Advancing Snow Accumulation Models in Needleleaf Forests

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September 19, 2024

# 1. Introduction

## 1.1 Background

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

## 1.2 Research Gap and Objectives

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

Thesis objectives and research questions

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

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

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

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

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

## 1.3 Organization of Chapters

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

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

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

Role in thesis: This paper is an advanced review article and corresponds to objective 1, research question 1.1 of the thesis and aims to answer the first research question of Objective 1 which is “What are the theoretical underpinnings and assumptions behind existing snow interception parameterizations?”. This advanced review will provide the context necessary for interpreting whether the theories and assumptions of existing parameterizations are true for the field observations collected in this study in the second part of objective 1.

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

**Article Category**: Advanced Review

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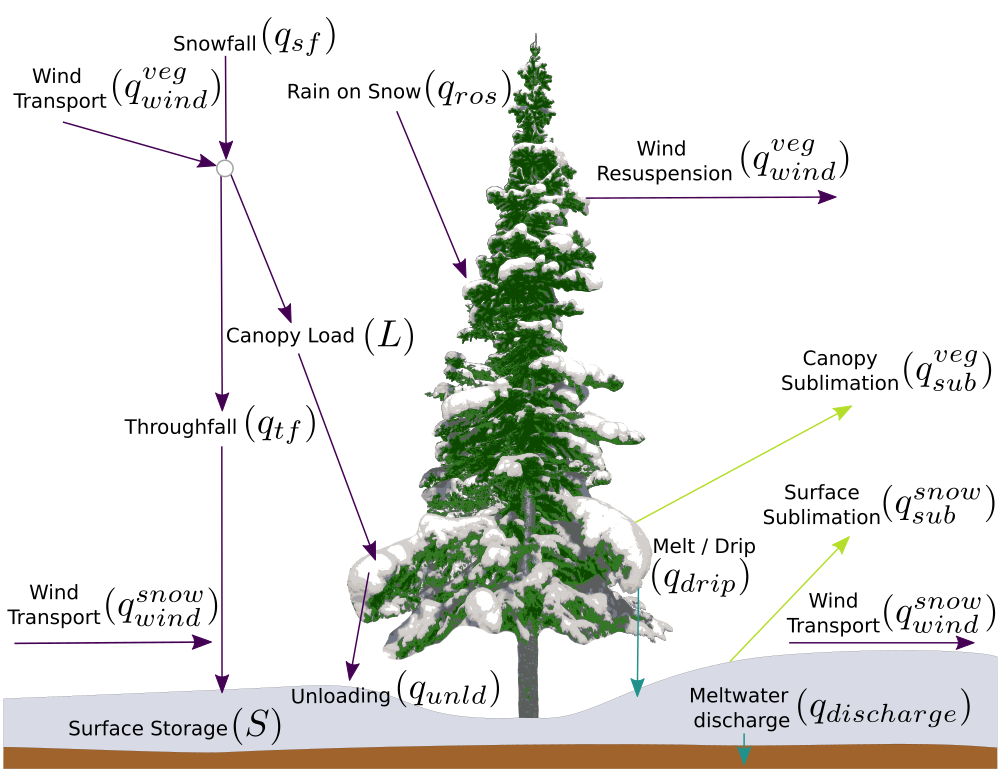
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**Abstract:** In needleleaf forests, up to half of annual snowfall may be ablated due to sublimation of snow intercepted in the canopy. However, limited and sparse observations of snow interception and ablation processes have hindered the development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

