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Point snowmelt models with different degrees of complexity — internal processes

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ABSTRACT

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Two point snowmelt models are compared under different weather and snowpack conditions. The research-oriented simulation model describes the coupled heat and mass flow distributed with depth whereas the operational model treats the snowpack as one piece and uses heat and liquid water storage factors. An identical approach to energy input is used in both cases. Parameters are derived externally from the literature. The distributed model gives satisfactory results for all periods analysed. The performance of the bulk model depends on snowpack conditions. Particularly during freeze–thaw cycles, proper calibration of parameters appears to be essential. An analysis of the state variables cold content and liquid water content indicates that the bulk model is not suited to a detailed simulation of internal processes.

INTRODUCTION

Accurate forecasts of snowmelt runoff are needed for many purposes such as flood warning, reservoir management and the coordination of power distribution. Snowmelt modelling for a variety of climatic conditions has been reviewed by Leavesley (1989).

Point snowmelt models represent an important component of forecasting tools. Depending on their application they may be classified either as operational or research-oriented simulation models. Operational models tend to be simply structured, whereas research-oriented simulation models are often quite sophisticated.

Both types of point models have been investigated. Anderson (1973) furnished a typical operational model combining a temperature-index method during radiation melt situations with a more detailed calculation of individual energy fluxes during advection melt situations. Internal processes within Anderson's model are represented by empirical relations that first lag and then attenuate the surface melt wave. Similarly, Braun (1985) parameterized the components of the energy balance and modelled mass and heat flow using the water retention concept and the concept of a maximum cold content.

Unlike operational models, research-oriented simulation models are typically distributed with depth, by subdividing the snowpack into layers. Anderson (1976) described heat flow by a set of finite-difference equations and used empirical relations for routing water through a pack. Jordan (1983a,b) focused on water movement and capillary pressure effects in wet snow. Both heat and mass flow are treated rigorously by Morris (1983), including physically based relations for snow metamorphism. More recently, Siemer (1988) reported on a somewhat simplified model of coupled heat and mass flow.

Point snowmelt models have been compared in numerous studies. Most analyses focus on different approaches to energy input (e.g. Anderson, 1976; Male and Granger, 1981; Morris, 1989). Little research, however, has been dedicated to the comparison of approaches to internal processes, although its importance has been widely recognized (World Meteorological Organization, 1986). Obled and Rosse (1977) compared a distributed and an isothermal point model. The simpler model was found to work satisfactorily during melt conditions including night-time refreezing, but not in the presence of prolonged frost. Bauwens (1988) arrived at essentially the same conclusions with regard to cold snow. During a cold spell, the simpler model introduced significant errors in cold content, but both models predicted the beginning of snowmelt successfully. During the snowpack ripening process, however, Bauwens found major differences and concluded that the water retention concept might not be reliable under these conditions.

The objective of this study is to compare a research-oriented and an operational point snowmelt model. The comparison focuses on two contrasting models of internal processes: a distributed model, which is essentially a multilayer model (Siemer, 1988), and a bulk model (Braun, 1985); it uses an identical approach to energy input in both cases. As, in many cases, lack of adequate data prevents proper model calibration, model parameters are derived externally from the literature. Model performance in terms of its practical relevance is assessed on the basis of (1) the time at which the snowpack reaches an isothermal state, and (2) meltwater outflow.

Model performance in terms of process representation is assessed on the basis of (1) cold content, and (2) liquid water content.

STUDY AREA, INSTRUMENTATION AND FIELD PROCEDURES

The Kühtai snow monitoring station is located about 30 km west of Innsbruck, Tyrol (47°12′N, 11°E), at an elevation of 1930 m above sea level (for location map, see Kirnbauer and Blöschl, 1990). It is situated in a valley within the high-relief environment of the Austrian Alps. In December the station is exposed to the sun for only brief periods during the day. The experimental plot is surrounded by typical timberline vegetation with Alpine roses, meadows and scattered cembra-pines.

The climate is characterized by relatively low precipitation (about 1100 mm year^{-1}) due to the sheltered location within the Alps. Typically, snowpack formation starts in November. The pack remains cold until March when it reaches its maximum depth of about 1.50–2.00 m. In late March the snowpack typically becomes isothermal and after that it is subject to superficial night-time refreezing. Snowmelt is most intense from late April until mid-May when the snow cover typically disappears.

The variables measured at the site include global radiation, albedo, net radiation, air temperature, humidity, wind speed and precipitation. An unshielded heated raingauge of the tipping bucket type is used to measure precipitation. As the site is quite sheltered by the orography and by some trees, the catch deficit of rain is low. Water equivalent and snow cover outflow are measured by a 10 m^2 lysimetric snow pillow. Lateral inflow to the lysimeter is prevented by a cut-off drain surrounding the device and by a 20 cm metal lip. Mass-balance computations indicate consistency of water equivalent and lysimeter outflow under most conditions. Snow temperatures are monitored at eight levels above ground and snow depths are measured by an ultrasonic device. All these data are recorded on a 15 min basis. Visual observations comprised cloudiness, snow accumulation, and amount and type of precipitation. As a rule, snow density profiles are measured at intervals of 2 weeks.

During a period of 2 weeks in April 1989, additional observations of snowpack characteristics were made. These included profiles of snow temperature and liquid water content at intervals of 3 h. Snow temperatures were measured by a thermistor. Liquid water content was measured by a capacitance probe designed by Denoth (Denoth and Schittelkopf, 1978; Denoth, 1989). It was essential to cut the pit wall just before measuring to avoid bias by lateral heat and water flux. Each time at least two profiles were examined to assess the horizontal variability of snow cover parameters. Under most conditions, this variability, at the metre scale, was small compared with temporal fluctuations.

More detailed information on the instrumentation of the site and its hydrological characteristics can be found in Kirnbauer and Blöschl (1990).

MODELS

The comparison of the point snowmelt models is based on two different approaches to internal processes, but on the same representation of energy input.

Energy and mass input

Net shortwave radiation is determined from measured incoming and reflected shortwave radiation. Incoming longwave radiation is parameterized on the basis of air temperature and water vapour (an Ångström-type relation), as well as cloudiness. The cloudiness value is derived from visual observations and from comparison between measured and potential solar radiation. Calculation of the outgoing longwave radiation is based on the Stefan–Boltzmann law using a surface emissivity near unity. The surface temperature is simulated in the distributed model and assumed to be 0°C in the bulk model.

