

Incorporating Effects of Forest Litter in a Snow Process Model

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ABSTRACT

Net solar radiation often dominates the snow surface energy exchange during ablation in many conifer forests. Reflection of solar radiation from the snow surface depends not only on snow properties, but also on forest litter lying on and within the snowpack. We know of no validated model reported in the literature that accounts for the influence of forest litter on snow surface energy exchanges. The purpose of this work is to test an existing algorithm's ability to accumulate forest litter in snow layers and to predict the subsequent effect of litter on the snow surface albedo. Field studies in a conifer stand of red spruce-balsam fir in northern Vermont, USA, provided key data for validation, including subcanopy radiation, meteorology, snow depth, and images of litter accumulation. We ran the litter algorithm coupled with the snow model SNTHERM for the ablation season, and predictions compared well with measurements of snow depth, snow surface litter coverage, and snow surface albedo beneath the conifer canopy. Model results suggest that for this forest and ablation season, the current litter algorithm realistically distributes litter in the snowpack through time with validated effects on snow surface litter concentration and albedo. The poor relationship between daily total wind speed and change in litter coverage on the snow surface suggest that, for this forest and ablation season, incorporating wind events into the algorithm will not improve the results.

Key Words: Albedo, Forest litter, Snow modelling

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INTRODUCTION

Forests are well known to alter the accumulation of snow on the ground and to modify near-surface micrometeorology, which controls snowmelt rates. Net solar radiation (incoming minus reflected) often dominates the snow surface energy exchange during ablation in many conifer forests (Price and Dunne 1976, Metcalfe and Buttle 1995, Harding and Pomeroy 1996, Davis et al. 1997, Hardy et al. 1997). The solar radiation incident on the snow surface depends on forest structure and varies with tree species, sky conditions, and solar angle. Reflection of solar radiation from the snow surface depends not only on snow properties (grain size, particle density, and liquid water content), but on forest litter (leaves, twigs, needles, bark, and branches) lying on and within the snowpack and protruding vegetation. Litter deposited on the snow surface accumulates in litter horizons as the snowpack develops. These litter horizons, usually separated by subsequent snowfalls, are re-exposed during melt. Net solar radiation in a forest environment thus depends on forest structure and time of year, as well as the accumulation and re-exposure of forest debris.

Many investigators consider albedo of the forest canopy (e.g., Otterman et al. 1988, Liston 1995, Betts and Ball 1997, Nakai et al. 1999, Ni and Woodcock in press) or the effects of dust and soot on snow surface albedo (e.g., Wiscombe and Warren 1980, Gerland et al. 1999). Others qualitatively describe the effect that protruding vegetation has on snow albedo (Pomeroy et al. 1998) or even make multiple measurements of net radiation beneath a forest (Price and Dunne 1976, Nadeau and Granberg 1986). Measurements of albedo beneath a forest canopy are rare, and when they do exist are limited (Harding and Pomeroy 1996, Pomeroy and Dion 1996). Most snow process models use the well-known fact that snow albedo decreases as snow metamorphoses to larger grains, while ignoring litter effects, which can be substantial (Jordan 1991, Dingman 1993, Albert and Krajewski 1998, Pomeroy et al. 1998). Progress in this area has been severely limited due to the lack of winter data on through-canopy radiation, snow albedo, and litter fall in forested environments.

A previous snowpack energy balance study in the boreal forest introduced a provisional technique to estimate litter fall and its incorporation in the snowpack (Hardy et al. 1998). The technique incorporates litter within accumulating snow layers with continued deposition during snow ablation, and reemergence of litter as the snowpack melts. When coupled with the snow model SNTHERM (Jordan 1991), the litter model provided the necessary correction to obtain agreement between model and actual snow ablation at the boreal forest site, but the previous study lacked quantitative litter and albedo data to validate the model. The purpose of this research is to provide further validation of the Hardy et al. (1998) litter model, using a comprehensive forest litter and albedo data set collected in a temperate forest in northern Vermont, USA (Melloh et al. in prep). Secondly, our objective is to assess opportunities to improve the equation that controls litter input rates to the model, to account for important meteorological events, especially high winds.

