Processes Governing the Ablation of Intercepted Snow

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# 1. Introduction

The seasonal snowpack is an essential component of water resources in cold-regions across the globe (Immerzeel et al., 2020; Viviroli et al., 2020), yet are under threat by rapid climate and land cover change (Aubry-Wake & Pomeroy, 2023; Fang & Pomeroy, 2023; López-Moreno et al., 2014; Szczypta et al., 2015). Forest canopies cover over half of the snow covered zone in the northern Hemisphere (Kim et al., 2017) and therefore, understanding these systems are crucial for making informed ecological, land management, and water resource decisions. Vegetation cover can significantly alter the quantity by up to 45% (Essery et al., 2003; Sanmiguel-Vallelado et al., 2020) and timing (Ellis et al., 2010; Safa et al., 2021) of snow that reaches the ground, through initial interception and subsequent ablation via sublimation, melt, and unloading. Needleleaf canopies are particularly effective at intercepting snowfall (Cebulski & Pomeroy, 2025a; Hedstrom & Pomeroy, 1998; Storck et al., 2002), where intercepted snow is subject to increased energy fluxes relative to the the subcanopy snowpack leading to increased rates of melt and/or sublimation (Parviainen & Pomeroy, 2000; Pomeroy et al., 1998; Roesch et al., 2001; Storck et al., 2002). The partitioning of snow to the atmosphere via sublimation (Parviainen & Pomeroy, 2000; Pomeroy et al., 1998) or to the ground through unloading and meltwater drip (Lumbrazo et al., 2022; Roesch et al., 2001; Storck et al., 2002) is highly sensitive to meteorological conditions and forest structure contributing to substantial variability across regions and snowfall events. Coastal humid environments typically exhibit reduced sublimation losses (Storck et al., 2002), while enhanced canopy energy exchange can modify both the timing and physical state of snow reaching the forest floor. Conversely, continental climates with colder and drier conditions may experience substantial canopy sublimation losses (Essery et al., 2003; Parviainen & Pomeroy, 2000; Pomeroy et al., 1998), though these can be mitigated by unloading rates (Lumbrazo et al., 2022; Lundquist et al., 2021; Roesch et al., 2001). Consequently, reliable models of snow accumulation and resulting streamflow in forested basins rely on a comprehensive understanding of interception processes (Clark et al., 2015; Essery et al., 2003; Pomeroy et al., 2022; Verseghy, 2017).

Recent work has highlighted the importance of distinguishing between the initial snow interception and subsequent ablation processes (Cebulski & Pomeroy, 2025b). This separation allows for individual parameterizations for distinct processes, improving both process representation and the modular design of contemporary models—thereby supporting broader applicability across diverse environments (Clark et al., 2015; Pomeroy et al., 2022). In addition, Lundquist et al. (2021) and Cebulski & Pomeroy (2025a) demonstrated improved representation of canopy snow processes without a maximum canopy snow load, typically included in the initial accumulation parameterisation. Together these studies (Cebulski & Pomeroy, 2025b; Cebulski & Pomeroy, 2025a; Lundquist et al., 2021) emphasize the need to revisit canopy snow ablation parameterisations, as existing routines were developed alongside accumulation schemes that already account for part of the ablation process. Moreover, canopy snow unloading parameterisations have demonstrated limited transferability across different climates and forest types (Lumbrazo et al., 2022; Lundquist et al., 2021), and this limitation has attributed as a key area of uncertainty in forest snowpack simulations in hydrological model intercomparisons (Krinner et al., 2018; Rutter et al., 2009).

Ablation of snow intercepted in the canopy as mass clumps of snow towards the ground, typically referred to as unloading, has been shown to be associated with air temperature (Katsushima et al., 2023; Roesch et al., 2001), ice-bulb temperature—which better represents the cooling effect of sublimation compared to air temperature—(Ellis et al., 2010; Floyd, 2012), canopy snowmelt rate (Storck et al., 2002), and wind speed as shown in Fig. 2 for (Bartlett & Verseghy, 2015; Katsushima et al., 2023; Roesch et al.; 2001, 2001), all of which are also a function of the canopy snow load. Additional detail on the individual parameterisations and associated uncertainties related to measurement difficulties and isolating individual process is discussed in Cebulski & Pomeroy (2025b).

Melt of snow intercepted in the canopy is typically represented by either an energy balance approach (Andreadis et al., 2009; e.g., Clark et al., 2015), as a function of air temperature (Roesch et al., 2001), or a function of ice-bulb temperature (Ellis et al., 2010; Floyd, 2012) (Fig. 1). Sublimation is represented using an energy balance approach (e.g., Essery et al., 2003; Verseghy, 2017) or an analytical parameterisation (Ellis et al., 2010) following Pomeroy et al. (1998). Both the Essery et al. (2003) and Pomeroy et al. (1998) parameterisation include an aerodynamic resistance term to decrease the latent heat flux from snow intercepted in the canopy as the canopy fills up with snow and its surface area decreases. However, the resistance term is based on earlier estimates of the maximum canopy snow load which has shown to be an underestimate in many other areas (Cebulski & Pomeroy, 2025a; Lundquist et al., 2021; Storck et al., 2002) and should be reconsidered using a larger maximum load. The merits of including more physically based energy balance methods compared to more empirically based functions for calculating snowmelt and sublimation have not been directly assessed using an event based process investigation.

Quantifying individual canopy snow ablation processes including unloading, melt, and sublimation remains challenging, even with sophisticated lysimetry (Storck et al., 2002) and eddy-covariance systems (Conway et al., 2018; Harvey et al., 2025; Helgason & Pomeroy, 2012b). Consequently, some studies have developed canopy snow ablation parameterizations using methods that do not distinguish individual processes such as above canopy albedo (Bartlett & Verseghy, 2015; Roesch et al., 2001). While these approaches offer useful indicators of overall model performance, they provide limited insight into the accuracy of individual process representations. Lysimeter-based measurements offer more direct process-level observations but are limited by freeze–thaw cycles and concurrent processes (Floyd, 2012; Storck et al., 2002). A hybrid diagnostic approach that combines individual process measurements with simulations, as well as, full-output metrics such as canopy snow load from a weighed tree has yet to be applied but is explored in this study.

The objective of this study is to determine if the theoretical underpinnings and assumptions behind existing canopy snow ablation parameterisations are supported by in-situ observations collected from a subalpine forest in the Canadian Rockies. This study specifically looks at canopy snow ablation after snowfall, initial interception has been discussed in Cebulski & Pomeroy (2025b).