To facilitate operational applications in future, measured net radiation is not used for calculating the energy input. Thus it may be used for checking the parameterization of counter radiation under melting conditions. A comparison on the basis of the Kühtai data gave encouraging results.

The parameterization of turbulent fluxes is based on a wind function with non-zero fluxes at low wind speeds. Ground heat flux is set to a constant value of $3\,W\,m^{-2}$. Precipitation, in the case of snowfall, is corrected by +10% for catch deficit. The aggregational state of precipitation is classified by a threshold wet bulb temperature of 1°C (Steinacker, 1983). All parameterizations are discussed in more detail in Blöschl et al. (1987).

Internal processes: distributed model

As the distributed point snowmelt model (Siemer, 1988) follows the approaches of Anderson (1976) (heat transfer) and Colbeck and Davidson (1973) (mass flow), only a brief review of the basic concepts is given here.

The snowpack containing ice, water, vapour and air is idealized as a continuum. Variables of state are dry density, liquid water content and snow temperature. The size of the ice grains is not considered.

Basic equations

Like most models described in the literature, Siemer's (1988) model is based upon the equations of conservation of mass and energy. The equation of conservation of momentum is replaced by the empirical Darcy law for flow in porous media. As the gravity term is the major driving force and exceeds the pressure gradient, the latter term is neglected. This assumption corresponds to the kinematic wave approach. Wankiewicz (1979) and Colbeck (1974) discussed the relative importance of the pressure gradient term in some detail; they suggested that capillarity is important at the wave front but can be ignored for most purposes. Similar results are reported by Dunne et al. (1976), Colbeck (1977), and Jordan (1983b), who showed that for the purpose of routing meltwater through a snowpack, there is little advantage in using a more complex model over the simpler kinematic wave approach.

Further equations used by Siemer's model are Fourier's law of heat conduction and Fick's law of diffusion. The penetration of shortwave radiation into the snowpack is described by an exponential extinction law. The equations of state are based on a simple assumption: the snow is allowed to exist in two states, cold-and-dry, or ripe, and there is an abrupt transition between the two. Compaction and settling are estimated using simple empirical relations based on the weight of the snowpack and snow temperature (Anderson, 1976).

Model parameters

Unlike the basic equations, model parameters tend to be site specific and difficult to determine properly. Lacking site measurements, most authors find parameters by calibration or employ parameters as reported in the literature. In this study, the parameter values of Anderson (1976) and Colbeck and Davidson (1973) are adopted (with the exception of the retention capacity) and are discussed in more detail below.

Effective thermal conductivity is calculated from a quadratic relation with snow density, with larger values of the conductivity at high densities. The diffusion coefficient is determined as a function of snow temperature, lower temperatures yielding smaller values of the diffusion coefficient. The radiation extinction coefficient is given as a function of snow density. However, within reasonable limits, the relation is not sensitive to density.

Calculation of the permeability of snow to water makes use of a power-law relation between permeability, effective water saturation and intrinsic permeability. The intrinsic permeability is calculated as a function of density, roughly following Shimizu (1970). Based on measurements at the Kühtai station, retention capacity is set to 10% by weight, which is consistent with the value used by Braun (1985).

The chosen approach to permeability implies that large water fluxes move more quickly through a snowpack than smaller fluxes. Typically, slower moving fluxes produced by early morning melt are overtaken by faster moving fluxes produced later in the day, thereby forming a shock front.

Solution technique

The governing partial differential equations are approximated by a set of finite-difference equations applied to a snowpack subdivided into layers. The equations are solved by an explicit scheme. The thickness of individual layers varies with time. After each time step, the thickness is checked; layers which exceed a maximum or minimum value are split or combined, respectively.

The numerical treatment of shock fronts follows a special technique presented by Siemer (1988): at each time step, liquid water content is calculated, starting at the top layer and proceeding downwards. Liquid water content may increase by melt within the layer or by water input. Liquid water content and water output of a given layer are evaluated on the basis of an analytical solution of the following initial boundary value problem: (1) constant liquid water content with height at the beginning of a time step, and (2) constant water flux input at the upper boundary during a time step.

Water input to the top layer is produced by rain. Water input to an intermediate layer is given by the meltwater output of its overlying neighbour.

Numerical stability, accuracy and computer time

Explicit solutions of the heat transfer equation are known to be unstable at large ratios of time-to-length increments. The procedure employed to calculate liquid water content is not subject to instability.

For analysing the combined effect of layer thickness and computational time step, simulation runs are performed and both variables are varied simultaneously. Numerical stability is assessed by comparing simulated snow surface temperatures with those of a stable case. Unstable cases may be easily detected by marked oscillations in surface temperatures. Results for three periods, each of 3 days duration, are shown in Fig. 1. Periods I and II correspond to cold snow and period III corresponds to wet snow with nighttime freezing. As would be expected, the time step allowed increases as the layer thickness increases. Based on these results, a linear relation (graph IV in Fig. 1) is derived for adjusting the time step used by the model with the minimum layer thickness given.

The numerical accuracy of the model was assessed by Siemer (1988) by comparing two basic cases with the analytical solution. These cases included cold and wet snow, respectively, and were based on a rigid grid. Analytical and numerical solutions matched closely when using layer thicknesses up to about 0.10 m.

