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Key Points:
- Canopy density effect on peak snow accumulation and snowpack duration varies with winter climates
- Canopy thinning is most effective in wet/warm winter climates for improving snowpack duration
- Greatest decrease in snowpack duration under warming is anticipated for snowpack under dense canopy in presently warm winter climates

Supporting Information:
Supporting Information may be found in the online version of this article.

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Forest Canopy Density Effects on Snowpack Across the Climate Gradients of the Western United States Mountain Ranges

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Abstract Controlled field experiments to disentangle the effect of canopy density from the effect of climate on snowpack dynamics are limited by the underlying linkage between canopy density and climate. Thus, based on observations alone, it is not well understood how variations in canopy density can affect snow processes under different climate regimes. To address this knowledge gap, this study uses a physics-based modeling approach to evaluate the sensitivity of snowpack dynamics to variations in canopy density across the climate gradients of the Western U.S. as represented by 228 Snow Telemetry (SNOTEL) sites. Within the model, we uniformly parameterize the canopy across sites to represent an idealized forest with high, medium, and low canopy density, respectively. The results illustrate that the effect of canopy density on the peak snow water equivalent (SWE) and duration of under-canopy snowpack is sensitive to winter climate (i.e., climatological winter precipitation and temperature). As canopy density decreases, the greatest increase in peak SWE and snowpack duration is found in wet/warm and dry/cold climates, where snowpack under low-density forest lasts longer than that in the open. In comparison, peak SWE and snowpack duration in wet/cold climates are less sensitive to changing canopy density. Thus, forest management actions (e.g., thinning and clearing) are likely to have disparate impacts on snow depending on local winter climate. Climate sensitivity of under-canopy snowpack suggests that snowpack duration under dense canopy in presently warm winter climates is expected to experience the greatest reduction under a warming climate.

Plain Language Summary In the Western U.S., forest management (e.g., clearing and thinning) has great potential for altering snow processes, which is particularly important for locations susceptible to low flows in the summer. With limited observations available to evaluate climate-forest-snow relationships, there is a lack of knowledge about how changing forest density can affect snow water storage and snowpack duration under different climate conditions. To address this gap, this study uses a physics-based snow model to simulate snow processes under changing canopy density for over 200 locations representative of the Western U.S. climate diversity. Results suggest that the effect of canopy density on snowpack water storage and duration varies with winter climate, and thus the effect of forest management on snow and water resources can vary substantially with climate. In wet/warm and dry/cold climates, a decrease in canopy density generally increases snowpack duration such that a low-density forest keeps snowpack longer than an open area in the same location. From the forest management perspective, canopy thinning in these climates provides better chances than forest clearing for enhancing snowpack duration and storage. In wet/cold climates, snowpack duration is less sensitive to changing canopy density.

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, Hou, & Leung, 2019; Yan, Sun, Wigmosta, Skaggs, Hou, Leung, et al., 2019), ecosystem function (Coughlan & Running, 1997; Wheeler et al., 2016), and economies (Sturm et al., 2017). In mountain forests, snowpack dynamics can be markedly impacted by canopy cover characteristics through canopy snow interception and sublimation, and influencing 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). Given the opportunities of managing forests for snowpack retention and sustaining low flows, a growing number of field studies (e.g., Dickerson-Lange et al., 2017; Harpold et al., 2015; Lawler & Link, 2011; Mazzotti, Currier, et al., 2019; Murray & Buttle, 2003; Musselman et al., 2008; Roth & Nolin, 2017; Veatch et al., 2009; Winkler et al., 2005) have been conducted to examine how forest impacts the snow regime in comparison to its neighboring open site. These field observations provide valuable insights and are essential for parameterizing and evaluating models related to canopy snow processes. For example, many field studies confirm that under-canopy peak snow water equivalent (SWE) is lower than that in the nearby open area, which is attributed largely to canopy interception that could account for up to 83% of snowfall (Martin et al., 2013). Field observations collected in maritime climates generally indicate that snow lasts longer in the open than the forest, except for locations influenced by wind-driven snow deposition or redistribution (Dickerson-Lange et al., 2017; Lundquist et al., 2013; Roth & Nolin, 2017; Rutter et al., 2009; Storck, 2000). On the other hand, there are disagreements in field observations conducted in other climates. For example, sensors collecting multi-year snow depth data at Boulder Creek, Colorado suggested longer snow duration in small forest openings compared to under-canopy areas (Harpold et al., 2015), while other studies (Rutter et al., 2009; Thyer et al., 2004) observed longer snow duration under the forest in similar cold and dry winter climates.

A key challenge in field studies is creating controlled experiments that vary only the climate while holding all forest characteristics fixed for determining the inter-related sensitivity of climate versus canopy on snow processes. In nature, canopy characteristics often covary with climate due to biomass-climate correlations on large scales such that temperate and boreal forests with greater biomass (i.e., taller trees and denser growth) occur generally in warmer and wetter climates (Keith et al., 2009; Liu et al., 2014; Stegen et al., 2011). Thus, the conclusions from aggregated observational studies (e.g., Lundquist et al., 2013) that snow lasts longer in the open in areas with warmer winters could be due to either the climate or to the denser forests associated with that climate. Moreover, field and satellite observations are generally constrained by local weather and canopy characteristics, which makes it inherently difficult to rely on field data alone to disentangle interactions between climate, snow and forest across climate gradients. Most snow observations also do not have long enough records to cover the range of interannual climate variability, which can interact with canopy to enhance or diminish the canopy effect on snow processes. For example, 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 paired open area (Gelfan et al., 2004). Thus, field studies alone, are not fully able to disentangle the effect of canopy density from the effect of climate on snow processes.

To address the knowledge gap, we applied a process-based snow model of the Distributed Hydrology-Soil-Vegetation Model (DHSVM, Wigmosta et al., 1994) to examine, based on model physics, how we expect varying canopy density to impact snow processes and the inter-related sensitivity of snow processes to climate and canopy density. Model experiments were conducted for 228 Snow Telemetry (SNOTEL) sites to represent the climate gradients of the Western U.S. mountain ranges. For each SNOTEL site, we configured DHSVM for an idealized forest with a range of canopy density, including high, medium and low canopy density, and a reference open condition (with no canopy cover and no canopy influence on snow processes). Canopy density is defined in the model in a two-dimensional sense, based on the canopy fractional coverage (FC) and the leaf area index (LAI). For each canopy density category, uniform canopy parameters were assumed across sites to allow for comparisons of snowpack sensitivity to changing climates, without confounding them with the heterogeneity in in situ canopy characteristics.

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 at a subdaily timescale. DHSVM simulates accumulation and melt of ground snowpack using a two-layer mass and energy balance model within each model pixel that is treated as a single, uniform snowpack. Ground snowpack is represented by a thin surface layer and a deep pack layer. Energy exchange between the atmosphere, overstory canopy, and snowpack is simulated by the energy balance at the snow surface:

$$Q = \mathrm{NSW} + \mathrm{NLW} + H + \mathrm{LE} + M \tag{1}$$

10.1029/2020WR029194

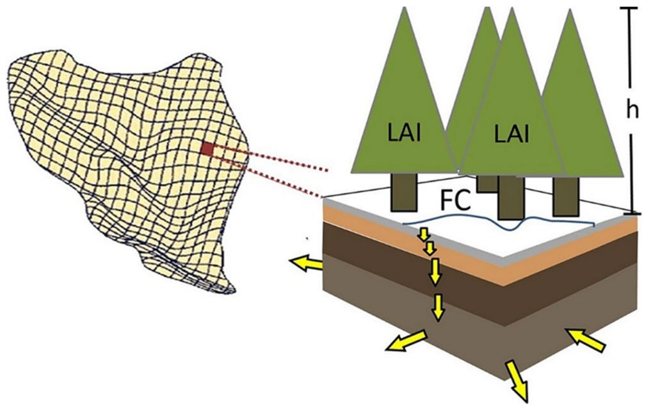

Figure 1. Distributed Hydrology-Soil-Vegetation Model (DHSVM) representation of a model pixel with a fractional coverage of forest canopy (FC). Forest canopy is characterized by leaf area index (LAI) and canopy height (h).

where Q is net energy input to snowpack, NSW is net shortwave radiation, NLW is net longwave radiation, H is sensible heat flux, LE is latent heat flux, and M is advected heat from rainfall to snowpack. Ground heat flux and heat conduction between the surface and pack layer are neglected given that they generally represent minor heat contribution to melt when compared to the other snowpack energy balance terms (Marks & Dozier, 1992). Mass and energy exchange between the surface layer and the pack layer occurs via the exchange of ice and meltwater. Excessive liquid water in the pack layer above its liquid water holding capacity is released to the underlying soil as snowpack outflow.

