Performance and Suitability of Single- and Multiple-Layer Snow Models for Operational, Moderate-Resolution, CONUS Snow Data Assimilation

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ABSTRACT

Two mass- and energy-balanced, vertically-distributed snow models were developed to support operational snow data assimilation. Both adopted the mathematical techniques of *Tarboton* and *Luce* (1996) for the calculation of snow surface temperatures and the snow thermodynamics of SNTHERM.89 (*Jordan*, 1991) for mass and energy fluxes, and both take account of the net mass-transport from the snow surface to the atmosphere by sublimation of saltation- and suspension-transported snow (*Pomeroy* and *Li*, 2000). The multiple-layer model differs from the single-layer model by explicitly representing vertically distributed mass and energy within the snowpack. Performance and suitability of the two models were examined using field-observed data, with a comparison in the mass and energy to results from SNTHERM.89 (*Jordan*, 1991), a well-known, multiple-layer, point model. The two multiple-layer models agreed very well in the estimation of snow mass and energy, while the single-layer model was significantly different from them. First, under cold meteorological conditions, the single-layer model poorly estimated the conductive heat flux within the snowpack due to the linear simplification of non-linear snowpack temperature profiles. Secondly, under warm conditions, there was a considerable difference in the timing and magnitudes of snowpack melt flux estimation, with daily snow melt starting earlier in the single-layer model. Consequently, the single-layer model estimated more snow water equivalent loss by melt outflow than the two multiple-layer models. This difference is attributed to the fact that the single-layer model estimates melt outflow based on the internal energy density of the entire snowpack, while the multiple-layer models estimate it based on the internal energy density of only the bottom snow layer. The internal energy density of the entire snowpack responds to energy inputs at the surface of the snowpack instantly, but the bottom layer internal energy density responds with a lag time. This lag time is controlled by the penetration speed of a wetting front generated by energy inputs at the snow surface. The multiple-layer snow model developed in this study is preferred as the physical engine for operational continental U.S. (CONUS) snow data assimilation because of its favorable performance, its simplicity (small number of state variables), and its efficiency in computation.

Key words: mass balance, energy balance, single-layer snow model, multiple-layer snow model

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INTRODUCTION

The National Operational Hydrologic Remote Sensing Center (NOHRSC) has developed an operational snow data assimilation system (SNODAS) for the coterminous U.S. The physical engine for SNODAS is a vertically distributed, physically based snow model. Two mass- and energy-balance snow models, a simple one-layer model and a more comprehensive five-layer model, were developed and examined for their performance and application suitability in SNODAS. Both models account for mass fluxes of snowfall, rainfall, sublimation from both the snow surface and from wind-transported snow, and snow melt-water outflux; for radiative, turbulent, and conductive energy fluxes; and for energy advected by precipitation. The single-layer model treats the snowpack and thermally active soil as one layer, and maintains only snow water equivalent (SWE) and snow energy content as state variables. The multiple-layer model treats the snowpack as three layers and the soil as two layers. It maintains water and energy contents for each snow and soil layer as state variables, and also maintains state variables describing the thickness of each snow layer (i.e., snow depth).

To evaluate the performance and suitability of these two snow models for SNODAS, the two were run in point mode for cold and warm snowpack conditions, and their results were compared to those of SNTHERM.89 (*Jordan*, 1991), a well-known, multiple-layer snow energy- and mass-balance model. Using SNTHERM as a standard, we examined the single- and multiple-layer models' ability to simulate snow surface temperature, snowpack internal energy, SWE, and melt-water outflux from the base of snowpack. During the cold case, the single-layer model poorly estimated the internal energy. During the warm case, the single-layer model estimated more SWE loss by snowmelt outflow. Overall, the multiple-layer model matched SNTHERM's representation of snowpack dynamics more closely than the single-layer model. Of particular importance for hydrologic applications, the multiple-layer model provided a much better representation of SWE, and of the timing, rate, and magnitude of melt water outflux, than the single-layer model.

The five-layer model is more representative of snowpack states than the single-layer model and more efficient in computation than SNTHERM. It therefore better meets the requirements of SNODAS, and is favored as the physical engine for SNODAS. The model is designed to be forced by hourly, 1-km gridded meteorological input data downscaled from mesoscale atmospheric model analyses, with three major state variables of water content, internal energy and thickness for each layer. The model generates as output fields the water content, snowpack thickness, and energy content, along with a large number of mass and energy fluxes at the snow surface and between snow and soil layers, for the coterminous U.S.

