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Aoraki Mount Cook: Environmental Change on an Iconic Mountaineering Route

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Aoraki Mount Cook is New Zealand's highest mountain and a popular destination for climbers. This study combined historical accounts, photos, and geophysical surveys with modern-day spatial analysis, popular narratives, and interviews to explore how conditions on the most popular climbing route up the mountain, the Linda Glacier route, have changed over time. Results highlight significant change on the lower section of the route due to ongoing downwasting of the Tasman Glacier; but higher on the mountain, changes in the route are more strongly associated with year-to-year variability in snow conditions. Even so, recent observations of new rock exposures and a shortening of the climbing season due to earlier crevasse exposure may be indications of longer-term glacier change.

Keywords: *Mountaineering; glacier recession; downwasting; crevasses; Tasman Glacier; Linda Glacier; New Zealand.*

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Prologue

In the beginning there was no Aotearoa (New Zealand), just ocean. When Raki wedded Papatuānuku, some of his children came down from the heavens in a great canoe to visit their new mother. After their visit, Aoraki the oldest son misquoted his karakia *(prayer) to lift their canoe back to the heavens, and the canoe fell into the ocean instead and overturned. As the 4 brothers clambered to the high side of the canoe, they were turned to stone. They remain today as the high peaks of Kā Tiritiri o Te Moana (Southern Alps), with Aoraki, the highest and most sacred ancestor of Ngāi Tahu (a tribal group of one of New Zealand's first peoples), forever linking the supernatural and natural worlds.*

(Te Rūnanga o Ngāi Tahu 2013).

Introduction

Glaciers around the world are retreating at a historically unprecedented rate (Zemp et al 2015), with well-documented implications for sea level rise and global water resources (Vaughan et al 2013). New Zealand glaciers are aligned with this trend (Chinn et al 2012), but they also respond to regional-scale climate variability (Mackintosh et al 2017), a characteristic particularly evident at the iconic Fox and Franz Josef Glaciers, which have advanced and retreated with decadal regularity (Anderson et al 2008; Purdie et al 2014). When mountaineering started to gain popularity in New Zealand in the late 1800s (Wilson 2015), a number of the large valley glaciers were still at or in close proximity to their Little Ice Age extents (Chinn 1996). Glacier retreat impacts mountain access and has a flow-on effect to mountain recreation and tourism (Ritter et al 2012; Purdie 2013; Wilson et al 2015).

Physical change in glacierized mountain environments is diverse, including changes to ice volume, surface conditions and debris cover, slope gradients, magnitude and distribution of crevasses, and frequency of rockfall and icefall (Ritter et al 2012; Purdie 2013; Deline et al 2015). Degrading permafrost has been linked to rockfall and slope instability (Keuschnig et al 2005; Gruber and Haeberli 2007; Fischer et al 2013), although relationships between rockfall and climate warming still present some uncertainties in the New Zealand context (Allen et al 2011; Allen and Huggel 2013). Increased icefall (ice avalanche) activity from hanging glaciers in the European Alps has highlighted complex feedbacks between climate warming and the thermal structure of such glaciers (Haeberli and Beniston 1998; Haeberli 2005; Fischer et al 2013; Deline et al 2015).

In recent decades, ice volume in New Zealand has decreased by approximately 30% (Chinn et al 2012; Willsman 2017), but relationships between ice volume and mountain access are not straightforward (eg Ritter et al 2012; Purdie 2013). In valleys, loss of ice volume leads to the exposure and enlargement of steep and unstable lateral moraine walls (Blair 1994; Deline et al 2015) and new rock exposures (Keuschnig et al 2005). In steeper topography, reductions in ice thickness can increase the surface gradient and crevassing (Fischer et al 2011; Ritter et al 2012).

Crevasses form when stress exceeds ice strength; tensile stress acts to open a crevasse, while compressive stress (due to the weight of the overlying ice) works to squeeze a fracture closed (Hooke 2005; van der Veen 2008). In theory, a reduction in ice thickness will reduce ice creep, surface strain, and crevassing (Nye 1957). But in the upper reaches of a glacier, reduced ice thickness can steepen the surface slope as bed topography becomes more strongly reflected at the surface, increasing tensile stress and ice fracture. In concert with ice thinning is increased rock exposure, which is usually highly jointed and generally steeper than the previous glacier surface (Ritter et al 2012). Research in the European Alps has demonstrated that increasing temperatures are resulting in more rapid depletion of the winter snowpack (Marty and Meister 2012). A thinner seasonal snowpack and loss of firn (compacted snow that has not yet turned into glacier ice) also results in earlier exposure of crevasses, and thinner snow bridges between crevasses can make route navigation more complicated and dangerous (Ritter et al 2012; Wilson et al 2015).

The observed reduction in glacier volume since the 1880s in New Zealand is associated with observed increases in temperature (Chinn 1996), which enhance snow and ice melt and raise the rain/snow elevation threshold. A temperature increase of 1.11°C per century has been estimated for Hokitika, the long-term climate recording site which most strongly correlates with observations in Aoraki Mount Cook (Mullan et al 2010). The temperature trends are similar for individual seasons, although the magnitude of the temperature increase is slightly lower for spring (Folland and Salinger 1995). Since 2007, the increasing temperature trend—estimated based on an average temperature lapse rate for the region of 5.5°C km^{-1} (Kerr 2005) and a recent (since 2007) mean daily summer temperature at Aoraki Mount Cook village of 14°C (NIWA n.d.)—is equivalent to raising the summer 0°C isotherm by 200 m per century to 2500 m. This temperature increase, particularly since 1951, is largely attributed to anthropogenic climate change (Bindoff et al 2013).

New Zealand glaciers are particularly sensitive to temperature changes as a result of their high precipitation regimes (Anderson and Mackintosh 2012). The mean annual (1971–2000) precipitation at Aoraki Mount Cook village has been estimated at 4300 mm, with 8000 to 10,000 mm estimated for the mountain itself (Kerr et al 2011). This precipitation can fall at any time of the year with little seasonal bias. The annual precipitation has a high interannual variability represented by a standard deviation of 15% at Aoraki Mount Cook village. No statistically significant long-term trend in precipitation has been observed in data for 1930 to 2000, although variability associated with multidecadal climate cycles has been identified (Kerr 2009).

Aside from the physical environment, much has changed in New Zealand alpine climbing over the years—for example, technical equipment, clothing, logistics, and knowledge of routes (Wilson 2015). These changes are generally viewed positively as making a summit bid more successful. Socially, shifts have been identified in motivation and time commitment to mountaineering activities, with more people opting for shorter (aircraft access) guided trips (Musa et al 2015; Wilson et al 2015).

Aoraki Mount Cook (hereafter Aoraki) is New Zealand's highest mountain and a key climbing destination (Figure 1). Attempts to climb Aoraki date back to the late 1800s (eg Green 1883). The Linda Glacier route (Figure 1B), the focus of the early attempts, is the least technical climbing route on the mountain, and consequently is the route most frequently climbed and most commonly used for descent (Palman 2001). Although less technical, the route is considered quite dangerous due to the risk of icefall and crevassing on the upper section of the glacier (Logan 1982; Palman 2001).

