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Distributed Snowmelt Simulations in an Alpine Catchment
2. Parameter Study and Model Predictions

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A distributed grid-based model is used (1) to analyze the importance of selected model parameters, (2) to simulate spatial distributions of snow cover properties in a small basin and (3) for a comparison with less sophisticated models as typically used in operational applications. Results indicate that variations of water equivalent with slope and local relief are of utmost importance for realistic distributed simulations but more moderately influence mean basin melt. Snow cover variables of which spatial distributions are simulated include the thermal and hydraulic state of the pack and hourly melt water release. All variables exhibit substantial variations in space and time. They are primarily controlled by topography and the delay of melt water in deep packs. The grid model is compared with a snow band model and a parametric model. The latter estimates the snowpack's areal extent from water equivalent. Simulated snow-covered areas suggest the grid model to be the most realistic. Differences in terms of mean basin melt derive from different assumptions associated with model structure.

1. INTRODUCTION

In the companion paper [*Blöschl et al.*, this issue] (referred to as paper 1) an attempt at modeling spatially distributed snowmelt in rugged terrain was presented. The model makes use of digital terrain data with 25 m grid spacing. Snowmelt is calculated for each grid element taking topographic variations of solar radiation into account. The model was tested by comparing simulated snow cover patterns with those derived from air photographs. In this paper this model is used to (1) analyze model behavior by varying model parameters, (2) simulate spatially distributed snow cover variables to analyze snow melt processes, and (3) compare results with those of less sophisticated models as typically used in operational applications. These topics are treated in sections 2, 3, and 4, respectively.

In the model presented in paper 1 there is particular uncertainty about the spatial distribution of initial water equivalent and about snow albedo. The distribution of water equivalent is based on a relation to terrain features. In this relation, the increase of water equivalent with elevation is derived from field data. The effect of using an inaccurate snow volume and gradient is described by, among others, *Buttle and McDonnell* [1987] and *Blöschl et al.* [1990], indicating both parameters to be of considerable importance for mean basin melt. In paper 1 the relation to slope is based on a literature review and the relation to terrain curvature has been arbitrarily chosen. Therefore, the influence of slope and curvature is analyzed here. For simulating snow albedo an aging curve approach from the literature was adopted [*U.S. Army Corps of Engineers*, 1956]. This is not always a good parameterization [*Mannstein*, 1985; *Marshall and Warren*, 1987; *Colbeck*, 1988] and may introduce significant errors [*Blöschl et al.*, this issue]. Here, albedo is varied within reasonable limits keeping the rest of the model parameters fixed.

Section 3 of this paper focuses on the spatial distribution of melt rates and the hydraulic and thermal state of the snow cover. Such distributions may contribute to the understanding of snowmelt processes in alpine terrain. Specifically, they may assist in developing concepts for spatially distributed hydrological models in such an environment [*Obled*, 1990]. At the small catchment scale of this study neither conventional point measurements [*Rau*, 1986] nor remote sensing techniques [*Rott*, 1986] are really capable of providing this information. This is a strong argument for using a distributed model. Because of the successful simulation of snow cover patterns [*Blöschl et al.*, this issue] it is believed that the model also produces reasonable distributions of melt rates and snow cover properties. It is recognized that these simulations will not be accurate from the deterministic point of view by comparison with detailed measurements. However, in this study the objective was not to give quantitative figures but to present typical distributions to be expected in an alpine catchment. The model should be capable of producing such distributions.

Section 4 represents an attempt to place the simulation results into the perspective of operational applications. There are two basic approaches of handling the variability of snow cover variables in a catchment. These are (1) subdivision of the catchment into subareas (commonly elevation zones [*World Meteorological Organization*, 1986]), and (2) a parameterization of the variability. The parameterization is usually based on a relation between mean basin water equivalent and the areal extent of the snow cover [*Anderson*, 1973*a*; *Ferguson*, 1986]. Here, one model of each type is selected and compared with the grid model. To investigate the influence of model structure alone, the same model for zonal snowmelt and the same initial snow storage volume is used in all cases.

All examples presented in this study are based on simulation runs during the 1989 ablation period in the Längental basin as described in paper 1.

