Lichenometric dating of the 'Little Ice Age' maximum in Mt Cook National Park, Southern Alps, New Zealand

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Abstract: Lichenometric dating studies using the yellow-green *Rhizocarpon* subgenus at the Eugenie, Hooker, Mueller and Tasman Glaciers in Mt Cook National Park, Southern Alps, New Zealand, reveal a 'Little Ice Age' maximum during the mid-eighteenth century (around AD 1725–1740). Lichenometric dating curves, constructed for Mueller Glacier in a preliminary study, were modified using local control points at the other glaciers. Modification was necessary because of variations in local ecological conditions. The 'Little Ice Age' chronology is similar for three out of the four glaciers studied. All except Tasman Glacier underwent a major glacier front oscillation directly following the 'Little Ice Age' maximum. After a slow but constant retreat during the second half of the eighteenth and the first half of the nineteenth centuries, the glaciers experienced major readvances during the second half of the nineteenth century (around AD 1860 and 1890/95), and during the early decades of the twentieth century. Tasman Glacier, as the exception, returned to its 'Little Ice Age' maximum frontal position during the late nineteenth century, overtopping pre-existing 'Little Ice Age' moraines, and therefore preventing detailed dating of these moraines. Differences in dating from previous lichenometric studies may be due to the different methods used.

Key words: 'Little Ice Age', relative-age dating, lichenometry, *Rhizocarpon*, glacier variations, Holocene, Mt Cook National Park, New Zealand.

Introduction

Mountain glaciers are useful tools for reconstructing Holocene climate change. The 'Little Ice Age' has been recognized as an episode of late-Neoglacial glacier advance in many mountain areas (Grove, 1988). However, research on glacier variations during the 'Little Ice Age' has mainly concentrated on mountain areas of the Northern Hemisphere (see, for example, Zumbühl *et al.*, 1983; Holzhauser, 1984; Matthews and Shakesby, 1984; Erikstad and Sollid, 1986; Bogen *et al.*, 1989; Furrer, 1990; Bickerton and Matthews, 1993; Luckman, 1993; 2000; Winkler, 1996; 2000a; Evans *et al.*, 1999; Winkler and Nesje, 2000). The Southern Alps of New Zealand is one of the few localities (such as, for example, Patagonia or the Southern Andes) for the study of Holocene glacier variations in the extratropical Southern Hemisphere (Burrows and Gellatly, 1982; Gellatly *et al.*, 1988). Since a supposedly synchronous global 'Little Ice Age' and Holocene glacier chronology (e.g., Röthlisberger, 1986) can be questioned given differences in the timing of the 'Little Ice Age' and recent glacier front fluctuations in Scandinavia, the European Alps and New Zealand (Grove, 1988; Winkler, 1996; 2000b; 2001; Winkler *et al.*, 1997; Nesje and Dahl, 2000), there is need for more detailed regional studies. Even if the 'Little Ice Age' is detected as period of glacier advance and enlarged glacier masses at almost all mountain glaciers, its timing and chronology is far from being uniform. Whereas glacier advances in the European Alps as early as during the thirteenth and fourteenth centuries AD are considered as the onset of the 'Little Ice Age', and several major advances took place there during this period (Furrer, 1990; Nicolussi and Patzelt, 2000), there was only one major advance in most parts of Scandinavia not occurring prior to *c.* AD 1680/90 (Bogen *et al.*, 1989). Such regional variations make it impossible to give a precise overall dating and definition of the 'Little Ice Age', although this term is widely used in the literature. Therefore, the term 'Little Ice Age' should be applied (as it is in this study) in a broader sense, i.e., describing the latest period of Holocene glacier advances terminating around the end of the nineteenth century AD. However, regional studies are additionally important as, despite regional differences, 'global' trends of glacier variations are frequently used in connection with discussions on 'global climate change' (Oerlemans, 1994; Haeberli *et al.*,

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1999). When simulating future glacier behaviour in order to develop strategies to deal with the consequences of changes in glacier mass and front positions (e.g., for hydroelectric power installations), regional differences that have taken place in 'Little Ice Age' chronologies have to be taken into account. They give valuable information about different reactions of the glaciers to fluctuations of the climate, as those can be expected during any future climate change as well.

In a previous study Winkler (2000a) constructed new lichenometric dating curves for Mueller Glacier. Applied to the dating of the 'Little Ice Age' moraines, they revealed considerable differences compared with previous studies (Burrows and Lucas, 1967; Burrows and Orwin, 1971; Burrows, 1973; Gellatly, 1982; 1984; 1985). One goal of the present study was to extend the application of the Mueller curves by including three more glaciers of varying types and sizes in the investigation. A second goal was to test whether the chronology of the 'Little Ice Age' in the Southern Hemisphere is similar to that of the Northern Hemisphere. As previous studies (Winkler, 2000a; 2000b) have already demonstrated some parallels between glaciers in the Southern Alps of New Zealand and glaciers in (maritime) Scandinavia, it was considered that more detailed dating of the 'Little Ice Age' in the Mt Cook National Park using lichenometry following recommended modern procedures (Innes, 1985a; Matthews, 1994) would allow better comparison. Also included in this paper is a detailed reassessment of results from previous studies that partially disagree with the date of the 'Little Ice Age' maximum presented here.

Study area

Hooker, Mueller and Tasman Glaciers are all large neighbouring valley glaciers, located east of the main divide of the Southern Alps in Mt Cook National Park (Figure 1 and Table 1). Eugenie Glacier is a small cirque glacier on the eastern slope of the main divide in Hooker Valley. The lower glacier tongues of the valley glaciers are all almost entirely covered with supraglacial debris and their glacier forelands each have a proglacial lake. The proglacial lake at Mueller Glacier began to be formed in the mid-1990s and it is still enlarging, prohibiting accurate location of the frontal position of the glacier. The proglacial Lake at Tasman Glacier (Tasman Lake) is also still increasing in size after its first appearance in the early 1980s (Kirkbride, 1993; Hochstein *et al.*, 1995) and in 1993 it had an area of 1.95 km^2 (Warren and Kirkbride, 1998) increasing to 2.5 km^2 in 1997/98 (Purdie and Fitzharris, 1999), with enlargement continuing in 2003 (author's observations). The proglacial lake at Hooker Glacier with a total area of 0.75 km^2 in 1995 (Warren and Kirkbride, 1998) has not enlarged substantially in recent years (T. Chinn, personal communication; author's observations), as a result of the response of its stationary glacier front to positive net balances during the past two decades (Chinn, 1999). There are no data or observations available for the recent glacier front behaviour of Eugenie Glacier.

