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Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States

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[1] The results of a 3 year field study to observe the processes controlling snow interception by forest canopies and under canopy snow accumulation and ablation in mountain maritime climates are reported. The field study was further intended to provide data to develop and test models of forest canopy effects on beneath-canopy snowpack accumulation and melt and the plot and stand scales. Weighing lysimeters, cut-tree experiments, and manual snow surveys were deployed at a site in the Umpqua National Forest, Oregon (elevation 1200 m). A unique design for a weighing lysimeter was employed that allowed continuous measurements of snowpack evolution beneath a forest canopy to be taken at a scale unaffected by variability in canopy throughfall. Continuous observations of snowpack evolution in large clearings were made coincidentally with the canopy measurements. Large differences in snow accumulation and ablation were observed at sites beneath the forest canopy and in large clearings. These differences were not well described by simple relationships between the sites. Over the study period, approximately 60% of snowfall was intercepted by the canopy (up to a maximum of about 40 mm water equivalent). Instantaneous sublimation rates exceeded 0.5 mm per hour for short periods. However, apparent average sublimation from the intercepted snow was less than 1 mm per day and totaled approximately 100 mm per winter season. Approximately 72 and 28% of the remaining intercepted snow was removed as meltwater drip and large snow masses, respectively. Observed differences in snow interception rate and maximum snow interception capacity between Douglas fir (*Pseudotsuga menziesii*), white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), and lodgepole pine (*Pinus contorta*) were minimal. *INDEX TERMS:* 1863 Hydrology: Snow and ice (1827); 1836 Hydrology: Hydrologic budget (1655); 1878 Hydrology: Water/energy interactions; 1894 Hydrology: Instruments and techniques; *KEYWORDS:* snow, interception, accumulation, melt, forest, harvest

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1. Introduction

[2] The processes that control snow accumulation and melt in areas unaffected by forest canopies are well understood for a range of climates including the maritime Pacific Northwest [e.g., *U.S. Army Corps of Engineers* (*USACE*), 1956; *Marks et al.*, 1998]. Numerical models that explicitly represent these processes are described by *Anderson* [1976], *Price and Dunne* [1976], *Jordan* [1991], *Tarboton et al.* [1995], *Price* [1988], and *Marks et al.* [1988]. Despite differences in computational complexity and parameterizations (e.g., snow albedo and atmospheric stability corrections), these models share a common mass and energy balance formulation [*Anderson*, 1976] and are remarkably similar in their prediction of snow accumulation and melt in open areas [*Koivusalo and Heikinheimo*, 1999].

[3] Prediction of the evolution of snowpacks in forested areas is more complex. Recent advances in understanding and modeling the effects of forest canopies on ground snowpack dynamics follow two main avenues: (1) quantifying the energy balance of the snowpack beneath the canopy [e.g., *Hardy and Davis*, 1998] and (2) quantifying canopy interception and its effect on snow accumulation beneath the canopy [e.g., *Hedstrom and Pomeroy*, 1998]. Data from various field experiments have demonstrated that forest canopies alter the snowpack energy balance in cold continental climates [e.g., *Hardy and Davis*, 1998] and maritime climates [e.g., *Beaudry and Golding*, 1983; *Marks*

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et al., 1998; *Berris and Harr*, 1987; *Storck et al.*, 1999]. Energy balance models have been shown to simulate beneath-canopy snow accumulation and ablation in cold climates adequately [e.g., *Davis et al.*, 1997]. However, they remain largely untested for such predictions in mountain maritime climates due primarily to a lack of high quality field data [*van Heesjwick et al.*, 1996; *Marks et al.*, 1998].

[4] Field studies, conducted primarily in cold continental climates, have demonstrated that a large percentage of annual snowfall can be intercepted [*Hedstrom and Pomeroy*, 1998] and that sublimation loss from intercepted snow is significant and reduces snow accumulation beneath forest canopies [*Lundberg et al.*, 1998; *Schmidt*, 1991]. Current understanding of snow interception processes is more limited in maritime climates where snow sublimation is not the dominant removal mechanism. *Miller* [1962, 1964, 1966, 1967] hypothesized that canopy morphology and climate would affect snow interception rates and maximum interception capacities and that intercepted snow could be removed from the canopy via three pathways: sublimation, mechanical removal (sliding leading to mass release), and meltwater drip. In cold climates, where melt of intercepted snow occurs infrequently, field data collected on sublimation processes provide a clear picture of forest canopy effects on ground snowpack accumulation [see, e.g., *Pomeroy et al.*, 1998]. Field experiments conducted in maritime climates have reported a wide range of snow interception maxima. *Sauterland and Haupt* [1967] report a maximum interception of 4 mm snow water equivalent (SWE) on conifers while snow interception approaching 30 mm SWE was reported by *Bunnell et al.* [1985] and *Calder* [1990]. Data that allow partitioning of the sublimation, mass-release, and meltwater drip pathways in maritime climates are even more limited.

2. Approach

[5] This paper describes a three year field campaign to measure snow interception and processes by which snow removal from mature forest canopies occurs in a mountainous maritime environment. The field studies were further intended to provide data to develop and test an energy balance model of forest canopy effects on beneath-canopy snowpack accumulation and melt. In consideration of the latter objective, observations were collected not only at the scale of an individual tree but also at spatial scales approaching that of forest stands. The development and testing of the energy balance model of snow accumulation and melt beneath a forest canopy specific to maritime mountainous climates will be presented in a later paper.

2.1. Experimental Design

[6] A two-tiered observation strategy was utilized to measure canopy interception as well as under-canopy snow accumulation and ablation. Large weighing lysimeters were used to measure the ground snowpack water equivalent and outflow under an entire tree crown and in large clearings (tier 1) while cut-tree experiments were conducted to measure canopy processes directly (tier 2). Differences in snow water equivalent and outflow between weighing lysimeters placed beneath a forest canopy and in an adjacent clearing were used to infer the net effect of canopy dynamics and isolate individual processes as much as possible including; interception, sublimation, occurrence of meltwater drip and sliding of snow (mass release). The interception measurements from the cut-trees were used to check the validity of the inferred interception measurements and to provide a means for determining the difference in snow interception among tree species. Continuous measurements of the variables driving the energy balance (i.e., precipitation, radiation, wind, temperature, and humidity) were also taken. Weekly snow courses were conducted to verify the weighing lysimeter data and provide data at the forest stand scale. Each component of the field campaign is described in detail starting with section 2.3.

2.2. Site Description

[7] The field measurements were conducted as a part of the Demonstration of Ecosystem Management Options (DEMO) experiment [*Aubry et al.*, 1999] during the winters of 1996–1997, 1997–1998 and 1998–1999. The DEMO study was intended to quantify the effect of alternative forest harvest strategies on vegetation, wildlife, snow hydrology and fungi in Pacific Northwest forests. The snow hydrology component of the experiment was located northwest of Crater Lake, Oregon at an elevation of 1200 m. in the Umpqua National Forest of southwestern Oregon. The annual precipitation at the site is approximately 2 m, 70% of which falls between October and April. Significant snow accumulation usually begins in late November. Snow is generally present in clearings throughout the winter with annual average maximum SWEs of 350 mm in clearings. Average winter temperatures are often near freezing and the snowpack is maintained by occasional heavy snowfall. Mid-winter melt of the snowpack is common and final melt occurs in late April or early May. Mature forest stands at the site range in age from 110–130 years. The canopy is dominated by Douglas fir (*Pseudotsuga menziesii*). White fir (*Abies concolor*), western hemlock (*Tsuga heterophylla*), Ponderosa pine (*Pinus ponderosa*) and Lodgepole pine (*Pinus contorta*) are also present.

[8] Four weighing lysimeters were used to measure ground snowpack accumulation and melt. Two weighing lysimeters (25 m^2 surface area each) were placed beneath a mature canopy. Two smaller lysimeters (12.5 m^2 each) were placed in a clear-cut and a shelterwood (partially harvested) site. The clear-cut lysimeter became operational in the winter of 1997–1998; all others became operational during the winter of 1996–1997. The shelterwood had a green tree retention (fraction of live trees remaining after harvest) of approximately 15%. The cut tree experiments were conducted in a natural regeneration area adjacent to the beneath-canopy weighing lysimeters. Stand level snow accumulation and melt were measured by manual snow surveys over a 26 ha area adjacent to the beneath-canopy weighing lysimeters. All sites were located within 3 km of each other on level terrain with no significant slope, aspect, or elevation differences.