**Graphical Abstract and Caption**

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



## 2.1 Introduction

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

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

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

### 2.2.1 Mass Balance

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

### 2.2.2 Energy Balance

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

## 2.3 Measuring Snow Interception and Ablation

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

### 2.3.1 Weighed Tree

### 2.3.2 Mass Balance Methods

#### 2.3.2.1 Snow Surveys

#### 2.3.2.2 Subcanopy Lysimeters

### 2.3.3 Remote Sensing

### 2.3.4 Tree Sway Frequency

### 2.3.5 Trunk Compression

## 2.4 Methods of Determination

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

### 2.4.1 Snow Interception Parameterizations

#### 2.4.1.1 Hedstrom & Pomeroy (1998)

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

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

#### 2.4.1.4 Event Based Snow Interception Parameterizations

### 2.4.2 Canopy Snow Ablation Parameterizations

#### 2.4.2.1 Sublimation

#### 2.4.2.2 Unloading and Drip

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

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

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

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

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

## 2.5 Discussion

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

## 2.6 Conclusion

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

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

## 2.7 Funding Information

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

## 2.8 Acknowledgments

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

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

This journal article aims to answer part of the second research question of Objective 1, “Are the theories and assumptions of existing snow interception parameterizations true for field measurements collected across diverse forest structures and climates?”. This will be achieved by presenting observations of interception from a study site few researchers have focused on, a subalpine discontinuous forest and contrast these results with existing theory developed in maritime and continental climates. This journal article is in progress for submission to the Hydrological Processes special issue “Canadian Geophysical Union 2023”.

##### 3.0.0.0.1 1. Introduction

##### 3.0.0.0.2 2. Methods

###### 3.0.0.0.2.1 2.1 Study Site

###### 3.0.0.0.2.2 2.2 Automated Interception Measurements

###### 3.0.0.0.2.3 2.3 Snow Surveys

###### 3.0.0.0.2.4 2.3.1 In-Situ Measurements

###### 3.0.0.0.2.5 2.3.2 UAV-LiDAR Measurements

###### 3.0.0.0.2.6 2.3.4 Discrete Event Interception Measurements

###### 3.0.0.0.2.7 2.3 Canopy Structure Products

##### 3.0.0.0.3 3. Results

###### 3.0.0.0.3.1 3.1 The influence of meteorology on snow interception

* The accumulation of canopy load over 26 snowfall events shown in [Figure 1 (a)](#fig-scl-w-sf) measured using the subcanopy lysimeters, exhibits the variability in I/P between and within the different events. The relatively low variability in I/P across and within the different events is attributed to variances in meteorological conditions.
* Frequency distribution of meteorological variables observed over the 26 snowfall events (**?@fig-hist-met-ip**).
* **?@fig-lai-met-ip** shows 15-minute average variables including: air temperature, relative humidity, wind speed, initial canopy snow load, hydrometeor diameter, hydrometeor velocity, versus 15 minute average snow interception efficiency for all 26 snowfall events.

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

Figure 1: Two plots showing the relationship between snowfall and interception. Plot (a) shows the cumulative event snowfall versus the corresponding state of canopy snow storage for each of the 26 snowfall events. Plot (b) shows total event snowfall versus the average interception efficiency for each event. Snowfall data was measured using the snowfall gauge at Powerline Station while throughfall data was measured using the three subcanopy lysimeters used for the calculation of canopy storage and interception efficiency. These lysimeters, each denoted by a distinct color (black, red, and green), correspond to varying canopy coverage (0.73, 0.78, and 0.82, respectively).

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| Figure 2: Scatter plots of discrete observations (green) of snow interception efficiency observed at 15 minute intervals using the subcanopy lysimeter and snowfall gauge against and binned data (black). Panels show (A) air temperature, (B) wind speed, (C) initial canopy snow load (the snow load observed at the beginning of the timestep), (E) hydrometeor diameter, (F) hydrometeor velocity. The black open circles show the mean of each bin and the error bars represent the standard deviations. The data were filtered to include observations with a snowfall rate > 0 mm/hr and a snowfall rate > the subcanopy lysimeter throughfall rate to minimize observations with unloading. Periods of unloading and melt were also removed through careful analysis of the weighed tree, subcanopy lysimeters, and timelapse imagery. |

###### 3.0.0.0.3.2 3.2 The influence of forest structure on snow accumulation

* Snow interception efficiency observed across the study site after a 24 hour snow accumulation event reveals the influence of forest structure on snow accumulation.
* The spatial distribution in I/P across the study site, calculated using throughfall from lidar measurements and snowfall from the Pluvio snowfall gauge is shown in [Figure 3](#fig-lidar-ip). Greater I/P is observed on the north (lee) side of individual trees which is inferred to be due to the predominately southerly winds observed over this event. This effect is more apparent on the southwest of the study site compared to north and eastern locations within the study site.

