The Application of SnowModel to Vehicle Mobility in Winter

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ABSTRACT

Vehicle mobility in snow is of particular interest to the U.S. Army. We applied SnowModel, a spatially distributed, physically-based snow evolution modeling system, to characterize snow in areas where military vehicles are tested in a greater effort to help determine vehicle mobility limitations in snow. We used SnowModel to simulate a full winter season over small domains in Wyoming, Michigan, and Vermont. Meteorological forcing for the model is generated from weather station data archived in the Integrated Surface Database and the Global Historical Climatology Network. In each domain, the model is run on a 10-meter grid and simulates snow accumulation and ablation and captures seasonal and spatial snowpack variability. Additional processes represented in the model include snow densification, blowing-snow redistribution and sublimation, interception, unloading, and sublimation within forest canopies, and snowpack ripening. To increase efficiency, we parallelized the SnowModel code and implemented it on a high-performance computing system, resulting in as much as a 95% decrease in model run time for domains with a large number of weather stations. Preliminary model results will be presented.

Keywords: GHCN, snow depth, snow water equivalent, snow liquid ratio, snow class

INTRODUCTION

Vehicle mobility in snow is of particular interest to the U.S. Army. Snow strength as it relates to vehicle mobility is particularly complex, especially over transient snowpacks that are subject to episodic freeze/thaw cycles throughout the winter season (Birkeland *et al*., 1995; Pielmeier and Schneebeli, 2003). While snow depth and snow density are critical snow characteristics that impact vehicle traction and floatation (e.g., Blaisdell *et al*., 1990), snowpack stratigraphy, liquid water content, presence of ice-layers and depth hoar are also important (e.g., Shoop *et al*., 2006; Pytka, 2010). Snow observations are often far and few between and are typically limited to snow depth, making assessing snow strength from these observations a challenge. To better predict snow cover impacts on vehicle mobility at fine spatial scales, a numerical model that can simulate the complex physical processes that determine snow strength is an essential tool. In this study, we use SnowModel, a spatially distributed, physically-based snow evolution modeling system, to characterize snow in areas where military vehicles are tested in a greater effort to help determine vehicle mobility limitations in snow.

SnowModel (Liston and Elder, 2006a) is a widely used and well-documented distributed energy and mass balance snow model. The meteorological forcing is determined via optimal interpolation and terrain downscaling of available surface station data to the model grid (Liston and Elder, 2006b). The SnowModel system is designed to be run on very high resolution grids ($\Delta x < 100$ m) and

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simulates the most important processes driving the accumulation and ablation of snow including: terrain slope and effects on incoming shortwave radiation; overhead canopy and cloud cover effects on shortwave and longwave radiation; canopy interception/unloading and sublimation of snowfall; snowpack densification and ripening; and liquid refreeze within the snowpack. Finally, a blowing snow transport model (Liston and Sturm, 1998) is incorporated into the SnowModel framework and simulates the lateral movement and enhanced sublimation of snow by the wind.

To correct for typically challenging and uncertain snow precipitation observations, a "data assimilation" technique can be applied within the SnowModel framework with the aim of accounting for precipitation undercatch. The assimilation technique uses available snow depth measurements and determines a correction factor, which is then used to backfill the precipitation forcing such that it closes the snow deficit between the model and observations at assimilation time. The intrinsic assumption underpinning this technique is that precipitation undercatch is the largest contributor to model error throughout the winter season, and that other model errors are secondary in nature.

While SnowModel has a high degree of physical realism, several processes impacting the surface energy balance are either oversimplified or neglected entirely. For instance, SnowModel has a fixed dry-snow albedo, and ignores the precipitation heat flux. Additionally, because SnowModel is designed to run with surface station data, the parameterizations for cloud cover, incoming longwave radiation, and temperature/wind/precipitation lapse rates are subject to large uncertainty.

The primary goal of this study is to investigate SnowModel as a predictive tool for snow strength metrics by assessing its ability to accurately simulate snow depth and snow density at different model resolutions over three Army training sites located within the United States with distinct terrain and land cover properties. By focusing primarily on model resolution, the effects of terrain and land cover on the modeled snowpack evolution can be evaluated.

DATA AND METHODS

We perform SnowModel simulations over three domains within the continental United States (Fig. 1). The simulations are run at three grid-spacings: Δx = 10 m, Δx = 100 m, and Δx = 1000 m to assess the impact of resolution on the simulated snowpack characteristics. From west-to-east, the study domains are West Yellowstone, the Keewenaw Research Center located on Michigan's Upper Peninsula (hereby KRC), and Camp Ethan Allen Training Site in Jericho, Vermont (hereby CEATS). The 10-m terrain and land cover grids used as the model static input are presented in Figure 2, and key domain statistics are located in Table 1. The domain sizes range from ~ 600 km^2 for KRC to ~3000 km^2 for West Yellowstone, and each domain contains a wide range of land cover types including mixed and evergreen forests, grass and shrub lands, and urban centers and road corridors (Fig. 2). The CEATS domain has the most variable terrain with nearly 1220 m of elevation between the domains highest and lowest grid point and KRC has the least terrain variability with only a 183 m maximum elevation difference.

In all three domains, the meteorological forcing for SnowModel is generated from surface station data archived in the National Oceanic and Atmospheric Administration (NOAA) Integrated Surface Database (ISD: Smith *et al*., 2011). The ISD aggregates quality controlled global hourly and synoptic (6-hourly) observations into a common ASCII format and includes standard meteorological parameters such as windspeed and direction, near surface air temperature and dewpoint, surface pressure, and accumulated precipitation. These data are aggregated into 3-hour average windspeed, direction, temperature, and dewpoint, and 3-hour accumulated precipitation for each forcing site. In each domain, only one ISD station is available (Fig. 2). Note that for the CEATS domain, the ISD station used is the surface weather station at the Burlington, VT airport, which is approximately 17 km west of the westernmost edge of the domain.

