NIWA
Taihoro Nukurangi

New Zealand Glacier Ice Volume 1978-2023

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Prepared by:
Gregor Macara
Andrew Lorrey

For any information regarding this report please contact:

Gregor Macara
Climate Scientist
Climate Data and Applications
+64 4 386 0509
gregor.macara@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Private Bag 14901
Kilbirnie
Wellington 6241

Phone +64 4 386 0300

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[signature]	Reviewed by:	Christian Zammit
[signature]	Formatting checked by:	Jess Moffat
[signature]	Approved for release by:	Alison MacDiarmid

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Executive summary

The Ministry for the Environment (MfE) and Stats NZ Tatauranga Aotearoa (StatsNZ) are required to report on the state of the environment using a pressure-state-impact framework, by the Environmental Reporting Act 2015. State of the environment reports and national indicators are produced by the joint Environmental Reporting Programme. These indicators are now being updated from the 2020 version, using the latest 2023 data available for New Zealand and following established methods. Here, the National Institute of Water and Atmospheric Research (NIWA) provides annual glacier ice volume for the period 1978-2023.

New Zealand glacier ice volume data were delivered to MfE as a .csv file along with this report.

Key findings presented in this report:

- From a starting ice volume of 53.29 km^3 in 1978 (Chinn, 2001), New Zealand's estimated ice volume in 2023 has reduced to 30.28 km^3.
- In 2023, New Zealand's glacier ice volume was 57% of the 1978 volume.
- From 2005, there is an 18-year trend of ice loss prevailing, with no years characterised by a large positive gain in ice volume.
- There are opportunities to refine the methodology used to estimate glacier ice volumes in New Zealand, which may lead to more robust estimates in future updates.

1 Introduction

The National Institute of Water and Atmospheric Research (NIWA) has been commissioned by the Ministry for the Environment (MfE) to update the glacier ice volume change in New Zealand from the previous accounts ending in 2020. To do this we have re-run the ice volume change calculation from 1978 to 2023 using the modified version of the Chinn et al. (2012) model (Willsman, 2017). This information is intended for use by MfE for environmental reporting and climate change analysis. MfE requested a brief summary report that highlights the updated glacier ice volume data obtained using the Willsman (2017) methodology. As this methodology has been described in detail in previous client reports (Willsman, 2017), only a short overview will be provided in this report (Section 2).

2 Methodology

The following is a short overview of the methodology to help interpret the calculations, and clarify why there are subtle differences in results presented compared to previous updates.

2.1 Derivation of ice volume estimates

The method for estimating ice volume change was developed by Trevor Chinn and others in 2007, and subsequently published in 2012 (Chinn et al., 2012). This method was used to estimate New Zealand's ice volume changes from and 1978-2020 (Macara & Willsman, 2021). The method utilises end of summer snowline (EOSS) measurements from New Zealand's index glaciers from 1977-2023. Details about the index glaciers can be found in recent EOSS reports (e.g. Macara, 2024).

Ice volumes are representative of glacier hydrological years (1 April – 31 March), such that the 2023 ice volume value represents the situation as at 31 March 2023. The EOSS used for the 2023 calculation represents the elevation (above sea level; asl) of the snowline remaining after the 1 April 2022 – 31 March 2023 year of snow accumulation and melt.

Steps taken to calculate ice volume (adapted from Willsman, 2017):

- Annual EOSS, average EOSS and mass balance gradient are used to calculate annual ice volume change for each index glacier;
- Annual volume change is divided by the respective index glacier area to derive an annual net balance. These annual net balances are averaged to derive an average annual net balance;
- Average annual net balance is applied to areas of the remaining glaciers (excluding 12 large debris-covered glaciers) to derive an annual volume change;
- Annual volume change applied to initial ice volume (53.29 km^3) taken from 1978 New Zealand Glacier Inventory (Chinn, 2001).
- Willsman (2017) differs from earlier reports (e.g. Willsman, 2011), by applying a longer and more recent mass balance gradient dataset obtained from Brewster Glacier (2000-2015; Cullen et al., 2017), i.e. accumulation rate 7.4 mm/m, ablation rate 14.5 mm/m.
  - Note, it was discovered that previous calculations used an accumulation rate of 7.1 mm/m for 11 of the index glaciers. The intended accumulation rate of 7.4 mm/m was applied to all index glaciers in this update.

