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Review

Changes of glaciers in the Andes of Chile and priorities for future work

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HIGHLIGHTS

- We provide the first detailed and complete review of glacier changes in Chile.
- Current studies are not sufficient to provide a synopsis of glacier changes in Chile.
- We identify with a mass balance model research issues to address in modelling studies.

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ABSTRACT

Glaciers in the Andes of Chile seem to be shrinking and possibly loosing mass, but the number and types of studies conducted, constrained mainly by data availability, are not sufficient to provide a synopsis of glacier changes for the past or future or explain in an explicit way causes of the observed changes. In this paper, we provide a systematic review of changes in glaciers for the entire country, followed by a discussion of the studies that have provided evidence of such changes. We identify a missing type of work in distributed, physically-oriented modelling studies that are needed to bridge the gap between the numerous remote sensing studies and the specific, point scale works focused on process understanding. We use an advanced mass balance model applied to one of the best monitored glaciers in the region to investigate four main research issues that should be addressed in modelling studies for a sound assessment of glacier changes: 1) the use of physically-based models of glacier ablation (energy balance models) versus more empirical models (enhanced temperature index approaches); 2) the importance of the correct extrapolation of air temperature forcing on glaciers and in high elevation areas and the large uncertainty in model outputs associated with it; 3) the role played by snow gravitational redistribution; and 4) the uncertainty associated with future climate scenarios. We quantify differences in model outputs associated with each of these choices, and conclude with suggestions for future work directions.

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1. Introduction

Glaciers worldwide are receding at a strong pace, with possible limited exceptions (e.g. Karakoram glaciers). The ongoing retreat has been documented by both local, ground observations e.g. Kaser et al., 2006; Bauder et al., 2007; Huss and Bauder, 2009; Zemp et al., 2009), remote sensing (e.g. Paul et al., 2004; Bolch et al., 2010, 2011; Kääb et al., 2012) and modelling studies (e.g. Radić and Hock, 2006; Huss et al., 2008; Immerzeel et al., 2012, 2013). Some regions of the Earth however have been documented much more extensively than others, because of well established data gathering efforts and abundance of long-term observations (Switzerland, Scandinavian countries, selected regions of North-America), because of their global relevance (Arctic and Antarctic) or because of growing interest due to their importance for water resources (the Himalaya–Hindu Kush–Karakoram region). In this context, the Andes of Chile have received relatively little attention. Chile's mountain system is made of a heterogeneous succession of cryospheric systems, extending from 18°S to 56°S and spanning a unique variety of climates on the globe, from the desertic North to the very wet Patagonian ice fields. In the middle, the central semi-arid Andes of Chile are one of the most interesting of such systems as they combine relatively large glaciers with densely populated valleys rich in agriculture and feeding large populated centres, including the capital city of Santiago. As their name indicates, the semi-arid Andes feature dry summers with almost zero precipitation and wet, cold winters during which snow accumulates at high elevations. Given its dependence on melt water during summer, when water needs are stronger, and its large population and increasing water demands, the central region is more markedly threatened by changes in climate and the projected warming of the atmosphere. For these reasons, a surge of interest has prompted studies of changes in glaciers and their effect on water resources in the region (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012; Ohlanders et al., 2013; Ragettli et al., 2013a). Another focus of current research has been on the Pascua-Lama region of the Norte Chico (29°S, a very dry environment with few small glaciers), where studies supported by mining companies have focused on mass balance monitoring and understanding of glacier–climate interactions at selected locations (Rabatel et al., 2011; MacDonell et al., 2012), together with a more recent attempt to understand processes at the catchment scale (Gascoin et al., 2013). In the scarcely populated South, where precipitation is abundant, the Northern and Southern Patagonian Ice Fields have been investigated mainly through satellite remote sensing studies used to reconstruct ice volume changes (e.g. Rignot et al., 2003; Rivera et al., 2007; Willis et al., 2012).

While on one side the number of investigations has been increasing recently, on the other side studies of glacier changes, and modelling studies in particular, are still limited, hindered by the scarcity of data, and have not yet reached a level such as to provide a country-wide picture of changes. In this paper, we first provide a review of changes in glaciers and related water resources as documented by recent works. We then discuss the types of investigations conducted, and identify a missing component in distributed, continuous mass balance and runoff glacier modelling work. The scarcity of these studies is due to a number of challenges associated with this type of work, which requires grid-based modelling over large domains and accurate knowledge of the climatic forcing over such domains, as well as a representation of processes at the glacier and catchment scale. We identify some of these issues and show through a modelling study how important some of these challenges are and how they could be addressed. We provide in particular four main examples of major scientific challenges. We then conclude this paper with a discussion of possible future work.

2. Review of glacier changes

Four main regions can be identified in Chile in terms of climate and glacier characteristics: 1) the arid north, from the Chile-Peru border (18°S) to 32°S, including the relatively well studied Norte Chico region (from 26 to 32°S); 2) the central Andes (32 to 38°S), characterised by a semi-arid climate with strong winter precipitation and very few summer precipitation events; 3) the southern Chilean lake district (38–41°S), where many of the glaciers are located on active volcanoes; and 4) the glaciers and ice fields south of 41°, with the two dominant features of the Northern and Southern Patagonia Ice Fields (between 46° 30′S and 51°30′S).

2.1. Glacier changes in the North

In the north, glaciers are very small and limited in number (Nicholson et al., 2009; Rabatel et al., 2011), because of the low precipitation and strong ablation (a large portion of which can be attributed to sublimation). Precipitation has a strong seasonality, and most of it is concentrated in the winter months between May and August (Nicholson et al., 2009; Favier et al., 2009; Rabatel et al., 2011). It also has a pronounced orographic dependence (Favier et al., 2009). Glaciers in the area belong to two main types: clean-ice glaciers (111 from the recent inventory by Nicholson et al. (2009)) and active rock glaciers (40). Unlike the central region, no debris covered glaciers have been observed. Most glaciers have been designated as glacierets because they are small and do not show signs of flow, and are difficult to distinguish from permanent snow cover, and permanent or semi-permanent snow cornices in particular. Glacier distribution in the region is strongly controlled by aspect, with about 80% of the glaciers located on slopes orientated towards southeast, south or southwest (Nicholson et al., 2009). The majority of clean-ice glaciers are located between 5000 and 5200 m a.s.l., while the majority of rock glaciers are between 4000 and 4400 m a.s.l. (Nicholson et al., 2009). The mechanisms by which glaciers form and survive in this distinctive climate are not clear and should be investigated (Favier et al., 2009; Nicholson et al., 2009). Gascoin et al. (2013) have suggested that in this arid, high elevation terrain glaciers form and survive thanks to preferential wind accumulation. Little is known about their mass balance (Rabatel et al., 2011) and contribution to river flow (Favier et al., 2009; Gascoin et al., 2011). Using a combination of ground observations, assumptions about mass losses and information about remotely sensed snow cover from MODIS, Favier et al. (2009) identified discrepancies between precipitation and runoff in several catchments of the region. They attributed them partly to the scarce knowledge of estimates of precipitation at high elevation, and partly to our lack of knowledge about ablation and mass losses of glaciers. Glacier changes in the region have only been reconstructed from remote sensing, from comparison of an inventory based on ASTER images from 2004 with earlier inventories based on aerial photographs from 1955 and 1984. The results of this analysis of area changes indicate that glaciers have been retreating since the 1950s, and at a rate higher than those of the central region (in % of their initial surface) (Nicholson et al., 2009). Rabatel et al. (2011) suggested that this shrinkage results primarily from a decreasing trend in precipitation observed in the sub-tropical region, and that no link between glacier area changes and temperature evolution exists. No modelling study of distributed glacier mass balance and runoff exists for the region.

