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Measured and modelled sublimation on the tropical Glaciar Artesonraju, Perú

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Abstract

Sublimation plays a decisive role in the surface energy balance of tropical glaciers. During the dry season low specific humidity and high surface roughness favour the direct transition from ice to vapour and drastically reduce the energy available for melting. However, field measurements are scarce and little is known about the performance of sublimation parametrisations in glacier mass balance and runoff models.

During 15 days in August 2005 sublimation was measured on the tongue of Glaciar Artesonraju (8°58′ S, 77°38′ W) in the Cordillera Blanca, Perú, using simple lysimeters. Indicating a strong dependence on surface roughness, daily totals of sublimation range from 1–3 kg m^{-2} for smooth to 2–5 kg m^{-2} for rough conditions.

Measured sublimation was related to characteristic surface roughness lengths for momentum (z_m) and for the scalar quantities of temperature and water vapour (z_s), using a process-based mass balance model. Input data were provided by automatic weather stations, situated on the glacier tongue at 4750 m ASL and 4810 m ASL, respectively. Under smooth conditions the combination z_m=2.0 mm and z_s=1.0 mm appeared to be most appropriate, for rough conditions z_m=20.0 mm and z_s=10.0 mm fitted best.

Extending the sublimation record from April 2004 to December 2005 with the process-based model confirms, that sublimation shows a clear seasonality. 60–90% of the energy available for ablation is consumed by sublimation in the dry season, but only 10–15% in the wet season. The findings are finally used to evaluate the parametrisation of sublimation in the lower-complexity mass balance model ITGG, which has the advantage of requiring precipitation and air temperature as only input data. It turns out that the implementation of mean wind speed is a possible improvement for the representation of sublimation in the ITGG model.

1 Introduction

Tropical glacier mass balances provide information about past and present climate in tropical mountain regions, where long-term climate data is scarce. Tropical climate is controlled by hygric seasonality and not by annual temperature cycles, as in the mid- and high latitudes. Since the mass balance of tropical glaciers is very sensitive to shifts in hygric conditions, they are suitable proxies for tropical climate change beyond the air temperature view (Kaser, 2001; Kaser and Osmaston, 2002). The mountain range of the Cordillera Blanca, Perú, harbours about one quarter of the area of all tropical glaciers (Kaser, 1999). Hence, a greater knowledge of the glacier mass balance signal in the Cordillera Blanca is vital to understand climate impacts on tropical glaciers.

The specific net mass balance of a point on the glacier surface is defined as the sum of accumulation and ablation. Accumulation is controlled mainly by local solid precipitation, the ablation processes are governed by the surface energy balance (e.g. Hoinkes, 1970; Kuhn, 1989). Wind drift, avalanches and calving processes may also contribute but are neglected for this paper. The surface energy balance is the sum of all incoming (positive) and outgoing (negative) energy fluxes on the glacier surface and can be written as

$$R + Q_S + Q_L + Q_G = F \qquad [W\,m^{-2}]. \tag{1}$$

R is the net all-wave radiation, Q_S and Q_L are the turbulent fluxes of sensible and latent heat, Q_G is the subsurface conductive and radiative heat flux and F is the resulting energy flux at the surface. F represents the energy used for melting, if the surface temperature T_S=0°C and F>0. Although precipitation can fall as rain on the lower sections of the glaciers in the Cordillera Blanca (Juen, 2006), it is neglected as a possible energy source because precipitation intensities are weak and rain temperatures are close to 0°C.

The Perúvian Andes belong to the outer tropics, which are characterised by one dry and one wet season (Kaser and Osmaston, 2002). During the dry season (May-September) specific humidity is low, and the vertical water vapour pressure gradient over the surface is generally positive downward, resulting in a negative Q_L. Sublimation occurs during most of the time, decreasing the energy available for melting drastically (Wagnon et al., 1999b), the reason being latent heat of sublimation (L_S=2848 kJ kg^{-1}) is 8.5-times higher than latent heat of fusion (L_M=334 kJ kg^{-1}). Therefore, it is crucial to know how much ice sublimates from a tropical glacier, in order to quantify the surface energy balance, and thus the mass balance.