The glacier forelands of all three valley glaciers are dominated by massive lateral moraines with crests up to 120 m (or more) above the glacier surfaces. Apart from these 'alpine type' lateral moraines (Winkler and Hagedorn, 1999), there are several smaller latero-frontal/frontal moraine ridges on the outer forelands of the Hooker and Mueller Glaciers. At Eugenie Glacier, an almost complete outer moraine loop enclosing a few small inner moraine ridges suggests that there was no confluence of the Eugenie and Hooker Glaciers during the 'Little Ice Age'. Some relict moraines southwest of the 'Little Ice Age' moraines at Hooker Glacier resulting from an older period of confluence could not be examined although the existence of pre-'Little Ice Age' moraines have previously been confirmed by earlier studies of the three valley glaciers (cf. Burrows, 1973; Gellatly, 1982; 1984; Winkler, 2000a; 2000b; 2001).

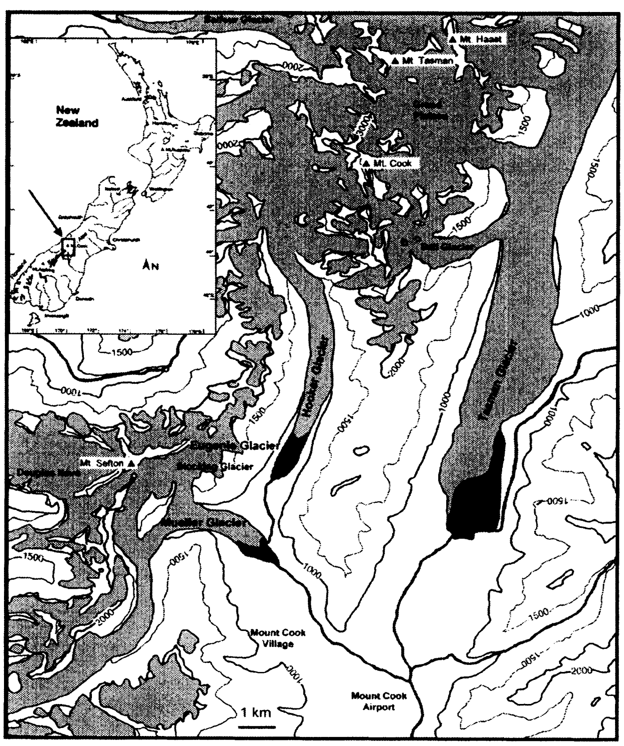

Figure 1 Map of the study area and its location in New Zealand. The glaciers studied are indicated.

Lichenometry and its application in Mt Cook National Park

Previous work

There have been earlier attempts to date Holocene moraines in front of the valley glaciers in Mt Cook National Park, and Mueller Glacier has been a key locality for the construction of lichenometric growing curves (cf. Winkler, 2000a). However, the dates of its 'Little Ice Age' and older Holocene moraines vary considerably between authors using different methods (e.g., dendrochronology, lichenometry, weathering-rind data, Schmidt hammer measurements; Table 2). A detailed summary of previous research is given in Winkler (2000a; 2000b).

Attempts to date 'Little Ice Age' moraines at Mueller Glacier using lichenometry have been made by Burrows and Lucas (1967), Burrows and Orwin (1971), Burrows (1973) and Gellatly (1982; 1984; 1985), respectively. However, because previous studies used different methods of uncertain validity, it was necessary to establish new lichenometric dating curves for Mueller Glacier (Winkler, 2000a). For example, semi-logarithmic dating curves according to recommended modern procedures (Innes, 1985a; Matthews, 1994) were not used and some of the fixed dating points used in these studies have been classified as unreliable by the present author (Winkler, 2000a), especially those derived from dendrochronology (Burrows and Orwin, 1971) and those from weathering-rind data (Gellatly, 1982). In previous studies, sample

Table 1 Glaciological data for the study glaciers (area, recent front position and debris cover taken from Chinn, 1996)

Glacier	Area (km^2)	Present snout altitude (m a.s.l.)	LIA snout altitude (m a.s.l.)[(1)]	Aspect of snout	Debris cover (%)	Remarks
Eugenie	0.75	1340	*c.*1000	SE	0	Cirque glacier
Hooker	17.32	870	870	S	25.08	Proglacial lake
Mueller	22.54	760	760	E	37.22	Proglacial lake (develop.)
Tasman	99.35	730	730	S	28.50	Proglacial lake

[(1)]Glacier snout during the formation of the outermost 'Little Ice Age' (LIA) moraine (cf. text).

sites were not restricted to the similar areal extent (cf. Innes, 1984a). Measurements were mainly carried out on distal slopes and crests of moraines (Burrows, 1973). In addition, whereas Burrows (1973) used the largest diameter of the single largest lichen, Gellatly (1982) used the diameter of the largest circle inscribed within the lichen thallus (short axis).

