Snow Interception Relationships with Meteorology and Canopy Structure 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 structure 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 structure 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 snow-leaf contact area adjusted for hydrometeor trajectory angle. 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. Vegetation structure 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 and 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, 2024). 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 forest structure and initial snow interception supported by in-situ observations?
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 Snow interception

The change in canopy snow load over time, (kg m-2 s-1), can be estimated from the mass balance:

where is the snowfall rate (kg m-2 s-1), (kg m-2 s-1) is the rate of rainfall falling on snow intercepted in the canopy, (kg m-2 s-1) is the throughfall rate (kg m-2 s-1), is the canopy snow unloading rate (kg m-2 s-1), is the canopy snow drip rate due to canopy snowmelt (kg m-2 s-1), is the wind transport rate in or out of the control volume (kg m-2 s-1), and is the intercepted snow sublimation rate (kg m-2 s-1). During periods with low air temperatures and low wind speeds, , , , , and can be assumed negligible. Figure 1 in Cebulski & Pomeroy (2024) presents a visual representation of this mass balance.

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

and throughfall, can be calculated 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, . This assumes the hydrometeors are following fluid points in the atmosphere.

# 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 kg m-2, typically occurring in late April. The PWL and FT forest plots include discontinuous stands of 70% subalpine fir (Abies lasiocarpa) and 30% Engelmann spruce (Picea engelmannii) (Langs et al., 2020). The PWL plot is located 120 m to the northwest of FT station and contains a forest clearing with a diameter of ~12 m, surrounded by a closed canopy. The FT plot has a discontinuous canopy without artificial clearings. The canopy coverages 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 surrounding the plot to the east of the PWL station is 10.5 m and surrounding the forest plot around the FT Station 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 for gap filling wind speed. Additional wind speed measurements were collected by two 3D sonic anemometers (Campbell Scientific CSAT3) installed at 2 m (raised to 3 m February 2022) and 13.5 m above the ground at FT station. Average wind speeds at these three heights were found to follow a logarithmic relationship. Thus, a wind profile was fitted to these measurements using the Prandtl-von Kármán log-linear relationship:

where is average wind speed (m s-1) at height, (m) above the ground, is the friction velocity (m s-1), is the displacement height (m), is the roughness length of momentum (m), and is the dimensionless von Kármán Constant (0.4).

Using wind speed measurements at three heights at FT station, collected during events when the instruments were confirmed to be free of snow, the function ‘optim’ from the ‘stats’ R package (R Core Team, 2024) was used to estimate the values and for [Equation 5](#eq-log-wind-profile) that best fit the observed mean wind speed. The parameters found for the wind speed profile include a of 0.58 m and of 0.50 m. See the supporting information for more information on the development and testing of the wind profile.

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). 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 15-minute interval 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 assumed to be throughfall. The throughfall rate, , was calculated by dividing the weight of snow in the SCL by the cross-sectional area of the SCL opening and determining the rate of change at 15-minute intervals. Canopy snow load was estimated at the same 15-minute intervals during these events using [Equation 1](#eq-canopy-mass-bal) and incorporating measurements of from the SCLs and from the PWL snowfall gauge. Rates of , , , , and were assumed to be zero for these periods. Interception efficiency was also calculated for these intervals using [Equation 2](#eq-ip). Timelapse imagery, mass change on a weighed tree lysimeter “hanging tree” (Pomeroy & Schmidt, 1993) and in-situ observations were used to ensure the ablation of snow intercepted in the canopy was minimal over each interval. Additionally, the measurements were filtered to include observations with a snowfall rate > 0 kg m-2 hr-1, throughfall rate > 0.05 kg m-2 hr-1 and a snowfall rate greater than the SCL measured throughfall rate to minimize observations with unloading. 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 (, kg m-2) using measurements of areal throughfall (kg m-2) from manual snow surveys and snowfall from the PWL Station snowfall gauge (see description of method in Pomeroy & Schmidt, 1993). The canopy structure surrounding three SCLs is shown in [Figure 2](#fig-scl-imgs) and was measured using hemispherical photography (Nikon Coolpix 4500 and EC-F8 hemispherical lens) and the hemispheR R package Chianucci & Macek (2023). The leaf area index and canopy coverage from hemispherical photo analysis is shown in [Table 1](#tbl-scl-lai-cc).

