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Clear-sky albedo measurements on a sloping glacier surface: A case study in the Bolivian Andes

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Abstract. An important potential source of error in snow albedo measurements under clear sky is the tilt of the surface when the sensors are placed parallel to the horizon. The error depends on the surface slope and aspect. A hemispherical radiation sensor receives its signal from within a surface area of several square meters, which generally is not a plane. Here we examined the influence of slope and aspect combinations related to surface irregularities on albedo measurements at two locations on the Zongo Glacier, Bolivia The slope and aspect distributions determined through topographic measurements were used to correct the albedo measurements. The corrections were different between the two sites but resulted in similar albedo changes: the substantial albedo reductions observed from morning until evening were measurement artifacts. Even for slight slopes, an error of a few degrees on the slope estimation or an error of roughly 20° on the aspect estimation had an appreciable influence on the corrections. If the topography around the measurement site is not precisely known, the most reliable method for determining the daily albedo is to observe the measurements around solar noon. Corrected albedo diurnal variations were low and symmetrical, centered on a minimum at noon During the dry season (the Southern Hemisphere winter), the diurnal fluctuations of the snow albedo on the Zongo Glacier seem to be controlled by the incidence angle cycle of solar radiation

1. Introduction

The interpretation of diurnal snow albedo fluctuations is a controversial subject Confusion often stems from observation errors In this study, we present a method for treating errors related to the horizontal mounting of the radiation sensors while the snow surface is inclined

Most authors have reported a decrease in snow reflectivity as the height of the Sun increases [e g, *Hubley* 1954, *Liljequist*, 1956, *Dirmhirn and Eaton*, 1975, *Ohmura*, 1981; *Yamanouchi*, 1983, *McGuffie and Henderson-Sellers*, 1985, *Wendler and Kelley*, 1988; *Cutler and Munro*, 1996] *Carroll and Fitch* [1981] only observed this decrease for low Sun angles. On the contrary, *Kondrat'yev et al* [1964] reported a maximum albedo around the solar noon

There are many factors that act on the diurnal albedo fluctuations under clear sky [*Warren*, 1982] The snow albedo depends on the angular and spectral distributions of the direct-beam and diffuse components of the global radiation. Snow reflectivity is nearly linear in the cosine of the zenith angle of the direct-beam radiation [*Marshall and Warren*, 1987] This dependence leads to a symmetrical cycle of the reflectance centered on a minimum at noon. The effective zenith angle of a purely diffuse radiation is approximately 50° [*Wiscombe and Warren*, 1980] The contribution of the diffuse radiation to global radiation acts on the angular distribution of the incident solar radiation, and therefore on the reflectance of the snow

The optical properties of snow also depend on the size and shape of snow grains, the concentration of surface absorbent impurities, the snow thickness, and the reflectivity of the snow underlying the surface (if the snow is less than roughly 10 cm thick), and finally the surface roughness on the microscopic scale These factors related to the snow metamorphism generally lead to an irreversible decrease of albedo

On the decimeter scale, if the surface roughness is not randomly oriented (e g, sastrugis, penitents), the diurnal cycle of the solar azimuth can cause an asymmetrical albedo cycle to appear [see *Kuhn and Siogas*, 1978, *Wendler and Kelley*, 1988, *Mondet and Fily*, 1999].

Instrumental errors can lead to an erroneous interpretation of snow albedo fluctuations. The photoelectric cell sensitivity depends on temperature, which under clear sky follows a marked diurnal cycle. Nevertheless, this dependence is low

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(approximately 0.15%/°C according to the technical specifications), and variations between the sensitivity of identical sensors mounted in pairs tend to offset each other.

The response of all commercial radiometers deviate from a proper "cosine law" [*Warren*, 1982]. Their sensitivity generally decreases starting from a solar zenith angle of 70°, leading to an overestimation of the albedo [*Dirmhirn and Eaton*, 1975]. This error has little effect on the calculations of energy flux since the energy contribution is low at large Sun angles.

According to *Ohmura* [1981], much of the diurnal variations of albedo reported in the literature may be the result of horizontal mounting of the instruments, while the glacier surface is typically inclined. The dominant effect is that the incident irradiance with respect to the local zenith angle is different from the irradiance incident with respect to the normal of the sloped surface [*Grenfell et al.*, 1994] To the extent that the radiation reflected by the snow has a large diffuse component, the slope of the surface has little effect on the measurements of the reflected radiation. The scale of the slope effect is generally known, but the effectiveness of the methods to correct this is difficult to evaluate.

If the instruments are mounted parallel to the surface, the local albedo is measured correctly [*Müller*, 1985; *Knap et al.*, 1999]. Yet, the surface of glaciers is not flat and evolves with ice flow. Besides, the effectiveness of this method depends on how precisely the sensors were positioned. During continuous measurements over long periods of time, it is safer to check the correct position of horizontally placed sensors.

Geometrical considerations allow linking the true surface albedo (α(true)) to the albedo measured with instruments placed horizontally (α(meas)). Given this type of relation and knowing a priori α(true) and α(meas), *Mannstein* [1985] calculated an effective slope and an effective aspect of the snow surface under the sensors. The author estimated α(true) from measurements on overcast days Yet cloud absorption of the incident solar radiation in the near-infrared wavebands results in a substantial increase in the snow albedo compared to a cloudless sky [*Warren*, 1982]. The steep surface slope of 27° obtained by *Mannstein* [1985] can be explained by his not taking into account this spectral shift effect

Estimating the mean slope and aspect angles of the surface, a relation between α(true) and α(meas) allows for correcting the albedo measurements. This method implies the hypothesis of a plane surface. In the literature, the method for estimating average angles is generally not detailed and the contribution of the surface roughness is rarely discussed. Here we apply the correction of albedo measurements proposed by *Grenfell et al.* [1994] taking into account the combinations of slope and aspect of the surface elements in the sensors' field of view.