Few sublimation measurements have been carried out so far, probably due to the minor role of sublimation in the surface energy balance on well observed mid-latitude glaciers. On tropical glaciers only Wagnon et al. (1999a,b) carried out intensive research on sublimation. Near the long term mean equilibrium line of Glaciar Zongo, Bolivia, they used lysimeters to directly measure sublimation and calculated the turbulent fluxes with the bulk method (see e.g. Garratt, 1992). They found that Q_L is the main sink of the surface energy balance and undergoes a significant seasonal variation. Sublimation rates $\dot{S}=Q_L/L_S$ reach monthly means of 1.1 kg m^{-2} d^{-1} in the dry season, dropping to 0.3 kg m^{-2} d^{-1} in the wet season, which is comparable to mean sublimation rates on alpine glaciers on dry days in summer ($\dot{S}\approx0.25$ kg m^{-2} d^{-1}; Kaser, 1982). Cullen et al. (2007) used eddy covariance instrumentation to assess Q_L during two days in the dry season on the summit of Kilimanjaro (East African inner tropics), obtaining $\dot{S}=1.44$ kg m^{-2} d^{-1}. Model results of Mölg and Hardy (2004) show long-term mean sublimation rates on Kilimajaro of 0.92 kg m^{-2} d^{-1}.

The vertical mass balance profile model developed and applied for the mass balance and runoff studies in the Cordillera Blanca by the Innsbruck Tropical Glaciology Group (Juen, 2006) parametrises sublimation based on the measurements on Glaciar Zongo because of missing data from the Cordillera Blanca. The Cordillera Blanca is influenced by the Intertropical Convergence Zone and Glaciar Zongo, which is situated 1300 km farther southeast (16° S, 68° W), is characterised by more subtropical climate conditions. Therefore precipitation patterns are assumed to be different and the use of the Glaciar Zongo data to parametrise sublimation in the ITGG model for the Cordillera Blanca is not optimal.

The current study aims to (1) quantify sublimation rates on a glacier of the Cordillera Blanca in the dry season by direct measurements, (2) optimise a process-based mass balance model by the measurements, (3) model the sublimation for different time scales, (4) improve the surface roughness parametrisation for tropical glaciers in the bulk method and (5) assess the way to parametrise sublimation in the ITGG model.

2 Measurement site and methods

As part of a field campaign in August 2005, sublimation was measured on the tongue of Glaciar Artesonraju (8°58′ S, 77°38′ W) in the northern part of the Cordillera Blanca. The areal extent of the glacier is 5.7 km^2, reaching from Nevado Artesonraju (6025 m) down to the end of the short and distinct tongue at 4750 m (Juen, 2006; Winkler, 2007). The mean equilibrium line altitude is about 5150 m. In 2005, the surface on many parts of the flat tongue showed an undulated structure (Fig. 1), with many penitentes, measuring a few centimeters to half a meter, and very deep cryoconite holes (partly more than 1 m). Only sublimation (no melting) occurred during night-time and in the mornings, which is known to cause high surface albedo (Juen, 2006). On most afternoons, melting got more and more dominant, and water was ponding in the hollows, which decreased the mean albedo of the tongue. The ponds froze again during the nights. All these features made the surface geometrically very rough (Fig. 1), and the surface albedo followed a clear diurnal cycle.

Since 2000, a stake network on Glaciar Artesonraju is maintained by the *Unidad de Glaciologa y Recursos Hdricos* of the Perúvian *Instituto National de Recursos Naturales* (INRENA). An automatic weather station – here referred to as surface energy balance station (SEBS) – was installed in March 2004 at an altitude of 4810 m on the tongue and is maintained by the French *Institute de Recherche pour le Dvelopp-ment* (IRD) and the INRENA. It measures the four components of the radiation balance (shortwave and longwave incoming and outgoing radiation), wind speed and direction, air temperature and relative humidity. Additionally, the Innsbruck Tropical Glaciology

Group installed a radiation balance station (RBS) at 4750 m near the terminus in 2004, where all components of the radiation balance, as well as ablation (using a sonic ranging sensor) are measured. The RBS has a specially designed mounting device with a cardan-like joint to ensure that the radiation instruments maintain their horizontal position (Kaser et al., 2004). One automatic weather station next to and one opposite the glacier are also operated by the Innsbruck group since 2004 (Juen, 2006).

To measure sublimation ten transparent, cylindric plastic pots were used as lysimeters at two sites of different altitudes. One of them was at the SEBS, where six pots were used. The sublimation measurements from there can be linked directly to the SEBS data and the record of the ablation stake at the SEBS. The remaining four pots were used at 4890 m, next to the highest stake of the ablation area (HAS). The sublimation measurements at the HAS can be related to the stake record at the HAS. Since the tongue of Glaciar Artesonraju is flat and walking distances are long, the 80 m difference in altitude between the two measuring sites was the maximum that could be reached within this specific field experiment. This is too small to derive the altitudinal gradient of sublimation and all the differences in measured sublimation between the SEBS and the HAS are presumed to be accidental, rather than due to different altitude.

