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Snow-Induced Thermal Variations Around a Single Conifer Tree

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ABSTRACT

The influence of trees on the ground thermal regime is important to the overall winter energy exchange in a snow-covered, forested watershed. In this paper, spatial zones around a single conifer tree are defined and examined for their controls on the snow cover, snow/ground interface temperatures and frozen ground extent. A large white spruce (*Picea glauca*), approximately 18 m tall with a crown diameter of 7.5 m, and located in northern Vermont, was the subject of this study. The tree was instrumented with thermistors to measure the snow/ground interface temperature between the tree trunk and 6 m from the tree into undisturbed snow. Four distinct zones around the conifer are defined that affect snow distribution characteristics: adjacent to the trunk, the tree well, tree crown perimeter, and the unaffected area away from the tree. At the time of peak snow accumulation and during the ablation season, snow depth and density profiles were measured. The area beneath the canopy accumulated 34% of the snow accumulated in the undisturbed zone. By the end of the ablation season, the depth of snow under the canopy had decreased to 18% of the undisturbed snow depth. Tree and branch characteristics of spruce in this temperate climate resulted in a different snow depth profile when compared to previous empirical relationships around a single conifer. Less snow beneath the canopy led to colder snow ground interface temperatures than measured in undisturbed snow. The depth of frozen ground in the different zones was modeled using a simple analytical solution that showed deeper frost penetration in the tree well than beneath the undisturbed snow.

Key Words: Forest hydrology, Frozen ground, Snow distribution, Snow/ground interface temperatures

INTRODUCTION

A forest canopy intercepts falling snow, altering the distribution of snow on the ground and the insulating properties of a continuous snow cover, thereby affecting the extent of frozen ground. In temperate (nonpermafrost) regions, the extent of winter frozen ground controls snowmelt runoff and infiltration processes. Understanding the spatially heterogeneous manner in which individual trees influence the snow and soil thermal regime is important for modeling hydrological processes in a forested environment.

Many investigations have documented snow accumulation on the ground to be inversely related to canopy density (Potts 1984, Bunnell et al. 1985, Golding and Swanson 1986, Hardy 1990). There are several factors that contribute to snow distribution in a forest. These operate at different scales and include meteorological conditions of the storm, forest structure and geometry, individual tree species, and both branch structure and flexibility (Bunnell et al. 1985). In conifer forests, tree wells develop during the winter months when the canopy intercepts snow, resulting in snow depletion beneath the tree crown. Pomeroy and Schmidt (1993) modeled the storage and sublimation of intercepted snow and found that the area beneath the canopy produces one-third less snowmelt water than adjacent clearings for trees of the boreal forest.

In Alaska's taiga, Sturm (1992) modeled snow depth as a function of radial distance from spruce tree trunks and showed that the lack of insulating snow near tree stems resulted in higher heat flux. Sturm (1992) documented a smooth increase in snow depth around a tree from $h_{\min}$ to h_{max} and his data were fitted to the equation:

$$h(r) = h_{\max} + (h_{\min} - h_{\max})\exp\left[-\left(\frac{r}{k}\right)^2\right] \quad (1)$$

where $h(r)$ = snow depth as a function of distance from the tree, r
$h_{\min}$ = snow depth at the tree trunk (or the minimum snow depth
$h_{\max}$ = undisturbed snow depth away from the tree
k = a fitting parameter related to the radius of snow affected by the tree crown (approximately the radius of the tree crown).

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Woo and Steer (1985) used field observations to establish the following polynomial relationship between mean snow depth and distance from the trunk for spruce trees in northern Ontario:

$$h(r) = \sum_{i=0}^{3} b_{\mathrm{i}}\, r^{i} \qquad (2)$$

where b is a polynomial coefficient relating to tree diameter and cardinal direction from the tree (this work used the mean coefficient for the four directions).

In a forest that included *Picea glauca* near Fairbanks, Alaska, Pruitt (1957) measured lower snow/ground interface temperatures in tree wells compared to forest openings. In an effort to characterize the subnivian environment, Pruitt (1957) noted that a critical snow depth of 0.15–0.2 m was required to dampen the air temperature fluctuations at the snow/ground interface. In western Montana, Saul and Potts (1986) measured greater frost depths in forests than adjacent clearings. Other investigations have shown that snow intercepted by a forest canopy results in greater penetration of frost beneath the canopy (Priehausser 1939, Viereck 1965). In Germany, Priehausser (1939) observed concurrently that soils were frost free in forest openings, while frost was present at canopy edges and increased in depth toward the tree trunks. In that study, frost depths beneath the canopy reached 0.17 m. The net effect of canopy structure in a forest is spatially heterogeneous snow depth, thermal regime, and frozen ground depth.

