

Low Latitude Glaciers: Unique Global Climate Indicators and Essential Contributors to Regional Fresh Water Supply. A Conceptual Approach.

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1. Introduction

Greenhouse gases in the atmosphere trap energy and, if their concentrations increase, e.g., from anthropogenic sources, the aggregate energy of the earth system increases as well. As a consequence, intensities of fluid dynamic processes (atmosphere and oceans), phase changing processes, biochemical processes, and the thermal status of the system will change in a complex and highly interactive manner. Manifold changes in local, regional and global climate are therefore to be expected, but are anything but easy to detect because: Firstly, climate itself is characterised by multi-scale dynamic variability of interacting processes and states. Thus, trends, fluctuations or changes can only be analysed for selected parameters and must be extracted from noise. Secondly, instrumental records, which concentrate on isolated parameters, are limited in time, and proxy -indicators, although covering longer time scales, show complex dependencies on climate, which can be difficult to interpret unequivocally. This paper emphasizes the role of low-latitude glaciers as i) climate proxies and ii) climate-dependent freshwater sources.

Among climate proxies, glaciers play an exceptional role. They exclusively follow physical laws in their response to climate and its fluctuations, and these laws are the same, independent of where the glaciers are located. The gain and loss of ice masses, the so-called mass balance, is the immediate result of weather conditions. In practice, the physical processes governing the mass balance of glaciers must be linked to climate variables by parameterisation. One of these variables is air temperature, which has the highest correlation with glacier fluctuations in the mid and high latitudes. This correlation is so strong, that simple, black box statistical models, which include ablation period temperature and winter precipitation, produce highly satisfactory simulations of glacier mass balances (e.g. Braithwaite and Zhang, 2000; Oerlemans, 2001). Without doubt, changes in air temperature can also be expected to have a distinct impact on fluctuations of low latitude glaciers. However, since seasonality in low-latitude climate is solely a function of the annual cycle of air humidity and thermal seasons are absent, low-latitude glaciers are particularly sensitive to a broad spectrum of climate variables, not merely air temperature. In order to examine the relationship between mass balance and different climate parameters on low-latitude glaciers, we first outline the general features of glacier mass balance (section 2) and low latitude climate (section 3), then present three examples where observed differential glacier retreats indicate an impact of changing humidity (section 4), and, based on these observations, propose a concept for an analytical model (section 5). Lastly, we discuss the characteristics of low-latitude glacier runoff and its importance for water supply (section 6) and address future research perspectives (section 7).

2. Glacier mass balance

The mass balance of a glacier is the immediate result of weather conditions and, in the long term, of climate. Changes in mass balance, in turn, directly impact glacier runoff. On the income side, the mass balance of a glacier is due to the accumulation of solid precipitation, whereas the expenditure side depends on the availability of energy for ablation. Ablation can be due to fusion and/or sublimation. The energy balance equation at a melting glacier surface can be defined as

$$SW_{in} (1-a) + LW_{in} + LW_{out} + H + C + L_s S + L_m M = 0 \quad (1)$$

where SW_{in} is the incoming short-wave radiation, a the short-wave albedo of the surface, LW_{in} the atmospheric long-wave emission toward the ground, LW_{out} the emission from the glacier surface, H the sensible heat flux, and C the conductive heat flow in the subsurface. $L_s S$ and $L_m M$ are the mass consuming terms of equation 1, where L_s and L_m are the latent heat of sublimation and melting, and S and M are the rates of sublimation and melt,

respectively. Conventionally, energy fluxes towards the surface are assumed to be positive. Most of the energy budget terms are closely linked to air temperature and/or air humidity. Air temperature controls most of the energy fluxes and is, in turn, primarily determined by the energy budget of the surrounding surfaces (Ohmura, 2001). However, air humidity and atmospheric moisture content also exert a great influence on the energy budget terms:

- The *incoming short-wave radiation*, SW_{in} , is markedly controlled by cloud cover.
- The reflectivity (*albedo*, α) of the surface strongly depends on snow cover.
- The *albedo* is higher on a sublimating surface than on a melting surface.
- Under constant temperature conditions, the *incoming long-wave radiation*, LW_{in} , emitted from the atmosphere, increases with atmospheric moisture content.
- The *latent heat flux of sublimation*, $L_s S$, depends on the vapour pressure gradient between the glacier surface and the air. Sublimation either consumes a surplus of energy or takes it from the uppermost snow or ice layers (C) by cooling the glacier surface. If a surplus of energy is consumed by sublimation, this energy is no longer available for melting. If, however, humid conditions reduce sublimation, an energy surplus becomes available for melting, which is eight times more effective at removing ice than sublimation.
- If sublimation cools the surface, *long-wave emission*, LW_{out} , from the glacier surface is reduced.

These energy fluxes are of particular concern when considering the response of glaciers to climate factors other than air temperature. Note that, contrary to changes in air temperature, a given change in air humidity can cause glacier responses of different signs. The ultimate response of a glacier to a change in air humidity is closely linked to the initial glacier-climate conditions.

3. Low-latitude climate characteristics

Compared to the mid and high latitudes, the low-latitude atmosphere is characterized by a pronounced thermal homogeneity where frontal activities are practically absent and daily temperature variations are by far higher than annual variations. Two principle features of global zonal circulation, the Inter-Tropical Convergence, ITC, and the trade winds, characterise three different climate regimes. Whereas the ITC is part of a wet climate, trade winds are connected with particularly dry conditions. The respective climate zones are known as the *tropics* and the *subtropics*. The annual cycle of solar radiation leads to an oscillation in the dynamic atmospheric circulation patterns, leaving only the *inner tropics* with continuously wet conditions. The *outer tropics* can be treated as an intermediate zone between the tropics and the subtropics; during the wet season, they have tropical conditions (wet), during the dry season, subtropical conditions (dry) (Kaser, 2001). Most of the low-latitude glaciers are found in the outer tropical regime, mainly because of the meridional lengthening of the austral summer ITC over South America (Kaser and Osmaston, 2002).

In essence, low latitude seasonality is clearly related to hygric cycles whereas thermal characteristics are highly homogeneous and annual temperature variations small (Kaser and Osmaston, 2002). Thus, ablation on low-latitude glaciers occurs all year round whereas accumulation prevails during the wet season. Beyond this, the above mentioned peculiarities of humidity-driven mass balance processes do not only appear from time to time and scattered over the ablation season, as for example in the Alps, but characterise entire seasons. During wet seasons, SW_{in} is usually reduced by more or less persistent cloud cover and α can be high due to snow cover. On the other hand, LW_{in} almost balances LW_{out} (Francou et al., 2003), sublimation is suppressed, and, as a consequence, melting is highly effective. This and the occurrence of precipitation induce a pronounced mass turnover during the wet season. During the dry season, the long-wave balance is negative and, additionally, sublimation consumes most of the available energy, which reduces ablation markedly (Wagnon et al., 1999^{1,2}, 2001). The dry season is thus characterised by a strongly reduced mass turnover. Due to these processes, air humidity, atmospheric moisture content, and the length of the respective seasons dominate the mass balance characteristics of a low-latitude glacier (Kaser, 2001, Francou et al., 2003).

A highly mass consuming scenario can be imagined as follows: if, after a dry season, the onset of the wet season occurs rather gradually, air humidity may rise, quickly turning sublimation into melt. Also, the atmospheric emissivity may increase and ablation will become considerably higher. At the same time, the reduction of SW_{in} , due to increasing cloud cover, is comparatively small. The extreme ablation rates will therefore only be stopped by precipitation and consequent albedo increase. Hence, the immediate occurrence of precipitation at the beginning of the wet period can be crucial for the positive mass balance of a low latitude glacier (Francou and others, 2003). Another scenario describes minor hygric changes which in turn have a highly mass conserving effect: it is the occurrence of precipitation from isolated storms during the dry season which can increase albedo

for weeks or even months, thereby decreasing ablation rates on the glacier. The frequency of such events can have a marked impact on glaciers.