Aoraki is regarded as a sacred ancestor of Ngāi Tahu (see the prologue), so climbers are encouraged not to stand upon the very top, respecting the mountain's cultural significance (Department of Conservation 2004). A shift to more inclusive perspectives of the mountain was cemented in 1998 when the New Zealand government returned legal ownership of Aoraki to Ngāi Tahu, renamed the mountain, and acknowledged a *tōpuni* (protective status) extending over the mountain. Ngāi Tahu subsequently gifted the mountain back to the people of New Zealand as an enduring symbol of the tribe's commitment to ongoing comanagement of the Aoraki Mount Cook National Park (Ngāi Tahu Claims Settlement Act 1998:57; Te Rūnanga o Ngāi Tahu 2013).

Climbers traverse the Grand Plateau (Figure 1C) before heading up the Linda Glacier. The upper section of the glacier is an ice shelf, requiring a steep traverse toward Zurbriggen Ridge. Climbers then move through a band of rock (the summit rocks) and up onto an ice cap that leads to the summit. The round-trip climb generally takes 10–18 hours starting from Plateau Hut, with an elevation gain of 1700 m. Some climbers still follow Green's (1883) footsteps, beginning their climb from the Tasman Valley and ascending the Haast Ridge. But today, if walking from the valley floor, it is more common for climbers to use the Boys Glacier to gain access to the Grand Plateau.

The aim of this study was to explore physical change on the Linda Glacier climbing route from the late 1800s to the present. We used a mixed-methods approach (Tolich and Davidson 2011) to consider the magnitude, spatial variability, and rate of physical change on the route, and

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FIGURE 1 Study area and climbing route. (A) Location of study site on South Island, New Zealand; (B) Linda Glacier route, September 2007 (red line); (C) overview of full route, including key locations mentioned in the text, and location of the surface elevation transect (dashed red line) and Linda Glacier route (solid red line). (Section B photo by D. Sproules, supplied by A. McBride, Alpine Guides Aoraki; base map for section C is World Imagery from ESRI)

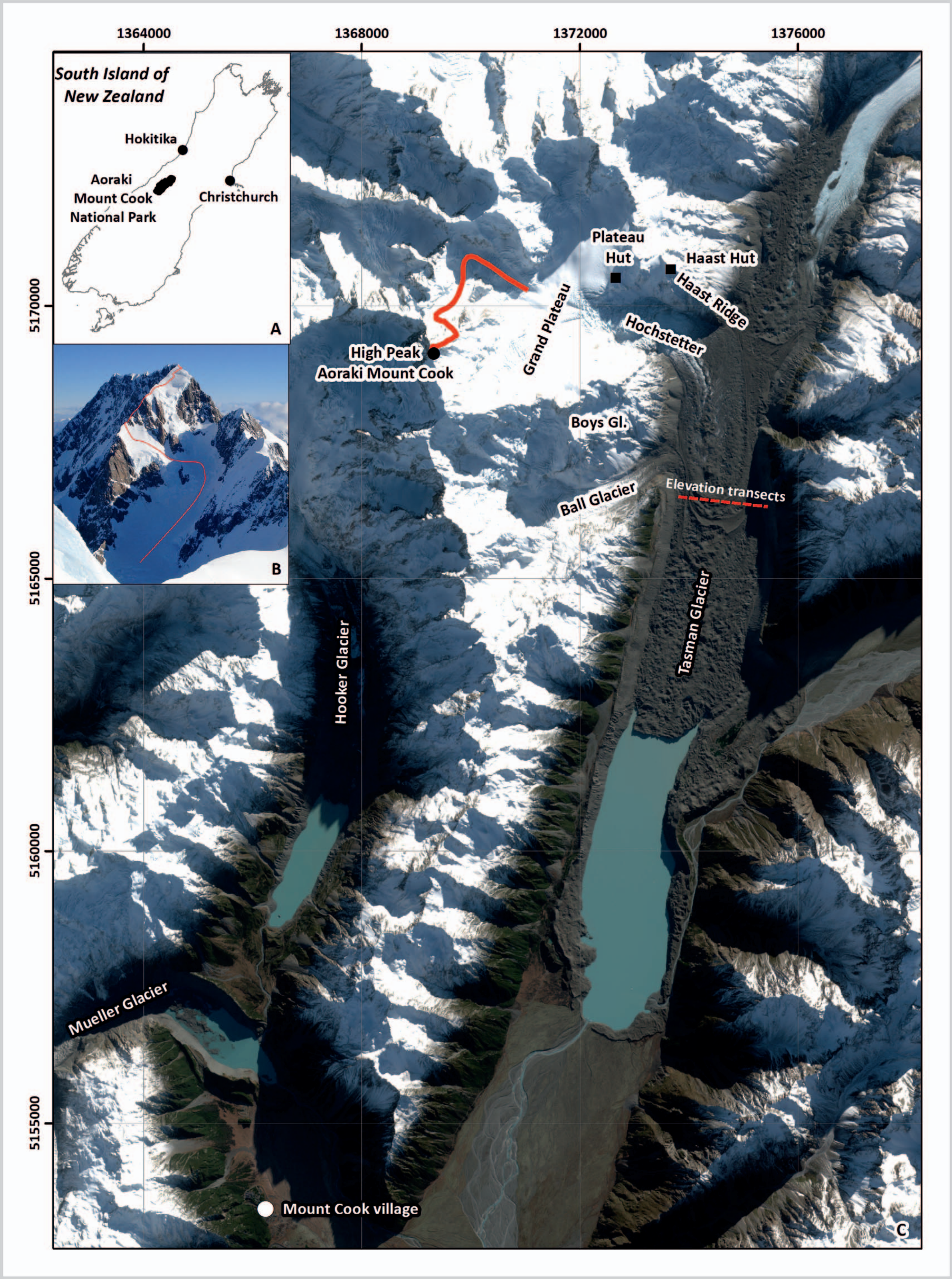

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TABLE 1 Tasman Glacier elevation survey data for transect near the Ball Glacier confluence. Transect is shown in Figure 1C.

Year	Average elevation (masl)	Surveyor	Source
1883	1149	R. von Lendenfeld	von Lendenfeld (1884)
1891	1128	T. N. Brodrick	Brodrick (1891)
1940	1078	A. P. Harper	Harper (1946)
1962	1044	B. E. Skinner	Skinner (1964)
1964	1016	Aerial	Department of Lands and Survey (1972)
1971	999	Department of Science and Industrial Research	Watson (1995)
1973	1002	Ministry of Works	Watson (1995)
1982	979	D. Claridge	Claridge (1983)
1986	973	Aerial	Department of Survey and Land Information (1992)
1986	969	M. Kirkbride	Kirkbride and Warren (1999)
1990	970	M. Hochstein	Watson (1995)
1993	969	M. Watson	Watson (1995)
1994	964	M. Watson	Watson (1995)
2000	946	Shuttle Radar Topography Mission	Farr et al (2007)
2007	948	B. Williams and J. Thomas	Available from corresponding author of this article
2008	946	P. Sirguey	Vivero et al (2012)
2013	927	R. Hart	Available from corresponding author of this article
2014	927	B. Anderson	Available from corresponding author of this article
2015	925	B. Anderson	Available from corresponding author of this article
2017	899	T. Kerr	Available from corresponding author of this article

explored how any changes on the route are perceived and experienced by people who have climbed the mountain.

