Annals of Glaciology 38 2004

Effect of summer snowfall on glacier mass balance

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ABSTRACT. It has been postulated that heavy summer snowfalls have a large impact on the mass balance of mid-latitude glaciers, because they simultaneously add mass to the glacier and reduce the amount of absorbed solar radiation. An automatic weather station (AWS) on the snout of Morteratschgletscher, Switzerland, registered a large summer snowfall event on 10–11 July 2000. Sonic rangers recorded about 20 cm of new snow on the snout and about 50 cm near the equilibrium line. We have used data from the AWS to study the impact on the melt process. The data show that in the ablation zone of the glacier the snow has melted and the effect on the albedo has disappeared after about 5 days. The suppression of the melt by the high albedo of the fresh snow is an important effect. For the ablation zone we find a feedback factor of about four, that is, the total effect of the snowfall event on the annual specific balance is about four times the amount of mass added during the event. We have also used a mass-balance model with 25 m spatial resolution to assess the impact of the snowfall on the net balance of the entire glacier. We find the strongest effects just below the equilibrium line. Averaged over the glacier, the amount of snow deposited was 224 mm w.e. The calculated effect on the total mass balance of the glacier is 354 mm w.e.

INTRODUCTION

A thorough understanding of the relation between glacier mass balance and meteorological conditions is a prerequisite for studying the response of glaciers to climate change. Traditional methods of analysis, involving statistics of annual mass-balance observations and climatological data from nearby stations (e.g. Lliboutry, 1974), have gradually been complemented by more detailed process studies. Glacio-meteorological experiments have been carried out on glaciers that involved the simultaneous operation of many stations (e.g. Van den Broeke and others, 1994; Greuell and others, 1997; Oerlemans and others, 1999). In addition, year-round automatic weather stations (AWSs) are operated now on a growing number of glaciers.

Although a great deal of climate research focuses on changes in the "mean state", it is a fact that extreme events can have a larger impact on many societal activities, and probably also on many natural systems. The natural system studied here is a valley glacier, the mass balance of which is affected by many processes. The sensitivity of the mass balance is normally investigated by forcing a calibrated mass-balance model with uniform changes in temperature and precipitation (e.g. Oerlemans, 1992; Brock and others,

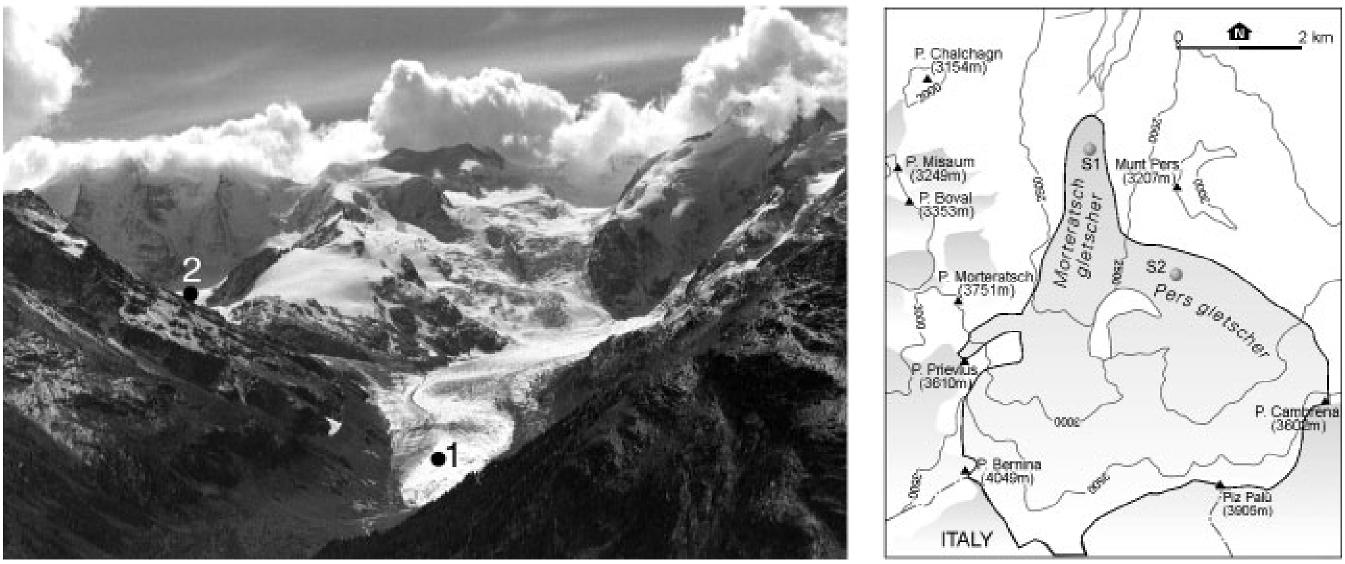

Fig. 1. Morteratschgletscher, Switzerland, photographed in September 2001, looking south. The approximate locations of sites 1 and 2 are indicated by black dots. The sites are also shown on the map (S1 and S2).

