Snow Interception Relationships with Meteorology and Canopy Density in a Subalpine Forest

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**Abstract:** Snow accumulation models differ in how snow interception and ablation processes are represented and thus their application to diverse climates and forest types is uncertain. Existing parameterisations of initial snow interception before unloading include inherently coupled canopy snow accumulation and ablation processes. This leads to difficulty in diagnosing processes and adding possible errors to simulations when incorporated as canopy interception routines in models that already account for canopy snow ablation. This study evaluates the theory underpinning parameterisations of initial snow interception using high-temporal resolution and fine-scale measurements of throughfall for events with minimal snow ablation and redistribution in both the canopy and on the ground. Relationships between these throughfall measurements, event meteorology, and a novel lidar-based canopy density measurement were assessed in two subalpine forest plots in the Canadian Rockies. Contrary to existing theories, no association of canopy snow load or air temperature with interception efficiency was observed. Instead, snow-leaf contact area emerged as the primary factor governing snow accumulation. A wind-driven snowfall event demonstrated that non-vertical hydrometeor trajectories can significantly increase snow-leaf contact area, thereby enhancing initial interception before ablation. Prediction of interception efficiency for this event was improved when adjusted for hydrometeor trajectory angle based on the wind speed at one-third of the canopy height. Snow-leaf contact area showed a high sensitivity to wind speed, increasing by up to 95% with a 1 m s-1 wind speed. The study proposes a new parameterisation that calculates throughfall, independent of processes that ablate snow from the canopy, as a function of snowfall, canopy cover, wind speed, and hydrometeor fall velocity. This new parameterisation successfully estimated subcanopy snow accumulation for a snowfall event at two forest plots of differing canopy density and structure. By separating canopy snow ablation from snow interception processes, this new model offers potentially improved prediction of subcanopy snow accumulation when combined with canopy snow ablation parameterisations.

**Keywords:** snow interception, throughfall, ablation, forest, snowpack, lidar, process-based modelling

# 1. Introduction

Over half of North America’s snow-covered zone is covered by forests (Kim et al., 2017), significantly impacting the accumulation and redistribution of snowpacks and subsequent snowmelt runoff. Essery et al. (2003) estimated that 25–45% of annual snowfall may be lost to the atmosphere due to sublimation of snow intercepted in forest canopies globally. Snow intercepted in the canopy can sublimate and melt at much higher rates than the subcanopy snowpack (Katsushima et al., 2023; Lundberg & Halldin, 1994; Pomeroy et al., 1998), reducing the amount of snow available for runoff. Canopy density is one of the primary factors controlling the partitioning of snowfall into throughfall and interception (Hedstrom & Pomeroy, 1998; Staines & Pomeroy, 2023) and thus governs the quantity of snow subject to sublimation from the canopy. Canopy structure metrics such as distance to canopy edge and total gap area have also shown strong correlations to throughfall measurements at the event-based (Moeser et al., 2015a) and seasonal (Mazzotti et al., 2019) timescales. Despite these relationships, forest thinning efforts aimed at limiting sublimation losses to increase snowmelt runoff do not always lead to a corresponding increase in spring streamflow (Golding & Swanson, 1978; Harpold et al., 2020; Pomeroy et al., 2012; Troendle, 1983). This may be due to increased ablation rates when forest cover is reduced, desynchronization of snowmelt timing, and sub-surface hydrology interactions (Ellis et al., 2013; Musselman et al., 2015; Pomeroy et al., 1997; Safa et al., 2021; Varhola et al., 2010). Given the significant impact of forest cover on snowpacks, along with the limited or absent monitoring networks for subcanopy snow accumulation (Rittger et al., 2020; Vionnet et al., 2021), land management, ecological conservation, and water resource decisions depend on reliable models of snow redistribution.

Hedstrom & Pomeroy (1998), working in the cold continental boreal forest, proposed that initial snow interception efficiency was controlled by the maximum canopy load which itself was a function of leaf area index and fresh snow density. Andreadis et al. (2009), incorporating measurements from several studies (Kobayashi, 1987; Pfister & Schneebeli, 1999; Storck et al., 2002), emphasized the role of leaf area index and air temperature in controlling the maximum canopy snow load. Although these two parameterisations incorporate different processes and relationships with air temperature, the Hedstrom & Pomeroy (1998) initial snow interception parameterisation has shown strong performance at sites across Canada, Russia, Switzerland, and Spain (Ellis et al., 2010; Gelfan et al., 2004; Pomeroy et al., 2022; Sanmiguel-Vallelado et al., 2022), while the Andreadis et al. (2009) parameterisation has produced accurate results in coastal environments (Andreadis et al., 2009; Clark et al., 2015). Subsequent research by Lundquist et al. (2021) and Lumbrazo et al. (2022) has revealed overestimation of subcanopy snow accumulation when combining the Hedstrom & Pomeroy (1998) routine with ablation parameterisations from different studies (i.e., Roesch et al., 2001). The coupling of ablation processes within existing snow interception parameterisations (Andreadis et al., 2009; Hedstrom & Pomeroy, 1998) may contribute to overestimates of throughfall, canopy snow unloading, and canopy snowmelt when combined with other canopy snow ablation parameterisations (Cebulski & Pomeroy, 2025). Additional observations that separate initial snow interception from ablation processes could help determine the applicability of the interception theories proposed by Hedstrom & Pomeroy (1998) and Andreadis et al. (2009). Hedstrom & Pomeroy’s (1998) theory also suggests that moderate wind speeds, which can result in more horizontal hydrometeor trajectories, increasing snow-leaf contact area and interception efficiency at the plot scale. This association has also been shown in rainfall interception studies to decrease throughfall of rain (Herwitz & Slye, 1995; Van Stan et al., 2011). However, the relationship proposed by Hedstrom & Pomeroy (1998), is typically not included in snow accumulation models as empirical testing of this relationship is lacking.

The objective of this paper is to evaluate the theories underlying existing snow interception models using high spatial and temporal resolution measurements of subcanopy snow accumulation for events with minimal canopy snow ablation. These new observations are investigated to address the following research questions:

1. Are the existing theories regarding the relationships between meteorology and canopy density and initial snow interception supported by in-situ observations collected in the Canadian Rockies?
2. How is initial snow interception influenced by non-vertical hydrometeor trajectory angles over a wind-driven snowfall event?
3. To what extent can these findings inform the development of a new parameterisation for initial snow interception?

# 2. Theory

## 2.1 Canopy snow mass balance

The change in canopy snow load over time, (mm s-1), can be estimated from the mass balance:

where is the snowfall rate (mm s-1), (mm s-1) is the throughfall rate (mm s-1), (mm s-1) is the rate of rainfall falling on snow intercepted in the canopy, is the canopy snow unloading rate (mm s-1), is the canopy snow drip rate due to canopy snowmelt (mm s-1), is the wind transport rate in or out of the control volume (mm s-1), and is the intercepted snow sublimation rate (mm s-1). Figure 1 in Cebulski & Pomeroy (2025) presents a visual representation of this mass balance.

Interception efficiency, (-), which is the fraction of snowfall intercepted over before ablation, can be calculated as:

During periods with low air temperatures and low wind speeds, , , , , and can be assumed negligible and thus the right side of [Equation 1](#eq-canopy-mass-bal) can be simplified and used as an approximation of to calculate as:

## 2.2 Hydrometeor trajectory angle

Herwitz & Slye (1995) calculate the trajectory angle of a hydrometeor, , as the departure in degrees (°) from a vertical plane as:

where is the terminal fall velocity of the hydrometeor (m s-1), which is a function of the hydrometeor diameter, and is the horizontal velocity of the hydrometeor (m s-1) which is a function of the within canopy wind speed, at height above ground, . In the absence of hydrometeor velocity observations, may be approximated from values in the literature (e.g., 0.8 m s-1 in Isyumov, 1971) and can be approximated by the horizontal wind speed. This assumes the hydrometeors are following fluid points in the atmosphere.

## 2.3 Within-canopy wind flow

Cionco (1965) showed that, may be approximated using the exponential formula:

where is the horizontal wind speed at the top of the canopy (m s-1), is an attenuation coefficient, is the height above ground (m), and is the average height of the canopy elements. Parviainen & Pomeroy (2000) provided a method to calculate using observations from two boreal forest jack pine stands, which was applied in this study.

# 3. Data and methods

## 3.1 Study site

This study was conducted at Fortress Mountain Research Basin (FMRB), Alberta, Canada, -115° W, 51° N, a continental headwater basin in the Canadian Rockies ([Figure 1](#fig-site-map)). Data from this study was collected between October 2021 and July 2023 within and surrounding two forest plots adjacent to the FMRB Powerline Station (PWL) and Forest Tower Station (FT) at ~2100 m above sea level as shown in [Figure 1](#fig-site-map). The average annual precipitation at PWL Station from 2013 to 2023 was 1045 mm, with the average peak annual snow water equivalent (SWE) reaching 465 mm, typically in late April. The PWL plot is adjacent to PWL station and the FT plot surrounds FT station and both include discontinuous stands of 70% subalpine fir (Abies lasiocarpa) and 30% Engelmann spruce (Picea engelmannii) (Langs et al., 2020). The canopy closures are 0.51 and 0.29 and the winter leaf area indices are 2.07 and 1.66 for PWL and FT respectively. The average height of the canopy within the PWL plot is 10.5 m and within the FT plot is 7.1 m. In August of 1936, most vegetation in FMRB burned during a large forest fire that affected most of the Kananaskis Valley (Fryer et al., 1988). Following the fire, the forest within the PWL and FT forest plots has naturally regenerated, though some trees have been removed for a powerline clearing and creation of a snow study plot.

