Global and Planetary Change 211 (2022) 103792

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Coincident evolution of glaciers and ice-marginal proglacial lakes across the Southern Alps, New Zealand: Past, present and future

Jonathan L. Carrivick[a,*], Jenna L. Sutherland[b], Matthias Huss[c,d,e], Heather Purdie[f], Christopher D. Stringer[a], Michael Grimes[a], William H.M. James[a], Andrew M. Lorrey[g]

[a] School of Geography and water@leeds, University of Leeds, Woodhouse Lane, Leeds, West Yorkshire LS2 9JT, UK
[b] School of Built Environment, Engineering and Computing, Leeds Beckett University, Leeds, West Yorkshire LS1 3HE, UK
[c] Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zürich, Zürich, Switzerland
[d] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland
[e] Department of Geosciences, University of Fribourg, Fribourg, Switzerland
[f] School of Earth and Environment, University of Canterbury, Christchurch, New Zealand
[g] National Institute of Water and Atmospheric Research LTD, Auckland, New Zealand

ARTICLE INFO

Editor: Jed O Kaplan

Keywords:
Glacier
Glacier lake
Proglacial lake
Ice-marginal lake
Overdeepening
Google Earth Engine

ABSTRACT

Global glacier mass loss is causing expansion of proglacial landscapes and producing meltwater that can become impounded as lakes within natural topographic depressions or 'overdeepenings'. It is important to understand the evolution of these proglacial landscapes for water resources, natural hazards and ecosystem services. In this study we (i) overview contemporary loss of glacier ice across the Southern Alps of New Zealand, (ii) analyse ice-marginal lake development since the 1980s, (iii) utilise modelled glacier ice thickness to suggest the position and size of future lakes, and (iv) employ a large-scale glacier evolution model to suggest the timing of future lake formation and future lake expansion rate. In recent decades, hundreds of Southern Alps glaciers have been lost and those remaining have fragmented both by separation of tributaries and by detachment of ablation zones. Glaciers with ice-contact margins in proglacial lakes ($n > 0.1$ km^2 = 20 in 2020) have experienced the greatest terminus retreat and typically twice as negative mass balance compared to similar-sized land-terminating glaciers. Our analysis indicates a positive relationship between mean glacier mass balance and rate of lake growth ($R^2 = 0.34$) and also with length of an ice-contact lake boundary ($R^2 = 0.44$). We project sustained and relatively homogenous glacier volume loss for east-draining basins but in contrast a heterogeneous pattern of volume loss for west-draining basins. Our model results show that ice-marginal lakes will increase in combined size by ~150% towards 2050 and then decrease to 2100 as glaciers disconnect from them. Overall, our findings should inform (i) glacier evolution models into which ice-marginal lake effects need incorporating, (ii) studies of rapid landscape evolution and especially of meltwater and sediment delivery, and (iii) considerations of future meltwater supply and water quality.

1. Introduction

Mountain glaciers are rapidly diminishing globally and that is of great concern for a wide variety of environmental and socio-economic reasons, including landscape stability (e.g. Carrivick and Heckmann, 2017; Anderson and Shean, 2021; Carrivick and Tweed, 2021) and associated natural hazards (e.g. Beniston et al., 2011), surface hydrology and water resources (e.g. Hirabayashi et al., 2010; Farinotti et al., 2019a), habitats and ecosystems (e.g. Milner et al., 2017). Whilst there has been extensive and intensive scrutiny of glaciers and of glacial meltwater production, including past, present and future patterns of change and magnitudes of change (e.g. Zemp et al., 2019; Huss and Hock, 2018; Hugonnet et al., 2021), relatively little research has dealt with concurrent emergence and expansion of proglacial landscapes (Haeberli et al., 2016, 2019), especially in the Southern Hemisphere.

Proglacial landscapes include many geomorphological components (Carrivick and Heckmann, 2017) and with diminishing glaciers these elements combine to dictate sediment yield (Carrivick and Tweed, 2021). Important considerations related to the emergence and expansion of proglacial landscapes, from a hydrological and geomorphological

* Corresponding author.
E-mail address: j.l.carrivick@leeds.ac.uk (J.L. Carrivick).

https://doi.org/10.1016/j.gloplacha.2022.103792
Received 16 December 2021; Received in revised form 15 February 2022; Accepted 16 March 2022
Available online 19 March 2022

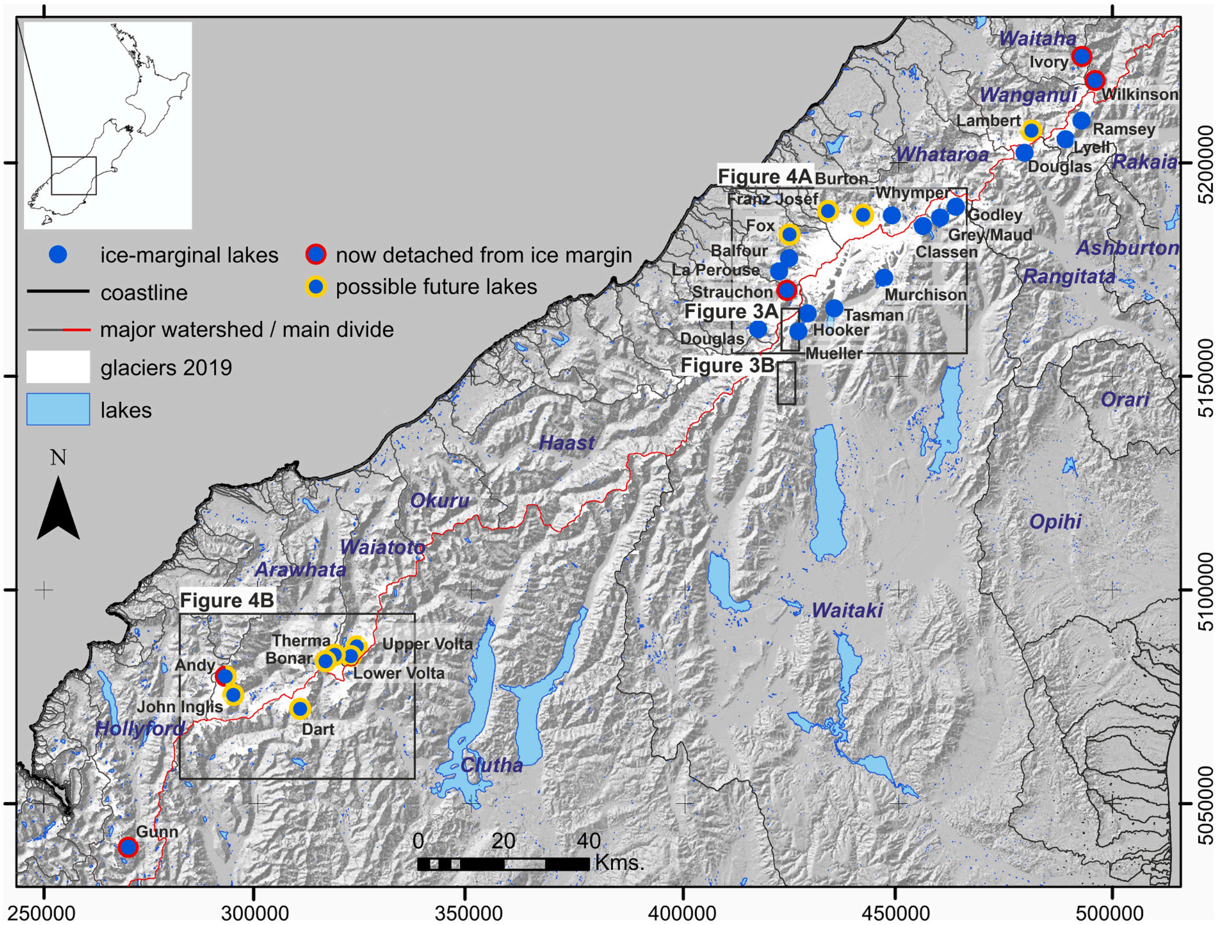

Fig. 1. Overview of the location of past (since the 1980s), present (including very recently formed) and future (for clarity only >0.5 km^2 are displayed) ice-marginal lakes across the Southern Alps of New Zealand, with major drainage basins and other lakes for context. Grid coordinates are in UTM 59S projection.

perspective, are where and when new lakes will form, how big those lakes will become and how persistent they could be. Some answers to those questions can come from (i) analysing past lake evolution, (ii) studying contemporary lakes, and (iii) projecting future lake evolution.

The coincidental increase in both number and area of proglacial lakes with global glacier mass loss during the last few decades is well known (Shugar et al., 2020), but there are very few studies that consider proglacial lake evolution on longer timescales. In Europe, lake evolution since the Little Ice Age (LIA) has been analysed across Austria since the end of the Little Ice Age where an increased rate of lake formation in recent years has been reported (Buckel et al., 2018). An increased number and area of lakes was observed across Switzerland between the LIA and the 1970s, a reduction occurred between the 1970s and 2000, followed by growth again to 2016 that produced the greatest number and area of lakes ever measured (Mölg et al., 2021). Across the Himalaya, Zheng et al. (2021) have identified ~7000 proglacial lakes and quantified a marked increase in the number and area of them since the 1990s. In the Southern Hemisphere, Emmer et al. (2020) show an increasing number and area of lakes across the Cordillera Blanca in Peru for the time period of 1948 to 2017. Whilst these studies are the first of their kind, a more nuanced approach could be employed, for example if the research emphasis is on hazards, then proglacial lakes could be categorised for dam type, such as achieved by Emmer et al. (2020), since most glacial lake outburst floods (GLOFs) globally are from ice-dammed lakes (Carrivick et al., 2016). If a motivation is to examine the effects of lakes on glacier dynamics, then selected proglacial lakes with ice-contact margins should be focused on.

The aim of this study is to analyse coincident geometric changes to glaciers and ice-marginal lakes across the Southern Alps of New Zealand. The motivation for this study comes from (i) a desire to understand the key physical components of landscapes soon to be exposed as glaciers inevitably diminish and mostly disappear (Anderson et al., 2021), and (ii) a focus on lakes with potential to affect ice dynamics (i.e., those proglacial lakes that are ice-marginal). Our aim is primarily achieved using (i) an inventory of ice-marginal lakes since the 1980s derived from Landsat imagery to quantify historical lake changes, (ii) an analysis of modelled glacier ice thickness to derive glacier bed topography that illustrates the three-dimensional structure of future lakes including bathymetric overdeepenings, and (iii) a glacier evolution model driven by climate scenarios that estimates the timing of glacial lake development coinciding with glacier terminus retreat.

1.1. Study site and previous work

The Southern Alps of New Zealand are a 700 km long barrier to prevailing westerly atmospheric circulation (Sturman and Tapper, 1996). The mountain range is relatively high (up to 3724 m. asl) and narrow (~50 km) and contains over 2900 glaciers as of the last national glacier inventory based on 2016 imagery (Baumann et al., 2021) (Fig. 1). Many of the inter-montane valleys are widened, straightened and overdeepened due to Quaternary glaciations (Barrell, 2011). Since the Last Glacial Maximum these major valleys have contained very large lakes within overdeepened basins (James et al., 2019) including lakes Wakatipu, Te Anau, Wanaka, Hawea, Pukaki, Tekapo and Ohau, for example (Sutherland et al., 2019a). Relative to ice volume during the LIA, the Southern Alps have lost an estimated 40% ice cover and the rate of loss has increased in recent decades (Carrivick et al., 2020a; Carrivick et al., 2020b).