In the presence of overstory canopy, DHSVM partitions a model pixel into a canopy-covered fraction (prescribed by FC) and an open fraction (i.e., 1-FC, Figure 1). The model assumes no interaction between the open and forest fraction such as shading and wind attenuation from forest canopy. Each snowpack energy balance term (Equation 1) is calculated separately for the forest and open fraction, which is then weighted by FC to calculate the pixel-level snowpack energy balance. Forest canopy is characterized primarily by LAI and canopy height. LAI that varies monthly is used to represent spatially aggregated small openings in forest canopy, and sub-pixel variability of forest elements such as spatial patterns of small openings is neglected. Generally, lower LAI values result in less canopy snow interception, more under-canopy shortwave radiation, and less under-canopy down-welling longwave radiation.

Snow-canopy processes are simulated by a one-layer mass and energy balance canopy model. At the pixel level, *NSW* received by snowpack is the area-weighted average of attenuated shortwave radiation from the canopy fraction and direct shortwave radiation in the open fraction:

$$\text{NSW} = (1-\alpha)(R_s(1-FC) + FC(R_{\text{dir}}\tau_b + R_{\text{diff}}\tau_d)) \tag{2}$$

where α is the snowpack albedo, which is estimated as a function of snow surface temperature and the days since last snowfall. Details of snow albedo curve parameterization and calibration are provided by Sun et al. (2019). R_s is incoming shortwave radiation and is partitioned into direct radiation (R_{dir}) and diffuse radiation (R_{diff}) based on the clearness index (Sun et al., 2015; Wigmosta et al., 1994), and τ_b is the fraction of direct shortwave radiation transmitted through canopy, which is estimated by the Beer-Bouger-Lambert law (Peixoto & Oort, 1992):

$$\tau_b = e^{-k\cdot\frac{h}{\sin\theta}} \tag{3}$$

where h is canopy height, θ denotes solar elevation angle, and k is monthly radiation extinction coefficient estimated as a linear function of LAI (Sun et al., 2015). NLW received by the snowpack is estimated by:

$$\text{NLW} = L_d(1-FC) + FC\cdot\sigma T_c{}^4 - \sigma T_s{}^4 \tag{4}$$

where L_d is downward longwave radiation emitted from the atmosphere, σ is the Stephan-Boltzmann constant, T_c is the canopy temperature approximated by air temperature in Kelvin, and T_s is snow surface temperature in Kelvin. Snowfall can be intercepted by canopy up to the maximum interception capacity, which is estimated as a function of LAI and air temperature. Intercepted snow can be removed from canopy through snowmelt, sublimation, and mass release. Melt of intercepted snow is simulated by the 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 occurs if sufficient snow is available and is estimated as a linear function of meltwater drip. Rain, snowfall not intercepted by canopy is combined with drip and mass release contribute mass and energy to the ground snowpack. The readers are referred to Wigmosta et al. (1994, 2002), Storck et al. (1998), and Andreadis et al. (2009) for more details of DHSVM snow model physics.

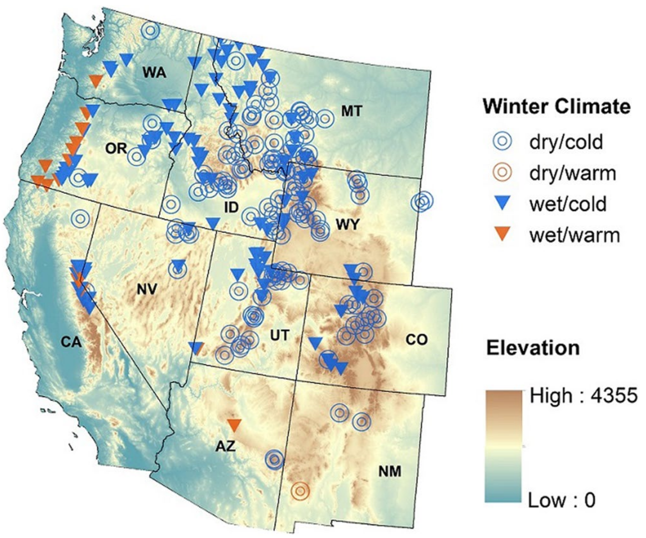

Figure 2. Climate gradients of the Western U.S. mountain ranges, represented by 228 SNOTEL locations, which are classified into four winter climate zones (wet/warm, dry/warm, wet/cold, and dry/cold) based on their winter (DJF) temperature and precipitation.

2.2. Study Domain and BCQC SNOTEL Data

Previously, Sun et al. (2019) calibrated and validated the DHSVM snow model to the daily SWE measurements at 246 SNOTEL stations assuming an entirely open condition and flat terrain. Their site selection was based largely on the quality and duration of meteorological and SWE measurements. Specifically, Sun et al. (2019) screened the raw daily measurements of temperature, precipitation and SWE from 805 active SNOTEL stations, using the rigorous three-stage quality control to identify missing data, remove erroneous values and outliers as described in detail by Yan et al. (2018). 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 data set is referred to as the Bias-Corrected Quality-Controlled (BCQC) SNOTEL data set, which includes daily records of precipitation, maximum and minimum air temperature, and SWE for 805 stations with varying durations.

From the BCQC SNOTEL data set, we found 246 SNOTEL stations with continuous meteorological and snow records over the longest common period, which was 2007–2013. We then chose 228 SNOTEL stations with a Nash-Sutcliffe Efficiency (NSE, Nash & Sutcliffe, 1970) of simulated daily SWE > 0.65. Over these 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 snow disappearance date (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 moving average of SWE over its subsequent 14 days is below 5 mm. The latter criterion avoids erroneous identifications of SDD when intermittent melt-out occurs due to limited snowfall and/or warm winters. For details of model configuration, parameterization and calibration procedures, the reader is referred to Sun et al. (2019).

We divided the 228 SNOTEL stations into four climate classes based on their climatological averages of winter (December through February, or DJF) temperature and precipitation, wet/warm, dry/warm, wet/cold, and dry/cold (Figure 2). By definition, winter temperature <−1°C is categorized as cold winter climate, and winter precipitation <300 mm (∼25th percentile of winter precipitation distribution across sites) as dry winter climate. For example, sites with winter temperature <−1°C and winter precipitation >300 mm are categorized as wet/cold. With this classification, only one SNOTEL station was classified as dry/warm. It should be noted that the categorization into simplified climate classes provides a framework to consider groupings of results, but results are presented across the spectrum of temperature and precipitation values.

2.3. Model Configuration and Experiments

Using the same snow parameters calibrated by Sun et al. (2019), we configured the snow model at each SNOTEL site to represent a range of changing canopy density, the forest with high, medium, and low canopy density, and the reference open condition. The canopy density is distinguished by two-dimensional parameter values including canopy fractional coverage and LAI as described in Table 1. As there are not consistent thresholds in the literature defining canopy density classes, we chose three variations of parameters that bracket the range of the canopy parameters reported in the literature to represent changing canopy densities (Dickerson-Lange et al., 2017;

Table 1
Distributed Hydrology-Soil-Vegetation Model (DHSVM) Parameters Used to Characterize the Open and Forest With High, Medium, and Low Canopy Density

Model parameters	Open	High-density forest	Medium-density forest	Low-density forest	Description
Fractional Coverage	0%	95%	70%	40%	Fraction of ground area covered by forest overstory
LAI (unit: m^2/m^2)	–	8	4.5	2	Monthly canopy leaf area index

Gelfan et al., 2004; Harpold et al., 2015; Lundquist et al., 2013; Martin et al., 2013; North et al., 2004; Roth & Nolin, 2017; Rutter et al., 2009; Storck, 2000; Thomas & Winner, 2000; Thyer et al., 2004). Because the effect of canopy height is secondary to canopy density (see Figures S1–S5 in Supporting Information S1), we use a 40 m canopy height in following analyses that is representative of mature conifer in the Pacific Northwest.