Lichenometric measurements

Lichenometric measurements carried out in Mt Cook National Park (cf. Winkler, 2000a) were generally following recommended procedures (cf. Innes, 1985a; Erikstad and Sollid, 1986; Bickerton and Matthews, 1993; Matthews, 1994) and ensured comparability with previous lichenometric studies by the present author (Winkler and Shakesby, 1995; Winkler, 2003; Winkler *et al.*, 2003). The measurements were restricted to the yellow-green *Rhizocarpon* subgenus (Innes, 1985b; Benedict, 1988; Poelt, 1988) without differentiating between *R. alpicola* and *R. geographicum*. Although there are some differences in growing rates and times before colonization between these two specimens (cf. Innes, 1982; 1983; Benedict, 1988), only few studies applied separate measurements, showing just minor improvement of the results (e.g., Bickerton and Matthews, 1992). As lichen populations within one region often show uniform composition (Erikstad and Sollid, 1986) and a separate measurement of *R. alpicola* and *R. geographicum* was not feasible in Mt Cook National Park with lichen populations much smaller than, for example, in southern Norway (the study area of Bickerton and Matthews, 1992), both specimens were included in the measurements, although unusual composition of the lichen population were recorded throughout the fieldwork. There was no differentiation between *R. alpicola* and *R. geographicum* in earlier attempts using lichenometry in this region.

Sample sites were taken as 25 m lengths of moraine proximal of the crest. The maximum width of sample sites was taken as 8 m where the proximal base of the moraine was not reached within this distance (e.g., at the lateral moraines). By measuring many sites on moraine ridges in all parts of the glacier foreland (Figure 2), it was expected that areas of optimal ecological conditions for lichen growth would be included. Among the factors influencing lichen growth in the Southern Alps and limiting accuracy of lichenometry, unstable (especially proximal) moraine slopes, thick and abundant supraglacial debris cover and strong competition with other lichens, mosses and vascular plants have to be considered (cf. Winkler, 2000a; 2001). In some cases, some discrimination had to be made because of varying growth conditions for lichens and consequently lichen sizes in different parts of the glacier forelands. Given the less than optimal conditions for the application of lichenometry compared to other regions such as, for example, southern Norway, the mean of the longest axes of the five largest lichens of the site with the largest mean value was used to calculate the lichenometric dating curve. Using the mean of the longest axis of the single largest lichens of five sample sites (Bickerton and Matthews, 1993) was, apart from the length of some moraine ridges, prohibited by the variability of growth conditions for lichens and the lack of five sites with comparable lichen populations and ecological conditions at some of the moraines investigated. The range of possible errors in the lichenometric dating resulting from local growth conditions for the *Rhizocarpon* subgenus in the Southern Alps has, in general, to be set higher than that reported by Matthews (1994), focusing on southern Norway (see discussion).

Historical evidence from Mueller Glacier (i.e., reports of the first explorers and surveyors and, in addition, first detailed maps; cf. Gellatly, 1985) provided three fixed points for the calculation of dating curves as a semi-logarithmic function (cf. Winkler, 2000a, for more details; Figure 3). The historical record available for the other glaciers studied was found not to be sufficient (in number and accuracy) for constructing separate local lichenometric dating curves. Therefore, the lichenometric dating curve from Mueller Glacier was used as a regional dating curve with the validity of the 'Mueller curve' checked by comparing dating results with the (sparse) historical records from the other glaciers given by Burrows (1973) and Gellatly (1985). Local variations of the regional lichenometric dating curves based on these 'local control points' provided alternative dates. In addition, Schmidt hammer

Table 2 Comparison of the data for the formation of the outermost 'Little Ice Age' and the youngest pre-'Little Ice Age' moraine at Mueller Glacier given by various authors (see also Winkler, 2000a; 2000b)

Reference	Dating method	M-MUE 'c'[(1)]	M-MUE 1[(2)]
Lawrence and Lawrence (1965)	Dendrochonology	prior to AD 1754 (1814)	prior to AD 1839 (*c.* AD 1765?)
Burrows (1973)	Lichenometry	AD 1750	*c.* AD 1790
Gellatly (1982; 1984)	Weathering rinds, lichenometry[(3)]	1490–2940 a BP[(4)](three advances)	580 a BP
Winkler (2000a; 2000b)	Schmidt hammer, lichenometry[(5)]	AD 500–1000 (one advance)	*c.* AD 1725/30

[(1)]Moraine in a latero-frontal position (southeastern foreland) distal to the 'Little Ice Age' moraines (see Winkler, 2000a; 2000b for details).
[(2)]Outermost 'Little Ice Age' moraine.
[(3)]Lichenometry primarily used for dating of M-MUE 1 (= outermost 'LIA' moraine at Mueller Glacier).
[(4)]Conventional ^{14}C years (radiocarbon datings used for the fixed dating points of the dating curve).
[(5)]Schmidt hammer applied to the dating of M-MUE 'c' (= youngest pre-'LIA' moraine) and lichenometry to the dating of M-MUE 1.

Figure 2 Sketch map of the glacier foreland of Mueller Glacier. The dated 'Little Ice Age' moraines are numbered. Pre-'Little Ice Age' moraines are indicated by letters (not studied here; modified after Winkler, 2000a).

measurements were used to provide an independent test of the 'Little Ice Age' age on the moraines studied and to distinguish them from older, pre-'Little Ice Age' moraines (see Winkler, 2000b and 2001, for more details).

Results

Mueller Glacier

The results derived from the use of the new lichenometric dating curves at Mueller Glacier indicate a 'Little Ice Age' maximum around AD 1725–1730 (AD 1721–1732 depending on which lichenometric dating curve was applied; Table 3).

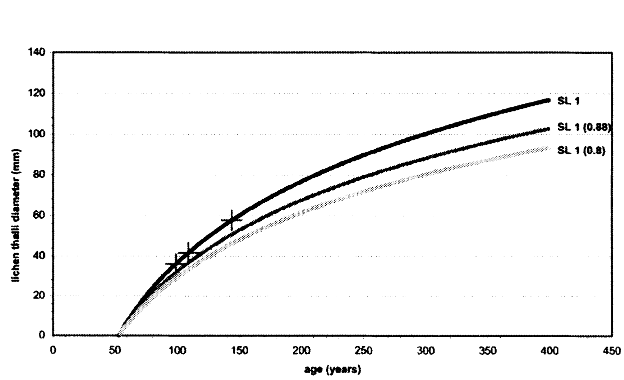

Figure 3 Regional lichenometric dating curve (SL 1), originally constructed for Mueller Glacier (fixed dating points marked). Two alternative versions showing reduced lichen growth and used for Hooker/Tasman Glacier (SL 1, reduction factor 0.88) and Eugenie Glacier (SL 1, reduction factor 0.8) are also provided (cf. text; modified after Winkler, 2000a).