2.3. Weighing Lysimeter

[9] Each weighing lysimeter was designed to measure ground snowpack water equivalent and outflow continuously and consisted of six main parts as shown in Figure 1. These include (from the bottom up): (1) tipping buckets to measure outflow, (2) load cells and base supports, (3) steel

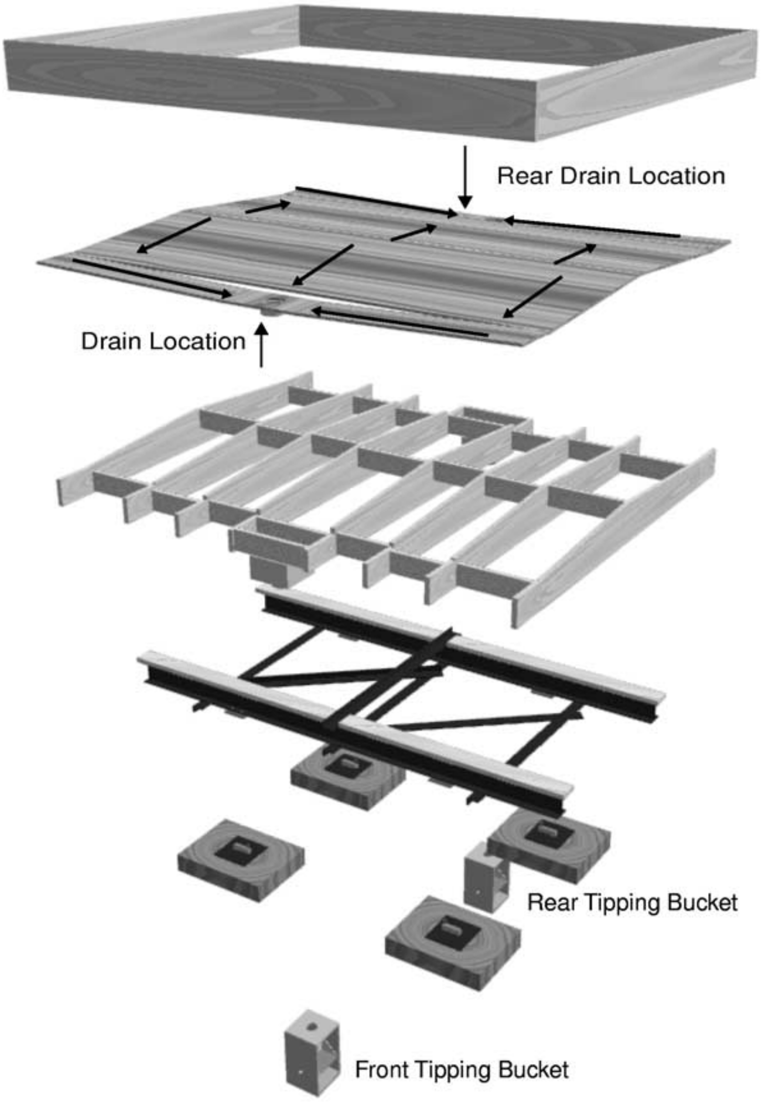

Figure 1. Exploded perspective drawing showing layered structure of weighing lysimeter including (from top) face planking, plywood decking (arrows indicate flow paths), wood joists, steel subframing, load cell platforms, and tipping buckets.

substructure to transfer the load directly to the load cells, (4) wood structure to ensure proper slopes for drainage to the tipping buckets, (5) a plywood skin and a waterproof liner, and (6) face panels to isolate the lysimeter's snowpack and outflow from the surrounding snowpack. Full details of the design and construction of the lysimeters are given by *Storck* [2000].

[10] Each lysimeter had a maximum design load of 800 mm of SWE and was weighed by four load cells positioned under the center of each quadrant of the lysimeter. The load cells were a standard shear beam deflection design with a total measurement error (including the effects of temperature, nonlinearity and hysteresis) of 0.05% of the full scale range. Thus each lysimeter had an expected measurement error of approximately 0.4 mm.

[11] Meltwater from each lysimeter was routed into one of two drainage strips and then toward the drain outlets so that each tipping bucket drained exactly half of the lysimeter surface area. The slope in each direction was approximately 0.05 m/m. A 72 mil polyethylene liner draped over a plywood deck served as the drainage surface. Previous lysimeter designs have been plagued by leaks at the drainage outlet due to failures in the adhesive during frequent freeze-thaw cycles and the relatively small diameter of the drain and drainage pipes, which are typically 38 to 55 mm in diameter [*Berris and Harr*, 1987; *Storck et al.*, 1999]. Following the failure of our initial drain design during the winter of 1996–97, the drains were reconstructed using 10 cm diameter plastic (schedule 40 ABS) floor drains and matching rings with a combination of compression fittings and roofing tar (Figure 2). The air gap between the drain and the collection basin allowed a proper weight measurement in the lysimeter even if the pipe to the tipping bucket froze. Outflow from each of the two collection basins was measured by separate 1 L capacity tipping buckets installed below grade in an insulated plywood enclosure.

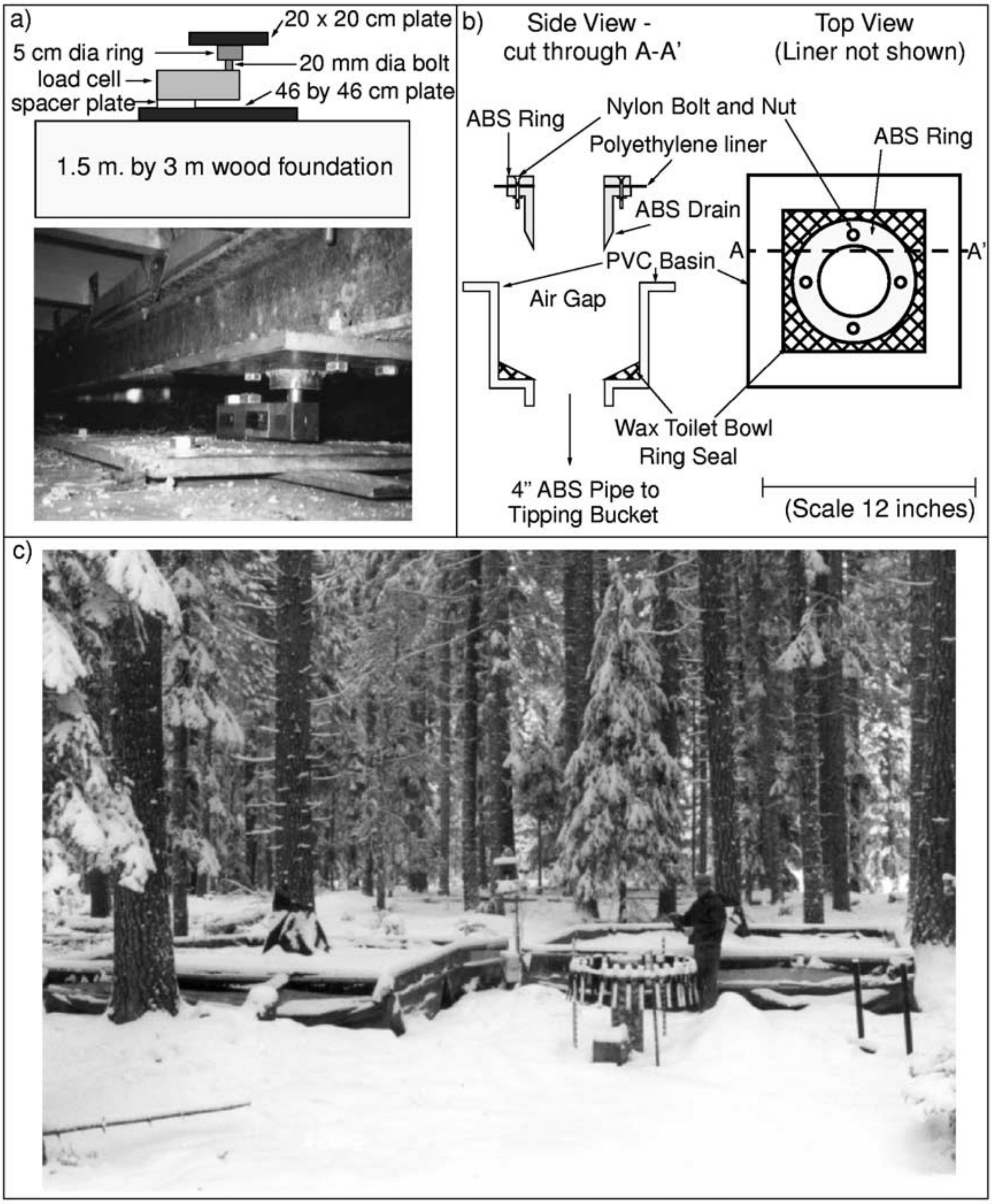

Figure 2. (a) Schematic and photograph detail of load cell installation, (b) schematic of drain design and air gap (side view is taken at cross section A-A', and (c) photograph of two beneath-canopy weighing lysimeters installed around adjacent Douglas fir trees. (A shielded precipitation gauge is shown in the foreground. The person in the foreground is approximately 2 m tall).

[12] Weighing lysimeters installed beneath the forest canopy were constructed around individual Douglas fir trees such that all throughfall from the crown was collected (Figure 2). To reduce bias due to differences among the individual trees, two independent lysimeters were installed around adjacent Douglas fir trees. Edge effects due to placement of the lysimeter beneath the canopy were minimized by the large sampled area and by the similarity of surrounding canopy cover. Field observations showed that mass release and drip from each tree was captured by the weighing lysimeters. Stemflow was routed into the lysimeter via a drip skirt fastened to each trunk but was not measured separately.

