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Solid precipitation on a tropical glacier in Bolivia measured with an ultrasonic depth gauge

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[1] An ultrasonic depth gauge was used to measure snowfall over a 2-year period near the equilibrium line of the Zongo glacier (2.4 km^2), Bolivia (16°S). Study of the influence of wind, air temperature, and air moisture on the measurements gives a quantification of snowfall at a 3-hour time step, with a sensitivity of 1 cm of snow. The density of fresh snow is estimated by comparison with rain gauge measurements. The year is marked by a dry season from May to August and a wet season from December to April, during which accumulation and melting coincide on the glacier. Snowfall events are associated with a wind of moderate speed from the valley (less than 4 m s^{-1}). Masses of moist air originate in the Amazon basin. The orographic effect produces precipitation at midday in the Andean valleys and in the afternoon in the high mountains. Nighttime snowfall events occur during periods of bad weather related to the regional atmospheric circulation and last several days. The density of fresh snow is high, about 250 kg m^{-3}, because of the high air temperature during snowfall events (over -3°C). The high snow density and the moderate wind speeds prevent snow drifting conditions, which results in low spatial variability of the accumulation on tropical glaciers. Accurate recording of snowfall at a short time step is important for the study of energy fluxes at the glacier surface because snowfall events greatly increase the albedo and solar radiation is generally the main source of melting energy. *INDEX TERMS:* 3354 Meteorology and Atmospheric Dynamics: Precipitation (1854); 1863 Hydrology: Snow and ice (1827); 1878 Hydrology: Water/energy interactions; *KEYWORDS:* glacier, precipitation, snow, tropics, snow density, ultrasonic depth gauge

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1. Introduction

[2] On the glaciers of the tropical Andes, ablation and accumulation coincide in summer. Contrary to glaciers in the high and mid latitudes, accumulation and melting are strongly related, which makes summer-accumulation type glaciers particularly vulnerable to possible climate warming [*Francou et al.*, 1995; *Kaser et al.*, 1996]. In the intertropical zone, seasonal variations in solar radiation and temperature are low; the fluctuations of the energy balance at the surface of glaciers are controlled by the cloud cover and precipitation [*Wagnon et al.*, 2001]. Snowfall events typically alternate with periods of melting at intervals of a few hours, causing strong variations in the surface albedo [*Sicart et al.*, 2001]. The objective of this study was to better quantify the snowfall events that temporarily cover the ablation area.

[3] Snowfall measured with rain gauges is generally deficient [e.g., *Larson and Peck*, 1974; *Sevruk*, 1989; *Duchon and Essenberg*, 2001]. Automatic gauges based on a tipping-bucket type measuring sensor require a heating element to melt any solid precipitation prior to measurement. However, the use of heated gauges is not recommended because they cause excessive evaporation loss [*Goodison et al.*, 1998]. An ultrasonic depth gauge provides a different measure of snowfall, measuring the relative surface height [*Gubler*, 1981; *Goodison et al.*, 1988; *Lecorps and Sudul*, 1989]. It generally monitors daily snow accumulation and melt [e.g., *Oerlemans and Knap*, 1998; *Hardy et al.*, 1998]. This study investigated the characteristics of the measurement method (precision, error factors and sensitivity) in order to measure snowfall on an hourly basis on the tropical Zongo glacier in Bolivia. Comparisons of ultrasonic and rain gauge measurements give an estimate of fresh-snow density, a parameter difficult to measure directly [*Goodison et al.*, 1981]. However, the unknown catch efficiency of the rain gauge in measuring snowfall limits the accuracy of the density estimate.

2. Location, Climate, and Measurements

2.1. Location and Climate Conditions

[4] The Zongo Glacier is situated in the Huayna Potosi Massif (16°15′S, 68°10′W, Cordillera Real, Bolivia) on the

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western margin of the Amazon basin and on the eastern margin of the Altiplano basin. This valley-type glacier is 3 km long and has a surface area of 2.4 km^2. The glacier flows out from 6000 to 4900 m above sea level (asl). Site characteristics are presented in detail by *Francou et al.* [1995].

