MODELING SHORT WAVE RADIATION PENETRATION INTO THE SNOWPACK: WHAT CAN WE LEARN FROM NEAR-SURFACE SNOW TEMPERATURES?

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ABSTRACT: Short wave radiation penetrates the top portion of the snowpack and is responsible for both sub-surface heating and fast changing temperature gradients during daytime. This affects snow metamorphism and hence weak layer formation and can affect mechanical properties of deeper layers. It is thus of crucial importance that snow-cover models represent this process as realistically as possible. Carefully measured near-surface snow temperatures can be used to check model performance in this respect. Numerical simulations performed with the Swiss snow-cover model SNOWPACK are thus compared to short time series of temperature measurements taken in the top 40 cm of the snowpack on a knoll located in the Columbia Mountains of British Columbia, Canada. In contrast to simpler models, SNOWPACK treats short wave radiation as a volume source of heat, like refreezing. It is shown that a multi-band approach is needed to obtain the best results. Switching off short wave radiation on a sunny day results in a reduction of temperature increase of about 5.2 °C at 15:00 at 10 cm depth while differences below 30 cm are negligible even later in the day.

KEYWORDS: snow-cover modeling, short wave radiation, near-surface snow temperature

1 INTRODUCTION

It is well known that short wave (SW) radiation penetrates the topmost snow layers of the snowpack, thereby depositing energy that warms up the near-surface snow immediately without any delay due to thermal conduction. How deep SW will reach into the snowpack, however, depends on many factors and in particular on snowpack layering, that is, snow microstructure and snow density, as well as on impurities. Detailed measurements and complex numerical models are required to accurately understand solar SW absorption in snow (see, for instance, Meirold-Mautner, 2004; Warren et al., 2006; Kaempfer et al., 2007). Unfortunately, these measurements and models do not allow for monitoring the evolution of near-surface snow temperatures with time. The latter is difficult and requires a careful design to avoid self-heating of the sensors by short wave absorption (Bakermans, 2006). Such reliable measurements can then be used to compare with outputs of snow-cover models. In other words, the ability of models to correctly reproduce near surface temperatures tells us how well SW absorption is treated by them.

In general, SW radiation will mostly affect the top 20 cm of the snowpack. Snow acts as a filter on SW, though, and SW will not penetrate the snowpack as deeply at all wavelengths. Furthermore, exceptionally high extinction coefficients are measured in the top centimeters of the snowpack (Meirold-Mautner and Lehning, 2004). Part of this energy, however, will not be absorbed by the snowpack but reflected back to the atmosphere and thus contribute to the high snow albedo.

Radiation penetration is one source for snowpack warming but the other surface energy fluxes can also lead to substantial warming of the upper portion of the snowpack, for instance, a thin cloud cover backscattering long wave radiation towards the snowpack on an otherwise clear day (Bakermans and Jamieson, 2006). Thus it is not always clear to which energy source an observed warming effect should be attributed. Numerical model simulations can help in this respect as they allow for unnatural boundary conditions such as switching off SW on sunny days, for instance.

In this contribution we will test different parameterizations of the extinction coefficient for snow against carefully measured near-surface temperatures. Switching off SW for one day shows evidently the warming due to SW penetration and to what depth a noticeable effect is still to be ex-

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pected. Possible consequences on the evolution of snow microstructure in the top portion of the snowpack will be briefly discussed.

2 DATA

Bakermans (2006) measured 10 near-surface snow temperatures down to a depth of 32 cm on a knoll located near Mt. Fidelity, 1940 m, in the Columbia Mountains of British Columbia, Canada. The longest experiment spans six days from 6 to 12 February 2006 under a variety of cloud cover conditions. We use the field data collected during this period to compare with model outputs. The measured data is linearly interpolated to correspond to snow temperatures at depths of 5, 10, 15, 20 and 25 cm below the snow surface. In particular, we will concentrate on 11 February that was the sunniest of all six days.

We use meteorological data collected on the nearby study plot of Mt. Fidelity, 1905 m, about 300 m from the knoll, to drive SNOWPACK, the Swiss snow-cover model developed at SLF (Lehning et al., 2002a, b). We are confident this data does represent accurately enough meteorological conditions on the knoll top (flat field) even though some discrepancies may arise from these separated locations.