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| Table 1: Canopy structure of the three subcanopy lysimeters (SCL) located proximal to the FT Station. Leaf area index (LAI) and Canopy Coverage was measured using hemispherical photo analysis with the R package hemispheR.   | Name | LAI (-) | Canopy Coverage (-) | | --- | --- | --- | | Sparse | 1.59 | 0.73 | | Mixed | 1.86 | 0.78 | | Closed | 2.11 | 0.82 | |

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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 flipped to provide a view from above (i.e., east is on the right side of each image). See [Table 1](#tbl-scl-lai-cc) for the canopy structure measurements of the canopy 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). A detailed description of the UAV, payload, and flight settings is provided in the supporting information. 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. This offset between flight lines was corrected using the BayesStripAlign software v2.24 (BayesMap Solutions, 2024). After strip alignment, the mean elevation bias in the point clouds 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 (subtraction of the two UAV-lidar point clouds), and generation of 0.05 m resolution rasters was conducted using the LAStools software package (LAStools, 2024). Post processing and resampling of raster data to a 0.25 m grid cell resolution was conducted using the ‘Terra’ R package (Hijmans, 2024). More details on the UAV-lidar processing workflow are provided in the supporting information.

## 3.5 Snow surveys

### 3.5.1 In-situ snow depth and density

Twelve in-situ fresh snow surveys (six pre- and post-snowfall event pairs) provided measurements of subcanopy throughfall depth and density at 30 locations following the transects shown in [Figure 1](#fig-site-map) to upscale the weighed tree snow load from kg to kg m-2 as in Pomeroy & Schmidt (1993). Minimal ablation and redistribution of snow was observed between the pre- and post-snowfall surveys. When conditions allowed for a UAV-lidar flight, the in-situ snow surveys were conducted following the UAV-lidar flight to assess the accuracy of the throughfall measurements and provide a fresh snow density for the calculation of SWE (kg m-2). 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:

Differential GNSS rover coordinates, with ± 2.5 cm 3D uncertainty, were taken at each snow sampling location so the locations could be queried later from the UAV-lidar rasters to assess measurement error and were also used as input for the UAV-lidar strip alignment. 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 13th and March 14th, 2023 to facilitate the measurement of snow accumulation and canopy structure 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.

## 3.6 UAV-Lidar canopy metrics

The canopy structure in the two UAV-lidar point clouds (March 13th and March 14th) was characterized 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, i.e., 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 coverage , and . is approximately equal to canopy coverage () for vertical snowfall trajectories.

## 3.7 Statistics and regression models

To determine how forest structure was associated with interception efficiency at different azimuth and zenith angles over the March 13–14 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 calculated using the ‘stats’ package in R (R Core Team, 2024). The was computed between a single raster of interception efficiency and each of the 32,760 rasters of , 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.

Linear and non-linear regression models were developed to assess relationships in the observed data. Linear models were fitted using ordinary least squares regression via the ‘lm’ function from the R ‘stats’ package (R Core Team, 2024) 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 via the ‘nls’ function in ‘stats’ package in R.

# 4. Results

## 4.1 The influence of meteorology on snow interception

Canopy snow load was estimated for 26 snowfall events and increased linearly with cumulative event snowfall 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 in [Figure 3](#fig-scl-w-sf) for certain troughs during specific events was caused by damage to the subcanopy lysimeter wiring due to animals and heavy snow loads.

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| Figure 3: Plot showing the cumulative event snowfall versus the corresponding state of canopy snow load calculated using the subcanopy lysimeters (SCLs) for each of the 26 snowfall events. The SCLs are denoted by a distinct colour (grey, yellow, and green), correspond to varying canopy coverage (0.73, 0.78, and 0.82, respectively). |

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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 (kg $\text{m}^{-2}$) | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | 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 | 0.7 | 0.8 | 1.0 | 21.7 | | 2022-01-02 | -15.9 | -10.6 | -5.8 | 0.2 | 1.9 | 4.2 | 0.1 | 0.7 | 1.0 | 32.9 | | 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 | 45.3 | | 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. |