https://doi.org/10.3189/172756404781815158 Published online by Cambridge University Press

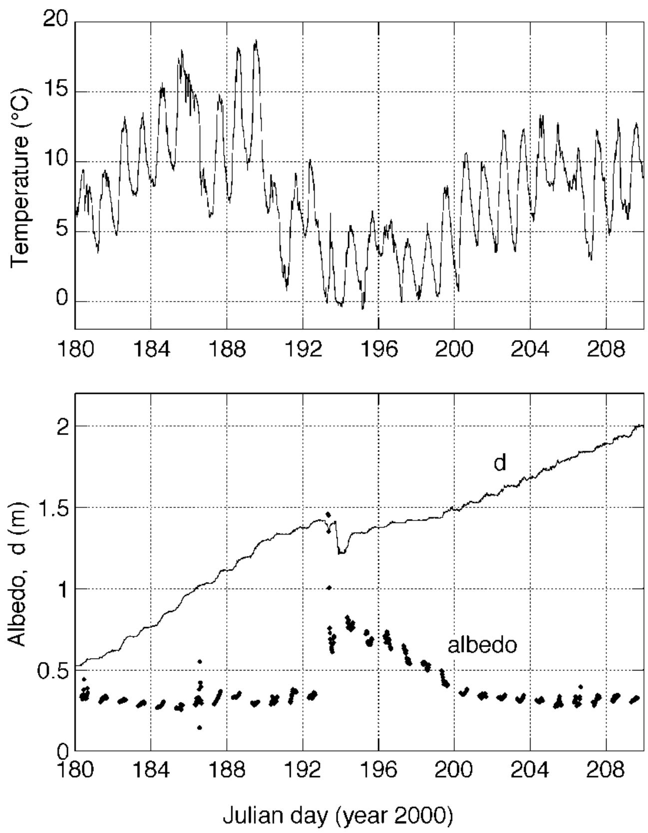

Fig. 2. Meteorological records from the AWS on the snout of Morteratschgletscher (site 1). The upper panel shows air temperature at ~3.5 m above the glacier surface. The lower panel shows the distance to the surface (d) measured with the sonic ranger and the surface albedo (half-hourly values only for 0800–1600 UT).

2000; Klok and Oerlemans, 2002). However, there is also a need to quantify the effect of less smooth climatic forcing like a heavy summer snowfall. It has been speculated that summer snowfall has a large effect on a glacier's mass balance (e.g. Greuell and Oerlemans, 1987). In recent years long series from energy-balance stations on glaciers have become available, which offer the possibility of quantifying the effect of summer snowfall on glacier mass balance more precisely.

In this paper, we use data from the AWS on Morteratschgletscher, Switzerland, to investigate one snowfall event in some detail. This AWS has been on the snout of Morteratschgletscher since October 1995. The snowfall event of 10–11 July 2000 was selected as the best case for this study. Morteratschgletscher (46°24′ N, 9°56′ E; Fig. 1) is 7.5 km long, has an area of 17 km^2 and spans an altitudinal range of about 2000 m. The glacier snout is at about 2000 m a.s.l.

The AWS is located at an altitude of about 2100 m (site 1), on a relatively flat part of the glacier (slope ~5°). The instrument support stands freely on the ice, and "sinks" with the melting surface. A sonic ranger (Campbell SR-50) is mounted on a tripod drilled into the ice. This provides information on ice-/snowmelt and snow accumulation.

The meteorological quantities measured are air temperature and humidity (Vaisala HMP35AC, with forced ventilation), atmospheric pressure, wind speed and wind direction (Young 05103), and the four components of the radiation budget (longwave in and out, solar in and out; Kipp CNR1). Additionally, battery condition, solar panel current, and tilt of the mast are recorded. In winter, snow temperatures are measured at four depths. The data are logged on a Campbell CR-10x. Sampling is done every minute, and 30 min averages are stored. An analysis of the data for the year 2000 was recently published (Oerlemans and Klok, 2002), which provides more information on the Morteratsch project including a discussion on the mass and energy budget for a full year.

