Annual Glacier Ice Volumes in New Zealand 1995 - 2005

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Executive Summary

This report details the current state of knowledge in developing an estimate of glacier ice volume (measured in water equivalents km^3) for New Zealand. The work described in this report is a significant step to better understanding New Zealand glacier responses to climate forcing.

This report represents a significant improvement of the original methodology for assessing glacier ice volume using data obtained from the end of summer snowline surveys. A working group was established in 2002 by the National Institute of Water and Atmospheric Research (NIWA) to develop a methodology to estimate annual glacier volume changes through the Southern Alps. Subsequently the method has been revised and updated, with new estimates made of volume changes from 1995 – 2006.

Much of the raw data used in this report originates from the 1978 New Zealand Glacier Inventory and the annual New Zealand Glacier Snowline Survey Programme, which commenced in 1977. This uses the end of summer snowline of 49 index glaciers as a surrogate for determining the annual mass balance of glacier ice.

The original and revised methods both derive an annual index glacier volume change using the end of summer snowline elevation and an integration of the mass balance gradients above and below the snowline. The original method then used a regression equation based on the area of each index glacier and the respective volume change. This was then applied to the Southern Alps ice area to determine annual volume change. The revised method uses the existing calculation of annual index glacier volume change and then derives an annual specific mass balance for each index glacier by dividing each volume by each index glacier area. This is then averaged for all the index glaciers to give a mean specific mass balance for the Southern Alps. The annual glacier volume variations are then calculated by applying the product mean specific mass balance from the index glaciers and the area of all glaciers making allowance for the reduction in glacier area with the growth of proglacial lakes. As well, additional ice volume losses due to reduction in trunk volume are accounted separately for thirteen larger glaciers.

Against the background trend of ice volume losses through calving into proglacial lakes and reduction in trunk volume of some glaciers, annual changes were driven by climate: all years with ice volume shrinkage had above average temperatures, and some had below average precipitation. Years with gains in ice volume had cooler temperatures and often above average precipitation.

By far the largest annual changes are due to mass balance changes arising from climate. However, the cumulative ice volume losses from the growth of proglacial lakes and trunk draw-down dominate over the entire period.

From an initial volume estimate of 52.26 km^3 in 1994/1995, New Zealand ice volume increases to 53.92 km^3 by 1996/97 (an increase of 3 percent). Volumes then reduced to 41.84 km^3 by 2001/02 before increases to 45.10 km^3 by 2004/05. There was an overall reduction of 14 percent for the period 1995/1996 to 2004/2005.

There has been only small loss due to mass balance from climate, but significant loss of ice volume for larger glaciers due to calving into growing glacial lakes and trunk down wasting. Ice volume for New Zealand has decreased by 7.16 km^3 over the 10 year period. 48% of this loss is from 13 of the largest glaciers in response to a regional warming of 1°C since the late 19th century, and 52% from annual variations in circulation and climate.

1. Introduction

The National Institute of Water and Atmospheric Research Ltd. (NIWA) was commissioned in 2002 to estimate annual glacier volume for New Zealand from 1995 – 2001 (Heydenrych et al., 2002). Statistics New Zealand (SNZ) now require revision of the methodology based on the experience of this first report and an update of the information for the period 2002 – 2005.

A working group comprised of NIWA (Jim Salinger, Clive Heydenrych and Andrew Tait) and Professor Blair Fitzharris (Otago University) and Trevor Chinn (Alpine and Polar Processes Consultancy) was established in 2002 to determine a suitable methodology to calculate the volume balance for each year. The working group met and made the necessary calculations to calculate volume estimates for the period 1993 - 2001. Subsequently members of the team (Chinn et al., 2007) have significantly updated the methodology. While the New Zealand Glacier Snowline Survey Programme has established a hugely valuable record of long-term glacier features, no data was available on the glacier volume for the Southern Alps prior to 2002. The present report thus forms the second calculation in New Zealand (and to our knowledge the world), in obtaining a regional annual glacier ice volume based on end of season snowline monitoring of glaciers.

Raw data used in the study are largely based on the 1978 New Zealand Glacier Inventory and the New Zealand Glacier Snowline Survey Programme, which commenced in 1977.