2. PARAMETER STUDY

In the distributed grid model an identical approach for distributing initial water equivalent and solid precipitation over the basin is used which is basically related to elevation,

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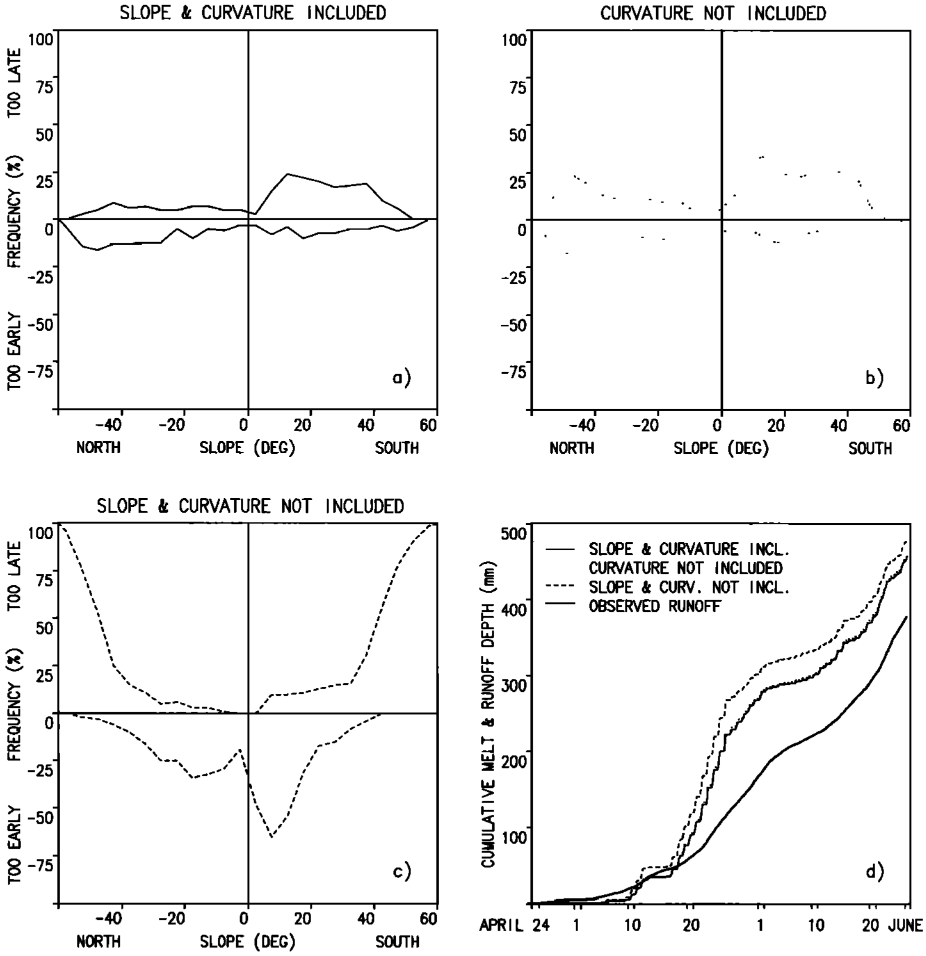

Fig. 1. Percent error in snow cover on north and south facing slopes, June 26, 1989 (too late: snow cover simulated, bare observed; too early: bare simulated, snow cover observed). Initial water equivalent is estimated as a function of (*a*) elevation, slope and curvature, (*b*) elevation and slope, and (*c*) elevation only. (*d*) Cumulative mean basin melt and runoff depths.

slope and curvature of the terrain. Three cases are considered here starting from the inclusion of all of these features and discarding one or two of them in subsequent cases. Here, the influence of the distribution of water equivalent is examined rather than that of the total volume of snow stored in the basin. Therefore, the same snow volume is used in all cases.

Two simulation runs are performed to assess the influence of snow albedo. Fixed albedoes of 0.5 and 0.7 are used, respectively. This is regarded as the range of areal albedoes to be expected during the ablation period in alpine terrain [*Anderson*, 1973*b*].

Depending on snow cover conditions the effect of inaccurate parameters on runoff may differ from that on snow cover. Therefore, the sensitivity is evaluated in terms of both snow cover patterns and mean basin melt. No effort was made to simulate runoff, but observed runoff depths are indicated for comparison. Errors in snow cover are evaluated by comparing simulated and observed snow cover patterns on an element-by-element basis for June 26. The elements are subdivided into classes according to slope and aspect.

