Annual glacier ice volumes, 1977-2016

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Contents

Tables

Figures

Executive summary

The Ministry for the Environment requires updated estimates of the glacier ice volume change in New Zealand. Earlier estimates were provided ending in March 2014 and this report extends the estimates to March 2016, and recalculates ice volume change from the starting values in 1977.

Glacier ice volumes originate 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 50 index glaciers for determining the annual mass balance of glacier ice, and geodetic survey information for 12 large low angle debris covered glaciers.

The two methods used in this report are applied separately due to the differing response of the 12 large glaciers which are losing ice mass steadily due to down-wasting of their trunks and the growth of proglacial lakes. The remaining glaciers in New Zealand have an annual net mass balance value applied to their respective areas. This annual net mass balance is calculated using mass balance gradient data measured at the Brewster Glacier applied to the height of the respective snowlines at each individual index glacier. An annual volume change is derived for each index glacier and from this an annual average net mass balance.

This report differs from earlier reports by using a longer more recent set of measured mass balance gradient data from the Brewster Glacier rather than data from 1965 to 1975 from the Ivory and Tasman Glaciers.

From an initial volume estimate of 54.02 km^3 in 1977 the volume reached a maximum of 56.21 km^3 in 1997 (an increase of four per cent). Volumes then began a general declining trend from 1998 with only a slight rise between 2002 and 2005, followed by near continuous decline in ice volume to 2016. By 2016 the total ice volume is 40.72 km^3. This represents a total loss of 13.29 km^3 (a 24 per cent decrease) from the starting volume at an average rate of -0.34 km^3a^{-1}.

There has been an overall ice loss due to mass balance from climate of 5.59 km^3 (10 per cent of the total decrease) over the period 1977 to 2016. The 12 large low angle debris covered glaciers have lost 7.7 km^3 of ice (14 per cent of the total decrease) to proglacial lake growth and trunk down-wasting.

1 Introduction

The National Institute of Water and Atmospheric Research Ltd (NIWA) has been commissioned by the Ministry for the Environment to update the glacier ice volume change in New Zealand from the previous accounts ending in 2014. To do this we have re-run the ice volume change calculation from 1977 to 2016 using the Chinn (2012) model. This glacier ice volume change component was included in four previous reports on surface water information: Woods and Henderson (2003), Henderson et al. (2007), Henderson et al. (2011), Willsman (2011), and Collins et al. (2015). This information is intended for use by the Ministry for the Environment for environmental reporting and climate change analysis.

2 Methodology

2.1 Definition of measured parameter

The annual total volume of ice in New Zealand is expressed in this report (Appendix A) in water equivalents, using the units of km^3 for figures, and for tables.

This report, as the does the previous reports, uses 0.9 to convert an ice volume to a water equivalent volume.

The starting ice volume for these calculations was determined by applying the current methodology to the 1978 New Zealand Glacier inventory (Chinn, 2001).

The glacier ice volumes are presented as a total volume for New Zealand rather than regional tables as specified in some earlier water accounting reports for Statistics New Zealand (Collins et al. 2015). This is due to the difficulty in applying the model to some of the very small ice areas and volumes in some of the regional areas.

Each glacial ice year runs from 1 April to 31 March, and is referred to by the year at the end of the period (e.g., the 2016 year runs from 1 April 2015 to 31 March 2016). This is the only time when glaciers can be observed separately from temporary snow.

2.2 Method for establishing glacier volume in New Zealand

The methodology for estimating ice volume change was developed by Chinn et al. in 2007, and was first used in a water accounting report in 2007 (Willsman et al. 2007). This methodology was subsequently published in 2012 (Chinn et al. 2012)

This methodology utilises the long, continuous record of annual end-of-summer-snowline measurements for a set of Southern Alps 'index glaciers' from 1977 to present. 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 (Figure 2-1).

