A SNOW MICROSTRUCTURE SUPPLEMENT TO SNTHERM MODEL

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ABSTRACT
SNTHERM is a one dimensional heat and mass transfer model that predicts change in surface temperature, temperature of snow and soil layers, settlement of the snowpack,liquid water content, melt water percolation within the the snowpack and refreezing of water within the layers with time. Input required for the model is meteorological data i.e. air temperature, relative humidity, wind speed, radiation data and fresh snow/rain precipitation rate. A major limitation of this model is that it predicts snow settlement, snow metamorphism and snow thermal conductivity based on empirical correlations without providing any information about the weak or strong snow layers. This information is vital for predicting the snow avalanches. A modified SNTHERM with grain metamorphism, bond growth, coordination number, dendricity and sphericity models included is implemented so that type of snow layers within a seasonal snowpack can be predicted with reasonable accuracy. Further, there is overall improvement in the model results with the inclusion of microstructure based thermal conductivity and viscosity models. The results obtained by implementing the new models are checked against published data. The study highlights the gaps in the understanding of snow microstructure which need to be filled with more work in near future.

***Keywords*: Thermal conductivity, Viscosity, Microstructure, Bond, Grain**

NOMENCLATURE

$\left(\frac{dT}{dz}\right)_{micropore}$	Microscopic temperature gradient across the pore space (K/m)
$\left(\frac{dT}{dz}\right)_{mean}$	Mean temperature gradient across snow layer (K/m)
$\left(\frac{dT}{dz}\right)_{mean,cell}$	Mean temperature gradient across cell (K/m)
$\left(\frac{dT}{dz}\right)_{microbond}$	Temperature gradient along the neck (K/m)
n_{ca}	Number of cells per unit cross-sectional area
n_{cl}	Number of cells per unit length
$\left(\frac{dT}{dz}\right)_{micrograin}$	Temperature gradient along the grain (K/m)
ϕ	Porosity
ς	Empirical constant (0.46)
θ_i, θ_w	Fractional volume of ice and water, respectively (m^3/m^3).
γ_s	Bulk density of snow (kg/m^3)
γ_s'	Bulk density of snow (g/cc)
Δt	Time step(s)
Δz	Thickness of volume element (m)
A	Mean cross-sectional area of the unit cell (m^2)
A_g, A_b, A_P	Cross-sectional area of grain, bond and pore, respectively (m^2)
A_{ip}	Cross-sectional area for series conduction in pores (m^2)
C_{KT}	Variation of saturation vapor pressure with temperature (N/m^2 K)
d	Diameter of snow grain/grain size (m)
d_c	Grain diameter (m) after time't'

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D_{es}	Effective diffusion coefficient for water vapor in snow (m^2/s)
d_i	Initial diameter of snow grain (m)
D_{va}	Effective diffusion coefficient for water vapor in air (2.0 x10^{-5} m^2/s)
F_k	Empirical correction factor
h	Spacing between the grains (m)
JG	SNTHERM's grain growth model
JT	SNTHERM's thermal conductivity model
JV	SNTHERM's viscosity model
k_{ap}	Conductivity in the pore space resulting from the combined effects of direct conduction of heat in the air space and transport of latent heat(W/m K)
k_e	Effective thermal conductivity, with effects of vapor diffusion (W/m K)
k_i, k_a	Thermal conductivity of ice and air respectively (W/m K)
k_w	Thermal conductivity of water (0.556 W/m K)
L_{is}	Ice series length (m)
L_{lv}	Latent heat of evaporation for water (2505.0 KJ/kg at 0^0C)
l_n	Neck length/Bond length (m)
L_p	Mean pore length (m)
L_{ps}	Series pore length (m)
L_{vi}	Latent heat of sublimation of ice (2838 KJ/kg at 0^0C)
L_{ws}	Water series length (m)
MT	Microstructure based thermal conductivity model
MV	Microstructure based viscosity model
N_2	2-D coordination number for snow
n_c	Number of cells in a given sample volume
$P_{vi, sat}$	Saturation vapor pressure over an ice surface at temperature T (K)
r_b	Bond radius (m)
r_g	Grain radius (m)
RKT	Empirical thermal conductivity model (equation (24))
R_w	Gas constant for water vapor (461.296 J/kg K)
SG	Satyawali grain growth model
ST	Empirical thermal conductivity model (equation (23))
sv	Sample volume (m^3)
T	Temperature of snow layer (K)
t	Time (s)
T_1	Temperature at bottom of snow layer (K)
T_2	Temperature of top of snow layer (K)
U'_{vb}	Mass vapor flux (kg/s)
U'_{vg}	Mass vapor flux (kg/m^2s)