The annual Snowline Survey Programme has monitored the end of summer snowline of 49 index glaciers as a surrogate for determining annual mass balance of glacier ice. The end of summer snowline level, referred to as the End of Summer Snowline (EOSS), indicates the previous glacial season of snow accumulation (Figure 1). If the long term EOSS remains at a steady height (approximately middle of the glacier), then the glacier will be in a steady state. If the long term EOSS is trending upward in elevation (defined as positive), then the glacier is in retreat. Conversely if the long term EOSS is trending downward in elevation (defined as negative) then the glacier is in a state of accumulation. Every season is defined relative to the long term EOSS as either positive (base height of accumulated previous season’s snow level is high) or negative (if snow level is low).

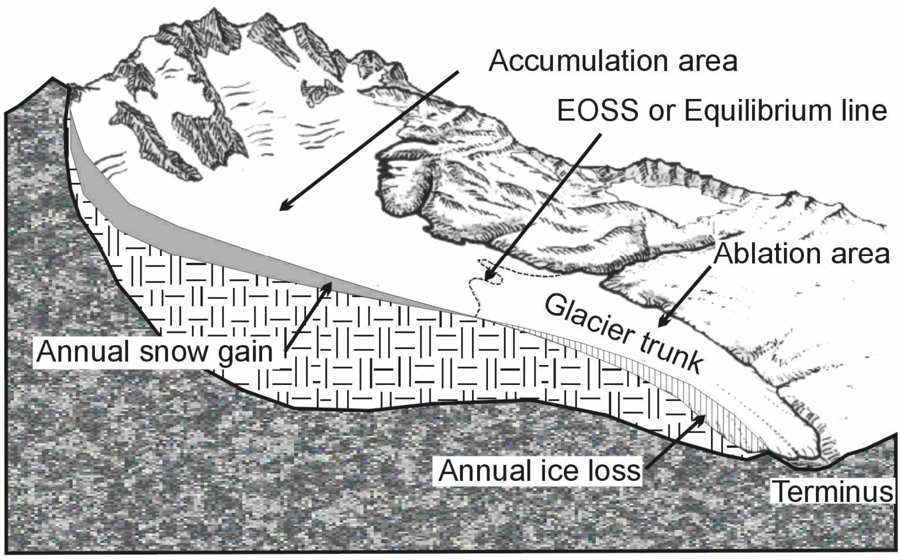

Figure 1. Basic parameters of a glacier showing the end of summer snow line (EOSS).

2. Methodology

2.1 Definition of measured parameter

After some discussions the working group agreed on the following parameters as appropriate indicators:

The annual total volume of ice of New Zealand, expressed in water equivalents (km^3).

Annual change in ice volume expressed in water equivalents (km^3) (with base year of 1978). The starting ice volume in 1994/1995 was determined by applying the current methodology to the 1978 New Zealand Glacier inventory.

Note that the conversion of an ice volume to a water equivalent (WE) volume is approximately 1 to 0.9.

The glacier data reported here are for changes in glacier volume over a glacier accounting year, which ends at the end of summer (e.g. end of March). This is the only time when glaciers can be observed separately from temporary snow. By the end of the water accounting year at the end of June some new snow will have fallen but the amount of glacier ice does not change significantly until the end of the following summer.

2.2 Method for establishing glacier volume in New Zealand

In 2002 the following methodology was used based on the measured data obtained from the index glacier monitoring since 1977, volume change (ΔV) (in WE) are to be calculated based on the following relationship:

$$\Delta V_{ti} = \frac{MBg_{ti}\left[A_{acc(ti)}(H\max_{ti} - EOSS_{ti}) - A_{ab(ti)}(EOSS_{ti} - H\min_{ti})\right]}{2}$$

Where:

$_t$ = years 1994-2002	Hmax = maximum elevation of glacier
i = index glacier	Hmin = minimum elevation of glacier
MBg = Mass balance gradient	EOSS = end of summer snowline altitude
A_{acc} = Area of accumulation	A_{abl} = Area of ablation

From mass balance monitoring on the Ivory and Tasman glaciers MBg was calculated to be 2.3 m/100m (western glaciers) and 1.1 m/100m (eastern glaciers).

Subsequent work has refined this methodology (Chinn et al, 2007).