For each SNOTEL site, the model was run at a 3-hourly time step forced by meteorological inputs including precipitation, air temperature, relative humidity, downward shortwave radiation, downward longwave radiation, and wind speed. All meteorological variables but wind speed were obtained from disaggregating daily meteorological records (i.e., maximum and minimum daily air temperature, and precipitation) from the BCQC SNOTEL data set using the MTCLIM algorithms (Bohn et al., 2013; Maurer et al., 2002; Thornton & Running, 1999). Subdaily precipitation presumed daily precipitation occurred at a uniform rate throughout the day. Subdaily air temperatures were estimated based on daily minimum and maximum air temperatures using a spline of third-order Hermite polynomials. Relative humidity was calculated from subdaily temperatures assuming that the daily minimum temperature is equal to the dew point. Downward shortwave radiation was calculated based on daily temperature range and dewpoint temperature using the Thornton and Running (1999) algorithm, where dewpoint temperature was estimated based on daily minimum temperature and precipitation. Downward longwave radiation was calculated as a function of subdaily temperatures using the method described by Prata (1996). Wind speed, which was not collected at SNOTEL stations, was taken from the wind speed field of a gridded meteorological data set (Livneh et al., 2013). As noted previously, the modeling intention is not to realistically represent the in situ forest cover or forest gap conditions, which are highly heterogeneous across sites. The goal is to examine, based on modeled physics, how peak SWE and snowpack duration change under varied forest density across the climate gradients. For selected sites representative of climate gradients, we also analyzed snowpack energy balance components to identify the key processes that determine the snowpack dynamics as canopy density changes.

2.4. Climate Sensitivity Analysis

Luce et al. (2014) revealed strong correlation between the climatology of winter temperature and precipitation and the climatology of snowpack storage across the Western U.S. Of particular interest to this study is how the climate-snow relationship varies as canopy density changes. Following the approach descried in Luce et al. (2014), we used their local polynomial regression approach to examine how climatological averages of winter temperature and precipitation influence the climatology of peak SWE and SDD across sites, as forest cover condition changes. In this case, interannual variations of climate and snowpack, as a result of climate variability at sites were not analyzed. For different canopy density categories, we also analyzed the sensitivities of average peak SWE and SDD to changing winter temperature and precipitation, respectively. For example, the temperature sensitivity of peak SWE measures how average peak SWE changes as a function of the temperature values of all sites. The local polynomial regression and the sensitivity analysis were conducted using the locfit package in R (Loader, 2020). Details about the approach can be found in Luce et al. (2014).

3. Results

3.1. Climate Sensitivity of Under-Canopy Snowpack

For open to any canopy density (ranging from no trees to high-density forest), local polynomial regression analysis (Figure 3) suggests a strong interaction between winter precipitation and temperature in their effects on peak SWE (with NSE values ranging from 0.87 to 0.90). As canopy density increases, peak SWE becomes slightly less sensitive to changing winter temperature and precipitation (Figure 4). The average peak SWE sensitivity to temperature over all sites for the open, low-, medium- and high-density forest is −45.4, −44.5, −43.8, and −39.4 mm/°C, respectively. The average peak SWE sensitivity to precipitation for the open, low-, medium- and high-density forest is 1.6, 1.5, 1.4, and 1.3 mm/mm, respectively. Despite the canopy density, temperature sensitivity of peak SWE is closely related to the precipitation conditions. For example, as demonstrated in Figure 4a, peak SWE at wetter locations shows greater sensitivity to changing temperature. Similarly, precipitation sensitivity of peak SWE also varies with the temperature condition. Generally, colder locations show greater precipitation sensitivity (Figure 4b). Among all locations, peak SWE in the wet/warm climates shows the greatest sensitivity

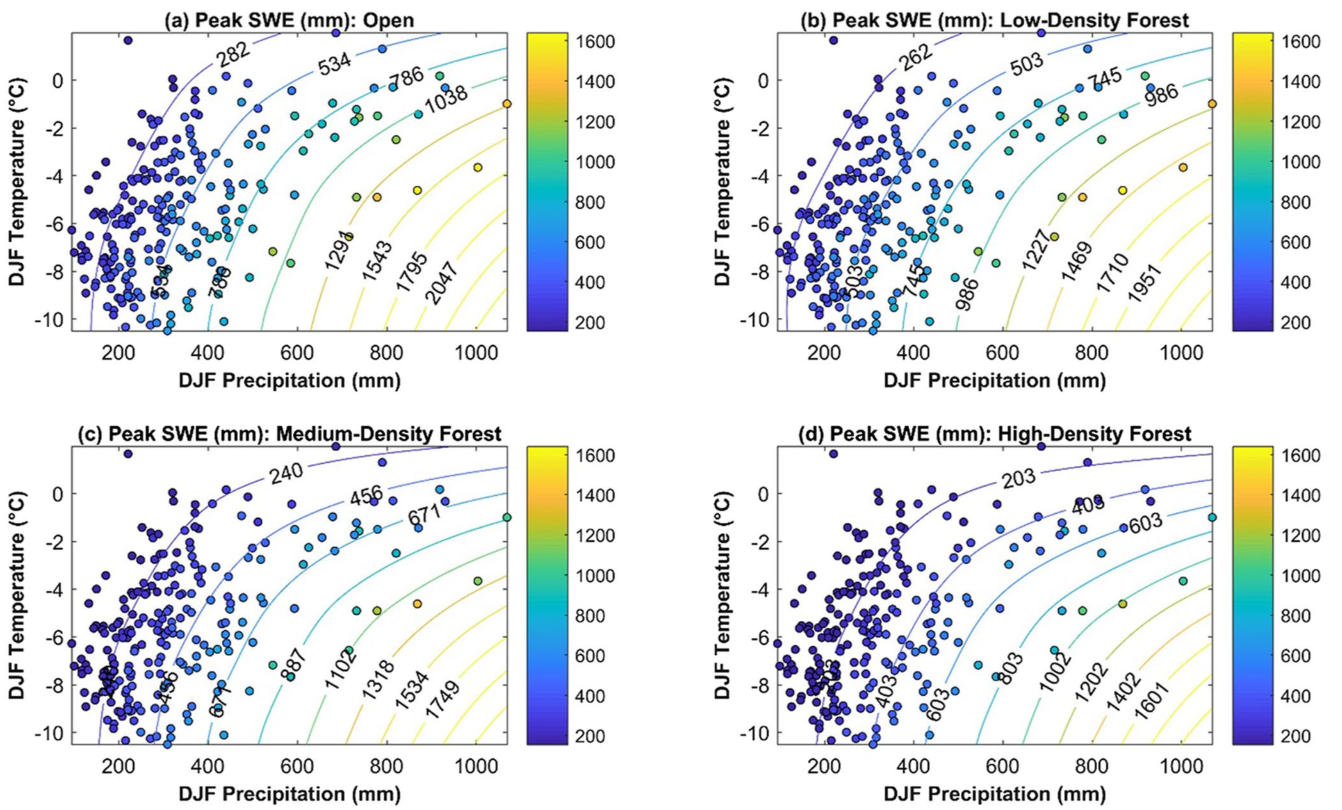

Figure 3. Peak snow water equivalent (SWE) as a function of December through February (DJF) precipitation and temperature. Contours are fitted surface for the data at SNOTEL sites using local polynomial regression. Units of contour levels are mm.