1. INTRODUCTION

During winters, a natural snowpack builds up layer by layer from one storm to another. Snowpack interacts with the meteorological parameters as well as with the soil. This differential energy exchange alters the thermal regime and thereby the mechanical properties of snow and the stability of the snowpack lying on a mountain slope. For finding out weak layer within a snowpack, an accurate heat and mass transfer model is desirable, which can predict the dynamic changes occurring within a seasonal snowpack with the marching of time over a wide area with meteorological data as the input. A number of heat and mass transfer models (Anderson, 1976; Brun et al., 1992; Durand et al., 1999; Lehning et al., 2002) for snow already exist but each of these models has some limitations. In the present work, SNTHERM (Jordan, 1991) model was chosen as the basis for the present work as it incorporates most of the phenomenon related to heat and mass transfer happening in the snowpack in a fairly precise manner. The model, however, includes a large number of empirical correlations and snow microstructure which is required for predicting the weak layers and their type is not incorporated.

2. SITE OF INVESTIGATION

The present study was done at the Patsio field station, located at an altitude of 3800 m above MSL in Greater Himalayan range of India. This place is marked by very low temperatures, and dry snow precipitation. During winters, minimum temperatures reach –30 ^{0}C here.

3. DATA COLLECTION AND RECORDING

Air temperature, wind speed, incoming short-wave radiation, reflected short-wave radiation, relative humidity, snowdepth,snowpack temperatures and soil temperatures were recorded hourly on the continuous basis through a fully automatic weather station(Figure 1).This weather station is commercially manufactured by MTX,Italia. Fresh snow precipitation was recorded every three hours with the help of snow stakes. Snow grain size, type and density were estimated through weekly stratigraphic tests. Grain size was estimated with the help of a hand held micromike.Grain type was identified just based on the experience and judgment.

4. MODIFICATIONS IMPLEMENTED

The modifications implemented in the existing SNTHERM (Jordan, 1991) model are mainly based on the work of Adams et al. (1993), Satyawali (1994, 1999) and Lehning et al. (2002). The modifications have been implemented in such a manner so that the modified SNTHERM model can be run with a large number of sub-model combinations of thermal conductivity, viscosity and grain metamorphism models. The brief description of the new models implemented in the SNTHERM model is as below :

4.1 Equilibrium grain growth and bond growth model

When mean temperature gradient across snow layers is less than –5 K/m, models proposed in (Lehning et al., 2002) for predicting the equi-temperature rate of grain growth and bond growth with time, are implemented in the present work.

4.2 Temperature gradient grain growth model

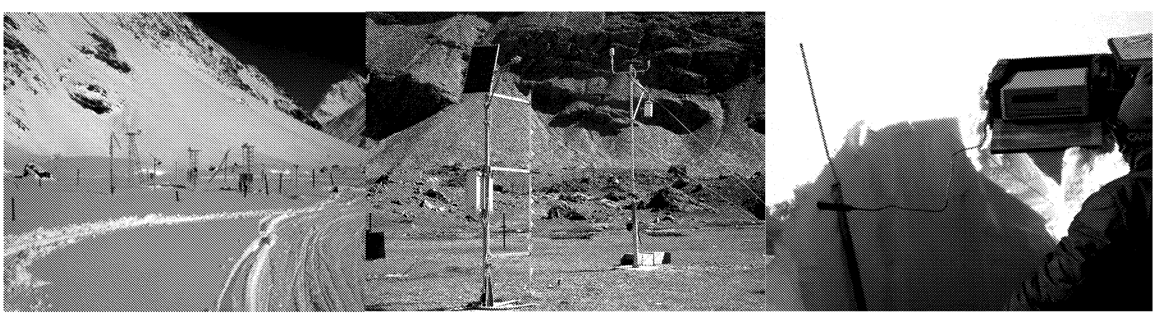
The semi-empirical equation proposed (Satyawali (1994, 1999)) for grain growth using the geometry shown in Figure 2 is:

$$\frac{\partial d}{\partial t} = \frac{U'_{vg}}{\rho_i} \qquad (1)$$

where mass vapor flux U'_{vg} is given as:

$$U'_{vg} = -\frac{D_{es}\, P_{vi,sat}}{R_w\, T^2}\left(\frac{L_{vi}}{R_w T} - 1\right)\left(\frac{dT}{dz}\right)_{micropore} \qquad (2)$$

D_{es} is the effective diffusion coefficient for water vapor(Jordan,1991) in snow (m^2/s). $P_{vi,\,sat}$ is the saturation vapor pressure over an ice surface at temperature T(K). L_{vi} is the latent heat of sublimation of ice (2838 KJ/kg at 0^0C). R_w is the gas constant for water vapor (461.296 J/kg K).



(a) (b) (c)

Figure 1. Detail of Patsio site (a) Complete view of Patsio observatory (b) MTX (company name) automatic weather station (c) Thermal conductivity of snow being measured in snow pit

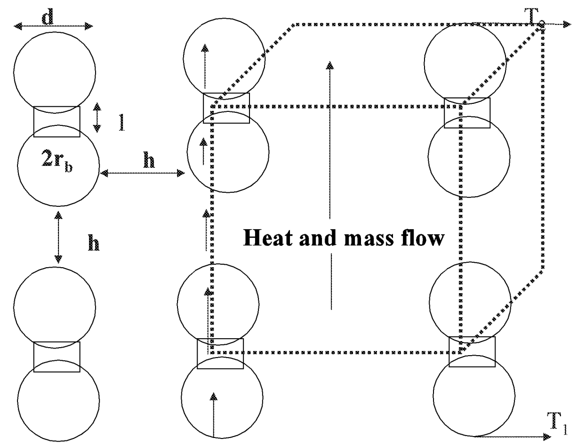


Figure 2. Assumed cubic packing of snow grains for grain growth and bond growth

The microscopic temperature gradient across the pore space (K/m) is given by the following relation:

$$\left(\frac{dT}{dz}\right)_{micropore} = \frac{k_e A}{k_a A_g}\left(\frac{dT}{dz}\right)_{mean} \quad (3)$$

Here, k_e is the effective thermal conductivity of snow, which includes the effects of vapor diffusion (W/m K). k_a is the thermal conductivity of air (W/m K) and $\left(\frac{dT}{dz}\right)_{mean}$ is the mean temperature gradient across the snow layer (K/m). The cross-sectional areas(m^2) of the grain(A_g) and bond(A_b), respectively, in terms of grain radius(r_g)(m) and bond radius(r_b)(m) are given by :

$$A_g = \pi r_g^{2} \quad (4)$$

$$A_b = \pi r_b^{2} \quad (5)$$

The cross-sectional area of the pore A_P (m^2) is given as:

$$A_p = (1-\theta_i-\theta_w)\left(\frac{A_g + A_b}{\theta_i}\right) \quad (6)$$

θ_i, θ_w are the fractional volume of ice and water, respectively (m^3/ m^3) (Jordan, 1991).

Based on the equations (4), (5) and (6), the mean cross-sectional area A of the unit cell is given as:

$$A = (A_g + A_b + A_P)/3 \quad (7)$$

In equation (6), Lehning et al. (2002) have considered only A_g. Considering that bonds are part of the total ice fraction within snow, we have added A_b to A_g.