ONE-LAYER MODEL

Snow Surface Temperature. The single layer model relies on snow surface temperature to estimate the heat exchange between snow and the atmosphere. It uses a physically based equilibrium approach to interactively find a snow surface temperature solution that balances all the energy fluxes at the surface, with an initial estimate of the equilibrium surface temperature set to the air temperature; that is,

$$Q(T_e) = 0 \tag{1}$$

where Q is the net heat flux at the surface, and T_e is the surface equilibrium temperature, and

$$Q(T_e) = Q_{ns} + Q_{il} - Q_{ol}(T_e) + Q_h(T_e) - Q_e(T_e) + Q_p + Q_g(T_e) \tag{2}$$

where Q_{ns} is net solar radiation, Q_{il} is incoming longwave radiation, Q_{ol} is outgoing longwave radiation, Q_h is sensible heat flux, Q_e is latent heat flux, Q_p is advected heat flux from precipitation, and Q_g is conductive heat flux.

Snow surface temperature can be estimated based on the theory of equilibrium surface temperature (*Tarboton* and *Luce*, 1996). If the equilibrium surface temperature is found below or at the freezing point, the snow surface temperature, T_s, is set to T_e, because the actual snow surface

temperature will gradually approach and eventually reach the equilibrium surface temperature. If T_s is found above the freezing point, it indicates that the snow is warming, and T_s is set to the freezing point, its maximum value. In reality, there may be no equilibrium surface temperature, as all energy fluxes will not be balanced at the surface. In the latter of the two cases, there will be a net energy input to the snowpack, causing snow to melt. Note that the heat flux convected by snowmelt water is excluded from Eq. (2) because Eq. (2) is a surface energy balance formulation.

Following the UEB model (*Tarboton* and *Luce*, 1996), the Euler predictor-corrector numerical method is used to solve Eq. (2) for the equilibrium surface temperature. First, the model predicts the snow surface temperature and the change in state variables given the state and meteorological driving variables at the beginning of the time step. Next, it updates the state variables with the predicted changes for the time step to account for the feedbacks in snowpack thermal conditions during the time step. It then advances the surface temperature one step further using the updated (predicted) values of the state variables. Finally, it uses the advanced surface temperature to correct the previous predicted surface temperature. Considering the magnitude of our hourly time step, the correction made to the predicted values is important, particularly for a shallow snowpack, as significant changes may occur over one hour.

Internal Energy. Snowpack internal energy is defined relative to a reference state of water at 0 ^{o}C in the ice phase. If the snow temperature is below 0 ^{o}C the internal energy is negative and depends on the temperature and mass of the snowpack. If the snow temperature is at 0 ^{o}C the internal energy is positive and depends only on the mass of liquid water in the snowpack. The snowpack internal energy value at the end of a time step is computed by adding the net input energy to the value at the beginning of the time step. Based on the snow surface temperature, the net input energy, $Q(T_s)$, is calculated by adding the melt water-convected heat flux, Q_m, to Eq. (2):

$$Q(T_s) = Q_{ns} + Q_{il} - Q_{ol}(T_s) + Q_h(T_s) - Q_e(T_s) + Q_p + Q_g(T_s) - Q_m \qquad (3)$$

SWE. The net mass flux, ΔW, is calculated with snow precipitation, P_{snow}, rain precipitation, P_{rain}, melt outflow rate, M, surface sublimation or condensation, E_s, and sublimation of blowing snow entrained from the snowpack in saltation and suspension, E_b:

$$\Delta W = P_{snow} + P_{rain} - M + E_s - \frac{3600}{\rho_w} E_b \qquad (4)$$

Note: E_b is in kg s^{-1} per unit area, and the other items are in m hr^{-1}. The SWE value at the end of a time step is computed by adding the net mass flux to the value at the beginning of the time step.

The single-layer snow model is based on our understanding of internal snowpack hydrological processes, boundary layer thermodynamics (*e.g. Anderson*; 1976; *Gray* and *Male*, 1981), and the technical experience of previous numeric snow modeling efforts (*e.g. Tarboton* and *Luce*, 1996). Obviously, by design it is incapable of representing the non-linear vertical temperature gradient within the snowpack. This temperature gradient influences mass and energy exchanges within the snowpack and between the snowpack and the atmosphere, the penetration of wetting fronts, and melt outflux. Compared with a multiple-layer snow model, the single-layer snow model was demonstrated to be less accurate in vertically distributing snowpack mass and energy under cold conditions due to its linear simplification of non-linear snowpack characteristics (*Blöschl* and *Kirnbauer*, 1991). However, it was also demonstrated that the single-layer model has a strong physical basis as well as performance comparable to a complex, multiple-layer snow model (e.g. SNTHERM.89) when the snowpack is isothermal (*Koivusalo* and *Heikinheimo*, 1999). Important advantages of the single-layer model are 1) it requires only two major snowpack state variables, which simplifies initialization, and 2) it is computationally efficient, which is an important consideration for operational purposes.

