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Franz Josef and Fox Glaciers, New Zealand: Historic length records

Heather Purdie [a,*], Brian Anderson [b], Trevor Chinn [c], Ian Owens [a], Andrew Mackintosh [b], Wendy Lawson [a]

[a] Department of Geography, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[b] Antarctic Research Centre, Victoria University of Wellington, PO Box 600, Wellington, New Zealand
[c] Lake Hawea Institute of Cryodynamics, 20 Muir Rd., LGM Hawea, RD2 Wanaka, New Zealand

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ABSTRACT

Compilation of modern and historical length change records for Franz Josef and Fox Glaciers demonstrates that these glaciers have lost ~3 km in length and at least 3–4 km^2 in area since the 1800s, with the greatest overall loss occurring between 1934 and 1983. Within this dramatic and ongoing retreat, both glaciers have experienced periods of re-advance. The record from Franz Josef Glacier is the most detailed, and shows major advances from 1946 to 1951 (340 m), 1965–1967 (400 m), 1983–1999 (1420 m) and 2004–2008 (280 m). At Fox Glacier the record is similar, with advances recorded during 1964–1968 (60 m), 1985–1999 (710 m) and 2004–2008 (290 m). Apart from the latest advance event, the magnitude of advance has been greater at Franz Josef Glacier, suggesting a higher length sensitivity. Analysis of the relationship between glacier length and a reconstructed annual equilibrium line altitude (ELA) record shows that the glaciers react very quickly to ELA variations — with the greatest correlation at 3–4 years' lag. The present (2014) retreat is the fastest retreat in the records of both glaciers. While decadal length fluctuations have been linked to hemispheric ocean–atmosphere variability, the overall reduction in length is a clear sign of twentieth century warming. However, documenting glacier length changes can be challenging; especially when increased surface debris-cover makes identification of the 'true' terminus a convoluted process.

1. Introduction

Glaciers are sensitive indicators of climatic variations on all time scales from millennia-long glaciations to decadal and inter-annual variations. Recent work on New Zealand moraine records (e.g. Schaefer et al., 2009; Kaplan et al., 2010; Putnam et al., 2010, 2012; Doughty et al., 2013) has improved our understanding of the timing and magnitude of the climatic events that led to the termination of the Pleistocene, subsequent re-advance during the late-glacial period, and general retreat through the Holocene. On a century scale, glacial retreat is an excellent indicator of the magnitude of warming that has occurred since the end of the Little Ice Age (LIA) (Oerlemans, 2005). On decadal timescales the temporary advance of some glaciers has been interpreted from various changes in meteorological conditions (Fitzharris et al., 1997; Hooker and Fitzharris, 1999; Chinn et al., 2005b). The basis of interpreting past glacial change on all of these time-scales, and its climatic significance, rests on the observation of the fluctuations of present-day glaciers and their climatic causes.

Records of glacier fluctuations are heavily biased towards the Northern Hemisphere and the European Alps in particular (Oerlemans, 2005), where there are historic documents, illustrations and photographs that extend back many centuries (Oerlemans et al., 2007 and references therein). In contrast, the Southern Hemisphere has few historic records of glacier change. There are a few records for South America that combine historic data and tree ring dates (Villalba et al., 1990), but the record from Franz Josef Glacier, in the Southern Alps of New Zealand, stands out. It begins in 1865, within a few years of the earliest written observations of any Southern Hemisphere glaciers, and contains observations at least every decade between then and the present. Fox Glacier has a record of similar duration but of lesser detail.

As well as representing a poorly measured zone of Earth's surface, Fox and Franz Josef Glaciers are also remarkable from a glaciological point of view. Both have similar topographies, descend as far below their equilibrium line altitudes (ELAs) as any glacier worldwide, and both have extremely sensitive and fast responses to climatic variations. The Franz Josef Glacier is the best studied of the two, for example, from Wilson (1896) and Bell (1910) to Oerlemans (1997) and Anderson et al. (2006). Length records at Fox and Franz Josef Glaciers are crucial to understanding links between climatic and glacier length variations. The records exist in a number of published and unpublished sources, and various versions with slight differences are shown by different authors (e.g. Chinn, 1999; Oerlemans, 2005; Anderson et al., 2008; Leclercq and Oerlemans, 2011). The different versions arise because of the varied sources of information and changing datum positions for length measurement. The aim of this paper is to present a coherent set of length change measurements that exist for these extraordinarily sensitive and responsive glaciers.

* Corresponding author.
E-mail address: heather.purdie@canterbury.ac.nz (H. Purdie).

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2. Study site

The total area of glacier cover in the Southern Alps in 1978 was 1158 km^2 (Chinn, 2001) and glacier ice spans an extraordinary elevation range for its latitude (42–44°S) from 280 m above sea level (a.s.l.) at the terminus of Fox Glacier to the highest peak (Aoraki/Mt Cook, 3754 m a.s.l.), with ELAs ranging from 2490 m at the northern end of the range to 1380 m in the south. Of the ~3100 glaciers in the Southern Alps, Fox and Franz Josef are two of the best known and are the third and fourth largest glaciers by volume respectively (Chinn, 2001). The glaciers in the Southern Alps experience a cool temperate climate with precipitation totals ranging from 12 m a^{-1} a few kilometres north-west of the main drainage divide to ~1.5 m a^{-1} at the eastern-most glaciers (Chinn, 1979; Griffiths and McSaveney, 1983; Kees, 2011; Stuart, 2011). The difference between the warmest and coldest mean monthly temperatures varies between 9 K in the west and 13 K in the east (Anderson and Mackintosh, 2012).

Franz Josef Glacier is presently (2014) just under 10.5 km long and covers ~35 km^2 on the western flanks of the Southern Alps of New Zealand at 43°29′ S, 170°11′ E (Fig. 1). The maximum elevation of the glacier is 2900 m a.s.l., although the bulk of the glacier consists of the upper névé area of broad gently-sloping snowfields at elevations ~1900 to 2400 m a.s.l. The glacier tongue descends steeply down a narrow valley terminating within a temperate rainforest at only ~300 m a.s.l. The adjoining Fox Glacier is slightly larger, at ~12.5 km long with an area of ~36 km^2. It also has a larger elevation range, with ice feeding from the western face of Mt Tasman at 3497 m a.s.l. Like Franz Josef, Fox Glacier has a broad high-elevation névé that funnels ice down a similar steep narrow tongue, and terminates below 300 m a.s.l. (Fig. 1).

3. Methods

3.1. Determining length change

Most of the data available on fluctuations of these glaciers are length changes, and these data come from several sources, with varying degrees of accuracy. Where possible, historic maps have been scanned and geo-referenced to a modern map projection (NZTM); the accuracy of this process is limited by the quality of the cartography, and the number of points on the map that can be used as ground control points. At Franz Josef Glacier a number of survey points used in early maps (e.g. Bell, 1910) were used in subsequent maps; these survey points have been located on the ground and their positions recorded using a global positioning system (GPS). At Fox Glacier spot heights from the topographical plan produced by C. Douglas and W. Wilson (Wilson, 1896) were used to geo-reference this first map, and subsequent maps and sketches were aligned based on prominent topography, and river channels. In addition to historic maps, photographs from a range of sources have been used to 'fill gaps' during times when no formal surveying

