Thesis Outline

Thesis Title: Advancing Snow Accumulation Models in Needleleaf Forests

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# Abstract

Needleleaf forests have an important control on the phase and partitioning of snowfall to the atmosphere, or to the ground influencing streaflow and land-atmosphere energy exchanges in many cold regions. In sub-humid forests, sublimation leads to reduced SWE below the forest canopy, whereas in humid forests, melt and drip of snow intercepted in the canopy are more important than sublimation and contribute to reduced subcanopy SWE through increased phase change of canopy snow to liquid meltwater. Despite the strong hydrological influence of these snow interception processes, sparse observations have lead to uncertainties in the applicability of representing these processes in hydrological models. These processes include the initial interception, sublimation, unloading, melt, drip and wind redistribution of canopy snow. Existing methods to quantify these processes have had issues in isolating individual processes (i.e., initial interception with unloading or unloading and sublimation). The combination of processes in existing measurements has led to process parameterisations which also combine processes presenting compatibility issues when combined in hydrological models.

This study aims to better understand snow interception and canopy snow ablation processes which act collectively to govern subcanopy snow accumulation in forested environments. The specific objectives of this thesis are: 1) Evaluate the suitability of existing snow interception and ablation parameterizations for application in needleleaf forests with differing canopy structure and meteorology. 2) Determine how new snow interception and ablation parameterizations could enhance the representation of processes important for subcanopy snow accumulation. To facilitate these objectives, observations of forest-snow processes and subcanopy snow accumulation were needed to evaluate the existing theories underpinning parameterisations that represent snow interception and canopy snow ablation processes. Novel methods to better isolate individual forest-snow processes were incorporated in this study to both evaluate the theories underpinning existing snow interception and ablation processes and to propose new relationships to better represent these processes. These observations were used to guide the development of new canopy snow mass and energy balance which was implemented in the Cold Regions Hydrological Modelling (CRHM) platform.

New observations of snow interception which limited the influence of ablation processes showed canopy density is the primary factor influencing subcanopy throughfall of snow. No relationships between initial snow interception and canopy snow load or air temperature were found. Canopy density was best represented by a metric snow-leaf contact area which incorporates the increase in contact area with increasing horizontal trajectory angle. This new parameterisation, which does not incorporate the unloading process, unlike existing theories, helps limit process mixing and aims to increase compatibility with various other canopy snow unloading parameterisations.

Observations of canopy snow unloading revealed that canopy snow load, shear stress, and canopy snowmelt collectively explained 80% of its variability. The exclusion of dry snow unloading or and energy balance-based canopy snowmelt routine in existing models was found to contribute to the misrepresentation of canopy snow load compared to the updated routine which incorporated both processes. These results show that three existing methods are best suited to a particular meterological conditions—either (cold/dry) or (warm/humid).

Validation of a revised canopy snow mass and energy balance at based on subcanopy SWE measurements at two needleleaf forests characterised by a cold-dry climate resulted in comparable absolute mean bias to an existing model. However, simulated subcanopy SWE at a temperate-coastal forest plot resulted in a major reduction in the simulated error compared to the existing model. The overestimation of subcanopy snow accumulation in the existing model was attributed to an underestimation of snow interception due to the maximum canopy snow load incorporated by the model in addition to the empirically derrived ice-bulb temperature thresholds used to predict the transition from dry snow unloading to melt-induced unloading which never triggered the melt process and resulted in nearly all canopy snow reaching the ground as snow rather than drip. In contrast, the revised model—which does not compute initial interception as a function of canopy snow load and predicts canopy snowmelt using an energy balance-based approach—led to a greater fraction of snow intercepted in the canopy and also more canopy snow reaching the ground as drip.

The outcome of this research presents a new canopy snow mass and energy balance that has shown improved performance in simulating subcanopy snow accumulation across both cold and temperature climates. The new method also limites mixing of separate processes which improves compatibility with the modular design of contemparary hydrological models.

# 1. Introduction

Melt of the seasonal mountain snowpack is an important source of streamflow across the globe, crucial for downstream ecosystems, energy production, and agricultural irrigation (Derksen et al., 2019; Viviroli et al., 2007). The high albedo and energy required to melt snow also provides a large-scale cooling effect for our planet by reflecting most of the incoming solar radiation and dissipating energy during spring melt (Henderson et al., 2018). Despite this importance, there is uncertainty in estimates of snow accumulation, especially in mountain forests, due redistribution of snow by wind and forest canopy (Ellis et al., 2010; Krinner et al., 2018; Rutter et al., 2009). In western Canada, diverse topography, climate and canopy structure results in highly variable snow accumulation, which presents a challenge in predicting the quantity of snow available for streamflow and downstream water resources (Ellis et al., 2010; Pomeroy & Gray, 1995). In the Northern Hemisphere, over 50% of snowmelt-dominated basins are covered by needleleaf forest (Kim et al., 2017). This extensive canopy coverage reduces the amount of snow that is available for streamflow through interception of snowfall and subsequent ablative processes (Ellis et al., 2010; Essery et al., 2003; Hedstrom & Pomeroy, 1998). Intercepted snow in the canopy is subjected to higher rates of sublimation compared to subcanopy snow due to greater surface area, turbulent energy exchange, and solar exposure (Pomeroy et al., 1998). Across the Northern Hemisphere, researchers estimate that 25 to 45% of annual snowfall may be lost to the sublimation of intercepted snow from the canopy (Essery et al., 2003). However, the time that snow resides in the canopy and is subject to sublimation is dependent on rates of unloading, melt, drip, and resuspension of snow. These processes lead to the spatial and temporal diversity in subcanopy snowpack accumulation and contribute to the higher uncertainty for the forested domain of hydrological models (Krinner et al., 2018; Rutter et al., 2009).

The high variability of snow accumulation in forests is not well represented due to a sparse and unrepresentative network of in situ observations, which are mostly located in clearings (Vionnet et al., 2021). Moreover, observing snow accumulation under forest canopies at large extents remains uncertain with current remote sensing technologies (Rittger et al., 2020). There is a need for reliable models of snow redistribution by forest and wind to estimate snow accumulation in mountains (Clark et al., 2015a; Pomeroy et al., 2007; Rutter et al., 2009). Existing snow interception parameterizations have been developed for both warm maritime (Andreadis et al., 2009; Storck et al., 2002) and cold continental (Ellis et al., 2010; Hedstrom & Pomeroy, 1998; Roesch et al., 2001) climates characterized by dense forest canopy. Accurate simulations of forest snow accumulation is often achieved if the parameterizations are applied in similar climates to where they were developed (Lundquist et al., 2021; Rasouli et al., 2019b; Roth & Nolin, 2019) or if they are combined into a hybrid parameterization and assessed at global and regional scales in a wide range of climates (Essery et al., 2003; Gelfan et al., 2004). Although accurate performance has been achieved across different climates in some studies (Essery & Pomeroy, 2004; Gelfan et al., 2004), other snow model comparisons (Krinner et al., 2018; Rutter et al., 2009) have shown reduced performance. The decision in earth system models to use parameterizations derived in warm or cold climates is often based on a simple temperature-based step function (Essery et al., 2003; Gelfan et al., 2004) and may require modification to better represent more transitional climates and forest types. The omission or simplified representation of processes and reliance on empirical calibrations likely contribute to model uncertainty when applied in climates and forests where other processes become important (Krinner et al., 2018; Lumbrazo et al., 2022; Lundquist et al., 2021; Moeser et al., 2015b; Roth & Nolin, 2019; Rutter et al., 2009).

Some of the processes currently not encoded in snow interception models include wind redistribution of snow during interception, rain on intercepted snow, hoarfrost, rime ice and the cohesion and adhesion of snow in the canopy. Roesch et al. (2001) and Bartlett & Verseghy (2015) created a wind unloading function for canopy snow that is based on measurements of snow albedo from Betts & Ball (1997) as an index for canopy snow ablation (i.e., unloading, melt, and sublimation) in a low wind environment of the boreal forest in Saskatchewan. However, Pomeroy & Dion (1996) found the relationship between albedo and intercepted snow load was not discernible for the same forest as the Betts & Ball (1997) study. Moreover, it is unclear the influence of sublimation and melt processes on the canopy snow ablation proxy measurement. Pomeroy & Dion (1996) used careful radiation measurements and snow loads from a weighed suspended tree and challenge the Betts & Ball (1997) observations the Roesch et al. (2001) parameterization is based on. Lumbrazo et al. (2022) provide a more recent assessment of canopy snow wind redistribution and provide the the first uncalibrated test of the Roesch et al. (2001) wind induced unloading parameterization. The results from Lumbrazo et al. (2022) generally showed poor performance in mountain forests of Colorado and Washington. Lumbrazo et al. (2022) additional process investigation on the influence of wind on canopy snow interception is required to better simulate mountain forest SWE accumulation.

The calculation of canopy snow melt is often oversimplified in many snow interception models. For example, (Ellis et al., 2010; Essery et al., 2016; Pomeroy et al., 2007) use empirical time-based melt calculations to melt snow intercepted in the canopy. While Clark et al. (2020) and Verseghy (2017) use a physically based energy balance model to melt snow in the canopy, both models assume that the surface temperature of vegetative elements are in equilibrium with snow intercepted in the canopy. This simplification likely leads to a positive bias in canopy snow melt predictions as the vegetative elements are known to have higher temperatures than snow clumps (Pomeroy et al., 2009). Once the canopy snow is at 0 °C and is melting, intercepted snow will reach the ground as clumps of wet snow or will drip as liquid water to the ground (Storck et al., 2002). The distinction between wet snow or liquid meltwater has important implications for the energy balance of the snowpack beneath the canopy, as liquid meltwater can add a large amount of advective energy. However, predicting the ratio of solid to liquid water unloading due to canopy snow melt remains an area of uncertainty (Roesch et al., 2001; Storck et al., 2002).

Future climate change is expected to change the dominant hydrological processes in mountain forests (Dettinger, 2014; Fang & Pomeroy, 2020; He et al., 2021; Viviroli et al., 2011). A report by Environment and Climate Change Canada (Bush & Lemmen, 2019), suggest an increase in air temperature of 2 °C from the 1986-2005 reference period by 2050 for the low emission scenario and 6 °C for the high emission scenario by the late 21st century. Bush & Lemmen (2019) project an increase in annual mean precipitation over all of Canada during the second half of the 21st century, with a larger increase in northern Canada. As the climate warm canopy snow melt and drip processes will likely become more common. However, since melt and drip of canopy snow is not well represented in current hydrological models, additional investigations are required to better understand these processes that are expected to become more prevalent with climate change.

Climate change is also expected to have profound effects on forest ecology which presents problems for snow interception parameterizations that have coefficients derived from individual sites and applied globally without change. Large portions of the boreal forest have been found to be experiencing significant ecosystem change and has been attributed to browning from drought (Dai, 2013), disease (Ruess et al., 2021), insects (Kurz et al., 2008), and fire (Kasischke et al., 2010; Kasischke & Turetsky, 2006). Following these disturbances greening occurs, which increases forest density in the disturbed regions (Ju & Masek, 2016; Keenan & Riley, 2018; Lantz et al., 2019; Sulla-Menashe et al., 2018). Across the globe, mountain ecosystems have also observed rapid vegetation changes with evidence for an increase in warm-adapted species and reduction in cold-adapted species (Gottfried et al., 2012). These changes in temperature, precipitation and forest ecology are expected to have strong modifications on how intercepted snow is partitioned through sublimation, unloading and drip (He et al., 2021). This introduces uncertainty when parameterizations and coefficients, developed in a 20th century climate are applied to new climates and forest ecosystems that are arising in the 21st century.

