Advancing Snow Accumulation Models in Needleleaf Forests

Alex Cebulski

September 20, 2024

# 1. Introduction

## 1.1 Background

This subsection of Chapter 1 will introduce background information, motivation, hydrological significance of the study topic, research gaps, and methods used in the study.

## 1.2 Research Gap and Objectives

This subsection of Chapter 1 will describe the overall purpose of the thesis and links the individual thesis objectives to research gaps.

Thesis objectives and research questions

Purpose: To better understand the processes that govern snow accumulation in forested environments.

1. Evaluate the suitability of existing snow interception and ablation parameterizations for application in needleleaf forests with differing canopy structure and meteorology.

* 1.1 What are the theoretical underpinnings and assumptions behind existing snow interception and ablation parameterizations?
* 1.2 Are the theories and assumptions of existing snow interception parameterizations supported by field measurements collected across diverse canopy structures and meteorological conditions?
* 1.3 Are the theories and assumptions of existing canopy snow ablation parameterizations supported by field measurements collected across varying meteorological conditions?

1. Determine how new snow interception and ablation parameterizations could enhance the representation of processes important for subcanopy snow accumulation.

* 2.1 How can the use of novel snow interception parameterizations enhance simulations of snow accumulation in forests with differing tree species, canopy structures, and meteorological conditions?

## 1.3 Organization of Chapters

This thesis contains 5 chapters, the first chapter includes an introduction and research plan while, the remaining chapters 2-5 each correspond to a journal article which aims to answer each of the research questions.

# 2. The Theoretical Underpinnings of Existing Snow Interception and Ablation Parameterizations

Manuscript Status: Invited for submission to the journal WIREs Water and is currently under review.

Role in thesis: This paper is an advanced review article and corresponds to objective 1, research question 1.1 of the thesis. This advanced review will provide the context necessary for interpreting whether the theories and assumptions of existing parameterizations are true for the field observations collected in this study in the second part of objective 1.

Author Contribution: Conducted literature review, committee members provided edits…

**Article Category**: Advanced Review

**Authors**:

A. Cebulski1 (ORCID ID - 0000-0001-7910-5056)

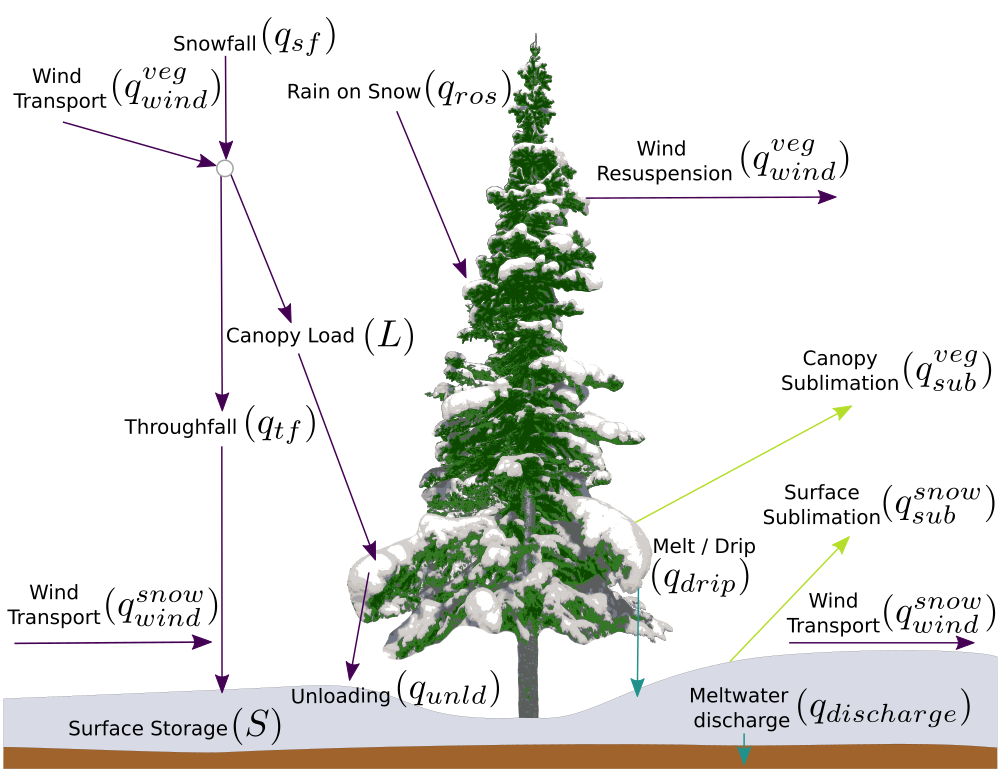
J.W. Pomeroy1 (ORCID ID - 0000-0002-4782-7457)

1Centre for Hydrology, University of Saskatchewan, Canmore, Canada

**Abstract:** In needleleaf forests, up to half of annual snowfall may be ablated due to sublimation of snow intercepted in the canopy. However, limited and sparse observations of snow interception and ablation processes have hindered the development of fundamental theories underpinning current estimates of snow accumulation in forests. Existing parameterizations for snow interception and ablation have been developed in locations with distinctive climate, tree species and forest structures, resulting in differing and non-comprehensive process representations. Consequently, their transferability across diverse landscapes and climates remains uncertain. Moreover, difficulties in isolating individual processes using field-based measurements contributes further uncertainty to validation of process representations in hydrological models. Specific gaps in the literature include challenges in differentiating snow throughfall measurements from canopy snow ablation, partitioning unloading rates and canopy snowmelt drainage, the assumption of vertical falling hydrometeor trajectories, the absence of wind resuspension parameterizations, and the limited testing of parameterizations in varied forests and climates. This review article aims to elucidate the theoretical foundations and assumptions underlying the current snow interception and ablation concepts and parameterizations in the literature to inform model-decision makers in selecting parameterizations and guiding future field-based observational studies. The theory and methods behind snow interception and ablation studies are also reviewed to provide the context necessary for examining the applicability of current parameterizations across contrasting environments.

**Graphical Abstract and Caption**

Snow interception and ablation processes are essential components of hydrological models and land surface schemes. Determining how to best represent these processes in models helps inform land management, ecological conservation and water resource decisions.



## 2.1 Introduction

Snow interception and ablation processes and their conceptual models have never been thoroughly reviewed, though reviews of individual processes exist (Lundberg & Halldin, 2001; Lundquist et al., 2021; Pomeroy & Gray, 1995; Van Stan et al., 2020). To determine a path forward for the improved prediction of snow accumulation in forested environments, it is essential to conduct a comprehensive review of the underlying theory and methodologies used to develop existing parameterizations. This article will also explore processes often overlooked in existing parameterizations, including non-vertical hydrometeor trajectories, horizontal wind redistribution of snow, and rime accretion. The article further examines the limited research on snow interception and ablation in forests with diverse species and structure has impacted process understanding and restricts transferability across differing environments. Additionally, the methods used to measure or approximate these mass and energy processes are also reviewed, providing the necessary context for interpreting the underlying assumptions of existing snow interception and ablation parameterizations.

## 2.2 The Mass and Energy Balance of Snow in the Canopy

Section 2 begins with discussing the symbology used to represent mass fluxes, energy fluxes and states of snow intercepted in the canopy. This section is written in the context of a winter needleleaf forest environment.

### 2.2.1 Mass Balance

Section 2.1 contains a mass balance equation for canopy snow load followed by a description of each of the terms in the equation. A figure is also shown which gives a visual of the mass balance processes important for canopy snow load. Coupled mass and energy equations for the calculation of melt and sublimation of snow intercepted in the canopy are also shown.

### 2.2.2 Energy Balance

Section 2.2 contains an energy balance equation for snow intercepted in the canopy followed by a description of the terms. A figure showing a visual representation of the energy balance processes is shown. A discussion of some of the simplifications made with this energy balance representation is then provided.

## 2.3 Measuring Snow Interception and Ablation

Section 3 covers the common methodologies used to measure snow interception and ablation. A description of the principle behind each method is given and any uncertainties related to the method are also discussed. The methodologies described include, weighed tree, mass balance methods, snow surveys, subcanopy lysimeters and remote sensing techniques.

### 2.3.1 Weighed Tree

### 2.3.2 Mass Balance Methods

#### 2.3.2.1 Snow Surveys

#### 2.3.2.2 Subcanopy Lysimeters

### 2.3.3 Remote Sensing

### 2.3.4 Tree Sway Frequency

### 2.3.5 Trunk Compression

## 2.4 Methods of Determination

Section 4 discusses the parameterizations available in the literature for the determination of the mass and energy balance processes discussed in Section 2. For each parameterization a description the study environment, climate, and methodologies used to derive it is provided. Section 4.1 discusses snow interception parameterizations followed by section 4.2 which discusses snow ablation parameterizations for sublimation, unloading and drip.