2.4. Cut-Tree Experiments

[13] A series of cut-tree experiments were conducted to measure snow interception directly and to study interspecies differences in interception. The design of the cut-tree measurement device is shown in Figure 3. Weighing lysimeters identical to those described earlier but with a

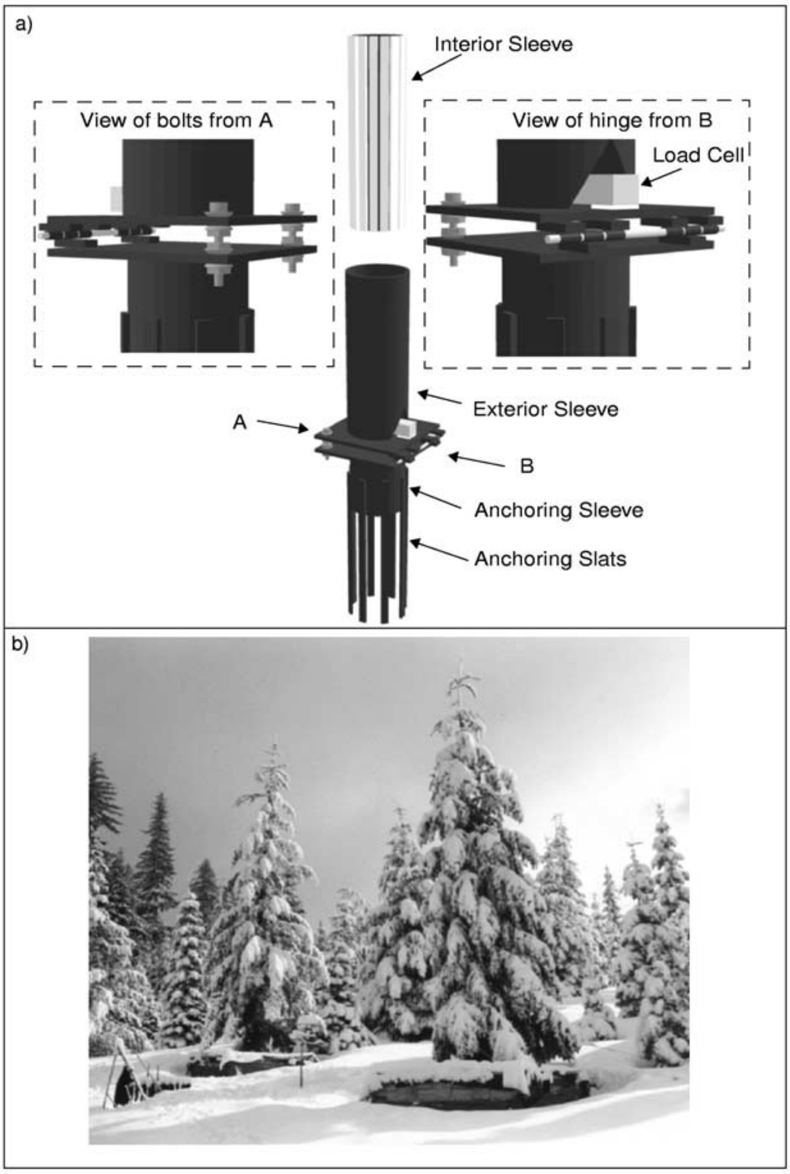

Figure 3. (a) Rendering of tree weighing device showing nested tube construction, anchoring sleeve and side perspectives of hinge and leveling bolts and (b) photograph of cut-tree experiment immediately after a snowfall of 40 mm SWE. The trees in the foreground and background are 8 and 11 m tall Douglas firs, respectively.

surface area of 6 m^2 were located beneath two of the cut trees. These weighing lysimeters were constructed around a tree such that the trunk protruded directly through the center of the lysimeter. After the tree was removed, the remaining stump was used to anchor a tree-weighing device so that the cut-tree and the under-canopy snowpack were weighed independently. The tree weighing device (Figure 3) was developed specifically to be easily portable (allowing mid-winter installation), to hold the trees at their cut end only, and to be insensitive to wind loading. It consisted of a pair of nested steel tubes with 10 mm thick walls. The interior tube, which held the cut tree, had a 15 cm outside diameter (OD) and the exterior tube had a 20 cm OD. A steel plate was welded to the bottom of the exterior tube and the bottom of the interior tube was capped with another steel plate. High-density polyethylene slats reduced the interior clearance between the two tubes to approximately 0.5 mm. The close tolerance of the design minimized potential for binding while the polyethylene reduced interior friction. A single 1100 kg load cell was placed through a hole cut in the side of the exterior tube such that the load axis was directly beneath the center of the interior tube. A support sleeve was used to anchor the cut-tree weighing device to the stump of the cut-tree. This sleeve consisted of a steel plate welded to a 20 cm OD steel tube. This sleeve was placed over the stump and was anchored in place through 1 meter long perforated slats welded to the exterior of the sleeve. Lag bolts were used to anchor the slats to the stump. The base plate of the exterior tube and the base plate of the anchor were connected with a single long hinge along one side of the steel plates and two bolts along the opposite side. The hinge facilitated insertion of the inner tube (bearing the full load of a tree) into the outer tube. Once the inner tube was completely inserted, the cut tree was pushed into position using a series of long poles with the hinge serving as a fulcrum point. Up to four cut-tree weighing devices were installed in the field, however, only two of these included weighing lysimeters.

2.5. Precipitation, Micrometeorology, and Manual Snow Surveys

[14] Precipitation was measured with a resolution of 1 mm by two unheated tipping bucket gauges at the shelterwood site and one located near the beneath-canopy lysimeter (Figure 2). The gauge was filled with a 3:2 mixture of propylene glycol and ethanol antifreeze solution [*McGurk*, 1992] topped with a thin layer of 10–30 weight motor oil, which prevented ethanol evaporation. Precipitation melted in the antifreeze reservoir and displaced an identical volume of antifreeze into a tipping bucket. To limit catch deficiencies, each gauge was shielded from the wind (Figure 2). Measurements of wind speed (RM. Young 3-cup anemometer), air temperature and relative humidity (Campbell Scientific CS 500 air temperature and relative humidity probe with a six plate radiation shield) and incoming short- and long-wave radiation (Eppley Black and White pyranometer and Eppley pyrgeometer) were taken at each weighing lysimeter site at 2-m above the soil surface. Summary statistics were recorded every 30 minutes. Weekly snow courses measurements were taken at 40 points on a uniform grid (80 by 80 meter spacing) over an adjacent 26 ha forest stand. Average canopy closure over the snow course area was approximately 70%.

3. Results

[15] There are significant gaps in the data records due to equipment failure (e.g., all outflow data from the 1996–1997 season after 1 January 1997 were affected by drain failure, and a herd of elk damaged the clear-cut lysimeter during the 1997–1998 season). When equipment malfunction was suspected, the data were reported as missing.

[16] Substantial differences in maximum snow accumulation at the shelterwood site occurred over the three years of measurements and follow large scale regional anomalies. The 1998–1999 season was characterized by a strong La-Nina event and had large snow accumulations at the shelterwood site (700 mm maximum SWE). The 1997/98 season occurred during a strong El Nino event and had low snow accumulations (225 mm). The 1996–1997 season was ENSO neutral and had more typical conditions for the Pacific Northwest (350 mm).

[17] Large differences between open and beneath-canopy snowpack SWE were observed during each of the three field seasons (Figures 4, 5, and 6). These differences are not well described by a simple relationship between beneath-canopy and open snow accumulation. Overall snow accumulation beneath the canopy was significantly less than that in open sites and final melt of the snowpack beneath the canopy occurred roughly one month earlier than in the open sites.

3.1. Weighing Lysimeter Data

[18] During the period from 11 November 1996 through 1 January 1997, snow interception processes limited under-canopy accumulation to approximately 50% of the accumulation in the shelterwood (Figure 4). The rain-on-snow (ROS) event of 29 December 1996 to 2 January 1997 (the only significant ROS event during the three years of field observations) resulted in significant loss of SWE from the shelterwood (86.9 mm) as well as the beneath-canopy weighing lysimeters (60.4 mm). Subsequently, the beneath-canopy and clearing snow accumulations continued to diverge, and by 1 March 1997, the below-canopy snowpack had almost completely melted while SWE in the shelterwood was 250 mm, close to the maximum for the year. Final snowmelt in the clearing occurred approximately one month later than beneath the canopy.

[19] During the 1997–1998 El Nino season the maximum SWE beneath the canopy was less than 50 mm while the maximum SWE in the shelterwood approached 250 mm. Some dense forest stands adjacent to the beneath-canopy site remained snow free during the entire winter season. Air temperature remained near freezing during the period from 6 January 1998 to 15 January 1998 and while snow accumulated at the shelterwood site there was no snow accumulation beneath the forest canopy. Final snowmelt beneath the canopy occurred approximately two weeks before final melt in the shelterwood.

[20] Much greater snow accumulation occurred at all sites during 1998–1999. Snow accumulation beneath the canopy was considerably less than at the shelterwood prior to 15 January 1999 with considerable accumulation at all sites thereafter. Accumulation and ablation of SWE in the clear-cut and shelterwood sites were nearly identical during the period of coincident observations. Final snowmelt beneath the forest canopy occurred approximately one month before final snowmelt in the shelterwood.

[21] The beneath-canopy snow course data exhibit a great deal of variability and range from considerably less than that observed by the beneath-canopy weighing lysimeters (in some cases zero) to more than that observed in the shelterwood site on almost every snow survey date (Figures 4, 5, and 6). The mean beneath-canopy SWE was greater than that observed by the beneath-canopy weighing lysimeters at each snow survey date. This difference was due to the placement of the lysimeters around and directly beneath two mature trees (100% effective canopy coverage) while the forest stand had an average canopy closure of approximately 70%. The variability on each snow survey date is due to the random placement of the snow survey points. Snow survey points located in small clearings accumulated snow at rates similar to the shelterwood while those located in areas of dense forest cover showed near zero accumulation irrespective of snowfall. The similarity in snow accumulation in forest canopy clearings and shelterwood was especially noticeable for the first snow survey of each season. As each season progressed, snow water equivalents in the forest clearings exceeded those in the shelterwood lysimeter due to the sheltering of the snow from wind and shortwave radiation.