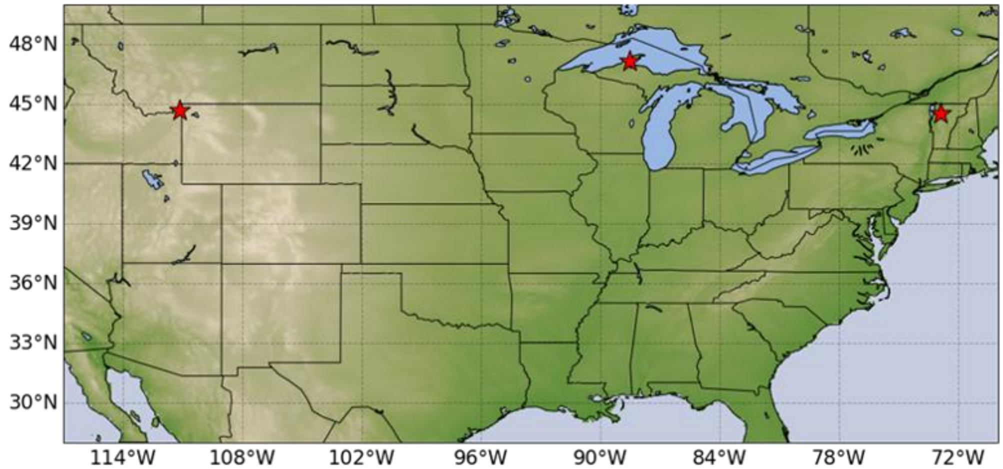

Figure 1. Map of United States with the three domain locations marked as red stars.

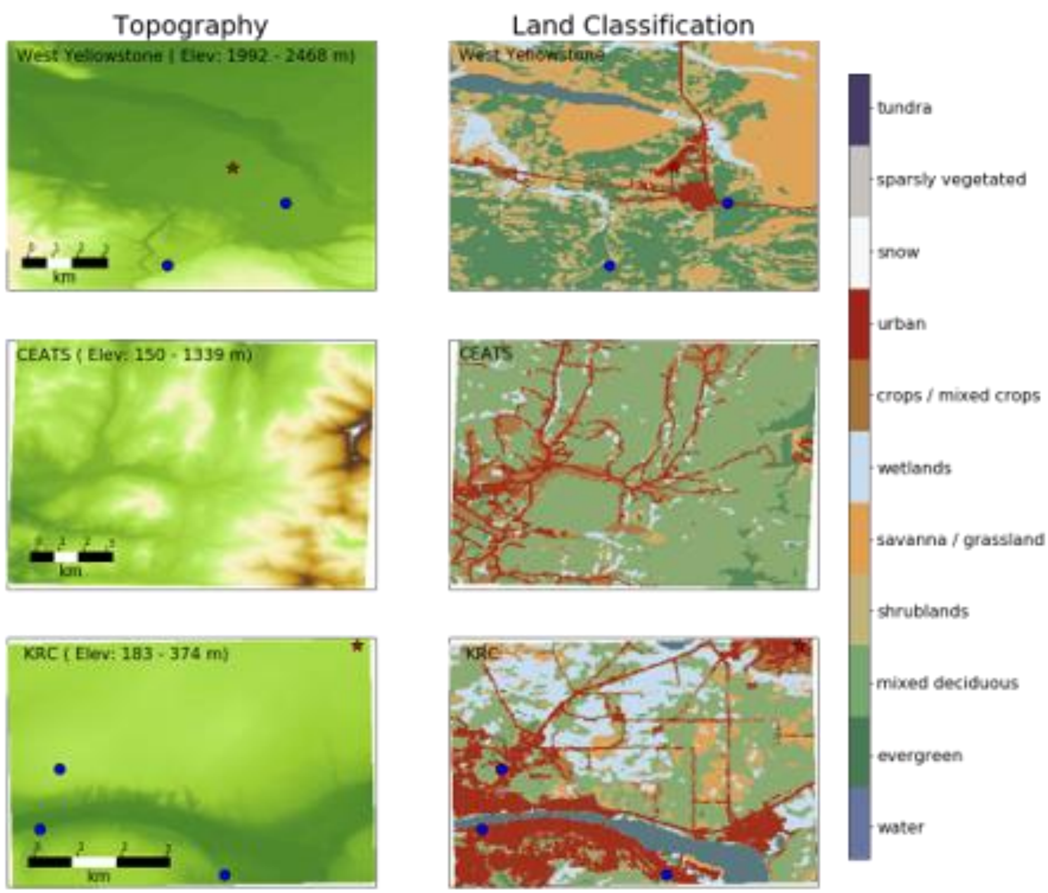

Figure 2. Detailed view of each domain. Topography is shown in the left column, and land classification is shown in the right column. ISD stations are marked as red stars, and GHCN stations are marked as blue circles. In each domain, the terrain is plotted for a 1219 m (4000 ft) range starting from the lowest domain elevation. Note that forcing station used for the Camp Ethan Allan domain is approximately 17 km west of the western domain edge and not shown in the figure.

Table 1. Summary statistics for each of the three SnowModel domains. All statistics are based on the 10-m resolution grid.

Name	Domain extent	Elevation	Forest fraction	Detailed forest
West Yellowstone	302.9 km^2	Lo: 1992 m Hi: 2468 m	53.4%	Coniferous: 53.3% Deciduous: 0.1% Mixed: 0% Short Coniferous: 0% Clear cut: 0%
KRC	59.7 km^2	Lo: 183 m Hi: 374 m	82.1%	Coniferous: 11.5% Deciduous: 57.4% Mixed: 13.4% Short Coniferous: 0% Clear cut: 0%
CLEATS	252.2 km^2	Lo: 150 m Hi: 1339 m	43.8%	Coniferous: 2.3% Deciduous: 33.7% Mixed: 7.7% Short Coniferous: 0% Clear cut: 0%

To supplement data from the ISD at the West Yellowstone and KRC domains, daily summary data from the Global Historical Climatology Network (GHCN: Peterson and Vose, 1997) is incorporated into the model forcing. These data only include daily average temperature and daily accumulated precipitation, and therefore do not affect the wind or humidity forcing.

The point station data are mapped to the gridded SnowModel domain using a Barnes optimal interpolation routine to distribute the point data across the grid. For the CEATS domain, no interpolation is applied since there is only one station in the forcing dataset. At this domain, the station data is applied uniformly across the grid.

