# Variability of Forest Canopy Effects on Snowpack Dynamics across the Climate Gradients of the Western United States Mountain Ranges

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**Key Points:**

- Influence of canopy density on snowpack dynamics evaluated across Western U.S. climate gradients
- Changing canopy density can shift the direction of differential snow peak accumulation and duration between adjacent open and forest plots
- Climate-forest-snow interactions exhibit considerable spatial and interannual variability

**Abstract**

Limitations inherent to field studies such as limited spatial and temporal coverage has made it very challenging, if not impossible, to explicitly disentangle the effect of canopy density from climate on snowpack dynamics. Hence, our understanding of how variations in canopy density can affect snow processes under diverse climate conditions has been limited. To address this knowledge gap, this study uses a physics-based modeling approach to represent most key processes that drive snow accumulation and melt in the open and forest with varied forest density, across the climate gradients of the Western U.S. mountain ranges, as represented by 228 Snow Telemetry (SNOTEL) locations. Simulations suggest that, under most winter climate conditions, canopy density exerts a strong influence on under-canopy snowpack dynamics and their controlling processes. Changing canopy density can shift the direction of the modeled differential peak snow accumulation and snow disappearance date (SDD) between the open and forest. For example, while simulated snowpack lasts longer in the open than the high-density forest at most wet/warm and dry/cold locations by up to 55 days, about 90% of all locations show a longer snow duration in the low-density forest by up to 27 days as compared to the open. Interannual variability in climate can also change the magnitude and direction of canopy impact on snow processes. By comparing model simulations to published field observations, we also identify conditions that require additional field observations to improve process-scale understanding of forest-snow interaction.

**Plain Language Summary**

Whereas field studies have documented canopy structure effects on snow processes, field data are insufficient to fully disentangle the effect of canopy versus climate on snow processes due largely to their limited spatial and temporal coverage. To understand how forest density can affect snow processes under diverse climate conditions, we use a physics-based modeling approach to simulate snowpack dynamics and identify the controlling processes at over 200 Snow Telemetry (SNOTEL) locations to represent the Western U.S. climate gradients. At each SNOTEL site, snow processes were simulated for the open and forest with varied canopy density. The model performance is evaluated against SNOTEL snow observations and published field observations. Simulations suggest that canopy density can have a strong influence on under-canopy snowpack duration and peak snow accumulation. As compared to the open condition, while simulated snowpack disappears earlier in the high-density forest at most wet/warm and dry/cold locations, snowpack in the low-density forest shows a longer duration under most winter climate conditions. Contrary to peak snow accumulation that is always lower in the high-density forest than that in the open, simulated peak snow accumulation in the low-density forest is similar to that in the open at most locations.

## 1. Introduction

Snow cover dynamics can have strong implications for water supply (Bales et al., 2006; Barnett et al., 2005; Mote et al., 2005; Sturm et al., 2017), flood risk (Hamlet & Lettenmaier, 2007; Sharma et al., 2018; Yan, Sun, Wigmosta, Skaggs, Leung, et al., 2019), ecosystem function (Coughlan & Running, 1997; Wheeler et al., 2016), and economies (Sturm et al., 2017). In forested environments, snow dynamics and hydrological regimes can be markedly impacted by natural and anthropogenic alterations in forest cover, including density and structure, through canopy snow interception and sublimation, and its influence on snowpack energy balance (Cristea et al., 2014; Essery et al., 2008, 2009; Hawthorne et al., 2013; Lundquist et al., 2013; Pomeroy et al., 2009; Storck et al., 2002).

