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The projected precipitation reduction over the Central Andes may severely affect Peruvian glaciers and hydropower production

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Abstract

Water from glaciers is crucial for the Peruvian hydropower production. Hence, we investigate the glacier-atmosphere and climate interactions in the Cordillera Vilcanota, considering scenarios of significant precipitation reductions until 2100. The glacier mass balance model ITGG-2.0 is used for analysing the energy balance components regarding the projections. The results indicate that a precipitation decrease not only affects the accumulation rate of glaciers but also influences the ablation energy availability. Therefore, glacier retreat in the Central Andes is expected to accelerate, making water availability unsustainable and likely leading to future shortages for the hydropower sector and for other water consuming systems.

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1. Introduction

Water resources are crucial for Peru's energy production, where more than 50% of the total energy is produced by hydropower plants [1]. During the dry season (austral winter), water availability of many hydropower plants is dependent on runoff from glacierized basins. The dry season contribution of glacier melt to the river Santa, Cordillera Blanca (Fig. 1b), for example, was estimated to be about 40% at catchment scale [2]. In this context, and with regard to increasing energy demands and to tensions between water users [3], studying atmosphere-glacier interactions, as well as possible influences of climate change on glacier mass balance and glacial runoff, is of great importance.

For the Tropical Andes, several studies at different spatial and temporal scales have already investigated these relations. By combining multiple data sources a massive ice loss for glaciers in the Cordillera Vilcanota, Southern Peru (Fig. 1c) was detected since 1985 [4]. However, the reaction of glaciers to climate change is complex and glaciers need a response time to find a new equilibrium. For example in the Cordillera Blanca, strong glacier retreats observed since the 1980s may in part be the response of the warming during earlier decades [5]. In some studies, glacier mass balance is modelled at catchment scale to estimate glacial runoff [e.g. 6–8] and for a limited number of glaciers in the Tropical Andes energy balance studies have been performed [e.g. 9–11]. At tropical latitudes, the seasonality of air temperature and solar radiation is low and the availability of melt energy throughout the year is dominated by other processes. Albedo determines the shortwave radiation budget [12] and sublimation was found to be an important process e.g. on Zongo glacier, Cordillera Real, Bolivia [13] and on Artesonraju glacier, Cordillera Blanca [14], during the dry season. On Zongo glacier, reduced melt rates are furthermore caused by reduced longwave emission for clear-sky conditions [15]. The seasonal variation of these processes can be related to the hygric seasonality of the tropics [16,17]. In the Cordillera Blanca, precipitation variability is the main driver of mass balance variability on interannual scale [18]. It was furthermore revealed that glacier melt calculations relying on temperature-index approaches are not suitable to model the relevant processes in tropical conditions [19].

As a consequence of the projected atmospheric warming, future severe glacier mass losses are expected in the Tropical Andes, leading to important water scarcity during the dry season once the glaciers have vanished [20]. For the 34% glacierized Llanganuco catchment, Cordillera Blanca, a strongly increased runoff seasonality for future conditions was found [6]. Results of a statistical runoff analysis by Baraer et al. [21] suggest that several watersheds in the Santa river catchment may have already passed the peak discharge.

A recent study [22] revealed that future precipitation over the Central Andes may decrease to levels never reached during the last millennium. In their study, they relate precipitation to upper level wind conditions and found that austral summer precipitation (DJF) over the Central Andes could decrease by 19-33% by the end of the 21st century. Such changes will severely affect water availability throughout the year, since hydropower, agriculture, and drinking water supply continuously rely on naturally stored water input from the austral summer period. In combination with the reduction of water input further changes in atmospheric conditions are expected.

Here, the aim is to investigate the consequences of a precipitation reduction on the melt water availability from Peruvian Glaciers. Therefore, we analyse the seasonal variation of energy sources for glacier melt for present and future conditions with the glacier mass balance model ITGG-2.0 [6]. We focus on the Cordillera Vilcanota, Southern Peru, where downstream water is used, among others, for hydropower generation.