FIVE-LAYER MODEL

A multiple-layer snow model was developed to address the limitations of the single-layer model described above, and to add snow depth as a state variable, which will permit assimilation of more widely available snow depth observations. The five-layer model was designed to better represent snowpack thermal processes and to vertically distribute snowpack mass and energy from layer to layer, and also to preserve as much of the simplicity of the single layer model as possible.

The temperature gradient of the snowpack is responsible for thermal processes including both water infiltration and snow-conducted and water-convected heat fluxes from layer to layer. The five-layer model represents the temperature gradient using a finite difference scheme of thin layer linear approximations. It arbitrarily divides the snowpack into up to three layers, depending on the thickness of the snowpack, and it divides the soil into two layers. The two uppermost snow layers are designed to remain relatively thin, which enables them to follow the hourly-sensible fluctuation of temperatures near the surface. The third layer is thicker and is designed to follow the daily fluctuation of the deeper snow temperature. The two soil layers affect the initial states of new snow, and serve as a secondary heat source or sink for the snowpack.

The multiple-layer model is based on algorithms similar to the single layer model and uses the same input variables to calculate mass and energy exchanges at the surface. It adds algorithms from SNTHERM.89 to treat snow compaction and internal snow and soil energy and mass exchanges. Unlike the single-layer snow model, it uses the difference between the equilibrium snow surface temperature, T_e, and the average temperature of the layer below, T_{next}, as well as the layer thicknesses of the uppermost layer, d_{first}, and of the layer below, d_{next}, to estimate the temperature gradient for conductive heat flux, Q_g, between the two layers:

$$Q_g = -K_s \frac{T_e - T_{next}}{d_{first} + 0.5 d_{next}} \qquad (5)$$

where K_s is the thermal conductivity of the snow or soil, and is weighted by the layer thicknesses of snow and soil if the lower layer is a soil layer. In Eq. (5) the equilibrium surface temperature is preferred over the average top layer temperature to address the sensibility of the snowpack to the atmospheric temperature.

Note, in Eq. (5) the average temperature of the lower layer is associated with the layer's internal energy and SWE. This is an advantage over the single-layer model, as the equilibrium surface temperature from the multiple-layer model is dynamically coupled with the lower layer. In addition, the internal energy of the lower layer is corrected with the predicted conductive heat flux from the top layer, and the corrected value is used to derive the surface equilibrium temperature as well as the change of state variables one step further. Thus, changes in the state of the lower layer are taken into account in solving the surface temperature and the associated surface energy fluxes, allowing the model to better simulate the actual internal snowpack thermal processes.

Internal Energy. Based on the snow surface temperature, the snowpack internal energy is calculated differently for cold and warm conditions. The cold condition applies when the surface temperature is below the freezing point and the snow internal energy from the previous time step is negative. No phase change should occur from snow to liquid water under the cold condition. The average temperature of the previous time step for the lower layer, the snow surface temperature of the current time step, and the thickness of the two layers are used with linear interpolation to compute the current average temperature for the top layer, T_{mean}. The top layer internal energy at the end of the current time step, U, is then updated using its average temperature and snow water equivalent, W, as

$$U = W c_s (T_{mean} - 273.15) \qquad (6)$$

where c_s is the specific heat of ice. Here, the latent heat of liquid water, if any, is considered to be minimal and is neglected. For the cold condition, all heat fluxes are not balanced at the surface until the surface temperature reaches its equilibrium level. It is therefore difficult to know the total

net heat flux to the snowpack from the beginning of a time step to the time when the surface equilibrium temperature is reached. However, Eq. (6) is a temperature-based method, and permits the internal energy to be directly estimated without the net energy flux estimation owing to the temperature gradient provided by the multiple layers.