For each index glacier, the change in volume for each glacier year is:

$$\Delta V_{it} = V_{acc} - V_{abl}$$

$$= [A_{acc} \text{ x } (H_{max} - EOSS).\ \delta b/\delta z_{\ acc}/2] - [A_{abl} \text{ x } (EOSS - H_{min}).\ \delta b/\delta z_{\ abl}/2]$$

(from above)

Then for each index glacier(i) the specific mass balance is calculated for each year (t) by dividing each volume change (ΔV_{it}) by the index glacier area (A_{it}).

$$b_{it} = \Delta V_{it} \ / \ A_{it}$$

The specific mass balance is then calculated for the whole of the Southern Alps as follows:

$$b_{itAlps} = 1/i \, \Sigma \, b_{it}$$

2.3 Extrapolating the index glacier volume changes throughout New Zealand

The annual glacier volume variations are extrapolated from the index glaciers to other glaciers of New Zealand using the value of glacier mean gain or loss (calculated above). Various studies have shown that EOSS for the Southern Alps tends to behave as a single regional entity in its response to annual climate variations (Lamont et al, 1999; Clare et al, 2002). Therefore, the product of a single depth term, which is the specific mass balance for the index glaciers obtained from the previous section, and the area of all glaciers in the glacier inventory, provide an estimate of total annual volume change. ΔV_{it} is summed cumulatively for all years for all glaciers. A total ice volume of 53.29 km^3 and an area of 1158.43 km^2 in 1978, as obtained for the glacier inventory, are taken as commencing values for these calculations for New Zealand.

Table 1: New Zealand glacier inventory (1978) ice volumes and areas by region (Chinn, 2001)

Region name	Regional glacier ice volume expressed as water equivalent (million m3)	Regional ice area (ha)	Regional glacier ice volume as fraction of NZ glacier volume
Auckland	0	0	0
Bay of Plenty	0	0	0
Canterbury	27532.33	41620	0.5166
Hawkes Bay	0	0	0
Manawatu-Wanganui	44.41	437.7	0.0008
Marlborough	6.84	224	0.0001
Nelson	0	0	0
Northland	0	0	0
Otago	3400	14673	0.0638
Southland	875.6	6549	0.0164
Taranaki	0	0	0
Tasman	0	0	0
Waikato	11.74	69	0.0002
Wellington	0	0	0
West Coast	21419.97	52270.3	0.4019
	53290.89	115843	

Ice area change is then the inventory ice area of New Zealand (A_a), less the area of the proglacial lakes (A_{gt}) – see below, for each glacier year (t). Regional volume analysis was completed using the regional ice areas in Table 1.

$$A_{at} = A_a - \Delta A_{gt}$$

Volume change for the Southern Alps for each glacier year (t) is calculated as:

$$\Delta V_t = A_{at}\, b_{it}$$

2.4 Accounting for longer term ice loss

In addition to annual climatic changes, there have been some significant additional ice volume losses due to the glaciers calving into expanding proglacial lakes, draw-down of the glacier trunk, and inherited recessions. These ice losses are accounted for separately for the Tasman, Hooker, Mueller, Classen, Maud, Grey, Godley, Ramsay, and Murchison Glaciers in the Canterbury region, the Therma and Volta Glaciers in the Otago region, and the Douglas Glacier in the Westland region.

a) The ice losses to lakes are calculated directly from the photographic record of lake growth and a number of bathymetric measurements. The ice volume lost to the growth of the proglacial lakes (V_l) for each glacier year (t) is derived from the product of the lake area (A_l) and the mean depth for each year (d).

$$\Delta V_{lt} = A_l\, d_{\ t}$$

b) Associated with lake expansion is the loss to draw-down effects of the glacier trunk levels. This volume (V_d) loss is calculated by the triangle method that uses the lake surface elevation (H_l), the equilibrium line elevation (ELA_{eq}), mean glacier width (W_g), and mean annual glacier length from the equilibrium line to the proglacial lake ice boundary (L_g). This approach assumes that the glacier's longitudinal profile has remained constant over the period and this may not be the case for the glaciers.

$$V_{dt} = (ELA_{eq} - H_l)W_g L_{gt}/2$$

c) Included with the draw-down loss are the losses from “inherited recession”. This is continuing loss from those larger glaciers with long-response times. By the time the mass balance reversals of this study commenced, these glaciers were still adjusting to the climate change from the cooler period at the end of the 19th century. Between then and the 1970s, temperatures have warmed by about 1°C. This type of loss has occurred by down wasting of the original convex parabolic trunk profiles to the 1970s near level or sag profiles. It is assumed that these losses are included in the draw-down calculations.