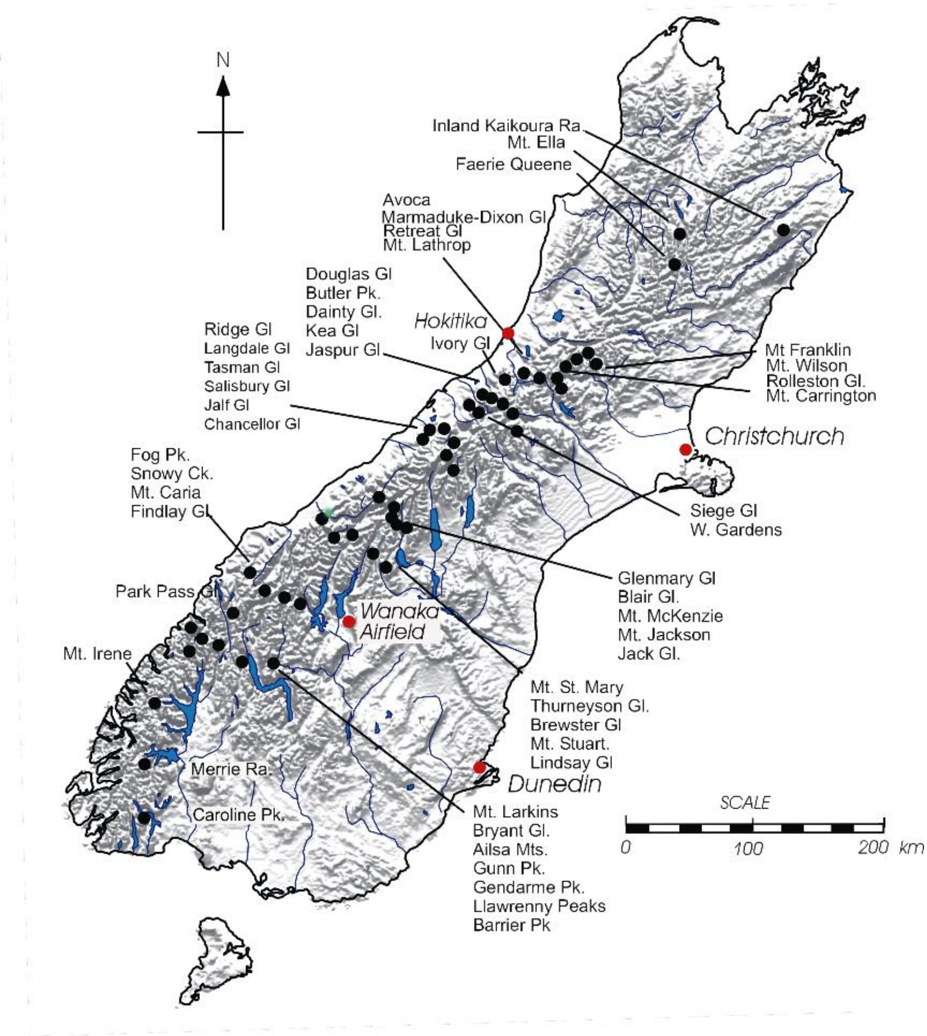

Figure 2-1: Map of the South Island showing the index glaciers.

The end of summer snowline level, referred to as the End of Summer Snowline (EOSS), indicates the previous glacial season of snow accumulation (Figure 2-2). 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, then the glacier is in retreat. Conversely if the long term EOSS is trending downward in elevation then the glacier is in a state of accumulation. Every season is defined relative to the long term EOSS as either negative (base height of accumulated previous season's snow level is high) or positive (if snow level is low).

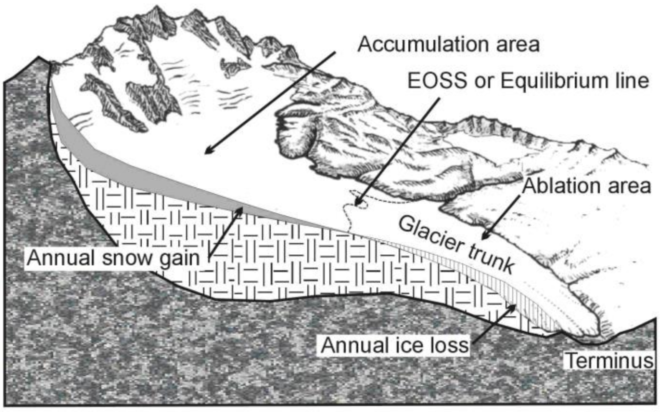

Figure 2-2: Basic parameters of a glacier showing the end of summer snowline (EOSS).

Index glacier data is updated and reported annually as a NIWA client report and the data for the period 1977 to 2016 is from the 2016 snowline annual report (Willsman, Chinn, Macara, 2017). Data from this index glacier report is used to estimate equilibrium line altitudes, annual mass balance and volume water equivalent changes for the over 3000 glaciers of the Southern Alps.

Two methods are employed to calculate ice volume changes.

Method One deals mostly with small and medium sized glaciers. It uses changes in snowlines, EOSS and mass balance gradients to calculate an annual ice volume change for each index glacier in water equivalent. This annual volume change is then divided by the respective index glacier area to derive an annual net balance, and then the index glacier balances for the year are averaged to derive an average annual net balance in metres of water equivalent. This annual net balance is then applied to the areas of the remaining glaciers (excluding the 12 large debris covered) to derive an annual volume change. This annual volume change is applied to the starting volumes from the 1978 New Zealand glacier inventory.

Annual net balance from the snowline data was derived using the Chinn (2012) method with both the original mass balance gradient values measured at the Ivory and Tasman Glaciers during the years 1965 to 1975, and recent mass balance gradient data from field and remote sensing measurements conducted on the Brewster Glacier over the period 2000 to 2015 (Cullen et al. 2016). Figure 2-3, indicates that the original mass balance gradient parameters used in the 2012 method calculations considerably overestimate the annual net balance compared to the Brewster Glacier measurements during negative balance ice loss years such as 2002, 2011, and 2012. A further comparison with ice volume change in a large area of the central Southern Alps made using a climate base model by Mackintosh et al. (2016) indicated that the scale of volume change calculated using the original 2012 mass balance gradients were greater than expected (Section 4 Validation). For these reasons the averaged Brewster Glacier mass balance gradient data (accumulation rate 7.4 mm/100m, and an ablation rate 14.5mm/m) was used for the annual net balance inputs to the model in this report.