[5] The Huayna Potosi Massif belongs to the outer tropics, characterized by a strong seasonality of the precipitation with a single wet season and a pronounced dry season [*Schwerdtfeger*, 1976]. The precipitation pattern is determined by the seasonal oscillation of the intertropical convergence zone (ITCZ). Between March and September, the ITCZ is located north of Bolivia and tropical anticyclones produce a dry climate. From October to March, the ITCZ moves to its most southerly position. Then, rainfalls of convective nature are linked to the rise of moist air from the lowlands to the east of the Andes, causing a wet climate producing around 70% of the annual precipitation [*Aceituno and Montecinos*, 1993; *Vuille et al.*, 1998]. The hydrological year is counted from the end of the dry season, 1 September. Precipitation on the Zongo glacier was examined during two hydrological years: 1998–1999 and 1999–2000. The limit elevation between rain and snow remained at about 4800 m asl, below the front of the glacier.

2.2. Measuring Instruments

2.2.1. Ultrasonic Depth Gauge

[6] Since September 1998, changes in the height of the glacier surface at 5150 m asl have been measured by an ultrasonic depth gauge (Campbell, UDG01) fixed 1 m above the surface to a construction drilled into the ice. The measurement is based on a multiple-echo process whose cycle is completed in a few seconds. The depth gauge records the accumulation of snow (height decrease of the sensor) or the melting of ice and melting or packing of snow (height increase). According to the manufacturer, the accuracy and the resolution of the UDG01 depth gauge are ±1 cm (or 0.4% of distance to target) and 1 mm, respectively [*Campbell Scientific*, 1993]. Operating temperature and humidity are –25 to 50°C and 5 to 95%, respectively. The parallelism with the surface and the height of the sensor are adjusted every two weeks. Rime was never observed to obstruct the sensor. During the two-year period 1998–1999 and 1999–2000, the surface of the glacier remained smooth, no penitents appeared.

2.2.2. Rain gauges

[7] A storage rain gauge (Pg, opening: 2000 cm^2, height: 1 m) was set up on the glacier on 1 September 1999 approximately 20 m away from the ultrasonic depth gauge. It contained 1 cm of oil to reduce loss by evaporation. Until the end of April 2000, the depth of the water was measured and the rain gauge was adjusted to a vertical position every two weeks. At an elevation of 3900 m asl, below the glacier in the rainfall zone, a tipping-bucket recording gauge (Pv, opening: 900 cm^2) measured precipitation every half hour at 0.1 mm increments.

2.2.3. Weather station on the glacier

[8] Air temperature (ventilated), wind speed and direction were measured every half hour by a Campbell automatic weather station located 5 m from the ultrasonic depth gauge. The height of the sensors was adjusted to 180 cm every 15 days.

3. Ultrasonic Depth Gauge Measuring Method

3.1. Influence of Temperature, Humidity, and Wind on the Measurements

[9] The speed of sound in the air depends on the temperature and humidity as well as on the speed of vertical wind [*Conturie*, 1954]. The dependence of the speed of sound (c) on the density of the air can be reduced to a function of the air temperature (T):

$$c = \sqrt{\frac{R\,T\,Y}{M}} \tag{1}$$

with R the constant of perfect gases = 8.31 J K^{-1} and Y = 1.4 for dry air and M the molar mass of gas (0.029 kg mol^{-1}). Around 0°C, the correction in temperature is on the order of 2 mm per Kelvin for a measurement of 1 m. The effect of moisture is obtained by replacing in (1) the air temperature T by its virtual temperature $T' = T(1-0.378e/p)^{-1}$, where e is the partial pressure of water vapor and p is the total pressure in the air. For T = 273 K and p = 540 hP (5150 m asl), a drastic variation in relative humidity from 40% to 100% causes a variation of 1.3 mm of the depth gauge measurement at a height of 1 m. The vertical wind speed is added to or subtracted from the speed of sound, depending on the direction. This disturbance is small because the measurement cycle of the ultrasonic depth gauge represents an average state of the atmosphere over a few seconds. Moreover, as the pulse travels the distance between the sensor and the surface in both directions (emission and return), the effects of the vertical wind speed tend to compensate each other.

[10] The measurements were corrected for temperature according to (1). No correction in the humidity of the air was made because its variability above the glacial surfaces and its influence on the ultrasonic measurements are lower than those of the temperature, and because the automatic humidity measurements are not very accurate in glacial environments [*Moore*, 1983]. The quality of the temperature and humidity corrections is limited as the measurements are made at only one level, although strong gradients in temperature and humidity can appear near the surface. According to *Goodison et al.* [1988], above the snow surfaces, where the surface layer is typically stable, the disturbances in the ultrasonic measurements related to the temperature vertical gradient and to vertical wind speeds are on the order of 1 mm for a height of 1 m.