3. Validation of the method

Studies of the Ivory Glacier from 1969 to 1975 (Anderton and Chinn, 1978) provide the only published mass balance data available to check (Table 2). The glacier was mapped twice using controlled vertical aerial photography, in April 1971 and May 1975. Differences for the period between these two maps provide a 4-year volume loss of -11.782 x 10^6 m^3 water equivalent. Full annual mass balance measurements on this small glacier (0.8 km^2) for the same period give a calculated volume loss of -8.438 x 10^6 m^3. Using snowline elevations, again for the same period, and the methodology of section 3.1, gives a –9.783 x 10^6 m^3 volume change. This result is between the two estimates from field and photographic measurements.

Discrepancies among these three estimates are attributed to a variety of factors. The Ivory Glacier was far from equilibrium with the climate when the mass balance studies were made. For example, the stake measurements of the mass balance surveys do not take account of ice lost from calving into an enlarging pro-glacial lake and the ‘draw-down’ effect of increasing ice discharge into the lake. The estimates using aerial photography assume a firn/ice density of 0.85, a value that is possibly too large.

The values for the ELA_{eq} are assumed to be reasonable, being derived from averages of EOSS for the Southern Alps over 29 years. The glacier areas are also considered accurate, being based on repeated photography and NZMS 1:50,000 topographic maps.

Larger errors are likely from:

Use of incorrect or inappropriate estimates of $\delta b/\delta z$.

Poor estimates of proglacial lake volumes because of insufficient depth measurements

Not applying inherited recession to long response glaciers without lakes.

$EOSS_{alps}$ errors associated with choice of sample of index glaciers.

Table 2. Changes in Ivory glacier for period April 1969 to May 1975 (ELA_{eq} = 1510m, minimum elevation = 1389, maximum elevation = 1850).

	EOSS (m)	Glacier area (ha)	Accum. Area (ha)	Measured area-averaged net balance ,Bn (m w.e.)	Annual Volume change = Bn x area (m^3 w.e) .)	Mass balance calculated (m)	Volume change from calculated Bn x area (m^3)
1969-70	1640	79.81	15.57	-2.11	-1.684E+06	-2.34	-1.869E+06
1970-71	1610	79.81	24.71	-1.32	-1.053 E+06	-1.49	-1.188E+06
1971-72	1645	79.81	14.69	-1.66	-1.325E+06	-2.45	-1.956E+06
1972-73	1580	79.81	29.63	-1.73	-1.381E+06	-0.90	-7.204E+05
1973-74	1695	78.79	9.09	-3.48	-2.742E+06	-3.38	-2.660E+06
1974-75	1850	74.76	0.00	-4.00	-2.990E+06	-5.95	-4.446E+06
Mean (m)				**-2.38**		**-2.75**	
Total (m3)					**-7.438E+06**		**-1.284E+07**

4. Results

The annual index glacier survey results in a mean annual EOSS (end of summer snowline), which has ranged between 1661 m and 2049 m over the 1977 to 2005 period (Figure 2). Figure 2 gives the 95% confidence limits in the estimates of EOSS;

these range from as large as +/- 140 metres to as low as +/- 40 metres. These ranges correspond to an annual New Zealand ice volume change uncertainty of +/- 1.15 km^3 to +/- 0.23 km^3 for this period. It should be noted that these estimates of uncertainty relate to the scatter of the observations rather than uncertainties in the $\delta b/\delta z$ and the method.