Southern Alps glaciers are situated in a cool temperate climate with an extreme precipitation gradient ranging from totals ~1.5 m a^{-1} at the most eastern glaciers up to ~12 m a^{-1} northwest of the main drainage divide (Henderson and Thompson, 1999). Aligned with global trends, Southern Alps glaciers are undergoing a period of accelerated retreat (Mackintosh et al., 2017). A relatively small number of these glaciers currently terminate in ice-marginal lakes (Chinn, 1999) (Fig. 1), however they are amongst the largest Southern Alps glaciers and volumetrically are the most important. Therefore, the expansion of ice-marginal lakes, and potential feedbacks for ice recession, is of great scientific and societal concern (Purdie et al., 2020). Past and present ice-marginal lakes were/are predominantly dammed within overdeepenings by voluminous outwash sediment and recessional moraine belts (e.g. Sutherland et al., 2019a, 2019b).

Initial research on modern ice-marginal lakes in the Southern Alps focused on determining water depth, characterising limnology and exploring the drivers of iceberg production (Hochstein et al., 1998; Warren and Kirkbride, 1998), in particular, thermal notch development (Röhl, 2006). The majority of research has focused on Tasman Lake, where ongoing expansion and deepening has resulted in periodic terminus buoyancy, which contributes to large magnitude calving events (Dykes et al., 2011; Robertson et al., 2012). Most recently, research has focused on developing an improved understanding of how subaqueous ice ramps, frequently found at the terminus, influence lake evolution (Purdie et al., 2016). Whilst assessments of the future expansion of the Tasman Lake have been undertaken (e.g. Kirkbride and Warren, 1999; Quincey and Glasser, 2009), there has been no reported inventory of ice-marginal lakes in New Zealand and no analysis of the evolution of these lakes on a regional scale.

1.2. Datasets and methods

1.2.1. Glaciers

Glacier outlines for the Southern Alps during the LIA are available from Carrivick, James, Grimes, Sutherland, and Lorrey (2020a, Carrivick, Tweed, Sutherland, and Mallalieu, 2020b) and were derived from geomorphological evidence of past glacier extent. Outlines for glaciers in 1978 were obtained from field and aerial observations by Chinn (2001), for 2009 (Sirguey and More, 2020) and 2016 by satellite image analysis (Baumann et al., 2021). We obtained the 1978 outlines from the Randolph Glacier Inventory (RGI v6.0) and the 2009 and 2016 outlines via GLIMS https://www.glims.org/maps/download. Our own 2019 glacier outlines are based on Sentinel 2A image mosaic-based classification (to mitigate topographic shadow problem) conducted in Google Earth Engine by Carrivick, James, Grimes, Sutherland, and Lorrey (2020a, Carrivick, Tweed, Sutherland, and Mallalieu, 2020b), but now in this study combined with a new a single image classification from April 17th 2019 to remove a mid/late season snow problem that only became apparent with the publication of Baumann et al. (2021) glacier outlines for 2016.

Subglacial topography and hence the site and size (area and volume) of glacier bed overdeepenings as possible future lakes was estimated in this study by differencing the ice surface and ice thickness 25 m grid resolution datasets of Farinotti et al. (2019b). This ice thickness data set is based on a consensus of four different ice thickness models that were run for the RGI v.6.0 geometry and were regionally calibrated using all available thickness observations (Welty et al., 2020). For parts of the landscape beyond this ice extent, landscape-wide bed topography was derived as in Carrivick, James, Grimes, Sutherland, and Lorrey (2020a, Carrivick, Tweed, Sutherland, and Mallalieu, 2020b) and James et al. (2019) by making a mosaic that combines contemporary bed topography with contemporary lake bathymetry and the 30 m ALOS year 2000 digital elevation model, in that order of priority. We are unable to account for sediment infilling since glacier disappearance as discussed in James et al. (2019).

Future glacier extent projections were made using the Global Glacier Evolution Model (GloGEM; Huss and Hock, 2015). This global-scale model describes the principal processes determining glacier surface mass balance (snow accumulation, ice melt, refreezing) and computes annual surface elevation change and thus glacier retreat or advance based on a mass-conserving parameterization (Huss et al., 2010). The model was calibrated to match glacier-specific geodetic observations of ice volume change between 2000 and 2019 (Hugonnet et al., 2021). GloGEM runs do not include the effect of supraglacial debris on glacier retreat rates explicitly, but neglecting the effect has a minor influence on long-term rates of mass change in the case that accurate data for model calibration (glacier-specific geodetic ice volume change) are given (Compagno et al., 2021). The model is discretized into 10 m elevation bands to facilitate large-scale application but results on area and thickness changes in individual bands are extrapolated to a 25 × 25 m grid. GloGEM is forced with gridded monthly data on 2 m air temperature and total precipitation from the ERA-5 re-analysis (Hersbach et al., 2020) for the past, and with results of 13 Global Circulation Models (GCMs) from the sixth phase of the Coupled Climate Model Intercomparison Project (CMIP6; Eyring et al., 2016) for the future and until 2100. GCM model runs are based on five different Shared Socio-economic Pathways (SSPs; Meinshausen et al., 2020) describing future greenhouse gas emissions. This approach is not dissimilar (but more detailed regarding the temporal and spatial resolution) to that of Zheng et al. (2021) who used GloGEM results forced by three different emission scenarios (Huss and Hock, 2018) for two (2050 and 2100) time steps of projected glaciers across the High Mountain Asia. In this study we focus on results of the intermediate scenario SSP2–4.5 which most closely corresponds to the current pledges of nations around the globe to limit atmospheric warming (Ou et al., 2021; CAT, 2021). Anderson et al. (2021) have examined the effect of choice of emission scenario on the glaciers of the Southern Alps, noting little effect before 2050 and then increasing divergence of model results of ice extent and volume to year 2099.

1.2.2. Ice-marginal lakes

Historical measurements of ice-marginal lake areas were obtained for Hooker, Mueller, Tasman, Classen, Maud-Grey, Godley, and Ramsay lakes (T. Chinn, pers. comm.; Willsman, 2017) for years from 1972 to 2007. This previously unpublished work compiled proglacial lake area data from Hochstein et al. (1995, 1998), Warren and Kirkbride (1998) and from some Landsat image interpretation. Only some glaciers and some lakes were included in this previous work, so in this study we manually digitised historical lake outlines for all ice-marginal lakes in 1990, 2000, 2010, and 2020 using Landsat mosaics for each decade. Unfortunately, no suitable images from the early 1980s are available across the Southern Alps. If a lake was/is/will be disconnected from a glacier then we have not included it for that time period. Landsat image acquisition was achieved using Google Earth Engine, within which we filtered the Landsat surface reflectance catalogues for images (i) from the austral summer (defined as November to April), (ii) with minimal (< 20%) cloud coverage. These image collections were interrogated to preferentially select images with the least cloud. In cases where there was some cirrus cloud coverage that had not been identified by the Landsat cloud scoring algorithm, we used a best quality mosaic. Whilst ordinary mosaicking produces a spatially continuous image by joining adjacent images together across a defined area, a best quality mosaic produces a continuous image by selecting the highest value of a given band within each pixel from the image collection (Google, 2021). In this case, we found through trial and error and visual inspection that the Landsat "brightness temperature" band produced the clearest (least cloud, least snow, least shadow) 30 m resolution mosaics. Owing to (suitable) image availability our lake inventories therefore have a slight mis-match in timing of the glacier inventories but span the same time period and with similar temporal density.

Our identification in this study of future lakes were derived using intersecting calculated future glacier extents with outlines of

Table 1
Past and present number and area of the largest ten glaciers in the Southern Alps, New Zealand. The table is ordered by 1978 area. The 2016 inventory is that of Baumann et al. (2021). Asterisks denote the following; *fragmented so quantity is for Classen, Maud, Grey and Godley combined; ** Thema, Upper Volta and Lower Volta combined; *** Mueller and Frind combined; **** Ramsay and Clarke combined. The LIA total is a minimum estimate because some glaciers have disappeared without leaving behind clear geomorphological evidence (Carrivick et al., 2020a; Carrivick et al., 2020b). The 2009 totals are not defined because the study of Sirguey and More (2020) was restricted to the Mt. Cook region only. The 2016 and 2019 totals are for all Southern Alps glaciers, not just the largest ten.

Period/Year	LIA	1978	2009	2016	2019	Change in area	Ice-marginal lake?
Glaciers (N)	NA	3516	Incomplete inventory	2918	2061	1978 to 2019 (%)	
Area (km^2)							
Tasman	113.5	95.2	87.67	81.9	76.9	−19.2	Y
Fox	40.2	34.7	34.3	32.2	31.1	−10.4	–
F. Josef	38.9	33.1	33.1	31.9	30.9	−6.7	–
Murchison	52.9	31.4	28.8	23.7	22.5	−28.4	Y
Godley	44.8	24.1*	NA	17.9*	15.7*	−34.9	Y
L. Volta	44.2	22.8	NA	17.6**	16.3**	−28.5	Y
Bonar	18.4	15.5	NA	14.58	13.5	−12.9	–
Hooker	19.3	14.4	13.3	11.6	10.7	−25.7	Y
Mueller	36.1	13.9	13.9	11.1***	9.9***	−28.8	Y
Ramsay	20.0	11.6	NA	9.2****	8.3****	−28.5	Y
Total (km^2)	1492	1156	NA	794.5	652.4		

overdeepenings that were thresholded to include areas >0.1 km^2. Due to the considerable uncertainties in ice thickness estimates (Farinotti et al., 2017) we follow the approach of Zheng et al. (2021) who used the Farinotti et al. (2019b) consensus ice thickness product (average of four thickness models for New Zealand). Since the glacier outlines used by Farinotti et al. (2019b) across the Southern Alps pertain to the RGI v6.0, and thus 1978, we are able to examine which overdeepenings (beneath the 1978 extent of glaciers) actually contained lakes in 2019,. Thus we not only identify the onset of formation of new ice-marginal lakes, but also enlargement of them. Future enlargement of existing lakes was quantified by merging the future intersect with the existing lake. We have to assume that overdeepenings become full of water and we cannot account for future sedimentation. Lakes that were projected to become disconnected from an ice-margin due to recession of a glacier out of its overdeepenings were no longer included in our analysis from that time onwards.

2. Results

2.1. Historical glacier evolution

Loss of glacier ice and reduced glaciated area across the Southern Alps of New Zealand has accelerated from during the LIA to the present day (Carrivick et al., 2020a; Carrivick et al., 2020b). The greatest losses of ice in recent decades (since 1978) have been for glaciers with ice-marginal lakes (Table 1). Our inventory of 2019 can be compared with that of 2016 (Baumann et al., 2021) to reveal high-resolution glacier-specific morphological changes. Notwithstanding the inherent uncertainty in each glacier inventory, there has been considerable change to the glaciers of the Southern Alps within a very short period of time (3 years). Specifically, separation of tributaries and loss of common ablation area, such as has occurred at Ramsay Glacier, Mueller Glacier (Fig. 3A), the three upper Godley valley glaciers and Lower Volta Glacier. These changes have resulted in multiple glaciers developing from what used to be a single terminus, and this needs to be considered with respect to the total number of glaciers that can be catalogued. Detachment or separation of a single glacier ablation area from a single accumulation area, usually via the loss of a connecting ice fall (e.g. such as has occurred at Douglas Glacier, Huddleston Glacier, Copland Glacier and Gulch Glacier), means that the remnant detached ice in the lower valley floor might soon stagnate. Elsewhere, there has been widespread terminus recession and even disappearance (i.e. complete loss of glaciers) for example within the Ben Ohau Range (Fig. 3B).