2.2. Glacier changes in the central region

In the central region, glaciers are larger and debris mantles are more common, together with active rock glaciers (Nicholson et al., 2009; Bodin et al., 2011). In the Aconcagua River basin, debris covered glaciers are approximately 1/3 of the total (Bown et al., 2008). Rock glaciers (the visible manifestation of ice-rich creeping mountain permafrost) are widely distributed and well developed in the central Andes, with a lower limit to their distribution at about 3000 m a.s.l. (Bodin et al., 2011). The region is characterised by what has been often referred to as a mediterranean climate, with mild wet winters and dry summers (Bown et al., 2008; Pellicciotti et al., 2008). Incoming solar radiation is very high during summer, and relative humidity is low (Pellicciotti et al., 2008). The precipitation at high altitudes (above 2500 m a.s.l.) fluctuates between <500 $\mathrm{mma^{-1}}$ in the northern semi-arid part, to up to 2500 $\mathrm{mma^{-1}}$ at 36°S. The 0 °C isotherm altitude decreases in the same latitudinal range, from about 4000 m a.s.l. at 32°S to 3000 m a.s.l. at 36°S (Carrasco et al., 2005). Glacier changes have been documented by Rivera et al. (2002) for the entire region and by Bown et al. (2008) for the Aconcagua River basin using remote sensing images (Istituto Geografico Militar maps from 1955 and 1997, Landsat TM (year 1987), Landsat ETM+ (year 1999), the Shuttle Radar Topography Mission (SRTM) DEM for the year 2000 and two ASTER images (for 2003 and 2006)). Nicholson et al. (2009) extended previous records for three glaciers in the region (Juncal Sur, Juncal Norte, Olivares Gamma) and compared them to those for three glaciers in the Norte Chico (Tronquitos, Guanaco and Estrecho). Glaciers in the region are shrinking, with lost-area ratios of three of the major glaciers of −2.4%, for Juncal Norte Glacier, −10.9%, for Juncal Sur, and −8.2% for Olivares Gamma over 51 years from 1955 (Rivera et al., 2002). The Aconcagua River basin (between 32 and 33°S) is one of the four major basins of the Central Andes (together with the Maipo (33°S), Cachapoal (34°S) and Tinguiririca (35°S)), and its upper section is one of the best studied of the glacierised basins in Chile (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012; Ohlanders et al., 2013; Ragettli et al., 2013a). An update of older glacier inventories for the basin has been carried out by Bown et al. (2008). The basin is located at the boundary between semi-arid and temperate conditions, and it contains 14% of the total ice between 32 and 35°S (Bown et al., 2008). It has experienced an area loss of 20% between 1955 and 2006. However, glacier changes are not homogeneous, and local effects seem to play an important role in determining this distinct response. The Juncal Norte Glacier, in particular, seems to exhibit a distinct change. Bown et al. (2008) estimated that it lost 1.5 $\mathrm{km^2}$ between 1955 and 2006. Variations of its front are smaller than those of other glaciers in the region, and of the neighbouring Juncal Sur glacier (Bown et al., 2008), pointing to the importance of local topographic effects on radiation receipts, spatial effects such as wind and gravitational redistribution, and the accurate description of the interplay between complex topography and energy fluxes reaching the glacier surface. Bown et al. (2008) suggested therefore that more accurate methods other than remote sensing should be used to detect and understand glacier variations. The temporal variability of glacier mass balance can also be large: mass balance observations from the small Echaurren Norte Glacier (0.226 $\mathrm{km^2}$ in 2008, 33.5°S) indicate a positive net mass balance for the period between 1977 and 1991 (Escobar et al., 1995), but an overall very negative net mass balance until 2008 (DGA, 2009). This is the only glacier in Chile for which such a long record is available, but results cannot be extrapolated given the small size of the glacier, which makes it less representative of regional patterns.

2.3. Glacier changes in the Lakes region

In the Chilean Lake district, glaciers are mostly located over active volcanoes, and this peculiar feature has been investigated in terms of their surface energy balance (Brock et al., 2007) as well as studies of mass balance (Rivera et al., 2005) and ice volumetric changes (Rivera et al., 2006). Volume changes are due to both the climate drivers and the effusive and geothermal activity of the volcanoes (Rivera et al., 2006). Volcanic activity can affect the glaciers in two opposed ways: by insulating the ice with ash and debris, resulting in reduced surface ablation, and by enhancing subglacial melting due to geothermal activity, resulting in greater thinning than in non-active volcanic environments. Rivera et al. (2006) found that glaciers on volcanoes were mainly shrinking in response to climatic driving factors, and in particular a decreasing trend in precipitation between 1930 and 2000. However, they also found that glacier response is highly heterogeneous and due to the specific eruption and activity histories of the individual volcanoes.

2.4. Glacier changes in the Patagonian region

The Patagonian Andes contain over 20,000 $\mathrm{km^2}$ of glaciers, representing the largest glacierised area in South America. Glaciers are mostly concentrated south of 45°S, with the Northern and Southern Patagonian Icefields covering about 4200 and 13,000 $\mathrm{km^2}$, respectively. Glaciers in Patagonia are strongly retreating and thinning (Rignot et al., 2003; Rivera et al., 2007; Masiokas et al., 2008; Willis et al., 2012), but very little is known about the reasons and how these changes are linked to changes in the climate (Masiokas et al., 2008; Schaefer et al., 2013). Masiokas et al. (2008) have attributed the recession to a trend towards drier and warmer conditions detected over the 1912–2002 period. They analysed a series of long, homogeneous annual, cold-season and warm-season regionalized temperature and precipitation records and showed that averaged warm season (October–March) temperatures have increased by 0.056 °C per decade, whereas cold season (April–September) precipitation (on average about 73.5% of annual totals) has declined at a rate of about 5% per decade. In one of the very few modelling studies, Schaefer et al. (2013) used a glacier mass balance model to evaluate the past and future surface mass balance of the Northern Patagonian Icefield, and found that accumulation increased from 1990 to 2011 as compared to 1975–1990, while calving losses doubled in 2000–2009 as compared to 1975–2000. They also used the model to predict future changes up to the end of the century, obtaining increasing rates of mass loss.

3. Distributed mass balance and runoff modelling at the catchment scale

As should be clear from the review of glacier changes above, most of the studies conducted in the Andes of Chile are based on remote sensing approaches used to reconstruct frontal variations (e.g. Rivera et al., 2002; Bown et al., 2008), areal changes (e.g. Rivera et al., 2002; Bown et al., 2008; Nicholson et al., 2009; Rabatel et al., 2011) and ice volumetric changes (e.g. Rignot et al., 2003; Rivera et al., 2007; Willis et al., 2012). From volumetric changes, geodetic mass balances can be inferred assuming that the accumulation and ablation areas can be identified and the densities of snow and ice can be assumed accurately.

These studies are important contributions to our knowledge of past changes, but have a number of limitations and must therefore be complemented by works of different temporal and spatial resolution, and of modelling nature: 1) they cannot provide any indication of changes between the dates of the images, and as such provide average or integrated changes usually over periods of several years or decades; 2) they also can be used, rather obviously, only for the past, so they cannot provide any indication of future changes; 3) and finally, they cannot offer any insight into the relationship between the climatic forcing and the consequent glacier changes, and therefore they are of limited utility when it comes to projecting these changes into the future (Cogley, 2012). In addition to the evidence of past changes in glacier area and mass they can provide valuable data sets that allow calibration of distributed, continuous glacier models (e.g. Immerzeel et al., 2012, 2013; Schaefer et al., 2013).

Together with the remote sensing studies, a second focus of current research in the Andes of Chile is on understanding the specific setting of glacier–atmosphere interaction. In a manner similar to the numerous energy-balance studies in other regions of the world (e.g. Wagnon et al., 1999; Mölg and Hardy, 2004; Klok et al., 2005; van den Broeke et al., 2004; Brock et al., 2010), these studies have been conducted at the locations of automatic weather stations (AWSs) installed on glaciers to understand the energy balance at the glacier surface, the sources of energy for melt, and their spatial and temporal variability (e.g. Brock et al., 2007; Pellicciotti et al., 2008; MacDonell et al., 2012). Such studies are key to understanding which processes and energy fluxes are relevant to total ablation, and their results allow simplifications of melt equations that can be included in more empirical models based on physical considerations (Pellicciotti et al., 2005, 2008). They also allow high resolution, accurate calculations of surface ablation rates that can be used as reference for simpler, more conceptual approaches and for calibration of their empirical parameters (Pellicciotti et al., 2008, 2012; Carenzo et al., 2009; MacDougall et al., 2011; Ragettli and Pellicciotti, 2012).

Other works in the region have looked at mass balance observations over periods of a few years (Gascoin et al., 2011; Rabatel et al., 2011), at runoff records together with mass balance observations to infer the contribution of glaciers to runoff (e.g. Gascoin et al., 2011), or at hydro-climatic trends and correlation of streamflow and meteorological records with climatic indices (e.g. Masiokas et al., 2008, 2010; Rubio-Alvarez and McPhee, 2010; Cortes et al., 2011).

Unlike in other mountainous, glacierised regions of the globe, only a few distributed modelling studies have been carried out in Chile. Schaefer et al. (2013) have applied a distributed (450 m grid size) mass balance model based on a temperature-index type melt equation to simulate the past and future response of the Northern Patagonian Icefield. The model was calibrated using both point and geodetic mass balance measurements from three of the non-calving glaciers of the icefield. The authors used the model calibrated in this way to predict strong increase in ablation from the year 2050 on, and a decrease in accumulation from 2080. The model did not include ice dynamics and was forced by only one climate scenario, an important limitation that will be discussed below. Ragettli and Pellicciotti (2012) applied a fully distributed, physically based model to study the exchange between glaciers and climate in the Juncal Glacier basin (33°S) during two summer seasons. The model was calibrated with a number of local, detailed field measurements and the authors showed how these could effectively constrain model parameters and avoid internal inconsistencies in process representation. This is the first study that has provided a quantification of the relative contribution of snow and ice melt to streamflow from a glacierised basin in the central Dry Andes and of its variability in time. The same model was applied by Ragettli et al. (2013a) for simulations over several years at the larger scale. The authors demonstrated the importance of considering gravitational snow redistribution and glacier processes in hydrological model applications to the Upper Aconcagua River basin.

