevations close to those of 1999, and by comparing snow patch sizes, snowline values for 1999 were interpolated for both sites.

Snowline elevation departures

The results for the 1999–2000 glacial year ending in March 2000 are given in Table 3 with all the snowline elevation data obtained on this project. The snowline departure results for this year average a high 150 m above the long-term ELA positions, indicating strong negative mass balances. This value is among the highest recorded in the 23-year history of this project (Figure 7). The 1990 high value is unreliable as it is from two glaciers only.

Results for individual glaciers

Results for individual glaciers are listed as departures from the steady-state ELA value in Table 3 and plotted in Figure 8. Snowline fluctuation histories for each individual glacier are given as histograms in the Appendices, as metres of departure from the steady-state ELA. Missing values are years of no survey, and arrows indicate measured zero values.

Accumulation maps for each of the individual glaciers for 2000 are also given in the Appendices. Photographs of each glacier appeared in the 1999 report (Chinn & Salinger 1999).

Browning Range snow cover

Photographs of the Browning Range site, taken at intervals over the 1999 and 2000 summers, were kindly supplied by Mark Crompton of Hokitika who is carrying out an independent study in the area. The diminishing areas of the snow cover has been examined to (a) assess the amount of melt, and therefore the rise in snowline that continues after the snowline survey flight, and (b) to attempt to extrapolate the altitude of the snowline which had risen above the glacier. Initially the photographed areas of snow cover were visually transposed on to the glacier base map and the mapped areas of diminishing coverage over the summer measured by digitiser. These maps are given in Figure 9 for the 1999 summer and Figure 10 for the 2000 summer.

The procedure was repeated using a digitiser to enhance the accuracy of measuring the areas of snow and ice cover. First the snow cover on the photograph was traced by digitiser in a geocoordinated mapping programme, together with features to be used as registration points (Figure 11A). This file was then exported to a "draw" programme where the traced photograph was perspectively distorted to fit the basemap as closely as possible (Figure 11B). The distorted area was then exported back to the mapping programme (using appropriate coordinates) and resized to obtain a precise value for the snow cover area (Figure 11C).

Snow cover depletion curves for the 1998–99 summer and for both visually mapped and digitised values for the 1999–2000 summer are compared in Figure 12. These results show, firstly, that there was very little snow area loss after the early March snowline survey flight, indicating that the associated rise in snowline altitude would be insignificant. This confirms that there is no significant rise of the glacier ELAs between the early March snowline flights and the end of the melt season. Secondly, the curves show that there was surprisingly little difference between the visually mapped and the digitised areas of snow cover. The offset of the snow-depletion curve for 1999 in Figure 12 shows the loss in glacier size over the past year.

The snow cover areas were also used in an attempt to extrapolate the values of the snowline altitudes where the snowline has risen above the glacier. Using past accumulation area data (area covered by the snow of the previous winter) and associated ELA values, the first curve of Figure 13 was plotted. This curve must pass through zero area at the glacier top. Then using the few values where the total glacier area is coupled to the ELA, the second curve was constructed. The difference between the two curves indicates the area of "exposed ice". This curve is exponential and is therefore unsuitable for extrapolating to estimate the value of the ELA where the curve intercepts the zero area value.

Fluctuations of glacier termini

The frontal positions of the Siege Glacier were carefully plotted from the oblique aerial photographs to test the feasibility of scaling the magnitude of the terminus changes using the high precision of a digitiser to scale distances. From the photographs available, the maximum (1978) and minimum (2000) frontal positions of the Siege Glacier were plotted by hand, and the positions for the remaining years interpolated from the photographs. The map of the front was digitised (Figure 14) and the distances to the ice fronts measured by digitiser from an arbitrary point in the stream. A plot of the results (Figure 15) gives very precise values of low accuracy for the rates of recession for this glacier.

Analyses

The snowline departure trend surface

The pattern of the 2000 snowline-elevation departures throughout the Southern Alps is presented diagrammatically in Figure 16, where the contoured trend surface shows some complex undulations. The pattern of strong negative balances is very similar to that of 1999 (Chinn & Salinger 1999). Some glaciers show a greater range of response to different annual climates than others, presumably due to glacier topography differences. This "sensitivity" to the climate leads to anomalies in the trend surface of Figure 16, and these climatically sensitive glaciers should have high standard deviation values in their record of annual snowlines. To test this hypothesis, the index glaciers have been sorted into descending order of standard deviations. Table 4 and Figure 17 show that a correlation exists between those glaciers with anonymously high departures and those with high standard deviations of their snowline departure record.

These differences in degree of response add noise to glacier-climate analyses and should be removed to analyse the response of glaciers to climate. This may be achieved by normalising the data for each year by ((v–m)/s.d., where v is value, m is mean, and s.d. is standard deviation. The trend surface for 1998 was treated in this manner (Chinn 1998) where the anomalies in the trend surface plot were significantly reduced.

Glacier representivity

The "representivity" of each glacier as an indicator of the overall annual climate of the Southern Alps is indicated by how well the annual value for an individual glacier correlates with the mean over the Alps. Correlation coefficients of individual snowline departures for each glacier correlated against the mean of all remaining values for each year are given in Table 5. The correlations give a surprising result as representivity appears to be independent of size, gradient, or topography. Those glaciers which would intuitively have been chosen as being the most representative and useful for this study, based on shape and size, are underlined. The high percentage of very good correlations gives confidence in the value of snowline studies as an indicator of the alpine climate.

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Table 1: **List of the 97 glaciers, additional to the index glaciers, photographed this year for analysis of termini fluctuations. Names in lower case give basin location of un-named glaciers.**

Glacier	No.	Glacier	No.	Glacier	No.
WHITE	664C/9	Bride Burn	752C/36	BAKER GL	868B/89
CROW	664C/47	Dredge Burn	752C/48	McCARDELL	875/10
CAMERON	685B/4	MARGARET	752C/54	OTOKO	875/11
REISCHEK	685C/13	WHITBOURNE	752C/74	EDISON	877/18
LYELL	685C/37	DART	752C/87	MARCHANT	880A/13
RAMSAY	685C/52	MAUD FRANCIS	752F/33	STRAUCHON	880A/18
Mathaias	685D/8	ROB ROY	752F/41	H. WALKER	880B/4
KAHUTEA	685E/57	MAKARORA	752J/8	DOUGLAS	880B/7
SCABBARD	693B/6	Arthur	846/37	FOX	882A/8
CLOVER	693B/56	TE PUOHO	851B/89	VICTORIA	882A/7
ROLLOVER	693B/59	Madeline Ck.	851B/104	BALFOUR	882B/4
ASHBURTON	688A/6	DONNE	851B/108	LA PEROUSE	882B/10
C. CAMPBELL	693C/19	TORNADO	863C/11	BURTON	888A/18
MCCOY	693C/34	BONAR	863A/14	SPENSER	888A/22
HECTOR	693C/44	SNOW WHITE	863B/19	FRANZ JOSEF	888B/4
SINCLAIR	693C/62	SNOWBALL	863B/23	BARLOW	893A/8
LAWRENCE	693D/17	SNOWBALL	863B/26	WIGLEY	893B/71
Canyon Ck.	711B/11	MARION	863B/29	WHATAROA	893B/2
MEMORIAL	711D/24	JOE	863B/43	WHYMPER	893B/44
RICHARDSON	711E/47	ANDY	863C/5	EVANS	897/13
METALILLE	711H/6	AXIUS	864/6	LORNTY	897/18
SLADDEN	711H/7	DONALD	864/45	MALCOLM	897/46
MUELLER	711H/10	PEAR DROP	864/52	LAMBERT	897/52
HOOKER	711H/20	THERMA	864/68	ADAMS	897/68
TASMAN	711I/12	DISPUTE	866/14	IVORY	901/9
MURCHISON	711J/11	ZORA	868B/7	BETSY JANE	901/22
FARADAY	711L/27	McKERROW	868B/29	COUNTY	901/27
HUTTON	711L/28	POET	868B/38	SALE	906B/24
CLASSEN	711M/22	SPENCE	868B/40	BARRON	906B/26
GREY-MAUD	711M/28	LE BLANC	868B/45	WILKINSON	906B/29
GODLEY	711M/35	ARTHUR	868B/52	MCKENZIE	906B/32
FITZGERALD	711M/44	Percy Ck	868B/60		
SEPARATION	711M/47	Baker Ck	868B/66		

Table 2: **Changes to some index glaciers that occurred over the month between the March snowline survey flight and a second flight on 10 April.**

Glacier	Change between March and April
Fog Pk.	Minor snowline rise plus fresh snow patches.
Mt. Stuart	Minor ablation loss at lower margins.
Lindsay Gl	Too distant to detect any change.
Brewster Gl	Detectable loss to lower accumulation area, upper changes obscured by fresh snow skiff.
Jackson Gl.	5–10% loss of accumulation area
Langdale Gl.	Most of March fresh snow lost, but snowline still unreliable. Snowpatches reduced slightly in size.
Tasman	Unmeasurable change with possible fresh snow.
Salisbury	About 5% accumulation area loss
Chancellor	Low patches of accumulation beside Fox Gl.gone.
Ridge	Unreadable fresh snow.
Glenmary	Unreadable fresh snow.
McKenzie	Fresh snow accumulation area developed at glacier top, minimal changes elsewhere.
Blair	Any changes obscured by fresh snow.
Thurneyson Gl.	Any changes obscured by fresh snow, snowpatch sizes unchanged

Table 3: **Results of the 2000 snowline survey. Departures of the 2000 snowlines from the steady-state ELA value in metres, together with the full set of data from past years gained on this programme.**

GLACIER	Inventory Number	ELA (m)	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	MEAN	STD. DEV.	No. of Obs
KAIKOURA RA	621/001	2525						5		-17				-15	95				-57	-17	-60			35	30	10	1	46	10
MT. ELLA	932B/012	2154						0							16					-84	-154	-27		5	96	111	-5	87	8
MT FAERIE QUEEN	646/006	2030						-90						-40	-40				-105	-101	-110	-98		-94	170	185	-32	113	10
MT. WILSON	None	1820	55	81			107		-23	-49	29	133	3	159	185				-75	-10	-62		-57	133	205	200	60	98	17
MT. FRANKLIN	911A/002	1850		-48	86	-90	-110		-184			-54	-77	-1	16				-200	-143	-192	-118		86	128	100	-50	109	16
ROLLESTON GL.	911A/004	1767	-17	1	-17	-3	-7	6	-127	-14	-22	9	11	-5	3				-147	-57	-147	-48	-127	45	83	93	-23	67	21
MT. CARRINGTON	646C/027	1665		5		28	-37	75	-100	-65		40	95	105	55				-120	-78	-108	-84	-87	11	240	287	15	116	18
MT. AVOCA	685F/004	1950		-40				0		-80	-40	10		25	21				-100	-10	-30	27	-60	85	130	80	1	64	15
MARMADUKE GL	664C/012	1865	-78	-70	43	-33	-63	-5	-171	-157	-85	-26	-40	30	-48	133			-210	-110	-190	-117	-164	108	129	118	-46	105	22
RETREAT GL	906A/004	1720		18		60	-28	36	-230		18	42			58				-51	-98	-255	38	-75	69	168	155	-5	117	16
BROWNING RA	906A/001	1564		41		44	0	41	-79		32	51			9				-82	-37	-84	23	-74	64			-4	56	14
DOUGLAS GL	685B/001	2120		11		-243		-98	-294	-320	-303	-208		11	92			-277	-340	-234	-311	-230	-303	140	160	170	-143	187	18
MT. BUTLER	685C/060	1835	-50	117	60	-29	-35	33	-185	-60	-65	15	-4	47	-29			-90	-131	-23	-185	-55	-171	73	103	153	-23	95	22
DAINTY GL	897/019	1918	4	93		29	-41	129	-60		-45	-37	-48	24	4			-67	-140	-37	-75	24	-56	134	212	110	8	88	20
KEA GL	897/007	1832		53		32	-97	122	-242		-132	-94	-95	-70	-48				-242	-104	-262	68	-164	66	188	178	-47	139	18
JASPUR GL	897/003	1735		33		53		-25	-165		-115	-52		-52	-39				-160	-130	-155	-102	-110	33			-70	75	14
SIEGE GL	893A/006	1630	42	82		30	36	36	-162		12	141		36	42			-217	-280	44	-290	34	-97	320	520	385	38	208	19
VERTEBRAE COL	893A/025	1893		-33		-12	-90	-62	-108		-99	-81	0	-46	-77			-136	-126	-102	-126	-102	-115	-58	135	59	-62	69	19
RIDGE GL.	711L/024	2244		61			-16	-8	-33		-50	-27		41	33				-100	-81	-112	-106	-154	-9	71	61	-27	70	16
LANGDALE GL.	711I/035	2238	-40	13			27	0	-53	-288	-148	-93	-121	-13	17			-268	-288	31	-288	-1	-288	90	62	37	-81	134	20
TASMAN GL.	711I/012	1790	-10	85	-90	20	-35	-30	-90	-95	-90	-10	-29	50	-30	310	-35	-100	-108	-20	-124	-35	-102	63	186	110	-9	103	24
SALISBURY GL	888B/003	1860	-33	-33		-18	-108	-33	-142	-101	-126	-51	-85	-131	-116			-179	-139	-88	-215	-108	-134	-8	170	122	-74	91	21
JALF GL	886/002	1732	43	48		26	-7	61	-172	-20	-88	38	7	26	27			-152	-162	20	-182	50	-133	55	318	323	6	134	21
CHANCELLOR DOM	882A/007	1830	22	21		3	-167	18	-285		-221	-152	-102	-22	-152				-280	-221	-285	29	-250	18	120	115	-94	139	19
GLENMARY GL.	711F/006	2186		52		-113	-76	-5	-51	-154	-78			-6	-6			-46	-79	-65	-67	-58	-134	14	86	62	-40	66	18
BLAIR GL.	711D/038	1980		32		-117	-55	-93	-168	-122	-127		-110	15	-104				-27	-115	-127	-40		-8	110	105	-56	83	17
MT McKENZIE	711D/021	1915		35		-5	-27	-13	-195	-73	-155	2	-25		-3				-133		-110	-5	-195	20	163	137	-34	101	17
JACKSON GL.	868B/094	2053		45		-3		25	-21	-63	-39		8		27				-61	-8	-35	19	-37	29	112	80	5	49	16
JACK GL.	875/015	1930		8		0	-45	21	-180	-102	-55	5	-25	-55	-32			-113	-177	-50	-175	28	-125	10	78	62	-46	78	20
MT. ST. MARY	711B/039	1910								-155		-75		-3	62			-60	-125	-60	-140	-55	-68	-21	215	220	-20	120	13
THURNEYSON GL	711B/012	1970	-36			-44	-27		-105	-88	-65	-32	-52	-20	0			-36	-60	-66	-102	-32	-70	-5	142	162	-28	70	19
BREWSTER GL.	868C/020	1905		55		-59	-50	66	-111	-105	-109	-63	-77		13			-54	-155	-115	-128	57	-126	77	375	250	-14	137	19
MT. STUART	752I/104	1728	-141	2		-78	-122	-52	-190		-108	-68	-50		-65				-193	-88	-213	-16	-161	-72	77	122	-79	89	18
LINDSAY GL	867/002	1754		-16		-102	-73	27	-194		-88	14	-139	18	10				-199	-144	-204	21	-109	46	121	116	-50	103	18
FOG PK	752E/051	1995				-79		27		-104		-65	-93	27	37				-101	-95	-107	-101	-105	103	127	113	-28	90	15
SNOWY CK	752C/103	2092		64		-51	41	-54	-59			-56	-50	-55	11				-34	-58		-35	-72	66	148	54	-9	65	16
MT. CARIA	863B/001	1426		16			-13	-2	-54		-3	3	-4	21	3				-51	-26	-60	-36	-31	-9	224	234	12	85	17
FINDLAY GL.	859/009	1664					-60	71	-82		-35	61	-42	21	-22				-89	-30	-103	-32	-84	55	226	169	2	94	16
PARK PASS GL.	752B/048	1815		88		-7	-37	43	-53	-50	-113	48	28		-21					-32	-205	-55	-125	57	147	128	-9	92	17
MT. LARKINS	752E/002	1962								-282		-282		118	74				-314	-112	-332	-180	-301	244	243	238	-74	240	12
BRYANT GL.	752B/025	1752	-12	132			11	28	-108	-97	-117	18	11		1				4	-24	-122	-82	-82	26	258	213	3	107	18
AILSA MTS.	752B/013	1605		38					-45	-10	-10	44	20		7				-41	-9	-50	-21	-12	16	225	180	22	79	15
MT. GUNN	851B/057	1533	82	105		-4	-2	77	-55		7		22		1				-48	-4	-62	-26	-13	26	269	277	38	100	17
MT. GENDARME	797G/033	1628					-58	-55	-148		-106	47	22		-48				-126	-76	-210	-112	-138	20	176	147	-44	109	15
LLAWRENNY PKS	846/035	1460		20			-52	12	-116		-20		-6		-31				-100	-52	-160	1	-139	18	210	197	-15	105	15
BARRIER PK.	797f/004	1632		80		-87	-109	-67	-254		-108		-77		-107				-204	-154	-272	-162	-234	50	268	171	-79	152	16
MT. IRENE	797D/001	1515		185					-108		11		11		22				-108	-3	-115	-17	-55	97	150	170	18	105	13
MERRIE RA.	797B/010	1505		150											40				-125	-85	-155	-80	-120	-60	183		-28	123	9
CAROLINE PK.	803/001	1425																	-205		-195	-123	-175	-43	175		-94	145	6
	NUMBER	49	15	39	5	31	35	40	40	25	38	37	34	32	48	2	1	14	47	47	48	47	44	49	47	45			810
	MEAN	1835	-11	42	16	-27	-41	7	-130	-107	-75	-22	-33	7	-1	222	-35	-128	-136	-67	-155	-44	-123	45	173	150	-27		
STD. DEV.		231	57	55	71	64	53	54	73	83	69	82	52	56	58	125		81	79	58	78	66	71	72	87	78			
No. below ELA (+ve balance)			9	6	1	19	29	17	40	25	32	19	22	15	19	0	1	14	46	44	48	34	44	11	0	0			
% with +ve M.B.			60	15	20	61	83	43	100	100	84	51	65	47	40	0	100	100	98	94	100	72	100	22	0	0			

Table 4: **The index glaciers sorted in descending order of the standard deviation of the full snowline record of each individual glacier.**

Glacier	Number	Std. dev	Glacier	Number	Std. dev
Mt. Larkins	752E/002	239.82	Mt. Wilson	None	98.13
Siege Gl	893A/006	207.85	Mt. Butler	685C/060	94.63
Douglas Gl	685B/001	187.06	Findlay Gl.	859/009	94.21
Barrier Pk.	797f/004	152.23	Park Pass Gl.	752B/048	91.54
Caroline Pk.	803/001	144.83	Salisbury Gl	888B/003	90.95
Kea Gl	897/007	139.46	Fog Pk	752E/051	89.69
Chancellor Dome	882A/007	138.89	Mt. Stuart	752I/104	88.72
Brewster Gl.	868C/020	137.41	Dainty Gl	897/019	87.74
Jalf Gl	886/002	134.17	Mt. Ella	932B/012	87.14
Langdale Gl.	711I/035	133.56	Mt. Caria	863B/001	84.90
Merrie Ra.	797B/010	123.39	Blair Gl.	711D/038	83.08
Mt. St. Mary	711B/039	120.15	Ailsa Mts.	752B/013	78.76
Retreat Gl	906A/004	116.99	Jack Gl.	875/015	77.53
Mt. Carrington	646C/027	116.25	Jaspur Gl	897/003	74.72
Mt Faerie Queene	646/006	113.41	Thurneyson Gl	711B/012	69.91
Mt. Franklin	911A/002	108.87	Ridge Gl.	711L/024	69.53
Mt. Gendarme	797G/033	108.68	Vertebrae Col	893A/025	68.85
Bryant Gl.	752B/025	107.11	Rolleston Gl.	911A/004	66.67
Llawrenny Pks.	846/035	105.49	Glenmary Gl.	711F/006	66.18
Marmaduke Gl.	664C/012	104.95	Snowy Ck	752C/103	64.52
Mt. Irene	797D/001	104.56	Mt. Avoca	685F/004	63.58
Lindsay Gl	867/002	103.48	Browning Ra	906A/001	55.68
Tasman Gl.	711I/012	102.74	Jackson Gl.	868B/094	48.67
Mt Mckenzie	711D/021	101.19	Kaikoura Ra	621/001	45.85
Mt. Gunn	851B/057	99.70			

***Table 5*: Correlation coefficients, in descending order, of individual snowline departures for each glacier correlated against the mean of all remaining values for each year. Glaciers intuitively considered to be the most representative are underlined.**

Glacier	R^2	Glacier	R^2
Caroline Pk	0.965	Kea Gl.	0.757
Barrier Pk	0.934	Mt Carrington	0.757
Llawrenny Pks	0.908	Vertebrae Col	0.754
Mt Ella	0.902	Marmaduke Gl.	0.753
Jackson Gl.	0.884	Jack Gl.	0.752
Jalf Gl.	0.883	Rolleston Gl.	0.752
Findlay Gl.	0.873	Mt. Caria	0.751
Siege Gl.	0.858	Lindsay Gl.	0.746
Mt Franklin	0.857	Fog Pk	0.744
Mt Gendarme	0.830	Jaspur Gl.	0.744
Thurneyson Gl.	0.822	Mt Butler	0.744
Mt Mckenzie	0.819	Mt Larkins	0.734
Brewster Gl.	0.812	Tasman Gl.	0.725
Mt Gunn	0.809	Mt Wilson	0.724
Mt Irene	0.807	Chancellor Dome	0.712
Ailsa Mts	0.802	Mt Avoca	0.695
Browning Ra.	0.800	Retreat Gl.	0.665
Dainty Gl.	0.795	Snowy Ck	0.642
Mt St. Mary	0.791	Langdale Gl.	0.630
Salisbury Gl.	0.782	Ridge Gl.	0.612
Merrie Ra.	0.776	Glenmary Gl.	0.611
Park Pass Gl.	0.776	Blair Gl.	0.574
Bryant Gl.	0.767	Kaikoura Ra.	0.544
Mt Stuart	0.767	Mt Faerie Queene	0.322
Douglas Gl.	0.762		

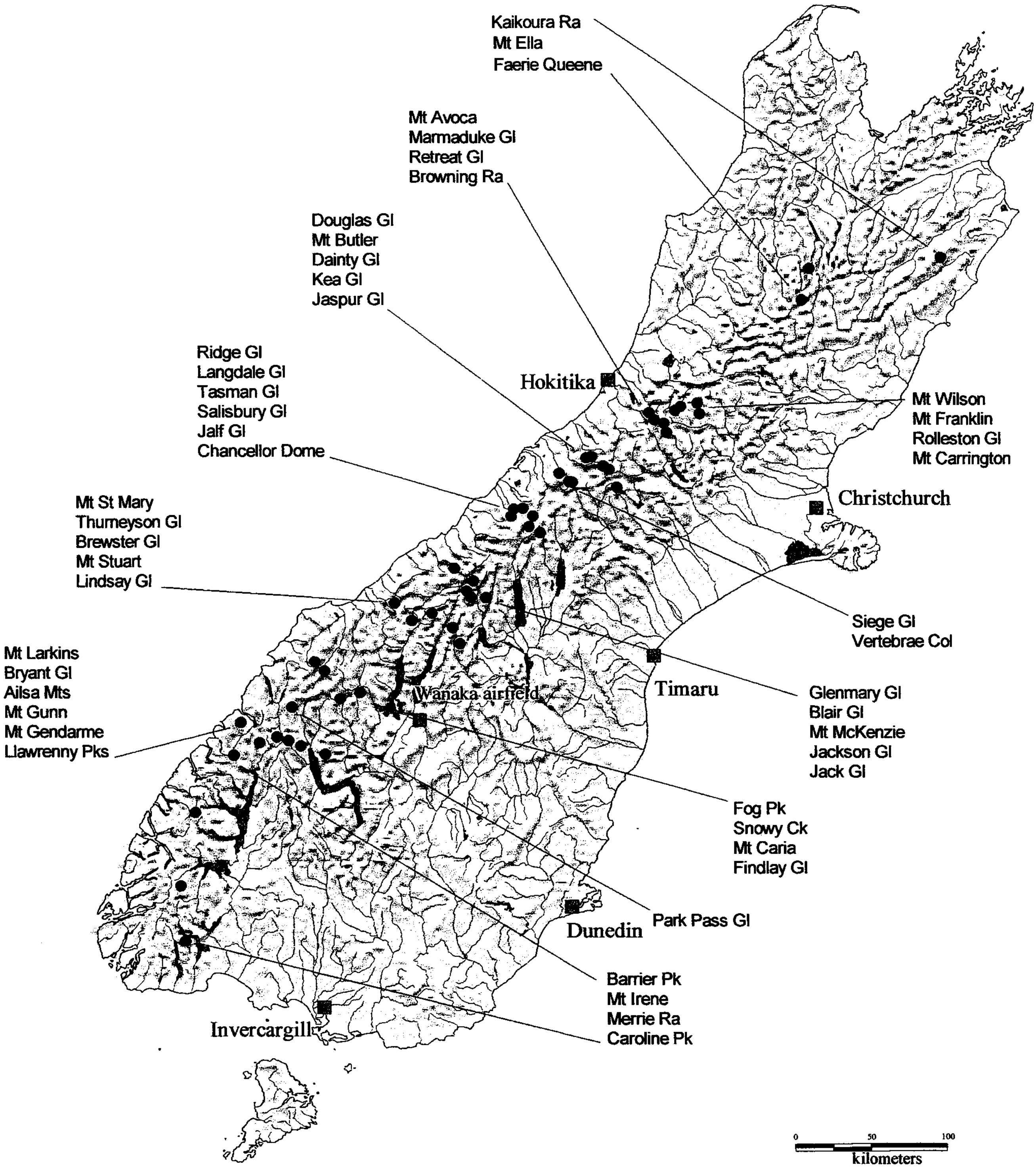


Figure 1: Location of the snowlines index glaciers.

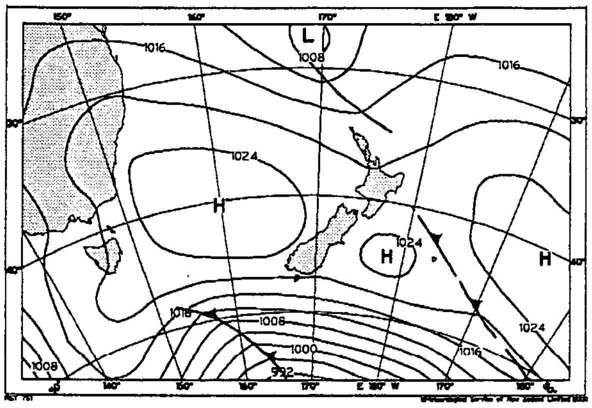


Figure 2: The weather situation at the beginning of March, Wednesday, March 1.

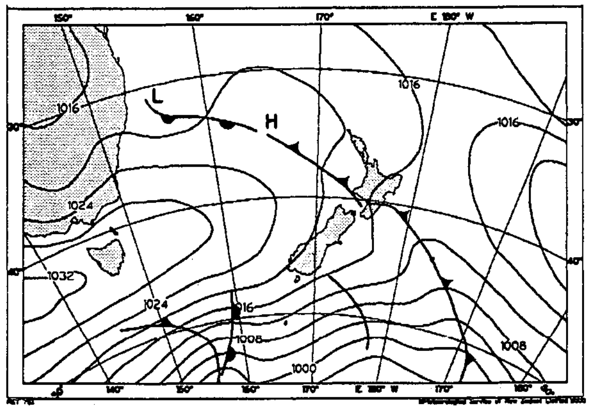


Figure 3: Forecast weather map of the situation for the first flight, leg 1, on Tuesday 7 March.

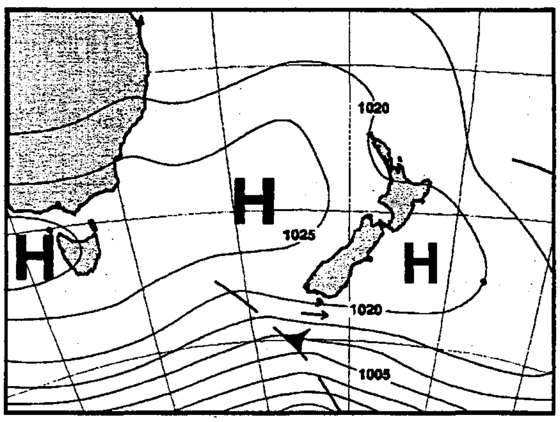


Figure 4: Weather map of the situation on Wednesday 8 March on which legs 2 and 3 were flown.

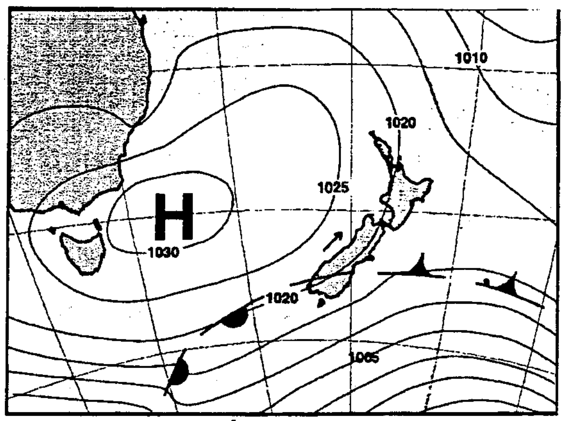


Figure 5: Weather map of the situation when leg 4 was flown in clear, calm conditions on Thursday 9 March.

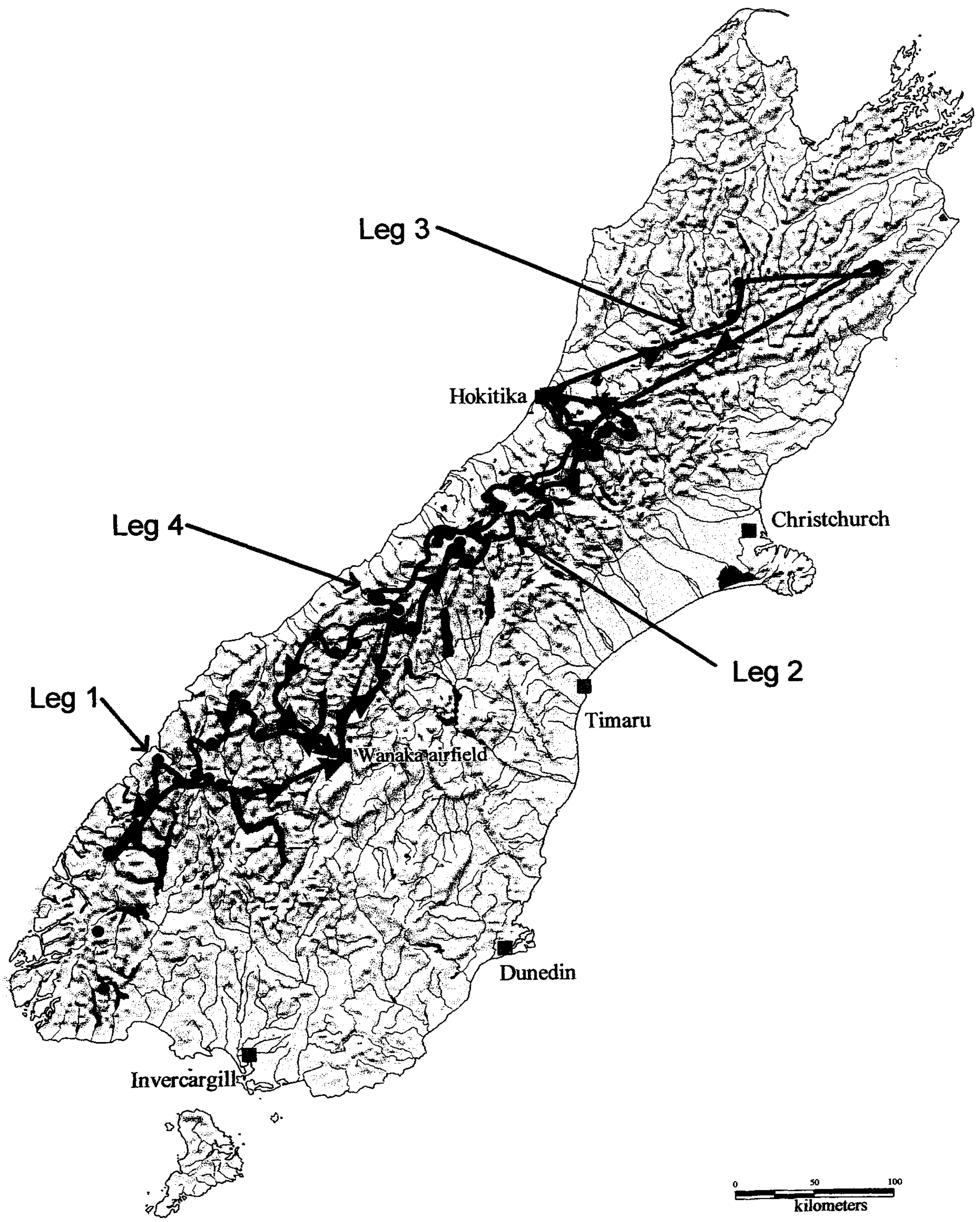


Figure 6 Flight paths for the 4 legs of the 2000 glacier surveys.

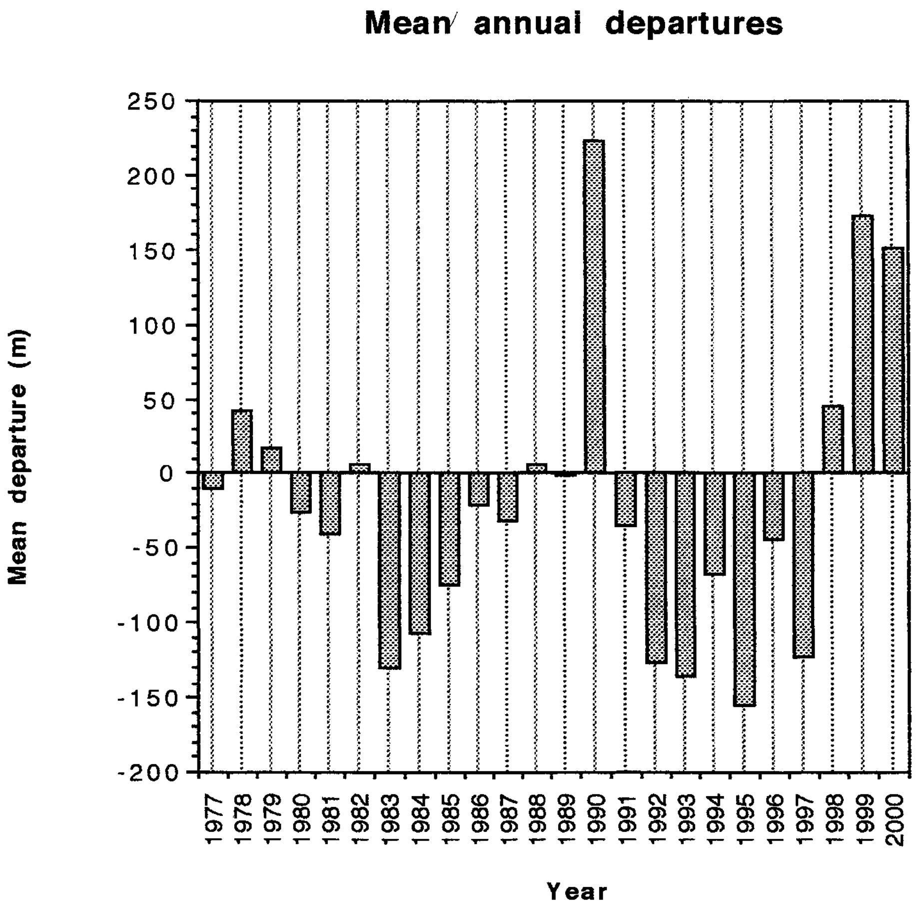


Figure 7. Mean annual snowline elevation departures from the steady-state ELA, for the 23 years 1977 to 2000.

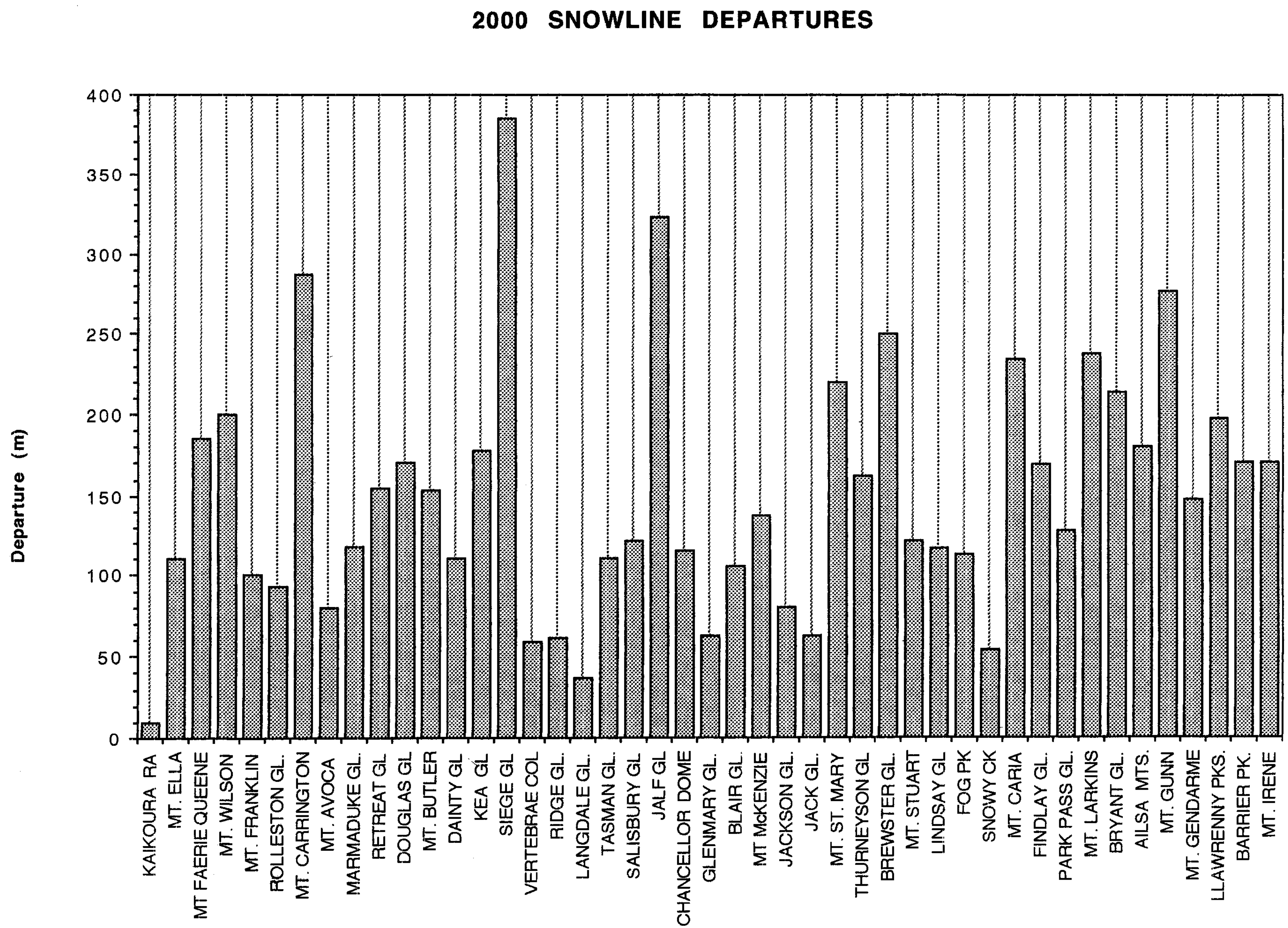


Figure 8: Histogram plot giving the 2000 snowline departures for each index glacier from the long-term ELA.

