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Glacier Snowline Survey 2003

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Executive Summary

Glaciers of New Zealand provide indisputable, enhanced responses to the changing climate, which are recorded by annual aerial surveys. These surveys measure the altitudes of end-of-summer-glacier snowlines of 50 selected index glaciers, which are used as a surrogate for annual glacier mass-balance. The survey has been made in most years since 1977, but rarely do conditions permit all of the index glaciers to be surveyed each year. The surveys are carried out by hand-held oblique photography taken from a light aircraft, where the position of the glacier snowline is recorded from a similar viewpoint each year.

The glaciers have shown a trend towards positive mass-balances for most of the 26-year monitoring period, although this trend may have reversed in 1998. All of the index glacier snowline elevations measured in the 2003-monitoring program indicate positive mass balances, ie below average equilibrium line altitudes (ELAs). An additional flight was made 17 days after the normal annual March flight and further summer snow melt resulted in the height of the mean ELA of 16 index glaciers climbing by 40m from the previous flight.

The low ELAs across the Southern Alps was a result of a weak EL Niño with well below average pressures east of the Chatham Islands and slightly above average pressures in the north Tasman Sea during the months May to November. These climate patterns resulted in windier westerly and southwesterly winds predominating over New Zealand during the glacier year. Furthermore seas cooled in spring with temperatures trending below average by November, resulting in thick snowpack persisting through the spring into a cooler than usual summer.

1. Introduction

The results presented in this report continue an annual glacier/climate photographic monitoring programme begun in 1977, of the position (altitude) of the end-of-summer snowline on 50 selected index glaciers, arranged in transects across the Southern Alps, (see Figure 1).

During 1977 a New Zealand glacier inventory was undertaken from Mount Ruapehu in the North Island at 39° 15' S to southern Fiordland at 45° 57' S. A total of 3144 glaciers were identified during the inventory. 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 north east, the Kaikoura ranges reach to over 2700 m, where active rock glaciers have developed under the dry climate. 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 the annual survey.

New Zealand has a humid maritime climate, with the Southern Alps lying across the path of the 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 1000mm in the eastern ranges. This creates steep eastward precipitation gradients and the mean altitudes of the glaciers closely follow these gradients (Chinn and Whitehouse, 1980).

1.1 Glaciers and climate change

Glacier fluctuations are amongst the clearest signals of climate change, because glaciers are highly sensitive indicators of the earth surface energy balance. Glaciers give distinct signals of past climate change from decades to millennia. Atmospheric changes are signalled by direct, immediate 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.

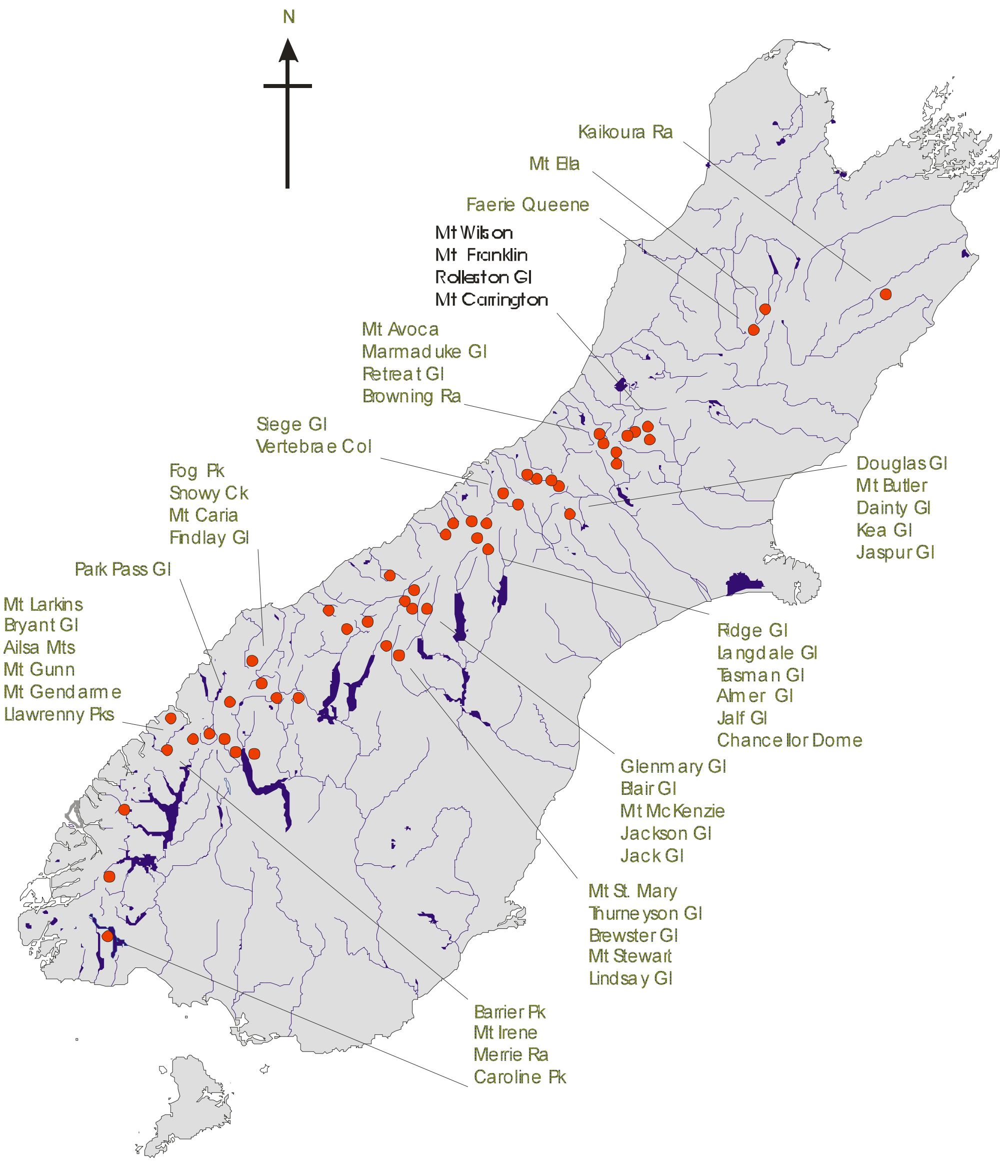

Figure 1 Location of the 50 index glaciers

1.2 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 retreats up-glacier as summer melt progresses, until it reaches a maximum altitude for the year at the end of summer (March - April). Located somewhere near the middle of the glacier, the end-of-summer snowline indicates an equilibrium line where snowfall 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 and Post, (1962), that is measured by the current snowline survey. 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 (ELA_o). 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 to glacier size. To avoid confusion between the annual and the long-term ELAs, some authors have also referred to the altitude of the annual glacier snowline as the end-of-summer snowline or EOSS.