As stated by *Mannstein* [1985], "the effective inclination and azimuth direction of the surface below the instruments can change in the course of the day, because different parts of the terrain are illuminated by the sun depending on the incidence of direct radiation and because the radiances of the reflected radiation are weighted by the sensor with respect to the cosine-law." The method proposed here can take into account the changes in the contributions of the surface elements to the total correction of the slope effect.

The method was applied to two sites of the Zongo Glacier in Bolivia [*Francou et al*, 1995]. Comparing the corrections, applied to two different topographies, provides an evaluation of the method. On tropical glaciers the net shortwave radiation is the main source of energy at the glacier surface, and its variations are controlled by the albedo [*Wagnon et al.*, 2001]. A correction of the slope effect was a necessary step toward the study of the climatic parameters controlling the surface albedo of tropical glaciers.

2. Location, Measurements, and Methodology

2.1. Location

The Zongo Glacier is located in the Huayna Potosi Massif (16°15' S, 68°10' W, Cordillera Real, Bolivia), on the western margin of the Amazon Basin, approximately 30 km

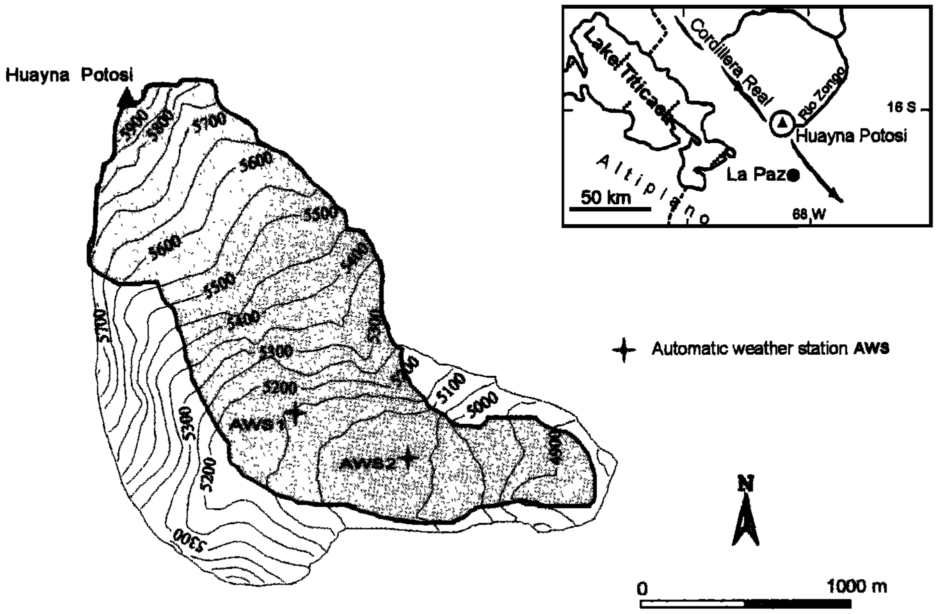

Figure 1. A simplified map of Zongo Glacier (2.1 km^2) showing the two automatic weather stations AWS1 and AWS2, located at 5150 m and 5060 m asl, respectively.