Research Questions:

1. How does air temperature, wind, canopy snow sublimation, and snowmelt influence the rate of canopy snow unloading?
2. To what extent do current theoretical models of canopy snow ablation align with in-situ observations?
3. What modifications of existing models, if any, are necessary to accurately represent ablation of snow intercepted in the canopy and what is the performance of the updated model?

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| Figure 1: The Ellis et al. (2010) and Floyd (2012) (E10) predicted unloading and drip rate (left) and the Roesch et al. (2001) (R01) unloading rate (right) with increasing air temperature. Wind speed for the RW01 parameterisation was set to zero. |

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| Figure 2: The Roesch et al. (2001) predicted unloading rate with increasing wind speed and constant air temperature of -10°C. |

# 2. Study Site and Instrumentation

The observations presented in this study were collected at Fortress Mountain Research Basin (FMRB), AB, -115° W, 51° N, a continental headwater basin in the Canadian Rockies at 2100 m above sea level. Air temperature, humidity, and wind speed were measured at a height of 4.3 m at Forest Tower (FT) Station (Fig. 3). Shear stress was calculated using the EddyPro software (LI-COR Biosciences) based on high-frequency wind measurements from a CSAT3 three-dimensional sonic anemometer (Campbell Scientific) installed at 3.0 m at FT station. The CSAT3 was frequently covered in snow during the analysis period, and thus to provide a complete record of shear stress, a linear relationship between was established between shear stress derived from the CSAT3 and the square of wind speed measured at 4.3 m at the FT station (*R2* = 0.71, *p* < 0.05, see supporting information). This relationship was then used to gap-fill shear stress during periods when the CSAT3 was snow-covered. The precipitation rate was measured by an Alter-shielded OTT Pluvio weighing precipitation gauge installed 2.6 m above ground at Powerline (PWL) Station (Fig. 3). Incoming and outgoing solar radiation was measured by a Kipp & Zonen CNR4 4-Component Net Radiometer installed 3.27 m above the ground at Fortress Ridge Station 2.0 km to the northwest of FT station (-115.2, 50.8). This windy exposed site was selected to reduce snow accumulation on the radiometer, in addition to the CNR4’s built-in heating element. Three subcanopy lysimeters, consisting of a plastic horse-watering trough with an opening of 0.9 m2 and depth of 20 cm suspended from a load cell, were installed to measure subcanopy snow accumulation. A weighed tree lysimeter (subalpine fir) suspended from a load cell (Artech S-Type 20210-100) measured the weight of canopy snow load (kg) and was scaled to an areal estimate of snow load (mm) using snow surveys as in Pomeroy & Schmidt (1993). Additional details on this study site and the meteorological and lysimeter measurements have been described in Cebulski & Pomeroy (2025a). Four tipping bucket rain gauges, 3 Texas Electronics TR-525M and 1 Hyquest Solutions TB4MM were installed along a 15 m transect adjacent to the dense canopy subcanopy lysimeter to measure canopy snowmelt drainage. To isolate the subcanopy lysimeter measurements of canopy snow unloading from throughfall, 15-min intervals were selected that met the following criteria: no atmospheric precipitation, and snow was observed to be intercepted in the canopy using the weighed tree and timelapse imagery investigation.

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| Figure 3: Map showing the location of flux towers and lysimeter instruments. The inset map on the upper left shows the regional location of Fortress Mountain Research basin. |

# 3. Methods

## 3.1 Statistics on Canopy Snow Unloading Relationships

### 3.1.1 Combined influence of predictors on unloading

The influence of air temperature, wind speed, snow load, melt, and sublimation on the unloading process was assessed using a multivariate ordinary least squares (OLS) regression. The analyses tested the following hypotheses:

1. Melt promotes unloading through loss of structural integrity, particle bond weakening, and lubrication.
2. Sublimation promotes unloading via structural degradation and bond weakening.
3. Wind promotes unloading through shear stress on snow, wind erosion, and branch movement.
4. Air temperature promotes unloading by increased elasticity branches and association with melt/sublimation.

Since many of these processes occur simultaneously and could not be isolated experimentally, different combinations of the independent variables were included in the regression to identify which sets of processes significantly influenced unloading. The subcanopy lysimeter unloading measurements had a high relative instrument error due to the relatively small accumulation of unloaded snow over the 15-min intervals. To improve instrument accuracy, while maintain consistency of the unloading measurements with wind speed, the 15-min interval measurements of unloading were aggregated over differing predictor variable bins. Air temperature and wind speed were measured at FT station, canopy snow load from the weighed tree lysimeter (scaled to the canopy of each respective subcanopy lysimeter), and canopy snowmelt and sublimation simulated using the Cold Regions Hydrological Modelling Platform (CRHM). A full description of the CRHM model is described in Pomeroy et al. (2007) and the up to date source code is available at https://github.com/srlabUsask/crhmcode. Sublimation was simulated using Equation 10 following Essery et al. (2003) and snowmelt calculated using available energy from Equation 3 and were both implemented as a new module in CRHM. Independent variable bins that had less than 0.1 mm of accumulated snow were removed, resulting in a mean instrument error of +/- 2% for the remaining bins. The individual processes found to be significant predictors of unloading in the multivariate regression (i.e., shear stress and canopy snow melt) were then isolated to parameterise a model of their effects.

### 3.1.2 Wind induced unloading

The influence of wind, shear stress and canopy snow load on unloading was assessed during intervals without canopy snowmelt. These periods were defined using simulated canopy snowmelt in CRHM and by visual analysis of time-lapse imagery. By excluding periods influenced by melt, the snow captured by the lysimeters is attributed primarily to wind-driven unloading. Although unloading resulting from snow metamorphism or thermally induced branch bending may also contribute, the observed unloading is interpreted to be predominantly wind-induced over these intervals. The relationship between wind speed, shear stress, canopy snow load, and unloading was analyzed using linear and non-linear least squares regression, with shear stress modelled linearly and wind speed modelled exponentially. The linear relationship between shear stress, canopy load, and unloading did not include an intercept term and was thus the coefficient of determination (*R2*) was adjusted following (Kozak & Kozak, 1995).

### 3.1.3 Canopy snowmelt induced unloading

A mass balance approach was incorporated to determine the unloading rate resulting from canopy snowmelt (, mm s-1). The influence of canopy snowmelt on was then assessed by fitting a linear model using an ordinary least squares regression. Since direct measurements of canopy snow unloading are challenging to obtain independently from canopy snowmelt drainage (Storck et al., 2002), the following mass balance was incorporated to determine as a residual:

where is the change in canopy snow load over time, (mm s-1), 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 due to melt (mm s-1), is the canopy snow unloading rate due to wind (mm s-1), is the canopy snow drip rate resulting from 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 (2025b) presents a visual representation of this mass balance.