Methods

Applying mixed methods to answer our research question enabled us to take a pragmatic approach and apply an appropriate combination of quantitative and qualitative techniques (Hay 2000; Tolich and Davidson 2011). We used historic maps, photographs, global positioning system and photogrammetric surveys, and satellite imagery to quantify change. We reviewed written accounts by early climbers, conducted email surveys and semistructured interviews with people who have climbed the route, reviewed online trip reports, and obtained information from hut logbooks. These descriptions of lived experiences provided important additional information about physical change not easily captured by cameras, satellites, or geophysical surveys.

Determination of physical change

Physical change on the Linda Glacier climbing route was quantitatively assessed for 2 features: the Tasman Glacier and the Linda Glacier (Figure 1C). On the Tasman Glacier, we assessed changes in surface elevation near the Ball Glacier confluence. When an ascent of Aoraki via the Linda Glacier route is made purely on foot, it is first necessary to access the Tasman Glacier and travel up it for some distance before ascending slopes leading toward the Grand Plateau. Intermittent surveys of surface elevation have been made on Tasman Glacier since the late 1800s. Methods have varied over time as technologies evolved. These data (summarized in Table 1) were projected to the same cross-glacier transect (Figure 1C), assuming an up-glacier surface slope of 2° following the method of Watson (1995). Where multiple elevations were surveyed at the same time, only those between New Zealand Transverse Mercator eastings 1,373,840 and 1,375,180 were averaged, providing a single comparable glacier elevation value.

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This limit was invoked to prevent a low-elevation bias caused by observations taken at the glacier edges.

These surveys provide objective measurements of how the surface of the Tasman Glacier has lowered over time. Where possible, the surveys were corrected to the same datum assuming the elevation of a shelter (Ball Hut) remained unchanged through the years. The precision of the surveys has varied with the technology but was expected to be less than the surface elevation variation, estimated at ±30 m, which was taken as the uncertainty estimate of each survey.

For the Linda Glacier, changes to ice thickness in the upper region were assessed by manual photographic analysis. Over the years, the Linda Glacier has been photographed by climbers from nearby summits and from aircraft. A total of 30 images spanning 120 years were reviewed for this project; 4 of these are shown in Figure 2. In the images, the same rock outcrops can be seen. If an ice mass is thinning, rock outcrops will increase in size and the distance between outcrops will diminish. The lack of knowledge of camera position and optical parameters for the images, and the lack of a high-resolution digital elevation model (DEM) for the region, meant orthorectification of the images was a nontrivial task.

As a pragmatic solution to the problem of obtaining absolute measurements from the oblique photographs, relative measurements of the vertical change in interrock distance compared to rock size were used as an index of glacier thinning. On each photo, the vertical extent between 2 rock outcrops in the middle of the glacier was compared to the vertical extent of the lower rock (distances x and y, respectively, in Figure 2D); the ratio between these measurements becomes smaller if the glacier thins and exposes more rock. This ratio was used as an index of the thickness of the upper Linda Glacier. We acknowledge that this method is subject to high uncertainty, as photographs were taken at different times of the year, from different locations, with different cameras. Despite this, the method provides a first approximation of potential change in the upper Linda Glacier.

In addition to the photographic analysis, an assessment of surface elevation change along the Linda Glacier route using DEMs from 1986 and 2008 was undertaken, but large potential errors of the DEM data in steep terrain (Columbus et al 2011) meant that the detected thinning and steepening fell within the potential errors of the 1986 DEM surface (*Supplemental material*, Appendix S1 and Figure S1, http://dx.doi.org/10.1659/MRD-JOURNAL-D-18-00042.S1).

Determination of change experience

To gain further understanding of changes on the Linda Glacier climbing route and how those changes are perceived and experienced, we consulted published historical accounts written by early climbers (eg Green 1883; Du Faur 1915; Bowie 1969; Dennistoun and Mannering 1999), present-day trip reports published online (eg, www.summitpost.org), and intentions recorded by climbers in logbooks at Plateau and Haast Huts, and conducted our own semistructured interviews and email surveys. We wanted to capture the opinions and experiences of amateur (recreational) climbers and professional guides who had climbed the route once or, ideally, multiple times over multiple years. Climber responses remained anonymous and were only tagged as recreational (Rec) or professional (Guide) perspectives. Notes were taken during interviews, and participants were invited to read the notes at the end to ensure accuracy. Participants could also request a copy of the interview notes for their own records. In the case of published historical accounts, the authors' names were recorded.

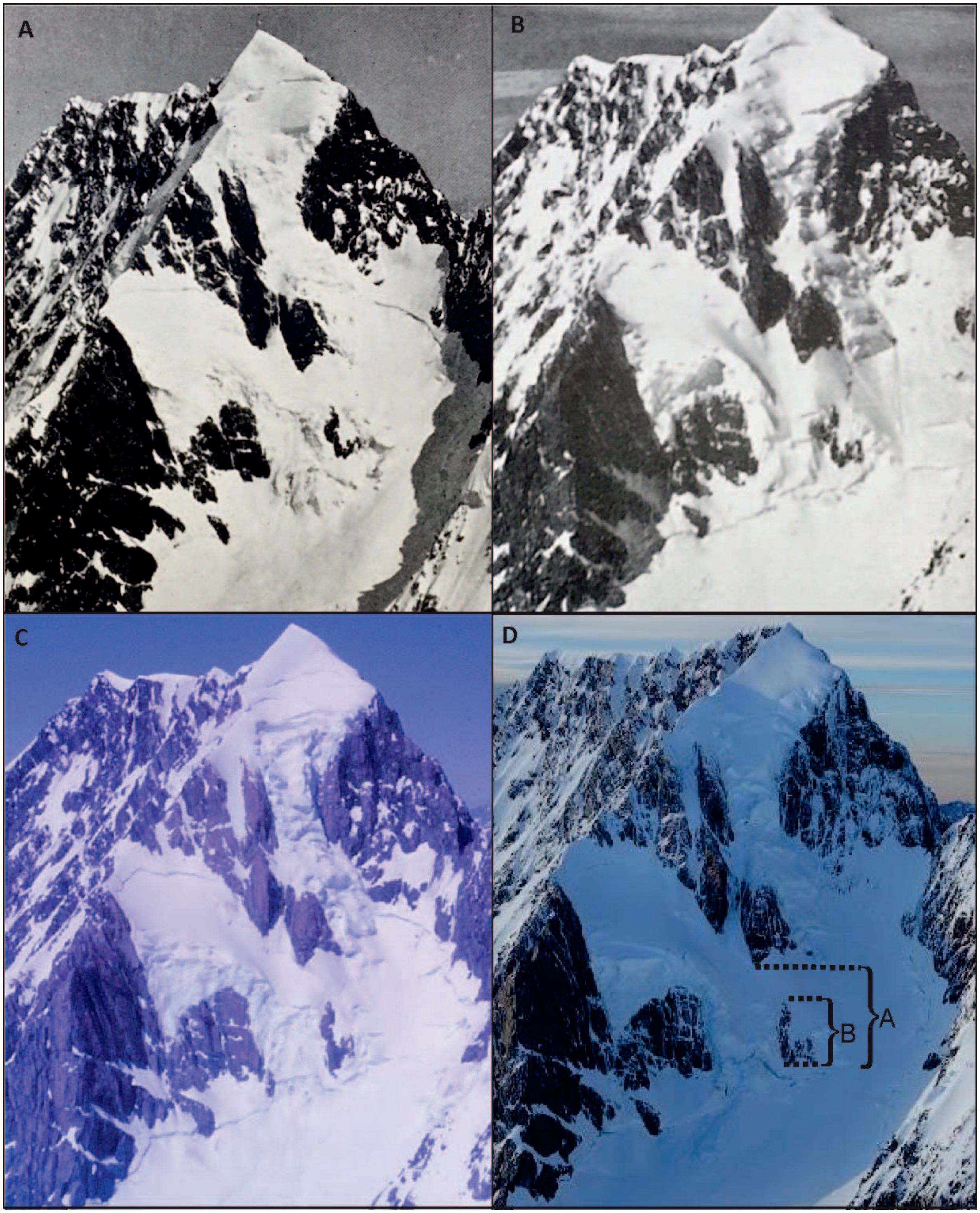
Nine interviews were conducted with professional guides. Guides were selected using snowball sampling (Hay 2000; Tolich and Davidson 2011) and the New Zealand Mountain Guides Association online public database. To connect with recreational climbers, a request for volunteers was posted in the New Zealand Alpine Club's *Climber* magazine. This magazine is sent to all club members and is available for purchase by the general public at retail stores. Eight recreational climbers responded and completed the survey. Additional information about the contemporary recreational experience was obtained from written accounts published on the Internet. All material relating to people's experience of the route—for example, information about rockfalls, crevasses, and time taken—was analyzed for keywords and themes, and coded based on recurring concepts and viewpoints (Tolich and Davidson 2011). Comparisons were made within and between the recreational and professional responses and between time periods. In total, 45 qualitative sources of information were used.