Because hydrological processes such as snowmelt runoff are governed by both snow distribution and the extent of ground freezing, it is important to characterize the effects of single trees and forests on those factors. The purpose of this paper is to characterize the snow distribution and the thermal regime around a single conifer tree in northern New England, and to estimate the maximum seasonal frost penetration around the tree. Distinct zones of snow accumulation are defined and a new model describing the distribution is presented. Theoretical estimates of the frost depth due to the snow interception patterns are described.

METHODS

A large white spruce (*Picea glauca*) chosen for this study is located at 460-m elevation within the Sleepers River Watershed in Danville, Vermont. This tree was chosen because it is a typical, yet large, conifer of this region and was isolated from other trees. The mean annual air temperature at this temperate site is approximately 4°C with an average snowfall of 2500 mm. The spruce tree used in this study stands alone and is approximately 18 m tall, with a crown diameter of 7.5 m and a trunk diameter at breast height (DBH) of 0.39 m. The conifer is located approximately 50 m from a spruce forest that has a measured canopy density of 90% (obtained as the mean of 20 canopy density measurements using a forest densiometer, as described by Lemmon [1956]). The tree is surrounded by short grasses with no fallen logs or branches nearby. The lowest branches of the canopy are within 1.0 m of the ground surface. The area beneath the canopy is comprised of a mixture of grasses and moss, suggesting high soil moisture.

This study covers the New England snow season from early December 1993 to mid-April 1994. Snow accumulation at the study site began on 5 December. Air temperatures in much of January and early February were lower than normal with extended periods below–30°C. A typical New England midwinter thaw occurred in mid-February. Peak snow depth (0.84 m) occurred in mid-March and the snow was completely melted by 18 April.

Measurements of snow/ground interface temperatures (SGIT), 2-m air temperature, and snow depth and density were collected at the site. Snow/ground interface temperatures were measured, using 19 Betatherm thermistors placed from the tree trunk (0 m) outward for 6 m at both 0.2- and 0.5-m intervals (closer spacing at the crown edge). The thermistor string was oriented on the north side of the tree. Thermistors were calibrated in an ice bath prior to installation in the fall of 1993 and were found to be accurate to 0.1°C. Snow/ground interface temperatures were measured from December 1993 through April 1994 with occasional interruptions due to power failures. Air temperatures were continuously measured with a Rotronics MP–100 temperature sensor mounted on a tower 20 m north of the tree. The open, unforested, area adjacent to the tree is the location of a weekly snow survey consisting of five measurements of snow depth and snow water equivalence (SWE) using an Adirondack snow sampler. These measurements were averaged to represent the snow depth, SWE, and density in the open. The variances in SWE at the open site were small, and ranged from 0.0002 m at the start of the snow season to 0.024 m near peak accumulation.

The influence of a single conifer on maximum frozen ground penetration was estimated using a modified Berggren equation (Aitken and Berg 1968). The mathematical model is used to calculate frozen ground depth in a multilayered system by assuming one-dimensional heat flow and an initially isothermal soil system (equal to the mean annual air temperature). The modified Berggren equation is another form of the Neumann solution for freeze–thaw phase change and results in the following equation:

$$x = \lambda \sqrt{\frac{48Knl}{L}} \tag{3}$$

where x = frost depth
λ = an empirical coefficient determined from the thermal properties of the snow or soil
K = thermal conductivity of the medium
n = a factor to convert an air index to a surface index
l = air freezing index
L = volumetric latent heat of fusion.

Climate data used in the computer model, for the 1993–1994 freezing season, included freezing degree day (1200°C day), length of freezing season (176 days), and the mean annual air temperature (4°C), all of which are used to compute the air freezing index. Snow and soil data used are layer thickness, moisture content and density. The model determines the snow and soil thermal conductivity (using Kersten's [1949] empirical equations), volumetric latent heat of fusion and volumetric heat capacity based on the input data. The model output is maximum frost depth. From soil maps published by Pionke et al. (1986) the soil at the study site was determined to be from the Calais series and described as a loam or silt loam.