### 2.4.1 Snow Interception Parameterizations

#### 2.4.1.1 Hedstrom & Pomeroy (1998)

#### 2.4.1.2 Storck et al. (2002) and Andreadis et al. (2009)

#### 2.4.1.3 Katsushima et al. (2023)

#### 2.4.1.4 Event Based Snow Interception Parameterizations

### 2.4.2 Canopy Snow Ablation Parameterizations

#### 2.4.2.1 Sublimation

#### 2.4.2.2 Unloading and Drip

##### 2.4.2.2.1 Hedstrom & Pomeroy (1998)

##### 2.4.2.2.2 Storck et al. (2002)

##### 2.4.2.2.3 Roesch et al. (2001)

##### 2.4.2.2.4 Bartlett & Verseghy (2015)

##### 2.4.2.2.5 Katsushima et al. (2023)

## 2.5 Discussion

In Section 5 the theories and assumptions of the parameterizations listed above are compared. Research gaps are also listed to give insight on where current snow interception and ablation parameterizations theories and assumptions may be invalid and where new observations and theoretical development is required. Advice for informing model-decision makers on choosing parameterizations is also given

## 2.6 Conclusion

Numerous conceptual models of snow interception and ablation have been developed, reflecting differences in the climate, canopy structure, and methodological approaches across previous studies. The choice of parameterization can significantly influence simulated outcomes, underscoring the importance of informed decision-making. However, acquiring the necessary knowledge from the literature to facilitate such decisions has proven challenging, with notable knowledge gaps persisting in process understanding. Difficulties in isolating snow interception processes in in-situ measurements may have resulted in parameterizations that are not isolated to a single process. Future work to help decouple canopy snow interception and ablation parameterizations could help minimize the over representation of certain processes and provide some clarity to model decision makers. This decoupling may have implications for canopy snow ablation parameterizations and thus should be revisited in the context of updated interception routines. Previous attempts to model snow accumulation and ablation in transitional climates had success by combining parameterizations derived from diverse climates. However, using combined parameterizations remains underutilized in contemporary models, and has the potential to better model transitional climates. Recent advances in lidar-based methods to measure subcanopy snow accumulation and canopy metrics has enhanced our understanding of how leaf contact area is influenced by snowfall trajectory angle and canopy snow load. However, further work is required to integrate these novel results into snow interception parameterizations. Parameterizations that ablate snow intercepted in the canopy differ in the level of detail in canopy snowmelt models and number of processes included snow such as wind induced unloading and resuspension, rime-ice accretion, and time-based unloading. Future work is required to determine the appropriate level of detail in canopy snowmelt models and the whether the relationships used in existing ablation parameterizations hold for other locations.

A comprehensive field-based investigation into canopy snow interception and ablation processes is needed to address these remaining research gaps. Utilizing observations of forest snow accumulation and canopy snow ablation across diverse forests and climates is crucial for assessing and refining existing theories of snow interception and ablation processes. This approach will enhance our understanding of where existing parameterizations fail, what processes drive model uncertainty, and how parameterizations can be modified to better represent forest snow accumulation.

## 2.7 Funding Information

Dean’s Scholarship – University of Saskatchewan Devolved Scholarship – University of Saskatchewan Discovery Grant – National Sciences and Engineering Research Council of Canada Global Water Futures Programme – Canada First Research Excellence Fund Canada Research Chairs Programme – Government of Canada Water Information Program Grant, Alberta Innovates

## 2.8 Acknowledgments

We wish to acknowledge financial support from the University of Saskatchewan, Natural Sciences and Engineering Research Council of Canada, Global Water Futures Programme, Alberta Innovates and the Canada Research Chairs Programme. We thank Martyn Clark for his advice in outlining the steps to derive analytical solutions from the ordinary difference equation representation of the parameterizations.

# 3. Snow Interception Relationships with Meteorology and Canopy Structure in a Subalpine Forest

Manuscript status: In preparation for submission to the special issue “Snow to Flow” in the Journal Hydrological Processes.

Role in thesis: This journal article aims to answer research question 1.2 of the thesis. This question will be answered through analysis of observations of interception from a study site few researchers have focused on, a subalpine discontinuous forest and contrast these observations with existing theory developed in maritime and continental climates.

Author Contribution: Conducted in-situ data collection, conceptualized research plan with comments from supervisor and thesis committee members, and lead author in collaboration with supervisor.

**Authors:**

A. Cebulski1 (ORCID ID - 0000-0001-7910-5056)

J.W. Pomeroy1 (ORCID ID - 0000-0002-4782-7457)

1Coldwater Laboratory, University of Saskatchewan, Canmore, Canada

**Corresponding Author:** A. Cebulski, alexcebulski@gmail.com

**Abstract:** Subcanopy snow accumulation models differ in how snow interception and ablation processes are represented and have uncertain applicability across diverse climates and forest types. Existing parameterizations of initial snow interception before unloading include inherently coupled accumulation and ablation processes, leading to difficulty in diagnosing processes and adding uncertainty to simulations when incorporated as canopy accumulation routines in models that already account for canopy snow ablation. This study evaluates the theory underpinning these parameterizations in-situ meteorological data, high-temporal resolution point-scale throughfall measurements, and fine-scale aerial lidar measurements of throughfall and canopy metrics collected from 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, forest structure emerged as the primary factor governing snow accumulation at the forest plot scale. A wind-driven snowfall event demonstrated that non-vertical hydrometeor trajectories significantly reduced throughfall depths across both forest plots. Prediction of interception efficiency for this event improved drastically when adjusted for hydrometeor trajectory angle based on a wind speed at one-third of the canopy height. Snow-leaf contact area showed high sensitivity to wind speed, increasing by up to 95% with a 1 m s-1 wind speed. The study proposes two new equations which model snow interception efficiency as a function of snow-leaf contact area adjusted for hydrometeor trajectory angle. This new parameterization successfully estimated interception efficiency for a snowfall event for the two forest plots in this study. By removing canopy snow ablation processes, this new model should offer improved performance in prediction of sub-canopy snow accumulation when combined with canopy snow ablation parameterizations.

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

## 3.1 Introduction

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

1. Are the existing theories regarding the relationship between meteorology and forest structure with snow interception supported by in-situ observations?
2. How 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?

## 3.2 Theory

### 3.2.1 Snow Interception

During calm snowfall periods, where ablation processes can be assumed negligible, the canopy snow load, (kg m-2) can be estimated as a mass balance:

where is the snowfall rate (kg m-2 s-1) and is the throughfall rate (kg m-2 s-1). This method avoids the influence of sublimation losses or drip from weighed tree lysimeters.

Interception efficiency, (-), which is the fraction of snow intercepted over was calculated as:

Throughfall, was be calculated as:

### 3.2.2 Hydrometeor Trajectory Angle

The trajectory angle, of a hydrometeor as the departure in degrees (°) from a vertical plane (i.e., 0° for vertical snowfall), is shown in Herwitz & Slye (1995) to be calculated 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 change in the hydrometeor (m s-1) which is a function within canopy wind speed, at height above ground, .

## 3.3 Data and Methods

### 3.3.1 Study Site

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

### 3.3.2 Meteorological Measurements

### 3.3.3 Lysimeter Data

|  |
| --- |
| 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). |

### 3.3.4 UAV-Lidar Data Collection Processing

### 3.3.5 Snow Surveys

#### 3.3.5.1 In-situ Snow Depth and Density

#### 3.3.5.2 UAV-Lidar Snow Depth

### 3.3.6 UAV-Lidar Canopy Metrics

### 3.3.7 Statistics and Regression Models

## 3.4 Results

### 3.4.1 The influence of meteorology on snow interception

[Figure 3](#fig-scl-w-sf) plots canopy snow load against cumulative snowfall over 26 snowfall events using the three SCLs and the PWL snowfall gauge. The duration and meteorology of each snowfall event is summarized in [Table 1](#tbl-sf-event-met) and shows air temperature over these periods ranged from a minimum of -24.48 to a maximum of -24.48°C. Wind speeds ranged from a minimum of 0.03 to a maximum of 0.03 with wind direction that was predominately from the southwest [Figure 4](#fig-wind-rose). Canopy snow load was observed in [Figure 3](#fig-scl-w-sf) to increase linearly with increasing snowfall without evidence of reaching a maximum. Variation in the slope of each line in [Figure 3](#fig-scl-w-sf), is attributed to differences in the meteorology and antecedent canopy snow load within and between the individual events.