New snow grain diameter after time't' is given by the following relation:

$$d_c = d_i + \frac{\partial d}{\partial t} t\phi^{\zeta} \quad (8)$$

where ς is an empirical constant (0.46), ø is porosity and ø $^{\varsigma}$ is the factor by which grain growth decreases with increase in density. d_i is the initial snow grain diameter.

$$\phi = 1 - \theta_i \quad (9)$$

4.3 Temperature gradient bond growth model

Similar to the grain growth model, bond growth model of Satyawali (1999) was implemented in the SNTHERM model. The basic theory behind bond growth model is same as the grain growth model discussed. Applying the basic concepts of heat and mass transfer, the final form of the bond growth equation is:

$$\frac{\partial r_b}{\partial t} = \frac{U'_{vb}}{2\pi r_b l_n \rho_i} \quad (10)$$

Mass vapor flux U'_{vb} (kg/ s) available for the bond growth is:

$$U'_{vb} = -\frac{D_{va}P_{vi,sat}}{R_w T^2}\left(\frac{L_{vi}}{R_w T} - 1\right)\left(\frac{dT}{dz}\right)_{microbond} \times (2\pi r_g^2 - \pi r_b^2) \quad (11)$$

r_b is the bond radius (m). $\left(\frac{dT}{dz}\right)_{microbond}$ is the temperature gradient along the neck (K/m), is related to $\left(\frac{dT}{dz}\right)_{micrograin}$ the microscopic temperature gradient along the grain (K/m) by:

$$\left(\frac{dT}{dz}\right)_{microbond} = \frac{A_g}{A_b}\left(\frac{dT}{dz}\right)_{micrograin} \quad (12)$$

$$\left(\frac{dT}{dz}\right)_{micrograin} = \frac{8r_g + 2l_n + h}{2r_g\left[\frac{2r_g}{h} + \frac{k_i}{k_a}\frac{h}{2r_g} + \frac{A_g}{A_b}\frac{l_n}{2r_g} + 5\right]} \times \left(\frac{dT}{dz}\right)_{mean,cell} \quad (13)$$

l_n is neck length (as estimated in Lehning et al. (2002))

$\left(\frac{dT}{dz}\right)_{mean,cell}$ is mean temperature gradient across unit cell (K/m)

$$\left(\frac{dT}{dz}\right)_{mean,cell} = \frac{T_2 - T_1}{8r_g + 2l_n + h} \quad (14)$$

For the given geometry, (Figure 2), porosity in terms of microstructural parameters can be defined as:

$$\phi = 1 - \frac{\frac{8}{3}\pi r_g^3 + \pi l_n r_b^2}{(4r_g + h + l_n)(h + 2r_g)^2} \quad (15)$$

Space between the grains 'h' is estimated by equating equations (15) and (9) and using a combination of Newton –Raphson and bisection method.

4.4 Dendricty and sphericity of snow

Snow grain shape is defined in terms of dendricity and sphericity. Dendricity estimates the irregular shape of the snow grain. Sphericity gives the idea about the roundness of the grain shape. In this work, we have implemented same empirical dendricity and sphericity equations for snow as that of Lehning et al. (2002) except that we have considered units of the rate of change of dendricity and sphericity as 1/day (Brun et al., 1989) instead of 1/s.

4.5 Microstructure based snow viscosity model

Snow is a viscoelastic material (Lehning et al., 2002) that undergoes large irreversible deformations. At low stresses, ice behaves as a nearly linear material. When the neck stress is more than 0.4 MPa, it is assumed that ice behaves as a linear viscoelstic material. We have implemented the work of Lehning et al.(2002) in the SNTHERM model .We have considered 2-D coordination number (Adams et al.,1993) in this work.

4.6 Microstructure based thermal conductivity model

Based on the work of Adams et al. (1993) and Lehning et al. (2002), effective thermal conductivity of snow is given as:

$$k_e = \frac{n_{ca}}{n_{cl}}\left[\frac{\pi^2 r_b k_i N_2 F_K}{32} + \frac{k_i k_{ap} A_{ip}}{L_{is}k_{ap} + L_{ps}k_i} + \frac{k_i k_w A_{iw}}{L_{is}k_w + L_{ws}k_i} + \frac{k_a A_p}{L_p}\right] \quad (16)$$

Again,we have considered 2-D coordination number in the equation (16).. L_{is} is ice series length(m).L_{ps} is the series pore length(m).