RESULTS

Tree zones and snowpack distribution around the conifer

A simple model is presented that describes the influence individual conifer trees have on snow distribution on the ground (Fig. 1). The area influenced by a conifer has been divided into four distinct zones: Zone 1 is the area adjacent to the tree trunk. Zone 2, or the tree well, is the area of snow depletion beneath the canopy. Zone 3, or transitional zone, is the area around the perimeter of the tree crown. Zone 4 is the zone of undisturbed, unaffected snow away from the tree's influence. In this study, the areas occupied by each of the zones were approximately 0.4, 18.0, 18.5 and ~90 m^2 for zones 1, 2, 3, and 4, respectively.

The distinctiveness and relative proportion of area occupied by each of the zones will vary, depending on tree species, geographic location and forest dynamics. For example, spruce trees (*Picea sp.*) of the boreal forest often have a small crown diameter (1.0 m) with the lowest, needled branches several meters above the snow surface. Consequently, the snow depth profile around the boreal trees have different characteristics than those described here. Similarly, Sturm (1992) documented a very different distribution of snow around deciduous trees in Alaska, a distribution also observed in northern Vermont.

The radial profile of snow depth around the large spruce tree was measured at peak snow depth and twice during the melt period (Fig. 2). Since the snow

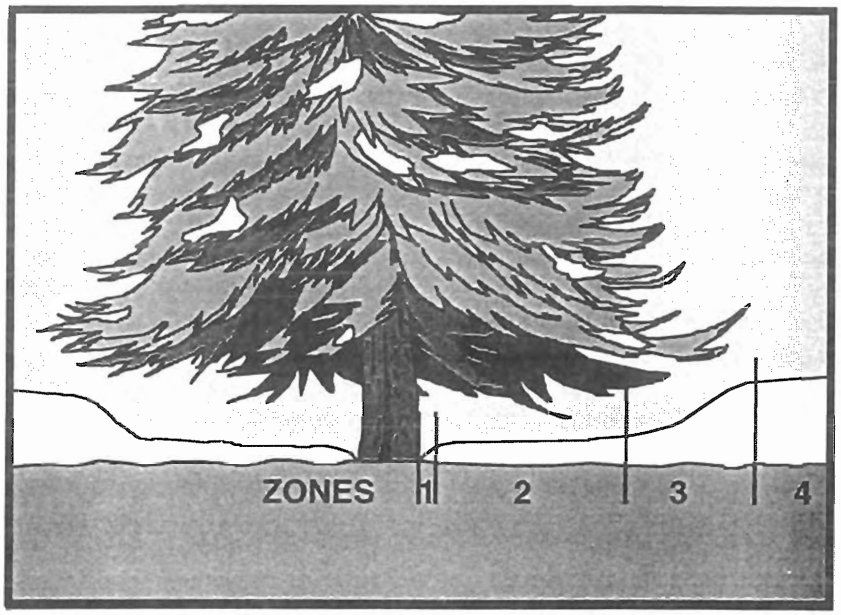

Figure 1. Model of snow distribution on the ground as influenced by a single conifer tree.

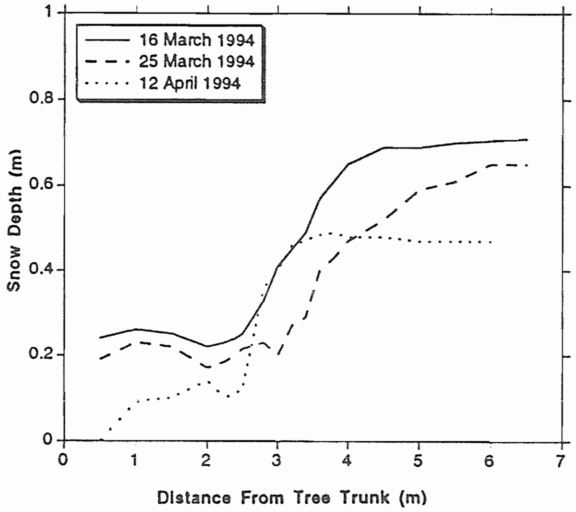

Figure 2. Snow depth profiles from the tree trunk to undisturbed snow at three different times. Zone 3 is represented by the area of the curve with the steepest slope.