STUDY AREA

The study area is located within a small conifer forest in the W-9 sub-watershed (0.47 km², 44°29'26"N, 72°09'28"W) of the Sleepers River Research Watershed (113 km²) in northern Vermont, USA. Robinson et al. (in prep) determined the forest characteristics of the plot. The conifer plot measures 22 m × 22 m and is dominated by red spruce–balsam fir (*Picea rubens*–*Abies balsamea*) (Fig. 1). The average tree height is 24.7 m and the average crown height is 8.0 m. Total DBH (Diameter at Breast Height or 1.5 m from the ground) per hectare of all standing trees, living and dead, is 358 m. The percent cover of the balsam fir calculated as Basal Area (BA) of live trees is approximately 61% compared to 39% for the red spruce. The young red spruce appear to be dying under the deep shade of the mature balsam fir, many not living beyond 0.1-m DBH. The shrub layer is void of any woody vegetation between 0.5 m and 2.0 m. The ground cover was not surveyed, but an abundance of fallen trees and balsam fir seedlings was observed.



Figure 1. Photo taken on 9 April 1999 (day 99) in the conifer forest. Note the litter on the snow surface and the abundance of fallen trees on the ground.

Approximately 0.8 km from the conifer site is the location of a meteorological station situated in a large open area and in operation since 1958. At the open site, the mean annual temperature is about 4°C and the mean annual precipitation is about 1080 mm. Snowfall averages 2540 mm with a maximum snow water equivalent (SWE) normally 225 to 300 mm (Pangburn et al. 1992).

METHODS

Forest characterization: Meteorological and snow measurements

Prior to the 1998/1999 snow season, the forest community surrounding the conifer site was quantified using sampling methods described in Daubenmire (1968) and Brower et al. (1990). Parameters analyzed included species composition, abundance, relative species density, and percent cover in shrub and tree layers. Robinson et al. (in prep) provide a detailed explanation of these sampling methods.

During the 1999 snow ablation season (late February through April) Melloh et al. (in prep) continuously measured incoming solar and longwave radiation through the canopy and reflected solar radiation from the snowpack using arrays of four up- and four downlooking radiometers (Eppley pyranometers, PSP) in the conifer site. Two uplooking Eppley pyrgeometers (PIR; 8- to 50- μ m wavelength) measured incoming longwave radiation beneath the conifer canopy. Two-meter, subcanopy air temperature, relative humidity, and wind speed were also measured in the conifer site. Measurement and deployment details are outlined in Melloh et al. (in prep). The meteorological parameters measured at the open site consist of air temperature and relative humidity, wind speed and direction (2-m and 6-m height), continuous snow depth, incoming and reflected solar radiation, incoming and outgoing longwave radiation, and precipitation.

The snowpack properties were measured and monitored two ways. First, an ultrasonic depth sensor measured snow depth from a single point in the forest. This depth gauge measured the distance from the sensor to the snow surface and provided a continuous record of snow depth for validation of our model runs. Second, snow depth and its variability were regularly measured by manual surveys, as were occasional measurements of snow density at the study site during the ablation season. At peak accumulation and to initialize the snow model, the snow density profile at 0.03-m vertical resolution using a 100-cm³ density cutter was measured along with snow temperatures using dial stem thermometers.

Snow surface and in-pack litter contamination

A novel, radio-linked camera system collected and transmitted real-time digital images of the snow surface condition. Melloh et al. (in prep) provide specifics of the design and deployment of the camera system. This technique documented snow surface litter chronology from February through April—its accumulation and re-exposure during melt. The downloaded and processed images were analyzed using image-processing software to create binary (pure black and white) images for statistical analysis. Stereologic parameters were computed automatically by passing test lines across the binary image and using equations for counting statistics, as described by Dozier et al. (1987). The point density statistic provided the two-dimensional litter coverage (%) at the snow surface, but a simple ratio of black to white areas could provide the same results.

In addition to measuring snow properties at peak accumulation (see above), snow samples approximately 0.3 m wide, 0.5 m long, and 0.1 m deep were collected to quantify the litter in the snowpack (Melloh et al. in prep). Each of the five samples was melted to separate litter from snow and drained of excess water; the litter was dried in a soil-drying oven for 24 hours and weighed (Robinson et al. in prep).

Snow process model

SNTHERM is an internationally recognized, one-dimensional mass and energy balance model for predicting snowpack properties and processes (Jordan 1991), and is the foundation for this snow modelling effort. SNTHERM calculates energy exchange at the surface and bottom of the snow cover, in-pack processes, grain growth, densification and settlement, melting and liquid water flow, heat conduction and vapor diffusion (Jordan 1991). Hardy et al. (1997, 1998) successfully applied SNTHERM to forested environments by linking it to a geometric-optic, radiative-transfer model (Li et al. 1995, Ni et al. 1997). SNTHERM computes reflected solar radiation using an albedo routine that accounts for changes in albedo due to grain growth, sun angle, and cloud cover (Marks 1988) and most recently, reduces albedo to account for the optical thinning of snow (Hardy et al. 1998). Since clean snow is unlikely below a forest canopy, Hardy et al. (1998) introduced a provisional routine to estimate litter fall on the forest floor that reduced the subcanopy snow albedo as forest litter accumulates. The routine allows the fractional coverage of litter in or on the snowpack to increase throughout the entire snow season according to eq. 1:

$$lc = 1.0 - (1.0 - lr)^{\text{day}} \quad (1)$$

where lc is the fractional litter coverage ($\text{m}^2 \text{m}^{-2}$), lr is the daily litter rate ($\text{m}^2 \text{m}^{-2} \text{d}^{-1}$) of the forest, and day is the number of litter accumulation days for which the litter coverage is calculated. The resulting albedo is a weighted average of litter albedo and clean snow albedo in proportion to their areal coverage. This litter routine was intended as a preliminary attempt at considering the well-known effect litter has on reducing albedo.

Snow model initialization

We ran the model from 1 March 1999 (day 60) through 23 April 1999 (day 113). The meteorological file used for the duration of the model run includes air temperature, relative humidity, and wind speed data from the conifer station. We used an air temperature threshold of 1.65°C to separate precipitation events as snow or rain. Using the incoming solar radiation from the open site and the mean of the four-uplooking PSPs from the conifer site, we established the transmissivity for each time step. Because of rapidly changing sun angles in the spring, we divided the modelling period into two periods and multiplied the mean transmissivity for each period by the unobstructed pyranometer data to obtain a value for the subcanopy incoming solar radiation. We allowed SNTHERM to estimate reflected radiation based on snow grain size, age, and litter coverage. The mean of the four-inverted PSPs provided reflected radiation data for albedo validation. We averaged the longwave data from both PIRs for longwave input.

Data for the snow properties required by the model (snow layer thickness, temperature, density, and grain size) were obtained from snowpit observations on 9 March 1999 and adjusted to represent the snow conditions for 1 March. Litter accumulated on the snow surface beginning with

the first snowfall. When a model run begins at peak accumulation, the litter content of the initial snow layers are computed using eq. 1 based on the number of days between snow events leading to maximum accumulation. In order to run the litter algorithm with SNTHERM, SNTHERM requires an additional column containing estimates of litter content in the snow input file. We used precipitation data from the open site to determine the timing of snowfall events leading up to 1 March and therefore computed litter coverage for each snow layer. To validate the model output we compared manual and continuous measurements of snow depth in the conifer forest; percent litter coverage derived from digital images; and our measurements of forest albedo, with SNTHERM output.

RESULTS

Dry spring weather (i.e., clear radiometers) permitted nearly continuous measurement of through-canopy incoming radiation and that reflected from the snow-covered forest floor in these stands from late winter through the snowmelt season (Melloh et al. in prep.). Subcanopy incoming solar radiation was compared with that measured in the open site, less than one kilometer away. Mean conifer transmissivity for the modelled period was 0.133. Longwave radiation data measured by the two PIRs were in very close agreement ($r^2 = 0.99$) and were averaged to represent the incident longwave component in the forest. As expected, the longwave component in the forest had higher values but much lower temporal variation than measured in the open site. Low wind speeds in the conifer site suggest that the turbulent fluxes are low and that the radiation balance dominates the surface energy fluxes.

Photos of snow surface

The electronic digital camera system successfully monitored snow surface conditions remotely using radio communications (Melloh et al. in prep). The twice-daily digital images of the snow surface document litter conditions from 4 March through the completion of melt on 21 April (e.g., Fig. 2). During this period, 50 images were of sufficient quality to process, of which 30 provided useful information. Twenty of the images either were free of litter due to a recent snowfall, suggested no change from the prior image, or contained bare ground. Analyses of the digital images provided percent surface litter coverage from maximum snow depth through spring as litter layers were re-exposed during meltout. The latest image with complete snow cover was taken 16 April with litter coverage of 25%. The next image was from 19 April and has a litter coverage of 56% and includes some bare ground. By 21 April all but 3% of the image was snow-free. The relationship between litter coverage derived from the digital images and the daily average albedo measured in the forested stand is described by a second order polynomial ($r^2 = 0.87$) (Melloh et al. in prep.).