A shift in climate 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 average or steady-state ELA_o is used as a surrogate for annual balance changes at each glacier (Chinn et al. in press; Chinn, 1995). It is the departure of the glacier snowline from the steady-state $ELA_{o,}$ ie. ELA_o - ELA-, that is reported here. These ELA departure values provide a measure of mass balance changes.

Glacier studies worldwide have demonstrated that the ELA_o lies at an altitude where the ratio of the accumulation area (AAR) to the total glacier area has an average value close to 0.6. For this programme, the steady-state ELA_o was initially obtained from AAR values of 0.6 for each glacier, and as more data was obtained, these approximate values, have been adjusted for most index glaciers.

2. Field methods

Collection of field data involves flying over the glaciers in a light aircraft to take 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 or ablation areas are mapped and measured by digitiser. The 'snowline altitude' is then accurately read from the glacier area-altitude curve.

2.1 The survey flights

On the flights, the "navigator" seated beside the pilot, holds a folder of photographs of each glacier. These photographs are used to closely duplicate the position from where previous photographs were taken. Photographs are taken by small and medium format SLR cameras, and since the 2001 flight, also in digital format. These surveys also provide the opportunity to record data on selected glacier termini, geomorphic features and events in addition to the index glaciers. The flights are generally flown between 9,000 ft (2,700 m) and 10,000 ft. (3,000 m). The higher the altitude the more easily the glacier snowlines can be defined and mapped, but civil aviation regulations do not permit normal flights to remain above 10,000 ft for prolonged periods.

Significant melt continues throughout February and March, but by April there is a high probability that the first winter 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. Every year the challenge of the survey is to measure the highest altitude reached by the rise of the glacier snowline as ablation losses proceed, before the first "winter" snowfall. A light fall of fresh snow will conceal the position of the snowline as effectively as a coat of paint. The problem has been standardised by setting the earliest date for the flight at March 1.

'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 the month of March before a fresh snowfall occurs.

2.2 March 2003 flight details

T. Chinn and C. Heydenrych (NIWA, Auckland) made the flights in a Cessna Cardinal 177 chartered from Wanaka Flightseeing at Wanaka airfield and piloted by A. Woods, a veteran of many of these survey flights. A high-wing aircraft is used, as it has no obstructing wing struts and a relatively high cruising speed.

This year an unseasonally heavy snowfall occurred over 18 to 20 February and spread up to 1 m of snow over many of the index glaciers. The survey flight was thus delayed to allow for the bulk of this new snow to melt and expose the true glacier snowline. In early March an anticyclone to the northeast of the country drew a warm, moist air-stream over the South Island, which greatly enhanced snowmelt. The survey was then made in the next available ridging anticyclone synoptic system.

On Friday 7 March, two weeks after the snowfall, the first flight was made from Wanaka along the west coast because of low level cloud on the east coast. The Alps were clear to Arthurs Pass with some cloud obscuring the Mts Wilson and Franklin region. The plane was refuelled at Greymouth and headed north to the Lewis Pass area, which was covered in cloud at the time, but a decision was made to continue northward towards the Kaikoura Range. Faerie Queene was also in cloud but the lower half of the glacier was photographed from beneath the cumulus layer and Mt. Ella was clear. A towering cumulus covered the Kaikoura Range and no view of the glacier was gained. No accommodation was available at either Hokitika or Greymouth and the overnight stopover was made at Hanmer Springs.

The next day, Saturday 8 March, the flight continued south with Mts Wilson and Franklin were now cloud free. The remainder of the eastern Alps were covered with no problems. After lunch and refuelling at Wanaka, the Fiordland section was completed (see Figure 2).

Throughout the Alps the majority of the glaciers still retained a February snow cover and most had their true snowlines covered. This year the winter snow was stained brown by aerosols from the Australian bush fires during December 2002 – January 2003 and was readily recognizable beneath the patchy clean February snow.