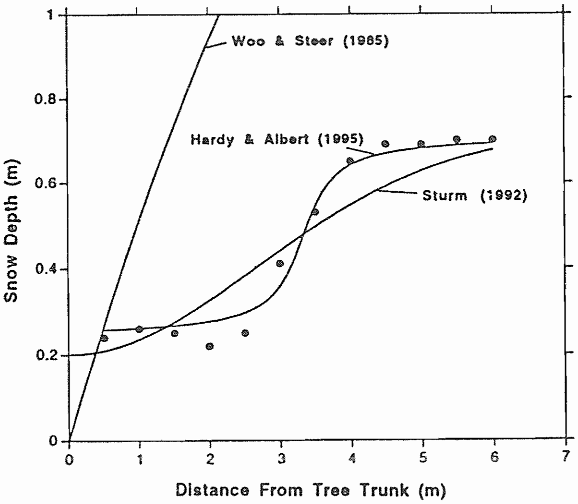

Figure 3. Snow depth profile data (solid circles) around the tree from the time of maximum accumulation (16 March) compared to empirical relations of Sturm (1992), Woo and Steer (1985) and this work. A fitting parameter of 380 was used in eq 1. Polynomial coefficients used in eq 2 were b_0 *=* *0.316,* b_1 *= 0.241,* b_2 *= -0.0518 and* b_3 *= 0.00357. Parameters used in equation (4) were* $\alpha = 3.0$ *and* $\beta = -9.5$

depth profiles were measured in different locations around the same tree, the distance to the zones varied slightly between measurements. Zone 3 begins where snow depth increases sharply and ends where the depth levels off. From these data the snow depth in the tree well (zone 2) at peak accumulation was 34% of that measured in the open (zone 4). During the ablation season snow depths in zone 2 decreased at a higher rate than those measured in zone 4, suggesting nonuniform ablation between the zones. In the boreal forest, Pomeroy and Schmidt (1993) observed SWE beneath the tree canopy equal to 65% of the undisturbed snow, while in Alaska's taiga, Sturm (1992) found snow depths at the tree trunk equal to approximately 20% of the undisturbed snow. Although these trees are all of the *Picea* sp., the varying tree and branch structure is likely responsible for these differences.

The profile data at the time of peak accumulation is compared with the models used by Sturm (1992) (eq 1) and Woo and Steer (1985) (eq 2) to predict snow depth with distance from the tree trunk (Fig. 3). For Sturm's model, a fitting parameter (*k*) of 380 was used. Both models, though optimized for this tree, fail to predict the snow profile for these data. However, Sturm's (1992) model possesses the flexibility to provide an acceptable relationship when the exponent in eq 1 is changed from two to five (M. Sturm, CRREL, pers. comm., 1995). The current data do not show a smooth transition from h_{min} to h_{max} as predicted by these equations; rather the zones have unique depth characteristics. Zones 2 and 4 depths are fairly uniform (variance = 0.0003 for zone 2 and 0.0005 for zone 4), compared to zone 3, which is the transition from the shallow depths beneath the conifer to the deeper snow in the undisturbed area (variance = 0.013). Neither eq 1 nor 2 accounts for this transitional zone as observed in this study. Therefore a new equation is proposed for snow depth profiles around conifers:

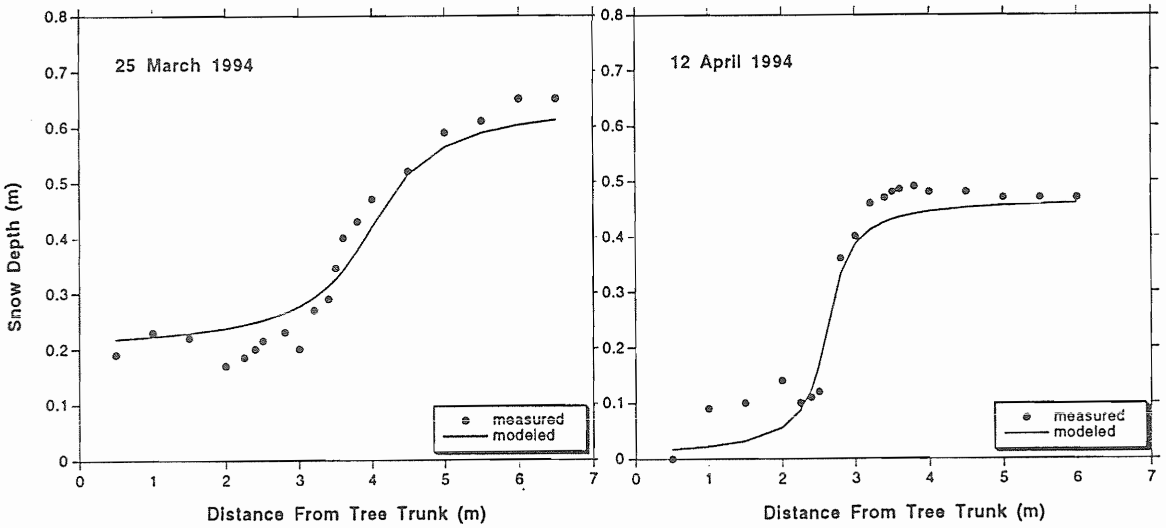

Figure 4. Equation 4 fitted to snow depth profile data for the measurements made during the ablation season. Model parameters for 25 March were $\alpha = 1.5$ *and* $\beta = -6$. *Model parameters for 12 April were* $\alpha = 4.2$ *and* $\beta = -11$.

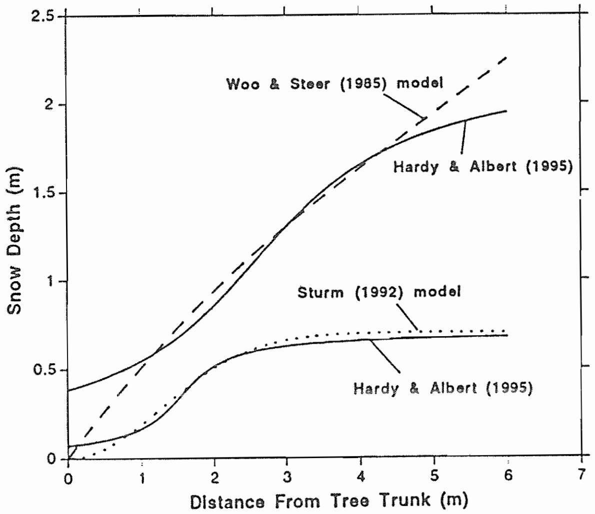

Figure 5. Equation 4 fitted to empirical relations of Sturm (1992) and Woo and Steer (1985). Model parameters for Sturm (1992) were $\alpha = 2$ *and* $\beta = -3.1$. *Model parameters for Woo and Steer (1985) were* $\alpha = 0.65$ *and* $\beta = -1.7$.

$$h(r) = \left(\frac{h_{\max} - h_{\min}}{\pi}\right) \arctan(\alpha r + \beta) + \frac{h_{\max} + h_{\min}}{2} \tag{4}$$

where α and β are adjustable constants related to tree well geometry. The constant α increases as the slope of the snow depth profile in zone 3 increases, while β equals $-\alpha r_0$ where r_0 is the location of greatest increase in snow depth. This equation also has the flexibility to accommodate the change in depth profile during the ablation season (Fig. 4).

Table 1. Comparison of mean snow depth, density and SWE data from the tree well (zone 2) and undisturbed open area (zone 4).

	Mean snow depth (m)		*Mean density (kg m^{-3})*		*SWE (m)*	
	Zone 2	*Zone 4*	*Zone 2*	*Zone 4*	*Zone 2*	*Zone 4*
16 March	0.24	0.71	320	295	0.077	0.21
25 March	0.20	0.65	315	265	0.063	0.17
12 April	0.09	0.47	400*	390	0.032	0.18

* Estimated.

The differences in branch and needle structure is the primary reason other models fail to predict the snow accumulation profile around this conifer. This tree has a large (3.5-m) crown radius, a dense branch and needle structure, and the branches extend near to the ground surface. These factors result in a tree with high snow interception efficiency, when compared to trees in the taiga which have a much smaller crown radius and sparse branches. It is evident from Figure 5 that eq 4 has the versatility to fit other data, that is, conifers with varying crown radius and density.

