Relationship between precipitation phase and air temperature: comparison between the Bolivian Andes and the Swiss Alps

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Abstract Determining the precipitation phase—rain or snow—is an important factor in modelling discharge in mountainous basins. In a study carried out in the outer tropical Andes Cordillera of Bolivia, half-hourly determination of precipitation phase was obtained by applying a suitable expert system, taking 11 meteorological parameters into consideration that are measured over 21 months at an altitude close to 4800 m. Straightforward relationships between the determined precipitation phase and observed air temperature were analysed in histograms that contain percentage occurrences of snowfall, rainfall and mixed precipitation events for 0.5°C air temperature increments. The graph shows a nearly identical distribution of percentage occurrences of snowfall in the Andes to that on a 1600-m high site in the Swiss Alps. This result suggests that, for hydrological modelling purposes in the outer tropical Andes, the same rain/snow threshold temperature as in the compared Swiss site can be applied.

Key words air temperature; Alps; Andes; Bolivia; hydrological modelling; meteorological data; precipitation phase; Switzerland

Relation entre phase de précipitation et température de l'air: comparaison entre les Andes Boliviennes et les Alpes Suisses

Résumé La détermination de la phase de la précipitation—pluie ou neige—est un facteur important dans la modélisation de l'écoulement des bassins de montagne. Au cours d'une étude menée dans la Cordillère des Andes tropicales externes de Bolivie, une détermination bi-horaire des phases de précipitation a été obtenue par un système expert approprié prenant en compte 11 paramètres météorologiques mesurés à une altitude proche de 4800 m pendant 21 mois. Des relations simples entre la phase de précipitation ainsi déterminée et la température de l'air observée ont été analysées sous la forme d'histogrammes des pourcentages d'occurrence des évènements neigeux, pluvieux ou mixtes, associés à des classes de température de l'air de 0.5°C. Le graphique montre une distribution des pourcentages d'occurrence des précipitations neigeuses quasi identique à celle d'un site des Alpes suisses, à une altitude de 1600 m. Ce résultat suggère que le même seuil de température pluie/neige peut être appliqué lors de la modélisation hydrologique dans les Andes tropicales externes et dans le site suisse comparé.

Mots clefs température de l'air; Alpes; Andes; Bolivie; modélisation hydrologique; données météorologiques; phase de précipitation; Suisse

INTRODUCTION

The determination of the precipitation phase—rainfall or snowfall—is an important factor in modelling snow-cover dynamics in the non-glaciarized areas of high mountain basins, because the hydrological processes of transformation of precipitation into surface flow, and consequently the approaches, are significantly different in snowfall or rainfall computations.

Open for discussion until 1 June 2006

In the tropical Andes Cordillera, Caballero *et al.* (2004), using the ISBA scheme (Boone & Etchevers, 2001), chose an air temperature threshold of –1.5°C to separate snowfall and rainfall events. This threshold was based on the results obtained during a period from 1998 to 2000 by Leblanc (2001) in his MSc study. However, these events were established using visual observations, with poor accuracy, especially because of the frequent confusion between "snowfall" and "snow cover" on the part of the observer.

From October 2001 to July 2003, a new project was carried out with a fully equipped automatic meteorological station, located a few hundred metres downstream of the North Charquini Glacier snout in Bolivia, at an altitude of 4795 m a.m.s.l. (16°17′11″S, 68°6′32″W), cf. Fig. 1. After first exploring a method designed to divide the precipitation phases, using two different raingauge recorders at Charquini station (L'Hôte *et al.*, 2004), Lejeune *et al.* (2003) decided to separate the half-hourly precipitation observations using an expert system based on 11 recorded meteorological parameters. However, the expert system required numerous, accurate and continuous observations, which are difficult to obtain in routine procedures; complete data were necessary.

Therefore, using the phase determinations established by Lejeune *et al.* (2003), the goal of the present study was to establish, for hydrological modelling purposes, straightforward relationships between the phase of precipitation and a single meteorological parameter, the observed air temperature.