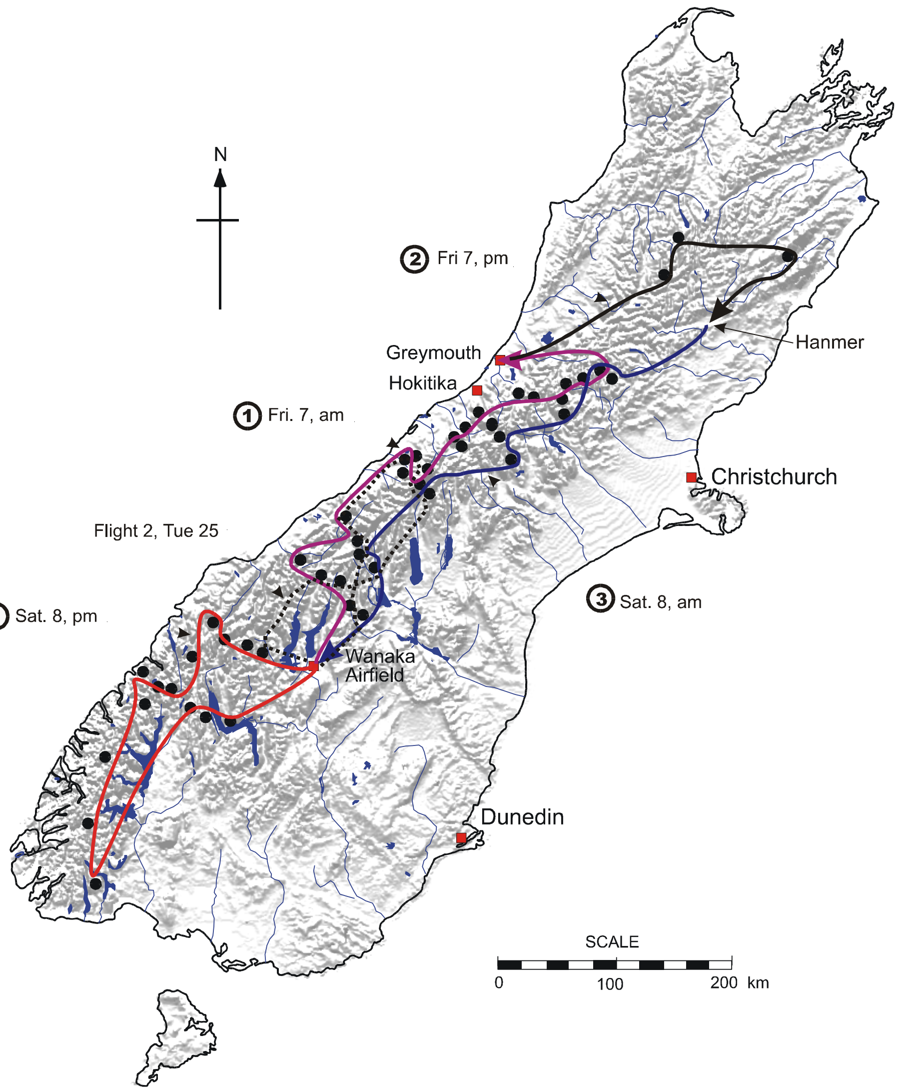

Figure 2 Flight paths for the two flights of the 2003 glacier surveys

2.3 The second survey flight

During 2003 an additional flight was made which was not part of the normal annual monitoring program. The opportunity arose because of a need to record surface reflectance for GLIMS images being studied by Dr Mathieu of Survey Department, Otago University. Dr Mathieu and his team made on-site measurements on the Glenmary and Ridge Glaciers at the same time as the first survey was made. The second flight was made 17 days after the first, and covered 16 glaciers of the Tasman, Landsborough and Haast transects between Mts Cook and Aspiring (see Figure 1).

Lindsay Glacier was lost to cloud of a humid trough approaching from the Tasman Sea. During the intervening 17-day period no further snowfalls took place and allowed for a further "calibration" to assess the additional rise of the snowlines over this period. All of the glaciers on the second survey showed large changes since the first flight with the majority retaining only a patchy residue of the February snow.

3. Derivation of the glacier snowline

The most significant problems in processing the results are recognising the position of the true end-of-summer snowline, especially when;

- There has been a recent summer snowfall, which effectively “paints out” the snowline.
- The snowline has been only partially recorded due to cloud cover, backlighting or other reasons.
- The current snowline is obscure or ambiguous due to limited discolouration of snowpacks of previous years.

Glacier snowline elevations are normally obtained from detailed mass balance studies where the snowline is mapped as the zero isohyet on the annual mass balance map. In this study the snowlines are derived from oblique aerial photographs by one of “three” methods, depending on the snow cover conditions at the end of summer. The procedures are given in Chinn, (1995) and in Chinn and Salinger (1999).

Firstly by digitising either the accumulation or ablation area to provide a definitive ELA; secondly by interpolating between photographs of past years where a number of snowlines are close in altitude; and thirdly by comparing the sizes of adjacent snowpatches when fresh snow or cloud obscures the snowline of the index glacier.

3.1 ELAs derived by digitising

This method gives the definitive ELA values upon which the interpolation and snowpatch methods rely. Here the end-of-summer snowline positions are carefully sketched from the photographs on to detailed base maps of each glacier. The resulting mapped accumulation or ablation zones are digitised using a GIS programme to accurately measure the areas. From the total ablation area for each glacier, the snowline elevation is then read off an area-altitude curve constructed for each glacier. (If the accumulation area was measured, the ablation area is found by total glacier area minus accumulation area). This method provides a single figure for the glacier ELA for the year regardless of the shape of the measured area as it eliminates subjective estimation of the altitude of the snowline. The difference between this altitude and that of the long-term ELA_o, indicates the annual mass balance of the glacier. Positive values or high snowline elevation signifies less snow and therefore a negative balance.

3.2 ELAs derived by interpolation

With the many photos now available, for many glaciers it may be more accurate and quicker to obtain the ELA value by interpolation. For each glacier photos for all years are arranged in increasing area of snow cover (descending order of ELAs). The current years photograph is then carefully compared and inserted into its appropriate place in the sequence. It has been found that very small differences in snow cover can easily be recognised and that two photos separated by many years can have identical snow coverage. The ELA value is interpolated from the ELA values of the adjacent years. Depending on the similarity of the ELAs, this method frequently places the value of the ELA within a few metres.

3.3 ELAs derived by snow-patch size when the snowline is obscure

Where the true end-of-summer snowlines are obscured by fresh snow, cloud or other reasons, the hidden snowline may be interpolated from the degree of snow cover surrounding the glacier, ie. the size of the intermittent snow patches. Fresh snow on rock has quite a different appearance from fresh snow on existing snow, and it is commonly possible to "see" the snow-patch outline beneath a light cover of new snow. As in the previous method, photographs of the glacier for all years are arranged in order of increasing snow cover on the glacier, which is also the sequence of the size of the snow-patches surrounding the glacier. The photograph from the latest survey is then slotted into its appropriate place in the snow-patch sequence. The ELA values are interpolated from those of adjacent glaciers as described above. This subjective assessment has proved to be surprisingly consistent (see Chinn et al, 2002). The fresh cover of new snow on the first flight of the 2003 survey made it necessary to use this method on the majority of the glaciers.

3.4 Derivation of the Long-term or Steady-state ELA_o value

Glacier studies worldwide have demonstrated that the ELA_o lies at an altitude which divides the accumulation area from the ablation area in a ratio of near 2:1. (Maisch, 1992). This accumulation area ratio (AAR) of accumulation area to the total glacier area has an average value close to 0.6 (Paterson, 1994). For glaciers in balance, the steady-state ELA_o would be the mean of many years' readings. However positive balances have dominated the New Zealand glaciers since this programme began in 1977 and thus the mean value of observed annual ELAs will lie somewhat below the true $ELA_{o.}$

For this study, values for the long-term ELA_o were initially derived by applying an AAR value of 0.6 (Gross, et al. 1976) to the area-altitude curve for each glacier. The ELA_o is read off the glacier area curves at 0.4 of the area up from the glacier terminus. This provides an approximate value only as measured AARs on glaciers in equilibrium vary from 0.5 to 0.75, depending on glacier topography and other factors. Many of the applied values of the ELA_o showed inconsistencies with other glaciers, ie. the annual ELA departure values were of the opposite sign or widely different from the majority of the other glaciers. In these cases the ELA_o values were adjusted to provide more consistent ELA departures. Latterly, with many years of data, regression plots have provided a method of defining the ELA_o with some accuracy. Further work on standardising the individual ELA_o for each glacier will be undertaken in the future.