A large body of research has explored the differences in snow cover dynamics in the open versus under canopy through field surveys and modeling approaches (Dickerson-Lange et al., 2017; Ellis et al., 2013; Essery & Pomeroy, 2004; Gelfan et al., 2004; Golding & Swanson, 1986; Harpold et al., 2015; Jost et al., 2007; Kittredge, 1953; Lawler & Link, 2011; Link & Marks, 1999; Lundquist et al., 2013; Mazzotti, Currier, et al., 2019; Murray & Buttle, 2003; K. N. Musselman et al., 2008; Travis R. Roth & Nolin, 2017; Rutter et al., 2009; Storck, 2000; Sun et al., 2018; Thyer et al., 2004; Varhola et al., 2010; Veatch et al., 2009; Winkler et al., 2005). Most of these studies found that under-canopy peak snow water equivalent (SWE) is lower than that in the nearby open site, which was attributed largely to canopy interception that could account for up to 83% of snowfall (Martin et al., 2013). Exceptions were found at locations characterized by a strong wind, where wind distributed snow from the open to the downwind canopy sheltered areas (Essery & Pomeroy, 2004; Golding & Swanson, 1986; Roth & Nolin, 2017; Winstral & Marks, 2002). On the other hand, field observations reported marked discrepancies in the differential snow disappearance date (SDD) between the open and forest associated with climate regime, canopy structure, and physiographical conditions such as slope and aspect. In supplementary Table S1, we provide a synopsis of recent studies across diverse climate regimes that provide data of paired open-forest snow observations and forest canopy characteristics.

Field observations are mostly consistent that snow duration is longer in the open than the forest in a warm winter climate, except for locations influenced by wind-driven snow deposition or redistribution (Dickerson-Lange et al., 2017; Lundquist et al., 2013; Travis R. Roth & Nolin, 2017; Rutter et al., 2009; Storck, 2000). Lundquist et al. (2013) analyzed SDD differences based on paired open-forest snow observations reported in the literature at 21 locations across the globe. Their study suggested that where average winter temperatures > -1˚C, snowpack persisted longer in the open relative to the forest due to enhanced longwave radiation from canopy that offset reduced shortwave radiation from shading, leading to higher midwinter melt in the forest. Dickerson-Lange et al. (2017) made comparisons of paired open-

forest snow observations at 14 field sites in the Pacific Northwest (PNW), where snow mostly lasted longer in the open than the forest for up to 13 weeks. Their analyses, different from Lundquist et al. (2013), suggested that canopy effects on snow accumulation set up the differential SDD between the open and forest in the Pacific Norwest. In cold-winter climates with limited precipitation, the influence of forest canopy on SDD is much less consistent based on the measurements reported in the literature. Sensors collecting multi-year snow depth data at Boulder Creek, Colorado suggested longer snow duration in small forest openings as compared to under-canopy areas (Harpold et al., 2015). Conversely, some studies (Rutter et al., 2009; Thyer et al., 2004) observed longer snow duration under the forest. Furthermore, interannual variability in climate can shift the direction of canopy impact. For example, as presented in supplementary Table S1, snow measurements collected over 17 snow seasons in northwestern Russia showed shifting effects of forest canopy from increasing to decreasing snow duration compared to the open area (Gelfan et al., 2004).

Despite the aforementioned studies, our understandings of the interacting controls of climate and forest structure on forest-snow interactions across diverse climate regimes have been limited. The challenge can be attributed to the common limitations of field studies, which sample limited locations and lack long-term continuous records to represent inter-annual variability of canopy-snow relationships. Whereas several studies have documented the importance of canopy structure on snow processes (Currier & Lundquist, 2018; Malle et al., 2019; Mazzotti, Currier, et al., 2019; Mazzotti, Malle, et al., 2019; Moeser et al., 2015; Keith N. Musselman et al., 2012; T. Roth & Nolin, 2017), they explored limited spatial extents and climate gradients, and thus the transferability of knowledge across forest settings and climate gradients are lacking. Furthermore, cross-site comparisons are often subject to inconsistent physiological conditions, observing periods, and sampling techniques (e.g., manual vs. sensor measurements). As a result, field studies are insufficient to fully disentangle the effect of canopy versus climate on snow processes.

To address this knowledge gap, a process-based snow model, the Distributed Hydrology-Soil-Vegetation Model (DHSVM; Wigmosta et al., 1994), is applied in this study to examine, based on physics, how we expect forest cover with varying canopy density to impact snow processes across the climate gradients of the Western U.S. mountain ranges, as represented by 228 U.S. Department of Agricultural (USDA) Natural Resources Conservation Service (NRCS) Snow Telemetry (SNOTEL) sites. To isolate canopy density effects from climate effects on snow processes, rather than trying to model the in situ forest cover conditions that are highly heterogeneous across sites, the snow model was configured at each SNOTEL site for four generic cover types, including the open, and the forest with high, medium and low canopy density. We acknowledge that, like any model, DHSVM has limitations (i.e., no wind-

related canopy snow unloading); however, it uses a physics-based approach to represent most key processes that drive snow accumulation and melt in a forest setting. We also compare our model results to published field observations to both assess general model performance and identify conditions that require additional field studies to better understand important processes.

