Modelling climate-change impacts on mountain glaciers and water resources in the Central Dry Andes

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Abstract

This paper presents energy balance model results for snow cover and glaciers of the Central Dry Andes of Chile and Argentina, both under present conditions and under future climatic scenarios. Despite the short period of available data, it is argued that modelling tools together with the analysis of the altitudinal distribution of glacier bodies and catchment hypsometry can give an insight into the future availability of melt water resources in the region. Results suggest that the water availability will increase in the medium term in the Dry Andes, followed by a rapid depletion, which will be more pronounced on the Chilean side and more gradual on the Argentinian side.

Introduction

The Central Dry Andes form a high mountain barrier dividing Chile and Argentina between around 31°S and 35°S. They run north–south reaching the highest elevation in the southern Hemisphere: Aconcagua is 6954 m a. s. l., while many other peaks rise over 6000 m. Their slopes descend abruptly towards the Pacific coast to the west sandwiching a narrow stretch of land within which some of the richest agriculture and largest populations in Chile are sustained. East of the Cordillera, the slopes descend more gradually towards the Argentinian Pampas (Figure 1). On both sides of the range the precipitation regime has a marked seasonality, with most precipitation at high altitudes occurring during the austral winter, while summers are dry and sunny. Although the Chilean piedmont has annual precipitation in excess of 500 mm, the Argentinian city of Mendoza only receives some 180 mm (Miller 1976). In both cases almost all crops are irrigated and represent an important element of the economy. The Mediterranean subtropical production is sold at high prices in the northern hemisphere due to inverted seasonality (Brignal *et al.* 1999). According to the wine producers' association in Chile, wine exports reached 744.2 million US dollars in 2003 (Viñas de Chile 2004). In Mendoza wine production is second in economic importance only to oil production, according to the Mendoza Tourist Board. Santiago hosts the largest population in Chile, in excess of five million people, while on the eastern side of the Andes, Mendoza and surrounding towns are home to more than one million inhabitants. Supporting this population and irrigated agriculture would be impossible without water derived from the snow and ice melt (Ribbe und Gaese 2004).

The importance of melt waters is demonstrated in Table 1. Precipitation is very low in the summer months, just 1 mm in December, while runoff is at its maximum, over 42 $m^3 s^{-1}$, on the Río Aconcagua at Río Blanco during the same month (Legates and Willmott 1990; LBA-Hydronet). This inverse pattern, with maximum discharge corresponding to minimum precipitation, is highly beneficial for human activities in the region, as the time of maximum heat stress, and thus water demand, coincides with the time of maximum availability. The mechanism for this asynchrony is the storage of water as snow and ice during the winter months in the Cordillera and its release through melt during the summer months. Whether the system is sustainable or not in the long to medium term depends on the balance between snow accumulation and ablation and the rate of melting of old water reserves in the form of glacier ice.

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The Central Dry Andes present a special peculiarity in comparison to glaciers and snow covered surfaces at other latitudes: the presence of penitentes. These are pinnacles of ice, up to several metres in height and sculpted by differential ablation by strong solar radiation under dry and cold weather conditions (Figure 2). Their name comes from their perceived similarity to the penitents who march in Easter processions in Spain and Latin America and wear distinctive white conical headdresses., These ice pinnacles were first described by Darwin (1839) during his voyage in the Beagle. For a detailed description of penitentes and the mechanisms leading to their formation see Lliboutry (1954); Corripio (2003) presents a detailed study of the energy balance of penitentes. This last demonstrated that on the penitentes most of energy is redirected to sublimation and temperature changes, which enhances the conservation of the snow cover and reduces ablation.

Penitentes are a labyrinth of ice and snow pinnacles which appear to be chaotic in distribution, but actually show a common pattern in their orientation that reflects the mechanism for their origin: differential ablation due to enhanced solar radiation at the troughs and cooling through sublimation at the peaks. They are invariably oriented toward the zenith angle of the sun at noon, with walls aligned preferentially from east to west. Penitentes are efficient coolers of the snow surface. The incoming solar radiation is distributed over a large surface area while the peaks are cooled due to sublimation and evaporation in a very dry atmosphere. They are therefore an efficient mechanism for the preservation of the snow cover.