|  |
| --- |
| Figure 3: Plot showing the cumulative event snowfall versus the corresponding state of canopy snow load calculated using the 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). |

|  |
| --- |
| Table 1: Meteorological statistics for the 26 snowfall events. |

|  |
| --- |
| 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-avg-event) shows mean event air temperature had a weak negative association (*p* < 0.05) with mean event interception efficiency, while the other two troughs displayed insignificant relationships (*p* > 0.05). Cumulative event snowfall had a consistent negative association with cumulative snowfall, however the relationships were insignificant for all three troughs (*p* > 0.05). Event mean wind speed exhibited a relatively strong positive association with interception efficiency for the sparse (*p* > 0.05) and closed (*p* < 0.05) SCLs. A negative insignificant association was observed for the mixed SCL (*p* > 0.05). The opposing relationship of wind speed and interception efficiency between the SCLs can be explained as the mixed SCL has an opening in the canopy [Figure 2](#fig-scl-imgs), that matches the prevailing wind direction shown in [Figure 4](#fig-wind-rose), thus increasing the amount snowfall entering the sub-canopy during increased winds. For the closed and sparse SCLs this increase in interception efficiency is interpreted to be due to an associated increase in canopy contact area as hydrometeor trajectory becomes more horizontal with increasing wind speed.

|  |
| --- |
| Figure 5: Scatter plots showing the mean air temperature and wind speed and total cumulative snowfall versus the mean interception efficiency measured by the 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). A linear regression line fit to the data is shown by the solid coloured lines and the corresponding adjusted r squared value. Significant relationships (p < 0.05) are marked by an asterisk beside the R2 value. |

[Figure 6](#fig-lai-met-ip) shows the association between interception efficiency measured by the three SCLs and the corresponding air temperature, wind speed, canopy snow load for the same 15-minute time interval. Panel A in [Figure 6](#fig-lai-met-ip) shows that 15-minute average air temperature measurements has a very low correlation (R2 < 0.032) with interception efficiency for all three SCLs with significant relationships (*p* < 0.05) only for the sparse and mixed troughs. The average interception efficiency observed within air temperature bins also does not exhibit any visual trend. However, a significantly greater median interception efficiency (*p* < 0.05) was found for air temperatures below -6 °C compared to colder air temperatures using non-parameteric Wilcoxon signed rank test.

|  |
| --- |
| Figure 6: Scatter plots of discrete observations (blue dots) and binned data (black dots with error bars) of meteorology, canopy load, and hydrometeor characteristics versus snow interception efficiency. Panels show (A) air temperature, (B) relative humidity, (C) wind speed, (D) initial canopy snow load (the snow load observed at the beginning of the timestep), (E) hydrometeor diameter, (F) hydrometeor velocity. The black open circles show the mean of each bin and the error bars represent the standard deviations. The data were filtered to include observations with a snowfall rate > 0 kg m-2 hr-1, throughfall rate > 0.05 kg m-2 hr-1 to minimize noise and a snowfall rate > the subcanopy lysimeter throughfall rate to minimize observations with unloading. Periods of unloading and melt were also removed through careful analysis of the weighed tree, subcanopy lysimeters, and timelapse imagery. |

Panel B in [Figure 6](#fig-lai-met-ip) shows that wind speed measured at FT Station had a slightly stronger correlation with interception efficiency with R2 ranging between 0.04 and 0.09 (*p* < 0.05 for all three SCLs) compared to the association with air temperature. The association between wind speed and interception efficiency was observed to be positive for the sparse and closed SCLs, while the mixed SCL exhibited a negative association. The opposing trend observed for the closed and sparse SCLs compared to the mixed SCL is consistent with the trend observed in [Figure 5](#fig-scl-ip-avg-event) for the event means and is also attributed to a change in snow-leaf contact area with shifting hydrometeor trajectories as a result of changing wind speed. Between wind speed bins of 0.25 and 2.75 m s-1 the mean interception efficiency increased from 0.58 to 0.66 and 0.48 to 0.61 for the closed and sparse forest SCLs respectively ([Figure 6](#fig-lai-met-ip), B). The mixed SCL declined from 0.59 to 0.45 for the same range in wind speed bins. A comparison interception efficiency between 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 efficiency compared to the low wind speed group for the closed and sparse SCL. Conversely, the Wilcoxon test showed the mixed SCL had significantly higher (*p* < 0.05) median interception efficiency for the low wind speed group.

[Figure 6](#fig-lai-met-ip), panel C shows canopy snow load, measured at the beginning of each timestep, shows a relatively weak significant negative relationship between the 15-minute observations (R2 < 0.4, *p* < 0.05) for the closed and sparse SCLs and a non-significant relationship was observed for the mixed SCL. The binned data show a small increase in interception efficiency was observed for all three troughs between canopy snow loads of 0 kg m-2 to 7 kg m-2. This was followed by a gradual decline in interception efficiency for snow loads greater than 7 kg m-2 with the closed and sparse SCL ([Figure 6](#fig-lai-met-ip), C). The interception efficiency measured by the mixed SCL also declines above 7 kg m-2 before increasing again around 16 kg m-2 and then declines again to a minimum interception efficiency of 0.39. A comparison of low (< 10 kg m-2) and high (> 10 kg m-2) canopy snow loads using the Wilcoxon rank-test showed the low canopy snow loads had significantly greater (*p* < 0.05) median interception efficiency compared to the high canopy snow load group. The location of the SCLs within gaps in the canopy may have contributed to these instruments registering a slight increase in interception efficiency as small branch gaps are covered by snow followed by a decline in interception efficiency as branches bend due to the weight of snow intercepted on the branch compressing it downwards and thus reducing the canopy coverage above the SCLs.

### 3.4.2 The influence of forest structure on snow interception

UAV-lidar measurements of throughfall and canopy structure metrics provide insights on how the forest canopy influenced subcanopy snow accumulation during a wind-driven snowfall event between March 13th and 14th. 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 temperature near 0°C to higher rates of snowfall late afternoon on March 13 coinciding with air temperatures around -2.5 °C. An average wind speed of 1.27 m s-1 and direction of 188° was observed 4.3 m above the ground at FT Station. A logarithmic wind speed profile shown in [Figure 7](#fig-wind-profiles) provided a good fit to observed wind speeds at 2, 3, 4.3 and 13.5 m above the ground and shows the Cionco (1965) exponential function was not appropriate for the sparse canopy surrounding FT station. The heavy snowfall over this event covered the two eddy covariance systems at FT station with snow limiting wind speed measurements to test this wind speed profile at different heights or provide a measurement of friction velocity for this event. [Figure 7](#fig-wind-profiles) shows 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. An average wind speed of 1.63 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 61.49°.

|  |
| --- |
| Figure 7: Wind speed profile fit to roughness length and displacement height parameters derived from anemometors at 2, 3, 4.3, and 13.5 m above ground at FT station and friction velocity observed over the March 13-14th snowfall event. The red triangle shows the mean observed wind speed at 4.3 m measured at FT station over the March 13-14 snowfall event. |

UAV-lidar measurements of throughfall shown in [Figure 8](#fig-lidar-tf-ip) aligned well with 28 in-situ manual throughfall measurements with a mean bias of -0.001 m and RMSE of 0.024 m. The mean bias between these two measurements were observed to be similar within canopy gaps and within tree wells, while tree wells resulted in a larger percent bias. All three SCLs and the weighed tree registered a 2 kg m-2 unloading event during a brief pause in snowfall early in the morning on March 14, prior to the UAV-lidar flight. This unloading event in addition to the moderate wind speeds observed during the snowfall event likely contributed to some redistribution of snow on the ground. The relatively small unloading event compared to the amount of snow that fell during the snowfall event and minimal evidence of observed wind redistribution on the ground is inferred to have not significantly altered the UAV-lidar throughfall measurements.