4. Interpretation of differential glacier retreat - three examples from the tropics

4.1 Peruvian Cordillera Blanca (Kaser and Georges, 1997)

The Peruvian Cordillera Blanca stretches 180 km from 8°30' to 10°S, reaches 6000 m a.s.l. at several summits, and is a massive barrier against persistent lower-troposphere easterlies, causing wetter conditions on the Amazon side and drier conditions on the Pacific side. The climate is typical for the outer tropics; the wet seasons (October - April) bring 70 - 80 % of the annual precipitation. In the far north, the Santa Cruz - Pucahirca group shows the largest east-west extension within the Cordillera Blanca. There, a significant retreat of glaciers between two quasi-stationary positions around 1930 and 1950 was reconstructed from air photographs.

The derived equilibrium line altitudes (ELAs), as well as their shift $\Delta ELA_{1930-1950}$, show marked spatial differences among the six glacier areas analysed, with a regional gradient from low values in the east to high values in the west. In the drier westernmost mountains, smaller scale patterns are superimposed on this east-west gradient, with high values of ELAs and $\Delta ELAs_{1930-1950}$ on the slopes exposed to the morning sun. The observed spatial patterns of ELAs can best be explained in terms of humidity: i) Conditions are wetter on the windward Amazon side than on the Pacific side of the Andean chain, causing the east-west trend, and ii) in the drier western mountains, the diurnal cycle of convective clouds leads to shading of the western slopes during the afternoon, causing a local decrease in effective solar radiation. The differential $\Delta ELAs_{1930-1950}$ cannot be explained by differences in air temperature changes which are unlikely to be very variable across a few tens of kilometers. However, temperature changes may have played a secondary role. The maximum temperature contribution to ELA changes can be determined by assessing $\Delta ELA_{1930-1950}$ of the wet eastern glaciers, which are minimally affected by changes in humidity. The combined effects of a differential decrease in precipitation and a differential increase in effective solar radiation are likely the primary drivers behind the observed spatial differences in $\Delta ELAs_{1930-1950}$. ELA changes are probably associated with a decrease in moisture advection from the Amazon basin, which would have affected humidity-related processes along the east-west gradient and would have weakened the diurnal convective cloud cycle.

We used a glacier-climate model (Kuhn, 1980) to estimate which combination of climate variables could have caused the observed $\Delta ELAs_{1930-1950}$. Based on the assumption that $\Delta ELAs_{1930-1950}$ of the wet eastern glaciers provide a maximum estimate of the temperature contribution to ELA changes in the Cordillera Blanca (see above), we calculated a temperature increase of 0.12°C. This temperature change can only explain 33 % of the largest observed ELA rise in the western mountains. The remaining change in ELA was estimated to be caused by a combination of a 2.7% ($0.4 \text{ MJ m}^{-2} \text{ d}^{-1}$) increase in SW_{in} ($I-a$), and a 13 % (155 mm a^{-1}) decrease in accumulation. Potential changes in sublimation were not calculated but probably played a significant role as well.

4.2 Rwenzori Mountains, Uganda/Congo (Mölg et al., 2003)

In the Rwenzori Mountains, Uganda/Congo, glacier retreat throughout the 20th century also shows a striking spatial variability. Spatially differential glacier retreat between 1906 and 1955, as well as between 1955 and 1990, can be observed across all altitude ranges up to the crests. This spatial pattern rules out temperature increases as the primary driver for the same reasons as discussed for the 1930 - 1950 glacier retreat in the Cordillera Blanca. Small-scale variability in glacier retreat can only be due to changes in a limited number of mass balance terms, all of which are related to atmospheric moisture content. A closer examination of glacial and climatic evidence leads to the following hypothesis: owing to a drier atmosphere since the end of the 19th century (Kruss, 1983, 1984; Hastenrath, 1984, 2001; Nicholson et al., 2000; Nicholson and Yin, 2001), both accumulation and convective cloud activity have decreased in East Africa. Consequently, increased incoming short-wave radiation, especially during the morning hours, induced differentially increased ablation on slopes exposed to the morning sun that could not be compensated for by mass advection. The results obtained from a combined radiation-terrain model, run for both a wetter and drier climate scenario, confirm this hypothesis. Model simulations closely reproduce observed spatial patterns of $\Delta ELAs_{1930-1950}$, with strong local losses in glacier surface area where incoming short-wave radiation is high.

