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ONE-DIMENSIONAL ENERGY FLUXES OF A SNOW COVER IN WINTER 1996/97 AT THE SCHAUINSLAND, BLACK-FOREST (GERMANY)

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1. INTRODUCTION

Behavior of snow cover and glaciers under changing climatic conditions is receiving much attention from scientists because of the growing concern regarding the possible future global warming and because of the significant changes in extent and volume of glaciers in the recent past.

Although glacier volume and extent may fluctuate due to instabilities in internal ice dynamics (e.g., Kamb et al., 1985), climatically controlled glacier mass balance represents the most fundamental control over the existence and size of any glacier. Thus, it is important to develop accurate models that can help predict glacier mass balance based on known or predicted climatic parameters. Such mass-balance models include calculation of snow- or ice-surface energy balance, which is determined by a combination of radiation balance as well as the sensible and the latent heat fluxes. In our work, we focus on verification of an existing energy-balance model (Schneider, 1998) using meteorological and snow-pit observations.

2. THE INVESTIGATION

In winter 1996/97 we investigated snow cover dynamic and one-dimensional energy fluxes at a site in Schauinsland, Black Forest, Germany. The site itself is a 1km long by 250 to 400 m wide meadow surrounded by coniferous forest. The location is on the northern ridge of the Schauinsland. The terrain has a gentle slope towards north-northeast. In the period from November 25, 1996 until March 5, 1997 we maintained an automatic weather station at a site next to the Station 'Schauinsland' of the Umwelt-Bundesamt (UBA, German Environmental Office) and recorded snow properties in a snow pit every four days.

2.1 Snow Data

Snow data was collected every two to four days from a fresh extended snow pit and from ablation sticks at the AWS and in its surroundings. In the snow pit we recorded the stratigraphy, the snow depth, the snow temperature, the snow density, the water content, the hardness in the different layers, the crystal forms, the grain size and the grade of metamorphism. Our procedures followed the standards defined by the International Commission of Snow & Ice of the International Association of Scientific Hydrology (Colbeck et al., 1990). The water equivalent volume of the snow cover was analyzed twice and an average was computed. The snow temperature was measured in each layer and, if possible, every 2 cm.

2.2 Meteorological Data

At the AWS we measured the air temperature and air humidity at 2.13 m and 0.85 m above ground surface, wind direction & speed at 2.4 m, short-wave radiation at 1.73 m, and long-wave radiation at 1.93 m. Snow temperature was measured at 5 cm, 10 cm and 30 cm. A heat flux plate was located 1 cm below the soil surface and soil temperature probes were located at 5 cm, 10 cm and 15 cm below the ground surface. Table 1 shows the brand and names of the instruments used. The data was collected with a Campbell Scientific Ltd. (U.K.) '21xl' and 'CR10' data logger connected to the local electricity supply. Data was obtained each 10 seconds and stored as 10-minute average values to a Campbell Scientific Ltd. (U.K.) 'SM 192-716' storage module.

TABLE 1: AWS Instrumentation

No	Measurement	Brand &instrument type
3	Air temperature - humidity	Vaisella 'HMP 35'
1	Short-wave radiation	Kipp & Zonen 'CM7'albedometer
1	Long-wave radiation	Schenk pyradiometer
1	Wind speed	Campbell 'A100R'
1	Wind direction	Campbell 'W 200 P'
1	Surface temperature	Heitronics 'KT 15'
1	Soil heat flux	Middleton 'CN3'
3	Snow temperature	Campbell '107'
3	Snow temperature	Campbell '107'

In addition to the AWS data we also obtained data on air pressure and precipitation from the nearby UBA. To compare the AWS data to the additional data from the UBA, we later transformed the 10-minute average readings taken with the AWS into averages over 3 hours, which is the temporal frequency of meteorological measurements at the UBA.

Partial loss of AWS data occurred between January 21 – 29, 1997 and at February 6, 1997 due to extreme weather conditions, which lead to an electric power failure and a frozen anemometer. The data was replaced and recalculated from data of the nearby Station of the German Environmental Office. Between December 23, 1996 and February 20, 1997 we directly measured the surface temperature with the 'KT15'. The shorter period was caused by electrical problems with the 'KT15'. For the remainder of the investigation period the surface temperature was calculated from the measured outgoing long wave radiation.