3.2. Measurement Uncertainty

[11] A measurement is modeled according to: $x_i = x_o + \varepsilon + \delta$, where x_i is the result of the measurement, x_o is the true length, ε is the total systematic error, and δ is the total random error. Since this study concerned the variations in surface height, the systematic errors are not considered ($\varepsilon = 0$). The model hypothesis is that the random error is a variable with a zero mean that obeys the normal law.

[12] To estimate the uncertainty on the measurement in the climate conditions of the Zongo glacier, we observed the measurements over two dry and cool days when neither snowfall nor melting occurred (Figure 1). The 89 measurements did not follow a trend. No relation appeared between the ultrasonic measurements and the wind speed, air temperature, or water vapor pressure. The standard deviation (SD)

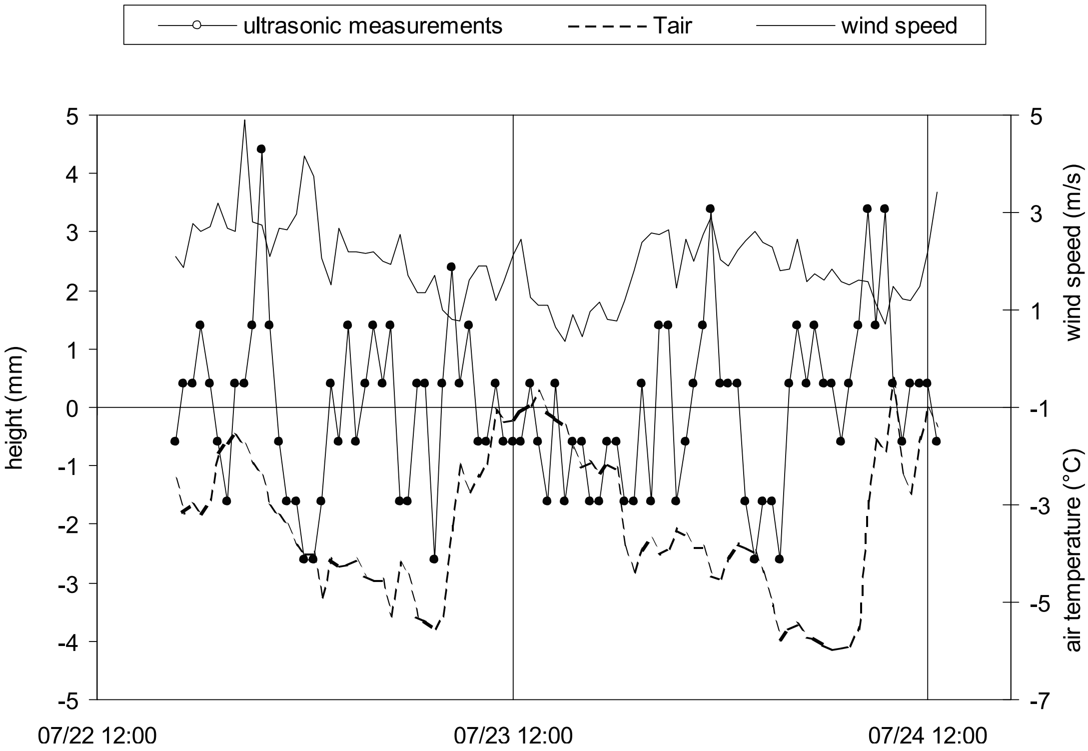

Figure 1. Half-hourly values of the ultrasonic depth gauge measurements from 22 to 24 July 1999 (left *y* axis). Air temperature and wind speed are also shown (right *y* axis). Neither snowfall nor melting occurred during these 2 days.

was 1.4 mm. Given the short measurement series, as a precaution we took $\sigma = 2$ SD = 3 mm as the standard deviation of the random error on the ultrasonic depth gauge measurements. At a confidence level of 99%, we calculated $3\ \sigma \approx 10$ mm, the same as the manufacturer's measure of accuracy.

3.3. Sensitivity of the Measurement and the Time Step of the Study

[13] Table 1 shows that over the year 1999–2000, 85% of the height variations over a half-hour period were less than 6 mm (2σ). Therefore, at a confidence level of 95%, 85% of the comparisons between two successive measurements were not significant. The means of several measurements were calculated to reduce the random errors, and a time step greater than half an hour was chosen to detect significant height changes.