These rapid changes of climate and forest ecology illustrate the pressing need to assess whether existing snow interception parameterizations are suitable for the uncalibrated application across diverse forest ecosystems and climates. If the physical processes important for snow interception are adequately represented in existing parameterizations, then more accurate model performance should be expected across diverse environments (Clark et al., 2016; Pomeroy et al., 2013). Therefore, the theory and assumptions of existing parameterizations need to be tested across variable climate and forest structures to ensure their applicability in these environments and whether modification is required. This will ascertain where current processes representations work and what processes are not presently included that should be.

To achieve this, first the theoretical underpinnings and assumptions of existing parameterizations must be tested across forests that have variable canopy cover, wind speed, and air temperatures. Previous work by Gelfan et al. (2004), has shown the (Hedstrom & Pomeroy, 1998; Pomeroy et al., 1998) snow interception parameterization to perform well when coupled with the Storck et al. (2002) wet-snow unloading and drip algorithm in northwestern Russia which frequently transitioned from 0 to -20°C in canopy cover ranging from 0.6 to 0.7. However, aside from the Gelfan et al. (2004) study, the evaluation of snow interception parameterizations has been limited and few studies have investigated their performance in mountain forests. Therefore, in-situ measurements are needed of canopy snow interception and the subsequent ablation of canopy snow in differing mountain climates (warm, transitional and cold) and forest structures (sparse to dense). These measurements will be used to test the theoretical underpinnings of existing parameterizations for application across environments that have differing processes important for forest snow redistribution.

To assess the performance of existing parameterizations, a modular and flexible model platform will be used to simulate the individual mass and energy balance fluxes and states of the canopy and snowpack. The advantage of modular and flexible model platforms is that it is possible to adjust process parameterizations while holding the remaining model parameters and mass and energy conservation equations constant (Clark et al., 2015a; Pomeroy et al., 2007). The Cold Regions Hydrological Model platform (CRHM, Pomeroy et al., 2007) will be used in this study as its snow interception algorithms have been successfully used in previous studies (Ellis et al., 2010; Pomeroy et al., 2012; Rasouli et al., 2019b; Sanmiguel-Vallelado et al., 2022) to assess snow interception processes in Spain, USA, and Canada (Alberta, Idaho, Yukon, and Saskatchewan). Since CRHM is a process-based model agnostic platform, individual state and flux variables including subcanopy snow accumulation, snow interception, sublimation, unloading, drip, and wind redistribution can be evaluated using differing parameterizations. To evaluate existing parameterizations of snow interception (Andreadis et al., 2009; Hedstrom & Pomeroy, 1998; Storck et al., 2002), and ablation of canopy snow by unloading (Andreadis et al., 2009; Ellis et al., 2010; Roesch et al., 2001), drip (Andreadis et al., 2009; Ellis et al., 2010; Storck et al., 2002) and sublimation (Pomeroy et al., 1998) CRHM will be run at four mountain forest research basins across western Canada and compared to in-situ observations. Insights gained from an evaluation of the theoretical underpinnings and assumptions on new and archival field observations will help inform the improvement of existing snow interception process representations. Modifications to the existing parameterizations to better represent snow interception processes will be validated on the associated change in error in simulated and observed forest snow accumulation and streamflow.

## 1.1 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?

## 1.2 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 one of the research questions.

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

Manuscript Status: The contents of this chapter have been compiled from a advanced review article published in the journal *WIREs Water*.

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

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.

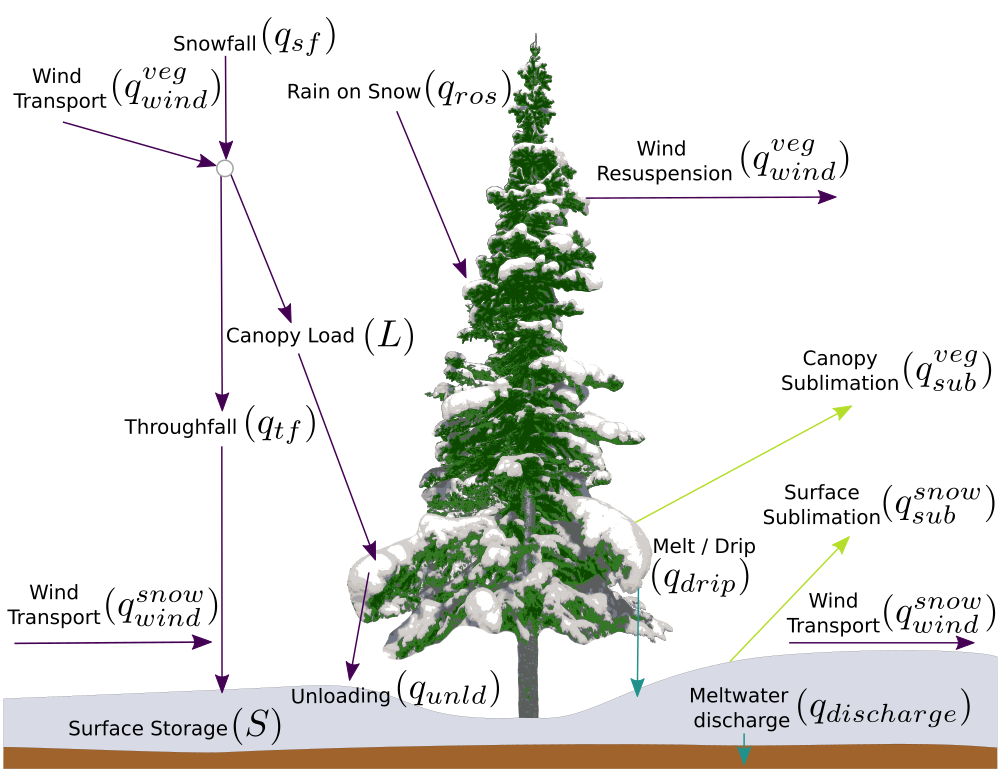
Author Contribution: Alex Cebulski conducted the literature review and initial drafts of the manuscript. Supervisor, committee members, and two anonymous reviewers provided edits.

## 2.1 Abstract

In needleleaf forests, up to half of annual snowfall may be returned to the atmosphere through 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 parameterisations for snow interception and ablation have been developed in locations with distinctive climate, tree species and forest structures, resulting in inconsistent and non-comprehensive process representations. This variability limits the transferability of these parameterisations across diverse landscapes and climates. Moreover, difficulties in isolating individual processes in field-based measurements has led to parameterisations that inadvertently coupled multiple processes, adding to uncertainty. Many studies have also simplified original parameterisations and do not include recent advances from observational studies. This review article aims to elucidate the theoretical foundations and assumptions underlying the current snow interception and ablation parameterisations to provide a better understanding of uncertainties in existing methods and identify priorities for future fieldbased observational studies. The methods behind snow interception and ablation studies are also reviewed to provide necessary context for examining current parameterisations. Specific gaps in the literature include determining the canopy snow storage capacity, challenges in distinguishing 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 parameterisations, and the limited testing of parameterisations in varied forests and climates.

**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.



## 2.2 Introduction

The melt of seasonal snowpacks is an important source of streamflow around the world, crucial for downstream ecosystems, energy production, drinking water supply and agricultural irrigation that directly support over 2 billion people (Viviroli et al., 2007, 2020). Despite this importance, there is uncertainty in estimates of snow accumulation due to redistribution of snow by wind and forest canopy (Ellis et al., 2010; Krinner et al., 2018; Rutter et al., 2009). In the Northern Hemisphere, over 50% of snowmelt-dominated basins are covered by needleleaf forest (Kim et al., 2017). This extensive canopy coverage reduces the amount of snow that is available for streamflow through interception of snowfall and subsequent canopy snow sublimation (Ellis et al., 2010; Essery et al., 2003; Hedstrom & Pomeroy, 1998). Intercepted snow in the canopy is subjected to higher rates of sublimation and melt compared to subcanopy snow due to greater surface area, warmer temperatures, turbulent energy exchange and solar exposure (Lundberg & Halldin, 1994; **Pomeroy1998?**). Across the Northern Hemisphere, researchers have estimated that 25–45% of annual snowfall may be lost to the sublimation of intercepted snow from the canopy (Essery et al., 2003). However, the magnitude of sublimation losses depends on the amount of snowfall that is intercepted in the canopy and the competing ablation processes including unloading, melt, drip, and resuspension of snow that control the duration that snow resides in the canopy. These processes contribute to spatial and temporal variability in the accumulation of snowpacks both between and within forested and non-forested landscapes (Krinner et al., 2018; Rutter et al., 2009). This snowpack variability is not well represented due to a sparse and unrepresentative network of in-situ observations, which are mostly located in forest clearings (e.g., Canada, (Vionnet et al., 2021)). Moreover, while high spatial resolution snow depth measurements from aerial lidar are useful for canopy-snow process investigations at the plot scale (e.g., Staines & Pomeroy, 2023), observing snow accumulation under forest canopies at large extents remains uncertain with current remote sensing technologies (Rittger et al., 2020; Stillinger et al., 2023). Therefore, there is a need for robust models of snow redistribution by vegetation to estimate snow accumulation in forests and generate predictions of how water resources will change with future climates (Pomeroy et al., 2007; Rutter et al., 2009; **Clark2015a?**). Such models require a comprehensive understanding of snow redistribution processes.

Existing theories of snow interception and ablation have primarily been developed for dense forest canopies in either warm maritime (Andreadis et al., 2009; Katsushima et al., 2023; Storck et al., 2002) or cold continental (Ellis et al., 2010; Hedstrom & Pomeroy, 1998; Roesch et al., 2001) climates. These isolated observations have resulted in distinctive theories of the key snow interception and ablation processes. Whilst parameterisations founded on these theories can yield accurate simulations of the timing and magnitude of forest snow accumulation when applied in similar climates to where they were developed (Lundquist et al., 2021; Rasouli et al., 2019a; Roth & Nolin, 2019) or when combined into a hybrid parameterisation and assessed at global and regional scales in a wide range of climates (Essery et al., 2003; Gelfan et al., 2004), large discrepancies in simulated subcanopy snow accumulation have been demonstrated in inter-model comparisons by (Krinner et al., 2018) and (Rutter et al., 2009). Some of the uncertainty in subcanopy snowpack simulations observed by (Krinner et al., 2018) and (Rutter et al., 2009) was attributed to differing snow interception and ablation process representation, in addition to model platform differences (**Clark2010?**). One example of differing process behaviour is the increase in canopy snow storage capacity with warmer temperatures shown by (Storck et al., 2002) and an opposing relationship suggested by (Hedstrom & Pomeroy, 1998). The difficulty in isolating individual processes such as throughfall, unloading, and drip in field measurements may have also contributed to unintentional coupling of processes in existing parameterisations. Issues arise when combining coupled parameterisations, such as snow interception parameterisations that also include ablation, with additional ablation parameterisations. Unless models have been calibrated to account for this (e.g., Hedstrom & Pomeroy, 1998), this combination can potentially result in some double-counting of the ablation process.