2. Study site and data

The Cordillera Vilcanota is the second largest glacierized mountain range in Peru, located in the south of the country (about 14° S, 71° W, Fig. 1). The climate is characterised by wet austral summers and dry winters. The region comprises the Quelccaya Ice Cap, the largest tropical ice cap on earth and Laguna Sibilacocha, a 15 km long, dammed glacial lake used for dry season water provision for hydropower generation downstream. Glaciers in the Cordillera Vilcanota span an elevation range of 4700-6364 m a.s.l. and covered an area of 279 km² in 2009 [23]. The glaciers are subject to strong area and volume losses. While glacier area reduced 33% between 1970 and 2009 [23], estimated mass loss was about 40-45% between 1985 and 2006 [4]. At the same time new glacial lakes developed [24].

The National Meteorological and Hydrological Service of Peru (SENAMHI) maintains an automatic weather station (AWS) on Quisoquipina glacier (13.8° S, 70.9° W, 5192 m a.s.l., Fig. 1c). Here, we use records of air temperature, albedo, downwelling and upwelling longwave and shortwave radiation recorded between 2011 and 2013. Fur-

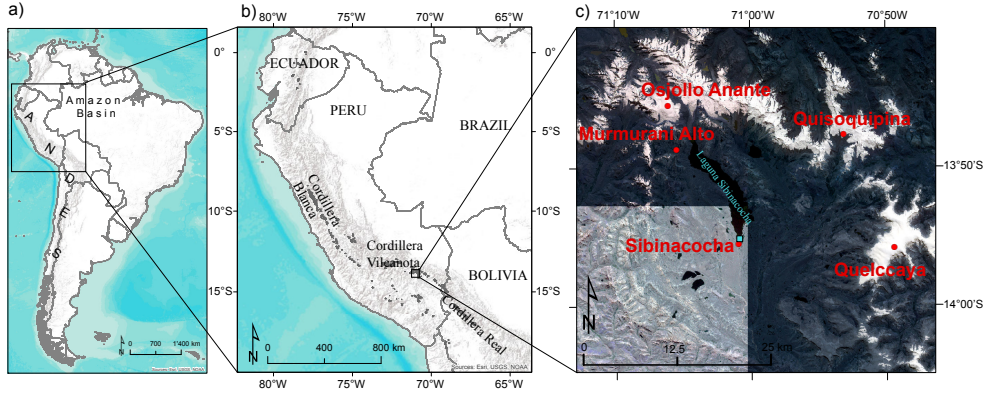


Fig. 1. (a) Overview map with the location of Peru; (b) Overview map of the Peruvian Cordilleras Blanca and Vilcanota and the Bolivian Cordillera Real; (c) Cordillera Vilcanota, RGB composite RapidEye satellite images from 2011, red dots indicate the meteorological stations. The Sibilnacocha dam (blue box) is part of the control system of the downstream hydropower plants Machu Pichu run by EGEMSA and Santa Teresa I run by Luz del Sur.

thermore, we use the following data: daily precipitation sums measured at a precipitation station (13.9° S, 71.0° W, 4870 m a.s.l.), run by the energy company EGEMSA, near to the outlet of Laguna Sibilnacocha; relative humidity, air temperature, pressure from Murmurani Alto AWS (13.8° S, 71.0° W, 5050 m a.s.l.) and wind speed from Osjollo Anante AWS (13.8° S, 71.1° W, 5540 m a.s.l.), both from Appalachian State University; and online available data from Quelccaya station (13.9° S, 70.8° W, 5680 m a.s.l.), University of Massachusetts Climate System Research Center are used.

