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Interannual variability in net accumulation on Tasman Glacier and its relationship with climate

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ABSTRACT

Mid-latitude maritime glaciers are responding quickly and directly to climate change. This response is expected to continue, and will result in maritime glaciers making a large contribution to sea level rise over the coming decades. Maritime glaciers in the New Zealand Southern Alps provide an opportunity to learn more about climate–glacier mass balance relationships in a high precipitation setting, and how these relationships might change in the future. Ice core and direct glaciological measurements are used to construct a 24-year record of net accumulation, the longest of its type in New Zealand. We demonstrate that variations in net accumulation on Tasman Glacier are more strongly influenced by temperature than by precipitation. Further, it is temperature during the ablation season that exerts most control. Atmospheric circulation patterns, in particular the state of the El Niño Southern Oscillation (ENSO) and Southern Annular Mode (SAM), were found to influence net accumulation. When the SAM is positive and the ENSO in a La Niña phase, easterly and northerly wind anomalies are enhanced, temperatures increase in the Southern Alps region and more negative glacier mass balances result. Conversely when SAM is negative and ENSO in an El Niño phase, westerly and southerly wind anomalies occur, and temperatures decrease in the Southern Alps region. In this case, glacier mass balance is more likely to be positive. However, relationships between glacier mass balance and these atmospheric circulation modes are not simply linear, with some of the lowest net accumulation years associated with inverse polarity between the SAM and the ENSO.

1. Introduction

As major climate changes have occurred during the last few decades, many long-term glacier mass balance monitoring programmes are reporting significant ice loss on alpine glaciers worldwide (WGMS, 2008). Modelling studies indicate that in certain regions, glacier mass balance could be almost twice as sensitive to a temperature increase as a temperature decrease of the same magnitude (Kuhn, 2003). Anecdotal evidence indicates that multiple years of net accumulation can be removed in a single summer with substantial above-average temperatures. Such could be the impact of a single hot year, like for example 2003 in the European Alps (Zemp et al., 2006), that improved understanding of climate–mass balance relationships is essential. This is especially relevant because globally, 9 out of the last 10 years have been the warmest on record (Hansen et al., 2010).

Maritime glaciers are particularly sensitive to temperature changes (Oerlemans, 1992, 1997; Braithwaite and Zhang, 2000; Anderson et al., 2008, 2010). However, there are few long-term records, and none from the mid-latitudes of the Southern Hemisphere. This lack of data can be attributed in part to difficulties in measuring mass balance in these environments, where annual accumulation can exceed ~6 m water equivalent (m w.e.), and the later development of regular mass balance monitoring programmes in these regions. Longer records of mass balance from these regions provide an opportunity to document and understand the processes controlling inter-annual variability in mass balance including the influence of changing atmospheric circulation.

Previous studies have identified relationships between the El Niño Southern Oscillation (ENSO) and glacier fluctuations in New Zealand and South America (Fitzharris et al., 1997; Clare et al., 2002; Chinn et al., 2005a; Fitzharris et al., 2007; Leiva et al., 2007). However, as yet, the potential influence of the Southern Annular Mode (SAM) on glacier

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mass balance has not been fully considered (Clare et al., 2002; Fitzharris et al., 2007). The SAM is a ring of pressure variability between 60°S and 45°S that affects the position and strength of the mid-latitude jet, in particular, the strength and frequency of circumpolar westerlies (Renwick and Thompson, 2006; Marshall, 2007). The SAM has been linked to changes in Australian precipitation (Meneghini et al., 2007; Karpechko et al., 2009), Antarctic temperature and precipitation (van den Broeke and van Lipzig, 2004; Tedesco and Monaghan, 2009), Antarctic sea ice extent (Lefebvre et al., 2004), and more recently to temperature and precipitation variability in New Zealand (Ummenhofer and England, 2007; Kidston et al., 2009). Due to its influence on westerly circulation, it is expected that this annular mode could provide some forcing to inter-annual variability in mass balance on glaciers in the Southern Alps of New Zealand.

Previously, there has been discussion as to whether New Zealand glaciers are more sensitive to changes in precipitation (Hessell, 1983) or temperature (Salinger et al., 1983; Anderson and Mackintosh, 2006). Lack of long-term (>10 yrs) mass balance measurements means that such research has relied on utilising records of glacier terminus position (Hooker and Fitzharris, 1999), mass balance proxies, for example, the equilibrium line altitude (Fitzharris et al., 1997; Clare et al., 2002), or model output (Woo and Fitzharris, 1992; Oerlemans, 1997; Anderson et al., 2006). To date no firm conclusion has been drawn, as both these climate parameters have a role to play in glacier mass balance fluctuations.

An important component of glacier mass balance is annual net accumulation. In temperate climates, annual net accumulation is the resultant effect of winter snow accumulation and summer melting, and represents the amount of snow accumulation that is actually available for glacier nourishment. Research on some mid-latitude maritime glaciers previously identified that the winter balance exerted most control on inter-annual variability in glacier mass balance, for example in Norway (Pohjola and Rogers, 1997; Nesje et al., 2000; Andreassen et al., 2005; Nesje et al., 2008) and western North America (Walters and Meier, 1989). However, since around 2000, warmer, drier summers are having increasing influence on glacier mass balance in these regions (Josberger et al., 2007; Winkler et al., 2009). In New Zealand, snow accumulation on glaciers can occur year around, but most snow accumulation occurs during the winter and spring seasons (April to October), with a slightly shorter (November–March) ablation season (Fitzharris et al., 1992). Relationships have been identified between atmospheric circulation and decadal-scale advance and retreat of New Zealand glaciers (Hooker and Fitzharris, 1999; Fitzharris et al., 2007), but seasonal controls on inter-annual variability in net accumulation have not been examined.

Records of net accumulation fluctuation are contained within ice cores (Mayewski and White, 2002), with annual layers identifiable via stratigraphy, stable isotopes and trace element concentrations (Legrand and Mayewski, 1997; Aizen et al., 2009) as well as by biological markers, for example, pollen (Nakazawa et al., 2005) or algae (Yoshimura et al., 2000). Ice core interpretation in maritime climates is more challenging than in polar areas, due to the presence and movement of melt-water (Koerner, 1997). For example, elution of ions and homogenisation of stable isotopes has been recorded in cores from Norway (Raben and Theakstone, 1994), Switzerland (Eichler et al., 2001), Patagonia (Shiraiwa et al., 2002; Schwikowski et al., 2005), Nepal (Yoshimura et al., 2000) and the Russian Altai (Kameda et al., 2003). However, some potential markers are more likely to stay in situ than others, for example fine dust particles may persist while soluble ions are removed (Raben and Theakstone, 1994; Kameda et al., 2003); and useful climate information was found to persist in an ice core retrieved from Baffin Island, Canada, a site with significant melting (Fisher et al., 1998; Goto-Azuma et al., 2002). The potential to derive net accumulation data from ice cores retrieved from New Zealand glaciers is yet to be fully explored, although information pertaining to moisture provenance is found in fresh winter snow (Purdie et al., 2010).

The New Zealand Southern Alps contain over 3100 glaciers (Chinn, 1996). Tasman Glacier is the largest, covering an area of ~95 km^2 and containing ~30% of New Zealand's ice volume (Chinn, 2001) (Fig. 1). But, like many glaciers globally, Tasman Glacier has been undergoing significant ice loss, and is now rapidly calving into a pro-glacial lake (Kirkbride and Warren, 1999; Röhl, 2006; Dykes et al., 2010). Through a combination of melting, downwasting and calving, the Tasman Glacier is losing volume at around ~0.1 km^3 per year (Thomas, 2009).

