Paper Draft: The influence of Meteorology on Canopy Snow Ablation Processes

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**Key Points:**

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

**Abstract:**

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

## 1 Introduction

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

Research Questions:

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

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| Figure 1: Example of the Hedstrom & Pomeroy (1998) (HP98) and Roesch et al. (2001) (RW01) parameterizations for the calculation of unloading and drip rates with increasing air temperature. Wind speed for the RW01 parameterization was set to zero. Note that the HP98 parameterization does not differentiate unloading processes (i.e., metamorphasism, wind-induced, melt) while the RW01 parameterization here calculates unloading and drip of canopy snow due to warming and melt alone and their wind-induced parameterization is shown separately. |

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| Figure 2: Example of the Roesch et al. (2001) (RW01) parameterization for the calculation of wind-induced unloading. Here the air temperature has been set to a constant of -10°C to set the unloading rate due to warming to zero. The parameterization was run for a range of canopy snow loads (5, 10, 15, and 20 mm). |

## 2 Study Site and Instrumentation

## 3 Methods

### 3.1 Partitioning the Canopy Snow Ablation Mass Balance

### 3.2 Modelled Canopy Snow Sublimation Rate

### 3.3 Probability of Unloading and Drip

## 4 Results

### 4.1 The apportionment of Canopy Snow Ablation Processes

[Figure 3](#fig-glob-unl-part) shows that the measured unloading and drip rate was the dominant process of the canopy snow ablation mass balance over two winter seasons. Simulated sublimation rates also make up a significant portion of canopy snow ablation and accounted for most of the residual measured ablation. This suggests that for the average conditions in this wind-exposed subalpine forest, wind redistribution of snow intercepted in the canopy is a relatively small component.

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| Figure 3 |

[Figure 4](#fig-wind-temp-unl-part) shows a large increase in the ablation residual with wind speeds above 3.5 m s-1 and little association with air temperature. The increase in the residual at high wind speeds is attributed to higher ablation rates measured by the weighed tree due which were not accounted for by corresponding increase in the unloading + drip rates. The difference between the residual + error term and the modelled sublimation rate is attributed to both an increase in horizontal wind redistribution of snow intercepted in the canopy and instrument error. Difficulties in measuring horizontal wind redistribution and quantify the instrument error limit the ability to partition the residual into these two processes. If it is assumed that the instrument error is constant across wind speeds, it could be determined that the increase in the residual + error term is primarily attributed to horizontal wind redistribution. However, since the sublimation parameterization in this simulation has not been tested in wind-exposed forest and may be an underestimate of true sublimation rates at high wind speeds. Therefore the increase in residual, compared to modelled sublimation could also be attributed to an increase in actual sublimation rate compared to the model. While these data could be used to parameterise a horizontal wind redistribution function, the uncertainty behind this residual term due to the aforementioned issues prove any resultant model to be too speculative.

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| Figure 4 |

### 4.2 The Influence of Meteorology on Unloading

[Figure 5](#fig-glob-prob-unl) shows the association between the probability of unloading + drip with air temperature and wind speed. The probability of unloading + drip was found to be high (close to 1) for air temperatures above 1 °C and above wind speeds of 2.5 m s-1. For wind speeds bins less than 1 m s-1 the probability of unloading was found to positively associated with air temperatures. However at higher wind speeds this association was observed to weaken, potentially due to some evaporative cooling. For air temperatures less than -6 °C a positive association between the probability of unloading + drip and wind speed was observed. Above -6 °C the reduced association between wind speed and probability of unloading + drip may be attributed to increased cohesion and adhesion of snow intercepted in the canopy attributed to an increase in liquid water content in the snow clumps. The low frequency of observations shown in [Figure 6](#fig-glob-freq-unl), for low and high air temperatures and wind speeds may limit the interpretation of these results.

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| Figure 5 |

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| Figure 6 |

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

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| Figure 7 |

### 4.3 Modelling Canopy Snow Unloading

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

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| Figure 8 |

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

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| Figure 9 |

wind\_err\_tbl <- readRDS('../../ablation-paper/data/modelled\_wind\_unloading\_error\_table.rds') |>   
 mutate(model = 'wind\_model')  
temp\_err\_tbl <- readRDS('../../ablation-paper/data/modelled\_temp\_unloading\_error\_table.rds') |>   
 mutate(model = 'temp\_model')  
  
rbind(wind\_err\_tbl, temp\_err\_tbl)

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

[Figure 10](#fig-mod-time-unld) and [Figure 11](#fig-mod-cpy-load-unld) show the decrease in unloading associated with increased duration in the canopy and increased unloading with increasing canopy snow load respectively. These figures show periods with snow intercepted in the canopy and filtered to below -6 °C and 2 m s-1 wind speed, where unloading attributed to these processes are observed to be reduced in [Figure 9](#fig-mod-wind-unld) and [Figure 8](#fig-mod-temp-unld).

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| Figure 10 |

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| Figure 11 |

## 5 Discussion

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

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

## 6 Conclusions

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

Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. *Hydrological Processes*, *12*(10-11), 1611–1625. <https://doi.org/10.1002/(SICI)1099-1085(199808/09)12:10/11<1611::AID-HYP684>3.0.CO;2-4>

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