- Willsman (2017) presents total Glacier Ice Volume for New Zealand (derived from regional estimates), as opposed to the regional breakdowns of some earlier reports (e.g. Willsman, 2011).
  - This is due to the difficulty of applying the methodology to very small ice areas/volumes in some regional areas, whereby estimates of considerable contemporary ablation theoretically result in complete ice loss.
  - The model calculations result in regional ice volumes of less than 0 km^3 for Southland (from 2022), Manawatū-Whanganui (from 2019), and Marlborough (from 2012). In this update, regions were excluded from the New Zealand total ice volume calculation once their modelled volume reached 0 km^3.
- Changes to the 12 largest debris covered valley glaciers in the Southern Alps are calculated using a geodetic method based on topographic and proglacial lake changes determined from repeated surveys. Two processes are considered:
  - 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 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 2023.
  - The second incorporates the development since the 1970s of proglacial lakes and the combined ice volumes lost to ice calving into the lakes. The proglacial lake growth for the recent period 2020 to 2023 was reassessed and any changes measured from relevant satellite images.

Note, the EOSS was not obtained during an official flight in 1990 and 1991. As such, observations of Tasman Glacier for these years are used to inform the calculations. Lorrey and Macara (2021) outline the caveats associated with this approach.

3 Results

From a starting ice volume of 53.29 km^3 (Chinn, 2001), New Zealand's estimated ice volume in 2023 has reduced to 30.28 km^3. New Zealand's glacier ice volume at 2023 is 57% of the 1978 volume. Figure 3-1 illustrates the interannual variability of New Zealand's estimated glacier ice volume for the period 1978-2023. The highest annual ice loss in the 1978-2023 record occurred in 2018, with 2.68 km^3 of ice loss. This is followed by 2019 and 2011, with 2.56 km^3 of ice loss, respectively. Note, tabular data are presented in Appendix A.

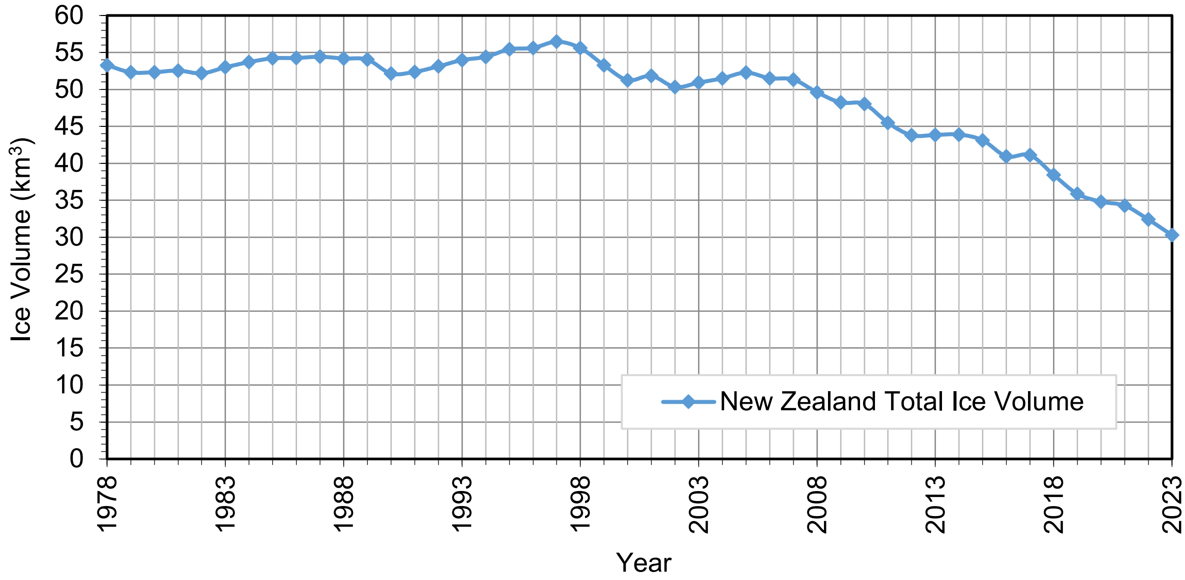

Figure 3-1: New Zealand total ice volume (km^3), 1978-2023.

As noted in Section 2, changes to the 12 debris covered valley glaciers are calculated separately. Figure 3-2 illustrates the interannual variability of estimated glacier ice volume for the 12 debris covered valley glaciers, and the remaining index glaciers.

