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Long-Term Records of Snow Cover Water Equivalent in the Swiss Alps
2. Simulation

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M.B. Rohrer and L.N. Braun
Swiss Federal Institute of Technology, ETH,
CH-8057 Zürich, Switzerland

The knowledge of the temporary snow-water equivalent storage term (*SWE*) is an important prerequisite for the assessment of short- and long-term runoff volumes and water quality aspects. Since *SWE* measurements are frequently not available, this variable is modelled on the basis of operationally measured meteorological data. For model verification fortnightly measured *SWE* values are used. The choice of the proper model depends on the aim of the simulation and the input data available: if *SWE* is the only variable to be modelled and time-series of daily total and new snow depths values are available, then a simple model based on Martinec (1977) employing settling curves for each snowfall event is suggested. If apart from *SWE* values other variables such as liquid water storage, snow albedo, *etc.* are to be modelled, and hourly input data are available, the conceptual energy and mass balance approach as presented here is suggested. The following variables, measured in hourly intervals, are used as input: air temperature, precipitation, wind speed, water vapour pressure, global radiation and cloud cover (term readings). This model was originally developed at a research-type station but can now be applied at up to 70 stations of the automatic network (ANETZ) of the Swiss Meteorological Institute (SMI). The modelled values are good estimates of the measured ones in the accumulation as well as in the ablation season.

Introduction

Knowledge on the spatial and temporal variation of the snow cover in the mountain environment can be gained by the analysis of direct measurements on the ground, by remote sensing methods or by various approaches which simulate the snow pack

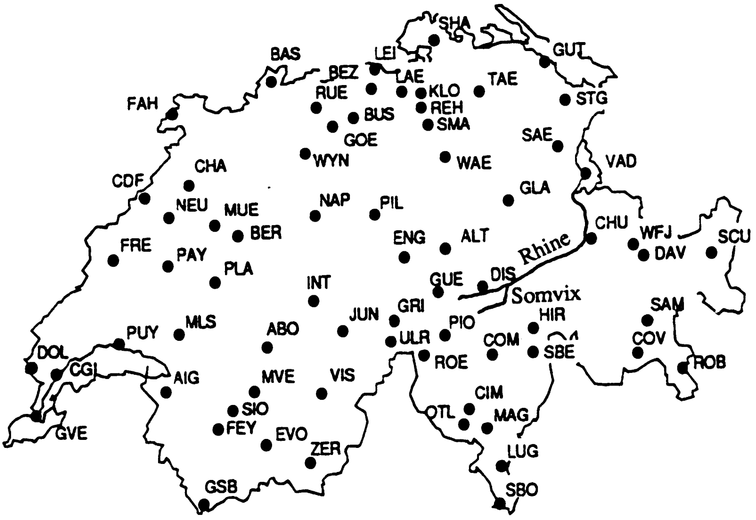

Fig. 1. Measurement network of the automatic stations (ANETZ) of the Swiss Met.Inst. as of 1991. Elevations of selected stations given in Fig. 4.

based on meteorological input variables. The choice of a particular methodology will largely depend on the problem that needs to be solved and on the availability of data. In the companion-paper by Rohrer, Braun and Lang (1993) an analysis of direct measurements of the snow-water equivalent taken at some 50 locations in the Swiss Alps over the past 50 years is presented. Here, the focus is put on the simulation of snow accumulation and melt by various methods. If one is interested for instance in the operational forecasting and prediction of streamflow, a methodology to assess the precipitation conditions of the past month may be of great interest. This approach strongly depends on the easy access to long-term records of the conventional and automatic stations network as well as to the current data of the Swiss Meteorological Institute (SMI). In a second part a rather simple and robust method is presented to simulate continuously the snow-water equivalent at a given location with daily observations of new as well as total snow depths. As these records are generally available at a great number of locations, this approach may serve as an efficient tool to assess the dynamic behaviour of snow storage in a high spatial resolution and over long time periods. Thirdly, an energy and mass balance snow model is presented which allows not only the monitoring of the total water equivalent, but various other variables such as the thermal state of the snow cover, the liquid water storage in the snow, the albedo of the snow surface, or the melt rates at a temporal resolution of one hour. This kind of model may be of interest in agriculture where the monitoring of runoff conditions may help to assess the danger associated with nutrient losses when liquid manure is applied on snow (Braun 1990). Such a detailed snow cover monitoring at a high temporal resolution is possible due to the automatic network (ANETZ) of the Swiss Meteorological Institute which can furnish the necessary input data in real-time at some 70 locations in Switzerland. Furthermore, meteorological records of this high temporal resolution are now available over more than 10 years, which allow impact assessment of possible climate changes on the snow cover that are more reliable than the approaches employing simple air temperature index-methods.