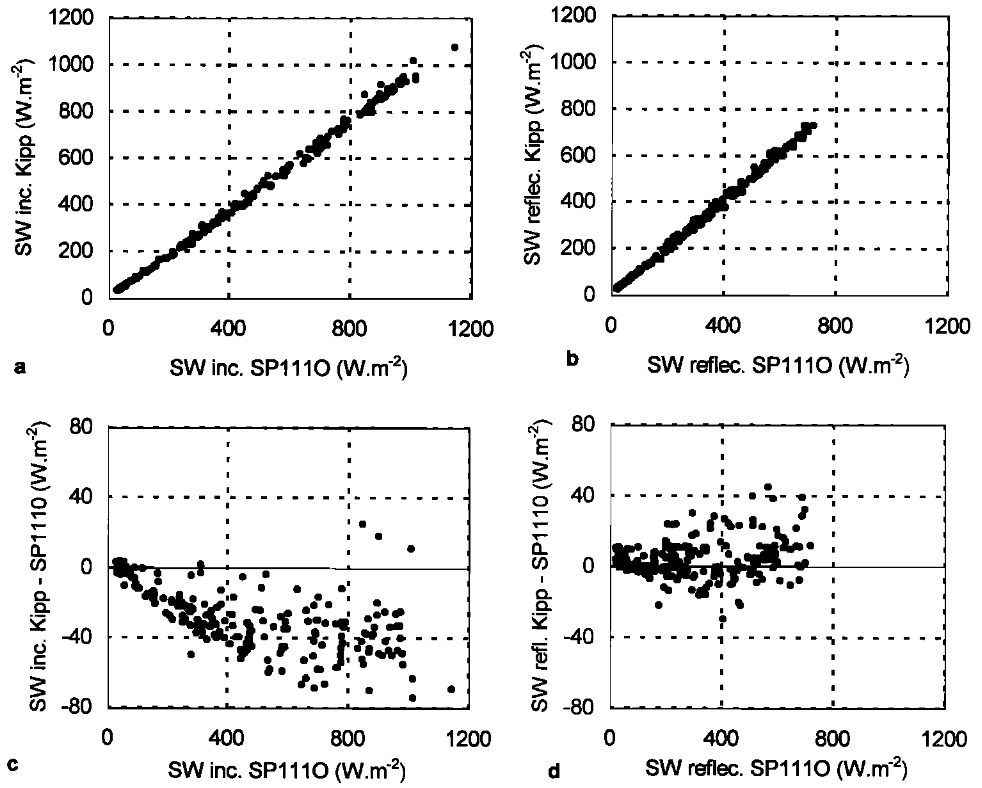

Figure 2. A comparison of data from the SP1110 and from the Kipp and Zonen pyranometers Each dot represents a half-hourly mean value. Period, July 8-23, 1999 Measurements during snowfall periods were eliminated. (a, c) Incident radiation measurements (b, d) Reflected radiation measurements. Figures 2a and 2b show solar radiation measured by the Kipp and Zonen sensor versus that measured by the SP1110 sensor (c, d) Differences between radiation measurements from both sensors versus the output from SP1110 sensor

north of La Paz. This valley-type glacier is 3 km long and has a surface area of 2.1 km^2 (Figure 1) The upper reaches are exposed to the south, whereas the lower section surrounded by two steep lateral moraines faces east The glacier flows out from 6000 to 4900 m above sea level (asl).

Huyana Potosi Massif belongs to the outer tropics, characterized by a marked seasonality of precipitation with a single wet season (December to March) and a pronounced dry season (May to August) [*Kaser et al.*, 1996] In the tropics, seasonal variation of extraterrestrial solar irradiance is low and global radiation fluctuations are mainly controlled by the cloud cover during the wet season [*Hastenrath*, 1991].

To investigate clear-sky albedo, we studied measurements from the dry season 2000 (from May 1 to July 23) at two sites of the glacier: AWS1 (Automatic Weather Station 1) installed at 5150 m asl and AWS2 at 5060 m asl. Solar noon was at about 1230 LT. Sunrise and sunset were at 0700 and 1800 LT, respectively. Because of surrounding mountains, sunshine was only from 0900 to 1530 LT at AWS1 and from 0830 to 1630 LT at AWS2. During the measurements period, the Sun was north, and the daily maximum of Sun elevation varied from 50° to 58°.

2.2. Albedo Measurements

Measurements of two back-to-back pairs of pyranometers horizontally mounted 1 m above the glacier surface were used in this study. AWS1 has two SP1110 pyranometers ($350 < \lambda < 1100$ nm), and AWS2 has two CM3 Kipp and Zonen pyranometers ($300 < \lambda < 2800$ nm) Accuracy of both sensor types is ± 5% according to the manufacturers. The downward pyranometer mounted at 1 m receives 86% of its signal from within a circle of a radius of 2 5 m at the ground [*Schwerdtfeger*, 1976].

The signals of the sensors are scanned at 15 s intervals by a data logger (Campbell Scientific, USA, model Cr10) which recorded 30 min mean values During the station's checks, which occurred approximately every 15 days, the sensors' height and horizontal position were carefully adjusted.

Outputs from the pairs of pyranometers were compared over a flat snow surface of the glacier at 5150 m asl from July 8 to July 23, 1999. As the Kipp and Zonen sensors have a larger spectral range response and were new and recently calibrated by the manufacturer, they were assumed to give the most accurate measurements. During the comparison period, weather varied from clear sky to snowfall days. The snowfall days were eliminated from the intercomparison.

Correlation between the different sensors' outputs was high (Figures 2a-2b), and differences between the sensors generally remained lower than 10% (Figures 2c-2d). We corrected the SP1110 output using a straightforward application of the linear regression equations for global and reflected radiation The slight heteroscedasticity of the relation between the sensors' outputs (Figure 2c), which is to say the errors do not all have common variance, gave in the regression a strong weight to the highest values, but its effect remained low

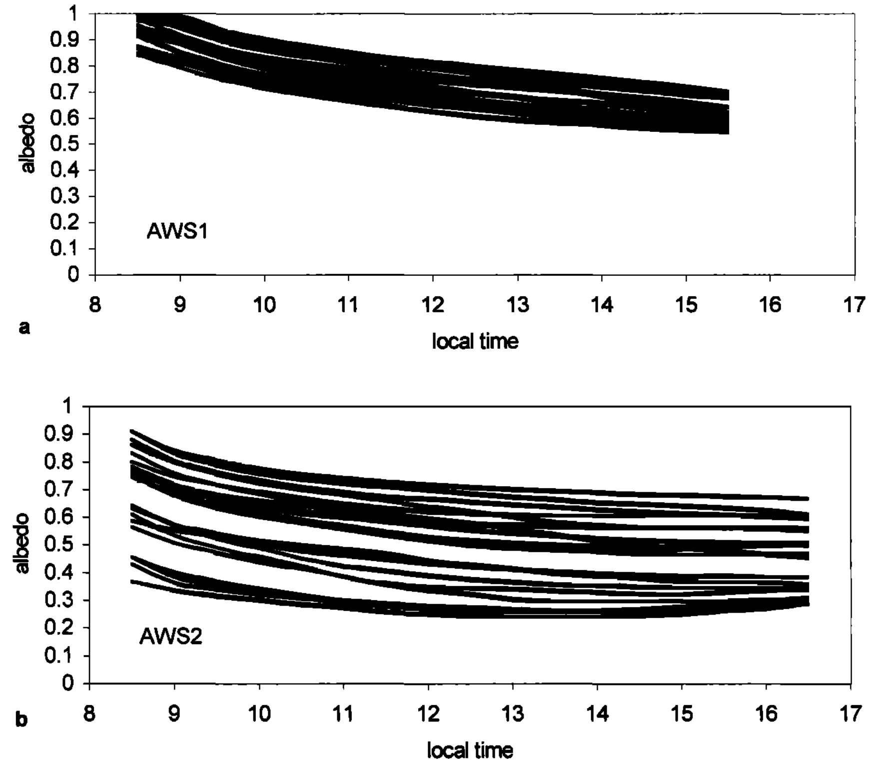

Figure 3. Albedo measurements without correction (a, b) Half-hourly mean values of albedo measurements at AWS1 and at AWS2, respectively, over 22 clear-sky days selected from May 1 to July 23, 2000