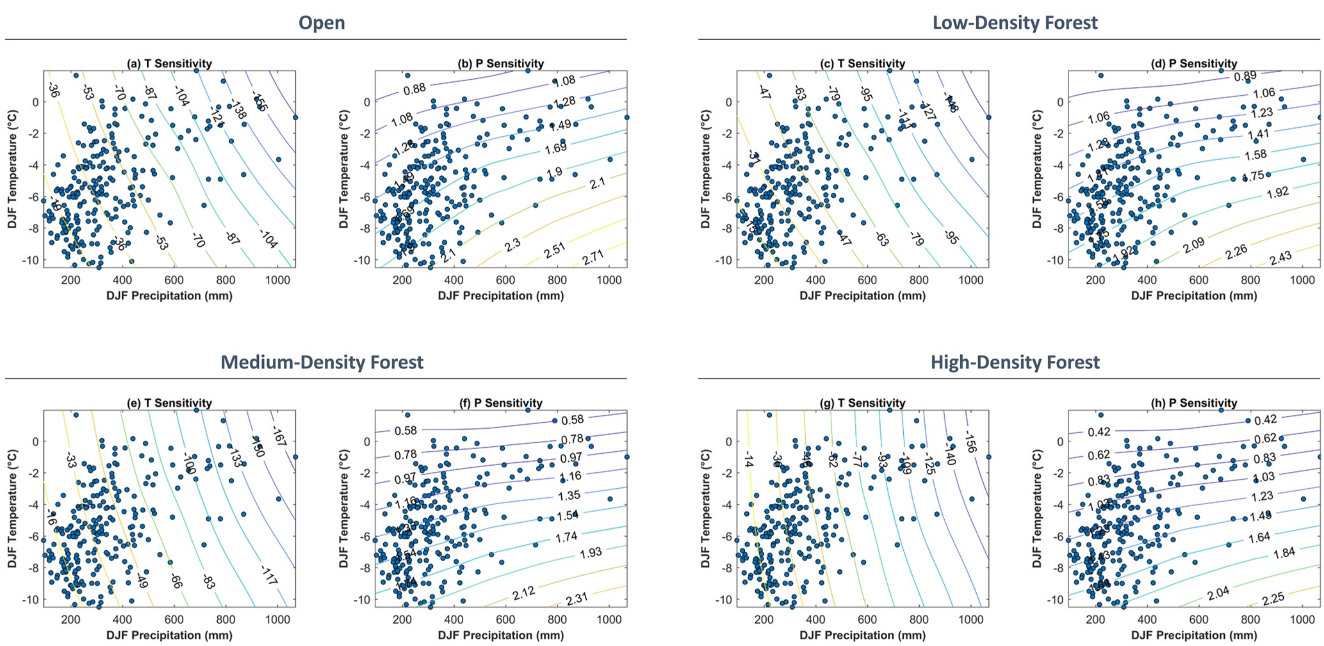

Figure 4. Sensitivity of peak snow water equivalent (SWE) to changing December through February (DJF) temperature (*T*; unit: mm-SWE/°C) and changing DJF precipitation (P; unit: mm-SWE/mm-P) calculated as partial derivatives of the contours shown in Figure 3 for (a–b) the open, (c–d) the low-density forest, (e–f) the medium-density forest, and (g–h) the high-density forest.

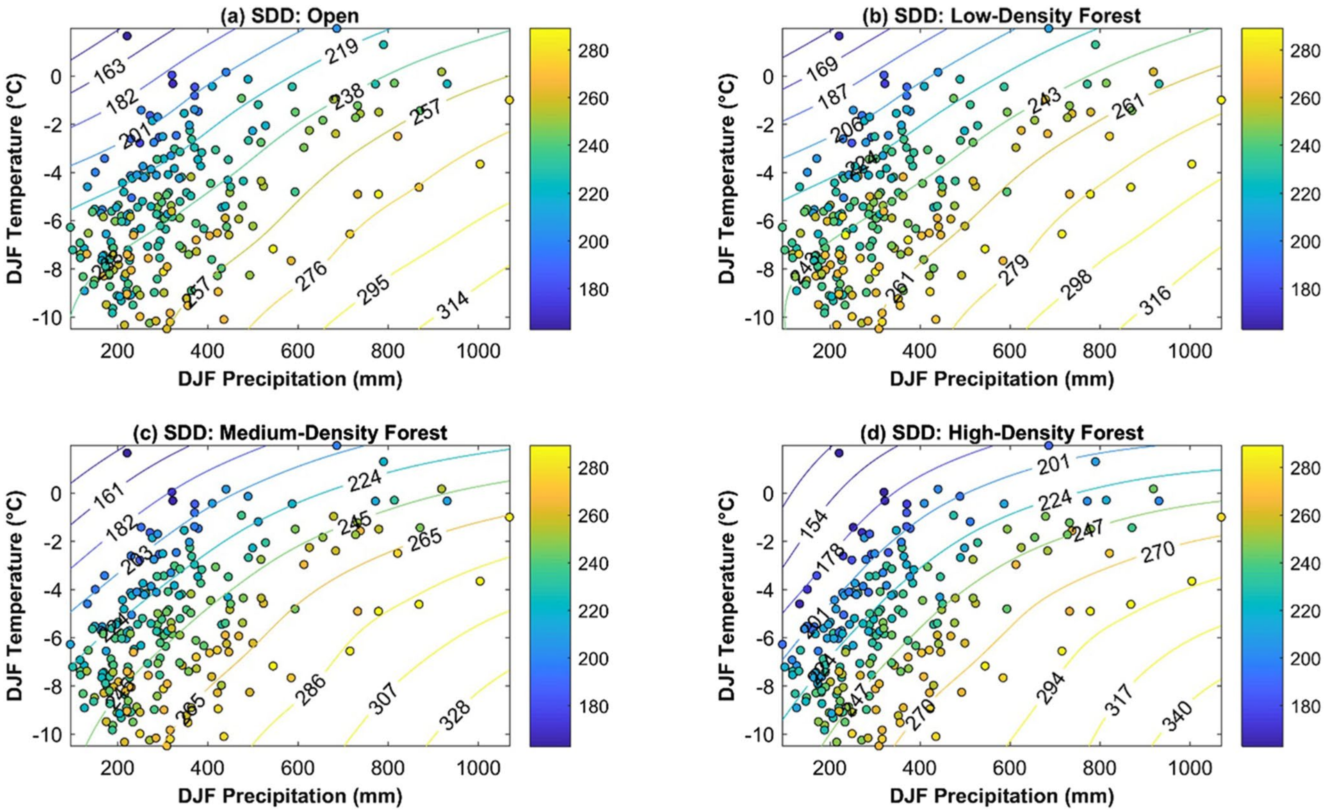

Figure 5. Snow disappearance date (SDD) as a function of December through February (DJF) precipitation and temperature. Values of contour levels indicate the number of days since the start of a water year (i.e., Oct. 1).

to temperature change, and the greatest sensitivity of peak SWE to precipitation change is found in wet/cold climates.

As canopy density increases, the interaction between winter precipitation and temperature generally decreases in its effect on SDD, indicated by decreasing NSE values from 0.79 to 0.60 (Figure 5). For example, SDD sensitivity to temperature under the high-density forest (Figure 6g) is quite similar across all precipitation ranges, indicated by contour lines more parallel to the precipitation axis. In comparison, for the open condition (Figure 6a), contour lines are more sloped across the range of precipitation and temperature, suggesting a joint sensitivity of SDD to both precipitation and temperature. Similar for the SDD sensitivity to precipitation, as canopy density increases, it becomes less related to the temperature conditions, suggested by more vertical contour lines to the temperature axis, as shown in Figure 6h relative to Figure 6b. In contrast, under the open and low-density forest conditions, the greatest SDD sensitivity to both temperature and precipitation is found in dry/warm climates (Figures 6a–6d). The average SDD sensitivity over all sites is generally greater as canopy density increases. Average SDD sensitivity to temperature for the open, low-, medium- and high-density forest is −6.5, −6.3, −7.9, and −9.2 days/°C, respectively. SDD sensitivity to precipitation for the open, low-, medium- and high-density forest is 0.08, 0.08, 0.12, and 0.16 days/mm, respectively.

3.2. Canopy Density Effect on Peak SWE

For each canopy density class, we calculated the relative difference in the mean annual peak SWE between the reference open condition and under the canopy (Figure 7), quantified by ΔpeakSWE (Equation 5). Given the modeling uncertainties, the relative difference was considered insignificant if ΔpeakSWE is within ±10%. As only one SNOTEL station was classified as dry/warm, the following analyses do not include dry/warm climates.

$$\Delta \text{peakSWE} = \frac{\text{peakSWE(open)} - \text{peakSWE(forest)}}{\text{peakSWE(open)}} \tag{5}$$