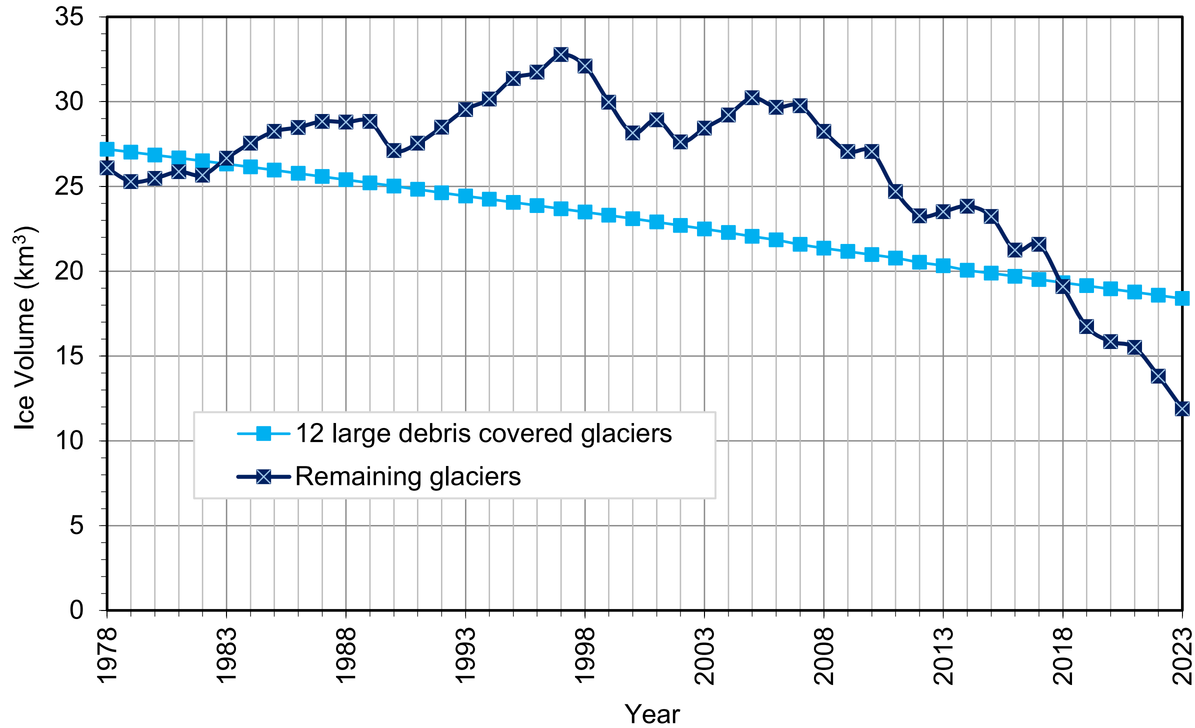

Figure 3-2: Annual changes to the components of New Zealand's total ice volume (km^3), 1978-2023.

3.1 Comparison with previous estimates

Section 2.1 describes differences in how New Zealand's total ice volume was estimated for the present update (1978-2023), compared to the previous update which covered the period 1978-2020 (Macara and Willsman, 2021). Figure 3-3 and Figure 3-4 illustrate the impact of the modified methodology. Specifically, annual ice volumes are now slightly higher than corresponding values presented in the 1978-2020 update (Macara and Willsman, 2021), primarily due to the application of corrected (higher) accumulation rates for 11 index glaciers.

Annual differences between the two dataset versions range from 0.02 km^3 to 0.27 km^3. The largest discrepancy of 0.27 km^3 occurred in 2007, with the previously reported New Zealand glacier ice volume (51.07 km^3) lower than the updated glacier ice volume (51.34 km^3). This discrepancy is equivalent to 0.5% of New Zealand's 1978 total ice volume. The reason for the difference peaking in 2007 is described below:

- In years with relatively small changes in ice volume, the accumulation area of the glacier at the end of summer is relatively high. Therefore, the cumulative impact of the corrected accumulation rate is proportionally higher.
- In years where there have been large decreases in ice volume, the accumulation area of the glacier at the end of summer being relatively low. Therefore, the cumulative impact of the corrected accumulation rate is proportionally lower.
- The ablation rate (14.5 mm/m) is higher than the accumulation rate (7.4 mm/m). In years of strongly negative mass balance (i.e. large ice volume decreases), relatively high ablation offsets the cumulative impact of the corrected accumulation rate (Figure 3-4).

