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 parameterizations 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 parameterizations 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. The relationship between these throughfall measurements, event meteorology, and a novel lidar-based canopy density measurement are 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, canopy density 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 improved dramatically when adjusted for hydrometeor trajectory angle based on a 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 parameterization that calculates throughfall, independent of processes that ablate snow from the canopy, as a function of snowfall, canopy cover, and wind speed. This new parameterization successfully estimated subcanopy snow accumulation for a snowfall event at two forest plots measured using lidar and snow surveys. 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 parameterizations.

**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 & Hallidin, 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; Storck et al., 2002), and thus governs the quantity of snow subject to sublimation from the canopy. However, 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, 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 new snow density. Unloading was found to be an exponential function of time that was observed only days or weeks after the interception event. Storck et al. (2002), working in temperate coastal forests, emphasized the role of leaf area index and air temperature in controlling the maximum canopy snow load. Gelfan et al. (2004) demonstrated accurate subcanopy snowpack simulations at study sites in Russia by treating the Hedstrom & Pomeroy (1998) and Storck et al. (2002) parameterizations separately while using a step-based function to choose either parameterization based on air temperature. A similar parameterization in the Cold Regions Hydrological Model (Pomeroy et al., 2022) has shown strong performance at sites across Canada, northern United States, Switzerland, and Spain. However, overestimation of subcanopy snow accumulation was reported by Lundquist et al. (2021) and Lumbrazo et al. (2022) when combining the Hedstrom & Pomeroy (1998) routine with ablation parameterizations from different studies (e.g., Roesch et al., 2001). The coupling of ablation processes within existing snow interception models (Hedstrom & Pomeroy, 1998; Storck et al., 2002) may contribute to overestimates of throughfall, canopy snow unloading, and canopy snow melt when combined with other canopy snow ablation parameterizations (Cebulski & Pomeroy, 2025). Additional observations of snow interception that exclude ablation processes could help determine the applicability of the interception theories proposed by Hedstrom & Pomeroy (1998) and Storck et al. (2002). 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. Is 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 parameterization for 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 rate of rainfall falling on snow intercepted in the canopy, (mm s-1) is the throughfall rate (mm s-1), 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) show 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 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 peak annual snow water equivalent (SWE) reaching 465 mm, typically occurring 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 closure of the two forest plots 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, the majority of 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 road 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 (SCL), 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) and catch efficiency by 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 (SCLs) were installed surrounding the FT Station ([Figure 1](#fig-site-map)) to provide measurements of throughfall as in MacDonald (2010). [Figure 2](#fig-scl-imgs) shows the three SCLs which 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. For 26 distinct snowfall events, where canopy snow ablation rates were deemed negligible, snow captured in the SCLs was determined to be predominantly from throughfall. Timelapse imagery, mass change on a weighed tree lysimeter “hanging tree” (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 SCL measured throughfall rate. While these careful manual mitigation and automated filtering strategies substantially reduce the contribution of unloading in the SCL throughfall measurements, a small contribution is still possible.

The SCL throughfall measurements were converted from weight, to weight per unit area by dividing the snow weight in the SCL by the cross-sectional area of the SCL opening. Canopy snow load was also estimated using [Equation 1](#eq-canopy-mass-bal), incorporating throughfall measurements from the SCLs and snowfall measurements from the PWL gauge. 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 small amount of snow captured in the SCLs and Pluvio instruments over the 15-minute intervals led to very high relative instrument errors. To reduce this relative error, throughfall and snowfall measurements were accumulated. While suitable instrument errors were found for longer time intervals (greater than 12 hours), at these intervals, the relationship between interception efficiency and meteorological measurements was more likely to be non-stationary. Therefore, to ensure consistency between throughfall and snowfall measurements and meteorological conditions, air temperature, wind speed, and initial canopy snow load (measured from the weighed tree) were binned and the snowfall and throughfall measurements were accumulated within each bin. Interception efficiency was subsequently calculated for each bin using [Equation 3](#eq-ip2) and the accumulated measurements of snowfall and throughfall.

