THE INFLUENCE OF FOREST CANOPY STRUCTURE ON SNOW INTERCEPTION: DESIGN AND IMPLEMENTATION OF A NEW MODEL

C. David Moeser[1]

ABSTRACT

Seasonal snow in forested areas can account for 17% of total winter terrestrial water storage. Snow interception ranges from 0 to 60% of the total annual snowfall in forested areas and creates large snow storage differences between open and forested environments. Many snowmelt models have included interactions of canopy with snow-cover, but these models included overly simplistic representations of interception processes and could not reproduce the natural heterogeneity in under-canopy snow cover. This study developed and implemented an interception model valid for discrete time steps, various scales, and heterogeneous canopy structure. New forest structure metrics derived from aerial LiDAR data were developed and introduced into the new model to better describe forest structure. Inclusion of these novel forest structure metrics allowed the new interception model to mimic the heterogeneous canopy structure layout, while prior modeling efforts demonstrated homogenous interception estimations even under highly heterogeneous canopy conditions. The large variance of estimated interception between points from the new model were validated from ~84,000 manual measurements and translated to approximately double the variance of under-canopy snow depth, snow-water equivalent, and canopy sublimation compared to prior models. (KEYWORDS: interception, forest snow hydrology, forest-snow interaction, snow distribution)

INTRODUCTION

In the United States, streamflow from forest land provides almost two-thirds of the total freshwater supply, with much of it coming from snow-dominated watersheds. Yet forest structures within these zones are affected by climate change, variations in land management, and a variety of natural disturbances, all of which create uncertainty regarding the fate of this major source of water. Climate-change impacts are projected to substantially increase the northern extent of the boreal forest, and one-third to two-thirds of the tundra could transition to forest by the end of the century (IPCC, 1997). Accurate estimations of snowmelt and runoff rates from forested areas are of great importance to hydrologic forecasters throughout the world. However, despite their importance, forest snowmelt and runoff are still poorly understood. The necessity to understand the interplay between forest structure and snow processes is made more important by alarmingly high global water withdrawal predictions ranging from an 18% to over 50% increase from the 2007 level (Rosengrant et al., 2002).

Snow accumulation and ablation processes in open areas are reasonably well understood and represented in many numerical melt models for various scales and climate regimes (Jordan, 1991; Marks et al., 1992). However, the processes within forested areas that dictate snow accumulation and ablation vary dramatically (unlike open areas). They demonstrate not only local (forest stand) and regional (landscape) fluctuations but also heterogeneity at extremely fine scales (individual canopy elements). The spatial properties of forest canopies greatly influence under-canopy snow physical properties, and create a much larger spatial heterogeneity of snow pack under-canopy as compared to open areas.

A substantial number of snowmelt models have included forest canopy representations. In 2007, an assessment of 33 of these models was performed (Rutter et al., 2009). This model inter-comparison initiative (SnowMIP2) constituted the first comprehensive assessment of the capabilities of these models to reproduce snow cover dynamics under canopy and revealed several important shortcomings. Not only was a best-fit model not found for the sites used, but performance (of all models) showed much lower consistency within forested areas than in open areas, which underscored the sometimes overly simplistic representation of canopy processes. All the models included in the comparative project that utilized a snow interception module (29 of 33) integrated canopy closure (CC) and / or leaf area index (LAI) to parameterize the canopy. However, field points that have the same LAI or CC can feature widely different large-scale canopy structures, such as open areas surrounding these points. Furthermore, the importance of the larger-scale forest structure has been highlighted as a major factor determining under-canopy

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[1] C. David Moeser, United States Geological Survey, 6700 Edith Blvd NE, Albuquerque, NM 87113

snow-water equivalent (SWE) accumulation patterns and the timing of under-canopy snowmelt (Golding and Swanson, 1986; Varhola and Coops, 2013). Specifically, a simplified representation of canopy structure can hamper the ability of current snowmelt models to accurately quantify the effect of forest canopy on snow accumulation and melt.

METHODS

In fall 2012, seven forest and two open-field areas were equipped with 1,982 surveyed and marked points for a three-year study (2012-2015) surrounding Davos, Switzerland. Approximately 84,000 interceptions, under-canopy snow depth (SD), and under-canopy SWE measurements were taken at these points, constituting the largest interception field study performed to date. Aerial LiDAR data (ALS) were available at all field areas from a flyover in 2010. Hemispherical photos were taken at all field areas. LAI and CC were estimated at all field points from the conversion of the birds-eye ALS perspective into a ground viewpoint angular perspective (synthetic images) using the technique derived from Moeser et al. (2014). Novel forest structure metrics were also created at each field point in order to describe the location of the points relative to canopy gaps from the implementation of the vector searching algorithm from Moeser et al. (2015a). A new interception model was created that integrated the novel structure metrics (Moeser et al., 2015b). This model along with the standard interception model (Hedstrom and Pomeroy, 1998) were integrated into the ‘Factorial Snow Model’ (FSM) snowmelt model (Essery, 2015). The integrated FSM model was run at all field points, and under-canopy SWE estimates from both model scenarios were compared with the field data and canopy structure layout (Moeser et al., 2016).