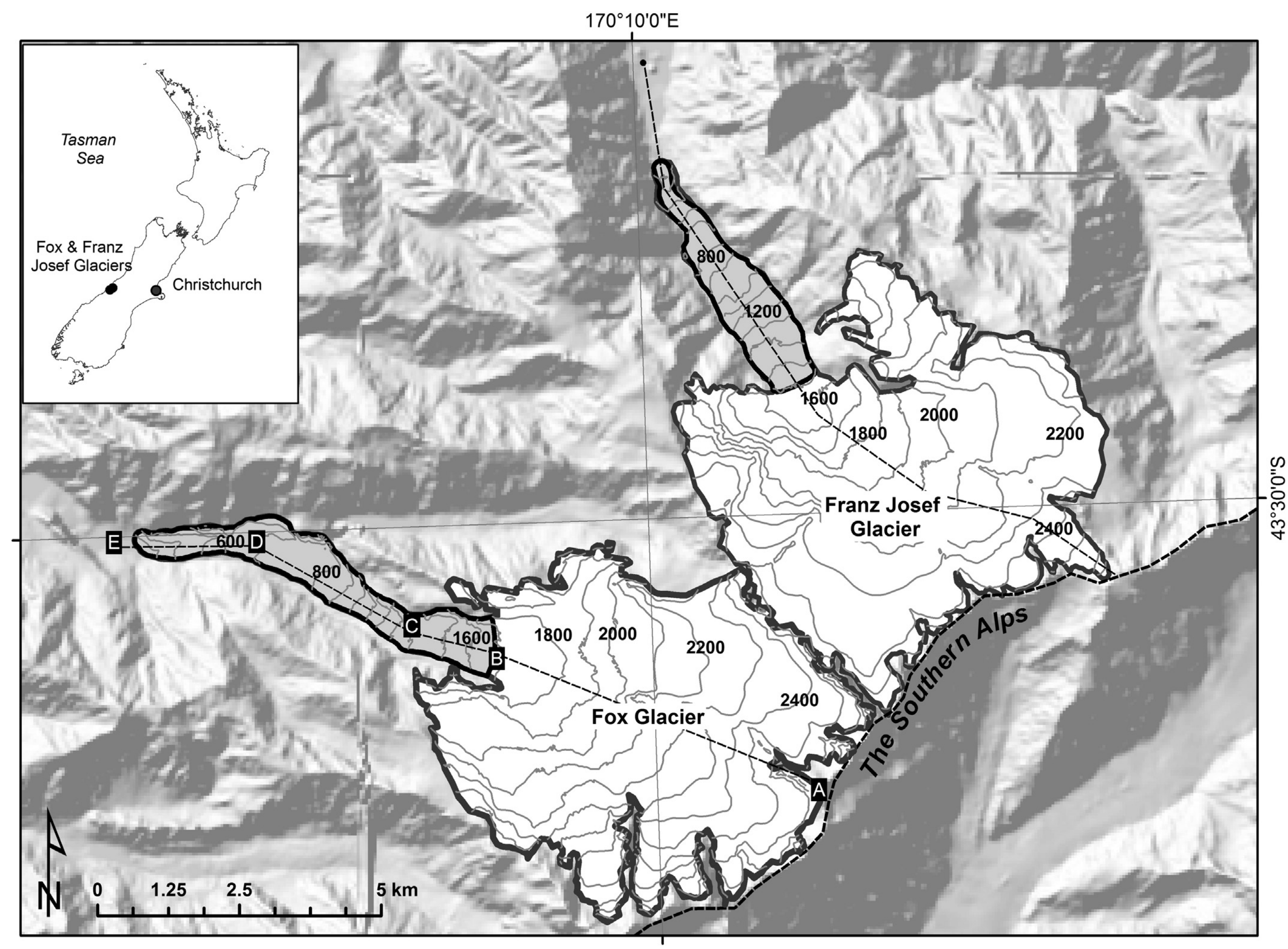

Fig. 1. Location of Franz Josef and Fox Glaciers in the Southern Alps, New Zealand. Glacier outlines are derived from ASTER imagery in 2009 and are accessible from the GLIMS database (More, 2012). Shaded regions on the lower glacier denote the portion used for area calculation. Dotted lines and associated points define the datum used for length calculations (also refer to Tables 1 and 2).

took place. Aerial photographs were preferred, but occasionally ground-based photographs were the only available data, with consequent higher error estimates. Most recent terminus surveys use a GPS as this method has the highest accuracy, but errors still occur as advancing termini are dangerous to survey due to the threat of ice fall and retreating termini are challenging to survey when the 'true' terminus is concealed beneath supra-glacial debris.

Representation of how a glacier 'terminal face' or 'frontal position' changes over time using maps is relatively straightforward, given the above limitations, but assigning a specific length to an irregular retreating glacier terminus is not. During periods of advance, glacier termini tend to form straight to slightly convex cross-valley outlines. During retreat, reduced velocities lead to increased compressive-flow and additional supra-glacial debris cover that can produce either an indefinite buried terminus position or an amorphous string of thermokarst masses of debris-covered ice that may or may not be connected to the active glacier. As much of such ice also lies beneath alluvium, these masses are normally, but frequently erroneously, labelled stagnant or dead ice. This issue is addressed later in the paper, but meanwhile in order to maintain consistency with the work of early surveyors (e.g. Bell, 1910; Speight, 1935), measurements quoted herein have been made to the furthest, connected, down-glacier point of terminus ice along the centreline of the glacier (Fig. 1).

3.2. Area changes

A few area changes are available from the Franz Josef mapping survey of 1893/94, the New Zealand series topographic maps of 1965 and 1987, and maps from 2009 ASTER satellite imagery (More, 2012). Historically, only the lower glacier trunks (Fig. 1) have been mapped in any detail so that for consistent area change calculations, the accumulation areas have each been assigned a constant value and only ablation area changes are considered. Glacier trunk outlines digitized from the above maps provided the calculated area changes.

3.3. Glacier timescales

The reaction time of a glacier is the lag time between an identifiable climatic event, resulting in a mass balance change, and the first reaction of the terminus position (Oerlemans, 2001). Response time, on the other hand, is defined by an e-folding constant, which is a measure of how long a glacier takes to make most (~⅔) of the adjustment to a new equilibrium state after a step change in climate/mass balance (Johannesson et al., 1989). It includes the initial reaction time plus the 'filling' time of adding ice volume that decreases at an exponential rate as the new equilibrium is approached. Both definitions of timescale are useful; reaction time is directly observable if the mass balance history is known, but it will vary with changes in climate forcing, and the mass balance history itself. Response time is a theoretical concept, defined as the time to move between equilibrium states and is therefore independent of the mass balance history. It is often considered a physical property of the glacier, but will vary for large geometry changes — for example Franz Josef Glacier will have a different response time estimated around its 1893 geometry than its 1983 geometry.

To infer the reaction time of these glaciers, we follow the approach of Adhikari et al. (2009) and correlate a reconstructed annual ELA record at Franz Josef Glacier with the glacier length record, adjusting the time lag to maximize the correlation coefficient. The lag is varied from 0 to 20 years and the lag with the highest correlation coefficient is taken as the reaction time of the glacier. While there is an annual ELA record from the Southern Alps derived from oblique aerial photography of 'end-of-summer snowlines' covering the period from 1977 to present (Chinn et al., 2005a) we do not use that record directly because the period is much shorter than the length records. Instead we use a reconstructed ELA record for Franz Josef Glacier based on climatic data recorded at Hokitika, 100 km to the north, since 1894 (Anderson et al., 2006).

4. Results

4.1. Length changes

4.1.1. Franz Josef Glacier length change 1500–2010

The Franz Josef Glacier has the most detailed record of terminus change for any Southern Hemisphere glacier. However, over the years most intensive surveying has tended to coincide with advance phases, and less attention has been paid during the less visually spectacular periods of retreat. A series of well-preserved moraines enabled estimation of glacier maximum lengths (via dendrochronology) during the period ~1600 to 1800 AD (McKinzey et al., 2004). At this time the glacier was around 14 km long (Table 1, Figs. 2 and 3a). A.P. Harper and C. Douglas (Harper, 1894) conducted the first formal survey in 1893, and later recorded that the glacier retreated for 10–12 years before an advance in 1907 (Harper, 1926). Bell (1910) reported on surveys conducted in 1908 and 1909, and the advance reached its maximum in 1909–1910. Speight continued to survey the terminus position (Speight, 1921; Speight, 1935; Speight, 1941) capturing retreat until 1921 followed by a minor re-advance in 1926, which ended around 1934 (Fig. 3a). After 1934 there was a period of rapid retreat, and by 1946 the terminus was over 1 km up-valley from its 1934 position (Speight, 1941; Suggate, 1952; Sara, 1979). This was followed by a small advance (340 m) between 1946 and 1951 (Suggate, 1952; Sara, 1970, 1979). Diagrams of the terminus produced by Suggate (1952) and Sara (1970) had some streams incorrectly labelled, although this issue was rectified by Sara (1979) in which distances between stream outlets on a revised figure match modern topographic maps.