4.3 Kilimanjaro, Tanzania/Kenya (Kaser et al., in press, Mölg et al., 2003)

The summit glaciers on Kilimanjaro, Tanzania/Kenya, are located between 5,800 and 5,900 m a.s.l. and are characterised by vertical ice cliffs along the glacier margins, sharp-edged morphology, and penitentes. From a physical viewpoint, all these ice features indicate that net short-wave radiation SW_{in} (1- a) and latent heat flux $L_v S$ provide most of the energy for ablation (e.g. Kraus, 1972). Ablation from positive air temperature (affected by sensible heat flux, H , and incoming long-wave radiation, LW_{in}) is likely absent, which is supported by measured air temperature on the summit's Northern Icefield (climate station operated by University of Massachusetts, Department of Geosciences), which never exceeded -1.6°C since the year 2000. An additional indication is the presence of permafrost at 4,700 m, lower than the tongue of the lowest-reaching slope glacier. The pronounced east-west orientation of the summit ice bodies, and the primary north or south orientation of the fast retreating ice walls both point to solar radiation as the main factor in maintaining glacier recession on the summit. In contrast to the stagnant summit glaciers, the convex-shaped slope glaciers still show dynamics but have retreated far above the altitude of their thermal readiness. The combined evidence from summit and slope glaciers strongly supports that modern glacier recession on Kilimanjaro, which began around 1880 (Hastenrath, 1984), is governed by atmospheric conditions that have been much drier than previously when glaciers experienced growth. This is consistent with glacier retreat on the two other glaciated massifs in East Africa, Rwenzori and Mount Kenya, which are both strongly affected by drier climate since the end of the 19th century (Kruss and Hastenrath, 1987; Mölg et al. 2003). Decreased atmospheric moisture since this time interval is indicated by climatic proxy data, such as historical accounts of lake levels, water balance models of lakes, paleolimnological data and wind and current observations in the Indian Ocean, which strongly impact East African rainfall (Hastenrath, 1984, 2001; Nicholson and Yin, 2001; Verschuren et al., 2000).

To evaluate the role of solar radiation in maintaining the rapid retreat of vertical ice walls on the summit glaciers of Kilimanjaro, we applied an ice-radiation geometry model to an idealized representation of the 1880 ice cap. Simulation results confirm that solar radiation is the primary climatic driver behind the retreat of the summit ice walls under drier climate conditions since ca. 1880 (Mölg et al., 2003).

5. An analytical model approach for investigating low-latitude climate-glacier relations

In the mid latitudes, temperature, moisture advection, and air humidity are strongly connected to high-frequency frontal activities. In contrast, in the low latitudes, temperature is quite constant throughout the year and moisture advection, as well as air humidity, is linked to persistent features of atmospheric circulation. Hence, low-latitude glacier history offers a promising view into the history of long-distance advection and convective transport of moisture, and provides information concerning past atmosphere and ocean dynamics and evaporation conditions on a regional to global scale. This is impressively shown by an analysis of glaciological data from the Central Andes (29°S - 30°S), at the boundary between the extratropical westerlies and tropical circulation patterns (Kull and Grosjean 2000). Changes in past glacier extent in this region appear to have been strongly linked to changes in precipitation patterns on millennial timescales. More recently, Francou et al. (2003) have successfully correlated a 10-year measured glacier mass balance series from Glaciar Chacaltaya, Cordillera Real, Bolivia, with atmospheric circulation characteristics derived from reanalysed atmospheric data.