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| |  | | --- | | (a) PWL I/P | |  |

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| |  | | --- | | (b) FT I/P | |

Figure 3: Interception efficiency calculated over a 24 hr snowfall event from March 13, 2023 to March 14, 2024 for the PWL forest plot (a) and FT forest plot (b) at a 25 cm resolution. White areas for the bottom row are 25 cm grids that did not have any lidar ground returns or have been masked due to disturbance and thus, no throughfall measurement for the I/P calculation.

* To determine how forest structure was associated with interception efficiency over the March 13-14 snowfall event, each portion of the hemisphere at each grid location was considered. The Spearman’s Correlation Coefficient calculated between the single raster grid of I/P and multiple canopy contact number at a given portion of the hemisphere (azimuth [0, 1, …, 359], zenith angle [0, 1, …, 90]) is shown in **?@fig-hemi-ip-cc**.

###### 3.0.0.0.3.3 3.3 Combined effects of Meteorology and Forest Structure

* The mean canopy contact number, obtained through voxel ray sampling across all azimuth angles [0, 1, …, 359] for each zenith angle [0, 1, …, 90], shown in [Figure 4](#fig-ta-ws-cc) demonstrates an exponential rise in contact number with increasing (more horizontal) trajectory angle. This underscores the influence of hydrometeor trajectory angle, which is a function of wind speed, on the apparent forest structure important for interception.

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Figure 4: Scatter plots showing the association of (a) hydrometeor trajectory angle and wind speed with mean contact number and (b) hydrometeor trajectory angle and wind speed with apparent canopy coverage calculated as a function of mean contact number. The dots represent the mean mean contact number (a) OR mean canopy coverage (b) across all azimuth angles of the the hemisphere [0, 1, …, 359] for a each zenith angle [0, 1, …, 90] at each forest plot. The colour of the dot represents the mean canopy coverage of each forest plot from nadir. Trajectory angle is calculated as zenith angle - 90°.

##### 3.0.0.0.4 4. Discussion

* This discussion will aim to answer the second research question of objective 1, “Are the theories and assumptions of existing snow interception parameterizations true for field measurements collected across diverse forest structures and climates?” for a discontinuous subalpine forest. This will be achieved by comparing the theories of existing snow interception parameterizations reviewed in Paper 1 from maritime and continental climates with the observations presented in the results here.

##### 3.0.0.0.5 5. Conclusions

* Forest structure is the main factor governing the fraction of intercepted snowfall at a particular site, with meteorological conditions contributing less to variability.
* [Figure 1](#fig-scl): Carefully selected snowfall events, prior to canopy snow ablation, did not approach a maximum snow load load, and interception efficiency was not observed to be associated with event size. This challenges existing snow interception parameterizations which rely on the assumption that interception efficiency is a function of maximum canopy snow load. While some rise in interception efficiency was observed alongside increasing canopy snow load, primarily attributed to increasing canopy coverage, the subsequent decrease in interception efficiency at higher loads implies that canopy snow ablation is proportional to canopy snow load.
* [Figure 2](#fig-met-ip): No influence of air temperature, relative humidity, hydrometeor velocity, hydrometeor diameter or canopy storage on interception efficiency was observed.
* [Figure 2](#fig-met-ip): Interception efficiency was shown to increase with wind speed and canopy snow load as a result of increasing snow-leaf contact area.
* [Figure 2](#fig-met-ip): High wind speeds were observed to decrease intercepted load due to increased snow unloading.
* [Figure 3](#fig-lidar-ip): Spatially distributed UAV-lidar measurements of throughfall from a snowfall event with steady wind shows reduced snow accumulation on the lee side of individual trees as a result of increasing snow-leaf contact area due to non vertical hydrometeors results.
* A new snow interception parameterization has been presented which calculates initial interception, before canopy snow ablation, as a function of snowfall rate and snow-leaf contact area ratio.
* A second new parameterization is proposed which calculates snow-leaf contact area ratio as a function of nadir canopy coverage, wind speed and canopy snow load.
* Caution should be taken in using this updated interception routine with existing canopy snow ablation parameterizations as they were developed using earlier snow interception routines that also included ablative processes.
* Future work will will involve a canopy snow ablation routine that is revised to work with this new snow interception routine.