Distributed mass balance and runoff models can have a varying degree of complexity in the physical representation of processes (Carenzo, 2012), but they all require distributed input. For high-elevation and glacierised catchments this implies that we must be able to extrapolate point observations at AWS locations to the grid cells of the spatial domain, which is characterised by steep topography, complex shading patterns and topographic constraints that can substantially modify

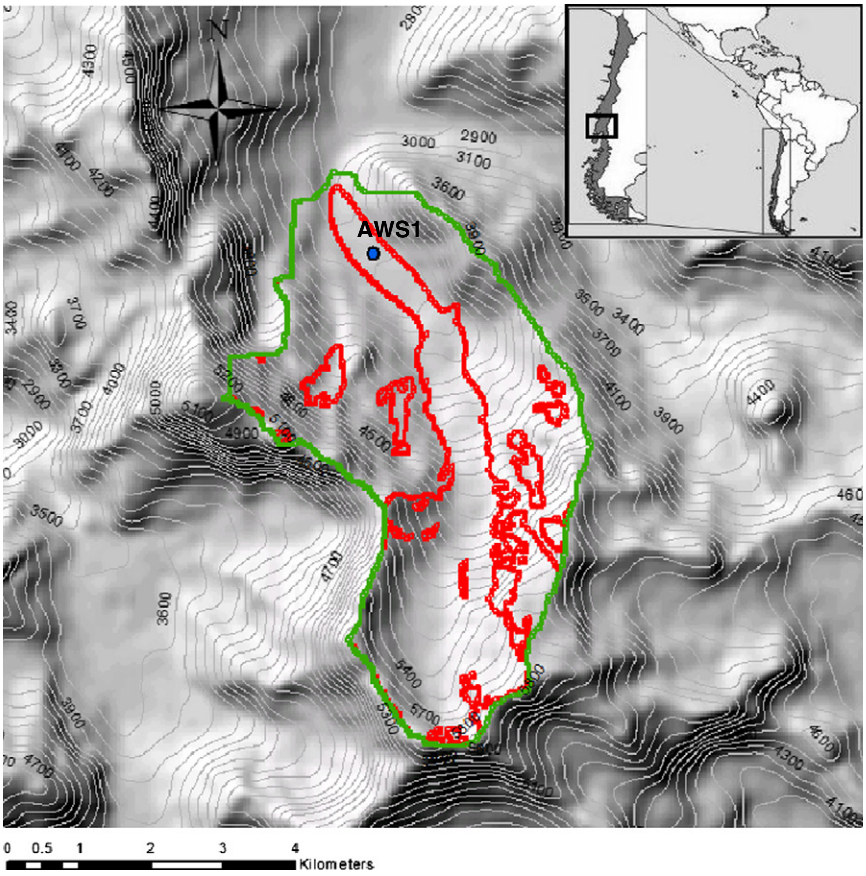

Fig. 1. Map of Juncal Norte Glacier (glacier outlines in red), showing the location of the automatic weather station (AWS1) used in the study. The image shows the ASTER GDEM of the glacier and the surrounding area. Grid size is 30 m. The image was relief shaded. Contour lines are shown every 100 m. The green line indicates the catchment border closed at the location of one streamgauge.

air temperature, radiative fluxes and wind flow (e.g. Petersen et al., 2012). This plays a key role, unlike at the point scale, in dictating the choice of the model, because more complex and physically-based models will require more input data that need to be spatially extrapolated or modelled. In distributed modelling, a further key issue is the correct representation of processes that move mass from one cell to the other, such as snow redistribution by wind and gravity (Warscher et al., 2013; Ragettli et al., 2013a). In the following sections we explore some of these aspects of distributed, continuous modelling of glacier melt, mass balance and runoff. We use Juncal Norte Glacier for this (Fig. 1), one of the best investigated glaciers in the central Andes of Chile (Pellicciotti et al., 2008; Bown et al., 2008; Ragettli and Pellicciotti, 2012; Ohlanders et al., 2013; Ragettli et al., 2013a), because data sets of different nature and high quality are available there.

4. Physically-based versus empirical models

Among glaciologists, two main approaches have been adopted for calculation of melt rates at the glacier–atmosphere interface. On one side, physically-based energy balance (EB) models represent the physics of the energy exchange at the glacier–atmosphere interface using physically-based equations, while temperature index models calculate melt as a function of air temperature alone (e.g. Pellicciotti et al., 2005; Reid and Brock, 2010). A number of intermediate models have been more recently suggested that bridge the gap between those two approaches (Hock, 1999; Pellicciotti et al., 2005, 2008). No model can be demonstrated to be clearly superior to any other, and their performance strongly depends on input data and temporal and spatial resolution of the application. It is clear that at the point scale of AWSs, where accurate meteorological data are available as input, EB models are superior to simpler, empirical models that necessarily neglect some of the processes or adopt simplified representations of others (Pellicciotti et al., 2005, 2008). However, at the scale of the entire glacier, where input meteorological variables need to be extrapolated from point observations to the grid cells of the domain, this superiority has been questioned (Carenzo, 2012), as EB models require a much larger number of meteorological input variables. Some of these, such as wind speed or longwave radiation, are difficult to model at high-elevation sites, and extrapolation techniques also fail because no clear elevation or other spatial dependency can be identified (e.g. Dadic et al., 2010b; Juszak and Pellicciotti, 2013). Even air temperature, which is commonly assumed to depend linearly on elevation, has been demonstrated to exhibit much more complex patterns and temporal variability than can be captured by simple lapse rates (LRs) (Shea and Moore, 2010; Petersen and Pellicciotti, 2011; Petersen et al., 2012), both for debris-free and debris-covered glaciers (Reid et al., 2012). On the other side, more empirical models rely on parameters that need calibration and are therefore both data demanding and site-dependent. It is therefore not yet clear which of the two approaches is superior at whole-glacier and larger scales, and this is especially so in a data scarce context such as that of the Chilean Andes.

Here, we apply in a distributed manner an energy balance (EB) model (Carenzo, 2012) and an enhanced temperature index (ETI) model (Pellicciotti et al., 2005, 2008) to the relatively well investigated Juncal Norte Glacier (Fig. 1). The ETI model uses setup and parameters calibrated or defined in a number of previous studies (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012; Ragettli et al., 2013a), and its application to Juncal Norte Glacier has been extensively validated (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012; Ragettli et al., 2013a). Its performance should thus be accurate at least for the glacier tongue and those sections of the glacier where the calibration data were measured. A key issue is the input data to the models. The EB model requires input of air temperature, relative humidity, wind speed and direction, incoming and reflected shortwave radiation and incoming and outgoing longwave radiation, as well as knowledge of surface properties such as aerodynamic surface roughness. The ETI model requires as input only air temperature and the net shortwave radiative flux, which can be modelled (Pellicciotti et al., 2005, 2011). Both models are applied for the ablation season 2008–2009, for which two AWSs were installed on the glacier tongue and one in the pro-glacial valley (see for details Pellicciotti et al. (2008); Ragettli and Pellicciotti (2012)). Because of lack of observations at high elevation and a general lack of knowledge about their spatial patterns over glaciers, wind speed and relative humidity are assumed constant in the EB model. Incoming longwave radiation was modelled using Prata's parameterisation (Pellicciotti et al., 2008). Snow albedo is parameterised in both models (Ragettli and Pellicciotti, 2012). Air temperature is distributed from the observations at the on-glacier AWS1 using a daily variable LR calculated from 12 T-Loggers setup on the glacier in the same season (details of the data and LRs can be found in Petersen and Pellicciotti, 2011) and it is the same for both models. In the ETI model, incoming solar radiation is modelled using a non-parametric model that takes into account the interaction of the solar beam with the topography (shading, multiple reflections, etc.) as well as transmission through the atmosphere (Pellicciotti et al., 2008; Ragettli and Pellicciotti, 2012). In the EB model, the solar radiation modelled in this way is additionally corrected using the record at the AWS (Carenzo, 2012). The parameters of the ETI model are taken from Ragettli and Pellicciotti (2012).