During the period 1958 to 1973 the Franz Josef Glacier terminus was surveyed at least once each year and on many occasions surveys were more frequent. From the early 1950s to early 1965 the glacier retreated, but an advance occurred from late 1965 to early 1968, which left the glacier just over 11 km in length (Sara, 1979) (Figs. 2 and 3b). The 1970s were dominated by retreat, and by 1983 the glacier was the shortest that it had been since measurement began (Hancox, pers. comm., 1994 Mosely, 1984) (Figs. 2 and 3c). Another advance phase was recorded in monthly detail between 1984 and 1990 by C. Woolmore (Westland National Park Board, pers. comm.). Although this advance appeared to cease temporarily in 1991, the glacier continued to expand through the mid-1990s (Hooker, unpublished data, refer to Table 1), and by 1999 the Franz Josef Glacier was over 11.4 km long, a length not seen since 1960 (Figs. 2 and 3c). An advantage to these ongoing surveys at Franz Josef Glacier was the installation of a survey peg (Peg 3) by R.P. Greville on a prominent roche moutonnée located in glacier forefield (Bell, 1910). This peg has been continuously used as a reference point for measurements up to the era of GPS survey. Regular GPS surveys from 1996 to present (Owens and Anderson — refer to Table 1) has meant that the two most recent advance phases (and intervening retreat) have been captured with at least annual resolution (Figs. 2 and 3d). After 1999 the glacier retreated over 400 m until in 2005 the next (and most recent) advance began. This most recent advance ceased in 2008 and the glacier is currently retreating.

4.1.2. Fox Glacier length change 1750–2009

Unlike that of Franz Josef Glacier, the Fox Glacier record suffers from a lack of regular surveys, with only thirty-seven data points covering over 250 years (Table 2). Distinctive trim-lines in present-day vegetation and glacial moraine (Wardle, 1973) have helped to estimate the extent of the glacier around the time of the LIA (given as ~1750 by Wardle, 1973). This date is not well constrained, but the advance presumably coincides with advances at Franz Josef Glacier, the dates of which are better constrained by McKinzey et al. (2004). The first geological survey was conducted by Douglas and Wilson in 1894

Table 1
Length change measured and estimated at Franz Josef Glacier from ~1500 to present. Six advances of varying magnitude have been recorded, these are highlighted with shading.

Year	Length (km)	Estimated error (±m)	Notes
~1500	14.86	200	McKinzey et al., (2004)
~1600	14.31	200	McKinzey et al., (2004)
~1800	13.88	200	McKinzey et al., (2004)
1867	13.17	100	Photograph by Pringle , National Library NZ
1893	13.14	100	Harper (1894)
1894	13.01	100	Harper (1894)
1908	13.00	20	Bell (1910)
1909	13.03	20	Bell (1910)
1914	12.96	20	Speight (1935 ,1941)
1921	12.85	20	Speight (1935, 1941)
1926	12.89	20	Speight (1935, 1941)
1934	12.91	20	Speight (1935, 1941)
1940	12.57	20	Speight (1941)
1946	11.89	20	Suggate (1952) & Sara (1979)
1951	12.23	20	Suggate (1952) & Sara (1979)
1956	12.12	20	Sara (1979)
1958	11.78	20	Sara (1979)
1959	11.51	20	Sara (1979)
1960	11.44	20	Sara (1979)
1961	11.29	20	Sara (1979)
1962	11.00	20	Sara (1979)
1963	10.82	20	Sara (1979)
1964	10.82	20	Sara (1979)
1965	10.76	20	Sara (1979), NZMS1, aerial photography SN1580
1966	11.11	20	Sara (1979)
1967	11.16	20	Sara (1979)
1968	11.14	20	Sara (1979)
1969	11.09	20	Sara (1979)
1970	11.06	20	Sara (1979)
1971	11.05	20	Sara (1979)
1973	10.92	20	Sara (1979)
1978	10.51	20	Sara (1979)
1981	10.24	20	Aerial photography SN5773
1982	10.13	20	Mosely (1984)
1983	10.01	20	Hancox (pers. comm. 1994)
1984	10.30	20	C. Woolmore (unpublished)
1985	10.51	20	Aerial photography SN8478 27/03/1985 & C. Woolmore
1698	10.66	20	C. Woolmore (unpublished)
1987	10.80	20	NZMS 260, aerial photography SN8585 25/02/1987
1988	10.91	20	C. Woolmore (unpublished)
1989	10.93	20	C. Woolmore (unpublished)
1990	10.94	20	C. Woolmore (unpublished)
1991	10.92	20	C. Woolmore (unpublished)
1992	10.98	20	C. Woolmore (unpublished)
1993	11.02	100	B. Hooker (unpublished)
1994	11.13	100	B. Hooker (unpublished)
1995	11.19	100	B. Hooker (unpublished)
1996	11.30	10	Owens GPS survey
1997	11.33	10	Owens GPS survey
1998	11.37	10	Owens GPS survey
1999	11.43	10	Anderson GPS survey
2000	11.33	10	Anderson GPS survey
2001	11.28	10	Anderson GPS survey
2002	11.18	10	Anderson GPS survey
2003	11.10	10	Anderson GPS survey
2004	11.01	10	Anderson GPS survey
2005	11.06	10	Anderson GPS survey
2006	11.19	10	Anderson GPS survey
2007	11.27	10	Anderson GPS survey
2008	11.29	10	Anderson GPS survey
2009	11.27	10	Anderson GPS survey
2010	11.25	10	Anderson GPS survey
2011	11.25	10	Anderson & Purdie GPS Survey
2012	10.79	50	Anderson partial GPS survey & aerial photographs
2014	10.47	50	Anderson photographic analysis

Points used for length calculations in NZTM coordinates (also refer to Fig. 1): Top of flowline 1379172E 5178956N, bottom of flowline (Bell (1910) Peg 3) 1370851E 5187974N.

(Wilson, 1896) providing more accurate measurement. Retreat followed (Figs. 2 and 4a), and although Speight (1935) noted that the glacier was advancing in 1934, lack of survey on either side of this date means that the record depicts only retreat from 1894 to the 1960s (Table 2 and Fig. 2). Aerial photography by Whites Aviation in 1948 enabled an estimation of the terminus position at

