Use of the ELA as a practical method of monitoring glacier response to climate in New Zealand's Southern Alps

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ABSTRACT. In lieu of direct glacier surface mass-balance measurements, equilibrium-line altitudes (ELAs) have been measured over a 28 year period at 50 selected glaciers distributed along the glacierized length of New Zealand's Southern Alps. Analysis of the data shows that ELAs are a useful measurement of glacier response to annual climate fluctuations, although there is much variability in the degree of response between glaciers in any given year. Comparisons of individual glacier annual ELA with the mean for all annual ELAs of the Southern Alps show a large variation of individual glacier response, with coefficients of variation (r^2) ranging from 0.53 to 0.90. The ELA data show detailed, but qualitative, annual mass-balance variations on both regional and individual glacier scales. The ELA record closely predicts glacier termini responses that follow after appropriate response time delays. The recorded variability in climate response for the Southern Alps suggests no single glacier is truly representative for detailed studies of glacier–climate relationships, and that a large number of ELA measurements may be as good an indicator of climate as a few mass-balance measurements. Given the appropriate mass-balance gradient, mass-balance values may be calculated for any of the monitored glaciers.

1. INTRODUCTION

1.1. The 'index' glaciers

The aim of this paper is to present results of measurements of the glacier equilibrium-line altitude (ELA) to show that ELA monitoring may be a simple and effective alternative to glacier surface mass-balance measurements for measuring the response of glaciers to climate (e.g. Chinn and Salinger, 1999, 2001). This study uses data from the Southern Alps of New Zealand where an inventory compiled by Chinn (2001) includes some 3150 glaciers exceeding 0.01 km^2 in area, that collectively have an area of 1158 km^2 and a volume of 53.3 km^3.

Arising from comprehensive aerial photography undertaken for the compilation of the New Zealand Glacier Inventory commencing in 1977, 50 'index' glaciers were selected for systematic annual ELA surveys (Chinn, 1995). The index glaciers were chosen to align in six transects across the Southern Alps, to sample both the wet western and the arid east alpine climates (Fig. 1). Northern and southern extensions sample the full latitudinal range of 750 km along the length of the Southern Alps. Individual glaciers were chosen for their simplicity of form, with even gradients about the equilibrium line. However, to gain the maximum spread of the transects across the Alps, reaching a maximum of 60 km, some of the small glaciers selected have less than ideal form. This paper presents results from the programme to demonstrate that the annual ELA can provide a simple and very effective means of monitoring glacier response to climate throughout the Southern Alps.

1.2. The equilibrium-line altitude (ELA)

The lower margin of the transient snowline at the end of summer indicates the equilibrium line, and its altitude has been defined by Meier and Post (1962) as the 'equilibrium-line altitude' (ELA) for that specific year. This line, normally visible as the contrast between the discoloured concentration of dust on firn and the clean snow of the previous winter, is the zero mass-balance value for that year, i.e. the ELA is the average elevation at which accumulation exactly balances ablation over a 1 year period (Paterson, 1994). This annual variable differs from the 'steady-state ELA', which is the average taken over many years of annual ELA values at a glacier in equilibrium. The steady-state ELA indicates the mean position of the ELA for the glacier to remain in equilibrium (Meier, 1962). To make the distinction between the annual ELA and the steady-state ELA, in New Zealand the annual ELA is also termed the end-of-summer snowline (EOSS) (Clare and others, 2002) while this paper employs the notation of the *Glacier Mass Balance Bulletins* (Haeberli and Herren, 1991; Haeberli and others, 1993, 1994, 1996, 1999, 2001) in which the steady-state ELA for zero glacier mass change is given as ELA_0.

2. REVIEW OF BACKGROUND GLACIOLOGY

2.1. The New Zealand ELA trend surface

The New Zealand mountains are exposed to a prevailing moist westerly circulation. Interannual climate variability is responsible for annual differences in the ELA in different parts of the Southern Alps. From year to year, the ELA trend surface shifts vertically with uniform mass-balance changes, or tilts with different circulation patterns (Lamont and others, 1999). Vertical shifts do not influence the representativity of an individual glacier, but tilting of the trend surface does. Lamont and others (1999) have demonstrated that in the Southern Alps the tilt axis lies approximately along the Main Divide, and correlations between ELA and mass balance should decline away from this axis. However, the tilt in the annual trend surface is found to be consistently small in the Southern Alps, suggesting that, despite the very different climate regimes of the wet western and arid eastern sides of the Main Divide, the entire Southern Alps behaves as a single climatic unit (Clare and others, 2002).