Fig. 2 shows cumulative melt simulated by the two models over the ablation season. It is obvious that simulations differ quite substantially: the EB model simulates less melt on the tongue but a much larger area contributes to ablation than in the ETI model. This is because the ETI model, as most of the empirical melt models, adopts a temperature threshold for the onset of melt. This was accurately calibrated using measurements and point EB simulations from the glacier tongue

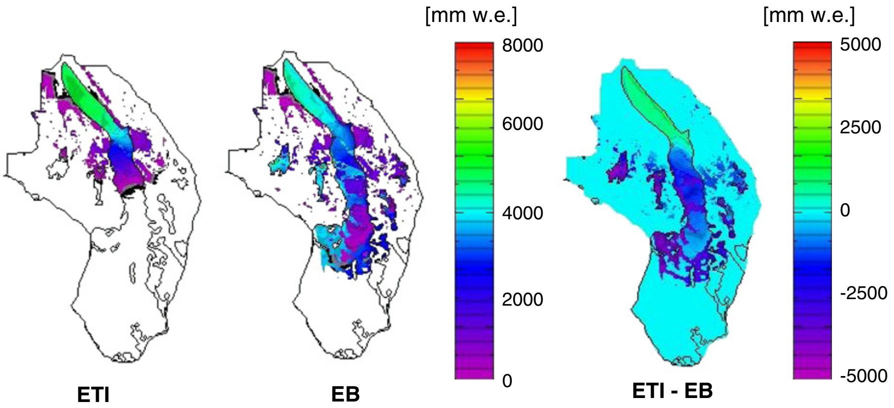

Fig. 2. Cumulative melt over the ablation season simulated by the ETI model (left), the EB model (centre) and their differences (right), calculated as ETI-EB, over Juncal Norte Glacier catchment, for the season 2008–2009 (details of the season are in (Ragettli and Pellicciotti, 2012)). The thin black lines indicate the glacier and catchment outlines (see Fig. 1). In the left and centre maps white indicates no melt. Patches of melt outside of the glacier are due to snow remnants.

(Ragettli and Pellicciotti, 2012) and the values obtained in this way were shown to have a physical meaning in relation to the energy fluxes at the glacier interface (Ragettli and Pellicciotti, 2012). However, those values might be different, but difficult to estimate in the absence of measurements, at higher elevations. In general, in the absence of validation data from the highest sections of the glacier, it is difficult, if not impossible, to evaluate which of the two ablation maps is more realistic. The slight overestimation of melt by the ETI model on the tongue (Fig. 2) is due to the slight overestimation of modelled solar radiation by the ETI model during the afternoon (results not reported). The solar radiation model incorporated in the ETI model does not use observations of solar radiation, but modelled values (in accordance with the parsimony in data requirement of the model). The EB model corrects the modelled solar radiation with the point observations at the AWS and therefore simulates the incident solar radiation more accurately at those locations where measurements are available (Carenzo, 2012). The two effects (overestimation on the tongue by the ETI and larger contributing area in the EB model) are of opposite sign. On average, mean cumulative ablation over the entire glacier is 643.4 mm w.e. for the ETI and 1469 mm w.e. for the EB model, respectively. That is, the EB model simulates much more melt than the ETI model.

5. Importance of correct characterisation of atmosphere–cryosphere–land surface interaction in high elevation catchments

Obviously, inaccurate input meteorological data translate into inaccurate model outputs or, through parameter calibration that leads to internal inconsistencies, to unwanted compensation of internal model errors. This problem has by now been recognised for the input climatic forcing of future simulations driven by general circulation models (GCMs) or regional climate models (RCMs), which can diverge substantially (Prein et al., 2011) and for which increasingly an ensemble of models is deemed necessary to evaluate the uncertainty associated with the climatic forcing (Horton et al., 2006; Schaefer et al., 2013; Immerzeel et al., 2013; Ragettli et al., 2013b). A still little investigated field, however, is that of the climate of mountains and glaciers. High elevation, glacierised catchments exhibit complex climatic patterns due to the interplay between rough topography, the presence of cryospheric components and feedback mechanisms. Only recently has attention been paid to the correct characterisation of meteorological variables at the interface between atmosphere, cryosphere and surface land at high elevation (Mölg and Kaser, 2011; Petersen et al., 2012; Juszak and Pellicciotti, 2013). On glaciers, air temperatures are modified substantially by the presence of a cold surface at 0 °C and development of air flows such as katabatic winds (Pellicciotti et al., 2008; Shea and Moore, 2010; Petersen and Pellicciotti, 2011; Petersen et al., 2012). Petersen and Pellicciotti (2011), for instance, using a distributed data set of air temperature observations, showed that over Juncal Norte Glacier LRs vary, and in particular they change at the onset of katabatic wind. LRs had a strong diurnal variability and this had to be taken into account in melt modelling to avoid overestimation of ablation rates (Petersen and Pellicciotti, 2011). These types of investigation require a fair amount of local ground data, but seem to be imperative if we want to match the increasing accuracy of model structure with input data of adequate quality.

Here we use air temperature data from a detailed, devoted experiment on Juncal Norte Glacier (Petersen and Pellicciotti, 2011) to show how the correct characterisation of the spatial fields of air temperature forcing a melt and mass balance model can have a substantial impact on model predictions. We compare three main extrapolation techniques, all requiring a fair amount of detailed, local knowledge about air temperature. In the first method (1), air temperature is extrapolated from the on-glacier AWS1 using the daily variable LR derived from the T-Loggers (Petersen and Pellicciotti, 2011). This represents the best way of generating distributed fields of air temperature over a glacier, because it uses data from the glacier boundary layer, which best represents the air temperature forcing. The second method (2) uses data off-glacier, at the Portillo station (see Ragettli and Pellicciotti, 2012, for the location of the station), and extrapolates this time series to the AWS1 on the glacier (using a mean LR for every hour of the day, averaged over the season, calculated between the two sites); it then uses the same daily variable LR as in method 1 to extrapolate data from AWS1 to the glacier grid cells (i.e. a daily variable on-glacier LR derived from the on-glacier observations). The third method (3) was used in Ragettli et al. (2013a) and is the option that would be adopted in glacio-hydrological models at the catchment scale, since it uses input time series from an off-glacier station at a certain distance from the glacier. Temperature data are extrapolated to the modelling domain using monthly LRs calculated between two off-glacier stations (Vilcuya, 1100 m a.s.l., and Portillo, 3000 m a.s.l.), and in addition to this a reduction of air temperature is applied on glacierised areas (to take into account the cooling effect of the glacier). This reduction is constant in space and time and was derived using the T-Loggers data of the 2008–2009 ablation season (see Ragettli et al. (2013a) for details of the method).

The model used is the ETI model discussed above, which was chosen because it was tested and validated for Juncal Norte Glacier both at the point (Pellicciotti et al., 2008) and distributed scale (Ragettli and Pellicciotti, 2012; Ragettli et al., 2013a). It is applied, as in the previous case, to the ablation season 2008–2009. Precipitation during that period was close to zero.

Results are shown in Fig. 3, together with the map of maximum temperatures over the period. It is evident that the first two methods give similar results in terms of temperature (Fig. 3a and b) and melt (Fig. 3d and e). Melt distribution with the third method is quite different (Fig. 3f). While the pattern and magnitude of melt over the tongue are similar, the model forced in this way prescribes melt at much higher elevations, where temperature is also higher (by almost 20 °C for maximum values) (Fig. 3). Average cumulative melt over the ablation season is 643.4 mm w.e., 692.9 mm w.e. and 1006.8 mm w.e. for methods 1, 2 and 3, respectively, indicating much higher melt when data are extrapolated from the off-glacier Portillo station without including the spatio-temporal variability typical of the glacier boundary layer. While it seems that the first two methods would provide more accurate results given that they take into account the specificity of processes on the glacier, no conclusive argument can be made without data from higher elevations, where very little if anything is known about the thermal regime of glaciers.