The SCLs were installed in locations selected to limit preferential throughfall and unloading by choosing locations with relatively continuous spatial distribution of canopy elements (i.e., canopy structure) and away from large branches which could preferentially unload snow. The canopy surrounding the SCLs led to reduced wind speeds and reduced the potential for gauge undercatch by the SCLs. The “mixed” canopy SCL had a slight canopy opening, shown in [Figure 2](#fig-scl-imgs), orientated towards the prevailing wind direction observed during the study period which allowed some preferential measurement of throughfall for snowfall trajectories aligned with this gap. Photographs of the three SCLs and surrounding canopy are shown in [Figure 2](#fig-scl-imgs). Leaf area index and canopy closure measurements of canopy density for each SCL are presented in [Table 1](#tbl-scl-lai-cc). A viewing angle of 60° from zenith was selected to describe the SCLs in the results section as non vertical hydrometeor trajectory angles were 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 in Pomeroy & Schmidt (1993). Although the weighed tree lysimeter provides a more direct measurement of canopy snow load compared to the SCLs, it was not used in the interception efficiency calculation as variations in the trees mass may be attributed to 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.

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| Table 1: Canopy density of the three subcanopy lysimeters (SCL) located proximal to the FT Station. Leaf area index (LAI) and canopy closure was measured using hemispherical photo analysis for varying viewing angles from zenith.   | Name | Angle From Zenith (°) | LAI (-) | Canopy Closure (-) | | --- | --- | --- | --- | | Sparse | 15 | 0.45 | 0.19 | | Sparse | 30 | 1.12 | 0.44 | | Closed | 15 | 1.58 | 0.54 | | Sparse | 45 | 1.43 | 0.56 | | Mixed | 15 | 2.00 | 0.63 | | Sparse | 60 | 1.56 | 0.64 | | Closed | 30 | 2.01 | 0.65 | | Mixed | 30 | 2.34 | 0.71 | | Mixed | 45 | 2.33 | 0.74 | | Mixed | 60 | 2.10 | 0.75 | | Closed | 45 | 2.47 | 0.76 | | Closed | 60 | 2.40 | 0.79 | |

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| Figure 2: Images of the three subcanopy lysimeters (SCL) and surrounding canopy located in sparse (a), mixed (b), and dense (c) canopy. The top row presents a side view of each SCL and the bottom row shows hemispherical photographs classified using the hemispheR R package. 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 canopy density measurements above each SCL. |

## 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 changed 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.

### 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 SCLs, 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) by using as the throughfall component () and the snowfall accumulation to the open () measured between the two lidar surveys at PWL station.

## 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, which often results from beam occlusion in vegetation and leads to reduced points near the ground. 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 (), hydrometeor trajectory angle (), and canopy snow load (). 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 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.

## 3.7 Statistics and regression models

Linear and non-linear regression models were developed to assess relationships in the observed data. Linear models were fitted using ordinary least squares regression to analyze two relationships: (1) between interception efficiency and meteorological variables and (2) between interception efficiency and leaf contact area. The latter was forced through the origin based on the theoretical justification that the dependent variable should be zero when the independent variable is zero. Kozak & Kozak (1995) noted, the default *R*2 value provided for least squares models forced through the origin by many statistical packages can be misleading. Therefore, these *R*2 values were adjusted using Equation 10 in Kozak & Kozak (1995). Non-linear models were fitted to investigate the relationship of leaf contact area with simulated trajectory angle using non-linear least squares regression. All statistical analyses were conducted using the R ‘stats’ package (R Core Team, 2024).

# 4. Results

## 4.1 The influence of meteorology on snow interception

[Figure 3](#fig-scl-w-sf) shows that canopy snow load increases linearly with cumulative snowfall across 26 snowfall events for both the SCL and weighed tree measurements with no evidence of approaching a canopy snow load capacity was observed for snowfall events up to 45 mm. 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 SCL and weighed tree measurements.