Climate scenarios we use in this study are based on global circulation model (GCM) outputs from CMIP5 (grid point 13.75° S, 71.25° W) and on the results of Neukom et al. [22]. Here, we focus on projections based on the high emission scenario RCP 8.5. In their work, Neukom et al. [22] suggest a precipitation reduction of 19-33% in the Central Andes for the summer months (DJF) by the end of the 21st century (2071-2100) with respect to 1971-2000, which is caused by changes in upper level wind conditions observed in a CMIP5 ensemble (Table S1, supplementary material of [22]). Under this scenario, increased aridity may result from reduced moisture influx from the Amazon basin due to such circulation changes [22].

3. Methods

The analysis of energy balance components causing ablation is performed with the glacier mass balance model ITGG-2.0 [6]. The model has a monthly resolution and the glacier mass balance is calculated combining the variation of the specific mass balance with altitude (vertical balance profile, VBP) and the specific mass balance at a reference elevation (Eq. 1) according to [16].

$$b_{zr} = c_{zr} - \tau F(f) [SW_{in}(1 - \alpha)]_{zr} + \epsilon_a \sigma T_a^4 - \sigma T_s^4 \Big|_{zr} + C_s (T_a - T_s) \Big|_{zr} \quad (1)$$

zr refers to the reference level, b_{zr} is the mass balance at this level, c_{zr} the accumulation, τ is the number of days per month, $F(f)$ describes the contribution of melt and sublimation to ablation, SW_{in} is the incoming shortwave radiation, α the albedo, ϵ_a the atmospheric emissivity factor, σ the Stefan-Boltzmann constant, T_a the air temperature, T_s the glacier surface temperature and C_s is a heat transfer coefficient. Equation 2 describes the calculation of the contribution of melt and sublimation to ablation.

$$F(f) = (1 - f)/L_M + f/L_S \quad \text{with} \quad f = Q_S / (Q_M + Q_S) \quad \text{where} \quad 0 \leq f \leq 1 \quad (2)$$

f describes the ratio of energy consumed for sublimation (Q_S). Q_M is the energy consumed for melt. L_M and L_S are the heat constants for fusion and sublimation. A detailed description of the VBP is given in [16]. Here, we focus on the application of ITGG-2.0 for modelling the energy balance at the reference level (here the freezing level, defined

as the level at which mean monthly air temperature is 0° C) for glaciers in the Cordillera Vilcanota. The variation of the energy, respectively, mass balance over the glaciated elevation range is not considered and the model is only used for energy balance calculations at the freezing level, where precipitation is assumed to be solid.

Necessary input data are air temperature and at least one moisture related record to which sublimation, atmospheric emissivity, albedo and downwelling shortwave radiation SW_{in} can be related if no further measurements are available. Often, the only available moisture record is precipitation. Linear relations between precipitation and the sublimation ratio f , the atmospheric emissivity ϵ_a (used for calculating the downwelling longwave radiation LW_{in}), albedo α and SW_{in} , respectively, are used to estimate each of these variables. For each linear interpolation, the limits of the corresponding variables have to be calibrated. In this study, for present conditions, mean monthly measured SW_{in} is used as a model input. However, α , ϵ_a and f are estimated from precipitation measurements at Sibinacocha station. Monthly mean measurements of albedo and up/downwelling longwave radiation at Quisoquipina AWS are used to define the ranges for the linear interpolation and the modelled f is compared to a bulk estimation of the latent heat flux according to [25] based on data from Murmurani Alto and Osjollo Anante. Furthermore, the standard temperature lapse rate $\delta T_a/\delta z = -0.0065^\circ C m^{-1}$ is used to extrapolate air temperature measurements to the freezing level. For future conditions, data are adopted from [22] and derived from CMIP5 RCP 8.5 models using a delta approach.

4. Results

4.1. Energy balance for present day conditions

The energy balance for present conditions is modelled at the monthly freezing level (mean $z_r=5080$ m.a.s.l.) using measured precipitation (Sibinacocha), air temperature (Quisoquipina) and SW_{in} (Quisoquipina) as input. We used mainly data for the period 2011-2013, during which long-term average monthly precipitation sums were recorded. Relations between precipitation and albedo, LW_{in} and f , respectively, are evaluated based on measured data.