This review builds on recent work by Friesen et al. (2015), Van Stan et al. (2020), and Lundquist et al. (2021), who examined data collection methods and theories of snow interception and canopy snow ablation. While Friesen et al. (2015) and Van Stan et al. (2020) provide broad overviews of the methodologies for measuring and modelling liquid water and snow intercepted in the canopy, they lack the detail necessary to interpret snow interception studies. Lundquist et al. (2021) trace the development of two widely-used snow interception models, Hedstrom & Pomeroy (1998) and the combined Storck et al. (2002) and Andreadis et al. (2009), and provide a model experiment that showed the maximum canopy snow load capacity may be unnecessary for modelling snow interception if a comprehensive canopy snow ablation routine is included. However, these reviews do not provide a complete description of the canopy snow mass and energy balance, include recent updates to parameterisations, or discuss the parameterisations required to represent canopy snow ablation. Additionally, they do not connect measurement uncertainties with inconsistencies in process understanding. This review addresses these gaps by first detailing the theoretical mass and energy balance of canopy snow, along with the methods used to measure these processes. Additionally, a comprehensive synthesis of the literature on snow interception and canopy snow ablation process representations is provided, incorporating recent advancements in the field. The review then connects uncertainties in measurement techniques, such as challenges in partitioning throughfall rates from canopy snow ablation and distinguishing unloading from canopy snowmelt drainage, to issues within current parameterisations of snow interception and ablation. The article will also explore processes often overlooked in existing parameterisations, including non-vertical hydrometeor trajectories, wind redistribution of snow in forests, and rime accretion. Lastly, it examines how 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.

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

The accumulation of snow under vegetation can be described using coupled mass and energy balance equations applied to control volumes representing the canopy and the snowpack. These control volumes are shown in Figures 1 and 2, where the canopy control volume includes snow, liquid water (stored within canopy snow), ice, and vegetation components, while the snowpack control volume represents snow accumulated on the surface. The mass and energy terms are represented as follows: the symbol in lowercase signifies mass flux, while the uppercase signifies energy flux. The state of snow water equivalent (SWE, kg m-2) is denoted by for snow intercepted in the canopy and S for the subcanopy snowpack. Fluxes that are repeated between the canopy and snowpack control volume have a superscript to specify what control volume they refer to (i.e., refers to the vegetation control volume and q^snow refers to the surface snowpack control volume).

### 2.3.1 Mass Balance

The change in canopy snow load over time, (kg m-2), may be represented as:

where (kg m-2 s-1) is the above canopy snowfall rate, (kg m-2 s-1) is the rate of rainfall falling on snow intercepted in the canopy (does not include rainfall falling directly on canopy elements), (kg m-2 s-1) is the throughfall rate, which is snowfall that passes through gaps in the canopy, (kg m-2 s-1) is the canopy snow unloading rate, (kg m-2 s-1) is the canopy snow drip rate due to canopy snowmelt and/or transmission of rainfall through snow intercepted in the canopy, (kg m-2 s-1) is the wind transport rate of snow by suspension in our out of the control volume, and (kg m-2 s-1) is the intercepted snow sublimation rate. In the treatment of rainfall interception, and are typically incorporated within the throughfall rate (i.e, Dingman, 2015; Van Stan et al., 2020). The rates in [Equation 8](#eq-canopy-mass-bal), except for , are a function of the snow load present in the canopy . Methods to estimate , , and are described in detail in [Section 2.5](#sec-parameterisations).

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| Figure 1: The mass balance of intercepted snow in a needleleaf forest canopy and the subcanopy snowpack. The colours of the arrows correspond to the water phase: solid (purple), liquid (blue) and vapour (light green). The head of the arrow indicates a positive flux either into the canopy (positive) or away from the canopy (negative). Fluxes may transition between positive and negative. In the case of sublimation from the canopy or snowpack, the flux may be positive (sublimation) or negative (deposition). This figure was adapted from Pomeroy and Gray (1995). |

The rate of snow in the canopy undergoing phase change, (kg m-2 s-1), may be calculated as:

where (J kg-1) is the latent heat of fusion, is the fraction of ice in a unit mass of wet snow (usually taken as 0.95-0.97, Gray & Landine (1988)).

The liquid meltwater output from snow intercepted in the canopy, (kg m-2 s-1) may be assumed to be approximately equal to once the snow has reached its water holding capacity. (W m-2) is the rate of energy available to melt canopy snow which is a function of . The processes influencing are shown in [Equation 4](#eq-canopy-energy-flux-mp15).

The rate of sublimation from snow intercepted in the canopy, (kg m-2 s-1) is determined by the latent heat flux, (W m-2). Thus, the sublimation rate of snow intercepted in the canopy may be calculated as (Stull, 2017, eq. 4.45):

where (J kg-1), is the latent heat required for sublimation.

### 2.3.2 Energy Balance

The processes providing energy available for, , or the rate of change of the bulk temperature of all constituents of vegetation, liquid water and snow, (K s-1) are shown in [Figure 2](#fig-canopy-energy-balance). The notation in [Figure 2](#fig-canopy-energy-balance) and in [Equation 4](#eq-canopy-energy-flux-mp15) uses superscripts to specify which control volume the flux refers to: the vegetation control volume (veg), the snow-atmosphere interface (sai), and the top of the canopy between the upper atmosphere and canopy air space (total). [Figure 2](#fig-canopy-energy-balance) shows the canopy air space which is a control volume used by some models (e.g., Clark et al. (2015a)) to differentiate the atmospheric conditions within and above the forest canopy.

The energy balance of the canopy is typically solved using a bulk approach in hydrological models which treats the canopy as a mixture of air, water, snow, ice, stems, and leaves ((**Clark2015a?**); Ellis et al. (2010); Parviainen & Pomeroy (2000)):

where (J m-3 K-1) is the volumetric bulk storage capacity for heat of all constituents of vegetation, liquid water and snow, (m) is the depth of the vegetation canopy, and (W m-2) are the net shortwave and longwave radiation heat fluxes to the canopy, (W m-2) is the advective energy rate, which may include energy added to the canopy by , and and (W m-2) are the turbulent fluxes of latent heat and sensible heat, respectively, from the vegetation elements to the canopy air space. A negative value corresponds to a transfer of energy away from the vegetation elements.

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| Figure 2: Conceptual representation of the physical processes important in the energy balance of the forest canopy and surface snowpack. Where and (W m-2) are shortwave and longwave fluxes, and (W m-2) are the turbulent fluxes of latent heat and sensible heat, (W m-2) is the advective energy rate, and (W m-2) is the ground heat flux. A superscript specifies which control volume the flux refers to: the vegetation control volume (veg), the snow-atmosphere interface (sai), and the top of the canopy between the upper atmosphere and canopy air space (total). The dashed lines represent radiation extinguished, reflected or re-emitted by the canopy, intercepted snow or surface snowpack. This figure was adapted from Clark et al. (2015a). |

With [Equation 4](#eq-canopy-energy-flux-mp15), for a cold canopy snowpack ( < 0°C), all energy goes into warming the control volume (increasing ) and no melt of canopy snow occurs (warming phase, = 0). Once reaches 0°C, increases as more energy becomes available for melt and equals zero (ripening and output phase) assuming the temperature of canopy snow is equal to that of the canopy when <= 0°C.

## 2.4 Measurement Techniques

### 2.4.1 Weighed Tree

Weighed tree lysimetry is one of the few direct methods to quantify the amount of snow intercepted in and ablated from the canopy. A cut tree is either weighed from a load cell on the ground (Lundberg & Halldin, 1994; Storck et al., 2002; Watanabe & Ozeki, 1964; e.g., **Schmidt1988?**) or an inline strain gauge suspended from the crown of the tree as shown in Figure 3 (Hedstrom & Pomeroy, 1998; e.g., Pomeroy et al., 1993). To scale the weight of snow in the canopy (kg) to per unit area (kg m-2), there are two methods described in the literature. Katsushima et al. (2023), Satterlund & Haupt (1967), and Watanabe & Ozeki (1964) estimated the projected crown area (m2) of the weighed tree to convert weighed tree measurements in weight (kg) to snow load per unit area (kg m-2). Pomeroy et al. (1993) and Hedstrom & Pomeroy (1998), calculated areal estimates of , using the mass balance method described in **?@sec-mass-bal-methods** along with fresh snow survey measurements of throughfall and point measurements of , to relate the weight change measured by the weighed tree to a per-unit-area measurement of . Although the weighed tree method offers a direct measurement of , it is limited to a point scale and can be impracticable for very tall trees due to challenges in constructing a tree mounting system. During periods of snowfall, measured by the weighed tree is attributed to intercepted snowfall and ablation ([Equation 8](#eq-canopy-mass-bal)). In the absence of and hence and , the change in canopy snow load can be attributed to the remaining processes in [Equation 8](#eq-canopy-mass-bal).

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| |  | | --- | | (a) | |  |

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| --- | --- |
| |  | | --- | | (b) | |

Figure 3: Weighed tree lysimeters, (a) Subalpine fir tree lysimeter loaded with snow, Fortress Mountain Research Basin, Alberta, Canada and (b) Black spruce tree lysimeter relatively free of snow, Havikpak Creek Research Basin, Inuvik, Northwest Territories, Canada.

### 2.4.2 Mass Balance Methods

Since is difficult to measure over spatial and temporal time scales, throughfall measurements can be used to infer canopy snow load as a residual based on [Equation 8](#eq-canopy-mass-bal). If the assumption is made during snowfall periods with calm winds and cool air temperatures that ablative processes are negligible, [Equation 8](#eq-canopy-mass-bal) can be simplified to:

Over a discrete time interval, , the change in canopy snow load, (kg m-2) may be calculated as:

where and are the average snowfall and throughfall rate over . and is the accumulated above canopy snowfall (kg m-2) and throughfall respectively.

Throughfall measurements of snow differ from rainfall measurements of throughfall which typically include (Van Stan et al., 2020). However, even for snowfall events with cold temperatures and calm winds, ablative processes are likely non-zero and thus true measurements of throughfall are difficult to ascertain.

#### 2.4.2.1 Snow Surveys

Snow surveys conducted below the canopy are one method to provide areal estimates of . Combined with measurements of , [Equation 6](#eq-dwdt-discrete) can be used to estimate . Throughfall depths may be converted to SWE using observed relationships between snow depth and snow density (e.g., Staines & Pomeroy, 2023) or modelled using empirical equations (e.g., Lv & Pomeroy, 2020). If the covariance between snow depth and density is found to be insignificant, Pomeroy & Gray (1995) recommend calculating SWE as:

where is the average snow density over the snow survey and is the depth of throughfall (m). may be determined using the difference in post-event and pre-event snow depth using rulers (e.g., Hedstrom & Pomeroy, 1998), or using aerial lidar derived surface models (e.g, Staines & Pomeroy, 2023). Uncertainties with these two methods include penetration of the ruler into the soil which falsely increases the snow depth, and errors associated with lidar methods of 5—20 cm (RMSE) described in Harder et al. (2020) and Staines & Pomeroy (2023). If a defined layer (i.e., natural ice crust or measurement plate) is present prior to a snowfall event, depths of snow above this layer may be taken as as in Moeser et al. (2015b). Automated acoustic snow depth sensors have also been used to measure as the difference in the change in snow depth to an open area and subcanopy (Lv & Pomeroy, 2020; Roth & Nolin, 2019). Regardless of the method chosen, care must be taken to ensure ablation of snow in the canopy and on the ground is minimal over the snowfall period to ensure [Equation 6](#eq-dwdt-discrete) is valid.

may be measured using gravimetric fresh snow density sampling. With this method a pit is dug to below the bottom of the new throughfall layer and a snow density sampler of a known volume is pushed horizontally into the new snow layer (e.g., [Figure 4](#fig-fsd)) and the resulting sample is weighed. Additional methods are available for the calculation of snow density including snow tubes, microwave radar, gamma ray, snow pillow, and snow scale. However, these methods have constraints in providing a density of a new snow layer and are more commonly applied to measure density of the entire snowpack to the ground.