The gridded station data is downscaled to the terrain using climatological lapse rates for temperature, moisture, and precipitation. No elevation adjustment is applied to windspeed because the physical processes that determine windspeed are much more complex and variable than the processes that determine temperature and moisture lapse rates. Minor terrain adjustments are applied to the windspeed and direction following Liston and Elder (2006b).

SnowModel Overview

Primarily, SnowModel is a mass and energy balance column model that solves the energy balance equation:

$$M = Q_s(1-\alpha) + Q_l - SH - LE - \varepsilon\sigma T_s^4 - G + L \tag{1}$$

and the mass balance equation:

$$\frac{dSWE}{dt} = P - E - R \tag{2}$$

where, in the energy balance, G is the conductive transfer of heat through the snowpack, Q_s is the downwelling shortwave radiation, α is the surface albedo, Q_l is the downwelling longwave radiation, SH and LE are the turbulent sensible and latent heat fluxes, respectively, L is the liquid refreeze heat flux, M is the melt flux, ε is the emissivity, σ is the Stefan-Boltzmann constant (5.67 x 10^{-8} W m^{-2} K^{-4}), and T_s is the snow surface temperature. In the mass balance, P, E, and R are rates of precipitation, evaporation/sublimation, and runoff, respectively. No distinction is made between frozen and liquid precipitation in the mass balance equation, since liquid is allowed to be retained in the snowpack via refreezing. The snowmelt energy flux (M) is computed as residual of the energy budget when T_s is determined to be above freezing, i.e., it is the energy required to maintain a snow surface temperature of freezing. Runoff is computed each timestep as the residual liquid (rain + snow melt) not retained within the snowpack.

Critically, a number of parameterizations are required to retrieve the energy and mass balance forcing terms from surface data. In particular, Q_s and Q_l are difficult to obtain from standard surface meteorological observations since they are strongly dependent on the 3D atmosphere. In SnowModel, a baseline Q_s is determined from latitude, time of day, elevation, slope and aspect, and day of year. It is then adjusted for cloud cover, where cloud cover is parameterized from surface temperature and moisture following Walcek (1994). Longwave radiation is parameterized from surface temperature and cloud cover following Iziomon *et al*. (2003). Finally, at grid cells where the land cover classification is vegetated, a canopy adjustment is made to Q_s and Q_l following Liston and Elder (2006a).

Precipitation observations are not intrinsically categorized as rain or snow, rather the rain/snow partitioning is performed in SnowModel using a simple temperature threshold:

$$f_s = \begin{cases} 1, & T_{air} \leq 0\ ℃ \\ 0, & T_{air} > 0\ ℃ \end{cases} \tag{3}$$

where f_s is the fraction of precipitation that falls as snow. At vegetated grid cells, the canopy can intercept a fraction of the snowfall where it is stored until it either sublimates or is added to the surface snowpack at a rate determined by the air temperature following Liston and Elder (2006a).

When snow transport is included in the model, the mass balance equation becomes:

$$\frac{dSWE}{dt} = P - E - R - \nabla \cdot Q_t - E_t \tag{4}$$

where $\nabla \cdot Q_t$ is the horizontal divergence of transported snow, and E_t is an additional sublimation term applied to the transported snow. $\nabla \cdot Q_t$ and E_t are computed following the parameterization described in Liston and Sturm (1998). Critically, this parameterization assumes that all snow is equally susceptible to wind transport regardless of character, and that all blowing snow is given a constant density.

Baseline Simulations

We first perform a baseline simulation for each domain using a common model configuration. These simulations are performed for a single winter season beginning in September and ending in June. The common simulations are performed with a horizontal grid-spacing of 10 m, a 3-hour time step, and with tunable parameter options as given in Table 2. These simulations are performed without data assimilation.

Table 1. Summary statistics for each of the three SnowModel domains. All statistics are based on the 10-m resolution grid.

Parameter description	Value
Shortwave radiation canopy gap fraction adjustment to canopy transmissivity	0.1
Threshold friction velocity for snow transport	0.25 m s^{-1}
Blowing snow density	300 kg m^{-3}
Dry snow albedo	0.8
Wet snow albedo for vegetated grid-cells	0.45
Wet snow albedo for non-vegetated grid-cells	0.6
Terrain curvature length scale for wind adjustment	700 m
Terrain slope weight for wind adjustment	0.58
Terrain curvature weight for wind adjustment	0.42

Experimental Configurations

The primary interest of this work is to investigate the effects of model resolution on snow depth and density as these variables have a strong impact on vehicle mobility. We chose to run the model at 100-m and 1000-m horizontal resolution over each domain. In these configurations, the 10-m terrain dataset is aggregated and averaged to match the coarser resolution grid. The 30-m land cover dataset is resampled to the coarser grid, assigning the majority land cover classification value within the coarse filter window.

Since SnowModel is a column land model, rather than a 3D Eulerian dynamic model, this is primarily an investigation of the impact that static terrain and prescribed downscaling has on snow since the underlying meteorological forcing is identical at all three resolutions. Critically, this experiment quantifies the benefits of performing high resolution simulations in data-sparse regions, and illuminates upon the relative roles of meteorology and terrain in determining snowpack evolution. Additionally, because SnowModel does not parameterize sub-grid partitioning of land or snow cover, model accuracy is expected to degrade with decreasing resolution as sub-grid effects become increasingly important.

Model Evaluation

The simulated snowpack is evaluated against any available snow depth and SWE *in situ* data within each domain. In the CEATS and KRC domains, only snow depth data is available and, accordingly, in these domains, model snow density cannot be assessed.

In West Yellowstone, two automated SNOw TELemetry (SNOTEL) stations are available, providing daily average snow depth and SWE data, thus allowing for an evaluation of model snow density. In addition to SNOTEL observations, high density snow depth observations collected at the training site during mid-winter are used to evaluate the model's ability to reproduce fine-scale snow depth variability at West Yellowstone.

At CEATS, there are five automated GHCN stations with snow depth data available. Of these, two are located in Underhill, VT, in the north central portion of the domain, two are located in Jericho, VT, on the western edge of the domain, and one is atop Mt. Mansfield at 1,204 m in elevation. The Underhill and Jericho stations are all at relatively lower elevations, ranging from 195 to 285 m, allowing us to further investigate the effect of terrain on modeled snow outputs.