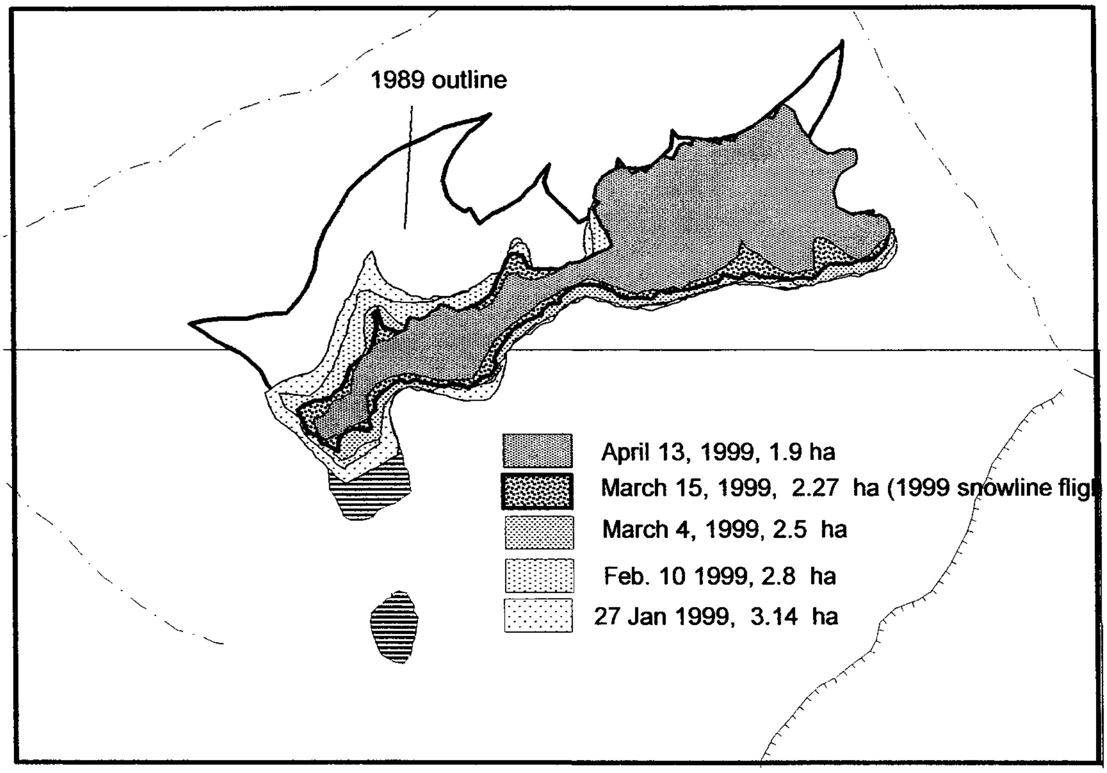


Figure 9: Map of the 1999 summer changes to the snow cover on Browning Range.

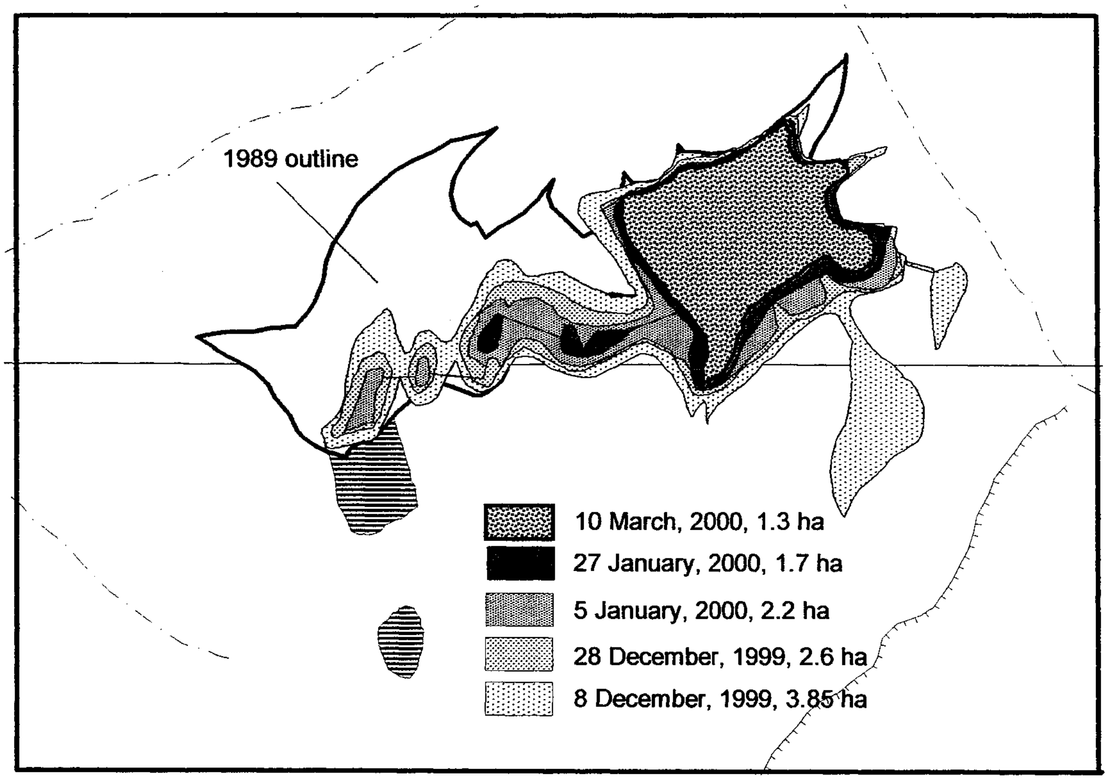


Figure 10: Map of the 2000 summer changes to the snow cover on Browning Range.

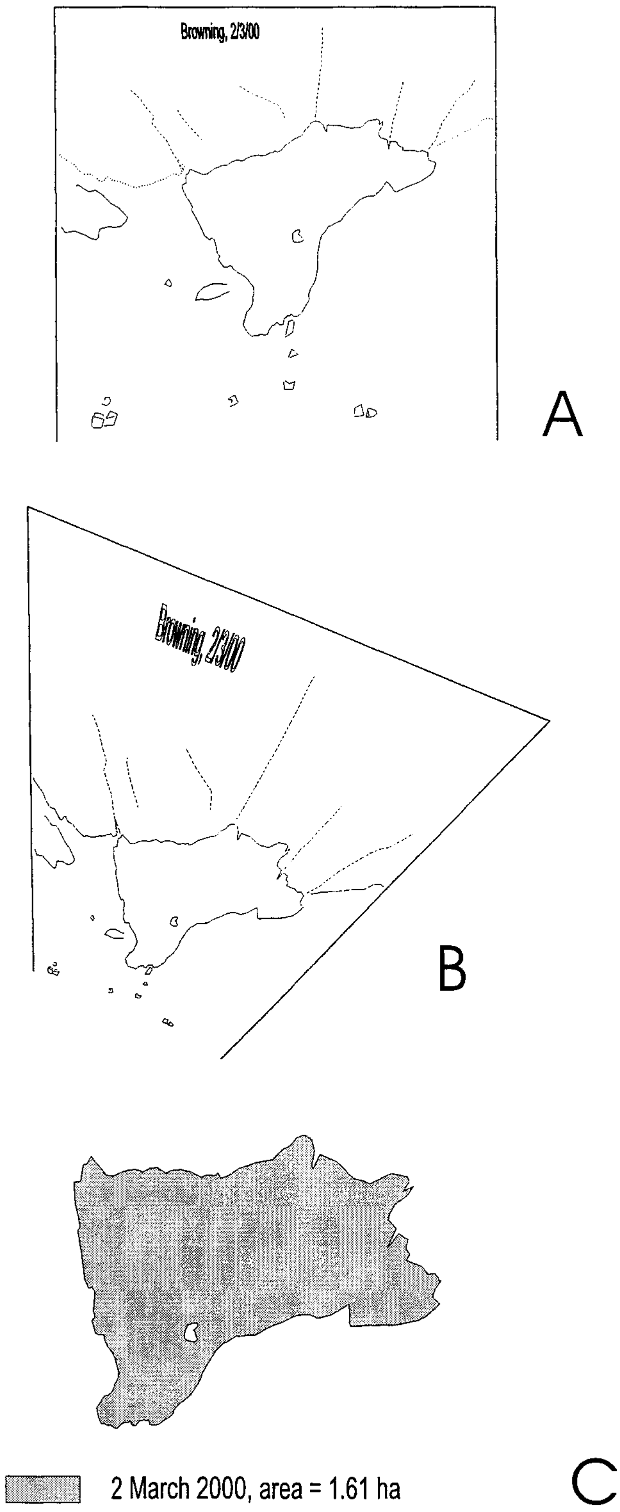


Figure 11: Processing steps in adjusting the snow cover seen in an oblique photograph to a measured mapped area. (A) The snow cover and topographic points for registration as traced by digitiser. (B).The traced photographed data distorted to fit the basemap. (C) The corrected snow cover area measured as a geocoordinated map.

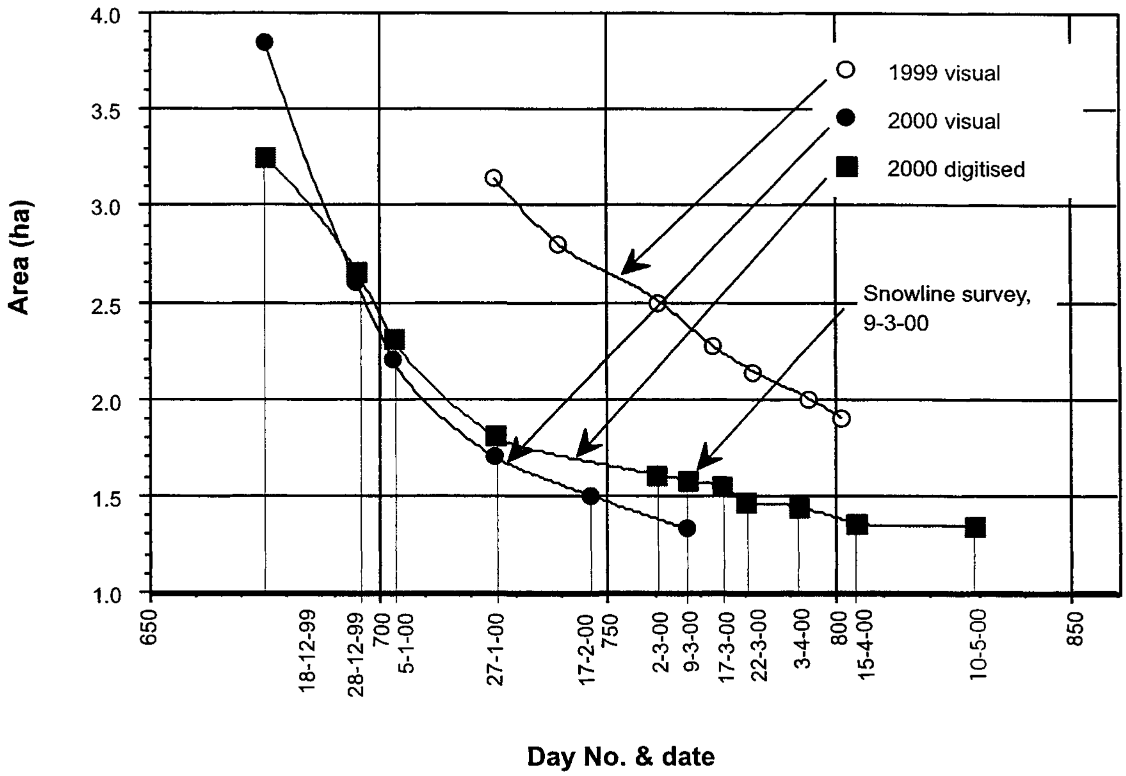


Figure 12: Plot showing the comparative rates of snow cover reduction over the 1999 and 2000 summers at Browning Range.

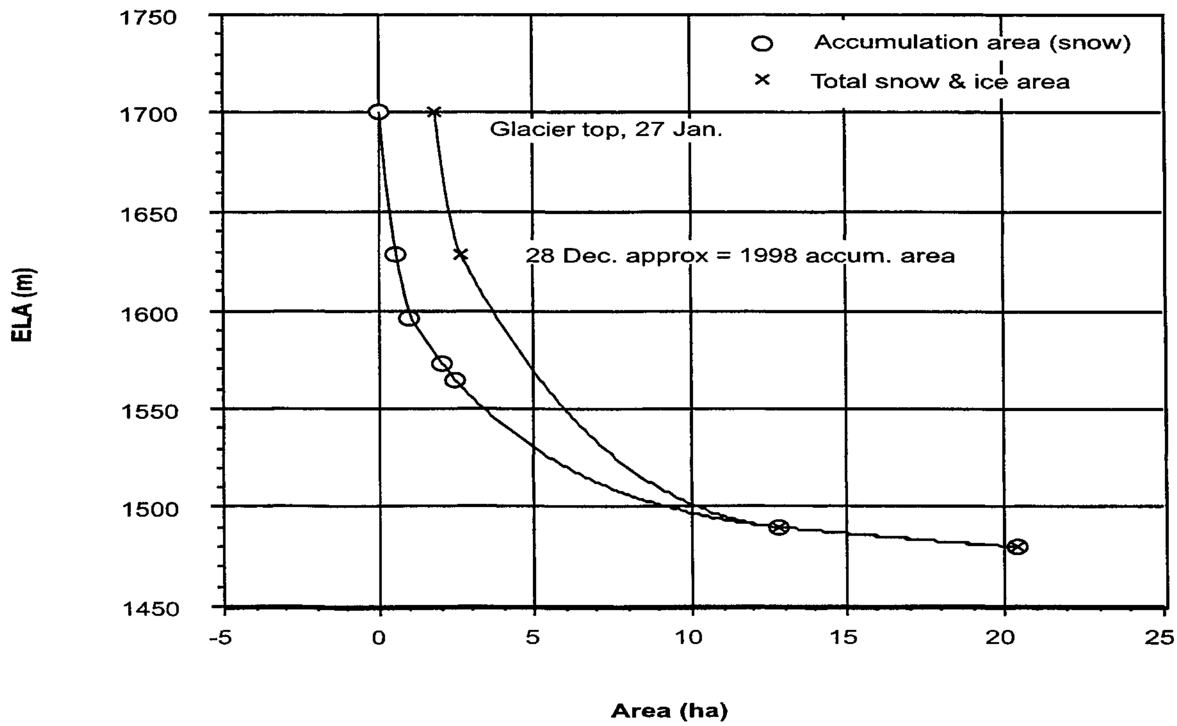


Figure 13: Plot of ELA (snowline altitude) values against both the accumulation area (area of previous winter snow remaining) and the total area of snow and ice at Browning Range.

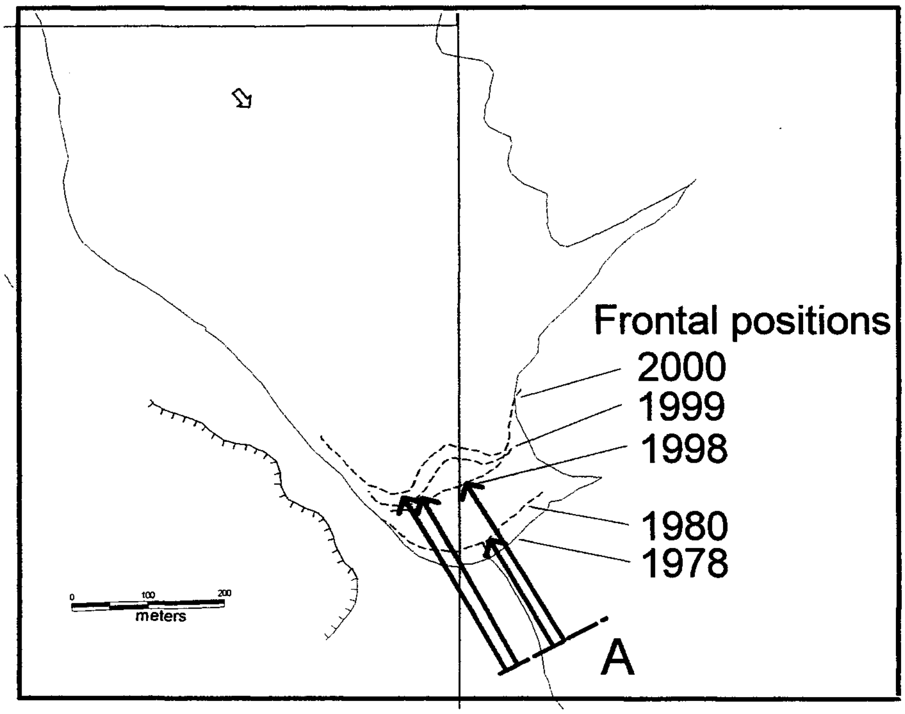


Figure 14: Digitised Map plotted from oblique aerial photographs, of the fluctuations to the front of Siege Glacier, with lines indicating distance changes from an arbitrary point A, measured by digitiser.

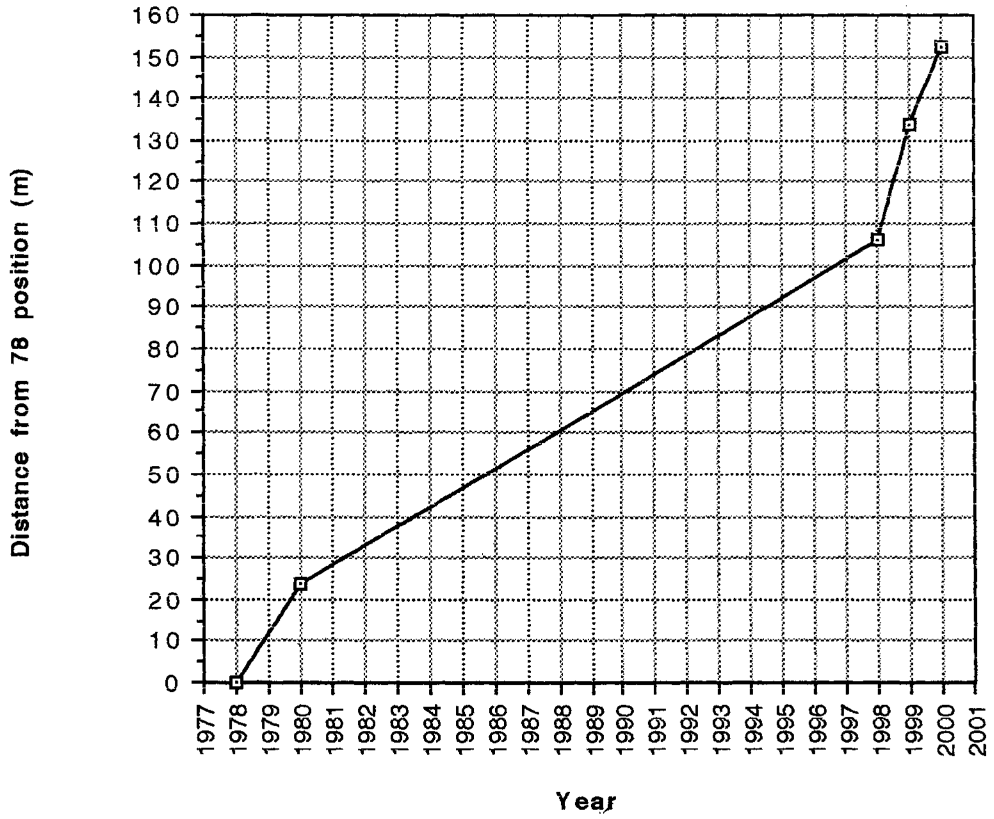


Figure 15: Plot of recession rates of Siege Glacier measured by digitiser.

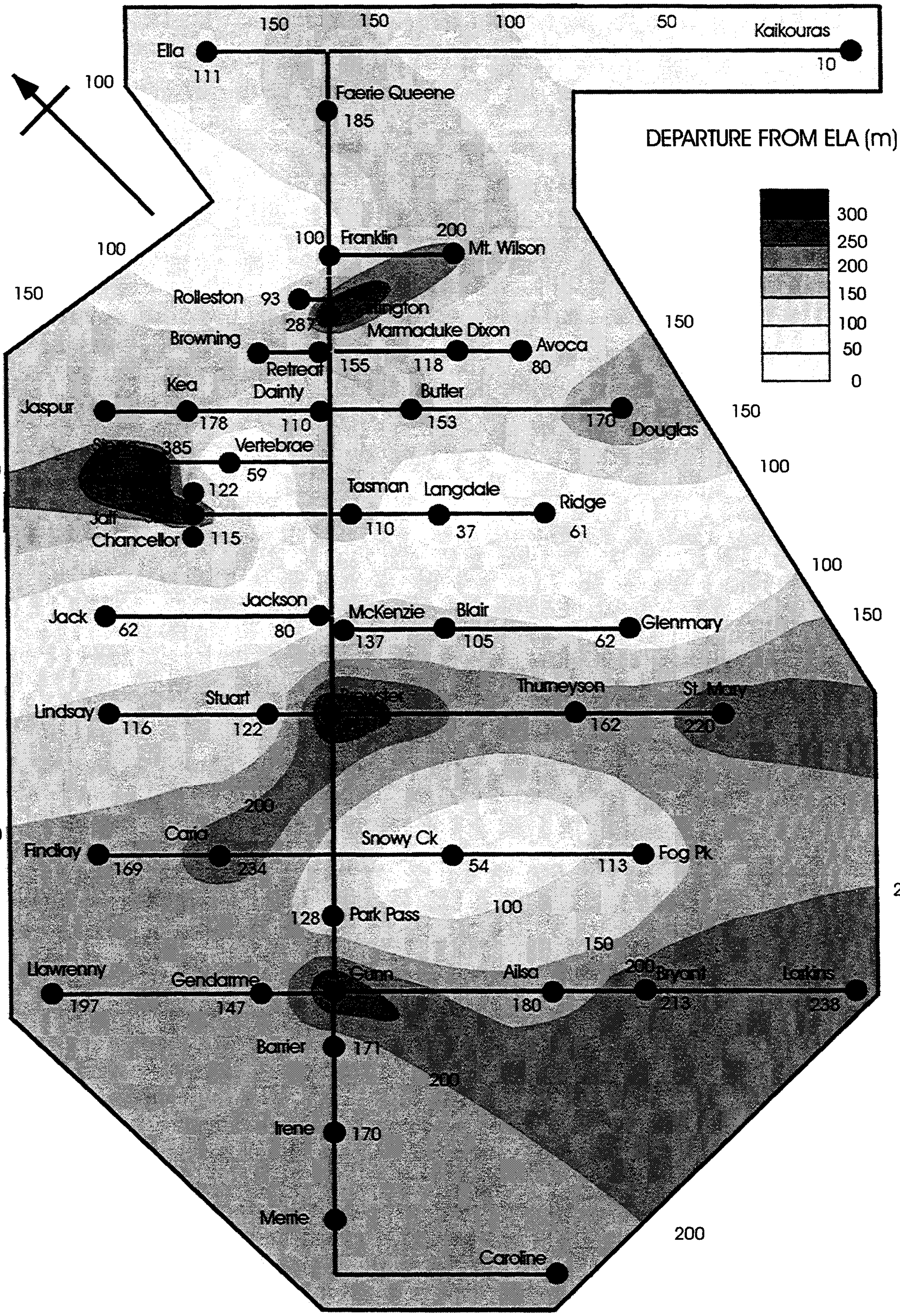


Figure 16: Diagrammatic trend surface of departures from the steady-state ELA, measured in m, for 2000. Plotted with respect to distance from the Main Divide, lateral exaggeration x 10.

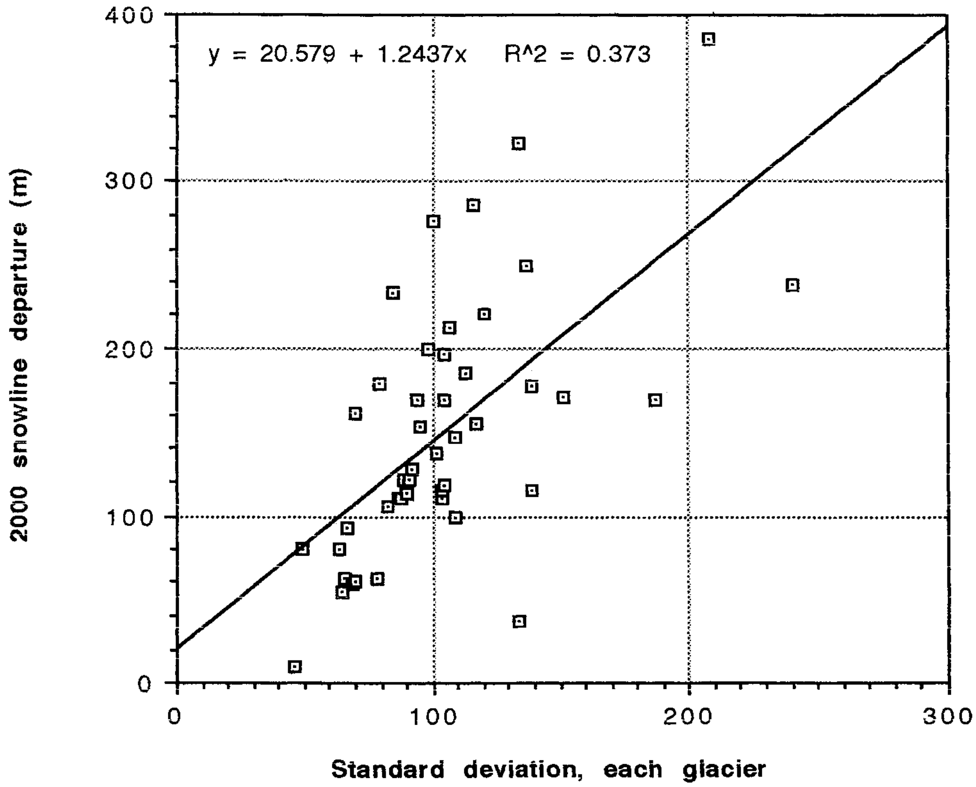
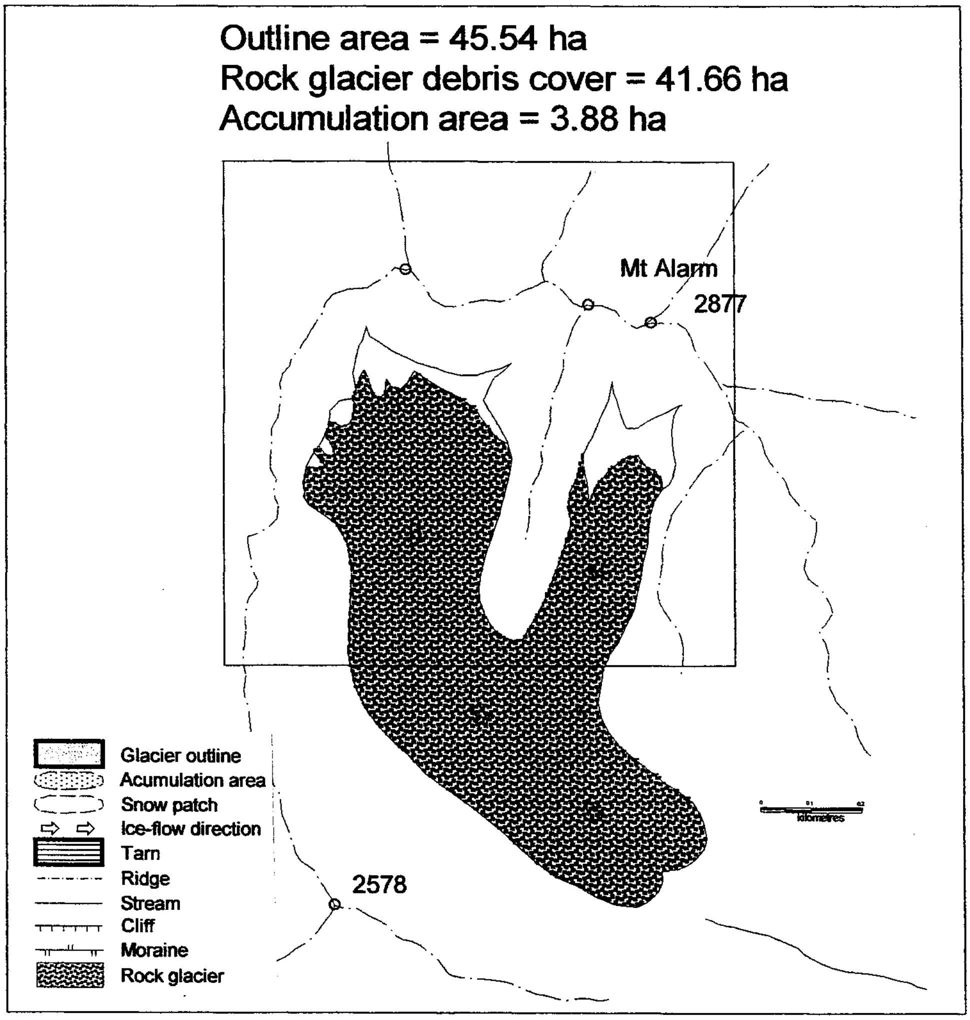


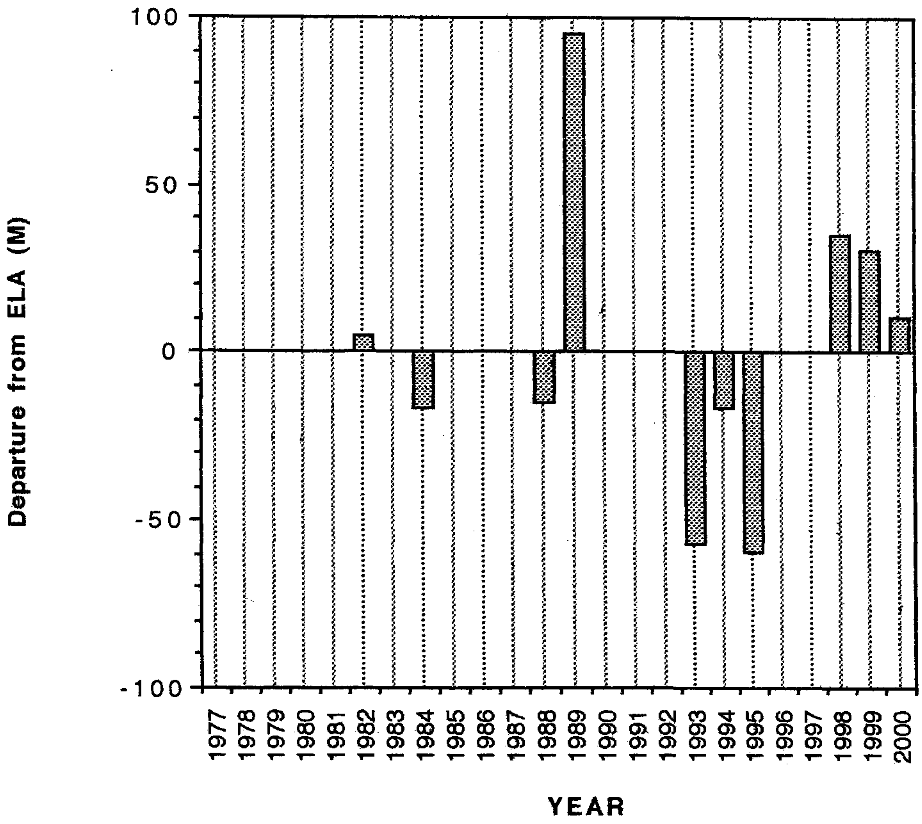
Figure 17: Standard deviations for all data on each glacier plotted against the 2000 snowline departures as an indicator of glacier sensitivity to climate variations.

Appendix 1:

Kaikoura Ra.

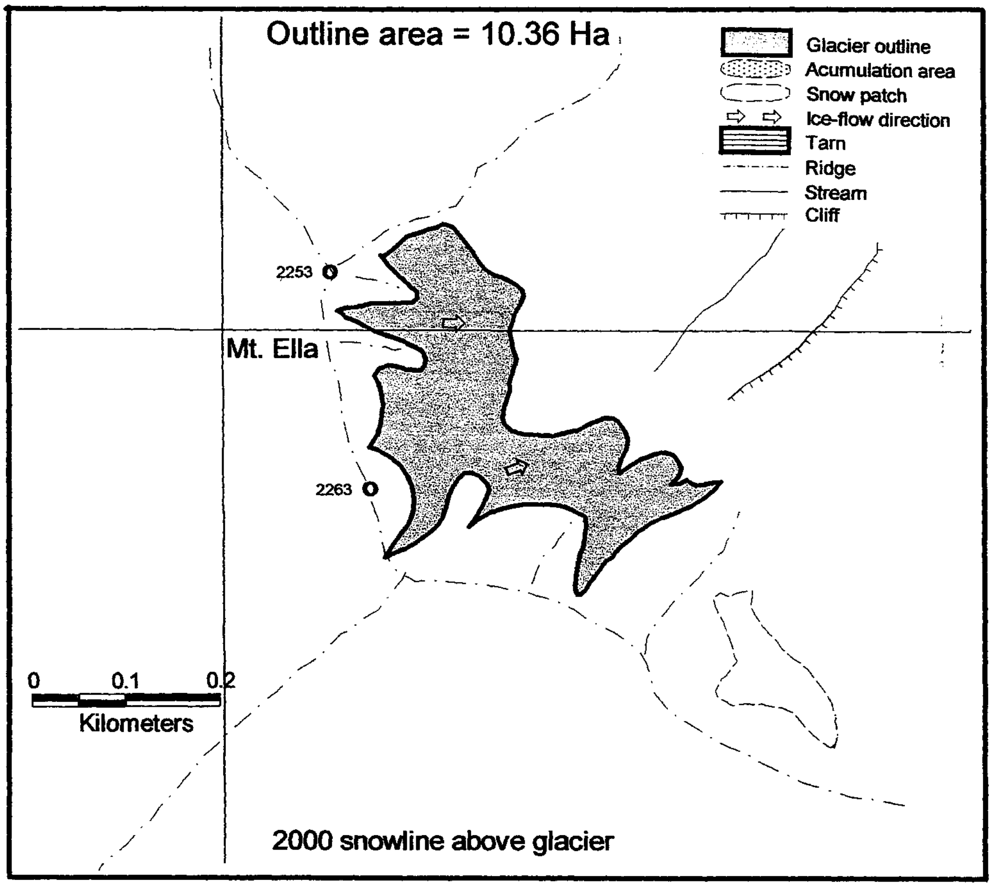
Glacier map and histogram plot of all recorded snowlines

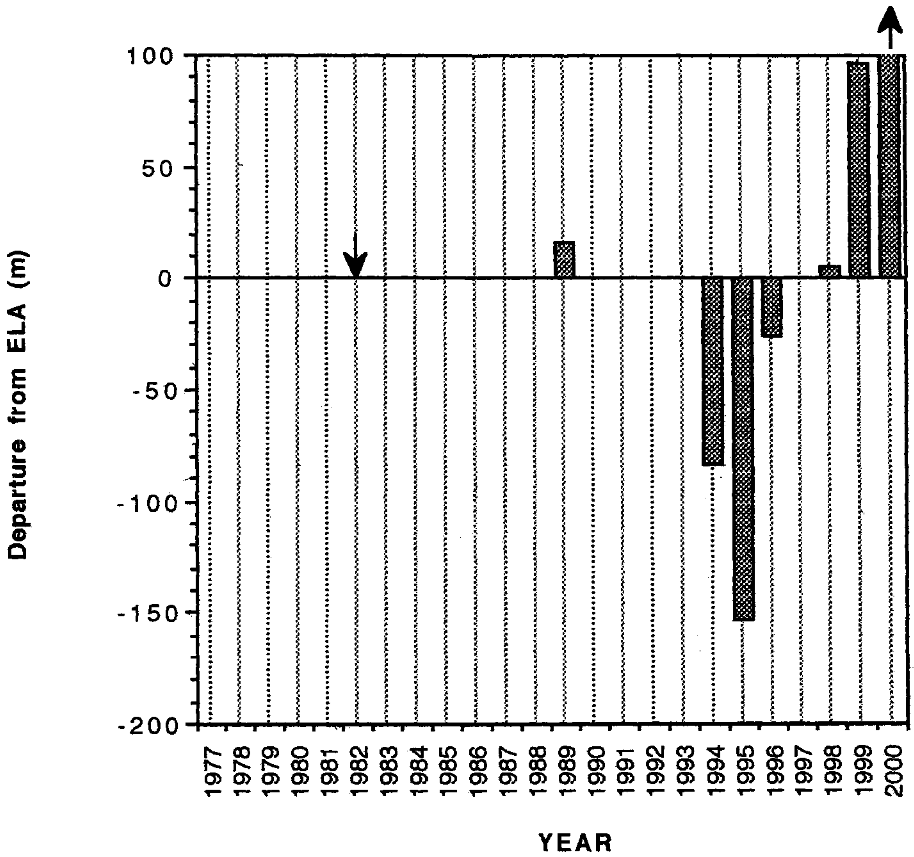




Mt Ella

Glacier map and histogram plot of all recorded snowlines

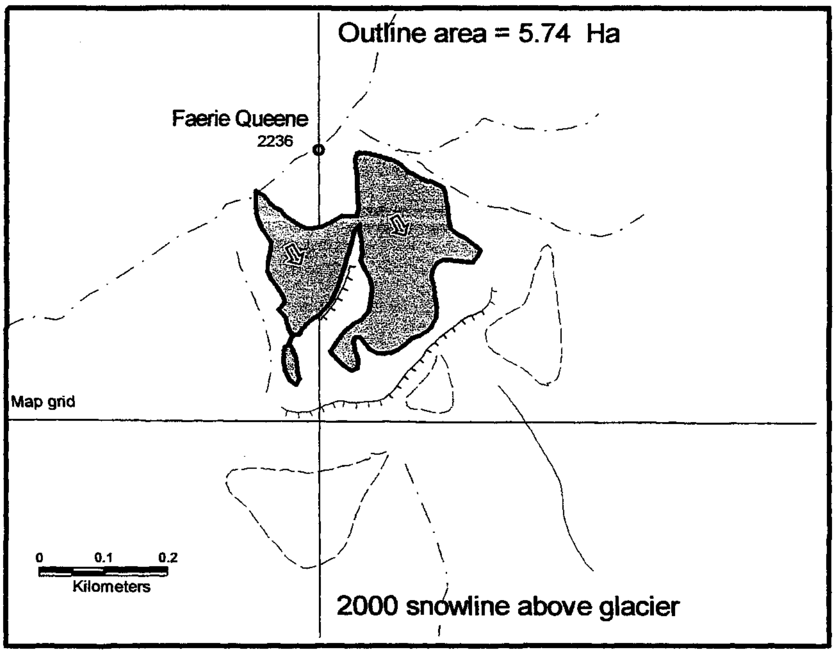


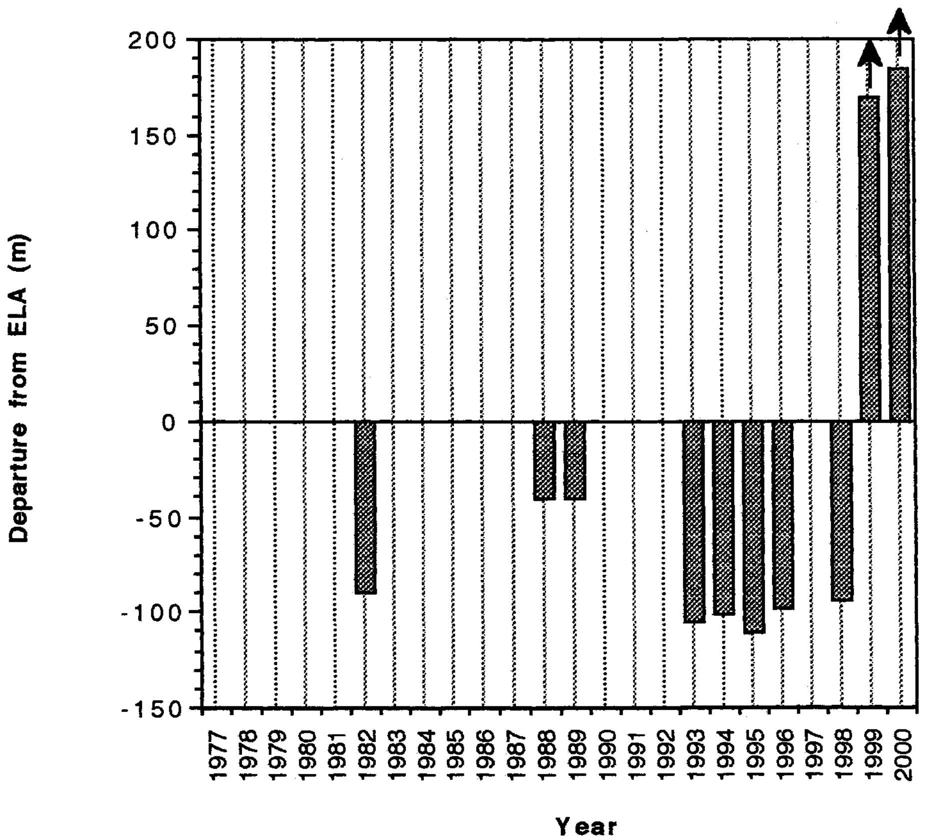


Appendix 3:

Mt Faerie Queene

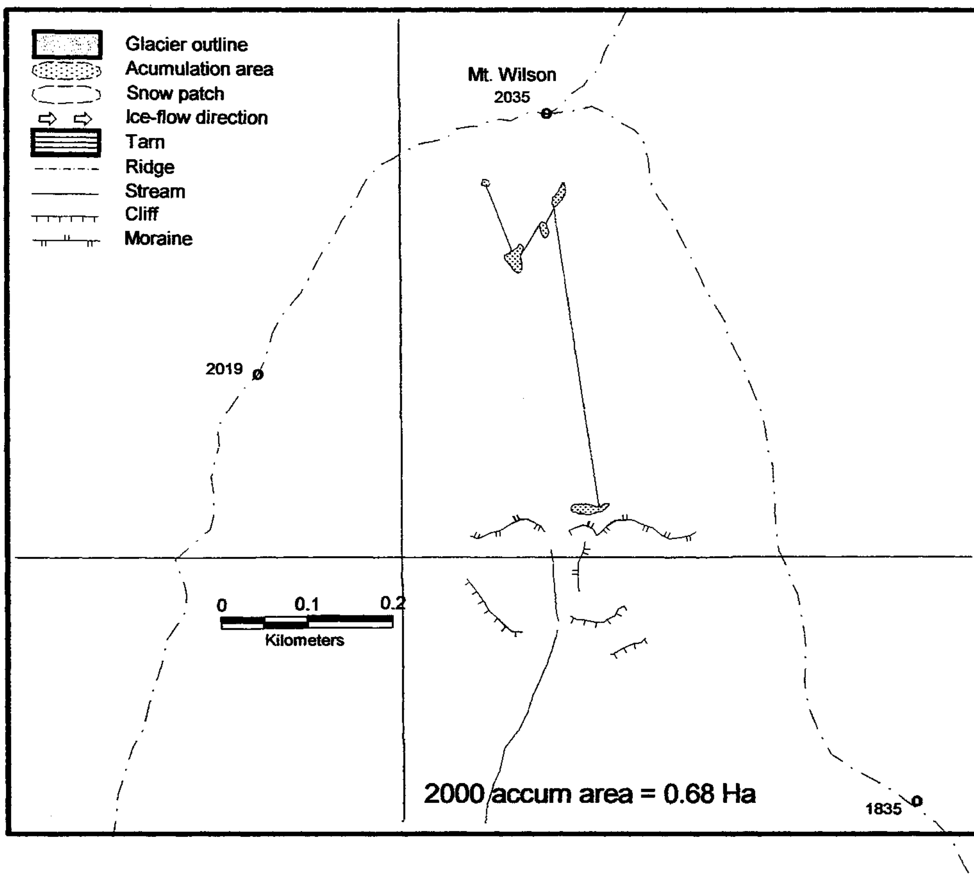
Glacier map and histogram plot of all recorded snowlines

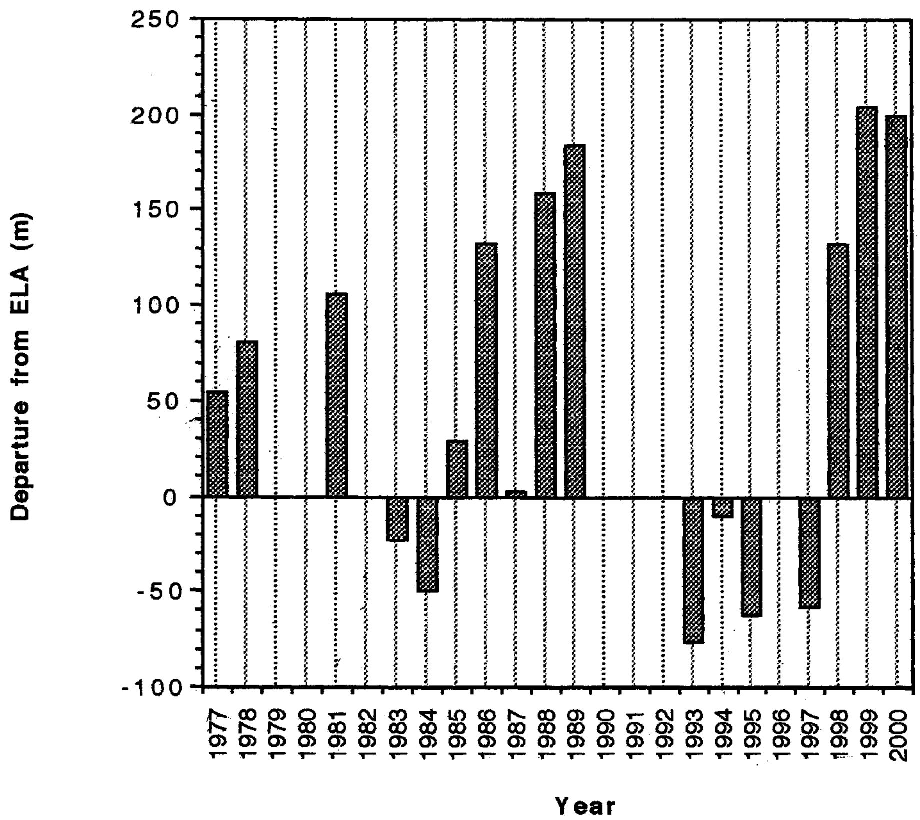




Mt Wilson

Glacier map and histogram plot of all recorded snowlines

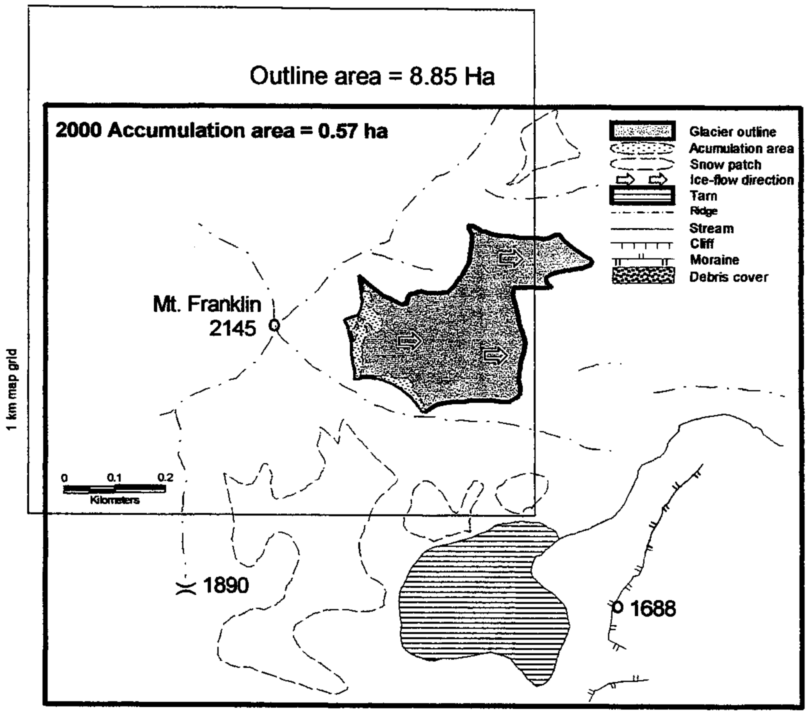


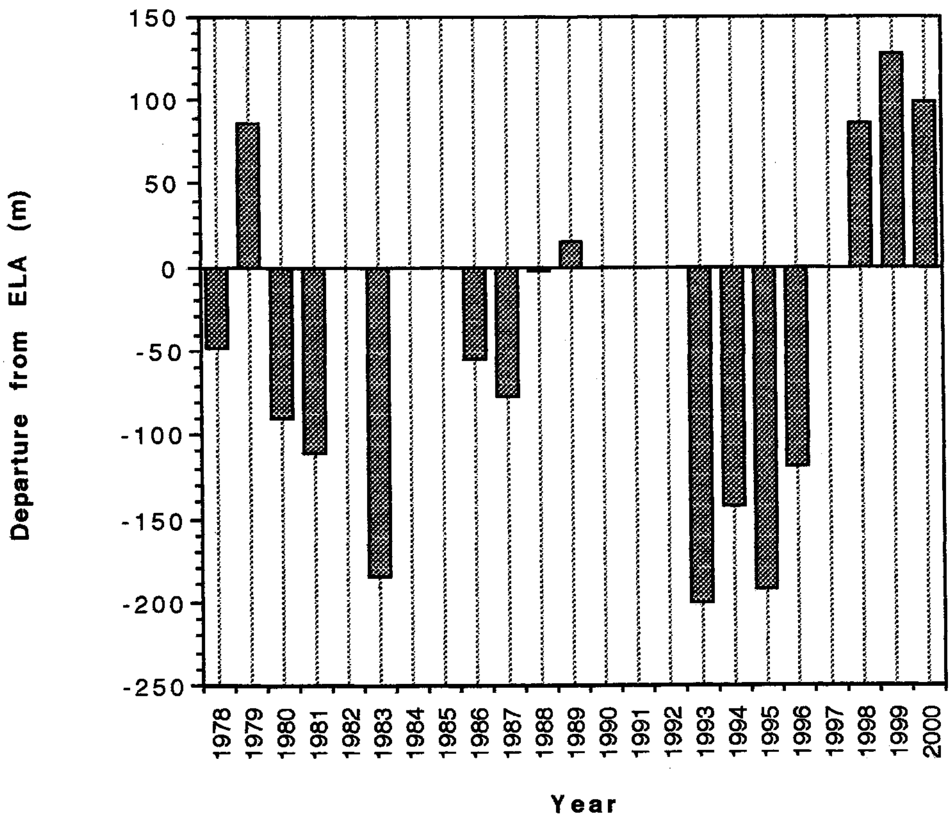


Appendix 5:

Mt Franklin

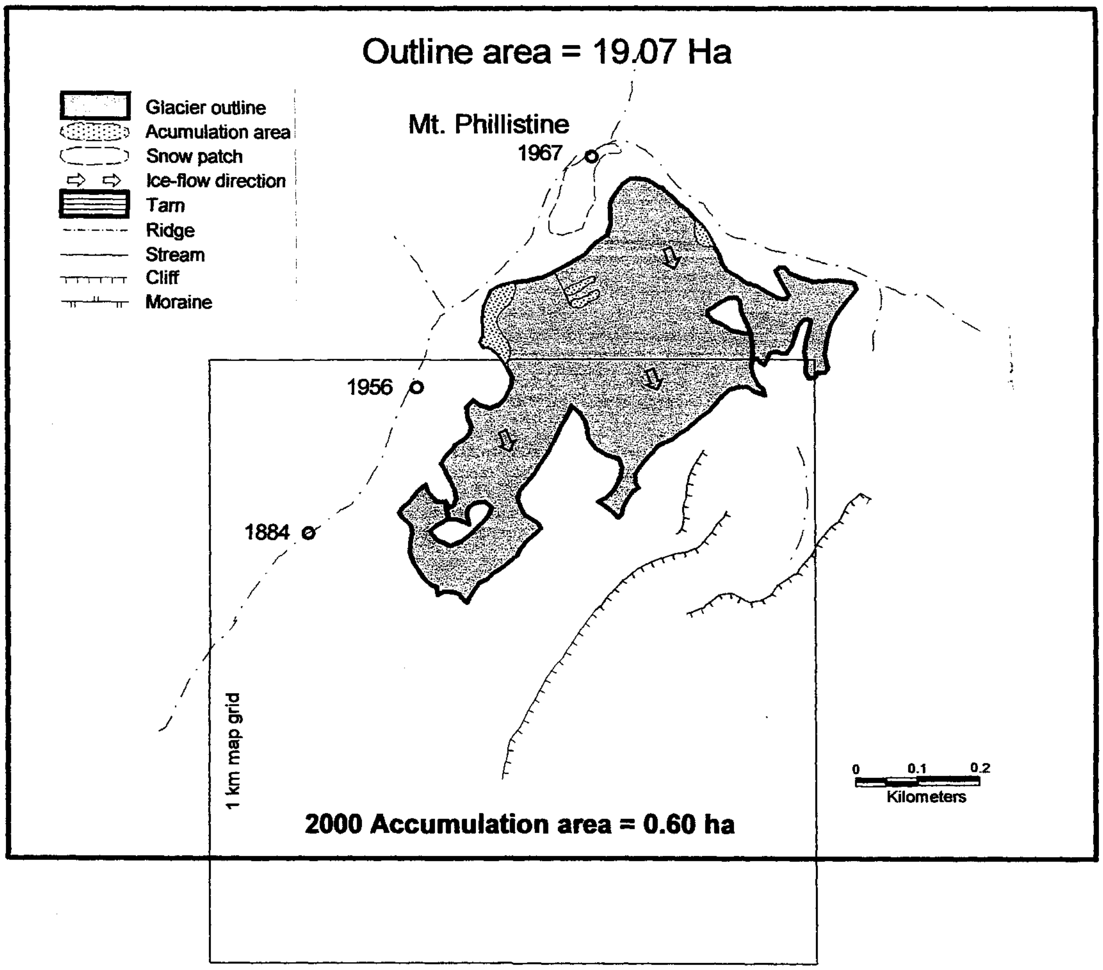
Glacier map and histogram plot of all recorded snowlines

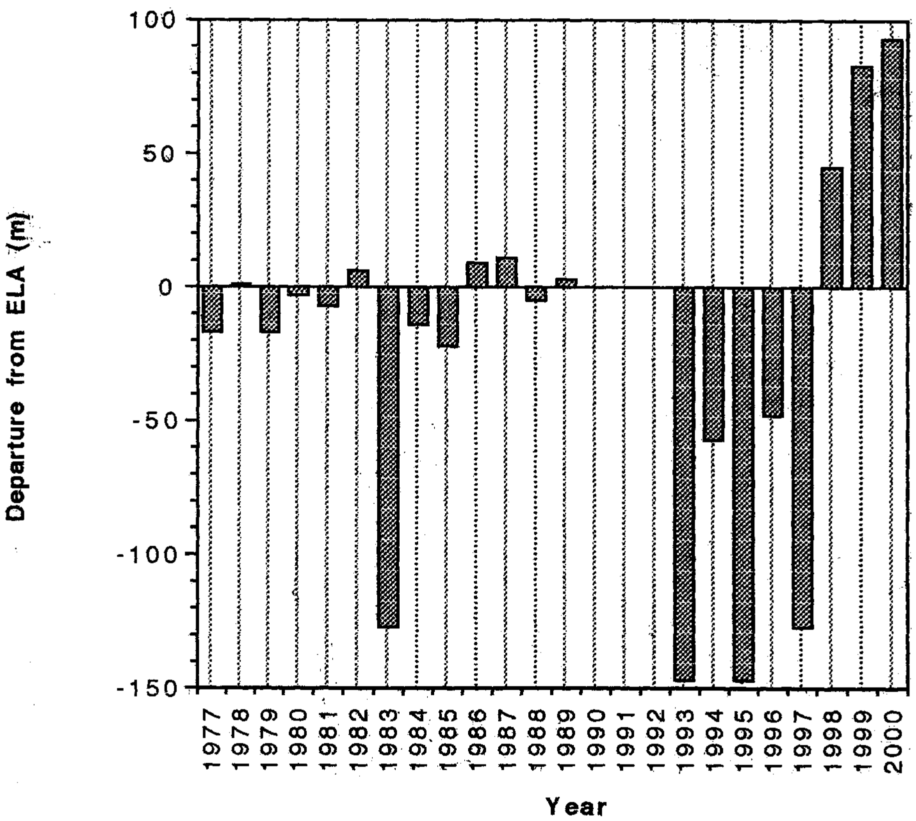




Rolleston Gl.

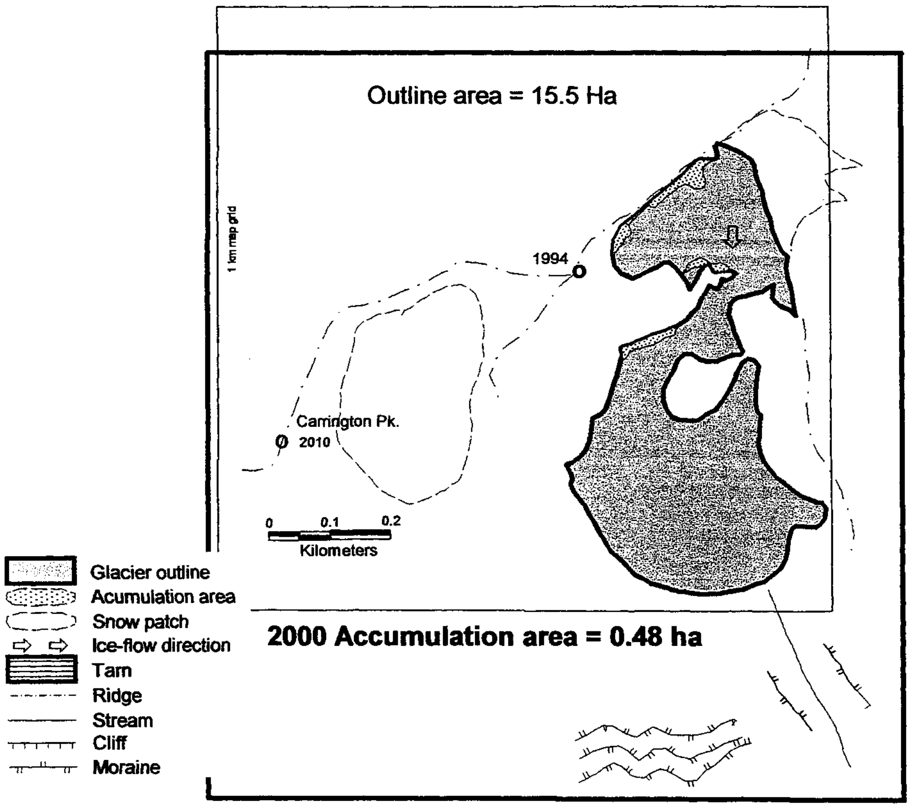
Glacier map and histogram plot of all recorded snowlines

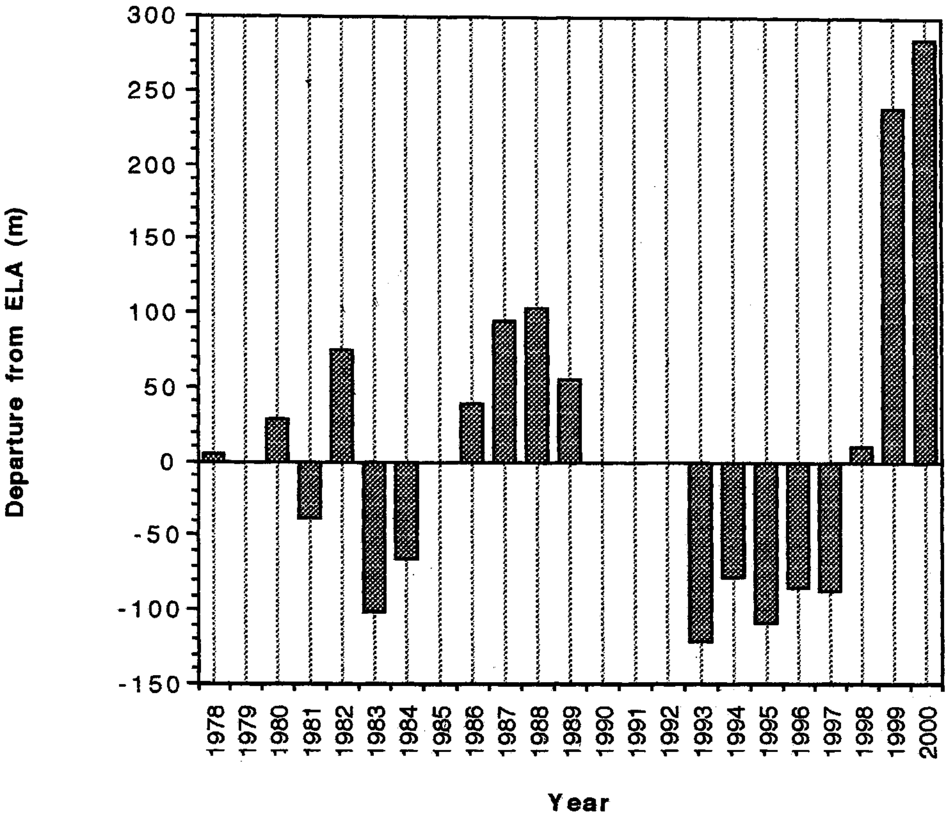




Mt Carrington

Glacier map and histogram plot of all recorded snowlines

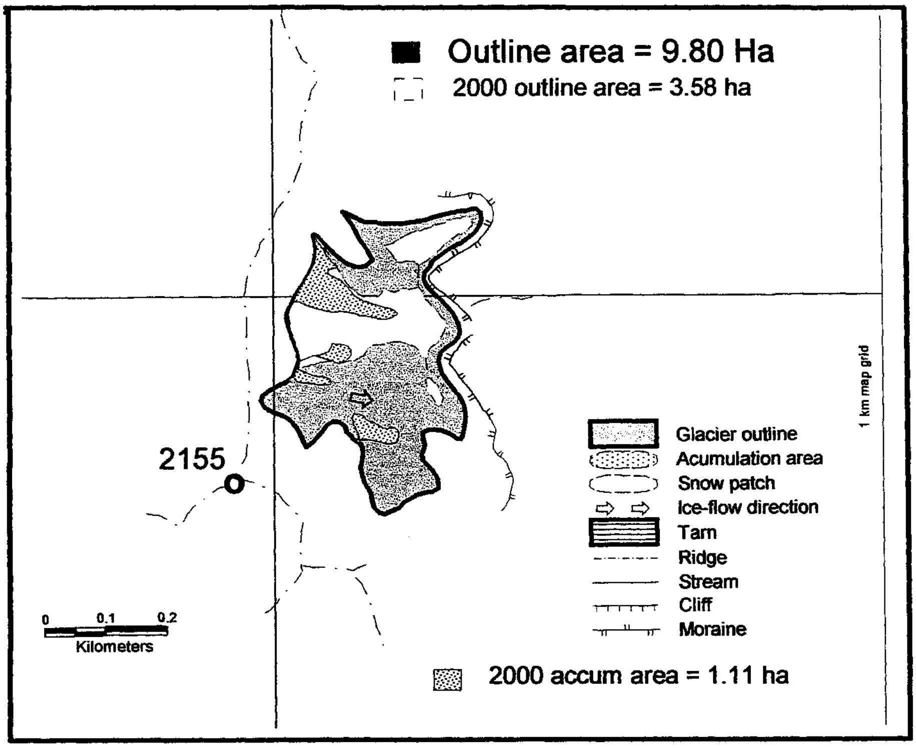


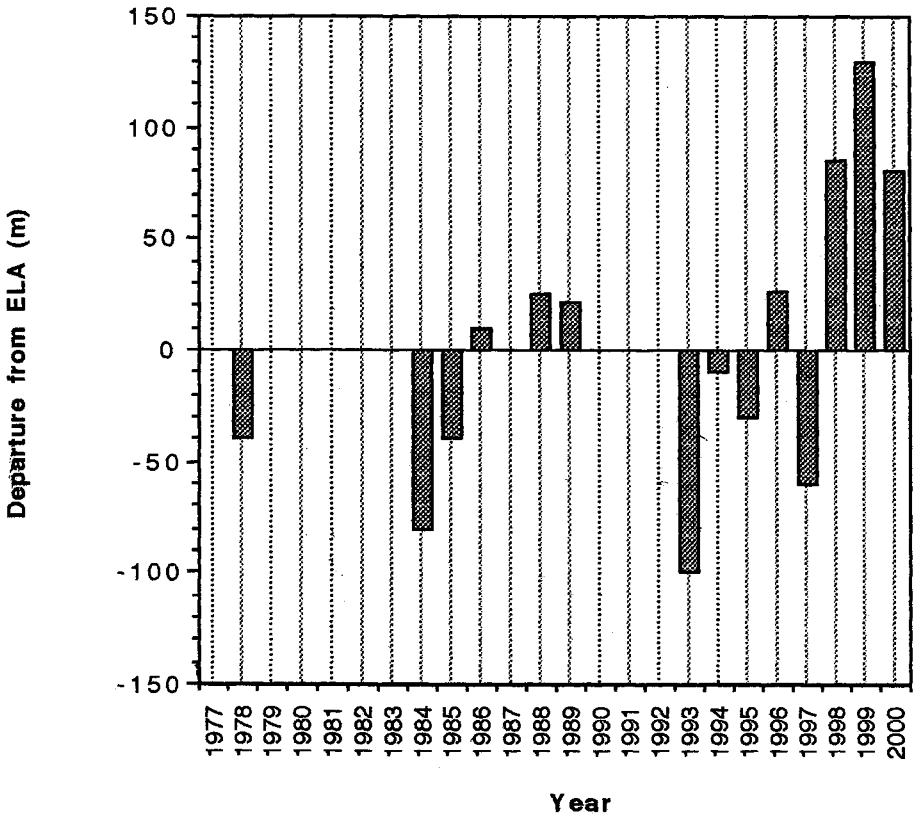


Appendix 8:

Mt Avoca

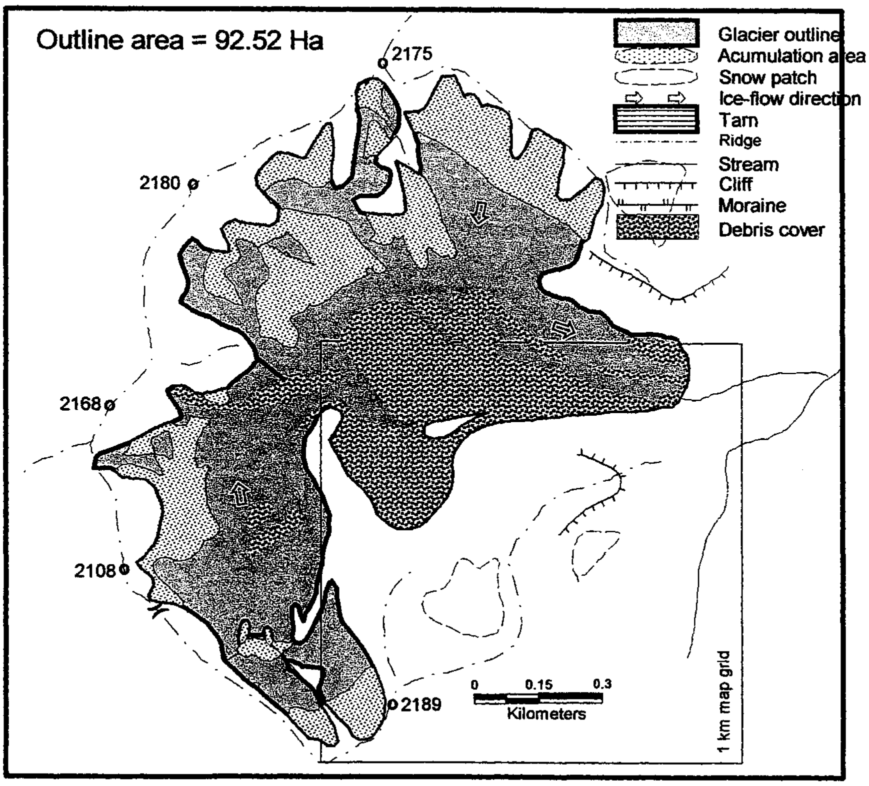
Glacier map and histogram plot of all recorded snowlines



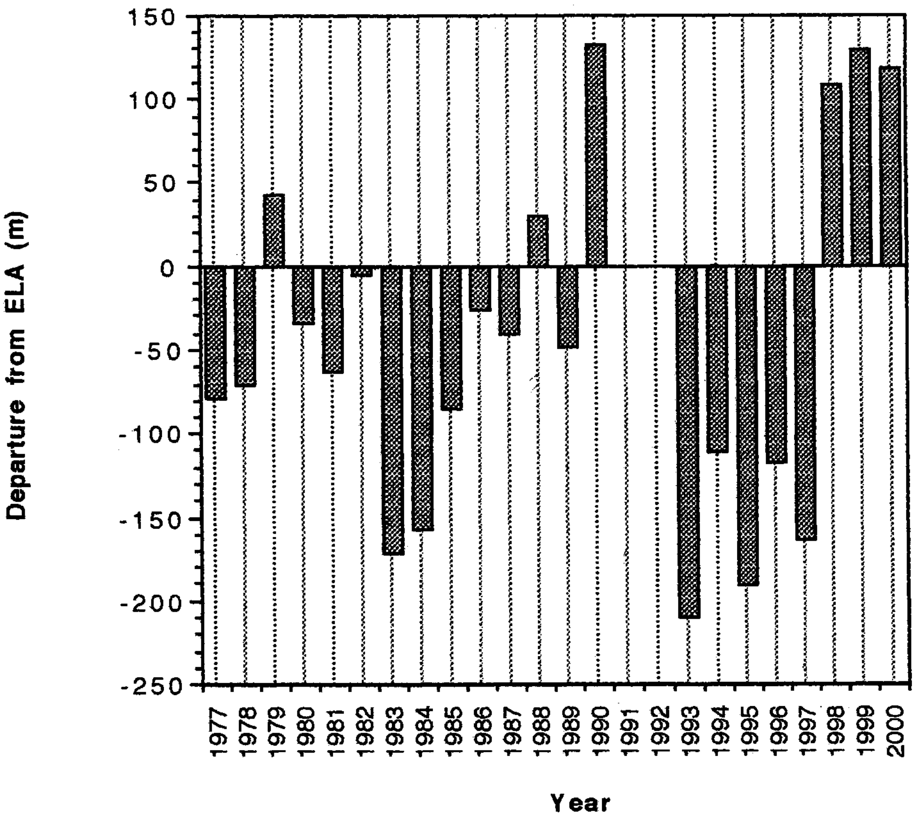


Marmaduke Gl.

Glacier map and histogram plot of all recorded snowlines



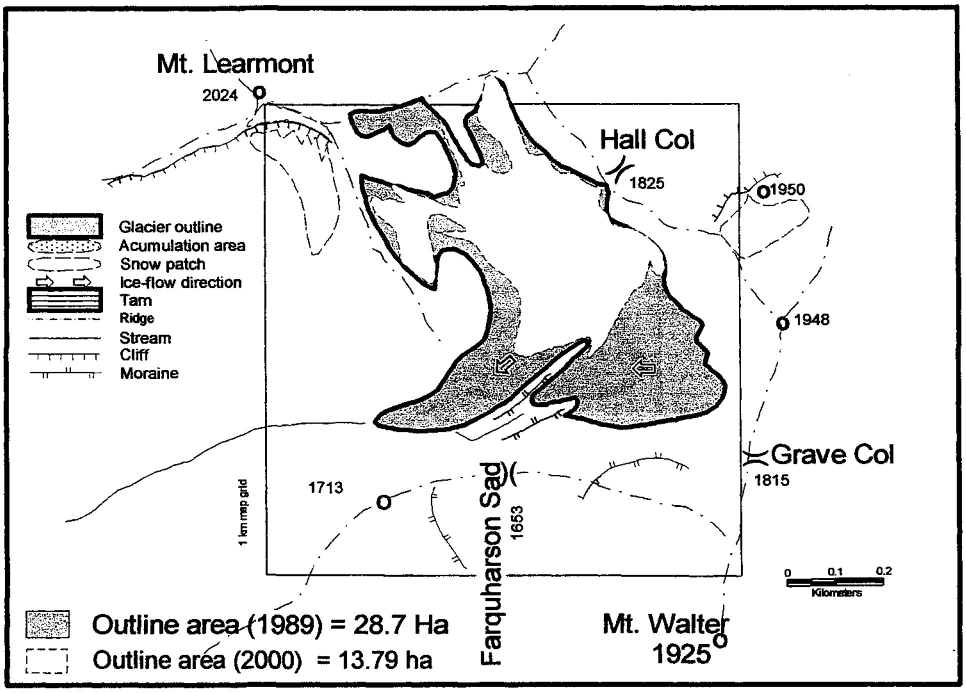
2000 Accum area = 23.75 ha

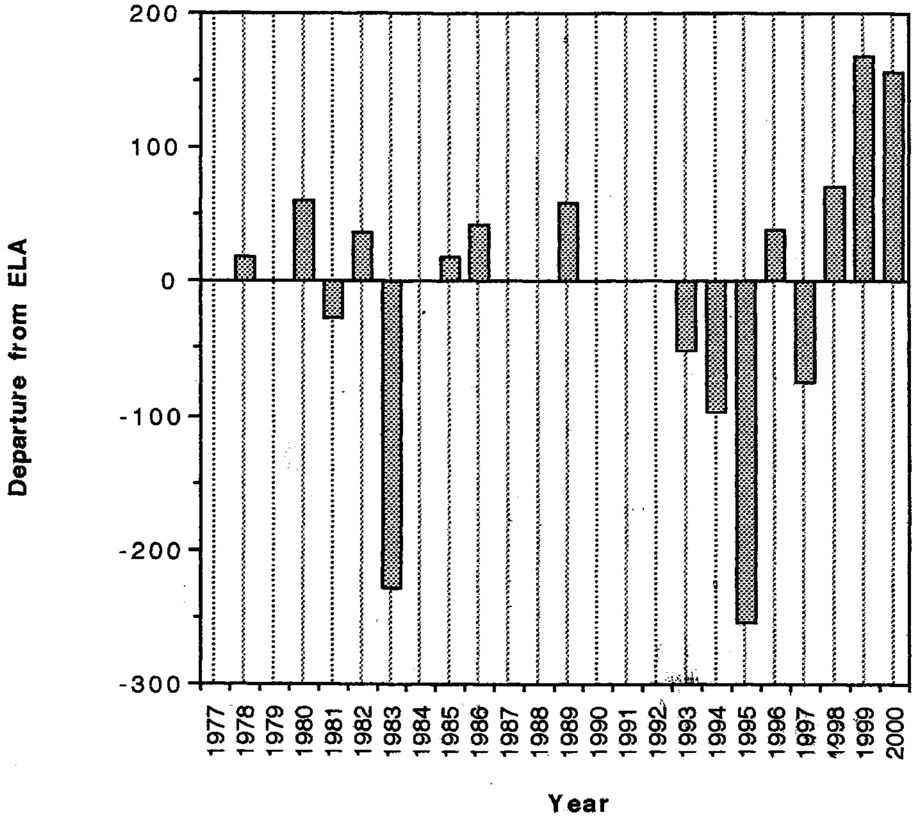


Appendix 10:

Retreat Gl.

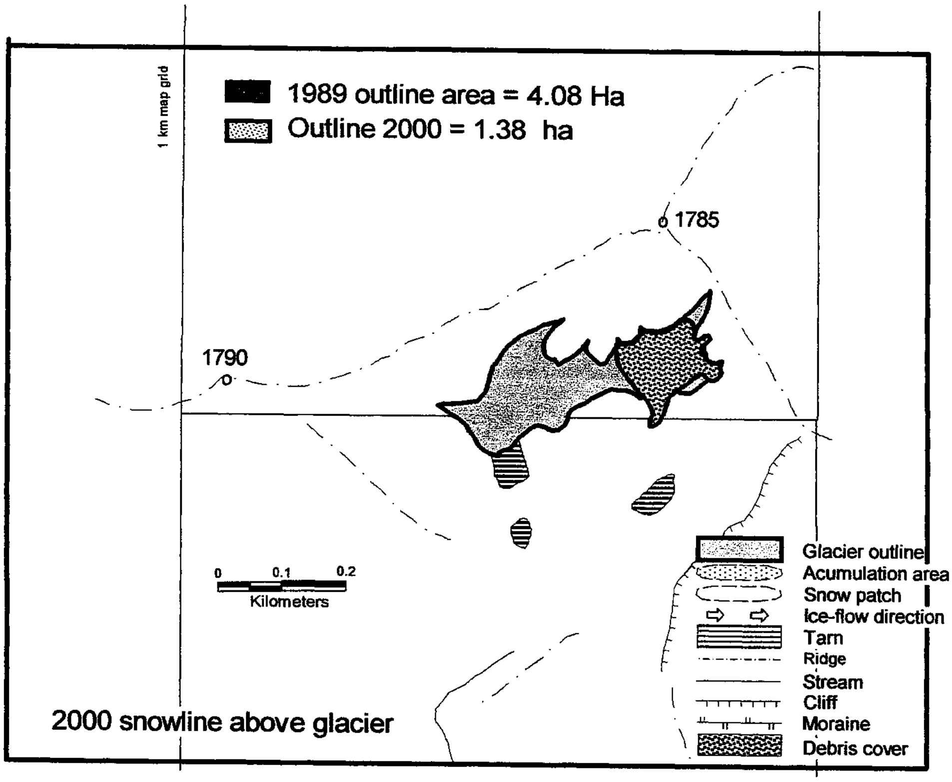
Glacier map and histogram plot of all recorded snowlines

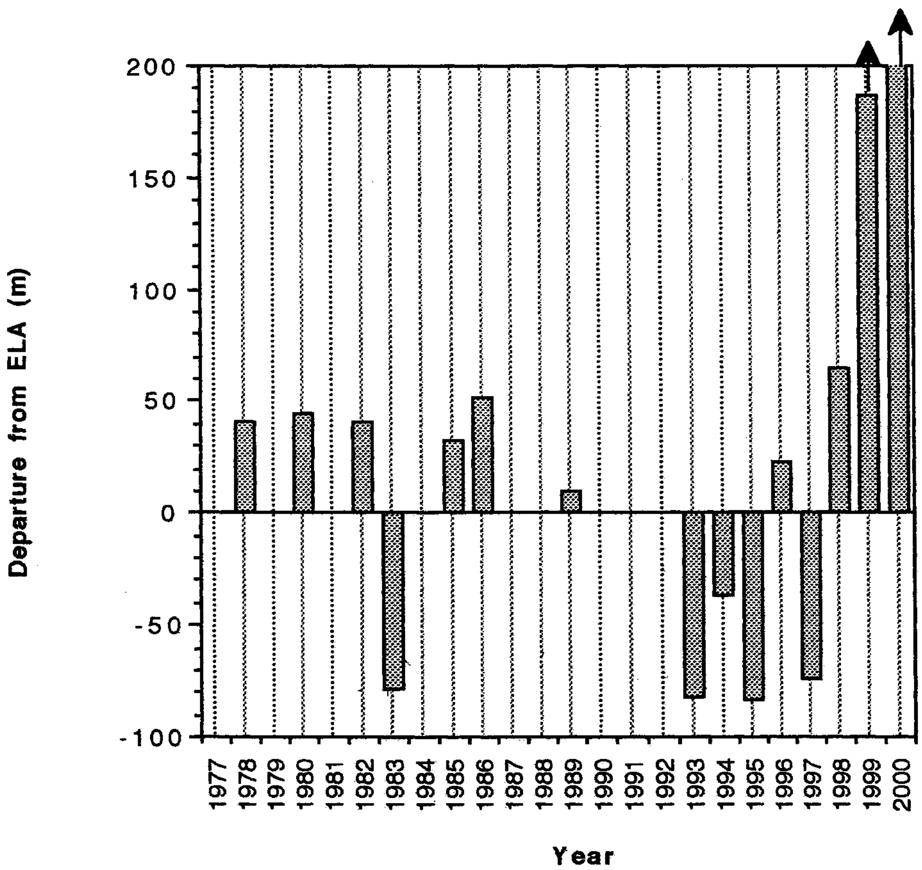




Browning Ra.