However, it was suspected that errors might be larger under more complex conditions. Therefore, simulation runs are made during a period of daytime thaw and nighttime freezing in late April. The minimum layer thicknesses are varied over a range of 0.02–0.15 m. Results, in terms of surface temperatures and meltwater outflow are compared with those based on a layer thickness of 0.02 m. Figure 2 shows the r.m.s. deviations. Deviations increase as the layer thickness increases and are generally large. Even layer thicknesses close to

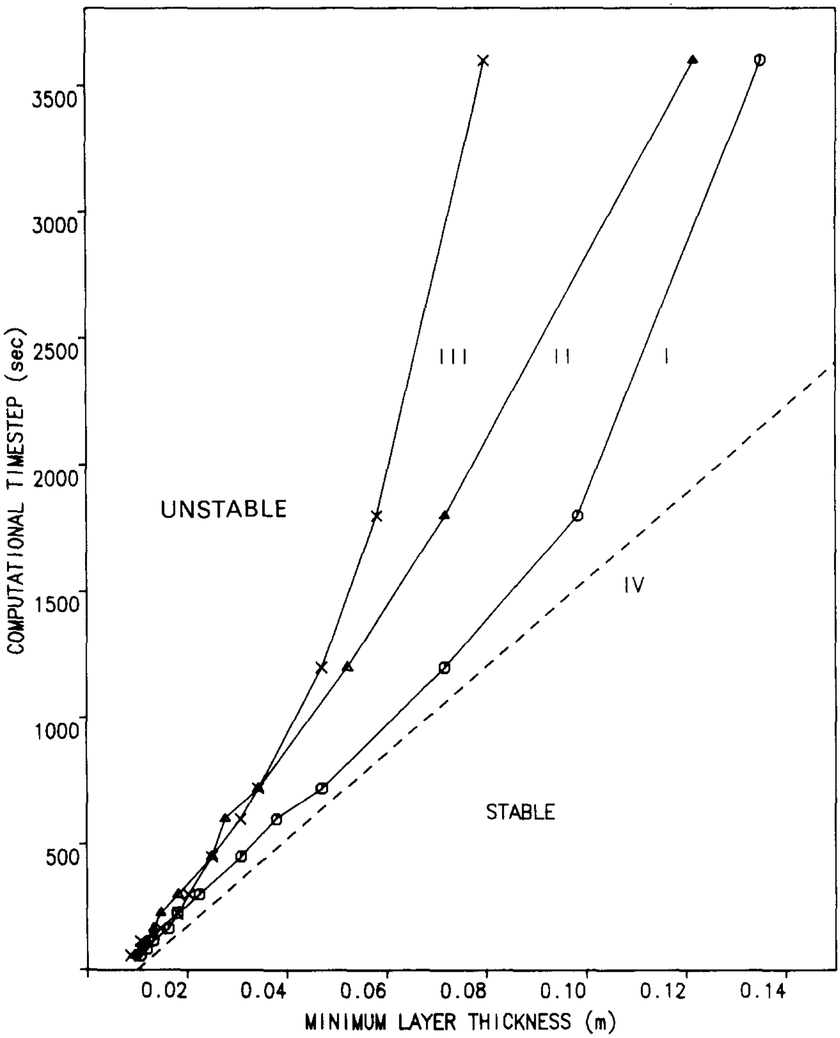

Fig. 1. Numerical stability of the distributed (multilayer) model derived from simulation runs for three periods (I, II and III). Line IV indicates the time step adjustment adopted.

0.02 m yield deviations of the order of 0.3°C and 0.15 mm h^{-1}, which correspond to 11% and 24% of the data's variance, respectively. It is believed that these deviations may be attributed, at least partly, to combining and splitting layers.

Further tests aim at evaluating the computer time requirements of Siemer's model. Simulations are based on a 28 day period in December with snow depths around 60 cm. Figure 3 presents the results obtained with a UNIX workstation of 3 MIPS. A significant increase in CPU time with decreasing layer thickness

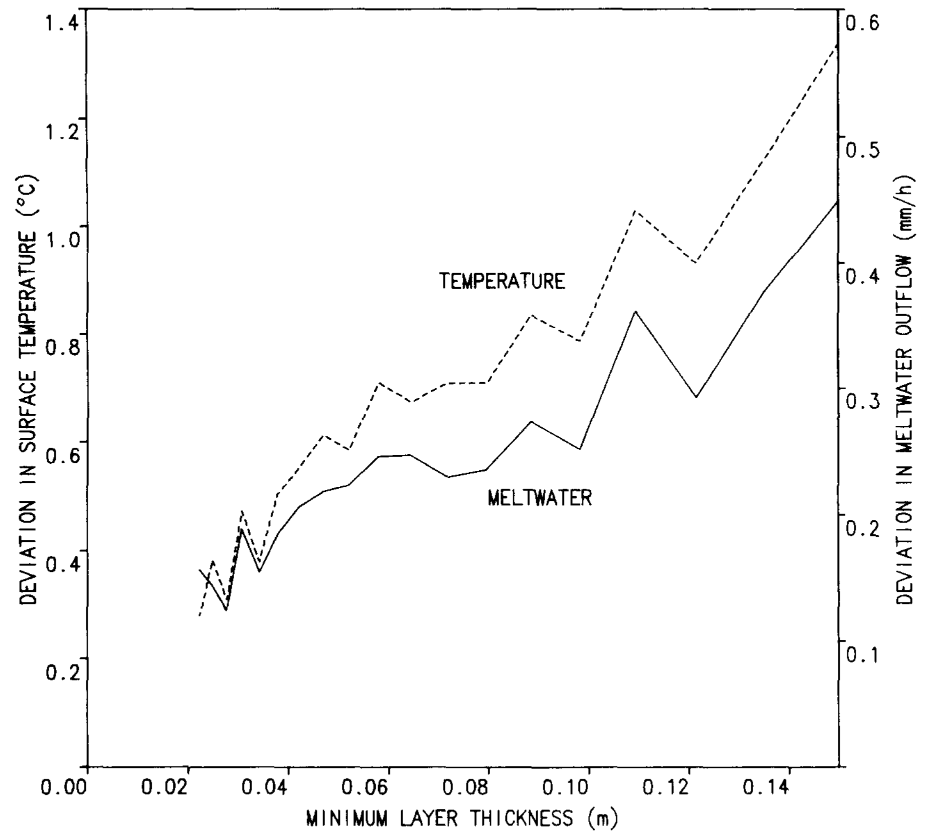

Fig. 2. Computational accuracy of the distributed (multilayer) model compared with using 0.02 m minimum layer thickness. Root mean square deviations in surface temperature and meltwater outflow are shown.

may be observed. For comparison, the computer time requirements of Anderson's model (Anderson, 1976) are given (line (a) in Fig. 3). This model uses an implicit scheme and is based on a time step of 1 h. A more efficient algorithm for solving the matrix than the one employed by Anderson reduces the CPU time insignificantly (line (b) in Fig. 3). This indicates that operations requiring most CPU time are not those solving the matrix. For thick layers, Anderson's model is less efficient because analytically derived complex derivatives are computed. For thin layers, however, Siemer's model requires more CPU time because the time step decreases dramatically according to the chosen time step adjustment.