Correlations between monthly averaged albedo measurements on Quisoquipina glacier and monthly precipitation sums are quite low ($R^2=0.28$ for 2012 and $R^2=0.38$ for 2013). In figure 2a monthly precipitation sums from Sibinacocha station and monthly averaged albedo measurements from Quisoquipina are plotted. It is visible that the albedo and precipitation amounts increase simultaneously, whereas the decrease of albedo is delayed. Therefore, for each month, correlations between precipitation sums of several (preceding) months and albedo were calculated. Best results ($R^2=0.60$ for 2012 and $R^2=0.64$ for 2013) were found summing up the precipitation of three months (albedo reference month and two preceding months). Consequently, this relation is used and not the previously described albedo calculation from monthly precipitation sums [6,14]. The minimum and maximum values used for the linear interpolation are listed in table 1.

The calculation of ϵ_a based on literature values ($\epsilon_{a,min} = 0.7$ and $\epsilon_{a,max} = 0.86$) resulted in overly negative net longwave radiation (LW_{net}) compared to measurements at Quisoquipina (average misfit: $-39 Wm^{-2}$). The average misfit ($-17 Wm^{-2}$) could be reduced using the values given in table 1. The residual misfits are mainly caused by too negative modelled LW_{net} in March/April and October/November and can furthermore be related to possible measurement inaccuracies at Quisoquipina of LW_{out} [26]. Therefore, a plausibility check for the chosen ϵ_a ranges was done by comparing averaged modelled monthly LW_{net} to averaged monthly LW_{net} measured at Quelccaya (average misfit: $-4.3 Wm^{-2}$).

The sublimation-melt ratio f is compared to a bulk estimation of the latent heat flux based on data measured at Murmurani (relative humidity and pressure) and Osjollo Anante stations (wind speed). The minimum and maximum of f and of the bulk latent heat flux coincide in time. But during the transition periods f remains too high/low. The R^2 can be improved from 0.63 to 0.79 if the five months running mean of the monthly precipitation (instead of the monthly precipitation sum) is used for each month to calculate f . This agrees with the findings by [14], who suggest that the estimation of f could be improved for the transition periods between dry and wet seasons.

4.2. Energy balance for future conditions

The consequences of a precipitation decrease on the albedo at the monthly freezing level are modelled with ITGG-2.0 using the same linear relation as for present conditions. This choice is based on the assumption that monthly

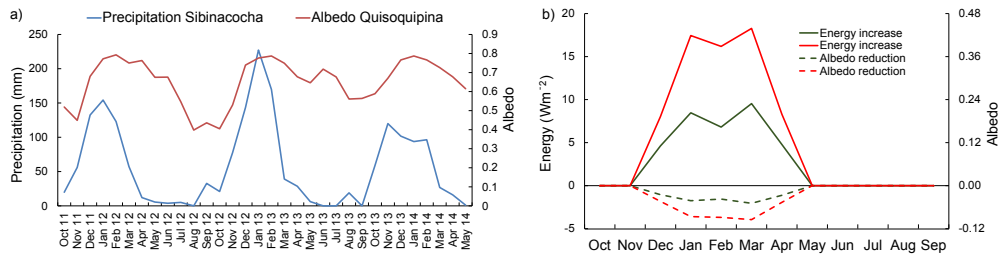


Fig. 2. (a) Monthly precipitation sums (blue) measured at Sibinacocha station and monthly averaged albedo (red) measured at Quisoquipina AWS; (b) Changes in albedo (red dashed line: -33% DJF precipitation, green dashed line: -19% DJF precipitation) and energy available for ablation (red solid line: -33% DJF precipitation, green solid line: -19% DJF precipitation).

Table 1. ITGG-2.0 interpolation ranges of humidity related parameters.