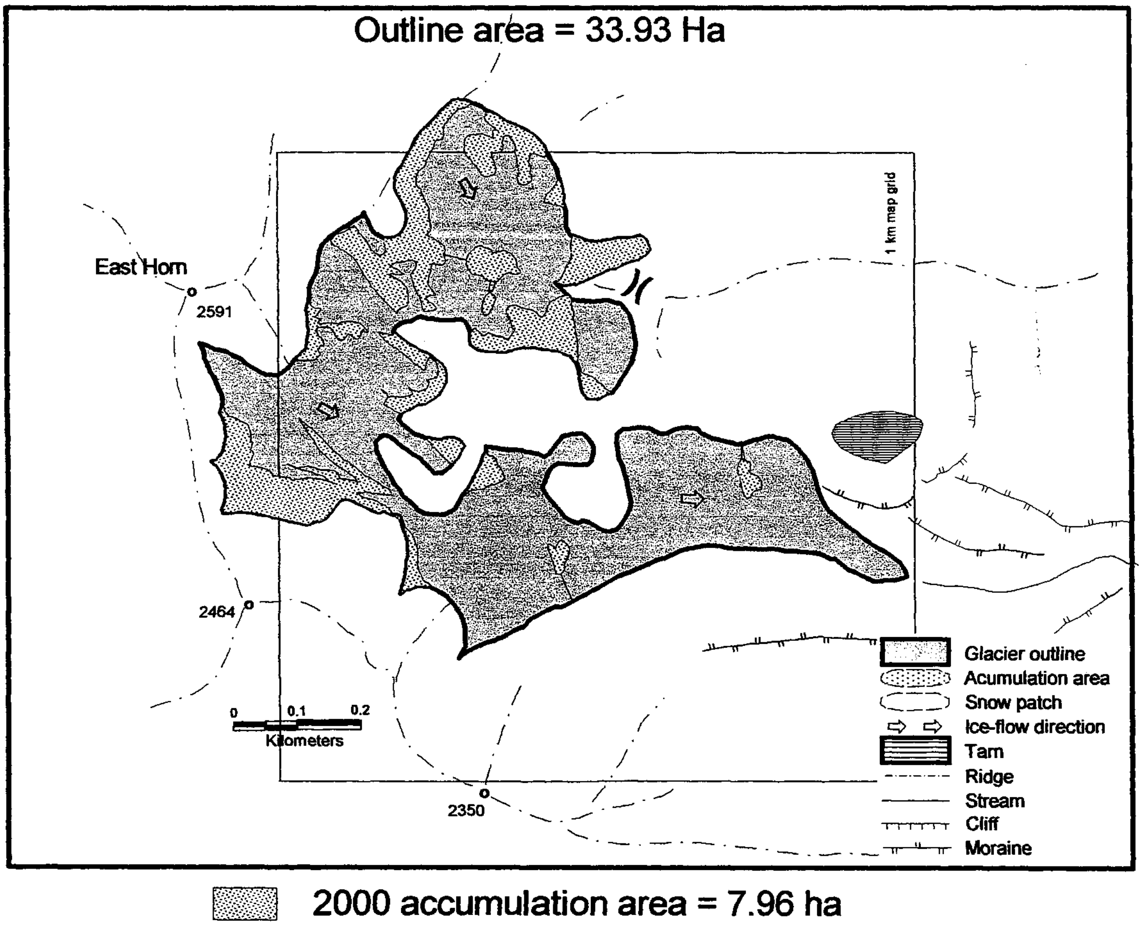
Glacier map and histogram plot of all recorded snowlines

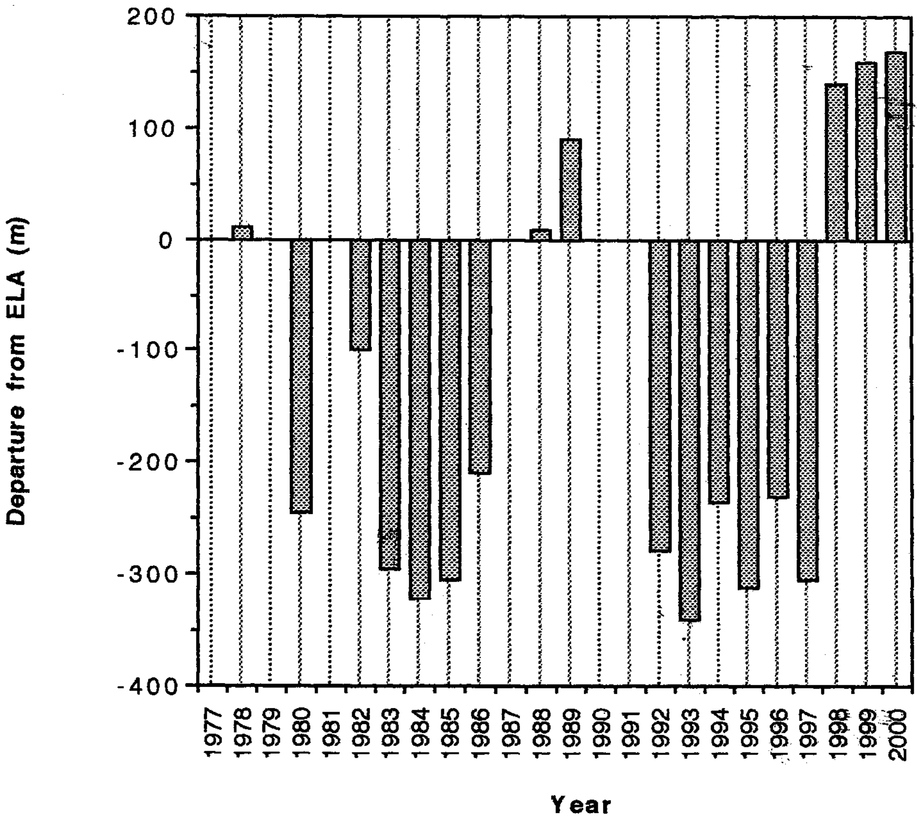




Douglas Gl.

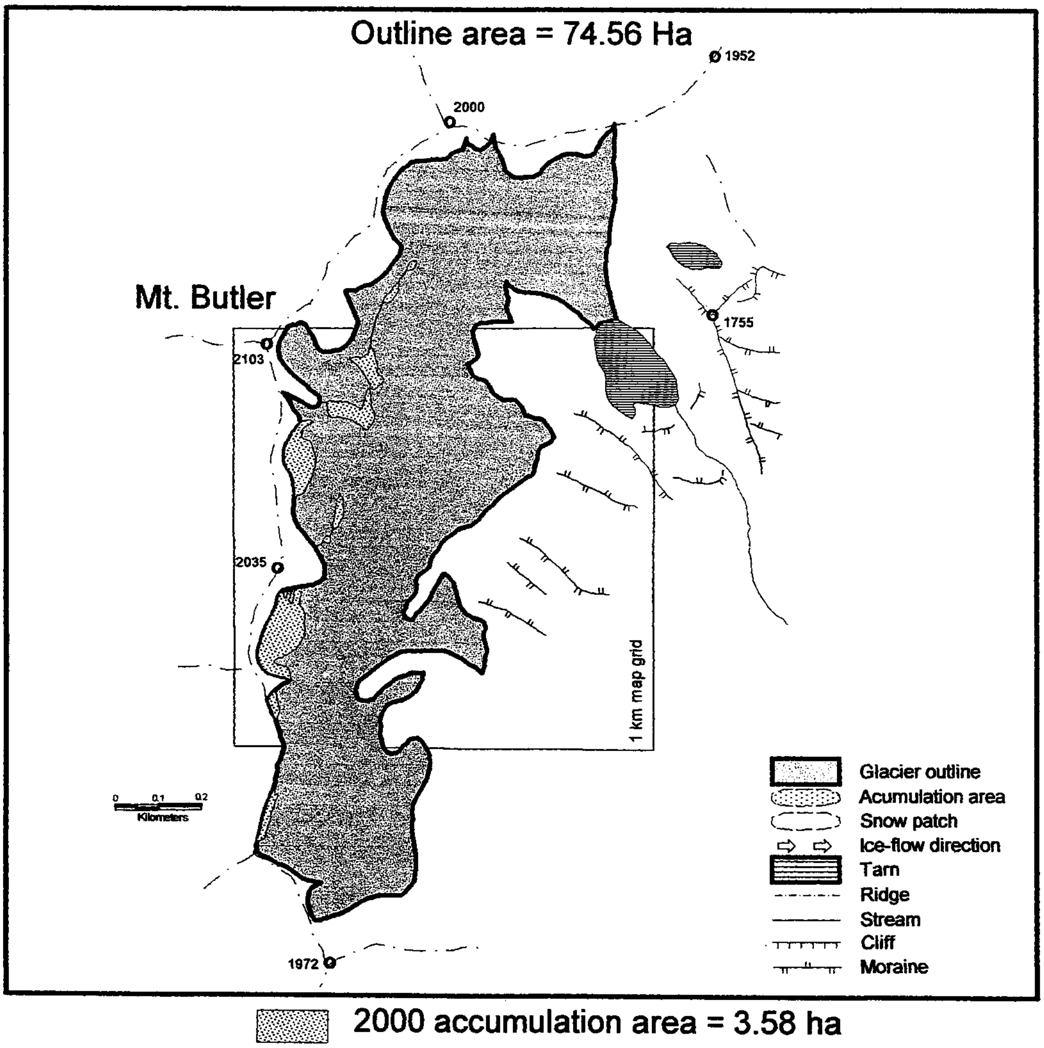
Glacier map and histogram plot of all recorded snowlines

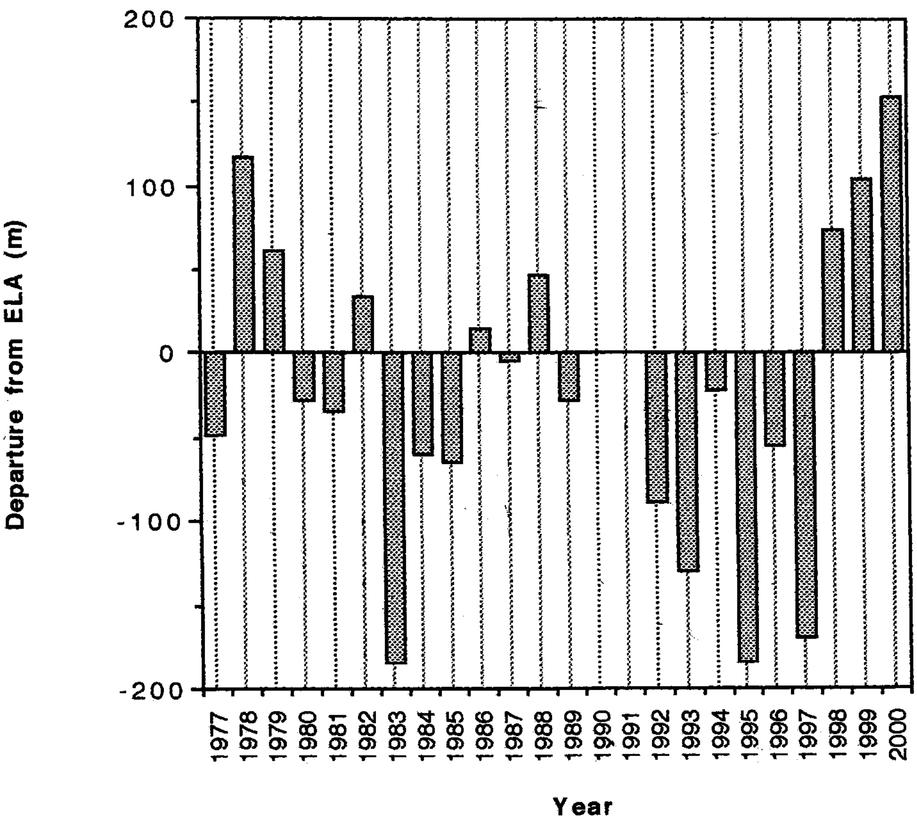




Mt Butler

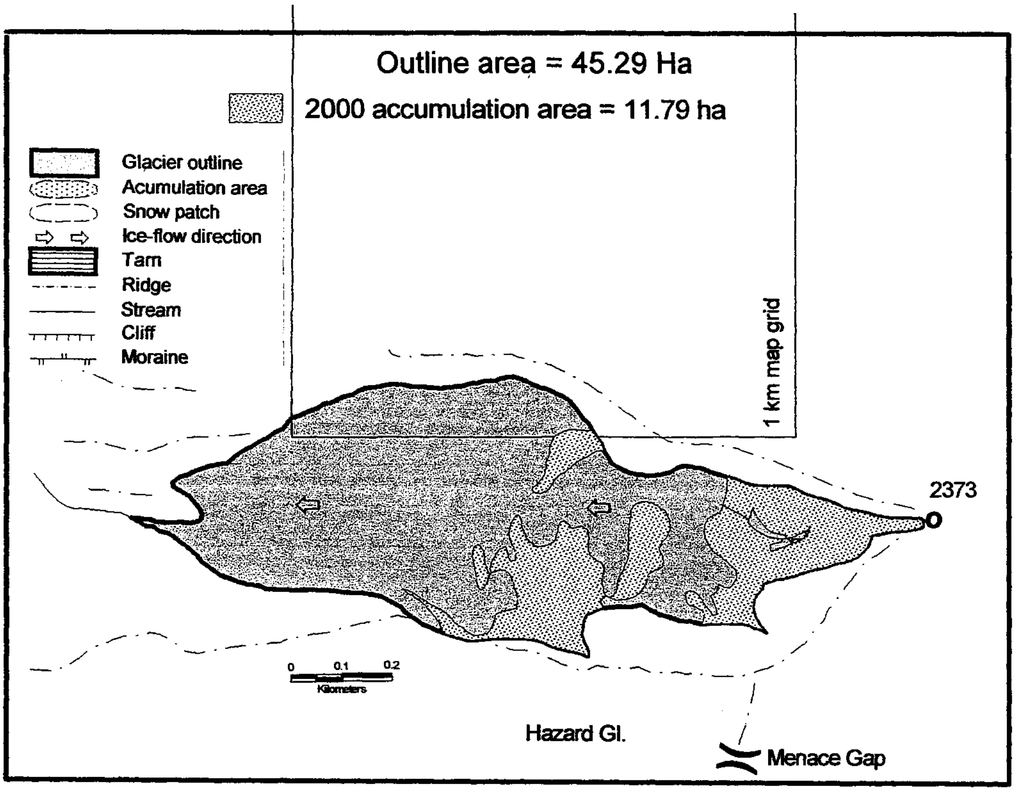
Glacier map and histogram plot of all recorded snowlines

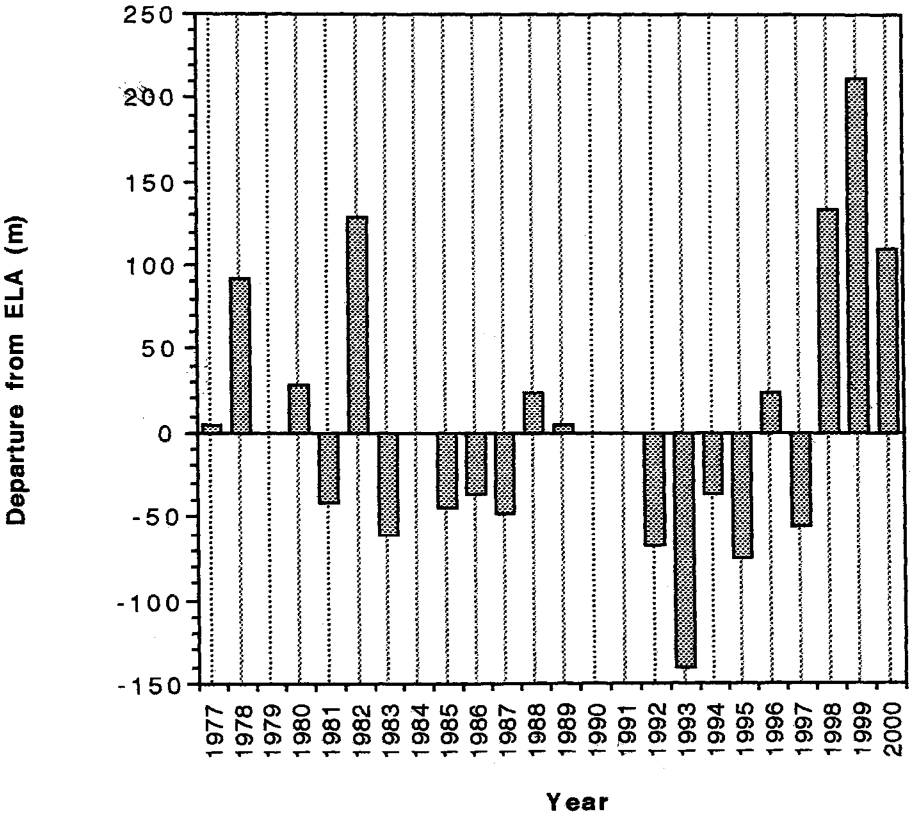




Dainty Gl.

Glacier map and histogram plot of all recorded snowlines

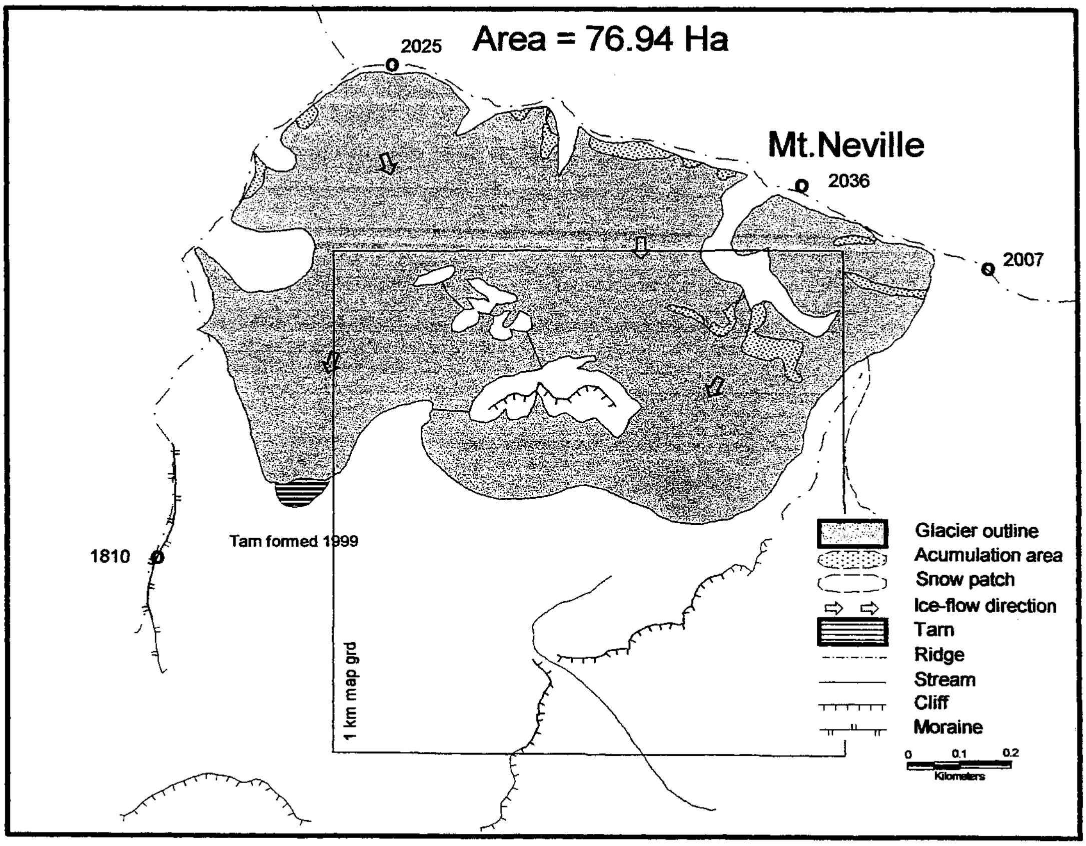




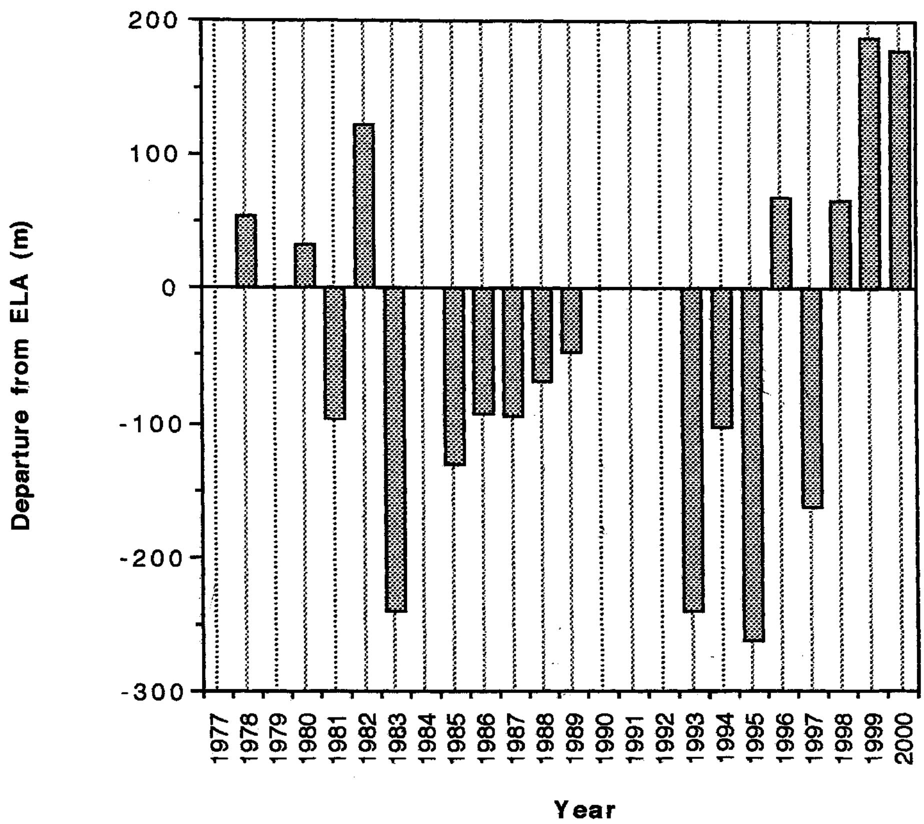
Appendix 15:

Kea Gl.

Glacier map and histogram plot of all recorded snowlines

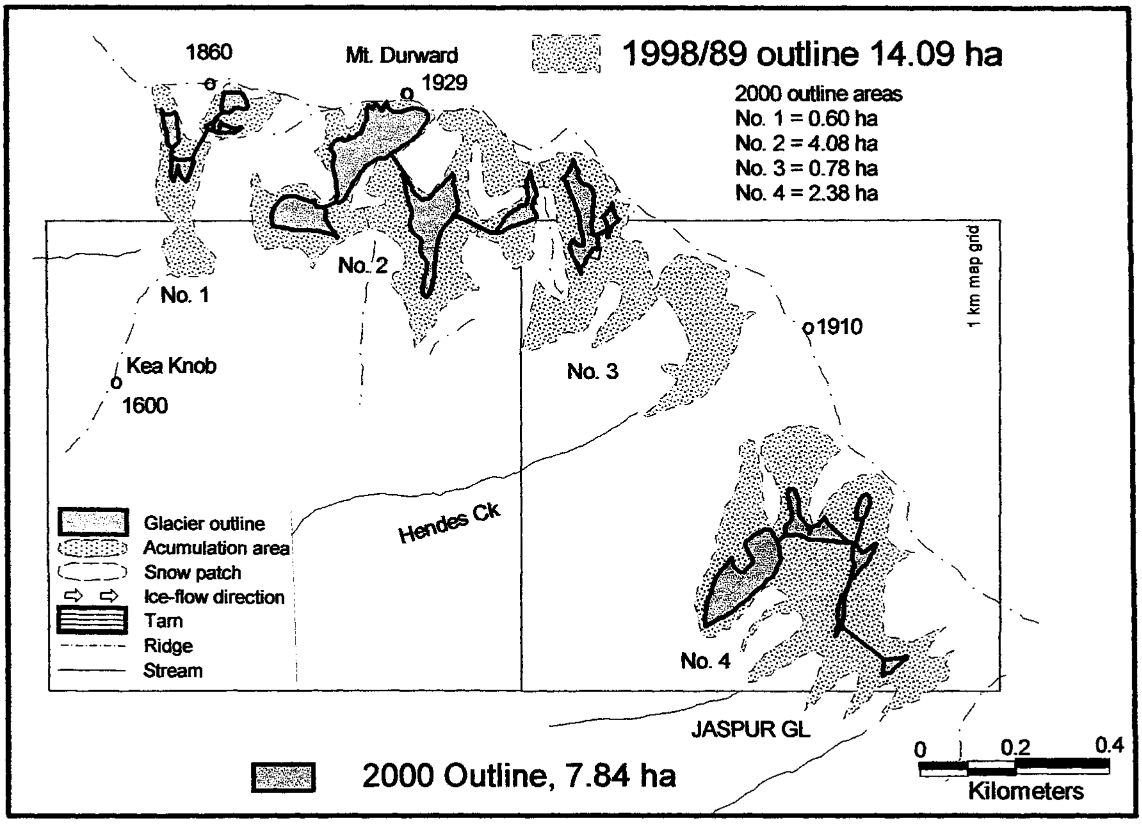


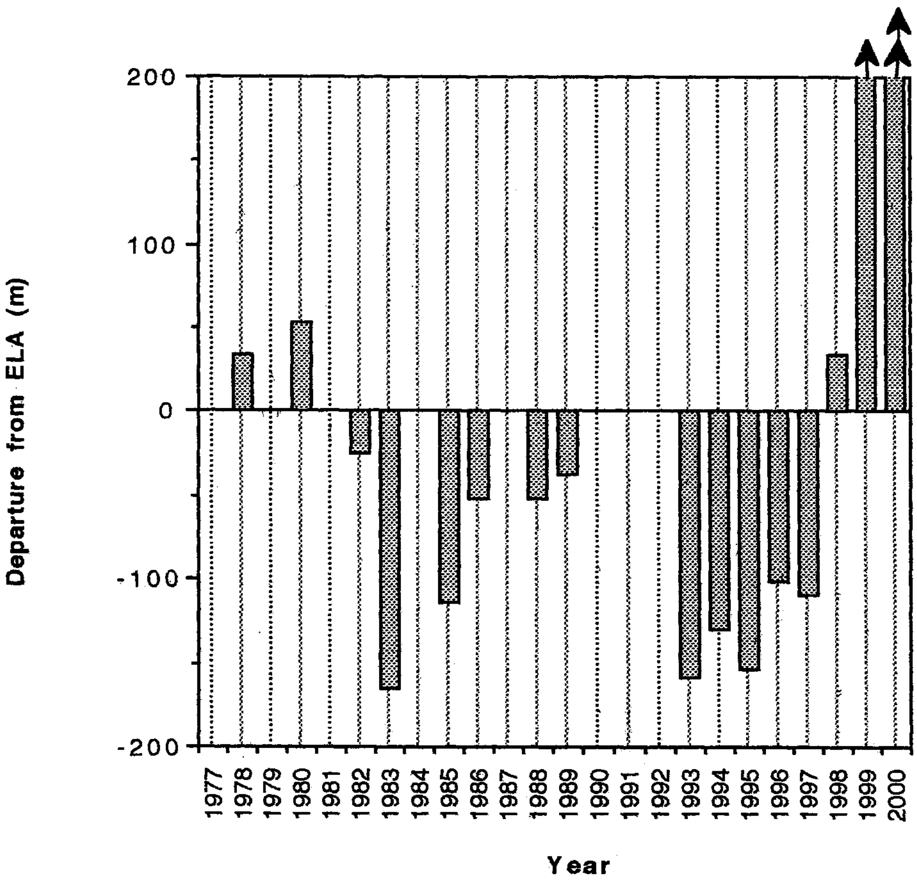
2000 accumulation area = 2.3 ha



Jaspur Gl.

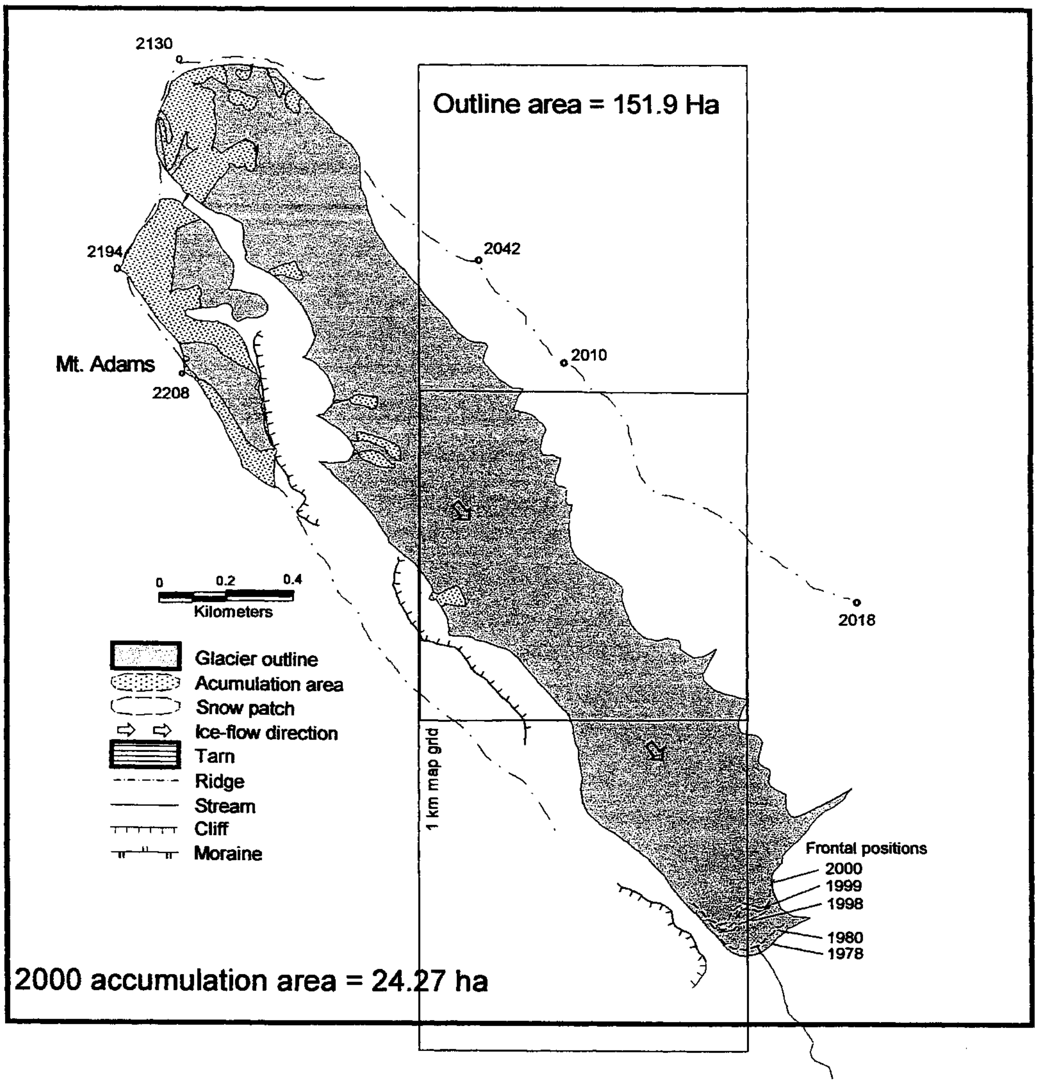
Glacier map and histogram plot of all recorded snowlines

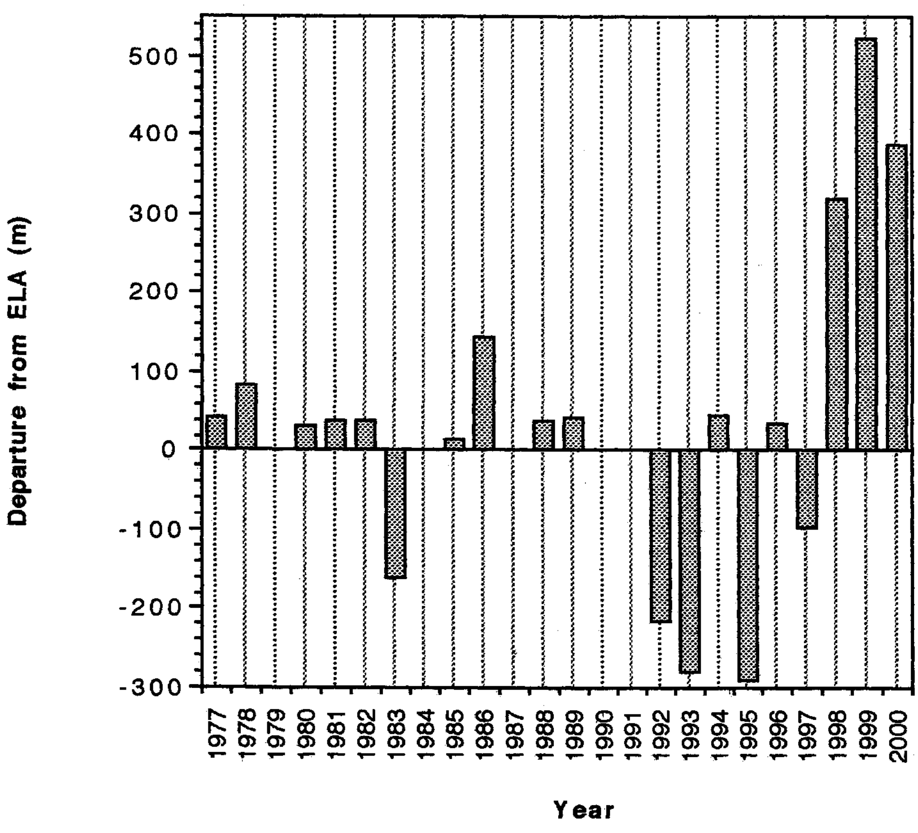




Siege Gl.

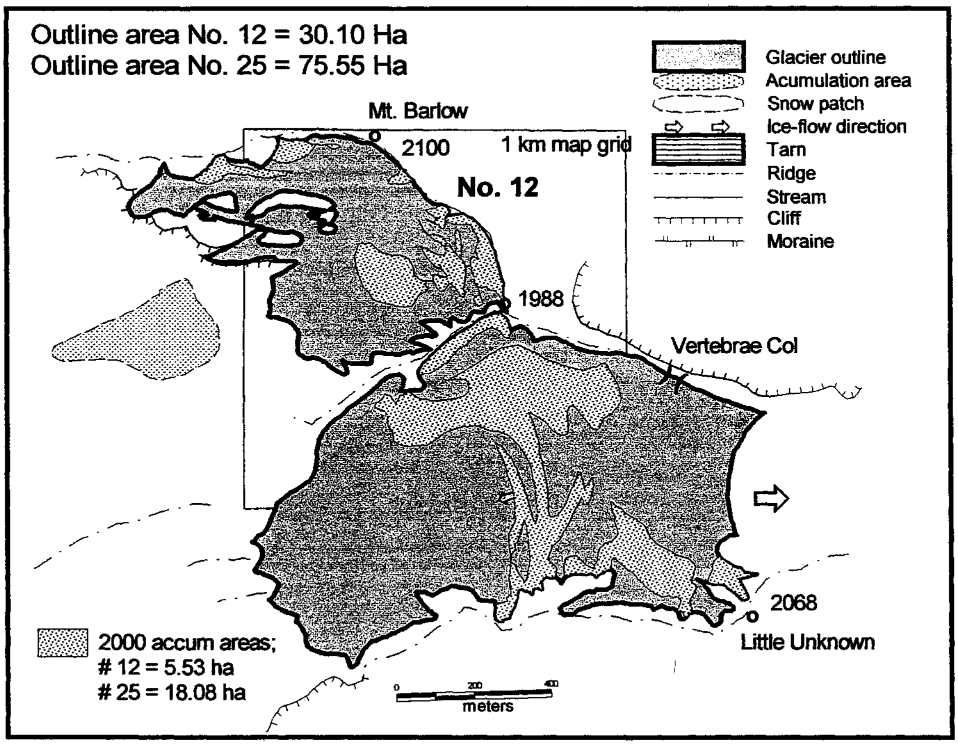
Glacier map and histogram plot of all recorded snowlines

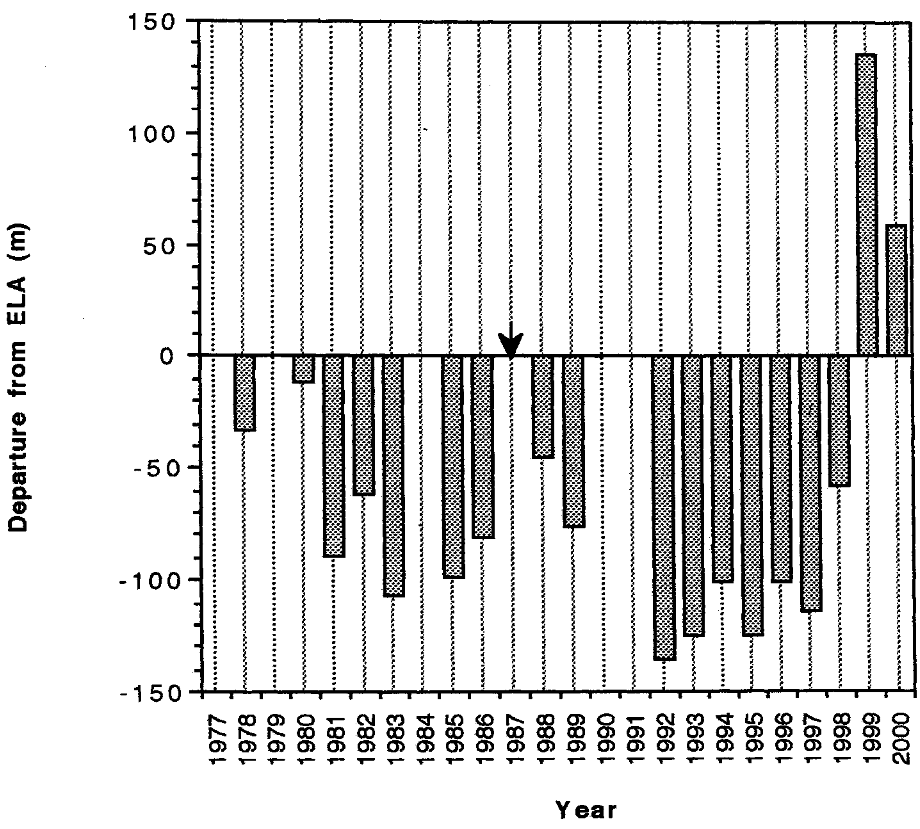




Vertebrae Col

Glacier map and histogram plot of all recorded snowlines

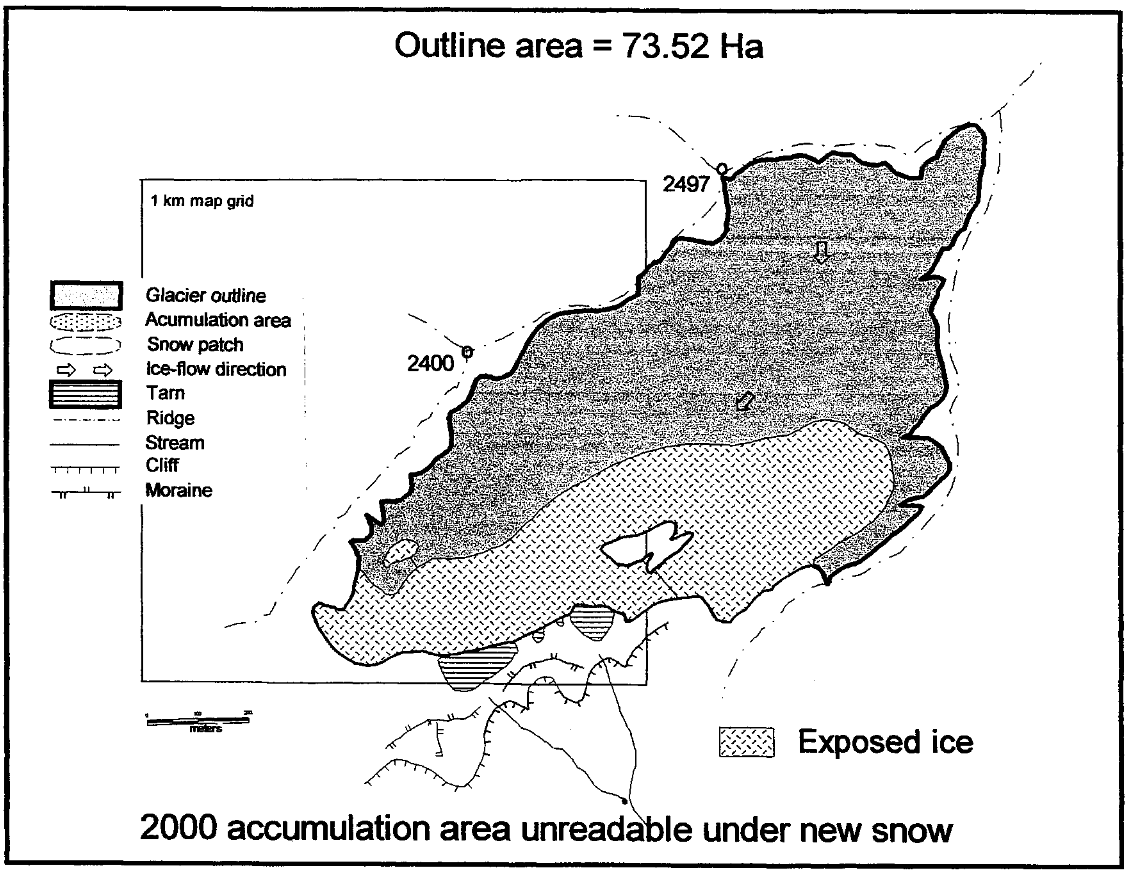


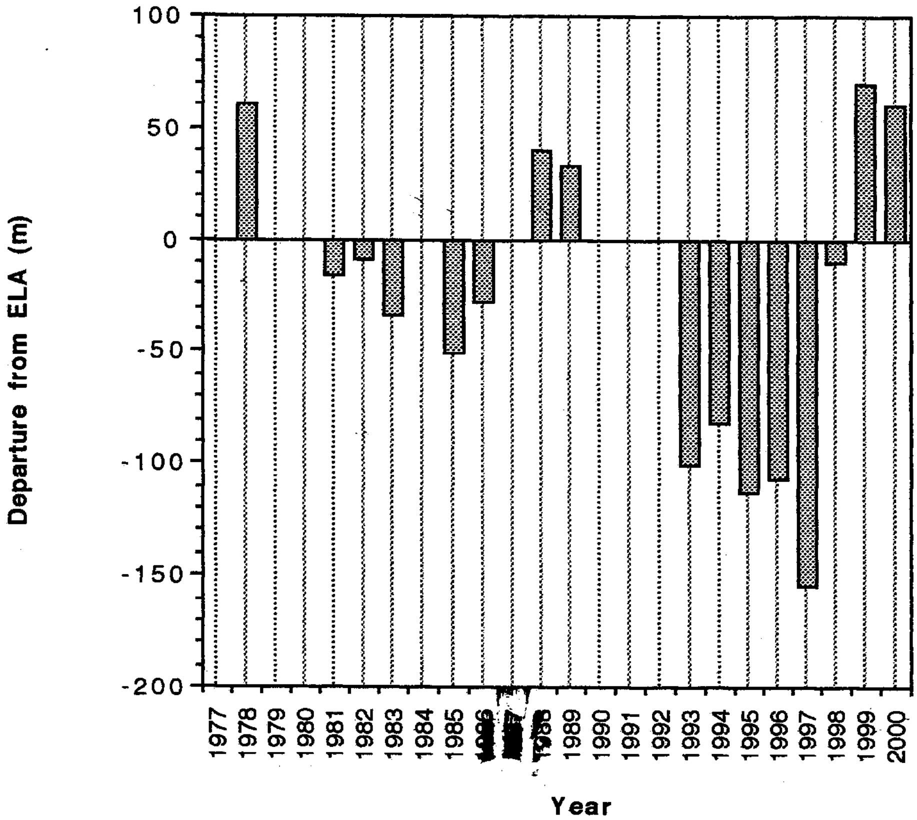


Appendix 19:

Ridge Gl.