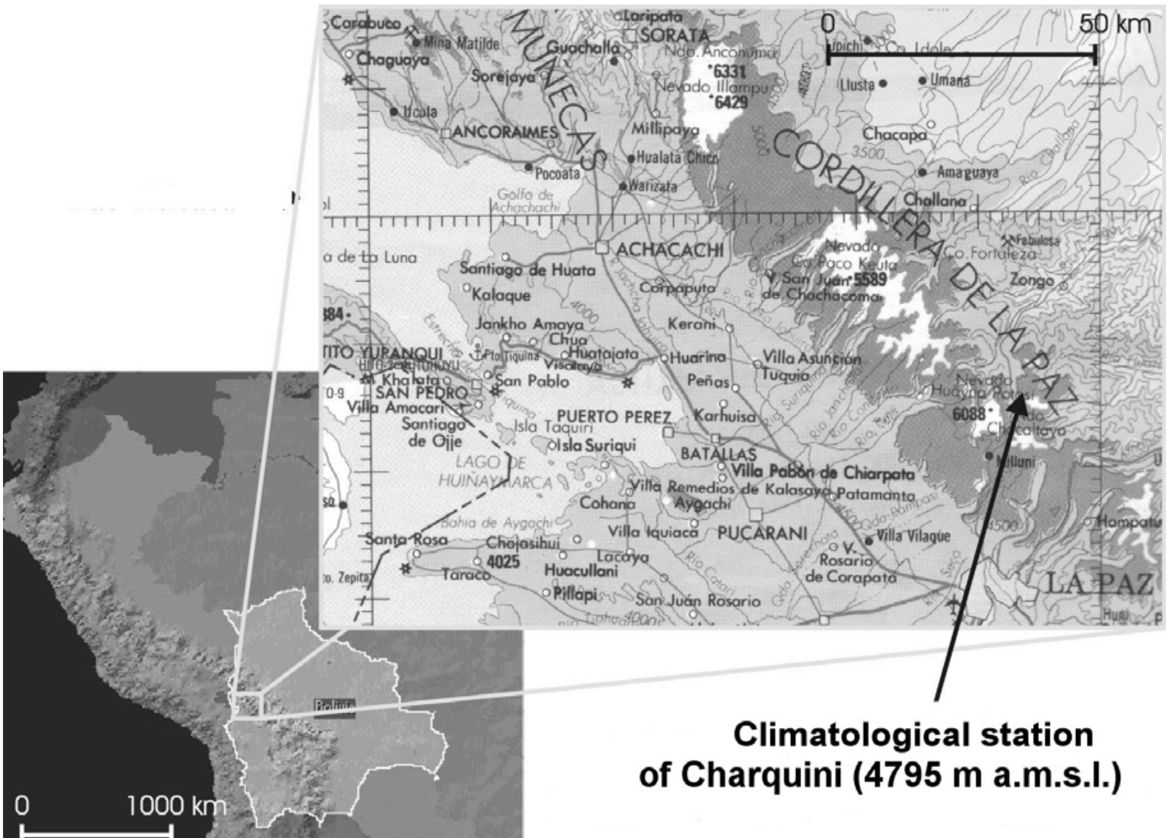


Fig. 1 Location of the study area in the Bolivian Andes.

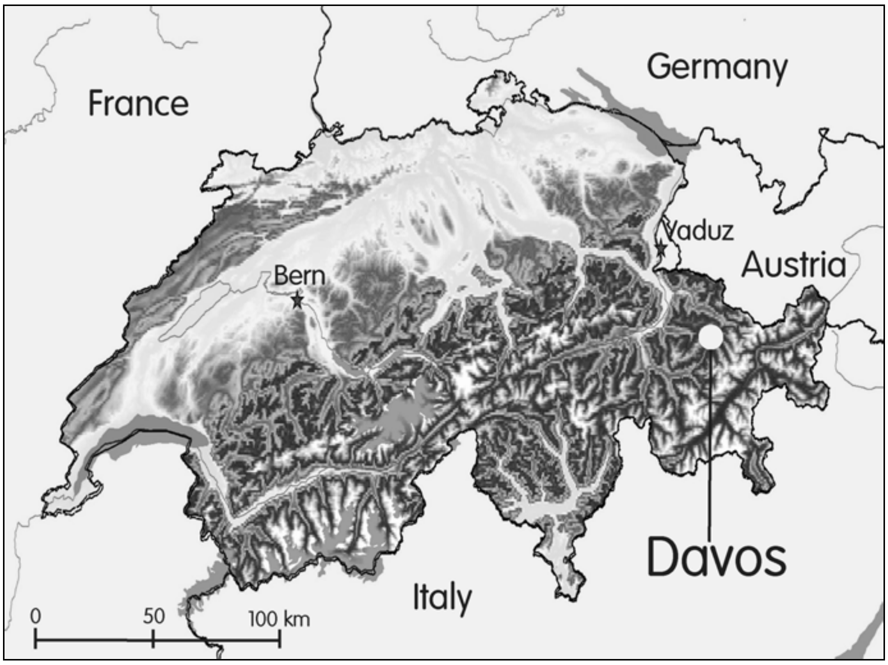


Fig. 2 Location of Davos in Switzerland.