Figure 1 shows simulation results with different assumptions on the spatial distribution of initial water equivalent. The percentage denoted by "too late" (Figures 1*a*, 1*b*, and 1*c*) refers to elements with snow cover simulated and bare ground observed, i.e., an overestimation of snow cover. When comparing Figures 1*a* and 1*b* one may observe that disregarding curvature slightly deteriorates model performance because of the differences in accumulation on ridges and in gullies. There is virtually no influence on simulated mean basin melt (Figure 1*d*). Disregarding slope (Figure 1*c*), however, has a dramatic effect on the simulated snow cover resulting in an overestimation of snow cover on steep slopes and an underestimation on flat slopes. The latter result derives from an underestimation of water equivalent in flat areas as the total volume of snow stored in the basin is required to match that of the standard case. Disregarding slope has a moderate influence on mean basin melt rates (Figure 1*d*). There is slightly earlier melt by comparison with the initial simulations which is due to the larger contributing area.

Figure 2 shows the influence of different assumptions of albedo on snow cover and melt. As would be expected, the snow cover on south facing slopes is more sensitive to albedo than that on north facing slopes (Figures 2*a* and 2*b*). On south facing slopes the changes in albedo may account for the errors in snow cover whereas on north facing slopes

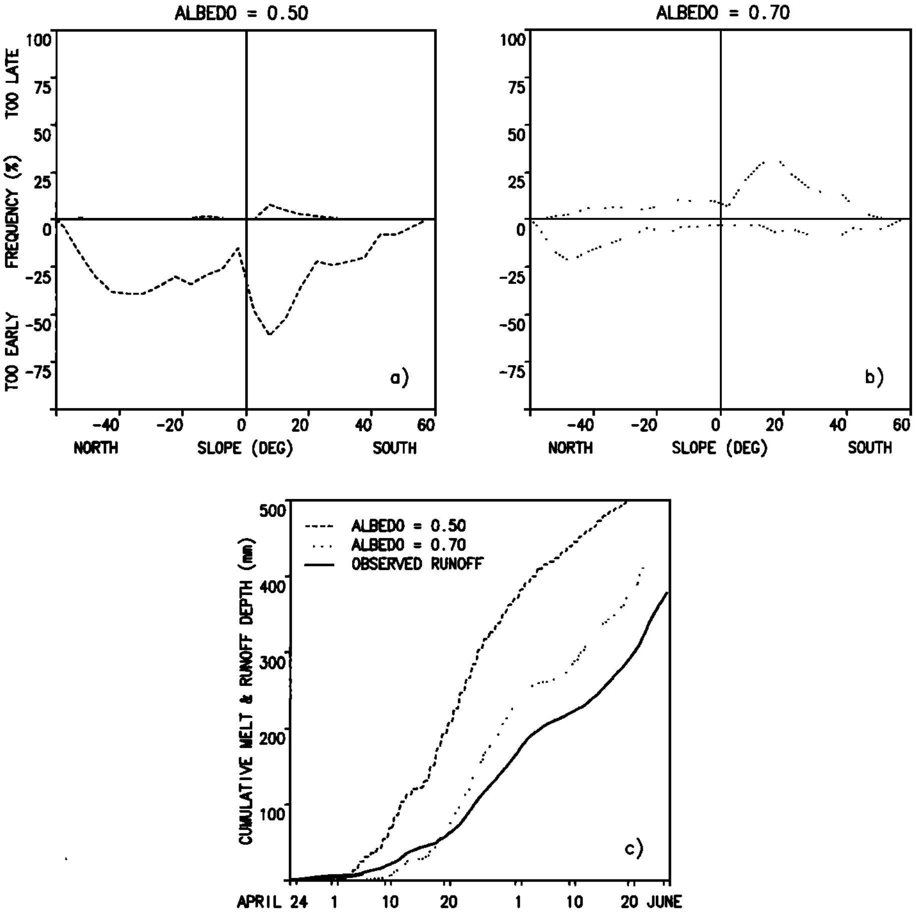

Fig. 2. Sensitivity of percent snow cover on north and south facing slopes to albedo, June 26, 1989 (too late: snow cover simulated, bare observed; too early: bare simulated, snow cover observed). Albedo is set to (*a*) 0.50 and (*b*) 0.70. (*c*) Cumulative mean basin melt.

both cases exhibit a marked underestimation. This indicates the influence of other error sources. Part of the discrepancy could derive from different albedoes on north and south facing slopes, which is consistent with the findings in paper 1. Clearly, errors may also be due to incorrect water equivalents (Figure 1*c*).

Figure 2*c* indicates that mean basin melt rates are very sensitive to albedo. Early in the ablation period using a lower value of albedo yields increased melt because of the enhanced energy input. Later in the season, however, less snow is left in the basin, resulting in reduced melt rates.