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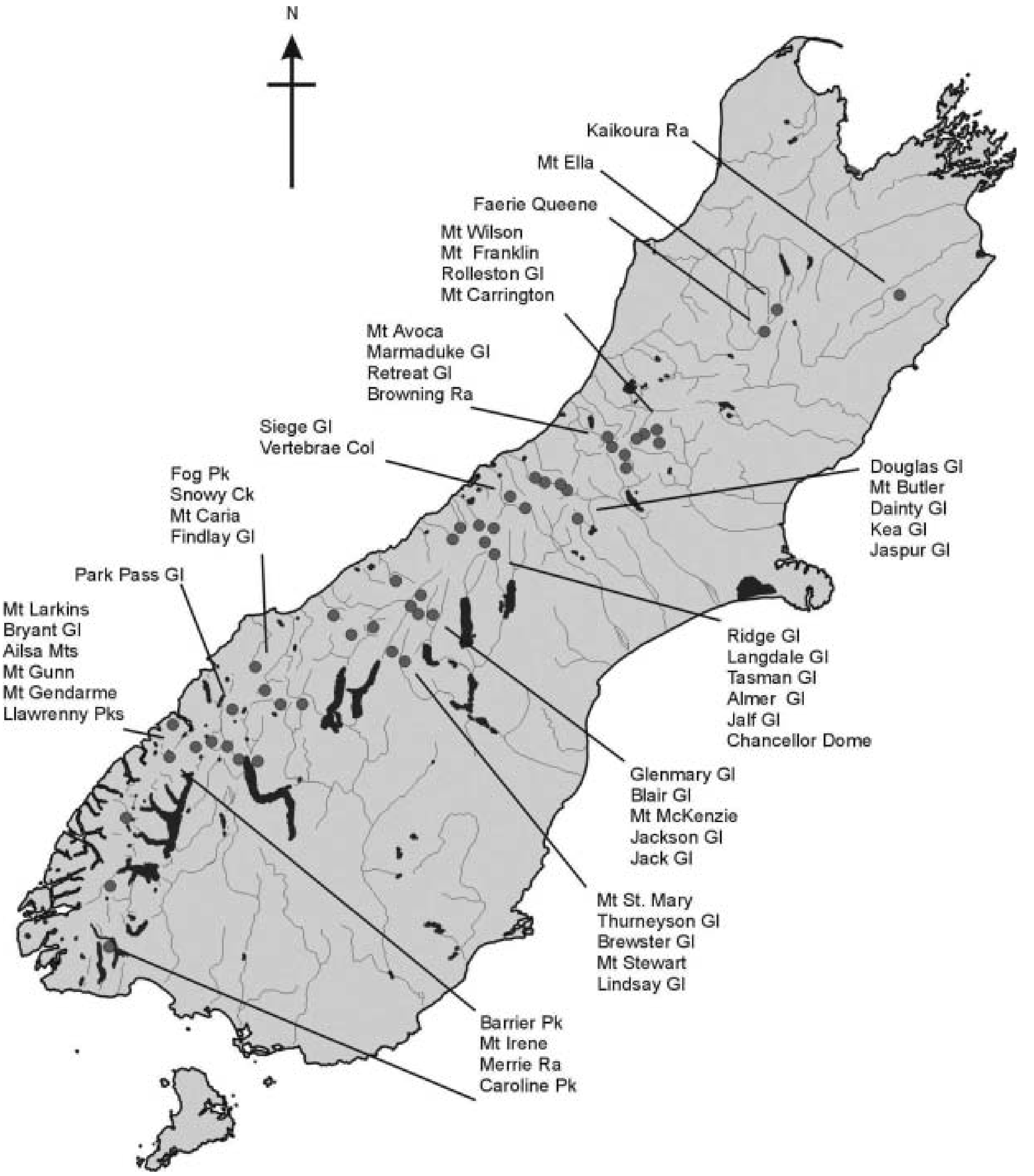

Fig. 1. The South Island, New Zealand, showing the distribution of the ELA index glaciers.

A trend surface for New Zealand glacier ELAs was compiled for a large number of glaciers in 1978 (Chinn and Whitehouse, 1980). This was effectively an ELA_0 surface because in 1978 most glaciers were close to zero balance. The ELA_0 trend surface is strongly warped upwards from the high-precipitation western glaciers towards the drier eastern glaciers. Superimposed on this tilted surface is a north-to-south latitudinal gradient of 1 m km^{-1}.

2.2. Glacier mass balances

Full mass-balance measurements for a period of 7 years are available for one glacier only, Ivory Glacier (Anderton and Chinn, 1978), together with a similarly short series of mass-balance measurements at points along the profile of the large Tasman Glacier (Anderton, 1975). These specific point measurements are not area-averaged for altitude intervals and are referred to as 'specific' balance values following the notation of Østrem and Stanley (1969). These studies were terminated in the mid-1970s, due mainly to cost, and routine glacier observations have been continued since that time by recording ELAs on the set of index glaciers.

The mass-balance data available for 7 years from Ivory Glacier were obtained as part of the International Hydrological Decade (1970s) programme (Anderton and Chinn, 1973, 1978; Hay and Fitzharris, 1988). This small cirque glacier has an area of 0.8 km^2 and a small altitude range 1400–1700 m (Fig. 2). It lies to the west of the Main Divide in the high-precipitation zone reaching 10 000 mm. Unfortunately the systematic ELA measurements reported here commenced after the mass-balance measurement programme on this glacier was terminated and the two datasets do not overlap in time. The Ivory Glacier balance measurements also coincided with a period of rapid recession accompanied by the accelerating growth of a proglacial lake. During the measurement period the Ivory Glacier ELA was high, and in one year rose above the glacier upper limit. The rapid recession and effective demise of this glacier by 1998 has prevented its inclusion with the index

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Fig. 2. Ivory Glacier in April 1969, early in the period of balance measurements.

glaciers. Measured mass balances and ELAs are listed in Table 1.

The Ivory Glacier research has provided data for the mass-balance gradient of the humid western alps, essential for calculating changes in ice volumes, one of the objectives of this programme. The first and most significant differences in glacier responses are due to mass balance gradient, termed the 'activity index' by Meier (1961), i.e. the change in annual net mass balance as a function of altitude. The larger the gradient, the greater the mass turnover and the greater the climate sensitivity of the glacier. Mass-balance gradients increase with increasing humidity (thus snowfall) and for continental areas are normally <5 mm m^{-1}, for maritime glaciers they usually exceed 15 mm m^{-1} (Holmlund and Fuenzalida, 1995), and at the extreme end of the range in the cold desert of the Antarctic Dry Valleys, gradients as low as 0.14, 0.36 and 0.55 mm m^{-1} for Jeremy Sykes, Alberich and Heimdall Glaciers, respectively, have been measured (Chinn, 1980). Mass-balance gradients measured at Ivory Glacier are 20 mm m^{-1} (Fig. 3). The extreme glaciers of New Zealand, with precipitation reaching 15 m a^{-1}, lie at the high end of the activity index range.

Tasman Glacier (Fig. 4) is New Zealand's largest glacier, some 28.5 km in length and covering 98.34 km^2, making it impractical to attempt a full area-averaged mass-balance measurement. Specific (point) mass-balance measurements were made on Tasman Glacier from 1965/66 to 1974/75, at seven sites along the longitudinal profile (Fig. 5; Table 2) (Chinn, 1969; Anderton, 1975). These specific point balance measurements are not area-integrated, but do provide

Table 1. Mass-balance measurement data from Ivory Glacier: AAR (accumulation-area ratio) estimated from measured accumulation area; ELA derived from AAR; Bw winter balance; Bs summer balance; Bn net (area-averaged) balance; BnG net balance gradient. Values in m w.e. (after Anderton and Chinn, 1973)

Balance year	AAR	ELA m	Bw m	Bs m	Bn m	BnG mm m^{-1}
1969/70	0.20	1640	2.1	–4.2	–2.11	2.52
1970/71	0.31	1610	3.9	–5.2	–1.32	4.18
1971/72	0.19	1645	3.0	–4.7	–1.66	2.05
1972/73	0.37	1580	3.1	–4.8	–1.73	2.31
1973/74	0.11	1695	1.6	–5.1	–3.48	2.96
1974/75	0	>1800	2.1	–6.1	–4.00	1.72
Mean						2.62