6. Importance of spatial processes of snow redistribution

Snow in high mountain, glacierised basins is redistributed mainly through two effects: wind and gravitational redistribution. A growing number of recent works have suggested that both processes are important and able to move considerable amounts of mass (MacDonald et al., 2009; Bernhardt and Schulz, 2010; Bernhardt et al., 2010; Gascoin et al., 2013). The effect of wind is complex and difficult to represent in models, since wind induces preferential deposition of precipitation (Lehning et al., 2008; Dadic et al., 2010a), moves snow by saltation and suspension (Bernhardt et al., 2009) and causes sublimation of blowing snow (MacDonald et al., 2009; Gascoin et al., 2013). Snow transport by wind has been demonstrated to be responsible for an increase in sublimation rates (Strasser et al., 2008). Taking into account the effect of wind on the distribution of snow depth and other properties of the snowpack requires models of high resolution and advanced physical representation of processes (e.g. Liston and Sturm, 1998; Essery et al., 1999; Liston and Elder, 2006; Groot Zwaaftink et al., 2011). In addition, distributed fields of wind speed and direction at high resolution are needed to force the numerical models. Air flow within the atmospheric boundary layer at high elevation is shaped by local topography, and over glaciers and snow cover further complicated by exchange of heat between the cold surfaces and the overlying air, as well as development of katabatic

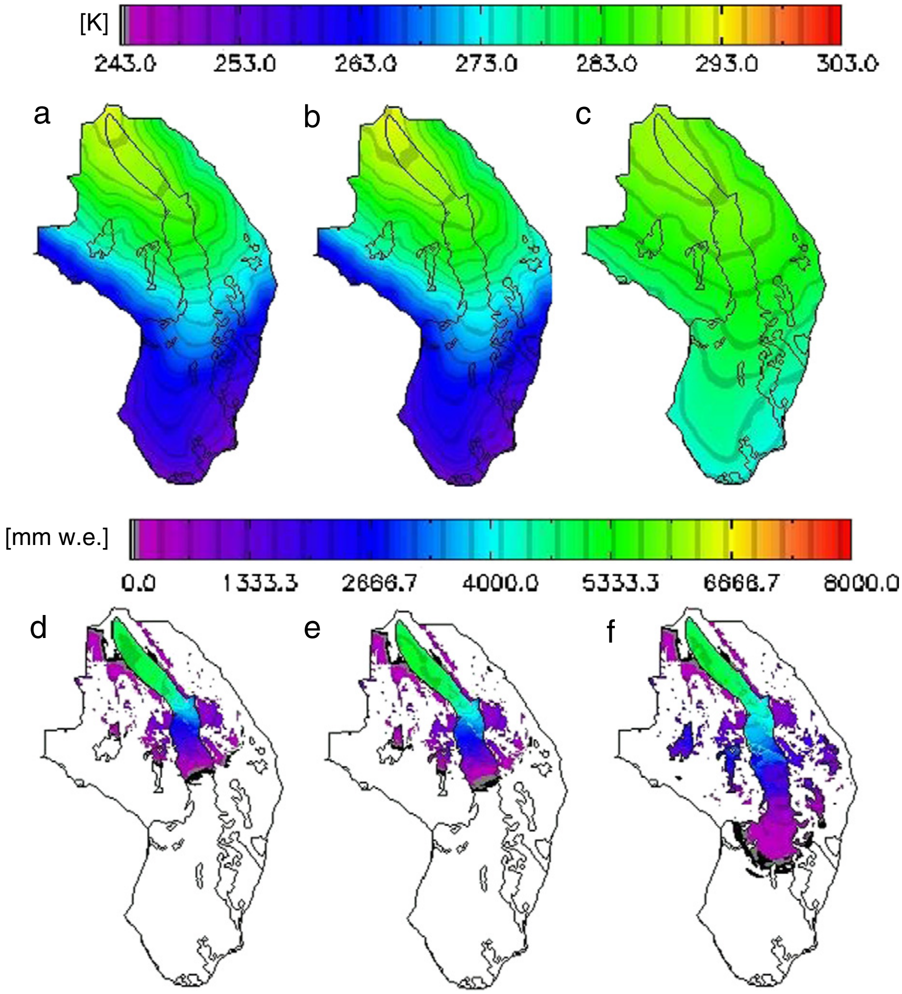

Fig. 3. Bottom three panels: cumulative melt calculated with the ETI model for the ablation season 2008–2009 over Juncal Norte Glacier catchment with the three temperature extrapolation techniques described in the text: 1) air temperature is extrapolated from the on-glacier AWS1 using the daily variable LR derived from the T-Loggers (d); 2) air temperature at the off-glacier station of Portillo is extrapolated to the AWS1 on the glacier (using the average daily variable LR between the two sites), and from there it is extrapolated with the same daily variable LR as in method 1 from AWS1 to the glacier grid cells (e); and 3) air temperature is extrapolated to the modelling domain using monthly LRs calculated between two off-glacier stations (Vilcuya, 1100 m a.s.l., and Portillo, 3000 m a.s.l.) and a reduction of air temperature is applied on glacierised areas. White indicates no melt. Top three panels: maximum air temperature extrapolated over the catchment over the period of record with the three methods: 1 (a), 2 (b) and 3 (c). Black lines indicate the glacier and catchment outlines (see Fig. 1).

flows. Wind speed and direction are notoriously difficult to model and extrapolate in models of mountainous terrain, and no suitable method exists to extrapolate wind speed across a glacier. Interpolation of spatial fields from ground observations, even when the latter are numerous, has so far had very limited success (Gascoin et al., 2013).

The effect of gravitational redistribution is better understood and better modelled (e.g. Gruber, 2007; Bernhardt and Schulz, 2010). Most approaches are mass conserving algorithms based on flow propagation schemes. Snow is displaced from each cell based on topographic flow considerations and controlled by the mobile mass and local slope. Avalanching is especially effective on steep and rough terrain. This process is responsible, together with wind induced transport, for the deep snow at the bases of steep slopes. These extreme snow depths have been suggested to explain the existence of some small glaciers at such locations (Kuhn et al., 1999).

In the Alps, it has been demonstrated that inclusion of snow gravitational redistribution routines improves the prediction of spatially distributed snow patterns and generates more realistic descriptions of Alpine water and energy balances (Bernhardt and Schulz, 2010). In the Himalaya-Karakoram (HK) region, avalanches triggered by the steep relief have been suggested to be a key component for the survival of glacier tongues at low elevation (Hewitt, 2011), but modelling studies are still missing. In the Andes, Gascoin et al. (2013) have made a first attempt at including wind-induced transport in a pioneering study on snow modelling at the catchment scale, but neglected the effect of gravitational redistribution. Ragettli et al. (2013a) demonstrated that the lack of a model component that reproduces snow gravitational redistribution in rough mountainous terrain in the Andes leads to important error compensations if models are calibrated against remotely sensed snow cover such as MODIS.

Here, we test the contribution of avalanching to mass balance over the Juncal Norte Glacier. We use the mass balance model described in Section 7 below coupled to the snow redistribution routine of Gruber (2007). In this approach, deposition is limited by the local maximum deposition in each cell and the available mobile mass that is the sum of the initial input to the cell and the received flow from the neighbouring cells. The maximum deposition in each cell (corresponding to the cell holding capacity) is independent of the mass flux and needs to be empirically determined, e.g. as a function of slope angle or surface characteristics, and calibrated. Given the lack of winter snow depth data sets for a suitable calibration of the approach, we use the parameters estimated for an alpine site (Carenzo, 2012). We run the model continuously with the temperature forcing 2 (Section 5) for 5 years (2005 to 2009) for which input data were available. Precipitation is extrapolated using station data from Riecillos (1290 m a.s.l.) and a logarithmic precipitation gradient (calculated between Riecillos

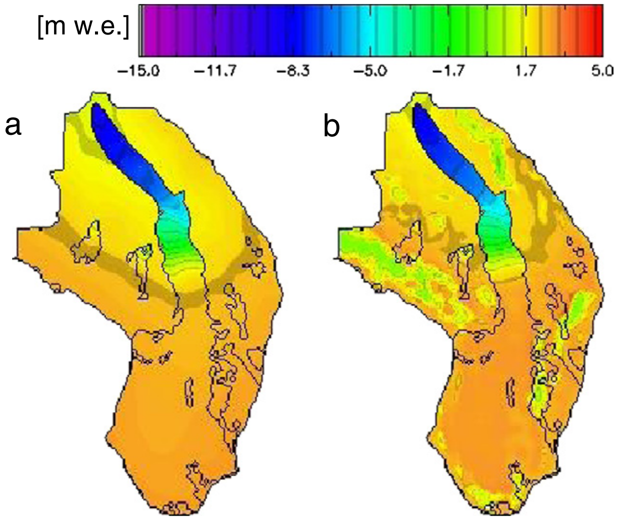

Fig. 4. Mass balance (mass gains minus mass loss) for the hydrological year 2005 over the Juncal Norte Glacier catchment, with (b) and without (a) snow redistribution. The mass balance model used is described in detail in (Carenzo, 2012). The think black lines indicate the glacier and catchment outlines (Fig. 1).

and Portillo and validated with a number of lower-lying stations in the Aconcagua River valley, details in Ragettli et al. (2013a)). Logarithmic lapse rates reflect more accurately the orographic forcing effect typical of high elevations, by which wet air masses are orographically lifted and discharge their moisture in proportion to the amount of lifting.

Fig. 4 shows mass balance maps for the hydrological year 2005 with and without snow redistribution. Avalanching produces a more heterogeneous pattern of mass balance (Fig. 4b), with more positive mass balances on the narrow gorge above the tongue and in upper sections above the gorge (darker orange in Fig. 4b compared to 4a), where snow is redistributed from the steeper slopes overlooking the glacier area. On some of the upper ridges, on the contrary, mass balance turns from positive to negative after redistribution. This effect might be relevant over long term simulations (for which no data were available for this study), but preliminary to this, work should be done to define appropriately the empirical parameters of the redistribution component (i.e. limiting deposition and slope limit), to which the model was demonstrated to be highly sensitive (Carenzo, 2012).