For the period December 13, 1996 to February 23, 1997 the values of air temperature and air humidity, wind-speed, radiation balance and soil heat flux were used to estimate the snow-cover energy balance.

2.3 Energy Balance Estimation

The energy balance (S) of the snow-cover is composed of the radiation balance (R), the latent heat flux (E), the sensible heat flux (H) and the soil heat flux (H_s).

$$S = R + H + E + H_s \qquad [1]$$

For positive values of S, energy is available to raise the snow temperature until melting is possible. In the opposite case water stored within the snow-cover will refreeze or the snow temperature will decrease (Schneider, 1999).

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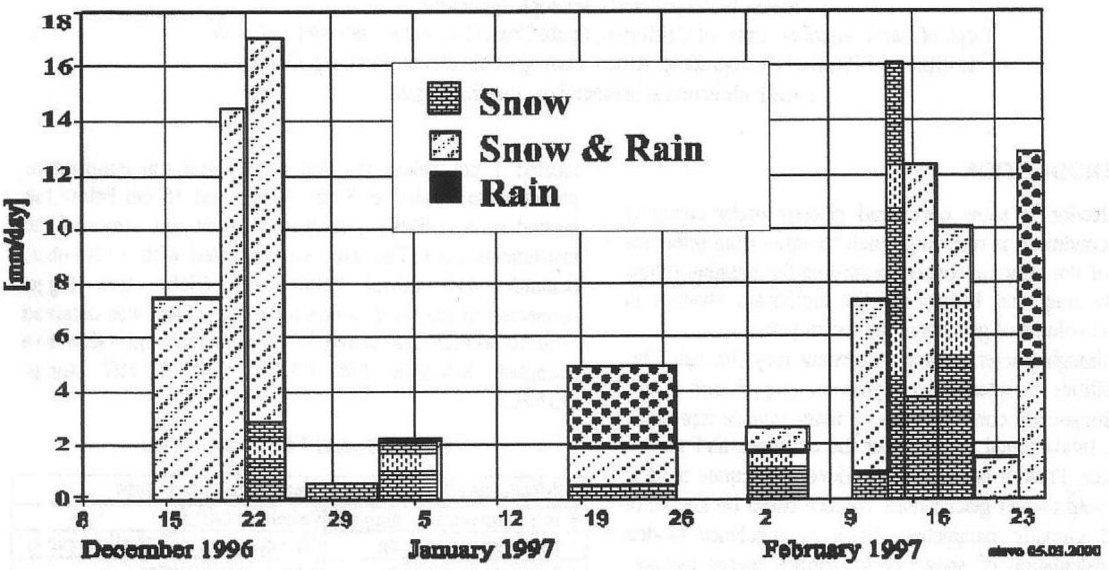
Figure 1: Precipitation at the Schauinsland during the investigation period, Dec. 13th 1996 until Feb. 26th 1997, divided into rainfall T > 0.5° C, snowfall T < 0° C and snowfall or rainfall 0° C < T <0.5° C



For our calculations the values for the radiation balance and soil heat flux were taken directly from the AWS measurement. Wind speed, air-temperature and air humidity were used to calculate the latent and sensible heat fluxes as turbulent heat fluxes. Wind speed was recalculated for the height of the temperature and humidity probes above the snow surface, assuming a logarithmic wind profile. The humidity gradient calculations we assumed a surface vapor pressure of 100 %.

For the calculations of energy transfer the stability of stratification above the snow-cover was taken into account using the bulk Richardson number discussed in Braithwaite (1995).

$$R_b = \frac{g\,(T_1 - T_s)\,z_0}{\overline{T}\,u_1^2} \quad [2]$$

T_1 and T_s = potential temperature at elevation 1 and at the surface, respectively, u_1 = wind speed at elevation 1,
g = 9.81, z_0 = surface roughness,

and $\overline{T} = T_1 + T_s / 275.15$ [3]