3.2. Cut-Tree Experiments

[22] The cut-tree measurements of snow interception showed considerable differences in maximum observed interception loads among the three years. Characteristics of the cut trees used during the three winter seasons are given in Table 1.

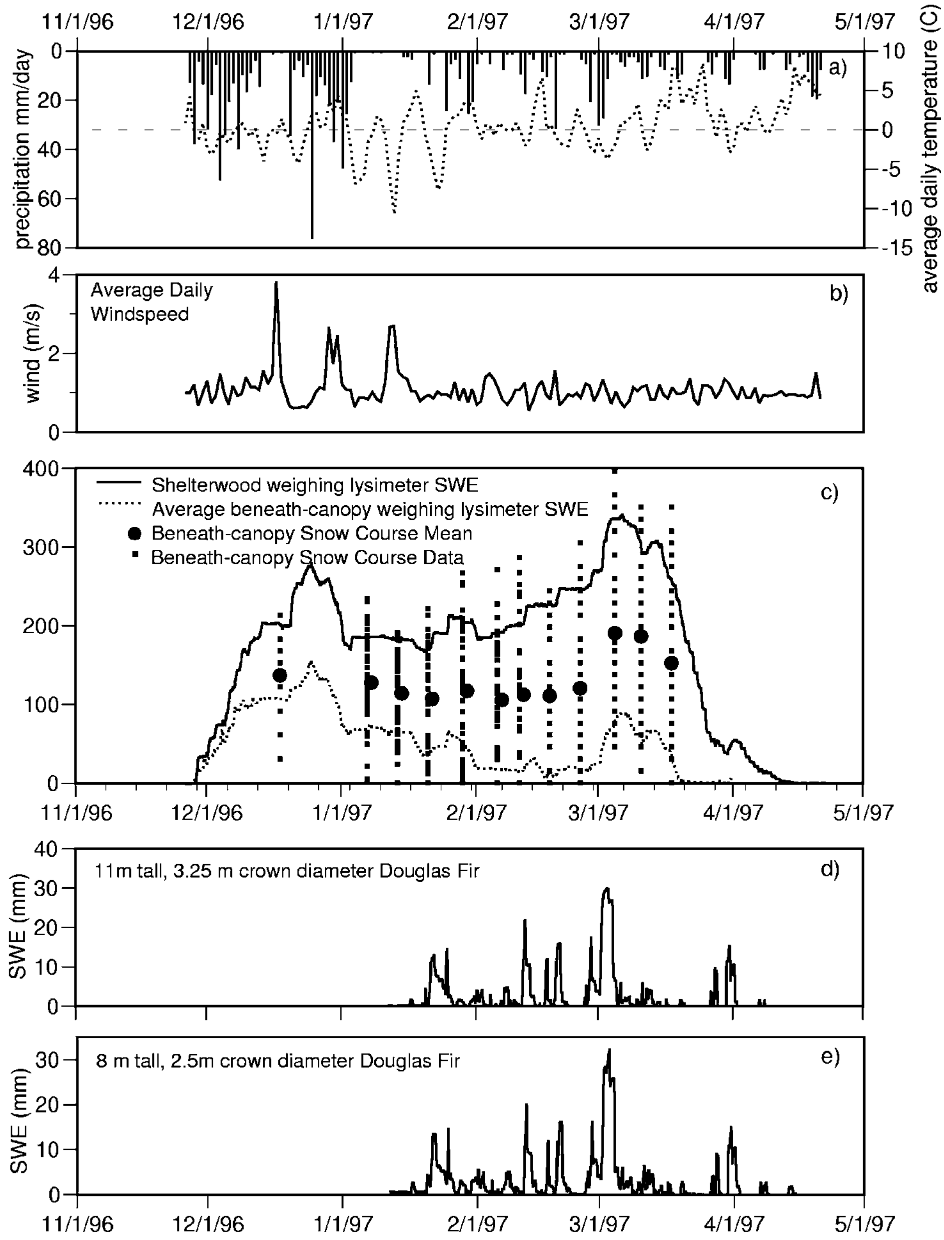

Figure 4. Summary results for 1996–1997 snow season. (a) Daily average air temperature and total daily precipitation, (b) daily average wind speed, (c) shelter wood and beneath-canopy SWE, and (d and e) intercepted snow load on two Douglas fir cut trees.

[23] Maximum snow interception approaching 30 mm of SWE was observed on the cut trees during both the 1996–1997 (Figures 4d and 4e) and 1998–1999 seasons (Figure 6d). In contrast, maximum snow interception did not exceed 15 mm during the much drier winter of 1997–1998 (Figures 5d and 5e). During all seasons, remarkably similar behavior in the loading and unloading of intercepted snow was observed among trees of different species and different size. Intercepted snow was quickly removed from the canopy immediately following the majority of snowfall events.

3.3. Snow Interception by a Mature Douglas Fir Canopy

[24] Figure 7 shows apparent maximum snow interception by the mature Douglas fir canopy above each of the beneath-canopy lysimeters. Data were obtained from 36 individual snowfall events over the three winter seasons and are presented individually for both below canopy weighing lysimeters (A and B in Figure 7). Some events were not observed by both beneath-canopy weighing lysimeters due to instrument malfunction. Total snowfall in the open during events was measured as the net change in weight of the shelterwood lysimeter. Snowfall events were assumed to begin after the air temperature fell below 1°C. Snow interception by the mature canopy was inferred as the difference between snowfall in the open and the net increase in weight of the beneath-canopy lysimeters. Because many snowfall events transitioned to rain, each event was assumed to end either immediately after precipitation ceased or air temperature rose above 1°C, whichever occurred first.

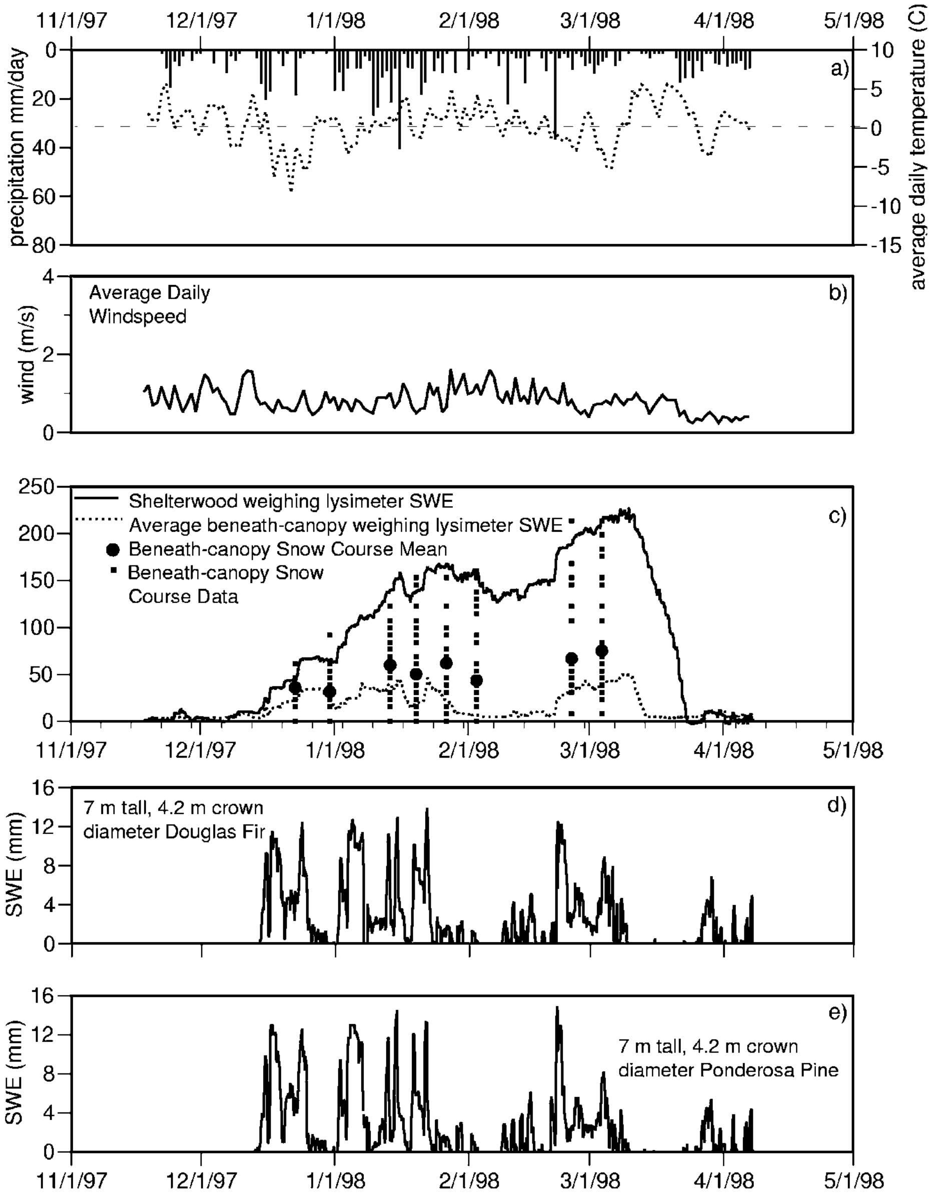

Figure 5. Summary results for 1997–1998 snow season. (a) Daily average air temperature and total daily precipitation, (b) daily average wind speed, (c) shelter wood and beneath-canopy SWE, and intercepted snow load on (d) Douglas fir and (e) ponderosa pine cut trees.