L_{ws} is the water series length (m). A_{ip} is the cross-sectional area for series conduction in pores (m^2). n_{ca} is the number of unit cells per unit cross-sectional area given as:

$$n_{ca} = (n_{cl})^2 \quad (17)$$

n_{cl} is the number of unit cells per unit length which is related to L_p , the mean pore length and n_c ,number of cells in a given sample volume 'sv' by the following relations:

$$L_p = \frac{1}{n_{cl}} \quad (18)$$

$$n_{cl} = (n_c)^{\frac{1}{3}} \quad (19)$$

n_c is estimated by the following relation:

$$n_c = \frac{sv \times \theta_i}{\left(\frac{4}{3}\pi r_g^3 + \pi r_b^2 l_n\right)} \quad (20)$$

In equation(20),we have included the effect of volume of the bonds .Based on the data by Adam et al.1993) and our experience, we propose following scheme for estimating the sample volume of snow :

For snow bulk density (γ_s) less than or equal to 300 kg/m^3

$$sv = \begin{cases} 0.03 & \text{for } \frac{r_b}{r_g} \le 0.1 \\ 0.02 & \text{for } 0.1 < \frac{r_b}{r_g} \le 0.2 \\ 0.01 & \text{for } 0.2 < \frac{r_b}{r_g} \le 0.3 \\ 0.005 & \text{for } \frac{r_b}{r_g} > 0.3 \end{cases} \quad (21)$$

For snow bulk density greater than 300 kg/m^3

$$sv = \begin{cases} 0.02 & \text{for } \frac{r_b}{r_g} \le 0.1 \\ 0.01 & \text{for } 0.1 < \frac{r_b}{r_g} \le 0.2 \\ 0.005 & \text{for } 0.2 < \frac{r_b}{r_g} \le 0.3 \\ 0.002 & \text{for } \frac{r_b}{r_g} > 0.3 \end{cases} \quad (22)$$

4.7 Empirical thermal conductivity models

Following empirical thermal conductivity models of snow are implemented in the modified SNTHERM program:

(a)Based on a large number of thermal conductivity measurements in snow, the following equations were given by Sturm et al. (1997) for predicting the effective thermal conductivity of snow:

$$\left.\begin{array}{l} \text{for } 0.156 < \gamma'_s \le 0.6 \\ k_e = 0.138 - 1.01\gamma'_s + 3.233(\gamma'_s)^2 \\ \text{for } \gamma'_s \le 0.156 \\ k_e = 0.023 + 0.234\gamma'_s \end{array}\right\} \quad (23)$$

Here, $\gamma'_s = \frac{\gamma_s}{1000}$

(b) In the winter period in year 2004,more than 200 thermal conductivity measurements(Aggarwal,2004) on dry snow were done using a portable thermal conductivity meter 'ISOMET 2104'(from Applied Precision Ltd.,Slovakia) on the natural snow at Patsio.Based on these measurements, the following empirical relation was obtained .

$$k_e = a' + b'\gamma_s + c'\gamma_s^2 + d'\gamma_s^3 \quad (24)$$

Where a'=3.9526x10^{-3}
b'=8.402x10^{-4}
c'=-1.7756x10^{-6}
d'=3.806358x10^{-9}

In this relation, it is assumed that the k_e includes the effect of heat transfer by sublimation of snow. It is considered that equations (23) and (24) are valid for dry snow only and when liquid water volume within a snow layer increases beyond 2%, its effect is added to these equations (Jordan, 1991). The modified effective thermal conductivity k_e' when liquid water is present in snow is given as:

$$k_e' = k_e + L_{lv} D_{es} C_{KT} \quad (25)$$

L_{lv} is the latent heat of evaporation for water (2505.0 KJ/kg at 0^0C). C_{KT} is the variation of saturation vapor pressure with temperature (N/m^2 K).