Results

Changing Tasman Glacier access

On 1 March 1882, from a camp on the terrace near the confluence of the Ball and Tasman Glaciers, Green, Kaufman, and Boss climbed up 20 m onto moraine and then up a further 7 m onto the Tasman Glacier's surface (Green 1883:199). They were embarking on the first attempt to climb Aoraki. They did not quite make it to the very top, but they proved the ascent route, which is now the most popular way to ascend and descend the mountain. Green's account of climbing Aoraki is a classic piece of New Zealand mountaineering history; his description of climbing up onto the Tasman Glacier provides one of the earliest benchmarks of the surface

FIGURE 2 Photos of the upper Linda Glacier taken from Mt Tasman by (A) F. Du Faur, March 1912 (Ross 1930a); (B) H. K. Douglas, December 1935 (Bryant 1938); (C) B. Keir, December 1961; (D) R. Measures, November 2015. The Linda Glacier thinning index was derived by comparing the distances marked in section D as "*x*" and "*y*."



elevation of the Tasman Glacier. Since this time the ice has been thinning, a process referred to as downwasting. These changes were apparent to climbers who regularly visited the glacier; for example, Harper (1946) documented a 50-m lowering between 1889 and 1940. By the mid-1960s, ongoing thinning meant access to the glacier involved a descent down a "steep and rotten moraine wall for some 300 ft [100 m] to the present level

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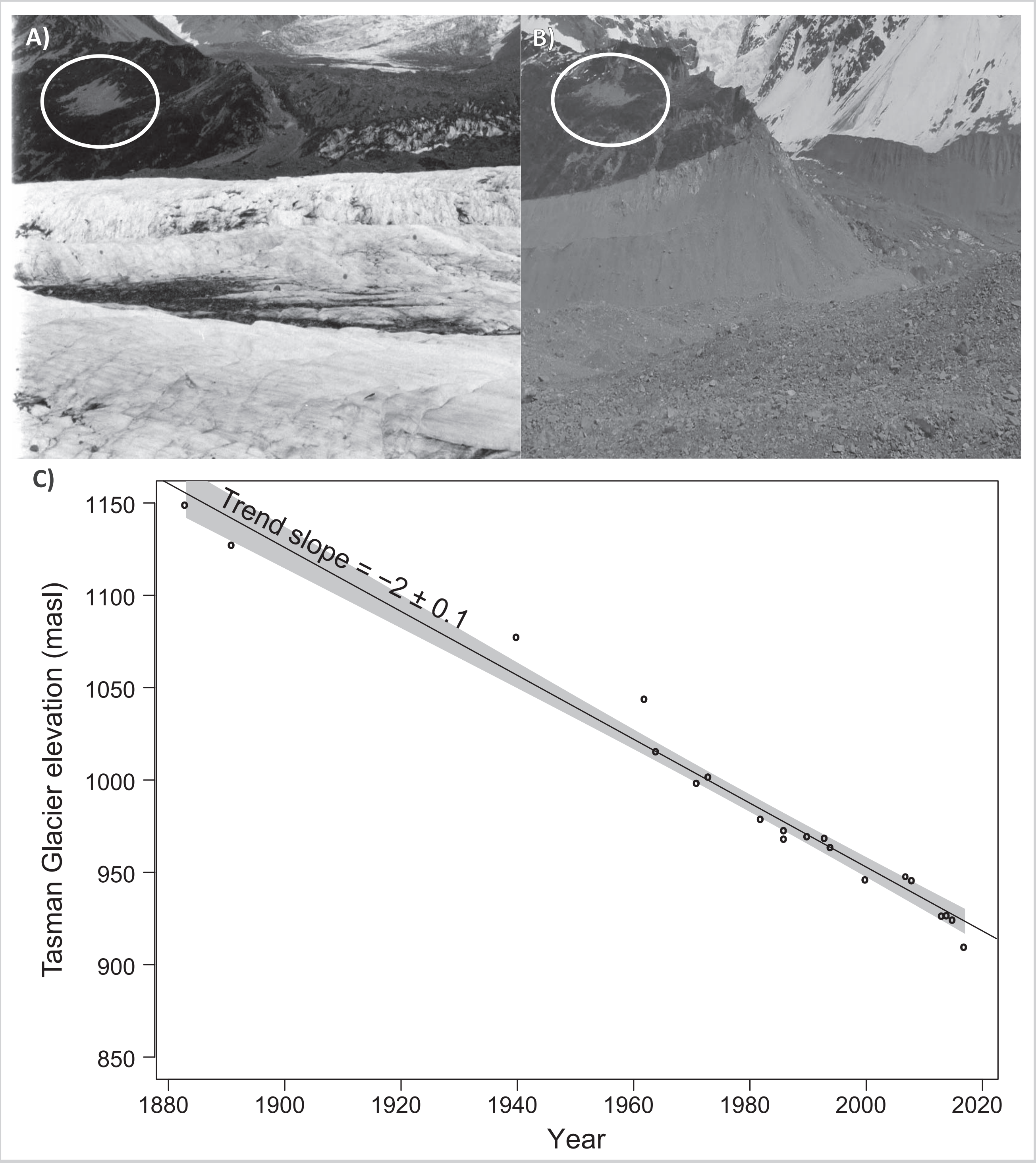
FIGURE 3 Changes on the lower Tasman Glacier. (A) Ball Glacier confluence in 1904 (photo courtesy of the Teichelmann Collection); (B) Ball Glacier confluence in 2017 (photo by T. Kerr); (C) elevations recorded 1883–2017 at the transect location shown in Figure 1C (data sources listed in Table 1). The circled scree slope in the top left in sections A and B provides an area of common reference.



of the moraine-covered ice" (Wilson 1968). Intermittent surveys (Table 1) in the region of Green's first observations have recorded over 200 m of surface lowering at an average rate of 2 m per year (Figure 3).