Table 2
Summary of the number and total area of measured and projected ice-marginal lakes across the Southern Alps of New Zealand. * is from Chinn (1996) and reflects all ice-marginal lakes without any size threshold applied. +is our 2019 inventory and for comparison Baumann et al. (2021) inventory totalled 794 km^2. Projections are based on the SSP2–4.5 scenario. Note that proglacial lakes that are no longer in contact with the ice margin are not counted anymore.

Year	Glaciated area (km^2)	Area lakes (km^2)	Lakes >0.1 km^2	Lake area (km^2) N > 0.1 km^2	Lakes >0.5 km^2	Lake area (km^2) $N > 0.5$ km^2
Measured						
1978	1156		11*			
1990		9.2	11	9.0	6	7.6
2000		12.2	14	12.2	7	10.3
2011		18.3	13	17.9	8	16.2
2020	652+	23.9	20	23.8	10	20.9
Projected						
2030	913	30.6	17	30.3	12	28.8
2040	830	34.5	18	34.4	13	33.1
2050	622	43.0	19	42.8	12	40.4
2060	614	46.7	20	46.6	13	44.7
2070	557	46.3	14	45.2	10	44.1
2080	526	45.7	13	45.4	9	44.0
2090	449	42.9	12	42.7	9	41.7
2100	419	43.7	10	42.9	9	42.3

2.2. Future glacier evolution

In this study we find that the choice of climate scenario has a big effect on the timing of glacier changes but not nearly so much on the type of change; overall glacier terminus retreat and thinning of the same style occurs with all scenarios but at a different time. We do not dwell on reporting our glacier changes because our glacier model results agree very well those of Anderson et al. (2021). In this study we modelled a ~ 50% reduction in total glacier volume to 2100, which agrees with their decline in volume of between 37% and 63% for the RCP2.6 scenario (their Table 2). Our projected 2100 ice distribution map (Fig. 4) is visually very similar to theirs for 2099 under RCP2.6 (their Fig. 7a).

Anderson et al. (2021) note considerable glacier-specific differences in evolution not only due to glacier size, shape and hypsometry but also due to factors such as debris cover and ice-marginal lakes that introduce non-linear feedback processes. Anderson et al. (2021) state that ice-marginal lake effects (a simple flotation threshold in their model) only have a minor effect on glacier evolution, yet report these lake effects to cause total ice volume to be 13% smaller by 2050 and 21% by 2099. In this study our analysis of the past, present and future glacier areas and coincident lake areas (Fig. 5) hint at a relationship between glacier and lake evolution that suggests two ice change groups: (i) one group where the glacier area change rate is approximately constant, and (ii) another where the glacier area change rate progressively slows with time to 2100 (Fig. 5). The latter is the pattern reported by Anderson et al. (2021). Strauchon, Mueller, Godley, Lyell and Ramsay glaciers are all projected to lose contact with their lakes before 2100.

2.3. Historical changes to ice-marginal lakes

There are 234 proglacial lakes across the Southern Alps located within the LIA extent of glaciers (based on Carrivick et al., 2020a, Carrivick et al., 2020b), with 220 of these lakes >0.5 km^2. The total combined area of these proglacial lakes, formed within the last few hundred years, is 29 km^2. There are 124 lakes within the 1978 glacier outlines with a total area of 7 km^2, three of which are >0.5 km^2. However, only 16 of these lakes were ice-marginal through the 1980s and 1990s (Chinn, 1996), and these were all predicted by our model, which in total had 18 overdeepenings >0.5 km^2 intersecting the 1978 glacier outlines. Thus almost 90% of the larger overdeepenings exposed by ice terminus recession through the 1980s developed ice-marginal lakes. There is an R^2 = 0.72 correlation between the areal size of the modelled overdeepenings and the area of lakes now within them. The measured-modelled discrepancy is due to the fact that several subaerially exposed overdeepenings presently only contain very small lakes, such as at Whymper Glacier, Balfour Glacier and La Perouse Glacier, where intensive sedimentation has occurred as will be elaborated in our discussion below.

By 2019, eleven of these eighteen modelled overdeepenings had been exposed due to ice margin recession and partially filled with meltwater to form lakes. Some of the lakes, such as at Strauchon Glacier, Ivory Glacier, Otoko Glacier, Gunn Glacier and Wilkinson Glacier are no longer ice-marginal because the glacier terminus position has receded up-valley out of the basin. There are 15 overdeepenings >0.5 km^2 within the 2019 glacier outlines. Of these overdeepenings, those presently partially containing an ice-marginal lake are at Lyell, Godley, Grey/Maud, Murchison, Tasman, La Perouse, Mueller and Hooker Glaciers. Of these overdeepenings that are >0.5 km^2 (and within the 2019 glacier outlines) those that are ice-covered are beneath Upper Volta Glacier (n = 2), Bonar Glacier (n = 3), the upper part of Franz Josef Glacier (n = 1) and the upper part of Andy Glacier on the Olivine ice plateau (n = 1). There are 50 modelled overdeepenings >0.1 km^2 within the 2019 glacier outlines, 80% of which are presently completely ice-covered.

Hochstein et al. (1995) report that Tasman Lake grew from ~0.1 km^2 in 1972 to 0.56 km^2 in 1982 and to 1.95 km^2 in 1993. Our analysis of Landsat imagery determines that since the 1990s the size of the ice-marginal lakes has steadily increased and new ice-marginal lakes have formed. We have measured the area of 20 lakes in the 2020 Landsat imagery and the outlines of all these lakes intersect our 2019 glacier outlines. They have a total area of 24 km^2 and almost all of them are >0.1 km^2 (Table 2). The decrease in the number of ice-marginal lakes between 2020 and 2030 (Table 2) arises because glacier terminus positions have retreated up valley sufficiently to be out of their lakes (e.g. Strauchon Glacier).

Combining the details of historical lake changes for individual glaciers with geodetic mass balance data for the period 2000–2020 (Hugonnet et al. ., 2021) reveals a positive correlation between the two (Fig. 6A). That correlation is not affected by separating glaciers on either side of the main divide. There is greater variability in the mean mass balance in situations where the proglacial lakes are growing faster relative to lakes growing slower (Fig. 6A). Furthermore, despite the (necessarily) small sample size, there is a statistically significant ($p <$ 0.01) difference between the mass balance of glaciers with ice-marginal lakes (mean ~ −0.5 m w.e./yr), and those that are land-terminating, again irrespective of geographic location (Fig. 6B). The mean mass balance of selected land-terminating glaciers analysed in this study is ~ −0.5 m w.e./yr, whereas it is up to twice as negative for lake-terminating glaciers (Fig. 6B). There is also a greater inter-site variability in the mass balance of glaciers across the Southern Alps that terminate in lakes compared to those that terminate on land (Fig. 6B). The anomaly of Tasman glacier (Fig. 6A) lends to a hypothesis about geometry of the lake being a possible driving factor, specifically related to the ice-contact lake boundary length because Tasman Lake nearly always has pronounced upslope-orientated embayment located on the north-eastern corner that leads lake evolution (Fig. 4A). This long narrow arm receives meltwater from upslope of the Hochstetter terminus and greatly increases the ice-contact length of Tasman Lake, but does not add much to the lake area. We find a positive (non-linear) relationship of R^2 = 0.44 between the ice-contact length and mean glacier mass balance for the time period 2000 to 2020 (Fig. 6C). That correlation increases slightly to R^2 = 0.48 if Tasman is excluded, showing it is not an outlier by this length (rather than area) metric.

2.4. Projected future ice-marginal lakes

There are five newly-formed ice-marginal lakes identified between the 2016 inventory (Baumann et al., 2021) and our analysis using 2019 and 2020 imagery, namely at La Perouse, Colin Campbell, Upper Volta, Bonar and Andy glaciers. These five lakes are suggested/corroborated by our analysis of overdeepenings and the glacier evolution model. In addition to all of the aforementioned lakes, several other lakes >0.5 km^2 are also projected, for example at Lambert and Upper Volta and Lower Volta glaciers to form around 2050 (Fig. 4A, B). Some ice-marginal lakes projected for 2020 have not materialised yet where intense sedimentation infills the basins as fast as they are exposed such as at Fox Glacier and Franz Josef Glacier (Carrivick and Rushmer, 2009) and at Dart, Burton and John Inglis glaciers, for example.

The 50 overdeepenings >0.1 km^2 within 2019 outlines total 46 km^2 area. By 2100, our projections suggest that only 15 of these will have been exposed sub-aerially due to ice-margin recession. However, the remaining area of overdeepenings that are ice-covered in 2100 is estimated to be 17 km^2 and so 29 km^2 area of overdeepenings will have become ice-free and with potential to form ice-marginal lakes between 2019 and 2100, in addition to the 23 km^2 area of ice-marginal lakes now (Table 2).

Overall, the historical rate of increase in lake size is projected to continue until the 2050s and then to diminish towards 2100 as more and more lakes lose their contact with the ice margin and are therefore not counted anymore (Table 2, Fig. 4, Fig. 5). The exact rate of lake growth varies between glaciers. Some lakes do not begin forming for several decades, whilst others become disconnected from the ice-margin as the glacier termini leave the overdeepened basin.

So far in this study we have refrained from reporting volumes of glaciers or of lakes because these volumes are subject to considerably more uncertainty than the areal size, location or number of glaciers and lakes. However, for water resources interests, we have aggregated total glacier volume and total lake volume per major drainage basin for selected time intervals to overview the patterns as well as the magnitude of changes. Overall, the east-draining basins experience profound order-of-magnitude losses in glacier volume for each of the time intervals we analysed (Fig. 7A,B,C,D). West-draining basins are more variable, with some barely altering in their total glacier volume at all and others experiencing large losses, especially between 2019 and 2050 (Fig. 7B, D).