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| Figure 1: Map showing the location of forest plots, flux towers, subcanopy lysimeter instruments, and survey transects. The inset map on the lower right shows the regional location of Fortress Mountain Research basin. |

## 3.2 Meteorological measurements

Measurements of air temperature and relative humidity (Vaisala model HMP155A), wind speed and direction (RM Young model 86000 2-D ultrasonic anemometer) were made 4.3 m above the ground at FT station ([Figure 1](#fig-site-map)). Wind speed measurements from a 3-cup anemometer (Met One model 014A), installed adjacent to the 2-D ultrasonic anemometer at 4.3 m, were used to fill data gaps in the 2-D ultrasonic anemometer records.

At PWL station, the snowfall rate was measured by an Alter-shielded OTT Pluvio weighing precipitation gauge 2.6 m above ground, corrected for undercatch following phase correction by Harder & Pomeroy (2013) using the catch efficiency equation of Smith (2007). The instrument accuracy of the OTT Pluvio specified in the instrument manual is +/- 0.1 mm or 0.2% (whichever is larger). Wind speed for undercatch correction was measured by a 3-cup anemometer (Met One model 014A) at a height of 2.6 m at PWL station. An optical disdrometer (OTT Parsivel2) provided measurements of hydrometeor particle size and vertical velocity. All measurements were recorded at 15-min intervals using Campbell Scientific dataloggers, except the Parsivel2 which was recorded at 1-minute intervals by an onsite computer.

## 3.3 Lysimeter measurements

Three subcanopy lysimeters were installed surrounding the FT Station ([Figure 1](#fig-site-map)) to provide measurements of throughfall for 26 distinct snowfall events, where canopy snow ablation rates were deemed negligible. The subcanopy lysimeter instrument design was adapted from MacDonald (2010) and consisted of a plastic horse-watering trough with an opening of 0.9 m2 and depth of 20 cm suspended from a load cell (Intertechnology 9363-D3-75-20T1) attached to an aluminum pipe connected between two trees ([Figure 2](#fig-scl-imgs)). The manufacturer-specified combined error of full-scale output for the load cells is +/- 0.02% with a temperature sensitivity of +/- 0.001%/5°C. The throughfall rate was calculated by dividing the weight of snow in the subcanopy lysimeter by the cross-sectional area of the opening and determining the rate of change at hourly intervals. Canopy snow load was estimated using [Equation 1](#eq-canopy-mass-bal), incorporating cumulative throughfall measurements from the subcanopy lysimeters and cumulative snowfall measurements from the PWL gauge for each of the 26 events. Interception efficiency was calculated using [Equation 3](#eq-ip2) and accumulated measurements of snowfall and throughfall at both hourly intervals and within bins of air temperature, wind speed, and initial canopy snow load measured from the weighed tree. The hourly interval measurements resulted in lower accumulations of snowfall and throughfall within each interval and thus had higher relative error compared to the binned measurements. To evaluate the association of hourly interception efficiency with air temperature, wind speed, and initial canopy snow load, linear models were fitted using ordinary least squares regression. The non-parametric Wilcoxon signed-rank test was also applied to compare the distribution of hourly interception efficiency measurements across differing groups of air temperature, wind speed, and initial canopy snow load. Timelapse imagery, mass change on a weighed tree lysimeter (Pomeroy & Schmidt, 1993), and in-situ observations were used to ensure unloading, melt, and wind redistribution of canopy snow was minimal over each interval. Additionally, the throughfall measurements were filtered to include observations that coincided with a snowfall rate > 0 mm hr-1 and a snowfall rate that exceeded the subcanopy lysimeter measured throughfall rate. While these careful manual mitigation and automated filtering strategies substantially reduced the contribution of unloading in the subcanopy lysimeter throughfall measurements, a small contribution is still possible.

The subcanopy lysimeters were installed to limit preferential throughfall and unloading by choosing locations with relatively uniform distribution of canopy elements and away from large branches which could preferentially unload snow. The canopy surrounding the subcanopy lysimeters led to reduced wind speeds and reduced the potential for gauge undercatch by these instruments. Photographs of the three subcanopy lysimeters and surrounding canopy are shown in [Figure 2](#fig-scl-imgs). Canopy density measurements, including leaf area index and canopy closure, are summarized in [Table 1](#tbl-scl-lai-cc). A viewing angle from zenith to 60° was selected to describe the surrounding canopy, as a range in hydrometeor trajectory angles was expected to influence the measurements at these locations. The canopy density metrics were measured using hemispherical photography (Nikon Coolpix 4500 and EC-F8 hemispherical lens) for a snow free canopy and analyzed with the hemispheR R package Chianucci & Macek (2023).

The weighed tree lysimeter, a live subalpine fir (Abies lasiocarpa) tree suspended from a load cell (Artech S-Type 20210-100) measured the weight of canopy snow load (kg). This weight was scaled to an areal estimate of canopy snow load (, mm) using measurements of areal throughfall (mm) from in-situ snow surveys and snowfall from the PWL Station snowfall gauge, following the method described in Pomeroy & Schmidt (1993). Three sets of in-situ snow survey locations were selected for scaling, each with a mean canopy closure corresponding to one of the subcanopy lysimeters. This resulted in three datasets of canopy snow load from the weighed tree, each reflecting the canopy density of a respective subcanopy lysimeter. Variations in the weighed tree mass were attributed to intercepted snowfall, canopy snow sublimation, unloading, and melt. Since the subcanopy lysimeter estimates of canopy snow load are not influenced by sublimation, they provided a measurement of interception efficiency with less uncertainty and thus were used for the interception efficiency analyses.

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| Table 1: Leaf area index (LAI) and canopy closure of the three subcanopy lysimeters located proximal to the FT Station.   | Name | LAI (-) | Canopy Closure (-) | | --- | --- | --- | | Sparse | 1.56 | 0.64 | | Mixed | 2.10 | 0.75 | | Closed | 2.40 | 0.79 | |

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| Figure 2: Images of the three subcanopy lysimeter instruments and surrounding canopy located in sparse (a), mixed (b), and dense (c) canopy. The top row presents a side view of each instrument and the bottom row shows hemispherical photographs. These hemispherical images are oriented with north at the top and have been mirrored to provide a view from above (e.g., east is on the right side of each image). See [Table 1](#tbl-scl-lai-cc) for the corresponding canopy density measurement. |

## 3.4 UAV-Lidar data collection and processing

The UAV (FreeFly Alta X) payload included a REIGL miniVUX-2 airborne laser scanner, an Applanix APX-20 inertial measurement unit (IMU) and global navigation satellite system (GNSS). The UAV was flown 90 m above the ground at a speed of 3 m s-1 following the path shown in [Figure 1](#fig-site-map). The methods outlined by Harder et al. (2020) and Staines & Pomeroy (2023) were incorporated to reconcile survey lidar, IMU, and GNSS data. A systematic vertical bias of up to 6 cm between UAV-lidar flight lines was observed in the resulting point clouds on March 13th and 14th, 2024 and was attributed to IMU position drift. After strip alignment, the mean elevation bias in the point clouds compared to the GNSS data was 0.000 m and the RMS error declined from 0.055 m to 0.038 m on March 13th and from 0.033 m to 0.029 m on March 14th. The point cloud density ranged from ~1200 returns m2 in sparse forest to ~2200 returns m2 in open clearings. Quality control, ground classification, calculation of surface elevation change was conducted on the point cloud data and then converted to 0.05 m resolution rasters. Further quality control was conducted on the 0.05 m raster data to remove values that exceeded the .999th quantile and then resampled to 0.25 m grid cell resolution by taking the median. A detailed description of the UAV, payload, flight settings, and software packages used is provided in the Supporting Information.

## 3.5 Snow surveys

### 3.5.1 In-situ snow depth and density

Event-based snow surveys provided measurements of subcanopy throughfall depth and density at 30 locations following the transects shown in [Figure 1](#fig-site-map). These measurements were used to upscale the weighed tree from weight to weight per unit area, assess the accuracy of lidar derived snow depth measurements, and provide a fresh snow density for the calculation of SWE (mm) from the snow depth measurements. Minimal ablation and redistribution of both the surface snowpack and/or snow intercepted in the canopy was crucial to ensure the snow survey measurements were attributed to throughfall. Therefore, only snowfall events with minimal canopy snow ablation as determined through in-situ observations, analysis of timelapse imagery, and mass change on the weighed tree lysimeter were selected. A 1000 cm3 Perla snow density wedge sampler (RIP Cutter, https://snowmetrics.com/shop/rip-1-cutter-1000-cc/) was used to measure the density of the fresh snow layer, (kg m-3) from snow pits. Throughfall depth measurements, were converted to SWE using the following equation:

If a pre-event crust layer was present, the depth of post event fresh snow accumulation above the crust layer was interpreted as throughfall over the event. In the absence of a defined crust layer, the difference in pre- and post-event snow depth to ground was interpreted as event throughfall. Interception efficiency, used in scaling the weighed tree, was calculated using [Equation 3](#eq-ip2) and the and cumulative snowfall measurements.

### 3.5.2 UAV-Lidar snow depth

Two uncrewed aerial vehicle (UAV) lidar surveys were conducted before and after a 24-hour snowfall event that occurred between March 13–14th, 2023 to facilitate the measurement of snow accumulation and canopy density within the FT and PWL forest plots. This period was selected based on two criteria: 1) it provided sufficient cumulative snowfall to result in a low relative error in UAV-lidar measured throughfall, and 2) minimal snow redistribution and ablation was observed, as confirmed by the subcanopy lysimeters, weighed tree, and time-lapse imagery. The change in surface elevation between the two UAV-lidar point clouds was interpreted as the increase in snow accumulation, , over the snowfall event. was calculated using [Equation 6](#eq-swe-tf) together with in-situ measurements of . The measurement error of the UAV-lidar derived was assessed using the in-situ snow depth observations which is shown in the Supporting Information. Spatially distributed measurements of , were then determined using [Equation 3](#eq-ip2) with as the throughfall component and cumulative snowfall to the PWL clearing.