In the scientific literature, very few data of this type are available. The most comparable work was proposed by Rohrer (1989) for the Davos weather station in the Swiss Alps (46°49′N, 09°51′E, 1590 m a.m.s.l.—Fig. 2). Here, the Charquini results are compared with Rohrer's at Davos.

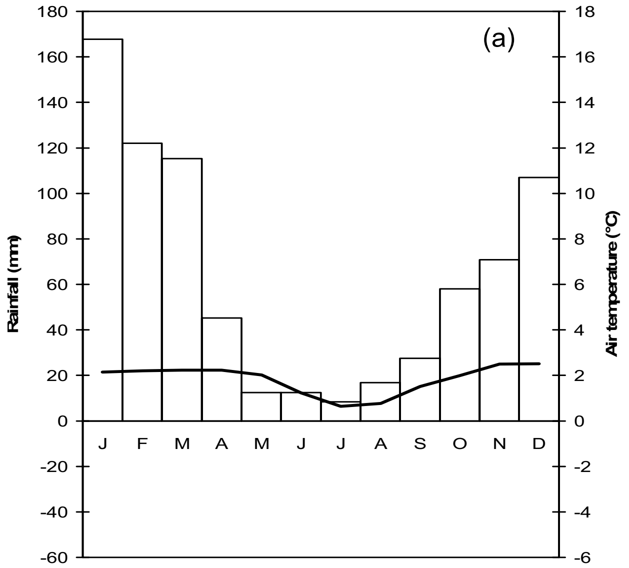
DATA AND METHODS

Climate at Charquini and Davos

The climate at the Charquini station can be characterized using the long-term observations at the neighbouring meteorological station of Plataforma located 2.0 km away at a similar altitude (4750 m). This station is monitored and observed by an employee of the Bolivian Power Company (COBEE). He was the observer who made the visual separation between snowfall and rainfall used in the Leblanc study (2001).

The mean annual precipitation measured at the Plataforma station with the local standard raingauge (without a wind shield) was 763 mm for the period 1987–2003. This amount is certainly underestimated. Taking into account snowfall control measurements made during short intense observation periods, it was concluded that the solid precipitation was not accurately measured by the Plataforma raingauge. Finally, it was assumed that the mean annual solid and liquid precipitation should range from 950 to 1050 mm. These Plataforma mean values can be retained as mean annual amounts at the Charquini station.

Figure 3 shows the mean monthly rainfall and monthly air temperature averages at Plataforma compared to the same averages at Davos, according to the Swiss Meteorological Office (MétéoSuisse).



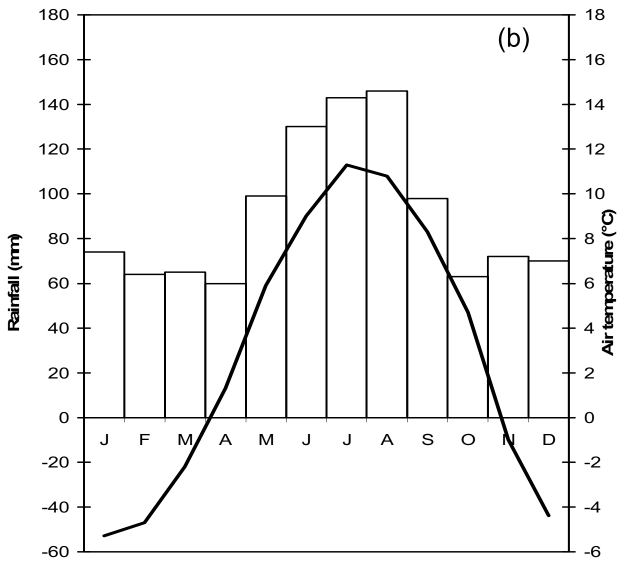


Fig. 3 (a) Plataforma weather station in the Andes: mean monthly rainfall (1987–2003) and monthly air temperature averages (1995–2003). (b) Davos weather station in the Alps: mean monthly precipitation (1961–1990) and monthly air temperature averages (1961–1990), according to MétéoSuisse. Bars represent precipitation and solid lines represent temperature.