Both albedo and the distribution of initial water equivalent are of utmost importance for simulating realistic distributions of snow cover properties. Whereas albedo equally controls the distribution of snow cover and mean basin melt, this is not so for the distribution of water equivalent. Mean basin melt shows only moderate sensitivity to variations of water equivalent with slope and curvature, which is clearly a result of averaging. For example, erroneous melt rates in gullies may compensate for those on tops when integrating melt rates over the basin. Therefore, given similar infiltration characteristics throughout the basin, snowmelt simulations may give good results in runoff predictions even if the distribution of water equivalent fails to resemble the actual one. *Golding* [1974] came to essentially the same conclusions in a field study in a forested catchment in Alberta. Golding reports that on average runoff predictions based on detailed measurements of distributed water equivalent were not superior to those using a few snow courses as an index. However, this is not necessarily the case for extreme situations when the areas contributing to runoff may significantly deviate from those during average conditions.

3. MODEL PREDICTIONS

For analyzing the spatial distribution of snow cover variables three days were selected during the initial period of the snowmelt season. After a cold spell in late April temperatures gradually increased in early May. May 5 was a fair weather day. In the lowest part of the catchment air temperatures varied from 2° to 12°C and little melting occurred. Subsequently, temperatures dropped below zero but rose again on May 9. On this day the weather was similar to that on May 5, but the "ripening" of the snow cover had significantly advanced [*Blöschl and Kirnbauer*, 1991]. Melting continued on the following days with similar average air temperatures. On May 11 overcast sky conditions prevailed with slight rainfall at noon.

Figures 3 and 4 present cross sections of the Längental basin showing topography and simulated water equivalent, liquid water content and cold content on May 5 at 7, 13 and 19 LT. Liquid water content is the total amount of liquid

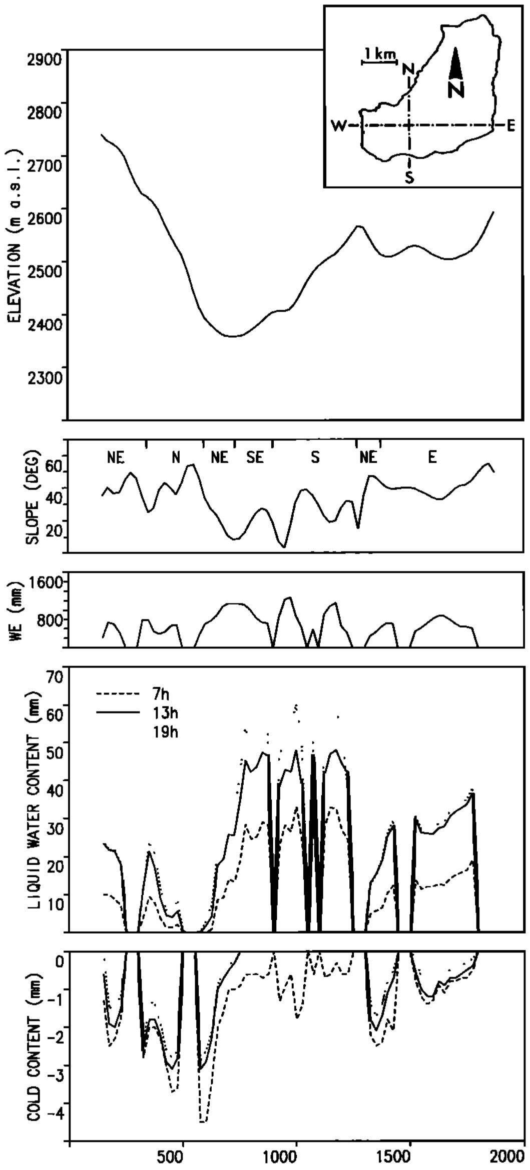

Fig. 3. Cross section showing topography and simulated water equivalent, liquid water content and cold content, May 5, 1989, for south-north transect. Inset map shows location of the cross section in the Längental catchment.

water stored in a pack. Cold content is the heat necessary to warm up a snowpack from subzero temperatures to 0°C in terms of melted water. These parameters are derived from profiles as simulated by the multilayer model in the grid points of the cross sections. Snow cover parameters exhibit considerable variability. In these cross sections water equivalent is controlled by slope and local relief rather than by elevation. Maximum liquid water contents appear on south facing slopes of low elevation. These strikingly contrast with the low liquid water contents at adjacent north facing slopes. Topography also induces differences in the diurnal fluctuations in liquid water content. On east facing slopes morning melt accounts for the increase in liquid water content from 7 to 13 LT and its remaining constant until 19 LT. On west facing slopes the greater increase during the afternoon indicates melt occurring later in the day. The distribution of cold content at 7 LT suggests that nighttime freezing prevailed in the basin. In the lower parts freezing occurred at the surface, whereas the rest of the pack remained wet. During the day, cold contents returned to zero, indicating an entirely soaked pack. In the upper parts of the catchment, zero cold contents were never reached on May 5 and considerable liquid water was stored. Apparently this was caused by surface melt and meltwater penetrating into a cold snowpack.