[25] Canopy interception is well described as approximately 60% of total snowfall for all events with storm snowfall less than 50 mm of SWE. The 95% confidence interval for the slope of the linear regression shown in Figure 7 is ±4%. Although a clear maximum on snow interception is not defined by these data, and hence no attempt was made to fit an asymptotic function, they suggest that it is at least 40 mm of water equivalent. The strongly linear relationship between apparent snow interception and snowfall for snowfalls less than 50 mm water equivalent suggests that differences in air temperature and wind speed do not strongly affect snow interception by the mature canopy over the range of micrometeorological conditions observed. It should be noted that most of these snowfall events occurred during periods of light wind (less than 2 m/s as observed at the shelterwood site) and relatively warm air temperatures (above −5°C).

[26] A similar linear trend describes the evolution of intercepted snow during the eight largest snowfall events (Figure 8a). Intercepted snow at 30 minute intervals during snowfall was calculated from the beneath-canopy and shelterwood lysimeter data as described above. The growth of intercepted snow is well described as 60% of snowfall for snowfalls less than 50 mm SWE for seven of the eight example events shown. The apparent linear growth of intercepted snow on the forest canopy during events provides guidance for modeling snow interception in maritime climates over the range of conditions observed here. These data also suggests that snow interception during light snowfalls (i.e., less than 10 mm of SWE) is well described by a

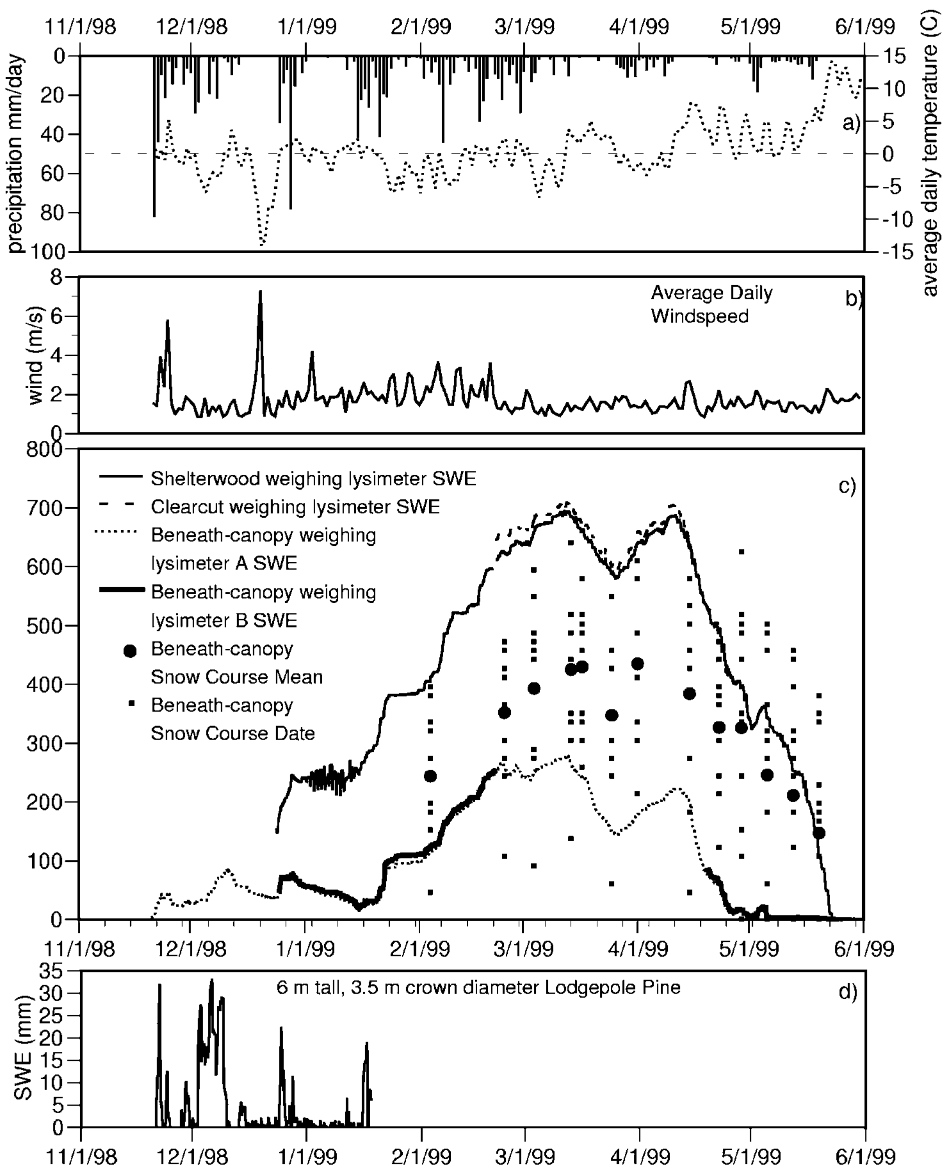

Figure 6. Summary results for 1998–1999 snow season. (a) Daily average air temperature and total daily precipitation, (b) daily average wind speed, (c) shelter wood, clearcut, and beneath-canopy SWE, and (d) intercepted snow load on a cut lodgepole pine tree.

linear growth form. Bias in modeling these frequent smaller events could lead to significant bias in the modeling of seasonal effects of snow interception on the ground snowpack water balance.

[27] During the eighth event (February 1999), 40 mm of SWE was intercepted during a snowfall of 80 mm SWE. The February 1999 event is of particular interest because it was the largest and coldest snowfall event during the three year study (Figure 8b). Early in this event, air temperature was slightly above freezing and growth of intercepted snow was 60% of snowfall. After approximately 32 mm of snowfall, the air temperature fell abruptly to −12°C and wind speed increased. These short-lived changes in meteorological con-

Table 1. Species, Height, and Crown Base Diameter Cut Trees From 1996 to 1999[a]

Season	Species	Height, m	Crown Base Diameter, m
1996/1997	Douglas fir (*Pseudotsuga menziesii*)	11	3.25
1996/1997	Douglas fir (*Pseudotsuga menziesii*)	8	2.5
1997/1998	Douglas fir (*Pseudotsuga menziesii*)	7	4.2
1997/1998	ponderosa pine (*Pinus ponderosa*)	7	4.2
1997/1998	white fir (*Abies concolor*)	6	2.0
1998/1999	lodgepole pine (*Pinus contorta*)	6	3.5

[a] Intercepted snow is expressed in millimeters of water equivalent based on the mass of intercepted snow load (kg) divided by the vertical projected area of the tree (m^2).

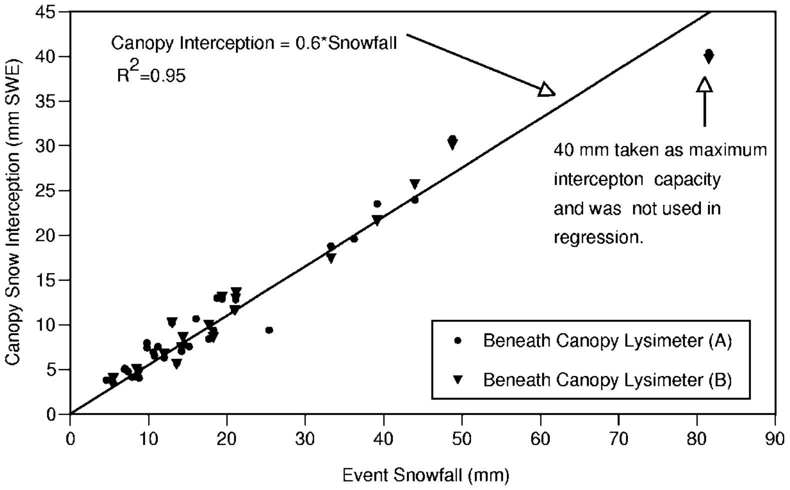

Figure 7. Estimated snow interception by a mature Douglas fir canopy (residual of open and beneath-canopy snow accumulation) as measured by two beneath-canopy weighing lysimeters for 36 snowfall events.

ditions correspond to a slight reduction in the rate of snow interception, which lasted until approximately 47 mm of accumulated snowfall. As the storm continued, conditions remained cold and winds decreased and snow interception proceeded at a rate close to 60% of snowfall up to 70 mm of total precipitation. A slight decrease in interception rate was observed from this point until the event ended.

[28] Since this was the only event during which conditions became significantly cold and windy during snowfall, no conclusions can be drawn as to the effect of wind and air temperature on snow interception rate. Nevertheless, due to the rare occurrence of cold snowfalls in maritime climates and the nearly constant interception efficiency during and between events observed here, the effect of wind removal during cold snowfalls seems less important in maritime climates than in colder climates simply because cold snowfalls do not occur as frequently. The February 1999 event (Figure 8b) is the exception. During this event, the snow interception rate varies with wind speed and temperature. The introduction of a variable interception rate in a snow interception model would also introduce a maximum time step requirement. If a snow interception model was implemented at too coarse a temporal resolution, the effect of these abrupt changes in wind and temperature would be ignored.