[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 is observed on the north (lee) side of individual trees, which is interpreted to be a result of non-vertical hydrometeor trajectories caused by the steady southerly winds observed over this event. In-situ 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 within the PWL forest plot, compared to the FT forest plot. This may be attributed to the taller trees and higher canopy coverage within the PWL forest plot compared to the FT forest plot, where given the same trajectory angle a taller tree will produce a larger footprint.

|  |
| --- |
| Figure 8: UAV-lidar measurements of the change in SWE (kg m-2) and interception efficiency over the March 13, 2023 24 hr snowfall event for the FT and PWL forest plots at a 25 cm resolution. Transparent areas represent grids that did not have any lidar ground returns (i.e., under dense canopy proximal to tree trunks) or have been masked due to disturbance. See the location of the two forest plots within FMRB in [Figure 1](#fig-site-map). |

[Figure 9](#fig-hemi-ip-cc) presents two hemisphere plots which illustrate the correlation between and interception efficiency at a 0.25 m horizontal grid cell resolution over differing azimuth and zenith angles for both the FT and PWL forest plots. These plots demonstrate 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 believed to result from non-vertical hydrometeor trajectories. At near-nadir zenith angles, [Figure 9](#fig-hemi-ip-cc) illustrates slightly lower . In addition to the inclined hydrometeor trajectories, this may be influenced by reduced UAV-lidar returns, as shown in [Figure 8](#fig-lidar-tf-ip), and higher percent error proximal to the trunks of individual trees due to reduced throughfall depths. However, this limitation does not significantly alter the interpretation of the results.

|  |
| --- |
| Figure 9: The Pearson Correlation Coefficient between rasters (25 cm 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. |

[Figure 10](#fig-lca-vs-ip) shows that the correlation between and interception efficiency, resampled to a 5 m resolution, is stronger when is adjusted for the observed shift in hydrometeor trajectory (Vector Based), compared to the nadir leaf contact angle (zenith angle of 0°). The strong association suggests that adjusted is a useful predictor of interception efficiency, before ablation. For the vector-based model, adjusted was calculated using the VoxRS dataset corresponding to the azimuth range and zenith angle with the highest for each plot as mentioned in the previous paragraph. 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.

|  |
| --- |
| 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 the 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 R2 values for the four different models are shown in the upper right of each panel calculated following the methods outlined in Kozak & Kozak (1995). |

The Nadir linear regression model provides a good overall fit to the observed data and closely follows the 1:1 line in [Figure 10](#fig-lca-vs-ip), with a value of 0.95 and 0.99 for the PWL and FT plot respectively. For the PWL plot, the observed points follow a linear relationship until a value of around 0.50 after which the increase in interception efficiency plateaus. After the Kozak & Kozak (1995) adjustment a negative R2 value was determined for the PWL plot. 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, for grid cells where interception efficiency is less than , may be attributed to 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). This later explanation explains the non-linear relationship observed for the PWL Nadir model in [Figure 8](#fig-lidar-tf-ip).

For the vector-based model, the relationship between interception efficiency and is better represented by a linear regression model for both plots with R2 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 plots respectively. The reduced slope for the vector-based models may be attributed to snowflakes that weaved through and/or bounced off branch elements in addition to some of the UAV-lidar measurement uncertainty which contained some unloading and redistribution. These processes would have reduced the fraction of snowfall that contacted the canopy that was intercepted.

Model error statistics are presented in [Table 2](#tbl-ip-mod-err) for the Nadir and vector-based models and show the vector-based model provides a better prediction of interception efficiency. The vector-based model reduced the RMSE from 0.099 to 0.062 for the FT plot and 0.146 to 0.095 for the PWL plot. The good model performance shown for the vector-based model demonstrates that using adjusted for observed event hydrometeor trajectory angle has the potential to be a predictor of interception efficiency, before ablation. However, the detailed point clouds required to derived the values used in this analysis are rarely available and thus more accessible methods to estimate must be obtained in order to use [Equation 5](#eq-lca-ip).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 2: Model error statistics provided for predictions of interception efficiency using [Equation 5](#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 Metrics | Model Slope | Mean Bias | MAE | RMS Error | R^2 | | --- | --- | --- | --- | --- | --- | --- | | FT | Nadir | 0.993 | 0.022 | 0.071 | 0.099 | 0.507 | | FT | Vector Based | 0.676 | 0.001 | 0.047 | 0.062 | 0.804 | | PWL | Nadir | 0.949 | 0.048 | 0.113 | 0.146 | NA | | PWL | Vector Based | 0.707 | 0.019 | 0.078 | 0.095 | 0.469 | |

### 3.4.3 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 the 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 large range in values for individual grid cells across each forest plot. Despite this large scatter, a systematic increase in the plot mean results from a rise in the number of canopy elements for more horizontal portions of the hemisphere, when averaged across each forest plot, over all azimuth angles (see solid lines top row, [Figure 11](#fig-lca-ht-ws)). The increase in from (i.e., ), 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 .90 around 60°, while the FT plot, which has lower , continues to rise quickly until around 75° afterwards the slope is reduced as a of one is approached.

|  |
| --- |
| 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). 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 velocity of 0.9 m s-1. The solid lines (VoxRS) represent the mean (top) or increase in mean (bottom) 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 6](#eq-lca-ac) (top) and [Equation 7](#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 used for the HP98 calculation. The line colour represents the forest plot, FT (black) and PWL (red) |

At the stand scale, increasing the hydrometeor trajectory angle results in a large rise in the VoxRS measured over relatively common estimated wind speeds. For example, with a wind speed of 1 m s-1 and estimated trajectory angle of 48°, the increased by a fraction of 0.14 and 0.12 for the PWL and FT forest plots respectively in [Figure 11](#fig-lca-ht-ws) (right panel). This is a percent increase in the plot from nadir of 28% and 40% for PWL and FT respectively. A similar rate of increase in was observed between both the FT and PWL forest plots up to around 60° or 1.5 m s-1. was also quantified across trajectory angles for both PWL and FT on March 14th, post snowfall, and showed a negligible effect of canopy snow load on .

A function is proposed here that calculates plot scale leaf contact area, (-):

where, is the increase in leaf contact area from which is a function of the zenith angle (hydrometeor trajectory) of interest. 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)). The logistic function used predict as a function of is:

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 resulting coefficients for , and after the nls fit to the VoxRS dataset 0.381, 46.864 and 25.8 respectively for PWL. For FT the resulting coefficients for , and from nls were 0.381, 46.864 and 25.8 respectively. A logistic function was selected to model this relationship, as its shape was deemed most appropriate to represent the change in with trajectory angle. This choice reflects the observed slow increase in at near vertical trajectory angles. The logistic function also captures the non-linear increase at more horizontal trajectory angles, where snowflakes encounter more canopy area in the middle and lower section of individual trees. Additionally, the function effectively represents the gradual leveling off of as it approaches full coverage (value of one).

Simulated using [Equation 6](#eq-lca-ac) is shown in the dashed lines in the top row of [Figure 11](#fig-lca-ht-ws) and follows closely to the VoxRS measured mean . Model error statistics shown in [Table 3](#tbl-lca-mod-err) demonstrate that [Equation 6](#eq-lca-ac) 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 3](#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.

The use of [Equation 7](#eq-lca-inc) requires estimates of for a snowfall event. The estimated trajectory angle of 61.49° resulting from the mean wind speed integrated over the canopy height was much higher than the trajectory angle closer to 20° observed in [Figure 9](#fig-hemi-ip-cc). Based on the wind speed profile in [Figure 7](#fig-wind-profiles) a trajectory angle of around 20° would have resulted from a mean wind speed of 0.36 m s-1 and 0.34 s-1 and a height above the snowpack of 1.32 m and 1.3 m for PWL and FT respectively. Based on the event average snowpack depth at FT station of 1.47 m, this corresponds to a height above the ground that is 2.79 m and 2.77 m for PWL and FT respectively and fraction of the mean canopy height of 0.27 m and 0.39 as a result of the differing tree heights within two plots. This corresponds to roughly one-third the canopy height, based on an average of the two forest plots, to achieve this low wind speed is interpreted to be a result of the conical shape of the needleleaf trees surrounding PWL and FT which have the majority of their canopy volume towards the ground. Although the wind speeds were observed to be higher near the top of the canopy, corresponding to higher trajectory angles, the reduced canopy volume at this height results in a smaller impact of these more horizontal trajectories.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 3: Model error statistics calculated for the prediction of leaf contact area from trajectory angle using [Equation 7](#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. A forested downwind distance of 100 m was used for the HP98 calculation.   | Model | Plot | Mean Bias | MAE | RMS Error | R^2 | | --- | --- | --- | --- | --- | --- | | HP98 | FT | -0.0991 | 0.0991 | 0.1212 | 0.7136 | | HP98 | PWL | -0.0665 | 0.0767 | 0.0912 | 0.5045 | | nls | FT | 0.0004 | 0.0013 | 0.0016 | 0.9997 | | nls | PWL | 0.0006 | 0.0023 | 0.0028 | 0.9991 | |

### 3.4.4 Throughfall Model Performance

The performance of [Equation 5](#eq-lca-ip) in estimating event throughfall was assessed for the March 13-14 snowfall event at the plot scale for both FT and PWL. Event throughfall was calculated using [Equation 3](#eq-event-tf) with interception efficiency modelled from [Equation 5](#eq-lca-ip) and integrating over the event time interval. The mean hydrometeor terminal velocity and total event snowfall was measured at PWL station, and wind speed was determined at height of one-third the mean canopy height using the wind speed profile in [Figure 7](#fig-wind-profiles). Additional model inputs include , measured from from UAV-lidar averaged over each forest plot, an value of 1 was chosen based on the close alignment of interception efficiency and to the 1:1 line in [Figure 10](#fig-lca-vs-ip), and the previously defined constants for [Equation 7](#eq-lca-inc) derived for the PWL and FT plots were incorporated.