Due to the change in the mass balance gradient parameters used for the calculations the entire data set from 1977 to 2016 was re run.

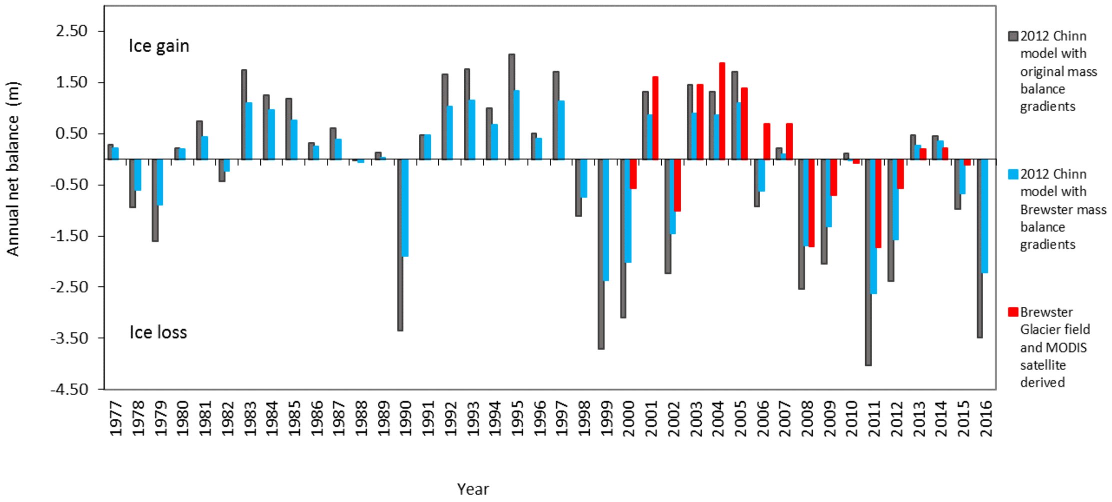

Figure 2-3: Annual net balance (water equivalent metres) for the period 1977 to 2016. Original mass balance gradient Chinn model result (grey), Chinn model output using Brewster data (blue), and measured balance (red) from the Brewster Glacier (direct field 2005 to 2016, and MODIS satellite image derived 2000 to 2004).

Method Two deals with the 12 largest debris covered valley glaciers in the Southern Alps (Table 2-1) and uses a geodetic approach based on topographic and pro-glacial lake changes determined from repeated surveys. These glaciers have substantial ice losses that are not able to be detected using Method One as these large glaciers are still adjusting to 20th century warming. They retain a surface area much greater than that conformable with an equilibrium state under present climate conditions. Ice loss calculations for these glaciers consider two processes. The first is “down-wasting” defined here as the net lowering of the surface profile by normal ablation and ice flow. The down-wasting rates (Table 2-1) were determined for the period 1977 to 2008 (Chinn et al. 2012) and these rates are assumed to have remained constant for this calculation to extend volumes to 2016. The second incorporates the development since the 1970s of pro-glacial lakes and the combined ice volumes lost to ice calving into the lakes.

Pro-glacial lake growth and ice margin recession at the glacier terminus is calculated directly from photographic records of lake growth that have been documented since 1980 (Chinn, 2002) and from bathymetric measurements and calculations (Warren and Kirkbride, 1998; Röhl,2006; Hochstein et al., 1998). Detailed rates of ice calving into lakes are also available for the Hooker and Tasman Glaciers (Kirkbride, 1993; Kirkbride and Warren, 1999; Hochstein et al., 1995; Hochstein et al., 1998; Purdie and Fitzharris, 1999; Kääb, 2002; Röhl, 2006; Purdie et al. 2016).

Integration of Method Two with Method One is difficult, but is largely accommodated by assuming that the latter calculation produces a near zero cumulative mass balance change between the beginning and end of the study period. Both methods are described in detail in Chinn et al. (2012).

Table 2-1: The 12 large protracted response glaciers with estimates of ice volume losses (w.e.) by down-wasting for the period 1977 – 2008 (Chinn et al. 2012). Under Methods column, key is as follows:

a = Central flow line (CFL) altitude change between aerial photograph map contours (APMC) in 1964 and 1986. Surface lowering (Δh) applied to ~1 km subsections from glacier terminus to altitude of ELA_0, thence from ELA_0 to top (Hmax) treated as zero change.

b = CFL change from 1986 APMC and 2007 GPS elevation survey to ELA_0, applied as in method a.

c = Method a with ~2 km subsections of tongue to ELA_0.

d = CFL change from 1986 APMC to 2007 GPS survey on lower 2km of the glacier, applied to 1km subsections of the glacier to the altitude of ELA_0, elevation change estimated above the 2007 GPS survey by proportionally lowering the 1986 CFL profile.

e = Lower glacier (2-3 km to terminus) CFL change from 1964 to 1986 from APMC single average from zero at ELA_0 to terminus, applied to glacier area.

f = 1986 altitude from Method e and estimated 2007 altitude from 1986 lake height and aerial photograph estimate of the cliff height, single average from zero at ELA_0 to terminus, applied to the area of the glacier.

g = 1986 to 2007 assumed the previous periods rate, as terminus has retreated out of a pro-glacial lake, oblique aerial photographs show down-wasting continuing.

