Sublimation of Intercepted Snow within a Subalpine Forest Canopy at Two Elevations

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ABSTRACT

To determine how elevation affects the sublimation rate from intercepted snow within a subalpine forest canopy, a cut subalpine fir and an artificial conifer were weighed at each of two elevations (3230 and 2920 m) at a U.S. continental site (39°53′N, 105°54′W) from 1 January to 1 May 2001. Measured stand characteristics included canopy density (67% and 75%) and basal area (43.4 and 24.1 m^2 ha^{-1}) for the higher and lower elevations, respectively. Temperature, relative humidity, net radiation, wind speed, and mass of snow on suspended trees provided data to determine whether sublimation rates of intercepted snow are more rapid at higher elevations associated with increased wind speed. Measurements showed the unexpected result that wind speed during sublimation periods was lower at higher elevations, probably because of terrain sheltering. The analysis examined 21 storm-free periods ranging in duration from 9 to 53 h. Sublimation rates per unit mass of intercepted snow were significantly larger at the lower-elevation site associated with warmer temperatures, lower relative humidity, and greater wind speeds. Application of meteorological data to an ice sphere model indicated that predicted mean sublimation rates of an ice sphere index were 23% $\pm$ 7% more rapid at the lower elevation due to weather factors alone. However, greater snowfall at higher elevations produced greater interception, resulting in substantially more snow being sublimated back to the atmosphere at the upper site. Over the study period, sublimation of snow intercepted by the test trees amounted to 20%–30% of total snowfall accumulated at the sites during the 21 storms selected for analysis.

1. Introduction

Sublimation from snow occurs when water vapor gradients form near ice crystal surfaces, usually at subfreezing temperatures (Schmidt 1972). Vapor pressure gradients form when the water vapor pressure of the atmosphere is different from that near the ice surface. Snow sublimation rate can be defined as the amount of mass lost per unit time. Sublimation rates depend on particle surface area to mass ratio, vapor pressure gradients, and rate of air exchange around the snow crystal surface (Pomeroy et al. 1997). Typically, sublimation rates are higher when large vapor pressure gradients exist and rapid air exchange occurs (Pomeroy et al. 1993).

The winter energy balance controls sublimation of intercepted snow within forest canopies (Schmidt 1991; Hood et al. 1999). Environmental factors defining the energy balance include forest structure, slope, aspect, and elevation (Meiman 1970; Troendle et al. 1993). Increased sublimation rates generally occur with increased forest-opening size, and on south-facing aspects with greater wind speeds and warmer temperatures (Bernier and Swanson 1993; Schmidt et al. 1998). However, sublimation rates may vary significantly with changes in slope, aspect, and in particular, elevation, because of associated changes in energy balance.

Previous research demonstrates that sublimation can significantly reduce the snow water equivalent (SWE) available for spring runoff and summer water supply critical to western states for agriculture and recreation. Conifer canopies may intercept up to 60% of annual snowfall, and a large percentage of this intercepted snow may subsequently sublimate back to the atmosphere

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(Hedstrom and Pomeroy 1998; Storck and Lettenmaier 1999). Troendle and Meiman (1986) estimated 30% to 50% of annual snowfall sublimates from dense conifer canopies in mountain forests in midlatitude, continental climates. Pomeroy and Gray (1995) estimated 25% to 45% of annual snowfall sublimates from the canopy in boreal, montane, and subalpine forests. The large surface-area-to-mass ratios of intercepted snow and its exposure to wind are important factors that enhance sublimation from the canopy (Schmidt and Gluns 1991).

Sublimation of intercepted snow may be the most significant process contributing to SWE loss in midlatitude, continental climates because most seasonally snow-covered areas that store summer water supplies in winter snowpacks are forested (Schmidt and Troendle 1992). Drainage basins in mountain regions have significant forest cover over a wide range of elevations. Little research has been completed examining differences in sublimation rates as a function of elevation. Because of the spatial variability of sublimation and its major role in regional water budgets, a greater understanding of the sublimation process is essential. The results of this study will be beneficial for hydrologic modeling and forecasting runoff from seasonally snow-covered, forested basins.

Frequent studies have measured and modeled sublimation from snow on the ground surface, intercepted snow, and blowing snow (West 1962; Schmidt 1972; Harlan 1974; Meiman and Grant 1974; Granger and Male 1978; Essery et al. 1999). Studies that have measured snow sublimation from suspended trees, while monitoring weather variables include Schmidt et al. (1988), Schmidt (1991), Schmidt and Troendle (1992), Pomeroy and Schmidt (1993), Hedstrom and Pomeroy (1998), and Schmidt et al. (1998).

Schmidt (1991) continuously weighed a 1.1-m-tall artificial conifer and applied an ice sphere model to measure and predict sublimation rates. The ice sphere model was first developed in the laboratory by Thorpe and Mason (1966) and later modified by Schmidt (1972, 1991). Details of this model are described in section 3. Direct mass measurements along with meteorological measurements showed that sublimation rates from an intercepted snow mass correlated well with predicted sublimation rates of a 1-mm-diameter ice sphere (Schmidt 1991). Schmidt et al. (1998) measured weather parameters and sublimation rates on opposing aspects, and the results indicated that sublimation rates were more rapid on south-facing slopes and that the ice sphere model accurately predicted the measured sublimation rates.

Several studies have measured sublimation from the southern boreal forest in Canada. Pomeroy and Schmidt (1993) estimated that the boreal forest canopy stores up to 60% of cumulative snowfall in midwinter, and a total of 30% of annual snowfall may be lost to sublimation. Pomeroy and Schmidt (1993) made continuous weight measurements of a full-size black spruce tree and took digitized photographs of the tree to measure sublimation. Use of fractal geometry and the physical sublimation measurements helped determine an exposure coefficient that can be applied to calculate sublimation rates from intercepted snow. Pomeroy et al. (1998) compared the modeled output of a series of process-based algorithms to physical interception and sublimation measurements made from a suspended tree. They found that the model correlated well with actual interception and sublimation measurements of up to 3 mm day^{-1} and that net sublimation losses accounted for two-thirds of total snowfall during the study period. Schmidt and Troendle (1992) conservatively estimated that for a winter of average snowfall, sublimation of intercepted snow would return 7.6×10^{10} m^3 of water to the atmosphere from a 1.7 million km^2 area in the western Canadian boreal forests.