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| Figure 3: Plot showing the cumulative event snowfall versus the corresponding state of canopy snow load calculated using the average of the three subcanopy lysimeters (left) and weighed tree lysimeter (right) for each of the 26 snowfall events. |

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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 snowfall measured at PWL station and the average throughfall of all three SCLs located within the FT forest plot (all from 15-min. measurements).   |  | 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. |

[Figure 5](#fig-scl-ip-bins) shows interception efficiency calculated from accumulated snowfall (Pluvio) and throughfall (SCL) measurements for bins of air temperature, wind speed, and initial canopy snow load for periods with minimal canopy snow ablation. Accumulated snowfall ranged from 2–107 mm and accumulated throughfall ranged from 0.6–47 mm across the bins. The absolute instrument error within each bin ranged from +/-0.01–0.02 mm for the throughfall measurements and from +/-1.70–2.60 mm for the snowfall measurements. The interception efficiency observed across differing bins of air temperature does not show any systematic trend ([Figure 5](#fig-scl-ip-bins)). While air temperature bins below -10°C show slightly higher interception efficiency for the sparse and mixed canopies, the high instrument error due to low accumulated snowfall and throughfall in these bins makes any potential trend with air temperature highly uncertain. An increasing trend in interception efficiency with increasing wind speed was observed for the sparse and closed canopies (Figure 6b). The high uncertainty in of interception efficiency measurements for wind speeds above 2 m s-1 limits this trend to below 2 m s-1. A small increase in interception efficiency is observed for the sparse and closed canopies when the snow load is less than 7 mm (Figure 6c). Interception efficiency later declined for snow loads greater than 7 mm for all three canopies before the uncertainty in the interception efficiency measurements becomes substantial.

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| Figure 5: Scatter plots showing the interception efficiency calculated from accumulated snowfall (Pluvio) and throughfall (SCL) 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 SCLs. |

## 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 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 shown in [Figure 6](#fig-lidar-tf-ip) to be more apparent in the PWL forest plot than the FT forest plot. This may be attributed to the taller trees and higher canopy cover of the PWL forest plot compared to the FT forest plot, as for the same trajectory angle a taller tree will produce a larger downwind footprint.

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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 VoxRS measurements. [Figure 7](#fig-hemi-ip-cc) shows a strong linear correlation between measured on March 13th and interception efficiency towards the southern portion of the hemisphere, aligning with the average event wind direction. For the PWL forest plot, the upper 97.5th percentile of the values shown in [Figure 7](#fig-hemi-ip-cc), were found between azimuth angles of 167°–217°. Similarly, for the FT forest plot, the upper 97.5th percentile of the Pearson Correlation Coefficient () 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. |

An estimate of that represented the event was selected from the VoxRS measurements based on the vector corresponding to the azimuth and zenith angles observed to have the highest in [Figure 7](#fig-hemi-ip-cc). The spatial distribution of the selected VoxRS measurements is shown in [Figure 8](#fig-lidar-cc-cp) and generally aligns with the spatial distribution of interception efficiency and throughfall shown in [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°). |

[Figure 9](#fig-lca-vs-ip) shows 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°. The stronger association for the vector-based calculation 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 (e.g., 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 leaf contact area measured from a zenith angle of 0°. 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 results in *R*2 values of 0.45 and 0.8 for PWL and FT respectively. 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. Model error statistics are presented in [Table 3](#tbl-ip-mod-err) for the nadir and vector-based models and show the vector-based model provided a better prediction of interception efficiency. Some of the scatter observed in the nadir model shown in [Figure 9](#fig-lca-vs-ip) may be explained by grid cells which observed a greater interception efficiency compared to the corresponding value and can be attributed to the inability of to represent the increase in interception observed within canopy gaps in [Figure 6](#fig-lidar-tf-ip). Conversely, grid cells where interception efficiency is less than , 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). The latter may explain the non-linear relationship observed for the PWL nadir calculation in [Figure 6](#fig-lidar-tf-ip).