On the basis of a comparison of Fig. 2 and Fig. 3, convenient minimum layer thicknesses may be determined to be about 0.04–0.10 m. For the computations, as presented below, the layer thicknesses are allowed to vary between 0.04 and 0.08 m.

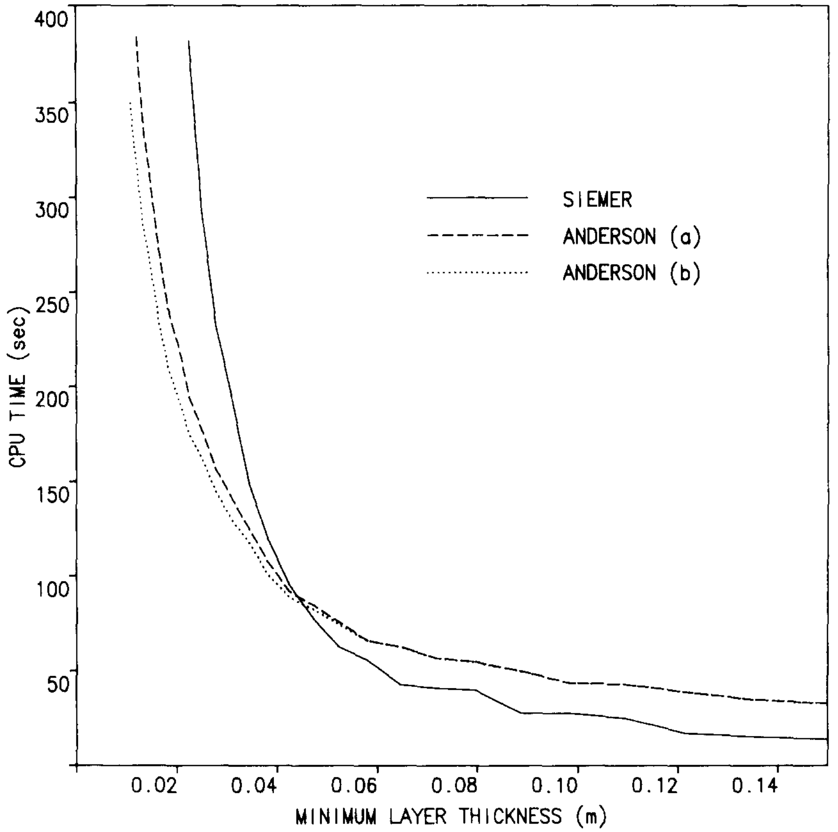

Fig. 3. CPU time requirements of simulating a 30 day period with three models evaluated on a UNIX workstation.

Internal processes: bulk model

Water retention concept

For modelling water storage in the snowpack, the bulk model employs the water retention concept, which is widely used in operational snowmelt models (Braun, 1985; World Meteorological Organization, 1986). In this approach, runoff at the base of the snowpack occurs when the water storage requirement is met. Based on a literature review, Braun set the retention capacity of a snowpack to 10% by weight and this value is used here. Attenuation and lag of the melt wave are not considered within the bulk model.

Cold content concept

In the bulk model, heat loss first refreezes water and then is summed up as cold content that first has to be reduced to zero before melt can start. The snow surface temperature is set to zero for both melt and non-melt conditions. To compensate for the inadequacy of this assumption, Braun (1985) introduced a maximum cold content and a factor of refreezing. The maximum cold content is an upper limit to accumulated heat loss, whereas the factor of refreezing basically reduces heat loss computed by the energy exchange model. Contrary to Braun's approach, in this study the maximum cold content (in terms of meltwater) is related to the water equivalent by a cold holding capacity. Based on Braun's optimized values, this parameter is set to 3% by weight. This means that a snowpack representing, for example, 1000 mm of water equivalent may have a cold content that is able to freeze 30 mm of water (i.e. $30 \times 333\,\mathrm{kJ\,m^{-2}}$). This value corresponds to the cold content of a snowpack with a linear temperature profile and a surface temperature of -10°C, considering the thermal properties of ice. Following Braun (1985), the factor of refreezing is set to 0.5, which means that only one-half of the computed heat loss is summed up as cold content.

RESULTS

Performance of the distributed model

Prior to the model comparison, the distributed model (Siemer, 1988) is analysed on the basis of distributed state parameters for two periods of contrasting snowpack conditions.

During the period of cold snow (25–27 January, 1988) cloudy skies and near freezing temperatures prevailed. Thus very small energy fluxes were expected. The snowpack was 75 cm deep and its upper 30 cm consisted of relatively new snow of low density and high surface albedo. Figure 4 shows snow temperatures as observed and simulated by Siemer's model. For purposes of comparison, simulations using Anderson's (1976) model are given. Both models yield similar results. The trend over the period of 3 days agrees well with the observations; however, there are non-systematic errors in the short-term variability. These are most pronounced at the beginning of the simulation period and during the night.

The period of ripe snow and nighttime refreezing (23–26 April, 1989) was largely characterized by fair weather. However, on 25 April and during the early hours of the following day the sky was overcast. Air temperatures varied around 0°C and increased slightly within the period. A total of 15 cm of snow fell on 22 April which decreased to a 5 cm layer during 23 April. The snow depth was about 80 cm and the average density was $380\,\mathrm{kg\,m^{-3}}$. Figure 5 presents snow temperatures and liquid water contents at four levels as simulated and observed. Calculated temperatures agree closely with measurements,