[14] For n measurements, the Student *t* tests comparing the means show that the sensitivity of the measurement method is reduced by $5\sigma/\sqrt{n}$, with the α risks (the risk of rejecting the hypothesis when it is true) and β risk (the risk of confirming the hypothesis when it is false) set at 5% [*Neuilly and CETAMA*, 1998]. To detect, in 90% of all cases, the snowfall events larger than 1 cm, the means of three measurements must be considered (n = 3). Table 1 shows that 80% of the height variations over a one-hour period are smaller than the errors on the measurement. Thus the differences between 3 consecutive measurements generally characterize only the error on the measurements, which can be reduced by the calculation of their mean.

[15] The height variations should be calculated over a time interval long enough to detect the true height changes during the snowfall and short enough to detect a snowfall before melting begins. In the valley, the rain gauge measurements showed that precipitation lasted at least half a day, and we observed that the bad weather usually arrived in the late morning and lasted until nightfall.

[16] A compromise was obtained with a 3-hour time step. Thus the method consists in comparing means of 3 consecutive measurements spread over one hour at 3-hour intervals, so as to detect height changes of more than 1 cm. Solid precipitation was represented by the decreases in the distance between the sensor and the surface, which were multiplied by the fresh-snow density to be converted into water equivalent.

4. Results and Discussion

4.1. Distribution of Precipitation Over 1 Year

[17] Figure 2 illustrates the progression of the daily ultrasonic measurements during the two years 1998–1999 and 1999–2000. Since melting and precipitation generally

Table 1. Probability Density of the Ultrasonic Depth Gauge Measurement Variations in Millimeters (Δh)[a]

	$-\infty < \Delta h < -6$	$-6 < \Delta h < 0$	$0 < \Delta h < +6$	$+6 < \Delta h < +\infty$
Differences between two successive depth measurements (30 min, 17,520 data)	7%	34%	51%	8%
Differences between three successive depth measurements (60 min, 8760 data)	9%	33%	47%	11%

[a] Measurements were made from 1 September 1999 to 31 August 2000.

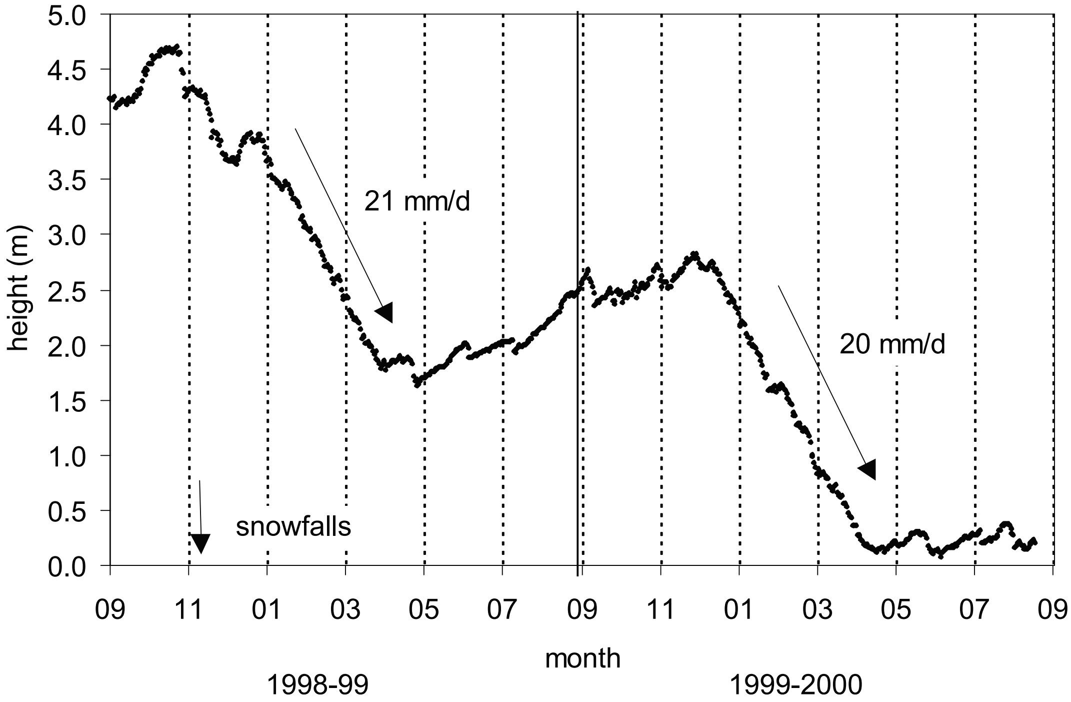

Figure 2. Daily measurements of the ultrasonic depth gauge at 2400 hours from September 1998 to August 2000.