The initial snow profile for 6 February consists of a thick layer of decomposing and fragmented precipitation particles on top of the old snow cover. Snow density within this quite homogeneous layer varies from 110 to 150 kg m^{-3} and one set of microstructure parameters suffices to describe this snow in SNOWPACK, that is setting both dendricity and sphericity to 0.5, grain and bond size to 0.3 and 0.075 mm, respectively.

3 MODELING ASPECTS

The simplest way to model radiation attenuation in snow is to use the extinction law of Beer-Lambert-Bouger, that is, an exponential decay of the downwelling radiation with depth:

$$I(z) = I_0 e^{-K_s z} \tag{1}$$

where I_0 is the net short wave flux penetrating the snowpack at the surface $z = 0$, $I(z)$ is the downward flux remaining at depth z (positive downwards), and K_s is the extinction coefficient for snow. Accordingly, an amount ΔI of energy is deposited between the top and bottom of any single layer, that is, one finite element of the model mesh. SNOWPACK treats this absorbed SW energy as a volume source of energy, much like the heat released during refreezing of free water.

The net surface flux I_0 being known, we need to find a suitable parameterization of the extinction coefficient K_s. One approach is to use a simple linear function of snow density ρ_s:

$$K_s = \frac{\rho_s}{a} + b \tag{2}$$

where a and b are freely adjustable parameters. Bohren and Barkstrom (1974) proposed a more elaborated parameterization that allows for a wavelength dependent treatment of the extinction coefficient:

$$K_s = 0.84\sqrt{\frac{k_i(\lambda)}{d}}\frac{\rho_s}{\rho_i} \tag{3}$$

where *d* is the grain diameter and ρ_i the density of ice. The absorption coefficient of ice, k_i, depends on the wavelength λ. Accurate values for k_i can be found in the literature (e.g. Warren et al., 2006). Still, Equation 3 is a simplification of the problem as it is valid for spherical grains only. On the other side, size defined as the greatest extension of a grain is known to poorly represent the electromagnetic properties of snow (Grenfell and Warren, 1999). Meirold-Mautner (2004) proposed to introduce an additional parameter f_b in Equation 3 to take account of this and other features the Bohren-Barkstrom model could not account for. The final equation used in SNOWPACK is then:

$$K_s = f_b(\Delta\lambda)\, 0.84\sqrt{\frac{k_i(\Delta\lambda)}{d}}\frac{\rho_s}{\rho_i} \tag{4}$$

where $\Delta\lambda$ represents a band of wavelengths. Indeed, a continuous function of λ would not be tractable and would hardly improve the results. Below we will term Equation 2 the broad band approach compared with the multi-band model of Equation 4 using 5 bands.

Most results presented in this paper were obtained using Neumann boundary conditions at the snow surface. For tests with SW absorption occurring to 90 % in the top centimeter of snow, however, the snow surface temperature calculated with Neumann boundary conditions is used to drive SNOWPACK with Dirichlet boundary conditions.

4 RESULTS AND DISCUSSION

4.1 Modeled vs. measured snow temperatures

Figure 1 shows both modeled and measured temperatures vs. time at three depths of 5, 15 and 25 cm as well as modeled temperatures only from 40 cm downward. The standard 5-band model run (solid line) using the best set of f_b parameters available compares very well with the measured temperatures (open circles) down to the depth of 25 cm below the surface. Note that the temperature range changes for each depth. While the temperature upswing nicely starts with the onset of incoming SW radiation around 8:30 on 11 February, the peak temperatures are slightly out of phase compared with the measurements. This can be explained by both heat conduction not being adequately modeled and whether energy is deposited at the correct depth by the penetrating SW radiation. We note that nearly as good results are obtained with optimized parameters for the broadband model (not shown), the amplitude of the temperature swing being larger near the surface. The time delay of the temperature peak relative to maximum net SW input of 84 W m^{-2} at noon increases from 13:30 to 21:30 at depths of 5 and 25 cm, respectively. Deeper in the snowpack, temperature evolution with time is thus dominated by the energy exchange that prevailed the days before and now slowly reached these depths. Nevertheless, weak upswings of a few tenths of a degree starting around 9:00 on 11 February can also be seen below 40 cm on the output of the standard run.