This major advance was followed by successively lesser advances or stillstands around 1740, 1860, 1895 and 1905 (see Winkler, 2000a, for more details). All measurements used in the final dating were from moraines on the southeastern part of the foreland as these provided the best local growing conditions and the largest individual lichens.

Hooker Glacier

At Hooker Glacier, lichenometric measurements were carried out on different parts of the glacier foreland (Figure 4). However, only the data from the frontal moraine system in the central southern part of the foreland were finally used. The lichens on the three innermost ridges of the complex lateral moraine system, identified as 'Little Ice Age' by Schmidt hammer measurements (cf. Winkler, 2000b), were smaller probably due to poorer growth conditions on lateral moraines compared with frontal or latero-frontal moraines. The frontal moraine complex comprises five individual ridges, spaced over a distance of 250 to 300 m between the outermost and the innermost 'Little Ice Age' moraines. Distal to the outermost 'Little Ice Age' moraine, some partially eroded remnants of older moraines exist (Winkler, 2001). The frontal 'Little Ice Age' moraines in the central foreland increase in height towards the outermost moraine ridge. A marked difference in the vegetation cover between the three inner (M 3–5) and the two outer ridges (M 1 and M 2) is clear. The inner moraines lack larger boulders and show signs of postdepositional modification. As a result, some of the 'Little Ice Age' moraines at Hooker Glacier provided only a few suitable sites for lichenometric measurements and showed large differences in lichen thalli sizes between sites on the same moraine ridge.

The mean values of the five largest lichens from Hooker Glacier moraines are mostly smaller than those of the corresponding moraines at Mueller Glacier (Tables 4a and 5; cf. Winkler, 2000a). There are three possible explanations: either the 'Little Ice Age' maximum occurred later at Hooker Glacier (i.e., *c.* AD 1780) or lichen growth at Hooker Glacier, on the moraines studied, is slightly slower than on the southeastern part of the foreland of Mueller Glacier in response to less than optimal growth conditions, or lichens could have taken longer to colonize. Smaller lichens at Hooker Glacier may be in response to slower glacier retreat from the moraines (small distance between individual moraine ridges) and/or instability of the moraine slopes of the frontal moraine complex with its complex morphology. Local climatic factors such as duration of snowcover, amount of precipitation and air temperature, however, cannot be ruled out. In order to test the possible explanation of slower lichen growth, lichen thallus sizes from the Hooker Glacier were compared with the corresponding five 'Little Ice Age' moraines on the southeastern and northeastern forelands of Mueller Glacier (Winkler, 2000a; cf. Table 5). Lichen sizes on the Hooker moraines are smaller than those on the Mueller moraines on the southeastern side by factors between 0.81 and 0.93. After some testing, one factor (0.88) showing consistency on older moraines was used to reduce the lichen growth as shown by the best-fit regional lichenometric dating curve for Mueller Glacier (Figure 3). Later, the resulting alternative dating curve was used to date the moraines at Hooker Glacier (Table 4a) and checked against historical information about advances of the neighbouring cirque glaciers around AD 1890 and *c.* AD 1905 (Burrows, 1973; Gellatly, 1985). This alternative dating curve gave a date of *c.* AD 1735–1740 for the outermost 'Little Ice Age' moraine and revealed subsequent moraine formation around AD 1770, *c.* AD 1860, 1890 and 1910 (see discussion).

Table 3 Lichenometric dating results for Mueller Glacier (taken from Winkler, 2000a)

Moraine	Mean of 5 largest lichens (mm)	SL 1[(1)]	SL 2[(1)]	SL 1w[(1)]	SL 2w[(1)]
M-MUE 1	94.8	**AD 1726**	1732	1723	1721
M-MUE 2	92.4	**AD 1737**	1742	1735	1732
M-MUE 3	55.8	**AD 1860**	1859	1860	1857
M-MUE 4	38.8	**AD 1895**	1893	1896	1893
M-MUE 5	33.2	**AD 1905**	1903	1905	1903

[(1)]Code of lichenometric dating curves. **SL 1: log y = 0.0075 x + 1.7252.** SL 2: log y = 0.0072 x + 1.7439. SL 1w: log y = 0.0076 x + 1.7199. SL 2w: log y = 0.0075 x + 1.7331. See Winkler (2000a) for detailed description of the construction of the lichenometric dating curves (SL 1 is based on best results from regression analysis, and used as a 'regional dating curve' in this study).

Eugenie Glacier

At Eugenie Glacier there was no historical evidence to provide a local control point. In addition, the glacier foreland is at a higher altitude than those of the other glaciers in this study. Both the original lichenometric growth curve for Mueller Glacier and the alternative version for poorer growth conditions at the Hooker Glacier were applied. A third dating curve representing further reduced lichen growth (chosen factor 0.8), due to the special local ecological conditions (high altitude) and few study sites (short moraine ridges), was also constructed based on thallus sizes ratios and used for testing purposes (Table 4b and Figure 3). The different lichenometric dating curves provide ages between AD 1723 and 1800 for the outermost 'Little Ice Age' moraine and ranges between AD 1814 and 1855 (M 2), 1861 and 1885 (M 3), 1884 and 1901 (M 4) and 1895 and 1908 (M 5) for the later inner moraines ridges (Figure 4). Different glacial dynamics caused by the different glacier type and field observations suggest that the older ages (i.e., AD 1723 or 1761) are more likely to represent the 'Little Ice Age' maximum here, taking into account the overall lichen population and ecological conditions (see discussion).