Fig. 1 gives an overview of the ANETZ stations network. Any details concerning the variables measured and characteristics of sensors employed can be found in SMA (1985) for instance.

Aggregational State of Precipitation

Discrimination between Rainfall and Snowfall

The correct classification of the aggregational state of precipitation has widely been recognized as being a key task in precipitation-runoff modelling (see *e.g.* Obled 1990). The relative frequency of snowfall, rainfall and mixed precipitation may show a dependency on the season as well as on the type of data acquisition (differences between conventional and so-called automatic stations) as shown by Rohrer (1989), Braun (1991) and Braun and Rohrer (1992). The high temporal resolution of precipitation and air temperature data of automatic weather stations allows a much more reliable classification of the aggregational state as compared to the conventional data. An investigation of the Davos data 1981-1988 revealed that if one takes data of a temporal resolution of 10 minutes as a reference assuming correct classifications, then the hourly data misclassify 1.8 % of precipitation events; if one uses only 3 term readings or daily mean values, 8,9 % and 13.8 % of events are misclassified, respectively. In all further investigations empolying ANETZ data the hourly data set was used, as any correction procedures are applied to these data by SMI, but not to the 10-minute resolution data.

Fig. 2 shows the aggregational state of precipitation as a function of air temperature and precipitation intensity for Davos. The rare snowfall observed at air temperatures above 1°C are all of low intensities and can be neglected for operational purposes. Practically no rainfall events are observed at this alpine location below 0°C, which is quite contrary to lowland stations, where freezing rain of appreciable intensities may occur.

Fig. 3 shows how the monitoring of the aggregational state of precipitation may help to interprete discharge hydrographs such as the one of the Rhine (Somvix tributary) for September 1984. On 5 September a strong precipitation event started off as rainfall, but changed quickly to snowfall over all elevations of the basin, causing a rapid recession despite high precipitation intensities. During the event on

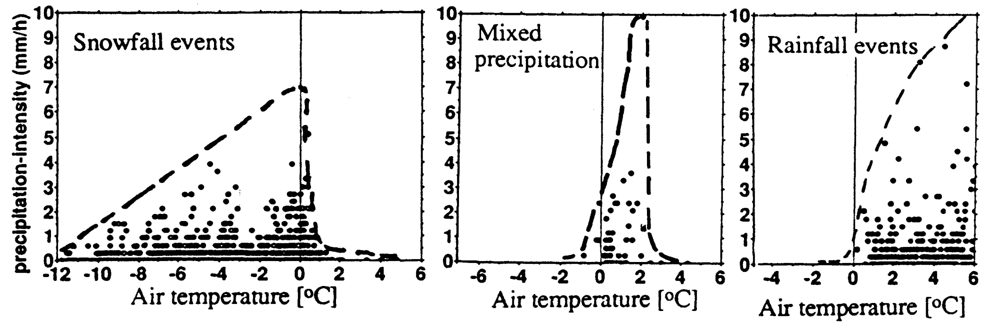

Fig. 2. Precipitation intensities at various air temperatures for snowfall, rainfall and mixed precipitation events at Davos (1,590 m a.s.l.) 1981-88.