A full study of the response of the glaciers of the Central Dry Andes to future climate change is beyond the scope of this paper, and we would argue, the available data in the region. Instead, we present here a detailed study of potential changes in the ablation regime during the crucial melt season based on available data from two glaciers and considering the influence of penitentes. We then hypothesise about the likely consequences of these results for the three catchments shown in Figure 1, through consideration of catchment hypsometry.

Investigating sensitivity of the Central Dry Andes to climate change

In this paper we set out to investigate the sensitivity of the Central Dry Andes to potential climate change. In particular, we wish to explore the potential response of the system in terms of summer ablation – the most important source of meltwater (and thus water) in the region. Our approach to the problem of modelling possible responses of the system is limited both by the complexity of potential feedbacks within the system and the scarcity of available data at appropriate scales both in terms of past change and potential future responses. In general, climate data are both temporally and spatially limited in the region. Rosenblüth et al. (1997) produced a time series showing warming rates of around 2°C per century between 1933-1992, at a latitude of 33°S. . Glacial response in the region appears to correlate with this warming trend, with Leiva (1999) showing a general pattern of glacier retreat in the region in the 20th century.

In considering the potential response of ablation to future climate changes in the Central Dry Andes, it is necessary to consider the region's main climatic influences. The region lies close to the interface between the influence of the southern westerlies (Kull *et al*. 2003) which are a strong driver of glacial systems further south in Patagonia (Villalba *et al.* 2003) and the mainly anticyclonic climate system experienced further north (Compagnucci and Vargas 1998). Changes in the magnitude or position of the westerlies would have significant effects on the regional climate through advection of moisture from the Pacific. For example, Kull et al. (2002) hypothesise that an intensification of the westerlies doubled precipitation at or around the Last Glacial Maximum at 29°S. Furthermore, as stated above, the region lies within the zone of influence of ENSO. Compagnucci and Vargas (1998) have shown how run-off in the Mendoza basin increases in El Niño years, most likely as a result of increased accumulation.

Any projection of future glacier response to climate change must take into account the availability of data and models to characterize the system (Haeberli et al. 1998). Approaches to modelling the response of systems to future change vary according to both the available data, and the nature of the questions being asked of the system. A key consideration is the spatial and temporal scales at which we wish to examine change. In this case, the key question under examination is, given current scenarios for climate change in South America, how will the availability of run-off change in the short to medium term within catchments fed by ablation from the Central Dry Andes? Furthermore, previous work has shown that penitentes significantly perturb the ablation regime with respect to more typical glaciers (Corripio and Purves 2005). Thus, a second question is, how will the distribution of penitentes change as a result of possible climate variability? Finally, the influence of any change in ablation regime will be strongly dependent on catchment hypsometry. Therefore, a third question is, does the hypsometry of catchments in the Central Dry Andes suggest significantly different responses to climate change?

Approaches to the modelling of ablation vary in complexity from point models, utilizing either the temperature index (e.g. Hock 2003) or more physically based energy balance approaches (Greuell and Konzelmann 1994) through to distributed mass and energy balance models taking into account differential ablation and accumulation (Klok and Oerlemans 2002). In this case, we apply a distributed energy balance model, which has been validated at a point, to study ablation. We have no data regarding accumulation, and therefore have only considered the ablation season.

Modelling ablation in the Central Dry Andes

A portable, light automatic Weather Station (AWS) was installed on the surface of two glaciers of the region and the information logged every 10 minutes to a Campbell CR10 data logger. These glaciers were Glaciar Juncal Norte at 3335 m a. s. l., 32.986°S, 69.956°W, and Glaciar Loma Larga at 4667 m a. s. l., 33.692°S, 70.0°W. The data, collected from December 2000 to February 2001, are: air and snow temperature, relative humidity, wind speed and direction and incoming and outgoing shortwave radiation.

