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Synoptic climate change as a driver of late Quaternary glaciations in the mid-latitudes of the Southern Hemisphere

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Abstract

The relative timing of late Quaternary glacial advances in mid-latitude (40–55° S) mountain belts of the Southern Hemisphere (SH) has become a critical focus in the debate on global climate teleconnections. On the basis of glacial data from New Zealand and southern South America it has been argued that interhemispheric synchrony or asynchrony of Quaternary glacial events is due to Northern Hemisphere (NH) forcing of SH climate through either the ocean or atmosphere systems. Here we present a glacial snow-mass balance model that demonstrates that large scale glacial advances in the temperate and hyperhumid Southern Alps of New Zealand can be generated with very little thermal forcing. This is because the rapid conversion of precipitation from rainfall to snowfall drives massive ice accumulation at small thermal changes (1–4°C). Our model is consistent with recent paleo-environmental reconstructions showing that glacial advances in New Zealand during the Last Glacial Maximum (LGM) and the Last Glacial Interglacial Transition (LGIT) occurred under very moderate cooling. We suggest that such moderate cooling could be generated by changes in synoptic climatology, specifically through enhanced regional flow of moist westerly air masses. Our results imply that NH climate forcing may not have been the exclusive driver of Quaternary glaciations in New Zealand and that synoptic style climate variations are a better explanation for at least some Late Quaternary glacial events, in particular during the LGIT (e.g. Younger Dryas and/or Antarctic Cold Reversal).

1. Introduction

Quaternary glacial signals from mountain belts in the mid-latitude Southern Hemisphere (mlSH), in particular from locations in New Zealand and southern South America, have become important for testing models of past and present interhemispheric climate teleconnections (e.g. Broecker, 1997; Moreno, 2001). It has been argued that synchrony of past glacial advances would be indicative of direct interhemispheric climate forcing via the atmosphere (e.g. Denton et al., 1999; Kaplan et al., 2004) whereas, asynchrony has been interpreted as a climate link through the thermohaline conveyor (e.g. Lowell et al., 1995). The focus in this debate has been on the absolute dating of Quaternary mlSH glacial advances, which are used as proxies to identify the level of global correspondence between distinct Northern Hemisphere (NH) and Southern Hemisphere (SH) climate signals.

In recent years, progress in cosmogenic and luminescence dating techniques has permitted the direct dating of glacial landforms (i.e. moraines) and deposits in mlSH mountain belts. Initial results from New Zealand and the southern Andes have been interpreted as demonstrating interhemispheric synchrony of LGM glacial advances and it has also been suggested that specific LGIT climate events known from the North Atlantic region (e.g. the Younger Dryas) can be directly correlated to mountain glacier advances in the mlSH (Denton and Hendy, 1994; Ivy-Ochs et al., 1999). It has further been argued that such level of correspondence is compelling for a model of direct atmospheric forcing of glaciations in the SH (Denton et al., 1999; Kaplan et al., 2004).

Despite some indications of interhemispheric synchrony for a limited number of LGM and LGIT glacial advances, the paleo-climatological interpretation of the data is not straightforward. In the case of New Zealand, numerical paleo-environmental reconstructions using speleothems and fossil beetle assemblages show that LGM cooling was very moderate (Hellstrom et al., 1998) and possibly as little as 2 to 3°C (Marra et al., 2005). Reconstructed Paleo-ELAs suggest cooling in the vicinity of of 4–5°C (Porter, 1975). These results are supported by General Circulation Model (GCM) calculations that predict 2 to 3°C lower sea-surface temperature (SST) in the Tasman Sea during the LGM (Hewitt and Mitchell, 1997) while sea-surface temperature reconstructions from forams suggest cooling between 3–7°C (Barrows and Juggins, 2005). In short, none of the reconstructions suggest large scale cooling during the LGM while the lower end of the reconstructions suggest cooling similar to the modern interannual variability associated with ENSO and other oscillatory systems.

For the LGIT, at least one glacial re-advance has been demonstrated for the Southern Alps (Denton and Hendy, 1994; Ivy-Ochs et al., 1999). However, this re-advance is neither universally detected in NZ's glacial records (e.g. Shulmeister et al., 2005) nor, critically, is a significant cooling apparent from pollen or other paleoecological records (e.g. Singer et al., 1998; Turney et al., 2003). At the very most, the pollen records suggest a pause in the post-glacial warming between 14.6–13.6 cal. ^{14}C years (McGlone, 1995). As both the LGM and LGIT glacio-chronological and paleoecological data appear robust, it has been difficult to resolve the occurrence of significant glacial expansions contemporaneous with only moderate cooling. The problem has wider implications because similar confusion has characterized the LGIT debate in southern South America with various authors proposing cooling or an absence thereof during the LGIT (e.g. Bennett et al., 2000; Moreno et al., 2001).