Then Equation 1 was rearranged to solve for during intervals without or as:

While some components of the canopy snow mass balance can be measured directly with relative ease, such as with the weighed tree, sublimation of canopy snow is more difficult to quantify directly especially in forested mountain environments (Conway et al., 2018; Helgason & Pomeroy, 2012b) and thus was simulated in this study in CRHM using Equation 10 as described in Essery et al. (2003). was measured where possible using the tipping buckets, however problems with freezing of liquid water in the devices limited the amount of that could be collected. Thus, was also supplemented with simulated canopy snowmelt () in CRHM as in Equation 3. Canopy snow ablation periods that were dominated by melt were selected for calculating where the contribution of and to canopy snow ablation was less than 5%.

# 4. Canopy Snow Energy Balance

The energy available for melting snow intercepted in the canopy, (W m-2), which is a function of the canopy snow load () was calculated as:

where and (W m-2) are the net shortwave and longwave radiation heat fluxes to the canopy snow, (W m-2), is the advective energy rate, and and (W m-2), are the turbulent fluxes of latent heat and sensible heat respectively (positive towards canopy snow), (J kg-1 K-1) is the specific heat capacity of ice, and (K s-1) is the change in canopy snow temperature over time.

was determined as:

where is the downwelling shortwave radiation (W m-2), is the albedo of snow intercepted in the canopy (-), (-) is the canopy transmittance to . was determined using Equation from Pomeroy et al. (2009) with half of the leaf area index (LAI), following studies (Kesselring et al., 2024; Weiskittel et al., 2009), who report that approximately 50% of the total leaf area is concentrated in the upper half of coniferous canopies. This provides an approximation of the mean to all snow intercepted in the canopy, and is a simplification from using a partial differential equation to determine the radiation incident to individual height layers within the canopy. Upwelling shortwave radiation reflected off of the surface snowpack is considered negligible contribution to the snow intercepted in the canopy as it is primarily blocked by vegetation elements underlying the canopy snow.

was approximated as:

where is the downwelling longwave radiation from the atmosphere (W m-2), is the longwave radiation upwelling from vegetation elements underlying snow intercepted in the canopy (W m-2), is the downwelling longwave radiation emitted from the underside of the vegetation elements reflected by the subcanopy snowpack (W m-2), and (W m-2) is the outgoing longwave radiation from the top and bottom of the canopy snow layer calculated as:

where is the emissivity (-) of snow taken as 0.99 and is the Stefan–Boltzmann (5.67e-10 W m-1 K-4). was approximated in this study as in Sicart et al. (2006) to take into account the influence of atmospheric moisture on emissivity. was calculated with the assumption that canopy elements were in equilibrium with the air temperature plus any change in vegetation temperature from the extinction of in the canopy (Pomeroy et al., 2009, Eq. 4).

was calculated as:

where is the specific heat capacity of water (J kg-1 K-1), is the specific mass of liquid water in precipitation (mm), is the rainfall temperature (K), is the specific mass of snow in precipitation (mm), and is the snowfall temperature (K).

was calculated as:

where is the air density (kg m-3), is the specific heat capacity of air (J kg-1 K-1), is the air temperature, and is the aerodynamic resistance (s m-1) which was approximated from Equation 4 from Allan et al. (1998) as:

where is the height of temperature measurement (m), is the displacement height (m) which was approximated as 2/3rd the mean canopy height, is the roughness length (m) which was approximated as 1/10th of the mean canopy height, is the wind speed measurement height (m), is von Karman’s constant, 0.41 (-), and is the wind speed measurement at (m s-1).

was calculated as:

where is a resistance for transport of moisture from intercepted snow to the canopy air space (Eq. 28 in Essery et al., 2003), and are the specific humidity (-) at the air temperature and canopy snow temperature respectively. If the height of the air temperature measurement differs from the humidity measurement the term in the Equation 9 should be adjusted to use the the humidity measurement height.

The above sensible and latent heat flux equations assume neutral atmospheric stability conditions, i.e., nearly adiabatic conditions (no heat exchange) which may be appropriate for application with snow which is intercepted in the roughness elements where stability corrections may not be required (Allan et al., 1998). This is also supported by the uncertainty of stability correction in forest canopies (Conway et al., 2018) and mountain environments (Helgason & Pomeroy, 2012a). Solving Equation 3 requires an iterative solution to determine and the remaining terms which are also a function of .

# 5. Modelled Canopy Snow Energy and Mass Balance

Various models of the canopy snow energy and mass balance were implemented in CRHM to facilitate their evaluation. In addition to the updated canopy snow model presented in this study, hereafter referred to as CP25, three other canopy snow models were implemented in CRHM following previous studies by Ellis et al. (2010) and Floyd (2012) (E10), Roesch et al. (2001) (R01), and Andreadis et al. (2009) who built on observations by Storck et al. (2002) (SA09). The E10 model includes canopy snow sublimation as described in Pomeroy et al. (1998), canopy snow unloading based on a maximum canopy snow load and exponential decay over time from Hedstrom & Pomeroy (1998) with modifications described in Floyd (2012) to handle canopy snow melt and drip processes using an ice-bulb temperature threshold. The R01 model represents canopy snow unloading and melt/drip using linear functions of wind speed and air temperature, as well as sublimation using the Pomeroy et al. (1998) parameterisation. The SA09 model unloads snow as a ratio of the canopy snowmelt rate, following observations by Storck et al. (2002) and does not include wind induced unloading. The snowmelt rate from Equation 3 was used to calculate the unloading rate for the Andreadis et al. (2009) unloading, and thus differs from the energy balance routine described in their study. Canopy snow sublimation in SA09 was represented based on the energy balance (Equation 3).

The retention of canopy snow meltwater differs between the four canopy snow models. For E10, liquid meltwater is not retained in the canopy and immediately drips before it can evaporate. The Roesch et al. (2001) air temperature function includes mass unloading of snow and drip and thus handles the removal of meltwater from the canopy and also does not evaporate. Canopy liquid water storage capacity (, mm m-2) from Andreadis et al. (2009) and the updated routine from this study was calculated as:

where is the fraction of the intercepted snow mass that can hold meltwater and is a storage constant of the vegetation elements. Andreadis et al. (2009) estimate equal to 3.5% and , and the two-sided LAI was used. In this study was set equal to 1% and and the one sided LAI was used, as in Ellis et al. (2010) for rainfall interception. The relative contributions of simulated canopy snowmelt (and associated unloading), sublimation, and wind-driven unloading from the CP25 model to total ablation were used to classify each events as either melt-dominated, sublimation-dominated, wind-dominated, or mixed-processes.