Moisture related parameter	Input	dry conditions	wet conditions
Albedo α	α	0.4	0.79
	Precipitation (3 month sum)	$6 \text{ mm } (3 \text{ m})^{-1}$	$410 \text{ mm } (3 \text{ mths.})^{-1}$
Emissivity ϵ_a	ϵ_a	0.77	0.93
	Precipitation	0 mm m^{-1}	130 mm mth.^{-1}
Sublimation/melt ratio f	f	0.85	0.1
	Precipitation (5 month running mean)	0 mm m^{-1}	100 mm mth.^{-1}

summer precipitation amounts in future lie within the annual variability for present conditions. The influence of a 19% respectively 33% precipitation reduction during the summer months (DJF) on albedo and ablation energy is shown in figure 2b (dashed: albedo decrease; solid lines: energy increase). The ablation energy may rise by about 15 Wm^{-2} due to the albedo decrease caused by a precipitation decrease.

Drier conditions due to decreased upper tropospheric easterly winds [22] will not only affect precipitation amounts but also lead to a reduced cloud coverage. This has likewise consequences on the radiation balance. Less cloud cover during summer lead to a reduced reflection of solar radiation and consequently an increase of SW_{in} . On the other hand, LW_{in} is expected to be attenuated by the reduced cloud cover.

Changes in LW_{in} for the present freezing level due to the precipitation - respectively cloud cover reduction - are modelled with ITGG-2.0 using the same linear interpolation as for present conditions (Fig. 3a). For the 33% DJF precipitation reduction scenario, averaged DJF monthly LW_{in} decreases by about 10 Wm^{-2} . However, cloud cover is not the only variable determining LW_{in} . It is known from GCMs that greenhouse gas (GHG) increases will generally lead to increased LW_{in} [27]. Therefore, the mean CMIP5 RCP8.5 LW_{in} is shown in figure 3b (black line). The projected LW_{in} (all CMIP5 RCP 8.5 models) annual mean increase is 23 Wm^{-2} and increases are highest during the austral winter. LW_{in} increases are persistently higher than the cloud cover related reductions by 10 Wm^{-2} modelled with ITGG-2.0 (Fig. 3b). The increased LW_{in} due to GHG, is thus only partly compensated by cloud cover reductions as modelled with ITGG-2.0. In the following steps, the CMIP5 mean model change is used.

The consequences of a reduced cloud cover during the summer months on SW_{in} are estimated by taking the 90% quantile of the CMIP5 RCP 8.5 model mean SW_{in} change (Fig. 4a). The grid value in the region of interest indicates a SW_{in} increase of 20% for 2071-2100 w.r.t. 1986-2005. A +20% correction is applied to the measured summer SW_{in} to model future conditions.

Sublimation rates depend on turbulence and on the humidity gradient between air and surface. The warming of the atmosphere causes an increase of the atmospheric specific humidity [28], respectively, vapour pressure, whereas vapour pressure at the glacier surface at melt conditions remains unaltered. Changes in vapour pressure were calculated from relative humidity and surface air temperature of the CMIP5 RCP 8.5 model mean for the dry season (JJA), when sublimation dominates over melt for present conditions (Fig. 4b). Dry season vapour pressure increases by 2.4 hPa for the period 2071-2100 w.r.t. 1986-2005. Therefore, the sublimation/melt ratio f cannot be related to precipitation for modelling future conditions.