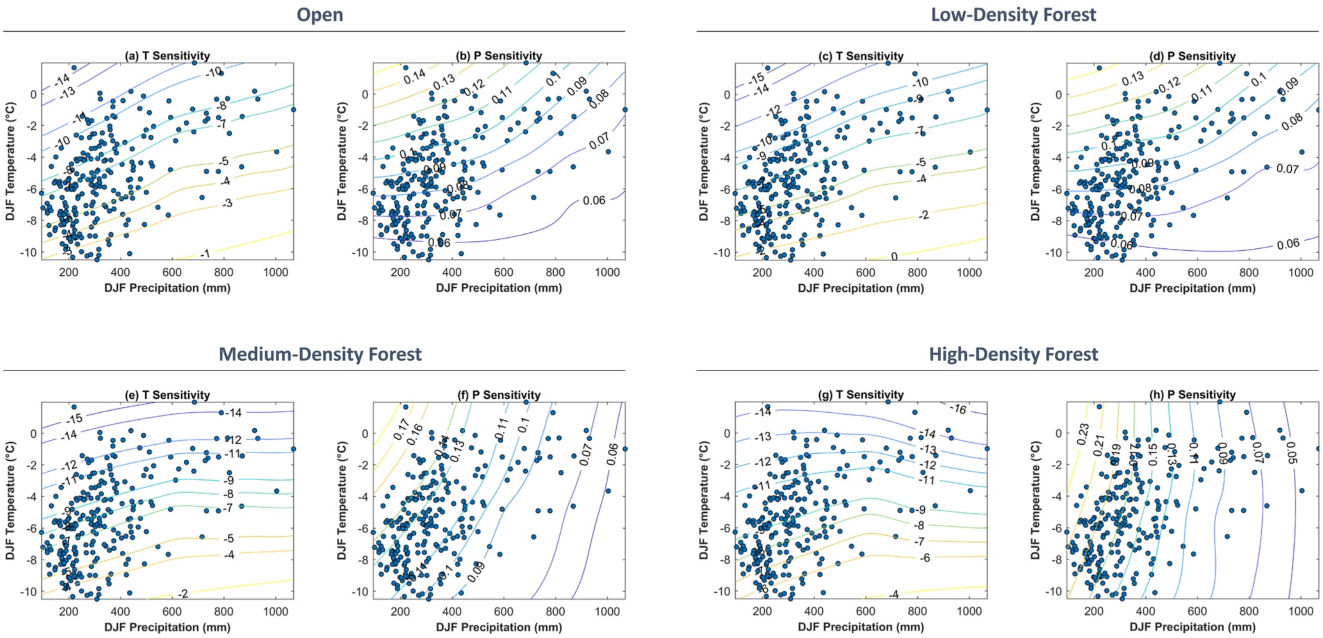

Figure 6. Sensitivity of snow disappearance date (SDD) to changing December through February (DJF) temperature (*T*; unit: day/°C) and changing DJF precipitation (*P*; unit: day/mm) calculated as partial derivatives of the contours shown in Figure 5 for (a–b) the open, (c–d) the low-density forest, (e–f) the medium-density forest, and (g–h) the high-density forest.

As expected, peak SWE decreases as canopy density increases across all sites. Compared to the open, the peak SWE difference is most pronounced in the high-density forest. Simulations suggest that peak SWE in the open is always higher than that in the high-density forest by 13%–78% (Figure 7a). For 75 (or 33%) SNOTEL sites located in wet/warm and dry/cold winter climates, peak SWE in the open is higher by more than 50% than in the high-density forest. Compared to the medium-density forest, peak SWE is higher in the open by 10%–28% at about 50% of the locations and is similar in magnitude (within ±10%) at the remaining locations (Figure 7b). In contrast, peak SWE in the low-density forest is similar to that in the open at over 80% of the locations, and interestingly, can be higher than the open at some locations, mostly in dry/cold climates (Figure 7c).

To identify the primary process controlling ΔpeakSWE under different climates, as canopy density changes, we decomposed simulated daily peak SWE into: (a) cumulative snow gain (positive changes in daily SWE), and (b) cumulative snow loss (negative changes in daily SWE). Comparing the open and the forest, the difference in their cumulative snow gain until the time of peak SWE is denoted by Δaccumulation that is dominated by differences caused by canopy interception, and the difference in cumulative snow loss is denoted by Δablation that is dominated by differences in melt rates. As illustrated in Figure 8a, the differential peak SWE between the high-density forest and the open is dominated by Δaccumulation under all climate conditions. As forest density decreases, the magnitude of Δaccumulation decreases primarily due to reduced canopy interception, while Δablation at more locations turns from negative values (i.e., higher melt rate in the forest) into positive values (i.e., higher melt rate in the open, Figures 8b and 8c). For about 57% of the locations, Δaccumulation < Δablation under low-density forest. This suggests that reduced canopy interception combined with slower melt under the lower-density canopy reduces the differential peak SWE.

3.3. Canopy Density Effect on SDD

Simulated mean SDD over 2007–2013 was compared between the open and the forest of varying densities. As in Lundquist et al. (2013), the differential SDD (ΔSDD, Equation 6) within ±3 days is considered negligible.

$$\Delta \text{SDD} = \text{SDD(open)} - \text{SDD(forest)} \tag{6}$$

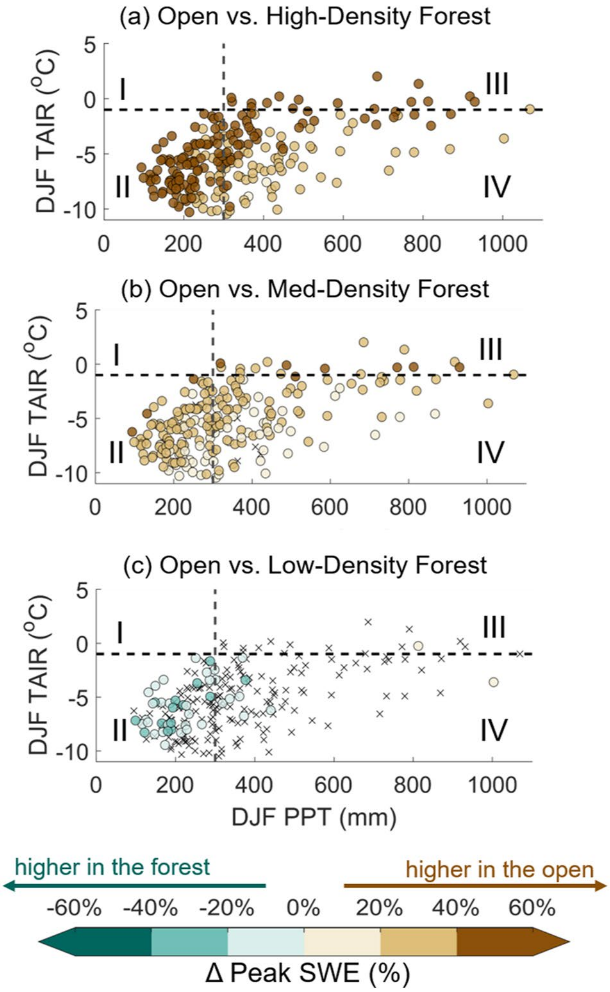

Figure 7. Relative difference in peak snow water equivalent (SWE) (ΔpeakSWE defined in Equation 5) between the open and (a) high-density forest, (b) medium-density forest, and (c) low-density forest as a function of December through February (DJF) precipitation and DJF temperature. ΔpeakSWE within ±10% is considered negligible and is marked by the "×" symbol. Each plot area is divided into four climate zones: zone I is dry/warm, zone II is dry/cold, zone III is wet/warm, and zone IV is wet/cold.

Overall, the effect of canopy density on ΔSDD varies with winter climates (Figure 9). Snowpack lasts longer in the open than in the high-density forest (ΔSDD > 0) at 58% of the locations by up to 55 days, mostly characterized by the wet/warm and dry/cold winter climates. Conversely, snowpack lasts longer in the high-density forest (ΔSDD < 0) at 42% of the locations by up to 31 days, mostly in the wet/cold climate. As forest density decreases, more locations (predominantly in the wet/warm and dry/cold climates) show earlier snow disappearance in the open relative to the forest (ΔSDD < 0); the magnitude of ΔSDD generally decreases, suggesting smaller differences in snowpack duration between the open and forest. Comparing snowpack in the medium-density forest to the open, 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 (Figure 9b). Comparing SDD in the low-density forest to the open, about 90% of the locations show early snow disappearance in the open by up to 27 days (Figure 9c).

To identify the processes controlling ΔSDD, we compared Δaccumulation and Δablation (defined in Section 3.2) at the time of first snow disappearance in either the open or under the forest (referred to as the first SDD hereafter). Comparing the high-density forest to the open, analysis (Figure 10a) suggests that ΔSDD in the wet/warm climate is dominated by Δaccumulation. This is consistent with the snow observations collected at several wet/warm locations in the Pacific Northwest by Dickerson-Lange et al. (2017). In the wet/cold (Figure 10d) and dry/cold (Figure 10g) climates, the controlling mechanism of ΔSDD varies from site to site, showing no strong correlation with winter meteorology. As forest density decreases, generally leading to smaller Δaccumulation, ΔSDD decreases for most locations. As canopy density decreases, the controlling mechanism of ΔSDD at more locations shifted from Δaccumulation to Δablation (e.g., Figures 10h and 10i), irrespective of winter climate regimes. Analysis of ΔSDD between the low-density forest and the open indicates that Δmelt is the dominant mechanism at all locations.

3.4. Canopy Density Effect on Snowpack Energy Balance

To understand the canopy density effect on some key components of the snowpack energy balance, we examined the monthly snowpack energy balance for three locations representative of the wet/warm, dry/cold, and wet/cold climate, respectively (Table 2). Two consecutive water years were analyzed including a wetter year 2011 and a drier year 2012. Year 2011 is also slightly colder than 2012 based on mean air temperature over the energy balance analysis period from November to May.