2.1 Measuring procedure

Holes of the size of the pots (diameter=127 mm, height=85 mm) were dug with an ice axe. The pots were filled with the excavated ice and weighed with an electronic balance. They were then placed in the holes ensuring that none of the rims were above the ice. So as to ensure the surface roughness wasn't changed. The pots were left in the ice for a certain time, then they were weighed again and placed back in the holes. The evolving mass difference can be interpreted as the sublimated mass within the respective time span. For further processing of the data, arithmetic means of the mass changes of all available pots were calculated. As measurements affected by precipitation were excluded, an increase in mass can only be due to vapour deposition on the ice surface (hoar), which occurred only sometimes before dawn. Incidentally, with this method of measuring it is not possible to distinguish between sublimation, defined as the direct transition from ice to vapour, and evaporation following preceded melting. As there is no difference in energy consumption and mass transport between the two processes, henceforth the term sublimation will be used for both.

Two measurement series of sublimation were obtained. One 10-day series with measurements at the SEBS and the HAS with a resolution of 2 h during daytime, and one 5-day series measured at the SEBS with a resolution of 30 min during daytime. In late afternoon the pots were emptied, refilled, weighed, inserted into a new hole, and left untouched until the next morning. Hence, it was possible to calculate a mean nighttime sublimation rate. Some gaps in the sublimation record occurred because of short showers or when the pots were renewed. During the 10-day series there is only one gap longer than 1 h in the record. It was caused by snowfall during the night from August 8th to 9th (day of year 220–221). During the 5-day series there is no gap longer than 1 h. The 30-minutes resolution data provided by the SEBS, were without gaps during the whole period of investigation.

Not all parts of the glacier surface are well represented by the smooth ice in the pots. To overcome this problem, penitentes (5–12 cm) from the surroundings were broken off and put on top of half of the samples during three full days of the 10-day series. By doing this, the contact surface for turbulent exchange was increased approximately by 50−100%. Sublimation rates increased significantly, and measurements “without penitentes” (P^-) had to be processed separately from the measurements “with penitentes” (P^+).

2.2 Assessing roughness lengths and surface emissivity with a process-based mass balance model

To solve Eq. (1) the surface energy balance module of the mass balance model described by Mölg et al. (2008) was used. It allows the calculation of F using air temperature, relative humidity and wind speed as essential inputs. Shortwave incoming (SW_{in}) and outgoing (SW_{out}) as well as longwave incoming (LW_{in}) and outgoing (LW_{out})

radiation (the components of R) can be parametrised or measured. In this study SW_{in} and SW_{out} were taken from the SEBS record. The LW_{out}-record of the SEBS regularly exceeds 320 $\mathrm{Wm^{-2}}$ during daytime, especially under clear-sky conditions. This corresponds to a black body temperature of more than 274 K, which is not possible on ice. The comparison with the LW_{out} data of the near RBS shows that the SEBS longwave radiation measurements suffer from the window heating offset (Obleitner and De Wolde, 1999). As the longwave data from the RBS seem to be representative for the sublimation measurement (nearly same altitude, same glacier surface structure, same shading effects) and do not exhibit this offset, the model inputs for LW_{in} and LW_{out} were taken from the RBS. The SW_{in} records from both stations are almost the same, but SW_{out} data often differ considerably when the transient snow line is between the two stations. As sublimation was measured near the SEBS, shortwave radiation data was taken from there. Q_G is solved from the temperature difference of the two uppermost model layers, and the turbulent fluxes Q_S and Q_L are calculated using the bulk method, which is based on the Monin-Obukhov similarity theory (e.g. Garratt, 1992). Within this theory, roughness lengths for momentum (z_m), temperature and moisture are defined. The latter two are almost equal (Andreas, 1987) and Mölg and Hardy (2004) made no differentiation for Kilimanjaro. Both together are labelled as scalar roughness lengths and are signified by z_s in the following.