4.2 Switching off short wave radiation

Switching off incoming SW radiation on the sunny 11 February 2006 evidences even more the effect of radiation with depth (see Fig. 1). Temperature peaks are reduced by 9.2, 2.9 and 1.2 °C at depths of 5, 15 and 25 cm, respectively. Below 40 cm depth, switching off SW radiation on 11 February results in small to negligible differences that persist over longer periods. Nevertheless, some of the five wavelength bands deposit small amounts of energy at those depths such that a slow warming of the snowpack may occur, provided the simulation is correct. However, below 40 cm, the broadband run yields temperatures even lower than the run without SW radiation.

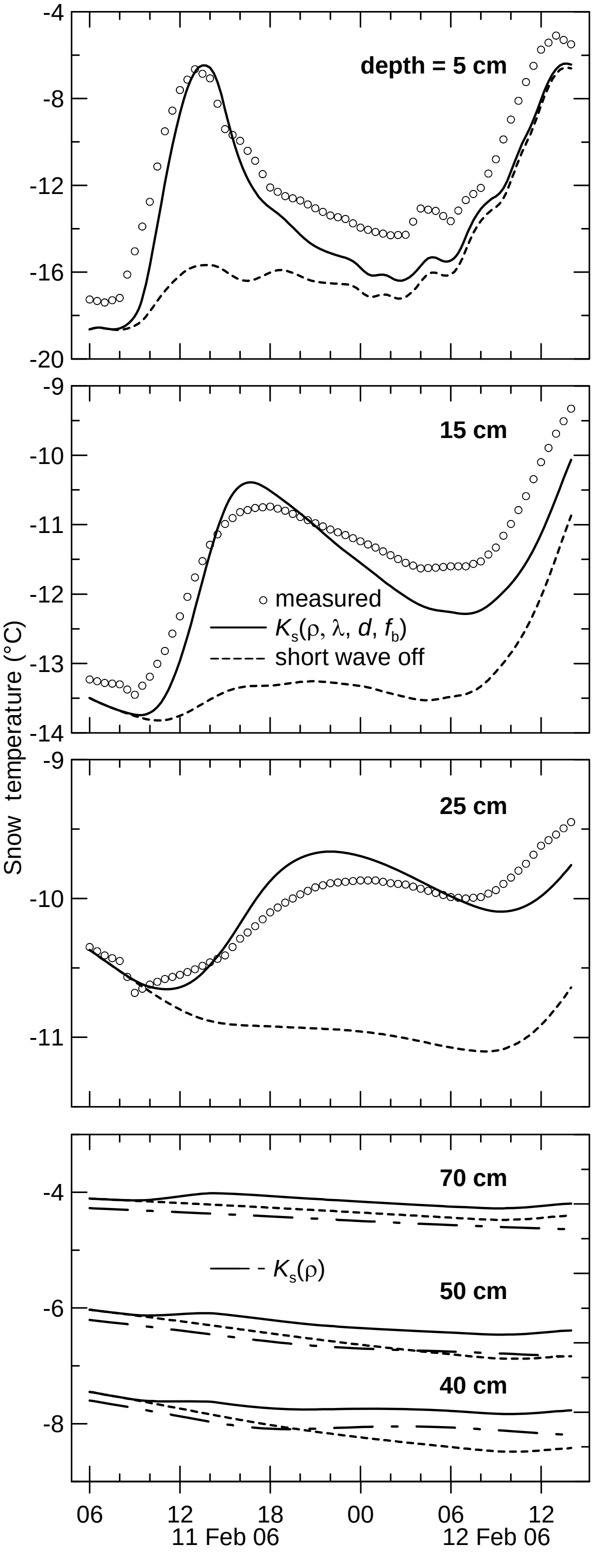

Figure 1: Measured (open circles) vs. modeled snow temperatures at various depths. Solid line represents the standard run with K_s from Equation 4, dotted line is with SW switched off and dash-dotted line is using K_s from Equation 2.