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| Table 3: Model error statistics provided for predictions of interception efficiency using [Equation 9](#eq-lca-ip) and for different values, as shown in the Model Slope column. Statistics are provided for the PWL and FT forest plots, using leaf contact area canopy metrics adjusted to zenith angles of (0°, 1°, … 30°) and azimuth angles (170°, 171°, … 220°) and nadir zenith angle of 0°. 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 | NA | | 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

[Figure 10](#fig-lca-ht-ws) shows that , measured from VoxRS prior to snowfall on March 13th, increases substantially with simulated hydrometeor trajectory angle and corresponding simulated wind speed. 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)). This is a fractional increase in the plot from nadir of 0.61 and 0.95 for PWL and FT respectively. The increase in from , with increasing trajectory angle is shown on the bottom row of [Figure 10](#fig-lca-ht-ws) and exhibits a similar relationship for both forest plots FT and PWL until trajectory angles reach approximately 60°. Beyond 60°, the PWL rate of increase slows as the approaches 1.0, while the FT plot, which has lower , 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 1 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 , and it 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 that 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°, and is equal to the canopy coverage. In contrast, for close to 90°, approaches a value of 1.0. The assumptions of [Equation 12](#eq-f-theta) include its application to a forest with relatively uniform structure (e.g., without large clear cuts) and where the mean height of the canopy is greater than the mean width of individual trees. Additionally, it is assumed that snowfall is not transmitted through the canopy and that overlapping of canopy elements is negligible.

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 shown in [Table 4](#tbl-lca-mod-err) 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. In contrast, [Table 4](#tbl-lca-mod-err) reveals that 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.

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| Table 4: Model error statistics calculated for the prediction of leaf contact area from trajectory angle using [Equation 11](#eq-lca-inc) (Eq. 11) 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)) parameterizations 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 coverage from the VoxRS dataset. Interception efficiency was calculated using [Equation 9](#eq-lca-ip) with the estimated leaf contact area 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.

[Figure 11](#fig-event-tf) illustrates that the new vector-based parameterization closely matches UAV-lidar measurements of throughfall. 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. [Table 5](#tbl-vb-plot-err) presents both observed and modelled values for interception efficiency and throughfall, along with corresponding error statistics. 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. This overestimation occurred because the nadir-based model approximated leaf contact area directly from canopy cover measurements (i.e., was not adjusted using [Equation 10](#eq-lca-ac)), resulting in a lower estimated contact area and consequently less snow intercepted in the canopy.

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| Figure 11: Bar chart comparing the observed and modelled mean change in throughfall (, mm) over the March 13-14th snowfall event averaged over forest plots FT and PWL. The ‘Nadir-model’ used [Equation 9](#eq-lca-ip) not adjusted for trajectory angle (e.g., ) and the Vector-based ‘VB-model’ which uses [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 5: 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 interception efficiency for measurements that partitioned ablation and initial canopy snow loading processes. However, other studies have presented positive (Andreadis et al., 2009; Katsushima et al., 2023; Roth & Nolin, 2019) and negative (Schmidt & Gluns, 1991; **Pomeroy1998?**) relationships between air temperature and snow interception. The limited association found here may be explained as air temperature influences processes that both increase or decrease interception efficiency, which may occur simultaneously and limit the overall effect. For example, warmer temperatures increase branch flexibility (Schmidt & Gluns, 1991) and can cause snow loaded branches to bend and thus reduce . In contrast, the cohesion and adhesion of snowfall has been shown to increase for warmer temperatures (Kobayashi, 1987; Pfister & Schneebeli, 1999) which could increase the efficiency constant (i.e., in [Equation 9](#eq-lca-ip)) thereby increasing interception efficiency as observed by Katsushima et al. (2023). However, the throughfall observations reported here were filtered to exclude periods of canopy snow melt, when higher liquid water content enhances cohesion and adhesion, and liquid water may freeze onto the canopy.