SWE simulations for the wet/warm site (Figure 11a) suggest that, regardless of canopy density and interannual climate variability, there is a significant amount of early melt (prior to peak SWE) that is over 35% of total snowfall. Compared to the open condition, the amount of early melt under varied canopy density is similar in year 2011 but is notably lower in the drier year 2012. This is because the melt energy is consistently greater in the open than that under the forest of varying densities during the snow accumulation season of year 2012 (Figure 12a). As a result, the difference in peak SWE between the open and forest is relatively smaller in year 2012 because slightly greater early melt in the open offsets the difference in accumulation due to canopy interception (Figures 11a). Unlike the wet/warm site, the dry/cold and wet/cold sites show negligible early melt (Figures 11b and 11c) for both open and forested conditions, due to nearly zero or negative net energy available for melt during DJF (Table 3). Hence, the differential peak SWE between the open and the forest in the dry/cold and wet/cold climates is dominated by the amount of canopy interception, which decreases as canopy density decreases. For all three

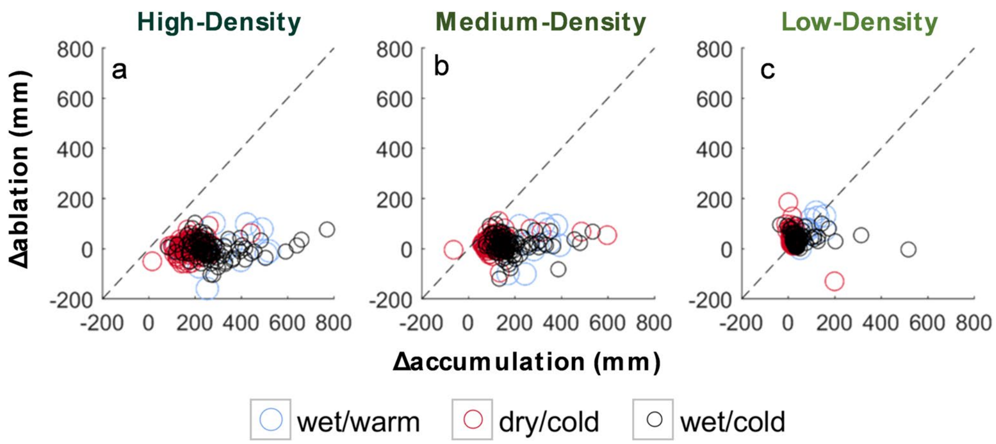

Figure 8. Difference in snow accumulation (Δaccumulation) versus difference in snow ablation (Δablation) at the time of peak snow water equivalent (SWE) between the open and (a) high-density forest, (b) medium-density forest, and (c) low-density forest. The SNOTEL locations are grouped by their winter climate condition indicated by different colors of circles.

sites, snowmelt after peak SWE is consistently higher in the open than under the forest due to higher melt energy available in the open during the melt season (Table 3). With lower canopy density, melt rates generally increase. This is because, when solar elevations are high, shortwave radiation dominates the snowpack melt energy (Figure 12, Table 3).

4. Discussion

In this study, we provide a model-based assessment of canopy density effects on peak SWE and snow disappearance dates across the climate gradients of the Western U.S. mountain ranges. By design, rather than trying to represent in situ forest cover conditions, uniform, generic canopy characteristics were used across sites for snowpack simulations under canopy density scenarios. Doing so allows for cross-site comparisons of climate sensitivity of snowpack, without confounding them with heterogeneity in local canopy conditions.

Snow measurements from SNOTEL stations were used to evaluate site-level model-simulated SWE for the open condition. While this open condition assumption may not be appropriate for SNOTEL stations located in forest gaps, we consider the natural variability of the SNOTEL siting to be part of the uncertainty in the snow model calibration, which contributes to the spread in the parameter values across all sites. Although it may be an interesting analysis to carefully examine model parameters at each site as a function of its location relative to adjacent topography and vegetation, such an analysis is beyond the scope of this study. For snowpack simulations using hypothetical canopy characteristics, we compare our model results to published snow data, in particular, paired open-forest field observations, to assess general model performance in terms of the open versus forest difference in peak SWE and SDD. In Table S1 in Supporting Information S1, we provide a synopsis of recent studies across diverse climate regimes that provide paired open-forest snow observations as well as general information about forest canopy such as LAI and FC. In general, our findings are consistent with the reported field values. For example, longer snow duration in the open than high-density forest in wet/warm climates (Dickerson-Lange et al., 2017; Storck, 2000), and significantly higher peak SWE in the open than the forest in wet/warm climate (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). For dry/cold climates, our simulations suggest mixed signs of ΔSDD consistent with observed values in Table S1 in Supporting Information S1. Nevertheless, assumptions used in this analysis and limitations inherent to DHSVM modeling of ground snowpack (discussed in Sun et al., 2019) and canopy snow processes warrant some discussion.

Three-dimensional characteristics of canopy structure such as stem density, stem arrangement, or vertical variation in leaf area are not represented in DHSVM. Canopy density is represented in the model by two-dimensional parameters, FC and LAI. Modifications of these parameters affect snow accumulation and ablation, as well as the total snowpack at a given time step, which is calculated as the average of the under-canopy snowpack

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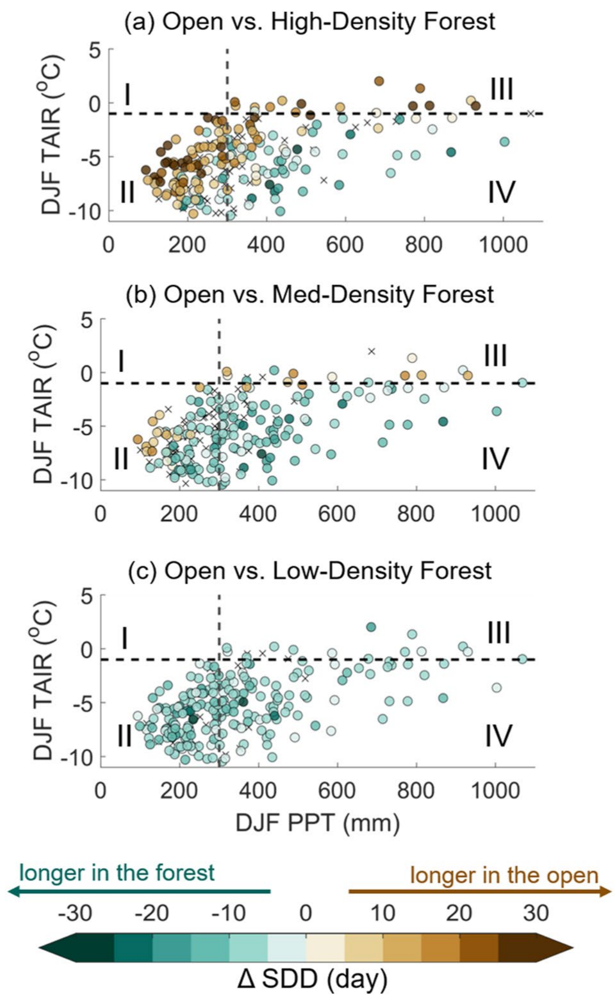

Figure 9. Differential snow disappearance date (SDD) (ΔSDD, unit: day) between the open and the (a) high-density forest, (b) medium-density forest, and (c) low-density forest as a function of December through February (DJF) precipitation and DJF temperature. A darker brown color indicates a longer duration in the open; ΔSDD within ±3 days is marked by the "×" symbol. Zone I is dry/warm, zone II is dry/cold, zone III is wet/warm, and zone IV is wet/cold.

and the open snowpack, as weighted by the fractional forest coverage. By varying these two parameters, the modeling framework simulates the effect of a range of canopy density values at an aggregated spatial scale (i.e., proportions of open and forest) for a gradient of climate conditions. While we test only three variations in canopy density, they are able to bracket the thresholds at which forest presence switches from accelerating to delaying snow disappearance compared to the open across a range of winter temperature and precipitation values. For instance, as forest density increases from zero (i.e., the open condition) to the low density class, the duration of snowpack becomes longer under all climates (ΔSDD < 0). As canopy density increases, snowpack duration becomes more sensitive to climate regimes (e.g., opposite signs of ΔSDD for wet/cold vs. wet/warm climates as demonstrated in Figure 9).