These surveys were made across the 2-km-wide Tasman Glacier in the vicinity of the traditional access to the glacier (Figure 1C). This debris-covered part of the glacier is low angled (2°) and undulating (±30 m). No notable (from a climber's perspective) change in glacier gradient has occurred in association with the surface lowering. The surveyed surface elevations are largely representative of the lowering of the overall lower Tasman Glacier surface (from Haast Ridge south).

This lowering of the glacier surface has increased the size of the descent required for climbers to access the glacier from the Ball Hut region (Figure 3). The descent is loose and crumbly with high potential for rockfall. In addition, the slope has had a series of slow failures and slumps due to the loss of support from the ice, including fractures on the adjacent hillside (Blair 1994; Deline et al 2015, see figure 15.2), indicating that the effect of ice thinning extends beyond the moraine wall.

Today, increased use of aircraft access, due in part to deteriorating conditions on the lower part of the route (Wilson et al 2015), means that few recreational climbers or guides fully retrace Green's footsteps, traveling up the Tasman Valley and along the Tasman Glacier, so the change on this part of the route is not always experienced. But for those who do walk the entire way, changes are obvious. For example, a recreational climber noted that in 1968 they had to "drop down onto the Tasman Glacier," being fully aware that Mannering's party in the late 1800s "had to climb up to get onto it" (Rec 1), and a number of respondents noted the deteriorating access via the moraine walls due to glacier recession (eg Recs 2, 4, and 6). This change in access is also reflected by a rapid decline in the number of climbers using the Haast Hut on their way to climb Aoraki since the early 1990s (*Supplemental material*, Appendix S2 and Figure S2, http://dx.doi.org/10.1659/MRD-JOURNAL-D-18-00042.S1).

Changes in Linda Glacier and the summit region

Comparison of early photographs with more recent photographs (Figure 2) shows very little discernible change in the upper Linda Glacier. The only notable change is to the summit itself, which was lowered by approximately 10 m during a major rockfall in December 1991 (Chinn et al 1992), with subsequent erosion and settling of the summit ice cap further reducing the elevation of the High Peak by another 20 m, giving a current summit height of 3724 m above sea level (Sirguey et al 2014). Results from the photographic analysis (Table 2) indicated no statistically significant ice-thinning trend over time (Figure 4).

From a mountaineering perspective, the access through the Linda Glacier is generally considered the determinant of whether or not the route can be successfully climbed. Crevasses and bergschrunds in the Linda Glacier have always presented a challenge. When Green's party first ascended the glacier (in March), they noted numerous crevasses in the lower section, requiring a lot of zigzagging, and further up, crevasses spanned the entire glacier width (Green 1883). Du Faur (1915) described winding back and forth around crevasses, crossing snow bridges, and even climbing down into and out of crevasses in order to negotiate a way through, in a December 1911 climb of Mt Dampier that required Linda Glacier access.

In this regard, interviews with and email surveys of climbers provided further insight. Half of the recreational climbers surveyed had climbed the route twice, with time between ascents ranging from 3 to 20 years. All of the guides had climbed the route multiple times, some more than 20 times over 3 decades (eg Guides 1, 4–6, 8, 9). The total number of experiences of the route from which the guides provided information exceeded 150, enabling them to comment on change over time, providing information that cannot be gained from one-off experiences.

Many of the guides (Guides 3–7, 9) and a recreational climber (Rec 6) noted a general shortening of the climbing season due to crevasses and bergschrunds being exposed earlier and becoming larger (Table 3), with some guides saying that now they generally would not book guided ascents after the first week of January (Guides 3 and 6). Although large interannual variability in conditions made it difficult for the guides to pinpoint the time of this change, they noted that through the 1980s and 1990s the route was in good condition from November to March, but since the 2000s, and particularly since around 2012, the route could be cut off by mid-January (Guides 3, 4, 9). Data on the last date of a successful ascent via the Linda Glacier, as recorded in the Haast and Plateau Hut logbooks, support the later ascent dates in the 1980s and 1990s, with some more recent years showing an earlier cutoff; but when viewed over the entire time period (1882–present), no trend is apparent (Figure 5).

There was strong agreement about an increase in the steepness of the upper Linda Glacier (see also *Supplemental material*, Appendix S1, http://dx.doi.org/10.1659/MRD-JOURNAL-D-18-00042.S1), believed to be associated with glacier thinning (Guides 1, 3–8, Rec 8). A number reported seeing increased (and new) rock exposure—for example on the upper ice cap (Guides 1, 3–8). This was viewed as a sign of thinning, and some respondents linked this to an increase in rockfall activity (Guides 3 and 5).

In concert with the above observations, all guides strongly emphasized the importance of seasonality, separating change they associated with environmental/climate change (eg downwasting) from interannual/seasonal changes (eg icefall, snow cover on the upper mountain). They noted that access through the Linda Glacier is strongly influenced by year-to-year variability in snowfall and summer melting. For example, Guide 4 noted, "If alpine glaciers get regular coverings of nice white snow during a summer season (even if only small), then this white cover reflects well and there is less severe crevassing during and [in the] late season." Here the guide identified the relationship between surface albedo and

TABLE 2 Upper Linda Glacier photo attributes and thinning index.

