Evaluating and Improving Snow Prediction in the National Water Model in New York State Using New York State Mesonet Data

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Abstract

When snow melts, the water drains into nearby streams and rivers which can impact water supply and flood hazards. The National Water Model (NWM) provides high quality forecast data for streamflow in the continental United States using mathematical representations of hydrologic processes. This research evaluates how the land surface model (LSM), Noah-MP, in the NWM simulates snowpack and snowmelt in New York State. To evaluate the representation of snow melt in Noah-MP, we examine point simulations at the New York State Mesonet (NYSM) sites where Noah-MP is forced by NYSM meteorological observations to avoid biases in the meteorological input and isolate the LSM formulation as the source of biases. Additionally, we examine distributed runs across the whole state forced by a gridded meteorological analysis. Compared to the NYSM snow depth observations averaged at all sites, the snow depth output in the ablation period of point-simulations is too high. Through controlled sensitivity experiments where an aspect of the model is altered in isolation, it is revealed that the snowpack in Noah-MP is strongly sensitive to a parameter of snow albedo decay, $\tau_0$. There is a bias in the melt rate in the model causing slow snow melt which can be changed by altering the $\tau_0$ value. Decreasing the value of $\tau_0$ causes the snow to melt faster and the predicted snow depth and snow water equivalent to be more similar to observations. Decreasing the value of $\tau_0$ and increasing the rate of albedo decay also causes the model albedo decay rate to be more similar to observations. Through evaluation of how albedo changes in the model for snow melt periods at NYSM sites, the NWM biases in the northeast United States can be more deeply understood.
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All of my opportunities at UAlbany have guided me to write this thesis and to the end of my undergraduate experience and beyond.
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1 Introduction & Motivation

1.1 Introduction

Snow is an important component of the hydrologic cycle in New York State because it stores water and subsequently releases that water as runoff. This water may enter a fresh water reservoir such as those in the Catskill Mountains which are the primary water supply for New York City. The timing of snow melt during the winter and spring is important for knowing how much water is available for New York City (Matonse et al. 2011). Runoff from melting snow packs can also cause flooding. Of all of the states, New York has the highest monetary loss from snow-melt floods between 1972 and 2006 (Changnon, 2008). One significant flood in New York State caused by rainfall and snow-melt took place in January of 1996 which claimed 10 lives and caused over $100 million in property damages (Lumia, 2000). In order to save lives and manage water resources, it is important to be able to predict snow melt events accurately using models.

The National Water Model (NWM) is a fully integrated hydrologic model created by NOAA in 2016 and it seeks to predict stream flow across the United States (NOAA, 2016). The NWM is a multi-scale, distributed, process-based hydrologic model that provides real-time estimates and forecasts of streamflow out to 30 days for over 2.7 million river reaches across the continental United States, Puerto Rico, and Hawaii (NOAA, 2016). The process of predicting water output down streams and rivers involves predicting snow processes. These are processes represented in a land surface model (LSM) called Noah-MP (NOAA, 2016). Noah-MP uses a 3-layer snowpack model to represent snow with each layer’s thickness dependent on the snow depth (Niu et al. 2011). This LSM uses the Biosphere Atmosphere Transfer Scheme (BATS) to
simulate snow albedo (Dickenson et al. 1993; Yang et al. 1997). BATS partitions snow albedo into visible and near-infrared direct and diffuse radiation. It also accounts for effects of solar zenith angle, snow grain size, and snow impurities such as dust. Snow cover fraction is parameterized by a function of ground roughness length, snow depth, and snow density (Niu and Yang 2007).