Not all drainage basins with glaciers have ice-marginal lakes and only four have experienced substantial (> 0.1 km^3) lake growth between 1990 and 2020 (Fig. 7E). However, according to model results in this study, 2020 to 2050 will be characterised by substantial proglacial lake growth at many sites that already have a lake and there will be development of many more ice-marginal lakes in drainage basins previously

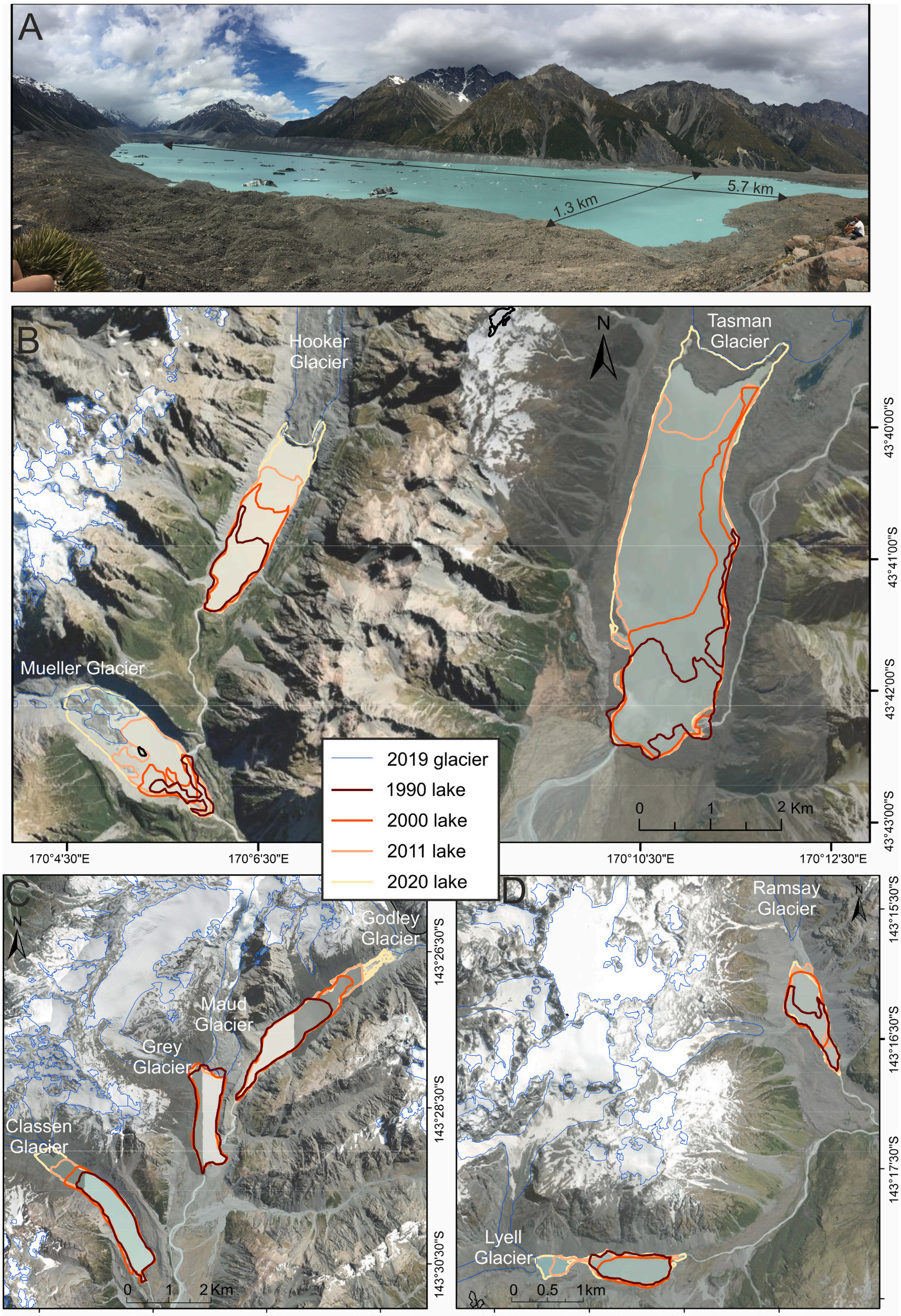

Fig. 2. Examples of ice-marginal lake evolution with 2019 glacier outlines and aerial photograph imagery for context. Tasman lake (A) is the largest and most rapidly growing ice-marginal lake and is in the Mount Cook/Aoraki region (B). Other relatively large lakes exist in the upper Godley Valley (C) and upper Rakaia valley (C). Note varying scale between panels. Background aerial photographs are Maxar images from April 2018 (B, C) January 2019 (D) made available within ArcGIS 10.6 as base imagery.

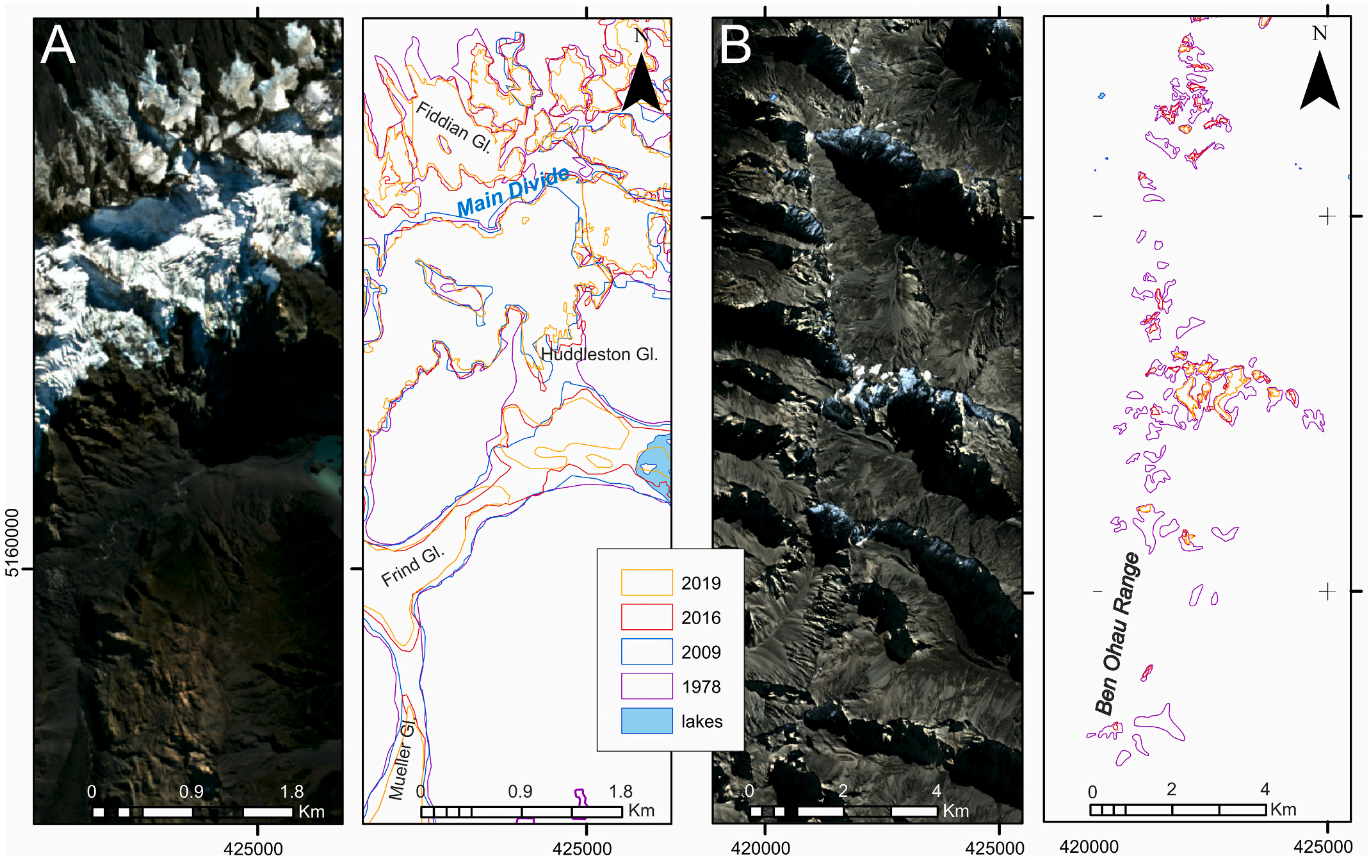

Fig. 3. Examples of rapid morphological changes to glaciers all within a few kilometres of each other, specifically fragmentation in the form of (i) detachment of Huddleston Glacier from Mueller/Frind and (ii) separation of Mueller Glacier and Frind Glacier, enlargement of nunataks (main divide ridge) and fast terminus recession such as at Fiddian Glacier (A) and complete loss of glaciers such as across the Ben Ohau Range (B). In both examples the background is a Sentinel 2A image from April 2019 to illustrate how the 2016 inventory is already quite significantly out of date.

without a lake (Fig. 7F). Given the amelioration of downstream runoff and water quality by lakes, this distribution and evolution of lakes is an important issue to understand. Between 2050 and 2100 the number of ice-marginal lakes and their volume could reduce concurrent with loss of contact with an ice-margin (Fig. 7G). That disconnection will make certain proglacial lakes even more vulnerable to sedimentation as hydraulic energy diminishes with distance from a glacier.

3. Discussion

3.1. Detecting and understanding the implications of rapid glacier changes

An ability to make frequent inventories of glaciers and of glacier lakes, enabled by cloud computing to acquire and process satellite imagery, has enabled rapid morphological changes to be detected more clearly and attributed to processes with greater certainty. Some of the differences between 2016 and 2019 in the number and area of glaciers (Table 1) might be quickly assumed to be due to methodological differences and error and uncertainty. However, rapid acceleration in recent years of changes to Southern Alps glaciers has been detected by Carrivick, James, Grimes, Sutherland, and Lorrey (2020a, Carrivick, Tweed, Sutherland, and Mallalieu, 2020b) and by Hugonnet et al. (2021). Indeed Hugonnet et al. (2021, p730) state “New Zealand, for example, shows a record thinning rate of 1.52 ± 0.50 m yr^{-1} in 2015-2019, which is a nearly sevenfold increase compared to 2000-2004”.

Overall, New Zealand temperatures have risen by 1.13 °C between 1909 and 2019 and that trend is consistent with warming observed in summer, autumn and winter since 1972 at 30 sites across New Zealand (Macara et al., 2020). These temperature changes explain the predominant component of glacier mass balance variability (Mackintosh et al., 2017), which since the late 1970s has been estimated from direct glacier observations (Chinn, 2001) that have demarcated notable ice recession (Chinn et al., 2012). Lorrey et al. (2022) recently reported that end of summer snowlines, which are a proxy for glacier mass balance, have risen on average by 150 m between the 2010 to 2019 decade and the 1985 to 1994 decade. The most recent decade has also seen an apparent acceleration of snowline rise. The implications from the collective observations and modelling results suggest as temperature has warmed, increased melt has occurred that has reduced glacier mass balance. The loss of ice has exposed what was formerly part of the subglacial reach, and increased the area of exposed glacier forelands or proglacial zones and the availability of topographic basins that can be occupied by meltwater.