To model the ablation of snow and ice in the region we use a physically based energy balance model: SnowDEM (Snow Distributed Energy balance Model). This is a highly distributed, multilayered snow energy balance model that takes full account of topographic influences and simulates incoming and outgoing shortwave radiation (direct, diffuse and reflected); incoming and outgoing longwave radiation (atmospheric thermal radiation and emitted from surrounding slopes); snow surface and subsurface temperature, and latent and sensible turbulent heat interchange with the atmosphere. The model is slightly modified from that described in Corripio (2003), which can be summarised in the following equation:

$$I_G(1-\alpha) + L\downarrow + L\uparrow + H + L_vE + Q_s + Q_M = 0 \tag{1}$$

where I_G is global shortwave radiation, α is albedo $L\downarrow$ is downward flux of longwave radiation, $L\uparrow$ is upward flux of longwave radiation, H and L_vE are sensible and latent heat fluxes, Q_s is internal heat flux within the snow pack, and Q_M is available heat for melting. Advective heat to the snowpack is neglected in this formulation. It could be computed providing that high resolution snow cover information were available as well as the thermal properties of the bare ground.

A detailed study of the effect of penitentes with a high resolution (1cm grid cell) synthetic model of penitentes surface energy balance has been described in previous works (Corripio, 2003, Corripio and Purves 2005). In this paper, in order to account for this influence whilst running a computationally tractable model, areas covered by penitentes were parameterised as areas of increased roughness length. An additional parameter to account for the increased efficiency of radiative cooling by penitentes is under research. Observation by the authors shows that at the initial stage of penitentes' formation there is always a thin radiative crust on the snow surface. This crust is found when the uppermost skin surface layer of the snow has a zero or slightly negative balance, while the subsurface layer has a positive net balance. This criteria has been confirmed by direct observation of the lowest limit of penitentes occurrence in the Central Dry Andes of Chile and Argentina (~ 4100 m a. s. l.) and it is used in this paper to distinguish between areas where increased roughness is applied to simulate the effects of penitentes. Figure 3 shows where this modelled skin surface net energy balance of around zero is found on the Juncal Norte and surrounding glaciers

Scenarios

In this study, we apply a very simple scenario for climate change to the region derived from the HadCM3 coupled atmosphere-ocean general circulation model (Gordon et al. 2000; Pope et al. 2000). The model was run for present conditions and for two climate change scenarios both based on a warming of 4K, as predicted by the HadCM3 coupled atmosphere-ocean general circulation model (Gordon *et al.* 2000 and Pope *et al.* 2000) for the end of the 21^{st} century, with an all anthropogenic forcing integration scenario. This warming is at the upper end of estimates for likely warming with, for example, Bradley *et al*. (2004) suggesting mean warming of the order of 2.5K at this latitude based on a scenario with 2 x CO_2 derived from 7 GCM simulations. However, our experiments are aimed not at predicting actual change in the system, but rather exploring the linkages between penitentes, ablation and orography.

In the first warming scenario, the model was run as for present day conditions, with increased temperature and relative humidity held constant (i.e. increased specific humidity) which implies an increase in actual atmospheric water vapour content. The changes in humidity are based on the hypothesis that increased sea surface temperatures would increase available moisture for transport and therefore cause an overall increase in specific humidity. All other input variables are held constant in this simple scenario with, in particular, no changes in accumulation modelled. This is for two reasons. Firstly, this is in line with our aim of exploring model sensitivities through a simple set of experiments, and secondly predictions for future change in precipitation are both uncertain and appear to be very low in this region. In the second scenario, the position of zero net energy balance at the snow surface was first calculated, and the surface re-parameterised according to the calculated upward migration of penitentes (Figure 3).

Results

Table 2 shows the input variables for the different runs. The model was run for the available data collected on the area. The daily average is considered representative of mean ablation during the ablation season. As the climatic conditions of the year of study are similar to those of the long term mean for the area, according to reanalysis data (NCEP/NCAR), it is not unreasonable to assume that these computed daily melts are representative of the average conditions in the region. The roughness length has an important effect on the evaporation/sublimation of the snow and on the sensible heat transfer with the atmosphere. The heat interchange with the atmosphere seems to be much higher on these snow covers than on those of higher altitude (Corripio 2003)

Model outputs for the present day were validated through the use of several ablation stakes in the vicinity of the AWS. The results are satisfactory, especially with regard to cumulative melt, as shown in Figure 4.