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| Figure 4: Gravimetric fresh snow density sample collection, Fortress Mountain Research Basin, Alberta, Canada. A 1000 cm3 snow density wedge sampler (RIP Cutter, https://snowmetrics.com/shop/rip-1-cutter-1000-cc/) is shown being pushed into the surface of the snowpack. The scale used to measure the weight of the sample is shown on the bottom right. |

#### 2.4.2.2 Subcanopy Lysimeters

Subcanopy lysimeters may provide measurements of and/or the downward ablation of snow in the canopy, and . When paired with an automated data logger, measurements can be taken over relatively shorter discrete time intervals compared to manual snow surveys. With this method, a trough or bucket is suspended from a load cell (e.g., [Figure 5](#fig-scl-2)) or installed on the ground (e.g., Storck et al., 2002) and measures the accumulated weight (kg) of snow entering the lysimeter. The surface area of the opening of the trough is used to convert the weight to a per unit area measurement in (kg m-2). For periods where, and can be considered negligible, the subcanopy lysimeters provide measurements of and using [Equation 6](#eq-dwdt-discrete) along with can be used to estimate . For periods without snowfall, the subcanopy lysimeters provide measurement of .

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| Figure 5: An example of a suspended subcanopy lysimeter installed at Fortress Mountain Research Basin, Alberta, Canada to measure rates of throughfall, unloading, and drip. |

Measurements of are difficult to ascertain due to its simultaneous occurrence with especially in warm temperatures. To isolate, , researchers(e.g., Floyd, 2012; Storck et al., 2002) have utilized tipping bucket rainfall gauges positioned beneath the canopy to quantify the drainage rate of liquid water from snow intercepted in the canopy. However, employing tipping buckets in temperatures close to 0°C presents difficulties as the mechanical apparatus can freeze, resulting in missed measurements. The simultaneous occurrence of during the melt process may provide an additional source of liquid water as ripe clumps of snow continue to melt into the tipping bucket device. The difficulty in isolating the multiple processes, as outlined in [Equation 8](#eq-canopy-mass-bal) and [Figure 1](#fig-mass-bal), that contribute snow beneath the canopy is the main limitation of using subcanopy lysimeters to measure snow interception and canopy snow ablation. Therefore, use of this methodology should be paired with other observations such as meteorological measurements, timelapse imagery or a weighed tree to help determine if unloading and drip are likely.

### 2.4.3 Remote Sensing

Remote sensing methodologies have proven effective in acquiring measurements of throughfall, canopy snow load, and ablation over larger spatial extents and more frequent temporal scales compared to the measurements discussed above (Bartlett & Verseghy, 2015; Calder, 1990; Floyd & Weiler, 2008; Russell et al., 2020). For example, Calder (1990) used a gamma ray attenuation system to continuously measure canopy snow load within a forest plot. However, the gamma ray technique has not been repeated in canopy-scale snow interception studies due to the danger of emissions from the radioactive source. Aside from the study conducted by Calder (1990), remote sensing methods generally do not directly measure canopy snow load in units of kg m-3. Instead, they provide a volumetric measurement of canopy load, a measurement of throughfall, an index based on above canopy albedo, or an areal fraction of canopy covered by snow.

One volumetric approach, as demonstrated by Russell et al. (2020), utilized autonomous terrestrial laser scanning (ATLS) to measure the volume of snow intercepted in the canopy. This method involves collecting ATLS point clouds for an individual tree during snow-free and snow-on conditions. The 3D approximations created from these point clouds are used to calculate the canopy volume for both conditions, while also accounting for branch bending and lidar beam occlusion. By subtracting the snow-on volume from the snow-free volume, an estimate of the snow intercepted in the canopy is obtained. Limitations with the ATLS method include challenges such as changes in tree geometry under snow loading and lidar beam occlusion which were only partially addressed by the Russell et al. (2020) method, and the difficulty of estimating the density of intercepted snow in the canopy. These challenges contributed to the weak correlation observed by Russell et al. (2020) when comparing results with measurements of canopy snow load obtained through weighed tree assessments. Indirect measurements of canopy snow load using aerial lidar throughfall measurements are discussed in [Section 2.4.2.1](#sec-snow-surveys).

The studies conducted by Roesch et al. (2001) and Bartlett & Verseghy (2015) utilized measurements of above canopy albedo, which is hypothesised to increase as snow is intercepted in the canopy and reduce light transmittance through the canopy. However, given the potential for fresh snowfall to cover the upward-facing radiometer and lead to erroneous albedo measurements, cleaning radiometers following snowfall events is crucial. A study using radiometer measurements that were cleaned after each snowfall event, by Nakai et al. (1999) highlights that very large canopy snow loads show an increase in above canopy albedo. For small snow loads (< 1.6 kg m-2) Pomeroy & Dion (1996) show that no relationship was found between canopy snow load and above canopy albedo over a mature pine canopy using a frequently cleaned radiometer. More recent work by Lv & Pomeroy (2019) shows that the normalised snow difference index calculated using Landsat satellite imagery dramatically increased with canopy snow load. Lv & Pomeroy (2019) also show a small, but detectable increase in albedo was found when the canopy was covered with snow. This method has limitations for smaller snowfall events in some tree species and canopy structures Pomeroy & Dion (1996) or when radiometer measurements are erroneous.

Time-lapse photography has been an important component of understanding canopy snow processes at the plot or individual tree scale since early work by Berndt & Fowler (1969) to quantify rime accretion on needleleaf canopy. Pomeroy et al. (1993) developed perimeter-area relationships to quantify the sublimation rate of intercepted snow, using photographs and fractal geometry, but found no unique relationship between oblique snow-covered canopy fraction, measured using digital images and Java image analysis software, and the mass of snow weighed on a suspended tree. A method to determine the snow-covered fraction of the canopy was developed by Floyd & Weiler (2008) using automated image analysis who noted limitations of this method due to condensation/frost build up on the camera lens and lighting conditions. Similar methodologies have also been utilized by several other studies to understand canopy-snow processes (Dong & Menzel, 2017; Garvelmann et al., 2013; Parajka et al., 2012). Recent work by Lumbrazo et al. (2022) involved citizen scientists to classify time-lapse images of snow in the canopy into an index of canopy snow-covered fraction to diagnose canopy snow ablation process models. Additionally, Harvey et al. (2025) show that a deep learning convolutional neural network model provided estimates of canopy snow presence from time-lapse imagery that had very close agreement to images analyzed by humans and also much better accuracy than the automated thresholding methods used by previous studies.

### 2.4.4 Tree Sway Frequency

The sway frequency of trees has been shown to decrease proportionally with increasing mass stored in the canopy (Papesch, 1984; Raleigh et al., 2022). A study by Raleigh et al. (2022) utilized a three-dimensional accelerator attached to the upper section of a tree to quantify wind induced movements and provide an index of canopy snow load. Raleigh et al. (2022) showed that the influence of thermal effects on tree rigidity must be considered when analyzing sway frequency in cold climates. Raleigh et al. (2022) notes additional challenges with this method including difficulties in isolating a separate relationship for tree sway frequency and thermal effects and relating changes in sway frequency to changes in snow load. Schmidt & Pomeroy (1990) show that the modulus of elasticity of tree branches varies with temperature below 0°C, indicating this technique is strongly impacted by freezing and thawing of trunks. Measurements of canopy snow load are also limited to periods of heightened wind where canopy snow is also likely to ablate.

### 2.4.5 Trunk Compression

Measurement of trunk compression, initially utilized for monitoring the mass of intercepted rain in the canopy (Friesen et al., 2008), has been adapted for measurement of canopy snow load by Martin et al. (2013). This method is based on Hooke’s law of elasticity to infer a change in mass through the trunk’s compression and expansion. However, uncertainties with this method include the need for individual tree-specific calibration for determining the modulus of elasticity. Additionally, factors such as transpiration, sap flow, wind, and temperature contribute to noise in the instrumentation, primarily through thermal expansion and wind induced compression of the trunk. The expansion and compression of trees with freezing and thawing discussed by Gutmann et al. (2017) suggests further research is required to apply this method to freezing trunks. Sensors with extremely high precision (± 1—2 µm) are also required for this method leading to high cost.

### 2.4.6 Eddy Covariance

The rate of canopy snow sublimation, (kg m-2 s-1), can be measured using the eddy covariance technique (Lundberg & Halldin, 2001; Molotch et al., 2007; Parviainen & Pomeroy, 2000; e.g., **Harding1994?**). With this method, an eddy covariance system measures the latent heat flux above the canopy resulting from evapotranspiration, evaporation, and sublimation of snow on the surface and in the canopy. During cool periods where evapotranspiration and evaporation rates are assumed negligible, the latent heat flux can be attributed to + and can be converted to + using [Equation 3](#eq-lsub). A second eddy covariance system installed beneath the canopy above the surface snowpack to measure , which can be used to isolate in the above canopy latent heat measurements (Molotch et al., 2007). Alternatively, the subcanopy snowpack sublimation rate may be assumed negligible, and a single eddy covariance system is used (Lundberg & Halldin, 2001; Parviainen & Pomeroy, 2000). Uncertainties in this measurement technique stem from assumptions such as negligible transpiration rates from surrounding vegetation, the requirements of a homogeneous surface, and slow variations in airflow properties. Many studies show a failure to close the above canopy energy balance when the canopy is snow-covered (e.g., **Harding1994?**). Harvey et al. (2025) also demonstrated that this method incorrectly identified for several days when the canopy was observed to be without snow in time-lapse images. They attributed this to differing flux footprints of the above and below-canopy eddy covariance measurements and/or sublimation of wind-suspended snow.

### 2.4.7 Snow Isotopes

Investigating the isotopic composition of water and snow has proven valuable for understanding hydrological (e.g., Galewsky et al., 2016) and snow (Beria et al., 2018) processes. During phase changes, snow undergoes isotopic fractionation, altering the relative abundance of heavier and lighter isotopes of hydrogen and oxygen among the different phases. While sublimation of snow intercepted in the canopy is known to enrich heavier isotopes in the remaining snow (Beria et al., 2018), relatively few studies have utilized snow isotopes to explore canopy snow processes (Claassen & Downey, 1995; Koeniger et al., 2008). Interpreting isotopic fractionation in canopy snow is challenging, as fractionation from cold, sublimating snow can be minimal (Schlaepfer et al., 2014), whilst wet snow undergoing sublimation, deposition, and melt shows varying degrees of fractionation (Beria et al., 2018). Additionally, some clumps of snow may completely sublimate while others partially sublimate or melt, complicating the link between isotope enrichment and a specific process. Chemical changes in intercepted snow have been shown by Pomeroy et al. (1999) to present similar complications on linking chemical changes to individual processes, limiting its usefulness for quantifying canopy snow mass exchange processes. Subsequent fractionation also can occur in the subcanopy snowpack as meltwater percolates and refreezes or the surface snow sublimates (Beria et al., 2018), which further complicates isolating specific processes.