Rapid disintegration of glaciers captured by high-resolution inventories has also been reported in Austria (Fischer et al., 2021) and glacier fragmentation can create problems for comparing glacier-specific metrics between the times when inventories are made (Fig. 2). The types of glacier changes reported in this study represent responses of glaciers to climate forcing, but they also highlight the importance of feedback mechanisms related to glacier mass loss. Specifically, the morphological changes and glacier-specific mass balance gradients will be influenced significantly in areas where there is presently lower surface slope angles over overdeepened subglacial basins near glacier termini. In locations where glaciers are expected to fragment, there should therefore be immediate and profound changes in the mass balance gradient (Anderson and Mackintosh, 2012). Besides glacier geometry, glacier surface characteristics are also important for glacier evolution modelling so it is important to realise that glaciers across the

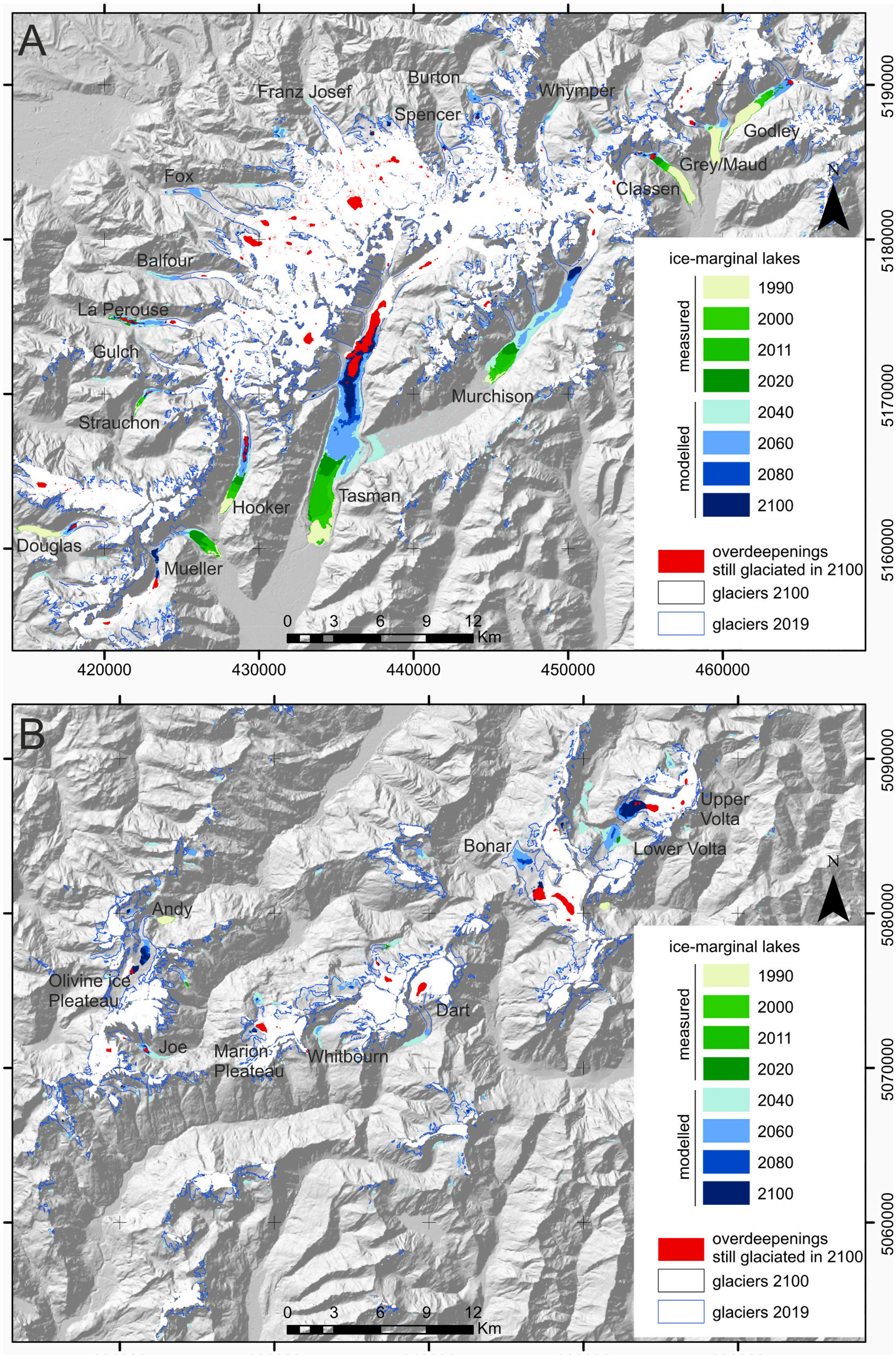

Fig. 4. Projection of future ice-marginal lake location, size and evolution for central Southern Alps within the Mt. Cook region (A) and the Mt. Aspiring region (B). For clarity only 20-year increments are shown for future projections and these are based on the SSP2–4.5 scenario. Note that the legend is cumulative, i.e. the area coloured for 2060 is the lake area in addition to that for 2040 and 2020, for example..

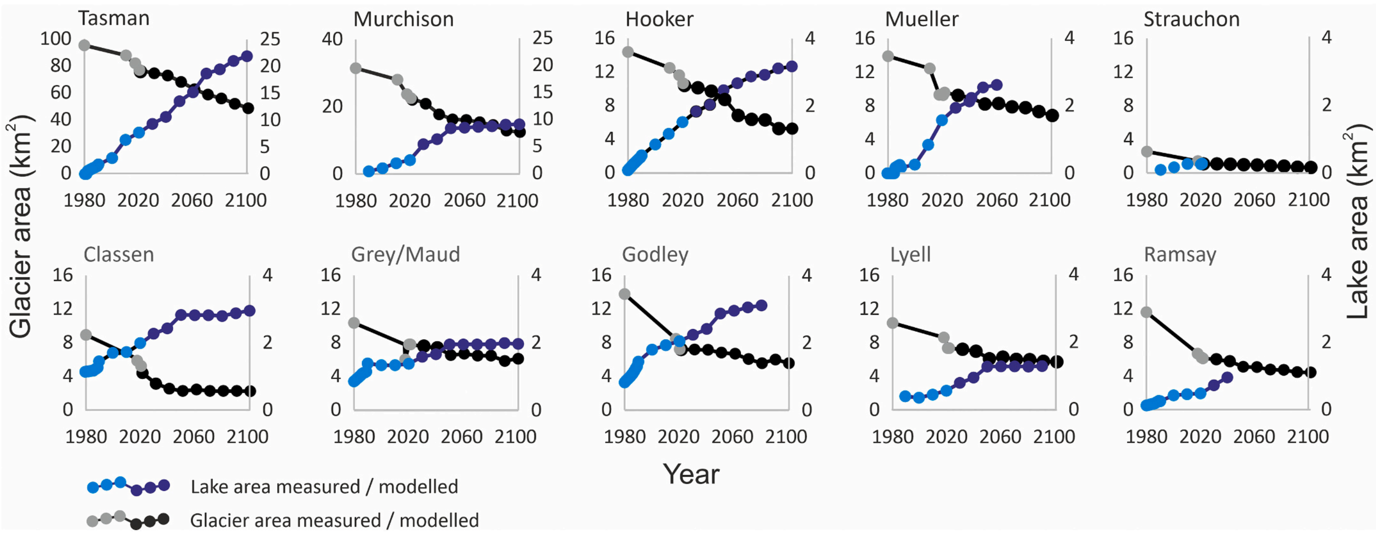

Fig. 5. Past, present and future glacier areas and lake areas, indicating the rate of change of each. These graphs are for the largest ten ice-marginal lakes only for brevity. Note that future glacier areas are the total for all of the projected disaggregated/fragmented parts of the 2019 original/single glacier. Note that the scale is different for Tasman and Murchison.

Southern Alps have been developing more debris-cover (Chinn, 1996; Kirkbride, 2000) and that now covers ~20% of the total glaciated surface area (Herreid and Pellicciotti, 2020), which is dominated by the thirteen largest glaciers.

3.2. Projecting the number and size of lakes

Previous work on estimating future glacier lake location and size has been dominated by usage of Glabtop (e.g. Allen et al., 2016; Colonia et al., 2017; Kapitsa et al., 2017; Drenkhan et al., 2018; Zhang et al., 2019; Magrani et al., 2020; Viani et al., 2020) which is a distributed ice thickness model by Linsbauer et al. (2012) from which glacier bed topography can be modelled. Where local depressions or basins in that subglacial bed topography (known as overdeepenings; Cook and Swift, 2012) are modelled, they can be interrogated for geometric changes (e.g. Magrani et al., 2020) and interpreted as favourable sites for ponding of meltwater and lake formation. Other mountain glacier ice thickness models such as VOLTA (James et al., 2019) or the HF-model (Huss and Farinotti, 2012) produce similar outputs and have been applied for the same purpose of estimating the position and size of glacier bed overdeepenings and hence future glacial lakes (e.g. across Patagonia and southern South America; Carrivick et al., 2016), the mountainous part of the Antarctic Peninsula (Carrivick et al., 2019), the southern Swiss Alps (Gharehchahi et al., 2020) or at a global scale (Huss and Farinotti, 2012). We also note that ice thickness models of this type best predict lake position and lake size for valley glaciers, not cirque glaciers (Otto et al., 2021).

Our usage of the Farinotti et al. (2019b) consensus ice thickness results has produced modelled overdeepenings that efficiently and correctly identified 80% of ice-marginal lake locations and also lake size 72% of the time (compared to measured) across the Southern Alps. That result reinforces the findings of agreement between Glabtop-modelled and measured overdeepenings by Viani et al. (2020) in northern Italy. Otto et al. (2021) identified disagreements between the Glatop- and HF-modelled overdeepenings and proglacial lakes across Austria, but those disagreements were for small mountain glaciers, not valley glaciers. Thresholding projected lakes by size as done herein and by Zheng et al. (2021) should remove a lot of this error. Where ice-marginal lakes have not developed within modelled overdeepenings across the Southern Alps that is visibly due to intense sedimentation causing basin-infilling; examples include Barlow/Ferrar, Kerrow, Otoko, Joe, Arthur, Richardson and Whitbourn glaciers and Marion Plateau, for example. Our usage of the Farinotti et al. (2019b) consensus ice thickness results has also gone beyond simply modelling the appearance of lakes and suggested the timing of future lake formation and the rate of growth of those lakes.

Sedimentation has also been noted to be the cause of lakes decreasing in size or even disappearing (Mölg et al., 2021; Otto et al., 2021). These environmental factors confound projections of future lakes not least because climate scenarios, on which the glacier evolution models depend have far greater uncertainty in rainfall (than in air temperature), which will alter rates of sediment fluxes via paraglacial slope adjustment and permafrost degradation (Carrivick and Tweed, 2021).

3.3. Projecting the timing of formation and lake evolution

Most studies of future ice-marginal lakes only consider glacier bed topography and thus treat future lakes as a binary presence/absence. They negate the timing of future lake formation and evolution (e.g. first appearance, or full development) because that is dependent on projections of glacier evolution, which are not trivial. One approach to circumvent this problem has been to extrapolate rates of change to glaciers from recent decades and to project those into the future (e.g. Zhang et al., 2019; Magnin et al., 2020). Slightly more mindful of the (changing) climate forcing, Drenkhan et al. (2018) and Emmer et al. (2020) both used projections of freezing level height to estimate the timing of exposure of formerly-ice-covered terrain.

Nevertheless, despite the uncertainty in the timing of future lake evolution due to the uncertainty in climate forcing on glacier evolution, using a mid-range climate forcing SSP2–4.5 it can be shown that (i) not many more ice-marginal lakes will form across the Southern Alps, (ii) the combined size of all the lakes could be expected to double by 2100 (Table 2), (iii) the number of lakes and the combined area of all lakes will increase during the next two to three decades, (iv) will be stable for two to three decades and then will diminish over the remaining two to three decades to 2100 as lakes disconnect from the ice margin (Table 2), (v) individual lake size will continue to increase at a rate no greater than the last decade to mid-21st century and then that rate will diminish towards 2100 (Fig. 4, Fig. 4). In general, the results of number and size and location of lakes for other climate scenarios SSP1–1.9, SSP1–2.6 and SSP3–7.0 are similar. With the high emission scenario SSP5–8.5 lakes are located in the same place and ultimately develop to the same size but lake growth occurs earlier and faster.