The remainder of the paper is organized as follows. Section 2 describes the DHSVM snow model, study domain, and input data, followed by model configuration and parameterization. Section 3 presents the model simulated snow accumulation and SDD in the open versus forest with changing canopy structures. Section 4 discusses our results in the context of the relevant literature, and section 5 concludes the paper.

## 2. Data and Methods

### 2.1 DHSVM Snow Model Physics

DHSVM is a physics-based hydrological model that was initially developed by Wigmosta et al. (1994) for modeling overland and subsurface hydrological processes governed by the mass and energy balance at each model pixel of 10-150 m defined by the input digital elevation model (DEM).

DHSVM simulates snow processes using a two-layer canopy submodel and a two-layer under-canopy snow submodel driven by the spatial input of meteorology, DEM, soil, and vegetation. The model treats each model pixel as a uniform, single snowpack. The canopy submodel simulates snow-related processes including radiation, wind attenuation, canopy snow interception, and the removal of intercepted snow from the canopy through snow sublimation, mass release and melt (Storck et al., 1998; Wigmosta et al., 1994, 2002). In DHSVM, canopy snow interception is limited by the maximum interception capacity, which is correlated with LAI. Melt of intercepted snow is calculated using a one-layer energy balance approach. When snowmelt exceeds the water holding capacity of canopy snowpack, meltwater drips from canopy and is added to the ground snowpack as rain. Mass release from the canopy can occur if sufficient snow is available and is estimated as a linear function of meltwater drip; the mass release is then added to the ground snowpack. Ground snowpack consists of a thin surface layer and a deep pack layer. Snow accumulation and melt are simulated by the energy balance at the snow surface, consisting of net radiation, sensible and latent heat, and advected heat by rain. The readers are referred to Wigmosta et al. (1994, 2002), Storck et al. (1998; 2000), and Andreadis et al. (2009) for DHSVM snow model physics.

### 2.2 Study Domain and BCQC SNOTEL Data

We selected 228 SNOTEL stations to represent the climate gradients across the Western U.S. mountain ranges (Fig. 1), consisting of PNW's maritime to maritime–continental climate gradients, the Intermountain West's continental climate, the Rocky Mountains' subarctic continental climate,

California's Mediterranean climate, and the Southwest's arid climate. The site selection procedures are as follows. First, the raw SNOTEL data (including daily measurements of SWE, minimum/maximum air temperature, and precipitation) from all 805 active SNOTEL stations were screened using the rigorous three-stage quality control filter (Yan et al., 2018) to identify missing data, remove erroneous values and outliers, and inconsistent data when the maximum SWE value in a water year is at least 5% greater than the cumulative precipitation. The screened data were then bias corrected for warm air temperature bias and snowfall undercatch following the approach described by Sun et al. (2019). The resulting dataset is referred to as the Bias-Corrected Quality-Controlled (BCQC) SNOTEL dataset that includes the 246 SNOTEL stations that share the longest common period of records over 2007–2013.

We previously calibrated/validated the DHSVM snow model forced by the BCQC meteorological data to the daily SWE measurements at these 246 SNOTEL stations assuming an entirely open condition and flat terrain (Sun et al., 2019). For this study, we further chose 228 (from 246) SNOTEL stations with a Nash-Sutcliffe Efficiency (NSE) (Nash & Sutcliffe, 1970) of simulated daily SWE > 0.65, which based on reported literature values indicates satisfactory to very good hydrologic simulations (Moriasi et al., 2007; Newman et al., 2015). Over the 228 stations, the simulated NSE is > 0.8 at 98.7% of the locations, and the overall mean NSE is 0.94. The percentage error in simulated peak SWE is within ±15% at 88.3% of the stations, and the overall mean error is -7.0%; the bias in simulated SDD is within 7 days at 77.9% of the stations, and the overall mean bias is 4.1 days. Here SDD is defined as the day when the modeled SWE is below 5 mm (Serreze et al., 1999), and the 14-day moving average of SWE is below 5 mm. The latter criterion avoids erroneous identifications of SDD when intermittent meltout occurs (i.e. intermittent snow cover) due to limited snowfall and/or warm winters. For details of model parameterization and calibration procedures, the reader is referred to Sun et al. (2019).