RESULTS AND DISCUSION

The synthetic images accurately estimated LAI and CC (r: 0.93 for CC and r: 0.83 for LAI) when compared to the parameters derived from hemispherical photos at 112 ground points (Figure 1). Two new forest structure metrics, ‘mean distance to canopy’ and ‘total gap area’, displayed the highest correlations to interception. The new metrics were used in tandem with CC to define the maximum interception capacity (I_{max}, mm) of a canopy element:

$$I_{max} = 2.167(x_1) - 3.410\,(x_1)^2 + 55.761(x_2) + 181.858(x_2)^2 - 2.493(x_3) + 0.499(x_3)^2 + 20.819 \qquad [1]$$

where x_1 is the log of mean distance to canopy (m), x_2 is the log of CC, and x_3 is the log of total gap area (m^2). Two physical processes, snow bridging and branch bending, were apparent at the field points, and an interception efficiency (interception / precipitation) function based upon precipitation values was formulated to mimic these processes. I_{max} and the efficiency distribution were then integrated to create a conceptual model of interception based upon the snow interception measurements.

$$I = \frac{I_{max}}{1+e^{-k(P-P_o)}} \qquad [2]$$

where P is total storm precipitation (mm), and the constants k and Po are 0.3 and 13.3, respectively. This model displayed a ~27% increase in R^2 (from 0.39 to 0.66) and a ~40% reduction in RMSE (from 5.19 to 3.39) as compared to the standard model at the point scale (Figure 2). When up-scaled to larger grid sizes, the model demonstrated further increases in performance.

Due to the inclusion of forest structure parameters (mean distance to canopy and total gap area) in the new model, modeled interception was able to better account for canopy structure layout, while prior modeling efforts demonstrated homogenous interception estimations even under highly heterogeneous canopy conditions (Figure 3). The large variance of estimated interception between points from the new model translated to approximately double the variance of under-canopy SD, under-canopy SWE, and snow-on-canopy sublimation when compared to prior models. This variance was dictated by the canopy structure, and analogous to the interception estimates, demonstrated a much better fit to the field data than prior modeling approaches. The new interception model resulted in SD simulations that were consistent with the small-scale patterns evident from the ground observations. The updated FSM represents one of the first snowmelt models that is able to reflect the spatial variability in forest snow caused by local heterogeneity in the canopy.