The suggestion of two groups of glaciers; one with projected rate of change approximately equivalent to that of the past, and one with a

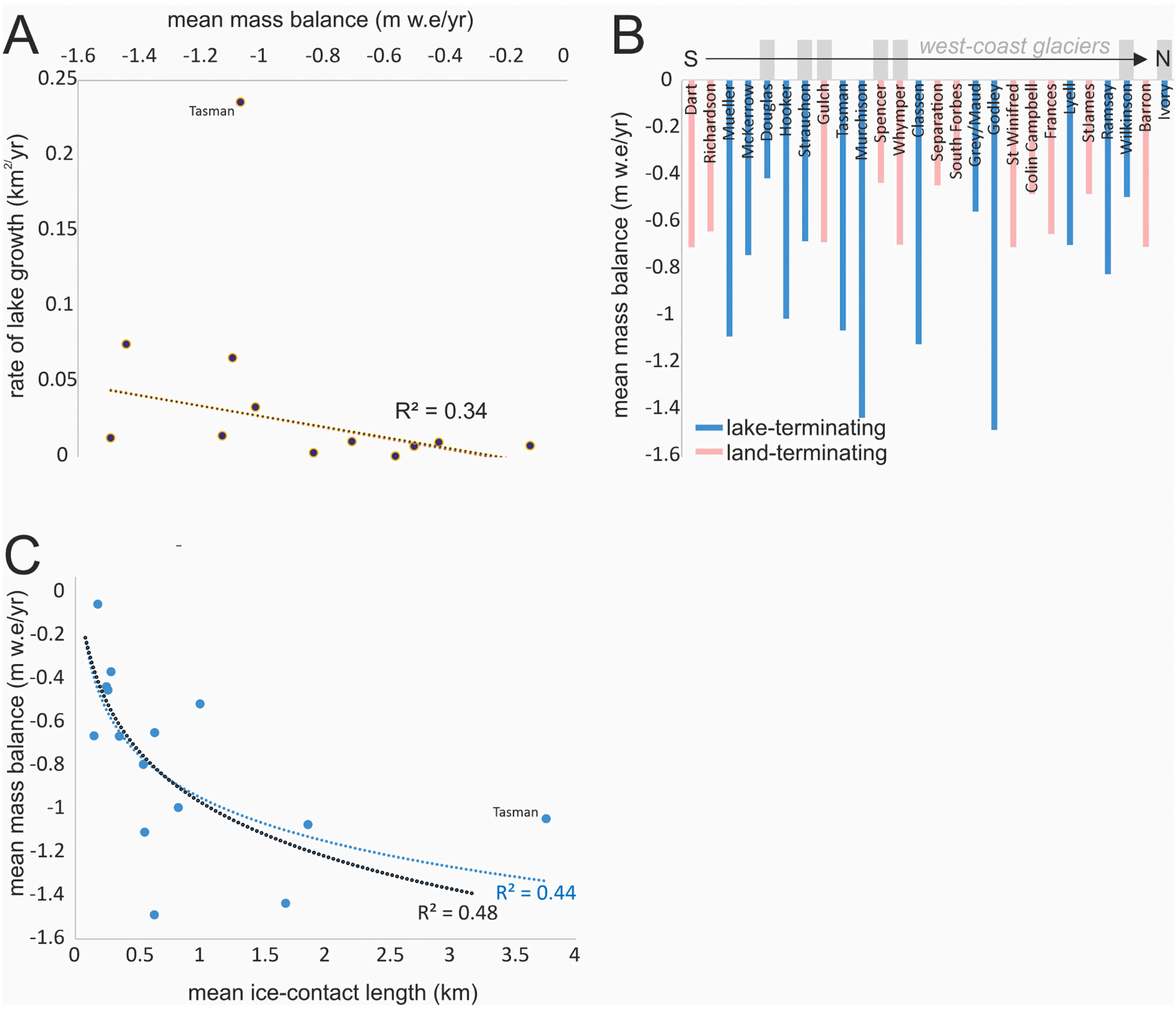

Fig. 6. Positive relationship between mean geodetic glacier mass balance 2000 to 2020 as from Hugonnet et al. (2021) and rate of lake growth (A). The mass balance (mean of 2000 to 2020) of glaciers with ice-marginal lakes is more negative (statistically significant at $p < 0.05$) to that of glaciers without, irrespective of geographic location (B). The length of an ice-contact boundary seems an important metric in relation to the effect of lakes on glaciers (C). Note that Tasman glacier is excluded as an outlier from the correlation statistic in panel A but does not form an outlier to the relationship in panel C. In panel B glaciers with lakes were paired with another glacier (land-terminating, i.e. without a lake) selected for being of a similar size and in a nearby valley.

projected decrease in rate of areal decline (Fig. 5) can be interpreted as reflecting the influence of local topography and glacier dynamics. More specifically, the size and geometry of any overdeepening, and in particular the length and gradient of a retrograde/reverse bed slope, are key determinants.

The Southern Alps have relatively few ice-marginal lakes today ($n = 17$; Table 2) as a proportion of the number of glaciers ($n = 2061$ in 2019 inventory; Table 1). In comparison, 40 lakes are projected at 23 glaciers of c. 600 across Austria by Otto et al. (2021), and 46 potential locations predicted for 183 glaciers in northern Italy by Viani et al. (2020). The density of lakes in these other studies might be higher than in this study because those studies have not discriminated ice-marginal lakes from other proglacial lakes. Nonetheless, the relatively low numbers of glacier lakes across the Southern Alps can be explained to be due to the very steep topography, the presence of relatively few valley glaciers (most are hanging or niche type glaciers), and the exceptionally high sediment flux which can quickly fill overdeepenings.

When glaciers were larger at the conclusion of the LIA, the density of ice-marginal lakes across the Southern Alps may have been higher because there were fewer glaciers (smaller individual glaciers were coalesced then) and because we have only focused on >200 large (> 0.5 km^2) lakes between estimated LIA glacier extents (Carrivick et al., 2020a; Carrivick et al., 2020b) and 1978 glacier limits (Chinn, 2001). Exactly how many lakes were ice-marginal or coincident during that timespan is uncertain. However, if the density of lakes was higher than present, then their influence on capturing meltwater generation and buffering sediment flux impacts (Carrivick and Heckmann, 2017; Carrivick and Tweed, 2021) may have been important and is an under-studied component of the proglacial landscape history of the Southern Alps.

3.4. Implications of lake formation and enlargement

The association identified between mean glacier mass balance (2000 to 2020) and rate of lake growth (Fig. 6A) can be interpreted to indicate a bidirectional relationship; that the presence and properties of a proglacial lake can influence glacier mass balance (Carrivick et al., 2020a, Carrivick et al., 2020b) and that glacier mass balance can influence lake evolution. That the correlation is not stronger and that fact that Tasman glacier may be an outlier could both be due to the relative importance of the contact length of the ice terminus with the lake. The length (and thickness) of glacier boundary with a lake was highlighted by Field et al. (2021) from an analysis of Gulf of Alaska glaciers as important for controlling lake evolution. We find a significant relationship between

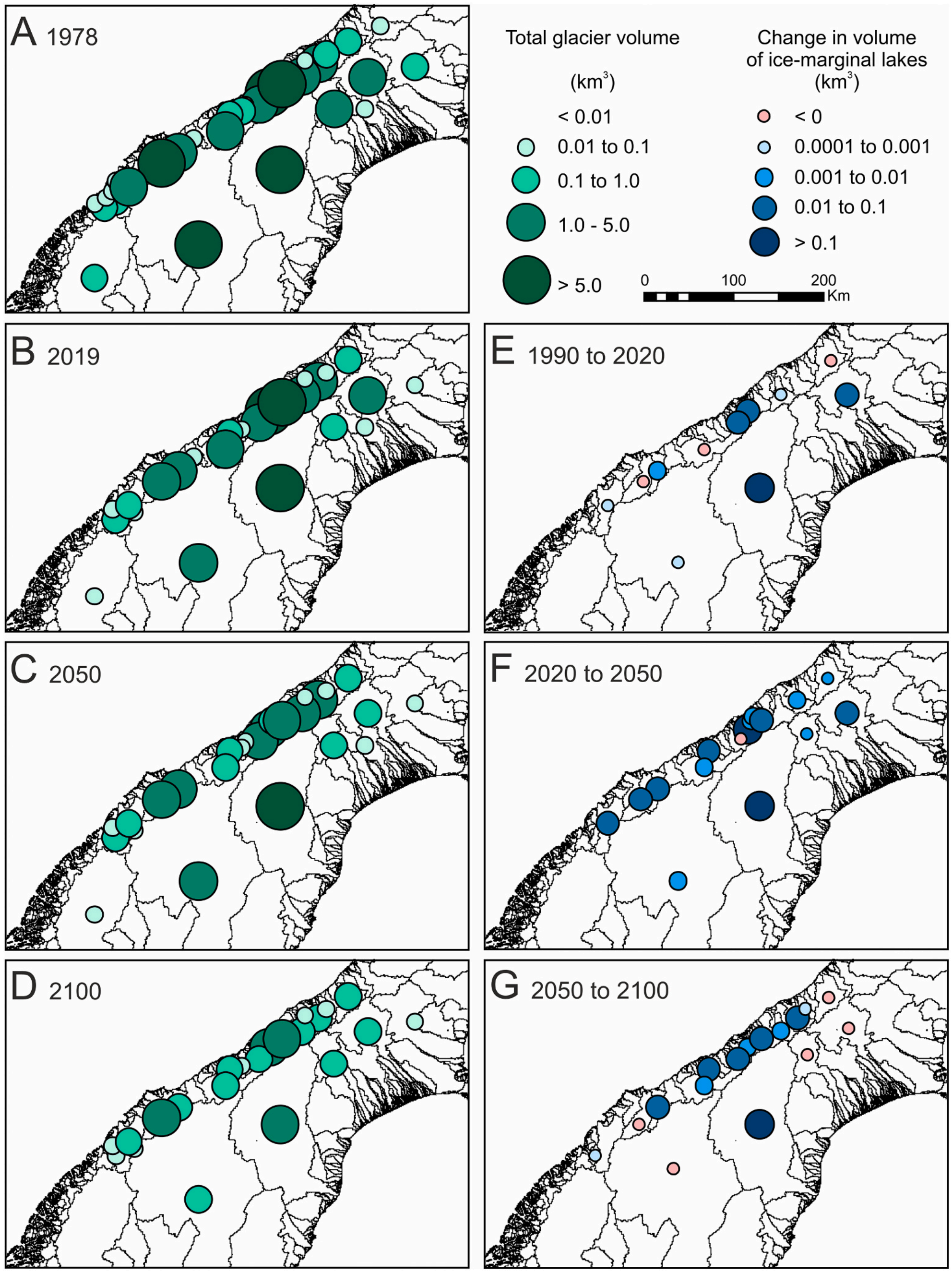

Fig. 7. Past, present and future coincident changes in the volume of glaciers and ice-marginal lakes across the Southern Alps, aggregated per river drainage basin. Results are based on glacier retreat modelled since 1978 and the corresponding growth of ice-marginal lakes according to the SSP2–4.5 scenario.

the mean length of an ice-contact lake boundary and the mean mass balance of a subset of Southern Alps glaciers (Fig. 6C). The implication of this finding is that the degree to which a lake affects the mass balance of a glacier, or vice versa, is not purely a function of lake size, but also relates to proglacial lake geometry. Our finding indicates that the mean mass balance between 2000 and 2020 for New Zealand glaciers that have ice-marginal lakes may be more negative than that of glaciers without lakes (Fig. 6B), which agrees with previous analyses of glaciers changes over the last few decades in Alaska (Field et al., 2021) and the Himalaya (e.g. Basnett et al., 2013; Thompson et al., 2016; King et al., 2018; Tsutaki et al., 2019). To a certain extent, more negative mass balance for glaciers with ice-marginal lakes compared to land-terminating glaciers can also be attributed by the general characteristics of such glaciers with wide, gently-sloping tongues which is an indication for long response times and, hence, a larger imbalance with current climate (Field et al., 2021). The direct effect of the ice-marginal lake on mass balance would need to be disentangled from glaciological effects with dedicated studies, such as numerical modelling experiments (Sutherland et al., 2020; Carrivick et al., 2020a; Carrivick et al., 2020b).