## 2.5 Parameterisations

### 2.5.1 Snow Interception Parameterizations

Snow interception parameterisations differ in their approximation of the maximum canopy snow storage capacity ([Figure 6](#fig-example-wmax-ip) a) and the fraction of snowfall intercepted ([Figure 6](#fig-example-wmax-ip) b), due to differences in the relationships and variables included in each parameterisation ([Table 1](#tbl-mod-desc)). This leads to large discrepancies in the predicted canopy snow load shown in Figure 7 and thus the amount of snow available for sublimation losses. The factors contributing to these model discrepancies can be grouped into intrinsic factors of the vegetative structure (e.g., canopy coverage, leaf area and surface temperature) and extrinsic factors (e.g., snowfall event meteorology, methodologies). Parameterisations for snowfall interception have all been derived for evergreen needleleaf forests and thus constrain the scope of this section (Hedstrom & Pomeroy, 1998; Satterlund & Haupt, 1967; Storck et al., 2002).

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| Figure 6: Panel (a) Comparison of the (**Hedstrom1998a?**) (HP98) and Andreadis et al. (2009) (SA09) canopy snow storage capacity parameterizations. Panel (b) shows interception efficiency for event totals as the change in event canopy snow load divided by the corresponding change in event snowfall in the open for parameterizations: HP98, Katsushima et al., (2023) (KA23), SA09, and Moeser et al., (2009) (M15). Initial canopy load is held at 0, air temperature is -5°C, LAI of 3.5 and the HP98 species coefficient for spruce (5.9 kg m-2). |

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| Figure 7: The state of canopy snow load (solid lines) for a cold and warm event using the parameterizations by Hedstrom and Pomeroy (1998) (HP98), Katsushima et al., (2023), combined Storck et al. (2002) and Andreadis et al., (2009) (SA09). The interception storage capacity is shown for the HP98 (purple) and SA09 (orange) parameterizations using a horizontal dashed line. The KA23 parameterization does not include a canopy snow storage capacity. To isolate the influence of snow interception parameterizations ablative processes have not been computed. Constants for these two plots include a wind speed of 1 m s-1, LAI of 3.5 (-) and the HP98 species coefficient for spruce (5.9 kg m-2). |

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| Table 1: Summary table describing the main differences between snow interception parameterisations.   | Model | Variables | General Description | Measurement Technique | | --- | --- | --- | --- | | Satterlund & Haupt (1967) | , , | initially rises due to rising which bridges gaps and increases . later declines when approaches due to branch bending which reduces and increases unloading. | Weighed tree lysimeter | | Hedstrom & Pomeroy (1998) | , , , , | starts high and then declines as approaches which reduces and increases unloading. This decline is stronger for warmer as branches bend more easily. | Snow survey mass balance | | Storck et al. (2002) | , , , | is constant over time and space. increases with and increases as a step function of due to higher cohesion and adhesion. When , new snow is unloaded to the surface snowpack. | Weighed tree lysimeter with subcanopy lysimeter | | Roth & Nolin (2019) | , , | increases with increasing and a lidar-derived canopy structure metric . | Paired open and forested acoustic snow depth sensors and aerial lidar canopy metrics | | Katsushima et al. (2023) | , , , | decreases with increasing when , increases with when is moderate, and decreases with and when . | Weighed tree lysimeter | |

#### 2.5.1.1 (**Hedstrom1998a?**)

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

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

#### 2.5.1.4 Event Based Snow Interception Parameterizations

### 2.5.2 Canopy Snow Ablation Parameterizations

#### 2.5.2.1 Sublimation

#### 2.5.2.2 Unloading and Drip

##### 2.5.2.2.1 (**Hedstrom1998a?**)

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

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

##### 2.5.2.2.4 Bartlett & Verseghy (2015)

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

## 2.6 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

## 2.7 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.

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

Manuscript status: The contents of this chapter have been compiled from a research article published in the journal *Hydrological Processes*.

Citation: **Cebulski, A. C.**, & Pomeroy, J. W. (2025). Snow Interception Relationships With Meteorology and Canopy Density. Hydrological Processes, 39(4), e70135. https://doi.org/10.1002/hyp.70135

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.

## 3.1 Abstract

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

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

# 4. Introduction

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

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

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

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

# 5. Theory

## 5.1 Canopy snow mass balance

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

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

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

During periods with low air temperatures and low wind speeds, , , , , and can be assumed negligible and thus the right side of [Equation 8](#eq-canopy-mass-bal) can be simplified and used as an approximation of to calculate as:

## 5.2 Hydrometeor trajectory angle

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

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

## 5.3 Within-canopy wind flow

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

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

# 6. Data and methods

## 6.1 Study site

This study was conducted at Fortress Mountain Research Basin (FMRB), Alberta, Canada, -115° W, 51° N, a continental headwater basin in the Canadian Rockies ([Figure 8](#fig-site-map)). Data from this study was collected between October 2021 and July 2023 within and surrounding two forest plots adjacent to the FMRB Powerline Station (PWL) and Forest Tower Station (FT) at ~2100 m above sea level as shown in [Figure 8](#fig-site-map). The average annual precipitation at PWL Station from 2013 to 2023 was 1045 mm, with the average peak annual snow water equivalent (SWE) reaching 465 mm, typically in late April. The PWL plot is adjacent to PWL station and the FT plot surrounds FT station and both include discontinuous stands of 70% subalpine fir (Abies lasiocarpa) and 30% Engelmann spruce (Picea engelmannii) (Langs et al., 2020). The canopy closures are 0.51 and 0.29 and the winter leaf area indices are 2.07 and 1.66 for PWL and FT respectively. The average height of the canopy within the PWL plot is 10.5 m and within the FT plot is 7.1 m. In August of 1936, most vegetation in FMRB burned during a large forest fire that affected most of the Kananaskis Valley (Fryer et al., 1988). Following the fire, the forest within the PWL and FT forest plots has naturally regenerated, though some trees have been removed for a powerline clearing and creation of a snow study plot.

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| Figure 8: Map showing the location of forest plots, flux towers, subcanopy lysimeter instruments, and survey transects. The inset map on the lower right shows the regional location of Fortress Mountain Research basin. |

## 6.2 Meteorological measurements

Measurements of air temperature and relative humidity (Vaisala model HMP155A), wind speed and direction (RM Young model 86000 2-D ultrasonic anemometer) were made 4.3 m above the ground at FT station ([Figure 8](#fig-site-map)). Wind speed measurements from a 3-cup anemometer (Met One model 014A), installed adjacent to the 2-D ultrasonic anemometer at 4.3 m, were used to fill data gaps in the 2-D ultrasonic anemometer records.

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

## 6.3 Lysimeter measurements

Three subcanopy lysimeters were installed surrounding the FT Station ([Figure 8](#fig-site-map)) to provide measurements of throughfall for 26 distinct snowfall events, where canopy snow ablation rates were deemed negligible. The subcanopy lysimeter instrument design was adapted from MacDonald (2010) and consisted of a plastic horse-watering trough with an opening of 0.9 m2 and depth of 20 cm suspended from a load cell (Intertechnology 9363-D3-75-20T1) attached to an aluminum pipe connected between two trees ([Figure 9](#fig-scl-imgs)). The manufacturer-specified combined error of full-scale output for the load cells is +/- 0.02% with a temperature sensitivity of +/- 0.001%/5°C. The throughfall rate was calculated by dividing the weight of snow in the subcanopy lysimeter by the cross-sectional area of the opening and determining the rate of change at hourly intervals. Canopy snow load was estimated using [Equation 8](#eq-canopy-mass-bal), incorporating cumulative throughfall measurements from the subcanopy lysimeters and cumulative snowfall measurements from the PWL gauge for each of the 26 events. Interception efficiency was calculated using [Equation 10](#eq-ip2) and accumulated measurements of snowfall and throughfall at both hourly intervals and within bins of air temperature, wind speed, and initial canopy snow load measured from the weighed tree. The hourly interval measurements resulted in lower accumulations of snowfall and throughfall within each interval and thus had higher relative error compared to the binned measurements. To evaluate the association of hourly interception efficiency with air temperature, wind speed, and initial canopy snow load, linear models were fitted using ordinary least squares regression. The non-parametric Wilcoxon signed-rank test was also applied to compare the distribution of hourly interception efficiency measurements across differing groups of air temperature, wind speed, and initial canopy snow load. Timelapse imagery, mass change on a weighed tree lysimeter (Pomeroy & Schmidt, 1993), and in-situ observations were used to ensure unloading, melt, and wind redistribution of canopy snow was minimal over each interval. Additionally, the throughfall measurements were filtered to include observations that coincided with a snowfall rate > 0 mm hr-1 and a snowfall rate that exceeded the subcanopy lysimeter measured throughfall rate. While these careful manual mitigation and automated filtering strategies substantially reduced the contribution of unloading in the subcanopy lysimeter throughfall measurements, a small contribution is still possible.

The subcanopy lysimeters were installed to limit preferential throughfall and unloading by choosing locations with relatively uniform distribution of canopy elements and away from large branches which could preferentially unload snow. The canopy surrounding the subcanopy lysimeters led to reduced wind speeds and reduced the potential for gauge undercatch by these instruments. Photographs of the three subcanopy lysimeters and surrounding canopy are shown in [Figure 9](#fig-scl-imgs). Canopy density measurements, including leaf area index and canopy closure, are summarized in [Table 2](#tbl-scl-lai-cc). A viewing angle from zenith to 60° was selected to describe the surrounding canopy, as a range in hydrometeor trajectory angles was expected to influence the measurements at these locations. The canopy density metrics were measured using hemispherical photography (Nikon Coolpix 4500 and EC-F8 hemispherical lens) for a snow free canopy and analyzed with the hemispheR R package Chianucci & Macek (2023).

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

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| Table 2: Leaf area index (LAI) and canopy closure of the three subcanopy lysimeters located proximal to the FT Station.   | Name | LAI (-) | Canopy Closure (-) | | --- | --- | --- | | Sparse | 1.56 | 0.64 | | Mixed | 2.10 | 0.75 | | Closed | 2.40 | 0.79 | |

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| Figure 9: Images of the three subcanopy lysimeter instruments and surrounding canopy located in sparse (a), mixed (b), and dense (c) canopy. The top row presents a side view of each instrument and the bottom row shows hemispherical photographs. These hemispherical images are oriented with north at the top and have been mirrored to provide a view from above (e.g., east is on the right side of each image). See [Table 2](#tbl-scl-lai-cc) for the corresponding canopy density measurement. |

## 6.4 UAV-Lidar data collection and processing

The UAV (FreeFly Alta X) payload included a REIGL miniVUX-2 airborne laser scanner, an Applanix APX-20 inertial measurement unit (IMU) and global navigation satellite system (GNSS). The UAV was flown 90 m above the ground at a speed of 3 m s-1 following the path shown in [Figure 8](#fig-site-map). The methods outlined by Harder et al. (2020) and Staines & Pomeroy (2023) were incorporated to reconcile survey lidar, IMU, and GNSS data. A systematic vertical bias of up to 6 cm between UAV-lidar flight lines was observed in the resulting point clouds on March 13th and 14th, 2024 and was attributed to IMU position drift. After strip alignment, the mean elevation bias in the point clouds compared to the GNSS data was 0.000 m and the RMS error declined from 0.055 m to 0.038 m on March 13th and from 0.033 m to 0.029 m on March 14th. The point cloud density ranged from ~1200 returns m2 in sparse forest to ~2200 returns m2 in open clearings. Quality control, ground classification, calculation of surface elevation change was conducted on the point cloud data and then converted to 0.05 m resolution rasters. Further quality control was conducted on the 0.05 m raster data to remove values that exceeded the .999th quantile and then resampled to 0.25 m grid cell resolution by taking the median. A detailed description of the UAV, payload, flight settings, and software packages used is provided in the Supporting Information.