At KRC, snow depth data are available at three GHCN stations. Two are located in Houghton, MI – one in the northwest, and one in the southeastern region of the domain. The third station in Quincy Hill, MI is located in the southwestern corridor of the domain. While all three stations sit at similar low elevations, the most northwestern station is separated from the others by a sizable body of water, Portage Lake. This allows for analysis of how well the model handles a variety of land cover types in a relatively small area, including water, which is unique among the testing sites.

RESULTS

While SnowModel was able to reproduce the winter accumulation and spring ablation of the snowpack with reasonable fidelity at all three domains, the model underpredicted the total amount of SWE and snow depth at nearly all evaluation sites for the baseline simulations (Figs. 3-5).

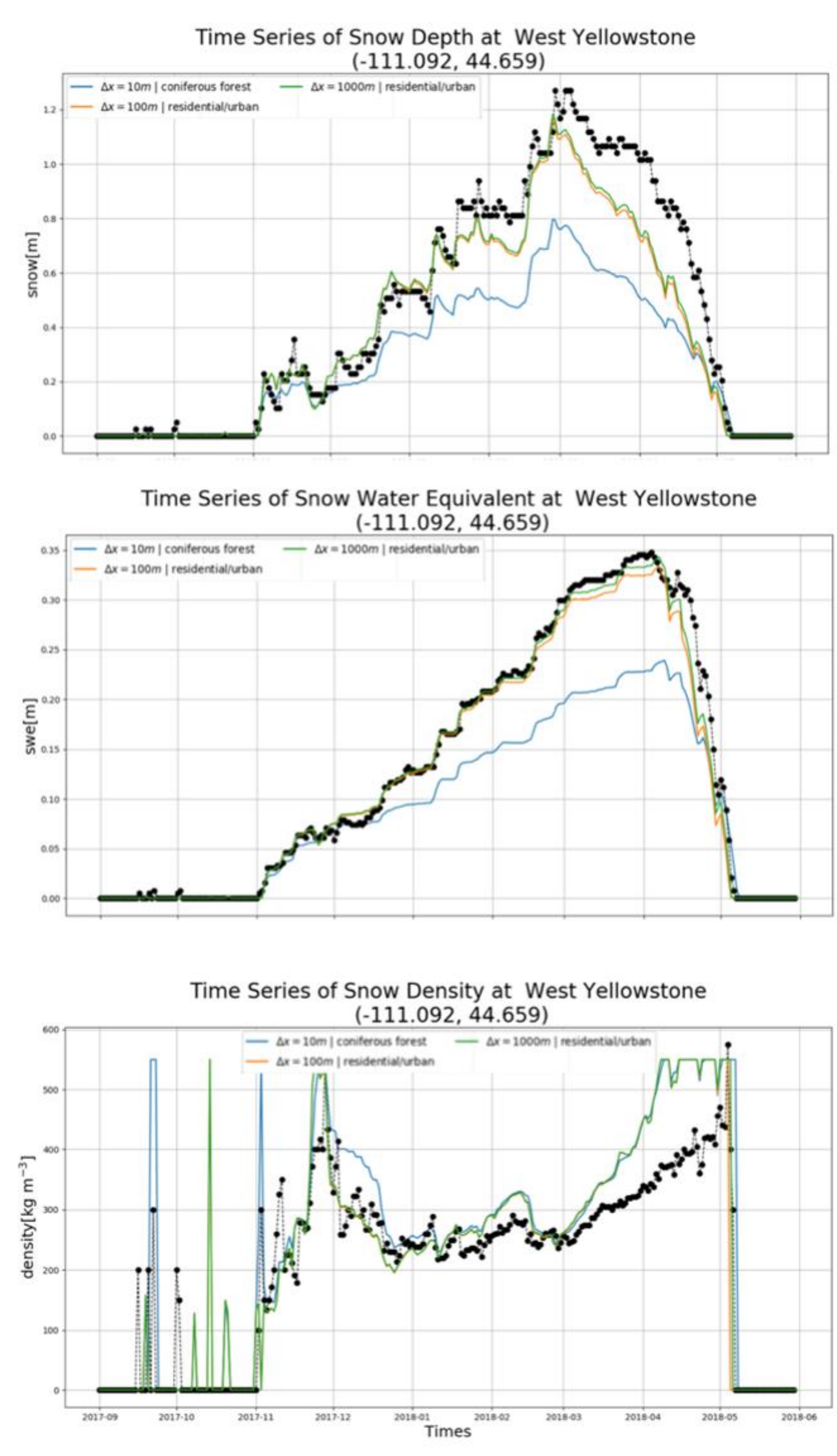

Figure 3. Time series of snow depth, SWE and snow density for the West Yellowstone SNOTEL site.