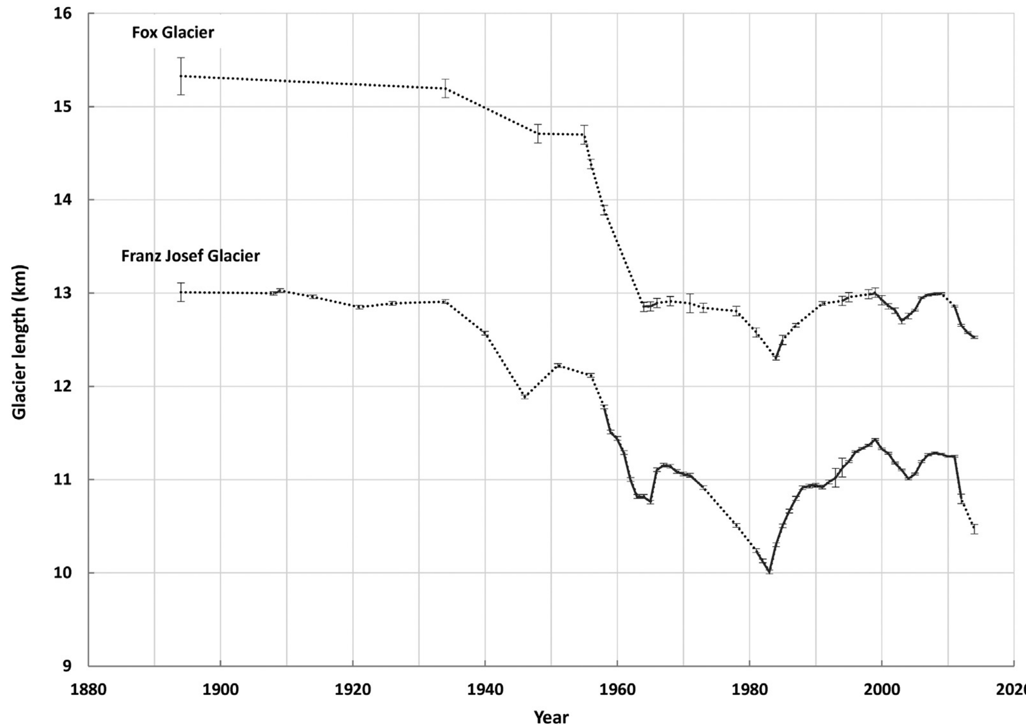

Fig. 2. Summary of length changes at Fox and Franz Josef Glaciers from 1894 to present. The overall pattern of advance and retreat is generally synchronous, but Franz Josef Glacier tends to lead phase changes by around a year. Where data are of annual frequency they are connected by a solid black line. Dotted lines represent intermittent measurement — as can be seen, an advance recorded at Franz Josef in the early 1950s was not recorded at Fox Glacier, but this is likely due to a lack of monitoring.

that time. However, heavy debris cover on the lower glacier meant that the estimated error was high. Although a number of glaciological measurements were made by Gunn (1964) in the mid-1950s these unfortunately did not include a terminus survey. Even so, his descriptions and photos enable the position of the terminus to be estimated for 1955 (Fig. 4b). This gap in records means that the advance which occurred at Franz Josef Glacier between 1946 and 1951, is not recorded at Fox Glacier. Further aerial photography (Whites Aviation) in 1958 shows the terminus to be very straight and clearly 'pinned' behind the spur immediately down-valley of Yellow Creek (Fig. 4b). The glacier position in 1965 is well confirmed by the first photogrammetrically-derived topographic map series (NZMS1), and an advance during the late 1960s was recorded by Sara (1979) who also mapped the position of the terminus in 1973, noting how the northern side was back to the 1965 position (Fig. 4b). Photographs from the personal collections of T. Chinn and J. Soons show that in 1984 the glacier was at its shortest since records began — a length of only 12.3 km (Figs. 2 and 4c). However, another advance immediately followed. This advance is not well confirmed. Length increases described by Hirtlreiter (1987) seem large (~400 m advance between Jan 1986 and Jan 1987) and it is hard to reconcile sketches in that publication with aerial photography from February 1987 which was used to produce the NZMS 260 topographic map. As at Franz Josef Glacier, this 1980s advance culminated in 1999 and the Fox Glacier was once again 13 km in length (Figs. 2 and 4c). Although no formal surveys were conducted during this time, terminal moraine deposited by the 1990s advance was surveyed by GPS in 2005 (Purdie et al., 2008). This moraine has subsequently been destroyed by glacial outwash. Oblique aerial photographs by T. Chinn captured the subsequent retreat in the early 2000s, and regular GPS surveys from 2004 onwards have recorded the most recent advance phase and present day retreat (Figs. 2 and 4d).

4.2. Area change on the lower Franz Josef and Fox Glaciers

When initially surveyed in 1893/94, the lower Franz Josef Glacier covered 6.5 km^2 (refer to shaded lower section of glacier tongue in Fig. 1). By 1965 this area had reduced to 3.2 km^2 and by 1987 to 3.1 km^2. By 2009, a period of advance meant that the area occupied by the lower glacier had increased to 3.4 km^2, although this was still more than 3 km^2 smaller than it had been in the late 1800s. In 1894 the lower Fox Glacier was 8.2 km^2 but by 1965 it had shrunk to 4.5 km^2. Changes in areal extent were small between 1965 and 1987, with a further loss of only 0.1 km^2. In 2009, after two advance and retreat phases the lower glacier tongue occupied 4.5 km^2, an increase of 0.1 km^2, but 3.7 km^2 smaller than the 1884 extent. It is important to note that these time-slices provide 'snap-shots' of area change. In some cases, for example between 1965 and 1987, total change has been even greater, with both glaciers reaching a minimum length in the early 1980s. Interestingly, there is similarity in the overall area change between the Fox and Franz Josef Glaciers between the late 1890s and 1987. However, the most recent advance has resulted in greater area change at Franz Josef, probably due in part to glacier geometry and the very confined valley in which it terminates.

4.3. Reaction time

Correlations between glacier length and a reconstructed record of annual ELA (Anderson et al., 2006) show that both glaciers have a very similar relationship between length and climatic forcing (Fig. 5). The strongest correlation at Franz Josef Glacier is when a lag of 3 or 4 years is applied. While the ELA reconstruction was carried out specifically for Franz Josef Glacier, the ELA history at Fox Glacier is expected to be similar, given that the two glaciers are adjoining. The estimated reaction time is similar at Fox Glacier, where the highest correlation occurs with a 3 year lag, although the correlation is almost as high when no lag is applied.

5. Discussion

The overall scale of retreat in the last two centuries at Franz Josef and Fox Glaciers has been large. Since the 1890s both glaciers retreated

~3 km until the mid-1980s, equating to a retreat rate of ~30 m a^{-1}. Glacial retreat of such magnitude is a global occurrence (WGMS, 2008). Leclercq and Oerlemans (2011) provide numerous examples of similar glacier length reductions, for example, Bolshoy Azau (Russia), Hintereis (Austria), Mer de Glacier (France), Nigardsbreen (Norway) and Torre (Argentina). Interestingly, gaps in glacier length records tend to coincide with periods of retreat. Andreassen et al. (2005) reported a revitalisation in glacier length monitoring in response to advance in Norway in 1995. Likewise interest in the measurement of New Zealand glaciers has tended to wax and wane with glacier advance and retreat (Tables 1 and 2, Fig. 6). Consequently, efforts to determine glacier response to climate via terminus position changes are hampered by the bias towards advance records. This tendency for more attention given to advance phases indicates that our knowledge of how glaciers retreat is limited. The only detailed monthly record by C. Woolmore (Table 1) when plotted (Fig. 6) shows intriguing annual fluctuations that have not been recorded elsewhere in New Zealand.