According to the manufacturers and the comparison between the sensors' outputs, the accuracy of albedo measurements is roughly

$$\frac{\mathrm{d}\,\alpha(\mathrm{meas})}{\alpha(\mathrm{meas})}=\frac{\mathrm{d\,SWinc}}{\mathrm{SWinc}}+\frac{\mathrm{d\,SWrefl}}{\mathrm{SWrefl}}\approx\pm10\,\% \qquad (1)$$

where SWinc and SWrefl are the incident and reflected solar irradiance, respectively.

Twenty-two clear-sky days were selected according to the observations during field visits and the regularity of the diurnal global radiation cycle at the two measurement sites. The diurnal change in clear-sky albedo measurements at AWS1 and at AWS2 are shown in Figures 3a and 3b, respectively. Only measurements during sunshine hours are shown because the signal-to-noise ratio of pyranometers rises to a high level in the shade.

The albedo measurements ranged from values of fresh snow, due to a low number of precipitation events, to values of old snow, which had undergone melting-refreezing cycles. Because of a thicker snow layer and a higher elevation, albedo was always higher at AWS1 than at AWS2. At AWS2, some low albedo values resulted from a very thin snow layer over dirty ice.

2.3. Topographical Measurements

A topographic survey was carried out around the two measurement stations on July 26 and 27, 2000. The relative *X-Y* coordinates were measured with a precision of approximately ± 1.0 cm. The relative altitudes were determined with a theodolite (precision of approximately ± 0.2 cm).

On the AWS1 (AWS2) site, the relative coordinates of 69 points (92 points) were measured in a square with one approximately 5 m (8 m) side centered on the sensors (Figures 4a-4b). The space between the measurement points varied from 50 to 100 cm. The interpolation of the altitudes between the measurement points was determined using the kriging method.

2.4. Correction of the Albedo Measurements

Considering a plane surface and an isotropic reflection α(true) and α(meas) are linked by [*Grenfell et al.*, 1994]:

$$\alpha(\mathrm{meas})=\alpha(\mathrm{true})\frac{\cos\left[\theta_{sun}+\theta_{surf}\cos\varphi\right]}{\cos\left(\theta_{sun}\right)}\left[1-\frac{\theta_{surf}}{2}\right]$$

$$=\frac{1}{\mathrm{cor}}\,\alpha\,(\mathrm{true}) \qquad (2)$$

where θ_{sun} is the solar zenith angle, θ_{surf} is the slope of the surface, and φ is the solar azimuth equal to 0 when the Sun is in the uphill direction of the slope. All the angles are expressed in radians. The first factor of the corrective term is the dominating factor and accounts for the projection of the incident irradiance onto the sloped surface [*Oke*, 1987]. For large solar zenith angles, the correction increases rapidly This equation was compared to measurements by *Grenfell et al.* [1994]

Every half hour, the albedo was corrected by the arithmetic mean of the corrective factors (cor) of the surface elements included within a radius of 2.5 m around the sensors (see circles in Figures 4a-4b) The polar coordinates of the

Table 1. Slope and Aspect Values of the Glacier Surface in a Circle of a 2.5 m Radius Around the Sensors at AWS1 and AWS2

	Mean Slope (deg)	Min Slope (deg)	Max Slope (deg)	Standard Deviation of Slope (deg)	Mean Aspect (deg)
AWS1	7.8	0.7	19.6	3.0	80
AWS2	3.2	0.2	9.3	1.4	110

Sun were calculated according to *Paltridge and Platt* [1976] for every half hour.

3. Results and Discussion

At AWS1 and at AWS2 the uncorrected albedo measurements decreased from very high values in the morning to a minimum at the end of the afternoon (Figures 3a-3b). The decrease is more marked at AWS1. On each site, the diurnal evolutions are remarkably parallel during the 22 clear-sky days.

Figures 4a and 4b show the elevation lines surrounding the two sites AWS1 and AWS2, respectively. Figures 4c and 4d show the histograms of the slopes. The slopes were steeper