Over the 228 SNOTEL stations, the elevations range from 975 m to 3536 m. The total winter precipitation from December through February (referred to as DJF precipitation hereafter) ranges from 95 mm to 1069 mm, and the mean winter air temperature from December through February (referred to as DJF temperature hereafter) ranges from -10.5 °C to 2 °C. Observed peak SWE ranges from 134 mm to 1578 mm. Peak SWE is relatively higher (> 800 mm) in the northern Rockies in Idaho, the Cascade Range, and higher elevations of Sierra Nevada due to greater winter precipitation (Serreze et al., 1999); peak SWE is lower (< 400 mm) in the Wasatch Range, Colorado Front Range, and Arizona/New Mexico due to limited winter precipitation and/or warm temperatures. The earliest SDD occurred in February in Arizona/New Mexico featuring higher winter temperatures and lower peak SWE; the latest SDD occurred in July in the PNW where the highest peak SWE was observed; SDD in the remaining regions ranges mostly from the end of April to late June.

## 2.3 Model Configuration

As noted above, the DHSVM snow model was previously calibrated and evaluated at the selected SNOTEL sites assuming an entirely open condition and level terrain by Sun et al. (2019). Using the same soil and snow parameters as Sun et al. (2019), we configured the snow model at each SNOTEL site for four generic cover types, including the open, and the forest with high, medium, and low canopy density. As canopy density is not an existing vegetation parameter in DHSVM, variations in density are distinguished by two parameters − canopy fractional coverage (i.e. the fraction of total area occupied by forest overstory) and leaf area index (LAI), as described in Table 1. The parameter values were chosen to span the range of the canopy parameters reported in the literature (Dickerson-Lange et al., 2017; Harpold et al., 2015; Gelfan et al., 2004; Lundquist et al., 2013; Martin et al., 2013; North et al., 2004; Roth & Nolin, 2017; Rutter et al. 2009; Storck, 2000; Thyer et al., 2004; Thomas & Winner, 2000). Because the effect of canopy height is secondary to canopy density (see Supplemental Fig. S1–S5), we focus our analyses on the 40 m canopy height with varied density in the following sections.

At each SNOTEL location, the model was implemented at a 3-hourly time step forced by the BCQC meteorological inputs taken from Sun et al. (2019), consisting of precipitation, air temperature, downward shortwave and longwave radiation, wind speed, and relative humidity. In order to mechanistically understand how variations in canopy density can affect snow processes under diverse climate conditions, the four cover conditions (i.e. canopy parameters) were evaluated at each SNOTEL site (Table 1). As noted previously, the modeling intention is not to realistically represent the in situ forest cover conditions, which are highly heterogeneous across the SNOTEL sites and their nearby forests. The goal is to examine how snowpack dynamics based on modeled physics respond to open versus varied forest density across the climates gradients.

# 3. Results and Discussions

We divided the 228 SNOTEL locations into four winter climate zones (wet/warm, dry/warm, wet/cold, and dry/cold) based on their winter meteorology as represented by DJF temperature and precipitation over 2007–2013. DJF temperature < -1 °C is categorized as cold winter climate, and DJF precipitation < 0.3 m (which is about the 25th percentile value of DJF precipitation across all sites) as dry winter climate (Fig. 1). For example, sites with DJF temperature < -1 °C and DJF precipitation > 0.3 m are categorized as wet/cold. As there exists only one site categorized as dry/warm, it is excluded from the following analyses. The DJF period was selected to facilitate comparisons between our model simulations and literature values (supplementary Table S1) under similar winter climates. Furthermore, as demonstrated in section 3.1, the DJF precipitation is more strongly correlated with peak SWE than spring (March through May [MAM]) precipitation.