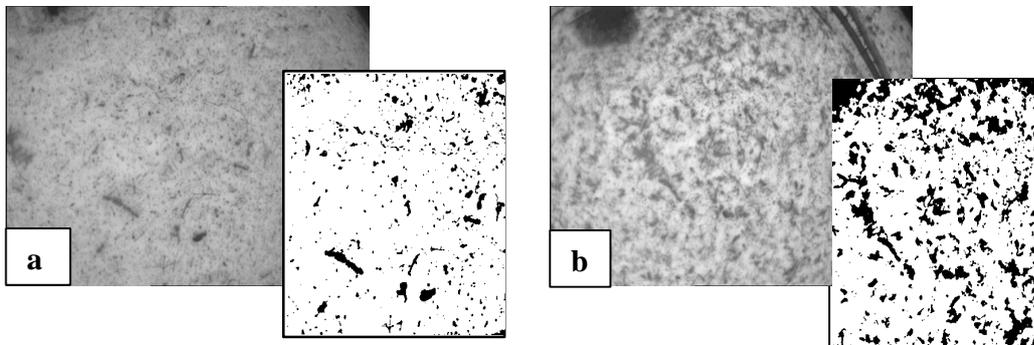


Figure 2. Two examples of digital images obtained from the remote camera system and the corresponding binary image. The images were obtained on 1 April (a) and 12 April (b) and represent 7% and 24% litter coverage, respectively.

Model run using litter routine

We compared measurements of snow depth, snow surface litter coverage, and snow surface albedo beneath the conifer canopy with results of a SNTHERM model run using the litter equation (eq. 1). We assumed a litter rate of 0.006 d^{-1} for this conifer site (an increase of 0.001 d^{-1} as previously used for a black spruce stand). The albedo of the conifer litter (0.15) was based on results of Oke (1987) and albedo measurements of the forest floor after complete snowmelt (Melloh et al. in prep). The ground in the conifer site was continuously snow covered for approximately 125 days, of which 48 days were modelled. The snow input file contained estimates of litter coverage, computed from eq. 1, in each existing snow layer from day 350, 1998, to day 60, 1999 (Table 1). The sum of the litter coverage in Table 1 is 0.45, which equals the daily litter rate (0.006 d^{-1}) multiplied by the number of snow days (75) between day 350, 1998, and day 60, 1999. There are two ways the fraction of litter on the snow surface increases. Either existing snow layers melt, leaving behind their litter on the snow surface, or additional litter accumulates on the snow surface through time. Similarly, litter leaves the snowpack late in the ablation season as the lowest snow layers melt and litter becomes part of the forest floor. The litter equation estimates total litter coverage of 53% in this conifer forest at the end of the snow ablation period.

On 9 March, while analyzing the snowpack profile in the conifer forest, significant litter horizons were noted at snow heights of approximately 31 cm, 39 cm, and 44.5 cm, with the most pronounced litter horizon at 31 cm. The collected snow and litter samples that were separated, dried, and weighed confirmed those observations (Fig. 3a). For comparison, we plot the modelled litter coverage in the snowpack, as determined by SNTHERM for day 68, and binned according to Figure 3a (Fig. 3b). The modelled litter coverage shows a similar profile of litter accumulation as the measured samples with the greatest accumulation mid-snowpack and the most significant litter layer at between 23- and 33-cm height. The most pronounced litter horizons occur when the period between snow events is longest.

Table 1. Snow property input file used to initialize SNTHERM. The input file is based on snow property measurements made in the conifer site on 9 March and adjusted for 1 March. Litter coverage is the percent coverage for the respective snow layer. The surface snow layer is at the top of the table.

| Temp. (K) | Snow height (m) | Density (Kg m^{-3}) | Grain size (m) | Litter coverage (%) |
|-----------|-----------------|--------------------------------|----------------|---------------------|
| 273 | 0.42 | 220 | 0.002 | 0.07 |
| 273 | 0.41 | 240 | 0.002 | 0.024 |
| 273 | 0.39 | 200 | 0.002 | 0.024 |
| 272 | 0.36 | 170 | 0.003 | 0.041 |
| 272 | 0.33 | 230 | 0.002 | 0.047 |
| 271 | 0.30 | 230 | 0.002 | 0.035 |
| 271 | 0.27 | 250 | 0.002 | 0.041 |
| 270 | 0.24 | 250 | 0.002 | 0.006 |
| 270 | 0.21 | 300 | 0.002 | 0.035 |
| 270 | 0.18 | 330 | 0.002 | 0.018 |
| 271 | 0.15 | 290 | 0.002 | 0.006 |
| 272 | 0.12 | 325 | 0.0025 | 0.018 |
| 272 | 0.09 | 340 | 0.003 | 0.018 |
| 273 | 0.06 | 220 | 0.002 | 0.058 |
| 273 | 0.03 | 400 | 0.003 | 0.018 |