In this paper we present a snow mass balance model from the Southern Alps of New Zealand to test the sensitivity of glacial accumulation to thermal changes. By doing so we analyse whether the emerging glacio-chronological and paleoecological records from New Zealand are in fact compatible and if minor thermal forcing is sufficient to cause full-scale glacial expansion in the Southern Alps. The question has wider relevance because under such a scenario we must consider the possibility that some Quaternary glacial advances in NZ, and by implication in parts of South America, were generated by synoptic climate variations alone, requiring little (during the LGM) or no (during the LGIT) climate forcing from the NH.

2. Glaciological setting: New Zealand

New Zealand is located in the Southern Hemisphere westerly wind belt and is characterized by an oceanic climate. The regional climate is profoundly affected by the NE–SW trending Southern Alps (41°–46° S) which constitute a ~3 km high topographic barrier in the pathway of the Southern Ocean Westerlies. Due to the interception and rapid orographic forcing of west flowing moist air masses, the central Southern Alps are amongst the wettest places on the planet. Annual precipitation near the alpine divide is commonly in excess of 9000 mm with observed maximum values at around 16 000 mm (Griffiths and McSaveney, 1983; Henderson and Thompson, 1999). Critical for the glaciological setting is the marked cross-alpine precipitation distribution and the presence of a narrow hyperhumid sector which stretches along the full length of the Southern Alps. Virtually all of New Zealand's ca. 3100 present glaciers are located in this sector (National Snow and Ice Data Center, 1999). Glaciers of these perhumid environments are characterized as high turn-over systems with large positive and negative mass balances, high glacial flow velocities and relatively short climatic reaction times (Woo and Fitzharris, 1992; Benn and Evans, 1998).

Glacial Equilibrium Line Altitudes (ELA)[1] in the Southern Alps closely reflect the steep windward-leeward precipitation contrast which causes ELA gradients in New Zealand to be up to 20 times steeper than those reported for arctic and subarctic regions (Andrews and Miller, 1972; Chinn and Whitehouse, 1980). Despite this distinct glaciological setting, Quaternary glacial records from the Southern Alps are often directly correlated to records from other mid-latitude mountain belts, in particular to those from the European Alps (e.g. Ivy-Ochs et al., 1999). A comparison of key glacial parameters of the two ranges (Fig. 1) shows that despite substantially greater mean elevations, the European Alps receive only a quarter to a third of the NZ precipitation values while its distribution is far more even. A direct consequence of the hyper-humidity in the Southern Alps is a strong depression of ELAs (Chinn and Whitehouse, 1980), which are generally about 1000 m lower than those in the European Alps (Mueller, 1976). The differences have important implications for mechanisms of glacial accumulation and the resulting glacial styles in the two mountain belts.

Because New Zealand's glaciological configuration is fundamentally related to the interaction between the Southern Alps and the Westerly wind belt, studies of regional paleo-circulation patterns are critical to the reconstruction of former glacial base condi-

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[1] The ELA separates glacial accumulation from ablation areas and represents the altitude at which the glacial mass balance is zero. Key factors influencing the position of the ELA are long term mean temperatures and total precipitation.

tions. Evidence for enhanced ocean upwelling (Fenner et al., 1992; Weaver et al., 1998) and maxima in dust flux (Thiede, 1979; Stewart and Neall, 1984; Carter et al., 1995) have generally been attributed to enhanced westerly flow during the LGM (e.g. Markgraf et al., 1992; Shulmeister et al., 2004). In addition, glacio-eustatic sea level lowering, increased the relative height of the Southern Alps which in turn intensified the orographic forcing of moist westerly air masses. It is therefore reasonable to assume that the pattern of a strong windward-leeward gradient of precipitation across the Southern Alps remained intact during Quaternary glacial periods. Such a scenario is supported by reconstructed paleo-ELAs from cirque floor elevations comparing the western/central alps to those of the eastern alps (Fig. 2). Results show that despite an estimated ~800 m ELA lowering (Porter, 1975), steep paleo-ELA gradients persisted in New Zealand during past glaciations.