For all calculations we assumed $z_0 = z_i = z_v = z_t$. A comprehensive discussion of values for z_i, z_v, z_t can be found in Oke (1978), where values range from 0.5 to 10 * 10^{-4} m. For our calculations of the latent and sensible heat flux we assumed $z_i = 10^{-4}$ m.

$$H = \frac{c_p k^2 \rho\, u_1}{P\;[\ln z_1/z_i * \ln z_1/z_T]}\,(T_1 - T_s)(1 - 5R_b)^2 \quad [4]$$

$$E = \frac{0.622\;L_v k^2 \rho\, u_1}{P\;[\ln z_1/z_i * \ln z_1/z_v]}\,(e_1 - e_s)\,(1 - 5R_b)^2 \quad [5]$$

P = air pressure, z_1 = height of the instruments
p = air density,
k= van Karman constant = 0.4
$z_i = z_v = z_t$ = roughness length of momentum, vapor & heat,
L_v = specific latent heat = $(2.498 - 0.0024*T)*10^6$ [J/kg]

2.4 Data Processing

We used the data to get the 30-minute-average values, which were then used in our energy balance calculations. The averaged values were checked for errors and any erroneous data were replaced by recalculating them with data from the nearby station of the German Environmental Office (UBA).

The height for all used instrument was adjusted to the varying snow depth. Snow data was considered valid for the period until the next snow pit measurements were taken. Humidity measurements were calibrated by assuming a maximum value of 100% of relative humidity.

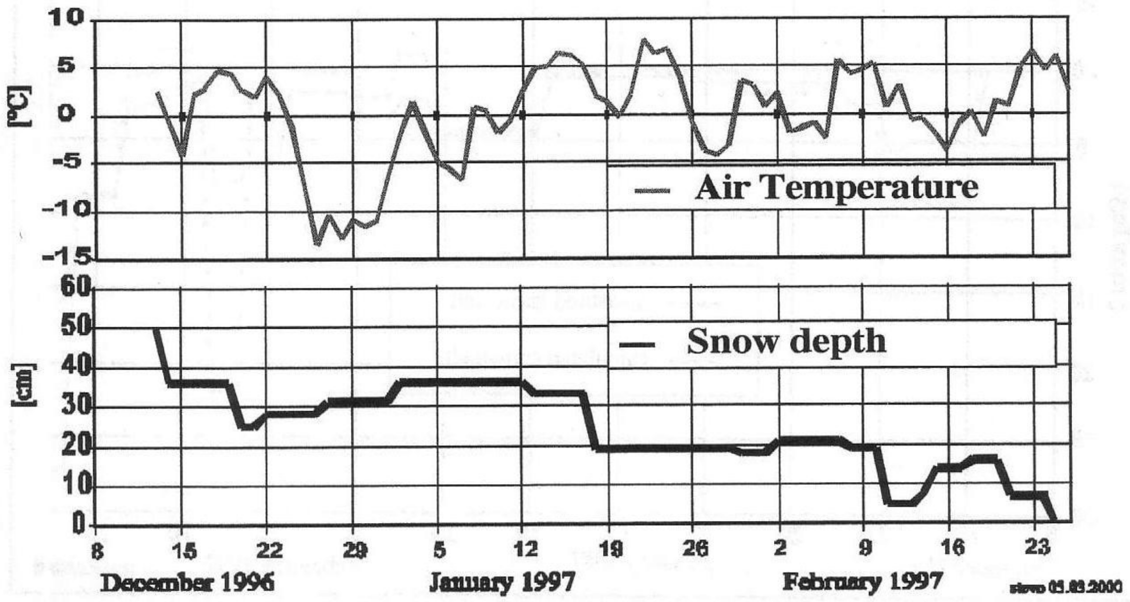
For calculating the turbulent heat fluxes the surface roughness was set for impulse, humidity and heat to $1*10^{-4}$ m. For periods in which the atmospheric stability prevented vertical exchange (Rb = 0.2) the turbulent heat flux rate was set to 0. Our program calculated the latent and sensible heat fluxes and added these to the radiation balance. Further snowmelt was calculated for positive heat fluxes in periods during which the surface temperature and the bottom temperature of the snow cover were higher than –0.5°C.