Predicted values of observed and modelled interception efficiency and are shown in [Table 4](#tbl-vb-plot-err) along with corresponding error statistics. [Figure 12](#fig-event-tf) shows the vector-based model, computed using [Equation 5](#eq-lca-ip) with adjusted for estimated hydrometeor trajectory angle, closely matches UAV-lidar measurements of throughfall with a positive mean bias of 0.1 kg m-2 for PWL and 0.1 kg m-2 for FT. [Figure 12](#fig-event-tf) shows the nadir model, computed using [Equation 5](#eq-lca-ip) and in place of , over predicted throughfall compared to the UAV-lidar measurements with a negative mean bias of -1.4 kg m-2 for PWL and -1.4 kg m-2 for FT. [Table 4](#tbl-vb-plot-err) shows the vector-based model has a very low absolute percent error compared to the Nadir model for PWL however for FT there is only slight improvement in absolute error. The positive bias was observed for the vector-based model was expected and is preferred compared to the nadir model as the UAV-lidar measurements of throughfall are inherently underestimates since they include some amount of unloading and redistribution. If measurements of throughfall without unloading and redistribution could have been collected it is expected the vector-based model would have further reduced error compared to the Nadir model for both FT and PWL. The improved performance of the vector-based model at PWL compared to FT, may be attributed to increased unloading and redistribution across the FT plot as a result of the sparser wind-exposed canopy.

|  |
| --- |
| Figure 12: Bar chart comparing the observed and modelled mean change in throughfall (𝚫 SWE, kg m⁻²) over the March 13-14 snowfall event averaged over forest plots FT and PWL. The ‘nadir’ data type used [Equation 5](#eq-lca-ip) but was not adjusted for trajectory angle and thus was used instead of , ‘obs’ corresponds to the UAV-lidar measured change in throughfall, and ‘VB’ is the change in throughfall predicted from the vector-based (VB) model which uses [Equation 5](#eq-lca-ip) with adjusted for trajectory angle. The black horizontal dashed line shows the accumulated SWE (kg m⁻²) over the snowfall event to the PWL station open clearing. |

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Table 4: Model error statistics for model estimates of snow interception efficiency (ip) and throughfall (tf) compared to measurements of ip and tf using UAV-lidar averaged over the FT and PWL forest plots. Units for ip and tf are (-) and (kg m⁻²) respectively. The ‘mod\_type’ column refers to the method used to estimate ip and tf. The vector-based (VB) method utilized [Equation 5](#eq-lca-ip) with adjusted for trajectory angle. The nadir method also utilized [Equation 5](#eq-lca-ip) but was not adjusted for trajectory angle and thus was used instead of . The obs\_val column contains measurements from UAV-lidar while the mod\_val column contains values from the respective mod\_type method. The Mean Bias was calculated as observed minus modelled and Perc. Error is the percent error between predicted and observed values.   | plot | val\_name | mod\_type | obs\_val | mod\_val | Mean Bias | Perc. Error | | --- | --- | --- | --- | --- | --- | --- | | FT | ip | VB-model | 0.22 | 0.24 | -0.02 | -7.77 | | FT | ip | Nadir-model | 0.22 | 0.20 | 0.02 | 9.58 | | FT | tf | VB-model | 22.30 | 21.81 | 0.49 | 2.22 | | FT | tf | Nadir-model | 22.30 | 22.91 | -0.61 | -2.73 | | PWL | ip | VB-model | 0.41 | 0.42 | 0.00 | -0.85 | | PWL | ip | Nadir-model | 0.41 | 0.37 | 0.05 | 11.72 | | PWL | tf | VB-model | 16.81 | 16.71 | 0.10 | 0.60 | | PWL | tf | Nadir-model | 16.81 | 18.20 | -1.39 | -8.26 | |

## 3.5 Discussion

The point scale observations presented in this study showed air temperature had little influence on interception efficiency [Figure 6](#fig-lai-met-ip) which differs from existing studies which suggested either a strong positive (Storck et al., 2002) or negative (Hedstrom & Pomeroy, 1998) relationship. An increase in initial interception efficiency before unloading was observed with increasing wind speed at two locations which were sheltered to the predominant wind direction [Figure 6](#fig-lai-met-ip). This was attributed to an associated increase in with wind speed. These results are consistent with observations by Schmidt & Troendle (1989) who observed a slight increase in interception with increasing wind speeds up to 6 m s-1.

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 in interception efficiency for larger canopy snow loads is attributed to the influence of canopy snow load on [Figure 6](#fig-lai-met-ip). While small, this effect is like 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. The observations presented in [Figure 6](#fig-lai-met-ip) and [Figure 3](#fig-scl-w-sf), differ from the Satterlund & Haupt (1967), Hedstrom & Pomeroy (1998), Storck et al. (2002) and Moeser et al. (2015) theories, as canopy snow load increased linearly with snowfalls up to 45 kg m-2 with no evidence of approaching a maximum canopy snow load. The strong exponential decline in interception efficiency observed with increasing event snowfall in Satterlund & Haupt (1967), Hedstrom & Pomeroy (1998), Storck et al. (2002) and Moeser et al. (2015) may be a result of increased unloading rates as branches bend under heavy snow loads and hence mix ablation and interception processes to varying degrees. The low sensitivity of interception efficiency with canopy snow load found in this study 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 between snow-off conditions from a single UAV-lidar scan compared to snow-on conditions derived from a combination of three UAV-lidar scans. The higher forest density in the Staines & Pomeroy (2023) study resulted in less canopy gaps and was thus not as influenced by branch bending. This may have resulted in a slightly higher influence of snow load on in the Staines & Pomeroy (2023) study, compared to negligible effect reported between the March 13 and 14 UAV-lidar surveys in this study. Still, the increase in resulting from snow load in Staines & Pomeroy (2023) was smaller compared to the substantial rise in due to trajectory angle presented in their study and as shown in [Figure 11](#fig-lca-ht-ws). Further evidence in support of canopy snow load not being directly related to interception efficiency or 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 combined with ablation process representations for canopy snow melt, sublimation, wind-induced unloading and temperature induced unloading. However, Lehtonen et al. (2016) note that in northern Finland heavy canopy snow loads have been observed to continue increasing until stem breakage, under conditions favorable for the formation of significant rime-ice accretion and limited ablation. 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, [Equation 5](#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 the rainfall interception literature (Valante et al., 1997). [Equation 5](#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 proposed interception efficiency to be constant over time and space. The theoretical basis of the value in [Equation 5](#eq-lca-ip) is that the association between and interception efficiency, as shown in [Figure 10](#fig-lca-vs-ip), does not follow a 1:1 line as falling snow hydrometeors may bounce off the canopy elements. However, as direct measurements of are not widely available, an value of 1 is suggested if is approximated from using [Equation 6](#eq-lca-ac), following the fit of the nadir model in [Figure 10](#fig-lca-vs-ip). The new snow interception routine is also similar to many recent rainfall interception studies, which calculate throughfall as a function of (e.g., Valante et al., 1997).

Measurements of interception efficiency and canopy structure collected in this study corroborated with the Hedstrom & Pomeroy (1998) theory and showed reduced throughfall on the lee side of individual trees [Figure 8](#fig-lidar-tf-ip). This was attributed to predominately non-vertical hydrometeor trajectory angles which can substantially increase plot-wide as shown in [Figure 11](#fig-lca-ht-ws). It was found that the mean hydrometeor trajectory angle over a snowfall event could be predicted by using the observed hydrometeor fall velocity and a 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 thought 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. While a wind speed selected at a height higher within the canopy may have a higher speed and thus more horizontal trajectory angle, less canopy elements at this height would be available for contacting incoming hydrometeors. Katsushima et al. (2023), also proposed the wind speed at one-third the canopy height for 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 one-third canopy height observed here to other environments due to differing tree structures and tree species such as those 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 wrapping around tree elements, turbulent flow, or differences in wind speed with height.