## 3.6 UAV-Lidar canopy metrics

The canopy of the study site was characterized from two UAV-lidar point clouds (March 13th and March 14th) using the voxel ray sampling (VoxRS) methodology for lidar data analysis, as developed by Staines & Pomeroy (2023). This method was chosen for its ability to provide canopy metrics that are less sensitive to the inherent non-uniform nature of lidar sampling data resulting from beam occlusion in vegetation. Using this method radiation transmittance, (-), was measured across the hemisphere at a 1° step, e.g., azimuth angles (0°, 1°, …, 359°) and zenith angles (0°, 1°, …, 90°) for each 0.25 m grid cell within the FT and PWL forest plots. The fraction of snow-leaf contact area per unit area of ground proposed by Hedstrom & Pomeroy (1998), and hereafter called leaf contact area (), was then calculated as:

where is a function of the canopy cover () and hydrometeor trajectory angle (). is the fraction of canopy area to total ground area when viewed from above, which differs from canopy closure, an angular-derived metric usually measured from the ground perspective.

To determine how was associated with interception efficiency at different azimuth and zenith angles over the March 13–14th snowfall event, the entire hemisphere at each grid location was considered. The relationship between interception efficiency and was found to be linear and thus the Pearson Correlation Coefficient was used. The Pearson Correlation Coefficient was computed between a single raster of interception efficiency and each of the 32,760 rasters of measured on March 13th, representing locations across the hemisphere (azimuth [0°, 1°, …, 359°], zenith angle [0°, 1°, …, 90°]) at 0.25 m grid cells spanning the FT and PWL forest plots.

The pair of azimuth and zenith angles corresponding to the that had the highest correlation with interception efficiency was selected for further analysis. This involved aggregating the interception efficiency and selected rasters from a 0.25 m resolution to 5 m, followed by fitting an ordinary least squares regression between these two variables. The regression was constrained to pass through the origin based on the theoretical principle that the dependent variable must equal zero when the independent variable is zero. To appropriately account for this constraint, the *R*2 values were adjusted according to Equation 10 presented in Kozak & Kozak (1995). The relationship between leaf contact area and simulated trajectory angle was investigated by fitting non-linear models using a non-linear least squares regression. All statistical analyses were performed using the R ‘stats’ package (R Core Team, 2024).

# 4. Results

## 4.1 The influence of meteorology on snow interception

Measurements of canopy snow load derived from the subcanopy lysimeters and weighed tree increased linearly with cumulative event snowfall for 26 snowfall events, without evidence of reaching a maximum ([Figure 3](#fig-scl-w-sf)). Over these events, air temperature ranged from -24.5°C to 1°C, wind speeds at 4.3 m height ranged from calm to 4.6 m s-1 ([Table 2](#tbl-sf-event-met)), and wind direction was predominately from the southwest during snowfall ([Figure 4](#fig-wind-rose)). Missing canopy snow load measurements, as shown in [Figure 3](#fig-scl-w-sf) for certain events, were caused by wiring damage from animals and heavy snow loads. Some of the variability in interception rates within and between different events may be attributed to small amounts of canopy snow unloading and melt, which could not be fully accounted for through the manual and automated filtering mitigation strategies in both the subcanopy lysimeter and weighed tree measurements.

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| Figure 3: Plot showing the cumulative event snowfall versus canopy snow load calculated using the mean of the three subcanopy lysimeters (left) and weighed tree lysimeter (right) for each of the 26 snowfall events. Both datasets represent canopy snow load for a canopy closure of 0.73 corresponding to the mean of the three subcanopy lysimeter canopies. |

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| Table 2: Meteorology of the 26 snowfall events. Air temperature and wind speed were measured at FT station. Interception efficiency is estimated from cumulative snowfall measured at PWL station and the average cumulative throughfall of all three subcanopy lysimeters located within the FT forest plot.   |  | Air Temperature (°C) | | | Wind Speed (m/s) | | | Interception Efficiency (-) | | | Snowfall (mm) | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Start Date | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Total | | 2021-12-23 | -6.2 | -5.3 | -4.6 | 0.6 | 3.1 | 4.6 | 0.1 | 0.5 | 0.9 | 21.7 | | 2022-01-02 | -15.9 | -10.8 | -5.8 | 0.2 | 1.8 | 4.2 | 0.0 | 0.5 | 1.0 | 31.6 | | 2022-01-17 | -14.8 | -7.8 | -0.8 | 0.2 | 1.1 | 1.8 | 0.0 | 0.6 | 1.0 | 12.9 | | 2022-01-31 | -24.5 | -12.1 | -6.4 | 0.1 | 1.0 | 1.7 | 0.2 | 0.7 | 1.0 | 9.1 | | 2022-02-14 | -9.9 | -9.0 | -8.5 | 0.4 | 0.8 | 1.2 | 0.2 | 0.5 | 0.8 | 1.7 | | 2022-02-19 | -4.7 | -3.2 | -2.5 | 1.3 | 2.3 | 3.6 | 0.3 | 0.6 | 0.9 | 11.1 | | 2022-03-01 | -8.3 | -5.4 | -1.0 | 0.1 | 1.0 | 3.1 | 0.4 | 0.8 | 1.0 | 9.9 | | 2022-03-07 | -12.5 | -8.6 | -4.4 | 0.3 | 0.8 | 1.7 | 0.3 | 0.7 | 1.0 | 9.5 | | 2022-03-14 | -2.7 | -2.1 | -0.8 | 1.0 | 1.6 | 2.9 | 0.2 | 0.6 | 0.9 | 8.4 | | 2022-03-19 | -3.1 | -2.8 | -2.5 | 0.0 | 0.7 | 1.3 | 0.3 | 0.5 | 0.6 | 6.6 | | 2022-03-23 | -7.9 | -5.3 | -0.9 | 0.8 | 1.2 | 1.8 | 0.4 | 0.6 | 0.9 | 1.6 | | 2022-04-04 | -3.5 | -2.9 | -2.1 | 0.6 | 1.0 | 1.9 | 0.0 | 0.4 | 0.6 | 3.4 | | 2022-04-18 | -5.2 | -4.0 | -2.7 | 0.4 | 1.1 | 1.9 | 0.1 | 0.5 | 0.9 | 7.4 | | 2022-04-22 | -2.8 | -1.8 | -0.5 | 0.4 | 0.8 | 1.2 | 0.1 | 0.5 | 1.0 | 9.8 | | 2022-05-09 | -4.9 | -4.3 | -3.2 | 0.1 | 0.4 | 0.9 | 0.2 | 0.5 | 0.9 | 8.1 | | 2022-05-19 | -4.9 | -2.1 | 0.3 | 0.1 | 0.4 | 0.9 | 0.2 | 0.6 | 0.9 | 7.1 | | 2022-06-13 | -1.1 | -0.3 | 0.6 | 0.1 | 0.1 | 0.4 | 0.0 | 0.5 | 0.9 | 45.4 | | 2022-12-27 | -3.0 | -2.7 | -1.9 | 0.6 | 1.1 | 1.8 | 0.2 | 0.5 | 0.9 | 4.5 | | 2023-01-27 | -11.5 | -7.3 | -4.5 | 0.6 | 0.9 | 1.2 | 0.1 | 0.5 | 0.8 | 10.4 | | 2023-02-19 | -14.3 | -9.5 | -6.3 | 0.2 | 0.8 | 1.4 | 0.2 | 0.7 | 1.0 | 18.1 | | 2023-02-26 | -9.2 | -8.4 | -6.6 | 0.2 | 1.0 | 2.1 | 0.3 | 0.5 | 1.0 | 5.4 | | 2023-03-13 | -8.9 | -3.6 | -0.1 | 0.3 | 1.3 | 2.2 | 0.0 | 0.5 | 1.0 | 27.4 | | 2023-03-24 | -7.9 | -5.7 | -3.5 | 0.1 | 0.5 | 1.2 | 0.1 | 0.4 | 0.7 | 23.8 | | 2023-04-01 | -8.9 | -7.7 | -4.7 | 0.1 | 0.6 | 1.4 | 0.4 | 0.6 | 0.8 | 11.4 | | 2023-04-10 | -1.1 | -0.5 | 0.3 | 0.1 | 0.3 | 1.0 | 0.2 | 0.4 | 0.6 | 18.0 | | 2023-05-08 | 0.2 | 0.6 | 1.0 | 0.4 | 0.6 | 0.8 | 0.6 | 0.6 | 0.7 | 3.5 | |

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| Figure 4: Wind rose showing the frequency of wind speed and direction over the 26 snowfall periods for the ultrasonic anemometer 4.3 m above ground at FT station. |

Linear regression analysis revealed no relationship between hourly interception efficiency (from the subcanopy lysimeters) and air temperature, wind speed or canopy snow load, either due to non-significant relationships (*p* < 0.05) and/or weak predictive power (*R*2 < 0.05) ([Table 3](#tbl-lysimeter-hourly-stats)). The Wilcoxon test indicated that the difference in hourly interception efficiencies for air temperatures above and below -5°C was not significant (*p* > 0.05, [Table 4](#tbl-scl-hrly-stats)). Additionally, the interception efficiency across differing bins of air temperature did not show any systematic pattern ([Figure 5](#fig-scl-ip-bins)). Although [Figure 5](#fig-scl-ip-bins) indicates potentially higher interception efficiency in sparse and mixed canopies at air temperatures below -10°C, these measurements have substantial uncertainty due to heightened instrument error associated with the small accumulations of snowfall and throughfall within these temperature ranges.

When examining wind speed effects, hourly interception efficiencies were found to be significantly higher (*p* < 0.05, [Table 4](#tbl-scl-hrly-stats)) during periods when wind speeds exceeded 1 m s-1 compared to calmer conditions in the sparse and closed canopies using the Wilcoxon test. The binned data also show an increase in interception efficiency with increasing wind speed for these two canopy types ([Figure 5](#fig-scl-ip-bins)). In contrast, the mixed canopy, which had a canopy opening towards the prevailing wind direction ([Figure 2](#fig-scl-imgs)), exhibited no significant difference (*p* > 0.05, [Table 4](#tbl-scl-hrly-stats)). Binned measurements of interception efficiencies corresponding to wind speed bins above 2 m s-1 ([Figure 5](#fig-scl-ip-bins)) contained considerable uncertainty resulting from lower snowfall and throughfall accumulation, reducing confidence in these particular findings across all three canopy environments.