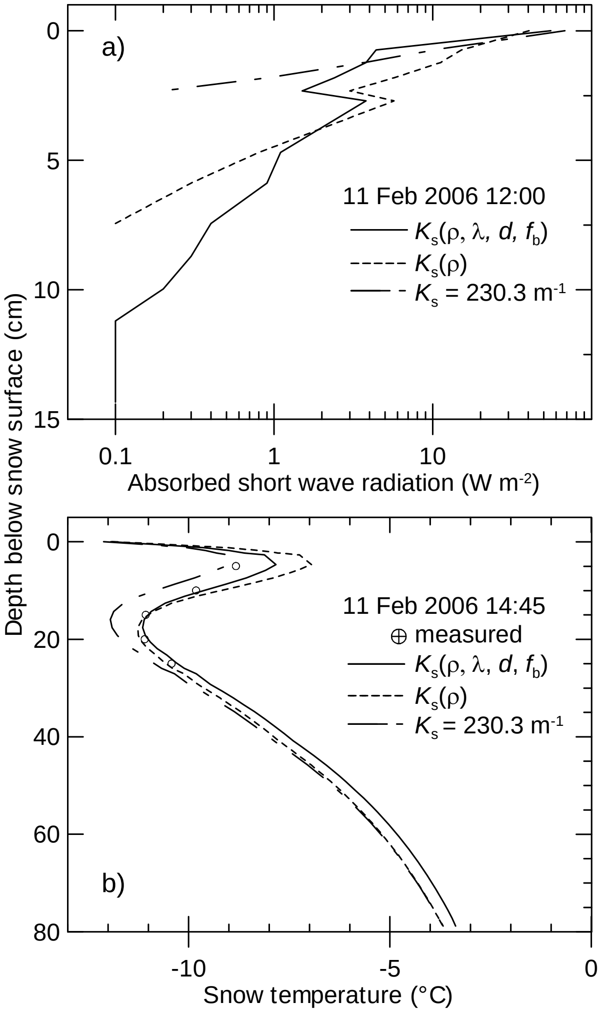

Figure 2: Comparison of three model runs with different parameterization of the extinction coefficient K_s (see text). a) SW radiation absorption at noon in the top 15 cm of the snowpack. b) Temperature profiles down to a depth of 80 cm at 14:45 that day. Five measured temperatures (open circles) are shown for comparison.

4.3 <u>Broad vs. multi-band model</u>

Figure 2a shows radiation absorption profiles at noon on 11 February for the 5-band model, the broadband model and a fixed extinction coefficient absorbing 90 % of the SW radiation within the top centimeter. Corresponding temperature profiles calculated for 14:45 the same day are shown in Figure 2b along with five measured temperatures. Note that all runs yield the same surface temperature as the two simpler models were driven with the surface temperature obtained with the standard 5-band model run.

The broad band model clearly overestimates temperatures near the surface and is consistently colder than the multi-band model below about 30 cm depth. The latter is a result of the broadband model depositing all SW radiation energy within the top 10 cm of the snowpack (see Fig. 2a). The run with a constant extinction coefficient shows that depositing even more SW radiation energy in the topmost centimeters of the snowpack would not only reduce the overestimated near-surface temperature but also yield temperatures at depths of 15 to 30 cm that are too low. The multi-band approach, however, absorbing SW radiation over a larger range of depths, yields the most promising results; even so, some unwanted warming in deeper layers may be observed (see Fig. 1).

5 SUMMARY AND OUTLOOK

Thanks to the high quality and reliability of the near-surface temperature measurements performed by Bakermans (2006), a best set of parameters for a multi-band parameterization of solar short wave absorption in snow could be found.

Switching off short wave radiation on a sunny day shows to what depth this energy source substantially contributes to the warming of the top portion of a snowpack consisting of nearly fresh snow. This also revealed shortcomings of the multi-band approach at depths below 30 cm. The latter, however, cannot be overcome by using a simpler broadband model for the extinction coefficient.

Remember also that while the quality of the measurements is unequaled, we presented results for one type of snow only. In future, different snow types need to be considered. Indeed, these comparisons also evidence how near surface snow temperature and temperature gradients can be affected by the different approaches used to model SW absorption in snow. Accordingly, near-surface snow metamorphism will also depend on this parameterization. Further studies, however, are needed to better quantify these effects.

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