All 2007 values were measured in April from a GPS survey using a Trimble 5700 RTK receiver and base using NZGD2000 datum, NZTM projection, corrected to Mt John, NZ reference station (Geodetic code MTJO), and heights transformed to MSL using the NZVD05 geoid model. A GPS elevation check with geodetic mark A9A1 at Mt Cook airport was <0.2 m from the orthometric (MSL) height. Map elevation sources refer to 1964 NZMS1 series, 1986 Topomap series, as published by Land Information New Zealand (LINZ).

Glacier Name	Period	Down-wasting Ice Volume loss(km3)	Down-wasting Ice Volume loss (w.e. km3)	CFL terminus vertical rate (m/yr) averaged over lower (km) of glacier	Methodology	Estimated Ice Volume loss 1977 - 2008 (km3)	Estimated Ice Volume loss 1977 - 2008 (w.e. km3)	Large glacier count
Tasman	1964 - 1986	1.46	1.3	-1.9 m/yr over 9 km	a			
	1986 - 2007	1.24	1.1	-2.1 m/yr over 9 km	b	1.96	1.74	1
Godley	1964 - 1986	0.99	0.88	-3.5 m/yr over 4 km	a			
	1986 - 2007	0.64	0.57	-3.9 m/yr over 4 km	b	1.12	1	2
Murchison	1964 - 1986	0.59	0.53	-1.7 m/yr over 10 km	a			
	1986 - 2007	0.79	0.7	-2.5 m/yr over 10 km	b	1.11	0.99	3
Classen	1964 - 1986	0.19	0.17	-1.0 m/yr over 3 km	a			
	1986 - 2007	0.28	0.25	-1.9 m/yr over 3 km	b	0.39	0.35	4
Mueller	1964 - 1986	0.23	0.2	-1.3 m/yr over 2 km	c			
	1986 - 2007	0.22	0.2	-1.4 m/yr over 2 km	d	0.33	0.27	5
Hooker	1964 - 1986	0.11	0.1	-0.9 m/yr over 2 km	c			
	1986 - 2007	0.14	0.12	-1.5 m/yr over 2 km	d	0.2	0.18	6
Ramsay	1964 - 1986	0.15	0.13	-1.5 m/yr over 2 km	e			
	1986 - 2007	0.12	0.11	-1.2 m/yr over 1 km	f	0.19	0.17	7
Volta/ Therma	1964 - 1986	0.1	0.09	-0.7 m/yr over 4 km	e			
	1986 - 2007	0.1	0.09	-0.7 m/yr over 4 km	g	0.15	0.15	8
La Perouse	1964 - 1986	0.13	0.12	-1.2 m/yr over 3 km	e			
	1986 - 2007	0.07	0.06	-0.71 m/yr over 1 km	f	0.13	0.12	9
Balfour	1964 - 1986	0.08	0.07	-1.5 m/yr over 2 km	e			
	1986 - 2007	0.08	0.07	-1.5 m/yr over 2 km	g	0.12	0.11	10

Glacier Name	Period	Down-wasting Ice Volume loss(km3)	Down-wasting Ice Volume loss (w.e. km3)	CFL terminus vertical rate (m/yr) averaged over lower (km) of glacier	Methodology	Estimated Ice Volume loss 1977 - 2008 (km3)	Estimated Ice Volume loss 1977 - 2008 (w.e. km3)	Large glacier count
Grey	1964 - 1986	0.07	0.06	-1.8 m/yr over 2 km	e			
	1986 - 2007	0.08	0.07	-1.0 m/yr over 1 km	d	0.12	0.11	11
Maud	1964 - 1986	0.05	0.04	-1.2 m/yr over 2 km	e			
	1986 - 2007	0.02	0.02	-0.7 m/yr over 1 km	d	0.05	0.04	12
					Total 1978 - 2008	5.87	5.22	

3 Results

The annual index glacier survey results in a mean annual EOSS, which has ranged between 1704 m and 2024 m over the 1977 to 2016 period of the snowline flights (Figure 3-1). A year with a high snowline indicates loss of snow and ice on the glaciers, conversely a year with a low snowline elevation equates to an annual gain of snow and ice. From 1977 to 2005 the annual snowlines have trended near or below average except for a higher snowline in 1990. A period of higher average snowlines occurred between 1998 and 2002, followed by three years of lower than average snowlines from 2003 to 2005. The last 10 years from 2006 to 2016 have snowlines that have trended high indicating loss of snow and ice in most years.