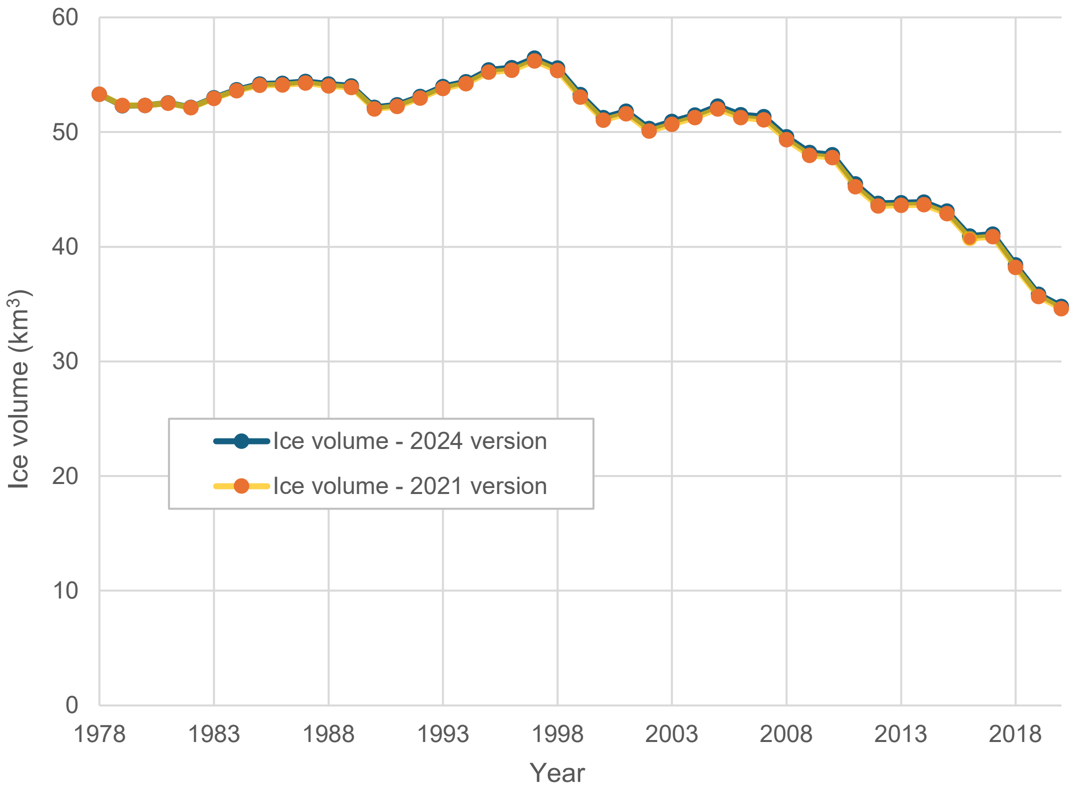

Figure 3-3: New Zealand total ice volume (km3), 1978-2020. The blue line represents the latest version of the data calculated for the present report. The orange line represents the previous version of the data calculated for Macara and Willsman (2021).