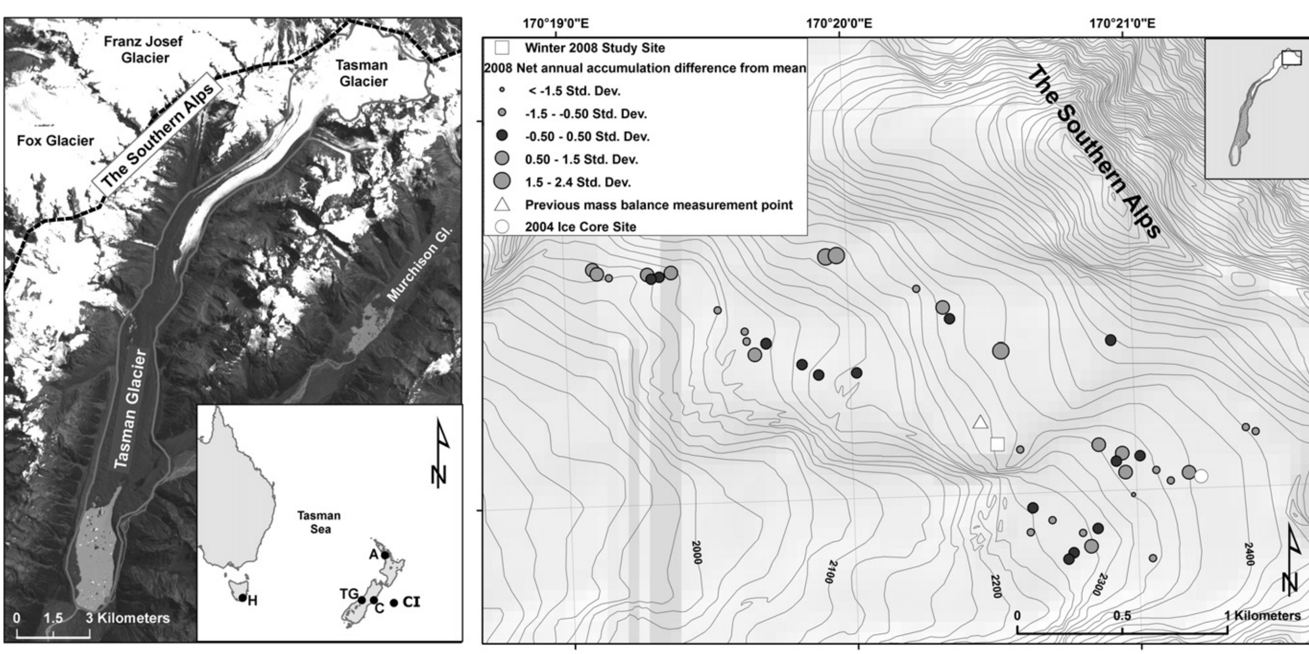

Fig. 1. A. The location of the Tasman Glacier in relation to the Southern Alps and other large glaciers. The insert shows the location of the study site (TG) in relation to New Zealand, and highlights the locations used for Trenberth indices, H = Hobart (Tasmania), A = Auckland, C = Christchurch and CI = Chatham Islands. B. Tasman Glacier accumulation area, including a previous net accumulation survey, the location of previous mass balance measurements, and the ice core site.

However, some mass gain was recorded in the accumulation zone of Tasman Glacier during the mid 1980s and 1990s (Chinn pers. comm. 2010), and a 3.9 m thickening was recorded in the ablation area in 1985, but this wave of mass diffused in the low-gradient tongue without any advance at the terminus (Kirkbride, 1995). Conversely some fast responding debris-free glaciers, for example the Fox and Franz Josef Glaciers, experienced terminus advance in the late 1980s and 1990s (Chinn et al., 2005b; Purdie et al., 2008).

In 2004 an ice core was taken from the accumulation area of the Tasman Glacier (Morgenstern et al., 2004). This was the first deep ice core taken from a New Zealand glacier for comprehensive analysis. This core helps fill a data gap in New Zealand mass balance records. By combining net accumulation data derived from the ice core with previous direct measurements, more than 20 years of net accumulation data can be gained, the longest record for any New Zealand glacier (Anderton and Chinn, 1978; Chinn, 1994; Anderson et al., 2010). We use this composite record to:

1. Analyse inter-annual variability in net accumulation on Tasman Glacier in relation to variations in climate and atmospheric circulation.
2. Evaluate whether annual or seasonal climate conditions exert more control on net accumulation variability.

2. Data and methodology

2.1. Measurement of net accumulation on Tasman Glacier

Net snow accumulation has been measured intermittently on Tasman Glacier since 1957 (Goldthwait and McKellar, 1962; Anderton, 1975; Chinn, 1994; Ruddell, 1995; Purdie et al., 2011a). Analysis of an ice core retrieved from the Tasman glacier in 2004 has added an additional 2 years net accumulation to the record (see results). By combining these data, Tasman Glacier has 24 years of net accumulation measurement (Table 1 and Fig. 2). Although these data are discontinuous, they provide the longest record of measured accumulation for any New Zealand glacier.

One limitation of the accumulation data presented in this study is that they have been collected at different sites (Fig. 1), using different methods. An assessment of the crevasse stratigraphy method found little difference (~0.15 m w.e) in deriving an annual estimate of accumulation from multiple crevasse measurements, whether by interpolation, clustering, or using the population median or mean; the mean is reported here. Sites for digging snow pits or coring are usually chosen to be relatively low gradient, thereby less affected by topographic influences on snow accumulation or ablation. Net accumulation has been measured in crevasses on Tasman Glacier in close proximity to other previous measurement sites. In 1987, a crevasse measured close to the 1960–70s measurement site (Fig. 1) recorded net accumulation that was 0.04 m w.e. less than the mean derived from all crevasse measurements that year. In 2008 a crevasse measured in a similar location to the ice core site (Fig. 1), recorded net accumulation that was 0.32 m w.e higher than annual mean for that year. Although a limited comparison, it does indicate possible variability of ±~0.36 m w.e when comparing net accumulation measurements at different measurement sites taken by different methodologies. Although not ideal, combining data from different sites and different methodologies is still considered worthwhile because no other data of this type exists.

2.2. The equilibrium-line-altitude record

A glacier's end-of-summer-snowline (EOSS) intentionally indicates the highest altitude attained annually by the transient snowline and is the elevation where annual mass balance is zero; referred to as the annual equilibrium line altitude (ELA_A) (Meier and Post, 1962). The ELA_A is a useful mass balance proxy, and has been used to estimate changes in glacier mass balance in areas where direct measurement is lacking (Braithwaite, 1984; Chinn et al., 2005a). The EOSS has been intermittently recorded for Tasman Glacier since 1955, with a near-complete record from 1977 onwards (Fig. 2), due to its inclusion in an annual aerial glacier survey conducted by the National Institute of Water and Atmospheric Science (NIWA) (Chinn, 1995; Willsman et al., 2009). The annual ELA_A for Tasman Glacier is regressed against the average of all other annual index glacier values measured throughout the Southern Alps for each respective year. This method provides relatively precise equilibrium (ELA_0) values for each index glacier, unaffected by the problems associated with averaging a limited number of ELA values. By being able to use 30 years of both positive and negative balances from 50 glaciers, the value for the long-

Table 1
Net accumulation measurements on Tasman Glacier.

Year	Net accumulation (m w.e.)	Study	Notes	ELA_A (m a.s.l.)
1959	3.10	(Goldthwait and McKellar, 1962)	Stakes and pits	1830
1960	5.53			–
1964	5.16	(Chinn, 1968; Chinn, 1969; Chinn, 1994)	Stakes, pits and coring	1750
1965	6.01	(Chinn et al., 2005a, 2005b)		–
1966	5.12	(Anderton, 1975)		1700
1967	2.40			1970
1968	5.54			1630
1969	4.58			1690
1970	1.25			2200
1971	1.96			1930
1972	3.63			1850
1973	4.45			1900
1974	2.78			1945
1975	1.83			2050
1987	4.68	(Ruddell, 1995)	Crevasse stratigraphy	1761
1988	3.12			1840
1989	3.76			1760
1990	1.34			2100
1991	3.80			1755
2004	5.87	Morgenstern and Mayewski (pers.comm. 2009), and analysis this study	Tasman Glacier Ice Core	1750
2005	4.60			1750
2007	3.97	This study.	Crevasse stratigraphy	1796
2008	2.43	Also see Purdie et al. (2011a)		2025
2009	3.95			1969