alternate on the same day, the daily height changes represent a net accumulation or a net ablation. From September to December, periods of heavy melting (several centimeters of ice/snow per day) alternate with snowfall events that become more and more frequent. The gradual build-up of the wet season is observed in the Andes from Bolivia to Peru [*Schwerdtfeger*, 1976]. The wet season lasts from December to April. On average, it snows 2 days out of 3, and the net daily accumulation is regular: roughly 20 mm of snow per day. At the end of April, the change to the dry season is sudden. A few snowfall events occur but in general the dry season is a period of low ablation until the end of August.

4.2. Daily Precipitation Distribution and Wind Regime

[18] The accumulation (cumulated height decreases) of snow at a 3-hour time step during the wet seasons in 1998–1999 (25 December to 10 April) and 1999–2000 (12 December to 1 May), was 3.5 and 3.8 m of snow, respectively. Between a 2-hour and a 5-hour time step, the amount of snowfall differs by less than 10%. The daily snowfall distribution on the glacier was bimodal, with maximums in the middle of the night and in the afternoon (Figures 3a and 3b). Two precipitation maximums were also observed in the valley: around midnight and at midday (Figure 3c).

[19] The wind speed at the surface of the Zongo glacier is generally low (2 m s^{-1} as a mean value), and remains lower than 4 m s^{-1} during precipitation. The local atmospheric circulation, i.e., valley wind during the day and mountain wind during the night, dominates the wind regime at the surface of the Zongo glacier. Precipitation is mostly associated with wind from the valley, especially in the afternoon. During the tropical wet season, meteorological conditions with weak large-scale forcing tend to produce light winds, that allows the generation of thermally forced circulation [*Garreaud*, 1999]. On glaciers at higher latitudes, winter precipitation is generally associated with strong winds caused by low pressure, but on tropical glaciers precipitation is not associated with storms. Much of the precipitation is of a convective nature because of the local heating of the land surface by solar radiation that is at its maximum in the wet season. Precipitation on the glacier lasts from half a day to several days, but is not intense on an hourly scale. The Amazon basin is a permanent source of condensation and energy; convective clouds form in succession, bringing persistent precipitation over the Andes.

[20] Maximum precipitation during the night occurs in the valley and on the glacier. The snow falling during the night has a lower density than that falling during the day because of the lower temperatures. Thus the nighttime snowfalls might be slightly overestimated by the ultrasonic depth gauge compared to daytime precipitation (Figures 3a and 3b illustrate the snow depths). Nevertheless, below the snow line, the Pv rain gauge recorded nocturnal precipitation comparable to that in the daytime (Figure 3c). *Aceituno and Montecinos* [1993] mentioned that during the wet season, there are alternate periods of 5 to 10 days of heavy and light convective cloud cover on the Bolivian Altiplano, related to dry and wet conditions, respectively. The wet conditions are responsible for most of the nighttime precipitation on the glacier. These rainy and dry periods are associated with the strengthening or weakening of the "High Bolivian", high-pressure system centered on the Altiplano at 200 hP [*Garreaud*, 1999].

4.3. Density of Fresh Snow

[21] Comparisons between the snow depths measured by the ultrasonic depth gauge and the water depths