# 6. Results

## 6.1 Unloading Relationships

Among the models tested, a multivariate linear regression incorporating canopy snow load, canopy snowmelt, and wind speed provided the highest explanatory power for predicting canopy snow unloading measured by subcanopy lysimeters (*R2* = 0.71, p < 0.05; Table 1). Shear stress was found to explain less variability compared to wind speed, when combined with canopy snow load and snowmelt (*p* < 0.05, *R2* = 0.71). Air temperature and canopy snow sublimation were not significant predictors in any model (*p* > 0.05; Table 1). A model including only canopy load, air temperature, and wind speed produced an *R2* of 0.11, though only canopy load and wind speed were statistically significant (*p* < 0.05). As shown in Fig. 4, unloading rates were substantially more variable across the canopy snowmelt and sublimation bins (0–2 mm hr-1) compared to the air temperature and wind speed bins (0–0.5 mm hr-1). Additional models with additional combinations of independent variables are presented in the supporting information section.

The mean unloading rate was observed to increase with increasing canopy load, air temperature, ice-bulb temperature depression, shear stress, and wind speed (Fig. 4). Despite the insignificant relationships, air temperature and canopy snow sublimation were positively associated with canopy snow unloading, though for sublimation this relationship was limited to sublimation rates between 0 and 0.3 mm hr-1 (Fig. 4). For sublimation rates higher than 0.3 mm hr-1, unloading is observed to decline with further increasing sublimation, as more canopy snow is partitioned to the atmosphere. A decline in unloading is observed for wind speed bins above 3 m s-1 possibly from some wind transport and entrainment into the atmosphere, and corresponding increased sublimation rates.

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| Table 1: Summary of multivariate linear regression results evaluating all combinations of predictor variables for canopy snow unloading including: canopy load (), wind speed (), canopy snowmelt rate (), canopy snow sublimation rate (), and air temperature (). Columns L to Ta show the coefficient estimate for each respective term, and the significance of each term is shown in brackets. Significance codes: \* = p < 0.05; ns = not significant (p > 0.05). The models are ranked by their corresponding AIC value.   | Model Name | Intercept |  |  |  |  |  |  |  | AIC | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | M1 | -0.11 (ns) | 0.02 (\*) | 0.08 (\*) | 0.40 (\*) | — | — | — | 0.79 | -12.8 | | M4 | -0.08 (ns) | 0.04 (\*) | — | 0.39 (\*) | — | 0.75 (\*) | — | 0.71 | 5.5 | | M7 | 0.13 (ns) | 0.02 (\*) | — | 0.32 (\*) | -0.22 (ns) | — | — | 0.54 | 10.0 | | M10 | -0.06 (ns) | 0.02 (\*) | 0.08 (\*) | 0.38 (\*) | — | — | 0.00 (ns) | 0.52 | -4.4 | | M24 | -0.00 (ns) | 0.02 (\*) | 0.05 (\*) | 0.36 (\*) | 0.13 (ns) | — | — | 0.37 | -2.0 | | M40 | 0.07 (ns) | 0.01 (\*) | 0.06 (\*) | — | — | — | 0.01 (ns) | 0.11 | 2.4 | | M63 | 0.22 (\*) | 0.00 (ns) | -0.01 (ns) | — | 0.07 (ns) | — | — | -0.02 | 39.8 | |

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| Figure 4: Scatter plots showing the mean unloading rate for differing bins of air temperature (°C), ice-bulb temperature depression (°C), shear stress (N m-2), canopy snowmelt (mm hr-1), canopy snow sublimation (mm hr-1), and wind speed (m s-1). Note: unloading was measured by the subcanopy lysimeters, air temperature and wind speed were measured at FT station, canopy snowmelt and sublimation were modelled in CRHM. |

### 6.1.1 The Influence of Wind on Unloading

Canopy snow unloading measurements from the subcanopy lysimeters, filtered to include intervals without canopy snowmelt, followed a positive linear relationship with shear stress and a positive exponential relationship with wind speed (Fig. 5). Based on these observed relationships the following equations were fit and tested:

The wind-driven unloading rate, , was represented as a linear function of shear stress:

where is the shear stress at mid canopy height and is a fitting constant.

An exponential function of wind speed was defined as:

where is the wind speed at mid canopy height, and and are fitting constants.

The shear stress relationship (Equation 11) accounted for slightly more variability in unloading (*p* < 0.05, *R2* = 0.61) compared to wind speed (*p* < 0.05, *R2* = 0.54) (Table 2). The mean bias of the shear stress model of 0.037 mm hr-1 is also lower compared to the wind speed model of 0.048 mm hr-1, additional model error statistics and fitting coefficients are provided in Table 2. Both models exhibited considerable scatter across the different bins, with notable uncertainty within each bin resulting from instrument error and other processes than wind contributing to unloading (Fig. 5). The wind-induced unloading rate was observed to be higher for bins with higher canopy snow load across nearly all bins (Fig. 5). The *R2* of both the shear stress and wind speed relationships is much higher than the amount of variance explained by wind speed when including intervals with melting snow (Table 1). The higher *R2* of the shear stress model compared to wind speed, coupled with the better physical representation of kinetic energy, provided the reasoning for selecting shear stress as the independent variable to predict wind-induced unloading in the model evaluation.

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| Figure 5: Canopy snow unloading rate measured by the subcanopy lysimeters versus shear stress (left) and wind speed (right) during periods without canopy snowmelt. The dots represent mean unloading rates within bins of shear stress and wind speed; error bars indicate +/- 1 standard deviation. The fitted lines show predictions from Equation 11 (left) and Equation 12 (right). |

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| Table 2: Summary of the performance and regression coefficients for the relationship between canopy snow unloading with wind speed (Equation 11) and shear stress (Equation 12), as shown in Fig. 5. Coefficients are developed for hourly unloading.   | Metric | Wind | Shear Stress | | --- | --- | --- | | Mean Bias (mm/hr) | 0.048 | 0.037 | | Mean Absolute Error (mm/hr) | 0.087 | 0.115 | | Root Mean Square Error (mm/hr) | 0.11 | 0.15 | | Coefficient of Determination () | 0.54 | 0.61 | | Coefficient a | 4.62e-03 | 3.31e-01 | | Significance of a | p < 0.05 | p < 0.05 | | Coefficient b | 3.93e-01 | NA | | Significance of b | p < 0.05 | NA | |

### 6.1.2 The Influence of Melt on Unloading

The ratio of canopy snow unloading (from Equation 2) to melt (simulated in CRHM using Equation 3) was observed to increase with canopy snow load (weighed tree) for events in which wind-driven unloading and/or sublimation contributed less than 5% to total ablation (Fig. 6). This ratio ranged from approximately 0–0.5 (-) for snow loads between 0 and 5 mm, and increased linearly to a maximum of 5 at a canopy snow load of 30 mm (Fig. 6). This relationship was represented by the following equation:

where is the ratio of unloading to canopy snowmelt and is the canopy snowmelt rate (mm hr-1). Equation 13 is similar to Equation 33 in Andreadis et al. (2009); however, instead of a constant value of 0.4 for , it was determined as:

where and were determined as 0.16 and -0.5, respectively, using an ordinary least squares regression.