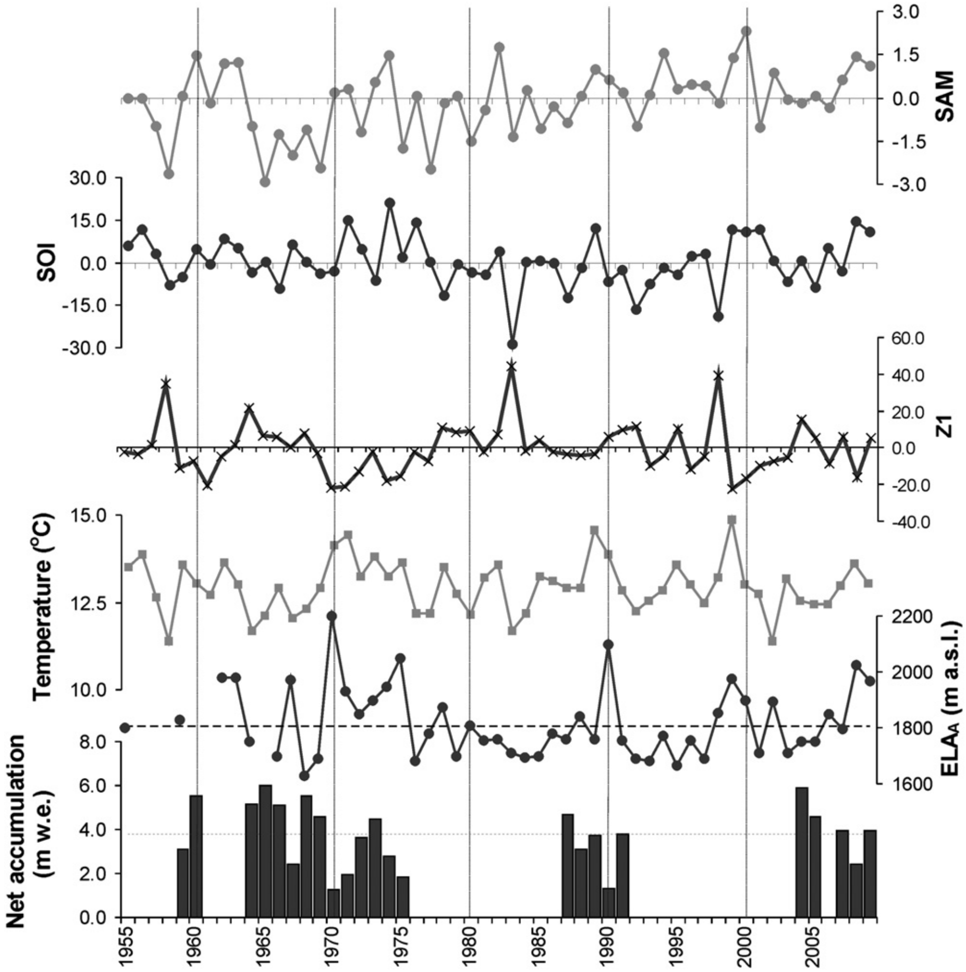

Fig. 2. Inter-annual variability in net accumulation and the ELA$_A$ on Tasman Glacier in relation to ablation season temperature, zonal (Z1) flow anomalies, and the SOI and the SAM. Average net accumulation and ELA$_0$ are represented as dashed lines.

term equilibrium line altitude has been derived by constructing a regression plot for each glacier (refer to Chinn et al., 2005a).

The derived steady state ELA (ELA$_O$) for Tasman Glacier for the EOSS study period is 1806 m a.s.l.; years with higher (lower) ELA$_A$ are representative of negative (positive) glacier mass balance (Willsman et al., 2009). The regional significance of the Tasman Glacier annual ELA$_A$ record can be assessed by comparing it to the mean annual Southern Alps ELA, a composite of 50 index glaciers. The correlation (r^2) for the period 1977–2009 is 0.83, indicating that the Tasman Glacier ELA$_A$ can be considered representative of wider glacier mass balance conditions in the New Zealand Southern Alps (Willsman et al., 2009). The Tasman Glacier ELA$_A$ record spans 50 years, and over this time there has been gradual downwasting (thinning) of the glacier tongue. Average downwasting in the altitudinal range of observed annual ELA variation (1500–2200 m a.s.l) from 1965 to 2008 is 13 m. This amount of downwasting is smaller than the estimated accuracy in deriving the ELA$_A$ from oblique aerial photographs ($\pm$20 m) therefore no correction is applied to the ELA$_A$ dataset to account for this. However, this issue may need to be addressed in future applications. In this study the Tasman Glacier ELA$_A$ record is used in addition to the intermittent net accumulation data to help assess glacier–climate relationships. A linear regression of net accumulation data with the ELA$_A$ record demonstrates that the two data sets are strongly correlated, with $r^2 = 0.75$ ($n = 22$). Therefore the Tasman Glacier ELA$_A$ for provides a reasonable proxy of net accumulation and vice versa (Fig. 3).

2.3. Analysis of the Tasman Glacier ice core

A 54 m ice core was obtained from the accumulation area of Tasman Glacier in October 2004 (Morgenstern et al., 2004). Although ice thickness at the site was estimated at ~130 m (Thomson, 2005), complications during the drilling process prevented sampling below 54 m depth. The core was extracted in ~1 m sections, with each section immediately sealed in plastic, labelled, and kept frozen at the site. The frozen core was transport to, and stored at, GNS Science Ice Core Research Facility, Lower Hutt, New Zealand, and in 2008 sub-sampled at 10 cm resolution using a continuous melter (Osterberg et al., 2006) in sterile conditions. Samples derived from the inner-most section of the core were analysed for major ions (Na^+, K^+, Mg^{2+},

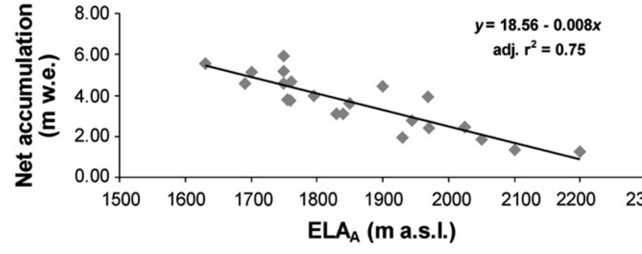

Fig. 3. Relationship between net accumulation measurements and the annual equilibrium line altitude (ELA$_A$).

Ca^{2+}, MS, Cl^-, NO_3^-, SO_4^{2-}), 26 trace elements, and stable water isotope, δD at the Climate Change Institute, University of Maine.

By the end of summer in the New Zealand Southern Alps, the snow surface of glaciers becomes visually discoloured, due to concentration of dust particles from summer surface melting and fewer snowfalls. This 'dirty' horizon is utilised in the crevasse stratigraphy method for determining annual layers (Pelto, 1988; Post and LaChapelle, 2000) and is also represented down an ice core as a spike in trace element concentration (Legrand and Mayewski, 1997).

2.4. Climate–accumulation relationships

To investigate the processes contributing to net accumulation variability, a number of climate data were analysed. The influence of local air temperature and precipitation was assessed using monthly data from the nearby Mount Cook village weather station (765 m a.s.l.) (NIWA, 2009). The Tasman Sea has been identified as a major contributor to snow accumulation on Tasman Glacier due to prevailing westerly flow (Purdie et al., 2010). Therefore mean monthly Sea Surface Temperature (SST) for the Tasman Sea were derived from gridded NCEP/NCAR reanalysis (Kalnay et al., 1996; Kistler et al., 2001).

To consider the influence of regional air-flow anomalies over the Southern Alps zonal and meridional indices of Trenberth (1976) were used. The zonal index (Z1) is the normalised monthly MSLP difference between Auckland and Christchurch (Fig. 1), where positive (negative) values are an indication of enhanced westerly (easterly) flow. The meridional index (M1) is the normalised monthly MSLP difference between Hobart and the Chatham Islands (Fig. 1) where positive (negative) values represent enhanced southerly (northerly) flow.

To investigate the influence of larger scale atmospheric circulation on net accumulation an index for the SAM was used (Marshall, 2003, 2009). This index is the difference in the normalised mean zonal pressure at 40 and 65°S, derived from 12 Southern Hemisphere weather stations, and characterises north–south shifts in the mid-latitude jet and fluctuations in jet strength (Marshall, 2007).

The ENSO is represented by the Southern Oscillation Index (SOI) (Australian Bureau of Meteorology, 2009) as the normalised anomaly of MSLP difference between Tahiti and Darwin. Although Trenberth and Shea (1987) identified lags in MSLP anomalies between Darwin and New Zealand, Mullan (1995) used simultaneous data for southern oscillation–climate relationships noting there was a strong zero–lag relationship between the SOI and zonal and meridional pressure gradients. As a check, SOI data was lagged by 1, 2 and 3 months, but lagged data produced weaker correlations with net accumulation data, so only results for simultaneous SOI data are reported in this paper. The Interdecadal Pacific Oscillation (IPO) is known to play an important role in New Zealand climate (Salinger et al., 2001) but is not considered in this paper because the accumulation data sets are too short for meaningful comparison to this ~30 year cycle.

Net accumulation is the product of mass gain/losses throughout the glacial year, thus we would expect that climatic conditions during the ablation and/or accumulation seasons to have important influence on the amount of snow accumulation left at the end of the mass balance year. Therefore, monthly data for each of the seven climate parameters were combined into an annual average (1 April–31 March), an ablation season average (1 November–31 March) and an accumulation season average (1 April–31 October) following Fitzharris et al. (1997). Precipitation data were summed as opposed to averaged over the same time periods. Following this, statistical analysis was conducted, using the Spearman's Rank test (Spearman, 1904) between all climate parameters and the Tasman Glacier net accumulation data and the ELA_A record. In addition, net accumulation data was regressed against the ELA_A record to assess the strength of this relationship.

3. Results

3.1. Net accumulation derived from Tasman Glacier ice core

A number of peaks in trace element concentration can be identified throughout the length of the core. The first two peaks occur at around 10 and 18 m depth, with another six significantly smaller peaks identified between 20 and 40 m depth. Below 40 m there is a large increase in trace element concentrations, in particular at 43 m depth. This concentration spike occurs at a density transition to 0.90 g cm^3 and where dirt bands are visible. It is possible that this spike is related to melt-water ponding and/or the presence of a former drainage conduit. It could also represent a previous discontinuous ice surface.