### 3.1 Climate-Snow Correlation

We first explored the correlation between modeled snow cover characteristics and observed winter meteorological variables using the Pearson's correlation coefficient (*r*) for each cover type (i.e. the open, and forest of varying densities). Snow cover characteristics are represented by the mean annual peak SWE and SDD over 2007–2013. Overall, correlation analyses suggest that relationships between the winter meteorological variables and snow cover characteristics change only slightly as cover type changes from open to forest with varied densities (Table 2).

DJF temperature shows no strong correlation with peak SWE (Pearson's *r* close to zero) and SDD (Pearson's *r* ranging from -0.49 to -0.44), indicating that locations with warm winters (e.g. in maritime climates) do not necessarily have lower peak SWE or shorter snow duration. As expected, peak SWE is strongly correlated with DJF precipitation (Pearson's *r* ranging from 0.72 to 0.82), such that peak SWE is higher at locations with higher winter precipitation (Fig. 2), although the timing of peak SWE at most locations falls between March and May independent of the cover type. On the other hand, correlation analysis between modeled peak SWE and observed MAM precipitation suggests a weaker correlation with Pearson's *r* ranging from 0.64 to 0.67, and no significant correlation is found between MAM temperature and SDD.

The slope of the regression line increases from 0.76 to 1.07 as forest density decreases, and the slope is highest (1.18) for the open condition, suggesting the secondary effect of canopy on peak SWE. Peak SWE and SDD are also positively correlated (Pearson's *r* ranging from 0.68 to 0.81), suggesting that a higher peak SWE is associated with a later SDD irrespective of cover conditions. On the other hand, SDD shows no significant correlation with either DJF precipitation or temperature under all cover conditions, suggesting more complex mechanisms beyond winter meteorology determining SDD, which are discussed later.

### 3.2 Open versus Forest: Peak SWE

The mean relative difference in simulated annual peak SWE (Δpeak SWE; Eq. 1) was analyzed between the open and the forest of varying densities. Given the modeling uncertainties, the difference was considered insignificant if $\Delta peak\ SWE$ is within ±10%. As expected, the peak SWE difference is most pronounced between the open and high-density forest, and generally becomes smaller as forest density decreases (Fig. 3).

$$\Delta peak\ SWE = \frac{peak\ SWE[open] - peak\ SWE[forest]}{peak\ SWE[open]} \quad (1)$$

Compared to the high-density forest, simulations suggest that peak SWE in the open is always higher than the forest with $\Delta peak\ SWE$ ranging from 13%–78% (Fig. 3a). At 75 (or 33%) locations, peak SWE in the open is higher by more than 50% than in the forest. Among these 75 locations, 37 locations are characterized by the dry/cold winter climate, and the remaining 38 sites are characterized by the wet/warm climate. In the wet/warm climate, the significantly higher $\Delta peak\ SWE$ in the open is consistent with the field observations (e.g., Andreadis et al., 2009; Dickerson-Lange et al., 2017; Lundquist et al., 2013; Martin et al., 2013; Roth & Nolin, 2019; Westrick et al., 2002), likely a result of higher canopy snow interception efficiency and/or midwinter melt that removes snow from the canopy. In the wet/cold climate, simulated $\Delta peak\ SWE$ is generally smaller, which based on previous field observations could be associated with higher chances of mass unloading from large snowfall events, weaker snow grain cohesion in cold temperatures, and lower chances of midwinter melt (Lundquist et al., 2013; Roth & Nolin, 2019). In the dry/cold locations that receive less snowfall, disregarding wind unloading effect on canopy snow (which is not represented in the model), the significantly higher $\Delta peak\ SWE$ in the open may be a result of canopy interception that is less likely to exceed the maximum canopy interception capacity, and higher sublimation loss from canopy intercepted snow in the forest (Mahat et al., 2013). For example, at the 37 dry/cold locations, the simulated annual sublimation is about 3–7% in the open versus 5-11% of annual snowfall in the forest, in which sublimation from canopy intercepted snow accounts for 3-6% of annual snowfall.