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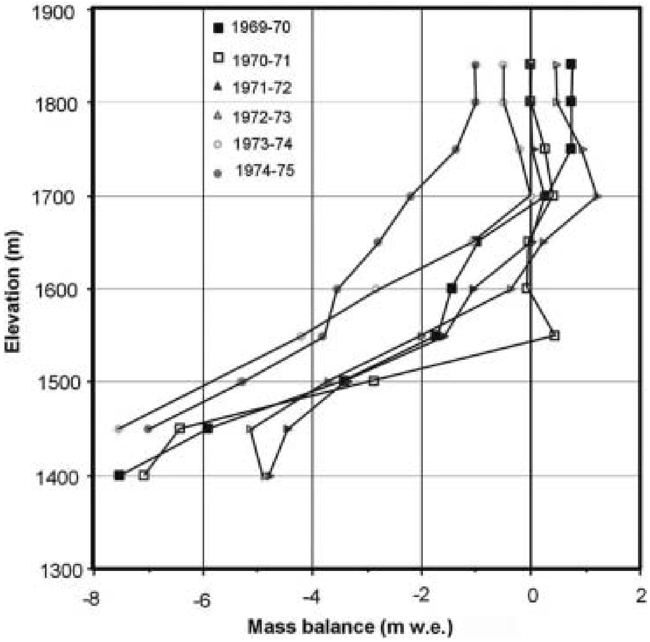

Fig. 3. Mass-balance gradients for Ivory Glacier.

measurements of the glacier's mass-balance gradient of 11.8 mm m^{-1}. ELA estimates from the Tasman Glacier balance measurements prompted the collection of past ELA data from dated photographs to provide New Zealand's longest (but incomplete) record of over 40 years of ELAs commencing in 1959. In this set of readings there are two years of outstandingly negative glacier balances, 1970 and 1990. The ELA values for this glacier have been subject to secular modification by some 50 m lowering of the glacier surface at the ELA over the past century.

The intermittent balance readings from the seven Tasman Glacier specific balance sites (Table 2) provide limited data to establish a relationship between Tasman Glacier mass balances and corresponding ELAs. Data for 1973/74 and 1974/75 were removed, as their ELAs were derived from the balances. The net balances at the three upper sites, correlated against the observed ELA, give r^2 values of 0.81, 0.97 and 0.48 for sites 1, 2 and 3, respectively. The ELA is normally close to site 4 of Figure 4. The results indicate that sites 2 and 3 give a very acceptable representation of the ELA. The lower correlation of the more exposed site 1 may be due mostly to wind deflation of snow. Simple linear curves fitted to the Tasman balance data provide values for mass-balance gradients (Fig. 5).

Net balance (Bn) values of Ivory Glacier are compared with the longest Tasman Glacier balance record at site 1 in Figure 6. Although there is apparent conformity of trend, there is no useful correlation. The loss of ice to Ivory Lake will have contributed to the discrepancy in the comparative balances. The comparison of ELAs of Ivory and Tasman Glaciers in Figure 7 shows a similar relationship of trend but no useful correlation, due in large part to the high ELA for 1969/70 on Tasman Glacier. Photographic evidence confirms that 1969/70 was indeed a year of exceptionally high ELAs, but this is not reflected in the Ivory Glacier balance measurements.

3. METHODS

3.1. ELA aerial surveys

The ELA can be determined directly in the field from mass-balance measurements and in principle can be provided by a few stakes spanning the equilibrium line which will also give the balance gradient at the ELA. Visually the ELA may be estimated from aerial reconnaissance or remote sensing

Fig. 4. The upper Tasman Glacier névé and snowline, March 1996. Numbers indicate stake sites for mass-balance measurements, 1966–75.

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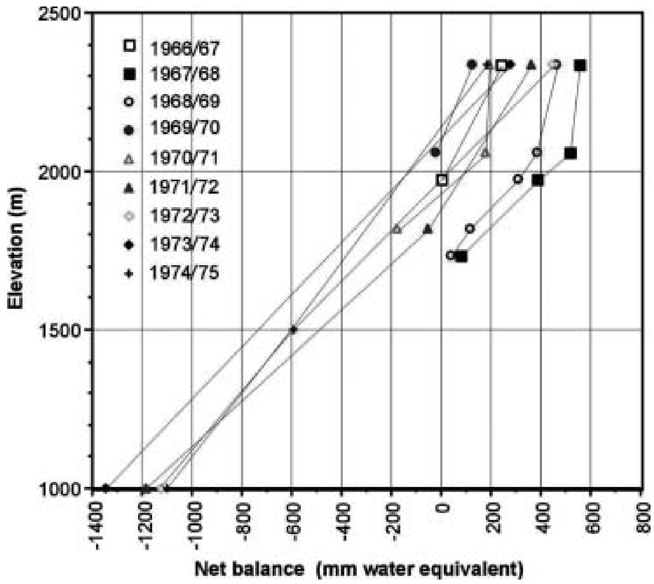

Fig. 5. Mass-balance gradients for Tasman Glacier.

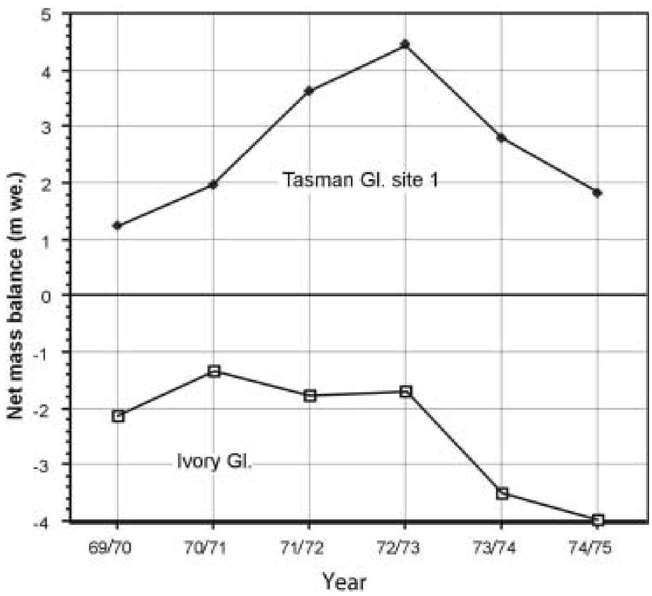

Fig. 6. Comparison of annual mass-balance measurements between Ivory and Tasman Glaciers.