Event average air temperature and interception efficiency were negatively associated for the mixed canopy (*R*2 = 0.1, *p* < 0.05), but not associated at the closed and sparse canopies ([Table 3](#tbl-lysimeter-event-stats) & [Figure 5](#fig-scl-ip-avg-event)). Cumulative event snowfall was not associated with event interception efficiency at any site (*p* > 0.05). Event wind speed was positively associated with interception efficiency for the sparse (*R*2 = 0.1, *p* > 0.05) and closed (*R*2 = 0.2, *p* < 0.05) canopies, both with limited canopy openings (Figure 2a,c) towards the prevailing wind direction shown in the wind rose in [Figure 4](#fig-wind-rose). However, interception efficiency in the mixed canopy, which is partially open towards the prevailing wind direction, was not associated with wind speed (*p* > 0.05).

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| Figure 5: Scatter plots showing the event mean air temperature, mean wind speed, and cumulative snowfall versus the event mean interception efficiency estimated using the SCLs for each of the 26 snowfall events. The colours (grey, yellow, and green), correspond to varying canopy coverage (0.73, 0.78, and 0.82, respectively). A linear regression line fit to the data for significant relationships (*p* < 0.05) is shown by the solid coloured lines. See [Table 3](#tbl-lysimeter-event-stats) for linear regression statistics. |

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| Table 3: Statistics corresponding to the ordinary least squares linear regression test between independent variables: mean event air temperature, cumulative event snowfall, and mean event wind speed, and the dependent variable mean event interception efficiency. The test was run separately for three levels of canopy coverage ().   | Dependent Variable | SCL Name |  | Adjusted | -value |  | | --- | --- | --- | --- | --- | --- | | Air Temperature (°C) | Sparse | 0.73 | -0.032 | 0.519 | 19 | | Air Temperature (°C) | Mixed | 0.78 | 0.141 | 0.033 | 26 | | Air Temperature (°C) | Closed | 0.82 | 0.008 | 0.297 | 20 | | Cumulative Snowfall () | Sparse | 0.73 | -0.038 | 0.568 | 19 | | Cumulative Snowfall () | Mixed | 0.78 | 0.030 | 0.197 | 26 | | Cumulative Snowfall () | Closed | 0.82 | -0.049 | 0.732 | 20 | | Wind Speed (m/s) | Sparse | 0.73 | 0.114 | 0.087 | 19 | | Wind Speed (m/s) | Mixed | 0.78 | 0.010 | 0.275 | 26 | | Wind Speed (m/s) | Closed | 0.82 | 0.192 | 0.030 | 20 | |

Fifteen-minute interval measurements of interception efficiency and air temperature shown in Figure 6a were not associated, despite significant relationships for the sparse and mixed canopies (*R*2 < 0.03, *p* < 0.05), due to low predictive power ([Table 4](#tbl-lysimeter-15min-stats)). The average interception efficiency across differing bins of air temperature also does not show any systematic trend (Figure 6a). However, a significantly greater median interception efficiency (*p* < 0.05) was found for binned measurements with air temperatures below -6 °C compared to those with warmer air temperatures using non-parametric Wilcoxon signed rank test.

Mean wind speed was weakly associated with interception efficiency for the sparse (*R*2 = 0.1, *p* > 0.05) and closed (*R*2 = 0.2, p < 0.05), but not for the mixed canopy (*p* > 0.05) ([Table 4](#tbl-lysimeter-15min-stats)). The binned data show an increasing trend in interception efficiency with increasing wind speed for the sparse and closed canopies (Figure 6b). A comparison of interception efficiencies binned for low (< 1 m s-1) and high (> 1 m s-1) wind speeds by the Wilcoxon signed rank test, showed that high wind speeds had significantly higher (*p* < 0.05) median interception efficiencies compared to the low wind speed bins for the closed and sparse canopy. Conversely, the Wilcoxon test showed the mixed canopy, which had an opening in the canopy towards the prevailing wind direction (Figure 2b), had significantly higher (*p* < 0.05) median interception efficiencies for the low wind speed bins.