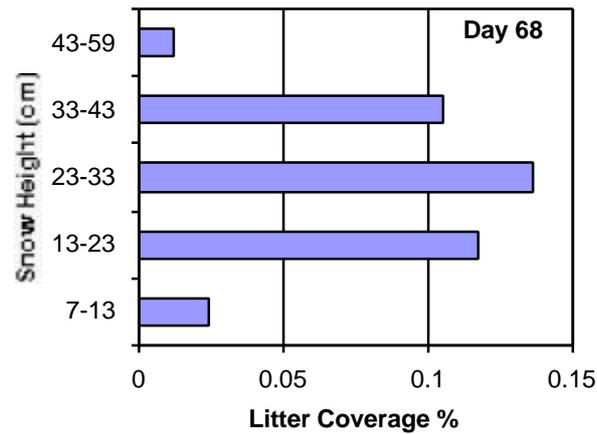
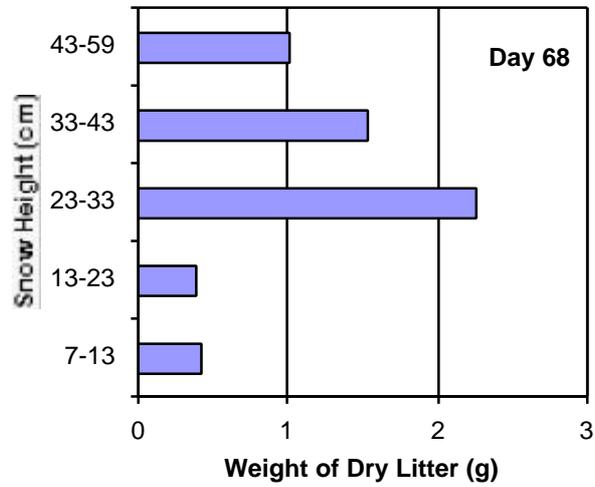


Figure 3. Profile of dry litter weights in the snowpack as collected on day 68 and processed by Robinson et al. (in prep) (Fig. 3a). Profile of SNTHERM-determined litter in the snowpack on day 68 (Fig. 3b). These data were binned to compare with field data.

Litter coverage profiles determined by SNTHERM during the model run were binned into 5-cm intervals and plotted for every ten days of model output (Fig. 4). The series of plots shows the distribution of litter in the snowpack through time and the increase in litter concentration as the snow melts. Snow depths for days 60, 70, 80, 90, and 100 were 42.1, 50.2, 40.1, 23.6, and 4.5 cm, respectively. Because SNTHERM outputs litter in nodes of varying thickness and combines and divides nodes, it is not practical to track individual litter horizons. Figure 4e suggests a surface litter coverage of 62% on day 100, compared with model estimate of total litter coverage of 53% at the end of the snow ablation period. This discrepancy is easily explained by the way SNTHERM accounts for litter in a melting snowpack. On day 100 the snowpack is 4.5 cm deep and contains a sum of 62% litter in five remaining snow layers. Just before complete ablation on day 107, the snow surface litter content is 53%. The “missing” litter is incorporated into the forest floor and not considered *snow surface* litter.