Year	Month (where available)	Thinning index	Photographer	Camera location (where available)	Source
1895	February	1.52	E. A. Fitzgerald	Mt Silberhorn	Fitzgerald (1896)
1912	March	1.58	F. Du Faur	Mt Tasman	Du Faur (1915); Ross (1930a)
1913	February	1.91	S. Turner	Mt Tasman	Turner (1922)
1930s		1.56	H. E. L. Porter		Ross (1930b)
1930s		1.54	H. E. L. Porter	Aerial	Kain (1954)
1930s		1.55	M. Bowie		Unpublished Bowie album held by Graham Langton
1935		1.62	H. K. Douglas		Bryant (1938)
1937	April	1.62	F. Alack		Alack (1963)
1937	January	1.72	J. Pascoe	Mt Silberhorn	Pascoe (1939)
1952		1.68	Unknown		Supplied by A. Cunningham
1954		1.59	M. Davidson		Hewitt and Davidson (1954)
1955	December	1.68	I. Pickens		Supplied by P. Jenkins
1959	December	1.77	J. Harrison		Wilson (1968)
1960	December	1.57	B. Keir	Mt Dixon	Supplied by B. Keir
1961	December	1.45	B. Keir	Mt Tasman	Supplied by B. Keir
1971		1.52	Unknown		Harris and Hasler (1971)
1983	April	1.74	L. Homer	Aerial	GNS Visual Media Library (http://vml.gns.cri.nz/assetbank-gns-science/action/viewHome; accessed on 16 October 2017), VLD ID 3622
1984		1.58	Unknown		Monteath (1984)
1987	November	1.65	C. Curry		Haynes (1994)
1989		1.51	Unknown		Monteath (1989)
1992	April	1.70	L. Homer	Aerial	Supplied by Margaret Low, Visual Media Librarian, GNS Visual Media Library (http://vml.gns.cri.nz/assetbank-gns-science/action/viewHome; accessed on 18 October 2017), VML number 3651
1994		1.46	C. Potton	Aerial	Potton (1994)
1994		1.48	C. Monteath	Mt Silberhorn	Palman (2001)
1998		1.48	G. Dickson	Mt Tasman	Supplied by I. Abaecherli
2000		1.50	C. Day	Mt Tasman	Supplied by C. Day
2006	February	1.49	G. Dickson	Mt Tasman	Supplied by I. Abaecherli
2007	September	1.52	D. Sproules	Mt Tasman	Supplied by Arthur McBride, Alpine Guides Aoraki Ltd. (Mount Cook National Park, Canterbury, NZ)
2008	September	1.57	P. Maxim	Mt Dixon	Supplied by P. Maxim
2011	December	1.52	D. Hegg	Mt Tasman	http://www.southernalpsphotography.com/Tramping/Mt-Cook-Westland/Mount-Tasman/i-9DtLLH2
2015	November	1.60	R. Measures	Mt Tasman	Supplied by R. Measures

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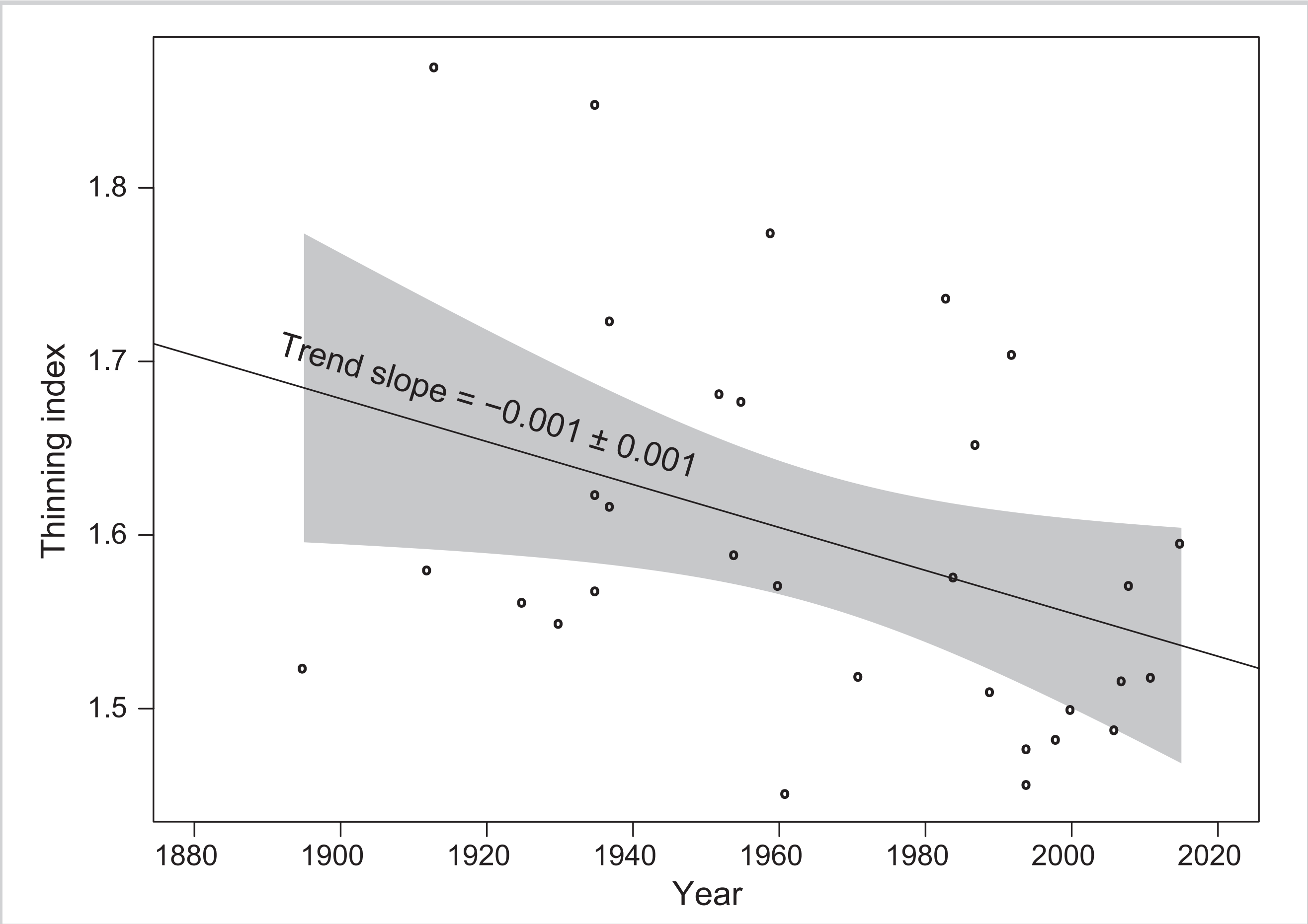
FIGURE 4 Thinning index for the upper Linda Glacier, 1895–2015, based on the ratio of photographed rock exposure (circles) as shown in Figure 2D. The grey area represents the 95% confidence level of the trend slope.



glacier melt and the importance of summer snowfall to glacier mass balance (Oerlemans and Klok 2004).

The cyclic behavior of icefall, especially in the upper part of the Linda Glacier, was noted to strongly influence access through crevasses and major bergschrunds, so in some years, access remains good even into late February (Guides 3, 5, 8). The condition of the summit rocks was also listed as a seasonal factor that influenced the technical difficulty of the climb—in particular, whether the summit rocks were covered with snow, ice, or bare rock (Guide 1, Recs 5, 8). Guides who had been climbing the route since the 1970s or 1980s generally related changes in the upper Linda Glacier with year-to-year variability, while newer guides associated some of the changes (eg crevasses opening earlier) with climate change.

Discussion

Ice thinning

A common theme highlighted throughout this research was the implication of ice volume loss for climber access. Downwasting of the lower Tasman Glacier surface (Table 1, Figure 3) has resulted in significant change on the lower section of the climbing route, with climbers now required to descend a large moraine wall to access the glacier. The steep, loose moraine wall also needs to be ascended in order to continue on to the Grand Plateau via either the Haast Ridge or Boys Glacier.