Figure 5 shows simulated hourly melt rates on May 9 and 11 at 13 and 19 LT. Patterns of meltwater release are complex and vary significantly between individual situations. Conditions on May 9 were typical of the onset of basin melt at the beginning of the ablation period. At 13 LT east facing slopes were dominated by morning melt. At 19 LT maximum melting occurred on west facing slopes and on south facing slopes of the upper portion of the basin. Particularly shallow packs exhibit large melt rates whereas in the deep packs of the valley floor meltwater did not penetrate to the ground.

Although on May 11 the temperature regime was similar to that on May 9 melting was more intense because during the previous days more liquid water was stored in the snow. Since cloudy skies prevailed there is less dependence of melt on aspect. At 13 LT there was a very intense meltwater release from the northern lower portion of the basin superimposed by low rainfall intensities at the bare areas of the entire basin. In the deeper packs of the valley floor the diurnal melt wave reached the ground at 19 LT resulting in high melt intensities. These packs were about 150 cm in depth. There is a certain tendency of areas of greater melt rates at 13 LT to exhibit lower melt rates at 19 LT and vice versa. This largely derives from differences in the timing of the diurnal melt wave. According to the kinematic wave approach as used for these simulations the shallow packs start draining before noon whereas the deeper packs start draining in the late afternoon (see, e.g., *Jordan* [1983]).

4. MODEL COMPARISON

The Models

Three snowmelt models of quite different structure are compared in this study. These are (1) a grid-based distributed model, (2) a snow band model, and (3) a parametric model.

The grid model is described in paper 1. In the snow band model the basin is subdivided into elevation bands each of which is considered to be homogeneous with respect to snow cover properties. The approach to simulating snowmelt for one zone is identical with that in the grid model. However, for the calculation of solar radiation input all zones are assumed to be flat and horizon screening is neglected. During ablation conditions, simulated snow-covered area decreases as the elevation bands fall bare. Mean basin melt is calculated by weighting zonal melt rates according to the hypsometric curve.

The parametric model is a feedback model for calculating the areal depletion of snow and follows *Ferguson* [1986] and *Buttle and McDonnell* [1987]. The model assumes a nonuniform distribution of initial water equivalent over the basin. The area covered by a certain water equivalent decreases linearly with increasing water equivalent and the melt rates