To summarise, the combination of hyper-humidity and a steep paleo-ELA gradient during Late Quaternary glaciations in the Southern Alps is responsible for a specific nature of glaciation in New Zealand. Firstly, very high levels of snowfall occurred in a ~20 km wide sector near the alpine divide which corresponded with the area of minimum ELA. Secondly, due to rainshadow effects and because the ELA rises sharply east of the divide, alpine areas only a short distance from the divide received significantly less snowfall and only the highest peaks penetrated the annual snowline. This resulted in a glacial pattern where large scale ice accumulation was concentrated in the narrow perhumid sector, while the contribution of all other areas to overall glacial accumulation in the Southern Alps was orders of magnitude smaller.

3. Temperature effects on snow mass balances in the Southern Alps

In the central Southern Alps present ELAs range between 1500 m–2100 m (Lamont et al., 1999). Critically, at these ELAs atmospheric temperatures remain above freezing for considerable periods of the year. This means that a significant portion of the large annual precipitation at and around ELA level falls as rain. This constitutes a substantial snow resource if climate cooling occurs as additional snow is generated without any synoptic changes. By comparison, in the European Alps present ELAs are on average 1000 m higher (2500 m–3500 m) and corresponding atmospheric temperatures remain too cold for rain to form a significant portion in the annual precipitation at ELA (Fig. 3b).

To investigate temperature effects on glacial accumulation in the perhumid Southern Alps we use a snow mass balance model[2]. The model calculates annual net snow accumulation for various cooling scenarios (–1 to –9°C in mean T) by analysing temperature related changes to the snow-rain-ratio, total annual precipitation and snow ablation rates.

Data are calculated for the central perhumid alpine sector (Fig. 3a) with an ELA of 1600 m (Chinn and Whitehouse, 1980; Clare et al., 2002) and a total annual precipitation of 9000 mm (Griffiths and McSaveney, 1983; Henderson and Thompson, 1999). The overall topography, ELA position and the amount of annual precipitation in this area represent average condition for substantial portions in the central alps. Temperature data used in the model are from the nearest climate station (Hokitika, Fig. 3a) and were converted to the ELA altitude by using a standard environmental lapse rate of 6°C/km. We calculated cooling related changes to net snow accumulation at ELA (1600 m) where the current snow mass balance is zero. Mean temperatures were then incrementally lowered to simulate potential atmospheric cooling.

Observations on snow proportions (Q_S) in total precipitation (P_{total}) are not available for the Southern Alps but it has been shown that snow proportions correlate well to mean monthly temperatures (Lauscher, 1954; Cehak-Trock, 1958). We calculated Q_S in P_{total} using a regression function derived empirically from 32 stations in the Swiss Alps (Sevruk, 1992) (Fig. 3b). Q_S results for the Southern Alps were then adjusted for the seasonal variation in precipitation by applying weighted averages from the observed monthly precipitation at the nearby Ivory Glacier (Anderton and Chinn, 1978; Fig. 3a). At ELA (1600 m) mean annual temperature is 2.3°C with a monthly range from

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[2] Full details on the model are provided in the supplement: http://www.climate-of-the-past.net/cpd/1/231/cpd-1-231-sp.zip

−2.1°C (July) to 6.4°C (February). Results show that at this elevation 49.2% (mm water equivalent) of the annual total of 9000 mm fall currently as snow while the remaining 50.8% (4570 mm) fall as rain. This provides an enormous potential additional snow source. For every 1°C of cooling in mean monthly temperature the percentage of snow as a proportion of precipitation grows by 5.5% (Fig. 3b).

Atmospheric cooling is likely to affect the amount of total annual precipitation received by the Southern Alps. Recent studies have suggested relatively wet conditions in New Zealand associated with enhanced Westerlies during the LGM (e.g. Eden and Hammond, 2003; Shulmeister et al., 2004) and LGIT (e.g. Pepper et al., 2004), while others argue that humidity was somewhat reduced during glacial periods (e.g. Hope et al., 2004). To account for uncertainties regarding the response of annual precipitation to atmospheric cooling, we use three precipitation scenarios (Fig. 4a). Scenario 1 assumes a cooling related decrease in annual precipitation and approximates the non-linear reduction through the temperature related variation in air mass saturation vapour pressure (SVP). In this scenario, variations in overall precipitation are calculated from SVP changes which are used as a proxy for the moisture capacity of the air. According to this a cooling of −5°C would reduce overall humidity by ~30%. In scenario 2, the reduction in annual precipitation is assumed to be half of that of scenario 1 and scenario 3 assumes wet conditions with precipitation totals equal to the present.