The modelled melt outputs are in fact, potential melt, that is the amount of melt that would be possible if the ground were covered by a snowpack of infinite depth. More realistic initial snow cover conditions would be preferable but direct measurements are not available. The differences between the results for present conditions and for future scenarios are summarised in Figure 5. The normalised values (blue bars) represent the different in melt weighted for the actual area of land in every altitudinal band. The results show a large increase at lower altitudes, of about 8 mm w. e. or between 17 and 22% of the present melt for those altitudes. The maximum increase in melt, between 34 and 48%, happens between 4100 and 4700 m a. s.

l., due to the upward migration of penitentes. This value of up to 11 mm w. e. is probably an underestimation, as some authors have observed a dramatic decrease of melting on penitentes covered areas (Kotlyakov 1974). At higher altitudes temperatures remain relatively low, and the slopes are steeper, leading to lower solar radiation interception, therefore melt remains lower for all scenarios.

Discussion

The analysis of the results together with the hypsographic distribution of land within these catchments (Figure 1), and the actual extension of glaciers suggest a maximum increase in melt in the areas of largest ice storage at present. This would imply a likely increase in future runoff generation on the ablation season. As GCM models do not appear to forecast an increase in winter precipitation, it seems that stored ice is likely to deplete rapidly. Some compensation may be brought about by an increase in El Niño events, which are associated with increased winter precipitation and increased winter glacier mass balance (see e.g. Leiva 1999). However, the depletion of ice storage will eventually lead to water scarcity and decreased runoff during the summer months. This situation will follow different patterns in different catchments, depending on the altitudinal distribution of land. Thus, the Mendoza river on the Argentinian side is likely to follow a progressive decay as the altitude level of enhanced melt increases, due to the almost linear distribution of land masses with elevation. On the other hand, in the Aconcagua River, on the Chilean side, runoff is likely to decrease rapidly after a period of much enhanced runoff. Here the surface area of land distribution has a peak between 4100 m and 4700 m a. s. l., precisely the area of maximum melt increase under the forecasted scenarios.

That increased temperatures will produce increased melt is not a surprising, or novel, result. However, what is especially significant in this region is that the melt regime is non-linear, due to the effect of the penitentes in mediating ablation. Penitentes are very efficient at cooling and preserving the snow surface. The fact that their lower limit is now located at the peak of glacier surface distribution will have a positive feedback on future increases in ablation, but this is not likely to last for a long time. As shown in Figure 3 the expected upwards migration of the penitentes is in some cases rather dramatic. Some glaciers whose main ice bodies are at present entirely above the penitentes line, will be entirely below for the new scenarios, such as the Juncal Sur, a very large glacier south of the highest peak in the Figure 4, or the Rio Plomo glaciers, on the lower right side of the figure, which are part of the largest glacier system on the Argentinian Dry Andes. Figure 5 shows that this increase in melt occurs precisely on the areas of maximum ice concentration in the mentioned glaciers.

It is also important to sound a note of caution with respect to these results. The scenarios used, and models applied are relatively simple and the uncertainties in many elements of the system are very high. In particular, in the scenarios presented here we have assumed that precipitation (and thus accumulation) and wind speeds, an important influence on turbulent heat fluxes, are unchanged. Nonetheless, at present precipitation is negligible during the ablation session, which is the period modelled here, and the main driver of local wind circulation is katabatic forcing which is likely to remain similar or smaller if glacier extent decreases.

Conclusions and further work

Despite the scarcity of data in the region of study, modelling results suggest that meltwater availability is likely to increase in the medium term, with faster depletion of glacier resources on the longer term. Due to local orography it appears that the rate of variation will be more pronounced in the Aconcagua and Maipo basins (Chilean side) and more gradual on the Mendoza basin (Argentinian side).

Given the importance of meltwater for the economy and populations of Chile and Argentina, and given the time necessary to adapt to new conditions, it would be desirable to be able to anticipate with better precision the timing and magnitude of changes in water supplies. The tools presented here seem to be appropriate for gaining insight into such changes, however, a better knowledge of the initial conditions is necessary. Firstly, reliable data on precipitation and snow cover is necessary. Secondly an updated inventory of glaciers is a prerequisite to estimating total runoff. Continuous meteorological data from a high altitude AWS would be required to model the annual cycle of accumulation and ablation, and to be able to approximate the vertical distribution of meteorological variables. Finally, our understanding of penitentes is incomplete and requires further field work to measure actual ablation in penitente covered areas, and development of techniques to efficiently apply an energy balance model fully representing fluxes within penitente fields as opposed to the roughness based parameterisation applied here.