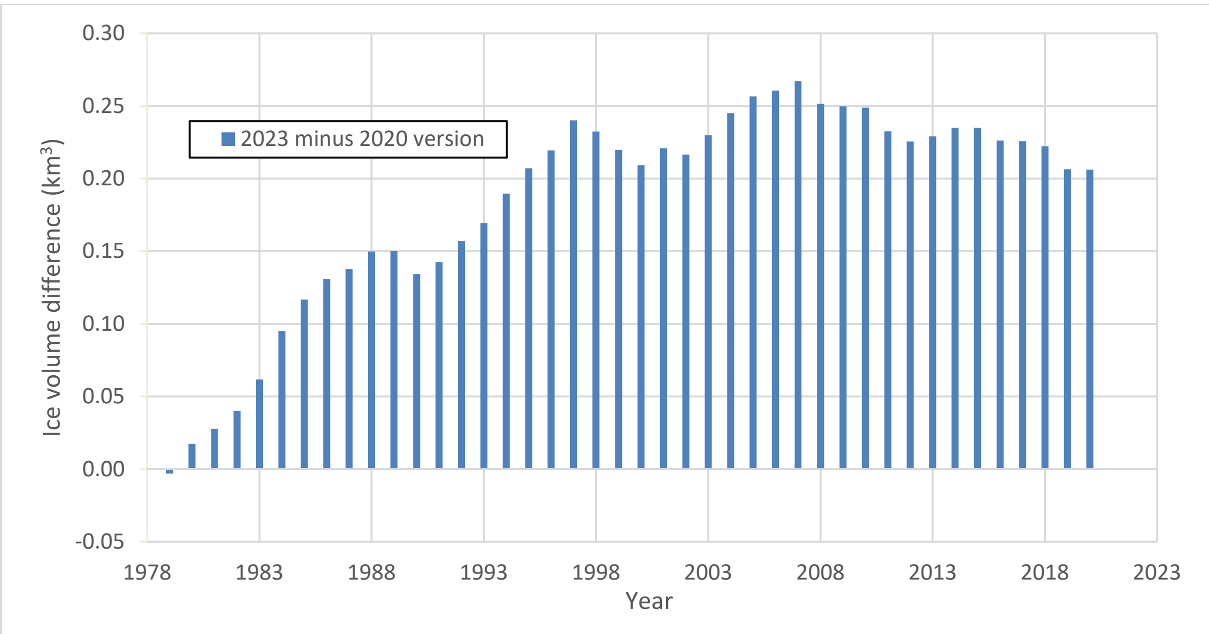

Figure 3-4: Difference between 2023 and 2020 versions of New Zealand total ice volume.

4 Discussion

This report presents an update to New Zealand's annual glacier ice volumes using the Willsman (2017) methodology. These volumes were last calculated through to 2020, with the present report calculating data for the period 1978-2023. The 2023 estimate (30.28 km^3) represents further evidence of considerable ice loss since 2007.

4.1 Comparison with previous estimates

As noted in Section 2.1, previous calculations (e.g. Macara and Willsman, 2021) included two errors that were carried through to estimates of New Zealand's glacier ice volume:

1. An accumulation rate of 7.1 mm/m was used for 11 of the index glaciers. This differed from the rate that should have been applied (7.4 mm/m), causing erroneously high ablation values for these glaciers.
2. The model results in estimated glacier ice volumes of less than 0 km^3 for Southland, Marlborough, and Manawatū-Whanganui. Negative values for Marlborough (from 2012) and Manawatū-Whanganui (from 2019) were included in previous estimates.

Ultimately, these errors resulted in annual total glacier ice volumes that were lower than they should have been. However, there has been no meaningful change to i) the pattern of interannual variability in total ice volume, and ii) the overall trend of considerable ice loss, particularly since 2007.

4.2 Future improvements

There are opportunities to improve the methodology used to estimate glacier ice volumes in New Zealand, and these may deliver more robust estimates in future updates. Improvements include refining the existing methodology and using new approaches.

4.2.1 Refining the existing methodology

Regional ice volume data are not presented in this report, following the precedent set by Willsman (2017). Nevertheless, the national total values are derived from regional estimates. The methodology results in regional ice volumes of less than 0 km^3 for Southland (from 2022), Manawatū-Whanganui (from 2019), and Marlborough (from 2012), while estimated ice volumes for Canterbury (excluding debris-covered glaciers) are now nearing 0 km^3. Additional investigation is required to assess such model estimates. However, in Canterbury it is clear from our contemporary EOSS flights (and associated index glacier photos) that more ice volume remains than is estimated by the model based on the preceding work of Chinn et al. (2012).

There are a range of factors that may contribute to the apparent overestimation of ice loss by the model, including i) the model overestimates the ablation rate, ii) the model underestimates the accumulation rate, and iii) the average annual net balance obtained from the EOSS index glaciers is not representative of all New Zealand glaciers. Such systematic errors may be small, but become increasingly apparent as they accrue through time.

Anderson and Mackintosh (2017) suggest that the existing methodology doesn't reflect observed glacier responses appropriately, and therefore overestimates the magnitude of glacier mass balance change. The authors propose an improved method of applying the mass balance gradient, by 'fixing' the mass balance gradient shift at the glacier's long-term average Equilibrium Line Altitude (ELA). Future glacier ice volume calculations should incorporate this modification.

Further refinement to the existing methodology may be achieved by reviewing the geodetic method of estimating changes to the 12 large debris covered glaciers. At present, a constant rate of down-wasting has been applied, but closer examination using, for example, Structure from Motion (Vargo et al., 2017) may reveal a more nuanced and dynamic rate of change.

4.2.2 New approaches

New approaches for reconstructing ice volume change have been investigated recently using EOSS index values, especially to determine how they can be transformed into ice volume changes with a more idiosyncratic, regional view of cryosphere change. Here, we discuss our unpublished work that combines several aspects of ongoing glacier observations supported by NIWA and our collaborators.