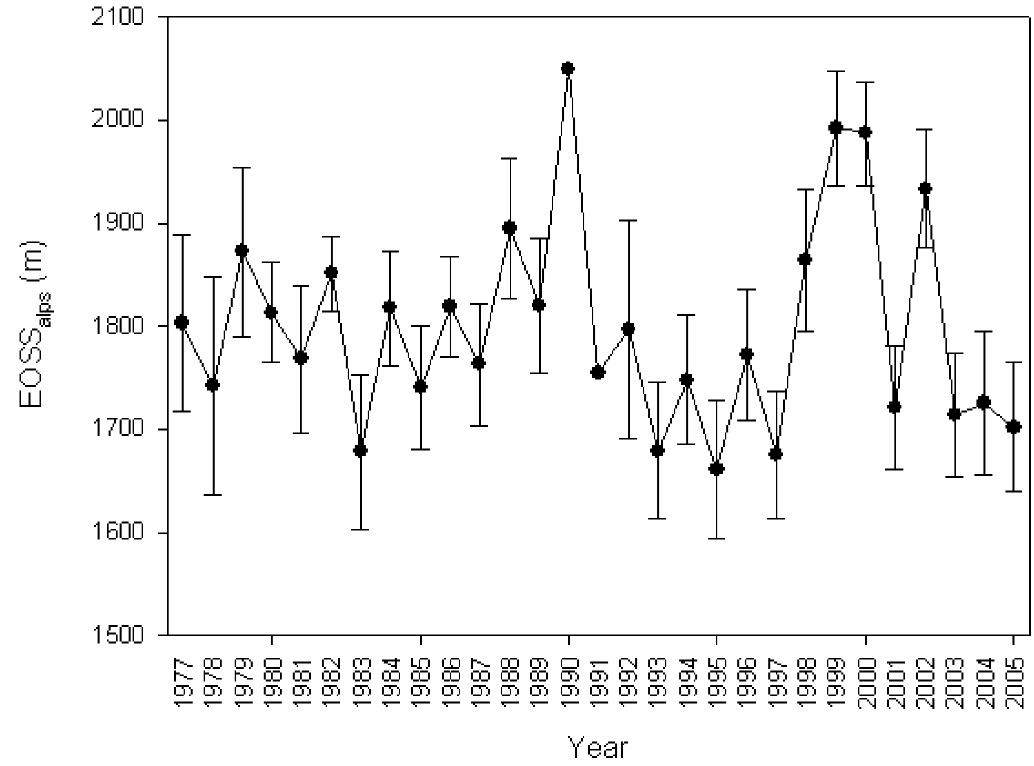

Figure 2. Changes in $EOSS_{Alps}$ from 1977 – 2005, with 95% confidence limits.

To permit regional accounting the 1978 New Zealand glacier inventory was subdivided by region using river basin number. The starting volumes and areas of each region are outlined in Table 1. The Canterbury, Westland and Otago regions contain 97 % of the starting ice volume, and the remaining areas are an extremely small fraction of the annual water accounts.

The annual change in ice volume for New Zealand is shown in Figure 3 for the years 1977/1978 to 2004/2005, from a starting volume of 53.29 km^3 in 1978 the volume had reached 52.26 km^3 at the first water accounting year of 1994/1995. By 2004/2005 the total volume had reduced to 45.10 km^3. The regional annual ice volume totals, and annual changes are listed separately in Appendix 1 and 2.

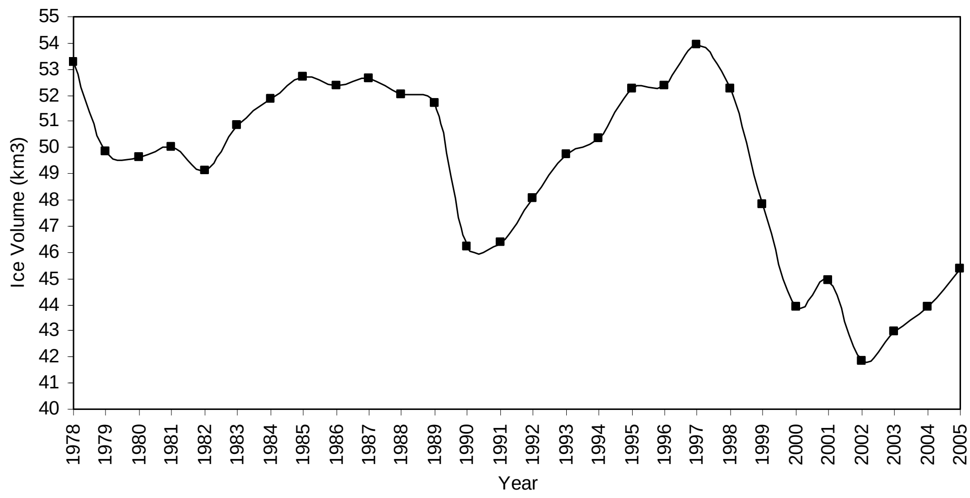

Figure 3. Total ice volume in New Zealand for 1978 to 2005.

Table 3. New Zealand Glacier Ice Volume changes from 1994/1995 to 2004/2005.