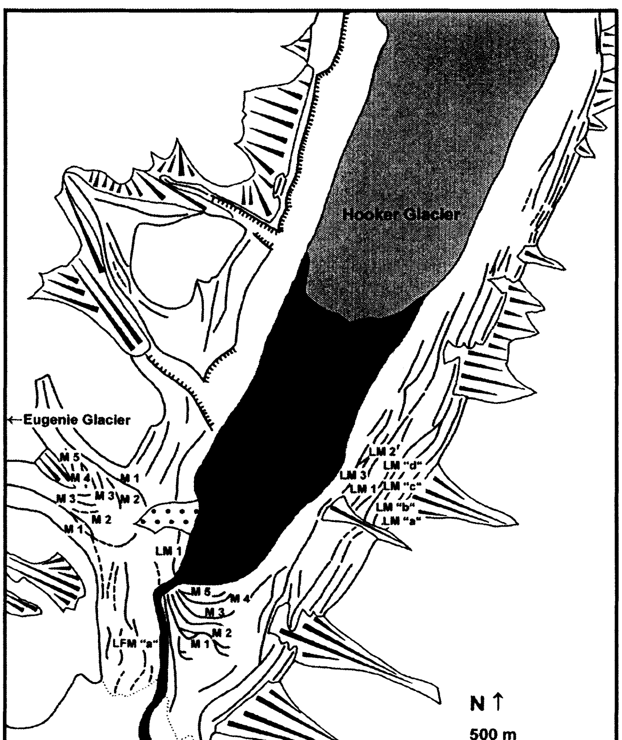

Figure 4 Sketch map of the glacier forelands of Hooker Glacier and Eugenie Glacier moraines with the dated moraines numbered.

Tasman Glacier

The glacier foreland of Tasman Glacier is different from those of Hooker and Mueller Glaciers (Figure 5). Although large 'alpine type' lateral moraines (*sensu* Winkler and Hagedorn, 1999) are present at Tasman Glacier, the extent of the southwestern glacier tongue's foreland is comparatively small. There is only one generation of pre-'Little Ice Age' moraines at Tasman Glacier, whereas there are (at least) three at both Hooker and Mueller Glaciers (cf. Winkler, 2000a; 2000b). The large number of Holocene glacier advances reported for Tasman Glacier is based exclusively on radiocarbon dated organic material and fossil soils found within the lateral moraines (e.g., Röthlisberger, 1986; Gellatly *et al.*, 1988). Apart from one pre-'Little Ice Age' moraine, there is no morphological evidence for other individual Tasman moraines similar to these of the other glaciers in the area (cf. critical remarks from Kirkbride and Brazier, 1998; Winkler, 2000b; see discussion).

The 'Little Ice Age' moraines in the southwestern foreland of Tasman Glacier mainly comprise a single, impressive moraine ridge over 100 m above the present glacier surface. It could best be described as a 'continuation' of the lateral moraine in a latero-frontal/frontal position. In a few places, this moraine is multicrested with small, individual ledges on the distal slope of the main moraine ridge (i.e., the youngest moraine ridge). Neither Burrows (1973) nor Gellatly (1982; 1985) found suitable fixed dating points for this glacier. However, Burrows (1973) mentioned that Tasman Glacier 'overtopped' the existing lateral moraine during an advance around AD 1890 and Gellatly (1982) provides evidence for a similar 'overtopping' *c.* AD 1914. Although no direct evidence can be found for the southwestern part of the foreland, the glacier surface may have reached the height of the crest of the dominant main moraine ridge in AD 1914 and 'overtopping' at this location cannot be excluded.

As local lichenometric growing curves could not be constructed at Tasman Glacier, the regional dating curves for Mueller Glacier and the alternative one for Hooker Glacier were applied. Lichen thalli tend to be comparatively small on the older 'Little Ice Age' moraines at Tasman Glacier. This is, however, unsurprising, bearing in mind the special ecological growth conditions for the *Rhizocarpon* subgenus at this site. On the older 'Little Ice Age' moraines, i.e., the ledges on the distal slope of the main moraine (Figure 5), only a few sites along crest and proximal slopes could be measured due to their restricted length. The location of these ledges means that they are quite unstable and may have been affected by 'overtopping'. This could explain why the largest lichens were found in a distal position close to the outer crest of the main moraine where the main ridge is double-crested (and not on one of the older ledges).

The data for the main moraine ridge suggest dates between AD 1879 and 1925, when the regional lichenometric dating curve for Mueller Glacier is applied, and dates between

Table 4 Lichenometric dating results for (a) Hooker Glacier, (b) Eugenie Glacier and (c) Tasman Glacier

Moraine	Mean 5 largest lichens (mm)	SL 1[1] (AD)	SL 1 (0.88)[2] (AD)	SL 1 (0.8)[3] (AD)
(a) Hooker Glacier				
M-HOK 1	81.6	1781	1737	
M-HOK 2	81.4 (74.0)[4]	1783 (1818)	1738 (1773)	
M-HOK 3	49.2	1878	1861	
M-HOK 4	36.2	1901	1892	
M-HOK 5	26.8	1916	1910	
(b) Eugenie Glacier				
M-EUG 1	76.4	1800	1761	1723
M-EUG 2	57.8	1855	1834	1814
M-EUG 3	44.2	1885	1873	1861
M-EUG 4	35.6	1901	1892	1884
M-EUG 3	31.0	1908	1901	1895
(c) Tasman Glacier				
M 0	54.8	1862	1843	
LFM 1.2	57.0	1857	1837	
LFM 1.3	61.6	1845	1821	
LFM 1.4	56.4	1858	1838	
LFM 1.5.1 (d)[5]	68.6	1825	1795	
LFM 1.5.1	47.2	1879	1865	
LFM 1.5.2	38.0	1897	1887	
M 1.5.1[6]	37.2	1897	1888	
M 1.5.2	19.2	1925	1922	
LM 1[7]	34.7	1902	1894	

[1]Regional lichenometric dating curve (see Table 3 and text).
[2]Lichenometric dating curve SL 1 adjusted to show reduced lichen growth (see text): SL 1 (0.88) : $\log y = 0.0075 \cdot \frac{x}{0.88} + 1.7252$.
[3]Lichenometric dating curve SL 1 adjusted to show reduced lichen growth (see text): SL 1 (0.8) : $\log y = 0.0075 \cdot \frac{x}{0.8} + 1.7252$.
[4]The measurement site SL 32.2 provided a higher mean of the five largest lichens (81.4 mm), but a smaller largest lichen (94 mm) compared to site SL 32.1 (largest lichen 97 mm; mean five largest lichens 74.0 mm).
[5]Site on the distal slope of LFM 1.5.1 (see text).
[6]Frontal section of M 1.5 (Figure 5).
[7]Single-crested lateral section (without older moraines (ledges) on distal slope).