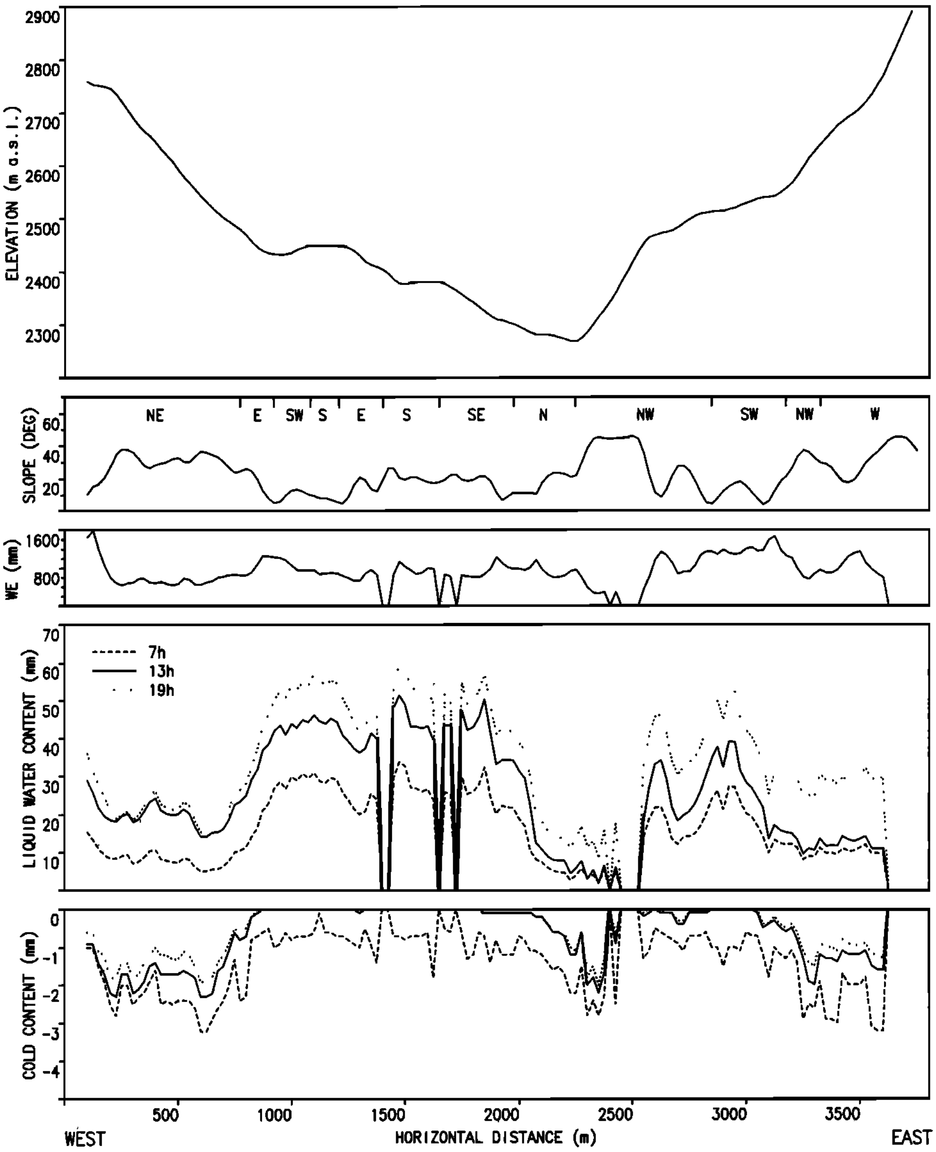

Fig. 4. Cross section showing topography and simulated water equivalent, liquid water content and cold content, May 5, 1989, for west-east transect. For the location of the cross section see inset map in Figure 3.

also decrease to zero at the point of maximum water equivalent. This assumption implies that maximum melt rates occur at the snowpack margins. Buttle and McDonnell found this model to be superior to other parameterizations when the snow cover is discontinuous. Elevational effects are introduced following *Ferguson* [1986]. Melt rates are calculated using the elevation above which lies an area equal to the current snow-covered area as simulated by the model. As snow melts the snow-covered area decreases and that elevation increases. The same "point" snowmelt approach as with the grid model and the snow band model is used here. Snow accumulation is not accounted for in the model presented by *Buttle and McDonnell* [1987]. In the Längental basin, however, solid precipitation during the ablation period is quite frequent requiring the inclusion of snow accumulation in the model. To comply with the distribution of water equivalent assumed above, accumulation too must be a maximum at the snowpack margin. Although this assumption obviously is very unrealistic it is an inherent feature of the model.

To investigate the influence of model structure only, all models are started with an identical snow storage volume and the distributions are adjusted accordingly. In the snow band model initial water equivalent is assumed to increase linearly with elevation and the gradient is found by a best fit to the field data observing the volume requirement. Therefore, 100% of the basin is snow covered at the model start. In the parametric model initial snow-covered area is set to the observed value derived from aerial photos.

Results of Model Comparison

Figure 6 shows snow-covered areas and cumulative melt rates as simulated by three models. A first evaluation of model efficiency based on a comparison of simulated and observed snow-covered areas indicates only small differ-