Recently, a process-based glacier model was developed, which incorporates the unique aspects of low-latitude climate-glacier interactions as a function of the different mass and energy balance processes (Kaser, 2001). The model calculates one of the most characterising features of glacier-climate relations, the vertical profile of the glacier mass balance, VBP , for both wet and dry conditions in the low latitudes. The key terms in the model are i) the duration of the ablation period, which usually lasts all year in the low latitudes, and ii) a parameter describing the contribution of melting and sublimation to ablation under a given availability of energy. Under dry climate conditions, energy is assigned preferably to sublimation, under wet conditions to melting. The VBP s for the mid latitudes, the wet tropics, and the dry subtropics, as calculated by the model, are shown in Figure 1. Modelled VBP s of the dry and wet season in the outer tropics correspond closely with those measured on Glaciar Uruashraju in the Cordillera Blanca (Kaser, 2001). The differences between the dry and the wet VBP are striking and clearly indicate how changes in the intensity and duration of seasons affect the state of a glacier. Mass turnover is extremely reduced under dry conditions and the vertical balance gradients are weak. Thus, small changes in mass balance have marked effects on the ELA and thus on the extent of the glacier. The wet VBP is characterized by a strong balance gradient on the tongue but a weak one in the accumulation area. Consequently, tongues are shorter than on mid latitude or dry glaciers.

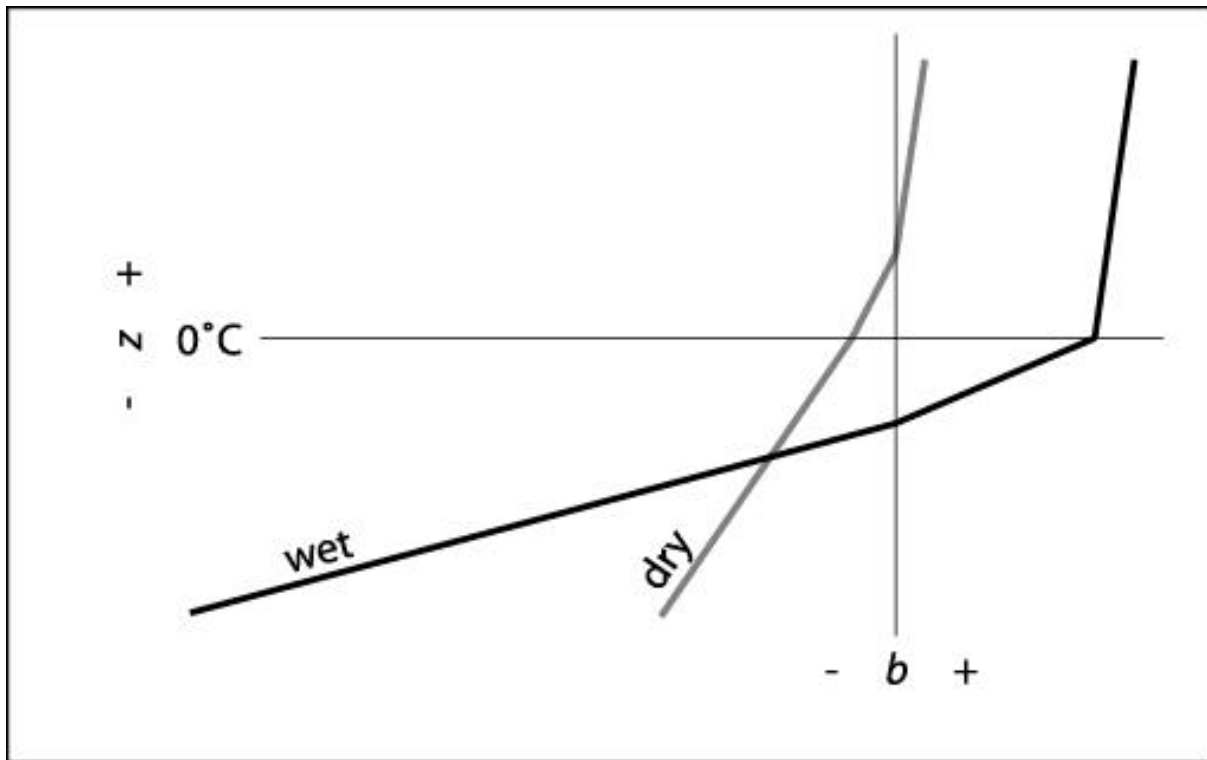


Fig. 1: Vertical profiles of specific mass balance on glaciers, as modeled for different climate regimes (after Kaser, 2001). z indicates the elevation and b the specific mass balance in kg m^{-2} ; positive mass balance (+) and negative mass balance (-). The inclination of the profiles indicates the mass turnover of a glacier where steep profiles (Subtropics/tropical dry seasons) represent weak mass turn over. Note that a mean annual profile from the outer tropics, averaged over a wet and a dry season, may look similar to the mid latitude one. However, despite this similarity, sensitivities to different climate variables are different.