Significantly higher hourly interception efficiencies (*p* < 0.05, [Table 4](#tbl-scl-hrly-stats)) were found for initial canopy snow loads below 10 mm compared to heavier snow loads across all three canopy types using the Wilcoxon test. Additionally, the sparse and mixed canopies exhibited significantly lower interception efficiencies (*p* < 0.05) for snow loads below 5 mm compared to those between 5–10 mm. The closed canopy displayed a similar initial increase for the binned data visible in [Figure 5](#fig-scl-ip-bins), but this was not statistically significant for the hourly data (*p* > 0.05, [Table 4](#tbl-scl-hrly-stats)). For the sparse and closed canopies, a slight increase in binned interception efficiency was observed as snow load increased up to 10 mm, followed by a decline when snow loads exceeded 10 mm ([Figure 5](#fig-scl-ip-bins)). For snow loads exceeding 15 mm, interception efficiency decreased in the sparse and closed canopies, while the mixed canopy showed an increase; however, these measurements carried high uncertainties due to lower accumulated snowfall and throughfall in these higher snow load bins. The differences between the relationships observed in the hourly-interval and binned interception efficiency measurements can be attributed to two factors: greater instrument uncertainty in the hourly measurements and the potential for the dependent and independent variables to be non-stationary over the hourly interval.

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| Table 3: Statistics corresponding to the ordinary least squares linear regression test between hourly interval measurements of independent variables: mean air temperature, mean wind speed, and initial canopy snow load and the dependent variable mean interception efficiency. The test was run separately for three levels of canopy coverage () corresponding to each subcanopy lysimeter (SCL).   | Dependent Variable | SCL Name |  | Adjusted | -value |  | | --- | --- | --- | --- | --- | --- | | Air Temperature (°C) | closed | 0.79 | 0.002 | 0.239 | 191 | | Air Temperature (°C) | mixed | 0.75 | 0.024 | 0.005 | 298 | | Air Temperature (°C) | sparse | 0.64 | 0.003 | 0.208 | 190 | | Initial Canopy Snow Load (mm) | closed | 0.79 | 0.029 | 0.011 | 188 | | Initial Canopy Snow Load (mm) | mixed | 0.75 | 0.010 | 0.049 | 294 | | Initial Canopy Snow Load (mm) | sparse | 0.64 | 0.031 | 0.009 | 187 | | Wind Speed (m/s) | closed | 0.79 | 0.025 | 0.017 | 191 | | Wind Speed (m/s) | mixed | 0.75 | 0.034 | 0.001 | 298 | | Wind Speed (m/s) | sparse | 0.64 | 0.046 | 0.002 | 190 | |

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| Figure 5: Scatter plots showing the interception efficiency calculated from accumulated snowfall (Pluvio) and throughfall (subcanopy lysimeter) measurements for bins of air temperature, wind speed, and initial canopy snow load (the snow load observed by the weighed tree at the beginning of the timestep) over the 26 snowfall events. The error bars represent the estimated combined instrument error of the snowfall gauge and subcanopy lysimeters. |

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| Table 4: Results of the Wilcoxon signed-rank tests comparing the distributions of hourly interception efficiency (IP) measured by the subcanopy lysimeters for differing groups of air temperatures (Ta), wind speeds (u), and initial canopy snow loads (L). The table reports the canopy corresponding to the subcanopy lysimeter (Canopy), null hypothesis (), -value, and sample size () and median IP for the ‘low’ group (e.g., Ta < -5°C) and ‘high’ group (e.g., Ta ≥ -5°C).   | Canopy | Null Hypothesis () | -value | (low / high) | median I/P (low / high) | Reject | | --- | --- | --- | --- | --- | --- | | closed | Median IP (Ta < -5°C) ≥ Median IP (Ta ≥ -5°C) | 0.282 | 76 / 115 | 0.56 / 0.62 | no | | mixed | Median IP (Ta < -5°C) ≥ Median IP (Ta ≥ -5°C) | 0.990 | 165 / 133 | 0.57 / 0.53 | no | | sparse | Median IP (Ta < -5°C) ≥ Median IP (Ta ≥ -5°C) | 0.864 | 72 / 118 | 0.54 / 0.5 | no | | closed | Median IP (u < 1 m/s) ≥ Median IP (u ≥ 1 m/s) | 0.004 | 116 / 75 | 0.53 / 0.65 | yes | | mixed | Median IP (u < 1 m/s) ≥ Median IP (u ≥ 1 m/s) | 1.000 | 165 / 133 | 0.6 / 0.5 | no | | sparse | Median IP (u < 1 m/s) ≥ Median IP (u ≥ 1 m/s) | < 0.001 | 110 / 80 | 0.43 / 0.59 | yes | | closed | Median IP (L < 10 mm) ≤ Median IP (L ≥ 10 mm) | 0.048 | 129 / 59 | 0.62 / 0.57 | yes | | mixed | Median IP (L < 10 mm) ≤ Median IP (L ≥ 10 mm) | < 0.001 | 218 / 76 | 0.57 / 0.49 | yes | | sparse | Median IP (L < 10 mm) ≤ Median IP (L ≥ 10 mm) | < 0.001 | 157 / 30 | 0.53 / 0.34 | yes | | closed | Median IP (L < 5 mm) ≥ Median IP (5 mm ≤ L < 10 mm) | 0.333 | 62 / 67 | 0.62 / 0.62 | no | | mixed | Median IP (L < 5 mm) ≥ Median IP (5 mm ≤ L < 10 mm) | 0.019 | 117 / 101 | 0.57 / 0.61 | yes | | sparse | Median IP (L < 5 mm) ≥ Median IP (5 mm ≤ L < 10 mm) | 0.043 | 90 / 67 | 0.49 / 0.6 | yes | |

## 4.2 The influence of canopy density on snow interception

UAV-lidar measurements of throughfall and canopy density provide insights on how the forest canopy influenced subcanopy snow accumulation during a wind-driven snowfall event between March 13–14th. This event totaled 28.7 mm of snowfall at PWL station and was characterized by a transition from low rates of snowfall and air temperatures near 0°C to higher rates of snowfall by late afternoon on March 13th coinciding with air temperatures around -2.5 °C. An average wind speed of 1.3 m s-1 and direction of 188° was observed 4.3 m above the ground at FT Station. The mean observed hydrometeor terminal fall velocity observed over the event was 0.9 m s-1.

The throughfall depth measured by UAV-lidar aligned with the in-situ manual measurements resulting in a mean bias of -0.001 m and RMSE of 0.024 m. More details on the accuracy of UAV-lidar snow depth measurements are provided in the Supporting Information section. [Figure 6](#fig-lidar-tf-ip) shows the spatial distribution of throughfall and interception efficiency at the PWL and FT forest plots. Reduced throughfall and greater interception efficiency was observed on the north (lee) side of individual trees, which may be due to non-vertical hydrometeor trajectories caused by the steady southerly winds observed over this event. Transparent areas within the forest plots in [Figure 6](#fig-lidar-tf-ip) represent grid cells that did not have any lidar ground returns (e.g., under dense canopy proximal to tree trunks) or were masked due to disturbance (e.g., walking paths in clearings). Visual observations on March 13th and 14th confirmed non-vertical hydrometeor trajectories and increased canopy snow loads were observed on the windward side of individual trees. This effect is more apparent in the PWL forest plot than the FT forest plot and may be attributed to the taller trees and higher canopy cover of the PWL forest plot compared to the FT forest plot ([Figure 6](#fig-lidar-tf-ip)).

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| Figure 6: UAV-lidar measurements of the change in snow water equivalent, SWE (mm) and interception efficiency, I/P (-), over the March 13–14th 24-hour snowfall event for the FT and PWL forest plots at a 0.25 m resolution. See the location of the two forest plots in [Figure 1](#fig-site-map). |

The VoxRS measurements of on March 13th were selected for analysis and represent the canopy of both forest plots without snow. Little difference in was observed between the March 13th and March 14th measurements. A strong linear correlation between measured on March 13th and interception efficiency was observed towards the southern portion of the hemisphere, aligning with the average event wind direction ([Figure 7](#fig-hemi-ip-cc)). For the PWL forest plot, the upper 97.5th percentile of the Pearson Correlation Coefficient () values were found between azimuth angles of 167°–217°. Similarly, for the FT forest plot, the upper 97.5th percentile of was found between azimuth angles of 171°–223°. The zenith angle found to have the highest correlation over this azimuth range was 22° ( = 0.7) and 21° ( = 0.83) for PWL and FT respectively. The high correlation coefficients found for non-vertical zenith angles for both PWL and FT are hypothesized to result from non-vertical hydrometeor trajectories.

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| Figure 7: The Pearson Correlation Coefficient between rasters (0.25 m resolution) of interception efficiency and leaf contact area (measured on March 13th) for each grid cell across the study site for each azimuth angles (0°, 1°, …, 359°) and zenith angles (0°, 1°, …, 90°) for the FT (left) and PWL (right) forest plots. |

The spatial distribution of measurements, selected based on the vector corresponding to the azimuth and zenith angles observed to have the highest correlation with interception efficiency in [Figure 7](#fig-hemi-ip-cc), is shown in [Figure 8](#fig-lidar-cc-cp). These measurements generally align with the spatial distribution of interception efficiency and throughfall ([Figure 6](#fig-lidar-tf-ip)).