Glacier Year	Annual volume change from climate (km^3)	Annual volume change from proglacial lake growth (km^3)	Annual volume change from trunk draw down (km^3)	Total annual change from all sources (km^3)	Total ice volume (km^3)
1994/1995	2.19	-0.035	-0.263	1.888	52.26
1995/1996	0.39	-0.035	-0.263	0.087	52.35
1996/1997	1.86	-0.035	-0.263	1.563	53.92
1997/1998	-1.35	-0.035	-0.263	-1.653	52.27
1998/1999	-4.11	-0.035	-0.263	-4.407	47.86
1999/2000	-3.62	-0.035	-0.263	-3.919	43.94
2000/2001	1.30	-0.029	-0.263	1.005	44.95
2001/2002	-2.74	-0.119	-0.263	-3.118	41.84
2002/2003	1.52	-0.131	-0.256	1.136	42.97
2003/2004	1.35	-0.131	-0.256	0.962	43.94
2004/2005	1.66	-0.223	-0.256	1.180	45.10
Totals	-3.74	-0.81	-2.61	-7.16	-7.16

Table 3 shows annual volume changes from all sources. By far the largest changes annually are those due to mass balance changes from climate. However, apart from changes in annual mass balance, there have been steady and significant ice volume losses for the Tasman, Hooker, Mueller, Classen, Maud, Grey, Godley, Ramsay, Murchison, Therma, Volta, Douglas, and Ivory Glaciers from the growth of pro-glacial lakes, and glacier trunk draw-down. These are estimated as 0.81 km^3 and 2.61 km^3 respectively, and represent a loss of 3.42 km^3 of ice volume over 10 years, or 0.34 km^3/a. The largest fraction of this long term ice loss has occurred in the Canterbury region.

This compares with an accumulated loss of ice from mass balance (annual climate input) of 3.74km^3. Cumulative change of total ice volume has been from 52.26 km^3 in 1994/1995 to 45.10 km^3 by 2004/2005 (a loss of 14 percent).

The annual total ice volumes and annual ice volume change are presented by regional water accounting area in Appendices 1 and 2 respectively.

The changes in $EOSS_{Alps}$ and its inferred specific mass balance and calculated volume change for New Zealand are compared with climatic conditions over the period 1995-2005 in Table 4. These show the importance of anomalies of temperature and precipitation coupled with atmospheric circulation. Positive $EOSS_{Alps}$ and negative mass balance glacier years with reductions in glacier volume all occurred with above average alpine temperatures. Two of these years (1999/2000, 2001/2002) had below average regional precipitation, more anticyclones and anomalous easterly circulation. Another year (1998/1999), had anomalous northwesterly circulation, which gave above average precipitation, but much warmer temperatures (+0.7°C above the 1971-2000 average). Negative $EOSS_{Alps}$ and positive mass balance years with increases in ice volume normally occurred when cooler westerly and southwesterly circulation anomalies dominated, usually with above average precipitation. This was particularly so for glacier years 1992/1993, 1996/1997 and 2004/2005.

Table 4. Generalised climate for the period 1994/1995-2004/2005 in the Southern Alps and inferred mass balance, and glacier snow input in water equivalents.

Glacier Year	Generalised Climate	Inferred mass balance	Glacier snow input (volume km^3)
1994/1995	Stronger westerlies overall, especially from Apr-Aug, and Nov-Dec. Much above average precipitation, and temperatures 0.3℃ below normal.	High	2.19
1995/1996	Overall, more frequent northerly flow, with much above average precipitation as a result of westerlies or north westerlies in Mar, Sep and Dec. Temperatures 0.1℃ above average.	Average-high	0.39
1996/1997	Overall slightly more frequent westerly circulation, producing higher precipitation, especially in Apr and Oct. Temperatures 0.3℃ below average.	High	1.86
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	-1.35
1998/1999	Stronger westerly and northwesterly winds over New Zealand, temperatures 0.8℃ above average, with above normal precipitation on the West Coast.	Less	-4.11
1999/2000	Very anticyclonic, with weaker westerlies than normal. Temperatures 0.7 C above normal, and rainfall slightly below normal.	Less	-3.62
2000/2001	More northwesterlies over the South Island, temperatures 0.2 C above normal. Rainfall close to average.	Average-High	1.30
2001/2002	Higher than normal pressures and more easterlies over the South Island, temperatures 0.3°C above normal, well below average rainfall.	Less	-2.74
2002/2003	Persistent westerlies and southwesterlies over New Zealand. Cooler spring, rainfall slightly above average in the west and south.	Average-High	1.52
2003/2004	More cyclonic westerlies and south westerlies over the South Island from September.	Higher	1.35
2004/2005	Cool westerlies during autumn and early winter (temperatures 0.4℃ below normal), then strong cold cyclonic southwesterlies through to December (temperatures 0.6℃ below normal), precipi tation overall close to average	High	1.66