Regardless of the snow internal energy of the previous time step, the warm condition occurs when the equilibrium surface temperature is found at or above the freezing point. This temperature could balance the energy fluxes at the snow surface if the actual snow temperature could rise above the freezing point. In reality, as the highest snow surface temperature cannot be above 0 ^{o}C, the energy fluxes are not balanced at the surface. Therefore, under the warm condition, net energy enters the snowpack from the air, a phase change from snow to liquid water occurs, and the actual snow surface temperature should be at 0 ^{o}C. Eq. (2) is used to compute the net energy flux for the top layer with the surface temperature equal to 0 ^{o}C. For the remaining snow and soil layers, Eq. (2) is simplified to give the net energy flux as

$$Q = \Delta Q_g - \Delta Q_m \tag{7}$$

There should be a third case where the snow equilibrium surface temperature is found below the freezing point and the snow internal energy of the previous time step is positive. It is not appropriate to estimate the internal energy for this case using the method for the cold condition, because there is a latent heat component due to the phase change from liquid to snow, or using the method for the warm condition, because the actual snow surface temperature is unknown for the time step (note that the equilibrium temperature can be significantly different from the actual snow surface temperature for this condition). Nevertheless, without a better solution, this third case is treated as the cold condition in the present snow model. As a result, the model will underestimate snow surface temperature, snowpack average temperature, and the internal energy for the time step, particularly if the snowpack is thick with a high liquid water content. However, for a thin snowpack, the error should be minimal relative to the model accuracy.

Water Equivalent. For the net mass flux of the top layer, the five-layer model takes into account the vapor diffusion, D_v, between the top layer and the next layer as an additional factor to Eq. (4) as

$$\Delta W = P_{snow} - P_{rain} - M - E_s - \frac{3600}{\rho_w} E_b - D_v \tag{8}$$

For the remaining snow and soil layers, the net mass flux equation is simplified as

$$\Delta W = \Delta M - \Delta D_v \tag{9}$$

PERFORMANCE OF THE SINGLE-LAYER AND THE MULTIPLE-LAYER MODELS

To examine the performance of the single-layer and five-layer models, each was run with identical meteorological forcing conditions for two different cases. The resulting snow surface temperature, SWE, snowpack internal energy, and snowmelt outflow over time were compared to SNTHERM results. The two tested cases were: 1) a cold case, where the initial snowpack and meteorological boundary conditions ensured that the snowpack would remain below the melting point throughout the model run, and 2) a warm case, where the initial conditions described a ripe snowpack and the meteorological boundary conditions allowed frequent melt episodes. For the cold case the hourly data set of *Jordan* (1991) is used. The data describe conditions of temperature, air relative humidity, wind speed, incident shortwave radiation, and precipitation for a 13-day period in Hanover, NH. These data were systematically altered to create a set of hypothetical data for the warm case. A bias (+1.5 ^{o}C) and a trend (+0.02 ^{o}C/hour) were added to the air temperature time series. The incident solar radiation time series was increased by 50% for each hour. The wind speed time series was increased by a factor of two for each hour.

All three models were initialized with 0.14-m SWE and a snow depth of 0.55 m (Figure 1). The initial conditions for the SNTHERM test case consisted of 14 snow layers. Both SNTHERM and the multiple-layer model had two soil layers (0-0.2 m, 0.2-1.0 m; only the upper layer is shown in Figure 2 for clarity). For the

single-layer model, the thickness of the thermally active soil layer was set to zero to permit comparison of internal snowpack energy with the other models.
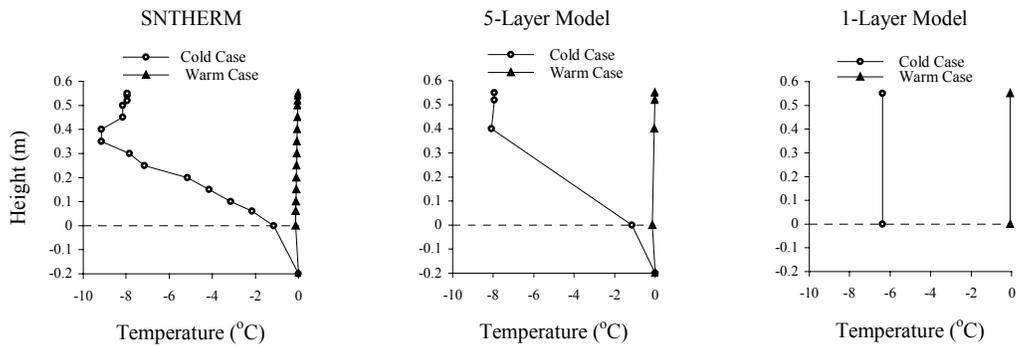

Figure 1. The initial snowpack temperature profiles.