An existing method 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). A new method is proposed which uses logistic function to calculate plot-wide as a 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 averages out. At this scale, [Equation 7](#eq-lca-inc), which uses trajectory angle alone, could be sufficient to determine and thus . However, [Equation 7](#eq-lca-inc) would not applicable to areas that have large continuous gap fractions (e.g., forested clear cuts) and should be limited forested areas. Further work is required to refine the relationship proposed in [Equation 7](#eq-lca-inc) across a range of tree species and densities. A better understanding of this relationship is also important for representing the change in light transmittance through the canopy with solar zenith angle (Niu & Yang, 2004). Also ref Dai et al. (2019) who propose a way to represent sub-grid variability and gap distribution in the canopy, important for them for subcanopy turbulence.

Although the performance improvement in the vector-based model compared to the Nadir model is relatively small the positive bias of the VB model is preferred due to uncertainties with the throughfall measurements. Throughfall measurements by UAV-lidar over the snowfall event are inherently overestimates due to some unloading and redistribution of snow, which were estimated to be about 2 kg m-2. Throughfall measurements that do not include unloading and redistribution would have been slightly lower and thus better matched the vector-based model. Conversely, the Nadir model which has a stronger negative bias, would result in further overestimates. Although the Nadir model provided good performance for this event, reduced performance would be expected for a snowfall event with stronger wind speeds which would further increase . While the vector-based model acts to increase interception efficiency with wind speed, several studies suggest 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). While these studies have been used to develop parameterizations for wind induced unloading, they were not based on direct measurements of canopy snow unloading and further research is required to better refine these relationships to understand how wind influences canopy snow unloading after it is intercepted. Once the vector-based model is combined with a wind-induced canopy snow unloading parameterization, the overall influence of wind on canopy snow interception will be balanced to some extent.

## 3.6 Conclusions

New observations of snow interception, collected over a wide range of meteorological conditions and canopy structures suggest forest structure is the primary factor governing subcanopy snow accumulation. These findings challenge the theoretical foundation of most existing snow interception parameterizations, which rely on canopy snow load and air temperature as key predictors. At the point scale, high-temporal resolution measurements revealed no evidence of a maximum canopy snow load, even for snowfalls up to 45 kg m-2, nor was there any indication of increased cohesion or branch bending affecting interception efficiency through air temperature. Instead, wind speed was found to either increase or decrease interception efficiency due to its influence on hydrometeor trajectory angle, which alters the apparent forest structure, or snow-leaf contact area.

At the forest plot scale, UAV-lidar measurements of throughfall collected over a wind-driven snowfall event confirmed the results observed at the point-scale and showed leaf contact area was the main factor governing the interception efficiency at a particular site. Canopy structure metrics adjusted for trajectory angle provided an improved predictor of interception efficiency compared to nadir canopy coverage. Plot-wide canopy structure was shown to be highly sensitive to simulated hydrometeor trajectory angles. For example, using VoxRS measurements snow-leaf contact area was observed to double for simulated hydrometeor trajectories associated with a wind speeds of 1 m s-1 compared to vertical hydrometeor trajectories. An existing theoretical relationship failed to represent the VoxRS measured increase in leaf contact area with simulated trajectory angles.

The lack of a strong association between air temperature or canopy snow load with interception efficiency, along with the clear influence of wind speed, underscores the need for a new snow interception parameterization. A new parameterization is proposed that calculates initial interception, prior to canopy snow ablation, as a function of snowfall and leaf contact area. This parameterization is consistent with many 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 the increase in leaf contact area from nadir canopy coverage as a function of hydrometeor trajectory angle. This updated snow interception parameterization showed good performance in the subalpine forest in this study, but further validation should be conducted in a range of climates, forest species, and canopy structures. Caution is advised when applying this updated routine with existing canopy snow ablation parameterizations, as these were developed in conjunction with earlier snow interception routines that also incorporated ablation processes.

## 3.7 Acknowledgments

We wish to acknowledge financial support from the University of Saskatchewan Dean’s Scholarship, Natural Sciences and Engineering Research Council of Canada, Global Water Futures Programme, Alberta Innovates and the Canada Research Chairs Programme. We thank Madison Harasyn, Hannah Koslowsky, Kieran Lehan, Lindsey Langs and Fortress Mountain Resort for their help in the field. Madison Harasyn, Alistair Wallace, and Rob White contributed to developing the UAV-lidar processing workflow.

## 3.8 Data Availability

The data that support the findings in this study will be made publicly available upon publication.

# 4. The Influence of Meteorology on Canopy Snow Ablation Processes

Manuscript status: This article is preparation for submission to the journal *Water Resources Research* by October 31, 2024. The results from this paper were presented at INARCH and AGU 2023.

Role in thesis: This journal article answers research question 1.3 of the thesis. It will present analysis of canopy snow ablation observations from Fortress Mountain Research basin collected over the 2022 and 2023 water years and contrast these against existing theories.

**Authors:**

A. Cebulski1 (ORCID ID - 0000-0001-7910-5056)

J.W. Pomeroy1 (ORCID ID - 0000-0002-4782-7457)

1Coldwater Laboratory, University of Saskatchewan, Canmore, Canada

**Corresponding Author:** Alex Cebulski, alexcebulski@gmail.com

**Key Points:**

* Direct measurements of the canopy snow mass balance using a tree weighing lysimeter and subcanopy lysimeter provide new insights on the interaction of canopy snow ablation processes with meteorology and canopy snow load.
* The primary processes contributing to canopy snow ablation observed in this study were unloading and drip (60%) with a slightly smaller contribution form sublimation (40%)
* Canopy snow unloading and drip was observed to be associated with air temperature, wind speed, canopy snow load, and the duration snow has been intercepted in the canopy.

**Abstract:**

The time that snow resides in the canopy, and is subjected to high rates of sublimation, is dependent on rates of canopy snow ablation processes. Previous studies have developed parameterizations to represent ablation processes including unloading, melt, drip and sublimation of snow intercepted in the canopy. However, these parameterizations have been shown to have uncertain transferability to new environments and have not yet been tested in discontinuous forest canopies. This study presents new in-situ measurements of canopy snow ablation processes and contrasts these observations with existing theories and models. Analysis of the canopy snow mass balance showed that unloading, drip and melt contributed to 60% of canopy snow ablation on average over two years with the remainder being attributed to canopy snow sublimation. The probability of unloading, drip and melt was observed to increase with air temperature and wind speed. However, the probability of wind induced unloading was observed to decrease at warmer air temperatures. The probability of unloading due to warming was also observed to decline when wind speeds were above 1 m s-1. The increase in cohesion and adhesion of snow in the canopy at warmer temperatures and cooling due to wind-induced evaporation may contribute to the interaction multivariate interaction between air temperature, wind speed and canopy snow unloading. Exponential relationships were observed between both air temperature and wind speed with unloading and drip, which were also dependent on the amount of snow intercepted in the canopy. In comparison to existing models, this discontinuous forest exhibited unloading and drip due to warming at lower air temperatures. Conversely, wind-induced unloading occurred at higher wind speeds than predicted by current models.

## 4.1 Introduction

The objective of this study is to determine if the theoretical underpinnings and assumptions behind existing canopy snow ablation parameterizations are supported by in-situ observations from this study site.

Research Questions:

1. What are the dominant processes driving canopy snow ablation as observed in this study site?
2. How do meteorological factors, such as temperature and wind, influence the rates and patterns of snow unloading?
3. To what extent do current theoretical models of canopy snow ablation align with the in-situ observations, and what modifications, if any, are necessary to accurately represent the observed processes?

|  |
| --- |
| Figure 13: Example of the Hedstrom & Pomeroy (1998) (HP98) and Roesch et al. (2001) (RW01) parameterizations for the calculation of unloading and drip rates with increasing air temperature. Wind speed for the RW01 parameterization was set to zero. Note that the HP98 parameterization does not differentiate unloading processes (i.e., metamorphasism, wind-induced, melt) while the RW01 parameterization here calculates unloading and drip of canopy snow due to warming and melt alone and their wind-induced parameterization is shown separately. |

|  |
| --- |
| Figure 14: Example of the Roesch et al. (2001) (RW01) parameterization for the calculation of wind-induced unloading. Here the air temperature has been set to a constant of -10°C to set the unloading rate due to warming to zero. The parameterization was run for a range of canopy snow loads (5, 10, 15, and 20 mm). |

## 4.2 Study Site and Instrumentation

## 4.3 Methods

### 4.3.1 Partitioning the Canopy Snow Ablation Mass Balance

### 4.3.2 Modelled Canopy Snow Sublimation Rate

### 4.3.3 Probability of Unloading and Drip

## 4.4 Results

### 4.4.1 The apportionment of Canopy Snow Ablation Processes

[Figure 15](#fig-glob-unl-part) shows that the measured unloading and drip rate was the dominant process of the canopy snow ablation mass balance over two winter seasons. Simulated sublimation rates also make up a significant portion of canopy snow ablation and accounted for most of the residual measured ablation. This suggests that for the average conditions in this wind-exposed subalpine forest, wind redistribution of snow intercepted in the canopy is a relatively small component.