In addition to sensitivity studies for testing the potential impact of different climate variables on glacier mass balance, the model can also be used to investigate the impact of seasonality on mass balance from a process-based point of view. Seasonality characteristics do not only vary spatially related to the location of atmospheric circulation features, but may also change with time, because circulation features change. Hence, process-based glacier-climate studies in the low latitudes promise interesting reconstructions of global climate history, including changes of the thermal status of the earth system as well as dynamic and phase-changing (e.g., condensation, evaporation) processes. First preliminary model applications for tropical glaciers show promising results and open up new perspectives for both sensitivity analyses and the reconstruction of climate history from past glacier extents. For instance, the retreat of glaciers on Cordillera Blanca during the Younger Dryas (12,900 to 11,600 cal yr BP), due to cold but probably dry conditions (Rodbell and Seltzer, 2000), is well simulated by the model (Juen et al., 2002).

6. The impact of glaciers on runoff

The lack of thermal seasonality in low latitudes does not allow the accumulation of a long-lasting snow cover outside the glaciers, leaving glaciers as the major seasonally changing water reservoirs in the low latitude mountains (Ribstein et al., 1995; Kaser et al. 2003). If the dry seasons are pronounced, as is the case in most of the glacierized low latitude mountains, glacier meltwater, although reduced by sublimation, is the only significant contribution to runoff. Contrary to the mid and high latitudes, glacier melt smoothes the seasonal variation of runoff (Kaser and Osmaston, 2002; Mark and Seltzer, this volume). Analyses from the Peruvian Cordillera Blanca show a high correlation between the reservoir capacity of catchment basins - i.e. the monthly or seasonal capacity of catchment basins to store precipitation - and their rate of glacierization (Kaser et al., 2003). Future resource management in quickly developing societies with increasing demands on freshwater has to take into consideration that a considerable amount of the water supply in the seasonally dry tropics is dependent on the consumption of water previously stored in ice. If, as in some less glacierized catchment basins (e.g. in the southern Cordillera Blanca), the "savings" will soon be consumed, there is no credit to be called upon and runoff will strongly follow the rainy seasons (Figure 2). But even if glaciers were to advance under colder

conditions, savings would be stored in glacier ice and less dry season runoff would be available, unless the amount and seasonal distribution of precipitation were to change markedly. Thus, less runoff has to be expected during future dry seasons and water management strategies have to increasingly concentrate on water quality preservation.