4.8 Layer identification

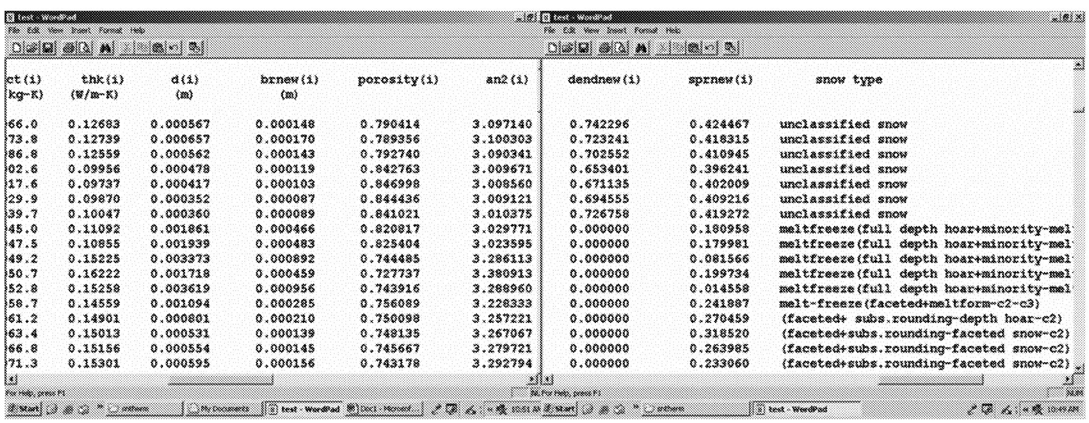
In the present work (Figure 3), an attempt is made to combine the various layer parameters into one parameter for identification of the snow grain type. In Lehning et al. (2002) , grain type is identified based on the snow grain diameter, dendricity and sphericity of snow. We have considered snow temperature and liquid volume additionally for identifying the melt-freeze layers.

4.9 Testing the implementation of modifications

The modified SNTHERM model was tested against the existing published data (Lehning et al., 2002; Adam et al.,1993; Satyawali (1994, 1999)) and a good correlation was obtained.

5. COMPARISON BETWEEN THE MODEL AND THE OBSERVED RESULTS

The modified SNTHERM model was run with a number of sub-models combinations from January 19 to March 22, 2006 for the Patsio field station .Some of the important combinations are shown in Table 1.It is to be noted here that in all the model simulations,equi-temperature and temperature gradient bond growth models as presented in sections 4.1 and 4.3 run as integral models.



ct(i) (kg-K)	thk(i) (W/m-K)	d(i) (m)	brnew(i) (m)	porosity(i)	an2(i)	dendnew(i)	sprnew(i)	snow type
66.0	0.12683	0.000567	0.000148	0.790414	3.097140	0.742296	0.424467	unclassified snow
73.8	0.12739	0.000657	0.000170	0.789356	3.100303	0.723241	0.418315	unclassified snow
86.8	0.12559	0.000562	0.000143	0.792740	3.090341	0.702552	0.410945	unclassified snow
02.6	0.09956	0.000478	0.000119	0.842763	3.009671	0.653401	0.396241	unclassified snow
17.6	0.09737	0.000417	0.000103	0.846998	3.008560	0.671135	0.402009	unclassified snow
29.9	0.09870	0.000352	0.000087	0.844436	3.009121	0.694555	0.409216	unclassified snow
39.7	0.10047	0.000360	0.000089	0.841021	3.010375	0.726758	0.419272	unclassified snow
45.0	0.11092	0.001861	0.000466	0.820817	3.029771	0.000000	0.180958	meltfreeze(full depth hoar+minority-mel
47.5	0.10855	0.001939	0.000483	0.825404	3.023595	0.000000	0.179981	meltfreeze(full depth hoar+minority-mel
49.2	0.15225	0.003373	0.000892	0.744485	3.286113	0.000000	0.081566	meltfreeze(full depth hoar+minority-mel
50.7	0.16222	0.001718	0.000459	0.727737	3.380913	0.000000	0.199734	meltfreeze(full depth hoar+minority-mel
52.8	0.15258	0.003619	0.000956	0.743916	3.288960	0.000000	0.014558	meltfreeze(full depth hoar+minority-mel
58.7	0.14559	0.001094	0.000285	0.756089	3.228333	0.000000	0.241887	melt-freeze(faceted+meltform-c2-c3)
61.2	0.14901	0.000801	0.000210	0.750098	3.257221	0.000000	0.270459	(faceted+ subs.rounding-depth hoar-c2)
63.4	0.15013	0.000531	0.000139	0.748135	3.267067	0.000000	0.318520	(faceted+subs.rounding-faceted snow-c2)
66.8	0.15156	0.000554	0.000145	0.745667	3.279721	0.000000	0.263985	(faceted+subs.rounding-faceted snow-c2)
71.3	0.15301	0.000595	0.000156	0.743178	3.292794	0.000000	0.233060	(faceted+subs.rounding-faceted snow-c2)