Sublimation was measured with the lysimeters and total point ablation is known from the daily visits of the stakes at the SEBS and the HAS. The surface energy balance module should simulate both, sublimation and ablation, correctly. It was optimised by finding suitable roughness lengths, which can hardly be measured directly. The model was run in 30-miN time steps, and three criteria where defined for the best combination of the roughness lengths:

I The total sublimation of the measuring period should be modelled correctly. For this purpose, the cumulative sums of measured and modelled sublimation were calculated ($\sum S_{meas}$), ($\sum S_{mod}$). For the most appropriate pair of z_m and z_s the relative difference Δ, defined as

$$\Delta = \frac{\sum S_{\mathrm{meas}} - \sum S_{\mathrm{mod}}}{\sum S_{\mathrm{meas}}} \times 100\%, \tag{2}$$

is minimal.

II The measured and calculated daily sublimation sums should agree. Therefore, the root mean square difference ($RMSD_{1d}$) between the two was calculated. For the ideal combination of the roughness lengths $RMSD_{1d}$ is minimal.

III The high resolution measurements should be met by the model. For this purpose, the root mean square difference between the 30-min values of the model and the measurements ($RMSD_{30\mathrm{min}}$) was calculated and is minimal for the best pair of z_m and z_s.

The emissivity coefficient of the ice surface (ϵ) was not measured directly. It was varied from 0.98 to 1 in the model. ϵ was set to the value leading to the best fit of the stake measurements and the modeled total ablation.

2.3 The vertical mass balance profile model (ITGG)

In the Cordillera Blanca long-term records are only available for temperature and precipitation (1953 to 1996). The monthly resolution is, however, too low as input for complex mass balance models. Temperature-index models also fail, because air temperature variations cannot properly account for ablation on tropical glaciers (e.g. Kaser and Osmaston, 2002).

The ITGG model thus was designed to meet both, the limited data availability and the mass balance characteristics of tropical glaciers. It was extended from a vertical mass balance profile model (Kaser, 2001) by Juen (2006, 2007). In order to represent all humidity-related energy and mass fluxes they are parametrised by combining monthly precipitation from the Cordillera Blanca with short term energy balance information from Glaciar Zongo. One of these parametrisations concerns the distribution of the available energy for melting and sublimation, which is expressed by

$$f = \frac{L_S S}{L_S S + L_M M}, \tag{3}$$

where f is the proportion of energy used for sublimation S (in [kg]) of the whole energy used for ablation (melting plus sublimation in [kg], $M+S$).

In this study the precipitation record of Llupa was used to assess monthly values of f. Llupa is situated near Huaraz at 3350 m a.s.l, 60 km south of Glaciar Artesonraju. The characteristics of precipitation in Llupa and on the glacier are assumed to be comparable, because both sites are west of the main Cordillera Blanca mountain range, the dominating meteorological divide (Kaser et al., 2003). The limits for f (see below) in the ITGG model (f_{ITGG}) were defined on the basis of Wagnon et al. (1999b), with small adjustments because Llupa has much lower maximum precipitation rates than Glaciar Zongo. f_{ITGG}=0.9 was chosen for a very dry month with no precipitation, and f_{ITGG}=0.1 for a wet month with 150 mm of precipitation. f_{ITGG} of a certain month was calculated with Eq. (4) using the respective monthly precipitation P and is valid for the whole glacier area.

$$f_{\mathrm{ITGG}} = \frac{0.1 - 0.9}{150\,\mathrm{mm}} P + 0.9 \tag{4}$$

For months with precipitation rates exceeding 150 mm, the value was set to P=150 mm.

As Wagnon et al. (1999b) conducted their study on Glacier Zongo under slightly different climatic conditions (see Introduction), the reliability of the results gained by this approach is not optimal. One of the aims of the current study is to assess the parametrisation of f_{ITGG}.

3 Results and discussion

3.1 Measurement results

Field measurements show that daily sublimation sums range from approximately $1-3\,\mathrm{kg\,m^{-2}\,d^{-1}}$ (mean: $1.4\,\mathrm{kg\,m^{-2}\,d^{-1}}$) for smooth ($P^-$) to $2-5\,\mathrm{kg\,m^{-2}\,d^{-1}}$ (mean: $3.5\,\mathrm{kg\,m^{-2}\,d^{-1}}$) for rough ($P^+$) conditions (Fig. 2).