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| Figure 8: UAV-lidar VoxRS measurements of leaf contact area measured on March 13th for the PWL and FT forest plots for zenith angles (PWL = 22°, FT = 21°) and azimuth angles (PWL = 167°, 178°, … 217°; FT = 171°, 172°, … 223°). |

The correlation between interception efficiency ([Figure 6](#fig-lidar-tf-ip)) and ([Figure 8](#fig-lidar-cc-cp)), resampled to a 5 m grid resolution, was higher compared to the association with leaf contact angle measured at a zenith angle of 0° ([Figure 9](#fig-lca-vs-ip)). The stronger association for the vector-based calculation is hypothesized to stem from a more accurate representation of the snowfall contact area and suggests that adjusted is a useful predictor of interception efficiency before ablation. An ordinary least squares linear regression forced through the origin was fit to the observed data points using the following equation:

where is an efficiency constant which determines the fraction of snowflakes that contact the elements and are stored in the canopy (i.e., intercepted) before canopy snow unloading or ablation processes begin.

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| Figure 9: Scatter plots showing the relationship between leaf contact area and interception efficiency rasters resampled to a 5 m grid cell resolution. The left plot (nadir) shows canopy coverage and the right plot (Vector Based) shows the leaf contact area averaged over rasters with zenith angles (PWL = 22°, FT = 21°) and azimuth angles (PWL = 167°, 178°, … 217°; FT = 171°, 172°, … 223°). The solid lines (Model fit) show an ordinary least squares linear regression forced through the origin and fitted to the PWL (red) and FT (black) data and the light grey dotted line shows a 1:1 line. The *R*2 values for the four different models are shown in the upper left of each panel calculated following the methods outlined in Kozak & Kozak (1995). |

For the vector-based model, the relationship between interception efficiency and resulted in *R*2 values of 0.45 and 0.8 for PWL and FT respectively. Model error statistics show the vector-based model provided a better prediction of interception efficiency compared to the nadir canopy coverage measurements ([Table 5](#tbl-ip-mod-err)). The increase in interception efficiency with follows a reduced slope compared to the nadir models with values of 0.72 and 0.69 for the PWL and FT vector-based models respectively. The reduced slope for the vector-based models may be due to snowflakes that weaved through and/or bounced off branch elements in addition to UAV-lidar throughfall measurement uncertainty which may have been slightly affected by unloading and redistribution. These processes would have reduced the fraction of snowfall that was stored in the canopy. Some of the scatter observed in the nadir model shown in [Figure 9](#fig-lca-vs-ip) may be explained by grid cells within canopy gaps which observed a greater interception efficiency compared to the corresponding canopy cover. Conversely, grid cells where interception efficiency is less than the canopy cover, may be affected by non-vertical trajectory hydrometeors making their way underneath the canopy as observed by the reduced interception efficiency on the windward edges of individual trees in [Figure 6](#fig-lidar-tf-ip).

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| Table 5: Summary of error statistics for the linear regression models relating leaf contact area to interception efficiency, presented in [Figure 9](#fig-lca-vs-ip). The Mean bias is the difference in the model and observed values, MAE is the mean of the absolute error, RMS Error is the root mean squared error, *R*2 is the coefficient of determination adjusted using Equation 10 in Kozak & Kozak (1995).   | Plot Name | Canopy Calculation | Model Slope (-) | Mean Bias (-) | MAE (-) | RMS Error (-) |  | | --- | --- | --- | --- | --- | --- | --- | | FT | Nadir | 1.01 | 0.024 | 0.072 | 0.101 | 0.49 | | FT | Vector Based | 0.69 | 0.003 | 0.047 | 0.063 | 0.80 | | PWL | Nadir | 0.96 | 0.049 | 0.115 | 0.148 | -0.31 | | PWL | Vector Based | 0.72 | 0.020 | 0.079 | 0.096 | 0.45 | |

## 4.3 The combined influence of trajectory angle and canopy density on snow interception

VoxRS measurements of prior to snowfall on March 13th, increased substantially with simulated hydrometeor trajectory angle and corresponding simulated wind speed ([Figure 10](#fig-lca-ht-ws)). The standard deviation in VoxRS measured , illustrated by the shaded area in [Figure 10](#fig-lca-ht-ws), exhibits the broad range in values for individual grid cells across each forest plot. Despite this large scatter, a systematic increase in the mean across both forest plots results from a rise in the number of canopy elements for more horizontal angles, when averaged across each forest plot, over all azimuth angles (see top left panel [Figure 10](#fig-lca-ht-ws)). This results in a large rise in over relatively common wind speeds. For example, with a wind speed of 1 m s-1 and estimated trajectory angle of 48°, would increase by 0.31 and 0.28 for the PWL and FT forest plots respectively ([Figure 10](#fig-lca-ht-ws)). The increase in from nadir measured canopy coverage with increasing trajectory angle exhibits a similar relationship for both forest plots FT and PWL until trajectory angles reach approximately 60° (see bottom row of [Figure 10](#fig-lca-ht-ws)). Beyond 60°, the PWL rate of increase slows as the approaches 1.0, while the FT plot, which has lower canopy coverage, continues to rise until around 75° as a of 1.0 is approached. was also quantified across trajectory angles for both PWL and FT on March 14th, post snowfall, and showed a negligible increase in compared to measured on March 13th without snow in the canopy.

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| Figure 10: Plots showing the relationship between hydrometeor trajectory angle (left column) and wind speed (right column) with mean plot-wide snow-leaf contact area, (top row) and the increase in mean plot-wide , i.e., (bottom row). The simulated hydrometeor trajectory angle is measured as degrees from zenith. Simulated wind speed was calculated as a function of hydrometeor trajectory angle by rearranging [Equation 4](#eq-ta) and an observed event hydrometeor fall velocity of 0.9 m s-1. The solid lines (VoxRS) represent the mean (top row) or increase in mean (bottom row) for a single zenith angle observed from VoxRS across all grid cells for each forest plot and across all azimuth angles. The shaded area represents one standard deviation above and below the observed VoxRS mean. The dashed lines (Fitted) represent predictions from [Equation 10](#eq-lca-ac) (top row) and [Equation 11](#eq-lca-inc) (bottom row). The dotted lines (HP98) represent the predictions from Equation 10 in Hedstrom & Pomeroy (1998). A forested downwind distance of 100 m was assumed for the HP98 calculation. |

A function is proposed here to calculate plot-scale leaf contact area, (-):

where represents the increase in leaf contact area from nadir measured canopy coverage (), and is a function of and . To estimate in the absence of detailed canopy measurements, the following function is proposed:

where quantifies the available void space within the canopy and represents the fraction of that space contributing to increased leaf contact area. Here, is approximated as:

where is a fitting coefficient, estimated to be ~0.91 through a non-linear least squares regression fit to the VoxRS measurements at both FT and PWL. The term reflects the relative increase in snow-leaf contact area, which in turn leads to a proportional decrease in the canopy void space (). Thus, for of 0°, is equal to the canopy cover. In contrast, for close to 90°, approaches a value of 1.0. The assumptions of [Equation 12](#eq-f-theta) include that represents a measurement of continuous canopy cover without large open areas many times greater than the mean canopy height and that snowfall trajectories are linear.

Simulated using [Equation 10](#eq-lca-ac) is shown in the dashed lines in the top row of [Figure 10](#fig-lca-ht-ws) and follows the VoxRS-measured mean closely. Model error statistics demonstrate that [Equation 11](#eq-lca-inc) performed well, with a mean bias and RMSE of -0.05 (-) and 0.05 (-) for PWL, and 0.03 (-) and 0.05 (-) for FT respectively ([Table 6](#tbl-lca-mod-err)). In contrast, the Hedstrom & Pomeroy (1998) method produced significantly less accurate estimates of , with a mean bias and RMSE of -0.2 (-) and 0.23 (-) for PWL, and -0.26 (-) and 0.32 (-) for FT respectively ([Table 6](#tbl-lca-mod-err)).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| Table 6: Model error statistics calculated for the prediction of leaf contact area from trajectory angle using [Equation 11](#eq-lca-inc) and Equation 10 from Hedstrom & Pomeroy (1998) (HP98) for the PWL and FT forest plots. Mean bias is the difference in the model and observed values, MAE is the mean of the absolute error, RMS Error is the root mean squared error and *R*2 is the coefficient of determination. The units for all metrics are dimensionless. A forested downwind distance of 100 m was used for the HP98 calculation.   | Model | Plot Name | Mean Bias (-) | MAE (-) | RMS Error (-) |  | | --- | --- | --- | --- | --- | --- | | HP98 | FT | -0.26 | 0.26 | 0.32 | -0.97 | | HP98 | PWL | -0.20 | 0.20 | 0.23 | -0.96 | | Eq. 10 | FT | 0.03 | 0.04 | 0.05 | 0.95 | | Eq. 10 | PWL | -0.05 | 0.05 | 0.05 | 0.90 | |

## 4.4 Throughfall model performance

The performance of the interception efficiency ([Equation 9](#eq-lca-ip)) and leaf contact area ([Equation 10](#eq-lca-ac)) parameterisations in estimating event throughfall was assessed against UAV-lidar measurements of throughfall at the plot scale for the March 13–14th snowfall event. In this assessment, the hydrometeor trajectory angle was approximated using [Equation 4](#eq-ta) combined with the mean event wind speed at one-third the mean canopy height (estimated from [Equation 5](#eq-cionco) and the observed wind speed at FT station) and hydrometeor terminal velocity (measured at PWL station). Leaf contact area was then estimated using [Equation 10](#eq-lca-ac) for the PWL and FT plots, incorporating the approximated hydrometeor trajectory angle and observed canopy cover () from the VoxRS dataset. Interception efficiency was calculated using [Equation 9](#eq-lca-ip) with the estimated leaf contact area from [Equation 10](#eq-lca-ac) and accumulated snowfall measured at PWL station for the event. An value, used in [Equation 9](#eq-lca-ip), of 0.978 (-) was found through calibration which provided the best fit between observed and simulated interception efficiency at the plot scale for both FT and PWL.