AD 1865 and 1922 for the Hooker Glacier curve (Table 4c). Clearly, these dates represent the withdrawal (or the last 'overtopping') of the glacier from the main, innermost moraine ridge around the turn of the nineteenth and into the twentieth centuries. The dates for the older 'Little Ice Age' 'moraines' (the aforementioned ledges) seem to be unreliable, as the position of the largest lichens indicates an older age for the 'Little Ice Age' maximum at Tasman Glacier.

Discussion

The results derived from using the new lichenometric dating curves incidate a 'Little Ice Age' maximum at Mueller Glacier about AD 1725/30 (cf. Winkler, 2000a). Taking the possible methodological range of error into account (see below), this dating estimate corresponds with a major advance around AD 1750 of the Fox and Franz Josef Glaciers west of the main divide proposed by Lawrence and Lawrence (1965). However, it is acknowledged that the difference in the timing of the 'Little Ice Age' maximum at Mueller Glacier compared with the results of earlier studies (Burrows, 1973; Gellatly, 1982) could be a function of differences in the lichenometric procedures used (cf. Innes, 1985a; Matthews, 1994; cf. discussion in Winkler, 2000a).

Historical evidence is insufficient to construct individual lichenometric dating curves for each of the other glaciers studied here. In addition, the application of the curve from Mueller Glacier involves some uncertainties. Since the local ecological conditions and lichen populations vary considerably on different parts of the glacier forelands (Winkler, 2001), it is possible that the Eugenie, Hooker and Tasman moraines do not provide comparable optimal growth conditions for the *Rhizocarpon* subgenus to those on the southeastern foreland of Mueller Glacier (where the regional lichenometric dating curves were constructed; cf. Winkler, 2000a). Therefore, alternative lichenometric dating curves based on reduced growing rates were constructed for the Hooker and Eugenie Glaciers.

Table 5 Comparison between the mean of the five largest lichens at Hooker and Mueller Glaciers (southeastern and northeastern glacier forelands of Mueller Glacier)

Moraine	Hooker Glacier 5 largest lichens (mm)	Mueller Glacier (SE foreland) 5 largest lichens (mm)	Mueller Glacier (NE foreland) 5 largest lichens (mm)	Ratio of 5 largest lichens Hooker/ Mueller (SE)	Ratio of 5 largest lichens Hooker/ Mueller (NE)
M 1	81.6	94.8	96.2	0.86	0.85
M 2	81.4[1]	92.4	83.2	0.88	0.98
M 3	49.2	55.8	55.4	0.88	0.89
M 4	39.2	38.8	35.8	0.93	1.01
M 5	26.8	33.2	26.6	0.81	1.01

[1]cf. Table 4a.

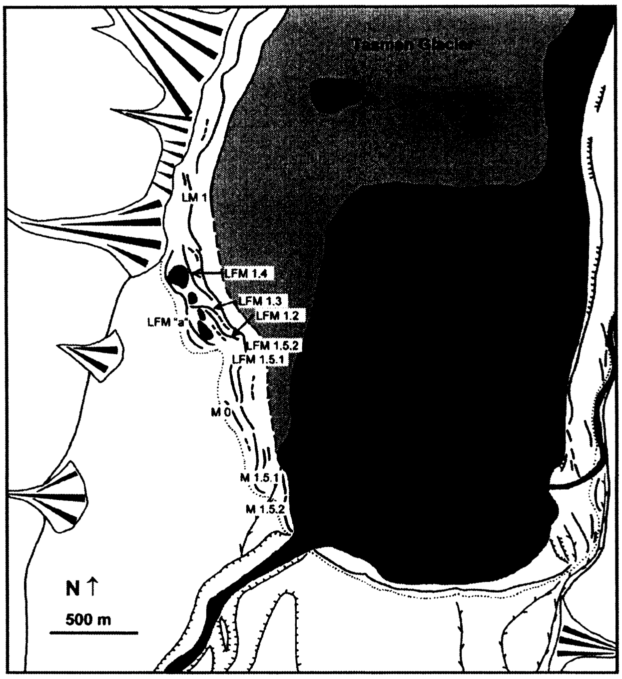

Figure 5 Sketch map of the southwestern glacier forelands of Tasman Glacier. The dated moraines are numbered.

An empirically derived ratio of lichen thalli from the corresponding Hooker and Mueller Glacier moraines was used for this purpose, bearing in mind that both glacier forelands have a similar number of 'Little Ice Age' moraines, pattern of vegetation cover and moraine morphology. As the longest axial measurements of lichen thalli on the foreland of Hooker Glacier and the northeastern foreland of Mueller Glacier were almost identical, it could be argued that the local growth rate for the *Rhizocarpon* subgenus is slower at Hooker Glacier compared with the southeastern foreland of Mueller Glacier. Alternatively, the timelag between moraine formation and lichen colonization could be longer at Hooker Glacier. In general, growing conditions on the frontal moraines of Hooker Glacier seem to be less favourable than those on the southeastern foreland of Mueller Glacier, where the regional dating curves were constructed. An explanation might be differences in microclimate or instability of the proximal slopes of the frontal moraines at Hooker Glacier, due to a melting ice core after moraine formation and predominant vertical ice loss owing to the short distance between the outer- and innermost moraines.