In the upper 20 m of the ice core enrichment of δD concurs with increased trace element concentrations, supporting interpretation that the first two peaks in trace element concentrations are representative of a former summer snow surface (Fig. 4). Numerous ice layers are present along the length of the core, and below 20 m, rapid homogenisation of δD and large increases in the Cl^-/Na^+ ratio (well above standard sea water), suggest that the integrity of the core has been reduced by melt-water percolation and refreezing (Shiraiwa et al., 2002; Schwikowski et

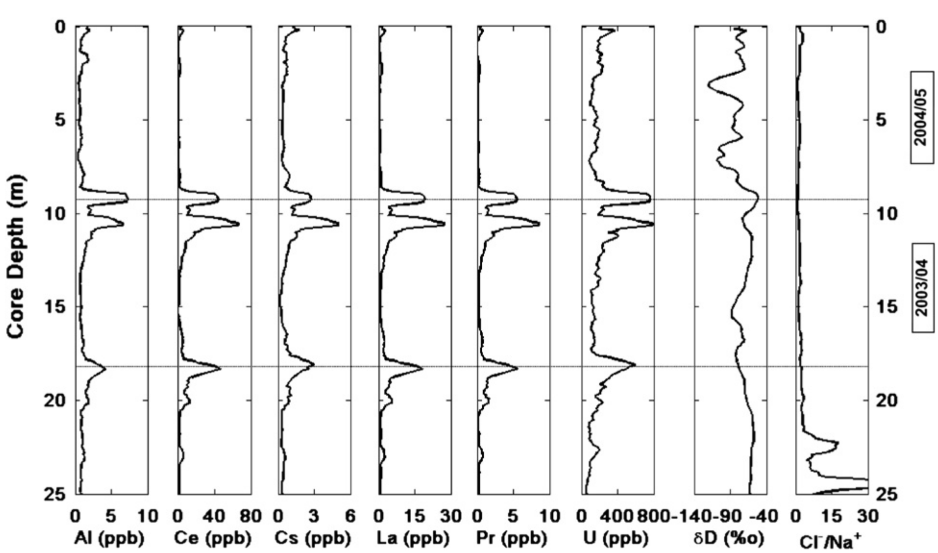

Fig. 4. Summer peaks in trace element chemistry and δD in the top 25 m of the Tasman Glacier ice core used to determine two additional years of net accumulation.

al., 2006). For this reason, only the upper 20 m of the core is used in this study. However, future analysis, including tritium dating (Morgenstern et al., 2004) may still derive important climate information, as other research has found that even sites with significant melting can retain a climate signal (Fisher et al., 1998; Goto-Azuma et al., 2002).

Within the upper 20 m of the core, 19 out of 26 trace elements analysed had peaks in concentration at around 10 and 18 m depth, for example Al, Ba, Ce, Cs, Co, La, Mn, Pb, Pr, U and V. Concentrations in major ions were more variable although methylsulphonate (MS) and SO_4^{2-} recorded peaks at 10 and 18 m depth. An interesting double peak occurs at 10 m with concentration spikes at both 9.2 and 10.5 m depth. This peak most likely represents the 2003/04 summer surface. Climate data from Mount Cook village shows an initial warming (melt) period in early spring, followed by high summer precipitation in January/February, with a return to drier conditions in March. Such a climate pattern could create a double peak in the ice core record with the initial melt surface re-buried by the summer snowfalls, then re-established in late summer. These early (October) and late (March) season melt surfaces have also been observed by the author (Purdie) on regular field trips to the glacier. Therefore the shallower peak at 9.2 m depth could represent the end-of-summer (March) snow surface. This double peak and the peak at 18.1 m depth are used to characterise two years of net accumulation data for Tasman Glacier.

The average density of the core between 0 and 9 m is 0.52 $g\,cm^3$, and between 9 and 18 m is 0.66 $g\,cm^3$. These average densities are used to convert core depth to metres water equivalent (m w.e.). The coring drill was set up below the snow surface in a snow-pit therefore an additional 0.83 m w.e. was added to the top (first) core section. Since the core was retrieved prior to the end of the mass balance year, accumulation and ablation need to be calculated from the period after the core was taken (25th October) through till the end of March. This was done by utilising temperature and precipitation data from local weather stations and a standard mass balance model (see Anderson et al., 2006; Purdie et al., 2011b). Together, this analysis results in estimated net accumulation for 2004 and 2005 of 5.90 and 4.60 m w.e. respectively (Table 1).

3.2. Inter-annual variability in net accumulation

Average net accumulation of all data is 3.79 m w.e. ($n=24$) with a standard deviation of 1.43 m w.e., indicating large inter-annual variability. There is little difference between the mean and median (3.88 m w.e.). Lack of continuous measurement means it is hard to assess decadal trends, particularly in net accumulation data. However, the longer ELA_A record reveals that the 1980s recorded the lowest average ELA_A (Fig. 2 and Table 1).

3.3. Correlation of climate parameters with net accumulation data

Statistically significant correlations ($p=0.01$) were found between net accumulation (and ELA_A) and annual and ablation season temperature and SST (Table 2 and Figs. 2 and 5). Statistically significant correlations were also found between the longer ELA_A record and annual and accumulation season precipitation totals. The ELA_A record also showed relationships ($p=0.05$) with annual and ablation season SAM and SOI. Both net accumulation data and the ELA_A produced statistically significant ($p=0.01$) correlations with the Z1, with higher net accumulation (lower ELA_A) associated with enhanced westerly flow during the ablation season and on an annual basis. Relationships with meridional index (M1) were not as strong ($p=0.05$), but did indicate increased net accumulation (lower ELA_A) with enhanced southerly flow.

Inter-annually, years with lower net accumulation (e.g. 1974, 1999, 2000 and 2008) were associated with warm ablation season temperatures, enhanced northerly and easterly flows and positive phases of the SOI and the SAM (Fig. 2). However, some of the lowest net accumulation years occur when the SOI and the SAM are out-of-phase, for example 1967 and 1990. The ablation season of 1990 was characterised by warm temperatures, no strong zonal wind anomaly, and high MSLP over the South Island (Figs. 2 and 6). In 1987 net accumulation was above average and this coincided with the SOI and the SAM being in negative phase. 1983 and 1998 were characterised by a strongly negative ablation season SOI. Although there are no net accumulation data for these years, in 1983 the ELA_A does show a depression of the EOSS in response to lower temperatures and more persistent westerly and southerly circulation anomalies; the SAM was also negative. In 1998, despite being a negative ENSO year, the SAM was neutral, and although westerly and southerly circulation anomalies occurred, cooling did not, MSLP remained high over the South Island, and a near-average ELA_A was the result (Figs. 2 and 6).

Table 2
Spearman's Rank correlation between net accumulation (m w.e.) and climate variables. Results in bold are significant at the 0.01 level and those in italics at 0.05. Note that if correlation results are consistent between net accumulation and the ELA_A, they will be of opposite sign, as a lower ELA_A is anomalous with a more positive mass balance, and therefore higher net annual accumulation.

Climate parameter and season	Net accumulation ($n=24$)		ELA_A ($n=49$)	
	Correlation co-efficient	p-value	Correlation co-efficient	p-value
Temperature				
–Annual	**−.525**	.008	.405	.004
–Ablation	**−.661**	.000	.510	.000
–Accumulation	−.166	.438	.191	.188
Precipitation				
–Annual	.192	.368	−.406	.004
–Ablation	.067	.756	−.102	.486
–Accumulation	.117	.585	−.419	.003
Sea surface temperature				
–Annual	**−.573**	.003	.556	.000
–Ablation	**−.704**	.000	.579	.000
–Accumulation	−.260	.220	*.301*	.035
Southern Annular Mode				
–Annual	−.144	.501	*.327*	.023
–Ablation	−.270	.203	*.344*	.017
–Accumulation	−.025	.907	.163	.269
Southern Oscillation Index				
–Annual	−.295	.162	*.283*	.049
–Ablation	−.292	.166	*.317*	.026
–Accumulation	−.169	.431	.197	.175
Zonal				
–Annual	.277	.191	−.278	.053
–Ablation	*.490*	.015	−.238	.100
–Accumulation	.008	.971	−.162	.266
Meridional				
–Annual	**.522**	.009	−.262	.069
–Ablation	**.556**	.005	−.214	.140
–Accumulation	.108	.616	−.156	.286

Due to potential non-linearity in relationships between net accumulation and the ELA_A with the SAM and the ENSO, a t-test was used to compare means during positive and negative phase years. Analysis was conducted on both ablation season and annual averages of the SAM and SOI. Years when either index is close to zero (i.e. 0 ± 0.2 for the SAM, and 0 ± 2 for SOI) are ignored, as during these years average pressure gradients and wind anomalies persist. Results in Table 3 show a statistically significant difference in average net accumulation and average ELA_A between positive and negative SAM years. For the SOI, the only significant relationship found was with the annual average SOI and the ELA_A.