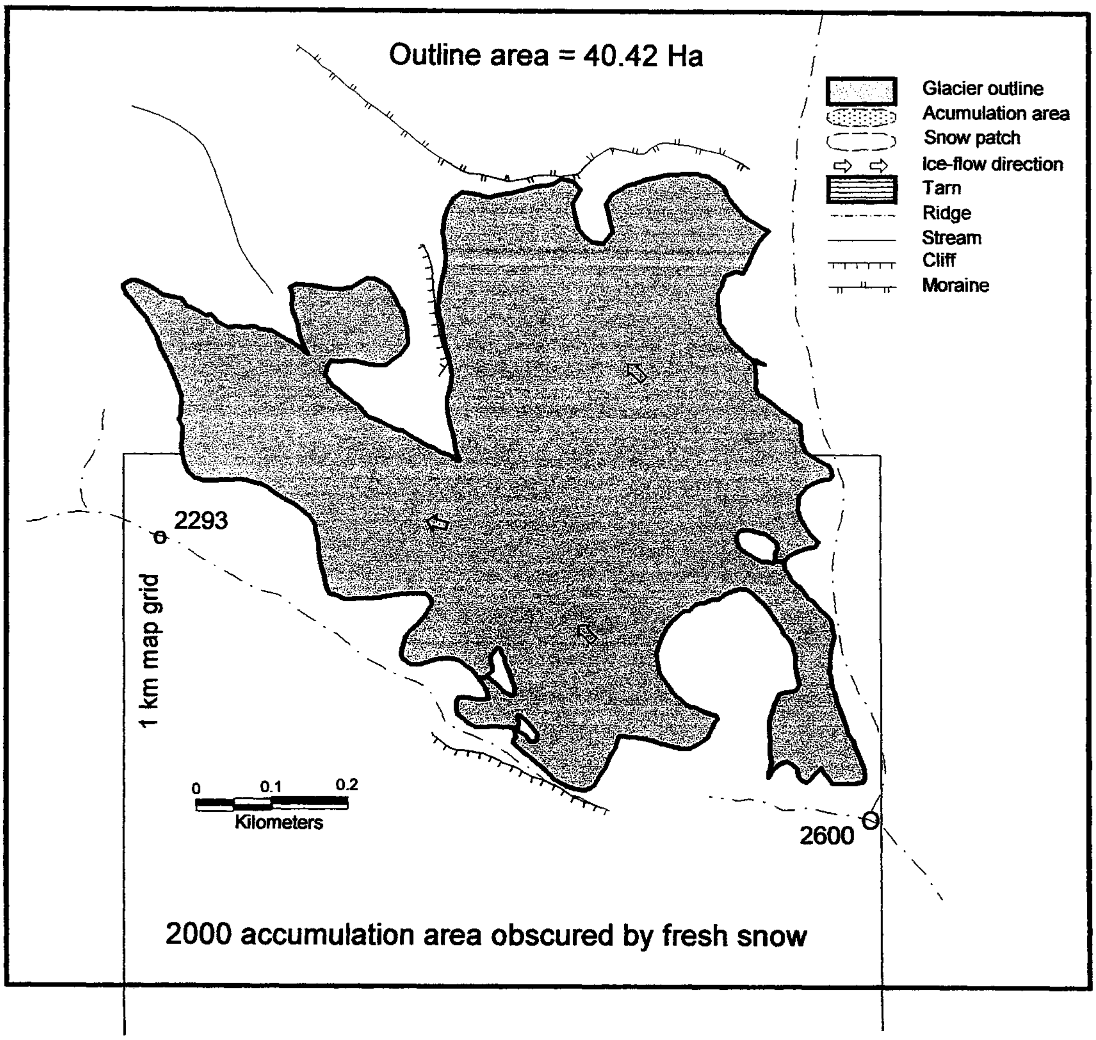
Glacier map and histogram plot of all recorded snowlines

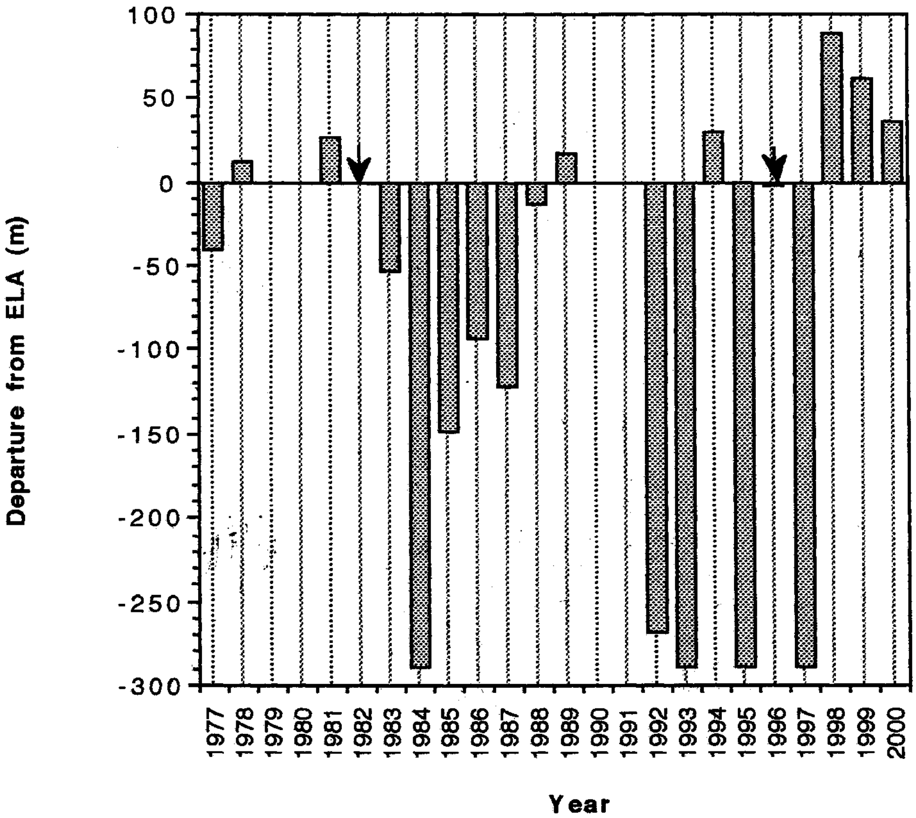




Langdale Gl.

Glacier map and histogram plot of all recorded snowlines

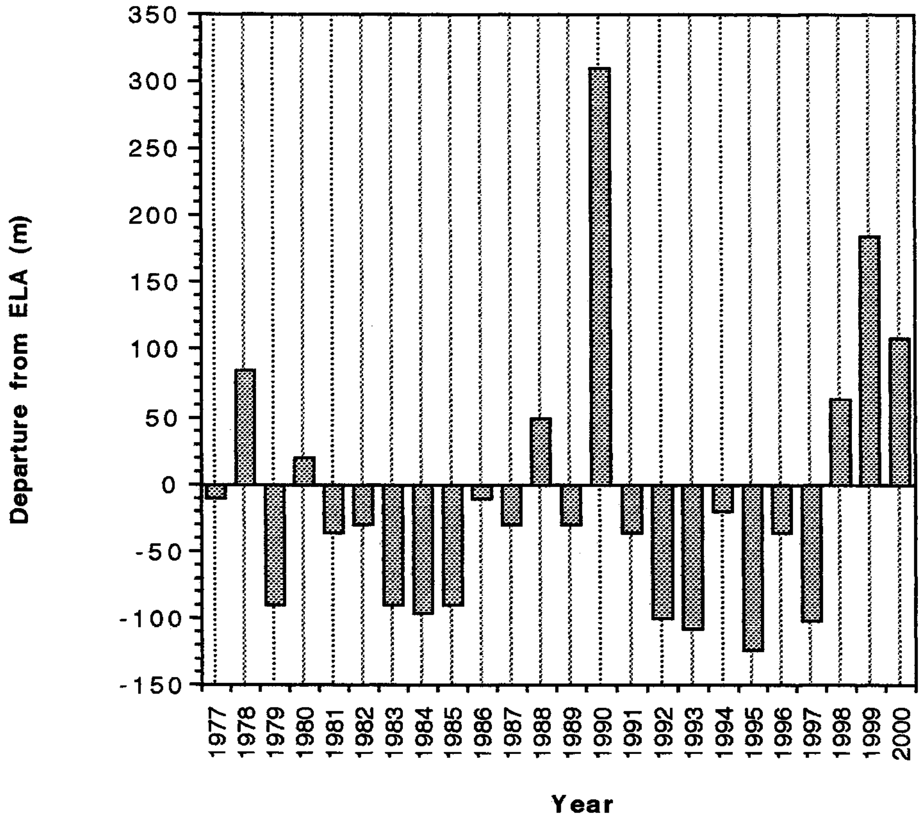




Tasman Gl.

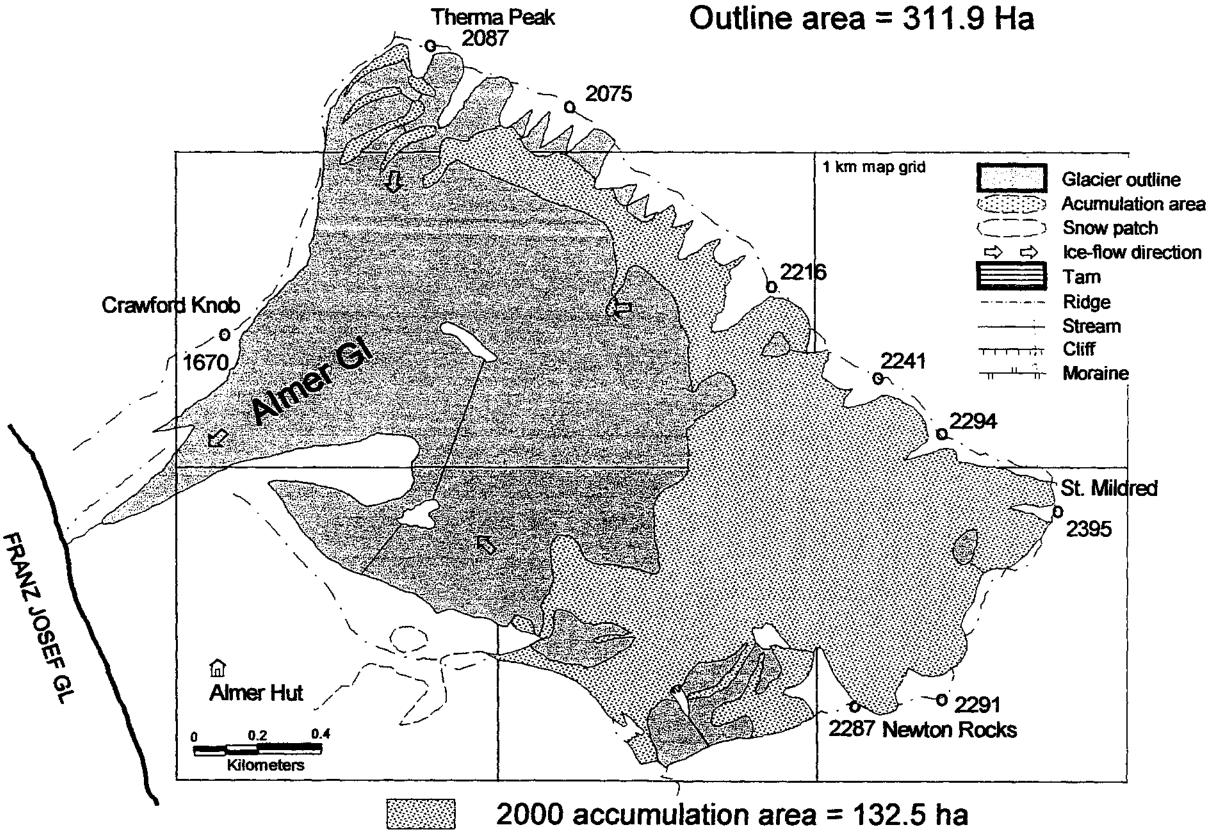
Plot of all recorded snowlines.

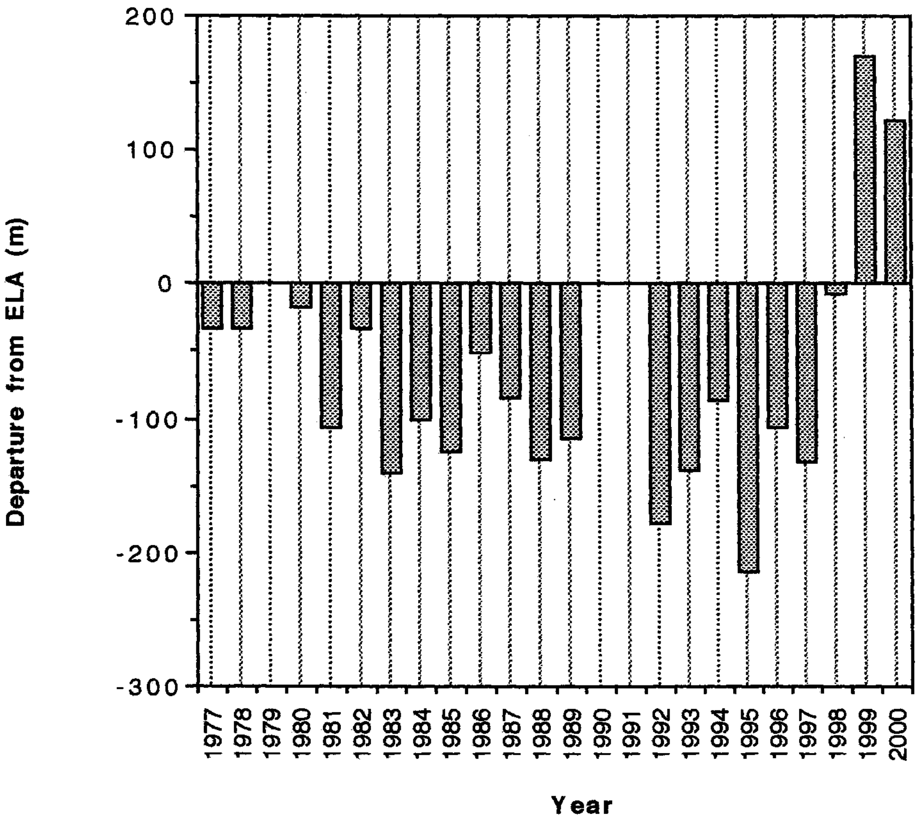
Glacier not mapped



Salisbury Gl.

Glacier map and histogram plot of all recorded snowlines

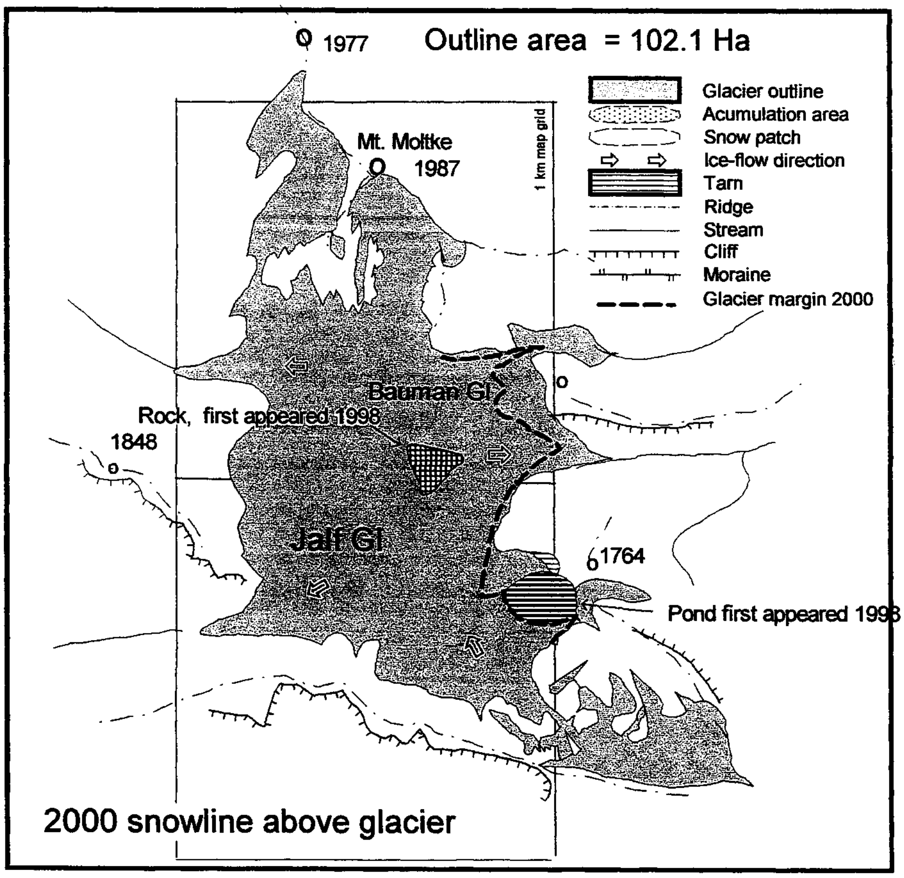


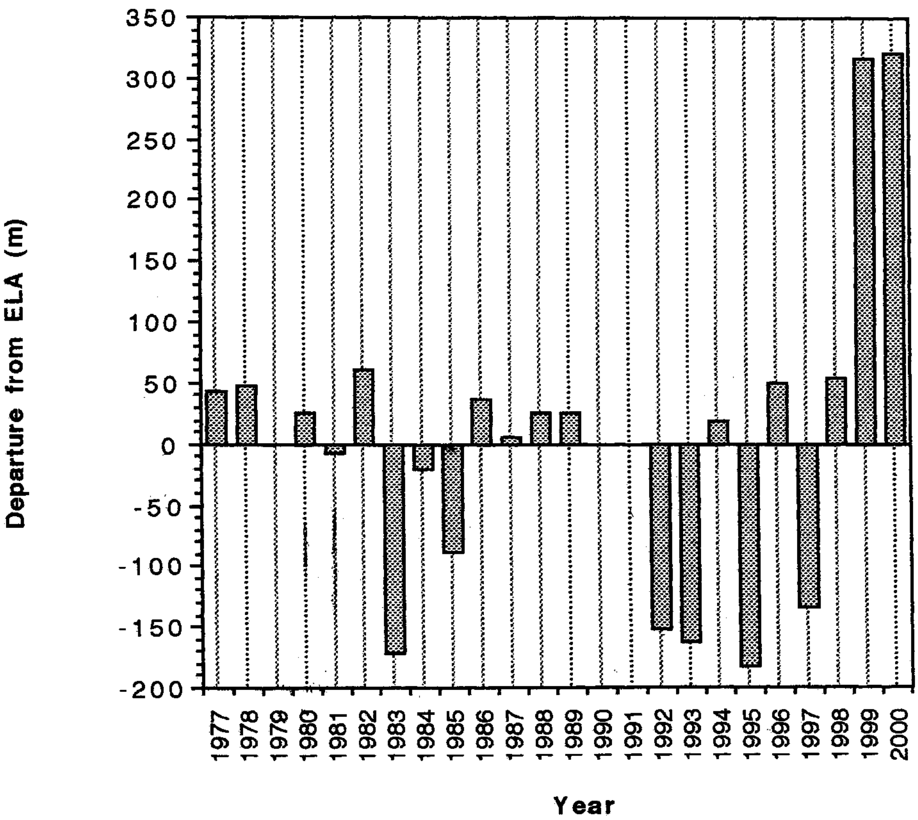


Appendix 23:

Jalf Gl.

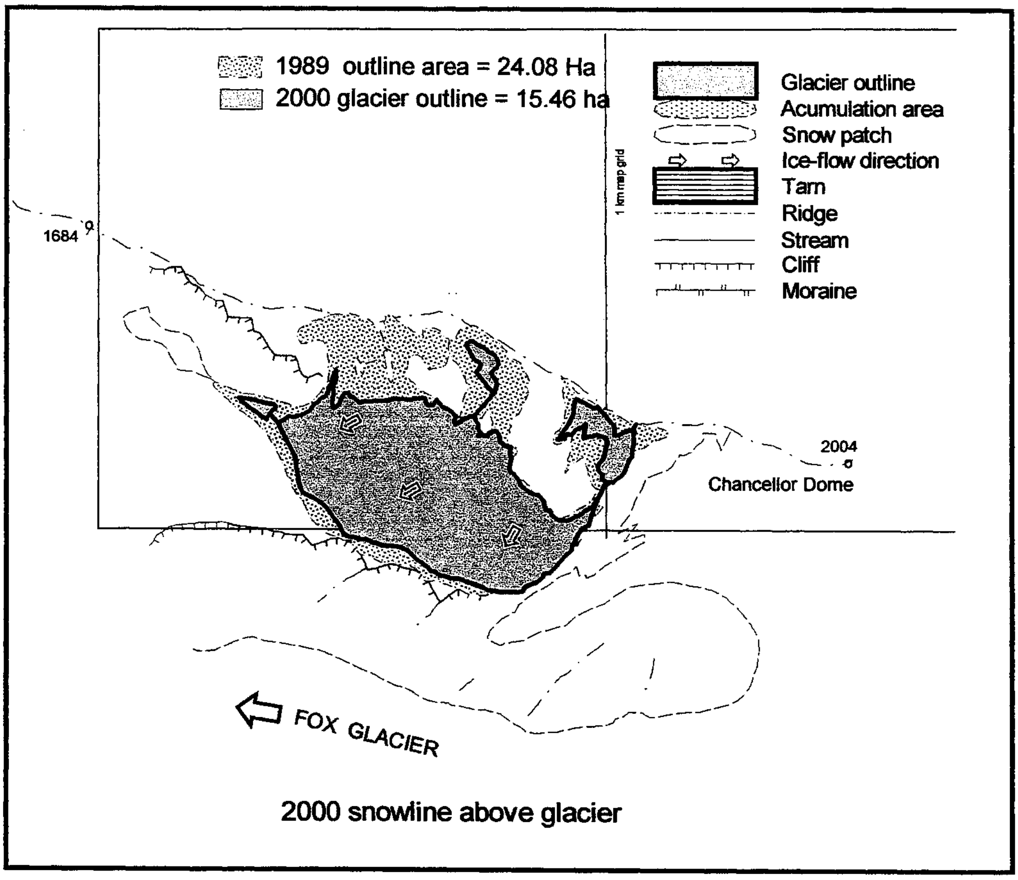
Glacier map and histogram plot of all recorded snowlines

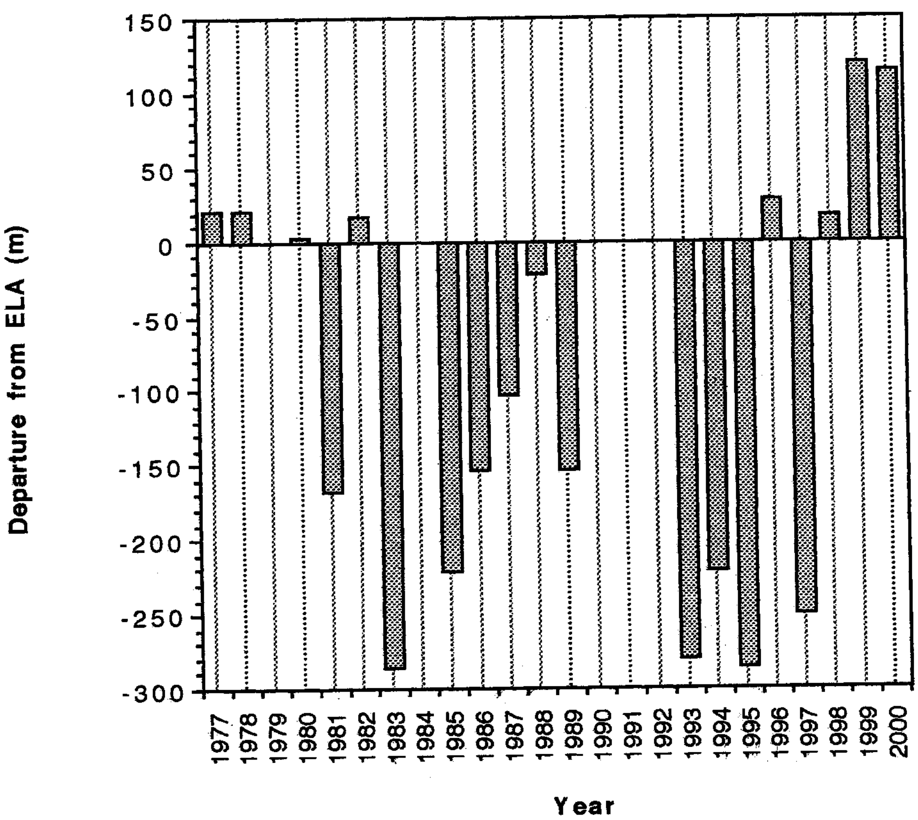




Chancellor Dome

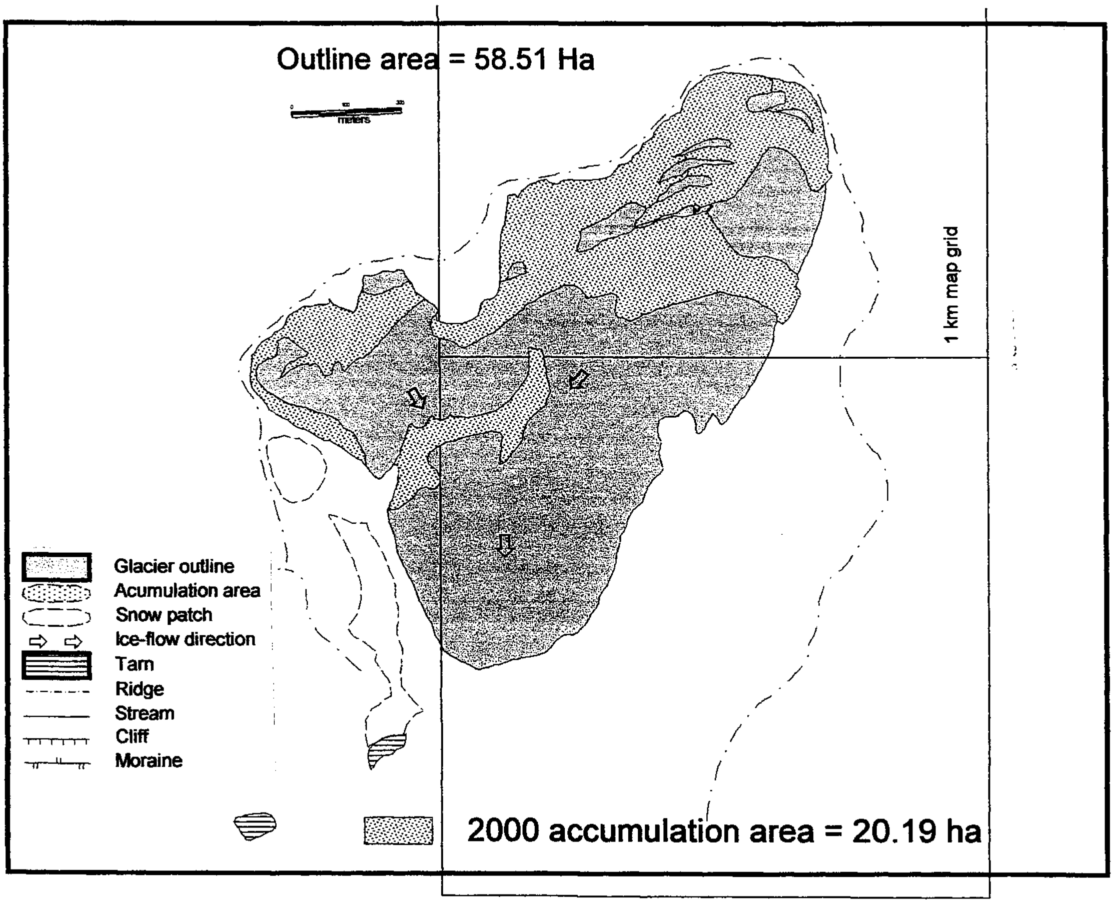
Glacier map and histogram plot of all recorded snowlines

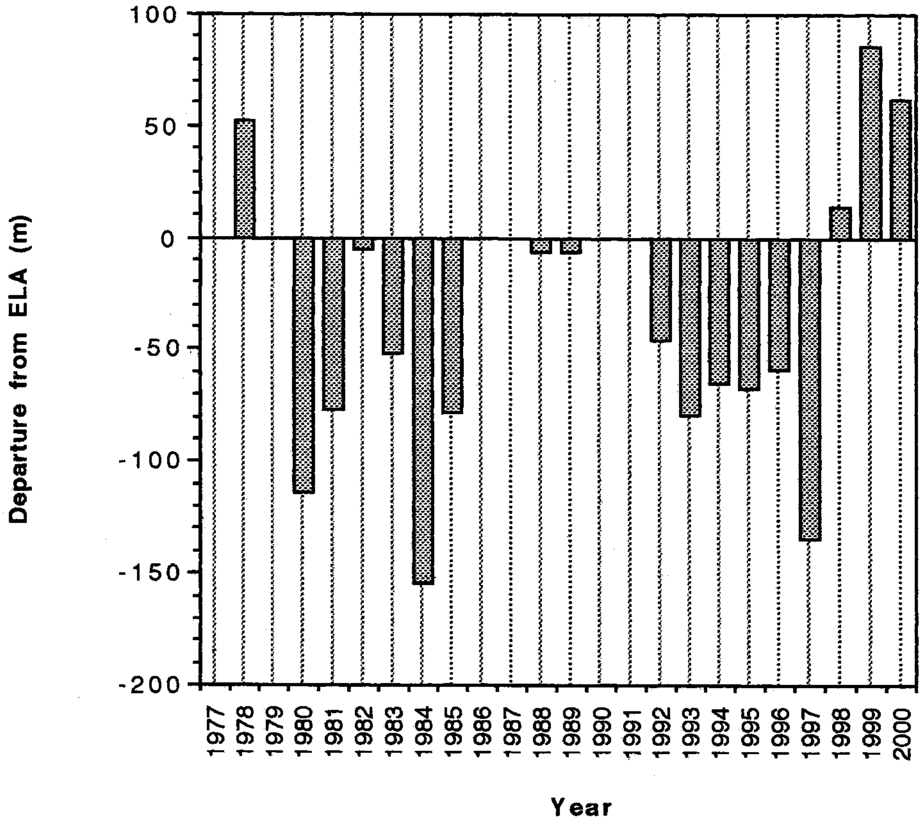




Glenmary Gl.

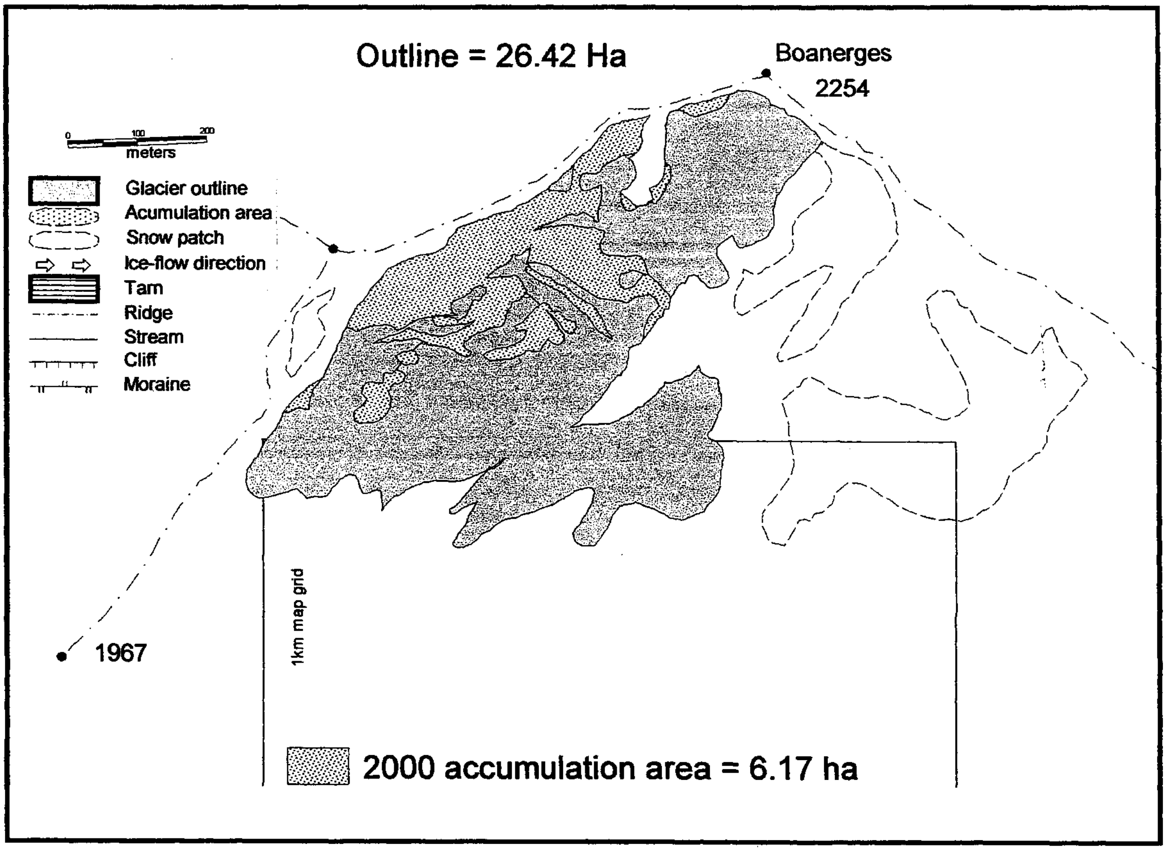
Glacier map and histogram plot of all recorded snowlines

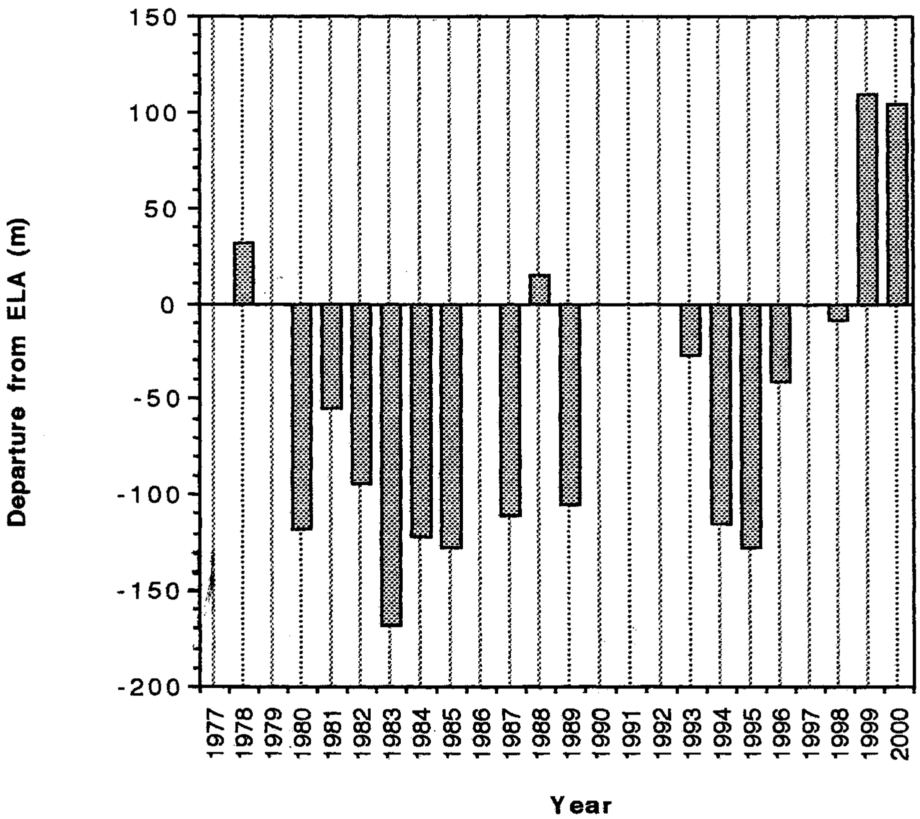




Blair Gl.