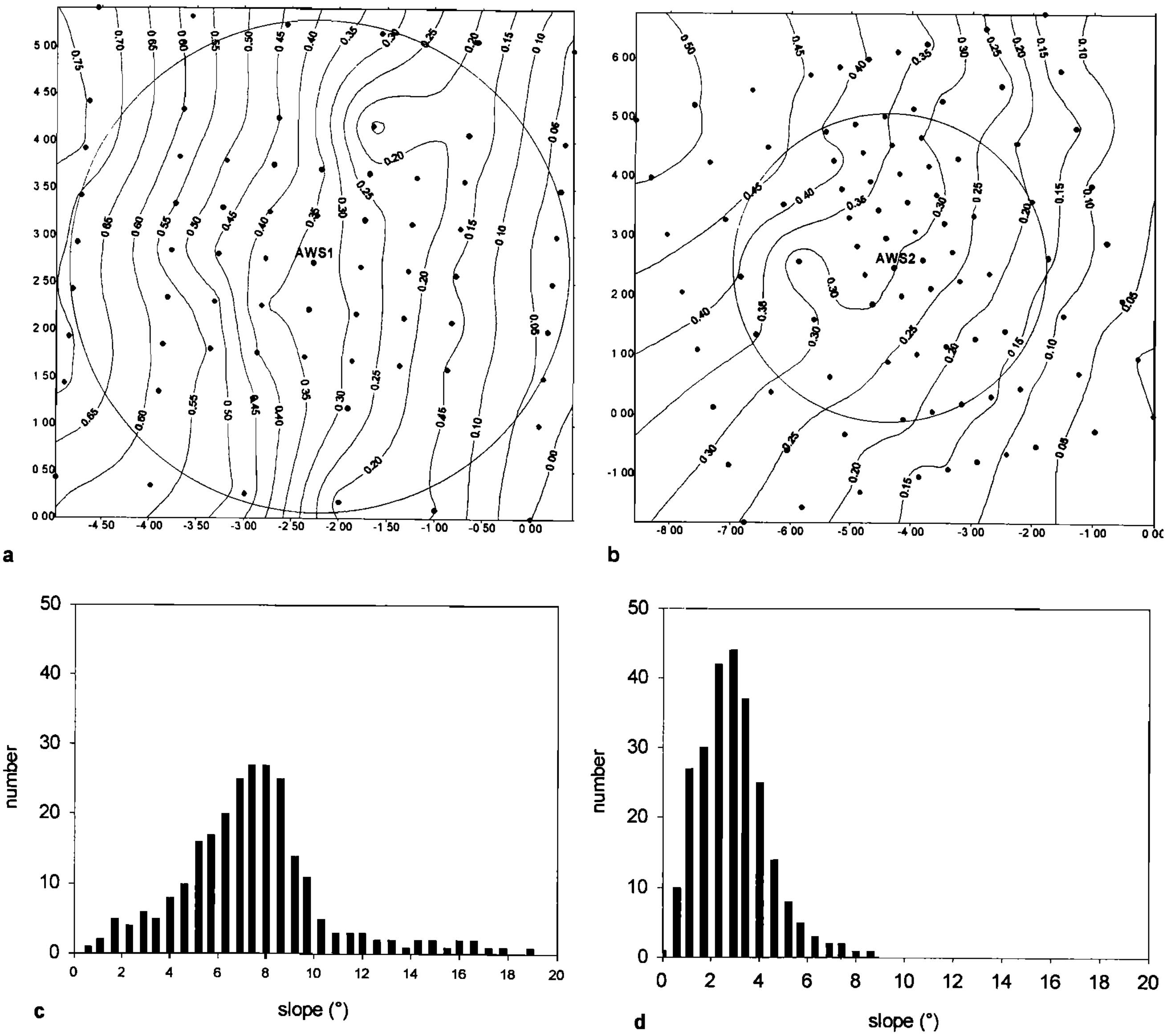

Figure 4. Elevation contour maps around AWS1 (a) and around AWS2 (b) were computed from topographic measurements taken on July 26-27, 2000. All the values are in meters. Dots show the 69 (92) points measured during the topographic campaign at AWS1 (AWS2). Interpolation of the elevation was computed using the kriging method. Circles show the area within which downward pyranometers mounted at 1 m receive 86% of their signal (radius 2.5 m). (c, d) Slope histograms of the pixels located at less than 2.5 m from the pyranometers at AWS1 and at AWS2, respectively. Each pixel represents a 16x16 cm^2 of the surface.