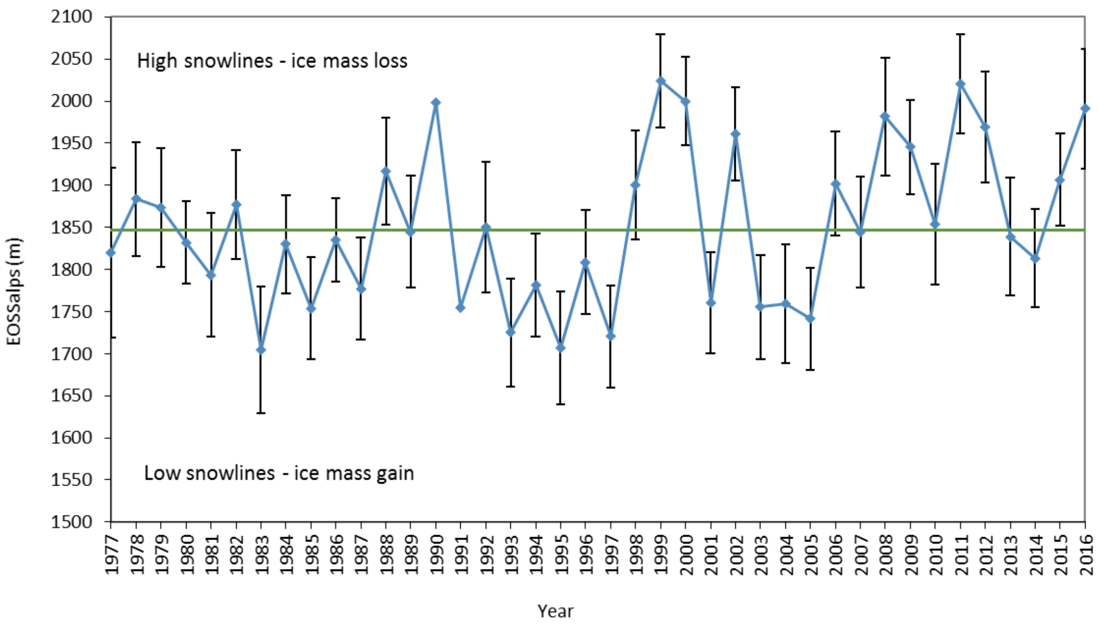

Figure 3-1: Mean end of summer snowline elevation for the period 1977 to 2016, with 95 per cent confidence limits. Note 1990 and 1991 only have one and two observations respectively. The green line denotes the average end of summer snowline elevation for the period 1977 to 2016.

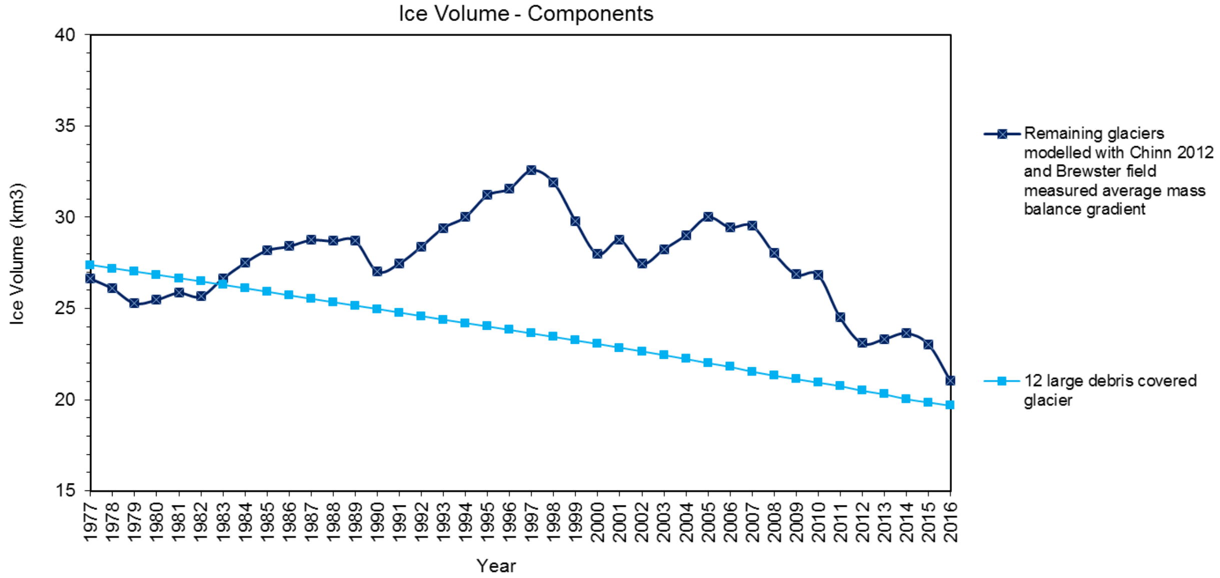

Figure 3-2: Annual ice volume (km3) components for the period 1977 to 2016. Method One uses a mass balance model to calculate volume change (dark blue line), and a geodetic model is used to calculate volume change at 12 large glaciers (light blue).