Interception efficiency showed no association (*R*2 < 0.05, *p* > 0.2) with the canopy load measured at the beginning of the 15-minute intervals ([Table 4](#tbl-lysimeter-15min-stats)). The binned data show a small increase in interception efficiency for all three canopies when the snow load is less than 7 kg m-2 (Figure 6c). Interception efficiency later declined for snow loads greater than 7 kg m-2 for all canopies, though this was inconsistent for the mixed canopy. A significantly greater (*p* < 0.05) median interception efficiency was found for canopy snow loads less than 10 kg m-2 than those with high initial canopy snow loads (> 10 kg m-2) using the Wilcoxon rank-test. Additional statistics from ordinary least squares regression test on the 15-minute interval measurements are provided in [Table 4](#tbl-lysimeter-15min-stats).

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| Figure 6: Scatter plots of 15-minute interval measurements (blue dots) and binned data (black open circles with error bars) of mean air temperature, mean wind speed, and initial canopy snow load versus mean snow interception efficiency. Panels show (a) air temperature, (b) wind speed, and (c) initial canopy snow load (the snow load observed at the beginning of the timestep). The black open circles show the mean of each bin and the error bars represent the standard deviations. See [Table 4](#tbl-lysimeter-15min-stats) for linear regression statistics. |

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| Table 4: Statistics corresponding to the ordinary least squares linear regression test between 15-minute 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 ().   | Dependent Variable | SCL Name |  | Adjusted | -value |  | | --- | --- | --- | --- | --- | --- | | Air Temperature (°C) | Mixed | 0.78 | 0.032 | 0.000 | 985 | | Air Temperature (°C) | Closed | 0.82 | 0.004 | 0.069 | 618 | | Air Temperature (°C) | Sparse | 0.73 | 0.007 | 0.019 | 603 | | Wind Speed (m/s) | Mixed | 0.78 | 0.017 | 0.000 | 985 | | Wind Speed (m/s) | Closed | 0.82 | 0.037 | 0.000 | 618 | | Wind Speed (m/s) | Sparse | 0.73 | 0.089 | 0.000 | 603 | | Initial Canopy Snow Load () | Mixed | 0.78 | 0.000 | 0.453 | 972 | | Initial Canopy Snow Load () | Closed | 0.82 | 0.051 | 0.000 | 607 | | Initial Canopy Snow Load () | Sparse | 0.73 | 0.025 | 0.000 | 592 | |

## 4.2 The influence of forest structure on snow interception

UAV-lidar measurements of throughfall and canopy structure provide insights on how the forest canopy influenced subcanopy snow accumulation during a wind-driven snowfall event between March 13th and 14th 2023. This event totaled 28.7 kg m-2 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. [Figure 7](#fig-wind-profiles) shows Cionco’s (1965) exponential function for within canopy wind speed was not appropriate for this sparse canopy. The predicted hydrometeor trajectory angles at varying heights, calculated using [Equation 4](#eq-ta) and the mean observed hydrometeor terminal velocity observed over the event of 0.9 m s-1 are also shown in [Figure 7](#fig-wind-profiles). An average wind speed of 1.6 m s-1 and direction of 188° was calculated by integrating the wind speed from the surface to the mean canopy height of FT plot. The corresponding trajectory angle calculated using [Equation 4](#eq-ta) from this integrated wind speed was 61.5°.

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| Figure 7: Wind speed profile using roughness length and displacement height parameters derived from anemometers at 2, 3, 4.3, and 13.5 m above ground at FT station over snow free periods and friction velocity estimated over the March 13–14th snowfall event. |

Throughfall depth measured by UAV-lidar was close to the 28 in-situ manual measurements with a mean bias of -0.001 m and RMSE of 0.024 m. More details on the accuracy of UAV-lidar snowdepth measurements are provided in the supporting information section. [Figure 8](#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 8](#fig-lidar-tf-ip) represent grid cells that did not have any lidar ground returns (i.e., under dense canopy proximal to tree trunks) or were masked due to disturbance (i.e., 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 8](#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 coverage 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 8: UAV-lidar measurements of the change in snow water equivalent, SWE (kg m-2) and interception efficiency, I/P (-), over the March 13, 2023 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). |

[Figure 9](#fig-hemi-ip-cc) shows a strong linear correlation between 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 9](#fig-hemi-ip-cc), 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 9: The Pearson Correlation Coefficient between rasters (0.25 m resolution) of interception efficiency and leaf contact area 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 correlation between and interception efficiency, resampled to a 5 m grid resolution, was higher when was adjusted for the observed shift in hydrometeor trajectory (Vector Based), compared to the leaf contact angle measured at a zenith angle of 0° (nadir) ([Figure 10](#fig-lca-vs-ip)). The azimuth and zenith angles observed to have the highest in [Figure 9](#fig-hemi-ip-cc) was used to adjust the vector based, in [Figure 10](#fig-lca-vs-ip). 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 (i.e., intercepted) before canopy snow unloading or ablation processes begin.