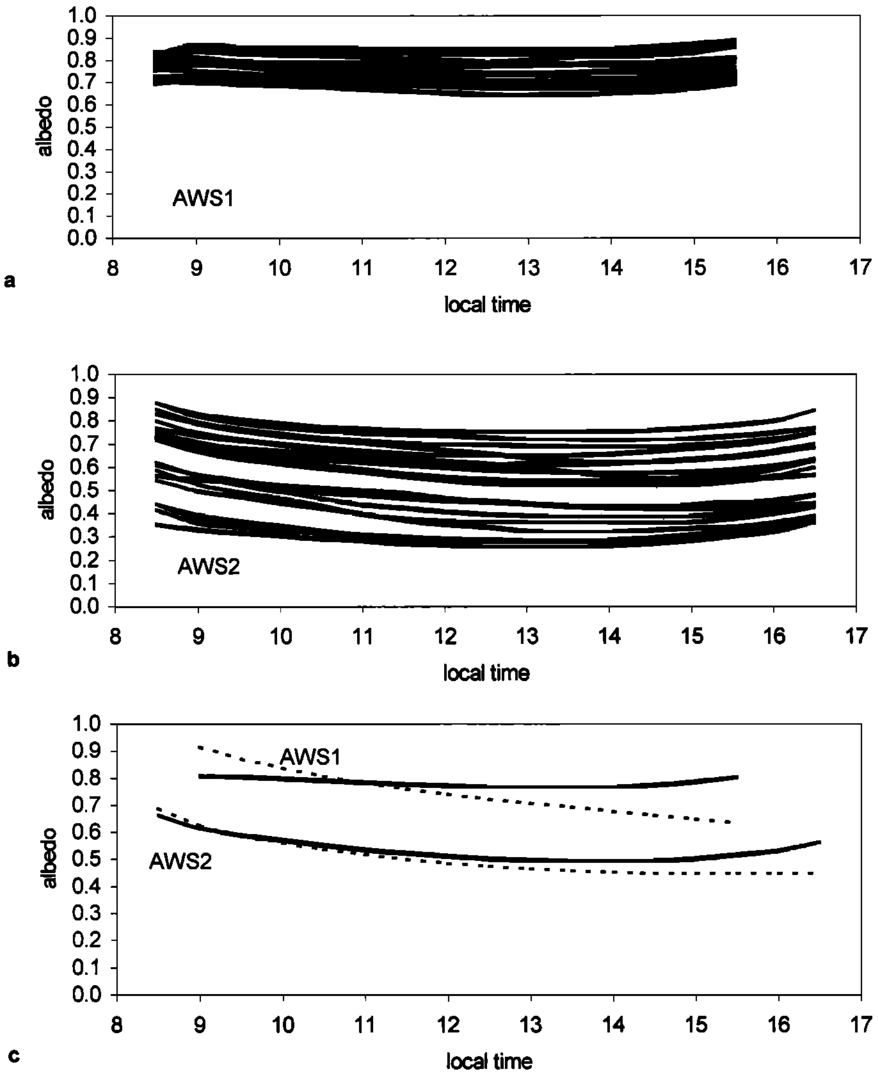

Figure 5. Correction of the albedo measurements. (a, b) Half-hourly mean values of the corrected albedo measurements at AWS1 and AWS2, respectively, over the selected 22 clear-sky days. Slope corrections were made with equation (2) applied to the pixels located within a circle of a 2.5 m radius centered on the pyranometers. (c) Half-hourly values computed as the averages of the half-hourly values on the 22 clear-sky days. Dashed lines are albedo measurements. Solid lines are corrected values.

at AWS1 than at AWS2 but remained low (the mean slope at AWS1 and AWS2 was 7.8° and 3.2°, respectively, Table 1). The standard deviation of the slopes' distribution at AWS1 was higher than at AWS2. The AWS1 surface faces east, slightly northeast (80°), while the AWS2 site is east-southeast (110°) (Table 1).

Figures 5a and 5b show albedo measurements under clear-sky corrected based on the different combinations of slope and aspect of the surface elements in a radius of 2.5 m around the AWS1 and AWS2 sensors, respectively. At AWS1 the correction varied on an average of –12% at the beginning of the day to +27% at the end of the day. At AWS2 it varied from –4% to +26% (Figure 5c). The distributions of the surfaces' aspects toward the east gave an overestimation of the albedo in the morning and an underestimation in the afternoon. The corrections were more substantial at AWS1 because of the steeper slopes. The corrections were not symmetrical relative to the solar noon because of the distribution of the slope azimuths slightly toward the northeast at AWS1 and slightly toward the southeast at AWS2.

The effect of the slope is only slightly greater than the global uncertainty on the albedo measurement (± 10%, equation (1)). However, we have seen in section 1 that the error on the albedo measurement is above all a systematic error. As stated by *McGuffie and Henderson-Sellers* [1985]: "it is unlikely that the direction of the probable deviation from the true value for the radiation will change during the course of the day." Yet, the corrections applied modify the shape of the albedo's evolution over the day. Correcting the slope effect led to a significant modification of the albedo's evolution.

An effect that could disturb the diurnal fluctuation measurements of albedo has not yet been discussed. On the Zongo Glacier, *Wagnon et al.* [1999] reported the midday appearance of a warm layer around 20-30 cm above the