(Braithwaite, 1984). For this study, ELA values are obtained from the positions of the glacier snowlines visible on oblique aerial photographs using methods similar to those discussed by LaChapelle (1962) and outlined in Chinn (1995). The risk of an early snowfall obliterating the visible snowline increases as the ablation season progresses, so the flights are timed for the first suitable flying weather after the beginning of March. Early snowfalls, cloud cover and other events have caused gaps in the record in most years (Chinn, 1995). There were no survey flights in 1979, 1990 or 1991 but some data for these years, mainly photographic, have been obtained for five, two and one, respectively, of the study glaciers.

Table 2. Specific (point) annual mass-balance measurement data from Tasman Glacier. Values in m w.e. (from Anderton, 1975)

Site	Altitude	1965/66		1966/67		1967/68		1968/69		1969/70	
		Bn	ELA	Bn	ELA	Bn	ELA	Bn	ELA	Bn	ELA
	m a.s.l.		m a.s.l.		m a.s.l.		m a.s.l.		m a.s.l.		m a.s.l.
1	2340		1700	2.40	1970	5.54	1630	4.58	1690	1.25	2200
2	2060	?		1.25		5.19		3.82		–0.25	
3	1975			0		3.82		3.11		?	
4	1822	1.1		?		?		1.17		?	
5	1735	?		?		0.80		0.42		?	
6	1500			?		?		?		?	
7	1000			?				?		?	
BnG				1.52		1.05		1.26		1.87	
		1970/71		1971/72		1972/73		1973/74		1974/75	
		Bn	ELA	Bn	ELA	Bn	ELA	Bn	ELA	Bn	ELA
	m a.s.l.		m a.s.l.		m a.s.l.		m a.s.l.		m a.s.l.		m a.s.l.
1	2340	1.96	1930	3.63	1850	4.45	1900	2.78	1945	1.83	2050
2	2060	1.74									
3	1975	–0.20		?							
4	1822	–1.75		–0.51							
5	1735	–1.90									
6	1500	–5.20		–3.50		–5.91		–3.86		–5.93	
7	1000			–11.85		–11.21		–13.44		–10.99	
BnG		1.08		0.84		0.85		0.83		1.05	
Mean	**1.15**										

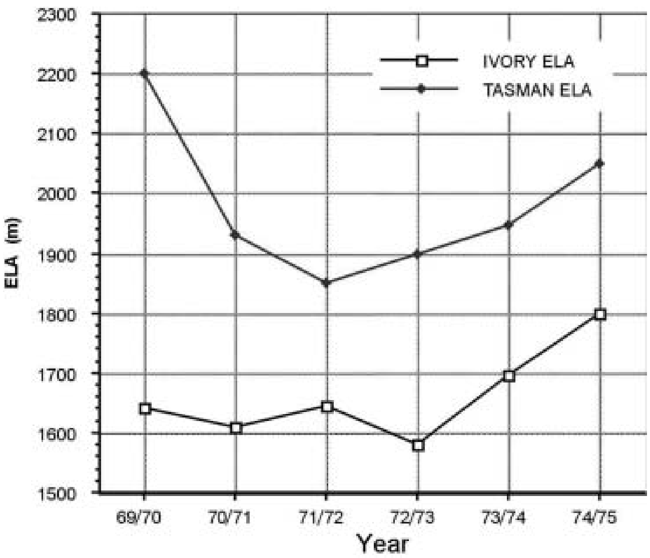

Fig. 7. Comparison of ELAs between Ivory and Tasman Glaciers.

3.2. Processing of ELA data

The end-of-summer snowline meanders across the glacier where the accumulation area may be fragmented. It also traverses a diverse range of elevations, often making it difficult to assign an average elevation to the snowline. This variability has been overcome by deriving the ELA from area–altitude curves plotted for each glacier. On a detailed base map, the snowline positions are carefully sketched from the photographs and the mapped ablation (or accumulation) area is digitized. From the ablation area for each glacier, the snowline elevation is integrated from the area–altitude curve. This method gives an accurate mean ELA value corresponding to the respective accumulation area. Not all years are digitized as it is relatively easy to directly interpolate years of similar ELAs between the digitized values by comparing photographs. Interpolated values have a high precision as individual differences between ELAs may be interpolated with ease to within a few metres (Chinn, 1995) although the accuracy of the absolute altitude may be low.

3.3. ELAs as departures from the ELA_0

End-of-summer snowline elevations are most meaningfully plotted as departures from the steady-state ELA_0 directly. The value of the ELA_0 is normally found by averaging snowline elevations over some decades for a glacier in equilibrium. Early in this study, it was not appropriate to use average ELA values to obtain the steady-state ELA_0 positions because (a) many glaciers had insufficient lengths of record and (b) in New Zealand the period of study has been dominated by positive glacial balances which would strongly bias normals. Instead, the steady-state ELA_0 positions were initially estimated by the accumulation-area ratio (AAR) where, on average, the ratio of the accumulation area to the full glacier area is close to 2 : 1 (Gross and others, 1977; Maisch, 1992). The first estimates of the steady-state ELA_0 were made using an AAR of 0.6, and the altitude for each glacier was read from the glacier's area–altitude curve constructed from topographic maps. For the small cirque glaciers the ELA_0 was initially assumed to lie at the mean elevation of the glacier.

4. RESULTS

There are now 28 years of ELA records from 50 New Zealand glaciers, with 27% missing data, leaving 1023 ELA values available. Each year's dataset shows high variability of the ELA departures between glaciers, arising from individual