4. The 2003 snowline results

4.1 Photographic coverage of the index glaciers

This year cloud cover prevented the survey of only one glacier, Kaikoura Range, while on the second ‘calibration flight’ Lindsay was under cloud and Jack was almost concealed beneath a solitary cloud.

On the first survey, all of the glaciers had low snowlines, so that no firn was present and minimal winter snow showed as discoloured patches, while bare ice areas showed only on the larger glaciers. The ELAs for this survey were derived mainly by the interpolation method described above.

Results from the second survey showed that was still some patchy February snow near the ELA on a few glaciers, but generally the true ELA was readily discernable. The majority of the ELAs were determined by the interpolation method.

4.2 ELA rise between the two surveys

Chinn et al 2002 have previously reported that the rate of annual change of the snowline altitude, in response to local climate variation, varies for each index glacier. The ELAs were derived for each of the 16 index glaciers covered in flights 1 and 2 (see Table 1). In the 17 days between the two flights, the mean ELA rise for all the 16 glaciers was approximately 40m.

4.3 Snowline elevation departures

Monitoring results for the 50 index glaciers for the 2002 - 2003 glacial year ending in March 2003, together with the means for all measured years from 1977 to 2003 are shown in Figure 4 and Figure 5 respectively. The snowline departure results for this year averaged 104 m below the long-term mean ELA_o position, indicating a return to the positive mass balance trend, which had appeared to cease in 1998.

Table 1. Snowline ELA for flights 1 and 2 for the 16 glaciers surveyed

	1	2	3
Glacier	**Flight 1 Measured ELA (m)**	**Flight 2 Measured ELA (m)**	**ELA Rise (m)**
Ridge	2090	2163	73
Langdale	1955	1975	20
Tasman	1666	1710	44
Salisbury	1650	1715	65
Jalf	1560	1600	40
Chancellor	1540	1570	30
Glenmary	2045	2115	70
Blair	1812	1845	33
McKenzie	1715	1770	55
Jackson	1985	2015	30
Jack	1745	1760	15
St. Mary	1780	1795	15
Thurneyson	1855	1873	18
Brewster	1740	1794	54
Stuart	1557	1570	13
Fog	1890	1962	72
Mean			**40.4**

Detailed data for the mean glacier ELA from 1977 to 2003 and individual data for each index glacier are given in Appendix 1 and Appendix 2 respectively. Missing values are years of no survey for the particular glacier. Appendix 1 indicates that 10 years had significant positive mass balance years (mean minus the standard deviation of all 50 index glaciers is less than zero). Only 3 years during this period had significant negative mass balance years (1999, 2000 and 2002).

Appendix 2 gives a data table, map and histograms of all measured snowline fluctuation histories as metres of departure from the steady-state ELA_o for each index glacier. Missing values are years of no survey, and arrows indicate measured zero values. The data table provides essential glacier data, snowline data statistics and a table of all measurements and immediate derived values. Photographs of each glacier are available in the 1999 Report, (Chinn and Salinger, 1999).

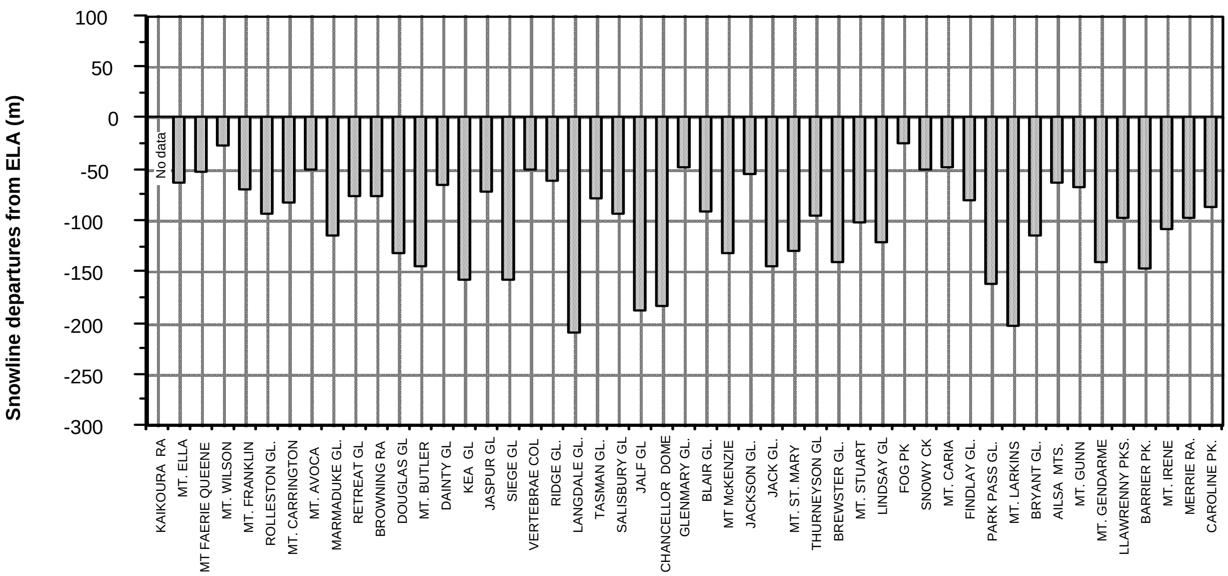

Figure 4 Histogram plot giving the 2003 snowline departures for each index glacier from the long-term ELA_o. Arrow indicates a zero value.