Recent studies have made significant advances in improving estimates of snow sublimation from the forest canopy. Numerous studies have applied various models and methods developed to extrapolate sublimation measurements made from a single tree to the entire canopy (Harding and Pomeroy 1996; Lundberg and Halldin 1994; Lundberg et al. 1998; Nakai et al. 1994, 1999; Parviainen and Pomeroy 2000; Pomeroy et al. 1998). These studies have made considerable progress; however, most of the models have been applied to study sites with relatively flat terrain. In large portions of the western United States, and in particular the Rocky Mountain Cordillera, uneven terrain and significant changes in elevation dominate snow-covered regions. Changes in elevation can drastically affect the governing factors controlling the sublimation process and ultimately add to the complexity in quantifying sublimation. Therefore, this study focuses on terrain effects, and in this case a considerable change in elevation, to gain a better understanding of sublimation processes at different elevations.

The objectives of this study were 1) to determine if sublimation rates from intercepted snow within a subalpine forest canopy were more rapid at higher elevations using mass measurements from suspended trees and an ice sphere model, 2) to predict sublimation rates of a 1-mm-diameter ice sphere at different elevations using the ice sphere model based on weather factors alone, and 3) to quantify differences in sublimation rates as a function of temperature, relative humidity, net radiation, and wind speed. We hypothesized that greater wind speeds at higher elevations would overpower lower temperatures and higher relative humidity, producing greater sublimation rates.

2. Measurements

a. Study site

Data for this study were collected in the West St. Louis Creek watershed in Fraser Experimental Forest

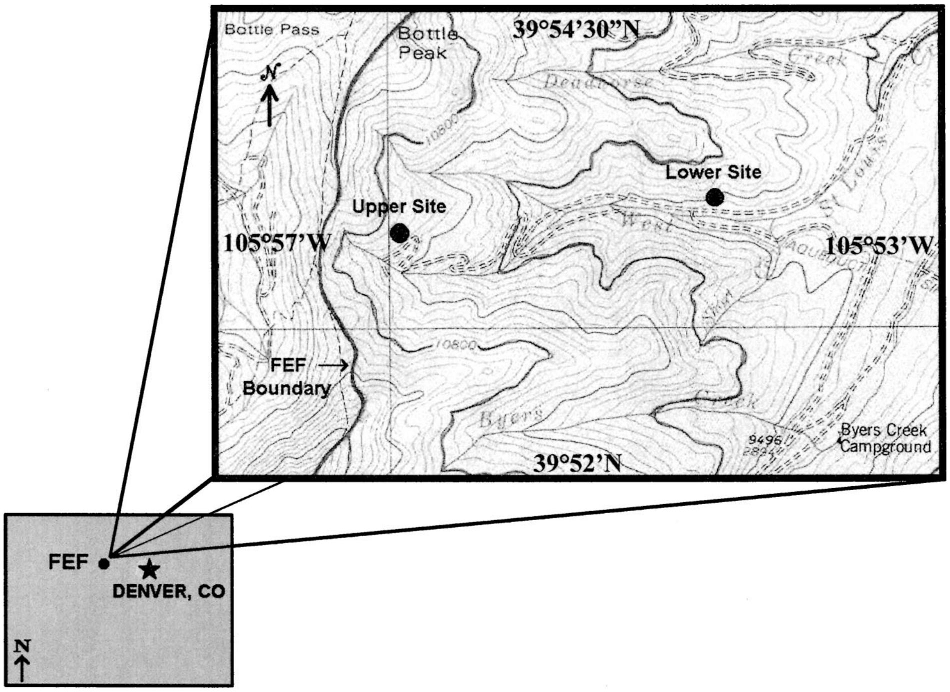

FIG. 1. Location of FEF and study sites within the West St. Louis Creek watershed.

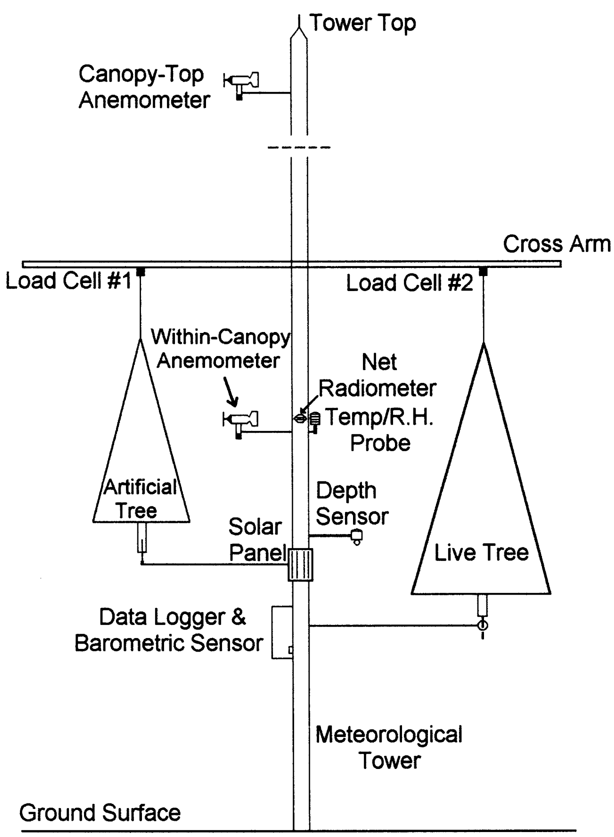

FIG. 2. Side view of upper-site weather station looking north. Tree and weather sensor positioning vary slightly from the lower site, and the figure is not drawn to scale.

(FEF), located in central Colorado (Fig. 1). The FEF is a 9300-ha basin of subalpine forest and alpine tundra in the Rocky Mountains. Elevations range from approximately 2700 to 3900 m. Lodgepole pine (*Pinus contorta*) typically dominates lower elevations with occasional aspen (*Populus tremuloides*), whereas subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) dominate upper elevations (Schmidt et al. 1998). The temperate, continental climate hosts annual temperature ranges of −40° to 32°C, with typical winter temperatures ranging from −30° to 0°C. The annual precipitation averages 710–760 mm, with nearly 67% in the form of snow from October through May (Alexander et al. 1985).