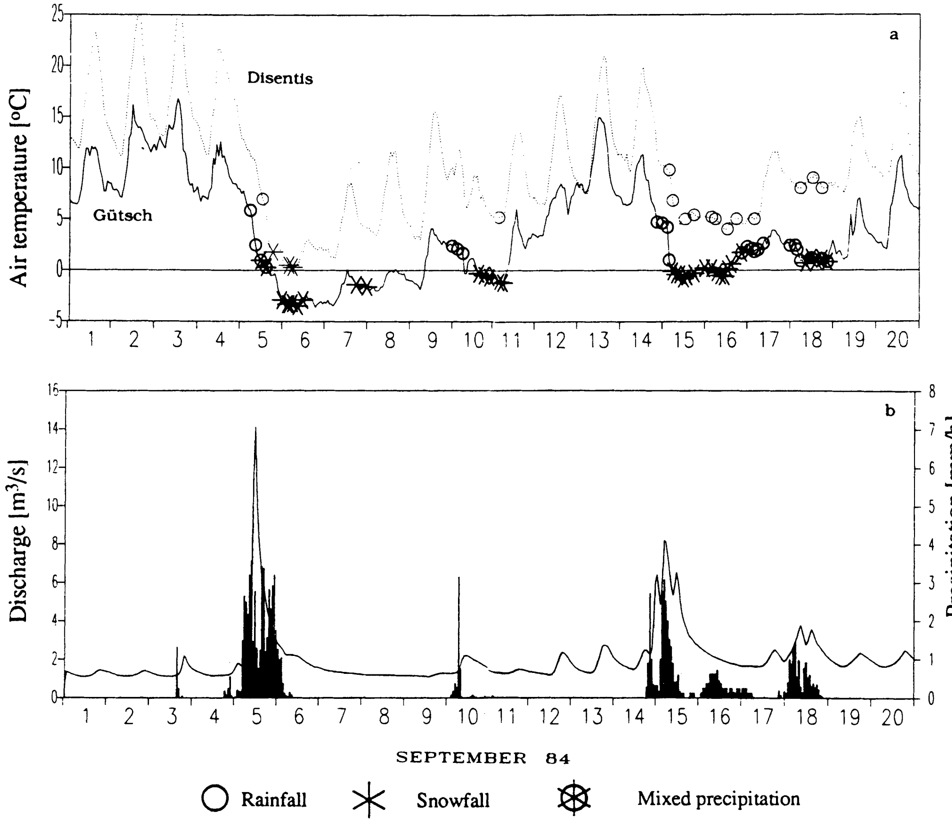

Fig. 3. a) The course of air temperature and observations of the aggregational state of precipitation at the ANETZ stations Gütsch (2,282 m a.s.l.) and Disentis (1,190 m a.s.l.) 1-20 September 1984.

b) Hourly precipitation (mean of stations Disentis and Piotta, 1,007 m a.s.l.) and discharge of the Somvixer Rhine (Swiss Hydrologic and Geologic Service). Figure from Lang *et al.* (1993).

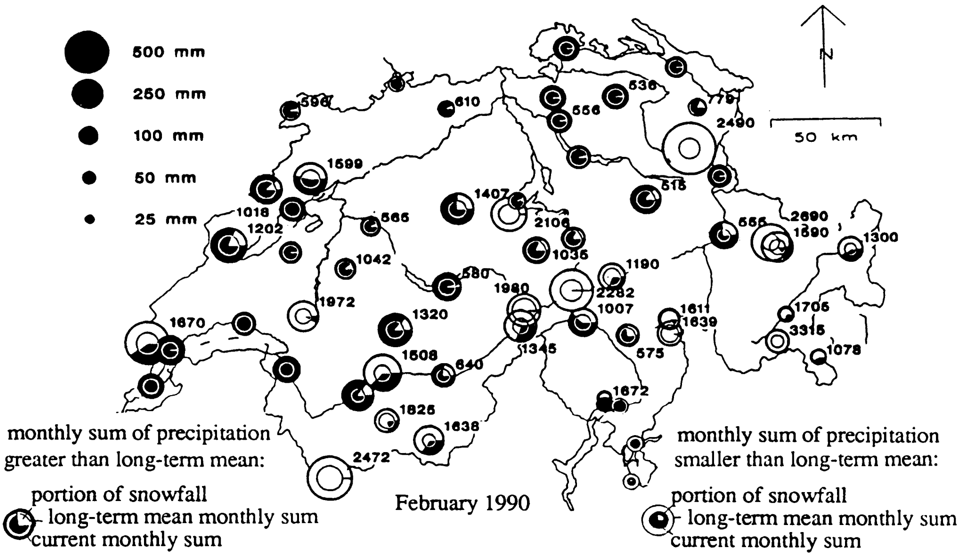

Fig. 4. Monthly sums of precipitation and calculated portion of snowfall at ANETZ stations (see Fig. 1) for February 1990 as an example. Figures indicate a.s.l. (m) of the meteorological stations.