7. Future simulations and additional uncertainties

In this section, we consider a fourth and key source of uncertainty, namely the choice of climate forcing scenarios. Several impact studies of glacier changes have been conducted with well calibrated glacio-hydrological models forced only by one climate scenario, be this one GCM or one RCM output (e.g. Machguth et al., 2009; Schaefer et al., 2013). There is growing awareness, however, that this will capture at most one of the many trajectories of possible climate change (Horton et al., 2006; Prein et al., 2011; Radić and Clarke, 2011; Immerzeel et al., 2013). This has nothing to do with natural climatic variability, but simply with structural differences between models. It has therefore been strongly suggested that impact studies should be driven by ensembles of climate model outputs. We therefore decided to test the effect that climate models have on the output of one well calibrated, distributed glacier mass balance and runoff model.

7.1. Climate scenarios

We have downloaded and downscaled 10 GCMs from the CMIP3 ensemble (Table 1). Projections of future precipitation and temperature are considered until 2050. Since for this time period the uncertainty due to the emission scenarios is rather small (Prein et al., 2011), only the emission scenario A1B is used, which represents a medium greenhouse gas emission scenario. The GCM outputs at monthly scale are downscaled to daily (precipitation) and hourly (temperature) resolution using a stochastic approach that provides an ensemble of 20 scenarios for each GCM. The main advantage of a stochastic approach is that it accounts for the natural variability of the climate (Fatichi et al., 2013; Ragettli et al., 2013b). Precipitation is downscaled by reparameterization of the Spatio-Temporal Neyman-Scott Rectangular Pulses (ST-NSRP) model (Burton et al., 2008; Bordoy and Burlando, 2013b). The methodology uses debiased climate model outputs and the scaling properties of the precipitation process to perturb the statistics needed for the model calibration (Bordoy and Burlando, 2013a,b). For the debiasing of climate model outputs and for the parameterization of the ST-NSRP model we use the statistical properties of observed daily precipitation from Riecillos and the period 1991–2010.

Table 1
GCMs considered in this study.

Model ID	Centre and location
NIES MIROC3 (medres)	Center for Climate System Research (University of Tokyo), National Institute for Environmental Studies, and Frontier Research Center for Global Change (JAMSTEC, Japan)
CCMA CGCM 3.1(T47)	Canadian Centre for Climate Modelling and Analysis (Canada)
CSIRO Mk3.0	Commonwealth Scientific and Industrial Research Organisation Atmospheric Research (Australia)
GFDL CM2	Geophysical Fluid Dynamics Laboratory (USA)
GFDL CM21	Geophysical Fluid Dynamics Laboratory (USA)
IPSL CM4	Institut Pierre Simon Laplace (France)
NCAR CCSM3	National Center for Atmospheric Research (USA)
NCAR PCM	National Center for Atmospheric Research (USA)
ECHAM5/MPI-OM	Max Planck Institute for Meteorology (Germany)
UKMO HadCM3	Hadley Centre for Climate Prediction and Research (UK)

Due to its different statistical characteristics, temperature is downscaled with a different approach. We use an ARIMA model to reproduce stationary time series of standardized hourly measured temperature. Standardization is necessary to separate the deterministic from the stochastic variability in temperature. We subtract the monthly mean from the measured hourly data, we divide by the monthly standard deviation and then remove the daily cycle by subtracting the average hourly value from each hour of each day. Then, the parameters of an ARIMA model are estimated and the model used to generate an ensemble of *20 stationary* series of 10-year length (2001–2010) with a Monte Carlo approach. Finally, the time series are shifted and rescaled on a monthly basis for every decade until 2050 according to the debiased GCM temperature outputs following the change factor approach (Hay et al., 2000) and the daily cycle is added back. The temperature downscaling approach is described in detail in Bordoy (2013). Six years of observed hourly data from Portillo (April 2004–March 2010) are available for the debiasing and the parameterization of the ARIMA model.

For the purposes of this study and in order to reduce computational burden, we retain the projections of only two of the downscaled GCMs and 20 stochastic time series of climate input for each GCM to drive the glaciological model. The following GCMs are retained: 1.) the ECHAM5/MPI-OM model of the Max Planck Institute for Meteorology, Germany, and 2.) the UKMO HadCM3 model of the Hadley Centre for Climate Prediction and Research, UK. The GCMs selected are chosen because of their good performance in simulating present day climate, their ability to represent ENSO events and because they represent well the range of future projections.

Both ECHAM5 and HadCM3 are among the models identified as the best in simulating present-day El Nino-Southern Oscillation (ENSO) variability (Oldenborgh et al., 2005; Guilyardi, 2005). ENSO has a direct and strong effect on the climate and hydrological regime of the Andes of Chile (Masiokas et al., 2006; Rubio-Alvarez and McPhee, 2010; Cortes et al., 2011). The performance of GCMs in reproducing observed ENSO

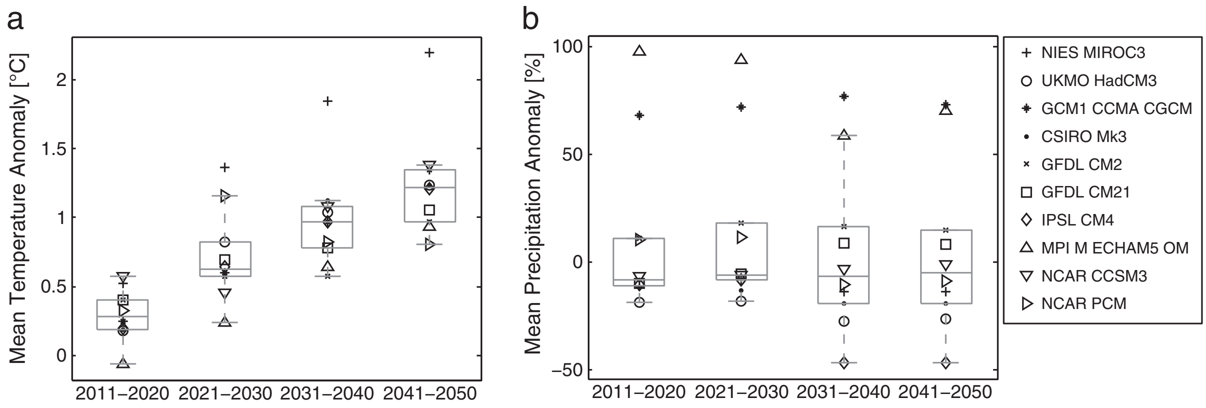

Fig. 5. a) Mean temperature and b) mean precipitation anomalies for the 10 downscaled GCMs: anomalies are calculated with respect to the control period 2001–2011 at the reference station (Portillo in the case of temperature and Riecillos in the case of precipitation). Box plots show minimum and maximum values that are not considered to be outliers (whiskers), 0.25 and 0.75 quantiles (box), and average (line inside box).

variability varies substantially (Oldenborgh et al., 2005; Guilyardi, 2005; AchutaRao and Sperber, 2006; Leloup et al., 2007; Jin et al., 2008). Indeed, most of the models are not able to reproduce the atmospheric response over South America to ENSO anomalies originating in the tropics (Vera and Silvestri, 2009). ECHAM5 was identified as one of the models with the best description of the hydroclimate features induced by ENSO in the Southern Hemisphere and regionally over South America (Vera and Silvestri, 2009). Jin et al. (2008) identify the HadCM3 model as the