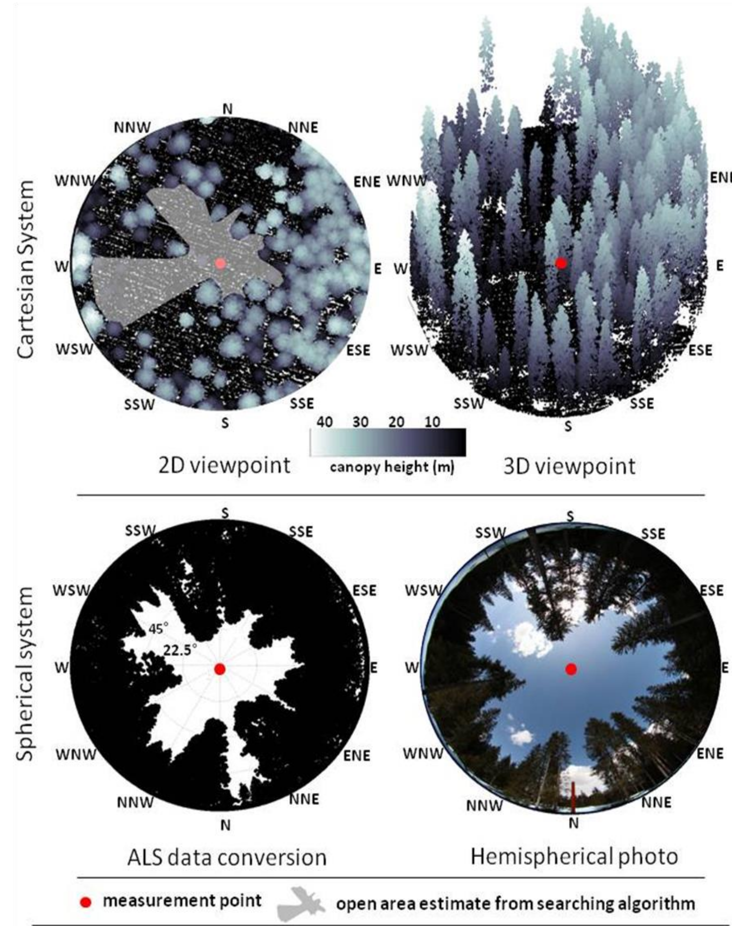

Figure 1. Aerial LiDAR data displayed in the standard downward-looking Cartesian viewpoint on the upper row. The upper right image is displayed in a 3D viewpoint. The upper left image, displayed in a 2-dimensional format, includes an example of a polygon created from the vector searching algorithm. From these polygons, 'mean distance to canopy' and 'total gap area' were estimated. The lower left image is an example of LiDAR data converted to mimic a hemispherical image from an angular upward looking viewpoint (synthetic image). These synthetic images were used to estimate CC and LAI. The lower right image is an actual hemispherical photograph.

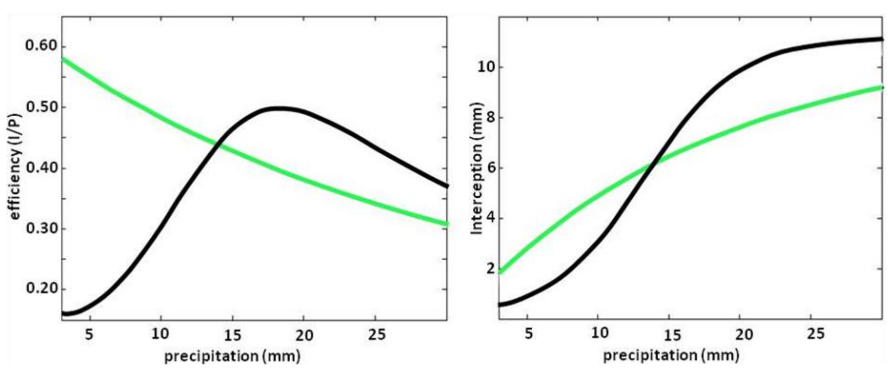

Figure 2. Left: The Moeser et al. interception model is seen in black and showed an initial exponential increase in efficiency before decreasing, representing snow bridging. The standard interception model (in green) showed an exponential decrease in efficiency starting from zero. Right: The Moeser et al. model showed an exponential increase (with the highest slope at P_0) until I_{max} was reached, at which point estimates level. The standard model showed increasing interception estimates with a slow reduction in slope until a maximum is reached.

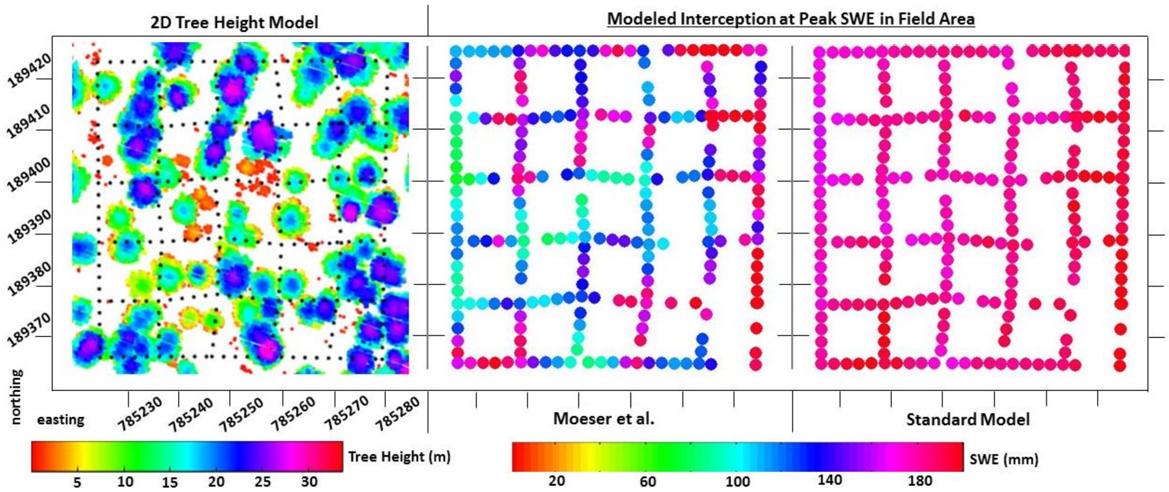

Figure 3. Left: Canopy height in a field area with sampling points represented as black dots. Center: Cumulative interception estimates from the new model at the sample points. Right: Cumulative interception estimates from the standard model at the sample points.

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