Glacier map and histogram plot of all recorded snowlines

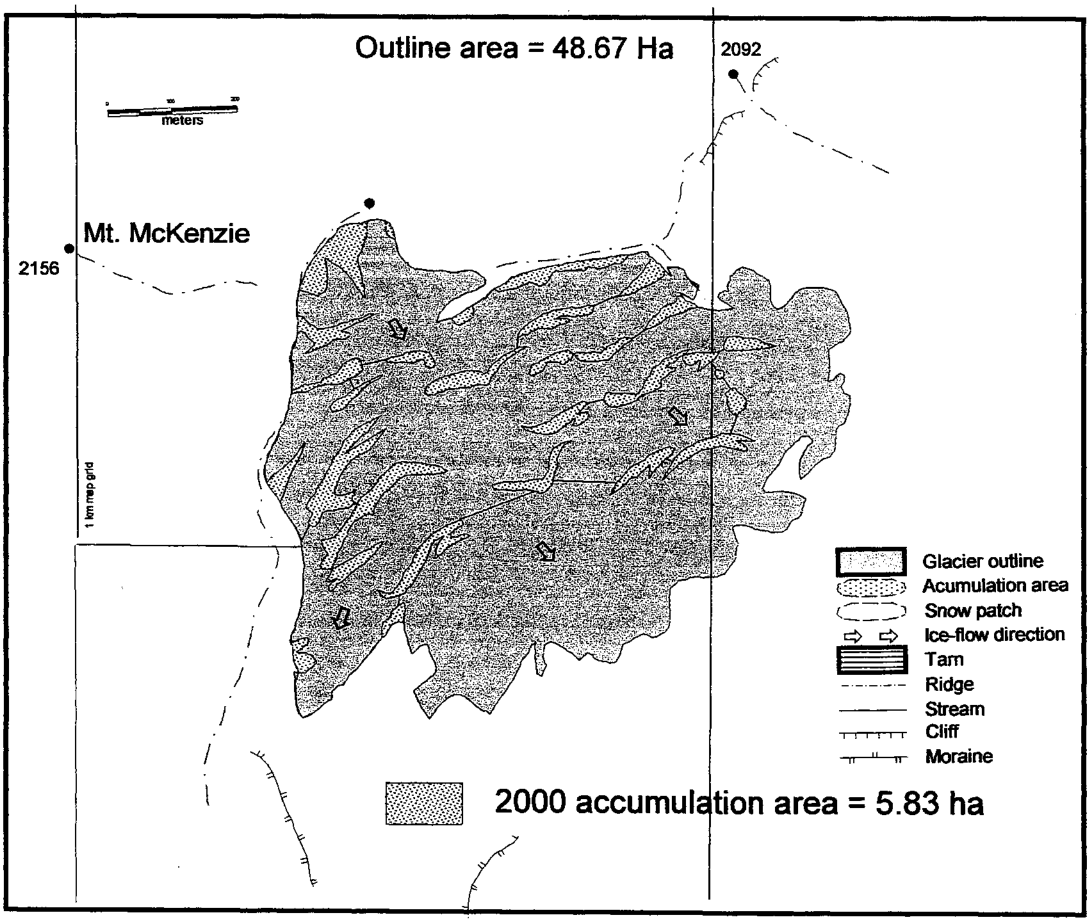


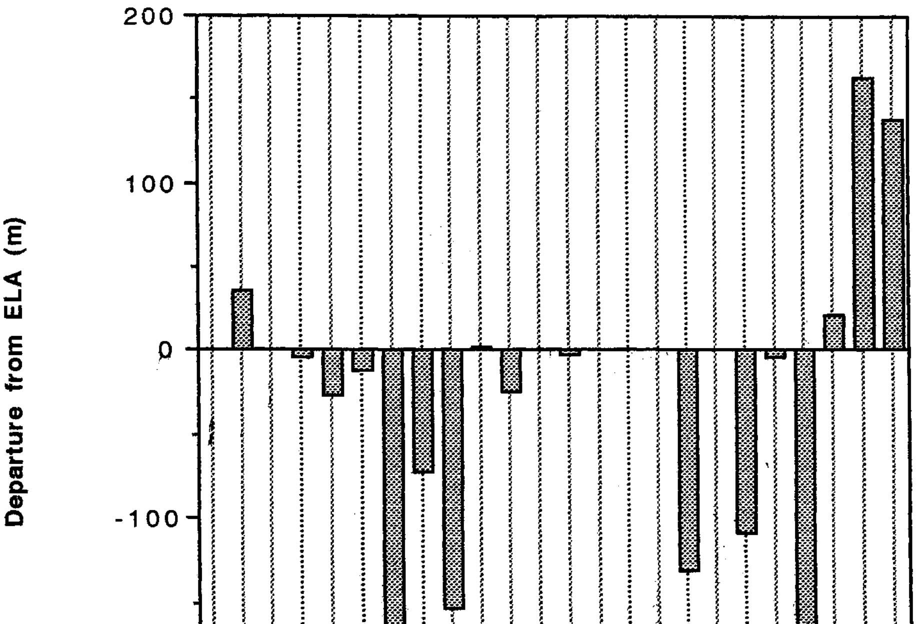


Appendix 27:

Mt Mckenzie

Glacier map and histogram plot of all recorded snowlines

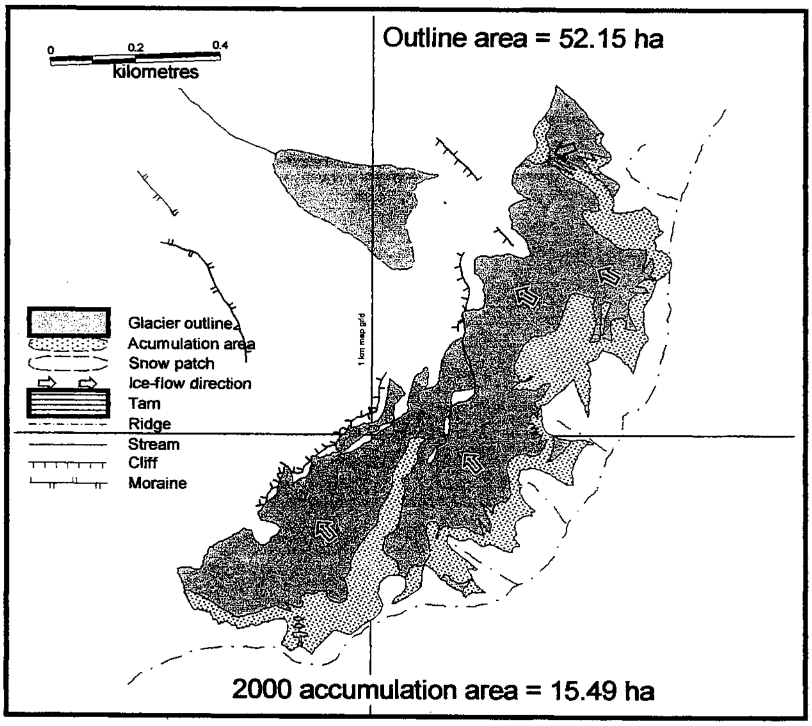


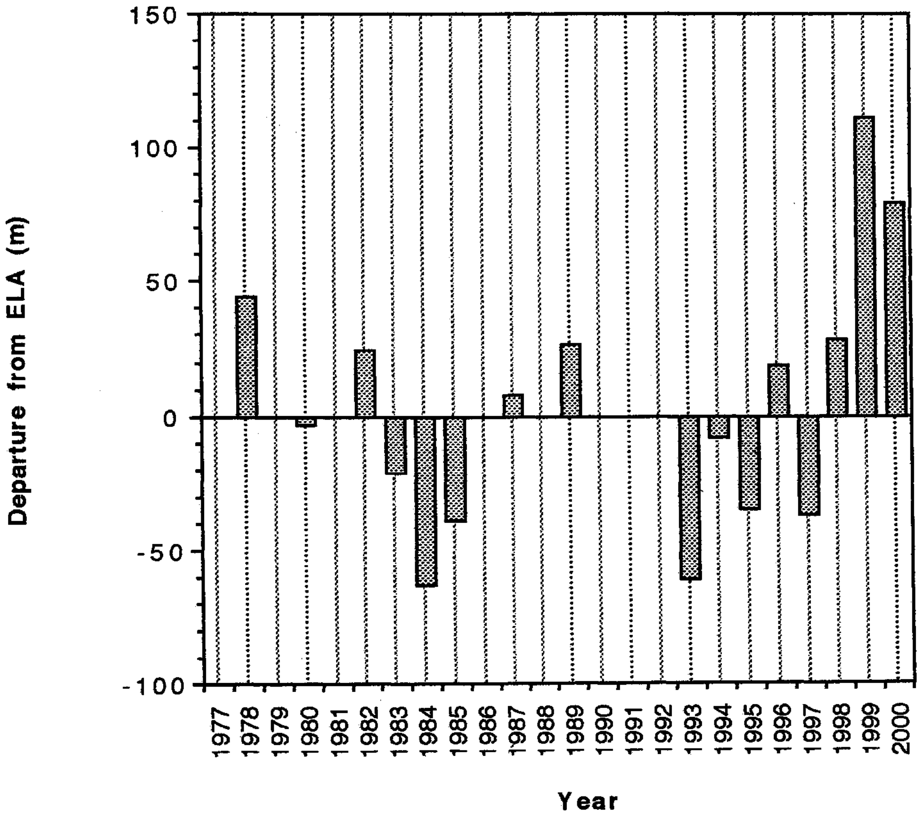


Appendix 28:

Jackson Gl.

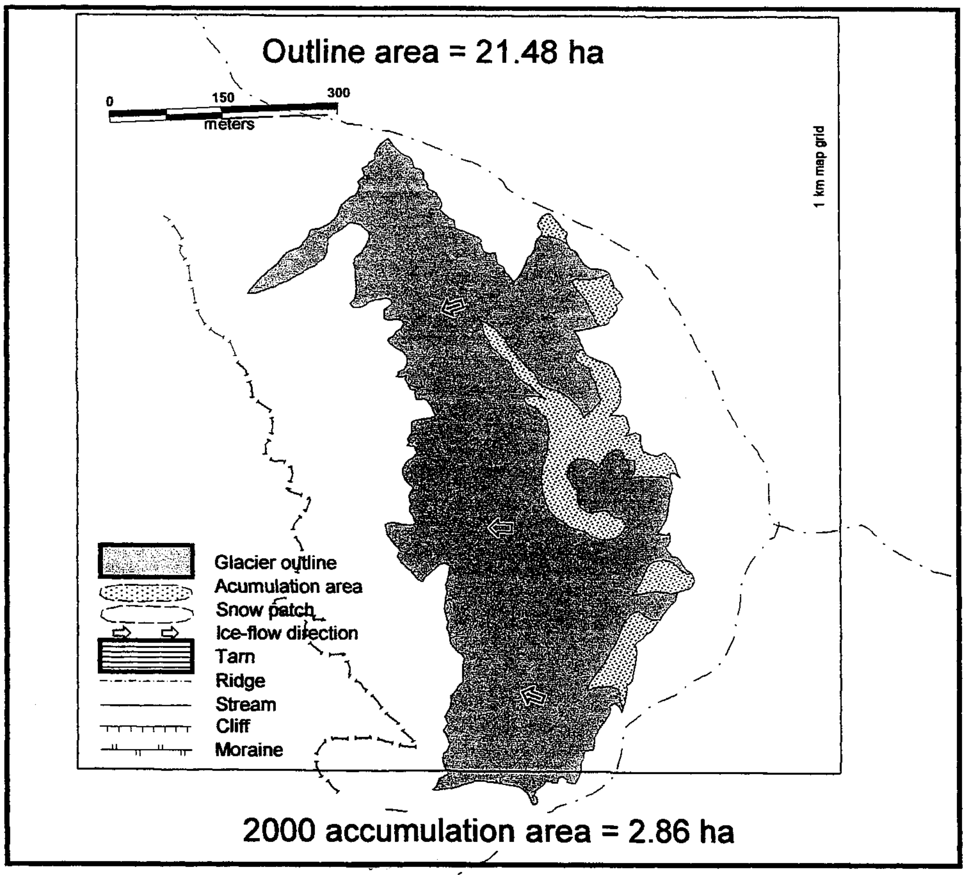
Glacier map and histogram plot of all recorded snowlines

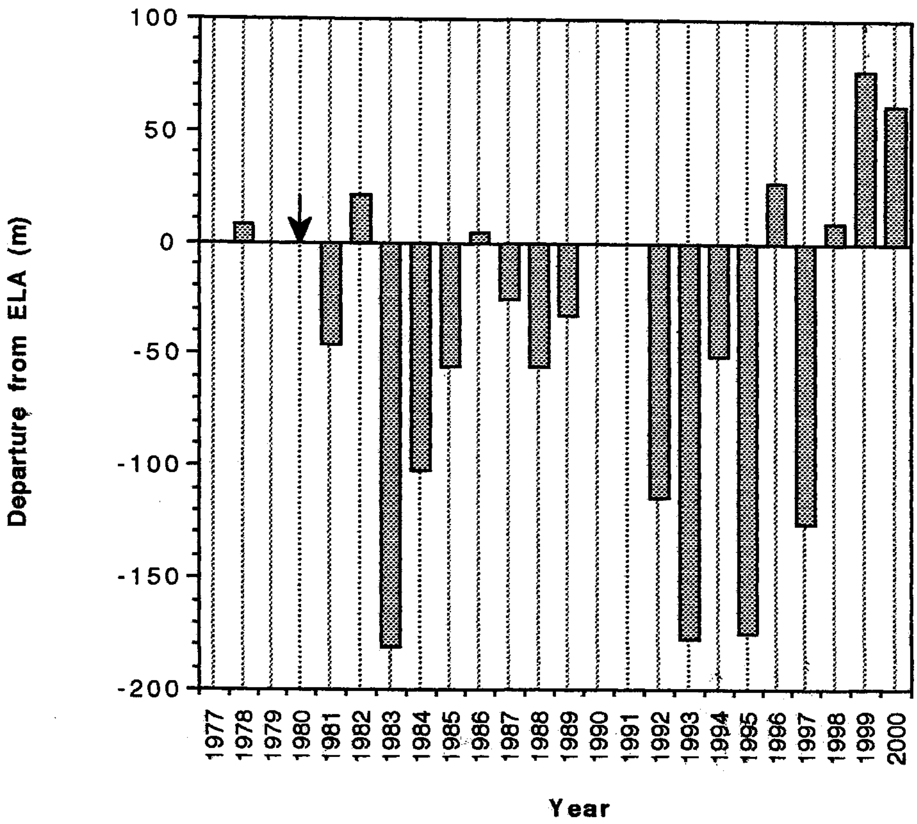




Jack Gl.

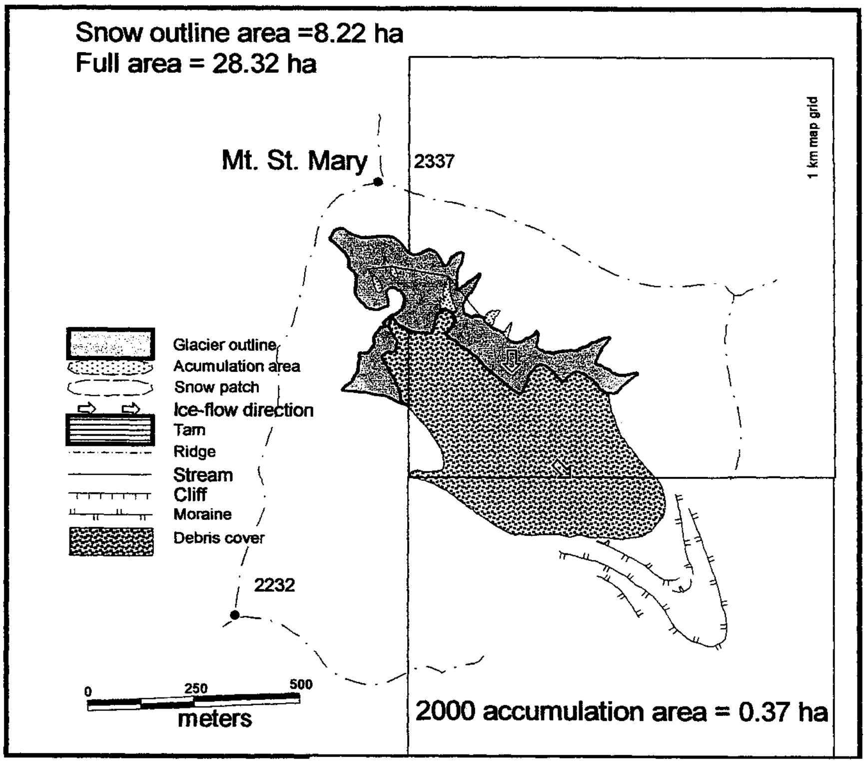
Glacier map and histogram plot of all recorded snowlines

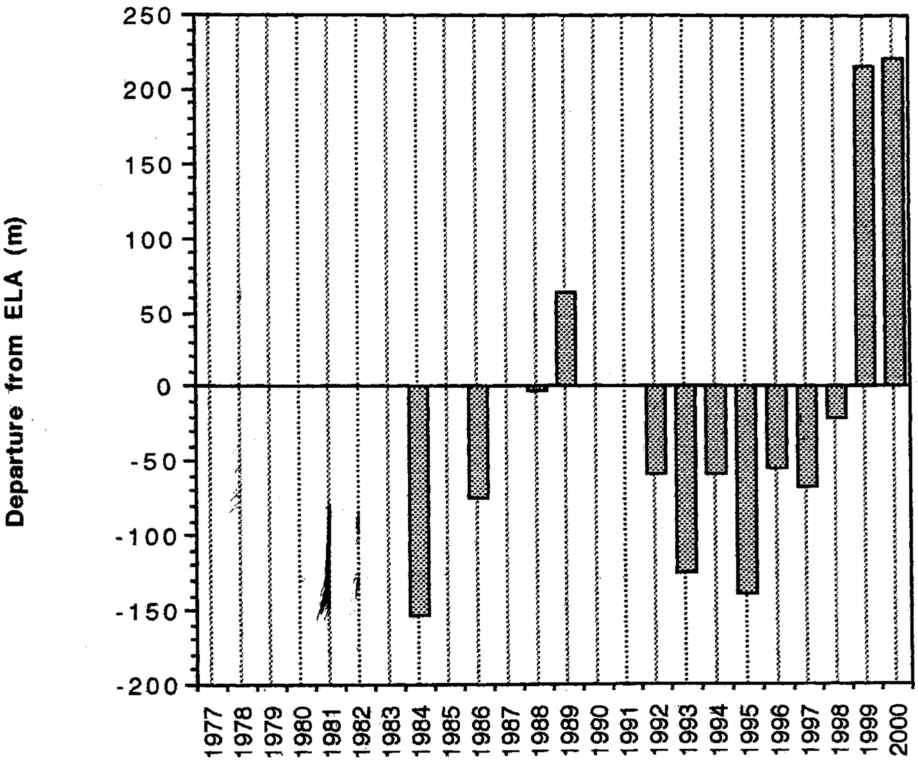




Mt St Mary

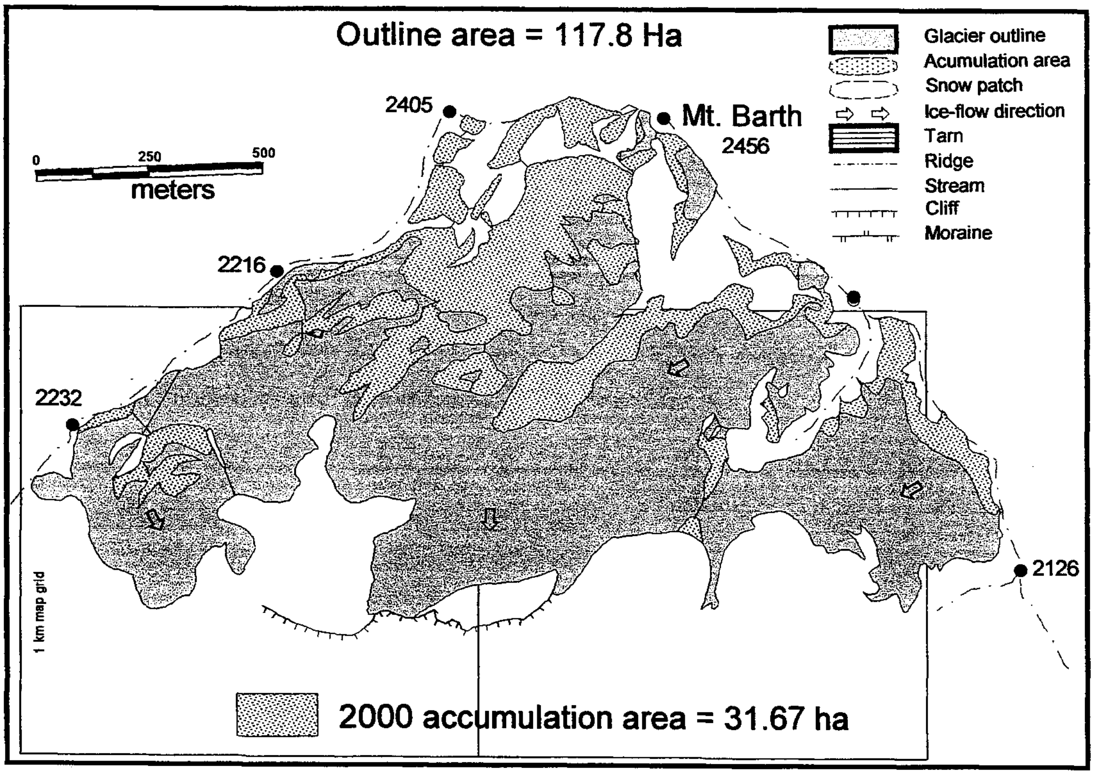
Glacier map and histogram plot of all recorded snowlines

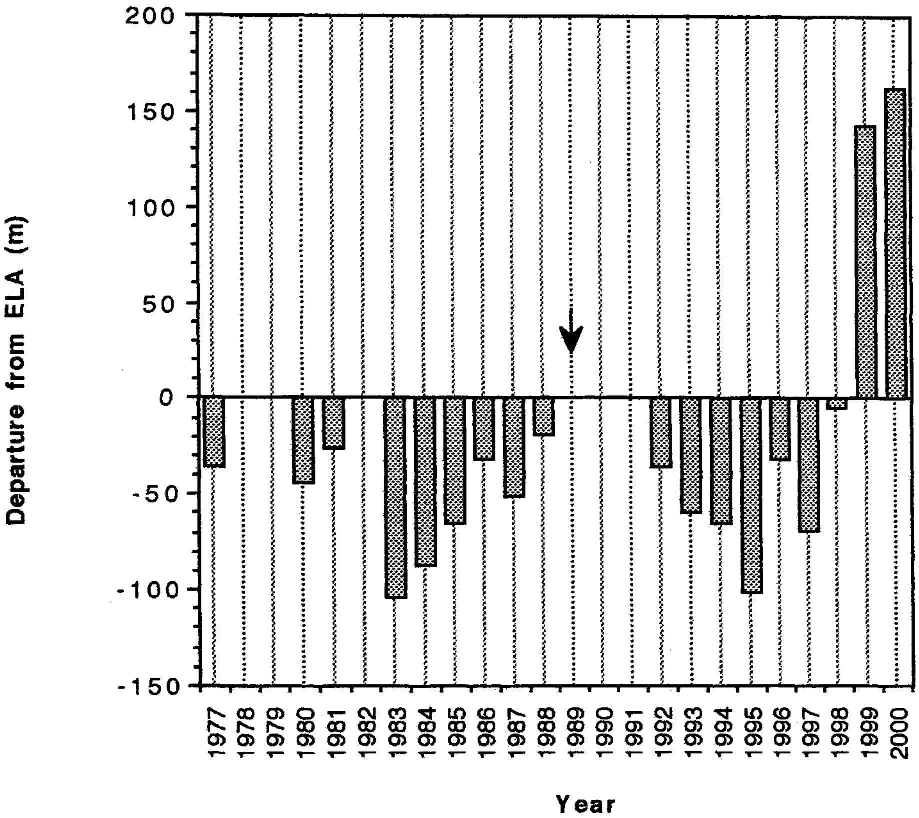




Thurneyson Gl

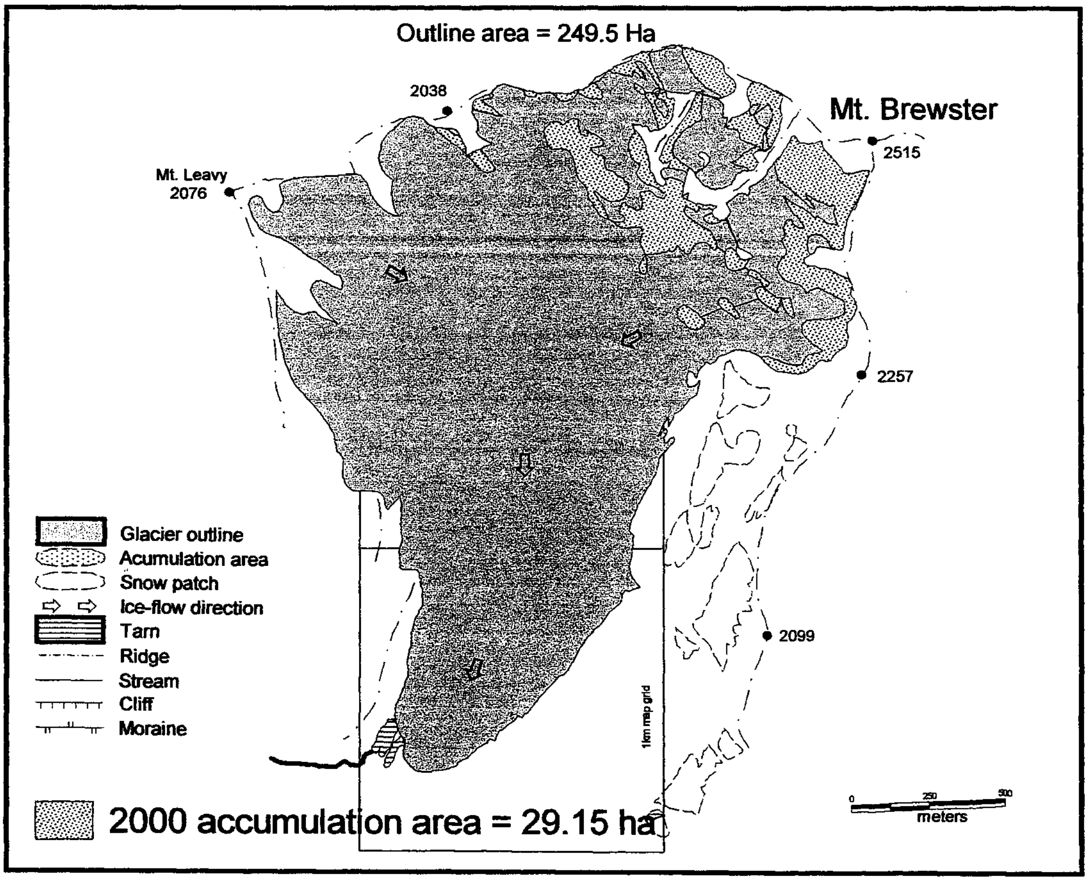
Glacier map and histogram plot of all recorded snowlines

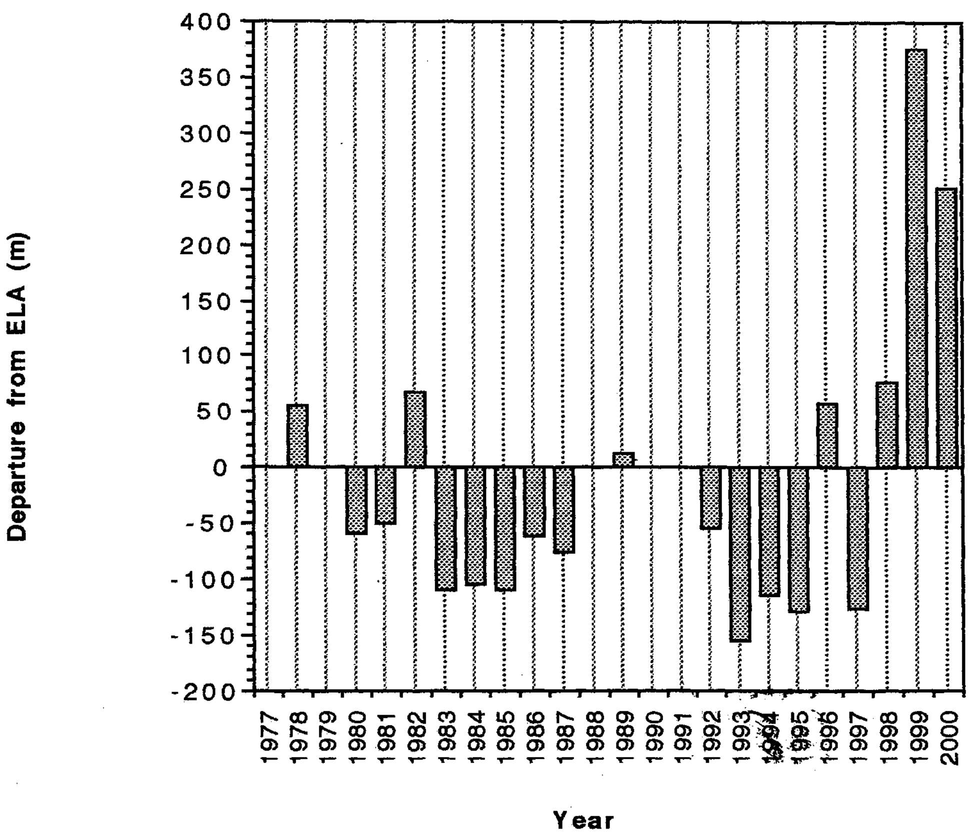




Brewster Gl.

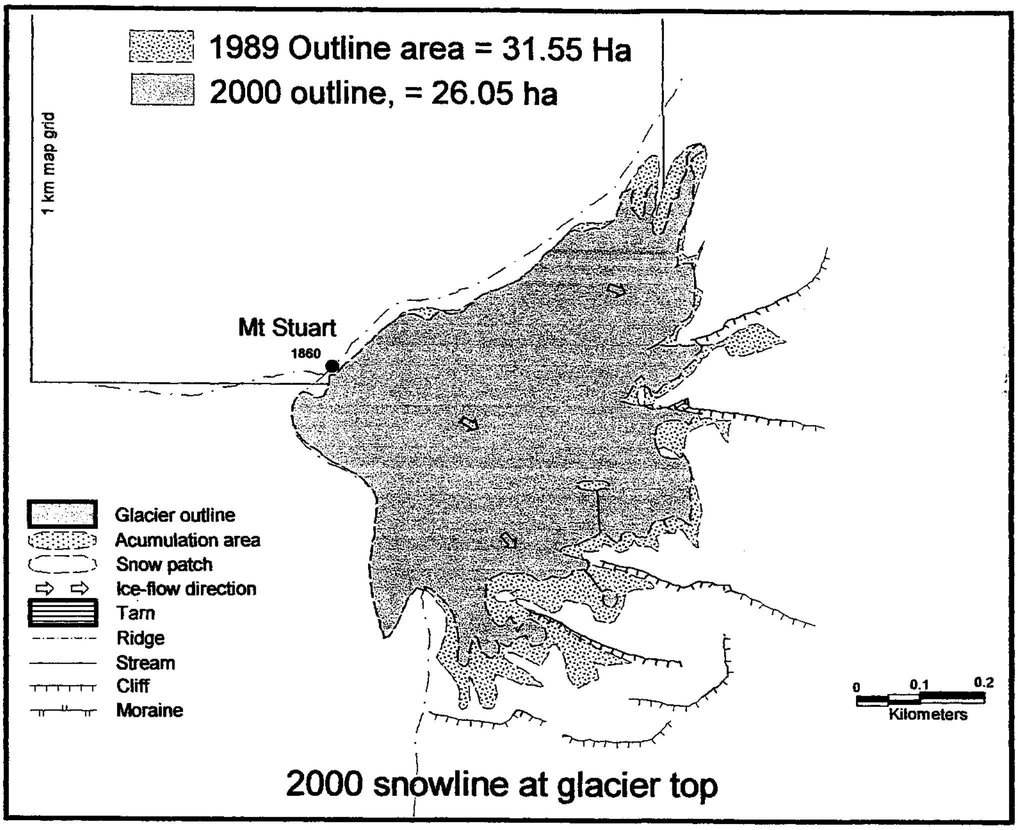
Glacier map and histogram plot of all recorded snowlines

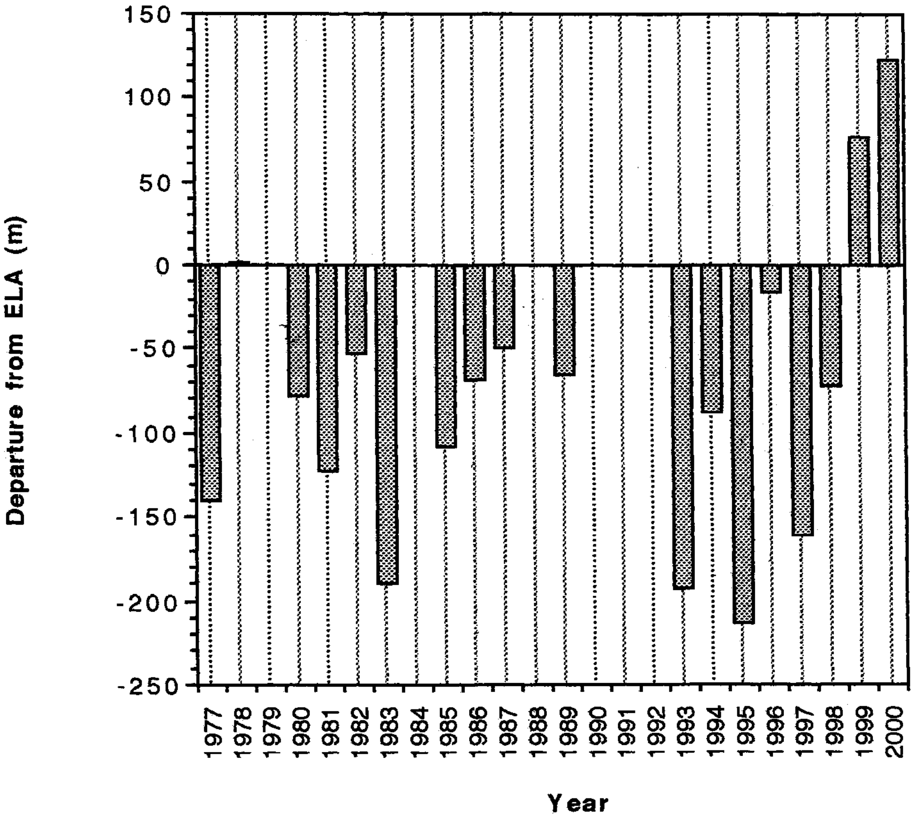




Mt Stuart

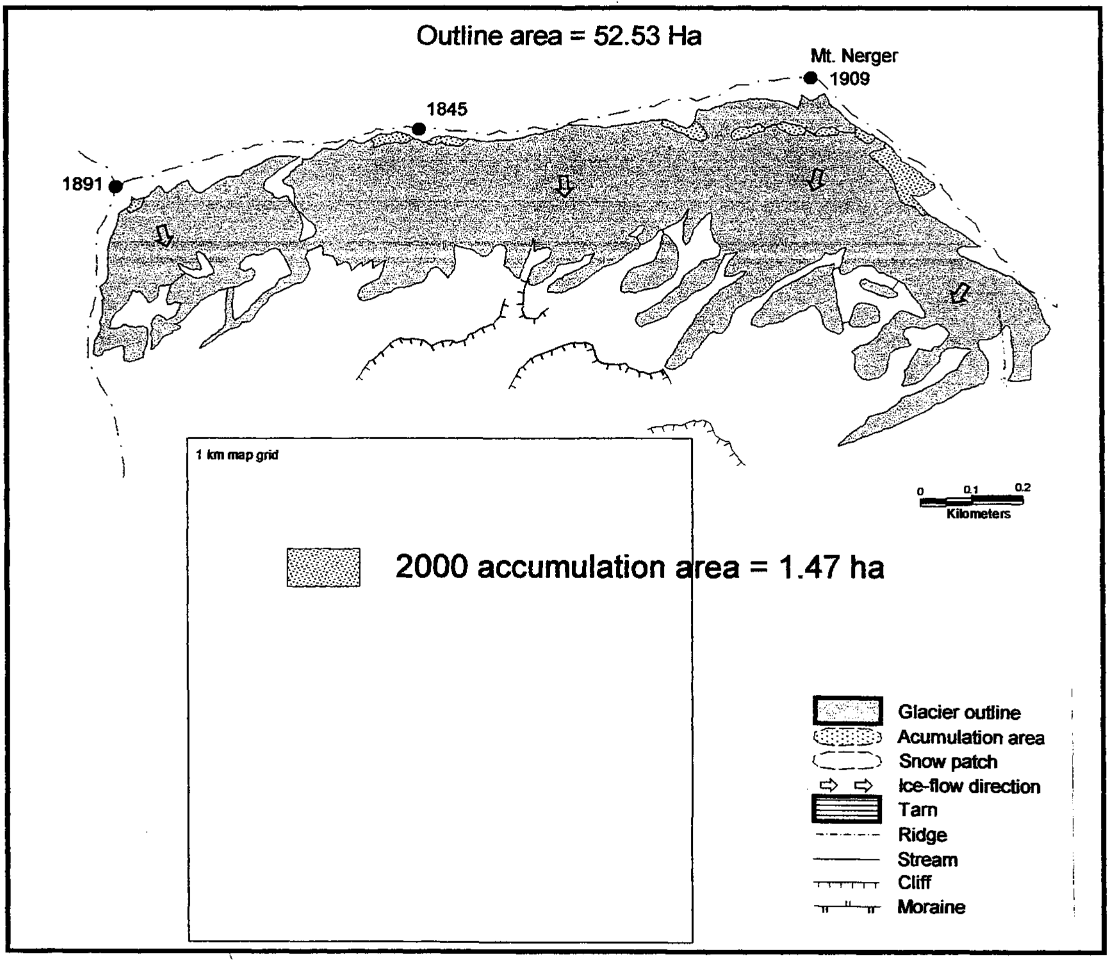
Glacier map and histogram plot of all recorded snowlines

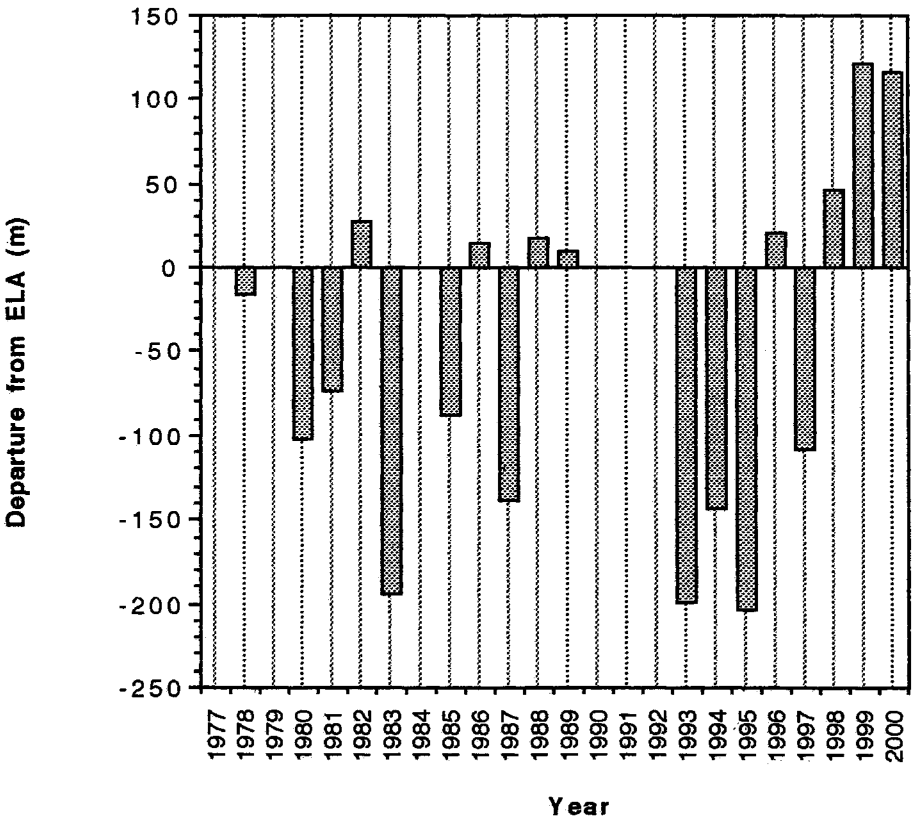




Lindsay Gl.