The two study sites are located on 30°–35°, south-facing slopes at 2920- and 3260-m elevation. The lower-elevation site is located 100 m above the narrow valley floor of West St. Louis Creek (Schmidt et al. 1998). The slope is dominated by lodgepole pine with scattered subalpine fir and is exposed to westerly storm winds and nighttime cold-air drainage (Schmidt et al. 1998). The upper-elevation site is located south of Bottle Peak and is dominated by subalpine fir with scattered lodgepole pine. This site is exposed to westerly winds but is not affected by nighttime cold-air drainage.

b. Instrumentation

Two meteorological towers (22 and 30 m) supported weather sensors and the suspended trees (Fig. 2). The towers were located in small clearings, large enough to securely install the towers, weather instruments, and suspended trees (surrounding trees were within 1–2 m of suspended trees). One subalpine fir and one artificial conifer were suspended at each site and continuously weighed by load cells (Interface SSM250) attached to a cross arm positioned in an east–west direction, 6 m above the ground, leaving 2–3 m between the base of the trees and the snow surface. Artificial conifers were used in addition to subalpine firs to serve as a control for the two sites and also to allow for an assessment of weighed artificial conifers as useful sensors for sublimation studies. Temperature, relative humidity, net radiation, wind speed and direction, and atmospheric pressure were measured at the height of the suspended trees. A second anemometer (R. M. Young 05103 Wind Monitor) was positioned above the surrounding forest canopy. Net radiometers (REBS Q-7.1) measured net radiation, and temperature/humidity probes (Vaisala HMP45C) with radiation shields sensed air temperature and relative humidity. The humidity probes measure relative humidity with respect to liquid water and not ice; however, this concern was accounted for in the ice sphere model calculations. Barometric sensors (Vaisala PTB101B) measured atmospheric pressure. Ultrasonic depth sensors (Judd Communications) measured snow depth at each site. Dataloggers (Campbell Scientific, Inc. CR10X) measured weather sensors and the mass of the suspended tree with intercepted snow every 10 s, recording 10-min averages.

The two artificial conifers used in this study were made with a tubular steel trunk and twisted wire branches with plastic needles. The two subalpine fir trees were cut from the nearby forest. In order to make data referencing more convenient, the cut subalpine fir trees are referred to as ''live'' trees in the following text, tables, and figures. Immediately after cutting, the bases of the live tree trunks were sealed with epoxy to reduce desiccation. The cut trees lost 1.3–1.4 kg of mass (9% to 12%) over the study period. Differences in tare weights before and after storms provided a linear correction for the change in live tree mass (Montesi 2002).

To prevent the live trees from swinging in the wind, a lag screw was inserted vertically into the base of the tree trunk, and held loosely in an eyebolt attached to a steel pipe extending from the tower. The screw restricted horizontal movement, but not vertical motion. A steel pipe of smaller diameter, extending vertically up into the tubular trunk and attached by a horizontal pipe to the tower, similarly restricted movement of the artificial trees. Fishing line, loosely attached from the tower to a branch on each live tree, prevented rotation. Because of their uniform shape and weight distribution, the artificial trees did not rotate.

Table 1 lists the specifications of the live and artificial trees. Upon completion of the field study, a random subsample of 25 branch tip lengths was measured from each tree to calculate the total leaf area of the artificial trees. The total leaf area is defined as the actual projected area of horizontal needles. Three branch tips from each tree were unraveled, and the surface area of the plastic needles was measured with calipers accurate to 0.00254 cm. The surface area per branch tip length was calculated and applied to the total length of branches to compute the total surface area of each tree. The cross-sectional areas of both the live and artificial trees were calculated from an average of four diameters measured to 0.0254 cm. To calculate the total leaf area of the live trees, all the needles for each tree were removed and dried in an oven for 48 h at 70°–75°C and weighed (Kaufmann et al. 1982). The average dry weight of two random subsamples of 500 needles were divided into the total dry weight of all the needles and multiplied by 500 to calculate the total number of needles on each tree. The length and average width (measured at three points) of two random 100 needle samples were measured to obtain the average surface area per needle. The average surface area per needle multiplied by the total number of needles equaled the total leaf area of each tree. The total leaf area was also calculated by using two different total leaf area to dry weight conversion factors. One was specifically calculated from each tree, and one was a published conversion factor calculated from a sample of subalpine fir trees (Kaufmann et al. 1982). For this study, an average of the specific conversion factor and the original method using the weight of the 500 needle subsamples was used to reduce the error in the leaf area estimations and because both methods produced similar results. Leaf area index (LAI) was calculated by dividing the total leaf area by the cross-sectional area.

TABLE 1. Live and artificial tree descriptions. Artificial tree values represent an average from both artificial trees.

Tree type	Height (m)	Start weight (kg)	End weight (kg)	Cross-sectional area (m^2)	Total leaf area (m^2)	Leaf area index
Upper live	2.7	14.50	13.16	2.14	16.7	7.8
Lower live	2.7	11.05	9.63	1.42	12.2	8.5
Artificial	1.9	6.65	6.65	0.88	9.1	10.3

3. Analysis and results

Periods of sublimation selected for analysis began immediately after storm cessation and ended with new snowfall or when nearly all snow was sublimated from the suspended trees. The snowfall during the 21 storm cycles selected for analysis accounted for 70% to 75% of total snowfall over the study period from January to May 2001. The selected periods totaled 620 h of sublimation with a range in duration of 9 to 53 h and a mean of 29 h. Selection criteria included 1) relatively few unloading events, with 2) long periods of continuous sublimation, and 3) little or no intermittent snowfall. Remaining unloading events (where snow fell from

TABLE 2. Summary table of meteorological data including temperature, relative humidity, and wind speed for upper- and lower-elevation sites with $n = 21$.

					Wind speed (m s^{-1})			
	Temperature (°C)		Relative humidity (%)		Above canopy		Suspended tree height	
Site	Mean	Range	Mean	Range	Mean	Max	Mean	Max
Upper	−5.7	−18, 5	76	20–100	1.4	2.5	0.4	0.8
Lower	−4.4	−17, 10	73	25–100	1.9	3.6	0.5	1.0

the trees) and periods of intermittent snowfall were removed from the analysis so that these losses would not be attributed to sublimation, leaving 550 h of raw sublimation data. Most unloading events were observed in the field; the remaining events were easily detected in the mass measurements as abnormally large decreases of intercepted snow mass over a 10-min interval. Although some unloaded snow is sublimated as it falls, the percentage of sublimated snow mass is exceedingly small compared to the mass of snow that reaches the ground. Additionally, the amount of snow sublimated from an unloaded mass of intercepted snow would be exceptionally difficult to measure. Therefore, we considered it unreasonable to attribute any unloaded snow to the sublimation process.

a. Meteorological data description

For each sublimation period, hourly averages, maximums, and minimums were compiled from the 10-min data for each weather variable. An average value of each weather variable was calculated for each sublimation period to create independence by storm with an $n = 21$. These data were statistically analyzed using summary statistics, paired t tests, and F-tests for equality of variance, to determine differences in energy balances between the upper- and lower-elevation sites. Levene's test for equality of variance was used when weather data were not normally distributed.