The new vector-based parameterisation closely matched the UAV-lidar measurements of throughfall ([Figure 11](#fig-event-tf)). Modelled throughfall from the vector-based model was 17.2 mm compared to the measured throughfall of 16.6 mm for PWL. For FT, the vector-based modelled throughfall was 21.5 mm, while the measured values where 22.1 mm. The vector-based model shows a lower mean bias of -0.6 mm for PWL and 0.6 mm for FT, in contrast to the nadir-based model, which overestimated throughfall for both plots ([Table 7](#tbl-vb-plot-err)). This overestimation arose from the nadir-based model’s approximation of leaf contact area from canopy coverage measurements (without adjustment via [Equation 10](#eq-lca-ac)), which yielded a reduced estimated contact area and consequently underestimated canopy snow interception.

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| Figure 11: Bar chart comparing the observed and modelled mean change in throughfall (ΔSWE, mm) over the March 13-14th snowfall event averaged over forest plots FT and PWL. The ‘Nadir-model’ calculated interception efficiency as a function of canopy coverage and the Vector-based ‘VB-model’ used [Equation 9](#eq-lca-ip) with adjusted for trajectory angle. ‘UAV-lidar’ corresponds to throughfall calculated using [Equation 6](#eq-swe-tf) incorporating UAV-lidar snow depth and snow density from in-situ snow pits. The black horizontal dashed line shows the accumulated SWE (mm) over the snowfall event to the PWL station open clearing. |

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| Table 7: Model error statistics for model estimates of snow interception efficiency (I/P) and throughfall (TF) compared to measurements of I/P and TF using UAV-lidar averaged over the FT and PWL forest plots. Units for I/P are (-) and TF are (mm). The vector-based model utilized [Equation 9](#eq-lca-ip) with adjusted for trajectory angle. The nadir model also utilized [Equation 9](#eq-lca-ip) but was not adjusted for trajectory angle and thus was used instead of . The ‘Obs. Value’ column contains measurements from UAV-lidar while the ‘Mod. Value’ column contains the modelled values. The mean bias was calculated as observed minus modelled and percent error is the percent error between predicted and observed values.   | Plot | Model Type | Value Name | Units | Obs. Value | Mod. Value | Mean Bias | Perc. Error | | --- | --- | --- | --- | --- | --- | --- | --- | | FT | VB-model | I/P | - | 0.23 | 0.25 | -0.02 | -9.01 | | FT | Nadir-model | I/P | - | 0.23 | 0.20 | 0.03 | 12.10 | | FT | VB-model | TF | mm | 22.12 | 21.53 | 0.59 | 2.67 | | FT | Nadir-model | TF | mm | 22.12 | 22.91 | -0.79 | -3.58 | | PWL | VB-model | I/P | - | 0.42 | 0.40 | 0.02 | 4.91 | | PWL | Nadir-model | I/P | - | 0.42 | 0.37 | 0.05 | 12.95 | | PWL | VB-model | TF | mm | 16.64 | 17.24 | -0.59 | -3.55 | | PWL | Nadir-model | TF | mm | 16.64 | 18.20 | -1.56 | -9.35 | |

# 5. Discussion

The point scale observations presented in [Figure 5](#fig-scl-ip-bins) indicate that air temperature had little influence on initial interception efficiency during periods where melt and unloading of snow were less likely. This finding aligns with Storck et al. (2002), who observed that variations in air temperature did not significantly affect initial interception efficiency. While other studies have reported both positive (Andreadis et al., 2009; Katsushima et al., 2023; Roth & Nolin, 2019) and negative (Hedstrom & Pomeroy, 1998; Schmidt & Gluns, 1991) relationships between air temperature and snow interception, the limited association observed here may be explained by competing temperature-dependent processes. Warmer temperatures simultaneously increase branch flexibility, reducing (Schmidt & Gluns, 1991; Schmidt & Pomeroy, 1990) and enhance snow cohesion and adhesion, increasing interception efficiency (Katsushima et al., 2023; Kobayashi, 1987; Pfister & Schneebeli, 1999).

Initial interception efficiency was found to increase with wind speed at two locations which were sheltered from the predominant wind direction ([Figure 5](#fig-scl-ip-bins)). This is hypothesized to be due to an increase in associated with non-vertical hydrometeor trajectories, as demonstrated by observations during a wind-driven snowfall event ([Figure 6](#fig-lidar-tf-ip)) and analysis of canopy density data ([Figure 10](#fig-lca-ht-ws)). These findings are also consistent with observations by Schmidt & Troendle (1989) who observed a slight increase in snowfall interception with increasing wind speeds up to 6 m s-1, Staines & Pomeroy (2023) who observed reduced canopy transmittance with increasing angle from zenith, and studies of rainfall interception by Herwitz & Slye (1995) and Van Stan et al. (2011).

The slight increase in interception efficiency for smaller canopy snow loads and decline for larger canopy snow loads is attributed to the influence of canopy snow load on ([Figure 5](#fig-scl-ip-bins)). Whilst small, this effect is consistent with the theory proposed by Satterlund & Haupt (1967) that interception efficiency increases as the canopy fills with snow bridging gaps in the canopy, while later declining due to branch bending and decreased canopy cover. However, at the plot-scale, Staines & Pomeroy (2023) showed that these two processes may partially compensate for each other as increases for closed canopies, as new snow bridges form in the canopy, but decreases in partially open canopy due to branch bending (i.e., Fig. 2 in Schmidt & Gluns, 1991). Still, the increase in resulting from snow load in Staines & Pomeroy (2023) was small compared to the substantial rise in due to trajectory angle presented in their study; which corroborates with the plot-scale observations of in this study ([Figure 10](#fig-lca-ht-ws)). Additional observations by Watanabe & Ozeki (1964), Calder (1990), and Storck et al. (2002) support the findings in [Figure 3](#fig-scl-w-sf) showing a linear increase in canopy snow load with increasing snowfall. Further evidence in support of the relatively small influence of canopy snow load on , is provided by Lundquist et al. (2021) who reported improved simulation of subcanopy snow accumulation without the use of a maximum canopy snow load, when linked with a comprehensive canopy snow ablation routine. The low sensitivity to canopy snow load found here may result from reduced inclusion of ablation processes in our measurements, limited influence of snow load on at this site, and/or the compensatory effects described by Satterlund & Haupt (1967).

The limited influence of air temperature and canopy snow load on initial interception reported here differs from the theories underpinning existing snow interception parameterisations (Andreadis et al., 2009; Hedstrom & Pomeroy, 1998; Moeser et al., 2015b; Satterlund & Haupt, 1967). Cebulski & Pomeroy (2025) note studies that have identified a relationship between air temperature and/or snow load and interception efficiency (Katsushima et al., 2023; Roth & Nolin, 2019; Schmidt & Gluns, 1991) did not specifically examine initial interception prior to canopy snow ablation. In addition, since a maximum canopy snow load was not observed in this study, the air temperature dependent canopy snow load capacities included in the Hedstrom & Pomeroy (1998) and Andreadis et al. (2009) models were not applicable. Since canopy snow ablation is strongly correlated with air temperature and snow load (Ellis et al., 2010; Floyd, 2012; Hedstrom & Pomeroy, 1998; Roesch et al., 2001) some of the previously observed relationships related to these variables may be explained by changes in ablation rather than initial interception. The coupling of ablation processes within existing models may contribute to overestimates of throughfall and canopy snow unloading when combined with other canopy snow ablation parameterisations due to ‘double counting’ (Cebulski & Pomeroy, 2025).

To address these issues, a new vector-based snow interception parameterisation is presented ([Equation 9](#eq-lca-ip)) which calculates initial interception efficiency as a function of and an efficiency constant, . This new parameterisation allows for canopy snow loading processes to be isolated from canopy snow ablation processes and is consistent with current rainfall interception theory (Valante et al., 1997; Zhong et al., 2022). [Equation 9](#eq-lca-ip) differs only slightly from the original Hedstrom & Pomeroy (1998) parameterisation (see Equation 6 in Hedstrom & Pomeroy 1998), in that it does not calculate interception efficiency as a function of canopy snow load and from the Storck et al. (2002) parameterisation who found interception efficiency to be constant. Further research is needed to explore how processes such as the increased cohesion and adhesion of snowfall to the canopy at warm temperatures, as observed by Kobayashi (1987), Pfister & Schneebeli (1999), as well as hydrometeor velocity, particle size, and shape suggested by (Katsushima et al., 2023), may influence the parameter, although these effects were not observed in this study. Since [Equation 9](#eq-lca-ip) intentionally excludes processes attributed to canopy snow ablation that were previously included in earlier snow interception models, these ablation processes must be incorporated in canopy snow ablation parameterisations to fully represent the canopy snow mass balance.

The exponential relationship proposed by Hedstrom & Pomeroy (1998) to scale with wind speed failed to reproduce the observations presented in [Figure 10](#fig-lca-ht-ws). Instead, plot-wide was found to increase as function of hydrometeor trajectory angle and canopy cover. However, the large scatter in measurements shown in [Figure 10](#fig-lca-ht-ws) suggests [Equation 11](#eq-lca-inc) is only applicable at the forest stand scale, or larger, where the sub-metre variability in resulting from directional differences averages out. Canopy cover measurements at larger scales may lack sufficient resolution to identify large open area components of forests, where the assumptions of [Equation 10](#eq-lca-ac) would not be valid, and should be estimated using horizontal canopy cover without adjusting for snowfall trajectory angle. If fine-scale canopy observations are available, canopy structure metrics such as the gap area indices described in Moeser et al. (2015a) could be helpful for identifying large gaps in the canopy. Moreover, our measurements show the hydrometeor trajectory angle required for [Equation 11](#eq-lca-inc), can be approximated from [Equation 4](#eq-ta) incorporating the hydrometeor fall velocity and the mean horizontal wind speed selected at one-third of the canopy height. This is consistent with Katsushima et al. (2023), who also proposed using a wind speed at one-third the canopy height for modelling unloading of canopy snow. The transferability of the snow-leaf contact area equation ([Equation 11](#eq-lca-inc)) remains uncertain, as it has only been tested at a single site with two tree species, and the relationship of with environmental factors is expected to vary across different climate conditions, canopy structures, densities, species, and ages. Additionally, [Equation 4](#eq-ta) assumes a linear hydrometeor trajectory, and does not consider non-linear patterns such as wind flow directions around tree elements, turbulent flow, or differences in wind speed with height. Staines & Pomeroy (2023) showed, at a proximal montane spruce-fir forest, that backflows and large eddies that occur within the canopy can contribute to mixed responses. Therefore, further testing and modification of [Equation 11](#eq-lca-inc) is needed in diverse forest environments.