Measured mean snow depth, density, and SWE data from zones 2 and 4 are compared in Table 1. As discussed above, and observed by others, the tree well accumulated less snow than the open area. Despite higher snow densities measured in the tree well, the SWE remained substantially higher in the open site. The higher density measured in zone 2 may be a combination of several factors: tree debris (needles) in the measured sample, meltwater drips from intercepted snow in the canopy, and altered energy fluxes. According to Yen's (1981) empirical relationship for effective thermal conductivity, the higher snow density in zone 2 means higher thermal conductivity

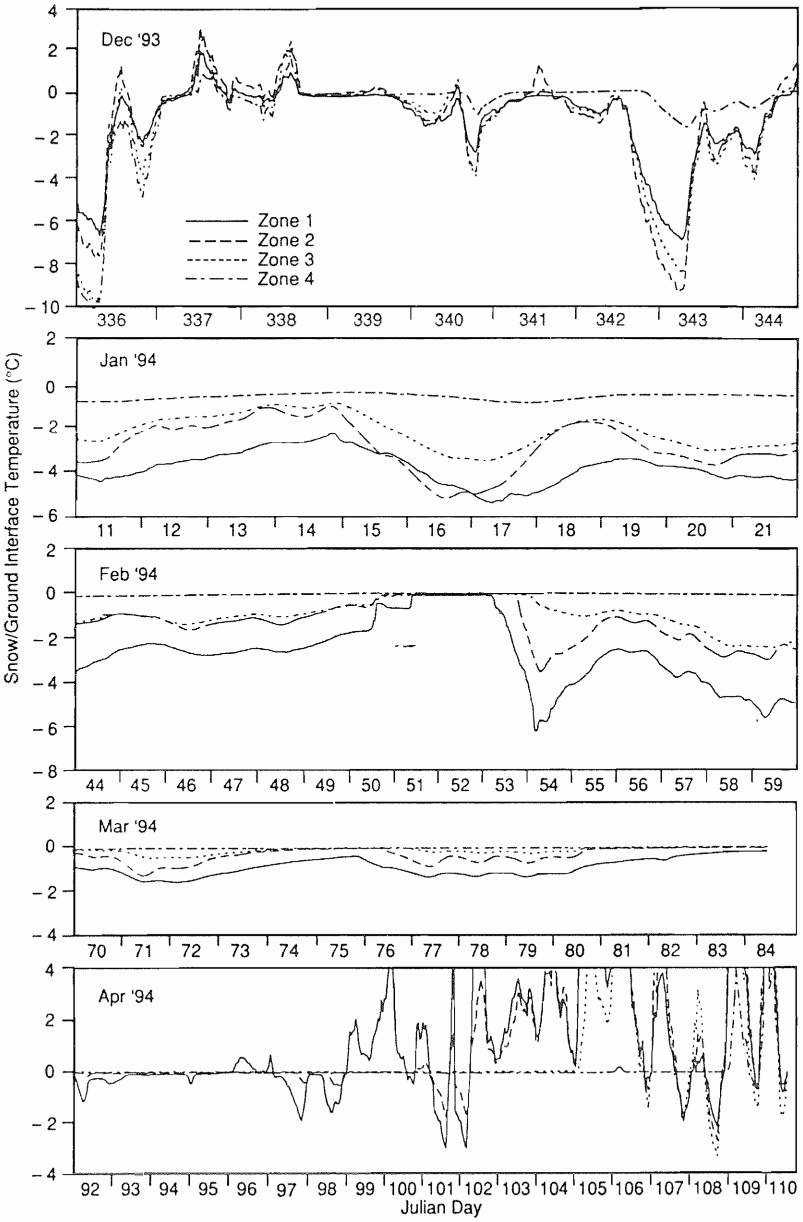

Figure 6. Average snow/ground interface temperatures at the four zones for select periods from December 1993 to April 1994.

compared to zone 4, allowing for greater heat transfer and frozen ground depth.

Thermal variations around the tree

Because the extent of frozen ground under a snow cover is driven by the temperature at depth (usually mean annual air temperature) and the SGIT, the SGIT was measured in each zone through time. Snow/ground interface temperatures (SGIT) were averaged within each zone (where $n = 1$ for zone 1; $n = 4$ for zone 2; $n = 4$ for zone 3; and $n = 6$ for zone 4) and plotted for approximately a 10-day period during the months of December 1993, January, February and March 1994 (Fig. 6). In order to justify the thermal distinctions between the zones, the standard deviation of the hourly data for zones 2, 3, and 4 was determined. The average of those deviations for the period of data in January, February and March is compared (Table 2). All standard deviations are less than 0.5°C

Table 2. Monthly averages of hourly standard deviation of SGIT in each of the four zones.