After the snowmelt was calculated for each 30-minute value. The daily average snowmelt was calculated for each period in between two snow pit recordings. These values then were compared with the values of water equivalent difference obtained from consecutive snow pit measurements.

For all periods the results were checked, if the weather conditions allowed the agreement or disagreement of the results, by factors such as heat input from precipitation, increase of water equivalent from precipitation or storage of snowmelt within the snow cover. For this we looked on the temperature records, the snow wetness, snow metamorphism and the amount of received precipitation (see figure 1).

To take the amount of precipitation into account, the recorded precipitation was divided into contributions by snow, snow and rain, and rain. Depending on the air temperature measured at 2 m we considered precipitation fallen at T< 0° C as snow, T > 5° C as rainfall. For precipitation fallen in between these two temperatures we

Figure 2 : Air-temperature and snow-depth at the Schauinsland during the investigation period, Dec. 13th 1996 until Feb. 26th 1997



looked closer at the weather conditions where necessary. These temperature thresholds were chosen following Wilhem (1975).

3. RESULTS & DISCUSSION

For the period from December 13, 1996 until February 23, 1997 we calculated a snowmelt of 253 mm from the energy balance estimation. A snowmelt water equivalent of 236 mm was estimated from the calculation of the turbulent heat fluxes and the radiation balance, where as 17 mm resulted from the soil heat flux. The comparison amount of measured snowmelt, measured in the snow pit, was 251 mm. Figure 2 shows the evolution of snow depth and air temperature for the period of the investigation.

The build-up of the snow-cover started at November 13, 1996. At December 13, 1996, when we started to record data, a snow cover of 61 cm with a water equivalent of 200 mm existed. Figure 3 shows the snow cover dynamics together with the daily air temperature at 2 m for the investigated period. During the period from December 13, to 20, 1996 rainfall dominated the weather. With no snow accumulation the snow cover decreased to 135 mm of water equivalent. During this first melting the higher amount of measured snowmelt is due to additional heat input from warm rainfall.

With temperature around the freezing point snowfall alternated with rainfall until December 24, 1996 when the air temperature fell below 0°C and 6 cm snow accumulated. Until December 29, 1996 the area experienced a Siberian high-pressure system with temperature as low as –17 °C. After December 29, 1996, under the influence of a warmer Atlantic air mass and at temperature around the freezing point, about 5 cm of snow accumulated. Between January 8, and 12, 1997 an inversion in temperature occurred due to smog and temperature far below zero in the valleys with temperature around zero in the higher elevations. Despite air temperatures around 6 °C at midday no significant snowmelt was registered until January 17, 1997. This was due to a low net radiation balance as a result of a high albedo and a highly negative long-wave radiation balance. At the end of this stable period the snow cover had a height of 45 cm and a water equivalent of 150 mm.

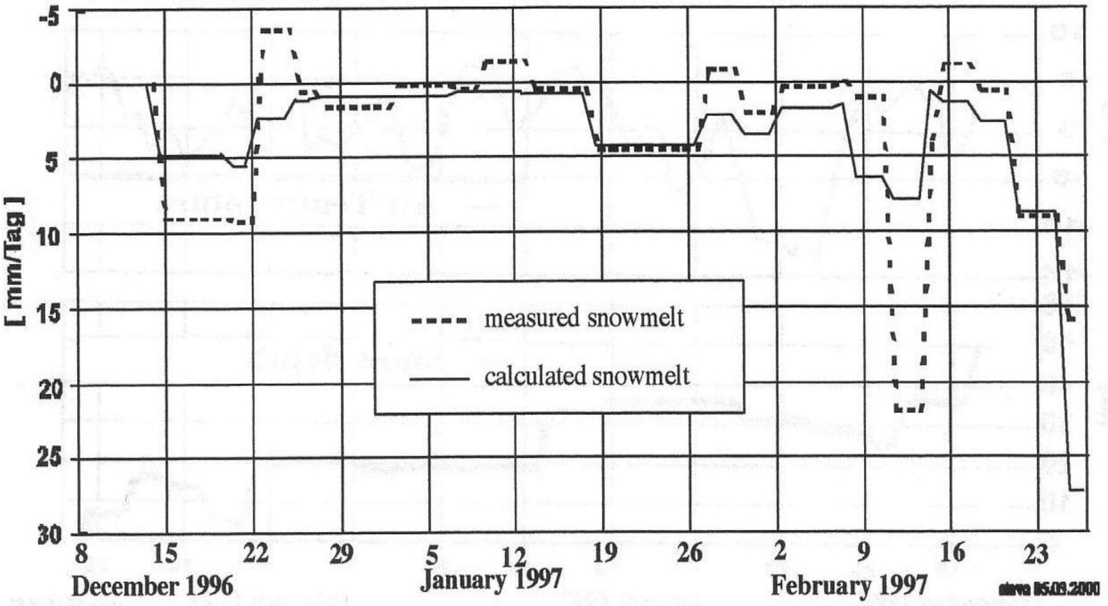
On January 18, 1997 higher temperature and rainfall lead to isothermal conditions within the snow-cover. Until January 26, 1997 the snow-cover decreased to a snow depth of 31 cm with a water equivalent of 130 mm. The amount of melted snow during this period was 25 mm of water-equivalent. Until February 7, 1997, with sunny days and clear skies during night, snow melted during the day. Instead of draining away, the melted snow remained within the snow-cover and refroze partially during the night. The difference between the estimated and measured snowmelt can be explained by this cycle of melting and refreezing and by an increase in the snow water content.