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TABLES

Table1. Inverted pattern of monthly discharge (m^3s^{-1}) and precipitation (mm) in the upper Aconcagua River basin, Chile at Río Blanco, 1420m a.s.l. Note the contrast between minimum precipitation (< 1 mm) in December, and the maximum discharge for the same period.

Month	J	F	M	A	M	J	J	A	S	O	N	D
Discharge Río Blanco	22.04	13.88	8.53	3.90	3.12	2.98	3.06	3.10	4.16	6.62	14.36	22.72
Precipitation Río Blanco	3	15	10	31	109	102	79	94	41	22	11	1

Table 2 Variables used for the different model runs. Ta is air temperature at 2 m screen level, RH is relative humidity, SW is shortwave radiation, Ts is snow temperature, Sk is sky view factor, modelled melt is in mm water equivalent (mm w. e.).

present conditions	**ΔT = + 4°C**	**ΔT = + 4°C + penitentes migration**
Ta	Ta + 4	Ta + 4
surface roughness .002 < 4100m; 0.20 > 4200m	surface roughness idem	surface roughness .002 < 4700m; 0.20 > 4800m
RH measured	RH measured	RH measured. Implies higher atmospheric water content
Wind measured	same wind	same wind
SW↓ measured + topography	SW↓ + topography	SW↓ as today, topography corrected
SW↑ measured	SW↑ as today	SW↑ as today, implies same albedo
Ts for validation	- -	- -