A weak trend was observed between initial interception efficiency (i.e., before unloading) with increasing wind speed at two locations which were sheltered from the predominant wind direction (Figure 6b). This is attributed to an associated increase in due to non-vertical hydrometeor trajectories. These results are 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 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 6c). While 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), show that these two processes may partially compensate for each other as increases for closed canopies, as new snow bridges gaps, but decreases in partially open canopy due to branch bending (i.e., Fig. 2 in Schmidt & Gluns, 1991). 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 shown in [Figure 10](#fig-lca-ht-ws). Moreover, additional studies (Calder, 1990; Watanabe & Ozeki, 1964) align with the observations in [Figure 3](#fig-scl-w-sf), which show a relatively 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 of interception efficiency with canopy snow load found in this study and others may be attributed to several factors: a reduced inclusion of ablation processes in the interception efficiency measurements, limited influence of canopy snow load on at this study site, and/or the compensatory effects outlined 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 parameterizations (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967; Storck et al., 2002). Cebulski & Pomeroy (2025) highlights the uncertainty in the extent to that ablation processes are included in common snow interception models. Since canopy snow ablation is strongly related to 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. Moreover, since a canopy snow load capacity 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. 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, and thus their measurements inherently include ablation processes. The coupling of ablation processes within existing snow interception models may contribute to overestimates of throughfall, canopy snow unloading, and canopy snow melt when combined with other canopy snow ablation parameterizations (Cebulski & Pomeroy, 2025).

To address these issues, a new vector-based snow interception parameterization, [Equation 9](#eq-lca-ip), is presented which calculates initial interception efficiency as a function of and . This new parameterization 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). [Equation 9](#eq-lca-ip) differs only slightly from the original Hedstrom & Pomeroy (1998) parameterization (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) parameterization who found interception efficiency to be constant. The theoretical basis of the parameter in [Equation 9](#eq-lca-ip) is that the association between and interception efficiency, as shown in [Figure 9](#fig-lca-vs-ip), unlike existing rainfall parameterizations (Valante et al., 1997) does not follow a 1:1 line, as falling snow hydrometeors may bounce off the canopy elements. 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. Moreover, the relationship of with air temperature and canopy snow load is expected to vary across varying combinations of climate, forest structure, species, and ages, requiring further research. For example, certain tree species or ages with very flexible branches may call for the explicit representation of variable with canopy snow load. 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 parameterizations to fully represent the canopy snow mass balance.

Measurements of interception efficiency, as shown in [Figure 6](#fig-lidar-tf-ip), align with the theory proposed by Hedstrom & Pomeroy (1998) which suggests reduced throughfall on the lee side of individual trees for a wind driven snowfall event. However, an existing exponential relationship proposed in 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 and . [Figure 10](#fig-lca-ht-ws) shows that at the plot scale, rises with increasing , as there is a greater number of grid cells which have more closed canopy at more horizontal angles. This has important implications for subcanopy snow accumulation as [Equation 9](#eq-lca-ip) suggests that a 30% increase in snow interception would be expected for 1 m s-1 wind speed and 0.9 m s-1 hydrometeor fall velocity based on the canopy metrics derived in [Figure 10](#fig-lca-ht-ws). However, the large scatter in measurments shown in [Figure 10](#fig-lca-ht-ws) suggests [Equation 11](#eq-lca-inc) is only applicable at the forest stand scale where the sub-metre variability in averages out. Still, [Equation 11](#eq-lca-inc) would not be applicable in areas that have large continuous gap fractions (e.g., large forested clear cuts) that are many times wider than the mean canopy height. Further testing of [Equation 11](#eq-lca-inc) is also needed in a wide range of forest species, ages, densities, and structures. Staines & Pomeroy (2023) have also shown that backflows and large eddies that occur within the canopy can also contribute to mixed responses.