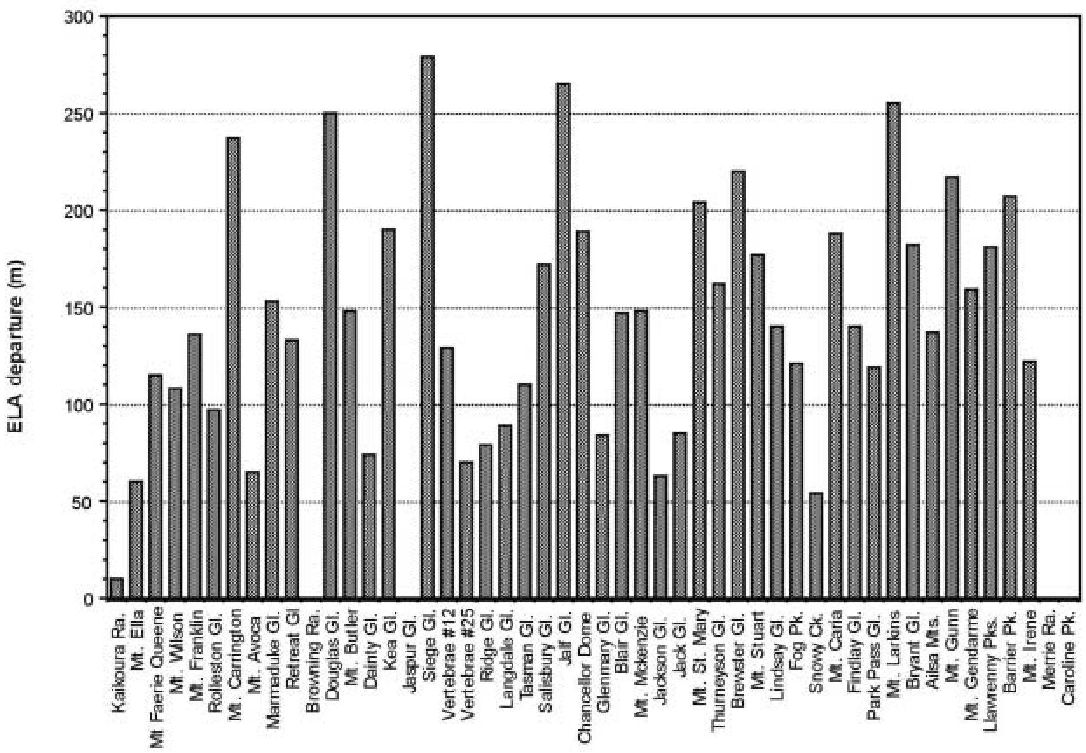

Fig. 8. The individual ELA departures of the New Zealand index glaciers for 2000 showing the ELA departure variability. Zero values are missing data.

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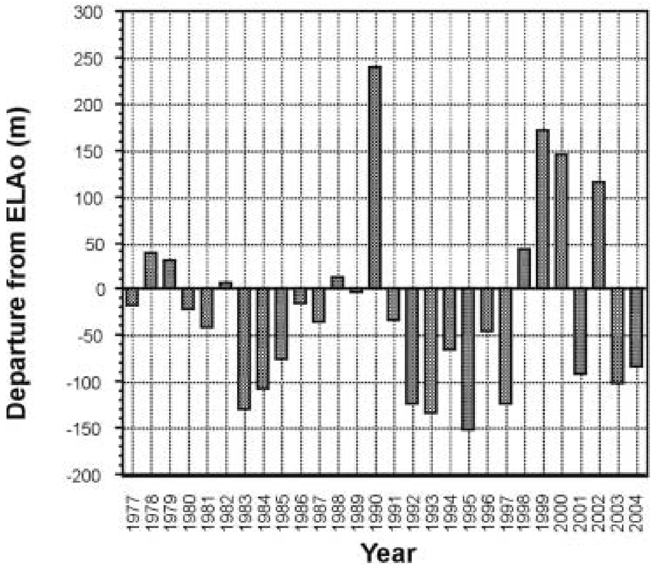

Fig. 9. Mean annual ELA departures of the New Zealand index glaciers. Positive values (high snowlines) indicate negative mass balances and negative values indicate positive mass balances.

glacier sensitivity to climate. Since climate factors will be similar at each glacier each year, this variability represents a strong topographic influence on the shift of the ELA. Figure 8 shows the ELA departures from the ELA_0 for 2000 (Chinn and Salinger, 2001), a high-ELA (negative balance with positive departures) year.

The annual series of mass-balance changes as indicated by the mean annual ELAs of Figure 9 shows a near three-decade period, from 1977 to 2004, of generally negative ELA departures or positive mass balances (e.g. Chinn and Salinger, 1999). ELA values were particularly low during the 1982/83 El Niño event, and during 1992, following the cooling effects of the 1991 Mount Pinatubo (Philippines) volcanic eruption. It is now known that when the ELA surveys commenced in 1977, the start of the measurements was coincident with a major change in atmospheric circulation, in particular the Interdecadal Pacific Oscillation (IPO) (Salinger and others, 2001). In 1998 there was an apparent IPO atmospheric circulation pattern reversal which was accompanied by a possible change to dominantly higher ELAs.

5. INTERPRETATION

5.1. Variability of the ELA

The data for the 2000 survey (Chinn and Salinger, 2001) are given in Figure 8, where a large variation across the glaciers is obvious. This apparently inconsistent behaviour of the departures from the ELA_0 across the glaciers is apparent for all measured years as shown in Table 3. Standard deviations are very high and much larger than the precision of the measurements. However, when each glacier is individually analysed it is found that the results are internally consistent, as the variability is a measure of the degree of the glacier response to the climate. For the same climate over a given year, different glaciers will have different values of ELA responses.

The results from each glacier were examined in turn to compare annual ELA changes with the mean annual values for all the index glaciers throughout the Southern Alps. To make this comparison, all values for each glacier in turn were removed from the 50 index-glacier or 'Alps' dataset, and the ELA departures of each individual glacier were regressed against the mean of the remaining 49 'Alps' means, using a simple linear fit:

$$y = \alpha(\text{Alps}) + \beta,$$

where y is the individual ELA departure, and Alps is the mean of all other index glaciers of the Southern Alps.

The data, arranged in descending order of coefficients of determination for each glacier with the 'Alps' mean in Table 4, are found to have acceptable r^2 values ranging from 0.90 to 0.53. This table provides the degree of 'representivity' of each index glacier, i.e. how close it indicates the mean ELA change throughout the Alps. The results suggest that the annual ELA survey might require that only a few of the most highly correlated glaciers be measured each year.

The slope, α, of the regression line varies considerably between glaciers. Figure 10 is an example of a steep-slope regression for Siege Glacier where a large range, 810 m, of measured ELAs have been found. Figure 11 is an example of a low-gradient regression, for Glenmary Glacier, which shows small ELA changes from year to year, over a measured range of 252 m. This gradient represents 'ELA sensitivity to climate'; however, since it has been shown that the climate over the Southern Alps is relatively uniform each year (Clare and others, 2002), the difference in regression slopes is thought to contain a large topographic influence.