Results in Fig. 4b show total annual snowfall for increasingly colder conditions as calculated when our precipitation scenarios are combined with the dynamic snow-rain ratio. As expected snowfall totals vary greatly depending on the assumed annual precipitation. The data generally reflect two compensating trends during cooling, firstly the continuing increase of Q_S in P_{total}, and secondly a cooling related decline in P_{total} (scenarios 1 and 2). Results indicate that the addition of large amounts of extra snow from the rain-snow conversion causes a dramatic effect on snow mass balances in perhumid environments. Snowfall increases (scen. 2) or remains high (scen. 1) even if annual precipitation declines substantially. If conditions are wetter (scen. 3) snowfall will expand vastly as large amounts of snow are added.

The projected annual snowfall total was then related to ablation for assessing net snow accumulation. We calculated snow ablation by using a degree day mass balance (DDMB) model in which mean daily temperatures are taken as an integrated index of the heat budget and where ablation is assumed to occur proportionally to the mean air temperature (e.g. Linsley, 1947). DDMB models have been widely tested under field conditions where they have shown to predict ablation reliably (e.g. Komarov et al., 1969; Braithwaite and Olesen, 1989; Jóhannesson et al., 1995; Braithwaite and Zhang, 2000). Calculation use the formula:

$$a(z) = \mathrm{k}\mathrm{T}_{\mathrm{sum}}(z) + \mathrm{H}_S; \qquad T > 0^\circ\mathrm{C}$$

where ablation (a) is computed for elevation (z), using the sum of positive mean daily temperatures ($\mathrm{T}_{\mathrm{sum}}$) at z. The positive degree days are multiplied with k representing an empirically derived degree day factor. We use a degree day factor of 4.5 mm day-1 deg-1 as was derived for Franz Josef Glacier in the central Southern Alps (Anderson, 2003). H_S is ablation from sensible heat (e.g. rain on snow) which contributes ~2% to annual ablation in the Southern Alps (Hay and Fitzharris, 1988). We tested the model by predicting ablation at the present ELA where annual snowfall is 4432 mm and no net accumulation occurs (mass balance 0). The model indicates 4359 mm of ablation, underestimating actual ablation by only 1.7%. Overall results in Fig. 5a show how snow ablation decreases at ELA under intensifying cooling from 4432 mm/a (present temperature conditions) until it virtually stops at 6.5°C cooling.

We then integrated all previously analyzed parameters (snow-rain proportions, total precipitation, snow ablation) to predict net snow accumulation in the central alps under increasingly cooler conditions. Results are shown in Fig. 5b where 0°C represents current climate conditions at the ELA with no net accumulation. The outcome indicates that net snow accumulation in the hyperhumid Southern Alps responds strongly positive to moderate cooling. Snow accumulation grows dramatically under all precipitation scenarios even when overall humidity declines substantially. A striking feature is the steep increase recorded for the early part of the cooling (1–4°C), where snow accumulation grows markedly mainly due to the rapid conversion from rain to snow. A cooling of only 2–3°C at present ELA would result in the net annual addition of ~15 vertical meters of snow (Fig. 5b). Interestingly, the gain generally slows with more severe cooling. For precipitation scenario 1 (driven by SVP changes) the snow accumulation trend will even reverse at around –6°C cooling with net annual accumulation starting to decline. The effect is caused by high snow proportions at this cooling and the effective halt of ablation after which the continuing decrease of total annual precipitation drives net accumulation down.

4. Discussion and conclusion

Heavy orographic precipitation in the central parts of the long (~800 km) but narrow (~80 km) Southern Alps results in some of the steepest recorded glacial ELA gradients on Earth. During Quaternary glaciations and associated low sea level stands, the relative height of the Southern Alps as a barrier for moist westerly air masses was further enhanced and ELA gradients were maintained or even steepened. Reconstructed paleo-ELAs (Porter, 1975; Chinn and Whitehouse, 1980) imply that ice accumulation during the LGM was concentrated in the perhumid central alps. These conditions produced a narrow ice cap, which covered a ~30 km wide sector near the alpine divide. From this high turn-over ice cap valley glaciers extended 50–70 km to their LGM terminal positions.

Our snow mass balance model indicates that glacial accumulation in the Southern Alps is sensitive to small thermal changes. Moderate cooling (3–5°C) is sufficient to increase snowfall dramatically and trigger large positive excursions in glacial mass balances. If this cooling is sustained under a 5000–8000 mm precipitation regime it would generate glacial advances of the scale recorded for the LGM. The sensitivity of glacial systems in New Zealand to moderate cooling is mainly due to extreme perhumidity and associated low ELA levels which cause present glacial accumulation areas in the Southern Alps to receive substantial amounts of rain. We suggest that the rain-snow conversion would impact rapidly as present precipitation maxima occur during the cooler Autumn and Spring seasons thereby requiring only moderate further cooling to initiate full rain-snow conversion.