Means and ranges of temperature and relative humidity, as well as the mean and maximum wind speeds observed above the canopy and at the height of the suspended trees are shown in Table 2. A summary of the results from the statistical analyses shows that the lower site experienced warmer mean and maximum temperatures, lower relative humidity, and greater wind speeds at the height of the suspended trees during the sublimation periods (Table 3). The lower-site mean and maximum temperatures were 30% warmer than those of the upper site (p value < 0.001). The lower-site mean relative humidity was only 3% drier than that of the upper site (p value $= 0.309$); however, the mean minimum relative humidity was 10% drier at the lower elevation (p value < 0.001). Lower-site mean and maximum wind speeds measured at the height of the suspended trees were 25% larger than those measured at the upper site; however, only maximum wind speeds were significantly larger at the lower site (p value < 0.001). The lower-site mean and maximum wind speeds measured above the canopy were 36%–44% larger than at the upper site (p value < 0.001).

b. Sublimation rate differences

Hourly averages and maximums were assembled from the 10-min sublimation data for each tree. Raw mean sublimation rates in grams per hour were calculated from the load cell data by summing the mass lost every 10 min over an hour interval for each hour of each sublimation period. The standard error for the raw hourly sublimation rates was ± 4 g h^{-1} for the artificial trees and ± 7 g h^{-1} for the live trees. This uncertainty is a result of the error in the variability of the mass measurements due to wind and tree instability, and the error associated with the load cell instruments themselves due to nonlinearity, hysteresis, and temperature fluctuations. To explore differences between sublimation rates from the upper and lower sites, the raw sublimation rates were normalized by test tree leaf area and by mass of intercepted snow. These normalizations were an attempt to

TABLE 3. Paired t-test results from upper- and lower-site temperatures, relative humidity, and wind speeds at the height of the suspended trees ($n = 21$).

Paired t test	Mean diff	Std error mean diff	95% C.I.* mean diff	p value
Upper mean temp–lower mean temp	−1.3°C	0.3°C	(−2.0°C, −0.6°C)	0.001
Upper max temp–lower max temp	−2.9°C	0.4°C	(−3.6°C, −2.2°C)	0.0001
Upper mean RH–lower mean RH	2.7%	2.6%	(−2.7%, 8.0%)	0.309
Upper min RH–lower min RH	10.3%	2.5%	(5.1%, 15.6%)	0.001
Upper mean wind–lower mean wind	−0.1 m s^{-1}	0.02 m s^{-1}	(−0.1 m s^{-1}, 0.04 m s^{-1})	0.705
Upper max wind–lower max wind	−2.8 m s^{-1}	0.3 m s^{-1}	(−3.3 m s^{-1}, −2.2 m s^{-1})	0.0001

* C.I. = confidence interval.

TABLE 4. Summary statistics for intercepted snow masses in kg ($n = 550$). Means and ranges are larger at the upper site and for live trees.

Tree type	Mean	Std dev	Std error	Range
Upper live	6.840	4.356	0.186	0.308–22.180
Upper artificial	5.355	2.903	0.124	0.156–17.047
Lower live	1.475	1.587	0.068	0.005–11.488
Lower artificial	1.979	2.074	0.089	0.008–10.333

TABLE 5. Summary table of raw and normalized mean sublimation rates for each tree at upper and lower elevations with $n = 550$.

	Raw rates		Rates per unit leaf area		Rates per unit mass	
Elevation and tree type	g h^{-1}	Std error	g h^{-1} m^{-2}	Std error	g h^{-1} kg^{-1}	Std error
Upper live	138	5.4	8.2	0.3	31	1.4
Upper artificial	79	3.1	8.6	0.3	23	1.3
Lower live	62	3.8	5.1	0.3	76	5.3
Lower artificial	51	2.9	5.6	0.3	48	3.3

remove differences in sublimation rates caused by differences in tree geometry and precipitation between sites. Sublimation rates per unit area were calculated by dividing the raw sublimation rates by each tree's respective total leaf area (g h^{-1} m^{-2}). Sublimation rates per unit mass were calculated by dividing the raw sublimation rates by the amount of snow intercepted on each tree (g h^{-1} kg^{-1}). The mass of intercepted snow was calculated by subtracting the tare weight of each tree from the respective load cell measurement; the difference equaled the intercepted snow mass. Summary statistics for intercepted snow masses can be found in Table 4.

The sublimation data was statistically analyzed with summary statistics, a randomized 2 × 2 block design analysis of variance, and F-tests for equality of variance, to test for differences between elevation and tree type. A randomized 2 × 2 block design was compatible with the data structure and was more efficient and powerful than individual paired t tests. The assumptions of the 2 × 2 randomized block design are normality, independence, and homogeneity of variance. The storms are considered independent events and plots of the residuals showed that the sublimation rates are normally distributed. Data were transformed to the square root scale to satisfy the homogeneity of variance assumption.

The raw measured mean sublimation rates for the 21 sublimation periods were 28–76 g h^{-1} (55%–123%) larger from the upper-site trees than from the lower-site trees. This result created a 27%–37% increase in the amount of water per unit cross-sectional area sublimated from the upper site with respect to the lower site. These differences were due to the fact that the upper-elevation site received 36% (103 cm) more snowfall from the 21 storms. In order to correct for this difference in precipitation, the raw sublimation rates were standardized to a unit mass of intercepted snow. The results from these analyses showed that the mean sublimation rates standardized to a unit mass were 25–45 g h^{-1} kg^{-1} (109%–145%) larger from the lower-site trees relative to the upper-site trees. These percentages may be overestimated due to instrument error when sublimation was measured with small masses of intercepted snow.

The results from the 2 × 2 analysis of variance test demonstrated that the raw mean and maximum sublimation rates and mean sublimation rates per unit leaf area were significantly larger at the upper-elevation site (p values < 0.001), whereas mean and maximum sublimation rates per unit mass of intercepted snow were significantly larger at the lower-elevation site (p value < 0.001). The raw sublimation rates and the sublimation rates per unit mass were significantly larger from the live trees relative to the artificial trees, whereas no significant differences existed between sublimation rates per unit leaf area between tree types at each elevation. Table 5 summarizes the raw and normalized mean sublimation rates, and Table 6 describes the mean sublimation rate differences between the two elevations and tree types. Raw sublimation rates and sublimation rates per unit leaf area and per unit mass are plotted for sublimation period 13 (2–3 March 2001) in Figs. 3, 4, and 5. Sublimation period 13 covered a relatively long period of continuous sublimation and is an accurate representation of the relationships between sublimation rates at different elevations described above.

c. *Total sublimation losses*

To calculate the rate of water equivalent lost to sublimation, the respective sublimation rates (g h^{-1}) for each tree were divided by the density of water (1.0 g cm^{-3}) and divided again by either the cross-sectional area or total leaf area of each tree. The result was water equivalent loss in units of millimeters per hour. Total

TABLE 6. Summary table of raw and normalized mean sublimation rate differences between elevation and tree type.