FIGURES

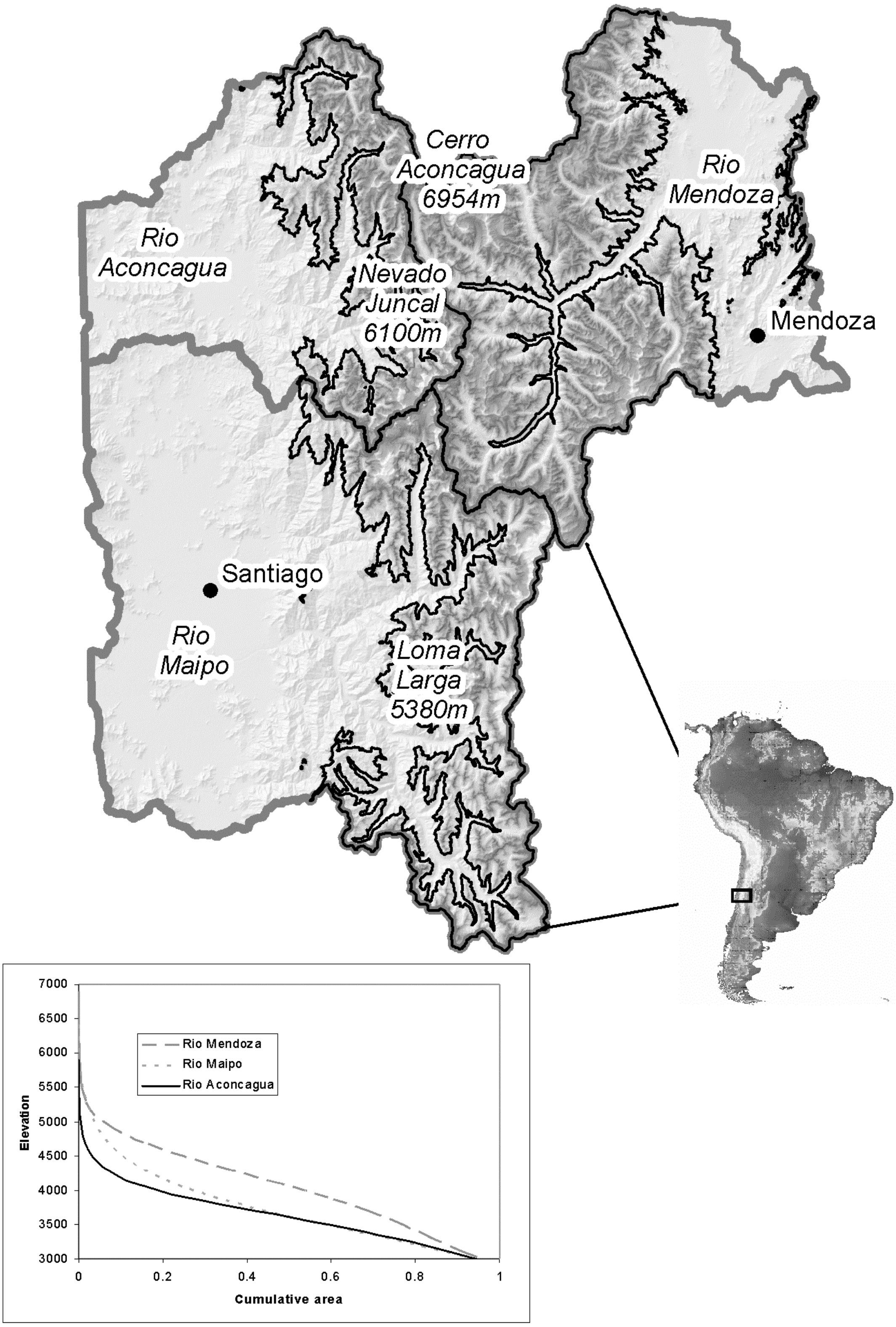

Figure 1 Map of the area of study, about 33°S and 70°S, showing the three main river catchments in the region and the hypsographic distribution of elevation above 3000m for each catchment. Regions used in calculation of hypsometry (above 3000m) are delineated by a thin black line. Note the more linear trend of the Mendoza basin and the rapid decline of surface area with altitude for the Aconcagua basin. DEM source: NASA SRTM

(http://www2.jpl.nasa.gov/srtm/), South America map source: NOAA NGDC Globe project (http://www.ngdc.noaa.gov/mgg/topo/globe.html)

Figure 2 Snow penitentes on the High Central Andes of Argentina. The pinnacles in the picture are two meters in height and they are known to reach up to five. They are formed by differential ablation of the snow surface: the peaks remain frozen and cold due to sublimation, while the troughs act as solar traps, enhancing their deepening. The sun in the figure is on

the west and the penitentes are tilted about 12° north, toward the position of the sun at midday.