Equation 13 resulted in a statistically significant relationship (*p* < 0.05, *R2* = 0.73) based on ordinary least squares linear regression (Fig. 6). Additional observations of canopy snowmelt from the tipping buckets were also used to estimate the canopy snow unloading-to-melt ratio (Fig. 6); however, the number of usable observations was limited due to freeze-thaw events that affected the instrument functionality. However, the sparse measurements are still useful in providing some indication of the validity of the CRHM canopy snowmelt/drip routine (Fig. 7). The CRHM estimated cumulative drip is higher than the tipping buckets for two out of the three melt events. A difference in the timing and magnitude of the observed and simulated values were expected due to both instrument uncertainties in the tipping buckets (freezing/thawing) and in the canopy snow energy balance simulation.

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| Figure 6: The ratio of canopy snow unloading (weighed tree residual) to snowmelt across different canopy snow load bins and events. Black dots represent the observed cumulative unloading divided by the cumulative simulated snowmelt from the updated CP25 canopy snow routine in CRHM. Red dots show the cumulative observed unloading divided by snowmelt measured by the tipping buckets. Multiple dots within a bin correspond to different events. The blue line represents the best-fit line derived from ordinary least squares regression. |

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| Figure 7: Cumulative canopy snow drip from the mean of the four tipping buckets (TB) and simulated in CRHM using Equation 3 (CP25). |

## 6.2 Event-based Evaluation of Canopy Load and Hourly Total Ablation Models

The updated canopy snow model (CP25)—which incorporates canopy snowmelt and sublimation based on the energy balance (Equation 3), wind-driven unloading (Equation 11), and melt-induced unloading (Equation 13)—was evaluated against measurements from the weighed tree lysimeter over 17 post-snowfall events. These events had air temperatures ranging from -30.5°C to 6.9°C and wind speeds from calm to 5.3 m s-1 (Table 3). Melt events exhibited >95% of ablation from melt related processes, with the exception of the 2022-04-23 event, where sublimation accounted for 13% of total ablation (Table 3). Events classified as sublimation- or wind-dominated showed negligible melt contributions, typically 0%, with the exception of where melt contributed 5%. Due to the frequent co-occurrence of wind and sublimation, these processes could not be as clearly separated from one another; sublimation contributed up to 40% for the wind-dominant events, and similarly, wind-driven unloading contributed up to 40% for the sublimation-dominated events.

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| Table 3: Meteorology of the 17 select ablation events. Air temperature, relative humidity, and wind speed were measured at FT station. The process fractions show the fraction of canopy snow ablation for each process.   |  |  | Air Temperature (°C) | | | Wind Speed (m/s) | | | Relative Humidity (%) | | | Process Fraction (-) | | | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | Start Date | Event Type | Min | Mean | Max | Min | Mean | Max | Min | Mean | Max | Melt | Wind | Subl. | | 2022-04-23 | melt | -1.8 | 2.0 | 5.3 | 0.4 | 0.8 | 1.2 | 35.8 | 60.2 | 82.8 | 0.85 | 0.01 | 0.13 | | 2022-06-14 | melt | 0.1 | 3.1 | 6.9 | 0.1 | 0.8 | 1.7 | 66.6 | 90.6 | 99.8 | 1.02 | 0.00 | -0.01 | | 2022-06-24 | melt | 0.8 | 3.4 | 5.7 | 0.2 | 0.6 | 1.1 | 82.5 | 89.7 | 97.8 | 1.01 | 0.00 | -0.01 | | 2023-05-08 | melt | 0.9 | 2.1 | 4.4 | 0.4 | 0.7 | 1.0 | 91.1 | 96.7 | 98.6 | 1.01 | 0.01 | -0.01 | | 2023-06-15 | melt | 0.5 | 3.0 | 6.8 | 0.7 | 1.1 | 1.6 | 76.7 | 93.3 | 99.4 | 0.99 | 0.03 | -0.01 | | 2023-06-21 | melt | -1.0 | 1.4 | 5.5 | 0.9 | 1.3 | 1.8 | 81.3 | 95.0 | 100.0 | 0.95 | 0.05 | 0.00 | | 2022-03-09 | mixed | -25.2 | -15.7 | -7.6 | 0.0 | 1.6 | 3.9 | 35.3 | 62.4 | 100.0 | 0.00 | 0.42 | 0.58 | | 2022-03-29 | mixed | -5.6 | 0.6 | 4.7 | 0.3 | 1.0 | 1.6 | 31.1 | 57.1 | 93.2 | 0.52 | 0.03 | 0.45 | | 2022-04-21 | mixed | -7.2 | -0.4 | 3.4 | 0.5 | 1.0 | 1.9 | 47.8 | 65.9 | 95.2 | 0.49 | 0.07 | 0.45 | | 2022-03-02 | sublimation | -3.9 | -2.1 | 0.9 | 0.0 | 0.9 | 2.1 | 59.4 | 88.0 | 97.6 | 0.00 | 0.38 | 0.63 | | 2022-03-20 | sublimation | -8.1 | -6.0 | -3.9 | 0.4 | 1.4 | 3.5 | 44.4 | 63.4 | 89.7 | 0.00 | 0.14 | 0.87 | | 2022-03-24 | sublimation | -8.7 | -2.7 | 3.8 | 0.1 | 1.1 | 3.6 | 29.3 | 55.0 | 99.6 | 0.05 | 0.20 | 0.76 | | 2023-03-14 | sublimation | -12.4 | -6.6 | 3.0 | 0.4 | 1.2 | 2.3 | 22.7 | 59.4 | 89.3 | 0.00 | 0.37 | 0.63 | | 2023-04-17 | sublimation | -6.4 | -4.4 | -2.2 | 0.9 | 2.0 | 4.3 | 23.8 | 50.6 | 85.7 | 0.00 | 0.18 | 0.86 | | 2022-12-01 | wind | -21.7 | -13.8 | -3.1 | 0.5 | 1.7 | 4.5 | 41.0 | 83.6 | 100.0 | 0.00 | 0.76 | 0.24 | | 2023-02-24 | wind | -30.5 | -21.3 | -14.8 | 1.4 | 2.4 | 5.3 | 53.9 | 83.5 | 100.0 | 0.00 | 0.87 | 0.14 | | 2023-02-26 | wind | -12.8 | -11.8 | -10.3 | 0.8 | 1.4 | 2.0 | 70.6 | 82.7 | 95.3 | 0.00 | 0.62 | 0.41 | |

Simulated canopy snow load using the CP25 model closely matched the weighed tree observations across all 17 events, demonstrating the most consistent agreement among the models evaluated (Fig. 8). When averaged by event type, CP25 maintained a consistently low mean bias, in contrast to existing models, which exhibited larger and more variable biases (Fig. 9). The large declines in canopy snow load for E10 (Fig. 8) are due to the maximum canopy snow load used in this model which ranged from 7 to 12 mm depending on the fresh snow density (which is a function of air temperature).