	Raw rates		Rates per unit leaf area		Rates per unit mass	
Elev and tree type diff	g h^{-1}	% Diff	g h^{-1} m^{-2}	% Diff	g h^{-1} kg^{-1}	% Diff
Upper live–lower live	76	123	3.1	62	−45	145
Upper artificial–lower artificial	28	55	3.0	54	−25	109
Upper live–upper artificial	59	75	−0.4	5	8	35
Lower live–lower artificial	11	22	−0.5	10	28	58

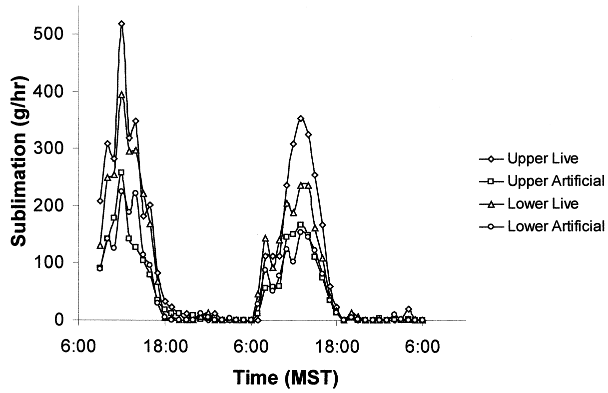

FIG. 3. Raw sublimation rates plotted vs time for sublimation period 13 (2–3 Mar 2001).

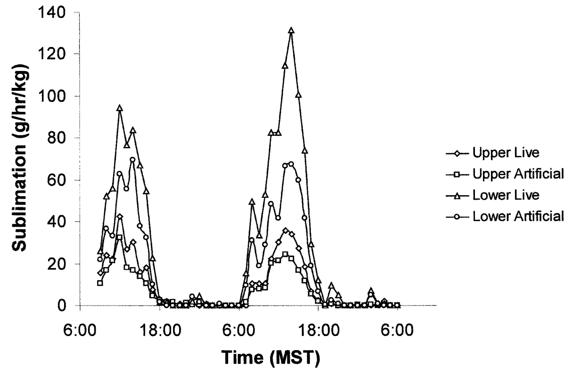

FIG. 5. Sublimation rates per unit mass of intercepted snow plotted vs time for sublimation period 13 (2–3 Mar 2001).

sublimation losses in mass and millimeters of water per unit cross-sectional area and per unit leaf area were computed over all 21 sublimation periods (Table 7). Table 8 shows the differences in water lost between elevation and tree type. The upper live, upper artificial, lower live, and lower artificial trees experienced 46, 30, 25, and 18 unloading or intermittent snowfall events, respectively. Removing data for the hours when these events occurred left 574, 590, 595, and 602 hourly sublimation rates to sum for each respective tree's total sublimation loss (Montesi 2002).

Substantially more water mass (36%–92%), water per unit cross-sectional area (27%–37%), and water per unit leaf area (36%–39%) was lost from the upper-site trees relative to the lower-site trees. In addition, substantially more water mass (14%–61%) was lost from the live trees relative to the artificial trees at each site. However, the artificial trees lost more water per unit cross-sectional area (41%–52%) and per unit leaf area (14%–17%) than the live trees (Table 8). Figure 6 shows the total sublimation losses in millimeters of water per unit cross-sectional area for the 21 sublimation periods. Overall, the live trees sublimated 20% and the artificial trees sublimated 30% of total SWE during the 21 storms.

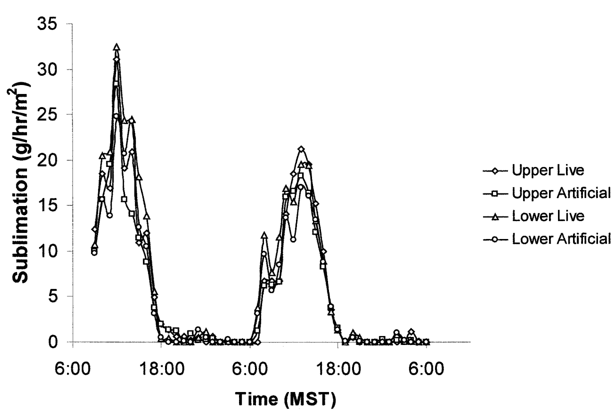

FIG. 4. Sublimation rates per unit leaf area plotted vs time for sublimation period 13 (2–3 Mar 2001).

d. Application of the ice sphere model

The ice sphere model used in this study was first developed in the laboratory by Thorpe and Mason (1966) and refined by Schmidt (1972, 1991). Thorpe and Mason (1966) predicted sublimation of an ice sphere by equating water vapor transfer and heat transfer at the surface of the ice crystal. This model assumes that the heat transferred to the particle for latent heat of vaporization is in equilibrium with the water vapor removed from the particle by diffusion and convection (Schmidt 1991). It also assumes that sublimation rates from a 1-mm ice sphere in the lab are comparative to sublimation rates from a snowpack in the field under identical environmental conditions. Last, it assumes that all natural, free-falling snowflakes are perfectly round spheres with a 1-mm diameter and are completely exposed to the local environmental conditions. With these assumptions in mind, the ice sphere model used the weather data to predict sublimation rates of a 1-mm ice sphere at each elevation.

The following heat and mass transfer equations were developed in Schmidt (1991). These equations were applied in this study to predict sublimation rates of a 1-mm ice sphere using the meteorological data collected at each site. Several studies provide a more detailed discussion of the development of these equations (Thorpe and Mason 1966; Schmidt 1972; Schmidt et al. 1998).

TABLE 7. Measured total water loss for each tree. Live trees lost more water in mass; however, the artificial trees lost more water per cross-sectional area and total leaf area.

		Total sublimation loss		
Tree type	Hours of sublimation	Mass (kg)	Per unit cross-sectional area ($mm\ m^{-2}$)	Per unit leaf area ($mm\ m^{-2}$)
Upper live	574	83.5	39.0	5.0
Upper artificial	590	51.9	59.1	5.7
Lower live	595	43.6	30.7	3.6
Lower artificial	602	38.2	43.4	4.2

TABLE 8. Summary table of differences in water lost between elevation and tree type.