Table 1 Annual, monthly and hourly statistics at Plataforma in the Andes (1995–2003 for temperatures; 1987–2003 for rainfall), and Davos in the Alps (1961–1990) according to MétéoSuisse.

Parameter	Plataforma	Davos
Mean annual air temperature (°C)	1.83	2.81
Difference between warmest and coldest monthly air temperature averages (°C)	1.87	16.6
Mean hourly air temperature variation within 1 day (°C)	9.0	unpublished
Mean annual rainfall (mm)	763	1082
Difference between wettest and driest mean monthly rainfall (mm)	169	86

A few comments can be made:

– First, the distribution curves of temperature throughout the year for the Andes and the Alps are out of phase (opposite), because of their locations in the southern and the northern hemispheres, respectively. A similar opposition is observed for precipitation, although the precipitation dynamics are significantly different in the tropical central Andes compared to the temperate continental Swiss Alps.
– Second, as indicated in Table 1, the mean annual values of the air temperature observed at Plataforma and at Davos are similar: respectively, 1.83 and 2.81°C. Nevertheless, at the Plataforma station, the amplitude of the seasonal temperature variation is very low: the difference between the warmest and the coldest mean monthly air temperature is 1.87°C due to the tropical climate. In contrast, in Davos, the seasonal amplitude is very high (16.6°C) due to the temperate continental climate. Table 1 confirms a large variation in hourly temperature within a single day: the average value is 9.0°C, thus substantiating the tropical character of the Plataforma climate.

– Finally, and in contrast to the temperature, the seasonal variation in precipitation between the wettest and the driest mean monthly amounts is greater at Plataforma (about 170 mm) than at Davos (about 90 mm), cf. Fig. 3 and Table 1.

Experiment and calculations at Charquini and Davos

The precipitation at Charquini station was observed at 1.75 m above ground level using an automatic raingauge recorder protected by a wind shield and based on weight measurements; alcohols and oil were added in order to avoid freezing and prevent evaporation. The air temperature was measured with a continuous ventilation device at 1.0 m above ground level (Georges & Kaser, 2002). Except for rare gaps of a few hours, the data file contains continuous records for 21 months between 20 October 2001 and 16 July 2003. Considering that the hydrological year runs from September to August, the incomplete annual precipitation amounts were 1025 mm from 20 October 2001 to 31 August 2002 and 1183 mm from 01 September 2002 to 16 July 2003. Nevertheless, the observations contain the two complete rainy season periods of four months (January–April) with 658.8 and 771.3 mm (about 65% of the annual amounts).

Lejeune *et al*. (2003) separated the half-hourly precipitation observations into two categories: (a) snowfall when the air temperature was equal to or less than –1°C and (b) rainfall when the air temperature was equal to or greater than +3°C. Furthermore, in order to divide the events within the air temperature range (–1°C to +3°C), they used an expert system based on 11 recorded meteorological parameters: precipitation intensity, albedo of the soil and its variation, ventilated air temperature and its variation, ground surface temperature and its variation, reflected long-wave radiation and its variation, and soil heat flux and its variation (for more details, see Lejeune *et al.*, 2003). This automatic method for determining the precipitation phases had already been successfully implemented in the French Alps (Etchevers *et al*., 2001; Lejeune & Etchevers, 2001). It gave good results at the Charquini station too, based on several simultaneous human observations: among 54 precipitation phases observed by a meteorologist in the field, 32 exact determinations were counted by the expert system, 20 were acceptable (mixed precipitation instead of snowfall or rainfall, or the reverse) and two phase determinations were erroneous.

In this study, a half-hourly time step was used to analyse the following parameters extracted from the input file of Lejeune *et al*. (2003): the ventilated air temperature and separated series of snowfall, rainfall and mixed precipitation. It must be noted that the mixed precipitation series contains some indeterminate phases (about 20% of the mixed series), because of uncertainties due to the expert system of Lejeune *et al.* (2003).

Consequently, taking into account a gap of 26 days from 18 April to 14 May 2002, there are 29 186 half-hourly observations, with 4395 occurrences of precipitation (15.1% of the total time steps). In order to limit the discussion to the specific range of air temperature at which snow may occur, the 4013 time steps with air temperature below 4.25°C were selected.