Longer-term trends are more difficult to discern because we lack net accumulation data in many key years. However, it is clear that the 1960s were characterised by generally higher net accumulation and a persistently negative phase of the SAM. ELA_A data indicate that this trend of generally positive balance (occasionally interrupted by a high

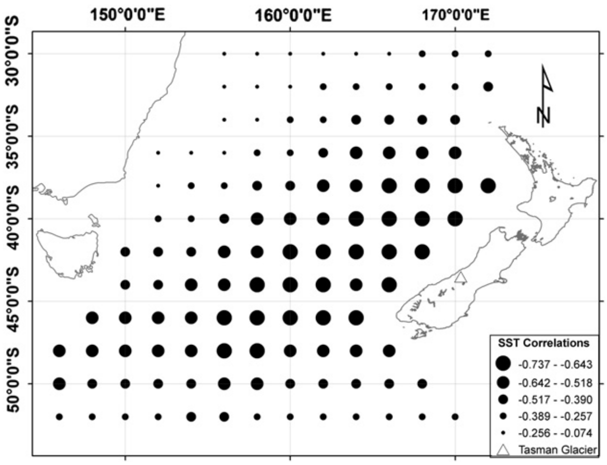

Fig. 5. Correlation map between SST in the Tasman Sea and net accumulation on Tasman Glacier during the ablation season.

melt year) probably continued until recently. Since around 2006 we have seen some low net accumulation years resulting from northerly circulation anomalies driving higher ablation season temperatures. These years have coincided with a positive trend in both the SAM and the ENSO.

3.4. Correlations between climate variables

To further understand the relationship between climate and glaciers, we also investigated the relationships between the climate patterns themselves. Statistically significant correlations were found between local Mount Cook temperature and SST throughout the year, but especially during the ablation season (Table 4). Mount Cook temperature was also positively correlated with the SAM, the SOI and SST, especially in the ablation season. SST positively correlated with the SOI in all seasons, despite no direct correlation being found between the SOI and net accumulation.

A number of significant correlations were found between the Z1 and the other climate variables, especially during the ablation season. Enhanced westerly flow was associated with decreased SST, increased precipitation, and reduced temperatures. Westerly flow was also enhanced when the SAM and the SOI are in negative phase. Although the M1 didn't correlate as strongly with local temperature and precipitation, significant relationships were found with SST and the SOI, with enhanced southerly flow associated with decreased SST, and

Table 3
Results of a two-tailed *t*-test for the difference in means in net accumulation (m w.e.) and the ELA_A (m a.s.l.) between positive (+ve) and negative (−ve) phases of the SAM and SOI. In each instance, the mean for + ve and −ve years is shown along with the associated *p*-value and *t*-statistic.

Parameter	Net accumulation	ELA_A
SAM—ablation season average	3.20 + ve 4.49−ve	1878 + ve 1783−ve
	$p=$ **0.05** $t=-2.10$	$p=$ **0.02** $t=2.45$
SAM—annual average	3.53 + ve 3.92−ve	1877 + ve 1779−ve
	$p=0.61$ $t=-0.53$	$p=$ **0.02** $t=2.41$
SOI—ablation season average	3.14 + ve 3.82−ve	1863 + ve 1799−ve
	$p=0.25$ $t=-1.19$	$p=0.13$ $t=1.54$
SOI—annual average	3.07 + ve 4.14−ve	1888 + ve 1787−ve
	$p-0.12$ $t-1.66$	$p-$ **0.02** $t-2.45$

the negative phase of the SOI. A number of relationships between the various climatic variables were at their strongest during the ablation season.

4. Discussion

4.1. Importance of temperature and precipitation on net accumulation variability

Changes in temperature and precipitation are embedded in large-scale atmospheric circulation variability. However, due to the direct and immediate influence that these two climate parameters have on glacier mass balance, the impact of local temperature and precipitation will be discussed first.

Ablation season temperature was found to correlate most strongly with inter-annual variability in net accumulation on Tasman Glacier, with increases in both local and SST associated with lower net accumulation. These strong temperature relationships were also found in the ELA_A record, with higher ELA_A occurring in years with warmer ablation season temperatures. Potential mechanisms that could explain these correlations are, 1. Higher ablation season temperatures result in higher annual melt rates along the full length of the glacier, including in the accumulation area, 2. Higher ablation season temperature raises the elevation of the freezing level, which in turn impacts on the proportion of solid-to-liquid precipitation received within the accumulation area, 3. Increased ablation season temperatures may be related to an increase in the length of the ablation season (reduced accumulation season) which would affect raw values of both mass gain and loss, and 4. Positive feedback from reduced albedo during summers with infrequent summer snowfall that results in a general darkening of the snow surface. Whatever the actual mechanism, these results are consistent with climate sensitivity studies from mass balance models, which have found

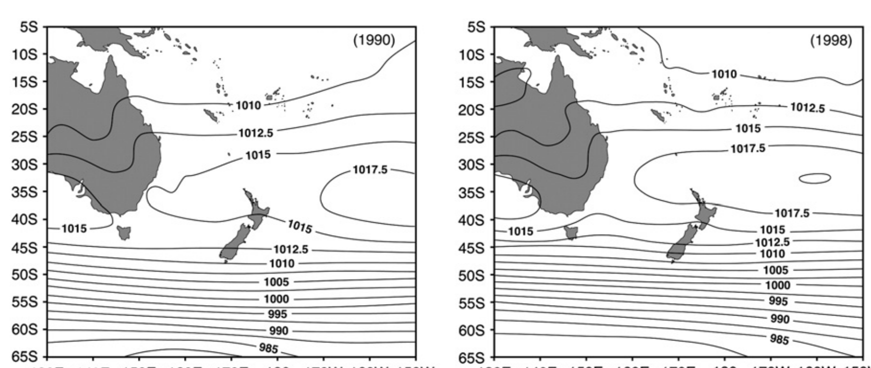

Fig. 6. Mean sea level pressure maps for the ablation seasons of 1990 (left) and 1998 (right). In 1990 both the SAM and SOI were relatively neutral with no clear zonal flow anomaly, but MSLP was high over the South Island resulting in warm temperatures and low net accumulation. In 1998 despite a strong El Niño, MSLP remained relatively high over the South Island and the ELA_A was slightly higher than average indicating an average to slightly negative mass balance.

that maritime glaciers in the Southern Alps have high temperature sensitivity (Oerlemans, 1997; Anderson et al., 2006, 2010; Anderson and Mackintosh, 2006).

Globally, warm summer temperature is having large impact on mid-latitude maritime glaciers (Josberger et al., 2007; Winkler et al., 2009). Previously Wolverine (Alaska) and South Cascade (Washington, USA) glaciers had strong correlation with winter balance due to fluctuations in the location of winter storm tracks, brought about in part by phase changes in the Pacific Decadal Oscillation (PDO), and changes in the strength of the Aleutian/Gulf of Alaska Low (Walters and Meier, 1989; Cayan, 1996; Hodge et al., 1998; Moore et al., 2002). However recently, warm dry summers have begun to strongly influence net balance on these maritime glaciers (Josberger et al., 2007). The situation is similar in Norway, where recent high summer temperatures appear to have effectively de-coupled glacier frontal variations on Nigardsbreen from net mass balance (Winkler et al., 2009).

In this study no significant relationship was found between winter precipitation and net accumulation, but a relationship was identified between the ELA_A and winter precipitation; although it was less significant ($p=0.05$) than ablation season relationships. This finding is surprising, and possibly indicates that the effect that temperature has on the partitioning of rain and snow with increasing elevation, and its effect on summer melting, effectively overrides any relationship between precipitation and accumulation that may have been apparent at the end of winter. In addition, the lack of relationship found between precipitation and the net accumulation data may be influenced by the shorter, fragmented nature of the net accumulation data set in comparison to the more comprehensive ELA_A data. Despite these issues, these findings are consistent with the shorter (6-year) annual and seasonal mass balance record at Brewster Glacier, 90 km to the south, which indicates that the inter-annual variability in total annual mass balance is most strongly influenced by summer balance (Anderson et al., 2010).

4.2. Influence of atmospheric circulation on net accumulation variability

Variability in atmospheric circulation patterns have major influence on MSLP, anomalous air flow, and SST, all of which provide forcing to local temperature and precipitation patterns (Sturman and Tapper, 2006). When the SAM and ENSO are in positive (negative) phase there is often anomalous northerly and easterly (southerly and westerly) flow over the Southern Alps resulting warm (cool) temperatures and decreased (increased) precipitation (Mullan, 1995; Salinger et al., 2001; Kidston et al., 2009). However, the strength of any anomaly as recorded in each relevant index, can vary significantly from year to year. In addition, it has been found that precipitation can also be enhanced in the Southern Alps region during positive ENSO (La Niña) phases (Ummenhofer et al., 2009). This finding of an at times straight forward relationship can be partially explained by the strong linear relationship found to exist between the ENSO and SAM in the Southern Hemisphere summer, with ~25% of inter-annual variability in the SAM described by temporal variations in the ENSO cycle (L'Heureux and Thompson, 2006). Therefore the relationships found between Tasman Glacier mass balance and the ENSO and the SAM are likely related to the effect that these circulation modes can have on ablation season temperatures. In addition, when these modes are in negative phase they have potential to delay the onset of summer melting due to albedo increases associated with spring and summer snowfall (Oerlemans and Klok, 2004) (Table 4).