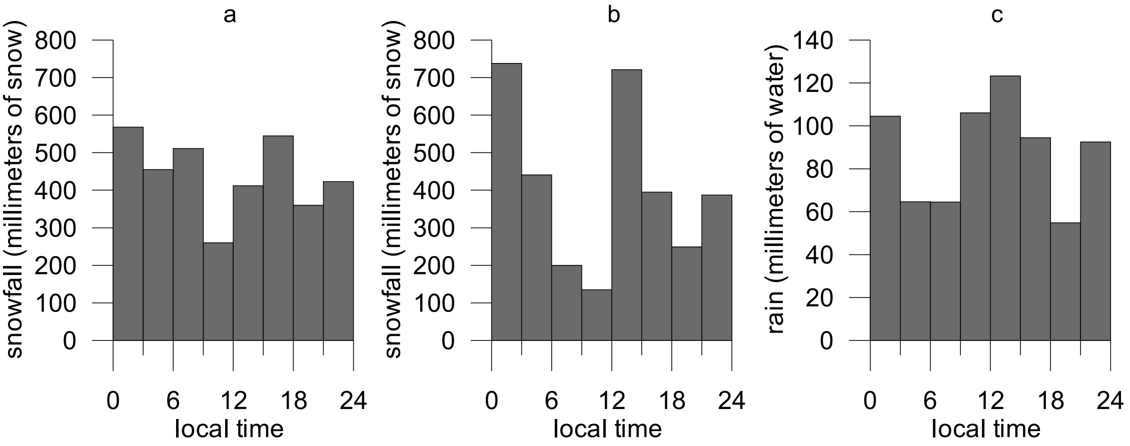

Figure 3. Distribution during the day of cumulated precipitation at a 3-hour time step. (a and b) Snowfall measured by the ultrasonic depth gauge on the glacier for the wet season of 1998–1999 (January–March, 98 days) and the wet season of 1999–2000 (December–April, 121 days), respectively. (c) Rain measured by Pv at 3900 m in the Zongo valley for the wet season of 1999–2000.

measured by the Pg storage rain gauge, at a distance of 20 m, give an estimate of the density of the fresh snow, provided that the systematic bias on the Pg gauge is known. As the wind speed during precipitation is generally below 4 m s^{-1}, the undercatch of the rain gauge for solid precipitation is lower than 50% [*U.S. Army Corps of Engineers*, 1956; *Larson and Peck*, 1974]. As a result, the density of the snow fallen in 3 hours at 5150 m asl was 200 ± 50 kg m^{-3} from September 1999 to January 2000, and 250 ± 50 kg m^{-3} until the end of April 2000 (Figure 4).

[22] From 12 December 1999 to 1 May 2000, a snow cover of 2.6 m accumulated at 5150 m asl, but the density profile was unknown (Figure 2). Snow-pit observations made at 5150 m asl at the end of the wet seasons of 1995, 1996, and 1997 reported snow densities varying from 400 to 500 kg m^{-3}. This density applied to the 2.6 m of snow gives a net accumulation during the wet season in