Improved measurement and definition of glacier retreat are essential if we are to better interpret inferred climate variability from studies of past glacial extent. Importantly, it has been found that glaciers may react more rapidly to a negative climate signal, with retreats more immediate than advances (Imhof et al., 2011). In addition, increased debris-cover at retreating glacier termini complicates the retreat process by retarding ice melt once the debris-cover is greater than a few centimetres thick (Östrem, 1959). Rather than simple frontal retreat, such glacier tongues lose mass by downwasting and thermokarst

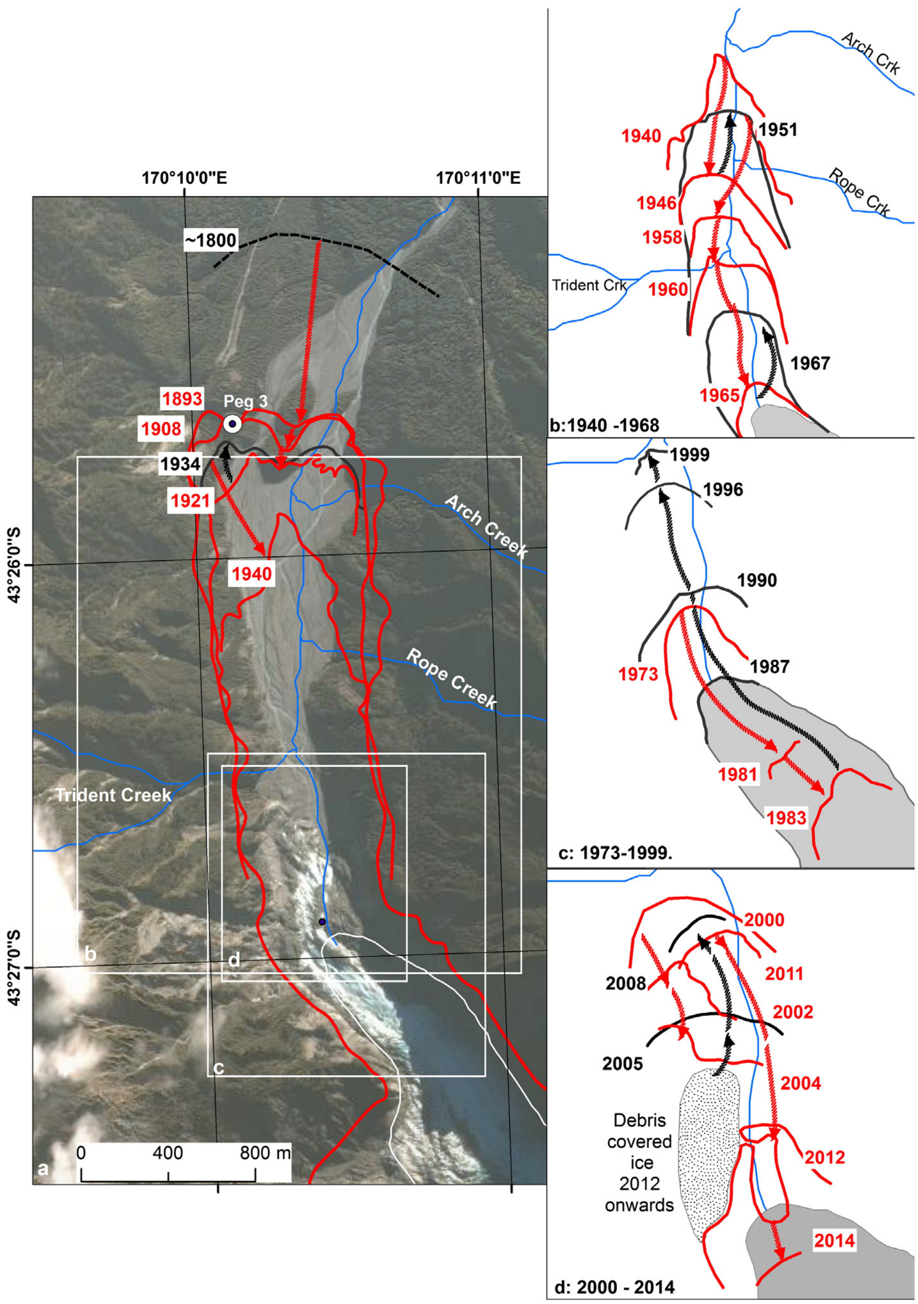

Fig. 3. Changes at the Franz Josef Glacier terminus 1800 to present. Black lines represent periods of advance and red lines periods of retreat. The 1987 glacier outline (derived from aerial photography) is shown for reference. (a) 1800–1940, general retreat with an advance in 1934. (b) 1940–1967, advances in the early 1950s and late 1960s. (c) 1973–1999, minimum (1983) and maximum (1999) extent recorded during recent time. (d) 2000–2014, the latest advance (2008) and present day retreat. Peg 3 was an iron bar placed in 1909 by R.P. Greville (Bell, 1910) and has been used as reference for subsequent surveys. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Length change of the Fox Glacier (measured and estimated) from 1750 to present. Advance phases are highlighted with shading.

Year	Length (km)	Estimated error (± m)	Notes
1750	16.01	200	Wardle (1973)
1894	15.33	100	Wilson and Douglas (1894)
1934	15.19	100	Wardle (1973) & Speight (1935,1941)
1948	14.71	100	Estimated from oblique aerial photo
1955	14.70	50	Gunn (1964)
1957	14.38	50	Estimated from oblique photo Chinn
1958	13.89	50	Estimated from oblique aerial Whites Aviation
1964	12.85	50	Estimated from photo by J. Soons
1965	12.86	50	NZMS1, aerial photograph SN1580 19/3/65
1966	12.90	50	Sara (1979)
1968	12.91	100	Sara (1979)
1971	12.89	50	Estimated from photo J. Soons
1973	12.84	50	Sara (1979)
1978	12.81	50	Sara (1979) and oblique photo J. Soons
1981	12.58	20	Aerial photograph SN5773 27/12/1981
1984	12.30	50	Estimated from oblique photos Chinn & Soons
1985	12.50	20	Aerial photograph SN8478, 27/03/85
1987	12.66	20	NZMS 260, aerial photograph SN8585 25/10/87
1991	12.89	50	Estimated from oblique photo Chinn & J. Soons
1994	12.92	50	Estimated from oblique photo Chinn
1995	12.96	50	Estimated from oblique photo Chinn
1998	12.99	50	Estimated from oblique photo Chinn
1999	13.01	50	Purdie GPS survey of moraine
2000	12.92	30	Aerial photo Chinn
2001	12.86	30	Aerial photo Chinn
2002	12.81	30	Aerial photo Chinn
2003	12.70	30	Aerial photo Chinn
2004	12.75	10	Anderson GPS survey
2005	12. 82	10	Purdie GPS survey
2006	12.95	10	Purdie GPS survey
2007	12.98	10	Purdie GPS survey
2008	12.98	10	Purdie GPS survey
2009	12.99	10	Purdie GPS survey
2011	12.86	10	Purdie GPS survey
2012	12.66	10	Purdie GPS survey
2013	12.58	10	Purdie GPS survey
2014	12.53	10	Purdie GPS survey

Points used for length calculations in NZTM coordinates (also refer to Fig. 1): A (top) 1373989E 5175241N, B 1368229E 5177602N, C 1366772E 5177919N, D 1364012E 5179399N, E (valley floor) 1361521E 5179380N.

processes, with barely any shift of the frontal position. When a glacier tongue becomes fully debris-covered with little to no visible ice, it is frequently described as 'stagnant' on grounds of appearance only. By definition, to be 'dead' the ice must be disconnected from the glacier and have ceased to flow (e.g. Kotlyakov and Smolyarova, 1990; Dobhal, 2011); indeed the debris-covered ice mounds remaining at the Fox in the 1960s gave every indication that they were disconnected 'dead' ice. However, photographic monitoring showed movement of these 'stagnant' debris covered mounds downstream of the re-advancing glacier (pers. comm. Alf Ure, Westland National Park Board, also see Fig. 7).

The retreat sequence often exhibited by low gradient, debris rich glacier termini is well illustrated at Fox Glacier. The process starts with the advance of a clearly identifiable terminus, with or without debris cover. During subsequent retreat, the ice inflow to the tongue reduces, instigating mass loss and surface sediment accumulation during downwasting (Fig. 8a). Terminus retreat is hindered by the 'ponding' effect if the ice has significant depth and thermokarst processes dominate. The thermokarst mounds will ultimately become detached from the main glacier, and may also part into separate masses hiding the true terminus 'position' (Fig. 8b). When the next re-advance begins, a wave of active ice can reconnect with the debris-covered ice masses, and the glacier 'front' steps from the advance wave to the downstream edge of the shifting thermokarst mound (Fig. 8c). At the cessation of this advance, the terminus may once again detach from the debris-covered ice leaving behind any persistent ice mounds (Fig. 8d). At Fox Glacier, the persistence of the 1950s dead ice mound (Fig. 4a) provided a measure of the original ice thickness, as once ice has a mantle of debris, ablation should remain relatively constant (Brook and Paine, 2012). Using the minimal measured ablation rates, the original depth of this ice is estimated at over 100 m, and the 'stagnant' ice mound, being within saturated gravels, maintained height by floating upwards to replace mass lost by ablation.