After February 7, 1997 with stormy rainfall and snowfall, snow depth varied considerably. With ablation rates of 4 to 8 mm water equivalent a day, the snow cover was depleted by February 23, 1997. Due to the retention in the snow-cover, the calculated snowmelt first exceeded the measured snowmelt where as in the second half of the snowmelt periods the measured water loss exceeded the calculated snowmelt. With the loss of the snow-cover the albedo changed abruptly at the afternoon of February 23, 1997.

4. ERROR ESTIMATION

A simple comparison of the modeled snowmelt of 253 mm with the measured snowmelt of 251 mm will likely overestimate the accuracy of the model. Schneider (1998) estimated an error of 25% for the model in former investigations. The relative error increases with a lower melt dynamic and decreases with a higher melt dynamic.

Figure 3: Calculated and estimated snowmelt at the Schauinsland during the investigation period, Dec. 13th 1996 until Feb. 26th 1997



5. CONCLUSIONS

The purpose of this investigation was to verify a one-dimensional energy balance model obtained during mass balance studies at the Antarctic Peninsula (Schneider, 1999, Schneider, 1998).

During the winter 1996/97 we maintained an AWS and obtained comparable snow data from snow pit measurements at a site on the Schauinsland in the Black-Forest (Germany). The meteorological data was used to estimate the energy balance. We also used direct measurements of the soil heat flux, the radiation balance, and calculated the magnitude of the turbulent sensible and latent heat fluxes. In the calculations of the turbulent heat fluxes, we used a surface roughness of 10^{-4} m ($z_i = z_v = z_t$) for the impulse, the heat and the vapor. The bulk Richardson number was used to calculate the atmospheric stability over the snow-cover. We assumed heat exchange for $Rb < 0.2$. From the energy balance of the snow cover we calculated the snowmelt, which could be compared with measured amount of snowmelt from the snow pits. For the period between December 13, 1996 and February 23, 1997 we calculated 253 mm water-equivalent snowmelt from the snow-cover energy balance estimation, which can be compared with 251 mm measured snowmelt.

Beside this remarkably close match between estimated and measured values, our investigation showed a weakness of the theoretical model, which sometimes produced incorrect estimates of snowmelt because the model does not consider processes occurring within the snow-cover. Particularly the retention of water during melting periods could not be considered in the current model, and that should be taken into account in future efforts to improve modeling of snow-cover dynamics.

Overall the investigation showed that the energy balance model derived for glacial mass balance studies in Antarctica was successfully applied at the Schauinsland in the moderate climate of the Black-Forest (Germany).

Possible future applications can be seen in regional climate models, glacier mass balance, subglacial hydrological studies and for solving sedimentological questions such as the estimation of sediment transport from glaciated areas by fluvial discharge.

6. ACKNOWLEDGMENTS

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