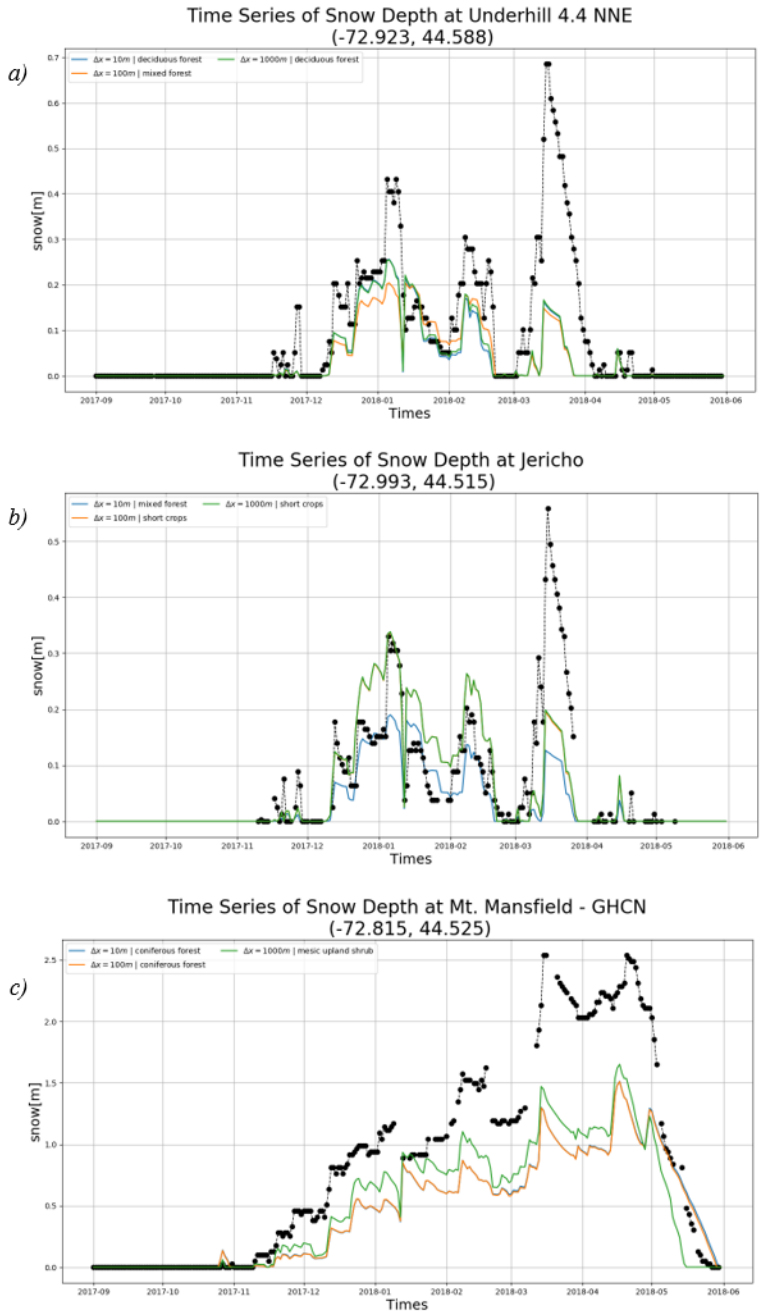

Figure 4. Snow depth, modeled (solid lines) and observed (connected points), at (a) Underhill, VT, (b) Jericho, VT, and (c) Mt. Mansfield for the 2017-2018 snow accumulation and ablation season. The three model resolution runs (10-m, 100-m, and 1000-m) are shown and the resulting land cover classification for each reported in the legend.

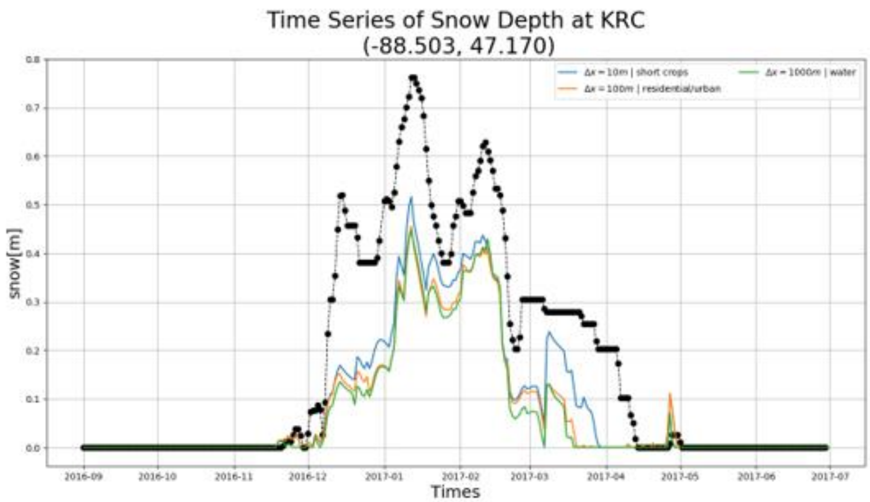

Figure 5. Snow depth, modeled (solid lines) and observed (connected points), at the KRC site for the 2017-2018 snow accumulation and ablation season. The three model resolution runs (10m, 100m, and 1000m) are shown and the resulting land cover classification for each reported in the legend.

All three domains showed qualitatively different snowpack characteristics. For example, the West Yellowstone domain showed a generally consistent accumulation season with a gradual increase in the amount of SWE on the ground, and a slow compaction of the snow. In contrast, the sites within the CEATS domain showed numerous melt events that entirely depleted the snowpack followed by a rapid replenishment of SWE. The exception to this behavior was at the Mt. Mansfield site which is located at an elevation ~4000 feet and is more characteristic of an alpine forest than the typical mid-latitude temperate deciduous forest. At KRC, the snowpack was most similar to that of the low-elevation CEATS sites, with occasional mid-winter melt events that interrupted the steady accumulation of snow.

In general, the baseline SnowModel configuration was able to reproduce the snowpack accumulation and melt in all three domains. In particular, the West Yellowstone simulation performed remarkably well with respect to the timing of maximum snow depth and the timing of melt out at each SNOTEL site (Fig. 3). However, snow depth was largely underestimated throughout the year at each site, with the maximum snow depth underestimated by approximately 0.4 and 0.6 m at each site, respectively. Concerningly, the West Yellowstone SNOTEL site is located in close proximity to the meteorological forcing location and is at the same elevation, thereby ruling out improper terrain downscaling as the explanation for the discrepancy. The model also appears to overestimate density during the late winter and early spring when the snow was undergoing compaction. The overestimate in density combined with the underestimate in SWE amplifies the underestimate in snow depth.

Intriguingly, model performance with respect to SWE and snow depth appears to improve as model resolution is degraded from 100-m to 1-km, contrary to expectations. However, upon examination, we find that the improvement stems from the fact that the resolution decrease causes the land classification to change from forested to unforested (Figs. 3-5). This strongly suggests that resolution has a minimal impact on simulated snow relative to the forest canopy impact. Yet, because SNOTEL observation sites are purposefully sited in clearings, it cannot be concluded that the forest canopy parameterizations are inaccurate from this analysis, since the observation is more representative of a non-forested location, despite its model land classification (Meromy *et al*., 2013).

Model performance for the CEATS domain largely mirrored that of West Yellowstone. The simulation performed well with respect to snow timing, though in most instances underestimated snow depth. Additionally, resolution degradation had a minimal impact on the results except where it resulted in a change from forested to non-forested land cover type.

Model performance at KRC is similar to performance in the other two domains, but a little more nuanced. While the model systematically underestimates snow depth, there is an apparent greater dependence on resolution that is unaccompanied by a change in canopy coverage.