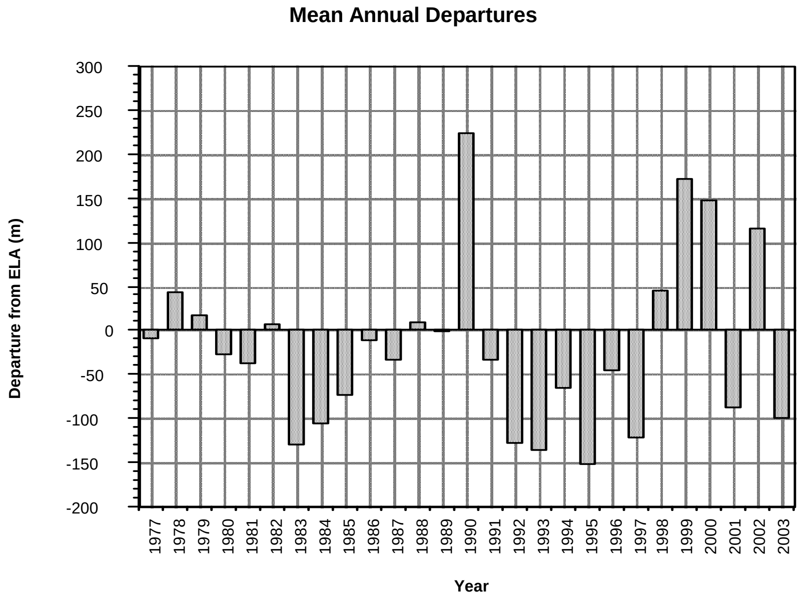

Figure 5 Mean annual departures from the ELA_o for all measured glaciers for the entire period of these surveys**.**

4.4 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 values for an individual glacier correlates with the mean value of the 50 index glaciers 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 2. The correlation plots for each glacier are given in the Appendices. The correlations give a surprising result where representivity appears to be independent of size, gradient or topography. The high correlations indicate that the ELA surface of individual glaciers have a strong relationship with the "mean ELA" of the whole alpine range.

Table 5 Correlation coefficients of individual snowline departures for each glacier correlated against the mean of all remaining values for the period 1977 - 2003.

Barrier Pk.	0.94
Caroline Pk.	0.94
Lllawrenny Pks.	0.93
Findlay Gl.	0.91
Vertebrae 25	0.90
Jalf Gl	0.90
Jackson Gl.	0.89
Mt. Larkins	0.89
Siege Gl	0.88
Mt. Irene	0.87
Mt Ella	0.87
Mt Stuart	0.85
Mt. Gendarme	0.85
Thurneyson Gl	0.85
Mt Butler	0.84
Mt. Franklin	0.84
Vertebrae Col	0.84
Chancellor Dome	0.84
Mt. St. Mary	0.84
Brewster Gl.	0.84
Mt. Carrington	0.84
Mt McKenzie	0.84
Lindsay Gl	0.83
Kea GL	0.83
Ailsa Mts.	0.83
Merrie Ra.	0.82
Park Pass Gl.	0.82
Marmaduke Gl.	0.82
Bryant Gl.	0.82
Salisbury Gl	0.82
Rolleston Gl.	0.81
Browning Ra	0.81
Mt. Gunn	0.81
Douglas Gl	0.80
Jaspur Gl	0.80
Fog Pk	0.80
Dainty Gl	0.80
Jack Gl.	0.79
Vertebrae 12	0.78
Tasman Gl.	0.78
Mt. Avoca	0.77
Mt Faerie Queene	0.76
Mt. Caria	0.75
Mt. Wilson	0.75
Retreat Gl	0.73
Ridge Gl.	0.72
Blair Gl.	0.70
Glenmary Gl.	0.67
Langdale Gl.	0.59
Snowy Ck	0.57
Kaikoura Ra	0.53

5. Discussion

5.1 The 2002 - 2003 glacial climate

For the 2002 - 2003 glacial year period, New Zealand temperatures were close to the 1971-2000 normals. However during May to November period a weak El-Nino influenced the New Zealand region, with well below average pressures east of the Chatham Islands and slightly above average pressures in the north Tasman Sea. This pattern resulted in windier conditions and persistent westerly and south westerly winds predominating over New Zealand (Figure 6). Seas cooled in spring with temperatures trending below average by November. This resulted in thick snowpack persisting through the spring into a cooler than usual summer.

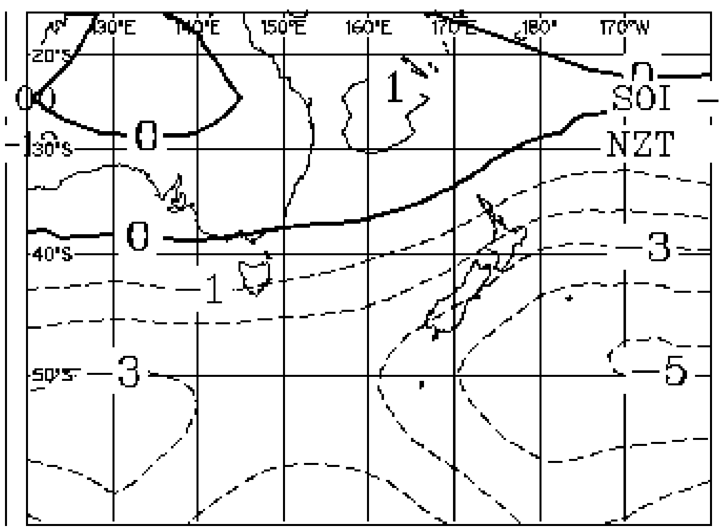

Figure 6 May – December 2002 mean sea level pressure anomaly.

5.2 Ice gain and loss

Glaciers accumulate the effects of net annual balance changes over years to decades. The effects of climate variations are delayed and distorted before being delivered to the terminus after individual glacier response times have elapsed. To assess the mass changes in response to climate fluctuations a cumulative plot of the "mass balance indices" (MBI) is presented in Figure 7. The MBI represents the steady state (ELA_o) minus the current season ELA. Snowline departure changes with negative ELA (ie lower snowline) result in positive MBI. Figure 7 shows clearly the general mass gain and mass loss to the glaciers. The reliability of use of the ELA as an indicator of mass balance change has been investigated by Chinn et al (In press), where the r values between the ELA and measured mass balance had an average value of 0.9 with a standard deviation of 0.07. Figure 7 also shows good agreement with the generalised climates given in Table 6.