|  |
| --- |
| Figure 15 |

[Figure 16](#fig-wind-temp-unl-part) shows a large increase in the ablation residual with wind speeds above 3.5 m s-1 and little association with air temperature. The increase in the residual at high wind speeds is attributed to higher ablation rates measured by the weighed tree due which were not accounted for by corresponding increase in the unloading + drip rates. The difference between the residual + error term and the modelled sublimation rate is attributed to both an increase in horizontal wind redistribution of snow intercepted in the canopy and instrument error. Difficulties in measuring horizontal wind redistribution and quantify the instrument error limit the ability to partition the residual into these two processes. If it is assumed that the instrument error is constant across wind speeds, it could be determined that the increase in the residual + error term is primarily attributed to horizontal wind redistribution. However, since the sublimation parameterization in this simulation has not been tested in wind-exposed forest and may be an underestimate of true sublimation rates at high wind speeds. Therefore the increase in residual, compared to modelled sublimation could also be attributed to an increase in actual sublimation rate compared to the model. While these data could be used to parameterise a horizontal wind redistribution function, the uncertainty behind this residual term due to the aforementioned issues prove any resultant model to be too speculative.

|  |
| --- |
| Figure 16 |

### 4.4.2 The Influence of Meteorology on Unloading

[Figure 17](#fig-glob-prob-unl) shows the association between the probability of unloading + drip with air temperature and wind speed. The probability of unloading + drip was found to be high (close to 1) for air temperatures above 1 °C and above wind speeds of 2.5 m s-1. For wind speeds bins less than 1 m s-1 the probability of unloading was found to positively associated with air temperatures. However at higher wind speeds this association was observed to weaken, potentially due to some evaporative cooling. For air temperatures less than -6 °C a positive association between the probability of unloading + drip and wind speed was observed. Above -6 °C the reduced association between wind speed and probability of unloading + drip may be attributed to increased cohesion and adhesion of snow intercepted in the canopy attributed to an increase in liquid water content in the snow clumps. The low frequency of observations shown in [Figure 18](#fig-glob-freq-unl), for low and high air temperatures and wind speeds may limit the interpretation of these results.

|  |
| --- |
| Figure 17 |

|  |
| --- |
| Figure 18 |

Removing periods above these thresholds, i.e., air temperature less than -6 °C and wind speed less than 2 m/s, shows that the probability of unloading increases based on the duration snow is intercepted in the canopy. The probability of unloading starts at around 0.5 when snow is newly intercepted in the canopy, followed by a decline to around 0.1 after about 10 hours, and following 24 hours the probability of unloading increases steeply up to near 1.0 at 100 hours.

|  |
| --- |
| Figure 19 |

### 4.4.3 Modelling Canopy Snow Unloading

Less confidence in the temperature unloading model, maybe better suited to use a physically based snowmelt model. The wind unloading model aligns well with the observations although, only two canopy snow load bins were used. This model is slightly less sensitive, with lower unloading rates at the same wind speeds compared to the Roesch et al. (2001) relationships.

|  |
| --- |
| Figure 20 |

The slight decline in unloading rate at 3.5 m s-1 for the 11 mm canopy snow load group is attributed to a single event where snow had been intercepted in the canopy for over 30 hours and may have been slightly more resistant to unloading compared to other events prior to this. Although lots of other obs with durations close to 30 hours and no obvious melt/refreeze so possibly more related to concurrent sublimation / wind redistribution. Although minimal wind redistribution observed at the pluvio. Could check disdrometer.

|  |
| --- |
| Figure 21 |

# A tibble: 6 × 6  
 `Mean Canopy Load (mm)` `Mean Bias` MAE `RMS Error` R2 model   
 <dbl> <dbl> <dbl> <dbl> <dbl> <chr>   
1 3.11 0.047 0.072 0.105 0.73 wind\_model  
2 10.8 0.018 0.109 0.143 0.73 wind\_model  
3 NA NaN NaN NaN 0.73 wind\_model  
4 2.86 0.035 0.079 0.1 0.67 temp\_model  
5 10.7 0.049 0.108 0.13 0.67 temp\_model  
6 NA NaN NaN NaN 0.67 temp\_model

[Figure 22](#fig-mod-time-unld) and [Figure 23](#fig-mod-cpy-load-unld) show the decrease in unloading associated with increased duration in the canopy and increased unloading with increasing canopy snow load respectively. These figures show periods with snow intercepted in the canopy and filtered to below -6 °C and 2 m s-1 wind speed, where unloading attributed to these processes are observed to be reduced in [Figure 21](#fig-mod-wind-unld) and [Figure 20](#fig-mod-temp-unld).

|  |
| --- |
| Figure 22 |

|  |
| --- |
| Figure 23 |

## 4.5 Discussion

The inclusion of processes that ablate snow intercepted in the canopy is prevalent in many parameterizations for the initial loading of snow within the canopy. Many of these processes are related to the amount of time that snow resides in the canopy prior to the interception measurement was conducted in addition to wind and temeprature induced unloading processes. After filtering out unloading due to temperature and wind the duration snow was intercepted in the canopy was found as a third important factor to consider. Unloading due to duration initially starts high while the snow is fresh and has low cohesion and adhesion and as the snow metamorphasizes the adhesion and cohsesion increases for the first 15 hours and the probability of unloading declines. After 15 hours the probability of unloading increases potentially due to increased sublimation and metamorphasism of snow intercepted in the canopy which reduces its adhesion and cohesion.

A new unloading routine could be established based on these observations after filtering to remove temperature and wind induced unloading which show the probability of unloading after this filtering is high after initial loading of snow intercepted in the canopy, followed by a decline in probability until around 15 hours, and increases afterwards. This could be combined with the unloading rate which was observed to be high as the snow was initially loaded in the canopy and then declines steadily with increasing duration.

## 4.6 Conclusions

* Over two winter seasons, the primary processes contributing to canopy snow ablation were unloading, drip, and sublimation. Wind redistribution of canopy snow was determined to be a small component of the mass balance.
* The probability of unloading was observed to increase with air temperature and wind speed. However, the probability of wind induced unloading was observed to decrease at warmer air temperatures. The probability of unloading due to warming was also observed to decline when wind speeds were above 1 m s-1. The increase in cohesion and adhesion of snow in the canopy at warmer temperatures and cooling due to wind-induced evaporation may contribute to the interaction multivariate interaction between air temperature, wind speed and canopy snow unloading.
* The duration that snow is intercepted in the canopy was found to first decrease the probability of unloading exponentially for the first 15 hours, followed by an exponential increase in the probability of unloading for the remaining duration that snow is intercepted in the canopy.
* Exponential relationships were observed between both air temperature and wind speed with unloading and drip, which were also dependent on the amount of snow intercepted in the canopy. In comparison to existing models, this discontinuous forest exhibited unloading and drip due to warming at lower air temperatures. Conversely, wind-induced unloading occurred at higher wind speeds than predicted by current models.

# 5. An Evaluation of New Snow Interception and Ablation Parameterizations in Three Mountain Forests in western Canada

Manuscript status: Model setup and simulations in progress writing has not started. Anticipated submission is to the journal *Water Resources Research* March, 2025.

Role in thesis: This journal article corresponds to research question 2.1 of the thesis, the model implementation and testing phase. New parameterizations and process understanding of snow interception and ablation processes from chapters 1, 2 and 3 will incorporated into the Cold Regions Hydrological Model (CRHM) platform to model forest snow accumulation at four research basins in western Canada. The updated parameterizations will be evaluated by including them in an updated CRHM canopy module. Simulated SWE using this updated moduled will be compared to observed SWE within the forested portion of each basin.