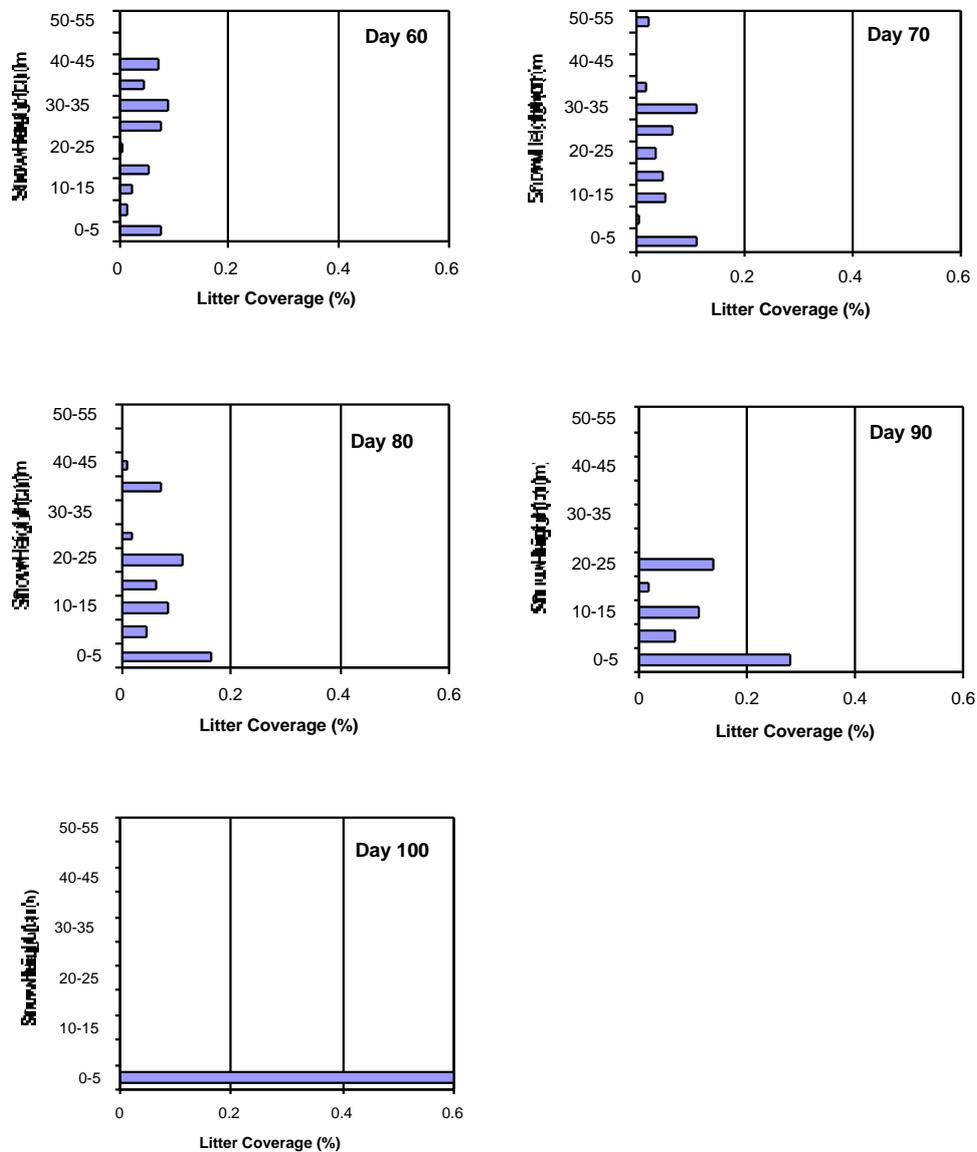


Figure 4. Time series of modelled litter coverage in the snowpack from day 60 to day 100, in 10-day intervals.

Figure 5 compares measurements of snow depth, snow surface litter coverage, and albedo in the conifer forest to results from SNTHERM. Modelled snow depth compares favorably with snow sensor data and manual measurements (Fig. 5a), but melted three days earlier. Modelled snow surface litter coverage tracked the measured litter coverage extremely well through the ablation season (Fig. 5b). Just prior to the model predicting complete snow ablation, the litter coverage increased dramatically to closely match the measured litter coverage. Finally, SNTHERM-predicted snow surface albedo gradually decreases as litter accumulates on the snow surface, reaching the albedo of the litter (0.15) at the time of complete snow ablation and three to four days earlier than the snow under the camera (Fig. 5c). Early in the modelling period (days 60 to 75), the measured albedo shows much variability as it responds to snow events, while the modelled

response is less pronounced. Between days 89 and 103, SNTHERM predicts a higher-than-measured albedo beneath the conifer canopy, although for much of that time the model is within the range of the 15-minute measurements.