15 September, however, cooling was not as strong, and rainfall was observed up to an elevation of about 2,000 m. As a result, discharge receded much more slowly as compared to the first case despite the lower precipitation intensities.

Operational Assessment of the Precipitation Conditions of a Given Month

For the prediction of discharge it may be advantageous to assess the current precipitation conditions: how large is the sum of precipitation in the previous month in comparison to the long-term mean, and what percentage fell as snow at the individual stations? Based on fixed air temperature divider T_0 typical for each station (range of values: 0.0-1.5°C, sensitivity of this parameter see below) a programme was developed to produce operational analyses of the precipitation conditions. One example is given in Fig. 4 for February 1990; together with comparison with the long-term mean of precipitation this kind of graph allows the operational assessment of the precipitation conditions for a given month for the whole of Switzerland, for instance for the purpose of prediction of discharge. Caution in the interpretation needs to be employed at stations where there is an obvious change in precipitation catch when moving from a conventional to an automatic station (as for instance for the mountain top Säntis station, 2,490 m a.s.l.): the long-term mean is based on the standard Hellman gauge measurement, while the current sum is taken from a heated tipping bucket rain rauge, known to catch more due to a different installation location.

Long-Term Simulation of the Snow-Water Equivalent: The Settling Curve Model

Here, a rather simple approach to simulate the snow-water equivalent of the total snow cover based on daily measurements of total snow depth and new snow depths is presented. It is based on Martinec (1977) who used this approach to calculate maximum snow loads on building structures based on settling curves of the individual snow-fall events. The snow depth (m) of a snowfall event H_{sn} after n days is calculated as follows

$$H_{sn} = H_{s0}(n+1)^{-k} \tag{1}$$

where

H_{s0} – new snow depth [m]
k – exponent, here = 0.3.

For each new snowfall layer, a mean density of RHO_0 = 100 kg/m³ is applied which was shown to be a very reliable estimate for a wide range in altitude and season (Rohrer *et al.* 1993). After n days, the mean density RHO_{sn} (kg/m³) of the snow layer s is given as follows

$$RHO_{sn} = RHO_0(n+1)^{-k} \tag{2}$$

The density $RHO_{\mathrm{tot}n}$ of the total snow cover on day n is the weighted mean of all modelled densities of the individual layers as follows

$$RHO_{\mathrm{tot}n} = \sum_{s=1}^{s=a} RHO_{sn} \frac{H_{sn}}{H_{\mathrm{tot}n}} \tag{3}$$

where

$H_{\mathrm{tot}n}$ – the sum of depths of all modelled snow layers H_{sn}
a – total number of snow layers.

If one multiplies the calculated snow density $RHO_{\mathrm{tot}n}$ by the measured snow depth $H_{\mathrm{pole}n}$ on day n at the measuring pole, the modelled snow-water equivalent SWE_{tot} (mm) of the total snow cover on day n is given as follows

$$SWE_{\mathrm{tot}} = H_{\mathrm{pole}n} RHO_{\mathrm{tot}n} \tag{4}$$

It was found that this original Martinec (1977) version meant to calculate the maximum *SWE* was insufficient for the continuous simulation of *SWE*, particularly during the ablation phase due to an underestimation of snow density $RHO_{\mathrm{tot}n}$. Therefore, this variable was extended by an additive term RHO_{add} whenever "melt conditions" were recognized by the condition that simulated total snow depth ($H_{\mathrm{tot}n}$) was larger than the measured one ($H_{\mathrm{pole}n}$). Consequently, a revised model version is suggested as follows