Keeping in mind that lakes dramatically alter downstream river discharge regimes and water quality, the spatially-discrete nature of our volumetric analysis of coincidental changes to glaciers and ice-marginal lakes across the Southern Alps (Fig. 7) means that water resource-related opportunities and risks can be targeted, such as for societal concerns including reservoirs, hydropower, tourism and sudden outburst floods. In addition, the modelling of future lake development reveals new aspects of the natural environmental system that will impinge upon or that underpin mountain landscape stability, biodiversity and ecosystem services.

4. Conclusions

Hugonnet et al. (2021) reported that the Southern Alps of New Zealand are now experiencing some of the most rapid and most accelerated changes in glacier mass loss anywhere in the World. Lorrey et al. (2022) report a 150 m elevation rise in end of summer snowlines across the Southern Alps and hence a much-decreased accumulation area of glaciers between 2010 and 2019 compared to 1985 to 1994. In this study we (i) quantify the recent glacier loss (number and combined area) between 2015 and 2019, (ii) observe rapid and profound changes in glacier morphology via fragmentation including separation of glacier tributaries and detachment of ablation zones, especially between 2015 and 2019, and (iii) quantify past, present and future ice-marginal proglacial lake development.

We conducted a systematic inventory of ice-marginal proglacial lakes across the Southern Alps and quantified a positive relationship between glacier mass balance over two decades and coincident lake growth. This finding is compelling for the need to include lake effects within glacier evolution models (Carrivick et al., 2020a, Carrivick et al., 2020b). We also suggest that glaciers with ice-marginal lakes have had a more negative mass balance (between 2000 and 2020) and exhibit greater variability in mass balance than land-terminating glaciers.

Projecting future glacier evolution and modelling the location and size of overdeepenings in glacier bed topography permitted the timing of new lake formation and the duration of the contact between lake water and the ice margin to be estimated. These findings show that ice-marginal lakes will be pervasive across the Southern Alps for many decades to come. There will be more and larger (~ 150% combined areal size) ice-marginal lakes within tens of decades from now and correspondingly more glaciers and more drainage basins will be affected by them. Given that ice-marginal lakes affect glacier behaviour, ameliorate meltwater discharge and efficiently trap meltwater-transported sediment (Carrivick and Chase, 2011), we contend that our findings will be of interest to glacier evolution modellers, water resource analysts, and studies concerned with landscape evolution and ecosystem services.

Data availability

Our image mosaics made in Google Earth Engine for our analysis of historical (1990, 2000, 2010, 2020) ice-marginal lakes and for 2019 glaciers can be found at https://drive.google.com/drive/folders/1DTbEeLuWo-PcbgoF9jJWKJz7IpHaiYEO?usp=sharing and https://drive.google.com/drive/folders/1PALioAik4J65OM5yz5aA1AV7xNvfKIU6?usp=sharing, respectively. Our 2019 glacier outlines, historical lake outlines and our overdeepenings, which mark the position and possible size of future lakes, are made available as shapefiles within a single supplementary zipped directory.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

JLC thanks the late Trevor Chinn for his enthusiastic discussions. Owen King is thanked for supplying the ALOS DEM. Parts of this work were completed whilst WHMJ, MG, JLS and CDS were in receipt of NERC PhD studentships grants NE/K500847/1, NE/L002574/1, NE/L002574/1 and NE/S007458/1, respectively. Contributions from AML and Southern Alps lake outline data from previous work were both supported by the NIWA Strategic Science Investment fund project “Climate Present and Past” contract CAOA2201.

References

Allen, S.K., Linsbauer, A., Randhawa, S.S., Huggel, C., Rana, P., Kumari, A., 2016. Glacial lake outburst flood risk in Himachal Pradesh, India: an integrative and anticipatory approach considering current and future threats. Nat. Hazards 84, 1741–1763.

Anderson, B., Mackintosh, A., 2012. Controls on mass balance sensitivity of maritime glaciers in the Southern Alps, New Zealand: the role of debris cover. J. Geophys. Res. Earth Surf. 117 (F1).

Anderson, S.W., Shean, D., 2021. Spatial and temporal controls on proglacial erosion rates: a comparison of four basins on Mount Rainier, 1960 to 2017. Earth Surf. Process. Landf. 47 (2), 596–617.

Anderson, B., Mackintosh, A.N., Dadić, R., Oerlemans, J., Zammit, C., Doughty, A., Sood, A., Mullan, B., 2021. Modelled response of debris-covered and lake-calving glaciers to climate change, Kā Tiritiri o te Moana/Southern Alps, New Zealand. Glob. Planet. Chang. 205, 103593.

Barrell, D.J.A., 2011. Quaternary Glaciers of New Zealand. In Developments in Quaternary Sciences, vol. 15. Elsevier, pp. 1047–1064.

Basnett, S., Kulkarni, A.V., Bolch, T., 2013. The influence of debris cover and glacial lakes on the recession of glaciers in Sikkim Himalaya, India. J. Glaciol. 59, 1035–1046.

Baumann, S., Anderson, B., Chinn, T., Mackintosh, A., Collier, C., Lorrey, A.M., Rack, W., Purdie, H., Eaves, S., 2021. Updated inventory of glacier ice in New Zealand based on 2016 satellite imagery. J. Glaciol. 67, 13–26.

Beniston, M., Stoffel, M., Hill, M., 2011. Impacts of climatic change on water and natural hazards in the Alps: can current water governance cope with future challenges? Examples from the European “ACQWA” project. Environ. Sci. Pol. 14, 734–743.

Buckel, J., Otto, J.C., Prasicek, G., Keuschnig, M., 2018. Glacial lakes in Austria-distribution and formation since the Little Ice Age. Glob. Planet. Chang. 164, 39–51.

Carrivick, J.L., Chase, S.E., 2011. Spatial and temporal variability of annual glacier equilibrium line altitudes in the Southern Alps, New Zealand. N. Z. J. Geol. Geophys. 54, 415–429.

Carrivick, J.L., Heckmann, T., 2017. Short-term geomorphological evolution of proglacial systems. Geomorphology 287, 3–28.

Carrivick, J.L., Rushmer, E.L., 2009. Inter-and intra-catchment variations in proglacial geomorphology: an example from Franz Josef Glacier and Fox Glacier, New Zealand. Arct. Antarct. Alp. Res. 41, 18–36.

Carrivick, J.L., Tweed, F.S., 2021. Deglaciation controls on sediment yield: Towards capturing spatio-temporal variability. Earth Sci. Rev. 221, 103809.

Carrivick, J.L., Davies, B.J., James, W.H., Quincey, D.J., Glasser, N.F., 2016. Distributed ice thickness and glacier volume in southern South America. Glob. Planet. Chang. 146, 122–132.

Carrivick, J.L., Davies, B.J., James, W.H., McMillan, M., Glasser, N.F., 2019. A comparison of modelled ice thickness and volume across the entire Antarctic Peninsula region. Geografiska Annaler Ser. A Phys. Geogr. 101, 45–67.

Carrivick, J.L., James, W.H., Grimes, M., Sutherland, J.L., Lorrey, A.M., 2020a. Ice thickness and volume changes across the Southern Alps, New Zealand, from the little ice age to present. Sci. Rep. 10, 1–10.

Carrivick, J.L., Tweed, F.S., Sutherland, J.L., Mallalieu, J., 2020b. Toward numerical modeling of interactions between ice-marginal proglacial lakes and glaciers. Front. Earth Sci. 8, 500.

CAT, 2021. Climate Action Tracker. https://climateactiontracker.org/ (last visited December, 2021).

Chinn, T.J., 1996. New Zealand glacier responses to climate change of the past century. New Zealand Journal of Geology and Geophysics 39, 415-428.Chinn, T.J., 1999. New Zealand glacier response to climate change of the past 2 decades. Glob. Planet. Chang. 22, 155–168.

Chinn, T.J., 1999. New Zealand glacier response to climate change of the past 2 decades. Global Planet. Chang. 22 (1–4), 155–168.

Chinn, T.J.H., 2001. Distribution of the glacial water resources of New Zealand. 2001. J. Hydrol. 40, 139–187.

Chinn, T., et al., 2012. Annual ice volume changes 1976-2008 for the New Zealand Southern Alps. Glob. Planet. Chang. 92–93, 105–118.

Colonia, D., Torres, J., Haeberli, W., Schauwecker, S., Braendle, E., Giraldez, C., Cochachin, A., 2017. Compiling an inventory of glacier-bed overdeepenings and potential new lakes in de-glaciating areas of the Peruvian Andes: approach, first results, and perspectives for adaptation to climate change. Water 9, 336.

Compagno, L., Huss, M., Miles, E.S., McCarty, M.J., Zekollari, H., Pellicciotti, F., Farinotti, D., 2021. Modelling supraglacial debris-cover evolution from the single glacier to the regional scale: an application to High Mountain Asia. Cryosphere Discuss. 1–33.

Cook, S.J., Swift, D.A., 2012. Subglacial basins: their origin and importance in glacial systems and landscapes. Earth Sci. Rev. 115, 332–372.

Drenkhan, F., Guardamino, L., Huggel, C., Frey, H., 2018. Current and future glacier and lake assessment in the deglaciating Vilcanota-Urubamba basin, Peruvian Andes. Glob. Planet. Chang. 169, 105–118.

Dykes, R., Brook, M., Robertson, C., Fuller, I., 2011. Twenty-first century calving retreat of Tasman Glacier, Southern Alps, New Zealand. Arct. Antarct. Alp. Res. 43, 1–10.

Emmer, A., Harrison, S., Mergili, M., Allen, S., Frey, H., Huggel, C., 2020. 70 years of lake evolution and glacial lake outburst floods in the Cordillera Blanca (Peru) and implications for the future. Geomorphology 365, 107178.

Eyring, V., Bony, S., Meehl, G.A., Senior, C.A., Stevens, B., Stouffer, R.J., Taylor, K.E., 2016. Overview of the coupled Model Intercomparison Project phase 6 (CMIP6) experimental design and organization. Geosci. Model Dev. 9, 1937–1958.