For the melt events, the two energy balance based models (SA09 and CP25) slightly over estimate the rate of canopy snowmelt and unloading, resulting in negative mean biases of 0.04 mm hr-1 and -0.09 mm hr-1 for CP25 and SA09 respectively. The slight improvement for CP25 compared to SA09 comes from the better representation of the increase in unloading for higher canopy snow loads as observed for the 2022-06-14 event which had much higher snow load of 30 mm. The air temperature (R01) and ice-bulb temperature (E10) models have much less consistency over these events and resulted in much greater range in mean biases for the temperature based methods (Fig. 9) and a mean bias of over 0.45mm hr-1.

The simulated canopy liquid water capacities of the CP25 and SA09 models are evident during all melt events where the simulated rate of ablation slows for small canopy snow loads below ~1.5 mm and ~0.3 mm for CP25 and SA09 respectively. For events other than 2022-04-23, the observed decline in the total ablation rate tends to initiate at canopy loads around 2 to 3 mm—higher than those predicted by CP25 and SA09. This discrepancy may result not only from differences in liquid water storage capacity but also from the presence of refrozen meltwater, which likely sublimates and/or melts more slowly than snow. However, both the CP25 and SA09 models treat the refrozen meltwater as new additions to the canopy snow reservoir.

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| Figure 8: Time series of canopy snow load for individual events measured by the weighed tree (Observed) and simulated using the various models. |

For the sublimation events, all models performed well with mean biases ranging from -0.01 to 0.02 mm hr-1, with a slight improvement in the the mean bias of the updated routine of 0.004 mm hr-1 (Fig. 9). An over estimation of canopy snowmelt by the ice-bulb temperature based E10 model causes the steep initial decline in canopy snow load for event 2022-03-02 which is not registered by the weighed tree or other models. However, the overestimation of ablation for this event by E10 is balanced out by underestimates for other sublimation events with some wind-driven unloading as this process is not included in this model (Table 3). For events 2022-03-02 and 2023-03-14 the R01 model overestimates canopy snow ablation due to an over estimation of wind-driven unloading (Fig. 8). The energy balance based routines are better able to represent the reduction in sublimation during cool clear nights, resulting from longwave radiation losses, and can be seen during some of the sublimation event nighttime periods, especially for the SA09 model which does not include wind-driven unloading (see 2022-03-24 and 2023-03-14 in Fig. 8). The E10 and R01 models estimate canopy snow sublimation using the Pomeroy et al. (1998) analytical model, which assumes that the canopy snow surface temperature remains in thermoequilibrium with the air temperature (Fig. 8). For the 2022-03-24 event, the CP25 and SA09 models initially underestimate the ablation rate which coincides with ~90% relative humidity and -5°C air temperatures followed by a steep increase in sublimation as temperatures warm above 0°C and relative humidity drops below 30%. Uncertainty in the air temperature, humidity, and radiation measurements used to drive the energy balance based models in addition to simplifications in the energy balance are interpreted to explain some of the simulation errors by CP25 and SA09.

The importance of representing wind-driven unloading is highlighted during wind-dominated events, where models that simulate this process exhibiting lower mean bias of 0.21 mm hr-1 for R01 and 0.29 mm hr-1 for CP25. In contrast, simulations that do not explicitly account for wind-driven unloading showed a higher mean bias exceeding 0.59 mm hr-1 (Fig. 9). Although the E10 model does not include wind-driven unloading, it performs best for the 2023-02-26 event (Fig. 8) due to its relatively slow time-based unloading rate compared to CP25 and R01 which over estimate total ablation for this event. The R01 model over estimates the mean event unloading for events 2022-12-01 and 2023-02-26 suggesting the rate of unloading coefficient may be too high for this site. The CP25 model is slightly more stable across the three wind-dominant events, but still underestimates total ablation for event 2023-02-24 which has peak wind speeds of over 5 m s-1. Over this event, 1.3 mm of snow entered the adjacent precipitation gauge and is interpreted to be from wind transport, as observed clear skies confirmed no atmospheric precipitation. The amount of snow observed to unload from the canopy into the subcanopy lysimeters during this event was consistent with simulated unloading in CRHM (see supporting information) suggesting that the remaining unaccounted-for snow was likely entrained into the atmosphere and sublimated and/or transported to distant sites.

For events where wind-driven unloading and sublimation both contribute significantly—i.e., 2022-03-09, 2022-03-02, 2023-03-14, and 2023-02-26, each with more than 0.4 contribution from both processes—the updated routine shows the highest consistency with observations (Fig. 8). In contrast, the mixed events on 2022-03-29 and 2022-04-21, which involved more than 0.45 contribution from both melt and sublimation, were best represented by the E10 model (Fig. 8).

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| Figure 9: Boxplots illustrating the distribution of mean event biases across different parameterisation sets for each event type, evaluated using observations from the weighed tree. The rectangle vertical extent represents the interquartile range (IQR), the horizontal line within each box indicates the median, and the whiskers extend to 1.5 times the IQR. Cicular points beyond the whiskers represent outliers. The diamond represents the mean of the event biases and the triangle is the RMSE. |

## 6.3 Canopy Snow Partitioning

During melt-dominated events, all four parameterisations showed relatively consistent partitioning of canopy snow, with most being delivered to the ground via unloading and drip, and only a small fraction returned to the atmosphere through sublimation and evaporation of melted snow (Fig. 10). For the sublimation-dominated events, the two parameterisations that include wind-driven unloading (R01 and CP25) had differing fractions of snow unloading to the ground with a higher fraction for R01 due to the higher wind-driven unloading rate compared to CP25. However, SA09 partitioned all snow back to the atmosphere via sublimation despite the moderate wind speeds observed over the sublimation events. The E10 parameterisation resulted in a greater fraction of snow reaching the ground compared to CP25 for 4 out of 5 of the sublimation events, due to the temporal unloading parameterisation in E10. For the wind events, R01 unloaded the highest fraction of snow to the ground over all three events compared to the other models. The SA09 parameterisation, similar to the sublimation events, returned all intercepted snow back to the atmosphere due to the absence of a wind-driven unloading parameterisation. Although CP25 and E10 include differing unloading processes, when averaged over all events the have a similar fraction of snow reaching the ground (70%) versus the atmosphere (30%) (Table 4). SA09 has the largest discrepancy which returned 40% of intercepted snow back to the atmosphere and the R01 with the least amount of snow reaching the atmosphere with 24%.