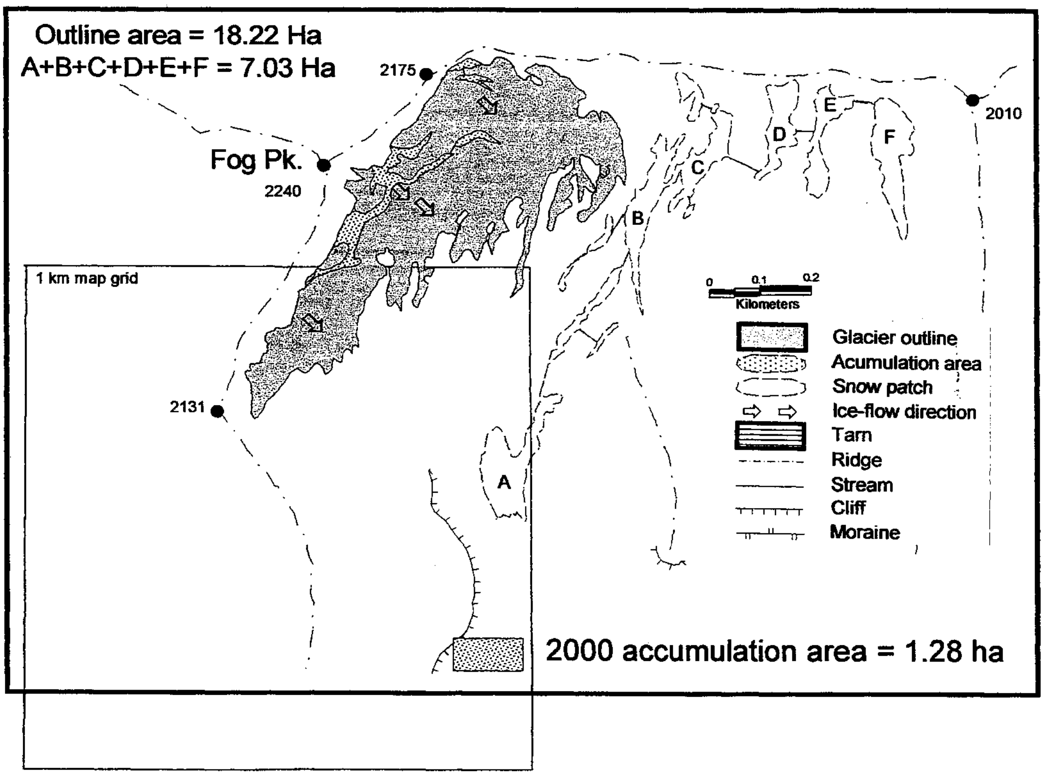
Glacier map and histogram plot of all recorded snowlines

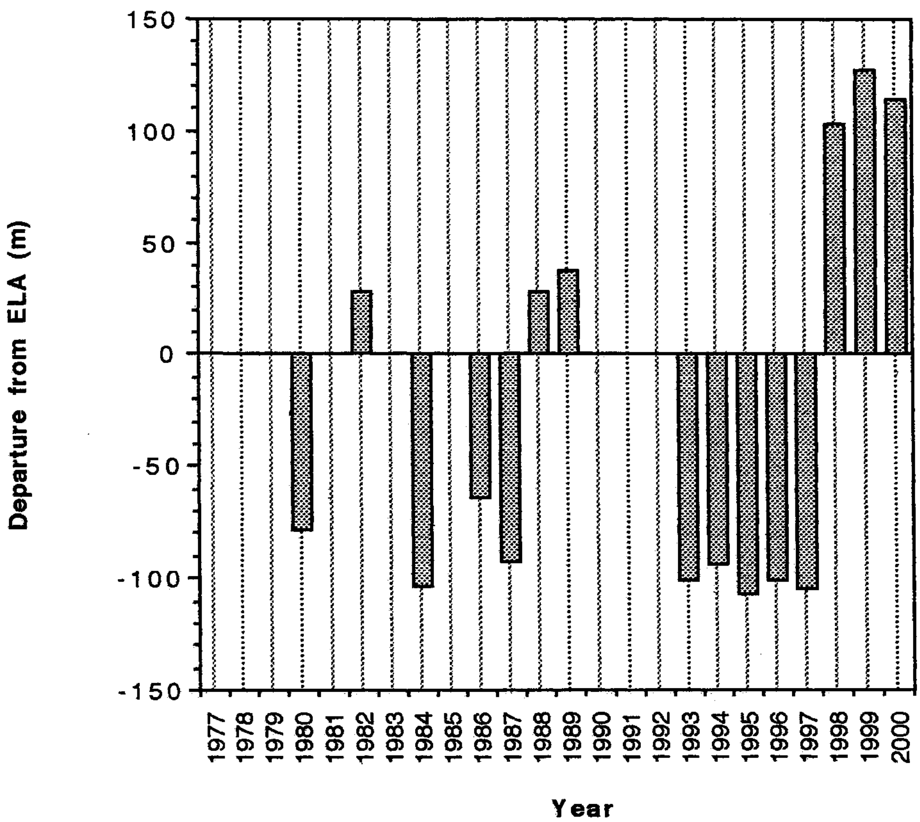




Fog Pk

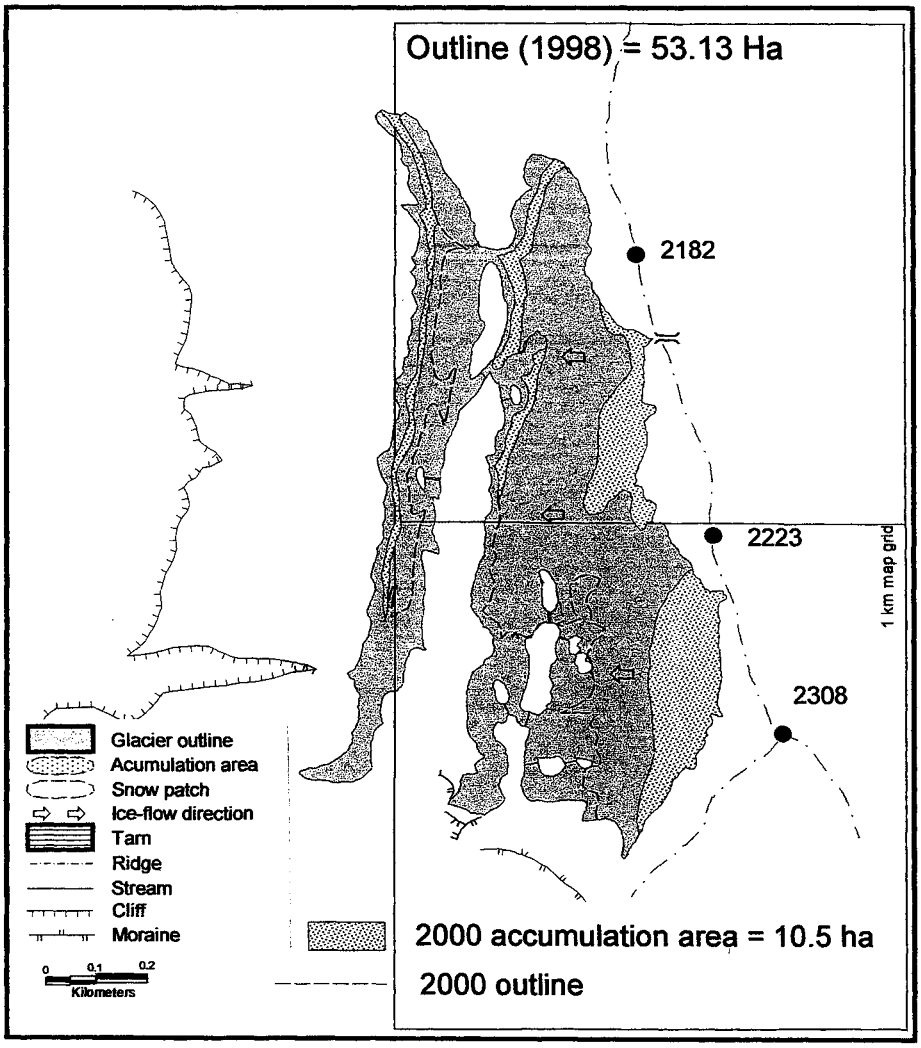
Glacier map and histogram plot of all recorded snowlines

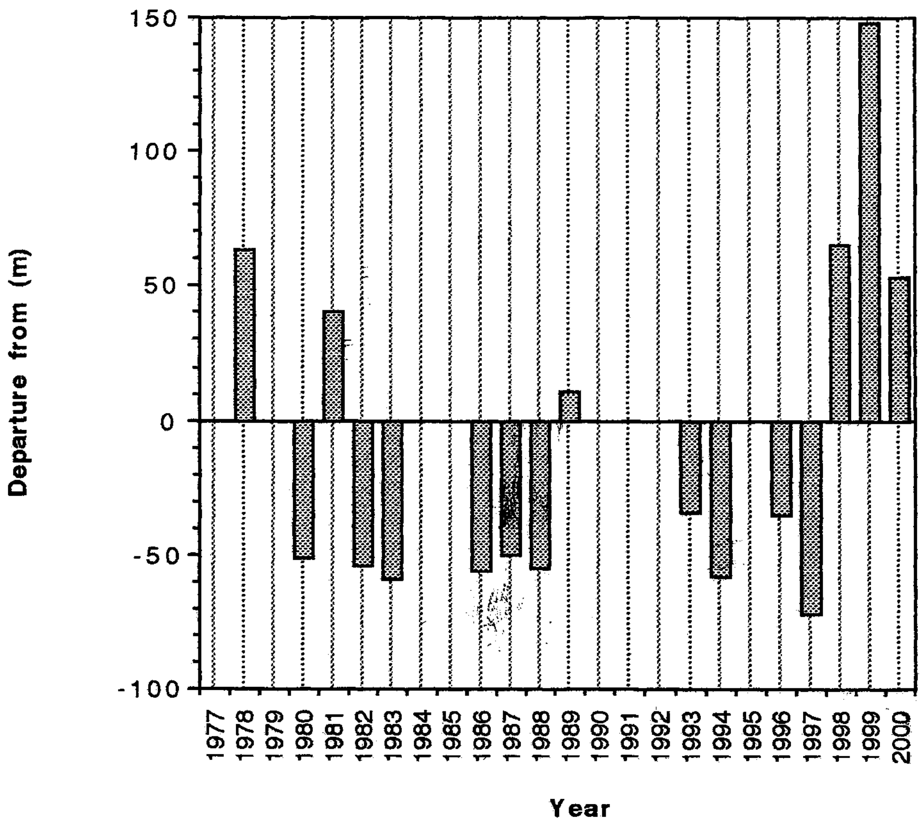




Snowy Ck

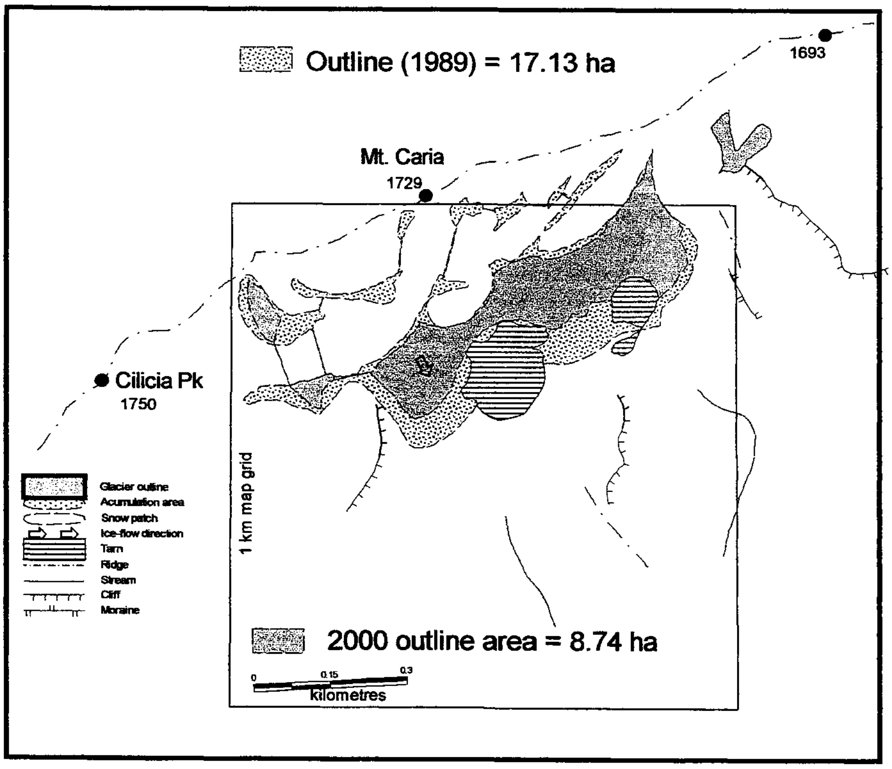
Glacier map and histogram plot of all recorded snowlines

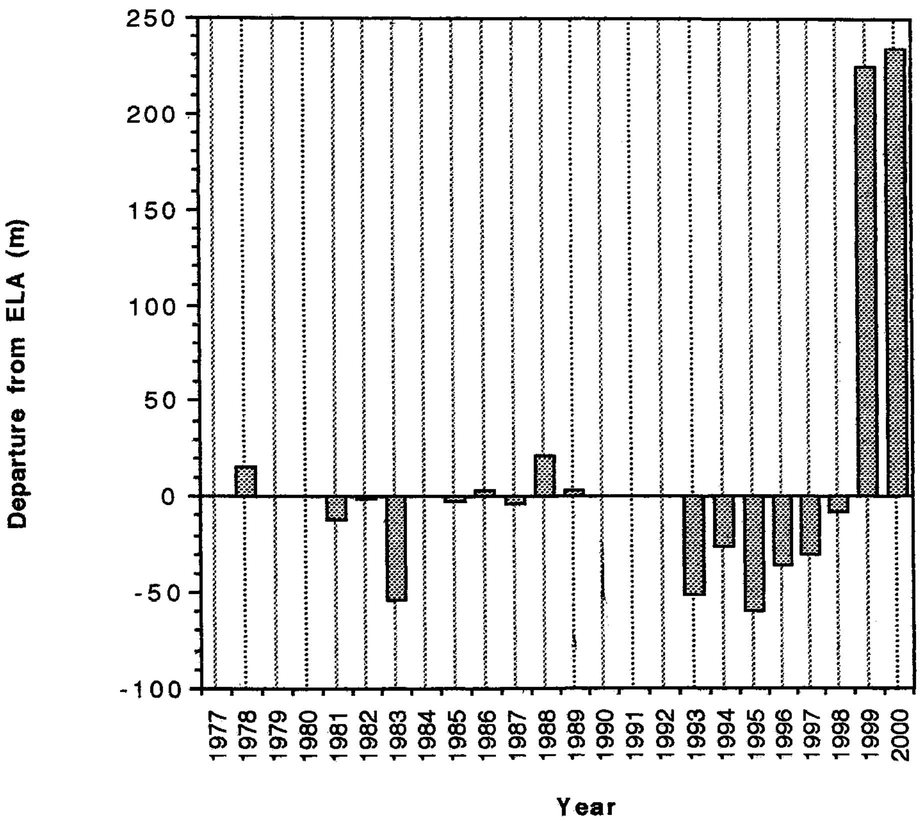




Mt Caria

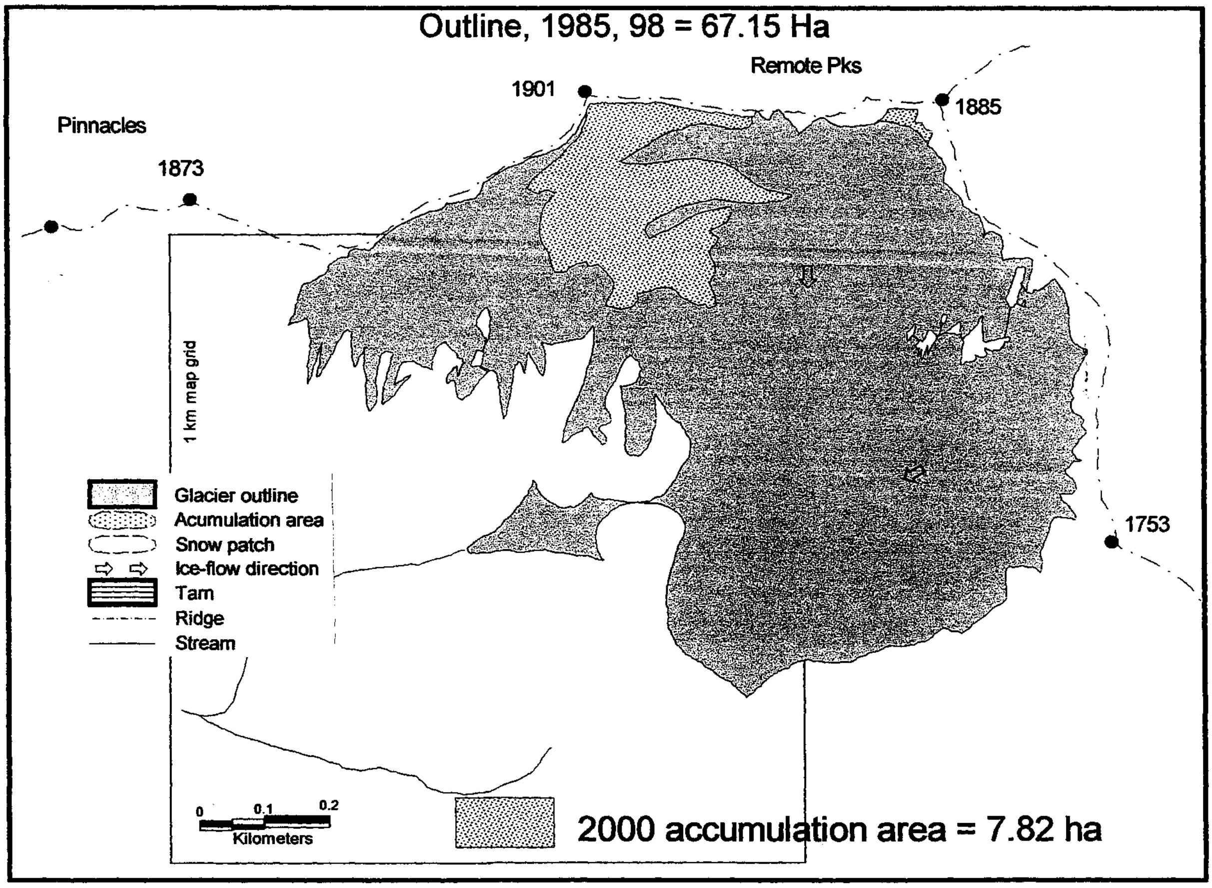
Glacier map and histogram plot of all recorded snowlines

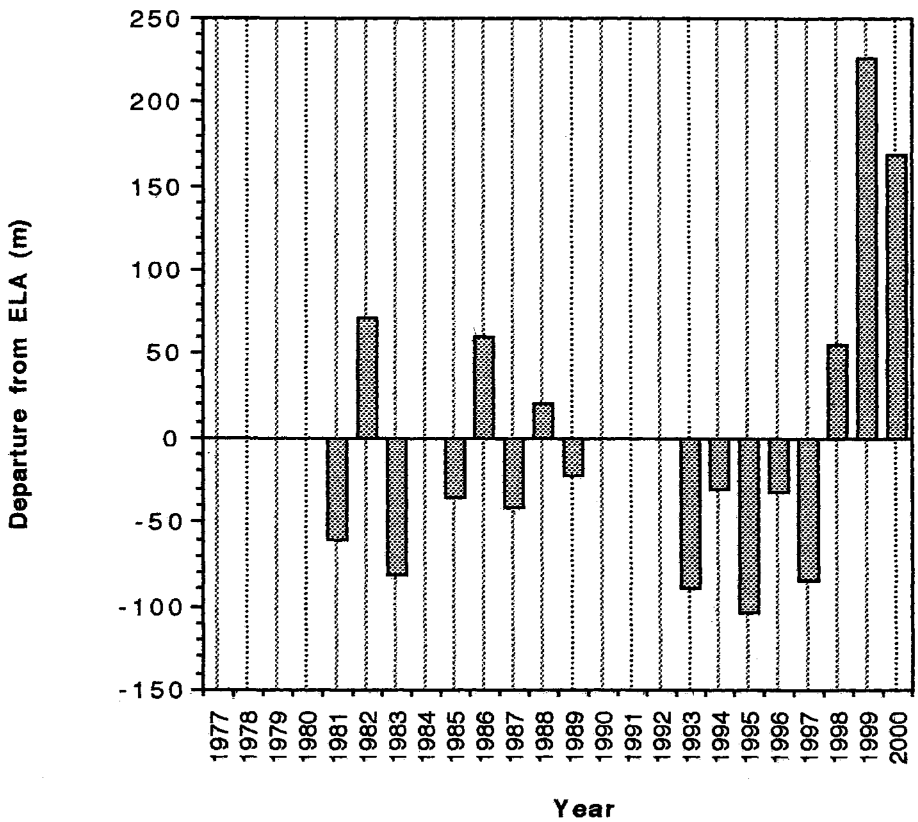




Findlay Gl.

Glacier map and histogram plot of all recorded snowlines

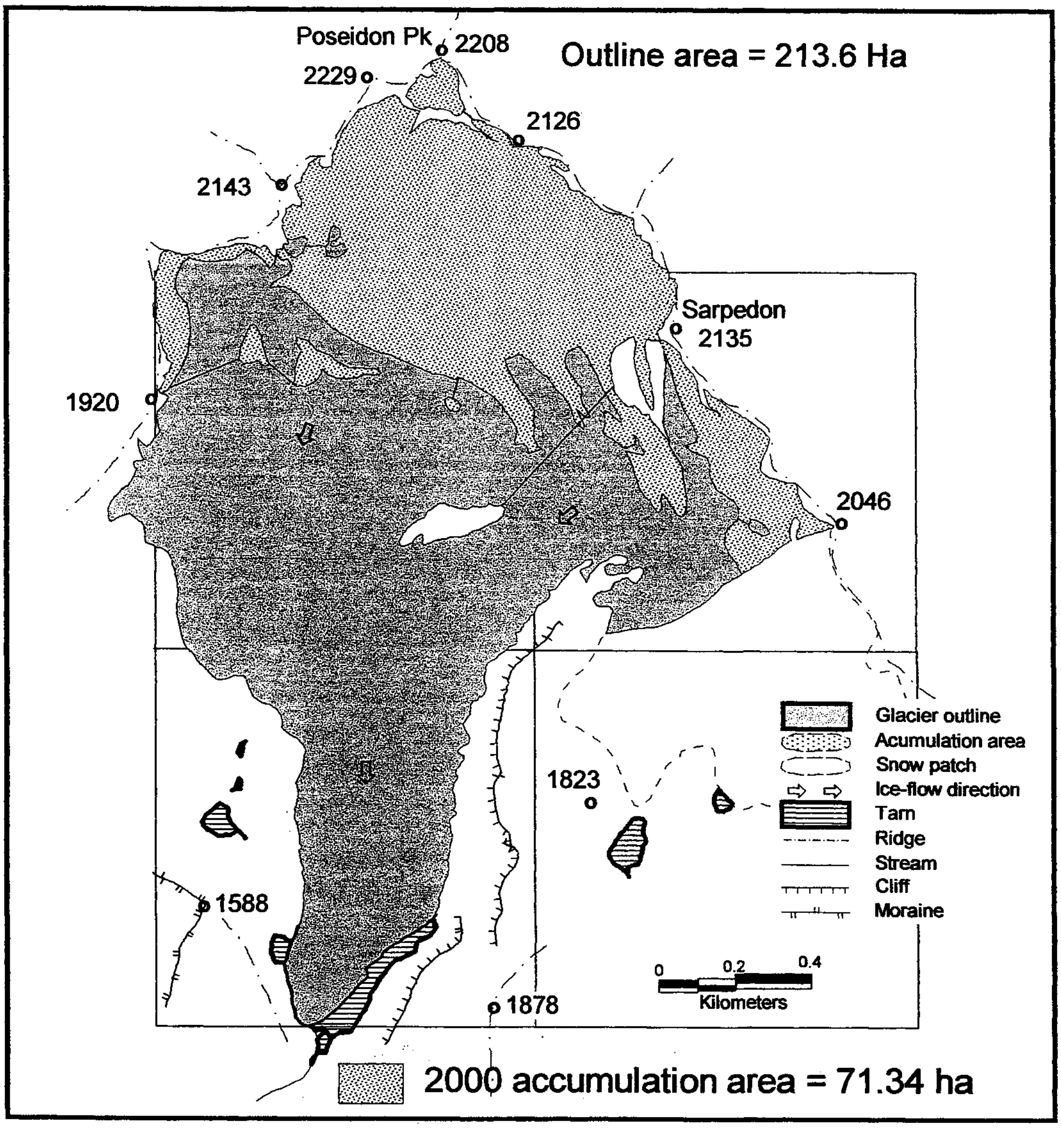


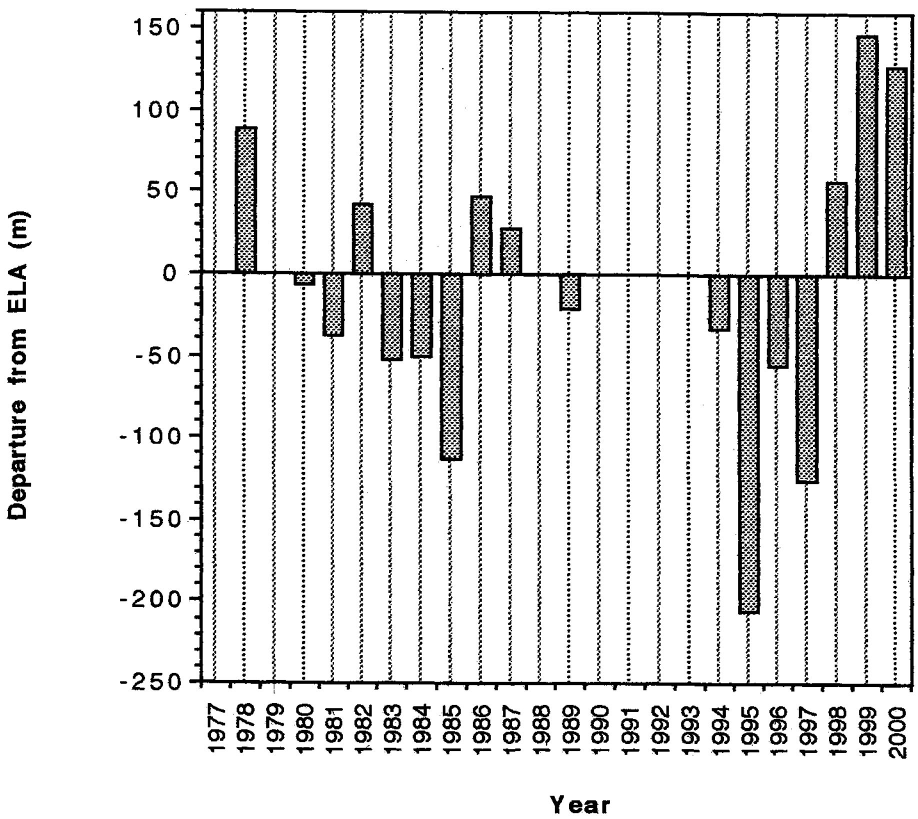


Appendix 39:

Park Pass Gl.

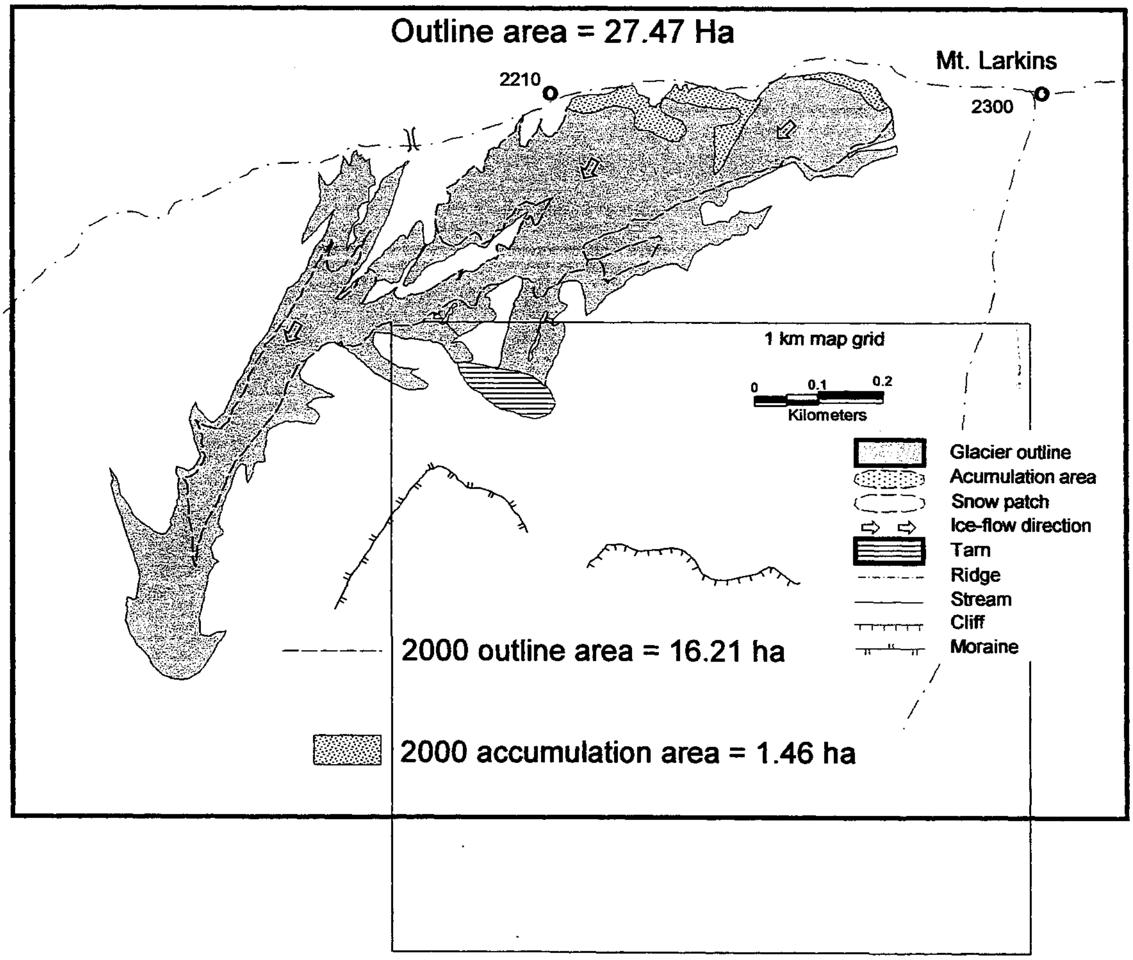
Glacier map and histogram plot of all recorded snowlines

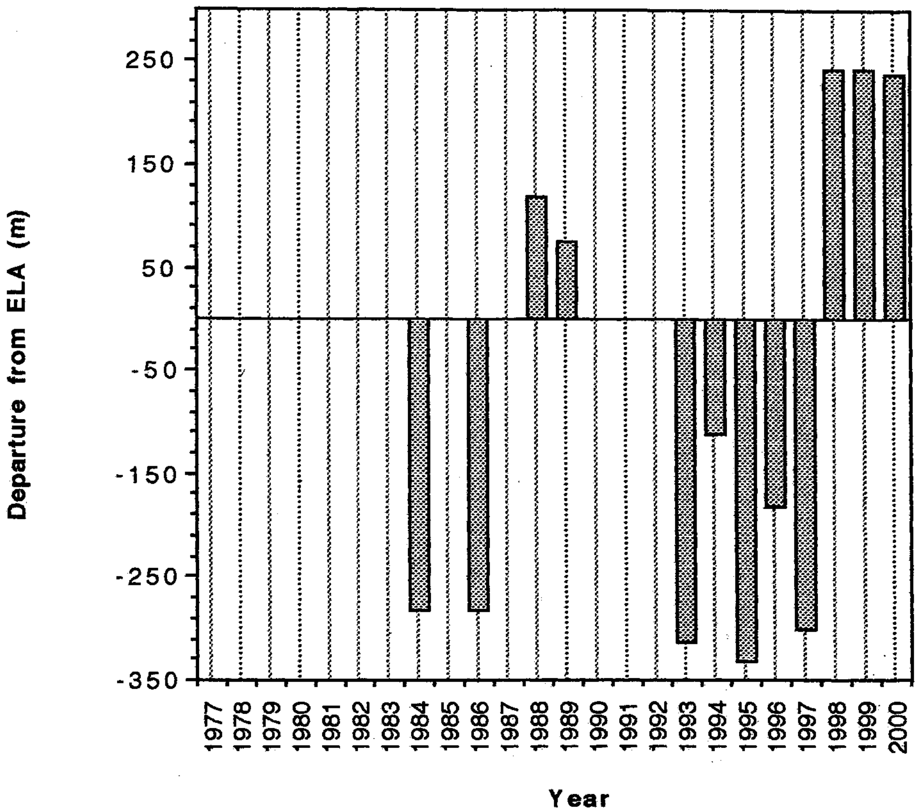




Mt. Larkins

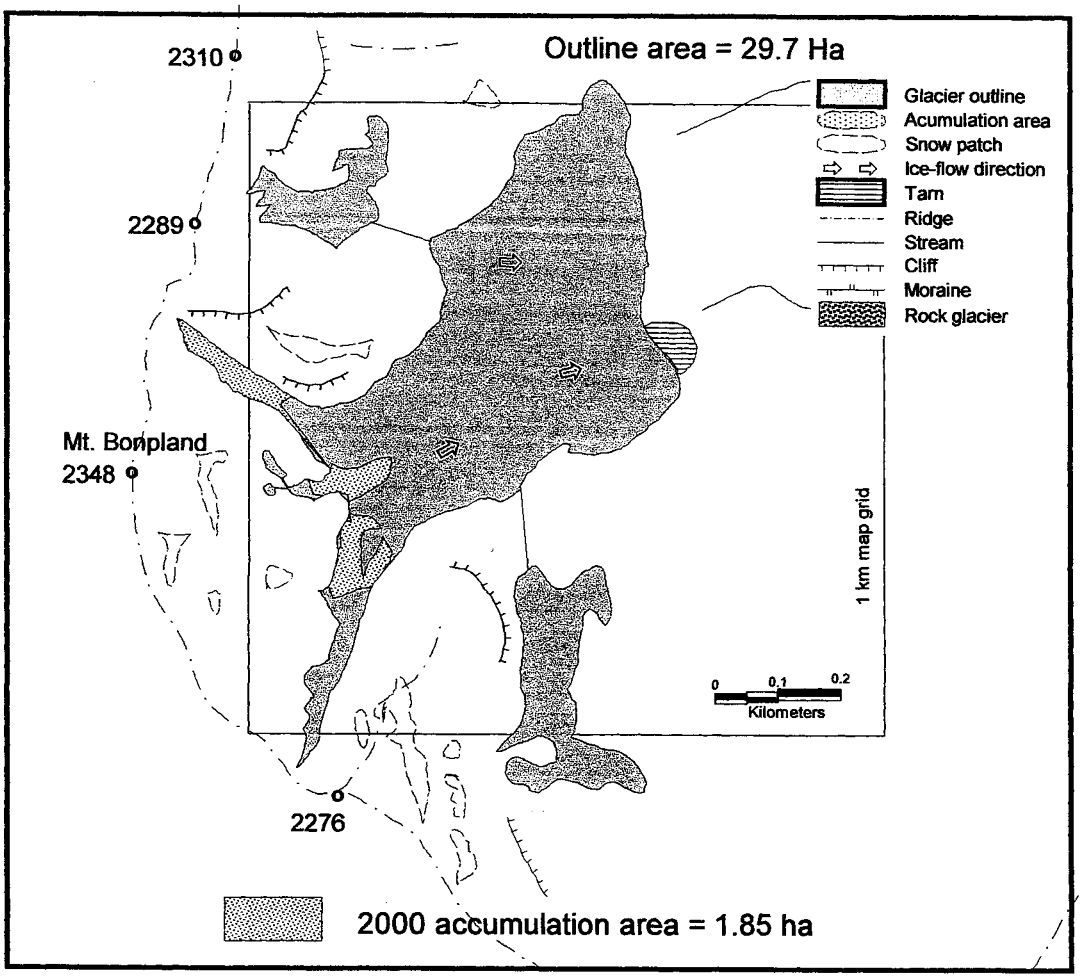
Glacier map and histogram plot of all recorded snowlines

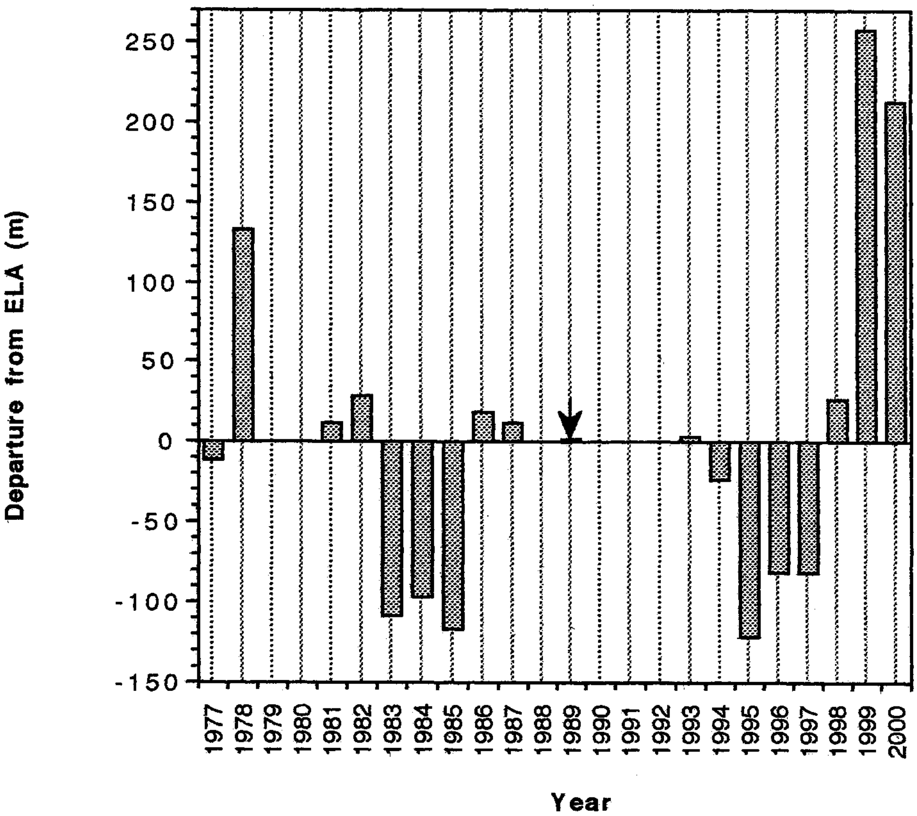




Bryant Gl.