5. Discussion

Annual volume change calculated from $EOSS_{Alps}$ and specific mass balance show considerable variability. This is because snow accumulation and ablation are very much a result of variations in temperature, precipitation and airflow over the Southern Alps. Years of considerable negative mass balance are marked by either above average temperature anomalies, and/or reduced precipitation in the Southern Alps and increased easterly circulation. One negative year had increased precipitation. This occurred in a situation with anomalous warm north westerly circulation patterns, rain at higher elevations with less snowfall, but additional snowmelt. Years with positive mass balances have below average temperature anomalies and above average or average precipitation. Generally these are associated with periods of stronger westerly or southwesterly circulation over New Zealand. These often occur under El Nino/Southern Oscillation (ENSO) conditions in the tropical Pacific, which increase the strength of southwesterly circulation across New Zealand (Salinger and Mullan, 1999). These occurred in 1994/95, 1997/98, 2002/03 and 2004/05. Apart from 1997/98, volume increases occurred in the other ENSO years.

The results show a significant decrease in ice volume in New Zealand from 1994/1995 to 2004/2005, despite only a slightly negative mass balance averaged over this period. The majority of the ice volume loss is a consequence of growth of proglacial terminus lakes, ice calving, downwasting and retreat of glacier trunks of the largest glaciers and 86% of this has occurred in the Canterbury region. Ice volume over the monitoring period, as derived from $EOSS_{Alps}$ and estimates of mass balance, show some cumulative change, with a loss from this source of 1.56 km^3 from an estimated total volume of 52.26 km^3 in 1994/1995. Overall, there has been significant loss of total ice volume for the Southern Alps between 1994/1995 and 2004/2005 of 7.16 km^3, or 14%. This equates to about 0.7 km^3/a.

The larger glaciers are not in equilibrium with the current climate and are still responding to climatic warming of the 20th century. Regional temperatures increased 0.5°C to the 1950s (Salinger and Mullan, 1999), and there has been a further increase of 0.4°C to 2005 (NIWA, 2006). The total warming since instrumental records commenced in the 19th century amounts to about 1°C. The ablation areas of the larger glaciers, especially east of the Main Divide of the Southern Alps, have been adjusting to this warming by down wasting of their trunks, and rapid retreat of their termini as pro-glacial lakes developed, These observations agree with the conclusion of Anderson and Mackintosh (2006) that temperature change is the major driver of Holocene glacier fluctuations in New Zealand. In contrast, most of the smaller glaciers have adjusted to most of the 20th century warming. They have only had a slight volume loss in response to the temperature increase of 0.3°C since 1977, because warming was partially offset by regional precipitation increases (Salinger and Mullan, 1999).

6. Conclusions

Based on annual EOSS data from the 46 index glaciers, this report presents a practical method to estimate annual changes of glacier ice volume for New Zealand (measured in km^3 water equivalents). Measurements of EOSS are used to calculate annual mass balance. A critical parameter is the vertical gradient of mass balance. Two values are used – one for the accumulation area, and the other for the ablation area. With this information and the New Zealand glacier inventory, ice volume changes have been calculated for New Zealand for the period 1994/1995 to 2004/2005. When the method is applied to the Ivory Glacier, there is good agreement (within 10-15%) with the decrease in ice volume measured at the Ivory Glacier using two independent methods.

Mass balances derived from $EOSS_{Alps}$ data between 1994/1995 to 2004/2005 show large inter-annual variability. Many years show a positive mass balance, so that despite ongoing warming, mass balance for the whole period is only slightly negative. As a result, there has been little cumulative change in ice volume for New Zealand from this source. EOSS data and estimates of mass balance indicate a net loss of glacier volume of 3.74 km^3 from an initial estimated 52.26 km^3 in 1994/1995. This is 52 % of an estimated total ice volume loss of 7.16 km^3 between 1994/1995 and 2004/2005. The remainder (3.42 km^3) of this has come from calving into pro-glacial lakes and trunk down wasting of 13 of New Zealand's largest glaciers. Overall, there has been an ice loss for New Zealand of 14 between 1994/1995 and 2004/2005. This equates to 0.7 km^3/a, which is considerably less than the rate estimated for the previous 100 years.

Changes in estimates of mass balance are very much driven by changes in circulation as demonstrated previously (Fitzharris et al, 1997; Clare et al, 2002). Glacier years with higher than usual easterly circulations and above average regional temperatures had negative mass balances. Glacier years with stronger westerly or southwesterly circulations and below average regional temperature had positive mass balances. Precipitation could be average or above average in these circumstances.