Considering what we already know about the ENSO and SAM it was anticipated to find that a decrease (increase) in net balance occurs in association with a positive (negative) phase of both indices. This was indeed the case in the majority of years, as 14 out of the 18 years when both indices were positive (negative), showed decreased (increased) balance. However, anomalies did occur (e.g. 1960). In this study we found that low (high) net accumulation can also occur when only one of these modes are in positive (negative) phase, for example 1971 and 1975 (1965 and 1993). In addition, positive (negative) balances can occur when both the ENSO and/or the SAM are neutral, for example 1970 (2004). In these years the same regional northerly-easterly (southerly-westerly) anomalous circulation occurs but without obvious large scale forcing (Fig. 2). Interestingly, some of the lowest net accumulation years (e.g. 1967 and 1990) coincide with the ENSO and the SAM being out-of-phase, and anomalous flow contrary to what is usually associated with low net accumulation. High ablation season temperatures in these years indicates that some other climate forcing is at work, clearly demonstrating that the ENSO and SAM do not explain all the variability in inter-annual mass balance. When primary forcings are weak or cancel each other out, secondary forcing mechanisms emerge to control net accumulation variability. This highlights how there is still much to learn about the way in which regional climate variability influences glacial mass balance in mid-latitude regions.

4.3. Recent and future trends in New Zealand climate

The period 1977–2005 has been one of unprecedented El Niño dominance (Power and Smith, 2007), with exceptional events in 1983 and 1998. The fluctuations in the ENSO are known to be modulated by multi-decadal variability in the Interdecadal Pacific Oscillation (IPO), with increased (decreased) El Niño events associated with positive (negative) IPO phases (Salinger et al., 2001). A change point in the IPO has been identified around 1977, with the period 1944–77 one of generally negative phase and 1978–98 a positive phase. Since 1998 the IPO has been predominantly negative (Salinger et al., 2001; Folland, 2008). Indeed the average Tasman Glacier ELA_A for the period 1955–1977 was higher (1770 m a.s.l.) than it was 1978–98 (1860 m a.s.l.), significant at $p=0.05$ (two-tailed t-test). However, net accumulation measurements in the late 1960s also show a short period of high net accumulation. This period of positive balance occurred in conjunction with a persistent negative phase of the SAM, supporting the idea that the SAM has a stronger influence on the New Zealand climate (Ummenhofer et al., 2009). In the last few years we have begun to see a more negative trend in mass balance in conjunction with increased northerly flow and a positive trend in both the SAM and the ENSO.

How projected climate change will impact atmospheric circulation variability is still uncertain. It is possible that El Niño events may become more frequent (Fedorov and Philander, 2000; Nyenzi and Lefale, 2006; Power and Smith, 2007), which could potentially result in increased accumulation and positive mass balance on some New Zealand and Patagonian glaciers (Fitzharris et al., 2007). However, if background warming in the region is in the vicinity of ~2 °C (Solomon et al., 2007) this would significantly impact on freezing levels and snow/rain temperature thresholds, so that El Niño events no longer result in positive mass balance as they do for the present-day glacier geometry. Climate models indicate that increasing CO_2 levels may result in an upward positive trend in the SAM (Fyfe et al., 1999), which might ultimately result in large warming of the Tasman Sea (Cai et al., 2005); a warming which could result in reduced net accumulation. Preliminary modelling of future glacier length changes in New Zealand supports the contention that even modest rates of warming, including precipitation increase, will overpower any effects of regional climate variability, and that glacier retreat is to be expected (Anderson et al., 2008).

5. Conclusions

Reconstructing net accumulation data from direct measurements and an ice core has enabled a comprehensive interpretation of mass balance–climate relationships to be made. Specifically, a direct comparison between net accumulation and various climatic and atmospheric circulation variables has shown that temperature, especially during the ablation season, exerts strongest influence on inter-annual variability in net accumulation on Tasman Glacier. Our results have shown that although a direct linear response between glacier mass balance and the

Table 4
Correlation matrix of relationships between all climate variables used for the analysis of net accumulation and ELA_A trends.

	Temperature			Precipitation			SST			SAM			SOI			Z1			M1		
	Ann.	Abl.	Acc.	Ann.	Abl.	Acc.	Ann.	Abl.	Acc.	Ann.	Abl.	Acc.	Ann.	Abl.	Acc.	Ann.	Abl.	Acc.	Ann.	Abl.	Acc.
T																					
Ann.	1.00																				
Abl.	**.765**	1.00																			
Acc.	**.855**	**.377**	1.00																		
P																					
Ann.	.045	−.102	.135	1.00																	
Abl.	−.020	−.092	.006	**.531**	1.00																
Acc.	.174	.050	.243	**.641**	−.168	1.00															
SST																					
Ann.	**.575**	**.482**	**.536**	−.241	−.209	−.078	1.00														
Abl.	**.609**	**.668**	**.404**	−.250	−.173	−.083	**.850**	1.00													
Acc.	*.327*	.153	**.460**	−.148	−.210	−.025	**.866**	**.494**	1.00												
SAM																					
Ann.	*.307*	.150	*.323*	.063	.244	−.057	**.304**	*.299*	.200	1.00											
Abl.	**.472**	**.480**	*.326*	.005	−.010	.136	**.377**	**.421**	.202	**.700**	1.00										
Acc.	.045	−.220	.209	.058	**.388**	−.210	.119	.063	.140	**.727**	.100	1.00									
SOI																					
Ann.	.252	.252	*.288*	−.178	*−.304*	.093	**.507**	**.428**	**.425**	.058	.233	−.096	1.00								
Abl.	*.316*	.252	**.361**	−.126	−.238	.129	**.503**	**.469**	**.374**	.198	**.374**	−.000	**.880**	1.00							
Acc.	.176	.203	.213	−.158	*−.275*	.096	**.427**	*.334*	**.391**	−.039	.107	−.136	**.942**	**.693**	1.00						
Z1																					
Ann.	−.014	−.160	.040	**.554**	.115	**.499**	*−.321*	**−.389**	−.175	−.185	−.149	−.180	**−.430**	**−.430**	−.138	1.00					
Abl.	**−.356**	**−.380**	−.235	**.362**	**.385**	.005	**−.471**	**−.591**	−.239	−.091	*−.307*	*−.321*	**−.376**	**−.513**	−.036	**.603**	1.00				
Acc.	*.278*	.155	.224	**.383**	−.186	**.693**	−.078	.016	−.119	−.207	.014	−.138	**−.386**	*−.308*	−.158	**.721**	−.039	1.00			
M1																					
Ann.	−.260	*−.277*	−.236	.065	.139	−.096	**−.374**	**−.411**	−.238	.029	.109	−.065	**−.600**	−.249	**−.585**	*.343*	.236	.165	1.00		
Abl.	−.177	**−.453**	−.028	−.034	.035	−.079	−.116	**−.362**	.117	.077	−.010	.058	**−.448**	−.237	**−.415**	.101	.080	.007	**.574**	1.00	
Acc.	−.215	−.074	*−.294*	.118	.175	−.061	**−.384**	*−.308*	*−.334*	.053	.221	−.077	**−.650**	−.248	**−.646**	**.352**	.216	.199	**.879**	.155	1.00

Note: Bold correlations are significant at 0.01, and italics at 0.05.

ENSO and the SAM exists at times, in some years the response is not linear, and fluctuations in these modes of atmospheric circulation cannot explain all the variance in net accumulation on Tasman Glacier. Understanding these non-linear responses are crucial, especially since they can be associated with very negative mass balance. With the IPO currently in a negative phase, there is a likelihood of increased La Niña events, which coupled with increasing persistence of the positive SAM, means we can expect to see more negative mass balance in New Zealand in the immediate future.