## 6.5 Snow surveys

### 6.5.1 In-situ snow depth and density

Event-based snow surveys provided measurements of subcanopy throughfall depth and density at 30 locations following the transects shown in [Figure 8](#fig-site-map). These measurements were used to upscale the weighed tree from weight to weight per unit area, assess the accuracy of lidar derived snow depth measurements, and provide a fresh snow density for the calculation of SWE (mm) from the snow depth measurements. Minimal ablation and redistribution of both the surface snowpack and/or snow intercepted in the canopy was crucial to ensure the snow survey measurements were attributed to throughfall. Therefore, only snowfall events with minimal canopy snow ablation as determined through in-situ observations, analysis of timelapse imagery, and mass change on the weighed tree lysimeter were selected. A 1000 cm3 Perla snow density wedge sampler (RIP Cutter, https://snowmetrics.com/shop/rip-1-cutter-1000-cc/) was used to measure the density of the fresh snow layer, (kg m-3) from snow pits. Throughfall depth measurements, were converted to SWE using the following equation:

If a pre-event crust layer was present, the depth of post event fresh snow accumulation above the crust layer was interpreted as throughfall over the event. In the absence of a defined crust layer, the difference in pre- and post-event snow depth to ground was interpreted as event throughfall. Interception efficiency, used in scaling the weighed tree, was calculated using [Equation 10](#eq-ip2) and the and cumulative snowfall measurements.

### 6.5.2 UAV-Lidar snow depth

Two uncrewed aerial vehicle (UAV) lidar surveys were conducted before and after a 24-hour snowfall event that occurred between March 13–14th, 2023 to facilitate the measurement of snow accumulation and canopy density within the FT and PWL forest plots. This period was selected based on two criteria: 1) it provided sufficient cumulative snowfall to result in a low relative error in UAV-lidar measured throughfall, and 2) minimal snow redistribution and ablation was observed, as confirmed by the subcanopy lysimeters, weighed tree, and time-lapse imagery. The change in surface elevation between the two UAV-lidar point clouds was interpreted as the increase in snow accumulation, , over the snowfall event. was calculated using [Equation 13](#eq-swe-tf) together with in-situ measurements of . The measurement error of the UAV-lidar derived was assessed using the in-situ snow depth observations which is shown in the Supporting Information. Spatially distributed measurements of , were then determined using [Equation 10](#eq-ip2) with as the throughfall component and cumulative snowfall to the PWL clearing.

## 6.6 UAV-Lidar canopy metrics

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

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

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

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

# 7. Results

## 7.1 The influence of meteorology on snow interception

Measurements of canopy snow load derived from the subcanopy lysimeters and weighed tree increased linearly with cumulative event snowfall for 26 snowfall events, without evidence of reaching a maximum ([Figure 10](#fig-scl-w-sf)). Over these events, air temperature ranged from -24.5°C to 1°C, wind speeds at 4.3 m height ranged from calm to 4.6 m s-1 ([Table 3](#tbl-sf-event-met)), and wind direction was predominately from the southwest during snowfall ([Figure 11](#fig-wind-rose)). Missing canopy snow load measurements, as shown in [Figure 10](#fig-scl-w-sf) for certain events, were caused by wiring damage from animals and heavy snow loads. Some of the variability in interception rates within and between different events may be attributed to small amounts of canopy snow unloading and melt, which could not be fully accounted for through the manual and automated filtering mitigation strategies in both the subcanopy lysimeter and weighed tree measurements.

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| Figure 10: Plot showing the cumulative event snowfall versus canopy snow load calculated using the mean of the three subcanopy lysimeters (left) and weighed tree lysimeter (right) for each of the 26 snowfall events. Both datasets represent canopy snow load for a canopy closure of 0.73 corresponding to the mean of the three subcanopy lysimeter canopies. |

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| Table 3: Meteorology of the 26 snowfall events. Air temperature and wind speed were measured at FT station. Interception efficiency is estimated from cumulative snowfall measured at PWL station and the average cumulative throughfall of all three subcanopy lysimeters located within the FT forest plot.   |  | Air Temperature (°C) | | | Wind Speed (m/s) | | | Interception Efficiency (-) | | | Snowfall (mm) | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Start Date | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Total | | 2021-12-23 | -6.2 | -5.3 | -4.6 | 0.6 | 3.1 | 4.6 | 0.1 | 0.5 | 0.9 | 21.7 | | 2022-01-02 | -15.9 | -10.8 | -5.8 | 0.2 | 1.8 | 4.2 | 0.0 | 0.5 | 1.0 | 31.6 | | 2022-01-17 | -14.8 | -7.8 | -0.8 | 0.2 | 1.1 | 1.8 | 0.0 | 0.6 | 1.0 | 12.9 | | 2022-01-31 | -24.5 | -12.1 | -6.4 | 0.1 | 1.0 | 1.7 | 0.2 | 0.7 | 1.0 | 9.1 | | 2022-02-14 | -9.9 | -9.0 | -8.5 | 0.4 | 0.8 | 1.2 | 0.2 | 0.5 | 0.8 | 1.7 | | 2022-02-19 | -4.7 | -3.2 | -2.5 | 1.3 | 2.3 | 3.6 | 0.3 | 0.6 | 0.9 | 11.1 | | 2022-03-01 | -8.3 | -5.4 | -1.0 | 0.1 | 1.0 | 3.1 | 0.4 | 0.8 | 1.0 | 9.9 | | 2022-03-07 | -12.5 | -8.6 | -4.4 | 0.3 | 0.8 | 1.7 | 0.3 | 0.7 | 1.0 | 9.5 | | 2022-03-14 | -2.7 | -2.1 | -0.8 | 1.0 | 1.6 | 2.9 | 0.2 | 0.6 | 0.9 | 8.4 | | 2022-03-19 | -3.1 | -2.8 | -2.5 | 0.0 | 0.7 | 1.3 | 0.3 | 0.5 | 0.6 | 6.6 | | 2022-03-23 | -7.9 | -5.3 | -0.9 | 0.8 | 1.2 | 1.8 | 0.4 | 0.6 | 0.9 | 1.6 | | 2022-04-04 | -3.5 | -2.9 | -2.1 | 0.6 | 1.0 | 1.9 | 0.0 | 0.4 | 0.6 | 3.4 | | 2022-04-18 | -5.2 | -4.0 | -2.7 | 0.4 | 1.1 | 1.9 | 0.1 | 0.5 | 0.9 | 7.4 | | 2022-04-22 | -2.8 | -1.8 | -0.5 | 0.4 | 0.8 | 1.2 | 0.1 | 0.5 | 1.0 | 9.8 | | 2022-05-09 | -4.9 | -4.3 | -3.2 | 0.1 | 0.4 | 0.9 | 0.2 | 0.5 | 0.9 | 8.1 | | 2022-05-19 | -4.9 | -2.1 | 0.3 | 0.1 | 0.4 | 0.9 | 0.2 | 0.6 | 0.9 | 7.1 | | 2022-06-13 | -1.1 | -0.3 | 0.6 | 0.1 | 0.1 | 0.4 | 0.0 | 0.5 | 0.9 | 45.4 | | 2022-12-27 | -3.0 | -2.7 | -1.9 | 0.6 | 1.1 | 1.8 | 0.2 | 0.5 | 0.9 | 4.5 | | 2023-01-27 | -11.5 | -7.3 | -4.5 | 0.6 | 0.9 | 1.2 | 0.1 | 0.5 | 0.8 | 10.4 | | 2023-02-19 | -14.3 | -9.5 | -6.3 | 0.2 | 0.8 | 1.4 | 0.2 | 0.7 | 1.0 | 18.1 | | 2023-02-26 | -9.2 | -8.4 | -6.6 | 0.2 | 1.0 | 2.1 | 0.3 | 0.5 | 1.0 | 5.4 | | 2023-03-13 | -8.9 | -3.6 | -0.1 | 0.3 | 1.3 | 2.2 | 0.0 | 0.5 | 1.0 | 27.4 | | 2023-03-24 | -7.9 | -5.7 | -3.5 | 0.1 | 0.5 | 1.2 | 0.1 | 0.4 | 0.7 | 23.8 | | 2023-04-01 | -8.9 | -7.7 | -4.7 | 0.1 | 0.6 | 1.4 | 0.4 | 0.6 | 0.8 | 11.4 | | 2023-04-10 | -1.1 | -0.5 | 0.3 | 0.1 | 0.3 | 1.0 | 0.2 | 0.4 | 0.6 | 18.0 | | 2023-05-08 | 0.2 | 0.6 | 1.0 | 0.4 | 0.6 | 0.8 | 0.6 | 0.6 | 0.7 | 3.5 | |

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| Figure 11: Wind rose showing the frequency of wind speed and direction over the 26 snowfall periods for the ultrasonic anemometer 4.3 m above ground at FT station. |

Linear regression analysis revealed no relationship between hourly interception efficiency (from the subcanopy lysimeters) and air temperature, wind speed or canopy snow load, either due to non-significant relationships (*p* < 0.05) and/or weak predictive power (*R*2 < 0.05) ([Table 4](#tbl-lysimeter-hourly-stats)). The Wilcoxon test indicated that the difference in hourly interception efficiencies for air temperatures above and below -5°C was not significant (*p* > 0.05, [Table 5](#tbl-scl-hrly-stats)). Additionally, the interception efficiency across differing bins of air temperature did not show any systematic pattern ([Figure 12](#fig-scl-ip-bins)). Although [Figure 12](#fig-scl-ip-bins) indicates potentially higher interception efficiency in sparse and mixed canopies at air temperatures below -10°C, these measurements have substantial uncertainty due to heightened instrument error associated with the small accumulations of snowfall and throughfall within these temperature ranges.

When examining wind speed effects, hourly interception efficiencies were found to be significantly higher (*p* < 0.05, [Table 5](#tbl-scl-hrly-stats)) during periods when wind speeds exceeded 1 m s-1 compared to calmer conditions in the sparse and closed canopies using the Wilcoxon test. The binned data also show an increase in interception efficiency with increasing wind speed for these two canopy types ([Figure 12](#fig-scl-ip-bins)). In contrast, the mixed canopy, which had a canopy opening towards the prevailing wind direction ([Figure 9](#fig-scl-imgs)), exhibited no significant difference (*p* > 0.05, [Table 5](#tbl-scl-hrly-stats)). Binned measurements of interception efficiencies corresponding to wind speed bins above 2 m s-1 ([Figure 12](#fig-scl-ip-bins)) contained considerable uncertainty resulting from lower snowfall and throughfall accumulation, reducing confidence in these particular findings across all three canopy environments.