The model assumptions account for a cooling related decrease in total annual precipitation, which is consistent with LGM humidity estimates suggested from New Zealand pollen (McGlone, 1995). Likewise, regional paleo-temperature reconstructions using speleothems and fossil beetle assemblages indicate that cooling during LGM and LGIT glacial advances was only moderate (Hellstrom et al., 1998) and possibly as little as −2 to −3°C (Marra et al., 2005). The benefit of our mass balance model is that it provides a mechanism that resolves the occurrence of substantial glacial advances in New Zealand contemporaneous with reconstructed drier conditions and under only moderate atmospheric cooling.

In New Zealand, hypsometric characteristics of areas immediately below snowline (∼1400–1700) in the perhumid zone, suggest that a moderate drop in ELA levels would bring extensive low angle surface areas above snowline. This factor is important because new permanent snow accumulations can only occur if slope angles are suitable. The effect is demonstrated for our study area where we calculated hypsometric integrals for a 10 km wide and 60 km long sector (S 43°17′1″/E 170°53′4″ to S 42°50′1″/E 171°29′0″) (Fig. 6). Results indicate that an ELA lowering of only 300 m would more than double the low angle surface area above snowline. In reality, the increase in suitable snow accumulation surfaces would be further enhanced by the extension of glacial tongues into the upper valleys where they raise the effective elevation of the valley floor.

Moderate cooling as a driver of Quaternary glacial advances in New Zealand has several important implications. Firstly, it accounts for sedimentological peculiarities associated with glacial sequences in the Southern Alps. Commonly noted features are the enormous scale of glacio-fluvial aggradation fans, the large proportions of water lain deposits in ice-proximal sequences and the widespread occurrence of stratified and only weakly compacted tills (e.g. Speight, 1940; Gage, 1965, 1985; Hart, 1996). The overall climatic implication is that conditions during deposition were clearly mild enough to provide nearly year-round availability of large volumes of melt-water.

Secondly, the low thermal forcing mechanism for glaciation in New Zealand implies that large glacial advances can be generated rapidly, and conversely, shut down rapidly since glacial conditions are sensitive to small thermal changes. This “flickering switch” feature of Quaternary glacial advance in the Southern Alps is likely to have resulted in a larger number of individual glacial oscillation than for example is observed in the more continental European Alps. This pattern may complicate attempts to directly correlate glacial signals from the NH to New Zealand.

Thirdly, moderate cooling as a glacial driver in New Zealand highlights the distinct possibility that regional (synoptic) climate phenomena were the principle cause for some Late Quaternary glacial events. It has been shown that modern glaciers in western New Zealand respond to synoptic circulation changes, where enhanced zonal flow (westerly/south-westerly) is associated with glacial advances and stronger meridional flow is associated with retreats (Lamont et al., 1999; Hooker and Fitzharris, 1999). The reason is that strengthened westerly flow increases orographic precipitation over the mountains and reduces ablation through enhanced cloud cover, while conversely, more persistent meridional circulation is associated with reduced precipitation and clear skies that cause increased ablation. Strong westerly flow, associated with glacial advances, mirrors the impact of El Niño on New Zealand. Recent spectral analyses on varved lake sediments have highlighted the possibility of a periodically enhanced inter-annual El Niño Southern Oscillation (ENSO) signal during the LGIT over New Zealand (Pepper et al., 2004). Speleothem data from the South Island (Hellstrom et al., 1998) now supported by uranium isotope data (Robinson et al., 2004) also indicate a period of enhanced precipitation at around 13 ka. Enhanced precipitation, perhaps in association with very minor cooling, would trigger glacial re-advances in the central parts of the Southern Alps such as at Franz-Josef Glacier (Denton and Hendy, 1994; Ivy-Ochs et al., 1999). These changes, however, would not impact on already deglaciated mountain systems such as the Tasman Mountains in NW Nelson (Shulmeister et al., 2005), nor on the pollen record (McGlone, 1995; Singer et al., 1998; Turney et al., 2003). A synoptic “wet” event as a driver of the LGIT re-advance in New

Zealand is therefore consistent with the available glacial record.