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| Figure 10: 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 right 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 0.47 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 0.71 and 0.68 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 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 5](#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 10](#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 8](#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 8](#fig-lidar-tf-ip). The latter explanation suggests the non-linear relationship observed for the PWL nadir calculation in [Figure 8](#fig-lidar-tf-ip).

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| Table 5: 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 | 0.99 | 0.022 | 0.071 | 0.099 | 0.51 | | FT | Vector Based | 0.68 | 0.001 | 0.047 | 0.062 | 0.80 | | PWL | Nadir | 0.95 | 0.048 | 0.113 | 0.146 | NA | | PWL | Vector Based | 0.71 | 0.019 | 0.078 | 0.095 | 0.47 | |

## 4.3 The combined influence of trajectory angle and forest structure on interception

[Figure 11](#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 11](#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 11](#fig-lca-ht-ws)). This results in a large rise in over relatively common estimated 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 11](#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 11](#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 11: Plots showing the relationship between hydrometeor trajectory angle (left) and wind speed (right) with mean plot-wide snow-leaf contact area, (top row) and the increase in mean plot-wide , i.e., (bottom row). The hydrometeor trajectory angle is simulated through VoxRS and 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 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) and [Equation 11](#eq-lca-inc) (bottom). 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, is the increase in leaf contact area from which is a function of . To estimate a non-linear least squares regression using a logistic function forced through the origin was fit to the VoxRS measurements at FT and PWL for simulated hydrometeor trajectory angles (see dashed lines in bottom row of [Figure 11](#fig-lca-ht-ws)). A logistic function was selected to model this relationship, as its shape reflects the slow increase in observed at near vertical trajectory angles, followed by a rapid increase to represent increase canopy area in the middle and lower section of individual trees, and the gradual leveling off as approaches a value of 1.0. The logistic function used to predict as a function of is:

Revised model is:

where is the is the plot scale leaf contact area (-), is the sky-view factor or gap fraction, is the trajectory angle of a hydrometeor, and k is calculated as:

where is the average canopy height (m) and is a scaling parameter found to be equal to 0.24 in this study.

where is the maximum value of , is the x-value of the sigmoid midpoint and is the logistic growth rate or steepness of the curve. The coefficients resulting from the non-linear least squares regression fit of [Equation 11](#eq-lca-inc) to the VoxRS dataset are presented in [Table 6](#tbl-lca-coefs). Simulated using [Equation 10](#eq-lca-ac) is shown in the dashed lines in the top row of [Figure 11](#fig-lca-ht-ws) and follows the VoxRS-measured mean closely. Model error statistics shown in [Table 7](#tbl-lca-mod-err) demonstrate that [Equation 11](#eq-lca-inc) performed well, with a mean bias and RMSE of 0.001 (-) and 0.0054 (-) respectively for PWL, and -0.0004 (-) and 0.0079 (-) for FT. In contrast, [Table 7](#tbl-lca-mod-err) reveals that the Hedstrom & Pomeroy (1998) method produced significantly less accurate estimates of , with a mean bias and RMSE of -0.201 (-) and 0.233 (-) respectively for PWL, and -0.260 (-) and 0.324 (-) for FT.