Hourly maxima during daytime reach $0.28\,\mathrm{kg\,m^{-2}\,h^{-1}}$ for P^- and $0.40\,\mathrm{kg\,m^{-2}\,h^{-1}}$ for P^+, while night-time sublimation is generally reduced. Mean values are mainly lower than $0.05\,\mathrm{kg\,m^{-2}\,h^{-1}}$, with three nights reaching means of $0.1-0.15\,\mathrm{kg\,m^{-2}\,h^{-1}}$ for P^-. For P^+ night-time sublimation is $0.05-0.2\,\mathrm{kg\,m^{-2}\,h^{-1}}$, so the difference to P^- during night-time is smaller than during daytime. This is assumed to be due to generally lower wind speeds during the nights, causing lower turbulent fluxes (cf. Fig. 3). Generally, the 50–100% surface increase from P^- to P^+ cannot describe the whole difference in sublimation. Enhanced ventilation plays an important role as well.

An extensive error estimation showed that the mean temporally weighted relative error in the sublimation rates is only 5.6%. The limited accuracy of the balance (±0.2 g) and of the time measurement (±2 min) are the two main sources of error. For the 2 h-resolution measurements during the 10-day series the relative error is 6.9%, for the night-time measurements it is 2.6%. However, the 30 min-resolution measurements during the 5-day series come up with a relative error of 27.7% because the time span is short and sublimated mass is low.

3.2 Optimal results for z_m, z_s and ϵ

After various model runs with different roughness length combinations, criterion (I) was easiest to use and finally led to the decision of which z_m and z_s to take. Using criterion (II) or (III) the model showed good results for many different roughness length combinations and therefore only played a minor role in decision making. Criterion (III) indicated that the correlation between model and measurement was better for

P^- ($RMSD_{30min}$=0.021 kg m^{-2} h^{-1}) than for P^+ ($RMSD_{30min}$=0.04 kg m^{-2} h^{-1}). For P^- conditions z_m=2.0 mm and z_s=1.0 mm led to the smallest Δ for both sites (Δ<6%). The best solution for P^+ conditions at SEBS and HAS was z_m=20.0 mm and z_s=10.0 mm, one order of magnitude greater than for P^- (Δ<17%). Figure 4 shows the good agreement of measured and modelled cumulative sublimation (thick lines).

The ratio z_s/z_m equals 0.5 in both cases, and so the surface counts as a "rough" surface according to Andreas (1987, Fig. 8). The roughness lengths for P^- are about the same as other authors found for glacier surfaces (e.g. Denby and Snellen, 2002; Cullen et al., 2007). For tropical Glaciar Zongo Wagnon et al. (1999a) do not distinguish between z_m and z_s. They assess different roughness lengths for every month ranging from 2–5 mm during the wet season to 10–30 mm during the dry season. These results correspond well with the values for P^- and P^+ conditions found in this study.

ϵ is a very sensitive parameter for deriving T_S from LW_{out} measurements. (Sensitivity studies showed that for the RBS data of 2005 a 1%-change from ϵ=1 to ϵ=0.99 results in melting conditions (T_S=0°C) during 59% of the time, instead of only 37%.) ϵ=0.998 turned out to be best for modelling the ablation at the SEBS, ϵ=0.999 for the HAS. Figure 4 shows the modelled total ablation (thin lines). The agreement with the stake records is acceptable, considering that the reading accuracy of the stakes may be as large as 10^{-2} m.

3.3 Model results for sublimation and melting

The high resolution model results for the sublimation rates are shown in Fig. 3 (gray lines). In contrast to the measurements, the modelled values have no gaps. The shape of the daily cycle (low values during night-time and high values during daytime) is reproduced well by the model, but amplitudes are often underestimated. Possibly, the stability correction used in the model (see Mölg and Hardy, 2004) is not accurate enough during very stable night-time layering and unstable daytime layering or the amplitude of the T_S input is too small. On a daily timescale these uncertainties balance to a large extent (Fig. 2).

Daily melting rates vary at least as much as daily sublimation rates (Fig. 2). During the field campaign there were days with no melting at all, and others with melting rates of more than 20 $kg\,m^{-2}\,d^{-1}$. This stands in good agreement with the observation of days with hardly any melting and days with extensive meltwater ponding on the flat parts of the surface. On 60% of the days more energy is consumed by sublimation than by melting under P^- conditions. When penitentes are developed (P^+), daily melting rates are even decreased by 10–12% and sublimation is doubled. Normally more than twice of the energy used for melting goes into sublimation at this point.