While increased resolution does not appear to degrade model accuracy substantially, land cover reclassifications notwithstanding, one potential benefit of running SnowModel at fine (<100 m) resolution is its potential to accurately simulate fine-scale spatial heterogeneity of snow depth by including snow redistribution by wind.

We further assess the model's ability to simulate fine-scale spatial heterogeneity by comparing simulated snow depth against manually collected snow depth observations in the West Yellowstone training site. At this site, numerous point snow depth measurements were collected within a small area (<1 km^2). These observations are evaluated against simulated snow depth from the 10-m run. This evaluation largely shows that simulated snow depth variability was substantially less than the observed variability, suggesting that running SnowModel at the 10-m DEM resolution does not adequately reproduce the observed spatial variability observed in reality (Fig. 6). We suspect that this is due to the coarse meteorological forcing and simple relationships governing changes in windspeed, temperature, and precipitation with elevation and land cover. Furthermore, in non-forested areas prone to drifting, small turbulent eddies, not simulated in SnowModel, are largely responsible for determining the high-spatial variability in snow depth (e.g., Liston *et al*., 2018). However, the high-density observations were collected on flat terrain during the mid-winter, and therefore it cannot be determined from this analysis whether or not the terrain-adjustments to incoming shortwave radiation improve the results at finer resolutions. It seems reasonable to believe the higher resolution will provide greater benefits in regions with complex terrain, where local-scale snow amounts are determined primarily by terrain features than by large-scale meteorology. More work is needed to fully assess the benefits of running SnowModel at higher resolutions.

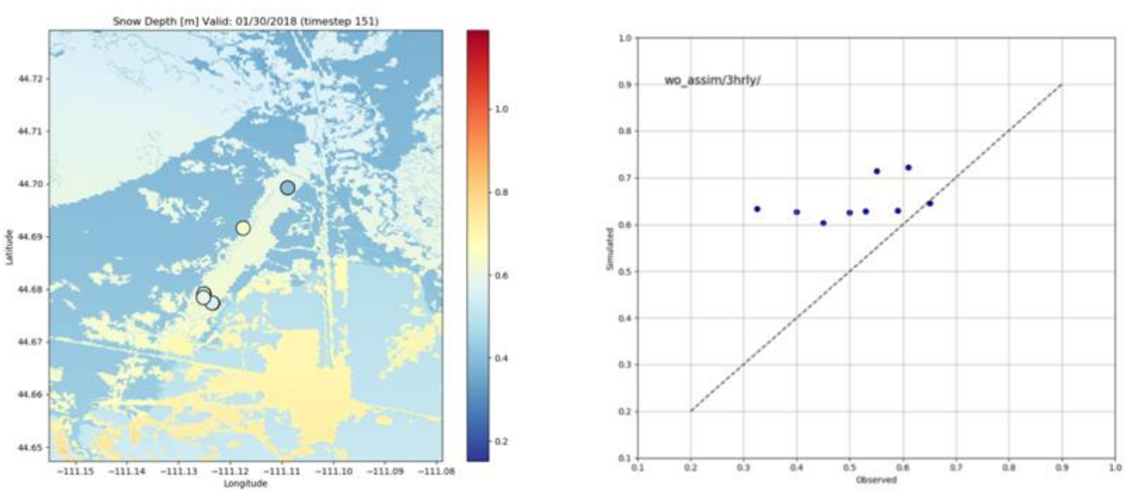

Figure 6. Left: Map of model simulated snow depth with points representing the observations for West Yellowstone domain. Right: Scatter plot of modeled versus observed snow depth from West Yellowstone.

DISCUSSION

The most interesting result from this study was the outsized role that the forest canopy played in governing the snowpack in all three domains. To investigate these impacts further, we examine the canopy parametrizations that affect the snowpack. Specifically, we focus on leaf area index (LAI) which quantifies the fractional leaf area coverage per unit ground area. In SnowModel, LAI is land-category and seasonally dependent following a modified cosine function that computes a LAI value that falls somewhere between winter minimum and summer maximum value. This function is geographically constant, i.e., it has no dependence on latitude or elevation. LAI is used to compute the canopy effects on all driving meteorology at the surface.

In particular, maximum canopy snow holding capacity is computed as:

$$S = 4.4LAI \tag{5}$$

where *S* is the maximum snow holding capacity. Snow can be removed from the canopy by either unloading or sublimation. Unloaded snow is added to the sub-canopy snowpack. Canopy unloading is determined to be 5 mm day^{-1} °C^{-1} when the air temperature is greater than freezing:

$$U = \begin{cases} \frac{5}{86400}(T_{air} - 273.15)\Delta t, \ T_{air} > 273.15 \\ 0, \ T_{air} < 273.15 \end{cases} \tag{6}$$

where *U* is the unloaded snow. SnowModel does not include wind unloading. Therefore, snow is only transferred from the canopy to the ground when the air temperature is above freezing. Canopy sublimation is determined using an energy balance approach and is not described in detail here; see Liston and Elder (2006a).

The canopy also has a strong influence on the surface energy budget by modifying the incoming radiative fluxes. Shortwave radiation is attenuated by the canopy by applying a canopy shortwave transmissivity (τ) to Q_s from MicroMet following:

$$\tau = e^{-0.71LAI} \tag{7}$$

and longwave radiation is modified according to:

$$Q_{l,can} = (1 - f_c)LW \downarrow + f_c \sigma T_{air}^4 \tag{8}$$

where, f_c is the longwave forest fraction:

$$f_c = 0.55 + 0.29 \ln(LAI) \tag{9}$$

To illustrate the impact of LAI, the annual cycle of the above variables is plotted for each forest type in SnowModel (Fig. 7). Coniferous forests have the greatest impact on the forcing data that drives SnowModel. Furthermore, unlike deciduous trees, their impacts persist throughout the winter season. This indicates that evergreen forests will have the highest impact on snow interception and radiation.