Each model was initialized with similar snow density profiles, which remained the same for both the cold and warm cases. For the cold case, each model was initialized with an internal energy content of -1774 kJ. In SNTHERM and the multiple-layer model, this energy deficit was distributed to reflect a typical temperature gradient in cold snowpack, with snow temperatures near 0° C at the snow/ground interface, and colder temperatures closer to the snow/air interface (Figure 1). For the warm case, each model was initialized with an internal energy content of 1374 kJ, reflecting an isothermal snowpack near 0° C (Figure 1).

Figure 1. The initial snowpack temperature profiles.

Performance of the 1-layer and the 5-layer models is shown in Figures 2 and 3 for the cold case, and in Figures 4 through 7 for the warm case, both in comparison to SNTHERM. It is shown that the snow surface temperatures estimated by all three models agree well. Overall, the agreement is better for the warm case than for the cold case. The 1-layer model and the 5-layer model tend to give a larger diurnal fluctuation of surface temperature than SNTHERM. Compared with SNTHERM, the internal energy, SWE, and melt outflow generated by the 5-layer model are much more favorable than the 1-layer model. The 1-layer model tends to underestimate snow internal energy for the cold case, and to overestimate SWE loss by melt outflow for the warm case.
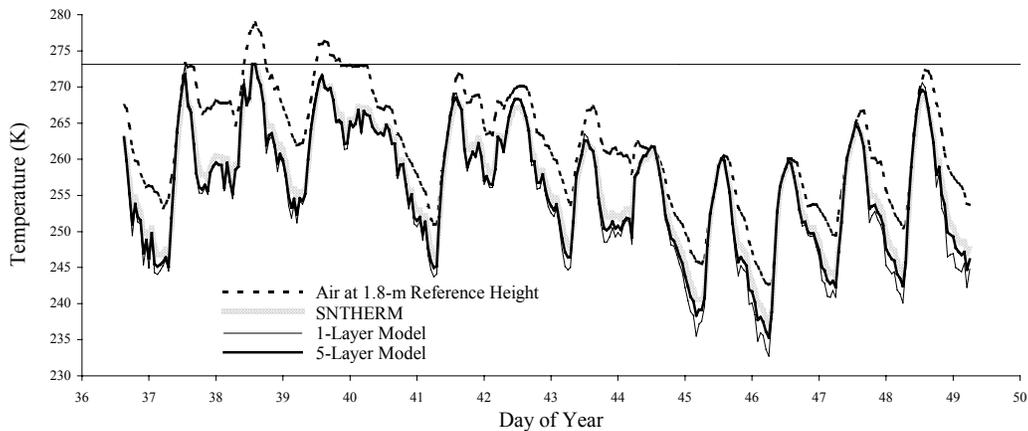

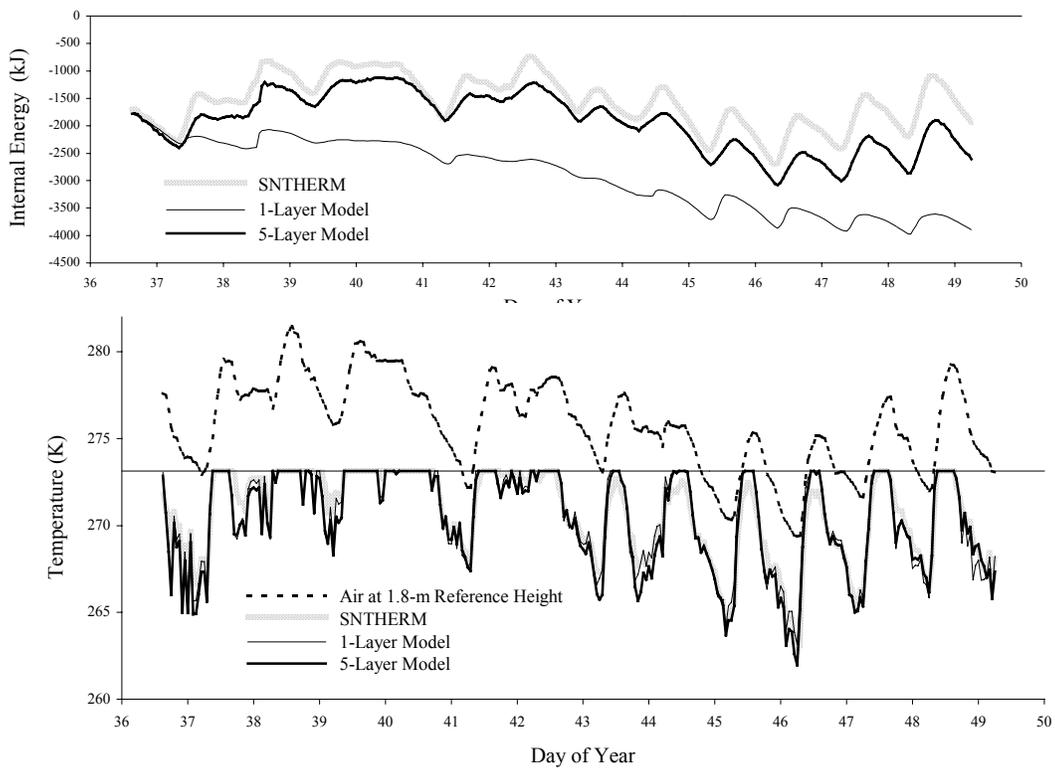**Figure 2**. SNTHERM snow surface temperature and snow surface equilibrium temperatures: cold case.