To assess f on a monthly scale, the surface energy balance was modelled from April 2004 to March 2005 and from August 2005 to December 2005 (17 months). f is very sensitive to the change of surface temperature (T_S) from 0°C to sub-freezing, i.e. over the diurnal cycle. Generally, at T_S=0°C, f is high, when sublimation is high. For T_S<0°C no melting is possible and f is always maximal, even though sublimation rates are very low. That's why it is not reasonable to calculate f for periods shorter than a few days.

Monthly values of f show a distinct seasonality with high values during the dry season and low values during the wet season (Fig. 5, gray lines). $f \geq 0.4$ only occurred from June to September, and it is always higher for P^+ than for P^- conditions, because higher roughness increases turbulence which enhances sublimation. Penitentes and surface roughness are normally higher in the dry season than in the wet season. Respectively, representative values of f for the whole ablation area of Glaciar Artesonraju are probably most realistic, when taking the P^- values in the wet season ($f_{P-} \approx 0.1$) and the P^+ values in the dry season ($f_{P+} \geq 0.7$).

3.4 Results for the ITGG model

Like the monthly f-values calculated with the process-based mass balance model (f_{P-} and f_{P+}), f_{ITGG} also shows a seasonal variation (Fig. 5). Absolute values of f_{ITGG} during the core dry season of 2004 and the wet season are similar to the mass balance model. The biggest differences occur during the transition periods in April and May 2004 and

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from September to November 2005. According to f_{ITGG} 70–90% of the available energy goes into sublimation during these periods, whereas f_{P-} and f_{P+} only range from 0.1–0.5.

This is partly because the limits for f_{ITGG} are based on Glaciar Zongo data (Wagnon et al., 1999b), where rapid transitions from clear-sky conditions to shower-like precipitation are supposed to be more likely than in the Cordillera Blanca. During months with low mean air humidity, when sublimation is enhanced and f is high, notable precipitation might fall on Glaciar Zongo. In the Cordillera Blanca, when monthly precipitation exceeds a certain threshold, mean air humidity is supposed to be generally high resulting in low f-values. This explains, to some extent, why f_{ITGG}, which is biased by the Glaciar Zongo conditions, is higher than f_{P-} and f_{P+} during the wet season. Moreover, f_{ITGG} is designed to represent the whole glacier, while f_{P-} and f_{P+} are modelled for a point on the tongue. In reality there is a high spatial variability in surface roughness (see Fig. 1).

Sublimation and f are not only humidity-related, but also wind speed plays a particular role in forcing the turbulent fluxes. Figure 5 shows the monthly mean wind speed (v) at the SEBS. There is a slight seasonality as well, with higher values during the dry season and lower values during the wet season. Hence, a simple approach including wind speed in the ITGG parametrisation looks as follows

$$f_{\mathrm{ITGG}}(\mathrm{windscaled}) = f_{\mathrm{ITGG}} \times \frac{5\,\mathrm{m\,s^{-1}}}{v}. \tag{5}$$

f_{ITGG}(windscaled) is plotted in Fig. 5 demonstrating the strong agreement with $f_{\mathrm{P-}}$ and $f_{\mathrm{P+}}$. Unfortunately, there is no long term record for wind speed available in the Cordillera Blanca, but the results shown in Fig. 5 are encouraging. Further studies may, e.g., explore downscaled reanalysis wind data for a better parametrisation of f_{ITGG}.

4 Conclusions

The importance of sublimation for the surface energy and mass balance on tropical glaciers during the dry seasons was confirmed by direct measurements using simple plastic pots as lysimeters. Low specific humidity and moderate wind speeds efficiently remove water vapour from the viscous sub-layer over the glacier, resulting in a high turbulent latent heat and moderate mass flux from the surface. As latent heat of sublimation is 8.5-times higher than latent heat of fusion this process cools the surface and reduces the energy available for melting very efficiently and, as a net effect, decreases ablation.

Surface roughness strongly increases turbulence, surface area and, thus, sublimation. During the time of investigation the tongue of Glaciar Artesonraju was well-structured, showing many penitentes. A differentiation between rough and smooth conditions was necessary and led to the definition of a lower and an upper limit of sublimation (P^-, P^+). In order to extend the measurement series from 15 days to 17 months, a process-based mass balance model was optimised by the sublimation measurements. The parametrisation of surface roughness on tropical glaciers could be reassessed and results from other studies were verified. Surface roughness lengths used in the bulk method (for momentum and scalars) are variable within one order of magnitude, depending on surface structure.