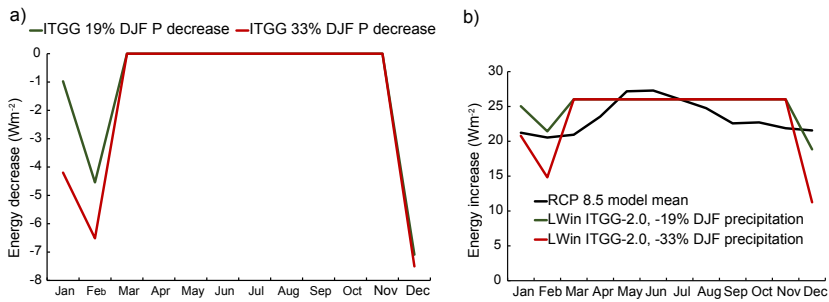


Fig. 3. (a) Modelled longwave radiation (LW_{in}) reduction due to a reduced cloud cover for drier conditions in summer for two scenarios (red: -33% DJF precipitation, green: -19% DJF precipitation); (b) RCP8.5 CMIP5 model mean LW_{in} increase for the grid cell over the Cordillera Vilcanota for 2071-2100 w.r.t. 1986-2005 (black) in comparison to ITGG modelled LW_{in} decrease added to the mean winter (JJA) RCP8.5 CMIP5 LW_{in} increase (red: -33% DJF precipitation, green: -19% DJF precipitation).

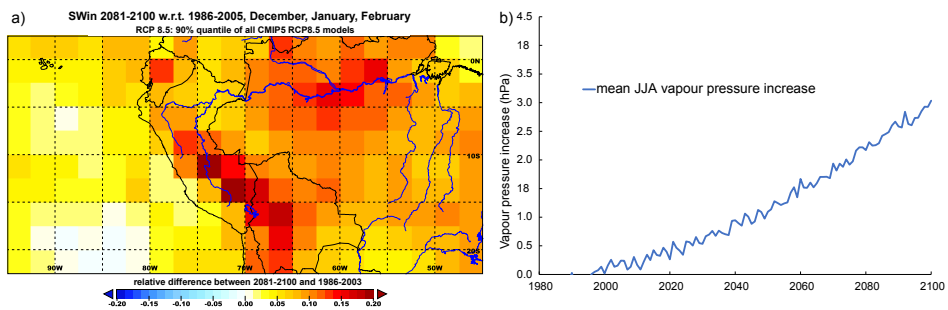


Fig. 4. (a) Changes of the summer (DJF) downwelling shortwave radiation (SW_{in}), 90% quantile of all CMIP5 RCP8.5 models, 2081-2100 w.r.t. 1986-2005; (b) Changes in vapour pressure for the dry season (JJA, blue line) for the grid cell over the Cordillera Vilcanota w.r.t. 1986-2005, calculated from surface air temperature and surface relative humidity of the mean output of all CMIP5 RCP8.5 models.

4.3. Energy sources

For present conditions, sources of ablation energy vary strongly throughout the year (Fig. 5a). Maximum melt rates at freezing level are calculated for the transition period between dry and wet season, when highest energy amounts are available. During this period SW_{in} is increasing and albedo is low. Later, during the wet summer season, SW_{in} is reduced due to cloud cover and more SW_{in} is reflected due to high albedo caused by snowfall events. At the same time LW_{in} is high and therefore LW_{net} is only slightly negative. In March, when albedo is still high, the reduced cloud cover leads to an increase of SW_{in} which is compensated by LW_{net} and ablation energy gets minimal. From May to July, energy is slightly higher than in March, April caused by higher SW_{net} . From August onwards, energy is constantly increasing caused by the increasing SW_{in} . The intra-annual variation of energy sources is still visible for future conditions, but, higher melt energy amounts are available throughout the year (Fig. 5b). In future, LW_{net} is constantly less negative, caused by increasing LW_{in} . LW_{net} is virtually zero during summer. SW_{net} increases from December to April caused by a reduced cloud cover and a reduced albedo.