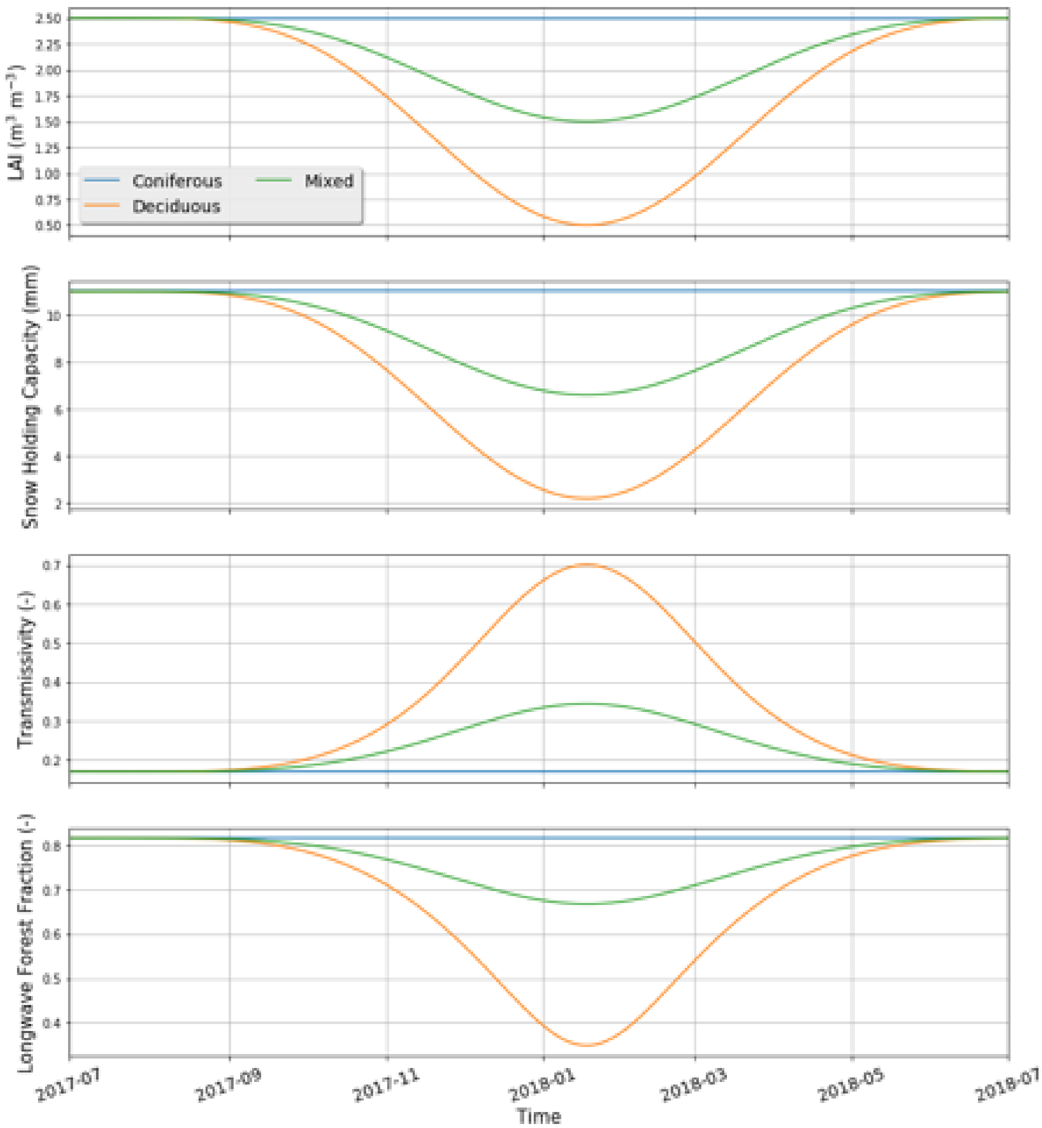

Figure 7. Seasonal cycle of LAI for the three main forest classifications from SnowModel with their impacts on snow holding capacity, shortwave transmissivity, and longwave radiation.

To assess the LAI parameterization, the simulated LAI for each region is computed by weighting each canopy LAI function by its domain fraction. The domain average LAI is then plotted against the MODIS derived LAI (MCD15: Myneni *et al*., 2016) averaged over the domain (Fig. 8). In general, the SnowModel LAI parameterization does not adequately capture the seasonal cycle of LAI. For instance, the modeled gradual decrease (increase) in LAI during the fall (spring) in the CEATS and KRC domains is at odds with the observed rapid transitions seen in the MODIS data. Furthermore, the assumption that LAI is constant throughout the year for the evergreen forests in West Yellowstone is not representative of the observed seasonal cycle. However, in contrast to SnowModel, MODIS LAI is not a combined LAI and stem area index (SAI) variable. Furthermore, the MODIS LAI product is subject to substantial error for snow covered evergreen trees (Tian *et al*., 2004). Therefore, caution should be exercised when interpreting differences between the MODIS derived and SnowModel LAI.