2. A SUMMER SNOWFALL EVENT

On 10 July 2000 (Julian day (JD) 192), a cold front swept from the northwest into central and southern Europe. In the cold air behind the front, there was widespread shower activity for several days. Such outbreaks of cold air from the northwest bring precipitation in the northern and western parts of the Alps, accompanied by a sharp drop in temperature and occasionally snowfall in the higher valleys. In a case like this, the Bernina mountain chain, in which Morteratschgletscher is located, normally receives little precipitation because it is in the precipitation shadow of the central Alps. However, the zone of heavy precipitation extended well into northern Italy. On JD193 about 20 cm of snow was deposited on the lower part of Morteratschgletscher, and more higher up.

Figure 2 shows a selection of meteorological data. The cold front passed on JD192 and this is clearly reflected in the air temperature. For JD192 and JD193 the mean air temperature was about 3°C, in sharp contrast to the weeks before in which maximum temperatures up to 18°C were measured. The distance to the surface as measured by the sonic ranger clearly shows the interruption of the melt process by the snowfall event. The record suggests that a few cm of snow fell in the night and early morning of JD193, and then more in the late afternoon and the evening.

Half-hourly albedos are also shown. Here the albedo is defined with respect to the glacier surface and not reduced to a horizontal plane (this would be difficult because even a simple correction method would require a partitioning of the shortwave radiation into a direct and a diffuse part). In Figure 2, albedo values are only shown from 0800 until 1600 UT, because for low sun angles spurious effects occur. The effect of the snowfall on the albedo is distinct, as expected. At the AWS site a characteristic ice albedo is 0.3. Once the snowpack is deposited, the albedo is about 0.75. This seems low for fresh snow but it reflects the fact that, in summer, surface melt will start immediately (or probably occurs already when the snow is falling). The albedo values of 1 and 1.5 seen on JD193 are unrealistic, of course. They are a consequence of snow cover on the upward-looking sensor, whereas the downward-looking sensor remains free of snow. This feature has been observed many times during snowfall. Also, in the case of riming or precipitation measured albedo values tend to be unrealistically high (e.g. some values on JD186).

Another sonic ranger was operated at about 2640 m a.s.l. (site 2, Fig. 1). Close-ups of the records from the sonic rangers are shown in Figure 3. On JD193 between 0000 and 0800 UT, snowfall at site 2 totaled about 20 cm; at site 1 only a few centimeters were deposited. Then, after a couple of hours it started to snow again, and continued until 2200 UT. This brought another 30 cm at site 2 and 20 cm at site 1.

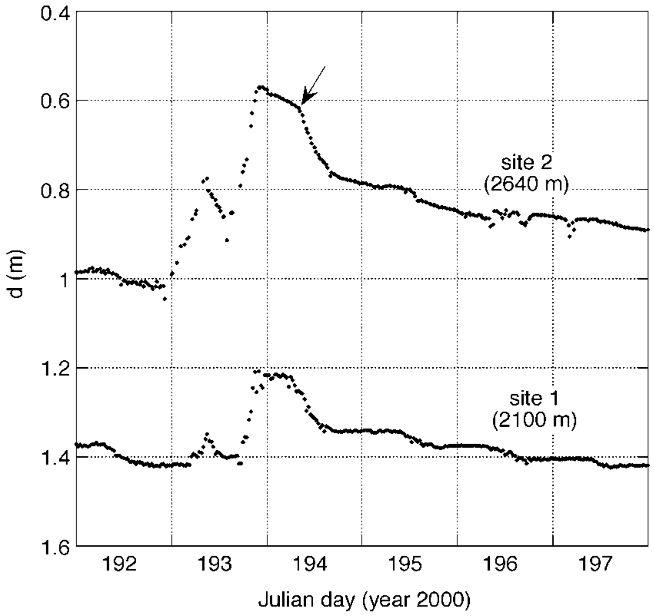

Fig. 3. Distance to the surface as measured by the sonic ranger at site 1 (2100 m) and site 2 (2640 m). Sample frequency is 30 min. Note that the vertical scale is reversed. The arrow markes the onset of significant melting.