#### 3.0.0.1 Paper 3: The Impact of Meteorology on Canopy Snow Ablation Processes: Insights from Field Observation in a Subalpine Forest

This journal article will present results of canopy snow ablation observations from Fortress Mountain Research basin collected over the 2022 and 2023 water years. This journal article will follow a similar story as in Paper 2 in that observations will be presented in the results section and in the discussion question 2 of objective 1 will be addressed. The results from this paper were presented at INARCH and AGU 2023.

##### 3.0.0.1.1 1. Introduction

Discuss the difficulty in obtaining canopy snow ablation measurements, especially over space.

##### 3.0.0.1.2 2. Methods

###### 3.0.0.1.2.1 2.1 Study Site

###### 3.0.0.1.2.2 2.2 Canopy Snow Ablation Measurements

###### 3.0.0.1.2.3 2.3 Canopy Snow Sublimation Modelling (in absence of usable Eddy Covariance data)

##### 3.0.0.1.3 3. Results

###### 3.0.0.1.3.1 3.1 Dominant Ablation Processes Observed

* This first section of the results will present the apportionment of canopy snow ablation, shown in [Figure 5](#fig-c-abl), determined using automated measurements of canopy snow ablation from the weighed tree and unloading from the subcanopy lysimeters
* The apportionment of how canopy snow ablation changes with temperature in [Figure 6 (a)](#fig-c-abl-temp) and wind speed in [Figure 6 (b)](#fig-c-abl-wind) will also be presented. Also discuss 0.5 mm/hr of canopy snow that was observed to be entrained above the canopy at wind speeds above 4 m/s.

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| Figure 5: The apportionment of canopy snow ablation determined using automated measurements of canopy snow ablation from the weighed tree and unloading from the subcanopy lysimeters averaged over two winter seasons. Sublimation was simulated using the Cold Regions Hydrological Model (Pomeroy et al., 2007). |

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Figure 6: The change in contribution of unloading and the residual to total canopy ablation. Calculated using automated measurements of ablation from the weighed tree and unloading from the subcanopy lysimeters.

###### 3.0.0.1.3.2 3.2 The Influence of Meteorology on Unloading

* The probability of unloading shown in [Figure 7 (a)](#fig-prob-unl) was observed to be higher with air temperatures above 0 °C and with wind speeds above 2 m/s. At air temperatures above -6 °C the effect of wind speed on unloading appears to be reduced.
* The observed unloading rate attributed to warming was higher at sub-zero temperatures when the canopy was loaded (> 6.5 mm) compared to when there was less than 6.5 mm of snow in the canopy ([Figure 8 (a)](#fig-qunld-temp)).
* High rates of unloading attributed to wind were observed across all wind speed bins when the canopy was loaded (> 6.5 mm). The unloading rate was observed to increase with increasing wind with less than 6.5 mm of snow in the canopy ([Figure 8 (b)](#fig-qunld-wind)).

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Figure 7: The probability and frequency of unloading for air temperature and wind speed bins pairs measured using automated measurements of unloading from the subcanopy lysimeters. The probability of unloading was calculated as the number of unloading events within each bin pair divided by the total number of occurrences of each bin pair.

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Figure 8: Average unloading rates measured by the subcanopy lysimeters for periods where wind speeds are less than 2 m/s (a) OR air temperature less than -6 °C (b). Uncertainty ranges shows the 5th and 95th percentiles.

##### 3.0.0.1.4 4. Discussion

This discussion will aim to answer the second research question of objective 1, “Are the theories and assumptions of existing snow interception parameterizations true for field measurements collected across diverse forest structures and climates?” for a discontinuous subalpine forest. This will be achieved by comparing the theories of existing canopy snow ablation parameterizations reviewed in Paper 1 from maritime and continental climates with the observations presented in the results here.