Sublimation consumes 10–15% of the total energy available for ablation during the wet season and 60–90% during the dry season. These results confirm the assumptions made for the lower complexity mass balance model ITGG, which is motivating because within the framework of the ITGG only precipitation records were used to parametrise the mentioned seasonality in sublimation. During the transition periods between dry and wet seasons further improvements could be reached by including wind speed in this parametrisation.

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Sublimation on tropical Glaciar Artesonraju

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Fig. 1. Tongue of Glaciar Artesonraju in August 2005. One can see the rough, undulated surface structure with many penitentes and cryoconite holes.

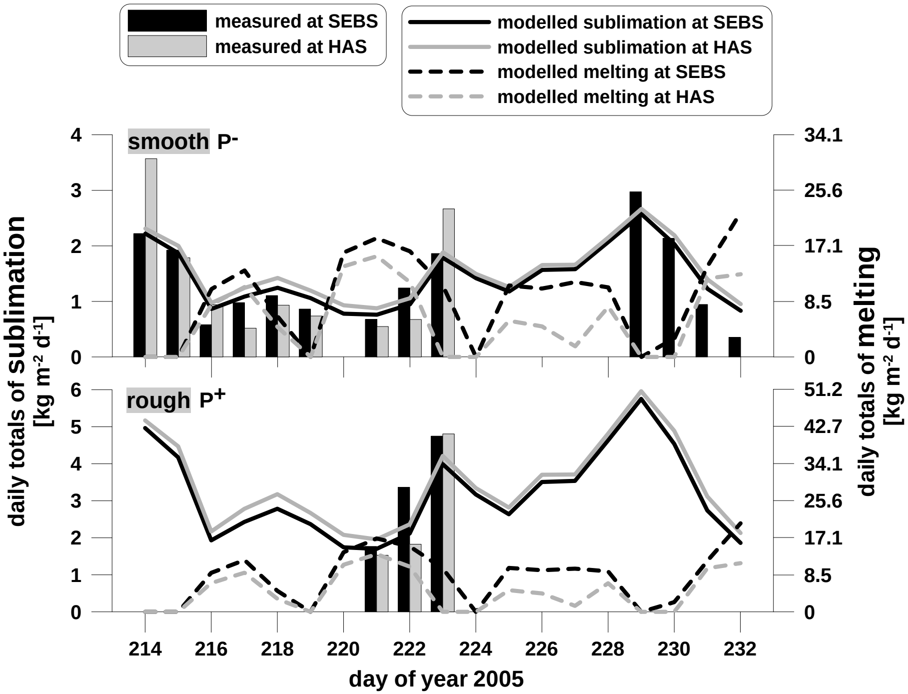

Fig. 2. Measured and modelled sublimation and melting on Glaciar Artesonraju. Daily totals of sublimation for the SEBS and the HAS from 2 August to 20 August 2005 are shown. Days without bars are days without data from measurements, and not without sublimation. The dashed lines show the daily totals of modelled melting. The axis corresponding to melting is on the right and is scaled by the factor L_S/L_M=8.5 compared to the axis for the sublimation values on the left (so energy needed for sublimation and melting are comparable). If the solid lines are above the dashed, sublimation consumes more energy than melting, and vice versa.

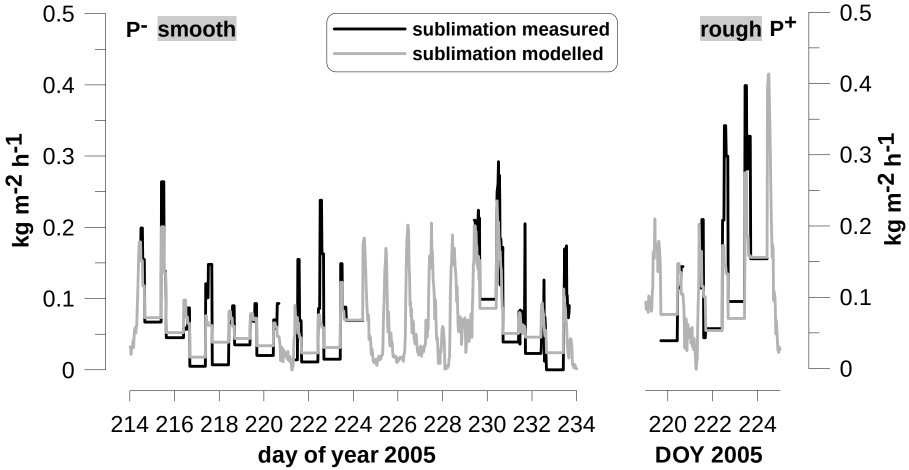

Fig. 3. Sublimation rates during the measuring series at the SEBS for P^- (left) and P^+ (right). The model values (grey) were obtained by taking z_m=2.0 mm and z_s=1.0 mm for P^- and z_m=20 mm and z_s=10 mm for P^+. They are averaged in correspondence with the temporal resolution of the measurements.