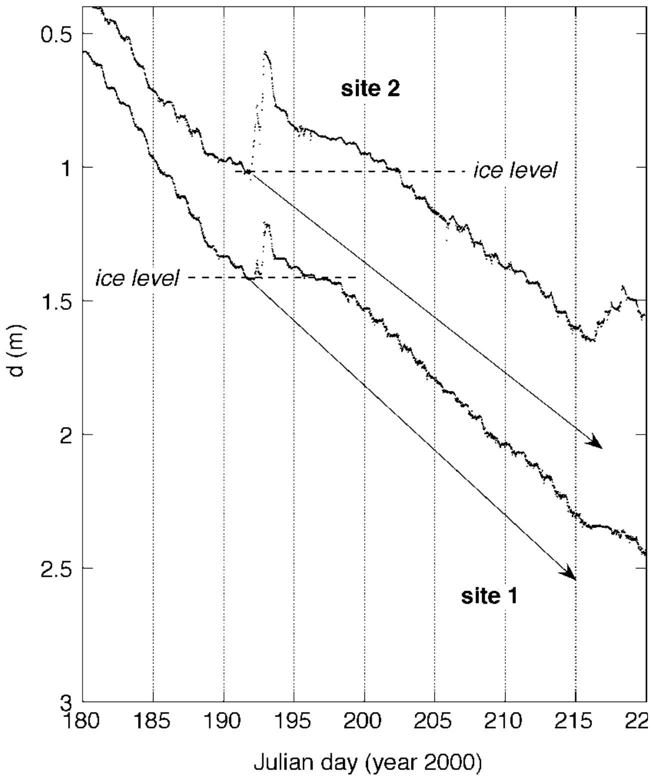

Fig. 4. Sonic ranger data for a 40 day period. The arrows are used to estimate the effect of the snowfall on the specific balance (as explained in the text).

The sonic ranger data from site 2 show how the snowpack evolves. Settling of the snow is clearly reflected in the data. The lowering of the surface accelerates markedly in the course of the morning, when air temperature rises and the radiation balance becomes positive (arrow in Fig. 3).

3. ASSESSING THE EFFECT ON THE MASS BALANCE

The effect of the snowfall event on the specific balance can be estimated from the records of the sonic rangers (Fig. 4). After JD200 the melt curves look quite regular again. However, the daily melt rates are not as high as for the period before the snowfall, but this can be understood on the basis of lower global radiation and air temperatures closer to the climatological average (Oerlemans and Klok, 2002).

The mean melt rate for the period JD203–215 was calculated from a linear regression. We found a value of 0.0485 m ice d^{-1} for site 1 and a value of 0.0419 m ice d^{-1} for site 2. The effect of the snowfall can now be estimated by extrapolating the melt curves from the ice level at the beginning of the snowfall (Fig. 4). The arrows in Figure 4 have slopes in agreement with the melt rates mentioned above. Assuming that these arrows represent the melt process as it would have occurred without the snowfall, the differences in the amount of melted ice (Δ_{ice}) are 0.25 m for site 1 (2100 m) and 0.42 m for site 2 (2640 m). In Table 1 these values are converted into mass and compared with the mass that was deposited as snow. Snow densities (ρ_{snow}) at sites 1 and 2 were assumed to be 300 and 200 kg m^{-3}, respectively. These relatively high values were chosen because during the period of snowfall air temperature was around the freezing point or slightly above. We define a feedback factor F that gives the ratio of the change in specific balance to the amount of mass deposited as snow. We then find $F = 3.9$ for site 1 and $F = 4.0$ for site 2.

As an alternative method for determining the impact of the summer snowfall, we have applied a calibrated mass-balance model recently developed for Morteratschgletscher (Klok and Oerlemans, 2002). This model has a 25 m spatial resolution and computes all components of the surface energy flux. It is forced with standard meteorological data from nearby climate stations. It is assumed that precipitation increases linearly with altitude, and the fraction of precipitation falling as snow is determined by the air temperature.

We have compared two model runs for 2000: one with the full meteorological dataset as forcing and one in which the precipitation on 10–11 July was set to zero. The difference in the calculated specific balance (Δb_{n}) thus provides an estimate of the effect of the snowfall event. It turned out that the amount of snow generated by the model at sites 1 and 2 was smaller than observed. Apparently, for this particular event the precipitation on the glacier was larger than at the synoptic weather stations from which the meteorological data driving the model are taken. These stations are located in a different valley, and the difference can be

Table 1. Evaluation of the amount of snowfall and the reduction of the amount of melted ice for the two sites where sonic rangers were operated

Site	*Snow depth*	ρ_{snow}	*Mass*	Δ_{ice}	ρ_{ice}	*Mass**
	m	kg m^{-3}	kg m^{-2}	m	kg m^{-3}	kg m^{-2}
1	0.19	300	57	0.25	900	225
2	0.47	200	94	0.42	900	378

*The last column gives the change in the specific balance due to the snowfall event.