3.4. Differences in Snow Interception Between Cut Trees

[29] Over the course of the three winter seasons, six cut trees of four different species were weighed to quantify differences in the growth of intercepted snow and the maximum interception capacity due to morphology. Data from the cut trees were also used to provide an independent check on inferred snow interception by the mature canopy.

[30] The growth of intercepted snow on the cut trees during twelve snowfall events is shown in Figure 9. Intercepted snow load is expressed in millimeters by dividing the mass of snow on the tree (kg) by the vertical projected area of the tree (m^2). Snowfall during events was measured by the shelterwood weighing lysimeter. For some events, intercepted water on the cut trees approached 5 mm at the onset of snowfall. In many cases this initial storage was due to rainfall interception prior to the onset of snowfall (these initial interception depths were typically observed to be 3 mm or less). In a few cases, the 5 mm initial storage was a residual from previous snowfall. The initial intercepted water at the onset of snowfall was removed from the analysis so that all event traces in Figure 9 start with zero interception. Observations from all simultaneously weighed cut trees during each event are shown.

[31] During 1996–1997 only two cut tree devices were installed (Figures 9a–9e). During 1997–98 two additional devices were installed (for a total of four) but one device failed (Figures 9f–9j). During the winter of 1998–1999 an early snowfall prevented the installation of all but one cut-tree experiment (Figures 9k and 9l).

[32] While snow interception by the mature canopy was well described for all events as a constant linear function of snowfall, no such clear relationship is seen from the cut-tree data. Individual snowfall events show considerable variability in the rate of growth of intercepted snow on cut trees, often initially exceeding the rate of snowfall. Interception rates above the rate of snowfall occur when snow falls at an angle to vertical.

[33] Despite the variability among events, variability among individual cut trees (either of different species or size) during a single event was considerably less. The two Douglas fir trees intercepted snow similarly during the 1996–1997 season despite their differences in size. The Douglas fir and ponderosa pine trees showed nearly identical patterns and magnitudes of snow interception during the 1997–1998 season (Figures 9f–9j). The rate and final magnitude of snow interception on the white fir during the 1997–1998 season were similar to Douglas fir and ponderosa pine trees during two of four events, but were lower during the other two events. Lodgepole pine was not simultaneously compared to trees of other species, however, it exhibited growth forms and interception capacities similar to the other species. This result is important for model parameterizations. Despite obvious differences in structure

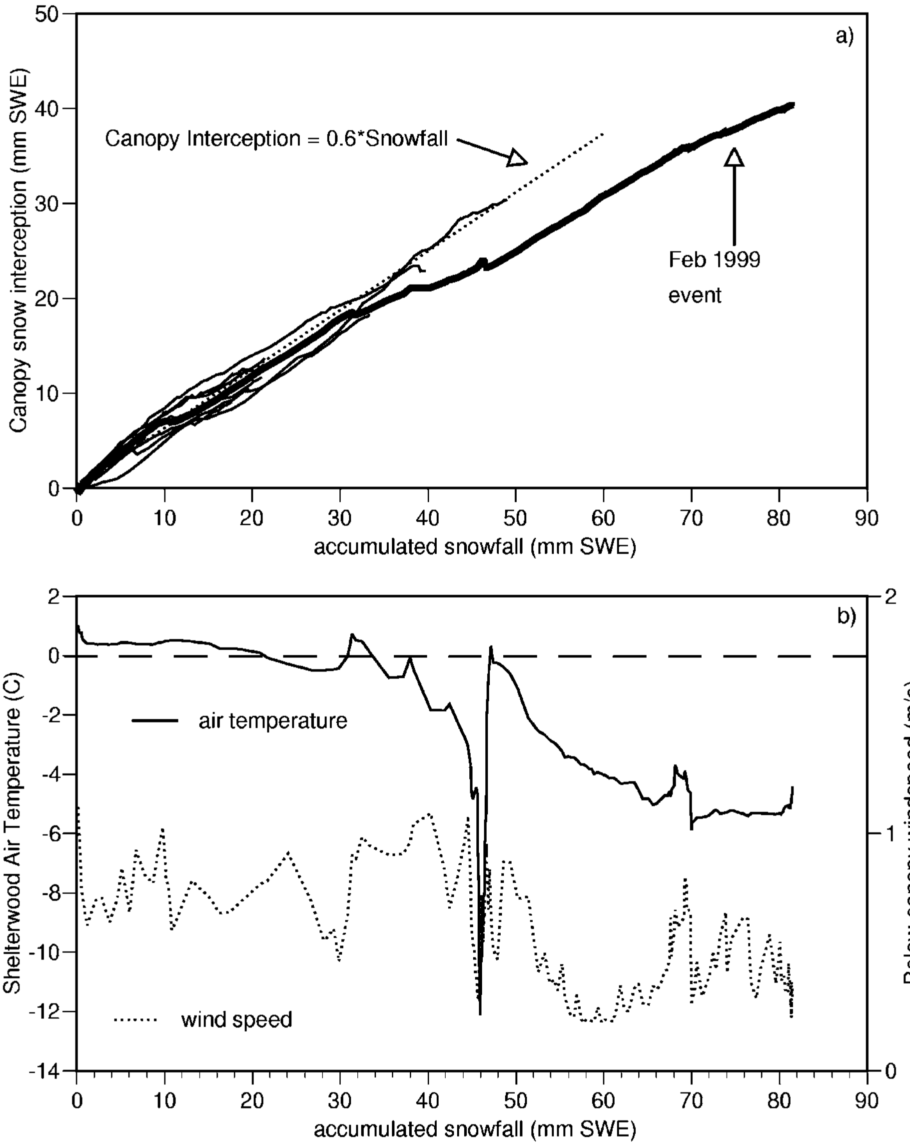

Figure 8. (a) Calculated growth of intercepted snow on the mature canopy during eight major snowfall events. (b) Air temperature and wind speed during February 1999 snow interception event plotted versus accumulated snowfall at the shelter wood site. Measurements of wind speed in the open were not available during this period.

and branch flexibility between ponderosa pine, Douglas fir, white fir and lodgepole pine, these differences apparently can be ignored in determining the relative rate and maximum amount of snow interception for the conditions that prevailed at the times and locations of the observations. Similar insensitivity to species type has been found in previous studies that have measured snow interception by weighing cut trees [*Satterlund and Haupt*, 1970] and cut tree branches [*Schmidt and Gluns*, 1991].

3.5. Seasonal Estimate of Intercepted Snow Sublimation-Wet Canopy Evaporation

[34] Comparisons among lysimeters provide a basis for estimating losses from intercepted snow in the mature canopy (Figure 10). Total accumulated water (SWE + accumulated outflow) is shown along with net loss, defined as the difference between total accumulated water measured by the shelterwood and the beneath-canopy weighing lysimeters. The net loss term includes all possible processes that could remove water from the canopy and not deposit it in the below canopy lysimeter. Thus net loss included sublimation of intercepted snow and evaporation of intercepted water but could also have included meltwater drip or mass release from intercepted snow that was not captured by the beneath-canopy weighing lysimeter. Great care was taken during the design and placement of the beneath-canopy lysimeters to minimize this source of error. During extended periods of time when snow was removed rapidly from the canopy via meltwater drip and mass release, estimated loss was near zero. This result suggests that the estimate of loss was not biased due to the size or placement of the lysimeters.

[35] Estimated annual loss during 1997–1998 was on the order of 100 mm and appears to be strongly dependent on