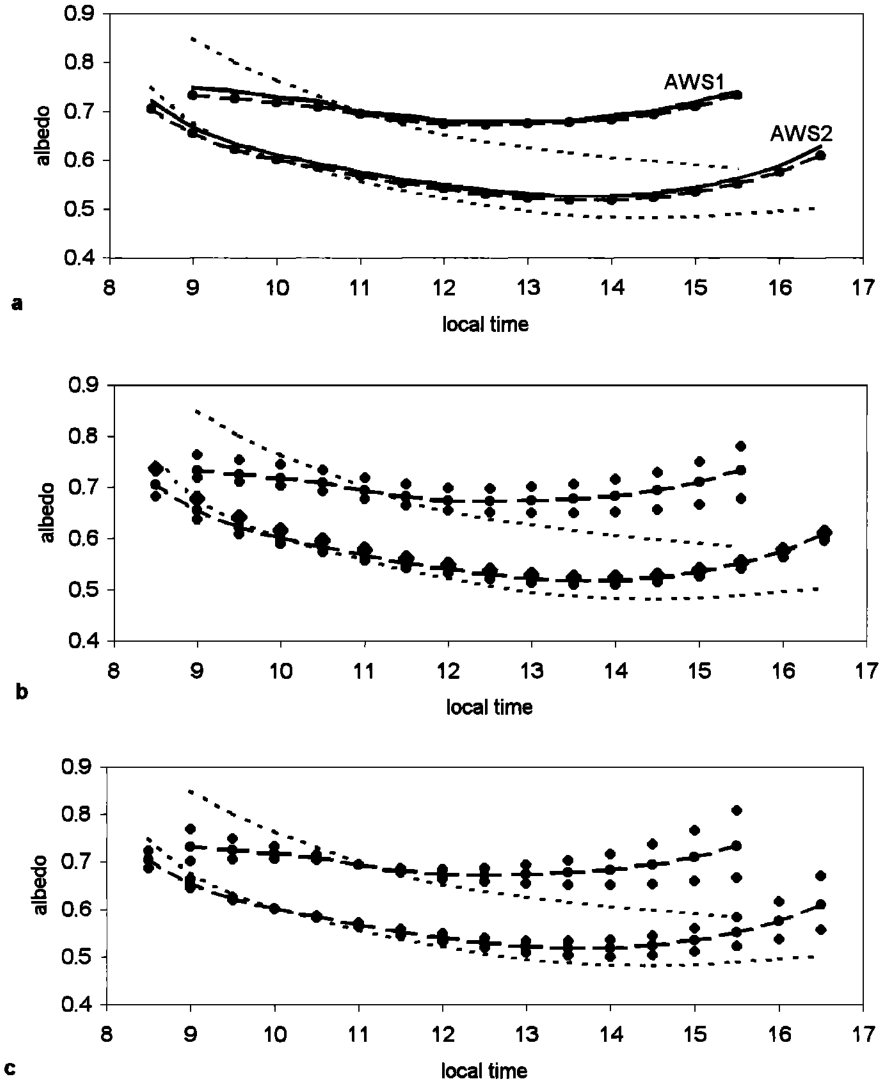

Figure 6. Sensitivity study on the measurements on May 30, 2000 In each panel, the top (bottom) curves show the values at AWS1 (AWS2) (a, b, c) Dashed lines show uncorrected albedo measurements and dots plus dashed lines show corrected albedo, based on the mean slope value and the mean aspect value. Figure 6a compares the corrected albedo, based on the distribution of slopes and aspects of the pixels (solid lines), to the corrected albedo, based on the mean slope value and the mean aspect value (dots plus dashed lines) Figure 6b shows a sensitivity study of the correction according to the aspect of the surface (top (bottom)) Diamonds show calculations with the mean aspect values plus 20° (minus 20°). Figure 6c shows a sensitivity study of the correction according to the slope of the surface. (top (bottom)) Diamonds show calculations with the mean slope values plus one standard deviation (minus one standard deviation).

surface. The warm layer may be due to the absorption of solar radiation by strong concentrations of water vapor. This phenomenon has also been reported in other climates [e.g., *De la Casinière*, 1974; *Meesters et al.*, 1997]. A periodic phenomenon such as this one could modify the spectral distribution of the incident solar radiation and therefore be the cause of a cycle in the albedo fluctuations. To measure the influence of the warm layer, radiation sensors should be placed closer to the surface than 1 m height Calculations were carried out to check the potential influence of the warm layer and showed that the shortwave irradiance absorbed by a layer of air 1 m thick saturated with water vapor would be below the uncertainties on the pyranometer measurements.

We applied the correction (equation 2) considering this time the mean aspect and the mean slope values (Table 1) of each of the two sites on May 30, 2000 (Figure 6). The result was very close to that obtained by considering the aspect and slope distributions (Figure 6a). The two surfaces around AWS1 and AWS2 can therefore be considered plane.

The sensitivity of the correction, based on the mean aspect and mean slope values, was examined on both sites At the AWS1 site, an error of 20° in the estimation of the aspect led to an appreciable error on the corrections (Figure 6b, top). The slopes around AWS2 were too small for an error on the aspect to have an influence on the correction on the albedo (Figure 6b, bottom). Figure 6c shows the sensitivity of the corrections to variations of the slope value of one standard deviation (3.0° at AWS1 and 1.4° at AWS2) from the mean value. At both sites a variation of a few degrees from the mean slope value causes large differences in the correction.

In clear weather the substantial albedo reductions observed on Zongo Glacier from morning until evening were measurement artifacts due to the horizontal mounting of radiometers above a sloping surface. A correction of the snow reflectivity measurements is necessary even for small surface slopes (a few degrees).

The roughness of the two surfaces studied was low. In this study, it was possible to make the corrections considering that the surfaces were plane. The correction is very sensitive to the precision of the slope estimation, but also of the aspect value on a surface area of several square meters. Great care must therefore be taken to ensure the precision of the topographic measurements of the surface seen by the downward radiometer.

The corrections improved the parallelism between the albedo changes at the two sites of different slope and aspect distributions. Thus they reduced the measurement problems related to the topographical specificity of the site.

The potential error on the measurements increases with the zenith angle of the solar incidence. If the topography around the measurement site is not precisely known, the most reliable method for determining the daily albedo value is to observe the measurements around solar noon.

Another approach is to make measurements under overcast sky, in which case the errors in the tilt of the sensors have less effect on the albedo measurements. However, to take into account the spectral shift effect of clouds [*Warren*, 1982], measurements would need to be done spectrally so that clear-sky albedo can be estimated by computation.

On each of the sites, the corrections of the slope effect do not alter the parallelism between the diurnal changes of the albedo within a wide range of values (from 0.3 to 0.8). After correction the diurnal changes in the albedo are reduced and a symmetrical change centered on a minimum at solar noon can be observed. The state of the snow transformation does not seem to have an influence on the diurnal changes of albedo. Here we examined measurements during the dry season, during which the fusion rates are low [*Wagnon et al.*, 1999]. Now that the sources of interpretation errors on the albedo fluctuations can be corrected, a study of the climatic parameters controlling the fluctuations of the surface reflectivity of the Zongo Glacier during the different seasonal cycles can be undertaken.

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References

Carroll, J. J., and B. W. Fitch, Effects of solar elevation and cloudiness on snow albedo at the South Pole, *J. Geophys. Res.*, *86*, 5271-5276, 1981.