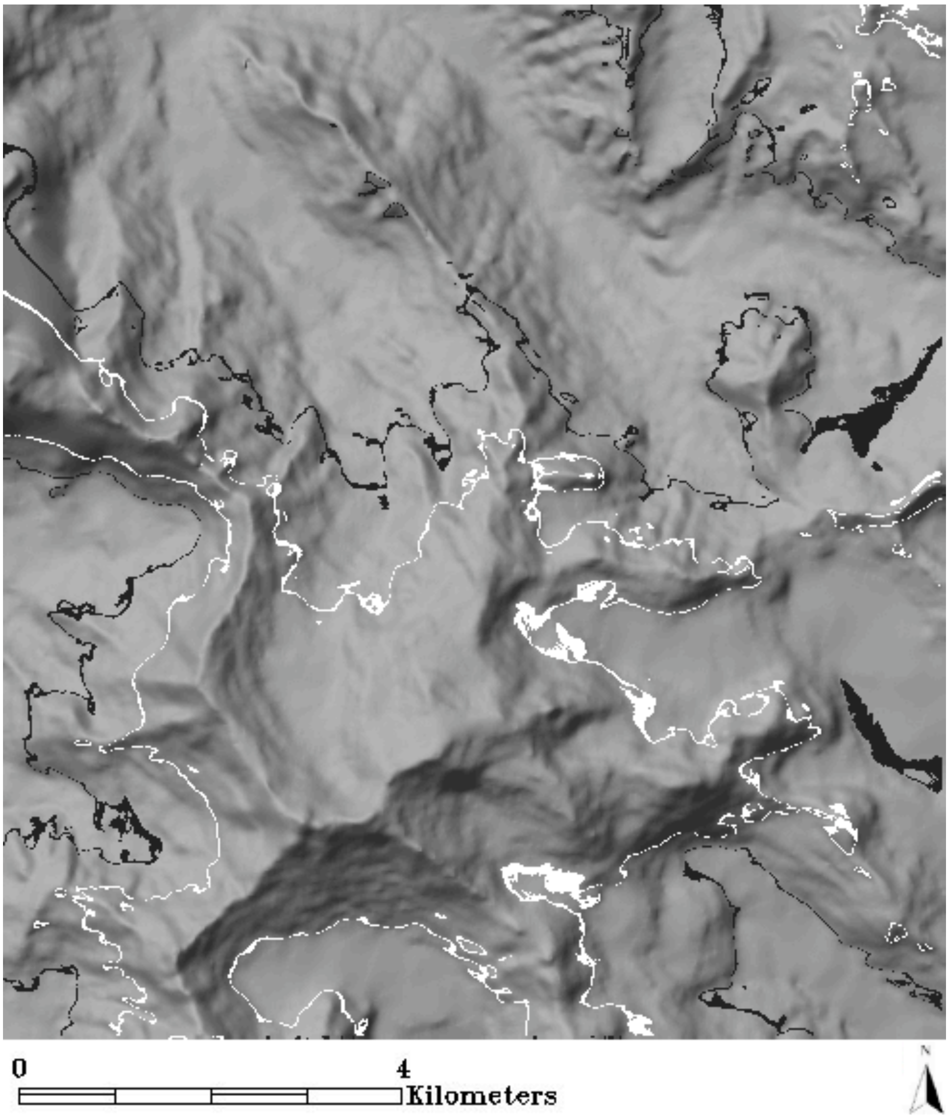

Figure 3 Penitentes migration for future climatic scenario. The black line is the observed and modelled present line, while the white one is the forecasted line for a $\Delta T = +4°C$. Note that the Juncal Sur and Río Plomo glaciers (lower centre right and bottom) are today completely covered in penitentes, while these would be almost absent in future scenarios. the highest peak on the lower section of the figure is the Nevado Juncal, 6110 m a. s. l. DEM source: Instituto Geográfico Militar, Chile.