Figure 3. The modeled internal energy of snowpack: cold case.

Figure 4. SNTHERM snow surface temperature and snow surface equilibrium temperatures: warm case.
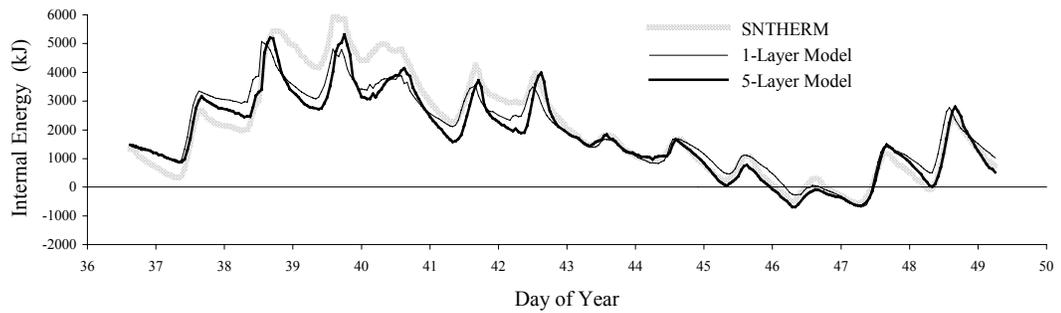

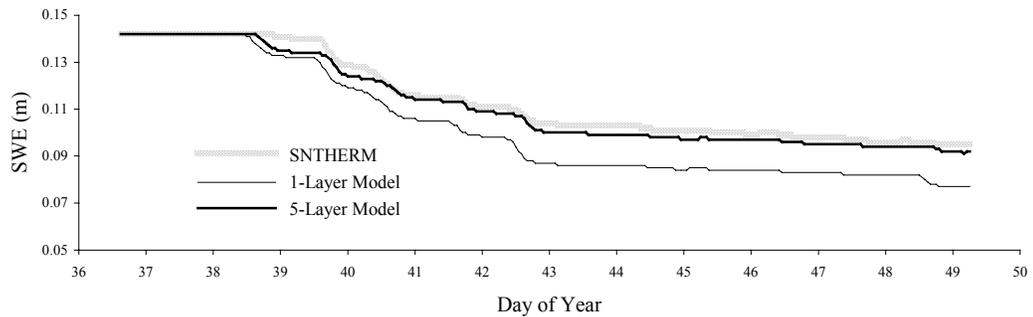**Figure 5**. The modeled internal energy of snowpack: warm case

Figure 6. The modeled SWE: warm case
Figure 7. The modeled snowmlet outflow: warm case