	Zone 2	*Zone 3*	*Zone 4*
January	0.48	0.82	0.19
February	0.34	0.44	0.14
March	0.18	0.13	0.03

with the exception of zone 3 in January. Zone 4 temperatures vary least with its deeper and uniform snow depth, while zone 3 shows the greatest variation (except in March) due to variable snow depths. Zone 2 standard deviations reflect a more uniform snow depth than those of zone 3, yet at the same time, the shallower snow cover allows greater response of SGIT to air temperature compared to zone 4. Similarly, Pruitt (1957) noted lower SGITs with greater fluctuations at the tree base (zone 1) compared to the warm and stable SGITs beyond the tree well (zone 4).

Prior to the snow cover on day 339 in December, SGIT temperatures were generally lower with distance from the trunk. Beginning on day 339, zone 4 was snow covered while the snow-free zones under the tree continued to respond more dramatically to air temperature fluctuations. By mid-January, zone 4 snow depths were approximately 0.6 m, providing enough insulation for the ground so that the ground heat flux caused warming at the snow/ground interface. The thermal regime around the conifer reversed such that SGITs were higher with distance from the trunk, a condition that remained until the zones became snow free in April. On day 16 through 21, note the lag in zone 1's response to air temperature changes. The lag is likely due to the rise in snow depth adjacent to the tree trunk, dampening zone 1's response to air temperature fluctuations. This additional accumulation at the trunk was observed on day 21, but not observed during subsequent visits, and could be attributed to settling of the snow in zone 2 while snow in zone 1 adhered to the tree trunk.

A typical New England midwinter thaw occurred in February (day 50-53) when air temperatures rose to +10°C, and the undisturbed snow depth decreased from 0.74 to 0.55 m. No precipitation was associated with this thaw. In response to the thaw, SGITs in all zones reached 0°C, with zone 1 the last to warm and the first to cool when temperatures dropped again. March SGITs were warmer than in January, because of deeper snow and warmer air temperatures, yet maintained a similar relationship between the zones. In April, the time series of SGITs allow one to determine when the zones become snow-free. Zone 1 was snow-free and tracking air temperatures by day 96, followed by zone 2 on day 100, zone 3 on day 105 and finally zone 4 on day 109 (9 days after snow beneath the conifer had melted). A delay of 4 to 5 days occurred between the zones becoming free of snow and tracking air temperature. In general, during the period of continuous snow cover, SGITs increased with distance from the tree. Less snow under the tree crown contributed to lower SGIT temperatures during this period, but once the SGITs reached 0°C, snowmelt and ground warming occurred from the tree trunk outward.

Estimates of frozen ground depth

Snow depletion beneath the conifer strongly influenced the SGIT. For a given air temperature, less snow beneath the tree resulted in higher temperature gradients and heat flux across the snowpack than in the open, so that more heat was lost in the tree well. Estimates of heat flux at peak accumulation, a time for which we have snow depth and density data and can estimate thermal conductivities, were made in zones 2 and 4. At the time of peak accumulation, the average heat flux from zone 2 (-13.2 W m^{-2}) was nearly five times greater than in zone 4 (-2.8 W m^{-2}). This is larger than the factor of two that was found around taiga conifers (Sturm 1992). Lower snow/ground interface temperatures at, and greater heat flow from, the tree well led to deeper penetration of frozen ground. A ground freezing model was used to estimate the depth of frozen ground resulting from reduction of snow cover under a conifer tree.

Many operational models of ground freezing use heat conduction equations, where the drivers for heat transfer are surface temperature (Lunardini 1981), thereby eliminating the need for complex surface energy budget calculations. In order to estimate the maximum depth of frozen ground at the start of the ablation season, the modified Berggren equation was employed using snowpack variables from the time of peak snow depth (16 March 1994). Given the thermal parameters of the soil and number of freezing degree days, the model uses an analytical solution of the heat conduction equation to determine maximum frost depth. The model was run using two soil moisture conditions, dry and saturated, where these extreme conditions defined the range of frost depths possible. The only variables which differed between zone 2 and zone 4 were the measured snow thickness and snow density. For this estimate, the soil was assumed uniform in both zones, and the presence of roots and soil inhomogeneities were neglected. Model estimates of maximum frozen ground depth are given in Table 3. In both the dry and saturated soil conditions, the frozen ground was deeper beneath the tree canopy than the undisturbed area. These calculations support the findings of Priehausser (1939) and Viereck (1965). Snow interception by the tree canopy and subsequent snow depletion can affect the depth of frozen ground beneath the tree by as much as seven times that expected in an open, undisturbed area.