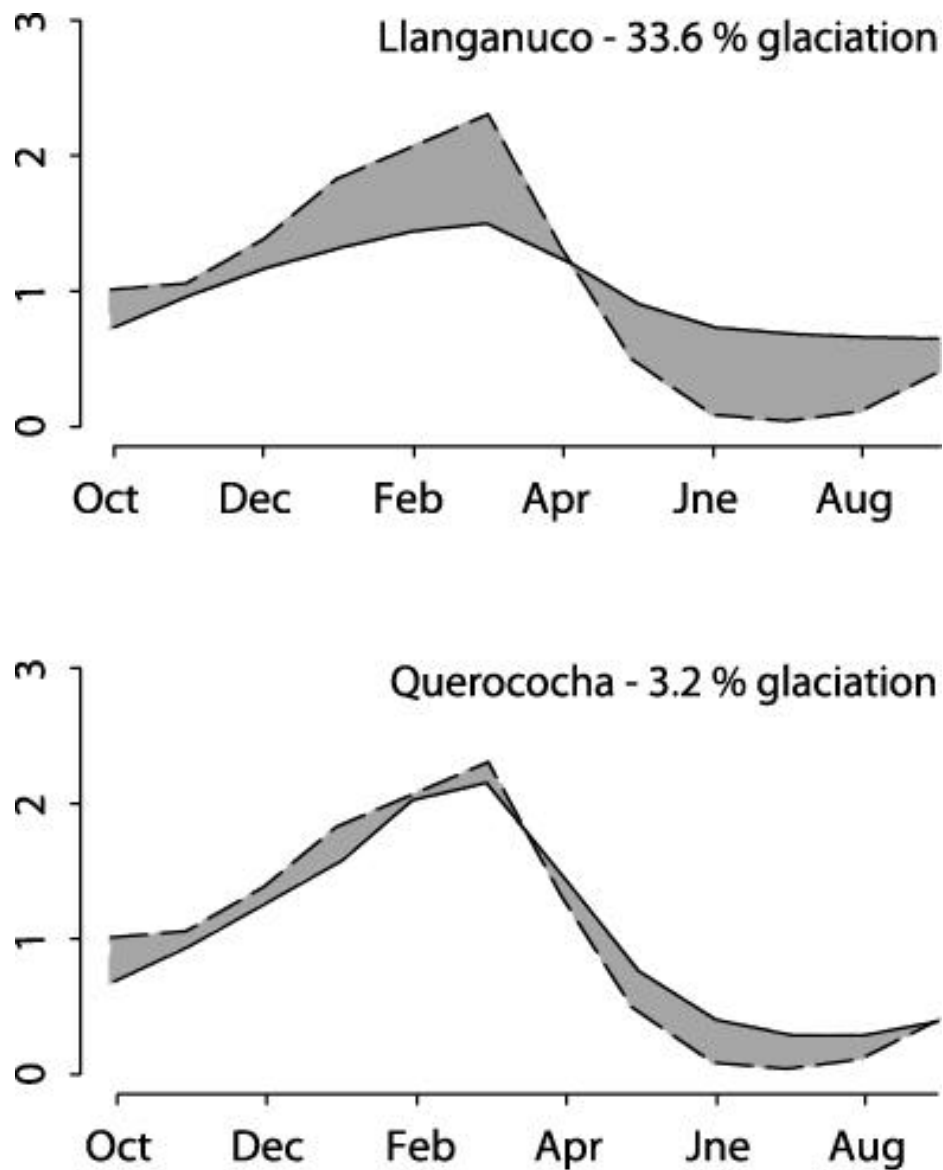


Fig. 2: Mean seasonal variations of precipitation (stippled lines) and runoff (solid lines) coefficients in catchments with different glacier coverage in the Cordillera Blanca, Peru. The coefficients indicate mean monthly deviations from long-term means where 1 is the mean. The shaded area is equivalent to the value of the reservoir capacity of the respective catchment area (after Kaser et al. 2003)

7. Future perspectives

Major climate changes include shifts of the large-scale atmospheric circulation patterns, such as the equatorial easterlies, the trade winds and the westerlies, all inducing strong moisture related gradients when crossing barriers such as the South American Andes (e.g. Kaser, 2002). If the energy content of the earth system changes, these circulation patterns will change their intensity and position with potential major effects on spatial humidity patterns and glacierization (Kull and Grosjean, 2000). In order to monitor such changes, a large-scale network of glacier mass balance measurements along climate gradients will be necessary. Ideally, glaciers should be monitored along the north-south chain of the Andes to assess shifts in large-scale atmospheric circulation. Along these transects, pairs of glaciers, from both the west and the east side of the mountain chain, should be

investigated to assess the orographic effects of the Andes on the glacier mass balance response to climate change. Similar monitoring networks along climate gradients in the Himalayas could lead to a better understanding of fluctuations in monsoon circulation (Kaser, Fountain and Jansson, 2003).

The glaciers on Kilimanjaro's summit plateau offer a particularly interesting tool for investigating climate change in the low latitudes. Under present atmospheric conditions, retreat on the vertical cliffs of these glaciers is unstoppable and they will vanish sooner or later. This raises questions concerning the former vertical structure, and thermal and dynamic conditions of the tropical atmosphere, which allowed glaciers to accumulate prior to the 1880s. The study of present climate-glacier interaction and the reconstruction of past glacier mass balances can help to understand convective dynamic processes at a local scale. In addition, these mass balances can be used to reconstruct patterns of atmospheric circulation and moisture conditions over East Africa and the global tropics.

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