##### 3.0.0.1.5 5. Conclusions

### 3.0.1 Chapter 3

This chapter corresponds to objective 2, to quantify the performance of current snow interception parameterizations against field observations in differing forest structures and climates. To achieve this objective one journal article is proposed:

#### 3.0.1.1 Paper 4: The Influence of Climate and Forest Structure on Snow Interception Parameterization Performance: Insights for Improved Process Representation in Mountain Forests

The content of this paper is still to be discussed with John.

The plan in the thesis proposal was to evaluate the CRHM canopy modules using measurements of sub-canopy SWE, interception and ablation measured at various spatial and temporal scales at Fortress Mountain, Marmot Creek, Wolf Creek, and Russell Creek. A limitation of this approach is the limited spatial coverage in continuous point scale process measurements (weighed tree, lysimeters), also doesn’t answer forest structure component of the objective. The advantage of this plan is more detailed process investigation (also assuming better weighed tree was installed fall of 2022 at Wolf Creek compared to the dead tree hung in 2021).

While not in the original proposal, after spending a week learning CHM with Chris Marsh I thought a similar analysis could be conducted using CHM by updating the canopy module and comparing simulated SWE to aerial lidar SWE across Fortress Basin and Russell Creek. This could be achieved using the monthly Fortress basin and Vancouver Island aerial lidar snow depth measurements. The disadvantage of this plan would be less detailed process investigation. The advantage is greater spatial coverage across variable forest structure and still contrasting climates (Fortress vs. Vancouver Island).

### 3.0.2 Chapter 4

This chapter corresponds to objective 3, determine how the modification of existing snow interception parameterizations better represent the processes important for snow accumulation and redistribution in mountain forests of differing structure and climate

#### 3.0.2.1 Paper 5: An evaluation of new snow interception and ablation parameterizations across diverse forest structures and climates

As in chapter 3, the content of this paper is still to be discussed with John.

The proposed content of this paper aims to answer the first research question of objective 3, what is the change in forest snow accumulation model error associated with an updated canopy snow interception parameterization?. To achieve this, insights gained from objective 1 and 2 will be used to inform the modification of existing snow interception parameterizations. The updated parameterizations will be evaluated by including them in an updated CRHM canopy module and compared simulated SWE to observed SWE within the forested portion of each basin. As in paper 4 this could also be conducted using CHM with implications for changing the analysis detail and spatial scaling.

#### 3.0.2.2 Paper 6: TBD

To answer the second research question of objective 3, “What is the change in forested basin streamflow model error associated with an updated canopy snow interception parameterization?”, a sixth paper would be required.

This paper would involve setting up CRHM (CHM does not have stream routing yet) for mountain basins with a high fraction of their snow-covered zone that is forested and running a sensitivity analysis on predicted streamflow using different versions of the CRHMs canopy module. Possible test basins that meet this criteria are: the Tsitika River (Coastal, 08HF004), Upper Penticton River (Interior Dry, 08NM240), Kuskanax Creek (Interior Wet, 08NE006), and White Gull Creek (Continental Cold Dry, 05KE010).

Further discussion with John should occur to ensure this paper is still justified. After reflection while creating and teaching the Runoff Module for GEOG 225, I realize that the uncertainty in the snowmelt-runoff portion of hydrological models may mask any sensitivity to changes to canopy module.

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# 5. Appendix for Chapter 1

### 5.0.1 Snow Interception Parameterization Derivations

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

where (kg m-2), is the canopy snow load before snowfall is added to the canopy, (kg m-2), is the change in canopy snow load due to snowfall. [Equation 1](#eq-hp98-int-orig) is written in this way in Hedstrom & Pomeroy (1998) since they had measurements of at the beginning of the storm. However, this equation further simplified here since:

and therefore:

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

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

### 5.0.2 Snow Unloading Parameterization Derivations

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

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

then:

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

# 6. Appendix for Chapter 2