From the sequence described above, there is clearly a problem in defining the ice front in a decaying thermokarst glacier. One (or the best) option is to select only the ice that remains connected to the glacier, even beneath the river bed (Fig. 8b). If re-advance occurs into this ice, then there will be two ice fronts, one at the end of the debris covered ice and the other at the front of the re-advance wave (Fig. 8c), and the observer has to make a decision of when to make the 'jump' in measurements from the retreating older ice, to the advancing new ice wave. Thus it is common for both advancing and retreating states to have two separate length measurements, one to the front of the active glacier and the other to the connected debris-covered ice, often incorrectly referred to as 'dead-ice'.

Clearly such a sequence of events not only presents challenges in determining a definitive glacier length, but has implications for deducing climate from dated moraine sequences, as processes of stagnation and reactivation may span a decade. Current retreat at Franz Josef Glacier is creating a mound of debris covered ice which has detached from the 'clean', non-debris-covered white ice. An option for maintaining records during such events is to record the down-valley position of both the debris-covered ice and the white ice. Although this does not solve the

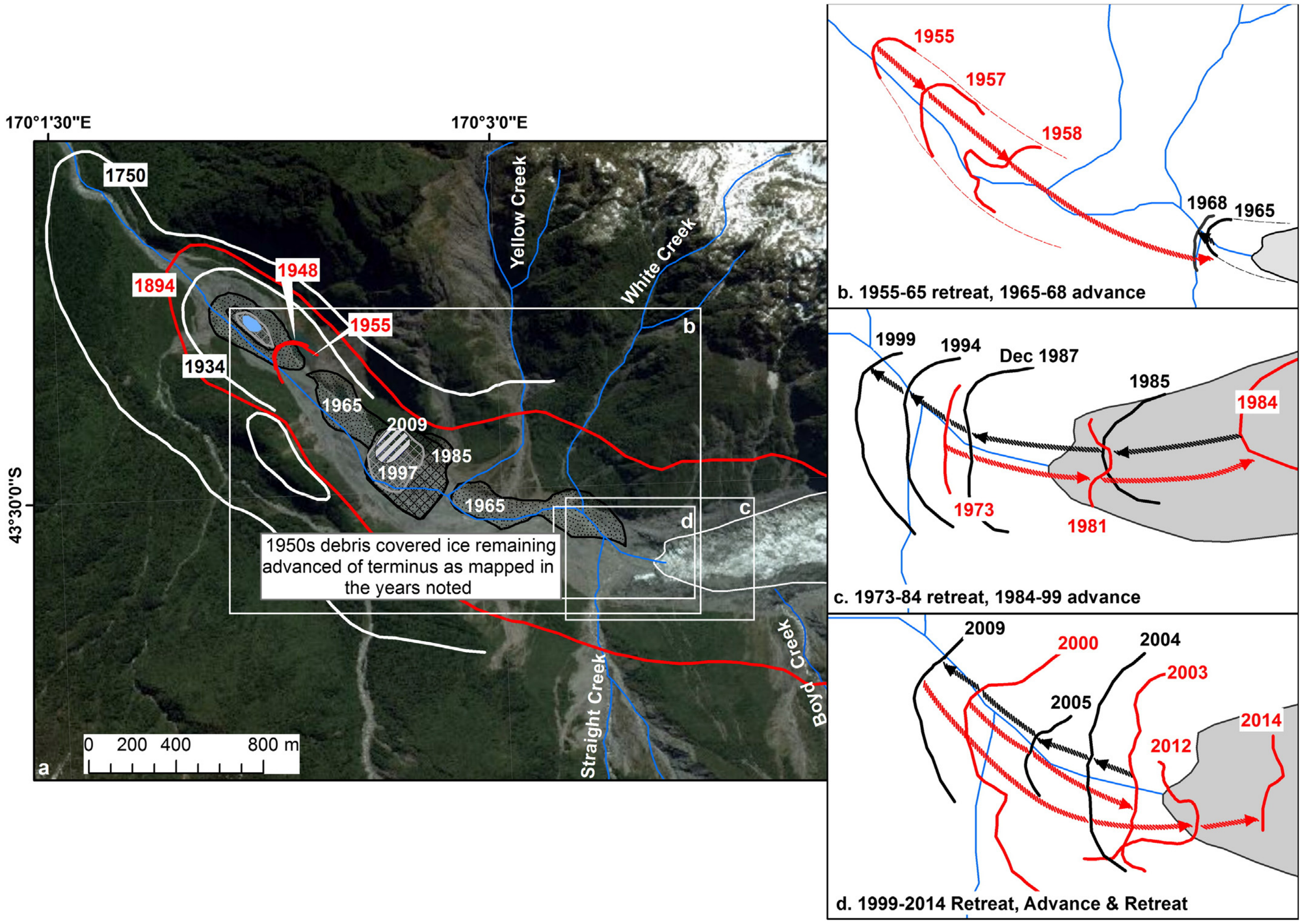

Fig. 4. Changes at the Fox terminus 1750 to present. Black lines represent periods of advance and red lines periods of retreat. The 1987 glacier outline from the topographic map is shown for reference. (a) 1750 to 1955, general retreat although advance was reported in 1934. Mounds of debris-covered ice which have remained in the glacial valley after periods of retreat are indicated and dated when they were mapped. (b) 1955–1968 a period of dramatic retreat (leaving much debris-covered ice), which culminated in a small advance in the late 1960s. (c) 1973–1999, minimum (1984) and maximum (1999) extent during recent time. (d) 2000–2014, the most recent advance and present-day retreat. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

question of which length to report, it prevents mis-interpretation of glacier behaviour by steps in the length record.

Although the overall trend of the Franz Josef and Fox Glaciers has been one of retreat, there have been significant periods of re-advance in the 20th century. In particular, since 1940s, four advance phases have been recorded at Franz Josef Glacier, with length increases of up to 1420 m. Closer inspection of the Franz Josef Glacier length record demonstrates that with the exception of the 1970s, advance phases tend to occur with decadal regularity. This is perhaps not surprising based on the results of previous studies that relate westerly flow anomalies and phases of the El Niño Southern Oscillation (ENSO) to glacier mass balance in the Southern Alps (Hooker and Fitzharris, 1999; Chinn et al., 2005b; Purdie et al., 2011). In particular, negative phases of ENSO are associated with positive mass balance, and positive ENSO phases with negative mass balance. However, the degree of phase persistence required to induce a terminus reaction will depend on individual glacier reaction time. For example, Tyson et al. (1997) found that advance phases at Franz Josef Glacier occurred 4–5 years after the onset of enhanced south-westerly airflow on the West Coast of New Zealand.