DISCUSSION

The 5-layer model works in the same manner as the single-layer model, except that the temperature gradients are determined layer-by-layer. It still assumes a linear profile, but the profile applies only to a much thinner layer. The essential difference of the multiple-layer model from the single-layer model is the use of finite short linear approximations to represent the non-linear temperature profile of the snowpack. This results in a finer vertical resolution, a more realistic temperature gradient, and hence a better layer-to-layer distributed solution of mass and energy
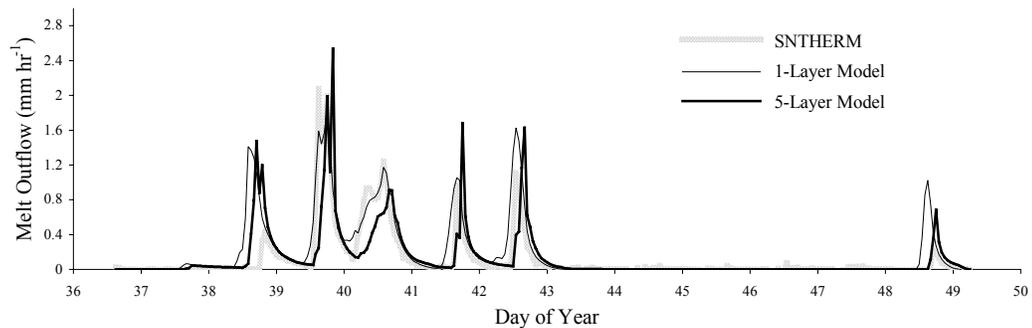
within the snowpack. Both the 1-layer model and the 5-layer model operate on the same temporal resolution of one hour, a finite temporal difference much longer than the 5-900 second resolution used by SNTHERM.

   Surface Temperature. Snowpack surface temperature is directly related to the net energy flux at the surface. The three models used identical meteorological driving data and similar algorithms to estimate each component of the surface heat flux, but used a different estimation for the conductive heat flux at the surface. Since the instantaneous conductive heat flux is small compared to turbulent fluxes and radiative heat fluxes, and becomes zero during snowmelt when the snowpack is isothermal at $0^{o}C$, the surface temperatures estimated by the three models are expected to be close to each other, especially for the warm case.
   The slight difference in surface temperature between the 1-layer model and the 5-layer model is related to the estimation of conductive heat flux to the surface (Figure 2). Conductive heat flux is directly related to the snowpack vertical temperature gradient. The 1-layer model estimates conductive heat flux based on the whole-snowpack temperature gradient given by its surface and average temperature, while the 5-layer model is based on the more accurate temperature gradient given by the top layer surface and the average temperature of the lower layers. As a result, the 1-layer model estimates a smaller conductive heat flux from the snowpack to the surface than the 5-layer model, and a colder surface temperature than the 5-layer model when the air temperature falls rapidly and a high temperature gradient exists near the surface of the snowpack.
   The diurnal fluctuation of snow surface temperatures is largely caused by meteorological conditions. The 1-layer model and the 5-layer model estimate snow surface temperature based on the assumption that meteorological conditions are constant over an hour. SNTHERM, however, first subdivides the hourly basic time step into 4 to 720 intervals, and then interpolates the hourly meteorological data for each interval. It imitates the gradual change of the actual meteorological conditions and adjusts the meteorological conditions the step by step over an hour. The larger diurnal fluctuation of snow surface temperatures by the 1-layer model and the 5-layer model appears to result from their coarser finite temporal difference of meteorological condition approximation.

Energy. The snowpack temperature profile is most responsible for heat exchange between the atmosphere and snow and between snow and soil. For all three models the internal energy corresponds well and undergoes strong diurnal fluctuations in the warm case, as a result of negligible conductive heat flux to the surface due to the 0 ^{o}C isothermal snowpack. However, it cannot be concluded that this is a true agreement in energy estimations, because the internal energy is a function of snow temperature and SWE, and a true agreement must be based on similar SWE. A further assessment of the internal energy estimation will be conducted later in relation to SWE estimation. The 1-layer model shows a weaker diurnal fluctuation and a lower internal energy level than the two multiple-layer models for the cold case. This difference is attributed to the difficulty of estimating conductive heat flux within the snowpack with a single layer, and the approximation of actual snow surface temperature with the equilibrium surface temperature.

When the air temperature is cold and falling and the snowpack is warm, the 1-layer model consistently estimates the conductive heat flux as a gain to the snowpack because the surface temperature is colder than the average temperature. In reality, under these conditions the entire snowpack cools off and releases heat to the atmosphere. The multiple-layer models are capable of representing this process. Like the 1-layer model, they estimate the conductive heat flux to the surface as a gain; however, this gain is then treated as a loss for the lower layer of the snowpack. As a result, the snowpack as a whole cools off and loses energy. When the air temperature is rising and the snowpack is cold, the snowpack temperature gradient is non-linear. For these cases, the 1-layer model will fail in estimating the net energy flux and the internal energy. Due to this uncertainty, the conductive heat flux was excluded from the calculation of internal energy in the 1-layer model. The internal energy would be shown higher than that in Figure 3 if the conductive heat flux were considered.