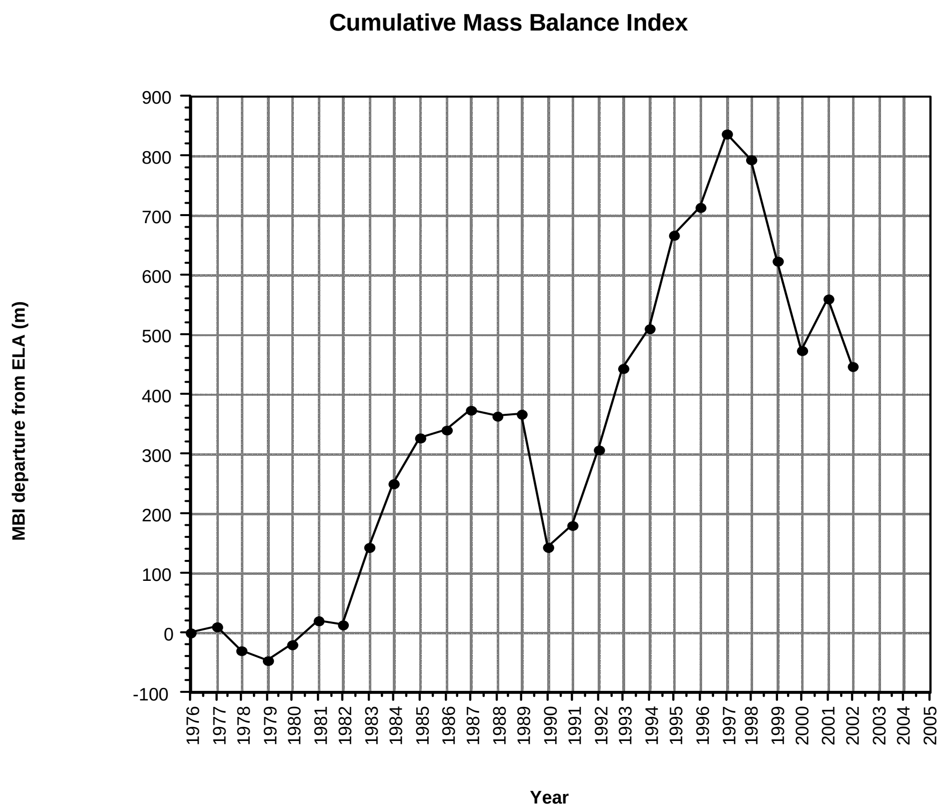

Figure 7 Cumulative Mass Balance Index for all 50 Index Glaciers

Table 6 Generalised climate for 2002 - 2003 year and previous 6 years in Southern Alps and inferred glacier snow input.

Glacier Year	Generalised Climate	Inferred glacier snow input
1996/1997	More lows tracking over New Zealand and easterlies over southern New Zealand. Temperatures 0.3°C below average.	Higher
1997/1998	Higher frequency of anticyclones and westerly winds over the south, southerlies further north. Temperatures 0.2 C below normal, but a very warm summer.	Average
1998/1999	Stronger westerly and northwesterly winds over New Zealand, temperatures 0.8°C above average, with above normal precipitation on the West Coast.	Less
1999/2000	Very anticyclonic, with weaker westerlies than normal. Temperatures 0.7 C above normal, and rainfall slightly below normal.	Less
2000/2001	More northwesterlies over the South Island, temperatures 0.2 C above normal. Rainfall close to average.	Average-High
2001/2002	Higher than normal pressures and more easterlies over the South Island, temperatures 0.3°C above normal, well below average rainfall.	Less
2002/2003	Persistent westerlies and southwesterlies over New Zealand. Cooler spring, rainfall slightly above average in the west and south.	Average-High

6. Acknowledgment

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7 References

Chinn, T. J. H. 1995. Glacier fluctuations in the Southern Alps of New Zealand determined from snowline elevations. *Arctic and Alpine Research* 27(2): 187—197.

Chinn, T. J. H. and Salinger, M. J. 1999. New Zealand Glacier Snowline Survey 1999. NIWA Technical Report 68. 119p. National Institute of Water and Atmosphere, Wellington.

Chinn, T. J. H., Heydenrych, C. and Salinger, M. J. 2002. New Zealand Glacier Snowline Survey 2002. NIWA Client Report AKL2003- 023, 20p. National Institute of Water and Atmosphere, Auckland.

Chinn, T.J.H.& Whitehouse, I.E. 1980: Glacier snow line variations in the Southern Alps, New Zealand. *In* World Glacier Inventory, pp. 219—228. *International Association of Hydrological Sciences Publication No. 126*.

Chinn, T.J.H, Heydenrych C. and Salinger M.J 2004 (In press). Use of the ELA as a practical method of monitoring glacier response to climate in the New Zealand's Southern Alps. International Jr. Glaciology.

IAHS(ICSI)/UNEP/UNESCO. 1998. Fluctuations of glaciers 1990-1995 (W. Haeberli, S. Suter and R. Frauenfelder (eds.). Paris, UNESCO.

Gross, G., H. Kerscher and G. Patzelt. 1976. Methodische Untersuchungen über die Schneegrenze in alpinen Gletschergebieten. Zeitschrift für Gletscherkunde und Glazialgeologie. 12, 223-251.

Maisch, M. 1992: Die Gletscher Graubuündens. Geographisches Institut der Universität Zürich.

Meier, M. F. & Post, A. S. 1962: Recent variations in mass net budgets of glaciers in western North America. *In* Proceedings of Obergurgl Symposium, pp. 63—77. *International Association of Hydrological Sciences Publication 58.*

Paterson, W. S. B. 1994. The Physics of Glaciers. Third edition, Oxford, Pergamon Press. 480 p.

Glossary

Ablation	All processes by which snow and ice are lost from a glacier
Accumulation	All processes by which snow and ice are added to a glacier.
Accumulation Area Ratio (AAR)	The ratio of the accumulation area above the equilibrium line, to the entire area of the glacier.
Departure of the ELA	The elevation difference between the long-term ELA_o and the annual snowline altitude. Positive departures mean a higher snowline and therefore a negative mass balance.
ELA	The mean altitude of the snowline or equilibrium line across a glacier at the end of summer.
ELA_o	The long-term or steady-state altitude of the ELA which will maintain the glacier in equilibrium with the climate.
Mass balance index	The negative of the ELA departure value. This gives values for annual changes with the same sign as the mass balance changes.
Shaded cells	Areas which have been measured by digitising.
Snowline elevation	The snowline elevation is synonymous with ELA when measured at the end of summer. All other snowline elevations apply to a transient seasonal snowline..
Total Area	The entire area of the glacier. This may change from year to year, especially on the smaller glaciers.