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| Table 6: Coefficients derived from the non-linear least squares regression fit of [Equation 11](#eq-lca-inc) to the VoxRS dataset.   | Plot Names |  |  |  | | --- | --- | --- | --- | | PWL | 0.66 | 34.58 | 22.14 | | FT | 1.18 | 69.13 | 26.98 | |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
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| Table 7: Model error statistics calculated for the prediction of leaf contact area from trajectory angle using [Equation 11](#eq-lca-inc) (nls) and Equation 10 from Hedstrom & Pomeroy (1998) 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 | 0.72 | | HP98 | PWL | -0.20 | 0.20 | 0.23 | 0.44 | | nls | FT | 0.00 | 0.01 | 0.01 | 1.00 | | nls | PWL | 0.00 | 0.00 | 0.01 | 1.00 | |

## 4.4 Throughfall model performance

The performance of Equations 9, 10, and 11 in estimating event throughfall was assessed against UAV-lidar measurements of throughfall for the March 13–14th snowfall event at the plot scale for both FT and PWL. Required values for the model included the event mean hydrometeor terminal velocity and event total snowfall which were measured at PWL station, and wind speed was taken as one-third the mean canopy height using the wind speed profile in [Figure 7](#fig-wind-profiles). Additional model inputs include the mean for each plot which was measured from the VoxRS dataset. An value of 0.836 (-) 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 12](#fig-event-tf) shows the vector-based model, computed using [Equation 9](#eq-lca-ip) with adjusted for estimated hydrometeor trajectory angle, closely matches UAV-lidar measurements of throughfall. Observed and modelled values of interception efficiency and are presented in [Table 8](#tbl-vb-plot-err) along with corresponding error statistics. Modelled throughfall from the vector-based model was 17 kg m-2 compared to the measured throughfall of 16.6 kg m-2 for PWL. For FT, the vector-based modelled throughfall was 21.8 kg m-2, while the measured values where 22.1 kg m-2. The vector-based model shows a lower mean bias of -0.3 kg m-2 for PWL and a negative bias of 0.3 kg m-2 for FT, compared to the larger mean bias of -1.6 kg m-2 for PWL and -0.8 kg m-2 for FT with the nadir-model (calculated using in place of ). This resulted in a large reduction in the percent error in predicted throughfall, from -9.4% with the nadir-model to -1.8% with the vector-based model for PWL. A smaller improvement was observed for FT, with the percent error in predicted throughfall declining from -3.6% with the nadir-model to -1.4% with the vector-based model.

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| Figure 12: Bar chart comparing the observed and modelled mean change in throughfall (, kg m-2) over the March 13-14 snowfall event averaged over forest plots FT and PWL. The ‘Nadir-model’ used [Equation 9](#eq-lca-ip) not adjusted for trajectory angle (i.e., ) 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 (kg m-2) over the snowfall event to the PWL station open clearing. |

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| Table 8: 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 (kg m-2). 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 | 0.24 | -0.01 | -4.67 | | FT | Nadir-model | I/P | - | 0.23 | 0.20 | 0.03 | 12.10 | | FT | VB-model | TF |  | 22.12 | 21.82 | 0.31 | 1.38 | | FT | Nadir-model | TF |  | 22.12 | 22.91 | -0.79 | -3.58 | | PWL | VB-model | I/P | - | 0.42 | 0.41 | 0.01 | 2.54 | | PWL | Nadir-model | I/P | - | 0.42 | 0.37 | 0.05 | 12.95 | | PWL | VB-model | TF |  | 16.64 | 16.95 | -0.31 | -1.84 | | PWL | Nadir-model | TF |  | 16.64 | 18.20 | -1.56 | -9.35 | |

# 5. Discussion

The point scale observations presented in [Figure 6](#fig-scl-ip-avg-15min) show air temperature had little influence on interception efficiency. This differs from existing studies which suggested either a positive (Storck et al., 2002) or negative (Hedstrom & Pomeroy, 1998) relationship. A weak relationship, that leaves 80–90% of variance unexplained, was observed between initial interception efficiency (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).