First, there is now a more realistic ice areal reduction factor that has been derived based on comparing the 1978 glacier inventory and the 2016 glacier inventory (Baumann et al., 2021), from which any long-term two-dimensional change in ice coverage can be benchmarked. Second, obtaining information about vertical change has been challenging, but in situ monitoring at multiple sites and 3D modelling with Structure from Motion have proven useful (Vargo et al., 2020). Third, transfer functions that rely on direct mass balance measurements at Brewster and Rolleston Glaciers have been used to estimate interannual ice volume changes from EOSS index values. The new approach incorporating a transfer function has also attempted to utilise a bias correction for in situ mass balance measurements based on Structure from Motion three-dimensional volume changes. Notable improvements using that type of approach have resulted in the modelled retention of some ice on Mt Ruapehu, in Otago, and for Canterbury up to the present day that better reflects observations. Last, additional and ongoing tests for the aforementioned new approach have examined a time-transgressive spatial footprint change. This uses sequences of EOSS photos at several index glacier sites to give a wider view of how inter-annual climate variability is impacting Southern Alps ice volume change through time.

The aforementioned advancements and trial approach using local information from different sources compares favourably to recent work that evaluated the scale of ice volume change since 2000 using remote sensing from satellites (Hugonnet et al., 2021). There are additional elements to explore for evaluating how well any ice volume approach works for glaciers of different size, in different settings (e.g. connected to large proglacial lakes) and in different regions. It is likely that a combination of methods would provide a much more useful, idiosyncratic view at a regional scale that could be used to investigate how ice resources are changing through time. Regardless, an accurate foundation of our understanding of ice volume each year is essential for determining the potential impacts on river flows and ecosystems that are directly influenced by changes in our cryosphere under a changing climate.

5 Summary and next steps

We continue to observe considerable loss of ice in New Zealand. However, it has become apparent that the methodology used to estimate glacier ice volume here requires refinement. Several opportunities to improve the calculations have been identified, and these should generate more robust estimates of New Zealand's regional and national glacier ice volume in future. NIWA would welcome the chance to discuss these opportunities with MfE, to determine how some of the new approaches can be accelerated to completion and then operationalised for use in regularly evaluating ice volume change.

6 Acknowledgements

We are indebted to Dr Trevor Chinn for initiating the Southern Alps EOSS programme. The ongoing EOSS surveys are funded by the NIWA Strategic Science Investment Fund (SSIF) contract for ‘Climate Present and Past’ (most recently CAOA2501). Collaborators on these surveys are thanked.

7 Glossary of abbreviations and terms

Ablation	Glacier loss through melting, sublimation or calving of snow and ice.
Accumulation	Glacier gain from input and retention of snow and ice.
Down-wasting	The net lowering of a glacier's surface profile by normal ablation and ice flow.
ELA	Equilibrium Line Altitude. A line of demarcation on a glacier where loss of ice and gain of snow and ice is equal.
EOSS	End of Summer Snowline.
Index glaciers	Glaciers that are regularly monitored and studied to provide details about variability and change of the cryosphere.
Mass balance	The calculation of ice loss or ice gain for a glacier over a specified interval of time.
Mass balance gradient	The change in mass balance that exists from the accumulation zone to the ablation zone on a glacier (typically this gradient increases with a decrease in elevation along a transect from the highest part of a glacier to its terminus).
MfE	Ministry for the Environment.
Moraine	Accumulation of unconsolidated debris that occurs in both currently and formerly glaciated regions.
NIWA	National Institute of Water and Atmospheric Research.
Proglacial lake	Formed during the retreat of a glacier, where the glacier meltwater is dammed by the remnant moraine.
StatsNZ	Stats NZ Tatauranga Aotearoa.

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Appendix A Ice volume data

Table A-1: Estimated national glacier ice volume (km^3), 1978-2023.

Year	Ice volume (km^3)	Year	Ice volume (km^3)
1978	53.29	2001	51.83
1979	52.31	2002	50.32
1980	52.33	2003	50.92
1981	52.55	2004	51.50
1982	52.17	2005	52.28
1983	52.99	2006	51.51
1984	53.70	2007	51.34
1985	54.21	2008	49.60
1986	54.25	2009	48.23
1987	54.42	2010	48.03
1988	54.18	2011	45.47
1989	54.03	2012	43.80
1990	52.14	2013	43.84
1991	52.37	2014	43.90
1992	53.12	2015	43.11
1993	53.97	2016	40.94
1994	54.40	2017	41.11
1995	55.43	2018	38.42
1996	55.61	2019	35.87
1997	56.45	2020	34.81
1998	55.59	2021	34.27
1999	53.26	2022	32.40
2000	51.25	2023	30.28