Cutler, P., and D. S. Munro, Visible and near-infrared reflectivity during the ablation period on Peyto Glacier, Alberta, Canada, *J. Glaciol.*, *42*(141), 333-340, 1996.

De la Casinière, A. C., Heat exchange over a melting snow surface, *J. Glaciol.*, *13*(67), 55-72, 1974.

Dirmhirn, I., and F. D. Eaton, Some characteristics of the albedo of snow, *J. Appl. Meteorol.*, *14*, 375-379, 1975.

Francou, B., P. Ribstein, R. Saravia, and E. Tiriau, Monthly balance and water discharge of an intertropical glacier: Zongo Glacier, Cordillera Real, Bolivia, 16°S, *J. Glaciol.*, *41*(137), 61-67, 1995.

Grenfell, T. C., S. G. Warren, and P. C. Mullen, Reflection of solar radiation by the Antarctic snow surface at ultraviolet, visible, and near-infrared wavelengths, *J. Geophys. Res.*, *99*, 18,669-18,684, 1994.

Hastenrath, S., *Climate Dynamics of the Tropics*, 488 pp., Kluwer Acad., Norwell, Mass., 1991.

Hubley, R. C., Measurements of diurnal variations in snow albedo on Lemon Creek Glacier, Alaska, *J. Glaciol.*, *2*(18), 560-563, 1954.

Kaser, G., S. Hastenrath, and A. Ames, Mass balance profiles on tropical glaciers, *Zeitschrift für Gletscherkunde und Glazialgeologie*, *32*, 75-81, 1996.

Knap, W., B. W. Brock, J. Oerlemans, and I. C. Willis, Comparison of Landsat-TM derived and ground-based albedo of Haut Glacier d'Arolla, Switzerland, *International Journal of Remote Sensing*, *20*(17), 3293-3310, 1999.

Kondrat'yev, K., K. Ya, Z. F. Miranova, and A. N. Otto, Spectral albedo of natural surfaces, *Pure Appl. Geophys.*, *59*, 207-216, 1964.

Kuhn, M., and L. Siogas, Spectroscopic studies at McMurdo, South Pole and Siple stations during the austral summer 1977-78, *Antarct. J. U.S.*, *13*, 178-179, 1978.

Liljequist, G. H., Energy exchange of an Antarctic snow field: Short-wave radiation (Maudheim 71°03'S, 10°56'W), in *Norwegian-British-Swedish Antarctic Expedition 1942-52, Scientific Results*, vol. 2, part 1A, 184 pp., Norsk Polarinst., Oslo, Norway, 1956.

Mannstein, H., The interpretation of albedo measurement on a snowcovered slope, *Arch. Meteorol. Geophys. Bioclimatol.*, *Ser. B-36*, 73-81, 1985.

Marshall, S. E., and S. G. Warren, Parameterization of snow albedo for climate models, *Int. Assoc. Hydrol. Sci. Publ. AISH*, *166*, 43-50, 1987.

McGuffie, K., and A. Henderson-Sellers, The diurnal hysteresis of snow albedo, *J. Glaciol.*, *31*(108), 188-189, 1985.

Meesters, A. G. C. A., N. J. Bink, H. Vugts, F. Cannemeijer, and E. A. C. Henneken, Turbulence observations above a smooth melting surface on the Greenland ice sheet, *Boundary Layer Meteorol.*, *85*, 81-110, 1997.

Mondet, J., and M. Fily, The reflectance of rough snow surfaces in Antarctica from POLDER/ADEOS remote sensing data, *Geophys. Res. Lett.*, *26*(23), 3477-3480, 1999.

Muller, H., Review paper: On the radiation budget in the Alps, *J. Climatol.*, *5*, 445-462, 1985.

Ohmura, A., *Climate and Energy Balance on Arctic Tundra, Axel Heiberg Island, Canadian Arctic Archipelago, Spring and Summer 1969, 1970 and 1972*, 448 pp., Zürcher Geogr. Schrift., Zürich, Switzerland, 1981.

Oke, T. R., *Boundary Layer Climates*, 435 pp., Routledge, New York, 1987.

Paltridge, G. W., and Platt, C. M. R., *Radiative Processes in Meteorology and Climatology*, 318 pp., Elsevier Sci., New York, 1976.

Schwerdtfeger, P., *Physical Principles of Micrometeorological Measurements*, 111 pp., Elsevier Sci., New York, 1976.

Wagnon, P., P. Ribstein, B. Francou, and B. Pouyaud, Annual cycle of energy balance of Zongo Glacier, Cordillera Real, Bolivia, *J. Geophys. Res.*, *104*, 3907-3923, 1999.

Wagnon, P., P. Ribstein, B. Francou, and J. E. Sicart, Anomalous heat and mass budget of Zongo Glacier, Bolivia, during the 1997-98 El Nino year, *J. Glaciol.*, *47*(156), 21-28, 2001.

Warren, S. G., Optical properties of snow, *Rev. Geophys.*, *20*(1), 67-89, 1982.

Wendler, G., and J. Kelley, On the albedo of snow in Antarctica: Contribution to I.A.G.O., *J. Glaciol.*, *34*(116), 19-25, 1988.

Wiscombe, W. J., and S. G. Warren, A model for the spectral albedo of snow, I, Pure snow, *J. Atmos. Sci.*, *37*, 2712-2733, 1980.

Yamanouchi, T, Variations of incident solar flux and snow albedo on the solar zenith angle and cloud cover, at Mizuho Station, Antarctica, *J. Meteorol Soc. Jpn.*, *61*(6), 879-893, 1983.

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