Synoptic climatology as a driver of glacial advances in hyperhumid mountain environments of the Southern Alps may provide an explanation for inconsistencies in glacial records of the SHml (Southern Alps, southern Andes), where climate signals and glacial advances have been recorded as both synchronous and asynchronous to Northern Hemisphere events. The situation in South America is somewhat different in that part of the discrepancy is created by the larger geographical area covered, but at least some of the records may be reconcilable using our model. However, even if our model does not apply in all cases, the likelihood that major advances in the SHml can be explained without invoking inter-hemispheric forcing, or indeed major thermal changes, challenges current understanding of global climate linkages.

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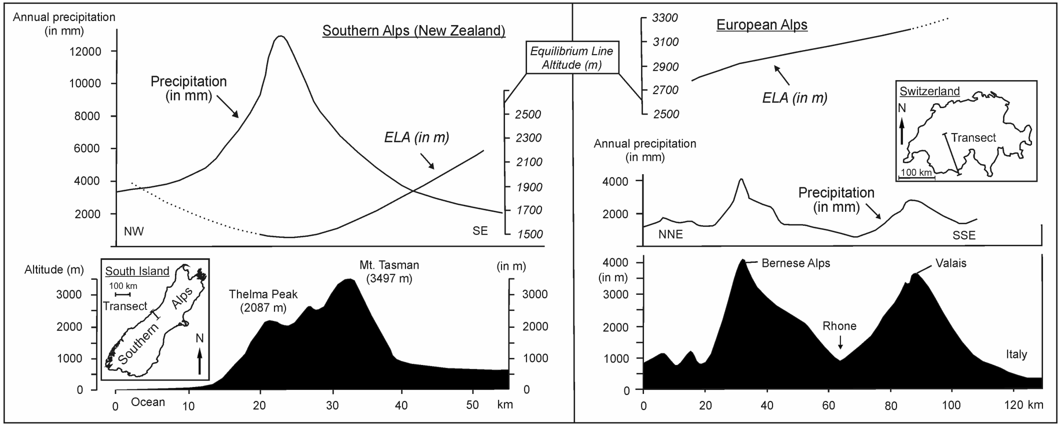

Fig. 1. Comparison of precipitation and ELA levels across the Southern Alps (Griffiths and McSaveney, 1983; Chinn and Whitehouse, 1980) and European Alps (Sturman and Wanner, 2001; Mueller, 1976) plotted at equal scales (except horizontal distances). In New Zealand heavy orographic precipitation is concentrated in a 15–20 km wide sector along the alpine divide with annual totals 3–4 times greater than in the European Alps. The marked distribution of precipitation causes a strong ELA depression and very steep ELA gradients. In the European Alps, the NNW-SSE rise in ELA is mainly due to the meridional temperature increase.

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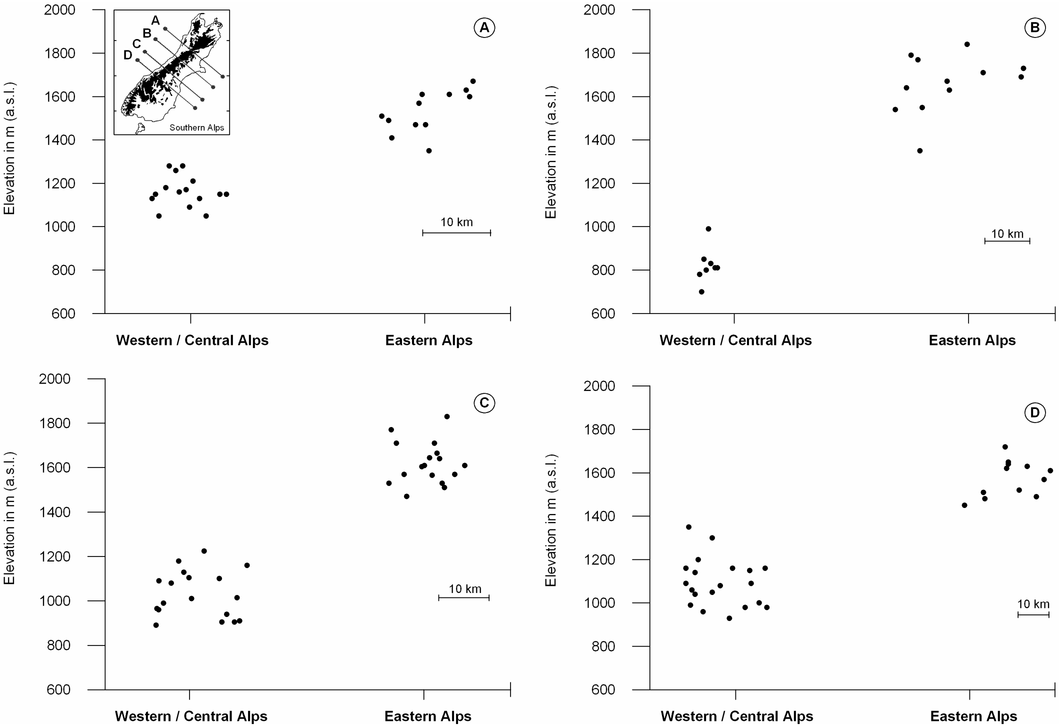