	Differences in water loss					
	Mass		Per unit cross-sectional area		Per unit leaf area	
Elev and tree type diff	kg	% Diff	mm m^{-2}	% Diff	mm m^{-2}	% Diff
Upper live–lower live	39.9	92	8.3	27	1.4	39
Upper artificial–lower artificial	13.7	36	15.7	37	1.5	36
Upper live–upper artificial	31.6	61	−20.1	52	−0.7	14
Lower live–lower artificial	5.4	14	−12.7	41	−0.6	17

The sublimation rate of a 1-mm ice sphere was calculated by applying

$$\frac{dm}{dt} = \frac{2\pi r\left[\left(\frac{p}{p_{sT}}\right) - 1\right]\mathrm{Nu} - Qf(T)}{L_s f(T) + \frac{1}{Dp_{sT}}}, \quad (1)$$

where dm/dt is the rate of change mass, r is radius of the sphere, p is the water vapor density of the environment, T is the temperature of the environment, p_{sT} is the saturation water vapor density at T, Nu is the Nusselt number, D is the diffusivity of water vapor in still air, L_s is the latent heat of sublimation, and Q is the net rate of heat transfer to the particle by radiation. The function $f(T)$ can be expressed as

$$f(T) = \left(\frac{1}{KT}\right)\left[\left(\frac{L_s M}{RT}\right) - 1\right], \quad (2)$$

where M is the molecular weight of water, R is the universal gas constant, and K is the thermal conductivity of air. The net rate of heat transfer to a snow particle by radiation is represented by

$$Q = \pi r^2(1 - \zeta)S_o, \quad (3)$$

where S_o is total incident radiation flux, and ζ is particle albedo. The Nusselt number is defined as

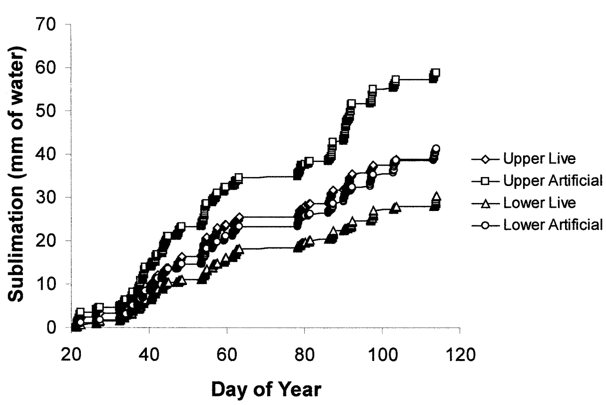

FIG. 6. Total sublimation losses in mm of water per unit cross-sectional area for each tree over the 21 sublimation periods. Upper-site trees sublimated more water than the lower-site trees for both tree types. Day of year "zero" is 31 Dec 2000.

$$\mathrm{Nu} = 1.79 + 0.606(\mathrm{Re}^{0.5}) \quad (4)$$

for ($0 < \mathrm{Re} < 10$), where Re is the Reynolds number that is written as

$$\mathrm{Re} = \frac{2rV}{\upsilon}, \quad (5)$$

where V is the ventilation speed, and υ is the kinematic viscosity of air.

Water vapor diffusivity in still air (D), kinematic viscosity of air (υ), thermal conductivity of air (K), latent heat of sublimation (L_s), and saturation vapor density (p_{sT}) vary with changes in temperature and atmospheric pressure. When computing sublimation rates, these variables must be changed accordingly as weather conditions change. Schmidt's (1991) application of the model used the total incident radiation flux and an estimate of particle albedo. In this study, we used net solar radiation to estimate the heat transfer by radiation to the ice sphere. Radiation heat transfer to the particle has a relatively small effect on sublimation rates of 1-mm ice spheres according to the model and past studies, although this may not be the case when calculating radiation budgets for an entire canopy (Schmidt 1991). Using net radiation instead of incoming solar radiation probably reduced predicted sublimation rates slightly, but we considered this a relatively insignificant difference.

Schmidt (1991) performed a complete model sensitivity analysis and reported that instrument errors in relative humidity and wind speed caused worst-case errors as large as 20% in the predicted sublimation rates of a 1-mm ice sphere. Improvements in humidity sensors have reduced these uncertainties slightly in the present study. An estimated uncertainty of ±15% in predicted sublimation rate caused by measurement errors corresponds to an uncertainty of $\pm 1.5 \times 10^{-4}$ g h^{-1}, for the same weather conditions used in the error analysis by Schmidt (1991).

Predicted sublimation rates for a 1-mm ice sphere were analyzed statistically using paired t tests to detect significant differences in predicted sublimation rates between the lower- and upper-elevation sites. The model predicted condensation for several hours (usually in early morning) when the load cells were actually measuring slight sublimation. This discrepancy results from humidity sensor errors at relative humidity near 100%.

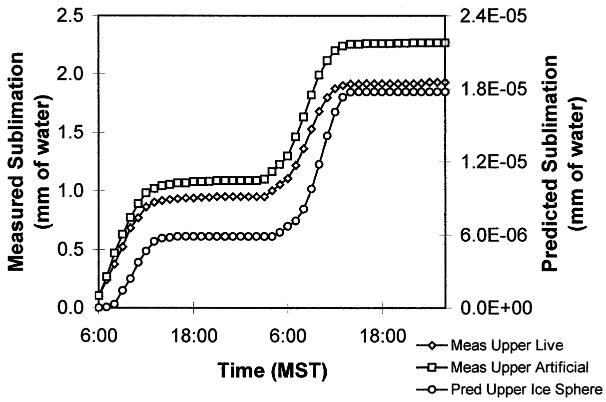

Fig. 7. Measured water losses per unit cross-sectional area for upper-site trees and predicted water losses per unit cross-sectional area for 1-mm ice sphere located at upper site over sublimation period 13 (2–3 Mar 2001).

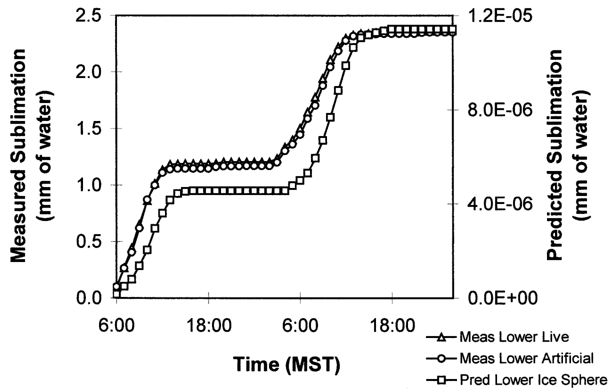

Fig. 8. Measured water losses per unit cross-sectional area for the lower-site trees and predicted water losses per unit cross-sectional area for 1-mm ice sphere located at the lower site over sublimation period 13 (2–3 Mar 2001).