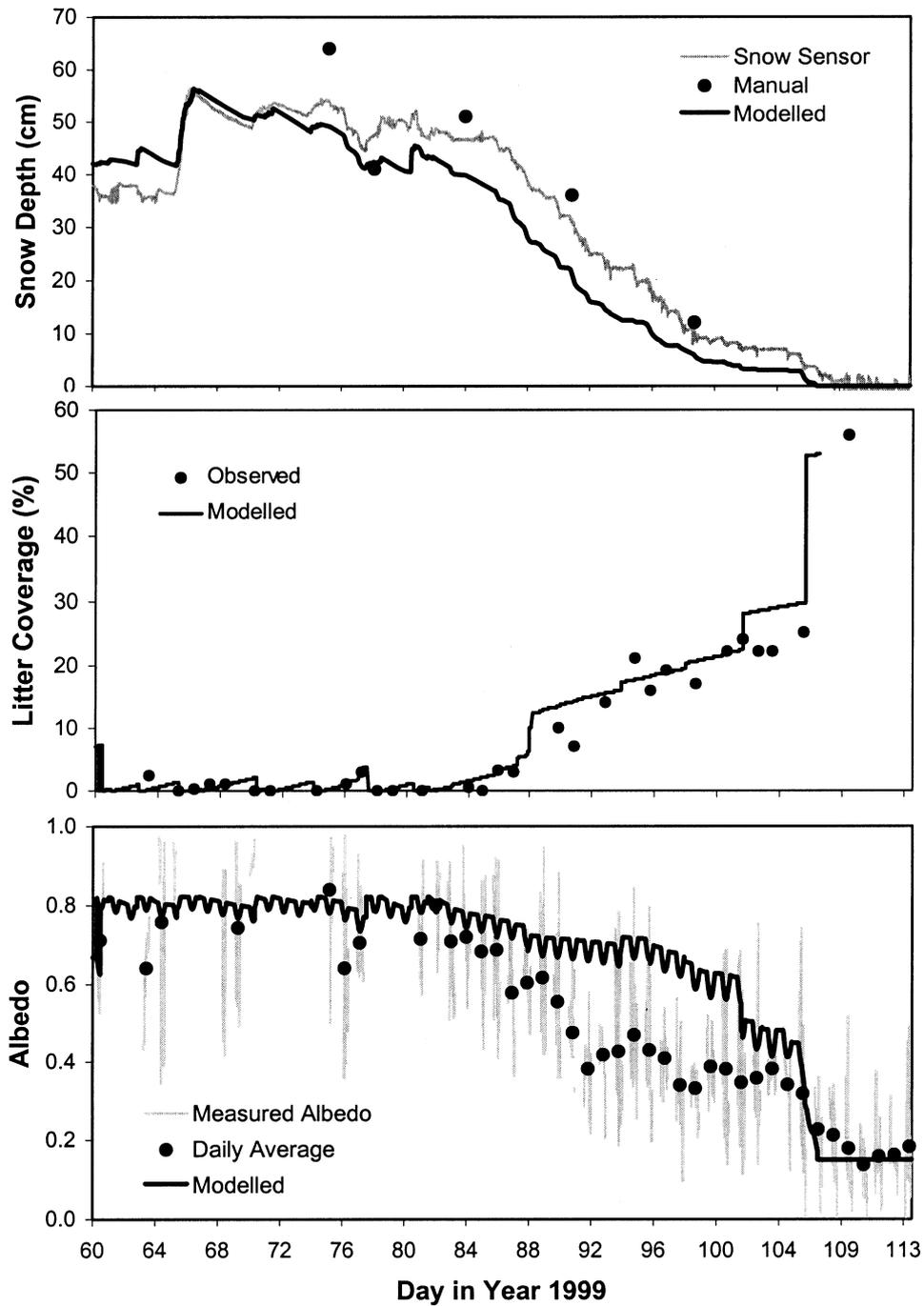


Figure 5. Results from SNTHERM model runs incorporating the litter algorithm and compared with a) measured snow depth, b) snow surface litter coverage, and c) measured albedo from the snow surface.

Influence of winds on litter coverage

We investigated the influence of winds on snow surface litter coverage to assess the importance of including this meteorological parameter in the litter algorithm. We conducted this analysis only for the period prior to rapid snow ablation (up to day 88), at which point it is difficult to separate the re-exposure of buried litter layers during snow ablation from the accumulation of additional litter. Two-meter wind speeds averaged over the 15-minute intervals in the conifer site during the snow ablation season never exceed 3.5-m s^{-1} . By summing the subcanopy wind speeds for days between litter observations, via snow surface photos (usually every one to three days), and dividing by the number of days between litter observations, we obtained a mean daily total wind speed. This daily total wind speed was compared with the corresponding change in percent litter coverage (Fig. 6), where positive values represented an increase in litter coverage since the last observation and negative values represent a decrease. Note the time scale does not represent consecutive days, but rather was based on days with observations of litter accumulation on the snow surface. For days 65 through 67, winds were steady while litter accumulated. For days 68, 70, and 71, the increasing winds corresponded to less litter on the snow surface because of the previous precipitation event. Days 77 and 78, as well as days 85 through 87, showed the opposite influence expected if these winds were to significantly increase litter fall on the snow surface. A least squares regression through a scatter diagram of litter change vs. daily wind speed yields an $r^2 = 0.24$, confirming this weak relationship.