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| Figure 10: Bar chart illustrating the proportion of intercepted snow that was either lost to the atmosphere or transferred to the ground through unloading or melt for each of the 17 selected ablation events. |

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| Table 4: Fraction of intercepted snow returned to the atmosphere or input to the ground for each parameterisation over the 17 select ablation events.   | Model | Atmosphere (-) | Ground (-) | | --- | --- | --- | | CP25 | 0.29 | 0.71 | | E10 | 0.31 | 0.69 | | R01 | 0.24 | 0.76 | | SA09 | 0.40 | 0.60 | |

# 7. Discussion

## 7.1 Processes Driving Canopy Snow Unloading

The measurements of canopy snow unloading (Table 1) provide support for the hypotheses that canopy snowmelt and wind-driven unloading—which are both also moderated by canopy load—are the primary processes driving canopy snow unloading. The ratio of unloading to canopy snowmelt was found to increase with increasing canopy snow load (Fig. 6), and differs from Storck et al. (2002) who originally found the ratio of canopy snow unloading to melt to be constant at 0.4. The measurement difficulties noted by Storck et al. (2002) limited their estimate of this ratio to a single mid-December event and thus did not observe any association with canopy snow load. Similar instrument difficulties limited our tipping bucket measurements of subcanopy snowmelt drainage to three events, but still showed an increasing trend in the unloading to melt ratio with snow load also confirming this hypothesis. Research by Roesch et al. (2001) and Katsushima et al. (2023) also found a relationship between unloading resulting from the melt process, but was represented by empirical functions of air temperature and solar radiation (Katsushima et al., 2023; Roesch et al., 2001). Although branch bending has been shown to be associated with air temperature (Schmidt & Gluns, 1991; Schmidt & Pomeroy, 1990), the increase in unloading with air temperature was mainly found to occurring around the melting point (Fig. 4) and thus in our observations did not need to be represented separately from unloading associated with canopy snowmelt. The maximum canopy snow load incorporated by the E10 model is also clearly seen to be too low, causing large deviations from the observed canopy snow load (Fig. 8). The improved representation of the melt events is also attributed to a new canopy snow energy balance described in Equation 3. This allows the rate of canopy snowmelt to better reflect the available energy and also Equation 13 helps represent the associated increase in canopy snow unloading with snowmelt (Fig. 8) compared to more empirically based functions (Katsushima et al., 2023; Roesch et al., 2001).

Wind driven unloading was found to increase exponentially with wind speed and increase linearly with shear stress (Table 2). This differs from previous studies who typically represent this process as a linear function of wind speed and canopy load (Bartlett & Verseghy, 2015; Katsushima et al., 2023; Roesch et al., 2001) as shown in Fig. 2. The higher *R2* found for shear stress compared to wind speed for predicting unloading—when excluding melt events (Table 2)—is due to the better relation of shear stress with the kinetic energy transfer from wind to snow, wind transport, and movement of the canopy. Still, the wind-driven unloading process resulted in the highest overall mean biases compared to the melt and sublimation dominated events (Fig. 9). Additional factors that may influence wind-driven unloading that are not considered in the new parameterisation (Equation 12) include differences in snow density, and increased liquid water content at warmer temperatures increasing cohesion and adhesion to the canopy which may provide some resistance to wind induced unloading. However, a statistically significant negative influence of air temperature on wind speed was not found, likely due to the strong positive association of air temperature and melt on unloading. Equation 12 also does not directly include wind transport or erosion of snow into the atmosphere

The density of snow intercepted in the canopy is expected to influence both wind-driven and melt-induced unloading processes, yet this factor is not explicitly represented in current models. Fresh, low-density snow typically exhibits lower cohesion and adhesion compared to older snow, which may have undergone freeze-thaw cycles or equitemperature metamorphaisism—processes that increase snow density and mechanical resistance to unloading. While vapour deposition and rime-ice accumulation is simulated in some models (e.g., Clark et al., 2015; Ellis et al., 2010) via the latent head flux parameterisation, it is usually treated as additions to the canopy snow reservoir. However, in humid or maritime regions rime can form dense, ice-like structures (e.g., Berndt & Fowler, 1969) with high resistance to unloading by either melt or wind (Lumbrazo et al., 2022). Although canopy snow density is expected to influence the ablation processes high enough canopy snow densities to influence the ablation process were not observed in this study, yet it remains a key research gap for some regions.

Some evidence of increased unloading associated with sublimation was observed (Fig. 4), consistent with some previous findings (MacDonald (2010)) theorized to be due to the reduction in structural integrity and bond weakening of the canopy snow clumps as snow particles are removed through sublimation. However, the relationship in Fig. 4 was weak and statistically insignificant and limited to relatively low sublimation rates. It is possible that this apparent associated arises from the concurrent increase in canopy energy inputs that promote both sublimation and other unloading mechanisms such as melt and wind-driven removal.

## 7.2 Performance Comparison of Unloading Parameterisations

The improved performance of the new CP25 model across a range of meteorological conditions—including warm and humid, cold and dry, windy, and mixed events—demonstrates the robustness of physically based representations of the energy balance and snow unloading processes (Fig. 8). In contrast, previously developed models had missing processes such as wind-driven unloading (SA09 and E10) or had temperature based representations of melt and drip processes (R01 and E10) which limited their applicability across varying environmental conditions. While the SA09 model—originally developed in a relatively warm maritime climate with limited wind influence (Storck et al., 2002)—performed comparably to CP25 during melt-dominated events, its lack of wind-induced unloading led to poor performance for wind- and sublimation-dominated events. This process omission caused SA09 to overestimate sublimation when averaged over all events, returning a much greater fraction of intercepted snow back to the atmosphere (Table 4). Moreover, the constant canopy snow unloading to melt ratio of 0.4 in the SA09 model led to reduced performance for one melt event with canopy snow loads up to 30 mm, where the CP25 model better predicted an increase in the canopy snow unloading to melt ratio. A lower liquid water holding capacity for the SA09 model led to a slight under estimation in canopy load for the tail end of most of the melt events.