On some glaciers the ELA values swing widely from year to year, while on others there are only small changes. The

Table 3. Mean annual values for ELA departures from ELA_0, for the New Zealand index glaciers, with annual means and standard deviations (see Fig. 13)

Year	Number of readings	Mean	Standard deviation
1977	15	–19	44
1978	40	38	51
1979	5	30	83
1980	32	–22	53
1981	36	–42	39
1982	41	7	44
1983	41	–131	64
1984	27	–109	64
1985	40	–77	45
1986	38	–16	45
1987	33	–37	39
1988	33	12	50
1989	49	–4	50
1990	2	239	
1991	1	–35	
1992	15	–125	79
1993	49	–135	69
1994	50	–67	42
1995	50	–153	70
1996	48	–46	55
1997	45	–125	52
1998	50	43	70
1999	48	170	71
2000	46	145	62
2001	50	–93	51
2002	49	114	62
2003	49	–103	44
2004	45	–84	54

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Table 4. The index glaciers arranged in descending order of values of coefficients of determination (r^2) of ELA departures, where each glacier is compared with the mean of the remaining glaciers of the Alps. The table effectively presents the degree of representativity of each index glacier

Glacier	r^2	Glacier	r^2
Llawrenny Peaks	0.90	Rolleston Glacier	0.81
Barrier Peak	0.90	Douglas Glacier	0.80
Vertebrae Col 25	0.89	Dainty Glacier	0.80
Caroline Peak	0.89	Salisbury Glacier	0.80
Mount Ella	0.87	Lindsay Glacier	0.80
Siege Glacier	0.87	Mount Gendarme	0.79
Findlay Glacier	0.87	Jack Glacier	0.79
Thurneyson Glacier	0.85	Merrie Range	0.79
Jackson Glacier	0.85	Mount McKenzie	0.78
Jalf Glacier	0.85	Tasman Glacier	0.78
Mount Irene	0.85	Jaspur Glacier	0.77
Mount St Mary	0.84	Mount Avoca	0.77
Mount Franklin	0.84	Vertebrae Col 12	0.77
Bryant Glacier	0.84	Mount Gunn	0.77
Mount Larkins	0.84	Fog Peak	0.76
Mount Butler	0.83	Mount Faerie Queene	0.76
Kea Glacier	0.83	Park Pass Glacier	0.74
Mount Stuart	0.82	Retreat Glacier	0.73
Marmaduke Glacier	0.82	Mount Wilson	0.72
Brewster Glacier	0.81	Ridge Glacier	0.72
Chancellor Dome	0.81	Blair Glacier	0.67
Browning Range	0.81	Glenmary Glacier	0.67
Ailsa Mountains	0.81	Langdale Glacier	0.59
Mount Carrington	0.81	Snowy Creek	0.56
Mount Caria	0.81	Kaikoura Range	0.53

close relationship between regression slope, α, and ELA range at each glacier is shown in Figure 12. The glacier with the largest ELA fluctuations, Siege Glacier, with a regression slope of 2.166 and an ELA range of 810 m, stands out as inconsistent in the annual plots (e.g. Fig. 8). One of the least responsive glaciers, Glenmary Glacier, with a slope of 0.549 and ELA range of 252 m in the annual plots remains close to the zero departure line of Figure 8.

It follows that the variability of annual ELA values is greatest when departures are greatest in years of strongly positive or strongly negative mass balances, with variability at a minimum in years close to zero balance when ELA departures are at a minimum. This is demonstrated in Figure 13 where, for each year, the mean annual departure standard deviations are compared with the ELA_0. A polynomial curve fitted to this plot shows that standard deviations of mean annual departures increase each side of a minimum at zero departure of the ELA_0.

5.2. Variability between adjacent glaciers

The best ELA departure correlations might be expected to be between two similar glaciers positioned side by side and measured independently. The New Zealand ELA programme includes two such adjacent glaciers, Vertebrae Col 12 and Vertebrae Col 25. They are of similar size and gradient and of the same aspect. The ELA departure values are correlated in Figure 14, where the relationship has a high percentage of explained variability of $r^2 = 0.906$. This value is as high as might be expected from two sets of mass-balance measurements made on such adjacent glaciers.

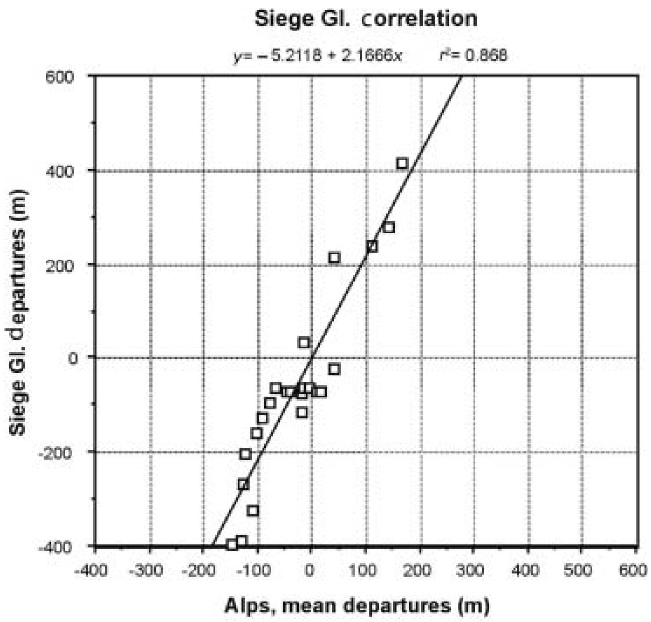

Fig. 10. Annual ELA departures at Siege Glacier correlated with the mean for the remainder of the 'Alps' index glaciers.

5.3. Derivation of precise values for the ELA_0

As the length of the record has increased, inconsistent ELA departure values for some glaciers have signalled anomalies in the assigned ELA_0 values. With many years of data it has become possible to derive a more precise value for the ELA_0 with some degree of accuracy. The method involves (a) an iterative process and (b) the assumption that, in general, the ELA changes throughout the Southern Alps behave as a single climatic unit (Clare and others, 2002) with all glaciers conforming roughly to positive and negative years. To obtain the ELA_0 for an individual glacier, the regression plots derived above were examined for each glacier. If the position of the ELA_0 is correct, then for the case when there is a zero mass-balance change throughout the Alps, the regression line should pass through the zero origin, i.e. $\beta = 0$. Therefore, the value of β is the value of the adjustment required to correctly position the ELA_0. All of the index glaciers have been tested and adjusted in this manner. Each adjustment makes a small change to the mean value for the Southern Alps, so that, as both the length of the record increases and the number adjustments increase, the ELA_0 values approach their true values.