Compared to the influence of wind speed, interception efficiency showed a smaller sensitivity to canopy snow load at the point scale ([Figure 5](#fig-scl-ip-avg-event)). 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 increasing, while later declining due to branch bending and decreased canopy coverage. However, the observations shown in [Figure 6](#fig-scl-ip-avg-15min) and [Figure 3](#fig-scl-w-sf), which minimized ablation processes, differ from those reported by Satterlund & Haupt (1967), Schmidt & Pomeroy (1990), and Moeser et al. (2015), as canopy snow load increased linearly with snowfalls up to 45 kg m-2 without approaching a maximum canopy snow load. The strong decline in interception efficiency with increasing event snowfall in Satterlund & Haupt (1967) and Schmidt & Pomeroy (1990) may have resulted from higher unloading rates as branches bent under heavy snow loads, hence mixing ablation and interception processes to varying degrees. In contrast, other studies (Calder, 1990; Lundquist et al., 2021; Watanabe & Ozeki, 1964) align with the observations in [Figure 6](#fig-scl-ip-avg-15min) and [Figure 3](#fig-scl-w-sf), showing little evidence of a reduced interception efficiency with increasing snowfall. 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).

Staines & Pomeroy (2023) showed a slight increase in VoxRS measured between snow-off and snow-on conditions. However, 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 and as shown in [Figure 11](#fig-lca-ht-ws). Both findings from Staines & Pomeroy (2023) corroborate the results reported in this study. 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. Lehtonen et al. (2016) also note that in northern Finland heavy canopy snow loads have been observed to continue increasing until stem breakage, under conditions favourable for the formation of significant rime-ice accretion and limited ablation, thus reducing . Models are available to predict the accretion of ice on tree canopies (e.g., Nock et al., 2016) however, further research is required to understand the canopy snow load required to cause stem breakage across different tree species and canopy loads.

These findings on the limited influence of air temperature and canopy snow load on initial interception challenge the theoretical basis of many existing snow interception parameterizations (Hedstrom & Pomeroy, 1998; Moeser et al., 2015; Satterlund & Haupt, 1967; Storck et al., 2002). To address this, a new snow interception parameterization, introduced in [Equation 9](#eq-lca-ip), is presented which calculates 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 10](#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), Storck et al. (2002), 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.

Measurements of interception efficiency and canopy structure, as shown in [Figure 8](#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 canopy coverage with wind speed failed to reproduce the observations presented in [Figure 11](#fig-lca-ht-ws). Instead, plot-wide was found to increase as logistic function of and . Significant scatter in VoxRS measured across the two forest plots, illustrated by the high standard deviation in [Figure 11](#fig-lca-ht-ws), resulted from directional (azimuth) and spatial differences in canopy structure. This large scatter suggests the observed relationships in [Figure 11](#fig-lca-ht-ws) are only applicable at the forest stand scale where the sub-metre variability in averages out. For example, at the point scale, the mixed canopy SCL which is open to the prevailing wind direction ([Figure 2](#fig-scl-imgs)), had an increase in throughfall with increasing wind speed ([Figure 5](#fig-scl-ip-avg-event) & [Figure 6](#fig-scl-ip-avg-15min)). However, [Figure 11](#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. Still, [Equation 11](#eq-lca-inc) would not be applicable to areas that have large continuous gap fractions (e.g., large forested clear cuts) that are many times wider than the mean canopy height. Staines & Pomeroy (2023) have also shown that backflows and large eddies that occur within the canopy can also contribute to mixed responses. Further work is required to refine the relationship proposed in [Equation 11](#eq-lca-inc) across a range of tree species and densities.

It was found that the mean event hydrometeor trajectory angle, required for [Equation 11](#eq-lca-inc), could be predicted 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 tree 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 (i.e., 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.

# 6. Conclusions

New observations of initial snow interception, collected over a wide range of meteorological conditions and canopy structures indicate that forest structure is the primary factor influencing subcanopy snow accumulation. At the point scale, high-temporal resolution measurements revealed no evidence of a maximum canopy snow load, even for event snowfalls up to 45 kg m-2, nor was there any indication of air temperature influencing the cohesion and adhesion of snowfall to the canopy or branch bending reducing canopy coverage. Instead, wind speed was found to influence interception efficiency by changing the hydrometeor trajectory angle, which can 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 coverage. 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, which demonstrated good performance at this study site.

The weak association between air temperature and canopy snow load with interception efficiency, as presented here and in other recent studies, 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 coverage. Additionally, a second equation is proposed to estimate leaf contact area as a function of hydrometeor trajectory angle and nadir canopy coverage. This updated snow interception parameterization performed well in the subalpine forest studied here. However, further validation is necessary in a range of climates, forest species, and canopy structures.

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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.

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