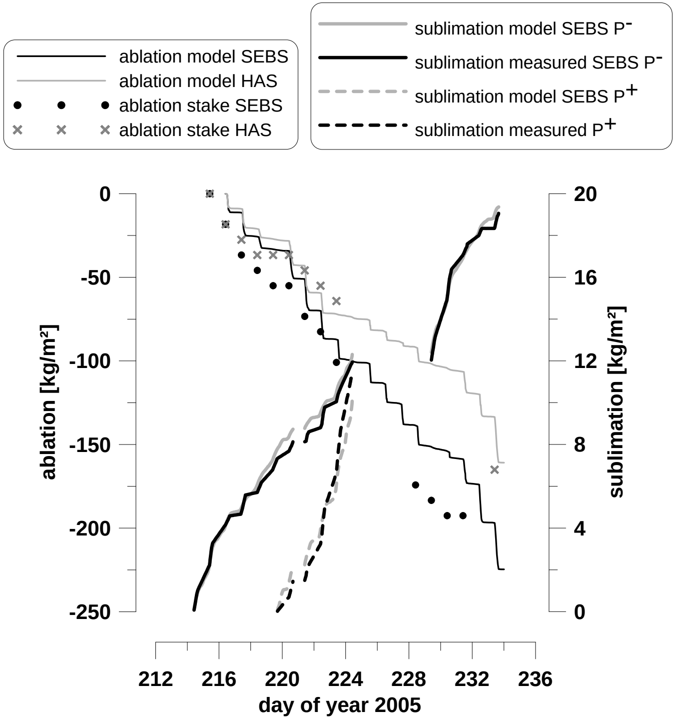

Fig. 4. Measured and modelled cumulative sublimation and ablation for the SEBS and the HAS. The gaps of the sublimation records refer to the gaps of the measurement series. Therefore, the sublimation values do not represent the actual sum of sublimated mass during the respective period. Note the different axis scaling, which was chosen to balance the figure graphically.

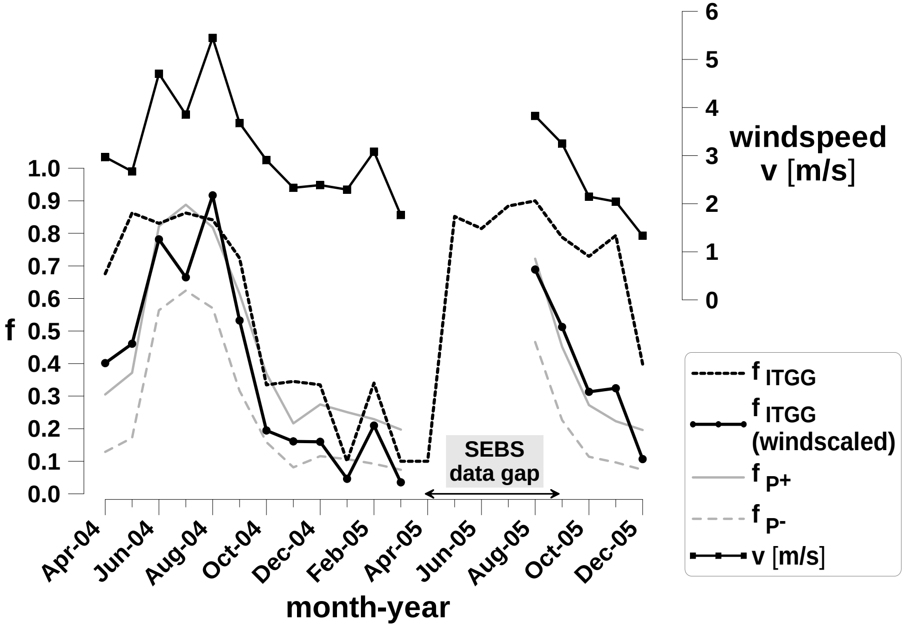

Fig. 5. Differently determined monthly values of *f* between April 2004 and December 2005. The uppermost graph refers to the right y-axis and shows the mean monthly wind speed (*v*), measured at the SEBS.