Compared to the medium-density forest, peak SWE is higher in the open at about half of the locations ($\Delta peak\ SWE$ ranging from 10%–28%) and is similar in magnitude at the remaining locations ($-10\% \leq \Delta peak\ SWE \leq 10\%$) (Fig. 3b). Compared to the low-density forest, peak SWE in the open becomes similar to that under the low-density forest at over 80% of the locations, and interestingly, can be lower than the low-density forest at some locations (Fig. 3c). As further discussed in this section, a slightly higher peak SWE in the low-density forest can be explained by negligible canopy interception combined with lower under-canopy melt energy during snow accumulation. However, field evidence is lacking to provide a reality check.

To quantitatively identify the primary control process of $\Delta peak\ SWE$ (i.e. canopy interception or midwinter melt), we compared the simulated differential cumulative SWE gains between the open and forest due to canopy interception ($\Delta\sum Gain$) versus the differential cumulative SWE losses from midwinter melt and sublimation between the open and forest ($\Delta\sum Loss$) up until the date of peak SWE (Eq. 2).

$$\Delta\sum Gain = \sum Gain(open) - \sum Gain(forest)$$

$$\Delta\sum Loss = \sum Loss(open) - \sum Loss(forest) \qquad (2)$$

Comparing the open to the high-density forest (Fig. 4a), simulations show that $\Delta\sum Gain$ is consistently higher than $\Delta\sum Loss$, suggesting that the difference in peak SWE between the open and forest (i.e. $\Delta\sum Gain - \Delta\sum Loss$) is dominated by $\Delta\sum Gain$ (i.e. canopy interception) under all climate conditions. Among all locations, $\Delta\sum Gain - \Delta\sum Loss$ ranges from 65 to 693 mm, in which $\Delta\sum Gain$ ranges from 15 to 770 mm and $\Delta\sum Loss$ ranges from -160 to 103 mm. A negative value of $\Delta\sum Loss$ indicates greater cumulative snow loss in the forest relative to the open at the time of peak SWE. The (positive/negative) sign of $\Delta\sum Loss$ shows no correlation with climate conditions. Rather it is determined by the site-specific snowpack energy balance, as further illustrated in section 3.4. Despite a higher $\Delta peak\ SWE$ in dry/cold locations, $\Delta\sum Gain$ is commonly smaller due to less total winter precipitation.

As forest density decreases, the magnitude of $\Delta\sum Gain$ becomes smaller due to reduced canopy interception; $\Delta\sum Loss$ at more locations turned from negative values (i.e. higher melt rate in the forest) into positive values (i.e. higher melt rate in the open) (Fig. 4b; c). A lower melt rate in the less dense forest is due to reduced longwave radiation emitted from canopy that offsets higher shortwave radiation during snow accumulation when longwave radiation dominates the radiation balance at low solar elevations (as demonstrated in section 3.4). The value of $\Delta\sum Gain - \Delta\sum Loss$ generally decreases with less dense canopy. In contrast to the high-density forest where $\Delta\sum Gain > \Delta\sum Loss$, $\Delta\sum Gain < \Delta\sum Loss$ under low-density forest at about 57% of the locations.

### 3.3 Open versus Forest: SDD

Simulated SDD over 2007–2013 was compared between the open and the forest of varying densities. Consistent with Lundquist et al. (2013), the differential SDD ($\Delta SDD$, Eq. 3) within ±3 days is considered negligible.

$$\Delta SDD = SDD(open) - SDD(forest) \quad (3)$$

Overall, the canopy density showed a marked effect on $\Delta SDD$. Compared to the high-density forest, snowpack lasts longer in the open by up to 55 days at 58% of the locations, mostly characterized by the wet/warm winter and dry/cold climates. Conversely, snowpack lasts longer in the forest at 42% of the locations by up to 31 days, mostly in the wet/cold climate. As forest density decreases, however, more locations in the wet/warm and dry/cold climates showed earlier snow disappearance in the open relative to the forest (Fig. 5). Compared to the medium-density forest, snowpack stays longer in the forest at 60% of the locations by up to 25 days, and lasts longer in the open at only 16% of the locations, mostly in wet/warm or very dry/cold locations, by up to 19 days (Fig. 5b). Compared to the low-density forest, about 90% of the locations show early snow disappearance in the open by up to 27 days (Fig. 5c).