Figure 3. Output of the modified SNTHERM code on Jan 30, 2006 (0700 hrs) showing new snow layer information

Table 1: Scheme for simulations for Patsio station (2005-2006)

Sub-models Combination	Simulation case Title	Remarks
JG, JV, JT	E	Existing SNTHERM model
SG, MV, MT	C	Modified SNTHERM model
SG, MV, RKT	A	
SG, MV, ST	B	

In Table 1, notations used have the following meaning:

JG =SNTHERM's grain growth model (Jordan, 1991)

JV=SNTHERM's viscosity model (Jordan, 1991)

JT=SNTHERM's thermal conductivity model (Jordan, 1991)

SG=Satyawali grain growth model (equation (1))

MV=Microstructure based viscosity model (refer section 4.5)

MT=Microstructure based thermal conductivity model (equation (16))

RKT=Empirical thermal conductivity model (equation (24))

ST= Empirical thermal conductivity model (equation (23))

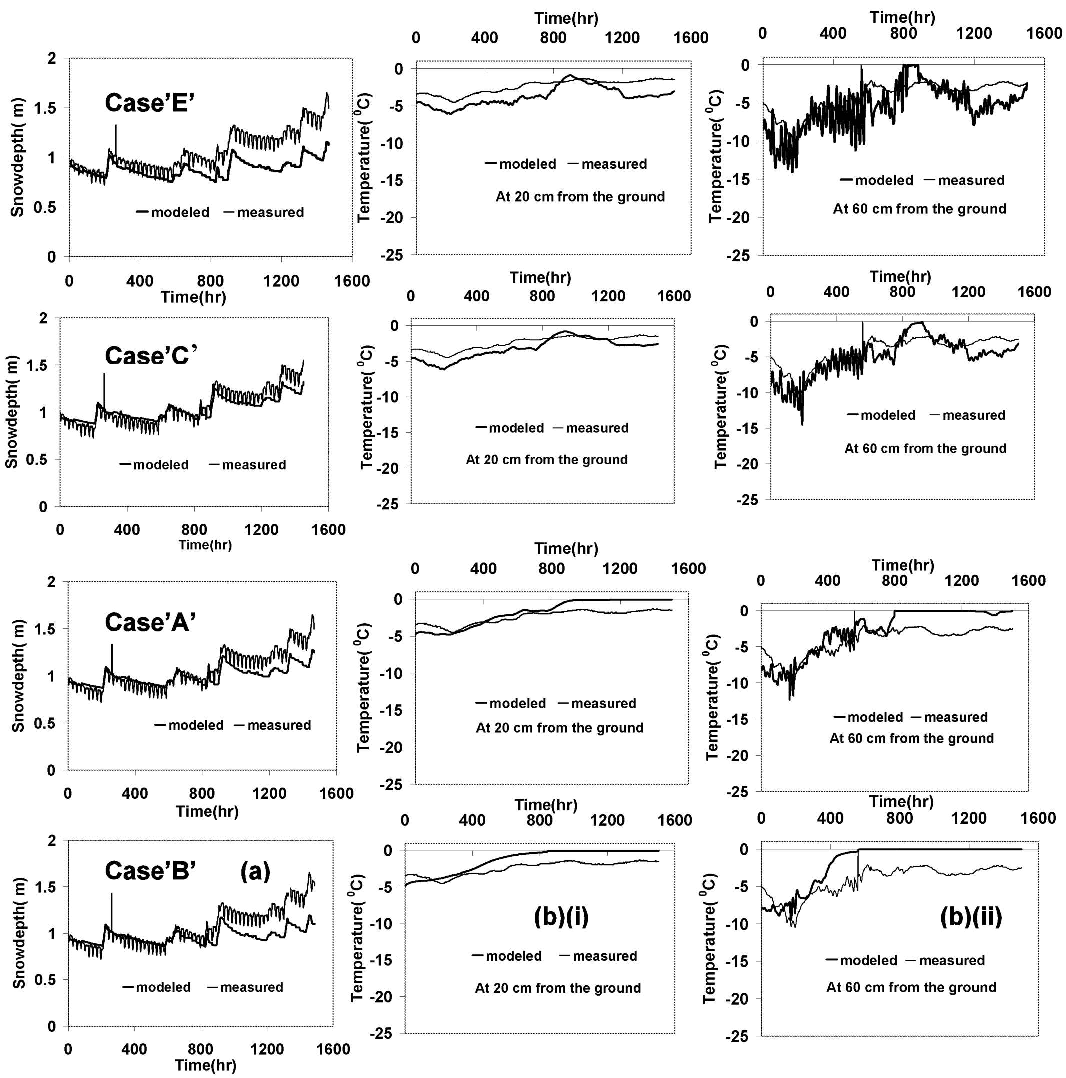


Figure 4. Modeled vs. observed (a) snowdepth (b) snowpack temperatures at (i) 20 cm snowdepth (ii) at 60 cm snowdepth

As is clear from the case 'E' (Figure 4), observed and simulated snowdepth values agree well till late February but afterwards, model is predicting lower snowdepth values than the observed ones. This is due to lower values of snow viscosity predicted by the model and hence faster settlement of snow takes place. Uncertainty in the viscosity is inter-dependent on the models of bond growth, grain growth and thermal conductivity. Minor fluctuations in the recorded snowdepth values are due to uncertainty in the measurement .Simulated temperatures show more fluctuations (Figure 4.b) than the observed ones, probably due to the higher values of the thermal conductivity predicted by the model.

In case 'C', there is strong correlation between the modeled and measured snowdepth values.Snowpack temperatures agree well till the end of February 2006, afterwards mismatch between the two values increases. The reason for this may be again due to uncertainty in the thermal conductivity values when snow is near melting temperature.