Recent climate swings driving positive mass balances have demonstrated how glacier behaviour is dependent on individual glacier reaction times. Glaciers with relatively short reaction times (<30 years), like the Fox and Franz Josef Glaciers, have gone through multiple advance–retreat cycles, while at the same time those with much longer reaction times (e.g. Tasman and Murchison Glaciers) have absorbed the positive pulses into their growing disequilibrium, with no advance at the terminus. Glacier advance in a generally warming climate is not unique to the highly responsive New Zealand glaciers. A number of maritime glaciers in Norway have also advanced during the 20th century

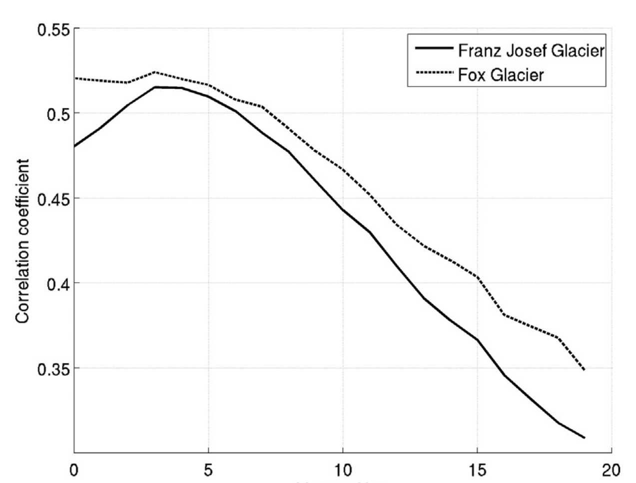

Fig. 5. Correlation coefficient between glacier length and reconstructed ELA at Fox and Franz Josef Glaciers for the period 1894–2010.

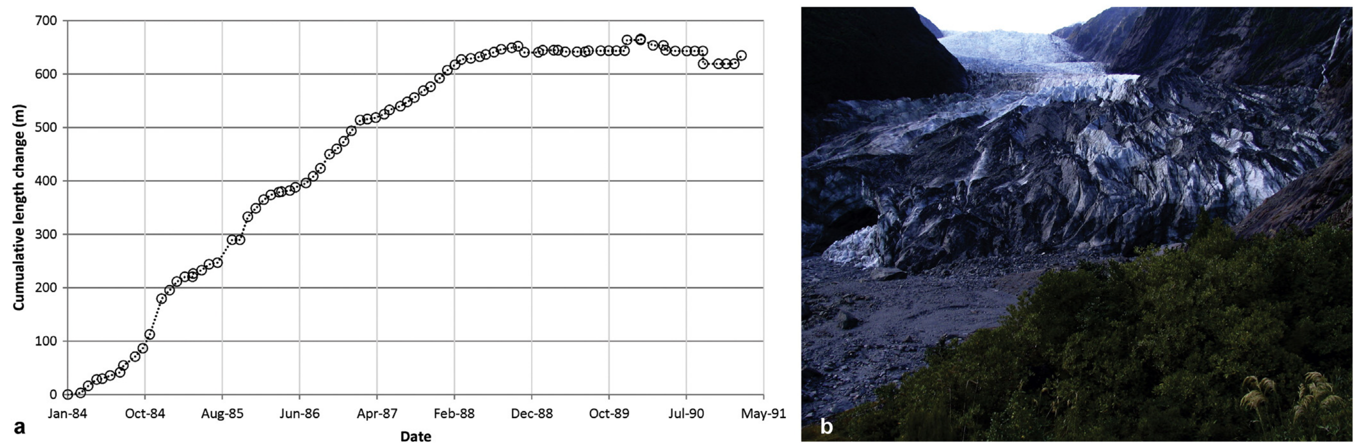

Fig. 6. (a) Monthly variability in the length of Franz Josef Glacier from January 1984 to February 1991 during an advance phase, as recorded by C. Woolmore. (b) The Franz Josef Glacier in 2008; interest in monitoring has tended to coincide with these spectacular advance phases.
Photo B. Campbell.

(Chinn et al., 2005b; Nesje et al., 2008; Imhof et al., 2011; Nussbaumer and Zumbühl, 2012), and advance has been recorded at a small number of Patagonian (Lopez et al., 2010) and Alaskan (Molnia, 2007) glaciers.

Despite the recent advance phases, glaciers in New Zealand have not regained significant mass lost from the rapid and dramatic retreat after the 1940s, and overall, ice mass in the Southern Alps continues to be lost at a high rate (Hoelzle et al., 2007; Chinn et al., 2012). Previous studies have linked decadal-scale variability of New Zealand glaciers with large-scale atmospheric circulation variability. In particular, a higher frequency of El Niño events are associated with enhanced westerly flow and increased precipitation in the Southern Alps (Fitzharris et al., 1997; Hooker and Fitzharris, 1999; Fitzharris et al., 2007). Furthermore, Salinger et al. (2001) demonstrated that the El Niño Southern Oscillation (ENSO) is modulated by the Interdecadal Pacific Oscillation (IPO), with positive phases of the IPO associated with increased frequency of El Niño events (Salinger et al., 2001), which Chinn et al. (2005b) concluded were coincident with increased precipitation and glacier advance. However Purdie et al. (2011) found that climatic conditions during the ablation season exert the greatest influence on net accumulation variability (Purdie et al., 2011) and modes of atmospheric variability like ENSO and the Southern Annular Mode (SAM) have been found to influence the New Zealand climate more strongly during the spring and summer seasons (Mullan, 1995; Kidston et al., 2009). As yet the precise meteorological driver for recent advance phases of the Fox and Franz Josef Glaciers is yet to be determined but it is clear from mass balance records that an increase in winter precipitation was the cause of the recent glacial advances in Norway, coincident with positive phases of the North Atlantic Oscillation (NAO) (Nesje et al., 2008; Imhof et al., 2011). Modelling has shown that Franz Josef Glacier is not very sensitive to precipitation changes, and that reconstructed mass balance variations over the 20th century correlate better to a combination of both temperature and precipitation (Anderson and Mackintosh, 2006; Anderson et al., 2006). Neither the coincidence of increased precipitation with the advance phase, nor the relative sensitivity of Franz Josef Glacier to temperature is evidence of causality.

Regardless of debate surrounding the primary climate driver for recent advances, it remains that maritime glaciers in the Southern Alps are some of the most highly sensitive in the world (Anderson and Mackintosh, 2012), and that due to the climate regime of the Southern Alps and geometry of the Franz Josef and Fox Glaciers, these glaciers both have exceptionally fast reactions to climate perturbations with the Franz Josef being the shortest by about one year. Comparisons with nearby observed small, steep, fast response glaciers like the Stocking (Te Wae Wae) (Salinger et al., 1983) provide almost synchronous fluctuation plots.

Estimations of reaction and response times for these glaciers vary. Initially, Franz Josef Glacier was reported to have a reaction time of 5–7 years (Suggate, 1950; Hessell, 1983; Woo and Fitzharris, 1992). Our estimate for reaction time is slightly shorter at 3–4 years, based on correlation between a climatically-reconstructed ELA record and

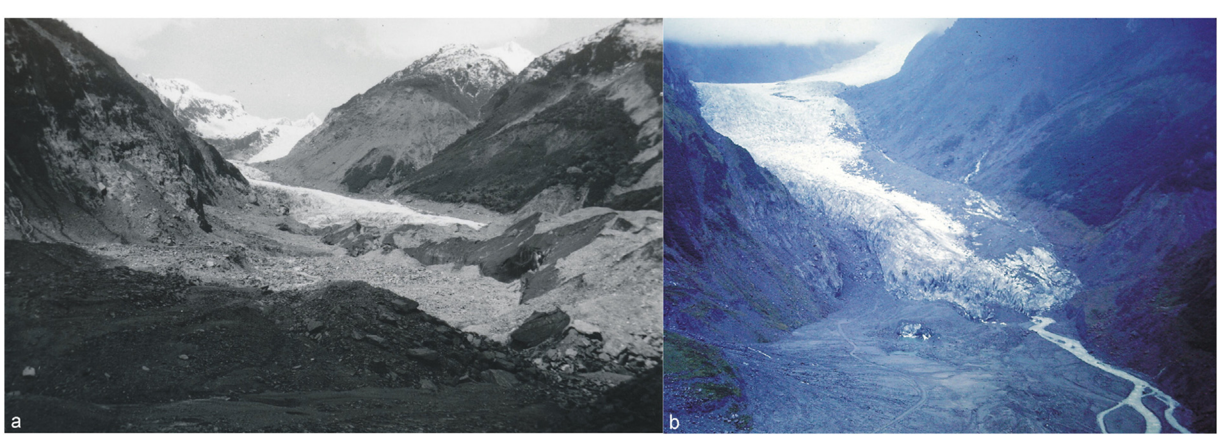

Fig. 7. Thermokarst development at Fox Glacier in (a) 1957, and (b) re-advance in 1968 that reactivated debris-covered ice visible in the river bed. Prior to this advance, the main glacier trunk had apparently detached from this debris-covered ice. Mounds of debris-covered ice from the 1950 era survived near the visitor car park until 2011 indicating a great depth of ice as ablation does not cease.
Photos T. Chinn.