Farinotti, D., Brinkerhoff, D.J., Clarke, G.K., Fürst, J.J., Frey, H., Gantayat, P., Gillet-Chaulet, F., Girard, C., Huss, M., Leclercq, P.W., Linsbauer, A., 2017. How accurate

are estimates of glacier ice thickness? Results from ITMIX, the Ice Thickness Models Intercomparison eXperiment. Cryosphere 11, 949–970.
Farinotti, D., Round, V., Huss, M., Compagno, L., Zekollari, H., 2019a. Large hydropower and water-storage potential in future glacier-free basins. Nature 575, 341–344.
Farinotti, D., Huss, M., Fürst, J.J., Landmann, J., Machguth, H., Maussion, F., Pandit, A., 2019b. A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nat. Geosci. 12, 168–173.
Field, H.R., Armstrong, W.H., Huss, M., 2021. Gulf of Alaska ice-marginal lake area change over the Landsat record and potential physical controls. Cryosphere 15, 3255–3278.
Fischer, A., Schwaizer, G., Seiser, B., Helfricht, K., Stocker-Waldhuber, M., 2021. High-resolution inventory to capture glacier disintegration in the Austrian Silvretta. Cryosphere 15, 4637–4654.
Gharehchahi, S., James, W.H., Bhardwaj, A., Jensen, J.L., Sam, L., Ballinger, T.J., Butler, D.R., 2020. Glacier Ice Thickness Estimation and Future Lake Formation in Swiss Southwestern Alps - the Upper Rhône Catchment: a VOLTA Application. Remote Sens. 12, 3443.
Google, 2021. Compositing and Mosaicking. Retrieved November 8, 2021, from. https://developers.google.com/earth-engine/guides/ic_composite_mosaic.
Haeberli, W., Buetler, M., Huggel, C., Friedli, T.L., Schaub, Y., Schleiss, A.J., 2016. New lakes in deglaciating high-mountain regions–opportunities and risks. Clim. Chang. 139, 201–214.
Haeberli, W., Oerlemans, J., Zemp, M., 2019. The future of alpine glaciers and beyond. In: Oxford Research Encyclopedia of Climate Science.
Henderson, R.D., Thompson, S.M., 1999. Extreme rainfalls in the Southern Alps of New Zealand. J. Hydrol. 38, 309–330.
Herreid, S., Pellicciotti, F., 2020. The state of rock debris covering Earth's glaciers. Nat. Geosci. 13, 621–627.
Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Dahlgreen., 2020. The ERA5 global reanalysis. Q. J. R. Meteorol. Soc. 146, 1999–2049.
Hirabayashi, Y., Döll, P., Kanae, S., 2010. Global-scale modeling of glacier mass balances for water resources assessments: Glacier mass changes between 1948 and 2006. J. Hydrol. 390, 245–256.
Hochstein, M., Claridge, D., Henrys, S., Pyne, A., Nobes, D., Leary, S., 1995. Downwasting of the Tasman Glacier, South Island, New Zealand: changes in the terminus region between 1971 and 1993. N. Z. J. Geol. Geophys. 38, 1–16.
Hochstein, M., Watson, M., Malengreau, B., Nobes, D., Owens, I.F., 1998. Rapid melting of the terminal section of the Hooker Glacier (Mt Cook National Park, New Zealand). N. Z. J. Geol. Geophys. 41, 203–218.
Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., Kaab, A., 2021. Accelerated global glacier mass loss in the early twenty-first century. Nature. 592 (7856), 726–731.
Huss, M., Farinotti, D., 2012. Distributed ice thickness and volume of all glaciers around the globe. J. Geophys. Res. 117, F04010.
Huss, M., Hock, R., 2015. A new model for global glacier change and sea-level rise. Front. Earth Sci. 3, 54.
Huss, M., Hock, R., 2018. Global-scale hydrological response to future glacier mass loss. Nat. Clim. Chang. 8, 135–140.
Huss, M., Jouvet, G., Farinotti, D., Bauder, A., 2010. Future high-mountain hydrology: a new parameterization of glacier retreat. Hydrol. Earth Syst. Sci. 14, 815–829.
James, W.H., Carrivick, J.L., Quincey, D.J., Glasser, N.F., 2019. A geomorphology based reconstruction of ice volume distribution at the last Glacial Maximum across the Southern Alps of New Zealand. Quat. Sci. Rev. 219, 20–35.
Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, I., Medeu, A., 2017. Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling. Nat. Hazards Earth Syst. Sci. 17, 1837–1856.
King, O., Dehecq, A., Quincey, D., Carrivick, J., 2018. Contrasting geometric and dynamic evolution of lake and land-terminating glaciers in the central Himalaya. Glob. Planet. Chang. 167, 46–60.
Kirkbride, M.P., 2000. Ice-marginal geomorphology and Holocene expansion of debris-covered Tasman Glacier, New Zealand. IAHS Publ. 211–218.
Kirkbride, M., Warren, C., 1999. Tasman Glacier, New Zealand: 20th-century thinning and predicted retreat. Glob. Planet. Chang. 22, 11–28.
Linsbauer, A., Paul, F., Haeberli, W., 2012. Modeling glacier thickness distribution and bed topography over entire mountain ranges with GlabTop: Application of a fast and robust approach. J. Geophys. Res. Earth Surf. 117 (F3).
Lorrey, A, Vargo, L., Purdie, H., et al., 2022. Southern Alps equilibrium line altitudes: four decades of observations show coherent glacier-climate responses and a rising snowline trend. J. Glaciol. In press.
Macara, G., Nichol, S., Sutherland, D., Liley, B., Paul, V., Srinivasan, R., 2020. Ministry for the Environment Atmosphere and Climate Report 2020: Updated Datasets Supplied by NIWA (NIWA Client Report no. 2020100WN). https://www.mfe.govt.nz/publications/environmental-reporting/ministry-environment-atmosphere-and-climate-report-2020-updated.
Mackintosh, A.N., Anderson, B.M., Lorrey, A.M., Renwick, J.A., Frei, P., Dean, S.M., 2017. Regional cooling caused recent New Zealand glacial advances in a period of global warming. Nat. Commun. 8, 1–13.
Magnin, F., Haeberli, W., Linsbauer, A., Deline, P., Ravanel, L., 2020. Estimating glacier-bed overdeepenings as possible sites of future lakes in the de-glaciating Mont Blanc massif (Western European Alps). Geomorphology 350, 106913.
Magrani, F., Valla, P.G., Gribenski, N., Serra, E., 2020. Glacial overdeepenings in the Swiss Alps and foreland: Spatial distribution and morphometrics. Quat. Sci. Rev. 243, 106483.
Meinshausen, M., Nicholls, Z.R., Lewis, J., Gidden, M.J., Vogel, E., Freund, M., et al., 2020. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions. Geosci. Model Dev. 13, 3571–3605.
Milner, A.M., Khamis, K., Battin, T.J., Brittain, J.E., Barrand, N.E., Füreder, L., Cauvy-Fraunié, S., Gíslason, G.M., Jacobsen, D., Hannah, D.M., Hodson, A.J., 2017. Glacier shrinkage driving global changes in downstream systems. Proc. Natl. Acad. Sci. 114, 9770–9778.
Mölg, N., Huggel, C., Herold, T., Storck, F., Allen, S., Haeberli, W., Schaub, Y., Odermatt, D., 2021. Inventory and evolution of glacial lakes since the Little Ice Age: Lessons from the case of Switzerland. In: Earth Surface Processes and Landforms.
Otto, J.C., Helfricht, K., Prasicek, G., Binder, D., Keuschnig, M., 2021. Testing the performance of ice thickness models to estimate the formation of potential future glacial lakes in Austria. Earth Surf. Process. Landf. 47, 723–741.
Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A.A., Hultman, N., McJeon, H., 2021. Can updated climate pledges limit warming well below 2° C? Science 374, 693–695.
Purdie, H., Bealing, P., Tidey, E., Gomez, C., Harrison, J., 2016. Bathymetric evolution of Tasman Glacier terminal lake, New Zealand, as determined by remote surveying techniques. Glob. Planet. Chang. 147, 1–11.
Purdie, H., Hughes Hutton, J., Stewart, E., Espiner, S., 2020. Implications of a changing alpine environment for geotourism: a case study from Aoraki/Munt Cook, New Zealand. J. Outdoor Recreat. Tour. 29, 1–10.
Quincey, D.J., Glasser, N.F., 2009. Morphological and ice-dynamical changes on the Tasman Glacier, New Zealand, 1990-2007. Glob. Planet. Chang. 68, 185–197.
Robertson, C.M., Benn, D.I., Brook, M.S., Holt, K.A., 2012. Subaqueous calving margin morphology at Mueller, Hooker and Tasman glaciers in Aoraki/Mount Cook National Park, New Zealand. J. Glaciol. 58 (212), 1037–1046.
Röhl, K., 2006. Thermo-erosional notch development at fresh-water-calving Tasman Glacier, New Zealand. J. Glaciol. 52, 203–213.
Shugar, D.H., Burr, A., Haritashya, U.K., Kargel, J.S., Watson, C.S., Kennedy, M.C., Bevington, A.R., Betts, R.A., Harrison, S., Strattman, K., 2020. Rapid worldwide growth of glacial lakes since 1990. Nat. Clim. Chang. 10, 939–945.
Sirguey, P., More, B., 2020. GLIMS Glacier Database. NSIDC, Boulder.
Sturman, A.P., Tapper, N.J., 1996. The Weather and Climate of Australia and New Zealand. Oxford University Press, USA.
Sutherland, J.L., Carrivick, J.L., Shulmeister, J., Quincey, D.J., James, W.H., 2019a. Ice-contact proglacial lakes associated with the last glacial maximum across the Southern Alps, New Zealand. Quat. Sci. Rev. 213, 67–92.
Sutherland, J.L., Carrivick, J.L., Evans, D.J., Shulmeister, J., Quincey, D.J., 2019b. The Tekapo Glacier, New Zealand, during the last Glacial Maximum: an active temperate glacier influenced by intermittent surge activity. Geomorphology 343, 183–210.
Sutherland, J.L., Carrivick, J.L., Gandy, N., Shulmeister, J., Quincey, D.J., Cornford, S.L., 2020. Proglacial lakes control glacier geometry and behavior during recession. Geophys. Res. Lett. 47 (p.e2020GL088865).
Thompson, S., Benn, D.I., Mertes, J., Luckman, A., 2016. Stagnation and mass loss on a Himalayan debris-covered glacier: processes, patterns and rates. J. Glaciol. 62, 467–485.
Tsutaki, S., Fujita, K., Nuimura, T., Sakai, A., Sugiyama, S., Komori, J., Tshering, P., 2019. Contrasting thinning patterns between lake-and land-terminating glaciers in the Bhutanese Himalaya. Cryosphere 13, 2733–2750.
Viani, C., Machguth, H., Huggel, C., Godio, A., Franco, D., Perotti, L., Giardino, M., 2020. Potential future lakes from continued glacier shrinkage in the Aosta Valley Region (Western Alps, Italy). Geomorphology 355, 107068.
Warren, C., Kirkbride, M., 1998. Temperature and bathymetry of ice-contact lakes in Mount Cook National Park, New Zealand. N. Z. J. Geol. Geophys. 41, 133–143.
Welty, E., Zemp, M., Navarro, F., Huss, M., Fuerst, J.J., Gaertner-Roer, I., Landmann, J., Machguth, H., Naegeli, K., Andreassen, L.M., Farinotti, D., Li, H., Contributors, GlaThiDa, 2020. Worldwide version-controlled database of glacier thickness observations. Earth Syst. Sci. Data 12, 3039–3055.
Willsman, A., 2017. Annual glacier ice volumes, 1977-2016. Prepared for Ministry for the Environment, NIWA Client Report 2017127EI: 20.
Zemp, M., Huss, M., Thibert, E., Eckert, N., McNabb, R., Huber, J., Barandun, M., Machguth, H., Nussbaumer, S.U., Gärtner-Roer, I., Thomson, L., 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature 568, 382–386.
Zhang, G., Bolch, T., Allen, S., Linsbauer, A., Chen, W., Wang, W., 2019. Glacial lake evolution and glacier–lake interactions in the Poiqu River basin, central Himalaya, 1964–2017. J. Glaciol. 65, 347–365.
Zheng, G., Allen, S.K., Bao, A., Ballesteros-Cánovas, J.A., Huss, M., Zhang, G., Li, J., Yuan, Y., Jiang, L., Yu, T., Chen, W., 2021. Increasing risk of glacial lake outburst floods from future Third Pole deglaciation. Nat. Clim. Chang. 11, 411–417.