# 6. 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>

Axelsson, P. (2000). Peter Axelsson 110. *International Archives of Photogrammetry and Remote Sensing*, *33*(4), 110–117. <https://www.isprs.org/proceedings/XXXIII/congress/part4/111_XXXIII-part4.pdf>

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>

BayesMap Solutions. (2024). *BayesStripAlign*. <https://bayesmap.com/products/bayesstripalign/>

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

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/<https://doi.org/10.1175/1520-0450(1965)004<0517:AMMFAF>2.0.CO;2>

Dai, Y., Yuan, H., Xin, Q., Wang, D., Shangguan, W., Zhang, S., Liu, S., & Wei, N. (2019). Different representations of canopy structure—A large source of uncertainty in global land surface modeling. *Agricultural and Forest Meteorology*, *269-270*(135), 119–135. <https://doi.org/10.1016/j.agrformet.2019.02.006>

Deems, J. S., Painter, T. H., & Finnegan, D. C. (2013). Lidar measurement of snow depth: A review. *Journal of Glaciology*, *59*(215), 467–479. <https://doi.org/10.3189/2013JoG12J154>

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. *Cryosphere*, *14*(6), 1919–1935. <https://doi.org/10.5194/tc-14-1919-2020>

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>

Hijmans, R. J. (2024). *terra: Spatial Data Analysis*. <https://cran.r-project.org/package=terra>

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>

Kozak, A., & Kozak, R. A. (1995). Notes on regression through the origin. *Forestry Chronicle*, *71*(3), 326–330.

LAStools. (2024). *Efficient LiDAR Processing Software (version 240220, academic)*. <http://rapidlasso.com/LAStools>

Lehtonen, I., Kämäraïnen, M., Gregow, H., Venälaïnen, A., & Peltola, H. (2016). Heavy snow loads in Finnish forests respond regionally asymmetrically to projected climate change. *Natural Hazards and Earth System Sciences*, *16*(10), 2259–2271. <https://doi.org/10.5194/nhess-16-2259-2016>

Lumbrazo, C., Bennett, A., Currier, W. R., Nijssen, B., & Lundquist, J. (2022). Evaluating Multiple Canopy-Snow Unloading Parameterizations in SUMMA With Time-Lapse Photography Characterized by Citizen Scientists. *Water Resources Research*, *58*(6), 1–22. <https://doi.org/10.1029/2021WR030852>

Lundberg, A., & Halldin, S. (2001). Snow interception evaporation. Review of measurement techniques, processes, and models. *Theoretical and Applied Climatology*, *70*(1-4), 117–133. https://doi.org/<https://doi.org/10.1007/s007040170010>

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>

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/<https://doi.org/10.1002/2014WR016724>

Natural Resources Canada. (2024). *Precise point positioning*. <https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php>

Niu, G. Y., & Yang, Z. L. (2004). Effects of vegetation canopy processes on snow surface energy and mass balances. *Journal of Geophysical Research D: Atmospheres*, *109*(23), 1–15. <https://doi.org/10.1029/2004JD004884>

Nock, C. A., Lecigne, B., Taugourdeau, O., Greene, D. F., Dauzat, J., Delagrange, S., & Messier, C. (2016). Linking ice accretion and crown structure: towards a model of the effect of freezing rain on tree canopies. *Annals of Botany*, *117*(7), 1163–1173.

Pomeroy, J. W., & Gray, D. M. (1995). *Snowcover Accumulation, Relocation and Management* (NHRI Scien, p. 144). National Hydrology Research Institute, Environment Canada, Saskatoon, Canada.

R Core Team. (2024). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. <https://www.r-project.org/>

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>

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

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>

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>

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., Gutmann, E., & Friesen, J. (2020). *Precipitation partitioning by vegetation: A global synthesis*.

Wheeler, K. (1987). *Interception and redistribution of snow in a subalpine forest on a storm-by-storm basis*. Western Snow Conference. <http://sites/westernsnowconference.org/PDFs/1987Wheeler.pdf>

# 7. Appendix for Chapter 2

### 7.0.1 Snow Interception Parameterization Derivations

The original formulation of Hedstrom & Pomeroy (1998) is:

where (kg m-2), is the canopy snow load before snowfall is added to the canopy, (kg m-2), is the change in canopy snow load due to snowfall. [Equation 8](#eq-hp98-int-orig) is written in this way in Hedstrom & Pomeroy (1998) since they had measurements of at the beginning of the storm. However, this equation further simplified here since:

and therefore:

The derivation of the Hedstrom & Pomeroy (1998) snow interception parameterization, **?@eq-hp98-int-numeric**, from [Equation 9](#eq-hp98-int-smpl) is provided by first combining [Equation 2](#eq-ip) and **?@eq-hp98-int-smpl1**:

here, it is assumed that is the average snowfall rate over the discrete time interval . Since , and are temporally constant over the discrete time interval they can be moved outside the integral. The analytical solution in **?@eq-hp98-int-numeric** is only possible because canopy snow interception is treated in isolation from the other processes in **?@eq-canopy-mass-bal**.

### 7.0.2 Snow Unloading Parameterization Derivations

The steps to get from **?@eq-hp98-flu** to **?@eq-hp98-exp-decay** are:

If the change in canopy snow load due to unloading alone is:

then:

note, since is temporally constant it can be moved outside the integral. The analytical solution in **?@eq-hp98-exp-decay** is only possible because unloading is treated in isolation from the other processes in **?@eq-canopy-mass-bal**.

# 8. Appendix for Chapter 3

# 9. Supporting Information

## 9.1 Detailed Description of UAV-Lidar Methodology

The REIGL miniVUX-2 laser operates at a near infrared wavelength with a laser beam footprint of 0.160 m x 0.05 mm (at 100 m above ground). The accuracy and precision of the miniVUX-2 is described by REIGL for a lab environment of 0.015 m and 0.01 m respectively (at 50 m above ground). The miniVUX-2 was configured with a laser pulse repetition rate of 200 kHz, field of view of 360°, scan speed of 31.09 revolutions s-1 and an angular step width of 0.0558°, resulting in an expected an average point cloud density of 107 returns m-2 for each flight path.

Georeferenced point clouds with x, y, and z coordinates for each laser return were generated following methods outlined by Harder et al. (2020) and Staines & Pomeroy (2023) to reconcile survey lidar, IMU and GNSS data. A ground-based GNSS system was positioned on a permanent monument during each survey and underwent precise point positioning (PPP) correction by Natural Resources Canada (2024). Differential GNSS correction of the UAV trajectory was conducted using the ground-based PPP GNSS observations and the POSPac UAV software. The UAV-lidar point clouds were then transformed from a sensor referenced coordinate system to a georeferenced coordinate system (EPSG:32611 - WGS 84 / UTM zone 11N) using the RIEGL Riprocess Software. A vertical offset 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), which reduces relative and absolute uncertainties in the vertical elevation of the point cloud using the ground control points (GCP) collected across the study site using a differential GNSS rover.

Quality control, ground classification and calculation of the change in between two UAV-lidar point clouds was conducted using the LAStools software package (LAStools, 2024). The ground classification was conducted using the “lasground\_new” function (LAStools, 2024) for both the pre and post snowfall event point clouds, with a step size set to 2 m and 8 substeps (ultra\_fine setting). The offset and spike options were set to remove points that are more than 0.1 m above or below the initial ground surface estimate surface which “lasground\_new” fits to the last returns. This function is based on an algorithm outlined by Axelsson (2000), describing the process of making the initial ground surface element.

The change in elevation between the two UAV-lidar surveys was interpreted as the increase in snow accumulation, over the snowfall event. This change was calculated using a point-to-grid subtraction method, using the “lasheight” function from the LAStools (2024) software, as in Deems et al. (2013) and Staines & Pomeroy (2023). The pre snowfall event point cloud from “lasground\_new” by “lasheight” to construct a “ground” TIN. Subsequently, the height of each post snowfall event point above the ground TIN, resulting in a point cloud representing . This point cloud was then converted into a raster of with a grid cell resolution of 5 x 5 cm using the “las2dem” function. Further quality control and resampling of the 5 cm raster of was conducted using the ‘Terra’ R package (Hijmans, 2024). Areas that were disturbed over the snowfall event during the in-situ snow survey and values that exceeded the .999th quantile were removed. To help remove any remaining noise a 25 cm raster was generated by computing the median of the 5 cm values within each 25 cm grid cell.

## 9.2 Linear Regression Models Through the Origin

Kozak & Kozak (1995) noted, the default R2 value provided for least squares models forced through the origin by many statistical packages can be misleading. Therefore, these R2 values were adjusted using Equation 10 in Kozak & Kozak (1995) and two statistical tests as described by Kozak & Kozak (1995) were used to verify whether a no-intercept model (forced through the origin) was appropriate for this data compared to a with-intercept model. The first test evaluated if the intercept of the with-intercept was significantly different from zero using p-value provided by the ‘summary’ function from the ‘stats’ package in R (R Core Team, 2024). The second test examined if there was a significant difference between the no-intercept and with-intercept models by testing if the residual sum of squares was different between the no-intercept and full model, assessed via Equation 15 in Kozak & Kozak (1995). If the first test indicated a significant difference, and the second did not, the no-intercept model could be deemed statistically justified (Kozak & Kozak, 1995).