The two components of ice volume calculation are shown in Figure 3-2. The remaining glaciers have a starting volume of 26.64 km^3 in 1977 and have varying volume changes from year to year as the mass balance model is applied. An overall increasing trend in the volume occurs from 1977 to a maximum of 32.58 km^3 at 1997, then a decreasing trend from 1998 to 2002. From 2005 to 2016 the trend has been negative with the volume decreasing to 21.05 km^3. By 2016 the volume lost is 5.59 km^3 from the starting volume which equates to an average of 6.2 m of ice over the area of these glaciers.

The 12 large debris covered glaciers have a starting volume of 27.38 km^3 in 1977 decreasing to 20.05 km^3 in 2016, the rate appears uniform as a result of averaging of the rates of down-wasting, and proglacial lake change over this period from the periodic geodetic surveys. This loss of 7.7 km^3 equates to an average of 31 m of ice over the 245 km^2 area covered by these glaciers.

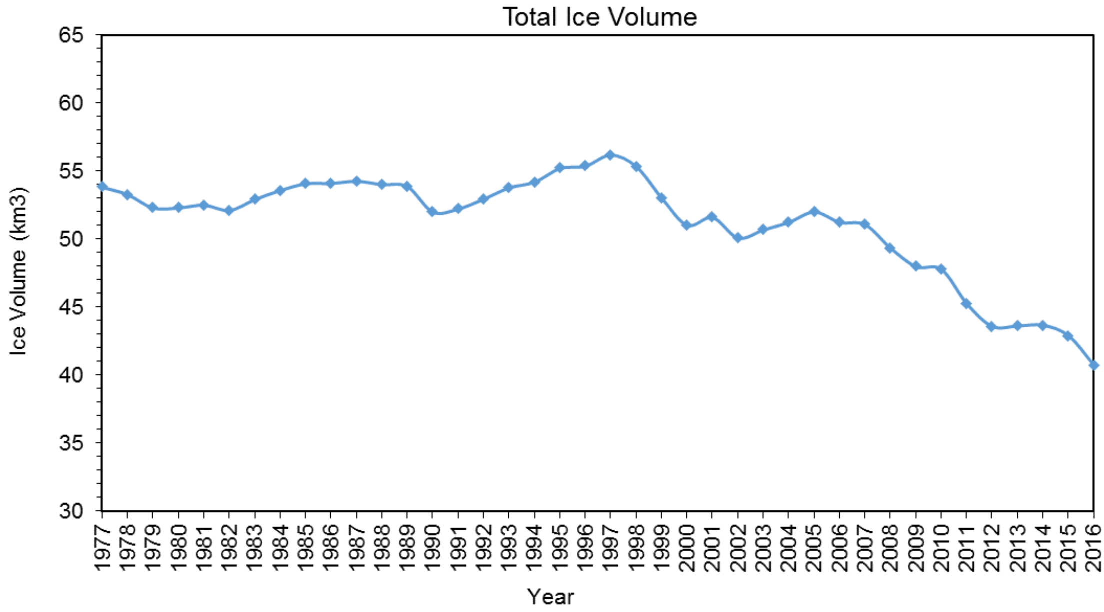

Figure 3-3: Annual ice volume (km3) for the period 1977 to 2016. Combined ice volumes from the 12 large debris covered glaciers and the remaining glaciers in New Zealand.

The total annual change in ice volume for New Zealand is shown in Figure 3-3 for the years 1977 to 2016, from a starting volume of 54.02 km^3 in 1977 the volume reached a maximum of 56.21 km^3 in 1997. A general declining trend began from 1998 with only a slight rise between 2002 and 2005, followed by near continuous decline in ice volume to 2016. By 2016 the total ice volume is 40.72 km^3. This represents a total loss of 13.29 km^3 from the starting volume at an average rate of -0.34 km^3a^{-1}.

4 Validation

The two methods used to calculate volume change require numerous assumptions, so assessment of errors is not straightforward. There are errors associated with the EOSS survey. The length of the ablation season can vary considerably, but for practical reasons, the survey is carried out in March. In some years snowlines can be obscured on glaciers and surrounding snow patches are used to estimate the altitude of the snow line. Details of these procedures and likely errors are discussed in Chinn et al. (2005). Errors from deriving the ELA can correspond to an uncertainty in annual ice volume change of 0.23 to 1.15 km^3 water equivalent.

Other errors are likely from:

(1) Estimates of mass balance gradient. The values used in this report are from single values from the Brewster glacier and these produced a volume change result that was significantly less than the previous differentiated higher mass balance gradients used on the “wetter” and “drier” index glaciers (Chinn et al. 2012). Using the Brewster glacier data and not differentiating the index glaciers resulted in a method one mass balance volume calculation that was 20 per cent greater by 2016 (Figure 4-1).