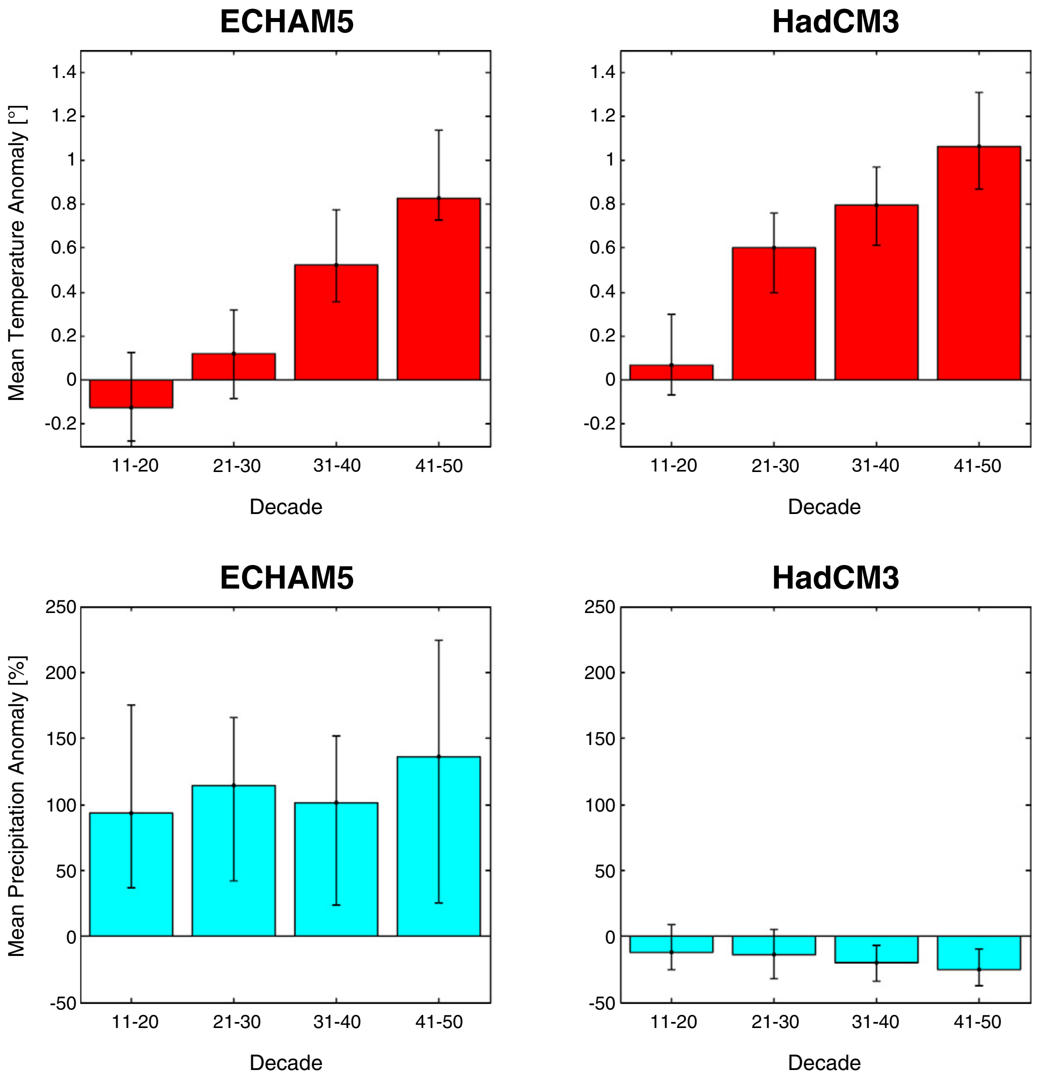

Fig. 6. Mean temperature (top panels) and precipitation (bottom panels) anomalies calculated on the basis of the stochastic ensemble (20 realisations) and the two GCMs (ECHAM5 and HadCM3) used in this study: anomalies are calculated with respect to the control period 2001–2011 at the reference station (Portillo in the case of temperature and Riecillos in the case of precipitation). Error bars represent the 90% confidence interval within the stochastic ensemble.

best at reproducing inter-annual sea surface temperature variability in the tropics.

Fig. 5 shows the mean temperature and precipitation anomalies (in °C and %, respectively) for each decade relative to the base period (2001–2010) and for each downscaled GCM. The spread among projections is large. While the GCM ensemble consistently projects an increase in temperature, the evolution of precipitation is much less clear. The mean of the ensemble indicates a relatively stationary future precipitation regime, but several models show either a strong increase or a strong decrease. ECHAM5 is one of the two models projecting a strong increase in precipitation, while according to HadCM3 future precipitation decreases. ECHAM5 is the only model which projects a decrease in temperatures for the present decade (2011–2020).

Fig. 6 shows the variability within the ensemble of the 20 retained stochastic time series of future precipitation and temperature for the two selected GCMs. The variability is especially high in the case of ECHAM5-derived precipitation. While for air temperature there are differences in the mean decadal anomalies but the pattern of increase is similar between the two models, mean precipitation projections differ dramatically in magnitude and sign (Fig. 6).

7.2. Glacier mass balance model

For the analysis of future glacier response, we use the ETI model coupled to an accumulation and glacier runoff component. The details of the mass balance model are described in Carenzo (2012) and the reader is referred to that publication for a complete explanation. Here we recall only the main model components and the setup used in this work. The choice of the ETI approach to simulate surface ablation is dictated by the fact that only precipitation and temperature are available as standard GCMs outputs, making the application of energy balance models impossible. The ETI model is forced using model outputs downscaled to the stations of Portillo (temperature) and Riecillos (precipitation), respectively. Extrapolation of the future temperature time series is then carried out using the extrapolation scheme 2 (Section 5). The initial maps of ice thickness that are necessary to run the model continuously were generated using the method by Farinotti et al. (2009). Ice flow is not explicitly included, given the lack of data about glacier flow in the region. While the model includes a parameterisation for geometry update due to ice flow (Huss et al., 2010), this needs calibration based on a time series of ice volumetric changes which are not available for the region. The lack of an ice flow component is a strong limitation of the model for long-term simulations, as mass is not allowed to flow from the upper to the lower glacier sections where conditions are conducive to melt. This would tend to produce glaciers that remain confined to their upper sections and the mass balance of which (calculated on the actual area) therefore becomes increasingly positive. Since the main aim of this section, however, is to investigate how uncertainty in climate models outputs translates into uncertainty in glacier response and not to determine the actual future glacier mass balance, we apply the model in this way, but we discuss the implications of this assumption in the section below.

7.3. Future simulations

Fig. 7 shows the annual mass balance projected by the model forced with the two selected GCMs, downscaled as described above, together with the 90% confidence interval of the 20 stochastic realisations for each GCM. Differences between the two GCMs are important. Mass balances are stable or positive for both GCMs, but with more positive mass balances for ECHAM5 and higher variability. Differences between the two GCMs are reflected even more strongly in the annual water production (Fig. 8), by which we indicate both melt and liquid precipitation in the catchment, and approximately corresponding to the catchment runoff after removal of evaporation and possible long term storage. Fig. 8 shows a stronger decline in water production for HadCM3 starting already from about 2010, and a much higher variability of projections for ECHAM5. The spread among realisations for ECHAM5 indeed is quite large, but not as large as to obscure the climatic signal. All in all, and due to the interaction of precipitation and temperature future scenarios, two very distinct trajectories of future changes in potential runoff are evident, one of decline and one of stable water trend (and possible increase in the last decade).

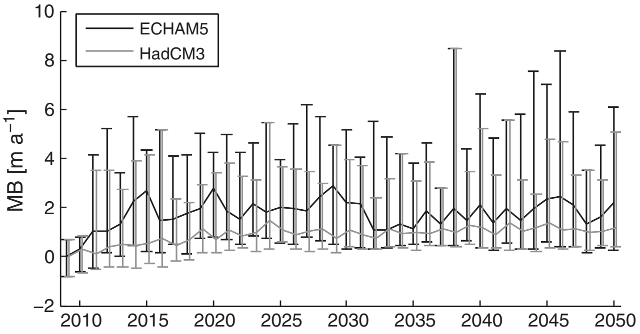

Fig. 7. Annual mass balance for Juncal Norte Glacier simulated by the mass balance model forced with the two (downscaled) GCMs. The solid lines indicate the median of the 20 realisations stochastically generated for each GCM, and the bars the 90% confidence interval of the realisations.

The positive mass balance projected by the model under the two forcings should be regarded with caution. There are a number of reasons that explain that pattern, related to the geometry and characteristics of Juncal Norte Glacier, to the climatic forcing and to the modelling assumptions. Juncal Norte Glacier is a large glacier with a high elevation range, reaching a maximum elevation of 6100 m a.s.l. Recent estimates of the ELA put it at about 4000–4200 m a.s.l. (Carrasco et al., 2005, 2008; Ragettli et al., 2013a), which correspond to an accumulation area ratio (AAR) of about 0.75. The high AAR is one of the reasons why the glacier currently maintains a tongue reaching as low as 3000 m a.s.l. Temperature increases lead to a relatively fast downwasting of the glacier tongue, which may further increase the AAR. The lack of an ice flow component in the model introduces an obvious error in the future projections, as mass is not allowed to flow gravitationally to the lower elevations. This effect would likely be important for a glacier with such a large accumulation area such as Juncal Norte Glacier. Parameterisations of ice flow that have a physical basis and can be applied with little calibration and validation data are still missing in current glacio-hydrological models. On one side, three-dimensional complex models of ice flow that calculate the full Stokes solutions of three-dimensional ice flow using finite differences or finite elements (Jouvet et al., 2008, 2011) are computationally demanding and require knowledge of the bedrock properties as well as numerous physical parameters (Jouvet et al., 2009). On the other site, more empirical parameterisations represent strong simplifications of processes while still requiring data for their calibration and validation.