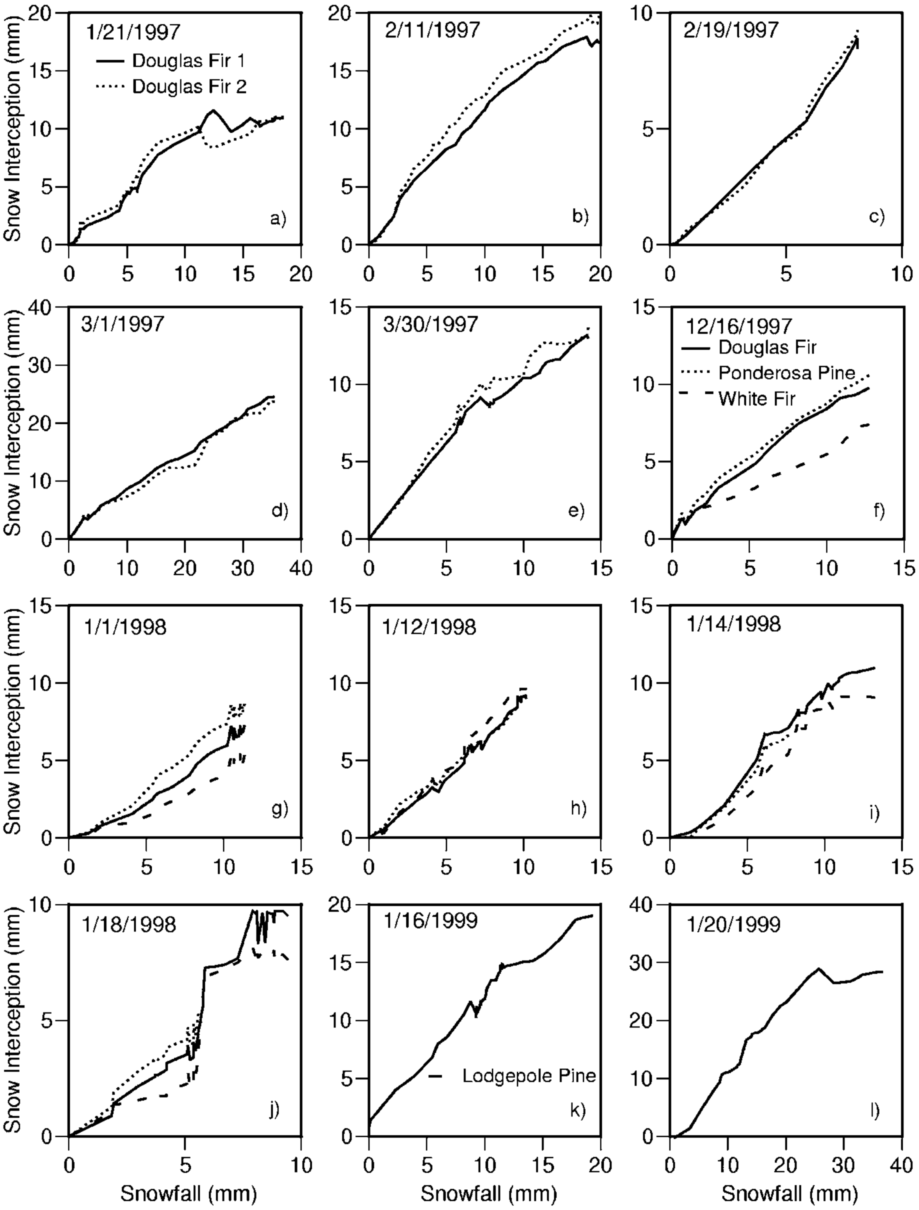

Figure 9. Snow interception versus snowfall for 12 snowfall events over three snow seasons ((a–e) 1996/1997, (f–j), 1997/1998, and (k and l) 1998/1999) as observed on cut trees.

local micrometeorology. During the relatively cold period from 1 December 1997 to 7 January 1998, during which air temperatures remained below freezing and wind speeds in the shelterwood averaged 0.85 m/s, estimated loss was 34 mm (~1 mm/day). During the warm, wet period from 7 January 1998 to 1 February 1998 during which wind speeds in the shelterwood averaged 0.89 m/s, estimated loss was only 4 mm (about 0.2 mm/day).

[36] These differences are explained by the patterns of snow interception (as measured by the cut-tree experiment) shown in Figures 5d and 5e. During both periods described above, significant snow interception occurred. However, during the period with high estimated loss, the snow remained on the canopy longer than during the period of negligible loss. A second period of significant interception loss, centered on 1 March 1998, corresponds to another lengthy interception event.

[37] Similar overall magnitudes and patterns of interception loss occurred during the 1998–1999 season. Early winter loss is not reported due to the failure of the data loggers at the shelterwood and clear-cut lysimeters through 20 December 1998. During the relatively warm period just prior to 1 January 1999, significant snow interception occurred (as evidenced by the cut tree weight in Figure 6d). Due to the rapid removal of snow from the canopy, total loss was negligible during this first event. Significant net loss of water due to canopy processes was observed during a later event, centered around 1 February 1999. The reduction in total water at the shelterwood site after 15 March 1999 (most noticeable around 15 April 1999) is

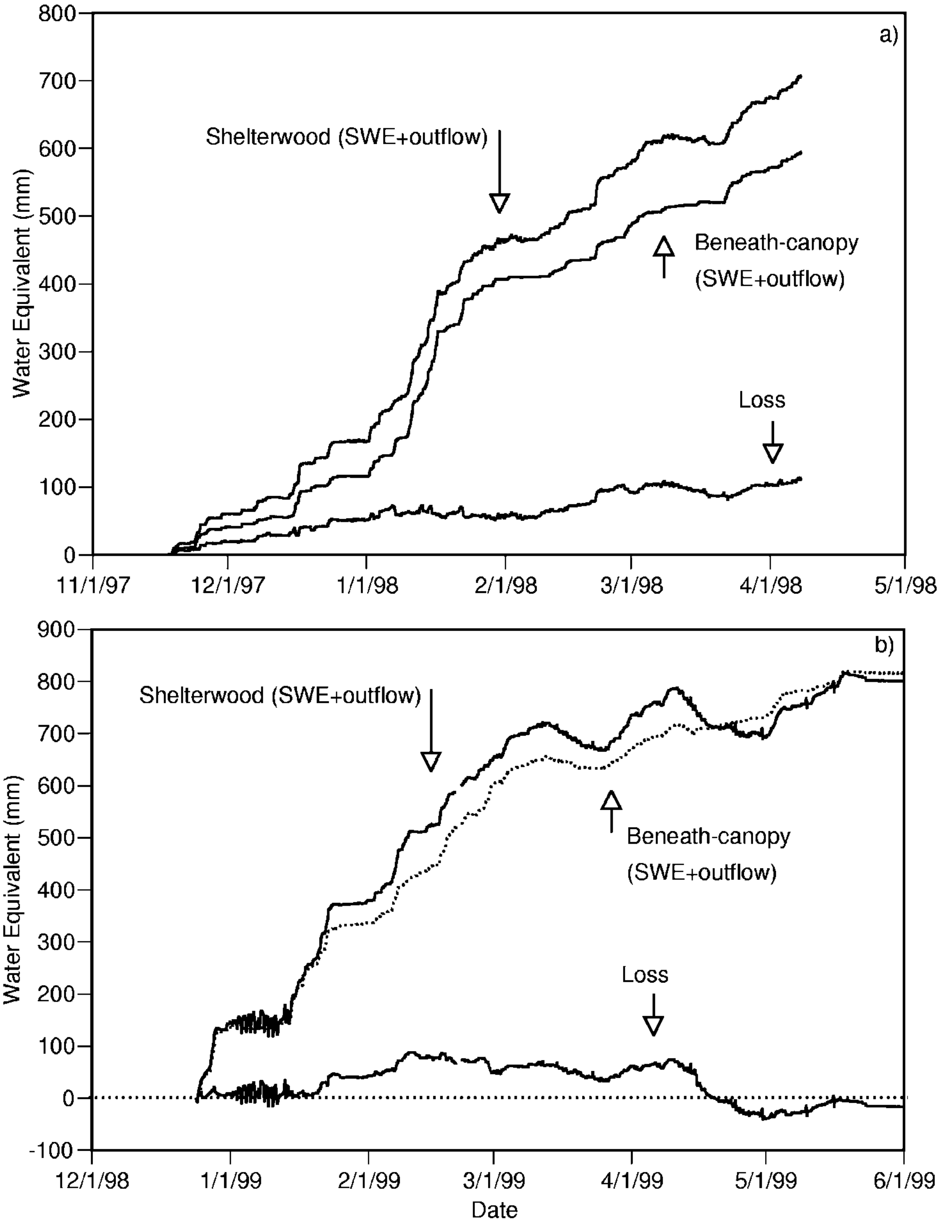

Figure 10. Estimated sublimation loss from intercepted snow (residual of shelter wood and beneath-canopy total water) over two winter seasons (1997/1998 and 1998/1999). Data for the 1996–1997 season are not shown due to the failure of the prototype lysimeter design.

caused by routing of meltwater out of the shelterwood lysimeter due to the depth of the snowpack (exceeding 2 m). After 1 May 1999 (and a considerable loss of snow depth), the shelterwood observation of outflow is correct. Since this meltwater was not measured as outflow, the estimate of total water at the shelterwood site was biased from 15 March 1999 to 1 May 1999. The net loss due to canopy processes during a bias free period (24 December 1998 to 24 February 1999), during which wind speed in the shelterwood averaged 2.0 m/s, was approximately one mm per day. If the seasonal estimate of total water at the shelterwood site is corrected for bias (by assuming that sublimation from the shelterwood lysimeter is negligible and closing the mass balance using the change in weight of the shelterwood lysimeter and readings from a precipitation gauge), the overall loss for the 1998–1999 season was approximately 100 mm of water equivalent, which is similar to the estimate for the 1997–1998 season.

3.6. Cut-tree Snow Sublimation

[38] Occasional high rates of sublimation from intercepted snow were measured by the cut tree experiments. Although a number of periods with high sublimation rates apparently occurred (as described above), they could not be isolated as pure sublimation events due to increases in the weight of the lysimeter below the cut-tree or the occurrence