6. DISCUSSION

6.1. New Zealand glacier changes indicated by ELAs

As ELA departure series are a surrogate for annual mass-balance series, the record, when presented as cumulative curves, may be compared with records of glacier front fluctuations. In Figure 15 the ELA record is presented as cumulative negative departures (ELA_0–ELA) to give the same sign as balance changes. For a comparison of trends, the longer Tasman Glacier ELA record is shown together with Franz Josef Glacier terminus fluctuations.

To separate the plots, the longer Tasman Glacier cumulative ELA data have been adjusted by +1000. The section of this curve which overlaps (i.e. since 1977) with the mean annual 'Alps' ELA curve conforms closely with a correlation

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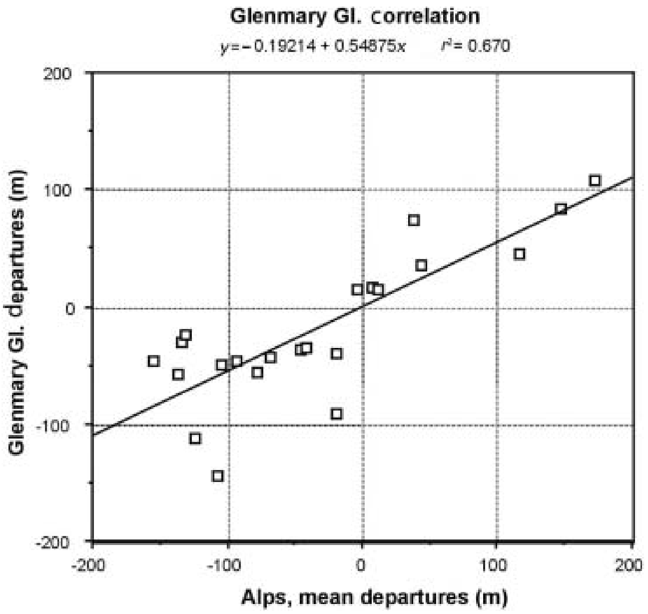

Fig. 11. Annual ELA departures at Glenmary Glacier correlated with the mean for the remainder of the 'Alps' index glaciers.

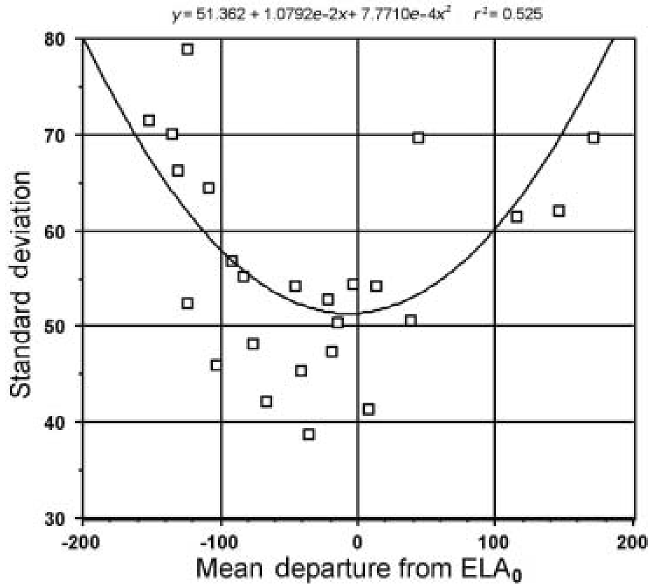

Fig. 13. Plot of annual standard deviations of each survey against respective mean annual departures. The fitted polynomial curve demonstrates increasing variability away from zero, i.e. the ELA_0.

coefficient of $r^2 = 0.88$. Thus the Tasman Glacier ELAs give a close approximation to the ELAs of the remainder of the Southern Alps. The Tasman Glacier plot suggests that the negative balance trend reversed in 1974, but the climatic data indicate that this reversal took place closer to 1977/78. A small error in the position of the ELA_0 and/or the fact that the glacier surface at the ELA has been subject to secular modification by some 50 m lowering of the glacier surface at the ELA_0 over the past century, could account for part of this discrepancy.

Both cumulative curves are compared with changes of the Franz Josef Glacier terminus. This highly responsive glacier has the longest and most detailed record of terminus changes of New Zealand glaciers. The data given here have been gathered from numerous sources and are adjusted to zero at 1959. This glacier began the latest readvance in 1983, and has a reaction time of 5–8 years (Hooker and Fitzharris, 1999). The plot shows consistent agreement, and correlates well with the ELA record when adjusted for reaction time.

A survey of the equilibrium of a sample of 64 alpine and valley glaciers was made by Chinn (1999). The percentage of these glaciers found to be advancing is also shown in Figure 15. To separate the plots, zero for these data is adjusted to –1000. This plot shows a minimal first reaction time of 3 years from the ELA trend change as indicated by Tasman Glacier, again suggesting that positive mass balances began affecting the glaciers prior to 1977. The increasing number of glaciers advancing conforms with the cumulative ELA increase.

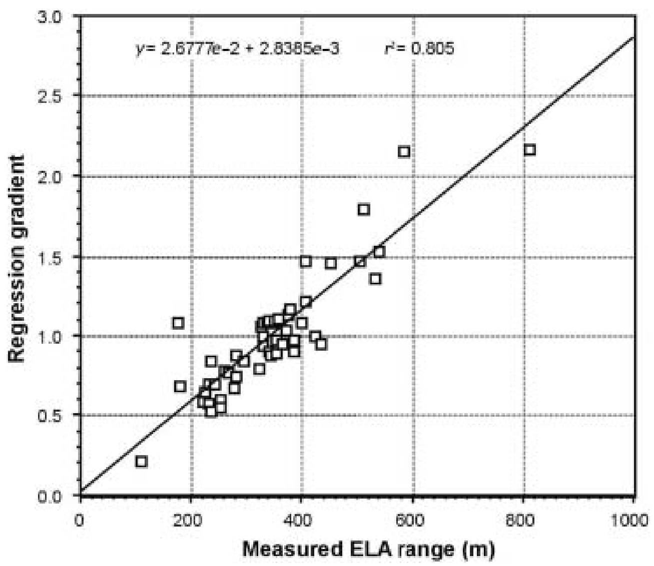

Fig. 12. Correlation between the regression gradient, α, of the ELA departures of each glacier with the 'Alps' mean, and their respective ELA departure ranges.