Significantly higher hourly interception efficiencies (*p* < 0.05, [Table 5](#tbl-scl-hrly-stats)) were found for initial canopy snow loads below 10 mm compared to heavier snow loads across all three canopy types using the Wilcoxon test. Additionally, the sparse and mixed canopies exhibited significantly lower interception efficiencies (*p* < 0.05) for snow loads below 5 mm compared to those between 5–10 mm. The closed canopy displayed a similar initial increase for the binned data visible in [Figure 12](#fig-scl-ip-bins), but this was not statistically significant for the hourly data (*p* > 0.05, [Table 5](#tbl-scl-hrly-stats)). For the sparse and closed canopies, a slight increase in binned interception efficiency was observed as snow load increased up to 10 mm, followed by a decline when snow loads exceeded 10 mm ([Figure 12](#fig-scl-ip-bins)). For snow loads exceeding 15 mm, interception efficiency decreased in the sparse and closed canopies, while the mixed canopy showed an increase; however, these measurements carried high uncertainties due to lower accumulated snowfall and throughfall in these higher snow load bins. The differences between the relationships observed in the hourly-interval and binned interception efficiency measurements can be attributed to two factors: greater instrument uncertainty in the hourly measurements and the potential for the dependent and independent variables to be non-stationary over the hourly interval.

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| Table 4: Statistics corresponding to the ordinary least squares linear regression test between hourly interval measurements of independent variables: mean air temperature, mean wind speed, and initial canopy snow load and the dependent variable mean interception efficiency. The test was run separately for three levels of canopy coverage () corresponding to each subcanopy lysimeter (SCL).   | Dependent Variable | SCL Name |  | Adjusted | -value |  | | --- | --- | --- | --- | --- | --- | | Air Temperature (°C) | closed | 0.79 | 0.002 | 0.239 | 191 | | Air Temperature (°C) | mixed | 0.75 | 0.024 | 0.005 | 298 | | Air Temperature (°C) | sparse | 0.64 | 0.003 | 0.208 | 190 | | Initial Canopy Snow Load (mm) | closed | 0.79 | 0.029 | 0.011 | 188 | | Initial Canopy Snow Load (mm) | mixed | 0.75 | 0.010 | 0.049 | 294 | | Initial Canopy Snow Load (mm) | sparse | 0.64 | 0.031 | 0.009 | 187 | | Wind Speed (m/s) | closed | 0.79 | 0.025 | 0.017 | 191 | | Wind Speed (m/s) | mixed | 0.75 | 0.034 | 0.001 | 298 | | Wind Speed (m/s) | sparse | 0.64 | 0.046 | 0.002 | 190 | |

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| Figure 12: Scatter plots showing the interception efficiency calculated from accumulated snowfall (Pluvio) and throughfall (subcanopy lysimeter) measurements for bins of air temperature, wind speed, and initial canopy snow load (the snow load observed by the weighed tree at the beginning of the timestep) over the 26 snowfall events. The error bars represent the estimated combined instrument error of the snowfall gauge and subcanopy lysimeters. |

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

## 7.2 The influence of canopy density on snow interception

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

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

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| Figure 13: UAV-lidar measurements of the change in snow water equivalent, SWE (mm) and interception efficiency, I/P (-), over the March 13–14th 24-hour snowfall event for the FT and PWL forest plots at a 0.25 m resolution. See the location of the two forest plots in [Figure 8](#fig-site-map). |

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

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| Figure 14: The Pearson Correlation Coefficient between rasters (0.25 m resolution) of interception efficiency and leaf contact area (measured on March 13th) for each grid cell across the study site for each azimuth angles (0°, 1°, …, 359°) and zenith angles (0°, 1°, …, 90°) for the FT (left) and PWL (right) forest plots. |

The spatial distribution of measurements, selected based on the vector corresponding to the azimuth and zenith angles observed to have the highest correlation with interception efficiency in [Figure 14](#fig-hemi-ip-cc), is shown in [Figure 15](#fig-lidar-cc-cp). These measurements generally align with the spatial distribution of interception efficiency and throughfall ([Figure 13](#fig-lidar-tf-ip)).

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| Figure 15: UAV-lidar VoxRS measurements of leaf contact area measured on March 13th for the PWL and FT forest plots for zenith angles (PWL = 22°, FT = 21°) and azimuth angles (PWL = 167°, 178°, … 217°; FT = 171°, 172°, … 223°). |

The correlation between interception efficiency ([Figure 13](#fig-lidar-tf-ip)) and ([Figure 15](#fig-lidar-cc-cp)), resampled to a 5 m grid resolution, was higher compared to the association with leaf contact angle measured at a zenith angle of 0° ([Figure 16](#fig-lca-vs-ip)). The stronger association for the vector-based calculation is hypothesized to stem from a more accurate representation of the snowfall contact area and suggests that adjusted is a useful predictor of interception efficiency before ablation. An ordinary least squares linear regression forced through the origin was fit to the observed data points using the following equation:

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

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| Figure 16: Scatter plots showing the relationship between leaf contact area and interception efficiency rasters resampled to a 5 m grid cell resolution. The left plot (nadir) shows canopy coverage and the right plot (Vector Based) shows the leaf contact area averaged over rasters with zenith angles (PWL = 22°, FT = 21°) and azimuth angles (PWL = 167°, 178°, … 217°; FT = 171°, 172°, … 223°). The solid lines (Model fit) show an ordinary least squares linear regression forced through the origin and fitted to the PWL (red) and FT (black) data and the light grey dotted line shows a 1:1 line. The *R*2 values for the four different models are shown in the upper left of each panel calculated following the methods outlined in Kozak & Kozak (1995). |

For the vector-based model, the relationship between interception efficiency and resulted in *R*2 values of 0.45 and 0.8 for PWL and FT respectively. Model error statistics show the vector-based model provided a better prediction of interception efficiency compared to the nadir canopy coverage measurements ([Table 6](#tbl-ip-mod-err)). The increase in interception efficiency with follows a reduced slope compared to the nadir models with values of 0.72 and 0.69 for the PWL and FT vector-based models respectively. The reduced slope for the vector-based models may be due to snowflakes that weaved through and/or bounced off branch elements in addition to UAV-lidar throughfall measurement uncertainty which may have been slightly affected by unloading and redistribution. These processes would have reduced the fraction of snowfall that was stored in the canopy. Some of the scatter observed in the nadir model shown in [Figure 16](#fig-lca-vs-ip) may be explained by grid cells within canopy gaps which observed a greater interception efficiency compared to the corresponding canopy cover. Conversely, grid cells where interception efficiency is less than the canopy cover, may be affected by non-vertical trajectory hydrometeors making their way underneath the canopy as observed by the reduced interception efficiency on the windward edges of individual trees in [Figure 13](#fig-lidar-tf-ip).

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| Table 6: Summary of error statistics for the linear regression models relating leaf contact area to interception efficiency, presented in [Figure 16](#fig-lca-vs-ip). The Mean bias is the difference in the model and observed values, MAE is the mean of the absolute error, RMS Error is the root mean squared error, *R*2 is the coefficient of determination adjusted using Equation 10 in Kozak & Kozak (1995).   | Plot Name | Canopy Calculation | Model Slope (-) | Mean Bias (-) | MAE (-) | RMS Error (-) |  | | --- | --- | --- | --- | --- | --- | --- | | FT | Nadir | 1.01 | 0.024 | 0.072 | 0.101 | 0.49 | | FT | Vector Based | 0.69 | 0.003 | 0.047 | 0.063 | 0.80 | | PWL | Nadir | 0.96 | 0.049 | 0.115 | 0.148 | -0.31 | | PWL | Vector Based | 0.72 | 0.020 | 0.079 | 0.096 | 0.45 | |

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

VoxRS measurements of prior to snowfall on March 13th, increased substantially with simulated hydrometeor trajectory angle and corresponding simulated wind speed ([Figure 17](#fig-lca-ht-ws)). The standard deviation in VoxRS measured , illustrated by the shaded area in [Figure 17](#fig-lca-ht-ws), exhibits the broad range in values for individual grid cells across each forest plot. Despite this large scatter, a systematic increase in the mean across both forest plots results from a rise in the number of canopy elements for more horizontal angles, when averaged across each forest plot, over all azimuth angles (see top left panel [Figure 17](#fig-lca-ht-ws)). This results in a large rise in over relatively common wind speeds. For example, with a wind speed of 1 m s-1 and estimated trajectory angle of 48°, would increase by 0.31 and 0.28 for the PWL and FT forest plots respectively ([Figure 17](#fig-lca-ht-ws)). The increase in from nadir measured canopy coverage with increasing trajectory angle exhibits a similar relationship for both forest plots FT and PWL until trajectory angles reach approximately 60° (see bottom row of [Figure 17](#fig-lca-ht-ws)). Beyond 60°, the PWL rate of increase slows as the approaches 1.0, while the FT plot, which has lower canopy coverage, continues to rise until around 75° as a of 1.0 is approached. was also quantified across trajectory angles for both PWL and FT on March 14th, post snowfall, and showed a negligible increase in compared to measured on March 13th without snow in the canopy.

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| Figure 17: Plots showing the relationship between hydrometeor trajectory angle (left column) and wind speed (right column) with mean plot-wide snow-leaf contact area, (top row) and the increase in mean plot-wide , i.e., (bottom row). The simulated hydrometeor trajectory angle is measured as degrees from zenith. Simulated wind speed was calculated as a function of hydrometeor trajectory angle by rearranging [Equation 11](#eq-ta) and an observed event hydrometeor fall velocity of 0.9 m s-1. The solid lines (VoxRS) represent the mean (top row) or increase in mean (bottom row) for a single zenith angle observed from VoxRS across all grid cells for each forest plot and across all azimuth angles. The shaded area represents one standard deviation above and below the observed VoxRS mean. The dashed lines (Fitted) represent predictions from [Equation 17](#eq-lca-ac) (top row) and [Equation 18](#eq-lca-inc) (bottom row). The dotted lines (HP98) represent the predictions from Equation 10 in Hedstrom & Pomeroy (1998). A forested downwind distance of 100 m was assumed for the HP98 calculation. |

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

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

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

where is a fitting coefficient, estimated to be ~0.91 through a non-linear least squares regression fit to the VoxRS measurements at both FT and PWL. The term reflects the relative increase in snow-leaf contact area, which in turn leads to a proportional decrease in the canopy void space (). Thus, for of 0°, is equal to the canopy cover. In contrast, for close to 90°, approaches a value of 1.0. The assumptions of [Equation 19](#eq-f-theta) include that represents a measurement of continuous canopy cover without large open areas many times greater than the mean canopy height and that snowfall trajectories are linear.

Simulated using [Equation 17](#eq-lca-ac) is shown in the dashed lines in the top row of [Figure 17](#fig-lca-ht-ws) and follows the VoxRS-measured mean closely. Model error statistics demonstrate that [Equation 18](#eq-lca-inc) performed well, with a mean bias and RMSE of -0.05 (-) and 0.05 (-) for PWL, and 0.03 (-) and 0.05 (-) for FT respectively ([Table 7](#tbl-lca-mod-err)). In contrast, the Hedstrom & Pomeroy (1998) method produced significantly less accurate estimates of , with a mean bias and RMSE of -0.2 (-) and 0.23 (-) for PWL, and -0.26 (-) and 0.32 (-) for FT respectively ([Table 7](#tbl-lca-mod-err)).

