Thesis Outline

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## Overview

This document links proposed thesis objectives to thesis chapters and proposed papers within each chapter.

## Thesis Summary

Purpose: To better understand the processes that govern snow accumulation and redistribution in mountain forests.

### Thesis objectives and research questions:

1. Evaluate the suitability of existing snow interception parameterizations for application in mountain forests with differing climate and forest structure.
   * What are the theoretical underpinnings and assumptions behind existing snow interception parameterizations?
   * Are the theories and assumptions of existing snow interception parameterizations true for field measurements collected across diverse forest structures and climates?
2. Quantify the performance of current snow interception parameterizations against field observations in differing forest structures and climates.
   * For what climatic conditions and forest structures are predictions from current snow interception models most uncertain?
   * How do the assumptions of existing snow interception parameterizations influence model performance?
3. Determine how the modifications of existing snow interception parameterizations could improve process representations that are important for snow accumulation and redistribution in mountain forests.
   * What is the change in simulated snow accumulation model error associated with revised canopy snow interception parameterizations across mountain forests of differing forest structure and climate?
   * What is the change in simulated streamflow model error associated with revised canopy snow interception parameterizations across forested mountain basins of differing forest structure and climate?

### Organization of Chapters

This thesis contains 4 chapters, the first chapter includes an introduction and research plan while, the remaining chapters 2-4 include journal articles related to the thesis objectives.

## Thesis Chapters

### Chapter 1

This chapter includes background information about the study. Including the following subsections:

#### Introduction

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

#### Research Plan

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

### Chapter 2

This chapter corresponds to objective 1 of the thesis, to evaluate the suitability of existing snow interception parameterizations for application in mountain forests with differing climate and forest structure. To achieve this objective three draft journal articles have been written:

#### Paper 1: The Theoretical Underpinnings of Existing Snow Interception and Ablation Parameterizations

This paper 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. This paper is an advanced review which has been invited for submission to the journal WIREs Water.

**WIREs Water Deadline:** June 28, 2024

**Abstract:**

In needleleaf forests, up to half of annual snowfall may be lost due to sublimation of snow intercepted in the canopy. However, a comprehensive understanding of snow interception and ablation processes has been constrained by a lack of observations. Existing parameterizations for snow interception and ablation have been developed in locations with distinct climate and forest structures, resulting in differing and incomplete process representations. Consequently, their transferability across diverse landscapes and climates remains uncertain. This review article aims to elucidate the theoretical foundations and assumptions underlying the current snow interception and ablation parameterizations in the literature. 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 diverse environments. Some gaps in the literature include challenges in differentiating throughfall measurements from unloading and drip, the assumption of vertical snowflake trajectories, the difficulty in partitioning unloading rates and canopy snow melt drainage, the absence of a wind resuspension parameterization, and the inadequate validation of parameterizations in wind exposed subalpine forests. By reviewing the theory, methods and assumptions of existing snow interception and ablation parameterizations this article aims to inform future model-decision makers in selecting appropriate parameterizations and guiding future field-based observational studies.

##### 1. Introduction

##### 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.

###### 2.1 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 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.

##### 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.

###### 3.1 Weighed Tree

###### 3.2 Mass Balance Methods

###### 3.2.1 Snow Surveys

###### 3.2.2 Subcanopy Lysimeters

###### 3.3 Remote Sensing

##### 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.

###### 4.1 Snow Interception Parameterizations

###### 4.2 Canopy Snow Ablation Parameterizations

###### 4.2.1 Sublimation

###### 4.2.2 Unloading and Drip

##### 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

##### 6. Conclusion

#### Paper 2: Combined effects of wind, air temperature and snowfall on snow interception 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”.

##### 1. Introduction

##### 2. Methods

###### 2.1 Study Site

###### 2.2 Automated Interception Measurements

###### 2.3 Snow Surveys

###### 2.3.1 In-Situ Measurements

###### 2.3.2 UAV-LiDAR Measurements

###### 2.3.4 Discrete Event Interception Measurements

###### 2.3 Canopy Structure Products

##### 3. Results

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

* The accumulation of canopy load over 26 snowfall events shown in [Figure 1](#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 ([Figure 2](#fig-hist-met-ip)).
* [Figure 3](#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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| Figure 1: Cumulative canopy snow storage measured using the subcanopy lysimeters plotted against cumulative event snowfall for five selected snowfall events. The colour of each line shows the average air temperature (a) and wind speed (b) over the duration of each event. |

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| Figure 2: Histograms of meteorological variables and interception variables for 15 minute observations over periods with snowfall over the study period. |

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| Figure 3: 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. |

###### 3.2 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 4](#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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Figure 4: Interception efficiency calculated over a 24 hr snowfall event from March 13, 2023 to March 14, 2024 at a 25 cm resolution. The entire extent of the lidar transect is shown on the left (a) and a close up of PWL\_E on the right (b). White areas are 25 cm grids that did not have any lidar returns 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 [Figure 5](#fig-hemi-ip-cc).

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Figure 5: Spearman’s Correlation Coefficient between rasters of interception efficiency and canopy contact number (25 cm resolution) across the study site for different portions of the hemisphere (azimuth [0, 1, …, 359], zenith angle [0, 1, …, 90]).

###### 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 6](#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 6: 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°.

##### 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.

##### 5. Conclusions

#### 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.

##### 1. Introduction

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

##### 2. Methods

###### 2.1 Study Site

###### 2.2 Canopy Snow Ablation Measurements

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

##### 3. Results

###### 3.1 Dominant Ablation Processes Observed

* This first section of the results will present the apportionment of canopy snow ablation, shown in [Figure 7](#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 8 (a)](#fig-c-abl-temp) and wind speed in [Figure 8 (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 7: 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 8: 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.

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

* The probability of unloading shown in [Figure 9 (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 10 (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 10 (b)](#fig-qunld-wind)).

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Figure 9: 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 10: 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.

##### 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.

##### 5. Conclusions

### 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:

#### 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).

### 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

#### 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.

#### 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.