Hours with predicted condensation were not included in the analysis, leaving 468 predicted hourly sublimation rates for analysis. The predicted mean sublimation rates from 1-mm ice spheres at the upper and lower sites were 8×10^{-4} g h^{-1} $\pm 3 \times 10^{-5}$ g h^{-1} and 1×10^{-3} g h^{-1} $\pm 4 \times 10^{-5}$ g h^{-1}, respectively. That is, predicted sublimation rates from 1-mm ice spheres based only on weather factors were 2×10^{-4} g h^{-1} larger (23% $\pm$ 7%) at the lower-elevation site (p value < 0.001).

Although on vastly different scales, Figs. 7 and 8 show that the predicted sublimation rate of a 1-mm ice sphere closely tracked the measured sublimation rate for all four trees and thus properly accounted for the associated weather factors. The predicted sublimation rate for a 1-mm ice sphere (grams per hour) was divided by the density of water and again by the cross-sectional area of a 1-mm diameter ice sphere, resulting in units of millimeters per hour. Figures 7 and 8 graph the measured and predicted sublimation rates in terms of cumulative water losses in millimeters. The magnitudes of water lost were unequal because the sources of sublimation were different; the measured sublimation losses were from entire intercepted snow masses, whereas the predicted sublimation losses were from a 1-mm diameter ice sphere. The model was beneficial to the experiment because the model predicts sublimation rates solely on meteorological data and is not affected by differences in precipitation and tree geometry.

4. Discussion

The primary goal of this study was to determine whether sublimation rates were more rapid at higher elevations associated with increased wind speeds using mass measurements and weather data applied to an ice sphere model. However, measurements showed the unexpected result that wind speeds during sublimation periods were lower at the higher elevation, probably because of terrain sheltering.

Analysis of meteorological data collected clearly demonstrate that significant differences existed between the energy balances of the suspended trees at different elevations because of differences in environmental factors (Tables 2 and 3). The results from the analyses of the meteorological data, the sublimation rates per unit mass, and the predicted ice sphere rates clearly indicate that sublimation rates were more rapid at the lower site. Warmer temperatures, lower relative humidity, and greater wind speeds recorded at lower elevations created favorable conditions for sublimation that ultimately led to a 10%–20% increase in sublimation rates from the lower-site trees. Although sublimation rates were more rapid at lower elevations, considerably more water was lost to sublimation at the higher-elevation site caused by 36% greater snowfall and, thus, greater interception and greater surface area exposed to sublimation. For the 21 sublimation periods included in the analysis, the upper-site trees sublimated 27%–37% (8–16 mm) more water per unit cross-sectional area than the lower-site trees, whereas the artificial trees sublimated 41%–52% (13–20 mm) more water per unit cross-sectional area than the live trees because of larger leaf area to cross-sectional area ratios. Over the 21 storms, the live trees sublimated 20% and the artificial trees sublimated 30% of total SWE (40% and 60% of intercepted SWE) back to the atmosphere. This estimate represents the percentage of SWE that was sublimated from the test trees, but only the portion of the total SWE that accumulated during the 21 storms selected for analysis. This estimate does not include snowfall from intermittent snow or smaller storm systems that occurred over the entire study period. The total sublimation estimate is also slightly conservative considering that the analysis did not include unloading events and time periods when relatively little snow remained on test trees.

Application of the ice sphere model determined whether sublimation rates of a 1-mm ice sphere were more rapid at higher elevations associated with weather factors alone. The results from the ice sphere model showed that the weather factors were properly accounted for at a greatly reduced scale (Figs. 7 and 8) and that sublimation rates were 23% $\pm$ 7% more rapid at lower elevations associated with warmer temperatures, lower relative humidity, and greater wind speeds. The ice sphere model also proved useful in separating the effects of energy balance parameters (temperature, relative humidity, wind speed, and radiation) from the precipitation effect in evaluating differences in sublimation of intercepted snow with changes in elevation. Thus, it was possible to clearly demonstrate that greater sublimation at the higher elevation was not the result of greater energy exchange, rather it was the result of greater precipitation, thereby rejecting our initial hypothesis regarding wind speed differences. Additionally, the results suggest that had wind speeds been higher at the upper site, sublimation rates would have increased accordingly. The results from a model sensitivity analysis determined that the upper-site sublimation rates would have equaled the lower-site sublimation rates had wind speeds been twice as large at the upper site.

The results of this study also allow for an assessment of weighed artificial conifers as useful sensors for canopy sublimation studies. Artificial trees have the advantages of 1) minimal change in tare weight over a measurement season, 2) easily measured leaf area, 3) identical structure, for interception comparisons. Their disadvantages as instruments include 1) stiffer branches that support greater snow load, 2) branch stiffness that does not respond to temperature like natural branches, and 3) questions about thermal transfer and friction between needles and snow. Overall, artificial trees proved to be most useful when comparing sublimation at different locations with multiple trees to remove differences associated with tree geometry. Artificial trees would also be useful for studies conducted over several seasons when identical tree structure is essential. However, it seems likely that modification of artificial trees could improve their usefulness as snow interception sensors. Removal of branches to better match leaf area distribution to natural species could be done while maintaining identical structure for comparisons. Perhaps trees could be manufactured with more flexible branches.

5. Conclusions

Greater wind speeds, warmer temperatures, and lower relative humidity were observed at the lower site. These observations along with the sublimation rate predictions from the ice sphere model resulted in the conclusion that mean sublimation rates were 10% to 20% larger at the lower site, associated with differences in the energy balances. Although sublimation rates were more rapid at lower elevations, the upper site trees sublimated 8–16 mm more water per unit cross-sectional area and 1–2 mm more water per unit leaf area than the lower-site trees. Even with more rapid sublimation rates at the lower site, more water was sublimated and returned to the atmosphere from the upper-site trees because of greater interception from greater snowfall.

At a greatly reduced scale, the predicted sublimation rates for a 1-mm ice sphere followed the measured rates for the test trees, indicating that the ice sphere model properly accounted for the weather factors governing the sublimation process. Therefore, with the appropriate measures of temperature, relative humidity, and wind speed, the ice sphere model may provide a method of mapping a potential, or index sublimation rate over a basin, which would include the effects of elevation.