The influence of trees on hydrologic processes has important implications for distributed snowmelt modeling in forested watersheds. Greater frost depth be-

Table 3. Model parameters used to predict frost depth in zones 2 and 4, using the modified Berggren equation, and the resulting frost depth (in bold).

	Zone 2		*Zone 4*	
	Snow	*Soil*	*Snow*	*Soil*
Dry soil				
Layer thickness (m)	0.24	1.0	0.7	1.0
Moisture content (%)	0	7	0	7
Density (kg m^{-3})	320	1600	295	1600
K (W m^{-1} K^{-1})	0.27	0.81	0.23	0.81
Frost depth (m)	—	**0.28**	—	**0.04**
Wet soil				
Layer thickness (m)	0.24	1	0.7	1
Moisture content (%)	0	23	0	23
Density (kg m^{-3})	320	1600	295	1600
K (W m^{-1} K^{-1})	0.27	1.77	0.23	1.77
Frost depth (m)	—	**0.08**	—	**0**

neath trees (zone 2) leads to reduced snowmelt infiltration compared to infiltration in forest openings (zone 4). Understanding this heterogeneity of frozen ground depths in forests is important to modeling snowmelt infiltration particularly in a sloped environment. Anderson and Neuman (1984) and Gray et al. (1986) showed that some well-known models were significantly improved when the reduction in percolation caused by frozen soil was incorporated into the models.

One important objective in snow hydrology is to understand how point data can be extrapolated to a larger scale. This is particularly important in forests, where complex interactions exist between energy and snow distribution. Adjacent to the tree used in this study is a small spruce forest with a canopy closure of 90% and trees of a comparable structure to the spruce used in this study. The water table in the forest is at a depth greater than 0.4 m. A vertical thermistor string was installed in the fall of 1993 to measure the soil and snow temperature profile at 0.1-m intervals. As a preliminary comparison between the thermal regime of the single isolated tree and the forest, snow and frost depths from the model are compared to those measured in the forest. At the time of peak accumulation there was between 0.3 and 0.4 m of snow at the thermistor string, and frozen ground penetrated to a depth of 0.3 m. The measured 0.3 m of frost depth in the forest compares well with the predicted 0.28 m of frost penetration in zone 2. Thus, examination of phenomena associated with an individual tree can yield insight in the behavior of a forest.

SUMMARY

This study documents the influence of a single conifer on snow distribution and snow/ground interface temperatures in a temperate climate. A model has been presented that divides that influence into four distinct zones around the tree. The maximum depth of frozen ground has been estimated in the tree well and in the undisturbed snow.

Snow depths increased in a nonuniform fashion with distance from the tree trunk, with the least snow at the trunk and the deepest snow in the area undisturbed by the conifer. Snow depth accumulation beneath the canopy (zone 2) was 34% of that accumulated in the open and resulted in more extreme temperature gradients beneath the canopy. The snow depth profile from the tree trunk to undisturbed snow did not fit previously determined relationships for trees in Alaska and northern Ontario. A new relationship was established that may better represent snow distribution around conifer trees in northern New England, yet has adjustable parameters that allow it to fit data gathered on other conifers. Less snow accumulation under the canopy resulted in colder snow/ground interface temperatures, stronger thermal gradients, and greater heat loss compared to the open sites. A modified Berggren equation estimated frost penetration beneath the canopy to be many times greater than that in the open for both saturated and dry soil moisture conditions. Greater frost depth under the tree at the onset of the snowmelt season suggests that meltwater generated under trees will encounter less permeable soils than in forest openings, leading to increased overland flow, especially at sloped sites. Spatially variable frozen ground, as estimated here, has major implications for snowmelt runoff, meltwater infiltration and ground water hydrology of forested watersheds. Future work will refine the model of snow zones, addressing the effects of overlapping canopy, species variations, and tree crown perimeter geometry, so that point data can more confidently be distributed over a forested watershed.

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