To calculate the relative percentage of occurrence for each phase (snow, rain, or mixed precipitation) associated with a specific air temperature category, the temperature observations were grouped into 0.5°C categories. The same air temperature distribution ranges were chosen as used by Rohrer (1989) at the Davos station from 1978 to 1987, where the monitoring equipment was similar to that used at Charquini: automatic raingauges and ventilated air temperature. Nevertheless, it should be noted that the method for determining the precipitation phase was different in Davos, with human observations eight times a day, as opposed to half-hourly readings by an automatic expert system used at Charquini.

RESULTS AND DISCUSSION

First, the Charquini recordings showed 43% snowfall, 37% rainfall and 20% other (mixed and undetermined precipitation) events, based on 4013 half-hourly precipitation events associated with temperature values below 4.25°C over 21 months.

Figure 4 shows the relative percentage occurrences of snowfall, rainfall and mixed precipitation determined in the Andes according to the results of Lejeune *et al*. (2003) and reconstructed in the Alps using Rohrer's paper (1989). The snowfall histograms (Fig. 4(a)) show percentages alternately smaller or greater in the Andes than in the Alps. The discrepancies are smaller than or close to 10%, except for the temperature range 0.5–1.0°C, with a discrepancy of approximately 25%. For this last temperature range, the greater percentage in the Andes can be compared to the symmetrical discrepancy on the mixed precipitation histograms (Fig. 4(c)). Nevertheless, these snowfall histograms show the rather good similarity of the snowfall distribution percentages in the Andes and the Alps.

On the rainfall histograms (Fig. 4(b)), one can observe that all the rainfall events occur in the air temperature ranges above 0.5°C, in both the Andes and the Alps. Moreover, for all the percentages of rainfall occurrence in temperature classes above 1.0°C, the Andean rainfall histogram has systematically lower values than the Alpine rainfall histogram, from 13% to 32%. These discrepancies correspond to the symmetrical differences observed for the same temperature ranges on the mixed precipitation histograms (Fig. 4(c)).

Figure 4(c), shows the relative percentage occurrences of the mixed or undetermined precipitation in the Andes and the Alps. The rather noteworthy dissimilarities between the histograms, mainly for the temperature ranges above 1.0°C, are symmetrical to the dissimilarities of the rainfall histograms.

The dissimilarities noted on each pair of histograms can be explained mainly by the different processes in determining the precipitation phases: human observations in the Alps and an expert system in the Andes; this explanation is confirmed by the symmetries described above. Other suggestions can be made to explain these dissimilarities such as: (a) the physical environment: latitude, air pressure (large difference in elevation), wind direction, etc.; and (b) the local climate differences: types of snow grain, variations in temperature during the day, etc.

Table 2 summarizes the results of the snowfall histograms (Fig. 4), linking the air temperature ranges in the Andes and the Alps with some characteristic percentage occurrences of snowfall events, frequently used in hydrological models: 50%, 90%, 95% and 100%. The temperature difference between Charquini and Davos, alternatively positive and negative, shows values less than or equal to 0.50°C.