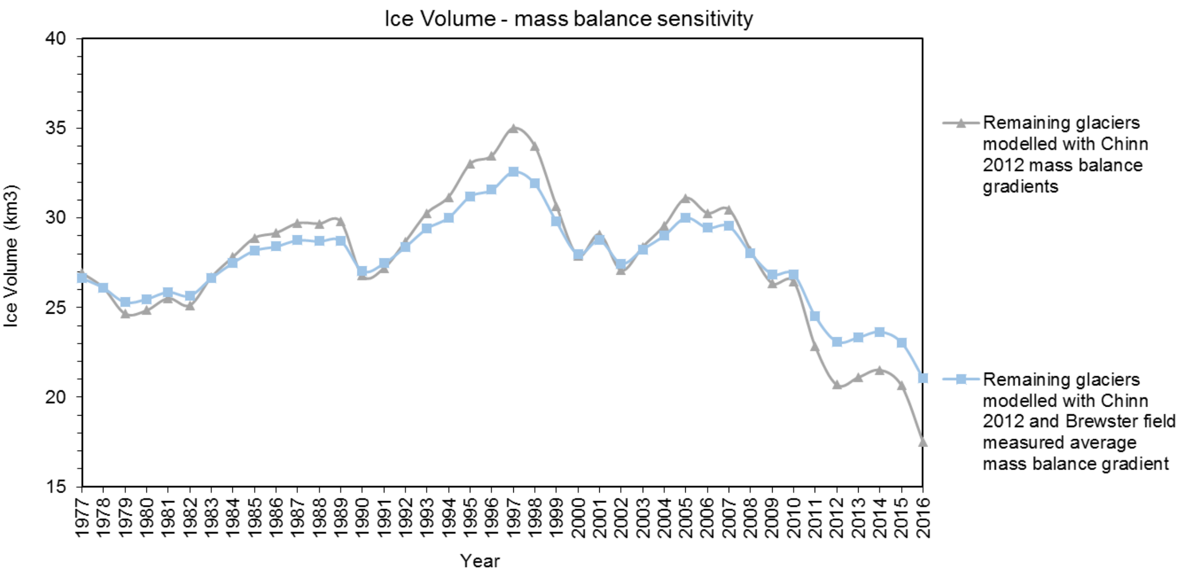

Figure 4-1: Sensitivity of the annual ice volume calculation on the remaining small to medium glaciers for the period 1977 to 2016. Grey line uses the mass balance gradients from studies on the Tasman and Ivory glaciers from the 1965 to 1975 (Chinn 2012). The blue line represents the volume change using the Brewster Glacier averaged mass balance gradient data as used in this report.

2) Estimates of pro-glacial lake volumes because of insufficient bathymetric measurements. Volume errors from this source are likely to be less than +/-10 per cent.

3) Estimates of topographic change at the 12 large glaciers as the last geodetic survey data was from 2007 and the rates of change are assumed to be constant from this. Volume errors from this source are likely to be +/-10 per cent. New satellite imagery is available for development of digital elevation models and further geodetic work in the future will better define the ice volume change in these large glaciers.

4) Glacier area for the mass balance calculation is assumed to be constant for the method one mass balance calculation. This is unlikely as annual survey photographs and mapping of the 50 index glaciers shows that all the glaciers have lost area and thinned since 2005. This implies that the glacial ice area for the entire southern alps has shrunk. This error is likely to result in overestimation of the change particularly since 2005.

5) Other smaller errors in the EOSS derivation method are noted in Chinn (2012) and these are likely to add uncertainty of +/-10 per cent.

A glacier mass balance simulation was run for a large area of the central Southern Alps using a climate base model by Mackintosh et al. (2016). This region contains approximately one-third of New Zealand's ice-covered area, and two-thirds of its volume. This model simulated increases of up to 0.5 km^3 in a year such as 1995 when the snowlines were low, and losses in volume of up to -0.7 km^3 during large negative ice loss years such as 2001. The mass balance model used in this calculation derived a gain of 1.2 km^3 for 1995, and a loss of -1.3 km^3 for 2001. There is a difference in the scale of the change during years with larger annual changes.

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Appendix A Annual Ice Volume change

Table A-1: Annual ice volume change from 1977 to 2016 . A mass balance and snowline altitude model has been used for 868 km2 of glacial ice (Method One - indicated by grey shaded column). Geodetic information has been used to calculate volume change at 12 large debris covered glaciers (Method Two - blue shaded).