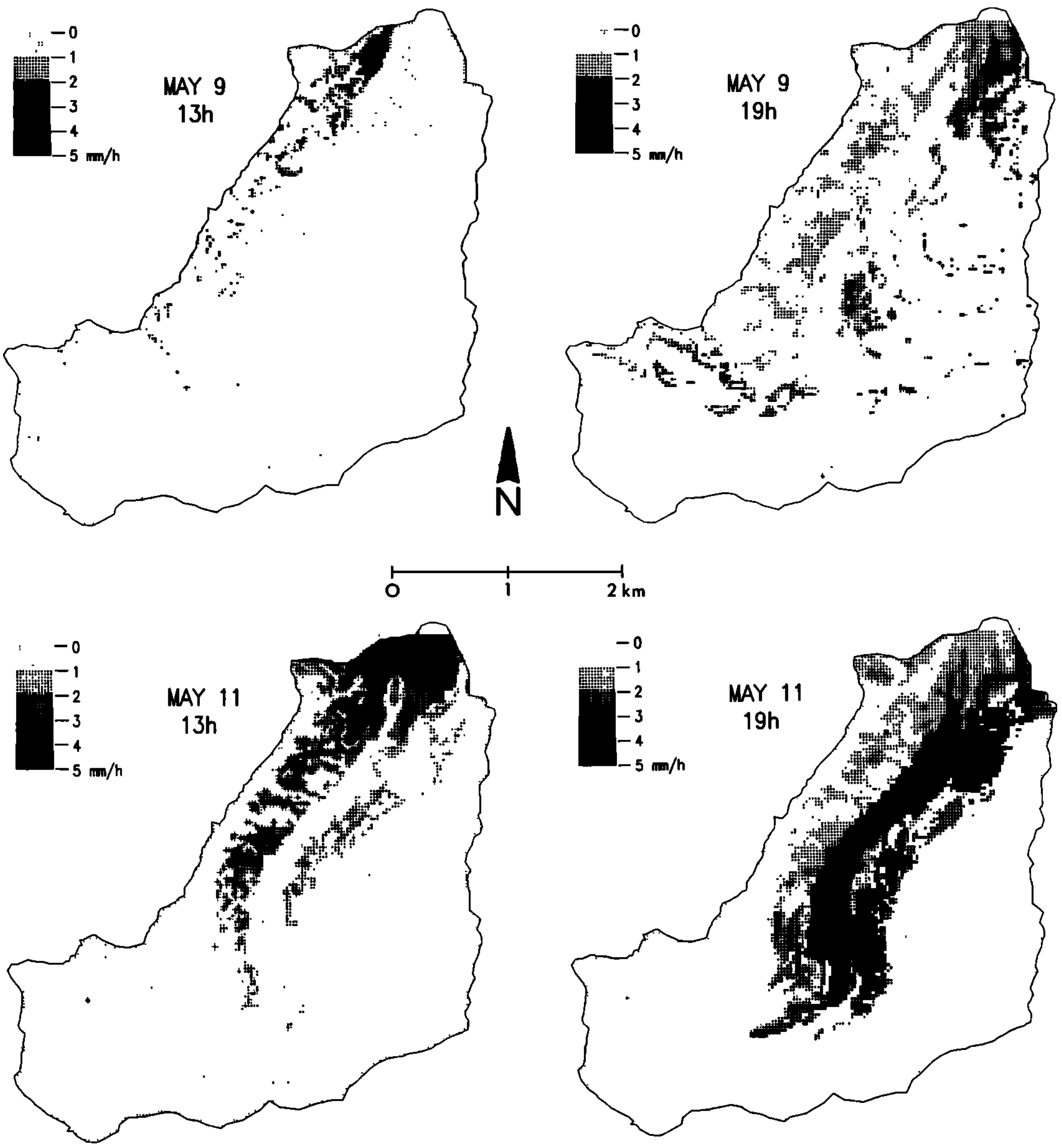

Fig. 5. Simulated melt rates in the Längental catchment on a clear sky day (May 9, 1989) and on an overcast day (May 11, 1989).

ences. There is a slight tendency to increased accuracy with increasing sophistication of the model used. However, there are significant differences in the variations with time. At the beginning of the period snow cover simulated by the grid model varies from 80 to 100% as steep slopes frequently are covered with snow and quickly fall bare. The snow band model yields 100% snow cover until May 12 and a faster depletion in late May as compared to the grid model. These differences derive from the snow band model's neglecting horizon screening and using a lower gradient of water equivalent with elevation. The decrease in snow cover in late May simulated by the parametric model is similar to that of the snow band model. However, snow-covered area decreases to a minimum of 15%. This is fairly unrealistic as compared to the expected value of about 50%. The subsequent increase in snow cover due to snowfalls is unrealistic too, but both errors compensate and yield an excellent estimate of snow-covered area in late June.

Figure 6 also shows simulations of cumulative mean basin melt. The snow band model yields an earlier onset of melt and a larger snowmelt volume with comparison to the grid model, largely a result of neglecting horizon screening. At the beginning of the period analyzed the parametric model gives similar melt rates to those of the snow band model. In late May, however, melt rates are significantly lower because of the substantial underestimation of snow-covered area.

Generally speaking, differences between the models in terms of snow-covered area and mean basin melt derive from assumptions associated with model structure. Among others, these include the distribution of water equivalent and the shading of solar radiation.