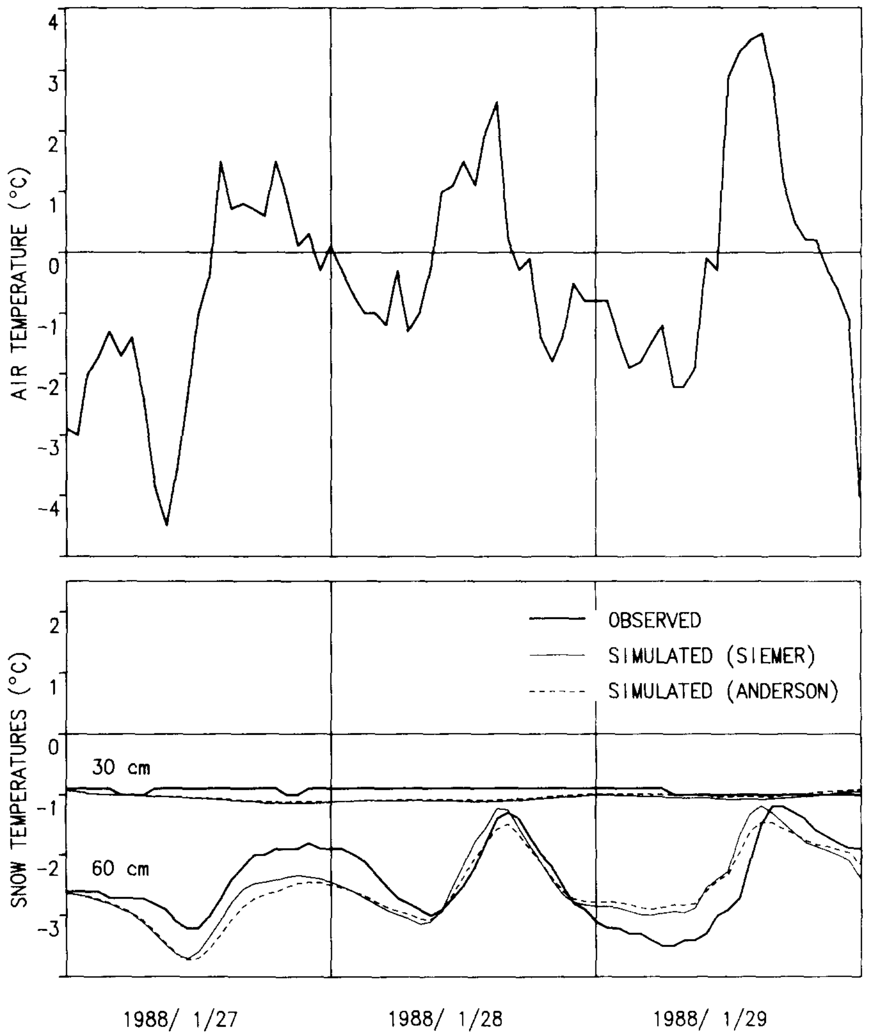

Fig. 4. Air temperatures (top) and snow temperatures at two levels above ground (bottom) for the period 27–29 January, 1988. The snow depth was approximately 75 cm.

although predicted values tend to be somewhat lower than observed (e.g. 23 April at the surface). Daily variations in liquid water content are roughly reproduced by the simulations. Surface values generally are underestimated, particularly at 5 cm below the surface on 23 April. On 25 and 26 April at 5 and 10 cm below the surface, the magnitude of liquid water content is underestimated, whereas the rise and the recession is quite satisfactory.

One day of the period (24 April) is analysed in more detail on the basis of profiles. On this day, the snowpack comprised three distinct sections. The top

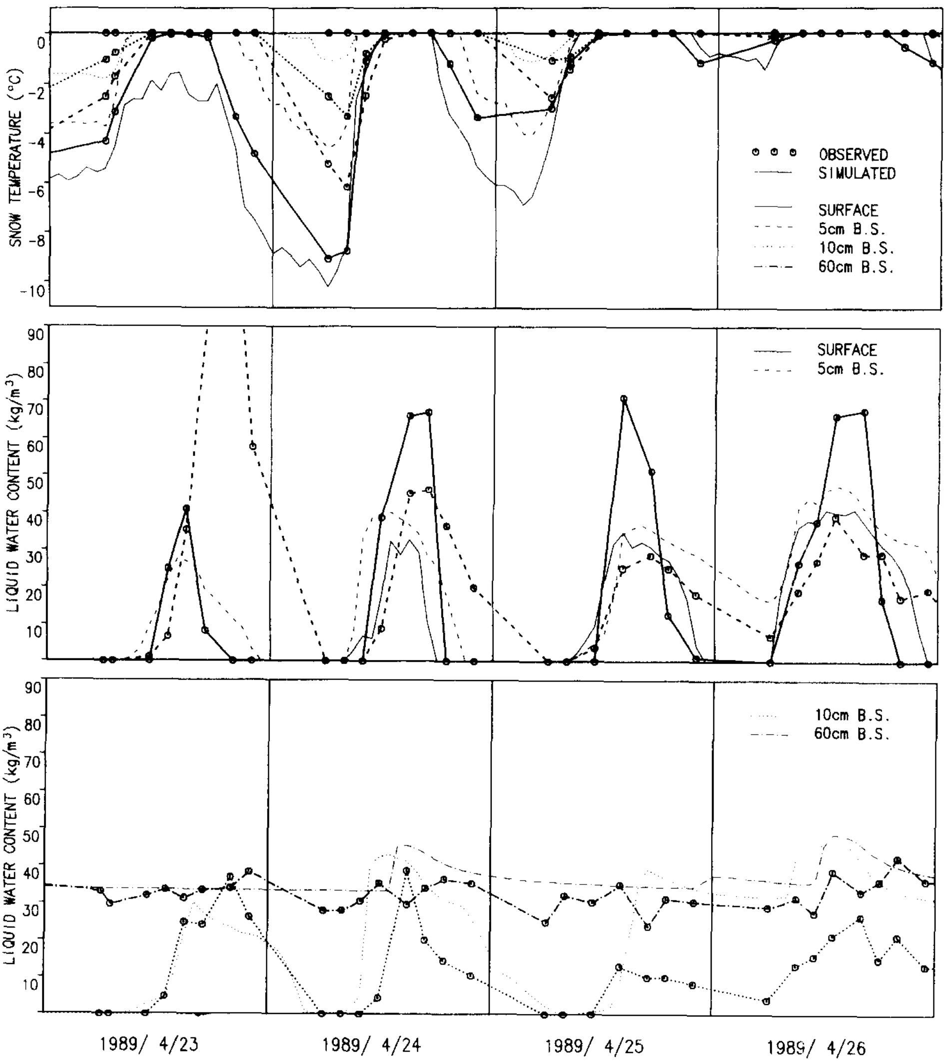

Fig. 5. Snow temperatures and liquid water contents at four levels below surface for the period 23–26 April, 1989.