To identify the processes (accumulation versus ablation) controlling $\Delta SDD$, we followed the approach of Dickerson-Lange et al. (2017) comparing $\Delta\sum Gain$ and $\Delta\sum Loss$ of simulated SWE until the time of first snow disappearance in either the open or under the forest (referred to as the first SDD hereafter) (Fig. 6). Our site-level analysis in the wet/warm climate suggests that $\Delta SDD$ between the high-density forest and the open is driven by the differences in snow accumulation ($\Delta\sum Gain$). This is consistent with the findings by Dickerson-Lange et al. (2017) based on snow observations collected at several wet/warm locations in the PNW. For the dry/cold and wet/cold climates, the controlling mechanism of $\Delta SDD$ between the open and the high-density forest varies from site to site, showing no strong correlation with winter meteorology. Overall, despite a higher loss rate in the open than under the forest at most locations ($\Delta\sum Loss > 0$), snow can still disappear earlier in the forest depending on the magnitude of the differences in snow accumulation. As forest density decreases, leading to smaller $\Delta\sum Gain$ (due to reduced canopy interception), $\Delta SDD$ decreases and at more locations is determined by $\Delta\sum Loss$ by the first SDD irrespective of winter climate regimes.

### 3.4 Site Examples: Time Series Analysis

We selected three sites representative of the wet/warm, dry/cold, and wet/cold climate, respectively (Table 3), to conduct time series analysis for two representative water years (a wetter and slightly colder year 2011, and a drier and slightly warmer year 2012). Fig. 7 presents the analyses of snow cumulative gains and losses in the open versus forest with varied densities, and Fig. 8 shows the monthly snowpack energy balance components (estimated by averaging the 3-hourly time series of simulations) of the open versus forest with varied densities.

Unlike dry/cold and wet/cold sites showing no significant midwinter melt, midwinter melt is evident at the wet/warm site in both the open and forest of varied densities, with over 35% of the snow melted before peak SWE (Fig. 7). Hence in the wet/warm climate the difference in peak SWE between the open and forest is affected by both interception and midwinter melt. At the wet/warm site, the midwinter melt rates in the open are generally higher than the forest, especially in the warmer year 2012 (Fig. 7a), when melt energy in winter months is consistently higher in the open as compared to the forests of different densities (Fig. 8a). On the other hand, higher midwinter melt in the open reduces the peak SWE difference resulting from canopy interception between the open and forest. For example, in year 2012, peak SWE in the open is 368 mm higher than under the high-density forest, in which $\Delta\sum Gain$ is 528 mm and $\Delta\sum Loss$ is 159 mm (i.e. midwinter melt offsets about 30% of the canopy interception). As forest density decreases, canopy interception and under-canopy snowpack melt energy decrease, which together lead to lower midwinter melt rates. The lower melt energy as the forest density decreases is a result of diminishing longwave radiation leading to lower net radiation.

At the dry/cold and wet/cold sites, with no significant midwinter melt under all cover conditions (i.e. $\sum Loss$ at the peak SWE close to 0), the difference in peak SWE between the open and forest is due primarily to snow accumulation or canopy interception (Fig. 7b, c). Hence, as canopy interception decreases with lower canopy density, the modeled difference in snow accumulation ($\Delta\sum Gain$) at peak SWE decreases. In contrast to the midwinter melt rates that decrease with lower canopy density at the wet/warm site, spring to early summer melt rates generally increase with lower canopy density. This can be explained by higher under-canopy snowpack melt energy, as canopy density decreases due to increased shortwave radiation that exceeds reduced canopy emitted longwave radiation when solar elevations are high (Fig. 8).

## 4. Future Work and Recommendations

In this study, we provide a one-model assessment of open versus forest snowpack dynamics across the climate gradients of the Western U.S. mountain ranges. While the model-simulated daily SWE was rigorously evaluated at a large number of SNOTEL sites for the canopy-free condition, the model has not been extensively evaluated in their neighboring forests, except for a previous study (Sun et al., 2018) that showed the model simulated radiation fluxes and SWE at the sub-hourly scale agreed very well with observations at paired open-forest sites in Idaho, USA (supplemental Fig. S6). We also acknowledge that limitations in the DHSVM snow model can result in modeling uncertainties that can be greater for certain climate conditions as discussed in Sun et al. (2019).