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REFERENCES

Alexander, R. R., C. A. Troendle, M. R. Kaufmann, W. D. Shepperd, G. L. Crouch, and R. K. Watkins, 1985: The Fraser Experimental Forest, Colorado: Research program and published research 1937–1985. USDA Forest Service General Tech. Rep. RM-118, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 46 pp.

Bernier, P. Y., and R. H. Swanson, 1993: The influence of opening size on snow evaporation in the forests of the Alberta Foothills. *Can. J. For. Res.,* **23,** 239–244.

Essery, R., L. Long, and J. W. Pomeroy, 1999: A distributed model of blowing snow over complex terrain. *Hydrol. Processes,* **13,** 2423–2438.

Granger, R. J., and D. H. Male, 1978: Melting of a prairie snowpack. *J. Appl. Meteor.,* **17,** 1833–1842.

Harding, R. J., and J. W. Pomeroy, 1996: The energy balance of the winter boreal landscape. *J. Climate,* **9,** 2778–2787.

Harlan, W. D., 1974: Snowpack evaporation in lodgepole pine. M.S. thesis, Dept. of Earth Resources, Colorado State University, 58 pp.

Hedstrom, N. R., and J. W. Pomeroy, 1998: Measurements and modeling of snow interception in the boreal forest. *Hydrol. Processes,* **12,** 1611–1625.

Hood, E., M. Williams, and D. Cline, 1999: Sublimation from a seasonal snowpack at a continental, mid-latitude alpine site. *Hydrol. Processes,* **13,** 1781–1797.

Kaufmann, M. R., C. B. Edminster, and C. A. Troendle, 1982: Leaf area determinations for subalpine tree species in the central Rocky Mountains. USDA Forest Service Research Paper RM-238, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 7 pp.

Lundberg, A., and S. Halldin, 1994: Evaporation of intercepted snow: Analysis of governing factors. *Water Resour. Res.,* **30,** 2587–2598.

——, I. Calder, and R. Harding, 1998: Evaporation of intercepted snow: Measurement and modeling. *J. Hydrol.,* **206,** 151–163.

Meiman, J. R., 1970: Snow accumulation related to elevation, aspect and forest canopy. *Proc. Workshop Seminar on Snow Hydrology,* Ottawa, ON, Canada, Canadian National Committee for the International Hydrologic Decade, 35–47.

——, and L. O. Grant, 1974: Snow–air interactions and management of mountain watershed snowpack. Completion Rep. Series 57,

Environmental Resources Center, Colorado State University, Fort Collins, CO, 33 pp.
Montesi, J. P., 2002: Sublimation of intercepted snow within a forest canopy at two elevations near Fraser, Colorado, U.S.A. M.S. thesis, Dept. of Earth Resources, Colorado State University, 146 pp.
Nakai, Y., T. Sakamoto, T. Terajima, H. Kitahara, and T. Saito, 1994: Snow interception by forest canopies: Weighing a conifer tree, meteorological observation and analysis by the Penman-Monteith formula. IAHS Publ. 223, 227–236.
——, ——, ——, K. Kitamura, and T. Shirai, 1999: Energy balance above a boreal coniferous forest: A difference in turbulent fluxes between snow-covered and snow-free canopies. *Hydrol. Processes,* **13,** 515–529.
Parviainen, J., and J. W. Pomeroy, 2000: Multiple-scale modeling of forest snow sublimation: Initial findings. *Hydrol. Processes,* **14,** 2669–2681.
Pomeroy, J. W., and R. A. Schmidt, 1993: The use of fractal geometry in modeling intercepted snow accumulation and sublimation. *Proc. 50th Eastern Snow Conf.,* Quebec City, QC, Canada, Eastern Snow Conference, 1–10.
——, and D. M. Gray, 1995: Snowcover accumulation, relocation and management. NHRI Science Rep. 7, National Hydrology Research Institute, Environment Canada, 134 pp.
——, ——, and P. G. Landine, 1993: The Prairie Blowing Snow Model: Characteristics, validation, operation. *J. Hydrol.,* **144,** 165–192.
——, P. Marsh, and D. M. Gray, 1997: Application of a distributed blowing snow model to the Arctic. *Hydrol. Processes,* **11,** 1451–1464.
——, J. Parviainen, N. Hedstrom, and D. M. Gray, 1998: Coupled modeling of forest snow interception and sublimation. *Hydrol. Processes,* **12,** 2317–2337.
Schmidt, R. A., 1972: Sublimation of wind-transported snow—A model. USDA Forest Service Research Paper RM-90, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO, 24 pp.
——, 1991: Sublimation of snow intercepted by an artificial conifer. *Agric. For. Meteor.,* **54,** 1–27.
——, and D. R. Gluns, 1991: Snowfall interception on branches of three conifer species. *Can. J. For. Res.,* **21,** 1262–1269.
——, and C. A. Troendle, 1992: Sublimation of intercepted snow as a global source of water vapor. *Proc. 60th Western Snow Conf.,* Jackson, WY, Western Snow Conference, 1–9.
——, R. L. Jairell, and J. W. Pomeroy, 1988: Measuring snow interception and loss from an artificial conifer. *Proc. 56th Western Snow Conf.,* Kalispell, MT, Western Snow Conference, 166–169.
——, C. A. Troendle, and J. R. Meiman, 1998: Sublimation of snowpacks in subalpine conifer forests. *Can. J. For. Res.,* **28,** 501–513.
Storck, P., and D. P. Lettenmaier, 1999: Predicting the effect of a forest canopy on ground snowpack accumulation and ablation in maritime climates. *Proc. 67th Western Snow Conf.,* Lake Tahoe, CA, Western Snow Conference, 1–12.
Thorpe, A., and B. Mason, 1966: The evaporation of ice spheres and ice crystals. *Br. J. Appl. Phys.,* **17,** 541–548.
Troendle, C. A., and J. R. Meiman, 1986: The effect of patch clearcutting on the water balance of a subalpine forest slope. *Proc. 54th Western Snow Conf.,* Phoenix, AZ, Western Snow Conference, 93–100.
——, R. A. Schmidt, and M. H. Martinez, 1993: Partitioning the deposition of winter snowfall as a function of aspect on forested slopes. *Proc. 61st Western Snow Conf.,* Quebec City, QC, Canada, Western Snow Conference, 373–379.
West, A. J., 1962: Snow evaporation from a forested watershed in the central Sierra Nevada. *J. For.,* **60,** 481–484.