The rate of thinning of the lower Tasman Glacier from 1883 to 2017 has been approximately 2 m per year; climbers already reported the impact of downwasting in the 1940s (eg Harper 1946). Annual surface ablation in this debris-covered region of the glacier is in the order of 7 m water equivalent (Purdie 2011), indicating that ice melt can account for the majority of lowering. The importance of surface lowering (geodetic adjustment) to glacier melt was highlighted by Huss et al (2012). Although the debris cover (which suppresses melting) is expanding upglacier over time (Kirkbride 2000), the fact that the surface is now 200 m lower than it was in the late 1800s means that, based on the measured temperature lapse rate (5.5°C km^{-1}, Kerr 2005), the near-surface air temperature in this region of the glacier will have increased by approximately 1°C, irrespective of climate change.

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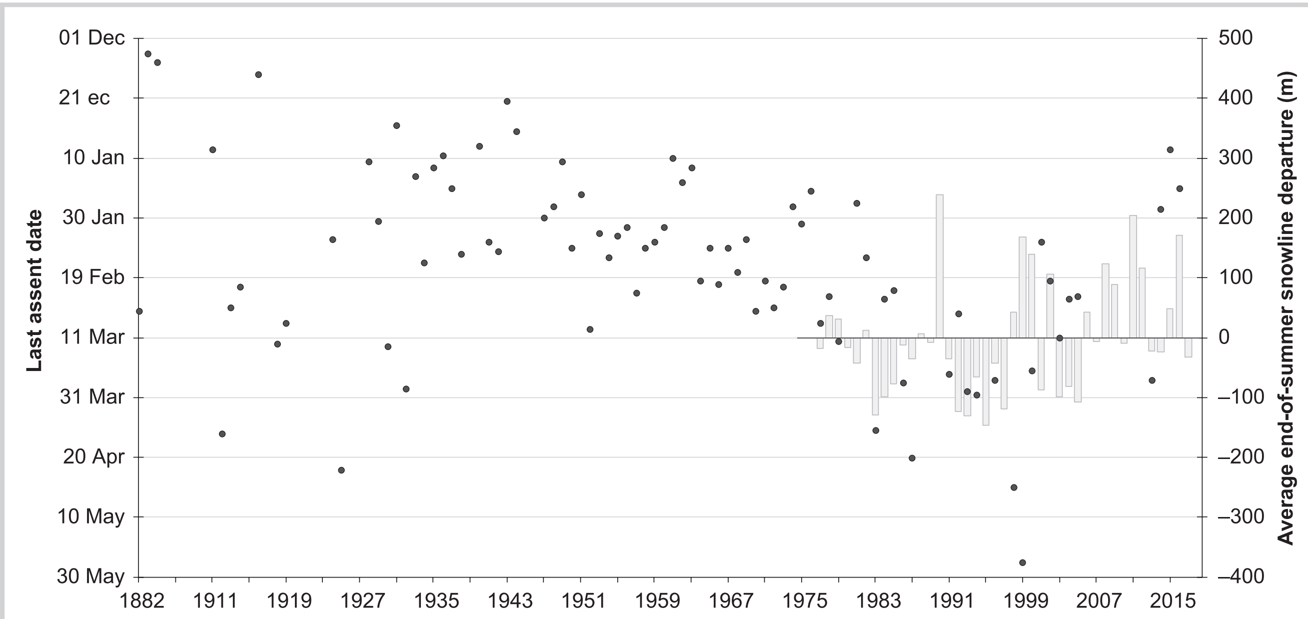
FIGURE 5 Last ascent of the year via the Linda Glacier route, 1882–2017, as recorded in Haast and Plateau Hut logbooks, and the average Southern Alps end-of-summer snowline departure from the long-term mean (m), 1977–2017, as reported in Willsman et al (2017).



Surface velocity in the region where climbers access the Tasman Glacier is approximately 80 m per year (eg Redpath et al 2013; Haritashya et al 2015), but significant interannual variability (30–115 m) was recorded between 2000 and 2010, with a notable velocity increase in 2008 (Redpath 2011) coincident with a period of rapid lake expansion (Dykes et al 2011). More recently (2012–2014), velocity has decelerated in this region (Haritashya et al 2015). This deceleration indicates that ice thinning is unlikely to be driven by dynamic processes (Meier et al 2007; Pritchard et al 2009).

The fact that our photographic analysis could not unambiguously determine a thinning trend in the upper Linda Glacier (Figure 4) is not surprising, considering the

TABLE 3 Key themes that emerged from observations by recreational climbers and local mountain guides on changes to the Linda Glacier route.

Theme	Observations
Crevasses and bergschrunds	Crevasses and bergschrunds are becoming exposed earlier in the season, which shortens the time window for ascents.
Rockfall	Rockfall activity is increasing, especially from areas that used to be ice covered (eg Mt Vancouver, Malaspina, and Silberhorn Ridge).
Steepening slopes	Steepening of the Linda Shelf (upper Linda Glacier) is thought to be associated with ice mass thinning.
Downwasting	Some guides and recreational climbers have noted that the glacier appeared to be thinning, resulting in increased rock exposure. In particular, on the summit ice cap (above the summit rocks), a new rock step is emerging.
Spatial variability	At higher elevations (eg upper Linda Glacier and the summit region), change is often associated with interannual variability and seasonality, while at lower elevations (eg Tasman Glacier access), there are clear signs of climate change.
Climbing time	It is generally taking longer to guide the route, due to a combination of more broken crevasse fields, steeper slopes, and more exposed rock, requiring more rope work to move clients safely through.
Icefall and avalanche	Respondents gave variable responses; the majority noted interannual variability and seasonality. Icefall and avalanche activity are important for filling bergschrunds and crevasses, creating seasonality in access. Some thought icefall activity was increasing, while others noted a possible decrease as the ice shelf got thinner.

guides' emphasis on the importance of seasonal variability. Even so, there are observations that indicate some change may be occurring—for example, slope steepening and new rock exposure. Temperature–elevation relationships (Cuffey and Paterson 2010) result in ice thinning being greater at lower elevations than higher up the mountain, but where a strong disequilibrium exists, glacier accumulation areas can experience significant thinning (Pelto and Hartzell 2004). Thinning at lower elevations with more subdued thinning at higher elevations has the effect of increasing the overall glacier slope, an effect exacerbated in regions with steep headwalls. Bed undulations are more strongly expressed at the surface of a thinner ice mass (Budd 1970; Schwitter and Raymond 1993; Gessese et al 2015), and undulations are enhanced on glaciers where basal sliding comprises a large component of ice movement (Gudmundsson 2003). Increased ice tension associated with steeper, more undulating ice results in crevassing (Colgan et al 2016). Lack of surface velocity data for the Linda Glacier (Ruddell 1995; Herman et al 2011) prevents assessment of whether variability in crevasse exposure can be attributed (at least in part) to temporal variability in ice flow.

Reports of new rock exposure high on the route do indicate that the ice mass may be thinning, but relationships between ice thinning and rockfall activity are more complex (Fischer et al 2012; Huggel, Clague, et al 2012). Poor-quality rock and rockfall activity have been characteristic of the route since it was first explored (Green 1883; Du Faur 1915). Over the years there have been a number of large rockfall events (Cox et al 2008; Allen et al 2011; Hancox and Thomson 2013), including the Aoraki Mount Cook rock avalanche, which saw 12 million m^3 of rock, snow, and ice collapse down the east face and onto the Tasman Glacier (Chinn et al 1992).