Year	Area remaining glaciers (km2)	Annual net balance (m). Chinn Index glacier model using Brewster MBG data	Annual volume change remaining glaciers (km3)	Volume remaining glaciers (km3)	Area 12 large debris covered glaciers (km2)	Annual volume change from ice loss to proglacial lakes (km3)	Annual volume change from trunk downwasting at 12 large debris covered glaciers (km3)	Volume 12 large debris covered glaciers (km3)	All glaciers total volume (km3)
	Mass balance Method (1)	Mass balance Method (1)	Mass balance Method (1)	Mass balance Method (1)	Geodetic Method (2)	Geodetic Method (2)	Geodetic Method (2)	Geodetic Method (2)	
1976/1977				26.64				27.38	54.02
1977/1978	898.07	-0.61	-0.55	26.09	260.36	-0.012	-0.169	27.20	53.29
1978/1979	898.08	-0.90	-0.80	25.29	260.15	-0.009	-0.170	27.02	52.31
1979/1980	898.08	0.20	0.18	25.47	259.95	-0.009	-0.170	26.84	52.31
1980/1981	898.08	0.43	0.39	25.86	259.77	-0.011	-0.170	26.66	52.52
1981/1982	898.08	-0.23	-0.21	25.65	259.04	-0.011	-0.170	26.48	52.13
1982/1983	898.08	1.10	0.99	26.64	258.73	-0.017	-0.170	26.29	52.93
1983/1984	898.08	0.95	0.86	27.50	258.46	-0.018	-0.170	26.10	53.60
1984/1985	898.08	0.76	0.68	28.18	258.23	-0.020	-0.170	25.91	54.09
1985/1986	898.08	0.25	0.23	28.40	257.49	-0.021	-0.179	25.71	54.12
1986/1987	898.08	0.39	0.35	28.75	257.17	-0.024	-0.163	25.52	54.28
1987/1988	898.08	-0.06	-0.05	28.70	256.84	-0.025	-0.163	25.34	54.03
1988/1989	898.08	0.04	0.03	28.73	256.48	-0.021	-0.163	25.15	53.88
1989/1990	898.08	-1.88	-1.69	27.04	256.01	-0.021	-0.163	24.97	52.01
1990/1991	898.08	0.47	0.42	27.46	255.70	-0.033	-0.163	24.77	52.23
1991/1992	898.08	1.03	0.93	28.39	255.39	-0.032	-0.163	24.58	52.96
1992/1993	898.08	1.15	1.03	29.42	255.09	-0.032	-0.163	24.38	53.80
1993/1994	898.08	0.67	0.60	30.02	254.71	-0.019	-0.163	24.20	54.21
1994/1995	898.08	1.33	1.19	31.21	254.35	-0.023	-0.163	24.01	55.22
1995/1996	898.08	0.40	0.36	31.57	254.09	-0.027	-0.163	23.82	55.39
1996/1997	898.08	1.13	1.01	32.58	253.83	-0.029	-0.163	23.63	56.21
1997/1998	898.08	-0.74	-0.66	31.92	253.57	-0.028	-0.163	23.44	55.36
1998/1999	898.08	-2.37	-2.13	29.79	253.32	-0.030	-0.163	23.25	53.04
1999/2000	898.08	-2.01	-1.81	27.99	253.03	-0.029	-0.163	23.05	51.04
2000/2001	898.08	0.86	0.77	28.76	252.60	-0.041	-0.163	22.85	51.61
2001/2002	898.08	-1.45	-1.30	27.45	252.13	-0.039	-0.163	22.65	50.10

Year	Area remaining glaciers (km2)	Annual net balance (m). Chinn Index glacier model using Brewster MBG data	Annual volume change remaining glaciers (km3)	Volume remaining glaciers (km3)	Area 12 large debris covered glaciers (km2)	Annual volume change from ice loss to proglacial lakes (km3)	Annual volume change from trunk downwasting at 12 large debris covered glaciers (km3)	Volume 12 large debris covered glaciers (km3)	All glaciers total volume (km3)
2002/2003	898.08	0.89	0.80	28.25	251.60	-0.041	-0.163	22.44	50.69
2003/2004	898.08	0.86	0.77	29.02	250.97	-0.050	-0.163	22.23	51.25
2004/2005	898.08	1.10	0.99	30.01	250.17	-0.064	-0.163	22.00	52.02
2005/2006	898.08	-0.62	-0.56	29.45	249.67	-0.041	-0.163	21.80	51.25
2006/2007	898.08	0.10	0.09	29.54	248.48	-0.101	-0.163	21.54	51.08
2007/2008	898.08	-1.68	-1.51	28.03	247.98	-0.053	-0.163	21.32	49.35
2008/2009	898.08	-1.31	-1.17	26.86	247.79	-0.028	-0.163	21.13	47.99
2009/2010	898.08	-0.01	-0.01	26.85	247.60	-0.028	-0.163	20.94	47.79
2010/2011	898.08	-2.61	-2.35	24.50	247.26	-0.03	-0.16	20.75	45.25
2011/2012	898.08	-1.57	-1.41	23.09	246.96	-0.09	-0.16	20.49	43.58
2012/2013	898.08	0.26	0.23	23.33	246.58	-0.03	-0.16	20.30	43.62
2013/2014	898.08	0.35	0.32	23.64	246.21	-0.11	-0.16	20.03	43.67
2014/2015	898.08	-0.67	-0.61	23.04	245.83	-0.01	-0.16	19.86	42.89
2015/2016	898.08	-2.21	-1.99	21.05	245.53	-0.02	-0.16	19.67	40.72
Sum		-6.23	-5.59	-5.59		-1.28	-6.43	-7.70	-13.29