10 cm layer was made up of relatively fine and new snow. Below it there was a 10 cm layer which had experienced extensive alternate freezing and thawing. It consisted of spherical grains of about 5 mm diameter. The rest of the snowpack was well packed with rounded grains of about 2 mm. Figure 6 shows snow temperature and liquid water content profiles. Temperatures are generally simulated well by both models. Simulations of liquid water content are poor, exhibiting two principal deficiencies: (1) measured liquid water contents vary with height (e.g. 15 h) whereas the simulations do not, and

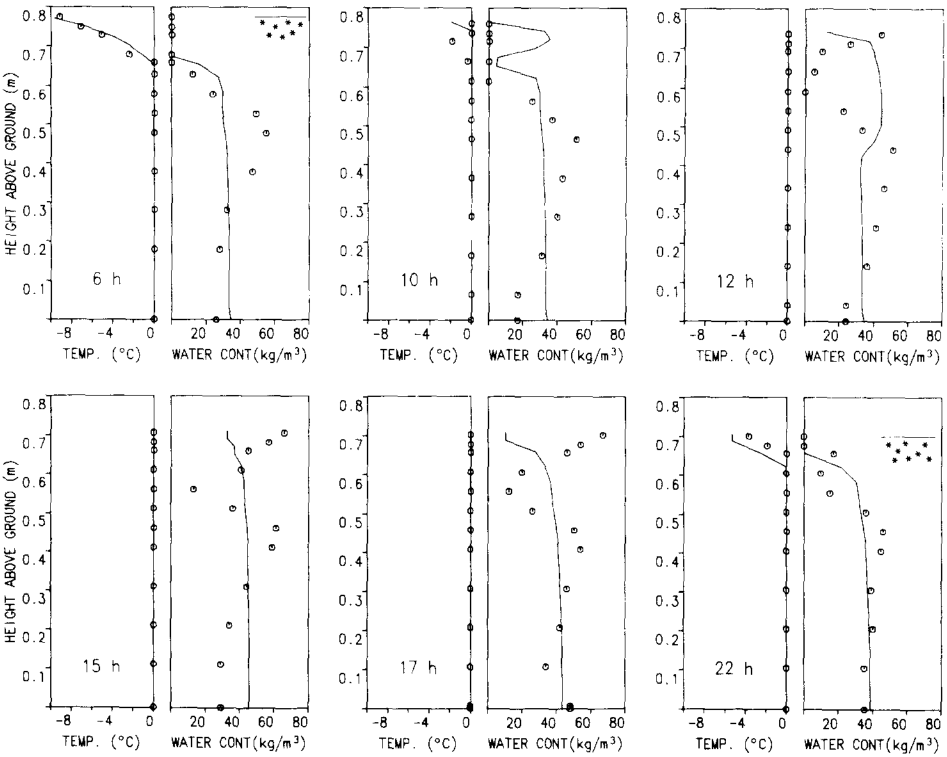

Fig. 6. Snow temperature and liquid water content profiles, 24 April, 1989. Circles and lines indicate observed and simulated values, respectively.

(2) the data indicate maximum liquid water content at the surface (e.g. 12 h) whereas the simulations yield a maximum several centimetres below the surface.

Comparison of the models

The model comparison is based on both cold and ripe snow conditions.

The period of cold snow (1–18 December, 1987) began with 5 days of fair weather and some snowfall from 6–8 December. The air temperatures then dropped and fair weather with low humidities prevailed. Around 15 December the air temperatures rose and the snowpack returned to 0°C. Snow depths varied around 60 cm and the average density was about 200 kg m^{-3}. Figure 7 shows cold content as simulated by the distributed and by the bulk model. Observed cold content is based on continuous measurements of snow temperatures. The distributed model yields good results with a slight tendency

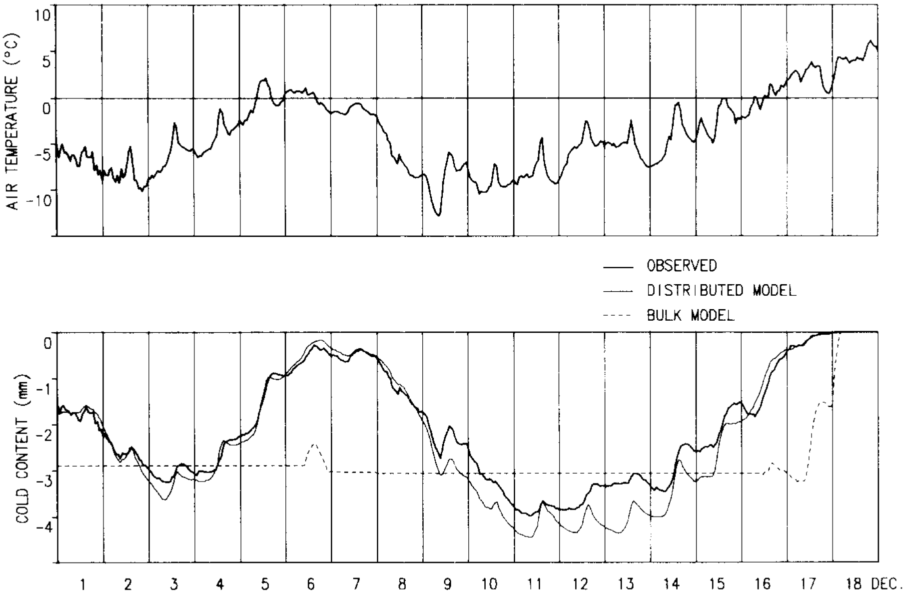

Fig. 7. Air temperatures (top) and cold content in terms of water required to warm up the snowpack to 0°C (bottom), 1–18 December, 1987.