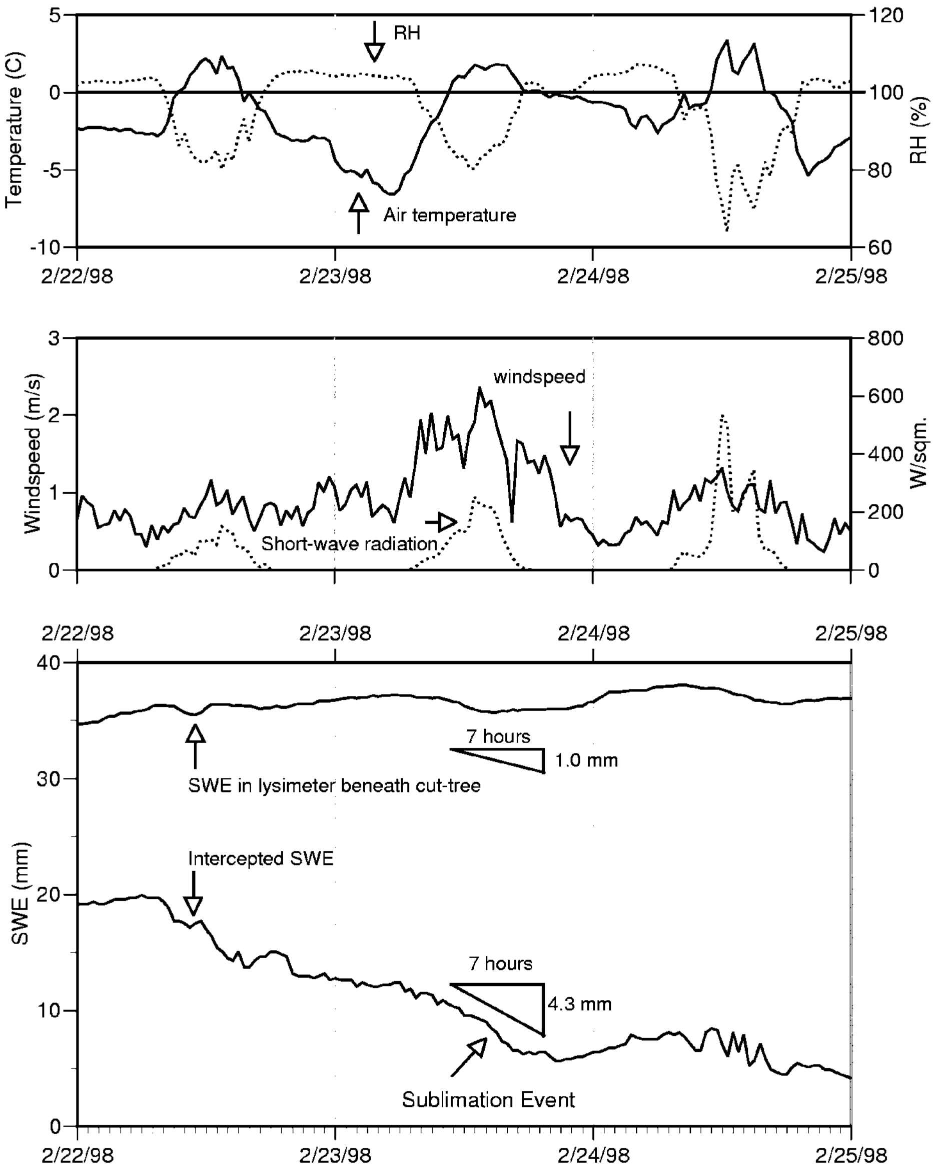

Figure 11. Loss of intercepted snow from a cut white fir tree during a rare precipitation free period during which intercepted snow remained on the canopy. No outflow was observed during this period from the lysimeter beneath the cut tree or the lysimeter at the shelter wood site.

of lysimeter outflow, both of which are indicative of melt of intercepted snow or removal from the canopy by wind action. Figure 11 shows observed micrometeorology, cut-tree snow interception, and ground SWE for a single event during which no outflow or increase in weight was recorded by the weighing lysimeter, thus the reduction in weight of the cut-tree was due entirely to sublimation and/or evaporation of intercepted water.

[39] Apparent sublimation of 4.3 mm SWE over seven hours was observed from the canopy on 23 February 1998. While this rate is high, opportunities for such high sublimation rates are limited due to the rapid removal of snow from the canopy via meltwater drip or mass release in most cases when conditions otherwise conducive to high sublimation are present. Apparent sublimation from the weighing lysimeter beneath the cut-tree during this event was one mm over seven hours, only 25% of that observed from the intercepted snow on the canopy. The combination of increased temperature, reduced relative humidity, higher wind speed and net radiation all contributed to the large apparent sublimation loss from the intercepted snow. Similar high rates of sublimation losses have been measured by cut-trees in cold climates [*Hedstrom and Pomeroy*, 1998; *Lundberg et al.*, 1998].

3.7. Partitioning of Meltwater Drip and Mass Release

[40] The two remaining mechanisms for removing intercepted snow from the canopy are meltwater drip and mass release. From the results above it is apparent that these two mechanisms must account for the majority of the difference in snow accumulation between forested and open sites. Unfortunately, both of these processes almost always

occur simultaneously and their measurement is confounded by changes in the ground snowpack after interception events. Consequently, the relative magnitudes of meltwater drip and mass release could not be determined when the snow in the beneath-canopy lysimeter was actively melting or rain was occurring.

[41] Despite these problems, estimates of the relative magnitudes of meltwater drip and mass release were obtained for the period from 1 to 14 December 1996 during which melt of the ground snowpack did not occur (i.e., canopy processes controlled ground snow dynamics) (Figure 6). Snow accumulation in the shelterwood was 195 mm while 111 mm accumulated beneath the canopy. During this same period, 84 mm of additional outflow was observed below the forest canopy. Assuming that 60% of all snowfall was intercepted by the canopy (117 mm total interception) and 40% was snow throughfall (78 mm direct throughfall), these data imply that 33 mm (28%) of the intercepted snow reached the ground as snow while 84 mm (72%) was removed as meltwater drip. These calculations suggest a ratio of mass release to meltwater drip of 0.4.

[42] Similar results are apparent for 7–25 December 1997 (Figure 6), during which 67 mm of SWE accumulated in the shelterwood while only 31 mm accumulated below the canopy. Outflow beneath the forest canopy exceeded that in the shelterwood by 11 mm during this period. Assuming that 60% of snowfall was intercepted (40.2 mm) and 40% became direct snow throughfall (26.8 mm), these results suggest that an additional 4.2 mm of mass release occurred. Relative to the increase in outflow of 11 mm attributable to meltwater drip, these results also suggest a ratio of mass release to meltwater drip of 0.4.

[43] While these results provide support for the dominance of meltwater drip over mass release of intercepted snow, they are by no means conclusive. The data suggest a hypothesis that the production of meltwater is the trigger for mass release of intercepted snow in the absence of wind removal. This hypothesis is supported by the observation that both mechanisms almost always seem to occur simultaneously. Adoption of a constant ratio between the two allows for a straightforward method of estimating mass release from meltwater drip for the climatic conditions and snow states of maritime regions. In colder climates, mass release may well occur in the absence of meltwater drip. In these cases, an explicit representation of wind removal of intercepted snow as well as meltwater drip and mass release will probably be necessary.

4. Summary and Conclusions

[44] The main conclusions that can be drawn from these experiments are the following.

1. Snow interception by mature canopies exerts strong controls on beneath-canopy snow accumulation in maritime climates with meltwater drip and mass release being the dominant removal processes for intercepted snow. Snow interception was well described as a linear function (60%) of snowfall for snowfall depths less than 50 mm SWE. An upper limit was not readily apparent, but clearly is at least 40 mm. Intercepted snow was often removed quickly from the canopy as snowmelt accompanied by mass release of intercepted snow. During conditions conducive for snowmelt, approximately 70% of intercepted snow was removed as meltwater drip while mass release accounted for the remaining 30%. During periods when air temperature remained below freezing after snowfall, sublimation was an important mechanism for removal of intercepted snow, with average annual totals of 100 mm SWE. Given that average winter precipitation depths in the region studied here are approximately 2 m, a loss of 100 mm of SWE through sublimation is less significant than in drier climates, were precipitation is less frequent and overall conditions are more conducive to sublimation. Even though this study observed instantaneous sublimation rates in excess of 0.5 mm per hour, meltwater drip and mass release are the dominant process affecting the ground snowpack in maritime mountainous climates. While neither of these represent a loss of water from the snow-soil system, these mechanisms reduce snow accumulation beneath the forest canopy.

2. For the events and conditions observed here, micrometeorological effects had relatively little effect on the rate of snow interception, and on snow interception capacity. Furthermore, morphological differences among Douglas fir, ponderosa pine, white fir and lodgepole pine trees appeared not to affect the rate or final magnitude of snow interception. Direct observations of intercepted snow load on cut-trees showed no pattern of differences in rate or capacity by species. Furthermore, the good agreement of a constant ratio of interception to accumulated snowfall for the mature canopies suggests that micrometeorological effects played a minor role for the range of conditions observed here. Unfortunately, few windy or cold events occurred, so any such conclusion must be tentative. During the coldest snowfall recorded, which also was the single largest snow interception event, a decrease in snow interception efficiency was noted as winds increased and temperatures decreased. However, as wind speeds decreased while temperature remained cold, interception efficiency reverted to 60% of snowfall.

3. The development of continuous simulation models of forest canopy effects on ground snowpack accumulation and ablation that can replicate the observed differences between open and beneath canopy snowpack evolution will be required to incorporate these data into a decision making framework. Given the complexity of the snow interception and removal pathways and their cumulative effect on the ground snowpack, canopy processes cannot be ignored in estimating snow accumulation beneath the forest canopy. Given these complex pathways, it is difficult to generalize the results observed here to provide guidance for water resource managers. The most effective use of this data to aid water resource managers would be through the development and/or verification of snow accumulation and melt models. The plot level data collected by the weighing lysimeters along with the detailed micrometeorological observations (including precipitation) could be used to verify one dimensional mass and energy balance formulations of snow accumulation and melt, including representations of snow interception and release by the forest canopy. The snow course data reported here could then be used to scale plot level models to the stand scale. If such a model could recreate these observed differences in snow accumulation and melt in open areas and beneath the forest canopy, it would be of

considerable aid to water resource managers for assessing the effects of forest harvest on watershed hydrology in maritime climates.

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