The reason for improvement in the match between the simulated and observed values in case'A' over case'C' till late February is probably due to better accuracy of the empirical thermal conductivity model for dry snow .Afterwards again the mismatch increases due to uncertainty in the values of the thermal conductivity of wet snow. In case 'B' simulated snow depth and temperatures have poor correlation with the observed values due to lower values of thermal conductivity predicted by the model.

It can be seen from Table 2 that model and observed results match for the bottom of the snowpack .Beyond 0.58 m depth of snowpack from the ground, matching between the predicted and simulated values is very poor.

Table 2. Model vs. observed snow type

Layer thickness (m)(from ground)	Simulated snow type	Observed snow type
0.0-0.28	Faceted	Faceted
0.28-0.58	Faceted+round Grain	Round grain
0.58-0.73	Full Depth hoar+ frozen water	Round grain
0.73-0.85	Full Depth hoar+ frozen water	Fresh snow
0.85-1.00	Unidentified snow	Fresh snow

8. CONCLUSION

Over all, when microstructure based viscosity model and thermal conductivity model along with Satyawali's grain and bond growth model are implemented in the existing SNTHERM model , the agreement between the predicted and measured snow depth and snowpack temperatures is good. There is further scope of improving (Baunach et al., 2001) the grain growth predictions. There is a need for improving the thermal conductivity model of snow especially when it is wet. In the present work, snow metamorphism models implemented are based on the assumption of steady state conditions of heat and mass transfer but a real snowpack, undergoes dynamic changes in the temperature gradients. This aspect can be taken into account for refinement of these models. Microstructure based models are preferred because these models predict inter-dependent behavior of snow microstructure parameters like grain diameter, bond radius etc. govern the values of thermal conductivity and viscosity and vice–versa, which is what happens in a real snowpack. At the same time, the importance of empirical correlations cannot be ignored because these help in checking the validity of the microstructure based models. In future, experiments under controlled conditions will be performed so that more systematic measurements of grain growth and layer identification are possible. These will be simulated by the modified code.

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