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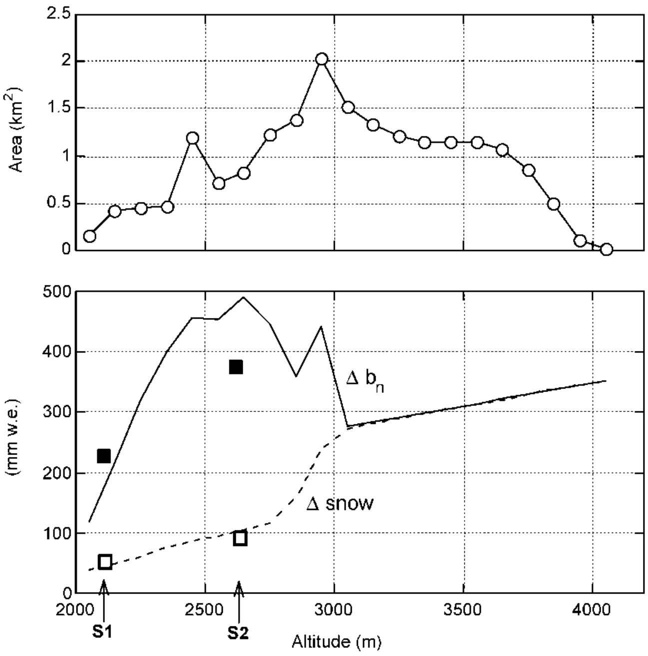

Fig. 5. The change in the specific balance due to the snow event as calculated with a mass-balance model. Differences in snowfall (Δ_{snow}) and specific balance (Δb_{n}) are plotted against altitude (lower panel). The measurements at S1 and S2 are also shown. The open squares refer to the amount of snow, and the black squares represent the inferred change in the specific balance. In the upper panel the area–elevation distribution (100 m intervals) is shown for reference.

understood in view of the large mesoscale variability of precipitation patterns in alpine terrain. The best approach therefore is to adjust the precipitation data from the synoptic weather station in such a way that the amount of snow generated in the model matches the observations at sites 1 and 2. To achieve this we had to multiply the amount of precipitation as registered at the weather stations (Samedan and Bernina Curtinatsch) by a factor of 2.3.

Figure 5 shows the difference in the specific balance (Δb_{n}) for the runs with and without the snowfall event (for 100 m altitude bands). The amount of snow (Δ_{snow}) that fell during the event is also shown. The dependence of Δ_{snow} on altitude shows the general linear increase in precipitation with altitude, as well as a stronger increase in a more limited altitude zone (2700–3100 m) related to the averaged position of the freezing level during the event. Above 3100 m the change in the balance equals the amount of snow. Here the amount of melt is small anyway and the change in surface albedo due to the summer snow is small. The feedback factor F as defined above varies from 3 at the glacier snout to a peak value of about 5 around 2300 m.

Altogether, the average amount of snow deposited on the glacier on 10– 11 July is 224 mm w.e. The calculated effect on the total annual mass balance of the glacier is 354 mm w.e. This yields $F = 1.6$ for the entire glacier.

4. CONCLUSION AND DISCUSSION

We have studied the effect of a summer snowfall on the specific balance of a glacier in two independent ways. Analysis of the AWS data suggests that a typical value for the feedback factor F in the ablation zone is ~ 4, which is in agreement with the results from the mass-balance model. For the entire glacier we found a much smaller value ($F = 1.6$), which is understandable because the high regions have a snow rather than ice surface all the time.

If summer snowfall increases the mass balance by typically 350 mm, how does this relate to the effect of a temperature anomaly, for instance? According to a sensitivity analysis performed with the mass-balance model (Klok and Oerlemans, 2002), a uniform increase in air temperature of 1 K results in $\Delta b_{\mathrm{n}} \approx 700$ mm. Two significant summer snowfalls could therefore compensate the effect of a 1 K higher mean temperature during the ablation season.

ACKNOWLEDGEMENTS

We are grateful to D. C. Trabant, R. March and M. Sturm for their comments and helpful suggestions on an earlier draft of this paper. We also acknowledge the skill and dedication of the technicians at the Institute for Marine and Atmospheric Research, Utrecht University, who keep the AWS running year by year.

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