5. Discussion and conclusion

The main finding of the present investigation is that the available energy for ablation at the freezing level may increase substantially if drier conditions prevail as postulated by [22]. Here, further consequences of air temperature changes have not been investigated. However, temperature changes may have crucial effects on glaciers. For instance, with warmer air temperatures during precipitation events, snow line will be located at higher elevation. This has consequences on albedo and accumulation rates. The here presented results refer to the freezing level where sensible

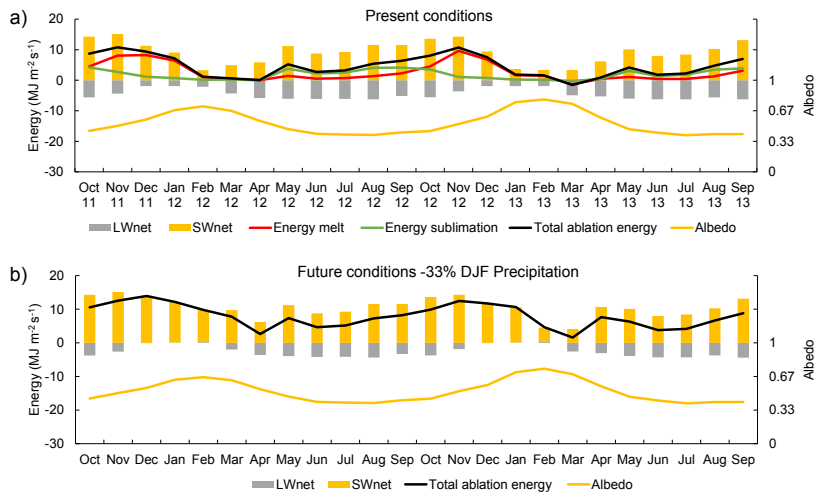


Fig. 5. (a) Modelled values of different terms of the energy and mass balance LW_{net} (grey bars), SW_{net} (orange bars), albedo (orange line), total ablation energy (black line), melt (red line) and sublimation (green line) at the monthly freezing level for the period October 2011 - September 2013; (b) Modelled values of different terms of the energy and mass balance LW_{net} (grey bars), SW_{net} (orange bars), albedo (orange line) and total ablation energy (black line) at the monthly freezing level for a hypothetical two years period with a 33% summer precipitation reduction.

heat fluxes are zero and precipitation is solid. However, this freezing level is projected to be located at higher elevations and this will have severe consequences on the altitudinal distribution of glaciers in the Cordillera Vilcanota.

This study presents an evaluation of present and future availability of ablation energy for glaciers located in the Cordillera Vilcanota, Central Andes. Whereas the wet season is characterized by low net longwave respectively shortwave radiation budget, both energy fluxes with an opposite sign are high during the dry season. It is shown that projected drier conditions (cf. [22]) may not only lead to reduced accumulation but also cause increases of ablation energy. Previously described intensifications of runoff seasonality will be concurrent with total runoff decreases, once the glaciers have changed to lower ice volumes. In a mid- and long-term perspective, drier conditions may therefore lead to annual runoff decreases for two reasons, being (i) a reduction of precipitation input for the hydrological cycle and (ii) an accelerated glacier retreat. At short time scales, runoff may increase unsustainably related to enhanced glacier melt rates. Therefore, it is crucial to be politically and socio-economically prepared for runoff decreases. Here, only projections of the most pessimistic CMIP5 scenario (RCP8.5) were used. However, even for the least pessimistic scenario (RCP2.6) precipitation reductions are probable due to less moisture input from the Amazon basin [22]. That the Amazon basin plays a central role as moisture source for the precipitation in the Cordillera Vilcanota is corroborated by the study of Perry et al. [29]. In their article, they furthermore discuss various low-level moisture sources, which are beyond the scope of this study. This analysis should be regarded as one critical step towards a better understanding of what drives glacier mass balance variability and water availability in this region. More knowledge is needed and it is therefore considered fundamental to strengthen monitoring activities in data sparse regions such as the Cordillera Vilcanota. Meanwhile, possible future runoff decreases should be considered in a comprehensive and integrative water management concept. In the Central Andes, the implementation of such a concept will be a prerequisite for a successful adaptation of the hydropower sector and the other stakeholders to future conditions.

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