For forested environments, wind-induced unloading of intercepted snow and subsequent redistribution are not represented by model physics, which can affect model accuracy in simulated snow accumulation in dry/cold climates due to lower cohesion of cold snow (Friesen et al., 2015; Kobayashi, 1987). To this end, a simple precipitation scaling approach based on remotely sensed snow depth distribution data can be applied to mimic preferential deposition and wind redistribution processes, without a considerable increase in model complexity (Mazzotti et al., 2020; Vögeli et al., 2016). An ensemble snow model approach is also a logical path forward to explore the sensitivity of canopy-snow dynamics to diverse model structures and physics representations under different climate conditions (Essery et al., 2009; Rutter et al., 2009). For example, with increased availably of remotely sensed snow and forest cover products, forest snow models have been enhanced at a higher resolution to characterize canopy structures at the sub-grid level, e.g. distinguishing under-canopy, canopy gap, and canopy edges (Currier & Lundquist, 2018; Jonas et al., 2020; Mazzotti et al., 2020; Mazzotti, Currier, et al., 2019; Sun et al., 2018; Webster et al., 2020).

By design, we assumed uniform tree characteristics across all climate gradients for a given forest density class. This was done to control for spatial heterogeneity in tree characteristics and focus on

climate effects on simulated snow dynamics. Furthermore, a flat terrain is assumed in simulations of all SNOTEL locations to exclude topographic impact in our evaluations of climate-forest-snow interactions, whereas studies have observed notable impacts of slope orientation on the net radiation balance of snowpack and subsequently melt processes (Bales et al., 2011; Ellis et al., 2011; Harpold et al., 2015). Generally, snowmelt accelerates on south-facing slopes and delays on north-facing slopes. However, the sensitivity of melt rates to changing slope-aspect can vary from location to location depending on solar geometry, meteorological conditions including sky cloudiness, and ground cover condition (Seyednasrollah & Kumar, 2014; Strasser et al., 2011). Future work will extend model assessment to the combined interactions of climate, forest cover, and slope-aspect on open versus forest snow cover dynamics across the Western U.S. climate regimes.

## 5. Conclusions

Through modeling the physics of the snow processes in the open versus forest of varying canopy density, this study evaluated how forest cover with varying canopy density versus the open condition can impact snow processes across the climate regimes of the Western U.S. mountain ranges. Simulations demonstrate that changing canopy density can shift the direction of the differential snow accumulation and disappearance timing between the open and forest, irrespective of climate conditions. For example, compared to the high-density forest, simulated snowpack, mostly in the wet/warm and dry/cold climates, lasts longer in the open by up to 55 days; compared to the low-density forest, most evaluated locations show a shorter snow duration in the open by up to 27 days. This is because canopy interception decreases with less dense canopy, leading to smaller differential peak SWE between the open and forest; meanwhile, melt rates under canopy can become higher than the open as a result of higher net radiation (i.e. the sum of shortwave radiation and canopy emitted longwave radiation). The model also demonstrates that the controlling processes of the differential peak SWE and SDD can change with varied canopy density. For example, the differential peak SWE between the open and forest is dominated by canopy interception for denser forest canopy under all climate conditions, although midwinter melt in the wet/warm winter climate can significantly offset canopy interception, in contrast to the dry/cold and wet/cold climates with negligible midwinter melt. As canopy density decreases, snow loss before peak SWE becomes a more important determinant than canopy interception.

The considerable spatial variability of forest-snow dynamics revealed in our simulations suggests that forest management actions are likely to have disparate impacts on snow accumulation and snowpack duration depending on local winter meteorology and forest conditions. In this regard, more robust inferences about the interacting controls of climate and forest on snow can substantially benefit from long-term paired open-forest snow measurements with better control for climate and canopy condition,

and slope-aspect differences, e.g., paired forest sites adjacent to selected SNOTEL stations. High quality in situ measurements and LiDAR-derived forest-snow data are also key to improving subgrid parameterization of forest-snow models and evaluating model performance to advance process-scale understanding of forest-snow interaction. Lastly, interannual variability in climate must also be considered, as it can change the magnitude and direction of impact (e.g., greater SDD in the open to greater SDD in the forest) at a given location.

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