Appendix 1. Index Glacier ELA's (1977 – 2003)

GLACIER	ELA	1977	1978	1979	1980	1981	1982	1983	1984	1985
Kaikoura Range	2490						5		-17	
Mt. Ella	2142						12			
Mt Faerie Queene	1985						-45			
Mt. Wilson	1820	55	81			107		-23	-49	29
Mt. Franklin	1814		-12	122	-54	-74		-148		
Rolleston Glacier	1763	-13	5	-13	1	-3	10	-123	-10	-18
Mt. Carrington	1715		-45		-22	-87	25	-150	-115	
Mt. Avoca	1965		-55				-15		-95	-55
Marmaduke Glacier	1830	-43	-35	78	2	-28	30	-136	-122	-50
Retreat Glacier	1742		-4		38	-50	14	-252		-4
Browning Range	1598		7		10	-34	7	-113		-2
Douglas Glacier	2040		91		-163		-18	-214	-240	-223
Mt. Butler	1840	-55	112	55	-34	-40	28	-200	-65	-70
Dainty Glacier	1954	-32	57		-7	-77	93	-96		-81
Kea Glacier	1820		65		44	-85	134	-230		-120
Jaspur Glacier	1725		43		63		-15	-155		-105
Siege Glacier	1736	-64	-24		-76	-70	-70	-268		-94
Vertebrae #12	1952		-13		33	-60	-33	-73		-67
Vertebrae #25	1916		30		25	-39	-8	-62		-50
Ridge Glacier	2226		79			2	10	-15	-141	-32
Langdale Glacier	2186	12	65			79	52	-1	-236	-96
Tasman Glacier	1790	-10	85	-90	20	-35	-30	-80	-95	-90
Salisbury Glacier	1810	17	17		32	-58	17	-92	-51	-76
Jalf Glacier	1790	-15	-10		-32	-65	5	-230	-78	-146
Chancellor Dome	1756	96	95		77	-93	92	-211		-147
Glenmary Glacier	2164		74		-91	-34	17	-29	-144	-56
Blair Glacier	1938		74		-75	-13	-51	-126	-80	-85
Mt McKenzie	1904		46		6	-16	-2	-184	-62	-124
Jackson Glacier	2070		28		-20		8	-38	-80	-56
Jack Glacier	1907		31		23	-22	44	-157	-79	-32
Mt. St. Mary	1926								-171	
Thurneyson Glacier	1970	-36			-44	-27		-105	-88	-65
Brewster Glacier	1935		25		-89	-80	36	-141	-135	-139
Mt. Stuart	1673	-86	57		-23	-67	3	-135		-53
Lindsay Glacier	1730		8		-78	-49	51	-170		-64
Fog Peak	1987				-71		35		-96	
Snowy Creek	2092		64		-68	66	-54	-59	-68	-72
Mt. Caria	1472		-30			-59	-48	-100		-49
Findlay Glacier	1693					-89	42	-111		-64
Park Pass Glacier	1824		79		-16	-46	34	-62	-59	-122
Mt. Larkins	1945								-265	
Bryant Glacier	1783	-43	101			-20	-3	-163	-163	-173
Ailsa Mountains	1648		-5					-88	-53	-53
Mt. Gunn	1593	22	45		-64	-62	17	-115		-53
Mt. Gendarme	1616					-46	-43	-136		-94
Llawrenny Peaks	1476		4			-68	-4	-132		-36
Barrier Peak	1596		116		-51	-73	-31	-218		-72
Mt. Irene	1563		137					-156		-37
Merrie Range	1515		140							
Caroline Peak	1380									
Count	**50**	**15**	**40**	**5**	**32**	**36**	**41**	**41**	**27**	**40**
Mean	**1836**	**-13**	**41**	**30**	**-22**	**-39**	**9**	**-129**	**-106**	**-75**
Std Deviation	**215**	**48**	**51**	**83**	**53**	**45**	**42**	**66**	**65**	**48**

Period of gain **Period of loss**

GLACIER	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
Kaikoura Range			-5	50				-57	-17	-60
Mt. Ella				28				-87	-72	-142
Mt Faerie Queene			5	5				-60	-57	-65
Mt. Wilson	133	3	160	185				-75	-10	-62
Mt. Franklin	-18	-41	35	52				-164	-107	-156
Rolleston Glacier	13	15	-1	7				-143	-53	-143
Mt. Carrington	-10	45	55	5				-170	-128	-158
Mt. Avoca	-5		10	6				-115	-25	-45
Marmaduke Glacier	9	-5	65	-13	168			-175	-75	-155
Retreat Glacier	20			36				-73	-120	-277
Browning Range	17			-25				-116	-71	-118
Douglas Glacier	-128		91	172			-197	-260	-154	-231
Mt. Butler	10	-9	42	-34			-95	-136	-28	-190
Dainty Glacier	-73	-84	-12	-32			-103	-176	-73	-111
Kea Glacier	-82	-83	-58	-36				-230	-92	-250
Jaspur Glacier	-42		-42	-29				-150	-120	-145
Siege Glacier	35		-70	-64			-323	-386	-62	-396
Vertebrae #12	-53		-13	-51			-96	-86	-68	-86
Vertebrae #25	-27		3	-20			-94	-84	-54	-84
Ridge Glacier	-9		59	51				-126	-61	-94
Langdale Glacier	-41	-69	39	69			-216	-231	83	-226
Tasman Glacier	-10	-29	50	-30	310	-35	-100	-108	-20	-124
Salisbury Glacier	-1	-35	-81	-66			-129	-100	-38	-165
Jalf Glacier	-20	-51	-32	-31			-210	-220	-38	-240
Chancellor Dome	-78	-28	52	-78				-206	-147	-211
Glenmary Glacier			16	16			-24	-57	-43	-45
Blair Glacier		-68	57	-62				15	-73	-85
Mt McKenzie	13	-14		8				-122	8	-99
Jackson Glacier		-9		10				-78	-25	-52
Jack Glacier	28	-2	-32	-9			-90	-142	-27	-152
Mt. St. Mary	-91		-19	46			-76	-141	-76	-156
Thurneyson Glacier	-32	-52	-20	0			-36	-60	-66	-102
Brewster Glacier	-93	-107		-17			-84	-185	-145	-158
Mt. Stuart	-13	5		-10				-138	-33	-158
Lindsay Glacier	38	-115	42	34				-175	-120	-180
Fog Peak	-57	-85	35	45				-93	-87	-99
Snowy Creek	-56	-67	-55	11				-34	-58	-62
Mt. Caria	53	-50	28	-43				-97	-72	-106
Findlay Glacier	32	-71	-8	-51				-118	-59	-132
Park Pass Glacier	39	19		-30					-41	-214
Mt. Larkins	-53		135	91				-275	-95	-315
Bryant Glacier	-13	-20		-30				-27	-55	-153
Ailsa Mountains	1	-23		-36				-84	-52	-93
Mt. Gunn		-38		-59				-108	-64	-122
Mt. Gendarme	59	34		-36				-114	-64	-198
Llawrenny Peaks		-22		-47				-116	-68	-176
Barrier Peak		-41		-71				-168	-118	-236
Mt. Irene		-37		-26				-156	-51	-163
Merrie Range				30				-135	-95	-165
Caroline Peak								-160	-47	-150
Count	**38**	**33**	**33**	**49**	**2**	**1**	**15**	**49**	**50**	**50**
Mean	**-13**	**-34**	**16**	**-2**	**239**	**-35**	**-125**	**-133**	**-65**	**-150**
Std Deviation	**51**	**39**	**54**	**54**			**79**	**70**	**42**	**72**