The temperature-based (E10 and R01) models showed inconsistent performance, particularly during melt events, where they generally underestimated ablation due to their reliance on air temperature or ice-bulb temperature as proxies for energy input into the canopy. Although E10 lacked a representation of wind-driven unloading, its exponential decay parameterisation partially compensated for this process, but still underestimated overall ablation for the wind-dominated events (Fig. 8). Conversely, R01 systematically overestimated wind-driven unloading, resulting in an overestimate of total ablation during both wind- and sublimation-dominated events (Fig. 8). The over estimation of wind-driven unloading from the Roesch et al. (2001) based model compared to the wind-driven unloading function developed in this study may be attributed to the use of above canopy albedo as a proxy of canopy snow unloading, while the subcanopy lysimeter based measurements used in this study observed a more direct measurement of the canopy snow unloading rate. However, the wind unloading coefficients are likely site specific (Lumbrazo et al., 2022) and related to forest structure and snow conditions which will require additional field-based investigations on canopy snow unloading to test their transferability. By explicitly representing canopy snow melt and sublimation as well as wind-driven and melt-induced unloading, CP25 achieved more consistent performance across a diverse range in canopy snow ablation events reducing event-to-event variability in bias.

The lack of wind-transport in the CP25 model explains the underestimation of wind-driven ablation for one of the wind-dominated ablation events (2023-02-24, Fig. 8). The wind transport of canopy snow to nearby sites over this event was observed to be relatively small at 1.3 mm of a total of 20 mm of canopy snow that ablated over the event. The amount of snow unloaded into the subcanopy lysimeters was found to agree with the CP25 model over this event (see supporting information) and therefore the ~9 mm of canopy snow ablation not accounted for by CP25 over this event is interpreted to be due to both uncertainties in the wind-driven unloading model (Fig. 5) and some entrainment of canopy snow into the atmosphere which was either transported to far away sites and/or sublimated. This is similar to findings Troendle (1983) but disagrees with Hoover & Leaf (1967) who suggested the majority of wind transported snow is transported to adjacent sites with minimal influence of sublimation.

## 7.3 Canopy Snow Partitioning

While the CP25 model shows improved accuracy across the melt-, sublimation-, and wind-dominated events there is still some uncertainty in the magnitude of snow that reaches the ground versus the atmosphere. For the melt events while the total ablation is closely matched for CP25, the amount of canopy snow meltwater that was evaporated was not measured in this study. The comparison of CP25 to the amount of canopy snow meltwater drainage into the tipping buckets (Fig. 7 width) provides the best validation of this partitioning and suggests there may be a slight over estimating in the amount of liquid water reaching the ground and thus an underestimating in canopy snow meltwater evaporation. This evidence is corroborated by the over estimation of total ablation at the tail end of the melt events for CP25 and suggests the canopy may be able to hold more liquid melt water and thus subject it to evaporation. Therefore, the liquid water holding capacity of the canopy remains uncertain, directly influencing how much intercepted meltwater is subject to evporation. Although the total interception loss from evaporation during the melt events was predicted to be minimal (Fig. 10); the weak performance of all models at the end of the melt events highlights the need for further research in this area. Similarly, while accurate performance of CP25 was achieved for sublimation events with low wind speed—and thus little wind-driven unloading—events with higher winds had uncertainty in the amount of snow unloaded versus sublimated.

There is large variability in the amount of snow partitioned to the atmosphere and to the ground depending on the canopy snow ablation routine that is selected (Fig. 10). For example, by not including wind-driven unloading as in the SA09 model, 10% less snow reached the ground over all 17 of the selected events (only 3 were considered wind-dominated) due to the longer duration snow was intercepted in the canopy compared to the CP25 and E10 models. Although E10 and CP25 include differing process representations a similar fraction of snow was simulated to reach the ground vs returned to the atmosphere. The agreement between CP25 and E10 is encouraging, since the E10 has been tested on subcanopy snow accumulation to perform well across the globe, but may have been getting the right answer for the wrong reasons due to the large deviation in process representation between CP25 and E10. For regions which intercept a larger amount of snow, where the E10 maximum canopy snow load would over estimate the amount of unloading, a greater deviation between the E10 and CP25 model is expected.

## 7.4 Future Directions

Physically based approaches such as CP25 are particularly relevant under climate change, where warming may reduce the reliability of temperature-dependent models like E10 and R01 as shown in Fig. 9. The improved representation of melt events by CP25 and SA09 supports the use of energy balance methods across a range of meteorological conditions, compared to temperature based routines (E10 and R01) which had reduced performance over these events. Among all canopy snow ablation processes, wind-driven unloading and introduced the most uncertainty. Although the revised model performed best at this site, further validation is required across a range of climates and forest structures. Since wind-driven unloading and sublimation are competitive processes, both strongly influence whether snow is returned to the atmosphere or reaches the ground.

Key limitations remain in measuring canopy snow sublimation (Conway et al., 2018; Harvey et al., 2025; Helgason & Pomeroy, 2012b) and separating snow unloading from meltwater runoff (Floyd, 2012; Storck et al., 2002), which are inhibiting the development and validation of parameterisations. While separating the initial interception and ablation processes—as proposed in recent work (Cebulski & Pomeroy, 2025b; Cebulski & Pomeroy, 2025a)—will improve process representation, these routines still need to be evaluated together. Incorporating the updated unloading schemes developed here could improve the representation of canopy snow ablation and, by extension, the partitioning of precipitation and canopy albedo in hydrological and land surface models. Nonetheless, further testing is needed across different sites, climates, forest types, and spatial scales to assess model transferability and performance.

# 8. Conclusions

* Canopy snow load, wind speed, and melt rate were statistically significant predictors of snow unloading, collectively explaining 80% of its variability.
* New parameterisations for wind-driven and melt-induced unloading are introduced, with key differences from previously established approaches.
* Shear stress, was found to be a stronger predictor of canopy snow unload (*R2* = 0.66) compared to wind speed (*R2* = 0.52) for non-melt periods.
* Snow unloading during melt events was linked to the canopy melt rate, and while consistent with existing ratio-based approaches, a new observation was that this ratio increased with greater canopy snow load.
* Observed drip from canopy snowmelt during three warm events generally matched simulated meltwater drainage, though some measurement uncertainty remains.
* The updated canopy snow ablation scheme—combining wind- and melt-induced unloading with an energy balance-based melt and sublimation routine—produced the most consistent results across varied meteorological conditions. However, wind-dominated events still showed the largest uncertainties.
* Partitioning of snowfall between ground and atmosphere varied most among parameterisations for wind- and sublimation-dominated events, while melt-driven events showed greater consistency across models.

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