Fig. 2. Minimum cirque floor elevations of the western/central and eastern Southern Alps. Clearly defined cirque basins were mapped along four 30 km wide transects as shown in inset of Fig. 4A. The data indicate that steep West–East precipitation and snowline gradients persisted during Quaternary glaciations.

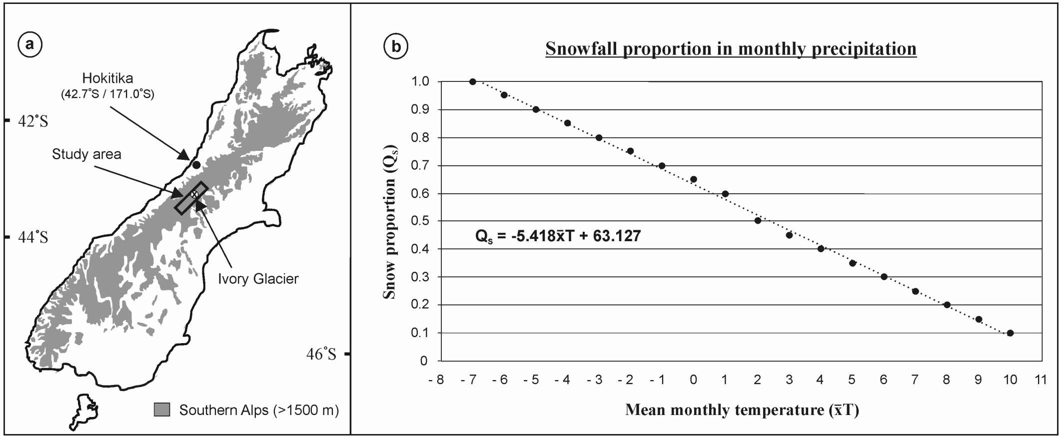

Fig. 3. Locations of study area, Hokitika climate station and Ivory Glacier in the Southern Alps **(a)**. Panel **(b)** shows the physical relationship between mean monthly temperature and the snow-rain ratio as derived from the Swiss Alps (Sevruk, 1992). The presented data apply to altitudes 1400–1600 m.

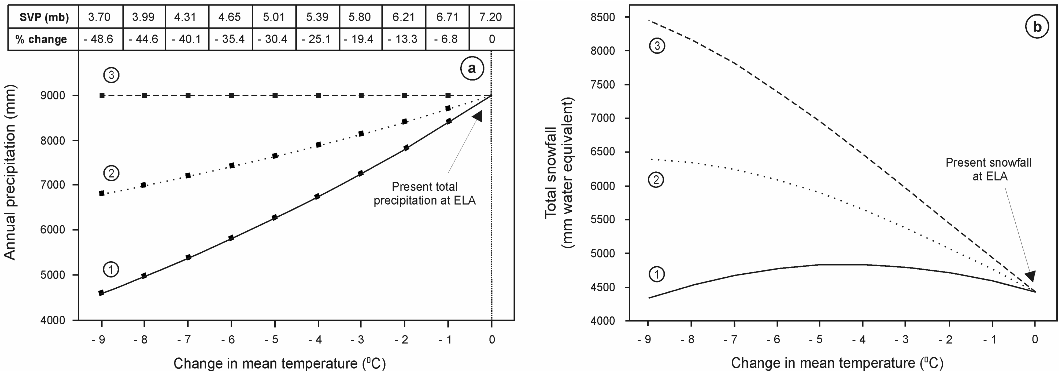

Fig. 4. The three annual precipitation scenarios **(a)**. Scenario 1 approximates cooling related changes through variations in air saturation vapour pressure (SVP) (see table in 4a). Scenario 2 assumes half the change of scenario 1, and scenario 3 assumes no change in precipitation. Panel **(b)** shows annual snowfall under cooling as a result of changes to the snow-rain ratio and variations in total annual precipitation. Snowfall is adjusted to the seasonal variation in precipitation.