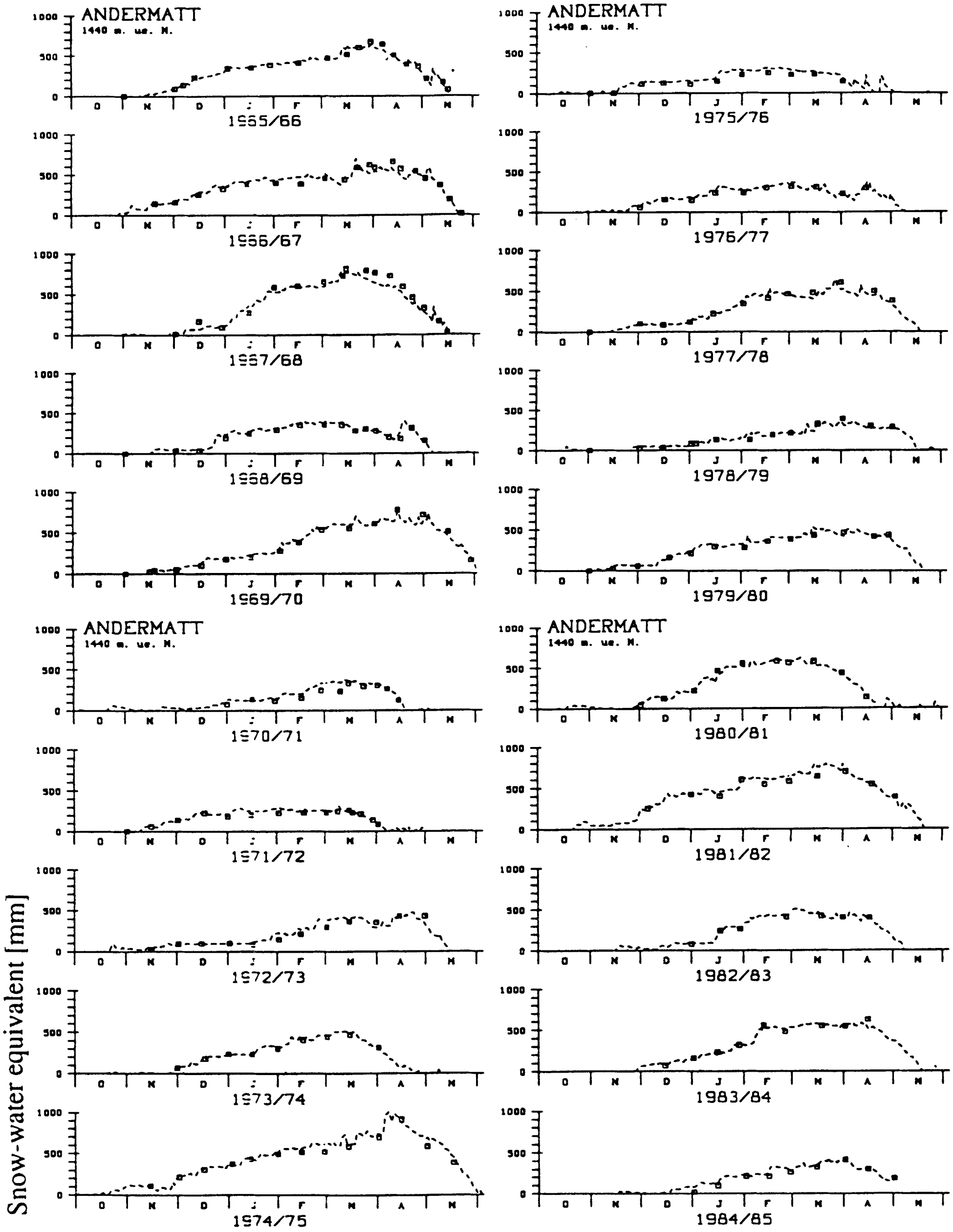

Fig. 5. Settling curve model (modified version) applied at Andermatt (1,400 m a.s.l.): comparison of simulated snow-water equivalent values (dashed line) with measured values (squares) for winters 1965/66 till 1984/85. Location see Fig. 1. Rohrer *et al.* (1993) p. 54.