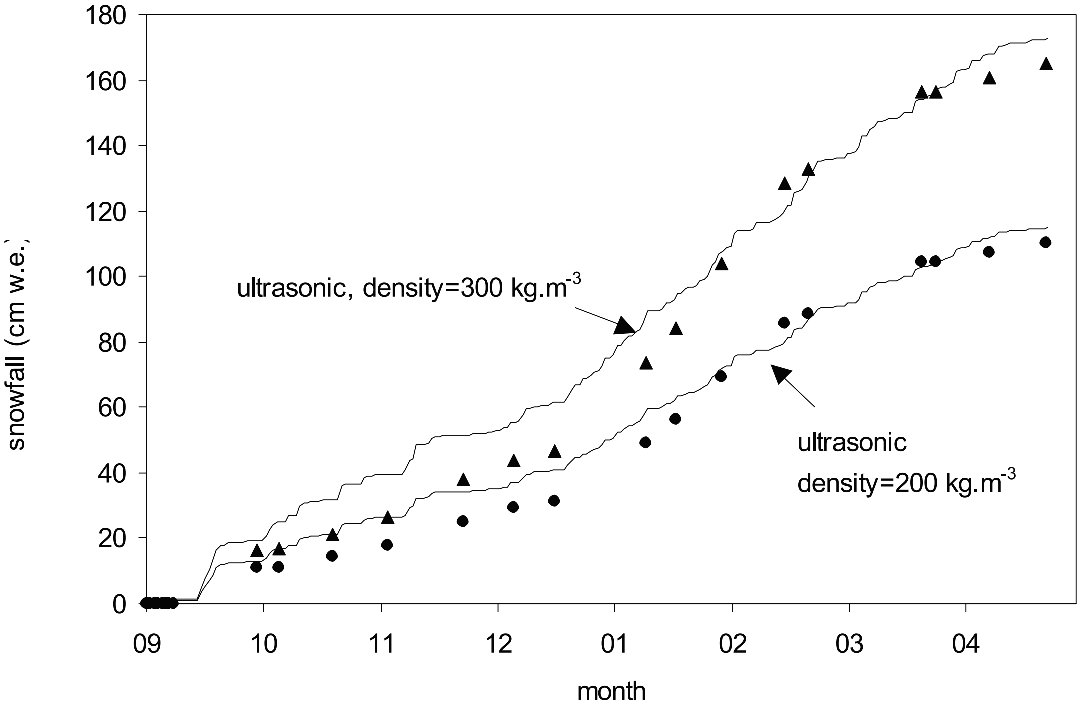

Figure 4. Snowfall measured at 5150 m asl on the Zongo glacier from September 1999 to May 2000. The lines show the accumulation of precipitation measured by the ultrasonic depth gauge, converted into water equivalent using densities of 200 and 300 kg m^{-3}. The circles represent the measurements from the Pg rain gauge placed near the ultrasonic gauge. The triangles represent the measurements of Pg increased by 50% to compensate for the catch deficiency.

2000 of 1 to 1.30 m w.e. To obtain around 1.15 m w.e. with the 3.8 m of snow accumulated at a 3-hour time step, the density of the fresh snow must be around 300 kg m^{-3}. This estimate (which neglects melting) is slightly greater than the fresh-snow density obtained by comparing rain gauge and ultrasonic measurements, but remains in the same range. From 28 to 29 March 2001, direct measurements on the glacier showed a snow density of 180 kg m^{-3} (6 samples) during snowfall events and of 290 kg m^{-3} (5 samples) a few hours later. A more accurate assessment of the fresh-snow density requires snow pits at the end of the wet season and more density measurements during snowfall events.

[23] At temperate latitudes, most of the authors agree on a value of fresh-snow density around, or slightly less than, 100 kg m^{-3} [e.g., *Grant and Rhea*, 1974; *Goodison et al.*, 1981; *Sevruk*, 1985]. The densities of fresh snow on the Zongo glacier, on the order of 150 to 300 kg m^{-3} in the wet season, are high because snowfall events occur during a warm period: 80% of the hourly air temperatures during precipitation were between −3 and 1°C. The snow becomes heavy as soon as it falls and the transformation of wet snow leads to a rapid increase in density. The high density of the fresh snow and the moderate wind speeds prevent snow drifting conditions, leading to a lower spatial variability of snow accumulation than on glaciers of higher latitudes. Note that high snow density insures accurate detection of the snow surface by the ultrasonic depth gauge.

[24] The higher mean density of fresh snow from January to March (period 1) than from September to December (period 2) can be related to packing because precipitation becomes more intense (Figures 4 and 2). It is not related to wind speed, which was not significantly different in period 1 (mean: 2.6 m s^{-1}, SD: 1.4 m s^{-1}) than in period 2 (mean: 2.0 m s^{-1}, SD: 1.1 m s^{-1}) during precipitation events. When the air temperature is close to 0°C, the snow density seems to increase with the temperature [*Meister*, 1985]. Indeed, the mean hourly air temperature during precipitation was −1.4°C (SD: 1.6°C) in period 1, whereas in period 2 this mean was −0.2°C (SD: 2.0°C).

5. Conclusion

[25] This study details a method for measuring snowfall with an ultrasonic depth gauge on tropical glaciers with contemporaneous precipitation and ablation seasons. Study of the influence of wind, air temperature and air moisture on the measurements gives a quantification of snowfall at a 3-hour time step, with a sensitivity of 1 cm of snow.

[26] The method is applied to the characterization of seasonal and hourly variations in precipitation on the Zongo glacier in Bolivia. Precipitation is generally associated with a valley wind of moderate speed. Masses of moist air, originating in the Amazon basin, produce precipitation at midday in the Andean valley, and in the afternoon in the high mountains. During the wet season, the alternation of periods of 5 to 10 days of dry and wet conditions, the latter producing heavy nighttime snowfalls on the glacier, is related to the regional atmospheric circulation. Comparing the snow depths measured by the ultrasonic depth gauge with the water depths measured by a rain gauge give an estimate of the density of fresh snow of about 150 to 300 kg m^{-3} in the wet season. Precipitation occurs with high air temperatures and the snow is in a melting condition as soon as it falls, leading to a low spatial variability of the snow accumulation on tropical glaciers.

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