Moraine formation around AD 1860, 1890 and 1910 at Hooker Glacier, according to the alternative lichenometric growing curve (factor 0.88), is supported by historical evidence and reports on a parallel glacier advance of Mueller and Hooker Glaciers (cf. Burrows and Orwin, 1971; Burrows, 1973; Gellatly, 1984; 1985). Although there is no evidence for older 'Little Ice Age' moraines, the alternative regional lichenometric dating curve seems to give appropriate dates for Hooker Glacier, with a date of *c.* AD 1735–1740 for the 'Little Ice Age' maximum at Hooker Glacier followed by a second advance (oscillation?) within the next few decades. This dating agrees well with the findings at Mueller Glacier. The number and configuration of the five individual frontal 'Little Ice Age' moraines (i.e., two closely dated outer moraines M 1 and M 2, then a considerable time gap between the formation of M 2 and M 3) and an overall comparably short distance between M 1 and M 5 (especially if the retreat since the middle of the twentieth century is taken into account) suggest a similar 'Little Ice Age' chronology for the Hooker and Mueller Glaciers.

However, as the dating curve is not derived from Hooker Glacier itself but only modified from the neighbouring Mueller Glacier, a considerable range of possible methodological error has to be taken into account. With different empirical derived ratios (Table 5) between corresponding Hooker and Mueller Glacier moraines (on the southeastern foreland), the results of dating curves using different factors could give an estimation of the error range for the final datings of the alternative lichenometric dating curve for Hooker Glacier using the factor 0.88. Leaving out the slightly out-of-line factor for M 5 (0.81), calculated results for the factors 0.86 and 0.93 give ranges of four years (M 5), six years (M 4), 11 years (M 3), 30 (25) years (M 2) and finally 32 years (M 1) between the older (factor 0.86) and the younger datings (factor 0.93). Even if these ranges increase while taking the factor 0.81 into account, an estimated accuracy level of ± 5 years for the youngest moraine and ±20 to 30 years for the oldest moraines seems realistic here (cf. Matthews, 1994), even under the specific conditions in the Southern Alps.

Eugenie Glacier probably experienced its 'Little Ice Age' maximum about AD 1760. However, there is a major uncertainty concerning whether the alternative lichenometric dating curve for Hooker Glacier should be applied to this glacier without any local dating controls. The number of moraines suggests at least some chronological parallels with those of the valley glaciers. The application of lichenometry at Tasman Glacier poses some methodological problems, as there is evidence for 'overtopping' of the main ridge of the 'Little Ice Age' moraine complex in the southwestern foreland at the end of the nineteenth century during a readvance. It is thus impossible to date the 'Little Ice Age' maximum at Tasman Glacier in detail. However the existence of a few large lichen thalli indicates that this could have occurred prior to the late eighteenth century with the glacier reaching a position close to its 'Little Ice Age' maximum during a readvance in the late nineteenth century.

The delay between the formation of the outer two 'Little Ice Age' moraines and the three inner moraines at Hooker and Mueller Glaciers suggest a slow but continious retreat during the second half of the eighteenth and first half of the nineteenth centuries. A readvance, well supported by historical evidence (Gellatly, 1984), is represented by moraines formed around AD 1860 (M 3). A second readvance around the end of the nineteenth century is supported by moraines of the Hooker and Mueller Glaciers (M 4) and also by historical evidence from Tasman Glacier (Burrows, 1973; Gellatly, 1984). The distance between the outer (M 1, M 2) and the inner 'Little Ice Age' moraine (especially the AD 1860 moraine, M 3) is less than 100 m in several locations at the Eugenie, Hooker and Mueller Glaciers. This suggests that Tasman Glacier, with its long reaction time, retreated little after the 'Little Ice Age' maximum before it advanced again nearly to its previous maximum during readvances at the end of the nineteenth century. A different behaviour of Tasman Glacier during the 'Little Ice Age' owing to its special glacial dynamics is, however, a conclusion supported by recent research showing that its reaction is partly decoupled from climatic variations (cf. Kirkbride, 1993; Kirkbride and Brazier, 1998). Accordingly, there is increasing doubt as to whether the Tasman Glacier is a suitable key location for construction of a Holocene glacier chronology for the Southern Alps, as postulated by Röthlisberger (1986) in previous work (cf. critical remarks by Kirkbride and Brazier, 1998; Winkler, 2000b).

Since its first application by Beschel (1950) there has been a partly controversial discussion on the value of this method to date moraines and its limitations from a biological point of view (cf. Jochimsen, 1966; McCarthy, 1999). Meanwhile, recommended modern procedures (cf. Innes, 1985a; Matthews, 1994) have successfully improved the method and minimized its potential sources of error. Several examples have shown the precision of lichenometry by comparison with independent historical dating evidence (e.g., Erikstad and Sollid, 1986; Bickerton and Matthews, 1992; 1993). Although a general discussion on the justification of lichenometry in dating 'Little Ice Age' moraines is far beyond the aims of this paper, the present author wants to address a few points relating to the specific sources of possible error in the study area (cf. Winkler, 2000a; 2001).

All glaciers studied, except Eugenie Glacier, are highly covered by supraglacial debris and the possibility of lichens colonizing this debris (cf. Matthews, 1973) and surviving following moraine formation cannot be excluded. On the other hand, with a thick supraglacial debris cover present, temporary ice cores could have been separated from the active ice during moraine formation (cf. Winkler, 2001), leading to unstable moraine slopes and postdepositional modification. This process could possibly have disturbed and (as a kind of compensation) delayed lichen colonization. Anyway, due to the thick supraglacial debris cover and its influence during moraine formation, the possible range of error between lichenometric dating and formation of the moraine is greater than, for example, in southern Norway.

Attention has to be drawn to the variability of the ecological conditions for lichens in the glacier forelands. Although recommended as best procedure by Matthews (1994), use of the mean of the largest lichens of five sample sites was prohibited by several moraines with fewer than five sites with comparable good ecological conditions and lichen populations. This procedure would have included sites with obviously slower lichen growth, and therefore would have led to an underestimation of the true age of the moraines. The use of the mean of the five largest lichens of the site with the highest values also provides security against the errors resulting from possible onset of lichen colonization on the supraglacial debris (cf. Innes, 1985a). Taking all these possible influences into account, an accuracy of ± 20 (30) years for the oldest moraines dated here is believed to be a realistic estimation.