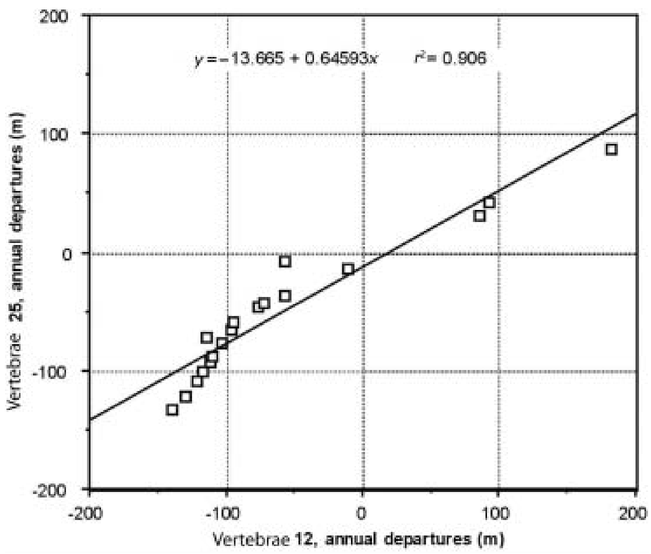

Fig. 14. Correlation of ELA departures between the adjacent Vertebrae Col glaciers. Annual departures of No. 25 with annual departures of No. 12 show an r^2 value of 0.906.

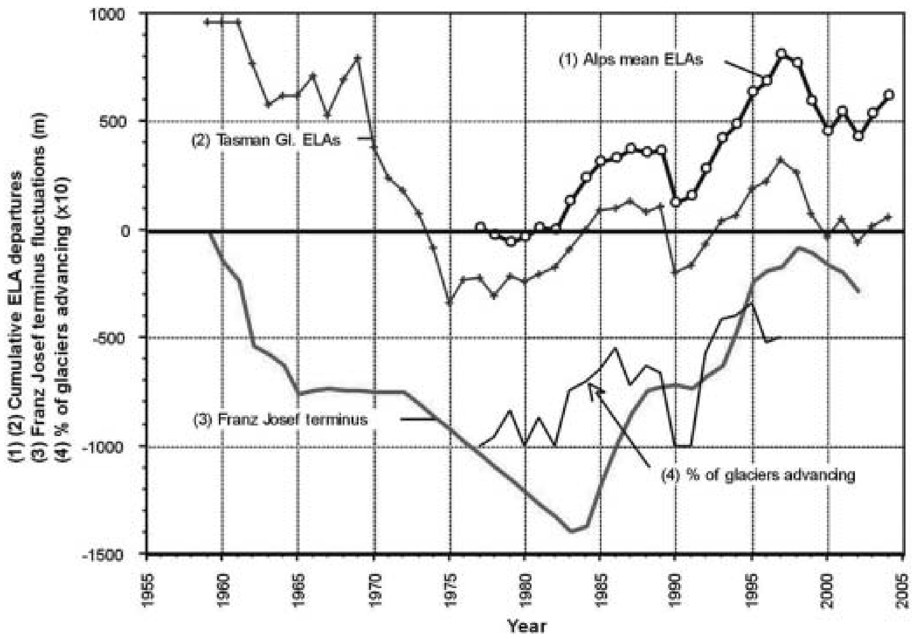

Fig. 15. Comparisons of cumulative mean negative ELA departures for the Southern Alps index glacier record with the longer ELA record of Tasman Glacier. Both are compared with the terminus fluctuations of Franz Josef Glacier and percentage of a sample of 64 advancing glaciers (from Chinn, 1999). To separate the plots, Tasman data have been adjusted by +1000, the Franz Josef Glacier data adjusted to zero at 1959, and percentage glaciers advancing adjusted to –1000 at 1976.

6.2. Atmospheric circulation and linkages to ELA

ELA values have given valuable information on mass-balance changes and climate variability in New Zealand. These data series have been used for a number of glacier–climate and atmospheric circulation analyses to relate glacier fluctuations to atmospheric circulation patterns on a hemispherical scale (e.g. Chinn and Whitehouse, 1980; Woo and Fitzharris, 1992; Fitzharris and others, 1997; Lamont and others, 1999; Clare and others, 2002). Examination of the links between climate and glacier change using atmospheric circulation, initiated by Fitzharris and others (1997), show that regional circulation patterns exert a strong control on glacier balance.

Glacier mass changes from the ELA record show good correlations with the El Niño–Southern Oscillation and the 18–20 year oscillation of the IPO and must ultimately be related to changes in the mode of atmospheric circulation. Positive mass balances and advances are associated with an increase in the prevailing west–southwest airflow. Negative mass balances, and retreats are associated with more northeasterly flow (Clare and others, 2002).

7. CONCLUSION

A 27 year record of ELAs measured on 50 New Zealand glaciers has demonstrated that annual monitoring of ELAs provides a useful record of annual responses of glaciers to climate. From the data, an accurate value of the ELA_0 for long-term glacier equilibrium may be calculated. Departures from the ELA_0 give an index of mass-balance changes. The photographic surveys also provide the opportunity to record a variety of glaciological data additional to the ELA record. The index glacier record shows individual differences in glacier responses to similar climates, and the year-by-year spatial variability of these responses. This response variability suggests that no single glacier is representative for intensive study of glacier–climate relationships, and emphasizes that simple data from a large number of glaciers over long periods may be more indicative of variations in climate than a few intensive studies. The large number of ELA values presented in this study smooth the enhanced and individually variable responses of glaciers to climate changes and fluctuations, giving a very precise measurement of the glacier response to annual climate variations. If the mass-balance gradient is known then, using the glacier topography, actual mass balance may be calculated.

The data presented here show that ELA gives a good indication of the alpine climate from year to year, and provides a much more useful record than glacier terminus positions. A widespread dataset of ELA values can also indicate which glaciers are most closely representative of a mountain region, and which are responding to non-climatic influences. This is demonstrated by the Tasman Glacier ELAs revealing that Ivory Glacier's mass-balance record contains a large non-climatic signal. In the absence of a mass-balance programme, the ELA provides a very effective and economical method of monitoring glacier changes with many applications, including the potential to derive mass-balance values.

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