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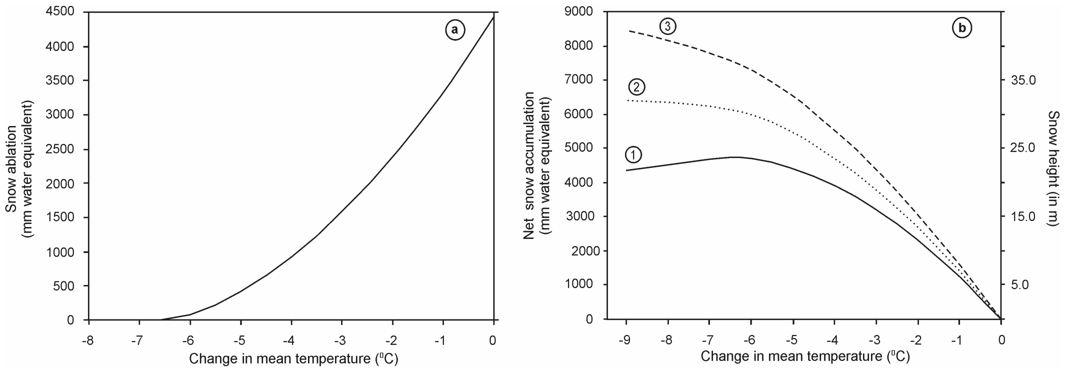

Fig. 5. Impact of cooling on snow ablation at present ELA as calculated by a degree day mass balance model **(a)**. Panel **(b)** shows projected annual net snow accumulation as a result of variations in annual precipitation, snow-rain proportions and ablation under −1 to −9°C cooling. Note the steep increase in snow accumulation at moderate cooling.

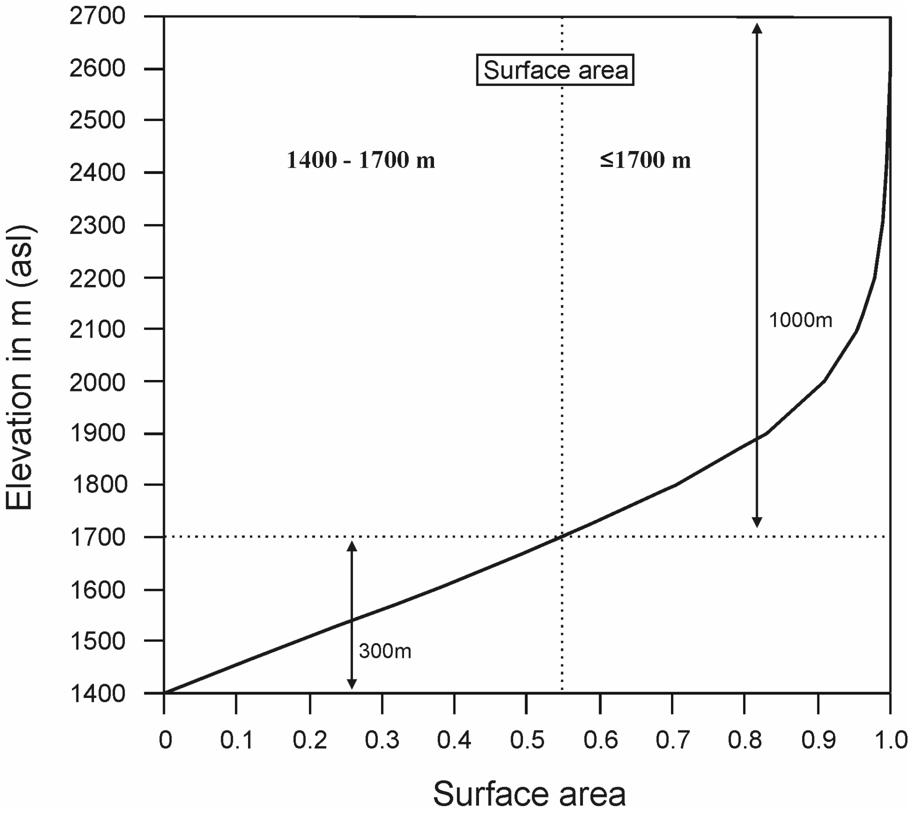

Fig. 6. DEM analysed hypsometry above 1400 m in the central Southern Alps showing the potential increase in low angle (less than 15°) surface areas above snowline from a 300 m ELA lowering (1700 m to 1400 m) The analysed alpine area is the study area as shown in Fig. 3a. The lowering would increase low angle surface area by 121.5%.