Table 1 – Continuous modelling of the snow-water equivalent using the original settling curve model (Martinec 1977) and the modified version: assessment of performance using the mean absolute deviation (mm) at 7 stations having data over at least 36 winter seasons; n = number of observed *SWE*-values

Station name	years	n	mean absolute deviation (mm) original version	 modified version
Andermatt	1948-1985	515	54.2	42.8
Grindelwald	1948-1985	315	39.1	33.8
Davos	1949-1985	368	34.3	33.9
Weissfluhjoch	1948-1985	569	56.4	47.9
Trübsee	1950-1985	341	112.8	91.2
St. Antönien	1947-1985	418	33.2	32.1
Zermatt	1947-1985	312	24.8	25.0

$$SWE_{\mathrm{tot}} = H_{\mathrm{pole}n}(RHO_{\mathrm{tot}n} + m\ RHO_{\mathrm{add}}) \qquad (5)$$

where

m – number of days during the interval 1 .. n with $H_{\mathrm{tot}n} > H_{\mathrm{pole}n}$.

The snow density of the total snow cover is increased this way until the limit of 450 kg/m^3 is reached.

Fig. 5 shows the application of this model to the Andermatt data set 1965/66 till 1984/85. As input data daily values of new snow depth and total snow depth are used. Over a wide range of conditions the simulated snow-water equivalent corresponds very well with the measured values.

Table 1 shows the performance (given as the mean absolute deviation) of the original and the modified settling curve model at 7 stations having data sets over at least 36 winter seasons. The modified version shows a higher performance practically in all cases, and the mean absolute deviation is less than 50 mm in all cases except Trübsee, where very high *SWE* values are observed. There, measured *SWE* exceeded 1,000 mm in 34 cases during the 36 observed winter seasons.

Energy and Mass Balance Snow Model

An energy and mass balance snow model which uses operationally measured meteorological data at automatic weather stations (ANETZ) was presented by Rohrer and Lang (1990) and is further discussed here. Based on the hourly input data air temperature, precipitation, wind speed, vapour pressure and incoming solar radiation, and with conventional cloud cover term observations, the main components of the energy balance including melt rates are calculated. When developing the model, great importance was given to use physically meaningful parameter values, to have only one parameter set for all stations where the model was applied, and to derive parameter values externally, if possible. It was found that the parameterization for snow albedo was of key importance to achieve reliable simulations of the snow-water equivalent.

Simulation of Snow Albedo

An approach to simulate the albedo A of snow going back to the U.S. Corps of Engineers (1956) was modified and tested on data as given by Eckel and Thams (1939) and Prohaska and Thams (1940)

$$A = A_0 + K^{-nr} \tag{6}$$

where

A_0 – lowest value of A, reached asymptotically, optimal value = 0.40
K – constant, optimal value = 0.44; $A_0 + K = 0.84$, highest albedo right after snowfall
r – recession constant, optimal value = 0.05 at air temperatures <0°C
0.12 at air temperatures >0°C
n – number of days since the last appreciable snowfall (snowfalls which surpass 3 cm in total over 3 days).

An independent validation of this approach is given by Plüss (1994) for the Weissfluhjoch-Davos study site at 2,560 m a.s.l. This parameterization of albedo proved to be acceptable for snow depths greater than about 10 cm (see Fig. 6). When the snow cover drops below this value, albedo is generally overestimated, and an approach as suggested by Kuz'min (1972) employing an nomogram relating albedo to snow depth and surface lowering due to melt might be advantageous on these occasions. The sensitivity of the recession parameter k is shown in Fig. 7 for the San Bernardino station. Optimal k values were found to be 0.05 at air temperatures <0°C and 0.12 at >0°C.

Sensitivity of the Air Temperature Divider T_0 and the Snowfall Correction Factor SCF

In the first part of this paper some results were presented concerning observations of the aggregational state of precipitation. Here, the sensitivity of two parameters controlling the amount of deposited snow are discussed in respect to the continuous simulation of the snow-water equivalent using the energy and mass balance model. Fig. 8 shows the sensitivity of the air temperature divider T_0 which determines whether precipitation falls as snow or rain at the Montana station (1,508m). Optimal value of T_0 was found to be 1°C for this station. The optimal value for each station was externally derived on the basis of measured values of new snow depth and observations of the aggregational state where available as described above (for more details see Rohrer 1992).