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References

Aizen, V., et al., 2009. Stable-isotopes and trace element time series from Fedchenko glacier (Pamirs) snow/firn cores. Journal of Glaciology 55 (190), 275–291.
Anderson, B., Mackintosh, A., 2006. Temperature change is the major driver of late-glacial and Holocene glacier fluctuations in New Zealand. Geology 34 (2), 121–124.
Anderson, B., Lawson, W., Owens, I., Goodsell, B., 2006. Past and future mass balance of ‘Ka Roimata o Hine Hukatere’ Franz Josef Glacier, New Zealand. Journal of Glaciology 52 (179), 597–607.
Anderson, B., Lawson, W., Owens, I., 2008. Response of Franz Josef Glacier *Ka Roimata o Hine Hukatere* to climate change. Global and Planetary Change 63, 23–30.
Anderson, B., et al., 2010. Climate sensitivity of a high precipitation glacier in New Zealand. Journal of Glaciology 56 (195), 114–128.
Anderton, P., 1975. Tasman Glacier 1971–1973, Ministry of Works and Development for the National Water and Soil Conservation Organisation, Wellington.
Anderton, P.W., Chinn, T., 1978. Ivory Glacier, New Zealand, an I.H.D. representative basin study. Journal of Glaciology 20 (82), 67–84.
Andreassen, L., Elvehøy, H., Kjøllmoen, B., 2005. Glacier mass-balance and length variation in Norway. Annals of Glaciology 42, 317–325.
Australian Bureau of Meteorology, 2009. The Southern Oscillation Index (SOI). http://www.bom.gov.au/climate/current/soihtm1.shtml 2009.
Braithwaite, R., 1984. Can the mass balance of a glacier be estimated from its equilibrium-line altitude? Journal of Glaciology 30 (106), 364–368.
Braithwaite, R.J., Zhang, Y., 2000. Sensitivity of mass balance of five Swiss glaciers to temperature changes assessed by tuning a degree-day model. Journal of Glaciology 46 (152), 7–14.
Cai, W., Shi, G., Cowan, T., Bi, D., Ribbe, J., 2005. The response of the Southern Annular Mode, the East Australian Current, and the southern mid-latitude ocean circulation to global warming. Geophysical Research Letters 32, 1–4. doi:10.1029/2005GL024701.
Cayan, D., 1996. Interannual climate variability and snowpack in the Western United States. Journal of Climate 9, 928–948.
Chinn, T.J., 1968. Snow surveys on the Tasman Glacier. New Zealand Alpine Journal 22 (2), 411–416.
Chinn, T.J., 1969. Tasman Glacier Snow Observations 1968–69 Glacial Year Report. Ministry of Works, Timaru.
Chinn, T.J., 1994. Snow and Ice Balance Measurements from the Tasman Glacier, Waitaki Catchment, New Zealand. Institute of Geological and Nuclear Sciences Ltd, Lower Hutt.
Chinn, T.J., 1995. Glacier fluctuations in the Southern Alps of New Zealand determined from snowline elevations. Arctic and Alpine Research 27 (2), 187–198.
Chinn, T.J., 1996. New Zealand glacier responses to climate change in the past century. New Zealand Journal of Geology and Geophysics 39, 415–428.
Chinn, T.J., 2001. Distribution of the glacial water resources of New Zealand. Journal of Hydrology (NZ) 40 (2), 139–187.
Chinn, T.J., Heydenrych, C., Salinger, M.J., 2005a. Use of the ELA as a practical method of monitoring glacier response to climate in New Zealand's Southern Alps. Journal of Glaciology 51 (172), 85–95.
Chinn, T.J., Winkler, S., Salinger, M.J., Haakense, N., 2005b. Recent glacier advances in Norway and New Zealand: a comparison of their glaciological and meteorological causes. Geografiska Annaler 87A (1), 141–157.