One disadvantage of the application of lichenometry in the Southern Alps is the lack of older fixed dating points that could improve the dating curves. Even if the semilogarithmic dating curves here have been successfully applied in many lichenometric studies and it is thought to represent the trend of the growth of an aggregated *Rhizocarpon* subgenus (Matthews, 1994), there is always an increasing uncertainty due to extrapolation beyond the oldest fixed point. Apart from a comparison with dating curves from other regions of similar lichen populations and ecological conditions (Winkler and Shakesby, 1995; Winkler, 2001), this critical problem remains unsolved due to the lack of historical evidence from the time prior to 1860 and alternative exact dating methods. However, recent investigation elsewhere have shown that extrapolation gives acceptable results, of course within a limited timespan and with a higher range of error (Winkler, 2003; Winkler *et al.*, 2003).

A 'Little Ice Age' maximum during the eighteenth century in the Mt Cook National Park is in agreement with the findings reported for southern Norway (Erikstad and Sollid, 1986; Bickerton and Matthews, 1993; Winkler, 1996; Winkler *et al.*, 2003) and for northern Norway (Innes, 1984b; Winkler, 2001; 2003). At the end of the twentieth century there were similar strong glacier advances in response to positive net balances in the Southern Alps (e.g., Franz Josef Glacier advanced over 1000 m between 1983/4 and 1999; Winkler, 2001; cf. Chinn, 1999; Chinn and Salinger, 1999) and in maritime Scandinavia (Winkler *et al.*, 1997; Winkler and Nesje, 2000). This indicates a possible common trend in maritime mountain areas in both hemispheres. The existence of pre-'Little Ice Age' moraines, with evidence for multiple Holocene glacier advances in Mt Cook National Park (Gellatly *et al.*, 1988; cf. Winkler, 2000b), however, suggest some affinities with the European Alps (Röthlisberger, 1986).

Only detailed regional glaciological studies, with especial attention to comparisons of glacier movements in maritime and continental mountain areas, can improve the record of 'Little Ice Age' climatic variations and further explore parallels between the Southern Alps and maritime Scandinavia, suggested by the recent glacial dynamics and the timing of the 'Little Ice Age' maximum. Multiple pre-'Little Ice Age' advances common in the Southern Alps and European Alps indicate that a comparison of their moraine chronologies also could be valid. As stated by Grove (1988) the 'Little Ice Age' is far from being a parallel and uniform period of glacier advance in the mountain areas of both hemispheres (Winkler, 2002). Improvements in glacier chronologies could lead to a better understanding of the complex relationship between glaciers and climate. For example, both the ENSO (El Niño–Southern Oscillation) and the NAO (North Atlantic Oscillation) are identified as important features explaining today's glacier behaviour (cf. Rogers, 1984; Fitzharris *et al.*, 1997; Pohjola and Rogers, 1997; Nesje *et al.*, 2000). Detailed investigation of the glacier behaviour in those regions mainly affected by ENSO (Southern Alps) and NAO (maritime Scandinavia) could help to find an answer to whether there is a possible connection between these two important climatic phenomena. As a 'global' glacier behaviour does not exist today, searching for similar patterns of regional differences in Holocene glacier chronologies could not only improve not only our knowledge on past climate change but also help to simulate future glacier behaviour.

Conclusions

Using a lichenometric dating curve established on the basis of historical evidence, the 'Little Ice Age' maximum at Mueller Glacier is dated to around AD 1725–1730, followed by readvances *c.* AD 1740, 1860, 1890/95 and 1905.

An alternative lichenometric dating curve for the *Rhizocarpon* subgenus based on a reduction in lichen growth by a factor of 0.88, owing to less favourable local ecological conditions for the *Rhizocarpon* subgenus at Hooker Glacier, indicates a 'Little Ice Age' maximum around AD 1735–1740, followed by readvances a few decades later (AD 1770?), 1860, 1890 and 1910. The moraine sequence at Hooker Glacier is comparable to Mueller Glacier in terms of the number of individual moraines, pattern of vegetation cover and distance between the individual moraines.

At Eugenie Glacier, the 'Little Ice Age' maximum probably occurred around AD 1760 (or AD 1725, if lichen growth rates are slower than those at Hooker Glacier). There are four subsequent moraines, mainly formed during the late nineteenth century.

'Overtopping' of the prominent, inner main 'Little Ice Age' moraine ridge of the complex (latero-frontal) moraine system in the southwestern glacier foreland by the readvancing Tasman Glacier resulted in major difficulties in dating the 'Little Ice Age' maximum. It apparently occurred prior to *c.* AD 1800. This position, nearly reached during readvances at the end of the nineteenth century, was confirmed by historical evidence.

The 'Little Ice Age' chronology for the glaciers in Mt Cook National Park studied here shows a maximum during the eighteenth century (between AD 1730 and 1740?) followed immediately by a second oscillation a few years or decades later. The glaciers retreated apparently during the second half of the eighteenth and the first half of the nineteenth centuries. Readvances during the second half of the nineteenth century led to a frontal position not far removed from the older 'Little Ice Age' moraines. At Tasman Glacier, these readvances caused the 'overtopping' of the older moraine crest. Owing to its long reaction time, the Tasman Glacier retreat was less than that of the other glaciers. The entire 'Little Ice Age' moraine sequence of all the glaciers is comparatively closely spaced with a further major retreat only occurring after AD 1930.

The timing of the 'Little Ice Age' maximum of the study glaciers agrees with a major advance of the Fox and Franz Josef Glaciers west of the main divide in the Southern Alps and with the 'Little Ice Age' maximum in southern and northern Norway.

There could be a basis for future fruitful investigation of a possible connection of ENSO and NAO as important influences on glacier mass balances if the similarities between the 'Little Ice Age' maximum and recent glacier behaviour in the Southern Alps and maritime Scandinavia, the regions affected by these climatic phenomena, were further improved by detailed studies on the Holocene glacier chronologies and climatic fluctuations.

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