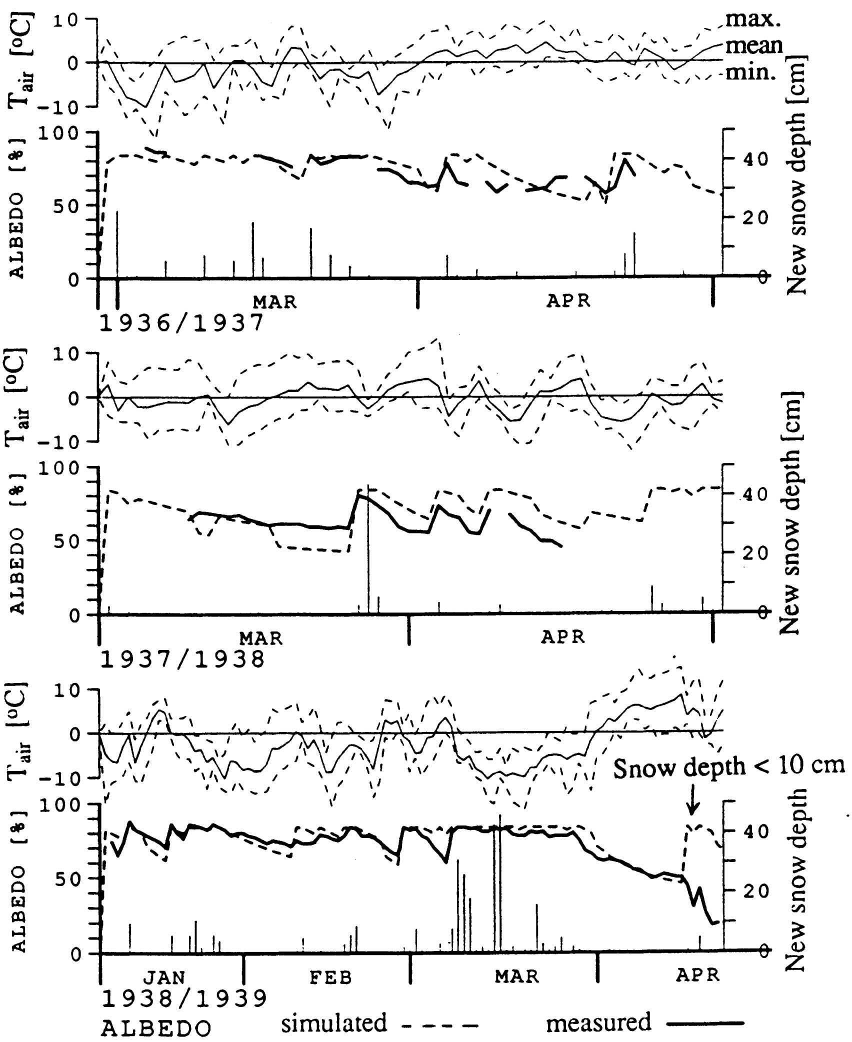

Fig. 6. Measured (solid line) and simulated (dashed) albedo of snow cover at Davos-Observatory during winters 1936/37 till 1938/39. Data based on Eckel and Thams (1939) and Prohaska and Thams (1940).

Fig. 9 shows the sensitivity of the snowfall correction factor SCF, which is a multiplicative parameter used to compensate for the well-known systematic undercatch of precipitation gauges, in particular the heated tipping bucket type as used in the automatic stations network ANETZ (for a thorough treatment of the problem see for instance Spiess 1987). Braun and Rohrer (1992) have shown that it might be advantageous to use an additive correction term based on comparisons between

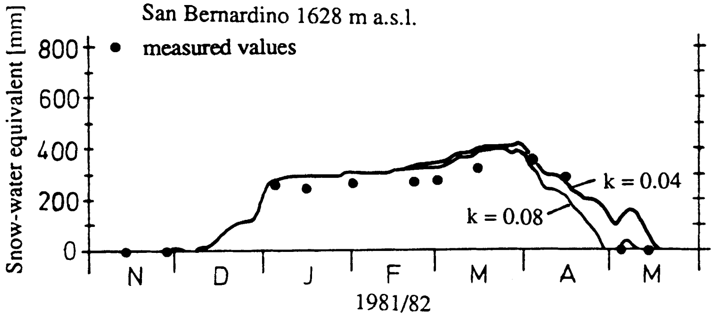

Fig. 7. Sensitivity of albedo modelling parameter k on simulated snow-water equivalent and comparisons to measured values at San Bernardino (1,628 m a.s.l.) 1981/82.