5. CONCLUSIONS

In a parameter study it is shown that a good appreciation of the distribution of water equivalent is of utmost impor-

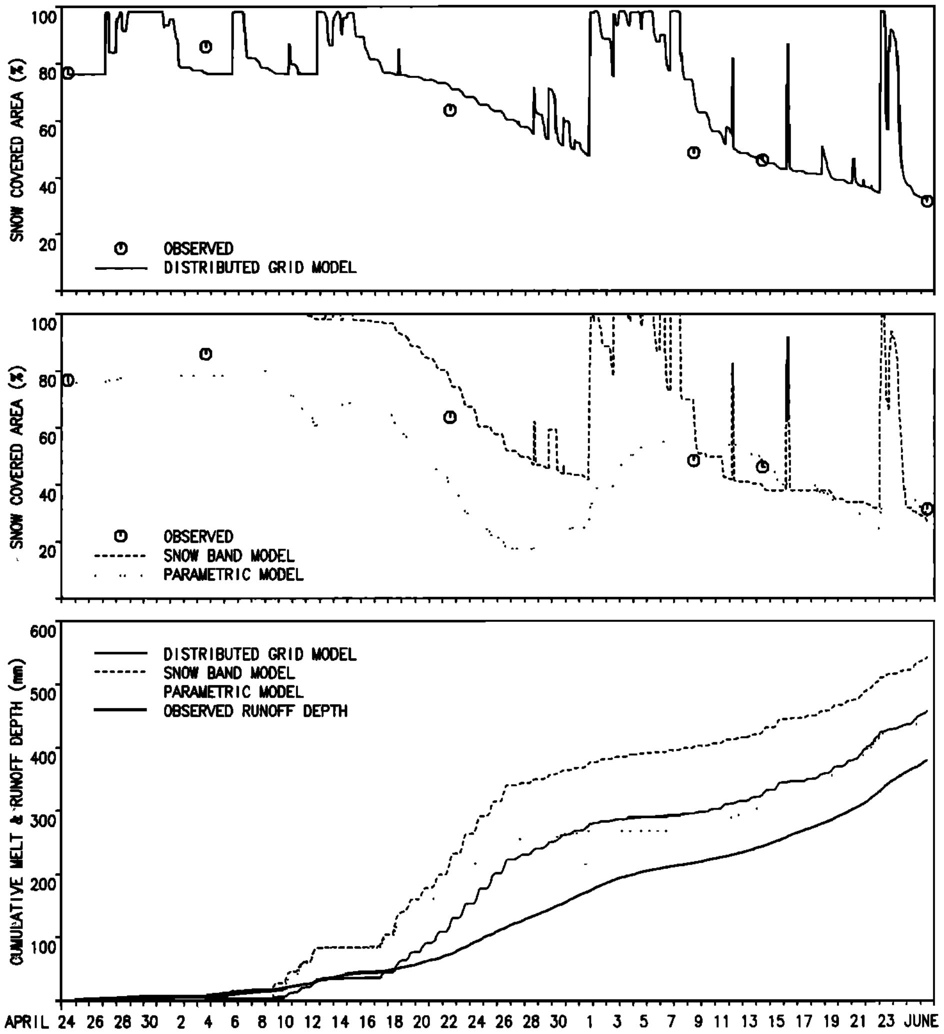

Fig. 6. Percent snow-covered area and cumulative mean basin melt as simulated by three models of different complexity, April 24 to June 26, 1989.

tance for realistic predictions of the spatial characteristics of the snowmelt process. However, in terms of mean basin melt the influence of variations of water equivalent with slope and terrain curvature is more moderate. Snow albedo strongly controls both snow cover patterns and mean basin melt.

Simulation results highlight the complex nature of the distribution of the hydraulic and thermal state of the snowpack. It is strongly affected by topography. Snowmelt patterns exhibit substantial variations with time and are controlled by topography and the delay of meltwater in deep packs.

A comparison of three models of different spatial complexity shows significant differences in variations in snow-covered area with time. The grid model appears to be more realistic than the snow band model and the parametric model. Differences in mean basin melt produced by the models are traced back to (1) different assumptions on the distribution of water equivalent, (2) the influence of shading effects, and (3) inadequacies in simulated snow-covered areas.

The results of the study suggest that for distributed snowmelt modeling in small alpine catchments the major problem remains the accurate estimation of spatial variations in albedo and water equivalent.

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