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8. Appendices

Appendix 1 Total regional ice volume (millions of m^3) totals for the period 1994/1995 to 2004/2005. The glacier volume water accounting year starts and ends at an end of summer (April - March).

Ice Volume (millions of m3) Year	Auck-land	Bay of Plenty	Canter-bury	Hawkes Bay	Manawatu-Wanganui	Marl-borough	Nelson	North-land	Otago	South-land	Taranaki	Tasman	Waikato	Welling-ton	West Coast	New Zealand
1994/1995	**0**	**0**	**24599.55**	**0**	**61.26**	**15.46**	**0**	**0**	**3118.16**	**1127.57**	**0**	**0**	**14.39**	**0**	**23327.04**	**52263.43**
1995/1996	0	0	24485.94	0	62.73	16.21	0	0	3122.67	1149.46	0	0	14.63	0	23500.83	52352.47
1996/1997	0	0	24897.74	0	69.80	19.83	0	0	3315.16	1255.26	0	0	15.74	0	24344.30	53917.83
1997/1998	0	0	24164.86	0	64.65	17.19	0	0	3098.12	1178.27	0	0	14.93	0	23728.83	52266.85
1998/1999	0	0	22452.55	0	49.03	9.20	0	0	2530.20	944.68	0	0	12.47	0	21863.45	47861.59
1999/2000	0	0	20914.29	0	35.26	2.16	0	0	2024.36	738.79	0	0	10.30	0	20219.22	43944.38
2000/2001	0	0	21130.79	0	40.19	4.68	0	0	2145.12	812.57	0	0	11.08	0	20807.11	44951.54
2001/2002	0	0	19824.58	0	29.78	0.00	0	0	1751.79	656.89	0	0	9.44	0	19563.67	41836.16
2002/2003	0	0	20026.51	0	35.58	2.97	0	0	1901.48	743.59	0	0	10.35	0	20254.66	42975.14
2003/2004	0	0	20166.27	0	40.72	5.59	0	0	2029.06	820.41	0	0	11.16	0	20866.83	43940.04
2004/2005	**0**	**0**	**20100.00**	**0**	**47.04**	**8.83**	**0**	**0**	**2196.36**	**914.97**	**0**	**0**	**12.15**	**0**	**21845.85**	**45125.21**

Appendix 2 Annual regional ice volume (millions of m^3) change for the period 1994/1995 to 2004/2005. The glacier volume water accounting year starts and ends at an end of summer (April - March).

Annual change in ice volume (millions of m3) Year	Auck-land	Bay of Plenty	Canter-bury	Hawkes Bay	Manawatu-Wanganui	Marl-borough	Nelson	North-land	Otago	South-land	Taranaki	Tasman	Waikato	Welling-ton	West Coast	New Zealand
1994/1995	**0**	**0**	**528.04**	**0**	**1.31**	**4.25**	**0**	**0**	**233.64**	**124.16**	**0**	**0**	**1.31**	**0**	**990.02**	**1882.73**
1995/1996	0	0	-113.61	0	0.23	0.75	0	0	4.51	21.90	0	0	0.23	0	173.79	87.80
1996/1997	0	0	411.79	0	1.11	3.62	0	0	192.50	105.80	0	0	1.11	0	843.46	1559.40
1997/1998	0	0	-732.88	0	-0.81	-2.63	0	0	-217.05	-76.99	0	0	-0.81	0	-615.47	-1646.64
1998/1999	0	0	-1712.31	0	-2.46	-7.99	0	0	-567.92	-233.60	0	0	-2.46	0	-1865.37	-4392.10
1999/2000	0	0	-1538.27	0	-2.17	-7.04	0	0	-505.84	-205.89	0	0	-2.17	0	-1644.23	-3905.61
2000/2001	0	0	216.51	0	0.78	2.52	0	0	120.75	73.78	0	0	0.78	0	587.89	1003.01
2001/2002	0	0	-1306.21	0	-1.64	-4.68	0	0	-393.33	-155.67	0	0	-1.64	0	-1243.44	-3106.61
2002/2003	0	0	201.93	0	0.91	2.97	0	0	149.69	86.70	0	0	0.91	0	690.98	1134.09
2003/2004	0	0	139.76	0	0.81	2.63	0	0	127.57	76.82	0	0	0.81	0	612.18	960.58
2004/2005	**0**	**0**	**66.27**	**0**	**1.00**	**3.23**	**0**	**0**	**167.31**	**94.56**	**0**	**0**	**1.00**	**0**	**979.02**	**1312.38**