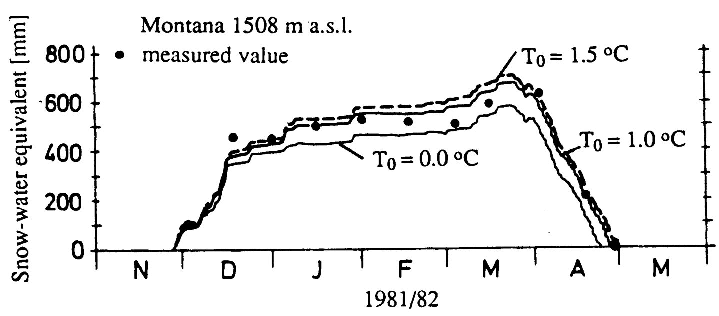

Fig. 8. Montana station (1,508 m a.s.l.) Sensitivity of air temperature divider T_0 when simulating water equivalent of total snow cover using the energy and mass balance snow model.

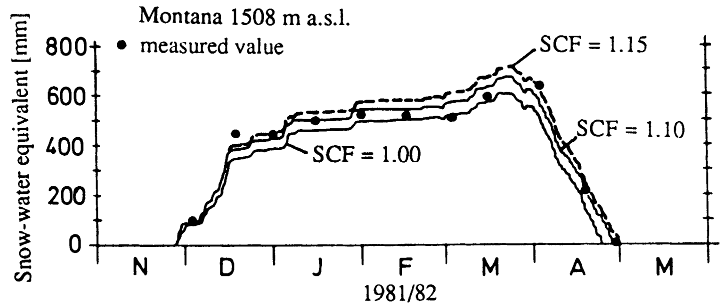

Fig. 9. Montana station (1,508 m a.s.l.) sensitivity of snowfall correction factor SCF.

water measured in the raingauge and the water equivalent of new snow as observed on the standard snow board. This additive term was found to be between 2.8 and 5.8 mm per snowfall event, and it had no apparent relationship with wind speed. An international project on the comparison of correction methods is under way (Goodison *et al.* 1989).

Summary and Conclusions

Together with the companion-paper by Rohrer, Braun and Lang (1994) this contribution tries to show the great value of long time series of snow-water equivalent measurements as they are available for Switzerland at some 50 stations with record lengths of up to 50 years. These direct measurements allow a climatological assessment of snow storage as part of the hydrological cycle, they form a valuable basis for forecasting and prediction of streamflow, and they allow the calibration and verification of various snow models. Depending on the purpose of a snow cover simulation and data availability, the following modelling approaches are presented:

a) a simple settling curve model which yields continuous snow-water equivalent values based on daily observations of new and total depths, and as these are generally available, this approach may be applied at many locations and over long time periods;

b) a method to assess the precipitation conditions of a given month based on climatological values, the aggregational state of precipitation and the current snow accumulation situation, employing high temporal resolution data of the automatic network (ANETZ) of the Swiss Meteorological Institute which are available in real-time;

c) a conceptual energy and mass balance snow model running on an hourly time step, enabling the monitoring of various other variables in addition to water equivalent such as the albedo, the thermal state of the snow cover, the liquid-water holding capacity, and the melt intensities at the base of the snow pack. This model now can be applied at any of the 70 ANETZ meteorological stations, which allow detailed snow cover – climate sensitivity studies and the monitoring of current snow conditions as they affect the quantity and quality of runoff, for example.

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Address:
Swiss Federal Institute of Technology ETH,
Winterthurerstr. 190,
CH-8057 Zürich,
Switzerland.