Period of gain **Period of loss**

GLACIER	1996	1997	1998	1999	2000	2001	2002	2003	Count	Mean	Std Dev
Kaikoura Range			30	15	10	-15	25		**12**	**-3**	**33**
Mt. Ella	-15		17	108	60	-22	46	-64	**12**	**-11**	**71**
Mt Faerie Queene	-57		-50	145	160	-55	55	-54	**13**	**-6**	**79**
Mt. Wilson		-57	133	205	200	105	185	-29	**20**	**64**	**97**
Mt. Franklin	-82		122	164	136	-104	121	-70	**19**	**-15**	**107**
Rolleston Glacier	-44	-123	49	87	97	-42	89	-94	**24**	**-19**	**68**
Mt. Carrington	-120	-137	-39	190	237	-135	210	-84	**21**	**-30**	**122**
Mt. Avoca	12	-75	70	115	65	-52	88	-52	**18**	**-12**	**64**
Marmaduke Glacier	-82	-129	143	164	153	-57	140	-117	**25**	**-11**	**106**
Retreat Glacier	16	-97	47	146	133	-60	93	-78	**19**	**-25**	**111**
Browning Range	-11	-108	30			-28	62	-77	**17**	**-34**	**57**
Douglas Glacier	-150	-223	220	240	250	-40	245	-134	**21**	**-51**	**186**
Mt. Butler	-60	-176	68	98	148	-95	90	-147	**25**	**-31**	**97**
Dainty Glacier	-12	-92	98	176	74	-58	126	-67	**23**	**-24**	**88**
Kea Glacier	80	-152	78	200	190	-150	195	-159	**21**	**-35**	**144**
Jaspur Glacier	-92	-100	43			-100	195	-74	**17**	**-49**	**93**
Siege Glacier	-72	-203	214	414	279	-126	239	-160	**22**	**-61**	**205**
Vertebrae #12	-68	-78	-29	226	129	-70	136	-55	**21**	**-22**	**85**
Vertebrae #25	-54	-71	-5	125	70	-33	80	-51	**21**	**-19**	**58**
Ridge Glacier	-88	-136	9	89	79	-116	74	-63	**20**	**-21**	**78**
Langdale Glacier	51	-226	142	114	89	-211	104	-211	**23**	**-38**	**137**
Tasman Glacier	-35	-102	63	186	110	-80	105	-80	**27**	**-9**	**101**
Salisbury Glacier	-58	-84	42	220	172	-95	50	-95	**24**	**-27**	**89**
Jalf Glacier	-8	-191	-3	260	265	-85		-190	**23**	**-59**	**131**
Chancellor Dome	-36	-176	92	194	189	-186	159	-186	**22**	**-34**	**141**
Glenmary Glacier	-36	-112	36	108	84	-46	46	-49	**21**	**-18**	**64**
Blair Glacier	2		34	152	147	-96	67	-93	**20**	**-18**	**83**
Mt McKenzie	6	-189	31	174	148	-99	56	-134	**21**	**-26**	**96**
Jackson Glacier	2	-54	12	95	63	-54	33	-55	**19**	**-14**	**48**
Jack Glacier	51	-102	33	101	85	-109	78	-147	**23**	**-27**	**81**
Mt. St. Mary	-71	-84	-37	199	204	-146	189	-131	**16**	**-35**	**128**
Thurneyson Glacier	-32	-70	-5	142	162	-92	135	-97	**22**	**-27**	**77**
Brewster Glacier	27	-156	47	345	220	-165	115	-141	**22**	**-46**	**136**
Mt. Stuart	39	-106	-17	132	177	-83	142	-103	**21**	**-22**	**92**
Lindsay Glacier	45	-85	70	145	140	-90	142	-123	**21**	**-25**	**106**
Fog Peak	-93	-97	111	135	121	-92	125	-25	**18**	**-16**	**90**
Snowy Creek	-35	-72	66	148	54	-88	28	-51	**22**	**-21**	**64**
Mt. Caria	-82	-77	-55	178	188	-52	153	-50	**20**	**-19**	**91**
Findlay Glacier	-61	-113	26	197	140	-79	109	-81	**19**	**-26**	**93**
Park Pass Glacier	-64	-134	48	138	119	-154	99	-163	**20**	**-27**	**99**
Mt. Larkins	-163	-312	261	270	255	-280	245	-205	**15**	**-47**	**233**
Bryant Glacier	-113	-113	-5	227	182	-118	87	-117	**21**	**-35**	**110**
Ailsa Mountains	-64	-55	-27	182	137	-55	37	-65	**18**	**-22**	**74**
Mt. Gunn	-86	-73	-34	209	217	-78	42	-68	**20**	**-24**	**94**
Mt. Gendarme	-100	-126	32	188	159	-131	34	-96	**18**	**-38**	**104**
Llawrenny Peaks	-15	-155	2	194	181	-71	137	-100	**18**	**-27**	**106**
Barrier Peak	-126	-132	86	304	207	-108	194	-148	**19**	**-36**	**149**
Mt. Irene	-65	-103	49	102	122	-125	165	-109	**16**	**-28**	**111**
Merrie Range	-90	-130	-70	173		-103	175	-100	**12**	**-31**	**126**
Caroline Peak	-78	-130	2	182		-105	195	-89	**10**	**-38**	**129**
Count	**48**	**45**	**50**	**48**	**46**	**50**	**49**	**49**			
Mean	**-46**	**-123**	**46**	**173**	**148**	**-91**	**117**	**-101**			
Std Deviation	**54**	**52**	**70**	**70**	**62**	**57**	**61**	**46**			

Period of gain **Period of loss**

Appendix 2. Index Glacier details