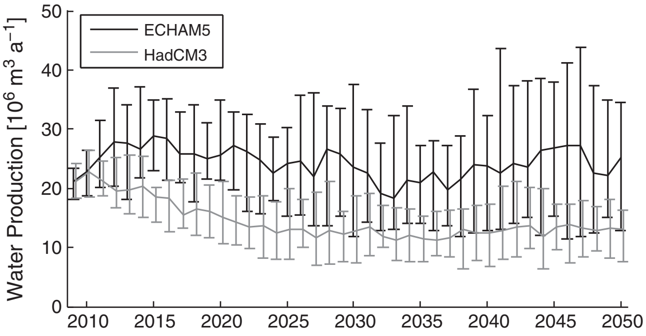

Fig. 8. Annual water production (corresponding to the total of melt and rainfall over the catchment of Juncal Norte Glacier) simulated by the mass balance model forced with the two (downscaled) GCMs. The solid lines indicate the median of the 20 realisations stochastically generated for each GCM, and the bars the 90% confidence interval of the realisations.

Huss et al. (2010) have suggested a parameterisation based on annual corrections of the glacier profile that account for the changes in glacier geometry due to the combined effect of flow and wasting. However, the parameterisation requires calibration with a series of DEMs for the specific glacier or at least for an ensemble of glaciers in the region and it is only valid for retreating glaciers (Huss et al., 2010). Other authors have modelled glacial movement assuming that all movement is due to basal sliding (thus neglecting internal ice deformation), modelled as a function of slope, bedrock properties and ice rheology, which are all strongly simplified (e.g. Immerzeel et al., 2012). Conceptual volume–area scaling relationships (e.g. Radić et al., 2008) have been used in large scale studies of future glacier predictions to estimate future volume projections (e.g. Radić and Hock, 2011) but require data for calibration if applied to small glaciers samples (Unger-Shayesteha et al., 2013).

Given the lack of appropriate methods for representing ice flow in grid-based glacio-hydrological models in data-scarce regions, glacier flow is not included in our approach. We are aware that this affects model outputs and might compromise the validity of our projections. However, our goal was to show that the spread in future climate scenarios is large and able to affect considerably future projection of glacier response. With this in mind, our work has shown that different projections of glacier mass balance and runoff can be large when models are forced with different GCMs. The actual values obtained might be plausible for a glacier such as Juncal Norte Glacier but need to be revisited once more accurate numerical models are available.

8. Concluding remarks

In this paper, we have provided a review of the current status of knowledge about the cryosphere in the Andes of Chile, with emphasis on methods used for these assessments. The most commonly used methods have been either remote sensing studies or detailed physically-based studies at a small number of well equipped and selected locations, which are not representative however of processes at the catchment scale. We have shown that a knowledge gap exists between these two approaches at the glacier and catchment scale, where process spatial distribution is crucial to simulate the response in terms of total mass and integrated runoff. This gap is currently being filled by studies that have emphasised the importance of process understanding at the glacier/catchment scale through advanced modelling (Ragettli and Pellicciotti, 2012; Gascoin et al., 2013; Ragettli et al., 2013a), but bridging the gap will require work on a number of aspects related to both model structure and our understanding of atmosphere–cryosphere processes. We have used modelling work done on one of the few relatively well studied glaciers in the central Andes with some of the best state-of-the-art models to identify uncertainties and knowledge gaps. We have provided examples showing how the complexity of process interplay, the model choices and knowledge gaps on key variables such as snow accumulation at high elevation can contribute to the uncertainty in glacier response simulations. The examples suggest research issues that should be looked at in the future years. Our main conclusions are:

1) Physically-oriented, distributed glacio-hydrological modelling studies in the Andes of Chile are rare. Remote sensing studies are an invaluable tool, but cannot provide explanations for changes and have a coarse temporal and spatial resolution. Point scale, process-based studies are also crucial for process understanding and shed light on the physics of the interaction between glaciers and climate. However, we argue that these should be integrated in larger scale modelling efforts with as much as possible of a physical basis. This obviously also calls for specific, targeted data collection efforts, which should be carefully and jointly planned, but could take advantage of model simulations because distributed modelling can suggest which variables and water balance components have the highest information content for model simulations, as well as which locations should be monitored (Ragettli et al., 2013b).
2) No final assessment can be made as yet of what type of melt model (energy balance versus enhanced temperature index model) is more appropriate – and more accurate – for simulation of glacier ablation at the glacier scale, not even for a relatively well studied glacier such as Juncal Norte. Most detailed field experiments are conducted on relatively low sites of easier accessibility, where both of the models considered here seem to perform in a similar manner (and where we are able to explain the remaining differences thanks to observations at AWSs). However, there are dramatic differences between the models at higher elevations, which result in more than double the amount of ablation over only one melt season (Dec to Feb). These differences could sum up to large errors over longer term simulations. Observations at higher elevations seem to be imperative, for both input meteorological variable and validation data (melt, snow water equivalent distribution). Especially for the EB model, which predicts melt for higher portions of the glacier, initial snow conditions at high elevations are crucial for accurate calculations of total melt rates.
3) Knowledge of the local climatic forcing at high elevations seems to be important and a pressing focus of future research. We have shown that, leaving aside knowledge about radiative fluxes or wind fields, even extrapolation of a variable such as air temperature is subject to high uncertainty and results in large differences in melt model outputs. Air temperature is the one variable that is used in all models of ablation and mass balance, regardless of their complexity and degree of adherence to the physics of processes. All the three modelling experiments presented here did indeed make use of local, ad hoc data sets measured in the field (albeit with a decreasing degree of accurate representation of the spatio-temporal variability of on-glacier air temperature). We suggest that future research should look into how to improve our understanding of climate in mountainous, glacierised catchments, and propose advanced methods to simulate this specific climate. One way forward could be through combinations of target field experiments at high sites with high resolution regional climate models such as WRF (e.g. Maussion et al., 2011; Mölg and Kaser, 2011; Collier et al., 2013).
4) Snow redistribution by wind and avalanches is receiving increasing attention in the scientific community and is recognised as a key factor affecting snow cover patterns, snow water equivalent and energy and mass balance estimates (e.g. Winstral and Marks, 2002; Warscher et al., 2013), as well as the magnitude and timing of melt and runoff (Gruenewald et al., 2010). Its understanding is difficult, however, as it requires data (about snow depth and density at high elevation and about wind and radiative fluxes in the upper sections of mountainous catchments) that are usually not available, and numerical models of the redistribution of snow and its loss by sublimation. Here, we could only partially assess the impact of snow transport by gravity, an important phenomenon for steep terrains. While it is evident that the process changes the patterns of mass balance over Juncal Norte Glacier, concentrating mass on the glacier and removing it from the surrounding slopes, our main conclusion is that without specific data about snow depth and density from the upper sections of the glacier and catchment, it is difficult to calibrate and validate models of snow gravitational redistribution. It seems thus imperative that data sets of this type need to be collected in the Andes of Chile. They should be from the accumulation areas of the glaciers and upper sections of catchments, and be distributed in nature, such as those provided by terrestrial or airborne LiDAR (e.g. Deems et al., 2013).
5) Uncertainty in future climate scenarios is important for future projections of glacier changes also in the dry Andes of Chile, confirming findings of numerous recent studies (e.g. Immerzeel et al., 2013). Our analysis has shown that there is a large spread in temperature and precipitation projections among the 10 downscaled GCMs. While temperature trends agree in sign if not in magnitude, future precipitation shows both increases and decreases. Our analysis of the impact of such large spread on glacier response considered

only two GCMs and 20 stochastic realisations of each, and was limited because of computational constraints and because our aim was not to provide a full assessment of glacier future changes but to indicate through sound modelling research directions and issues to be addressed. Based on our results, it seems important that future glacier and water projections take into account ensembles of climate scenarios as well as the intrinsic variability of climate, which can be large, especially for precipitation (Deser et al., 2012).

6) Despite the growing number of high quality studies in the Andes of Chile, a country-wide picture of changes in glaciers and water is not yet available, neither for the past nor for the future. We conclude this paper by suggesting that distributed, physically-oriented modelling efforts should be carried out on a number of representative catchments covering the remarkably different climatic regions of Chile, designed so as to be truly comparable, i.e. using the same input forcing, calibration data, model structure and physical representation of processes (Immerzeel et al., 2013). In the actual state of knowledge, modelling results are difficult to compare given differences in the model equations, spatial structure (e.g. lumped versus distributed), temporal resolution and differences in the input data (Ragettli et al., 2013a). Advanced distributed glacio-hydrological models need to incorporate knowledge from detailed point scale modelling works as well as to use remote sensing products such as geodetic mass balance or glacier surface velocities for model calibration and validation. They should be forced by latest ensembles of GCMs or RCMs and downscaling techniques that are able to reproduce the specific climate of high-elevation catchments as well as to account for the intrinsic variability of the climate. This perspective of future research requires a fair degree of interdisciplinary research and cooperation, but might pave the way for an extensive, truly comparative and state-of-the art assessment of glacier and climate changes in Chile.

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