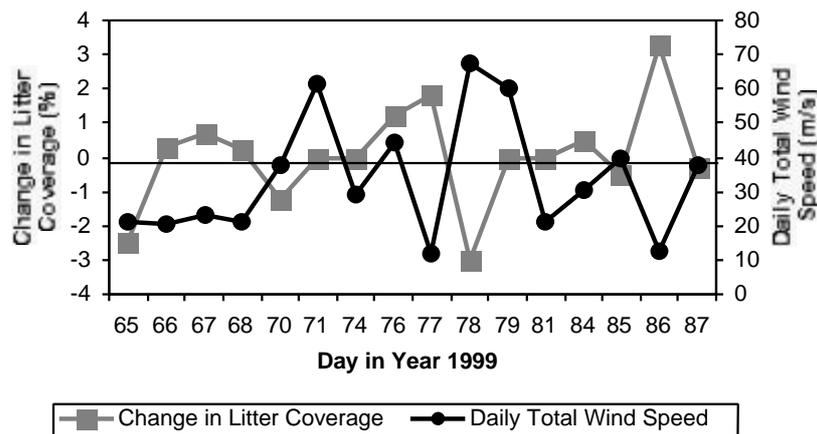


Figure 6. Mean daily total wind speed in the conifer forest compared to change in litter accumulation for the days prior to the onset of rapid snow ablation.

DISCUSSION

Measurements of snow surface litter coverage and subcanopy albedo from a conifer forest in northern Vermont, USA (Melloh et al. in prep) provided validation data for the litter algorithm developed by Hardy et al. (1998). Images obtained from the digital camera system were key to providing near-daily information on the snow surface litter accumulation for model validation. Multiple measurements of the subcanopy snow albedo were required to have confidence in the solar components beneath a forest canopy. SNTHERM, coupled with the litter algorithm, estimated forest litter concentrations in all snow layers, for every time step as output by the model. SNTHERM estimates of in-pack forest litter compared favorably with measured litter in the snowpack on 9 March, and show a logical progression of concentrations through the ablation season.

The litter algorithm, as coupled with SNTHERM, predicted snow depth, litter coverage, and snow surface albedo beneath this forest canopy. Both the predicted snow depth and litter coverage

compared well with measurements and field observations. Snow depth predictions may improve by considering the shading effects of litter on the snow surface late in the ablation season. Snow surface albedo predictions during the early portion of the model run are less variable than the measurements. During this period, snow on the radiometers required removal of some albedo data, so these daily average values include some missing time steps. The higher model predictions of snow surface albedo in the forest from days 89 to 103 is explained by the nature of this particular conifer forest. The camera capturing snow surface litter images views a 1- ? 1-m area that is clear of fallen tree stems. The predicted litter coverage on the snow surface captures that condition well. However, three of the four downlooking PSPs had one or more large fallen tree stem(s) in the field of view (see Fig. 1), thereby reducing the albedo significantly compared to snow without protruding logs (Pomeroy et al. 1998). The absence of these logs would increase measured albedo as viewed by the downlooking PSPs. Additionally, the model predicts a thin (less than 10-cm) snowpack from day 96 on, yet for the albedo estimates, the model considers litter on the snow surface only. Radiation penetration and subsurface litter coverage considerations would further reduce albedo predictions and are part of future model refinements.

Initially, our intent was to test the litter equation (eq. 1), which previously was not validated with forest litter and albedo data. We then planned to modify the routine by incorporating effects of weather events to improve the litter algorithm. This complex, yet poor relationship ($r^2 = 0.23$; $m = -0.042$) between daily total wind speed under the canopy and change in litter coverage on the snow surface suggest that, for this forest and ablation season, incorporating wind events into the algorithm will not improve the results.

CONCLUSIONS

The field data provided by Melloh et al. (in prep) allowed the first validation of a previously proposed algorithm to incorporate the effects of forest litter on snow surface albedo into a snowmelt model. The simple algorithm allows litter to accumulate on the snow surface as a function of time and a given litter rate. Our modelling results suggest the algorithm is successful in accurately estimating the fractional coverage of forest litter on a snow surface. This estimate improved SNTHERM's ability to predict the snow surface albedo and subsequent rate of snow ablation.

To further validate the algorithm, the model should run for a variety of forest types and with more PSPs to catch the inherent variability of the solar components beneath a forest canopy. Current research (ablation season 2000) extends the work of Melloh et al. (in prep) by installing 20 Eppley PSPs (10 uplooking and 10 downlooking) in one mixed species stand, and repeating the measurement sequence described above. We will further test the litter algorithm in the mixed species stand.

ACKNOWLEDGMENTS

This work is funded by Department of the Army project number AT24-SP-003, *Interaction of Solar Radiation, Litter, and Albedo in the Forest During Snowmelt*, for R. Melloh, J. Hardy, and P. Robinson. We appreciate helpful discussions and reviews by B. Davis and G. Koenig.

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