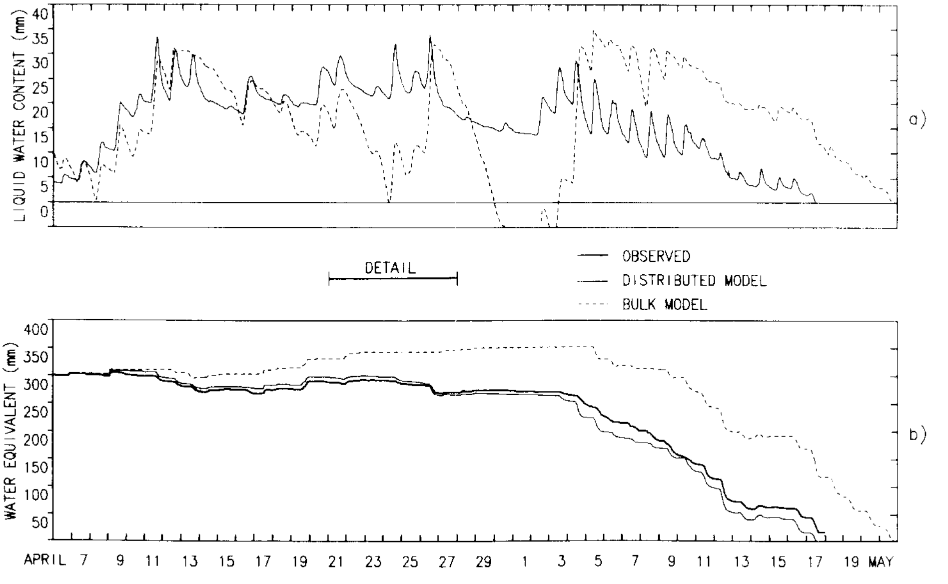

Fig. 8. Bulk liquid water content (a) as simulated by two models, and (b) simulated and observed water equivalent, for the period 6 April to 21 May, 1989. The detail refers to Fig. 9.

to underestimation. Cold content as simulated by the bulk model substantially deviates from the observed values. However, the time at which the snowpack reaches an isothermal state is predicted quite well.

Further model comparisons are based on a period of ripe snow (6 April to 21 May, 1989). Skies were mostly overcast and frequent snowfalls occurred. There were only a few fair days (such as 2–9 May) on which most of the melting took place. Near-freezing temperatures prevailed, the interval from 27 April to 1 May being somewhat colder. At the beginning of the simulation period, the snow depth and density were 85 cm and 350 kg m^{-3}, respectively. Liquid water content and water equivalent are analysed. Figure 8(b) illustrates that the distributed model simulates water equivalent properly, whereas the bulk model overstates the water equivalent. Errors are largest during the period of freezing and thawing cycles in April and amount to 100 mm over 29 days. However, during well-defined melting conditions in May, the bulk model gives satisfactory results. A comparison of liquid water contents as simulated by the models (Fig. 8(a)) exhibits significant discrepancies. These are most striking around 23 April and at the end of April, representing cold periods.

Figure 9 gives more detailed insight into processes during the subperiod from 21–27 April. To suppress errors prior to the period, both models were restarted on 21 April with the same measured initial conditions. Therefore, differences from Fig. 8 may be observed. Figure 9(a) shows estimates of the surface energy balance as simulated by the models. This is the energy per time interval available at the surface for processes such as melting, freezing, and cooling. For the bulk model this is, in case of heat loss, the flux reduced by the factor of refreezing. During daytime, when the surface temperature may be expected to be at 0°C, the simulations are identical, whereas during nighttime there is some discrepancy. Figure 9(b) presents simulated and observed values of bulk liquid water content, which is the total amount of water stored in the snowpack. Except for 23 April, the distributed model yields good estimates. Results obtained with the bulk model exhibit substantial differences from the observations.

Figure 9(c) shows cold content as simulated and observed. The distributed model generally gives satisfactory results but overstates cold content on 24 April. According to the bulk model, cold content remains at zero over the period analysed owing to the model concept and a wet snowpack.

Melt rates (Fig. 9(d)) are somewhat overestimated by the distributed model. In particular, on 26 April, the rise of the melt wave is simulated too soon. In the other cases, representation of both timing and recession of the hydrograph is excellent. The bulk model, overall, slightly underestimates melt rates and gives no melt on 24 April.

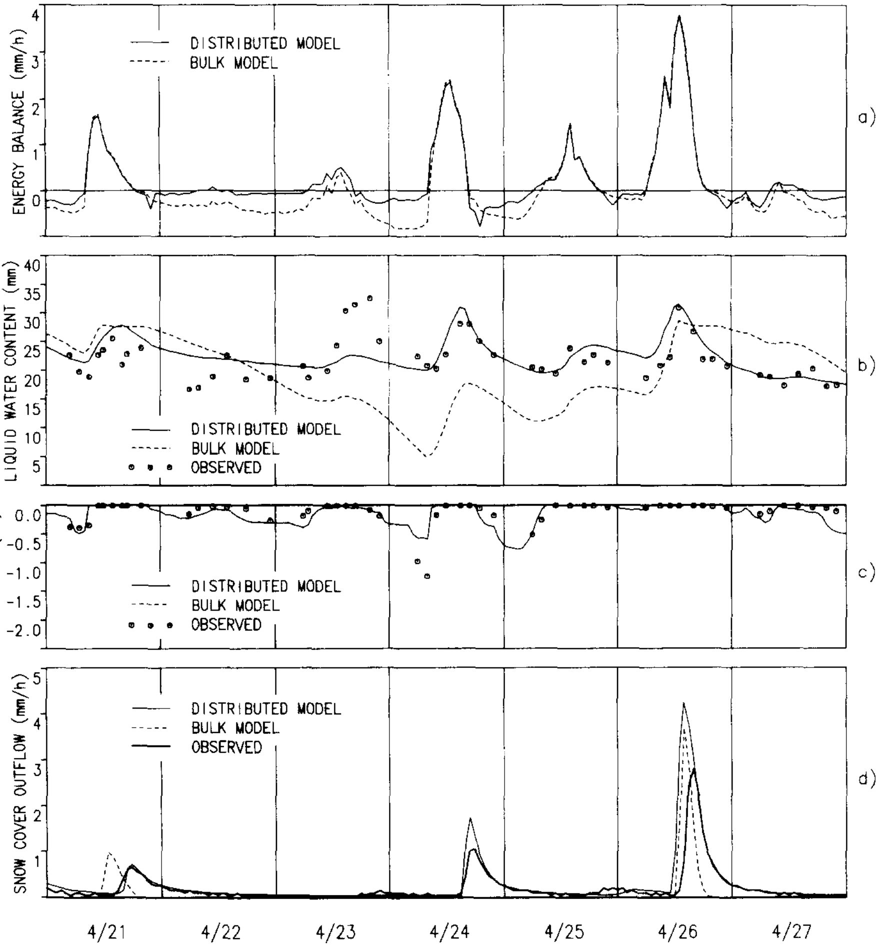

Fig. 9. Observed and simulated snowpack variables for the period 21–27 April, 1989. (a) Surface energy balance in terms of potential melt rates; (b) bulk liquid water content; (c) cold content in terms of water required to warm up the snowpack to 0°C, and (d) snow cover outflow.