The mountains in Aoraki Mount Cook National Park are highly faulted, including well-exposed faults on Haast Ridge and the east face of Aoraki (Cox et al 2012). The fractured nature of the rocks and relatively rapid uplift mean that rockfall activity is normal and not necessarily associated with changing climate (Cox et al 2015). A recent increase in rockfall activity in a number of alpine regions (eg the European Alps and Alaska) has been linked to ice thinning, which exposes the underlying steep, highly fractured rock surfaces (Huggel, Allen, et al 2012; Deline et al 2015), but a direct link to degrading permafrost and increased air temperatures remains tenuous (Allen et al 2009; Fischer et al 2012; Huggel, Allen, et al 2012). The Linda Glacier route has always been known for rockfall activity, but reports of new activity from previously snow- and ice-covered slopes suggest the route is changing. However, rockfall has many drivers, so any change in rockfall activity must be considered in a wider geologic and geomorphic setting.

Internationally, research on the implications of changing snow and ice volume for alpine recreation has mainly focused on skiing (eg Olefs and Fischer 2008; Steiger and Mayer 2008; Uhlmann et al 2009; Olefs et al 2010; Fischer et al 2011). Indeed, Beniston (2003) suggested that mountaineering and hiking may in part compensate for the loss of skiing in some alpine regions. In a case study of the Austrian Alps, Ritter et al (2012) identified a number of phenomena that our findings have mirrored—for example, thinner snow bridges, an increased number of open crevasses, and increased danger of rockfall. In a study of the North Cascades, Hammond and Pelto (2015) noted that although glacier thinning led to fewer crevasses as ice flow slowed, increased melt rates meant that crevasses were wider and exposed earlier as seasonal snow was reduced, making navigation more difficult.

Spatial and temporal variability on the Linda Glacier route

Temperature–elevation relationships drive spatial variability in a number of alpine processes, including snow and ice melt, the partitioning of snow and rain, and albedo feedbacks (Oerlemans and Klok 2004; Anderson et al 2010; Anderson and Mackintosh 2012). Variability in these processes over space has led to change being more apparent lower on the climbing route than at higher elevations. At lower elevations there was clear agreement between changes measured by physical survey and changes observed and experienced by climbers, none more so than the extensive downwasting of the lower Tasman Glacier (Figure 3). Higher up the route, measured physical change was harder to quantify (Figures 2 and 4). Climbers associated change higher up on the mountain with year-to-year variability in snow accumulation, icefall activity, and weather conditions during the climbing season, but described changes at lower elevations in the context of climate change. These results are reflective of research on glaciers in the European Alps, where at high elevations glacier mass balance is dominated by winter precipitation, but at lower elevations increasingly negative mass balance and surface lowering were evident due to summer warming (Vincent 2002; Fischer 2010).

The dominance of seasonal and short-term processes at higher elevations makes it hard to discern long-term change. New Zealand's maritime climate means that snow falls in mountain regions year round, although mostly in winter and spring (Fitzharris et al 1999). Clearly the depth of the snowpack at the beginning of the climbing season will influence the time taken for crevasses in the Linda Glacier to become exposed the following summer. Seasons with high snow accumulation were noted as having the added bonus that increased avalanche activity further filled crevasses. The rate at which the seasonal snow melts away, exposing crevasses and removing snow bridges, is influenced by seasonal weather (eg air temperature, cloud cover, frequency of rain or snow) and the longer-term warming trend.

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In addition to fluctuations in seasonal snow, icefall activity was also acknowledged to strongly influence access up the Linda Glacier. Icefall activity (ice avalanche) is known to follow cyclic patterns (Alean 1985; Pralong and Funk 2006). For example, in the French Alps, a hanging glacier took 6 months to recharge after a substantial collapse (Vincent et al 2015). Although glacier mass balance strongly influences ice flux in the fracture zone and hence icefall frequency, in temperate (warm) ice, heavy rain or warming also increases icefall activity (Pralong and Funk 2006). In Aoraki Mount Cook, the frequency of ice avalanche in the Mueller Glacier area was found to be significantly higher in summer, and relationships were found between event frequency and meteorological conditions, especially temperature and rainfall (Iseli 1991; Kochel et al 2018).

Although there are no mass balance measurements for the Linda Glacier, since 1977 a photographic survey of the position of the end-of-summer snowline has been conducted for 50 Southern Alps glaciers, providing a mass balance proxy (Willsman et al 2017). These data show that, from the mid-1980s through the 1990s, the end-of-summer snowline on glaciers in the Southern Alps was generally lower than their long-term average (1977–2017) (Figure 5), and a number of glaciers advanced (Chinn 1999; Mackintosh et al 2017). Periods of positive mass gain on New Zealand glaciers have been attributed to discrete periods of reduced air temperature associated with anomalous southerly winds and low sea surface temperature in the Tasman Sea region (Mackintosh et al 2017). Airflow and sea surface temperature anomalies in the New Zealand region have also been linked to the Interdecadal Pacific Oscillation (Salinger et al 2001), which entered a positive phase in 1978, favoring positive glacier mass balance, but returned in 2000 to a negative phase, favoring negative mass balance (Fitzharris et al 2007; Henley 2017). Since 2006 the cumulative mass balance of glaciers in the Southern Alps has been negative (Willsman et al 2017). The ensemble of processes that influence climbing conditions high on Aoraki makes it challenging to conclude whether the observed breakup of the Linda Glacier in the most recent years is a flow-on effect of the long-term warming trend, or another chapter in the story of decadal-scale variability.

Conclusions

Environmental change has affected climbers' access to Aoraki Mount Cook. Significant thinning of the lower Tasman Glacier means climbers now have to negotiate a steep, unstable moraine wall in order to access the glacier. Consequently, fewer climbers fully retrace the original route pioneered by Green and his companions in the late 1880s.

Most of the climbers interviewed for this study associated changes to the route higher up the mountain with year-to-year variability in snow accumulation, snowmelt, and icefall activity. The dominance of interannual variability was supported by our photographic evidence, which found no notable change over a 120-year period. Despite this, climber observations of steepening slopes and new rock exposures may be a sign that the ice mass is starting to thin. Separating long-term change from annual and decadal-scale variability is challenging. Recent and ongoing improvement to satellite image resolution and processing will be of value to future change assessments.

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Supplemental material

APPENDIX S1 DEM analysis.
APPENDIX S2 Haast Hut logbooks.

FIGURE S1 Ice thinning as revealed by a decrease in surface elevation. (A) Thinning on the summit ice cap with associated slope steepening. Inset shows the section of the route shown in the graph. Error bars are plotted for both years, but the errors for the 2008 DEM are so small as to be almost invisible at the scale of the graph; (B) surface elevation changes on the standard route along the upper Linda Shelf. The 2008 DEM data were supplied by Pascal Sirguey, School of Surveying, University of Otago.

FIGURE S2 (A) Declining use of the Haast Hut over time; (B) the third version of the Haast Hut, built in 1971. (Photo by R. Bellringer, New Zealand Department of Conservation)

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