Clare, G.R., Fitzharris, B.B., Chinn, T.J., Salinger, M.J., 2002. Interannual variation in end-of-summer snowlines of the Southern Alps of New Zealand, and relationships with Southern Hemisphere atmospheric circulation and sea surface temperature patterns. International Journal of Climatology 22, 107–120.
Dykes, R., Brook, M., Winkler, S., 2010. The contemporary retreat of Tasman Glacier, Southern Alps, New Zealand, and the evolution of Tasman proglacial lake since AD 2000. Erdkunde 64 (2), 141–154.
Eichler, A., Schwikowski, M., Gaggeler, H., 2001. Meltwater-induced relocation of chemical species in alpine firn. Tellus 53B, 192–203.
Fedorov, A., Philander, S., 2000. Is El Niño Changing? Science 288, 1997–2002.
Fisher, D., et al., 1998. Penny Ice Cap cores, Baffin Island, Canada and the Wisconsinan Foxe Dome connection: two states of Hudson Bay ice cover. Science 279 (5351), 692–695.
Fitzharris, B.B., Hay, J.E., Jones, P.D., 1992. Behaviour of New Zealand glaciers and atmospheric circulation changes over the past 130 years. The Holocene 2 (2), 97–106.
Fitzharris, B.B., Chinn, T.J., Lamont, G.N., 1997. Glacier balance fluctuations and atmospheric circulation patterns over the Southern Alps, New Zealand. International Journal of Climatology 17, 745–763.
Fitzharris, B., Clare, G.R., Renwick, J., 2007. Teleconnections between Andean and New Zealand glaciers. Global and Planetary Change 59, 159–174.
Folland, C., 2008. Interdecadal Pacific Oscillation Time Series. Meterological Office Hadley Centre for Climate Change, Exeter, UK.
Fyfe, J.C., Boer, G.J., Flato, G.M., 1999. The Arctic and Antarctic Oscillations and their projected changes under global warming. Geophysical Research Letters 26 (11), 1601–1604.
Goldthwait, R., McKellar, I., 1962. New Zealand Glaciology. Antarctic Research (Geophysical Monograph Series No. 7), Publication No 1036. American Geophysical Union, Washington, D.C. 209–216 pp.
Goto-Azuma, K., Koerner, R., Fisher, D., 2002. An ice-core record over the last two centuries from Penny Ice Cap, Baffin Island, Canada. Annals of Glaciology 35, 29–35.
Hansen, J., Ruedy, R., Sato, M., Lo, K., 2010. Global surface temperature change. Reviews of Geophysics 48. doi:10.1029/2010RG000345.
Hessell, J.W.D., 1983. Climatic effects on the recession of the Franz Josef Glacier. New Zealand Journal of Science 26, 315–320.
Hodge, S., et al., 1998. Climate variation and changes in mass of three glaciers in Western North America. Journal of Climate 11, 2161–2179.
Hooker, B.L., Fitzharris, B.B., 1999. The correlation between climatic parameters and the retreat and advance of Franz Josef Glacier, New Zealand. Global and Planetary Change 22, 39–48.
Josberger, E., Bidlake, W., March, R., Kennedy, B., 2007. Glacier mass-balance fluctuations in the Pacific Northwest and Alaska, USA. Annals of Glaciology 46, 291–296.
Kalnay, E., et al., 1996. The NCEP/NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77 (437–471).
Kameda, T., et al., 2003. Seasonality of isotopic and chemical species and biomass burning signals remaining in wet snow in the accumulation area of Sofiyskiy Glacier, Russian Altai Mountains. Polar Meteorology and Glaciology 17, 15–24.
Karpechko, A., Gillet, N., Marshall, G., Screen, J., 2009. Climate impacts of the Southern Annular Mode simulated by the CMIP3 models. Journal of Climate 22, 3751–3768.
Kidston, J., Renwick, J., McGregor, J., 2009. Hemispheric-scale seasonality of the Southern Annular Mode and impacts on the climate of New Zealand. Journal of Climate 22, 4759–4770.
Kirkbride, M.P., 1995. Ice flow vectors on the debris-mantled Tasman Glacier 1957–1986. Geografiska Annaler 77A, 147–157.
Kirkbride, M., Warren, C., 1999. Tasman Glacier, New Zealand: 20th-century thinning and predicted retreat. Global and Planetary Change 22, 11–28.
Kistler, R., et al., 2001. The NCEP–NCAR 50-year reanalysis: monthly means CD-ROM and documentation. Bulletin of the American Meteorological Society 82 (2), 247–267.
Koerner, R., 1997. Some comments on climate reconstructions from ice cores drilled in areas of high melt. Journal of Glaciology 43 (143), 90–97.
Kuhn, M., 2003. Redistribution of snow and glacier mass balance from a hydrometeorological model. Journal of Hydrology 282, 95–103.
Lefebvre, W., Goosse, H., Timmermann, R., Fichefet, T., 2004. Influence of the Southern Annular Mode on the sea ice–ocean system. Journal of Geophysical Research 109 (C09005). doi:10.1029/2004JC002403.
Legrand, M., Mayewski, P., 1997. Glaciochemistry of polar ice cores: a review. Reviews of Geophysics 35 (3), 219–243.
Leiva, J.C., Cabrera, G.A., Lenzano, L.E., 2007. 20 years of mass balances on the Piloto Glacier, Las Cuevas river basin, Mendoza, Argentina. Global and Planetary Change 59, 10–16.
L'Heureux, M., Thompson, D., 2006. Observed relationships between the El Niño–Southern Oscillation and the extratropical zonal-mean circulation. Journal of Climate 19, 276–287.
Marshall, G., 2003. Trends in the Southern Annular Mode from observations and reanalyses. Journal of Climate 16 (24), 4134–4145.
Marshall, G., 2007. Half-century seasonal relationships between the Southern Annular Mode and Antarctic temperatures. International Journal of Climatology 27, 373–383.
Marshall, G., 2009. The Southern Annular Mode. http://www.antarctica.ac.uk/met/gjma/sam.html 2009.
Mayewski, P., White, F., 2002. The Ice Chronicles. University Press of New England, Hanover.
Meier, M.F., Post, A.S., 1962. Recent variations in mass net budgets of glaciers in Western North America. IASH Publication 58, 63–77.
Meneghini, B., Simmonds, I., Smith, I., 2007. Association between Australian rainfall and the Southern Annular Mode. International Journal of Climatology 27, 109–121.
Moore, G., Holdsworth, G., Alverson, K., 2002. Climate change in the North Pacific region over the past three centuries. Nature 402, 401–403.
Morgenstern, U., Mayewski, P., Bertler, N., Ditchburn, B., 2004. Ice core research in the New Zealand Southern Alps. Geophysical Research Abstracts 6.
Mullan, B., 1995. On the linearity and stability of Southern Oscillation–climate relationships for New Zealand. International Journal of Climatology 15, 1365–1386.
Nakazawa, F., et al., 2005. Dating of seasonal snow/firm accumulation layers using pollen analysis. Journal of Glaciology 51 (174), 483–490.
Nesje, A., Lie, O., Dahl, S.O., 2000. Is the North Atlantic Oscillation reflected in Scandinavian glacier mass balance records? Journal of Quaternary Science 15 (6), 587–601.
Nesje, A., Bakke, J., Dahl, S., Lie, Ø., Matthews, J., 2008. Norwegian mountain glaciers in the past, present and future. Global and Planetary Change 60, 10–27.
NIWA, 2009. NIWA Climate Database. http://cliflo.niwa.co.nz/2009.
Nyenzi, B., Lefale, P., 2006. El Nino Southern Oscillation (ENSO) and global warming. Advances in Geoscience 6, 95–101.
Oerlemans, J., 1992. Climate sensitivity of glaciers in southern Norway: application of an energy-balance model to Nigardsbreen, Hellstugubreen and Alfotbreen. Journal of Glaciology 38 (129), 223–232.
Oerlemans, J., 1997. Climate sensitivity of Franz Josef Glacier, New Zealand, as revealed by numerical modelling. Arctic and Alpine Research 29 (2), 233–239.
Oerlemans, J., Klok, E., 2004. Effect of summer snowfall on glacier mass balance. Annals of Glaciology 38, 97–100.
Osterberg, E., Handley, M., Sneed, S., Mayewski, P., Kreutz, K., 2006. Continuous ice core melter system with discrete sampling for major ion, trace element, and stable isotope analyses. Environmental Science and Technology 40, 3355–3361.
Pelto, M., 1988. The annual mass balance of North Cascade Glaciers, Washington, USA, measured and predicted using an activity index method. Journal of Glaciology 34 (117), 194–199.
Pohjola, V., Rogers, J., 1997. Atmospheric circulation and variations in Scandinavian glacier masss balance. Quaternary Research 47, 29–36.
Post, A., LaChapelle, E., 2000. Glacier Ice. University of Washington Press, Singapore.
Power, S., Smith, I., 2007. Weakening of the Walker circulation and apparent dominance of El Niño both reach record levels, but has ENSO really changed? Geophysical Research Letters 34 (L18702). doi:10.1029/2007GL030854.
Purdie, H., Brook, M., Fuller, I., Appleby, J., 2008. Seasonal variability in velocity and ablation of Te Moeka o Tuawe/Fox Glacier, South Westland, New Zealand. New Zealand Geographer 64 (1), 5–19.
Purdie, H., Mackintosh, A., Bertler, N., Baker, J., Rhodes, R., 2010. Isotopic and elemental changes in winter snow accumulation on glaciers in the Southern Alps, New Zealand. Journal of Climate 23 (18), 4737–4749.
Purdie, H., Anderson, B., Lawson, W., Mackintosh, A., 2011a. Spatial variability in snow accumulation on glaciers in the Southern Alps, New Zealand: as revealed by crevasse stratigraphy. Hydrological Processes 25, 54–63.
Purdie, H., Mackintosh, A., Lawson, W., Anderson, B., 2011b. Synoptic influences on snow accumulation on glaciers east and west of a topographic divide: Southern Alps, New Zealand. Arctic, Antarctic and Alpine Research 43, 82–94.
Raben, P., Theakstone, W., 1994. Isotopic and ionic changes in a snow cover at different altitudes: observations at Austre Okindbreen in 1991. Annals of Glaciology 19, 85–91.
Renwick, J., Thompson, D., 2006. The Southern Annular Mode and New Zealand climate. Water and Atmosphere 14 (2), 24–25.
Röhl, K., 2006. Thermo-erosional notch development at fresh-water-calving Tasman Glacier, New Zealand. Journal of Glaciology 52 (177), 203–213.
Ruddell, A.R., 1995. Recent glacier and climate change in the New Zealand Alps, unpublished PhD thesis, University of Melbourne, Melbourne.
Salinger, M.J., Heine, M., Burrows, C.J., 1983. Variations of the Stocking (Te Wae Wae) Glacier, Mount Cook, and climatic relationships. New Zealand Journal of Science 26, 321–338.
Salinger, M.J., Renwick, J., Mullan, A., 2001. Interdecadal Pacific Oscillation and South Pacific climate. International Journal of Climatology 21, 1705–1721.
Schwikowski, M., et al., 2005. Identification of precipitation source regions at Fiescherhorn Glacier using the deuterium excess Annual Report, Paul-Scherrer Insitiute. http://lch.web.psi.ch/files/anrep05/27.pdf2005.
Schwikowski, M., Brutsch, S., Casassa, G., Rivera, A., 2006. A potential high-elevation ice-core site at Hielo Patagonico Spur. Annals of Glaciology 43, 8–13.
Shiraiwa, T., et al., 2002. High net accumulation rates at Campo de Hielo Patagonico Sur, South America, revealed by analysis of a 45.97 m long ice core. Annals of Glaciology 35, 84–90.
Solomon, S., et al. (Ed.), 2007. Climate change 2007: the physical science basis. Contribution of working group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
Spearman, C., 1904. The proof and measurement of association between two things. American Journal of Psychology 15, 72–101.
Sturman, A., Tapper, N., 2006. The Weather and Climate of Australia and New Zealand. Oxford University Press, Melbourne, Melbourne.
Tedesco, M., Monaghan, A., 2009. An updated Antarctic melt record through 2009 and its linkages to high-latitude and tropical climate variability. Geophysical Research Letters 36, L18502.
Thomas, J., 2009. Volume change of the Tasman Glacier using remote sensing, unpublished MSc thesis, University of Canterbury, Christchurch.
Thomson, J., 2005. A radio echo sounding survey of the Tasman Glacier névé area, Mount Cook National Park, New Zealand, Institute of Geological & Nuclear Sciences, report 2005/08. Lower Hutt.
Trenberth, K., 1976. Fluctuations and trends in indices of the Southern Hemisphere circulation. Quarterly Journal of the Royal Meteorological Society 102, 65–75.
Ummenhofer, C., England, M., 2007. Interannual extremes in New Zealand precipitation linked to modes of Southern Hemisphere climate variability. Journal of Climate 20, 5418–5440.

Ummenhofer, C., Gupta, A., England, M., 2009. Causes of late twentieth-century trends in New Zealand precipitation. Journal of Climate 22, 3–19.

van den Broeke, M., van Lipzig, N., 2004. Changes in Antarctic temperature, wind and precipitation in response to the Antarctic Oscillation. Annals of Glaciology 39, 119–126.

Walters, R.A., Meier, M.F., 1989. Variability of glacier mass balances in Western North America. In: Peterson, D.H. (Ed.), Aspects of Climate Variability in the Pacific and Western Americas: American Geophysical Union Geophysical Monograph, 55, pp. 365–374.

WGMS, 2008. Fluctuations of Glaciers, 2000–2005, Volume IX. In: W. Haeberli, M. Zemp, A. Kaab, F. Paul and M.e. Hoelzle (Editors). ICSU (FAGS)/IUGA (IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland.

Willsman, A., Chinn, T., Hendrikx, J., Lorrey, A., 2009. Glacier Snowline Survey. National Institute of Water & Atmospheric Research Ltd, Christchurch.

Winkler, S., Elehøy, H., Nesje, A., 2009. Glacier fluctuation of Jostedalsbreen, western Norway, during the past 20 years: the sensitive response of maritime mountain glaciers. The Holocene 19 (3), 395–414.

Woo, M., Fitzharris, B.B., 1992. Reconstruction of mass balance for Franz Josef Glacier, New Zealand, 1913 to 1989. Arctic and Alpine Research 24 (4), 281–290.

Yoshimura, Y., Kohshima, S., Takeuchi, N., Seko, K., Fujita, K., 2000. Himalayan ice-core dating with snow algae. Journal of Glaciology 46 (153), 335–340.

Zemp, M., Haeberli, W., Hoelzle, M., Paul, F., 2006. Alpine glaciers to disappear within decades? Geophysical Research Letters 33. doi:10.1029/2006GL026319.