As discussed earlier, the snow surface temperature is forced to be equal to the equilibrium surface temperature if the latter is found below 0 ^{o}C, regardless of how long it takes for the snow surface to reach its equilibrium stage. For the cold case, the 1-layer model estimated the net energy flux for the time step, using the assumed surface temperature which represented only an instantaneous condition for the snowpack. However, the 5-layer model first estimated the average temperature of the top layer using the equilibrium surface temperature and the average temperature of previous time step for the next layer, and then derived the internal energy for the top layer based on its average temperature. Thus, the average temperature was representative not only temporally (time-based) but also spatially (layer-based), resulting in a better estimation for the conductive heat flux and the internal energy for the top layer. This may explain why the diurnal fluctuation in internal energy is lower in the 1-layer model than in the 5-layer model.

Mass. For the cold case, the only significant mass flux component for any of the models was snowpack sublimation. The snowpack gained small amounts of mass at night, and lost mass each day. All other mass fluxes were either absent or negligible. In the warm case, all three models estimated mass loss due to the outflow of melt water from the base of the snowpack. SNTHERM estimated significant melt outflows on Days 39-42, and again on Day 48. Both the 1-layer and 5-layer models estimated a significant outflow event on Day 38, preceding SNTHERM by one day. The 1-layer model always preceded the other models in releasing meltwater each day, and generally released larger amounts. Consequently, the 1-layer model estimated a greater overall loss in SWE from warming than the 5-layer model and SNTHERM. Under warm conditions, when the temperature gradient throughout the snowpack is isothermal or nearly so (i.e. linear), multiple layers provide little advantage with respect to the estimation of the temperature gradient and its effects on surface temperature and net energy exchanges.

During a melt period, both the 5-layer model and SNTHERM represent the penetration of the net surface heat flux in the form of a convective heat flux carried by water from the surface layer to lower layers, and estimate melt outflow based on the bottom layer internal energy density (i.e., internal energy per unit of mass). The internal energy density of the underlying layers is increased layer-by-layer, creating a non-linear vertical distribution of heat energy and liquid water content within the snowpack. Warming may occur in the upper layers, but not necessarily in the lower layers. Meltwater infiltrating into the lower layers can refreeze if the underlying layers are cooler,

releasing its latent heat and warming the lower layers, or the water may simply reach layers with sufficient liquid water retention capacity to prevent further drainage. The representation of the snowpack as multiple layers provides the opportunity for surface meltwater to be retained within the snowpack.

In contrast, the 1-layer model assumes a vertically uniform distribution of snowpack internal energy and estimates melt outflow based on the internal energy density of the entire snowpack. The heat deficit of the entire snowpack layer must be satisfied before additional energy input will cause melt. Once the heat deficit is met and the liquid water retention capacity is exceeded, all further melt will result in outflow from the snowpack. Consequently, the initiation of surface snowmelt in the single-layer model is typically delayed each day with respect to the multiple-layer models, but once it begins and the liquid water retention capacity is exceeded, there is nothing to reduce drainage from the snowpack, and excessive melt water outflow may result.

Considering the overestimation of SWE loss by the single-layer model, it is now conclusive that the 5-layer model is consistent with SNTHERM in internal energy estimation, and the 1-layer model actually is not, as the 5-layer model gave similar internal energy based on a similar estimate of SWE, but the 1-layer model gave similar internal energy based on a smaller estimate of SWE. Even though the total internal energy from all three models is close, the single-layer model gave a higher energy density to the snowpack than the other two.

CONCLUSIONS

The single-layer snow model estimates snow mass and energy that is similar to the two multiple-layer models. However, it is unable to represent the nonlinear vertical temperature gradients and internal energy distributions within the snowpack. As a result, in the cold case, the 1-layer model underestimates the snowpack internal energy, and in the warm case, it is unable to represent the simultaneous multiple processes of upper-layer warming and lower-layer refreezing. Consequently, the 1-layer model overestimates snowmelt outflow. The 5-layer model more closely simulates the results of SNTHERM, especially during warm conditions. With only three state variables and a simpler mathematical and computational basis, it is more parsimonious and efficient than SNTHERM, which is an important consideration for distributed modeling at high spatial resolution over large regions. The 5-layer model's close agreement with SNTHERM's SWE is an important capability for supporting the assimilation of ground- and airborne-based snow observations into the model. Its ability to represent vertical gradients and structure gives it potential to estimate optical albedo and microwave scattering properties for remote sensing data assimilation.

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