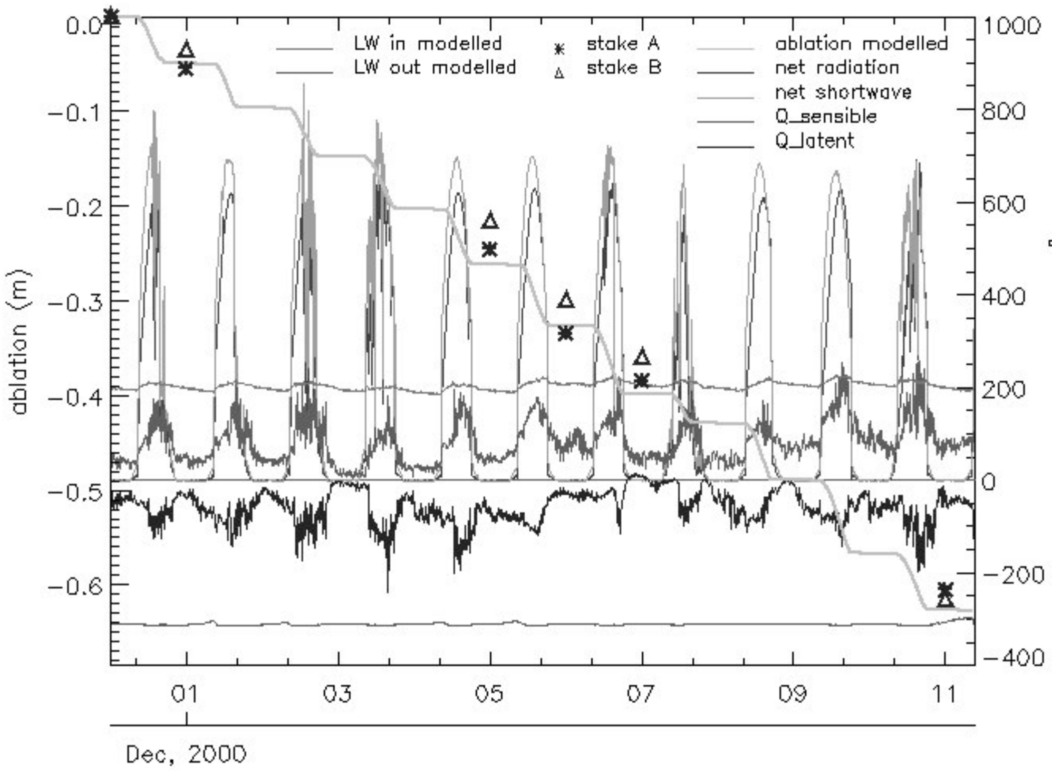

Figure 4 Plot of the different energy balance components during 10 days of December for the AWS location (3305 m a. s. l.) on Juncal Norte glacier, Central Chile. Superimposed is the modelled melt (stepping line) and the measured melt at two nearby ablation stakes (black triangles and stars).

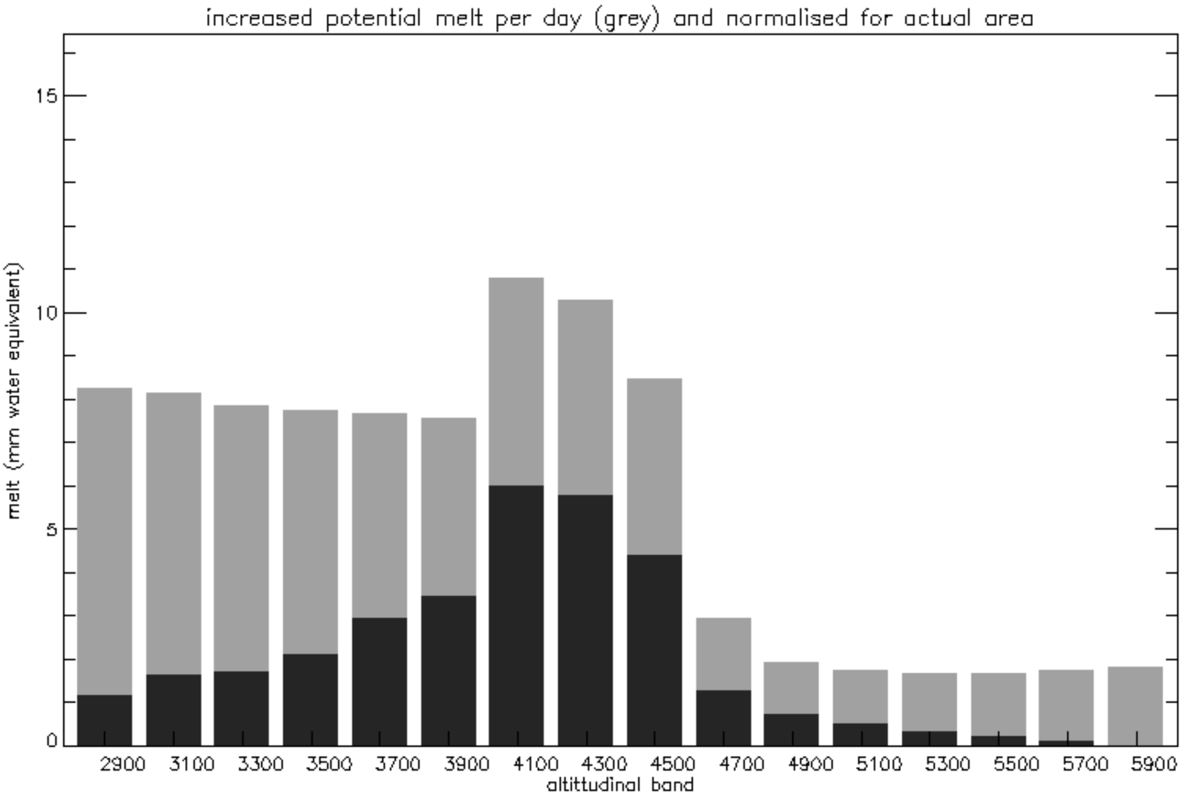

Figure 5 Melt variation for future climatic warming. Grey bars are the differences in melt between present modelled conditions and a future scenario of increased temperature by 4°C and upward migration of the penitentes line. Dark bars are the normalised differences in melt weighted for the actual surface area at every altitudinal band (nondimensional units).