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| Table 7: Model error statistics calculated for the prediction of leaf contact area from trajectory angle using [Equation 18](#eq-lca-inc) and Equation 10 from Hedstrom & Pomeroy (1998) (HP98) for the PWL and FT forest plots. Mean bias is the difference in the model and observed values, MAE is the mean of the absolute error, RMS Error is the root mean squared error and *R*2 is the coefficient of determination. The units for all metrics are dimensionless. A forested downwind distance of 100 m was used for the HP98 calculation.   | Model | Plot Name | Mean Bias (-) | MAE (-) | RMS Error (-) |  | | --- | --- | --- | --- | --- | --- | | HP98 | FT | -0.26 | 0.26 | 0.32 | -0.97 | | HP98 | PWL | -0.20 | 0.20 | 0.23 | -0.96 | | Eq. 10 | FT | 0.03 | 0.04 | 0.05 | 0.95 | | Eq. 10 | PWL | -0.05 | 0.05 | 0.05 | 0.90 | |

## 7.4 Throughfall model performance

The performance of the interception efficiency ([Equation 16](#eq-lca-ip)) and leaf contact area ([Equation 17](#eq-lca-ac)) parameterisations in estimating event throughfall was assessed against UAV-lidar measurements of throughfall at the plot scale for the March 13–14th snowfall event. In this assessment, the hydrometeor trajectory angle was approximated using [Equation 11](#eq-ta) combined with the mean event wind speed at one-third the mean canopy height (estimated from [Equation 12](#eq-cionco) and the observed wind speed at FT station) and hydrometeor terminal velocity (measured at PWL station). Leaf contact area was then estimated using [Equation 17](#eq-lca-ac) for the PWL and FT plots, incorporating the approximated hydrometeor trajectory angle and observed canopy cover () from the VoxRS dataset. Interception efficiency was calculated using [Equation 16](#eq-lca-ip) with the estimated leaf contact area from [Equation 17](#eq-lca-ac) and accumulated snowfall measured at PWL station for the event. An value, used in [Equation 16](#eq-lca-ip), of 0.978 (-) was found through calibration which provided the best fit between observed and simulated interception efficiency at the plot scale for both FT and PWL.

The new vector-based parameterisation closely matched the UAV-lidar measurements of throughfall ([Figure 18](#fig-event-tf)). Modelled throughfall from the vector-based model was 17.2 mm compared to the measured throughfall of 16.6 mm for PWL. For FT, the vector-based modelled throughfall was 21.5 mm, while the measured values where 22.1 mm. The vector-based model shows a lower mean bias of -0.6 mm for PWL and 0.6 mm for FT, in contrast to the nadir-based model, which overestimated throughfall for both plots ([Table 8](#tbl-vb-plot-err)). This overestimation arose from the nadir-based model’s approximation of leaf contact area from canopy coverage measurements (without adjustment via [Equation 17](#eq-lca-ac)), which yielded a reduced estimated contact area and consequently underestimated canopy snow interception.

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| Figure 18: Bar chart comparing the observed and modelled mean change in throughfall (ΔSWE, mm) over the March 13-14th snowfall event averaged over forest plots FT and PWL. The ‘Nadir-model’ calculated interception efficiency as a function of canopy coverage and the Vector-based ‘VB-model’ used [Equation 16](#eq-lca-ip) with adjusted for trajectory angle. ‘UAV-lidar’ corresponds to throughfall calculated using [Equation 13](#eq-swe-tf) incorporating UAV-lidar snow depth and snow density from in-situ snow pits. The black horizontal dashed line shows the accumulated SWE (mm) over the snowfall event to the PWL station open clearing. |

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| Table 8: Model error statistics for model estimates of snow interception efficiency (I/P) and throughfall (TF) compared to measurements of I/P and TF using UAV-lidar averaged over the FT and PWL forest plots. Units for I/P are (-) and TF are (mm). The vector-based model utilized [Equation 16](#eq-lca-ip) with adjusted for trajectory angle. The nadir model also utilized [Equation 16](#eq-lca-ip) but was not adjusted for trajectory angle and thus was used instead of . The ‘Obs. Value’ column contains measurements from UAV-lidar while the ‘Mod. Value’ column contains the modelled values. The mean bias was calculated as observed minus modelled and percent error is the percent error between predicted and observed values.   | Plot | Model Type | Value Name | Units | Obs. Value | Mod. Value | Mean Bias | Perc. Error | | --- | --- | --- | --- | --- | --- | --- | --- | | FT | VB-model | I/P | - | 0.23 | 0.25 | -0.02 | -9.01 | | FT | Nadir-model | I/P | - | 0.23 | 0.20 | 0.03 | 12.10 | | FT | VB-model | TF | mm | 22.12 | 21.53 | 0.59 | 2.67 | | FT | Nadir-model | TF | mm | 22.12 | 22.91 | -0.79 | -3.58 | | PWL | VB-model | I/P | - | 0.42 | 0.40 | 0.02 | 4.91 | | PWL | Nadir-model | I/P | - | 0.42 | 0.37 | 0.05 | 12.95 | | PWL | VB-model | TF | mm | 16.64 | 17.24 | -0.59 | -3.55 | | PWL | Nadir-model | TF | mm | 16.64 | 18.20 | -1.56 | -9.35 | |

# 8. Discussion

The point scale observations presented in [Figure 12](#fig-scl-ip-bins) indicate that air temperature had little influence on initial interception efficiency during periods where melt and unloading of snow were less likely. This finding aligns with Storck et al. (2002), who observed that variations in air temperature did not significantly affect initial interception efficiency. While other studies have reported both positive (Andreadis et al., 2009; Katsushima et al., 2023; Roth & Nolin, 2019) and negative (Hedstrom & Pomeroy, 1998; Schmidt & Gluns, 1991) relationships between air temperature and snow interception, the limited association observed here may be explained by competing temperature-dependent processes. Warmer temperatures simultaneously increase branch flexibility, reducing (Schmidt & Gluns, 1991; Schmidt & Pomeroy, 1990) and enhance snow cohesion and adhesion, increasing interception efficiency (Katsushima et al., 2023; Kobayashi, 1987; Pfister & Schneebeli, 1999).

Initial interception efficiency was found to increase with wind speed at two locations which were sheltered from the predominant wind direction ([Figure 12](#fig-scl-ip-bins)). This is hypothesized to be due to an increase in associated with non-vertical hydrometeor trajectories, as demonstrated by observations during a wind-driven snowfall event ([Figure 13](#fig-lidar-tf-ip)) and analysis of canopy density data ([Figure 17](#fig-lca-ht-ws)). These findings are also consistent with observations by Schmidt & Troendle (1989) who observed a slight increase in snowfall interception with increasing wind speeds up to 6 m s-1, Staines & Pomeroy (2023) who observed reduced canopy transmittance with increasing angle from zenith, and studies of rainfall interception by Herwitz & Slye (1995) and Van Stan et al. (2011).

The slight increase in interception efficiency for smaller canopy snow loads and decline for larger canopy snow loads is attributed to the influence of canopy snow load on ([Figure 12](#fig-scl-ip-bins)). Whilst small, this effect is consistent with the theory proposed by Satterlund & Haupt (1967) that interception efficiency increases as the canopy fills with snow bridging gaps in the canopy, while later declining due to branch bending and decreased canopy cover. However, at the plot-scale, Staines & Pomeroy (2023) showed that these two processes may partially compensate for each other as increases for closed canopies, as new snow bridges form in the canopy, but decreases in partially open canopy due to branch bending (i.e., Fig. 2 in Schmidt & Gluns, 1991). Still, the increase in resulting from snow load in Staines & Pomeroy (2023) was small compared to the substantial rise in due to trajectory angle presented in their study; which corroborates with the plot-scale observations of in this study ([Figure 17](#fig-lca-ht-ws)). Additional observations by Watanabe & Ozeki (1964), Calder (1990), and Storck et al. (2002) support the findings in [Figure 10](#fig-scl-w-sf) showing a linear increase in canopy snow load with increasing snowfall. Further evidence in support of the relatively small influence of canopy snow load on , is provided by Lundquist et al. (2021) who reported improved simulation of subcanopy snow accumulation without the use of a maximum canopy snow load, when linked with a comprehensive canopy snow ablation routine. The low sensitivity to canopy snow load found here may result from reduced inclusion of ablation processes in our measurements, limited influence of snow load on at this site, and/or the compensatory effects described by Satterlund & Haupt (1967).

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

To address these issues, a new vector-based snow interception parameterisation is presented ([Equation 16](#eq-lca-ip)) which calculates initial interception efficiency as a function of and an efficiency constant, . This new parameterisation allows for canopy snow loading processes to be isolated from canopy snow ablation processes and is consistent with current rainfall interception theory (Valante et al., 1997; Zhong et al., 2022). [Equation 16](#eq-lca-ip) differs only slightly from the original Hedstrom & Pomeroy (1998) parameterisation (see Equation 6 in Hedstrom & Pomeroy 1998), in that it does not calculate interception efficiency as a function of canopy snow load and from the Storck et al. (2002) parameterisation who found interception efficiency to be constant. Further research is needed to explore how processes such as the increased cohesion and adhesion of snowfall to the canopy at warm temperatures, as observed by Kobayashi (1987), Pfister & Schneebeli (1999), as well as hydrometeor velocity, particle size, and shape suggested by (Katsushima et al., 2023), may influence the parameter, although these effects were not observed in this study. Since [Equation 16](#eq-lca-ip) intentionally excludes processes attributed to canopy snow ablation that were previously included in earlier snow interception models, these ablation processes must be incorporated in canopy snow ablation parameterisations to fully represent the canopy snow mass balance.

The exponential relationship proposed by Hedstrom & Pomeroy (1998) to scale with wind speed failed to reproduce the observations presented in [Figure 17](#fig-lca-ht-ws). Instead, plot-wide was found to increase as function of hydrometeor trajectory angle and canopy cover. However, the large scatter in measurements shown in [Figure 17](#fig-lca-ht-ws) suggests [Equation 18](#eq-lca-inc) is only applicable at the forest stand scale, or larger, where the sub-metre variability in resulting from directional differences averages out. Canopy cover measurements at larger scales may lack sufficient resolution to identify large open area components of forests, where the assumptions of [Equation 17](#eq-lca-ac) would not be valid, and should be estimated using horizontal canopy cover without adjusting for snowfall trajectory angle. If fine-scale canopy observations are available, canopy structure metrics such as the gap area indices described in Moeser et al. (2015a) could be helpful for identifying large gaps in the canopy. Moreover, our measurements show the hydrometeor trajectory angle required for [Equation 18](#eq-lca-inc), can be approximated from [Equation 11](#eq-ta) incorporating the hydrometeor fall velocity and the mean horizontal wind speed selected at one-third of the canopy height. This is consistent with Katsushima et al. (2023), who also proposed using a wind speed at one-third the canopy height for modelling unloading of canopy snow. The transferability of the snow-leaf contact area equation ([Equation 18](#eq-lca-inc)) remains uncertain, as it has only been tested at a single site with two tree species, and the relationship of with environmental factors is expected to vary across different climate conditions, canopy structures, densities, species, and ages. Additionally, [Equation 11](#eq-ta) assumes a linear hydrometeor trajectory, and does not consider non-linear patterns such as wind flow directions around tree elements, turbulent flow, or differences in wind speed with height. Staines & Pomeroy (2023) showed, at a proximal montane spruce-fir forest, that backflows and large eddies that occur within the canopy can contribute to mixed responses. Therefore, further testing and modification of [Equation 18](#eq-lca-inc) is needed in diverse forest environments.

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

# 9. Conclusions

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

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

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

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# 11. Data Availability

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

# 12. 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.

Citation:

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.

# 13. 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 module will be compared to observed SWE at a point within the forest of each research basin.

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