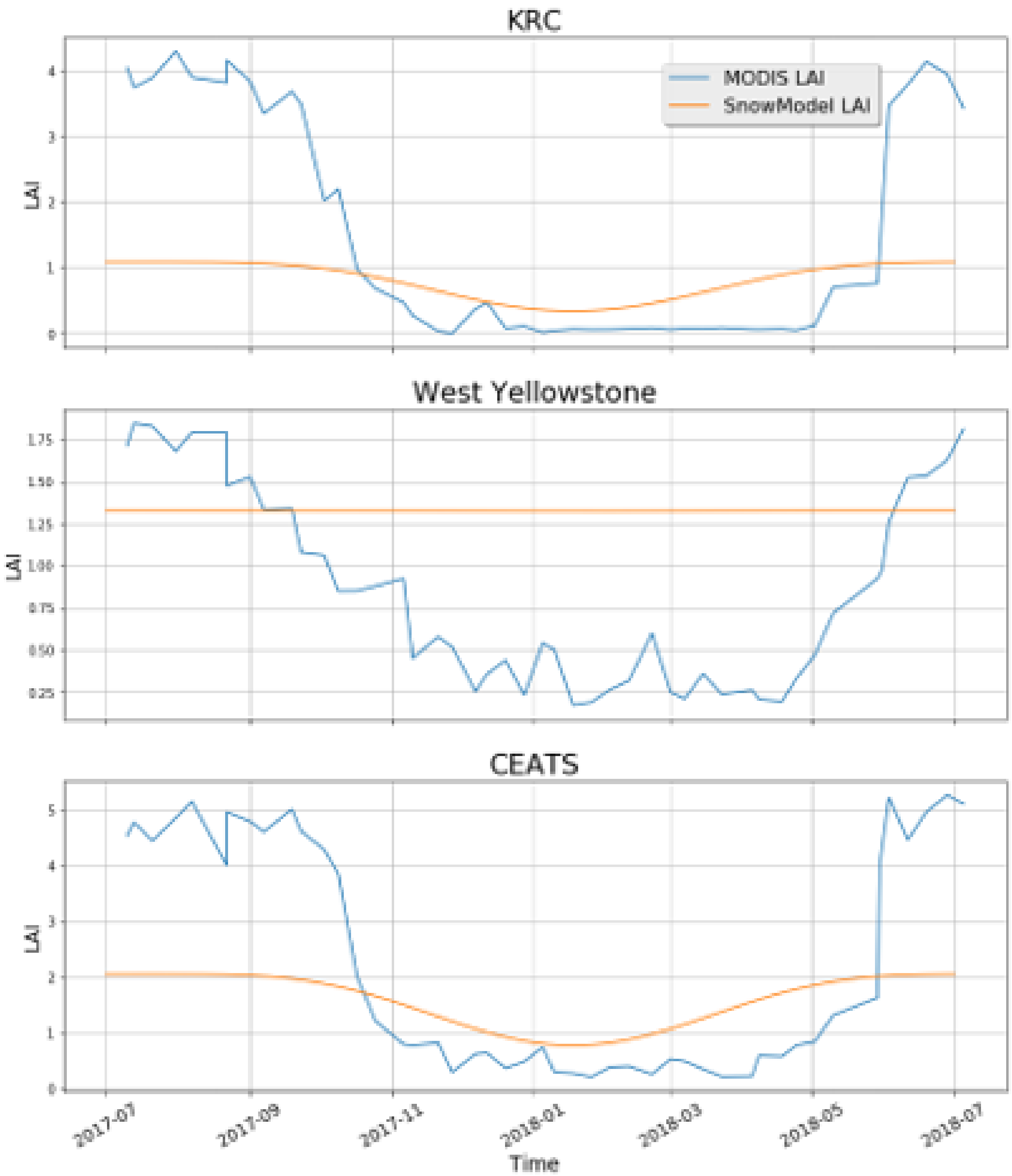

Figure 8. Mean MODIS LAI plotted for each domain against mean LAI from SnowModel. SnowModel LAI is computed by weighting the LAI from all land cover types within each domain.

While we have no direct sub-canopy measurements, we speculate that simulated snow beneath a canopy is subject to large inaccuracies due to its simplified snow unloading parameterization and its overly simplistic representation of the LAI seasonal cycle. We anticipate that these inaccuracies are most likely to lead to a low bias in snow and are likely to be highest for evergreen forests. Combined with the model's general overestimation of snow density, the snow underestimation potentially leads to a substantial overestimate in vehicle mobility. That is, under forest canopies the model produces less, and more dense, snow than in reality.

We note further that the observational comparisons can be disproportionally skewed by the presence of a canopy. Meteorological data is purposefully sited such that it is in a clearing to minimize the impacts of forest on the observations. In particular, this explains the relatively poor performance of SnowModel in the West Yellowstone domain, as gauged by SNOTEL.

Finally, the conclusions of this study are based on a single snow year and the generality of these conclusions is unclear. For example, preliminary evaluation of a SnowModel simulation performed over the CEATS domain during the 2018-2019 season shows much less agreement with available observations, indicating that more work is required to fully understand SnowModel performance in temperate forests.

CONCLUSIONS

In general, SnowModel is able to reproduce the seasonal cycle of snow depth in most instances with reasonable fidelity for numerous different snowpacks, indicating that it has the potential to be a valuable tool for assessing and predicting vehicle mobility in snow covered environments. Limited snow density measurements indicate that the model tends to overestimate snow density in the late-winter and spring. However, density was only evaluated at the West Yellowstone site, so it is unclear as to whether or not this finding is applicable to snowpacks in other regions.

We find that model resolution has a nearly indiscernible direct impact on simulated snow in all three domains between 10-m – 1-km. This is unsurprising in that the meteorological forcing is essentially uniform throughout each domain, and effects of terrain are muted since in all domains, the terrain variability is generally moderate enough such that the model elevation only varies ~100-200 m between the coarse and fine resolutions. Furthermore, because all three domains have substantial tree cover, wind redistribution of snow is limited. However, it is somewhat surprising that neglecting sub-grid snow cover fraction at 1-km resolution had almost no direct impact on the results.

While resolution did not directly affect the results, land cover changes due to down sampling high resolution data had a substantial impact. The effects were particularly significant for grid cells that changed from forested to non-forested or *vice versa* during the down sampling process.

Further investigation into the overwhelming impact of land cover revealed that the seasonal cycle of LAI is likely misrepresented by SnowModel for all major forest types such that canopy effects on snow holding and radiation are likely overestimated throughout the winter. Overestimated canopy effects are likely greatest for evergreen forests with long periods of time of below-freezing snow temperatures. Based on this analysis, caution should be exercised when evaluating modeled snow mobility impacts at grid cells classified as forested. Specifically, we speculate that vehicle mobility is subject to being overestimated for forested land cover types due to a high bias in simulated snow density, and a low bias in simulated snow amount. Combined, these biases lead one to believe that the under-canopy snow is denser and less deep than it likely is in reality.

SnowModel has the ability to “back-correct” an assumed precipitation undercatch observation deficiency using observed snow depth through a form of data assimilation. The results presented here indicate that a high degree of caution needs to be exercised when employing this technique, to ensure that the precipitation correction is being applied correctly. For example, instances when the snow depth used in the assimilation process is located at a grid cell classified as forest canopy, it has the potential to overcorrect the precipitation leading to vastly overestimated snow depth at all proximity grid cells classified as non-forested.

It is possible that the SnowModel canopy parametrization could be improved by updating the LAI seasonality using new relationships available from more recent satellite missions (e.g., MODIS), and by incorporating more sophisticated snow unloading parameterization. These improvements would likely lead to greater confidence in vehicle mobility predictions derived from SnowModel.

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