the length record, with little apparent difference between Fox and Franz Josef Glaciers. Estimates of response time at Franz Josef Glacier using numerical models are 15–25 years (Oerlemans, 1997; Anderson et al., 2008). For Fox Glacier, Purdie et al. (2008) estimated a response time of 9 years, using the method of Johannesson et al. (1989). This method requires the ice thickness to be known and, while ice thickness data are not available for the full length of Franz Josef Glacier, the estimate from Anderson et al. (in press) based on mass flux calculations shows a longitudinal average thickness of 178 m, which is very close to the estimated ice thickness at the ELA (170 m). The resulting response time estimate is ~9 years, using ablation at the terminus of 20 m w.e. a^{-1} (Anderson et al., 2006). It should be noted that Johannsson's method does not take into account the height–mass balance feedback which may be significant to these glaciers, which could lead to an underestimation of the response time. Furthermore, the ice thicknesses of these glaciers are incompletely known, as bed surveys have only been carried out in some areas.

Recently, Leclercq and Oerlemans (2011) have demonstrated the utility of glacier length change records for providing a global temperature proxy, adding value to the ongoing efforts of both scientists and enthusiasts who have maintained glacier terminus surveys over many decades.

However, more detailed study of the relationships between reaction time and climate is desirable to better accommodate lags between

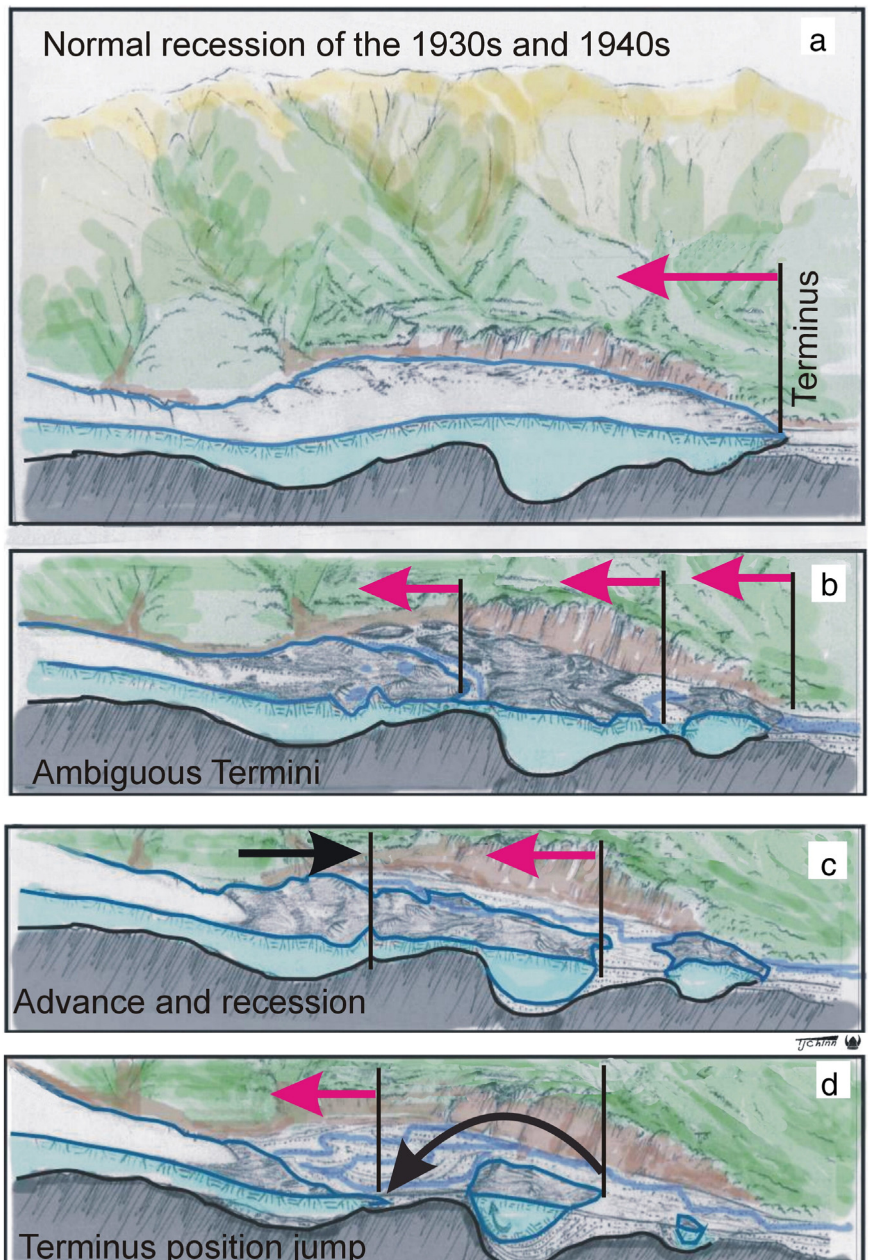

Fig. 8. The Fox Glacier demonstrates the complexities of glacier length introduced by thermokarst development. (a) Normal recession of the 1930s and 1940s with increasing debris concentration on the ablating trunk; (b) thermokarst development of the 1950s introduces ambiguous positions for the glacier terminus; (c) with the 1968 re-advance some of the 'dead ice' in the valley moved, indicating that much of the ice beneath the river bed remained connected to the glacier. (d) General 'normal' retreat after the length had made the shortening jump from the persistent dead ice mound to the active frontal ice.
Figure by T Chinn.

climate forcing and glacier response. In particular, potential differences between reaction times associated with advance and retreat phases, and the impact that thermokarst processes have on terminus disintegration.

6. Conclusion

Glaciers in the Southern Hemisphere are globally under-represented in glaciological databases. However, the Franz Josef and Fox Glaciers have an extensive length-change record. Although Franz Josef Glacier is well represented in the literature, this study includes previously unpublished data, and all measurements have been carefully collated so that the different baselines and measurement methods have been taken into account and a single, coherent and up-to-date record presented. The Fox Glacier record has received far less attention than the Franz Josef and particular attention has been given to search all known sources providing frontal positions, with particular emphasis on any records of the start and end of advance or retreat phases. We expect that these records will become the standard terminus position records for these glaciers, a record that will be augmented with ongoing monitoring, and to which any subsequent historic data as yet undiscovered is revealed in the future.

These records are unique in that they show six or more advance phases during an overall retreat of ~3 km from their positions in the late 1880s. The magnitude of the 1983–1999 advance is large, with almost half of the length lost between 1894 and 1983 regained at Franz Josef Glacier, and about a third regained at Fox Glacier. Advances were possible because these glaciers can have very short reaction times, estimated at 3–4 years. The reactions of these two glaciers therefore provide two of the most sensitive and detailed climate-reaction records of any glacier worldwide. While the two glaciers are very similar in the timing of response, Franz Josef Glacier has advanced approximately twice as far as Fox Glacier during 3 of the last 4 advance periods, indicating a greater sensitivity to climatic variations, at least in the part of the length range captured by these measurements.

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