DISCUSSION

Performance of the distributed model

Simulations of snow temperatures with the distributed model give reasonable results (Figs. 4–6). This finding is not surprising; Anderson (1976) and Obled and Rosse (1977) found temperatures less difficult to simulate than other snowpack variables. Errors in cold content (Fig. 9) are mostly attributable to a misrepresentation of snow density. Some discrepancies in the short-term variability of temperatures (Fig. 4) suggest the influence of processes not considered rather than a requirement for adjusting the model, e.g. by calibrating the parameter of thermal conductivity.

Overall, the distributed model gives unsatisfactory simulations of liquid water content. There are two main deficiencies.

(1) Variations of liquid water content with depth are not reproduced by the simulations (e.g. Fig. 6 at 15 h). This is largely a consequence of the retention capacity. Within the distributed model, retention capacity is represented by a constant value disregarding snow structure. Clearly, the influence of snow structure is most decisive. This is most obvious in the layer of coarse grains 10–20 cm below the surface on 24 April (Fig. 6). Similarly, the model fails to simulate above-average water retention. On 23 April, the surface layer consisted of new snow that had been exposed to intense solar radiation for one day. In this layer, measured liquid water contents were several times larger than those simulated (Fig. 5). The examples presented illustrate that the retention capacity may vary within a wide range. This finding is quite consistent with the wide scatter of values reported in the literature (e.g. Wankiewicz, 1979; Braun, 1985).

(2) Observation indicates that melting is most intense at the snow surface (e.g. Fig. 6 at 12 h). This may also be seen from Fig. 5 (e.g. 24 April) as the observed liquid water content at 5 cm lags behind that at the surface. Similar observations were reported by Denoth and Foglar (1985). Simulations, however, yield a maximum of melting and consequently a maximum increase in liquid water content about 5 cm below surface. This difference has potentially important implications on surface temperature and, hence, surface energy exchange (e.g. 23 April in Fig. 5). Obviously, the discrepancy is related to the representation of shortwave radiation penetrating into the snow. This is surprising in view of the fact that a well-established value of the extinction coefficient is used (e.g. Gerdel, 1948; Anderson, 1976; Fukami et al., 1985).

Comparison of the models

Model behaviour is studied on the basis of selected snowpack conditions. Periods presented include (1) cold snow, (2) freeze–thaw cycles, and (3) well-established melting conditions.

(1) A slight underestimation of cold content by the distributed model during the cold snow period (Fig. 7) is probably due to an underestimation of surface temperature. Cold content, predicted by the bulk model, bears little resemblance to the observations. Within the bulk model, a surface temperature of 0°C had been assumed whereas observed values decreased to a minimum of −15°C. During the period analysed, the energy balance was dominated by longwave radiation and turbulent transfer, both fluxes being

very sensitive to surface temperature. Consequently, the simulated energy balance was always negative and cold content remained at the minimum value allowed. This is not surprising as the bulk model is basically a melt model forced to represent non-melt conditions. It is obvious from Fig. 7 that the controlling parameter under these conditions is the cold holding capacity.

Apparently, the cold content concept used in the bulk model is not physically meaningful. For snowmelt runoff simulations, however, the proper timing of reaching an isothermal state is more important than the variations of cold content with time during a cold spell. Simulations presented here, as well as other simulations performed, show that the bulk model gives reasonable estimates of the timing of reaching an isothermal state. Thus, despite a poor process representation, the bulk model may be successfully applied to cold snow conditions. For a similar case, Bauwens (1988) found that high model performance does not necessarily imply proper process representation. Simple approaches to cold storage, indeed, had been used successfully in catchment models (World Meteorological Organization, 1986).

(2) During a period of freeze–thaw cycles (April 1989 in Fig. 8), the bulk model yields significantly poorer estimates of water equivalent as compared with the distributed model. The reason for this may be seen by looking at Fig. 9(b). The bulk model properly reproduces the daytime rise in bulk liquid water content, whereas the nighttime recession appears to be incorrect. During periods of an increase in liquid water content the assumption of a surface temperature of 0°C generally holds. However, the amount of refreezing water and, consequently, the decrease in liquid water content, is overstated by the bulk model owing to an underestimation in the nighttime energy balance.

Figure 9 also shows that under these conditions, the controlling parameter within the bulk model is the factor of refreezing. A reduction in that parameter might be expected to improve model performance. Clearly, this implies calibration. Consequently, an optimal parameter value is related to snowpack evolution and climate, disallowing its application to other locations. Furthermore, optimal values of the factor of refreezing are believed to be related to the chosen approach to surface energy exchange. This may be one reason why values as optimized by Braun (1985) are not applicable in this study.

(3) During well-established melting conditions (May 1989 in Fig. 8) nighttime refreezing is insignificant. Consequently, the assumption of a surface temperature of 0°C holds and both models give good results. Different assumptions on water percolation and storage appear to be less critical under these conditions. Estimates of water equivalent obtained with the water retention concept of the bulk model are nearly as good as those based on the more complex kinematic wave approach.

CONCLUSIONS

The distributed model, representing a research-oriented simulation model, gives satisfactory results under all conditions analysed. However, for a variety of reasons, profiles of liquid water content are poorly simulated.

The bulk model, representing a model typically used in operational applications, performs differently in terms of process representation and practical relevance (including the timing of reaching an isothermal state after a cold spell and melt rates during a well-established melting period). For both situations, simulations are successful. Mixed conditions such as ripe snow and nighttime refreezing appear to be more crucial and are not reproduced properly. Process representation is checked by examining the state variables of cold content and bulk liquid water content. Comparisons indicate that these variables are not simulated adequately by the bulk model.

All simulations have been performed with externally derived parameters from the literature. Calibration of parameters within the bulk model (namely the factor of refreezing) on the basis of site data may be expected to improve model performance significantly. However, in the absence of data for such calibration, the more detailed model appears to be more appropriate.

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