Although the vector-based model showed relatively modest improvement over the nadir model, it is preferred due to its lower error compared to the UAV-lidar measurements and better representation of physical processes. Developed and tested at the forest plot scale (hectares), the vector-based model is suitable for hydrological models discretized by forest density at this scale, though the relationship between snow interception and snow-leaf contact area should be applicable at larger scales. Previous subcanopy snow accumulation models were developed based on process understanding at varying scales: Hedstrom & Pomeroy (1998) used snow survey transects at the forest plot scale with observations at intervals ranging from days to weeks, whilst Storck et al. (2002) relied on point-scale lysimetry observations at 30-minute intervals. Recent evidence from Staines & Pomeroy (2023) and the results presented here suggest that some of the process understanding developed in previous studies may not be applicable at larger extents or finer temporal resolutions. The theoretical basis of the vector-based model is supported by observations across a broad range of meteorological conditions and forest densities and aligns with globally tested rainfall interception models (e.g., Valante et al., 1997; Zhong et al., 2022), suggesting potential broader applicability, though further validation is required.

# 6. Conclusions

New observations of initial snow interception, collected over a wide range of meteorological conditions and canopy densities indicate that leaf contact area is the primary factor influencing subcanopy snow accumulation. At the point scale, measurements revealed no evidence of a maximum canopy snow load, even for event snowfalls up to 45 mm, nor was there any indication of air temperature influencing the cohesion and adhesion of snowfall to the canopy. Instead, wind speed was found to influence interception efficiency by changing the hydrometeor trajectory angle, which led to a substantial increase in snow-leaf contact area.

At the forest plot scale, UAV-lidar measurements of throughfall aligned with the point-scale observations demonstrating that leaf contact area was strongly associated with interception efficiency at a particular site. Leaf contact area, which incorporates changes in canopy density with hydrometeor trajectory angle, proved to be a better predictor of interception efficiency compared to nadir-calculated canopy cover. When averaged across each forest plot, leaf contact area was shown to be highly sensitive to hydrometeor trajectory angle, increasing by 61–95% for trajectory angles associated with a 1 m s-1 wind speed. An existing theoretical relationship failed to adequately represent the measured increase in leaf contact area with simulated trajectory angles. As a result, a new relationship is proposed as a function of canopy cover and hydrometeor trajectory angle, approximated from wind speed and hydrometeor terminal fall velocity, demonstrated accurate performance at this study site.

The weak association between air temperature and canopy snow load with initial interception efficiency, as presented here and in earlier studies, coupled with novel insights on the influence of wind speed on leaf contact area, suggests the potential benefits of a new snow interception parameterisation. A new parameterisation is proposed that calculates initial interception as a function of snowfall and leaf contact area. This parameterisation is consistent with rainfall interception studies, which also separate canopy loading and ablation processes, and calculate interception as a function of canopy cover. Additionally, a second equation is proposed to estimate leaf contact area as a function of hydrometeor trajectory angle and nadir canopy cover. This updated snow interception parameterisation performed well in the subalpine forest studied here at the forest plot scale. However, further validation is necessary in a range of climates, forests, and spatial extents.

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# 8. Data Availability

The data that support the findings in this study are available at https://doi.org/10.5281/zenodo.14018893.

# 9. References

Andreadis, K. M., Storck, P., & Lettenmaier, D. P. (2009). Modeling snow accumulation and ablation processes in forested environments. *Water Resources Research*, *45*(5), 1–33. <https://doi.org/10.1029/2008WR007042>

Calder, I. R. (1990). *Evaporation in the uplands* (p. 148). Wiley.

Cebulski, A. C., & Pomeroy, J. W. (2025). Theoretical Underpinnings of Snow Interception and Canopy Snow Ablation Parameterisations. *WIREs Water*, *12*(e70010). <https://doi.org/10.1002/wat2.70010>

Chianucci, F., & Macek, M. (2023). hemispheR: An R package for fisheye canopy image analysis. *Agricultural and Forest Meteorology*.

Cionco, R. M. (1965). A mathematical model for air flow in a vegetative canopy. *Journal of Applied Meteorology (1962)*, *4*(4), 517–522. <https://doi.org/10.1175/1520-0450(1965)004<0517:AMMFAF>2.0.CO;2>

Clark, M. P., Nijssen, B., Lundquist, J. D., Kavetski, D., Rupp, D. E., Woods, R. A., Freer, J. E., Gutmann, E. D., Wood, A. W., Gochis, D. J., Rasmussen, R. M., Tarboton, D. G., Mahat, V., Flerchinger, G. N., & Marks, D. G. (2015). A unified approach for process-based hydrologic modeling: 2. Model implementation and case studies. *Water Resources Research*, *51*(4), 2515–2542. <https://doi.org/10.1002/2015WR017200>

Ellis, C. R., Pomeroy, J. W., Brown, T., & MacDonald, J. (2010). Simulation of snow accumulation and melt in needleleaf forest environments. *Hydrology and Earth System Sciences*, *14*(6), 925–940. <https://doi.org/10.5194/hess-14-925-2010>

Ellis, C. R., Pomeroy, J. W., & Link, T. E. (2013). Modeling increases in snowmelt yield and desynchronization resulting from forest gap-thinning treatments in a northern mountain headwater basin. *Water Resources Research*, *49*(2), 936–949. <https://doi.org/10.1002/wrcr.20089>

Essery, R., Pomeroy, J. W., Parviainen, J., & Storck, P. (2003). Sublimation of snow from coniferous forests in a climate model. *Journal of Climate*, *16*(11), 1855–1864. <https://doi.org/10.1175/1520-0442(2003)016<1855:SOSFCF>2.0.CO;2>

Floyd, W. C. (2012). *Snowmelt energy flux recovery during rain-on-snow in regenerating forests* (p. 180) [MSc. Thesis, University of British Columbia]. https://doi.org/<https://dx.doi.org/10.14288/1.0073024>

Fryer, B. Y. G. I., Johnson, E. A., Fryer, G. I., & Johnson, E. A. (1988). Reconstructing fire behaviour and effects in a subalpine forest. *The Journal of Applied Ecology*, *25*(3), 1063–1072. <https://doi.org/10.2307/2403766>

Gelfan, A. N., Pomeroy, J. W., & Kuchment, L. S. (2004). Modeling forest cover influences on snow accumulation, sublimation, and melt. *Journal of Hydrometeorology*, *5*(5), 785–803. <https://doi.org/10.1175/1525-7541(2004)005<0785:MFCIOS>2.0.CO;2>

Golding, D. L., & Swanson, R. H. (1978). Snow accumulation and melt in small forest openings in Alberta. *Canadian Journal of Forest Research*, *8*(4), 380–388. <https://doi.org/10.1139/x78-057>

Harder, P., & Pomeroy, J. W. (2013). Estimating precipitation phase using a psychrometric energy balance method. *Hydrological Processes*, *27*(13), 1901–1914. <https://doi.org/10.1002/hyp.9799>

Harder, P., Pomeroy, J. W., & Helgason, W. D. (2020). Improving sub-canopy snow depth mapping with unmanned aerial vehicles: Lidar versus structure-from-motion techniques. *The Cryosphere*, *14*(6), 1919–1935. <https://doi.org/10.5194/tc-14-1919-2020>

Harpold, A. A., Krogh, S. A., Kohler, M., Eckberg, D., Greenberg, J., Sterle, G., & Broxton, P. D. (2020). Increasing the efficacy of forest thinning for snow using high-resolution modeling: A proof of concept in the Lake Tahoe Basin, California, USA. *Ecohydrology : Ecosystems, Land and Water Process Interactions, Ecohydrogeomorphology*, *13*(4). <https://doi.org/10.1002/eco.2203>

Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, *12*(10-11), 1611–1625. <https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1611::AID-HYP684>3.0.CO;2-4>

Herwitz, S. R., & Slye, R. E. (1995). Three-dimensional modeling of canopy tree interception of wind-driven rainfall. *Journal of Hydrology*, *168*(1-4), 205–226. <https://doi.org/10.1016/0022-1694(94)02643-P>

Isyumov, N. (1971). *An approach to the prediction of snow loads* [PhD thesis]. The University of Western Ontario (Canada).

Katsushima, T., Kato, A., Aiura, H., Nanko, K., Suzuki, S., Takeuchi, Y., & Murakami, S. (2023). Modelling of snow interception on a Japanese cedar canopy based on weighing tree experiment in a warm winter region. *Hydrological Processes*, *37*(6), 1–16. <https://doi.org/10.1002/hyp.14922>

Kim, E., Gatebe, C., Hall, D., Newlin, J., Misakonis, A., Elder, K., Marshall, H. P., Hiemstra, C., Brucker, L., De Marco, E., Crawford, C., Kang, D. H., & Entin, J. (2017). NASA’s snowex campaign: Observing seasonal snow in a forested environment. *2017 IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*, 1388–1390. <https://doi.org/10.1109/IGARSS.2017.8127222>

Kobayashi, D. (1987). Snow accumulation on a narrow board. *Cold Regions Science and Technology*, *13*(3), 239–245. <https://doi.org/10.1016/0165-232X(87)90005-X>

Kozak, A., & Kozak, R. A. (1995). Notes on regression through the origin. *Forestry Chronicle*, *71*(3), 326–330. <https://doi.org/10.5558/tfc71326-3>

Langs, L. E., Petrone, R. M., & Pomeroy, J. W. (2020). A 18O and 2H stable water isotope analysis of subalpine forest water sources under seasonal and hydrological stress in the Canadian Rocky Mountains. *Hydrological Processes*, *34*(26), 5642–5658. <https://doi.org/10.1002/hyp.13986>

Lumbrazo, C., Bennett, A., Currier, W. R., Nijssen, B., & Lundquist, J. (2022). Evaluating multiple canopy-snow unloading parameterizations in SUMMA with time-lapse photography characterized by citizen scientists. *Water Resources Research*, *58*(6), 1–22. <https://doi.org/10.1029/2021WR030852>

Lundberg, A., & Halldin, S. (1994). Evaporation of intercepted snow: Analysis of governing factors. *Water Resources Research*, *30*(9), 2587–2598.