It was found that the mean event hydrometeor trajectory angle, required for [Equation 11](#eq-lca-inc), could be approximated from [Equation 4](#eq-ta) using the observed mean hydrometeor fall velocity and the mean horizontal wind speed selected at one-third of the canopy height above the ground. A wind speed at one-third the mean canopy height is hypothesized to be important for canopy snow accumulation as a large fraction of the horizontal cross-sectional area is at this height for most needleleaf canopies. Katsushima et al. (2023), also proposed the wind speed at one-third the canopy height for modelling unloading of canopy snow as it corresponds to the centre of gravity when the horizontal projection of the canopy is assumed to be a triangle. However, there is uncertainty in the transferability of the canopy height observed here to other environments due to differing forest structures and tree species. This may include forests with a larger trunk space or have more of their canopy contact area at higher heights above the ground (e.g., some deciduous canopies). Moreover, [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.

Although the improvement in performance of the vector-based model over the nadir model was relatively small, the vector-based model is preferred due to its overall lower error compared to the UAV-lidar measurements and better representation of physical processes. While the vector-based model acts to increase interception efficiency with wind speed, several studies have shown that canopy snow ablation increases as a result of wind induced unloading (Bartlett & Verseghy, 2015; Betts & Ball, 1997; Lumbrazo et al., 2022; Roesch et al., 2001; Wheeler, 1987). Thus, representing both the increase in initial interception due to inclined hydrometeor trajectory angles and the subsequent increase in canopy snow unloading will be important in subcanopy snow accumulation models. This new vector-based model has been developed and tested based at the forest plot scale (hectares) and is therefore currently suitable for application in hydrological models at this scale that are discretized by forest density. Previous models were developed based on process understanding at varying scales: Hedstrom & Pomeroy (1998), based on snow survey transects at the forest plot scale (intervals ranging from days to weeks), and Storck et al. (2002), based on point-scale 30-minute interval lysimetry observations. 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 scales or finer spatial and temporal resolutions. Therefore, the process understanding presented here may be more suitable for application at larger extents and finer temporal resolutions, however, further testing is required to support this theory.

# 6. Conclusions

New observations of initial snow interception, collected over a wide range of meteorological conditions and canopy densities indicate that forest 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 with minimal ablation, nor was there any indication of air temperature influencing the cohesion and adhesion of snowfall to the canopy or branch bending reducing canopy cover. Instead, wind speed was found to influence interception efficiency by changing the hydrometeor trajectory angle, which lead 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 the primary factor influencing interception efficiency at a particular site. Leaf contact area, which incorporates changes in the number of canopy contacts 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 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 VoxRS-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), which demonstrated good performance at this study site.

The weak association between air temperature and canopy snow load with interception efficiency, as presented here, coupled with the influence of wind speed on leaf contact area, highlights the need for a new snow interception parameterization. A new parameterization is proposed that calculates initial interception as a function of snowfall and leaf contact area. This parameterization 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 parameterization 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 larger 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>

Bartlett, P. A., & Verseghy, D. L. (2015). Modified treatment of intercepted snow improves the simulated forest albedo in the Canadian Land Surface Scheme. *Hydrological Processes*, *29*(14), 3208–3226. <https://doi.org/10.1002/HYP.10431>

Betts, A. K., & Ball, J. H. (1997). Albedo over the boreal forest. *Journal of Geophysical Research: Atmospheres*, *102*(D24), 28901–28909. <https://doi.org/10.1029/96JD03876>

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>

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) [PhD 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., & Hallidin, 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. J. (2010). *Unloading of intercepted snow in conifer forests* (Master of {{Science}} August; pp. 0–93). University of Saskatchewan.

Moeser, D., Stähli, M., & Jonas, T. (2015). 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>

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., & 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. *Jap. Govt. Forest Exp. Sta. Bull*, *169*, 121–140.

Wheeler, K. (1987). Interception and redistribution of snow in a subalpine forest on a storm-by-storm basis. In *55th annual western snow conference*. Western Snow Conference.