We acknowledge that spatial arrangements of sub-pixel scale forest elements, such as edges between forested and open areas and the size and frequency of canopy gaps, are important for capturing sub-pixel snow distribution and variability. For example, Mazzotti, Malle, et al. (2019) used high resolution Light Detection and Ranging (lidar) observations of snow depth and forest metrics to demonstrate a continuous relation between snow depth and distance from a canopy edge rather than a binary under-canopy versus open classification. Mazzotti et al. (2020, 2021) showed the importance of properly representing the spatial arrangement of canopies and also representing snow covered fraction within relatively small grid cells (50 m). For instance, Mazzotti et al. (2021) showed that using bulk canopy metrics that do not account for the subgrid canopy structure could result in biased estimates of peak SWE. However, it is yet difficult to characterize the fine-scale canopy structure broadly, in great part due to the lack of such data across climatic gradients. Because forest-snow field observations spanning climates and forest types are not cheap, the modeling results presented here provide a clear organizing framework for prioritizing locations and types of future field observations and identifying locations that could benefit from fine-scale canopy snow measurements and modeling.

Wind-related snow preferential deposition, wind-induced unloading of intercepted snow and subsequent redistribution are not represented by the model, which are important to represent especially for simulating snow accumulation at locations with high wind speeds and locations in dry/cold climates with lower snow cohesion (Friesen et al., 2015; Kobayashi, 1987). We recommend improving model representation of wind processes and looking at specific forest arrangement as a function of climate as a subject for future work. This research notes the need for long-term paired open-forest snow measurements with better control for climate and canopy conditions, particularly for locations with greater sensitivity of snowpack to variations in climate and/or canopy density, for example, the dry/cold and wet/warm sites. Additional observations of sub-canopy longwave and shortwave radiation, such as Malle et al. (2019) and Mazzotti, Malle, et al. (2019), and turbulent fluxes could help constrain and validate parameters for snowpack energy balance. Lastly, uncertainties exist in this analysis associated with model parameterization of canopy snow processes. Given the close interrelation between processes (e.g., canopy loading, unloading, and sublimation) controlling under-canopy snowpack, interactions between parameters need to be carefully examined in uncertainty analysis. Despite limitations in DHSVM modeling and simulations, it should be noted that sensitivity experiments with physics-based models offer an avenue to isolate climate impacts from canopy density impacts on snow processes, which is not possible based on field observations alone.

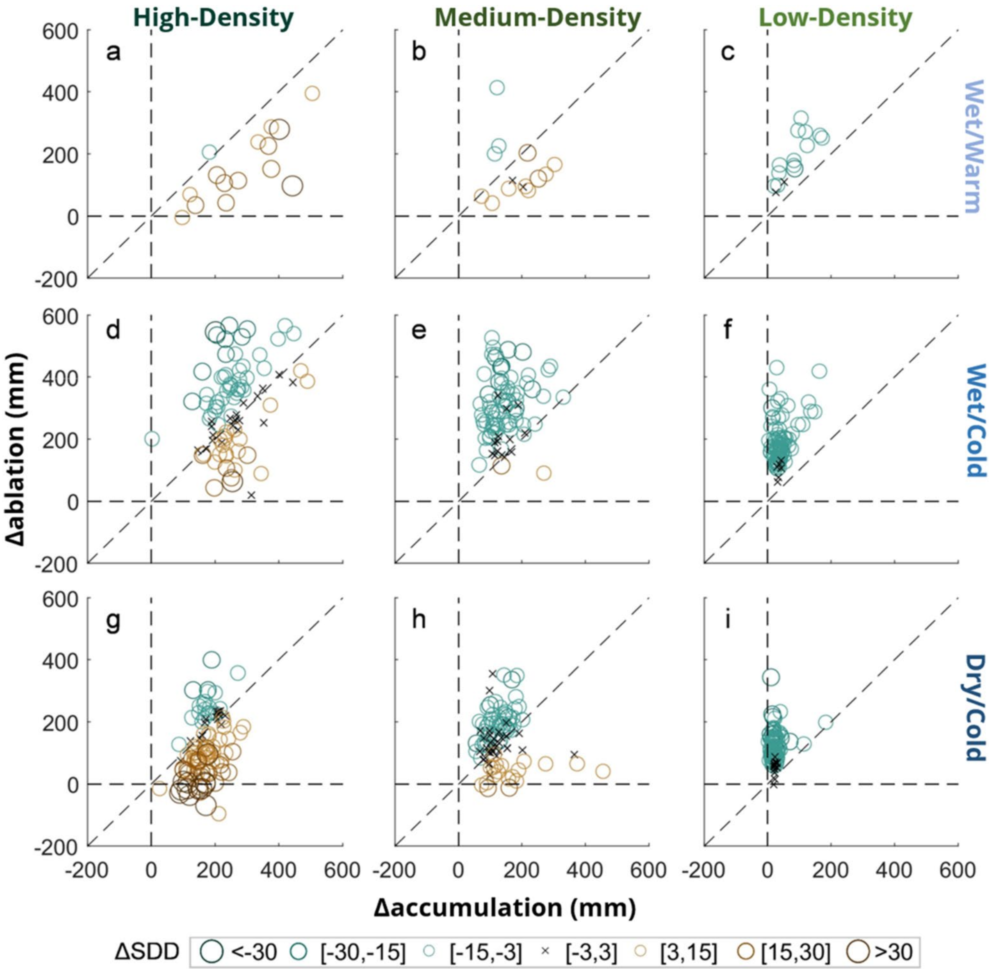

Figure 10. Differences in snow accumulation (Δaccumulation) versus ablation (Δablation) at the time of first snow disappearance date (SDD) between the open and forest of varied density at the (a–c) wet/warm, (d–f) wet/cold, and (g–i) dry/cold climate. The SNOTEL locations are grouped by ΔSDD. Green circles indicate a longer duration in the forest, and brown circles indicate a longer duration in the open.

5. Conclusions

Due to the covarying nature of climate and canopy density, field observations alone are not yet able to fully isolate the impact of canopy density from the impact of climate on snowpack dynamics. To address this gap, this study uses a physically consistent modeling approach to examine the effects of canopy density variations, due to location, disturbance, or forest management activities, on peak snow accumulation and snow disappearance timing across the climate gradients of the Western U.S.

Local polynomial regression analysis reveals strong interactions between winter precipitation and winter temperature in their effects on peak SWE for the open and forest with varying canopy density. As canopy density increases, the interacting effect of winter precipitation and temperature on SDD generally decreases. Despite the density of forest canopy, deep snowpack with late snow disappearance is found mostly in wet/cold climates, while shallow snowpack with early snow disappearance appears mostly in warm or dry climates. Climate sensitivity analysis of under-canopy snowpack suggests that canopy density has little effect on the sensitivity of peak SWE to changing winter climate (including both precipitation and temperature). SDD, on the other hand, shows an increasing climate sensitivity as canopy density increases. Despite the canopy density, peak SWE in the wet/warm sites is likely to experience the largest

Table 2
Selected Sites for Snowpack Mass and Energy Balance Analyses

Climate	Latitude	Longitude	Location
Wet/warm	42.08	−123.34	Bigelow Camp, OR
Dry/cold	44.98	−111.95	Short Creek, MT
Wet/cold	39.76	−107.36	Bison Lake, CO

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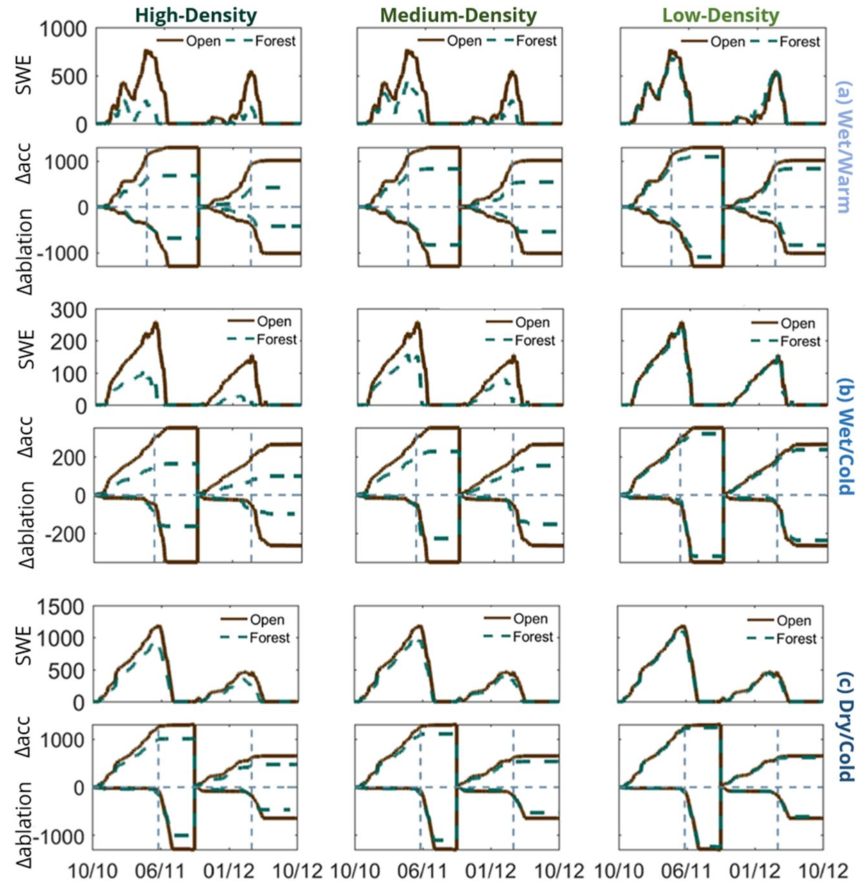