Lundquist, J. D., Dickerson-Lange, S., Gutmann, E., Jonas, T., Lumbrazo, C., & Reynolds, D. (2021). Snow interception modelling: Isolated observations have led to many land surface models lacking appropriate temperature sensitivities. *Hydrological Processes*, *35*(7), 1–20. <https://doi.org/10.1002/hyp.14274>

MacDonald, J. P. (2010). *Unloading of intercepted snow in conifer forests* (p. 93) [MSc. Thesis]. Department of Geography, University of Saskatchewan.

Mazzotti, G., Currier, W. R., Deems, J. S., Pflug, J. M., Lundquist, J. D., & Jonas, T. (2019). Revisiting snow cover variability and canopy structure within forest stands: Insights from airborne lidar data. *Water Resources Research*, *55*(7), 6198–6216. <https://doi.org/10.1029/2019WR024898>

Moeser, D., Morsdorf, F., & Jonas, T. (2015a). Novel forest structure metrics from airborne LiDAR data for improved snow interception estimation. *Agricultural and Forest Meteorology*, *208*, 40–49. <https://doi.org/10.1016/j.agrformet.2015.04.013>

Moeser, D., Stähli, M., & Jonas, T. (2015b). Improved snow interception modeling using canopy parameters derived from airborne LiDAR data. *Water Resources Research*, *51*(7), 5041–5059. <https://doi.org/10.1002/2014WR016724>

Musselman, K. N., Pomeroy, J. W., & Link, T. E. (2015). Variability in shortwave irradiance caused by forest gaps: Measurements, modelling, and implications for snow energetics. *Agricultural and Forest Meteorology*, *207*, 69–82. <https://doi.org/10.1016/j.agrformet.2015.03.014>

Parviainen, J., & Pomeroy, J. W. (2000). Multiple-scale modelling of forest snow sublimation: Initial findings. *Hydrological Processes*, *14*(15), 2669–2681. <https://doi.org/10.1002/1099-1085(20001030)14:15<2669::AID-HYP85>3.0.CO;2-Q>

Pfister, R., & Schneebeli, M. (1999). Snow accumulation on boards of different sizes and shapes. *Hydrological Processes*, *13*(14-15), 2345–2355. <https://doi.org/10.1002/(SICI)1099-1085(199910)13:14/15<2345::AID-HYP873>3.0.CO;2-N>

Pomeroy, J. W., Brown, T., Fang, X., Shook, K. R., Pradhananga, D., Armstrong, R., Harder, P., Marsh, C., Costa, D., Krogh, S. A., Aubry-Wake, C., Annand, H., Lawford, P., He, Z., Kompanizare, M., & Moreno, J. I. L. (2022). The cold regions hydrological modelling platform for hydrological diagnosis and prediction based on process understanding. *Journal of Hydrology*, *615*(128711), 1–25. <https://doi.org/10.1016/j.jhydrol.2022.128711>

Pomeroy, J. W., Fang, X., & Ellis, C. R. (2012). Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. *Hydrological Processes*, *26*(12), 1891–1904. <https://doi.org/10.1002/hyp.9248>

Pomeroy, J. W., Marsh, P., & Gray, D. M. (1997). Application of a distributed blowing snow model to the arctic. *Hydrological Processes*, *11*(11), 1451–1464. <https://doi.org/10.1002/(sici)1099-1085(199709)11:11<1451::aid-hyp449>3.0.co;2-q>

Pomeroy, J. W., Parviainen, J., Hedstrom, N., & Gray, D. M. (1998). Coupled modelling of forest snow interception and sublimation. *Hydrological Processes*, *12*(15), 2317–2337. <https://doi.org/10.1002/(SICI)1099-1085(199812)12:15<2317::AID-HYP799>3.0.CO;2-X>

Pomeroy, J. W., & Schmidt, R. A. (1993). The use of fractal geometry in modelling intercepted snow accumulation and sublimation. *Eastern Snow Conference*, *50*, 231–239.

R Core Team. (2024). *R: A language and environment for statistical computing* [Manual]. R Foundation for Statistical Computing.

Rittger, K., Raleigh, M. S., Dozier, J., Hill, A. F., Lutz, J. A., & Painter, T. H. (2020). Canopy adjustment and improved cloud detection for remotely sensed snow cover mapping. *Water Resources Research*, *56*(6), n/a. <https://doi.org/10.1029/2019WR024914>

Roesch, A., Wild, M., Gilgen, H., & Ohmura, A. (2001). A new snow cover fraction parameterization for the ECHAM4 GCM. *Climate Dynamics*, *17*(12), 933–946. <https://doi.org/10.1007/s003820100153>

Roth, T. R., & Nolin, A. W. (2019). Characterizing maritime snow canopy interception in forested mountains. *Water Resources Research*, *55*(6), 4564–4581. <https://doi.org/10.1029/2018WR024089>

Safa, H., Krogh, S. A., Greenberg, J., Kostadinov, T. S., & Harpold, A. A. (2021). Unraveling the controls on snow disappearance in montane conifer forests using multi-site lidar. *Water Resources Research*, *57*(12), 1–20. <https://doi.org/10.1029/2020WR027522>

Sanmiguel-Vallelado, A., McPhee, J., Esmeralda Ojeda Carreño, P., Morán-Tejeda, E., Julio Camarero, J., & López-Moreno, J. I. (2022). Sensitivity of forest–snow interactions to climate forcing: Local variability in a Pyrenean valley. *Journal of Hydrology*, *605*. <https://doi.org/10.1016/j.jhydrol.2021.127311>

Satterlund, D. R., & Haupt, H. F. (1967). Snow catch by conifer crowns. *Water Resources Research*, *3*(4), 1035–1039. <https://doi.org/10.1029/WR003i004p01035>

Schmidt, R. A., & Gluns, D. R. (1991). Snowfall interception on branches of three conifer species. *Canadian Journal of Forest Research*, *21*(8), 1262–1269. <https://doi.org/10.1139/x91-176>

Schmidt, R. A., & Pomeroy, J. W. (1990). Bending of a conifer branch at subfreezing temperatures: Implications for snow interception. *Canadian Journal of Forest Research*, *20*(8), 1251–1253. <https://doi.org/10.1139/x90-165>

Schmidt, R. A., & Troendle, C. A. (1989). Snowfall into a forest and clearing. *Journal of Hydrology*, *110*(3-4), 335–348. <https://doi.org/10.1016/0022-1694(89)90196-0>

Smith, C. D. (2007). Correcting the wind bias in snowfall measurements made with a Geonor T-200B precipitation gauge and alter wind shield. *87th AMS Annual Meeting*.

Staines, J., & Pomeroy, J. W. (2023). Influence of forest canopy structure and wind flow on patterns of sub-canopy snow accumulation in montane needleleaf forests. *Hydrological Processes*, *37*(10), 1–19. <https://doi.org/10.1002/hyp.15005>

Storck, P., Lettenmaier, D. P., & Bolton, S. M. (2002). Measurement of snow interception and canopy effects on snow accumulation and melt in a mountainous maritime climate, Oregon, United States. *Water Resources Research*, *38*(11), 1–16. <https://doi.org/10.1029/2002wr001281>

Troendle, C. A. (1983). The potential for water yield augmentation from forest management in the rocky mountain region. *Journal of the American Water Resources Association*, *19*(3), 359–373. <https://doi.org/10.1111/j.1752-1688.1983.tb04593.x>

Valante, F., David, J. S., & Gash, J. H. C. (1997). Modelling interception loss for two sparse eucalypt and pine forests in central Portugal using reformulated Rutter and Gash analytical models. *Journal of Hydrology*, *190*(1-2), 141–162. <https://doi.org/10.1016/S0022-1694(96)03066-1>

Van Stan, J. T., Siegert, C. M., Levia, D. F., & Scheick, C. E. (2011). Effects of wind-driven rainfall on stemflow generation between codominant tree species with differing crown characteristics. *Agricultural and Forest Meteorology*, *151*(9), 1277–1286. <https://doi.org/10.1016/j.agrformet.2011.05.008>

Varhola, A., Coops, N. C., Weiler, M., & Moore, R. D. (2010). Forest canopy effects on snow accumulation and ablation: An integrative review of empirical results. *Journal of Hydrology*, *392*(3-4), 219–233. <https://doi.org/10.1016/j.jhydrol.2010.08.009>

Vionnet, V., Mortimer, C., Brady, M., Arnal, L., & Brown, R. (2021). Canadian historical snow water equivalent dataset (CanSWE, 1928–2020). *Earth System Science Data*, *13*(9), 4603–4619. <https://doi.org/10.5194/essd-13-4603-2021>

Watanabe, S., & Ozeki, J. (1964). Study of fallen snow on forest trees (II). Experiment on the snow crown of the Japanese cedar. *Japanese Govt. Forest Exp. Sta. Bull*, *169*, 121–140.

Zhong, F., Jiang, S., van Dijk, A. I. J. M., Ren, L., Schellekens, J., & Miralles, D. G. (2022). Revisiting large-scale interception patterns constrained by a synthesis of global experimental data. *Hydrology and Earth System Sciences*, *26*(21), 5647–5667. <https://doi.org/10.5194/hess-26-5647-2022>