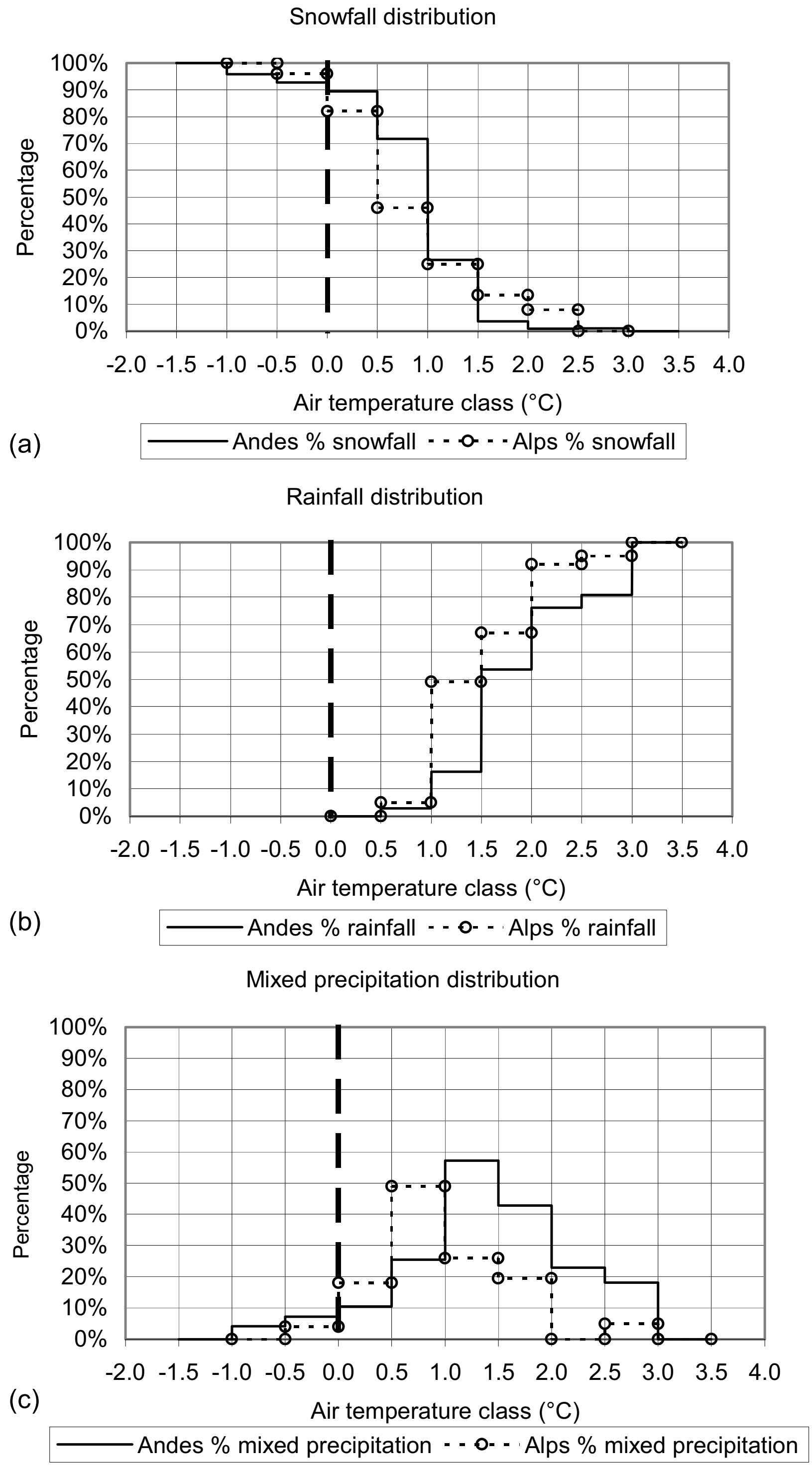


Fig. 4 Relative percentage occurrences of (a) snowfall, (b) rainfall and (c) mixed precipitation associated with the 0.50°C air temperature categories in the Andes and in the Alps.

Finally, with respect to possible seasonal dissimilarities at Charquini, the complete two-year rainy-season sample (January–April) and the two-year transition-season sample (September–December) each showed identical percentages to the full annual

Table 2 Air temperature classes associated with characteristic percentages of snowfall occurrence, usable for hydrological purposes in the Bolivian Andes. Comparison with data at Davos in the Alps, according to MétéoSuisse.

Percentage snowfall	Air temperature class (°C): Andes (Charquini)	Alps (Davos)	Difference (°C) Charquini – Davos
0%	3.00–3.50	2.50–3.00	+0.50
10%	1.25–1.75*	1.75–2.25*	–0.50
50%	0.75–1.25*	0.50–1.00	+0.25
90%	0.00–0.50	–0.25–0.25*	+0.25
95%	–1.00– –0.50	–0.50–0.00	–0.50
100%	–1.50– –1.00	–1.00– –0.50	–0.50

* for this case, intermediate values were calculated in the 0.50°C-increment categories.

data. However, the 2-year dry-season sample (May–August) was too small to obtain significant results.

CONCLUSION

The main result of this comparative study, based on precipitation data from the Andes and the Alps, is the good similarity between the percentages of snowfall occurrence *vs* air temperature histograms, in spite of the different climate, altitude and procedures for determining precipitation phases. The empirical relationship obtained between the air temperature ranges and the percentages of snowfall occurrence can be used in hydrological modelling approaches, whatever the season in the Andes. For instance, in modelling, identical air temperature thresholds between snowfall and rainfall events can be assigned in the Andes and the Alps.

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