Figure 11. For three sites representative of (a) wet/warm, (b) dry/cold, and (c) wet/cold climate: time series of snow water equivalent (SWE), which are decomposed into Δaccumulation and $\sum$ ablation for water years 2011–2012. $\sum$ ablation are plotted in negative values to be better distinguished from Δaccumulation. Vertical dashed blue lines in the lower subplots indicate the timing of peak SWE.

decrease as climate warms, and wet/cold sites likely experience the largest decrease in peak SWE as precipitation decreases. For the high- and medium-density forest, SDD temperature sensitivity is greatest in warm climates (despite the dry/wet condition), and its precipitation sensitivity is greatest in dry climates (despite the warm/cold condition); under the open and lower-density forest, greatest SDD sensitivity to both temperature and precipitation is expected in dry/warm climates.

Results suggest that the canopy density effect on peak SWE and SDD varies with winter climate. Relative to wet/cold climates, reducing canopy density in wet/warm and dry/cold winter climates shows a greater effect on peak SWE and SDD. In particular, as canopy density decreases in wet/warm and dry/cold climates, snowpack shows a switch from lasting longer in the open to lasting longer in the forest. This is because, as canopy density decreases, the energy-driven snowmelt becomes the dominant influence on snowpack duration, relative to canopy interception during snow accumulation. The modeling framework and results presented here offer an organizing framework that can be used to support forest management that considers how managing forest can improve the resiliency of snow and water resources at different locations. For example, simulations suggest that canopy thinning in wet/warm and dry/cold sites can effectively improve snow water storage and snowpack duration. In nature, because canopy density is correlated with climate such that canopies tend to have a higher density in wet/warm climates than dry/cold climates, canopy thinning is likely more effective in wet/warm climates. Lastly, given a higher snowpack sensitivity to changing canopy density in wet/warm and dry/cold winter climates, locations in these climates can benefit from fine-scale canopy snow modeling.

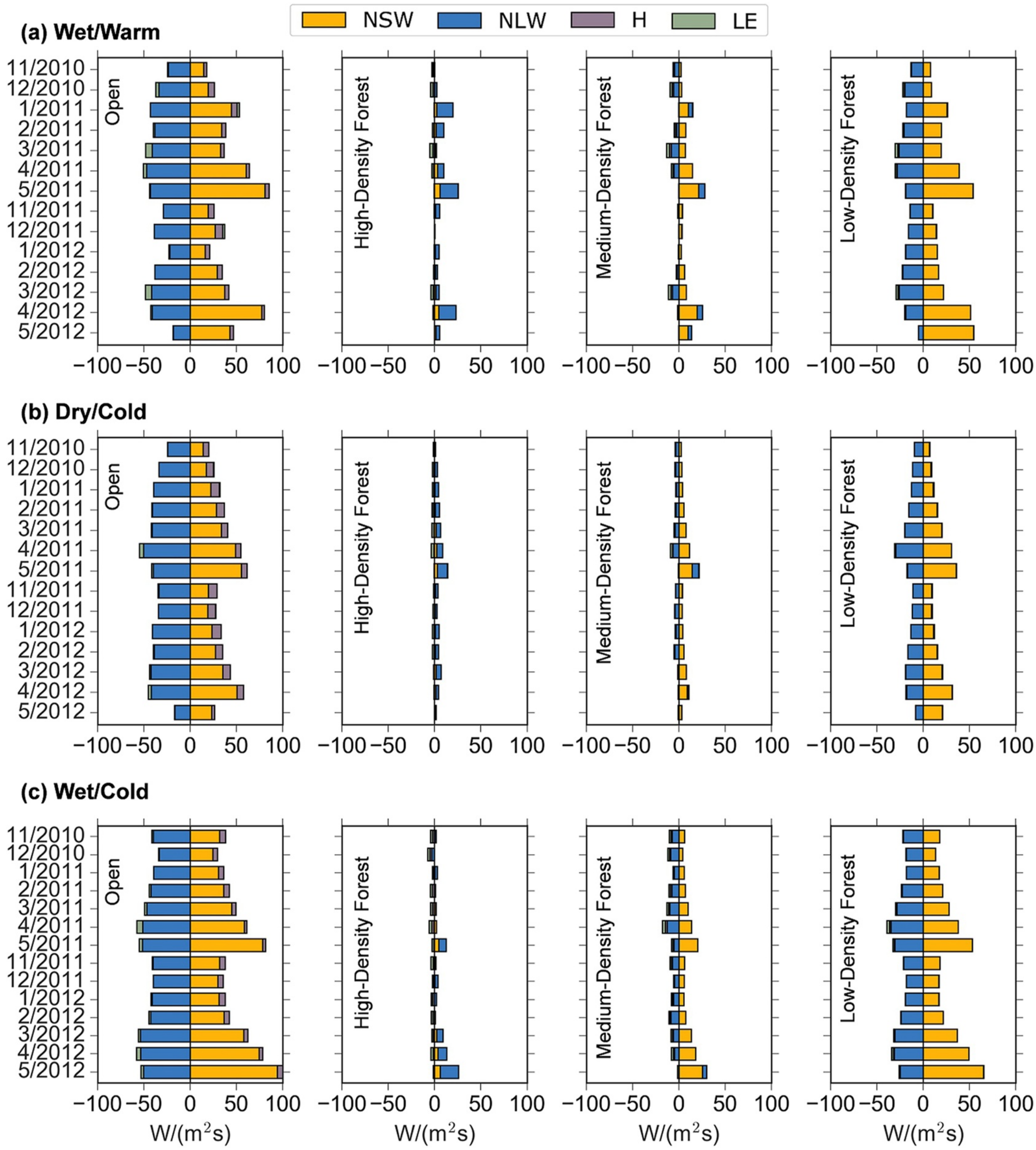

Figure 12. For three sites representative of (a) wet/warm, (b) dry/cold, and (c) wet/cold climate, simulated monthly snowpack energy balance components for water years 2011 and 2012 in the open, high-density forest, medium-density forest, and low-density forest. The period from June to October is excluded when snow is normally thin or not present in either the open or the forest. NSW is net shortwave radiation, NLW is net longwave radiation, H is sensible heat, and LE is latent heat.

Table 3
Summary of Seasonal Snowpack Energy Balance for Three Representative Sites

		NSW			NLW			Q		
Canopy condition	Climate zone	Wet cold	Wet warm	Dry cold	Wet cold	Wet warm	Dry cold	Wet cold	Wet warm	Dry cold
Open	DJF	27.2	24.0	16.6	−39.8	−35.7	−38.0	0.1	3.0	0.1
	MAM	64.8	52.5	36.6	−51.2	−38.7	−38.7	16.8	17.0	9.2
Low density	DJF	17.7	16.6	10.8	−20.1	−19.2	−13.7	−2.6	−3.9	−0.8
	MAM	45.5	40.2	26.0	−30.2	−20.5	−18.6	10.5	16.3	7.3
Medium density	DJF	6.8	5.6	4.3	−6.7	−0.8	−3.5	−5.6	2.2	−0.8
	MAM	17.7	14.1	8.9	−5.7	−0.7	−0.3	5.1	8.5	6.4
High density	DJF	1.6	1.3	1.2	1.1	5.8	3.4	−5.9	2.8	−0.3
	MAM	4.4	3.6	2.1	7.3	8.9	5.2	3.9	7.4	4.4

Note. NSW is net shortwave radiation, NLW is net longwave radiation, and Q is net energy input to snowpack. The unit of all terms is in W/m^2. DJF represents mean values over December through February, and MAM represents mean values over March through May of water years 2011–2012 of water years 2011–2012.

Data Availability Statement

The DHSVM model and BCQC (bias correction and quality controlled) SNOTEL data can be accessed at https://dhsvm.pnnl.gov/.

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