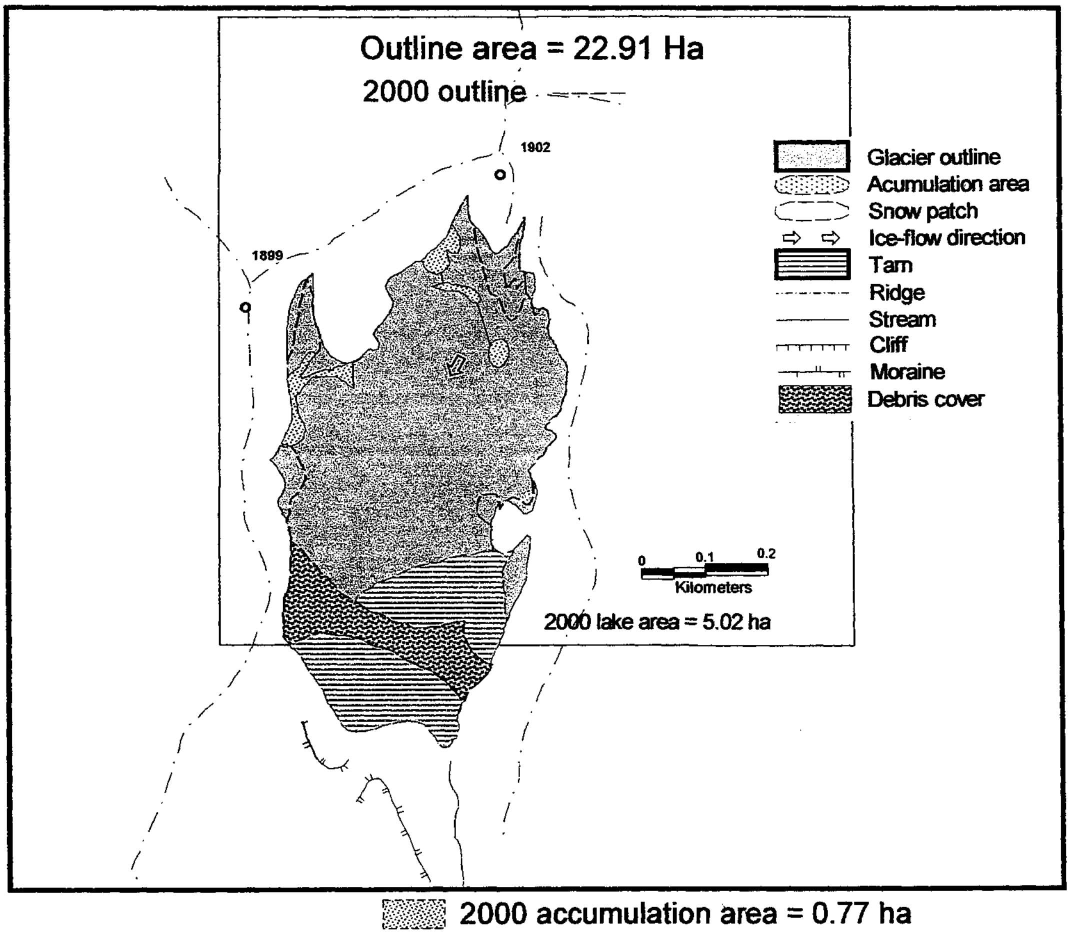
Glacier map and histogram plot of all recorded snowlines

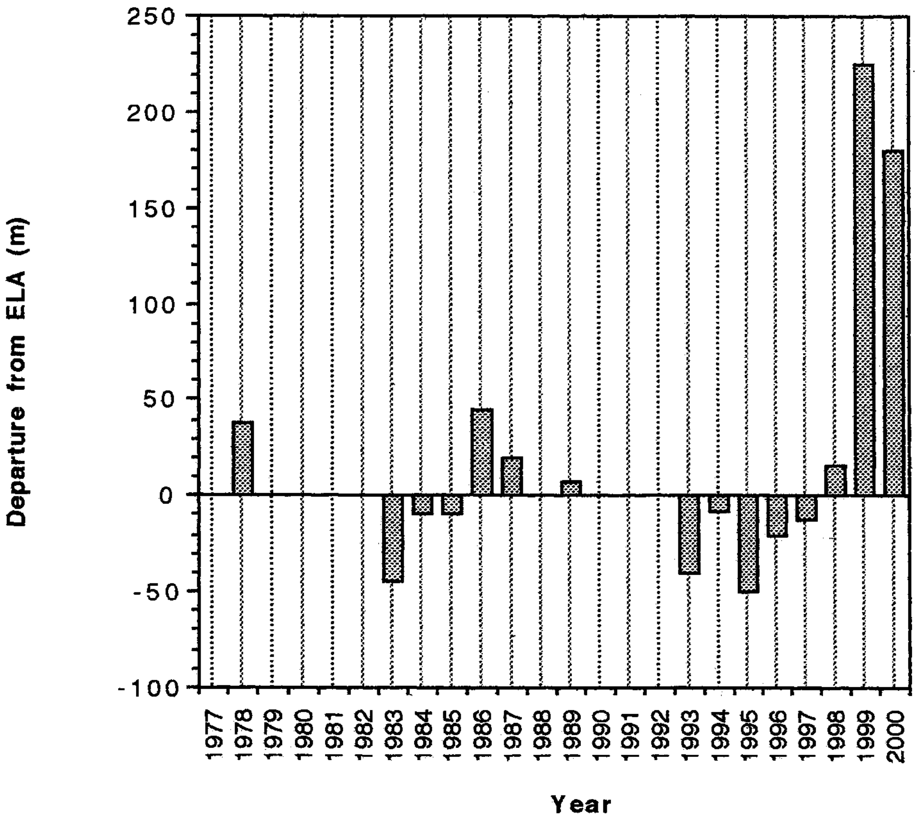




Ailsa Mts

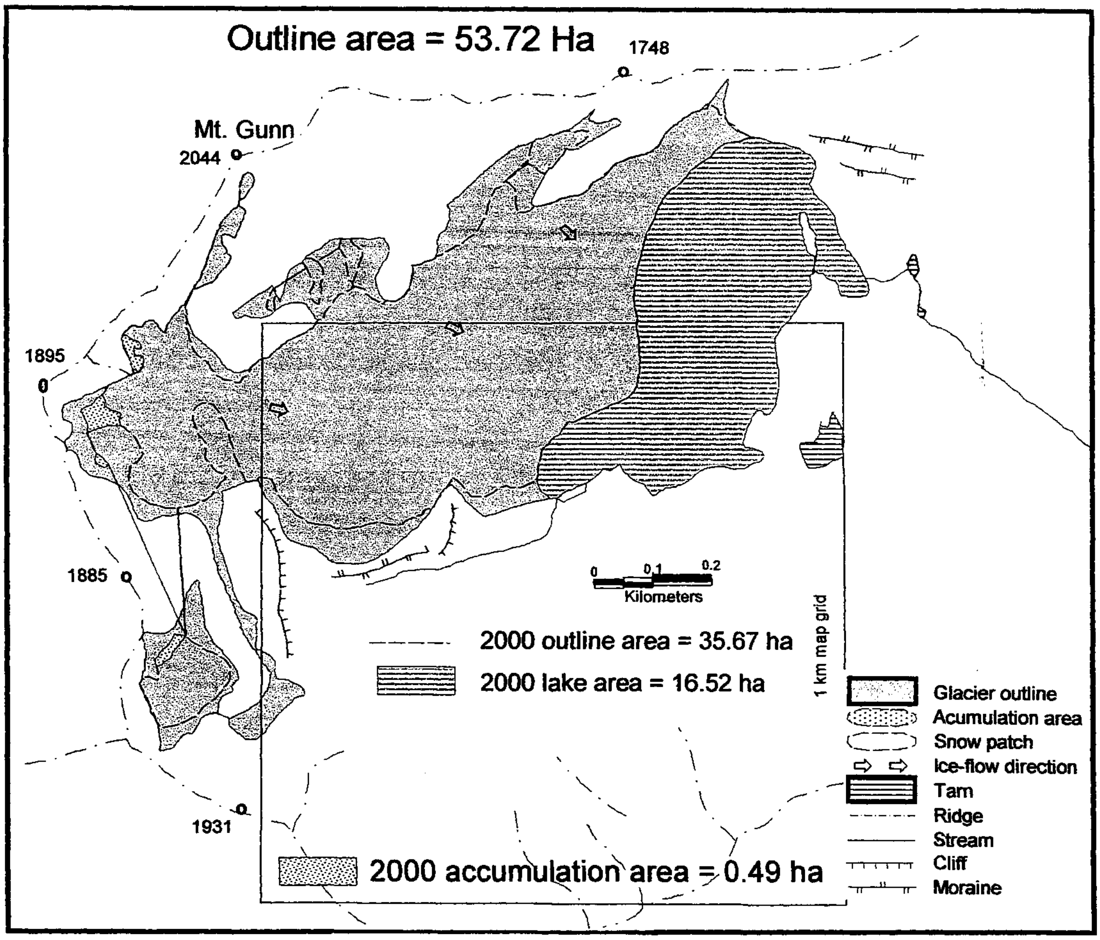
Glacier map and histogram plot of all recorded snowlines

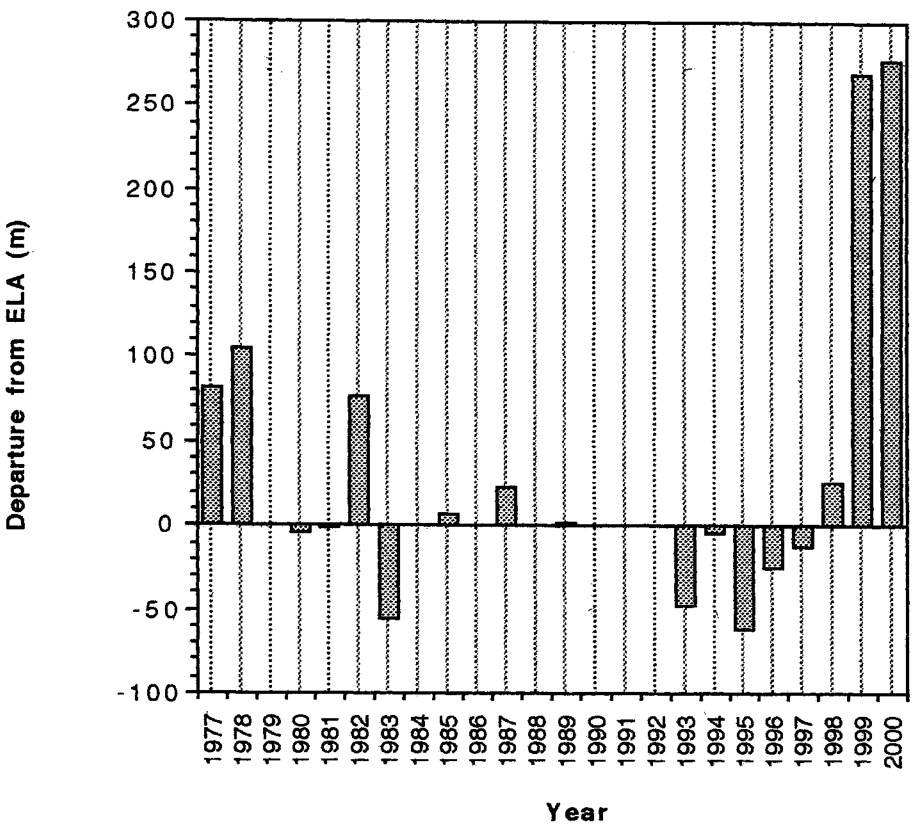




Mt. Gunn

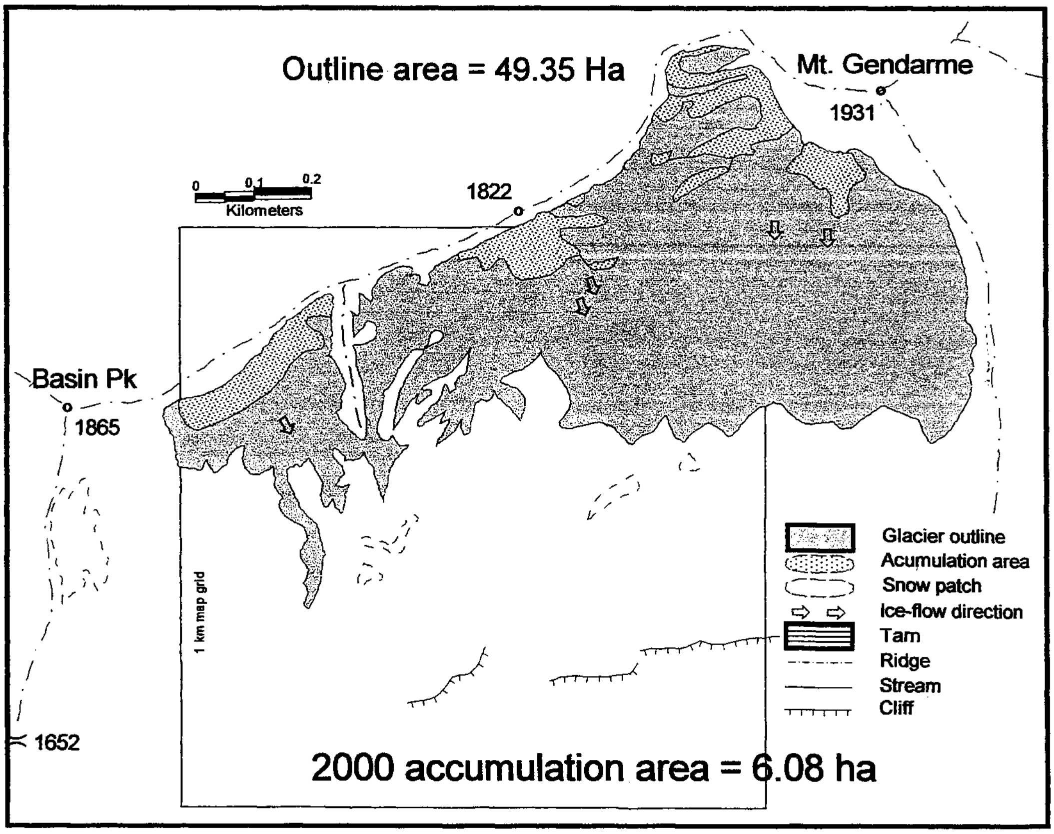
Glacier map and histogram plot of all recorded snowlines

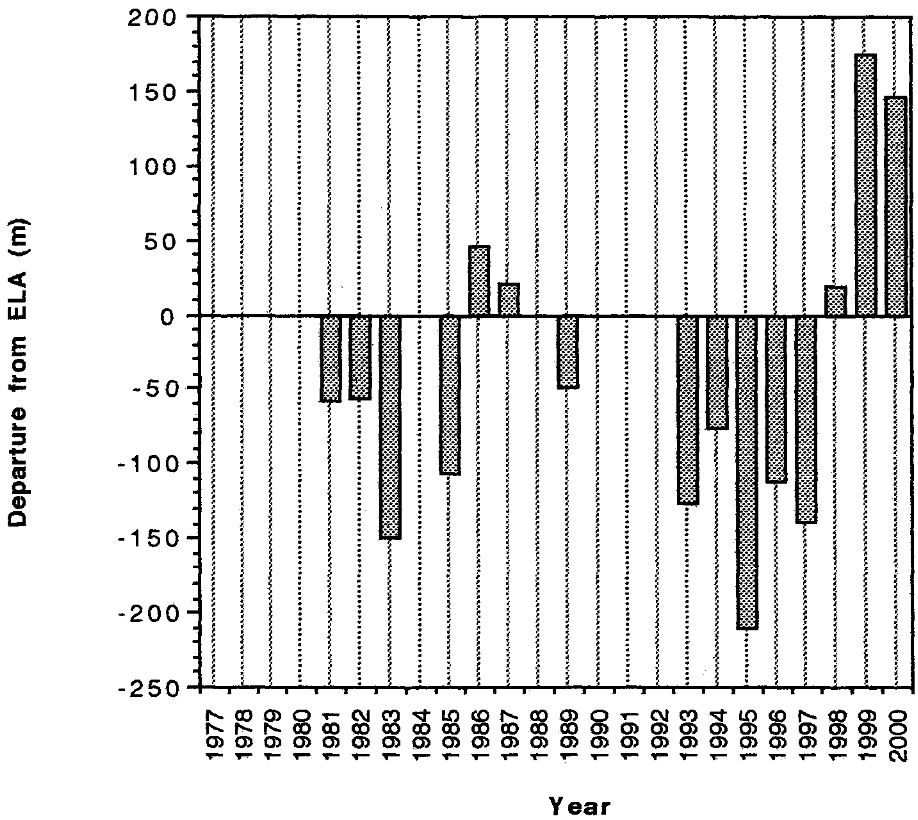




Mt. Gendarme

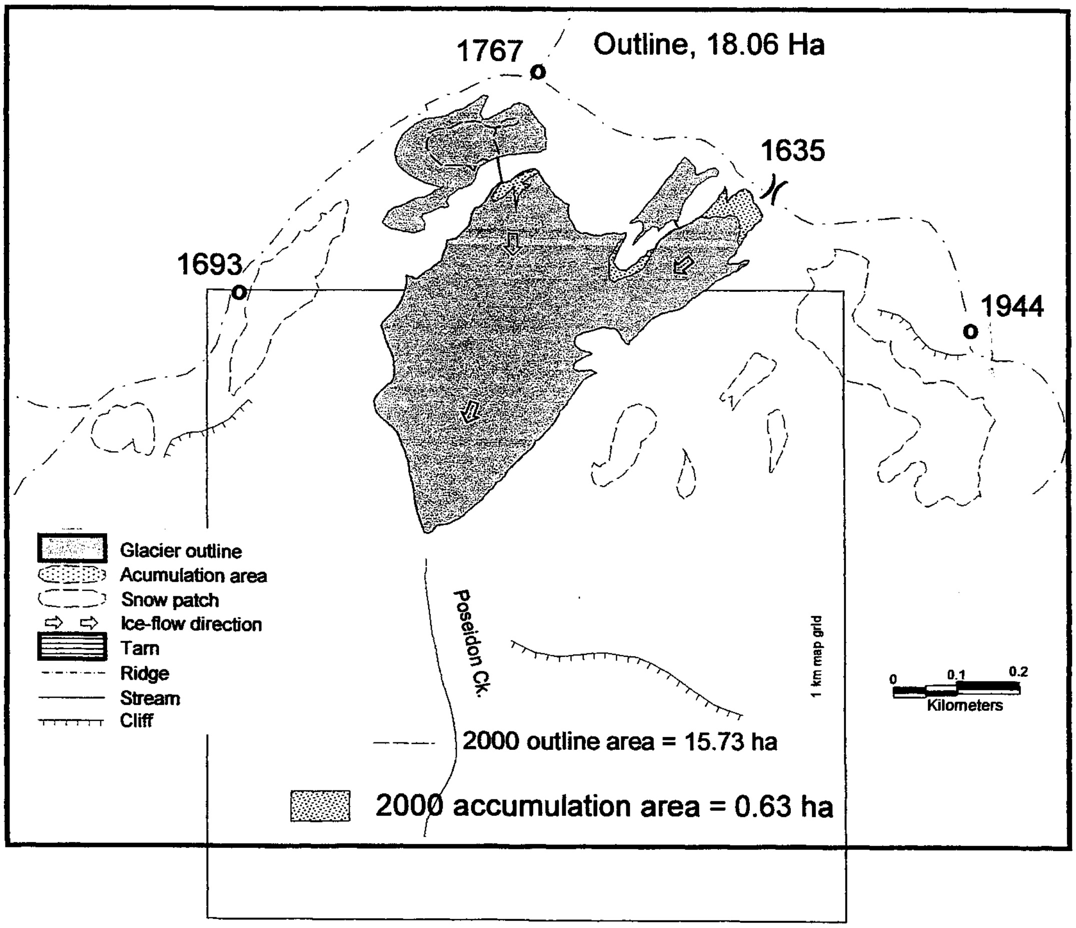
Glacier map and histogram plot of all recorded snowlines

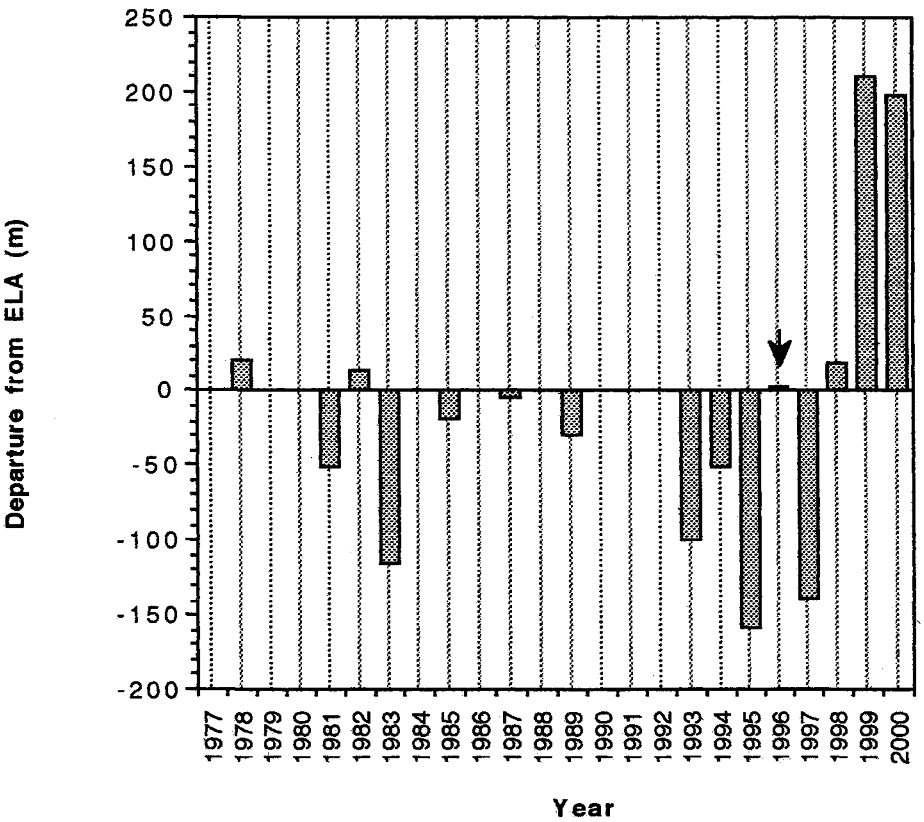




Llawrenny Pks

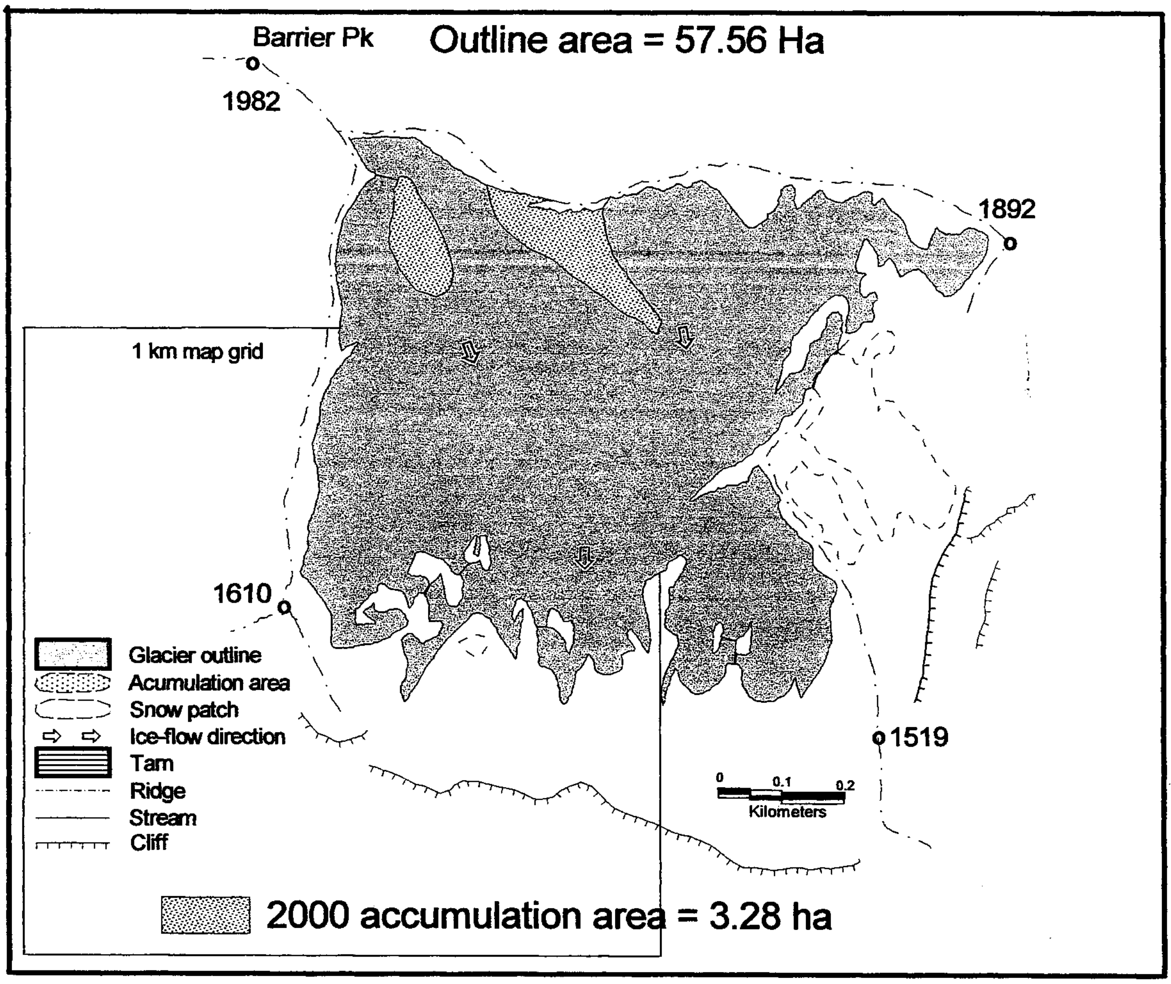
Glacier map and histogram plot of all recorded snowlines

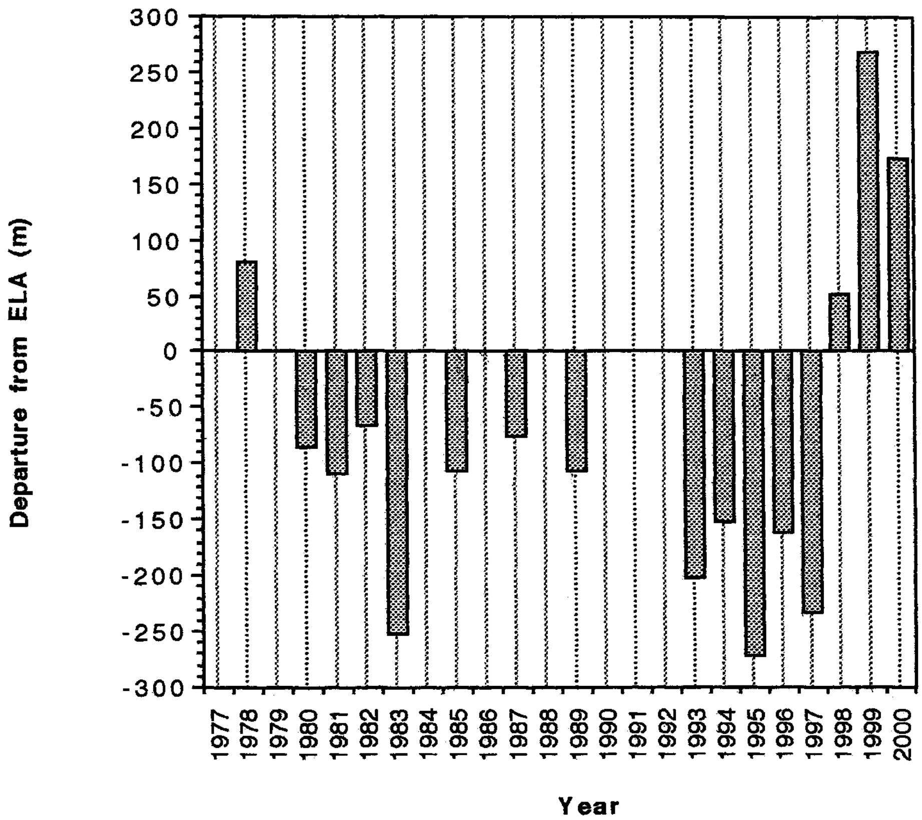




Barrier Pk

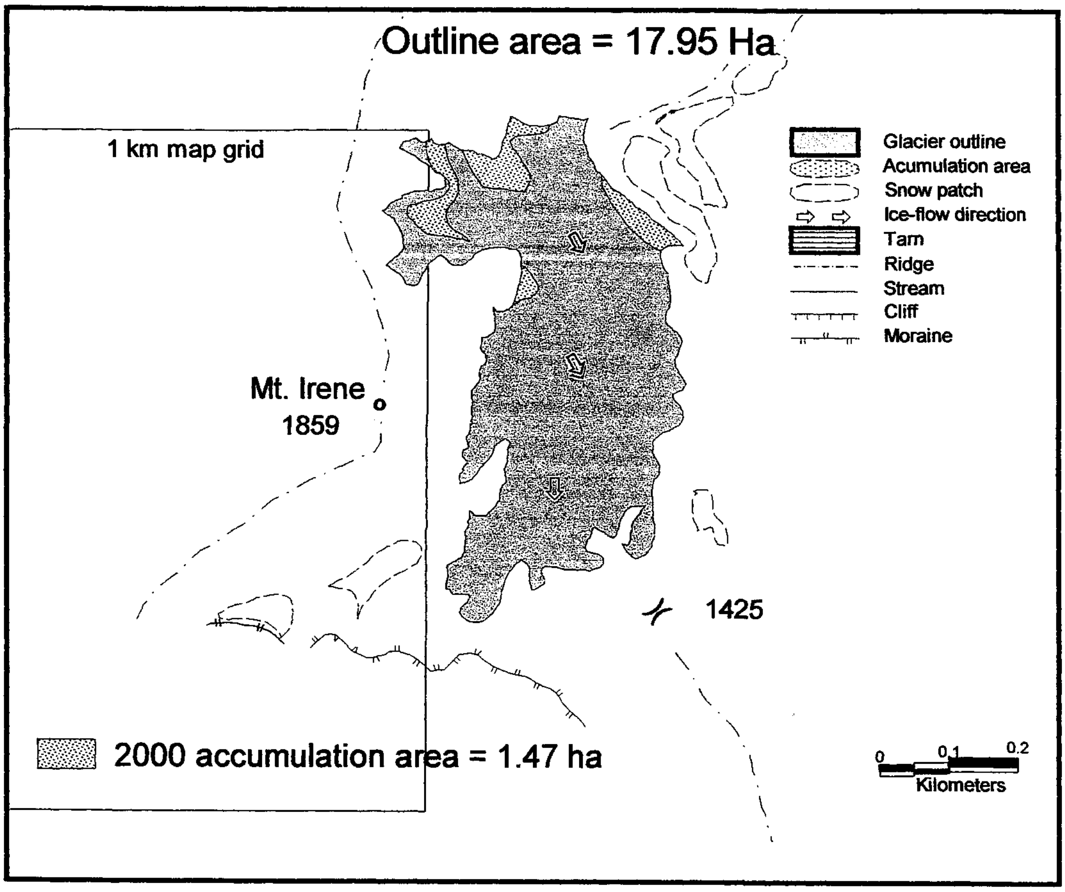
Glacier map and histogram plot of all recorded snowlines

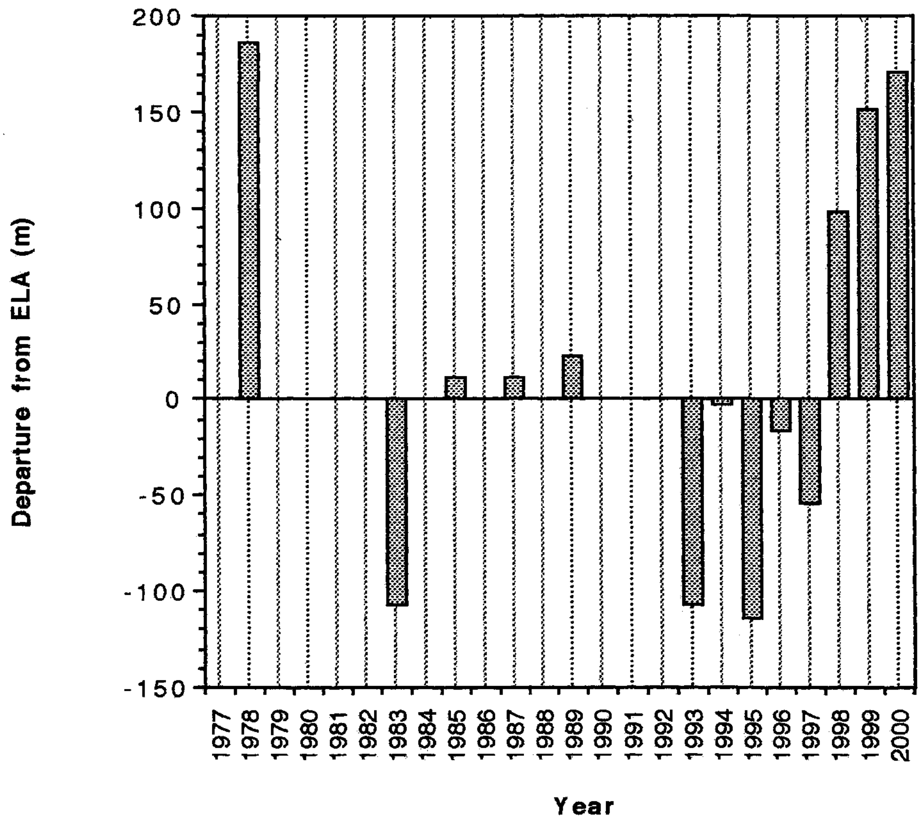




Mt Irene

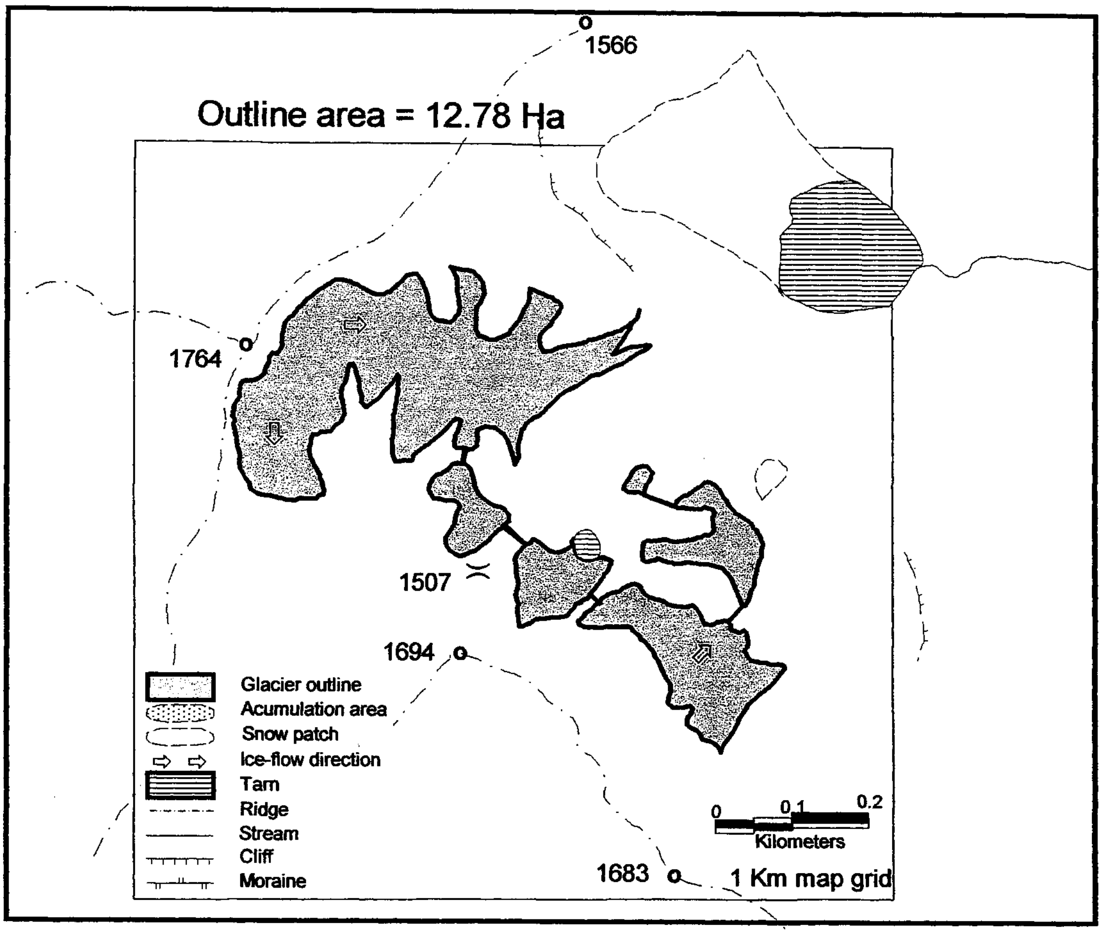
Glacier map and histogram plot of all recorded snowlines

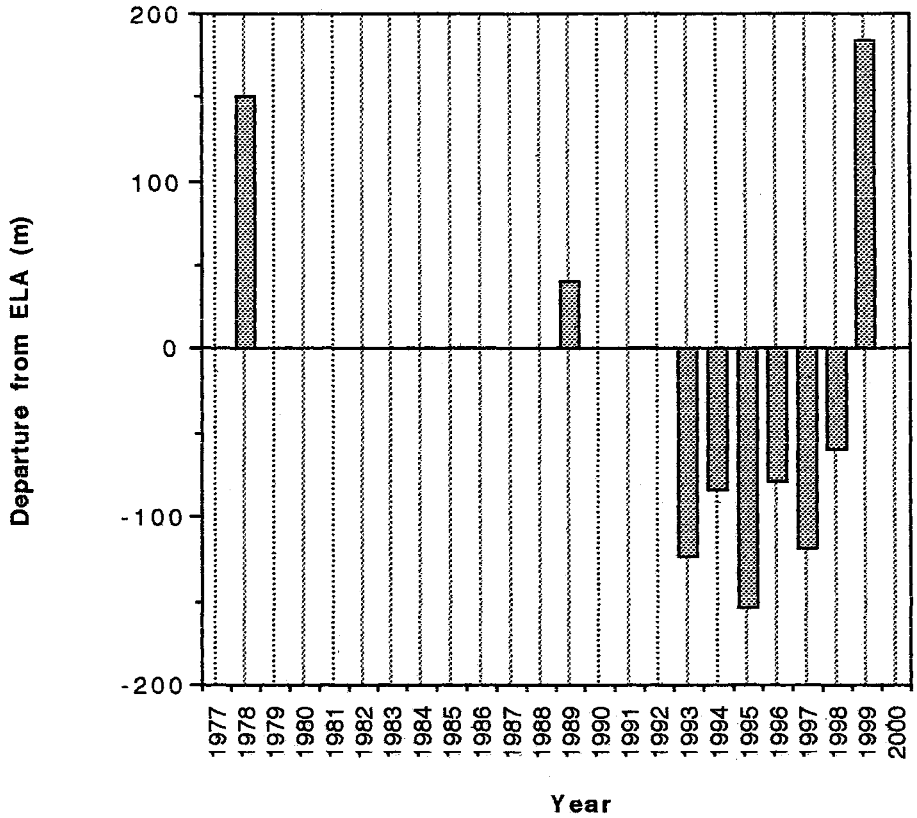




Merrie Ra.

Glacier map and histogram plot of all recorded snowlines





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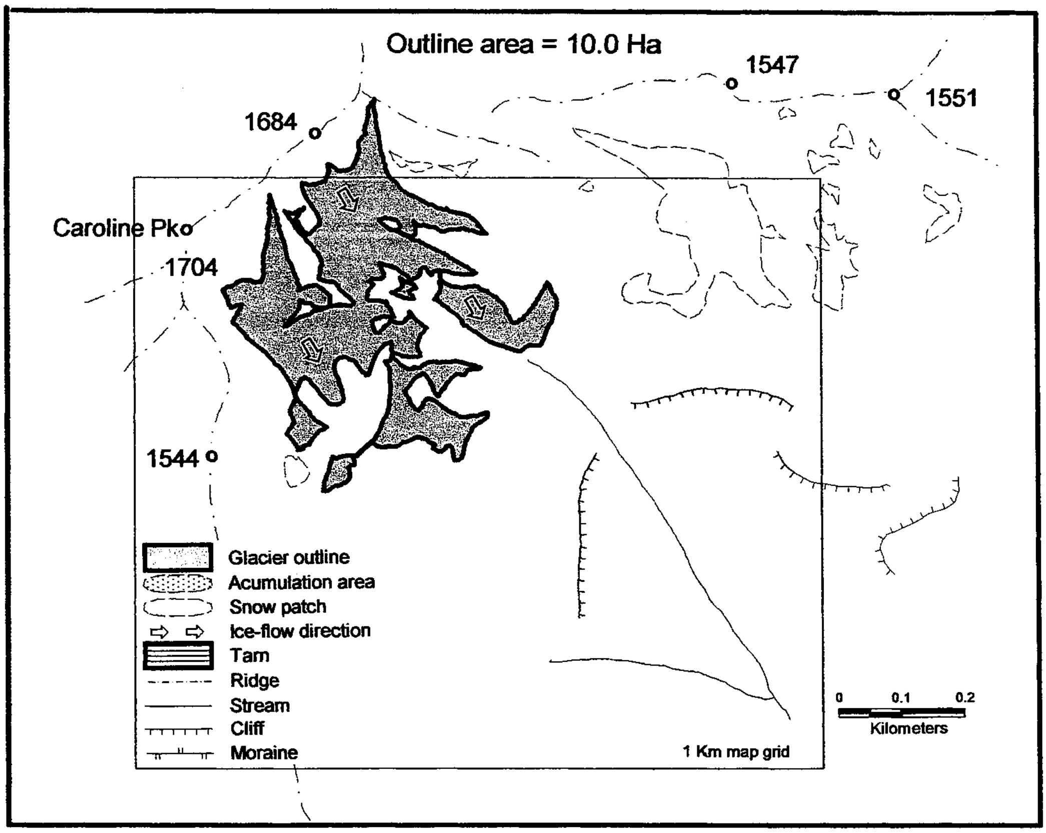
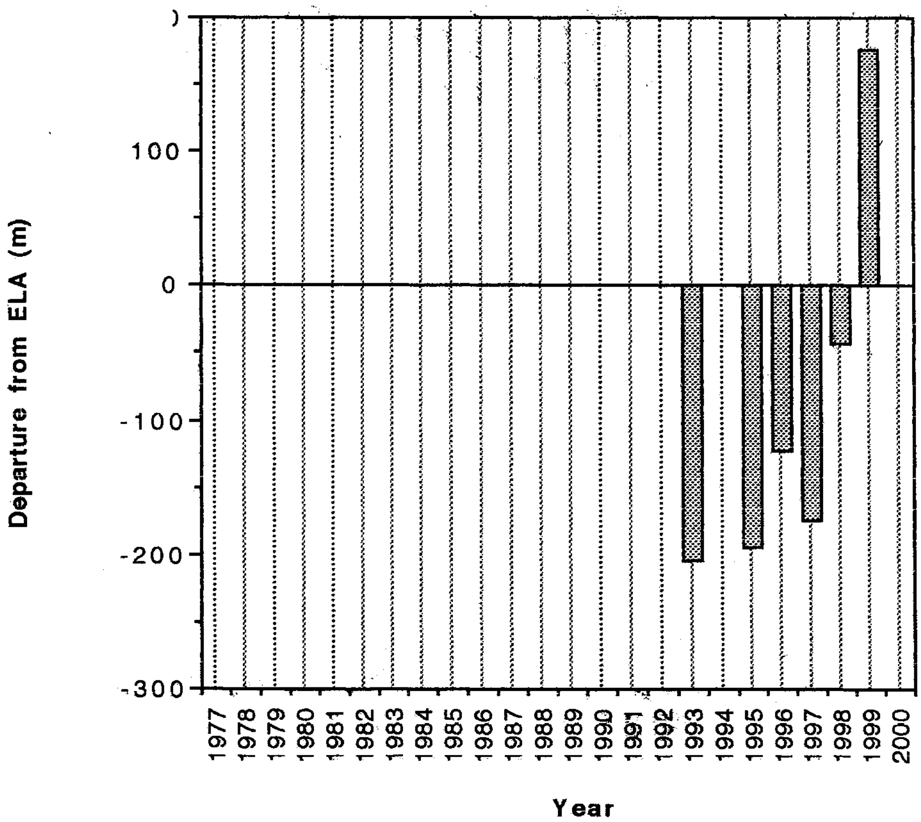
Caroline Pk

Glacier map and histogram plot of all recorded snowlines





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