1.2 Motivation and Goals

There has been previous literature on how Noah-MP performs with snow prediction in the western United States (e.g. Wrzesien et al. 2015; Minder et al. 2016; You et al. 2020). These studies explored the biases and sensitivities that Noah-MP has on complex terrain in the west. The conclusion was reached by You et al. (2020) that Noah-MP is “a feasible option for simulating snow processes in high latitude, arid, and semiarid regions.” Such studies have not been done to evaluate the NWM in the Northeast which is not high latitude or arid. This study is motivated by this gap in knowledge because the snow in the Northeast is not as deep or persistent as in the mountainous west. The first goal is to reveal how accurately or inaccurately Noah-MP can predict snow in New York State by comparing retrospective runs of the model to observational data. Then, the second goal is to examine where the inaccuracies in snow depth are coming from in the model by testing and adjusting physics parameterizations. In this research project, there is a focus on the ablation period and how albedo is represented in the model by adjusting the albedo decay formulation.
Previous research provided results on the effects of forcing error on Noah-MP snow simulations and ablation errors. This research revealed that the LSM is sensitive to forcing errors in temperature and precipitation with a negative precipitation bias and positive temperature bias (Naple, 2021). Analysis of winters in 2018-19, 2019-20, and 2020-21 revealed that although the biases might imply underestimated snow depth, there is actually a positive snow bias. (Naple, 2021) This suggests that there are likely errors due to physical parameterizations as well as the forcing errors (Naple, 2021). This continuation of research seeks to remove forcing error by forcing simulations with observations and further understand how altering the albedo decay formulation impacts the snow ablation errors.

2 Data and Methods

This research makes use of the observational data from the New York State Mesonet (NYSM) to analyze model performance. To isolate the parameterization error from the forcing errors, the observation data was used to force and evaluate simulations of Noah-MP within the NWM. Both single column and distributed simulations of Noah-MP were used to gain more understanding of the NWM specifically about snow depth.

2.1 Data

2.1.1 New York State Mesonet

Observational data for this study comes from the NYSM (http://nysmesonet.org/; Brotzge et al. 2020). The NYSM provides high quality meteorological observations with high temporal
and spatial density. The NYSM is a network of weather stations throughout New York State including 126 standard stations with locations shown in Figure 1. The standard stations collect meteorological data for: temperature, humidity, wind speed and direction, pressure, solar radiation, snow depth, and soil information (Brotzge et al. 2020). For this study, an important sensor from the standard network for this study is a Campbell Scientific SR50A acoustic snow sensor located over a white snow board (Brotzge et al. 2020). This sensor measures snow depth by measuring the amount of time it takes for a sound wave to return to the sensor after bouncing off the surface. High quality snow depth observations are important for this study so the performance of snow depth prediction in the NWM can be evaluated. Of the 126 sites, 17 of them additionally collect flux data relating to the surface energy budget including incoming and outgoing shortwave and longwave radiation (Covert, 2019). This flux data is used to calculate the observed albedo for this study. The NYSM flux sensor is a Kipp & Zonen CNR4 sensor measuring incoming and outgoing shortwave radiation by pointing pyranometers upward and downward (Covert, 2019). Additionally, 20 “snow” sites have additional sensors for snow measurements including the snow water equivalent (SWE) which is the water content of the snow. SWE is shown along with the snow depth because snow depth decreases when the snow is compacted or melting. It is important for hydrology to know when the snow is melting and creating run off which is better indicated by the SWE. The SWE is measured using a Campbell Scientific CS725 gamma-ray sensor that relates naturally emitted soil gamma-radiation attenuated by the water in the snowpack to the SWE. One source of error with this sensor is that sometimes the soil moisture will be measured as SWE when there is a low snow depth. There are differences between the CS725 and manual observations of SWE depending on the land use type.
of the area where the measurement was taken and potential errors in both measurements, but they are generally similar (Naple, 2021).

2.1.2 Point Simulations

Single column “point” simulations of Noah-MP were run by project collaborator Theodore Letcher who has produced an in-depth technical report on aspects of this NWM research project (Letcher, 2022). The purpose of running these simulations was to retrospectively evaluate how well snow depth was predicted by Noah-MP by comparing predictions to NYSM observations. These simulations were run at the location of the 126 NYSM sites and one of the benefits of running simulations at one point is that the land classification can be set to the conditions of that location. The land cover was classified as grassland in the model at all sites.
because most NYSM sites are on open land and do not have effects of a canopy (Letcher, 2022). Another benefit of point simulations at weather stations is that the observations can be directly used as inputs for the simulation which minimizes biases in forcing data especially in temperature and precipitation (Letcher, 2022; Naple, 2021). The NYSM measurements used to force the single column configuration are: temperature, windspeed, relative humidity, downwelling solar radiation, accumulated precipitation, and surface pressure (Letcher, 2022). Downwelling longwave radiation in the model was pulled from HRRR model simulated data, which uses the Rapid Radiative Transfer Model (RRTMG: Iacono et al. 2000). The HRRR longwave radiation is extracted from the nearest grid cell to each NSYM site location, and HRRR hourly output is linearly interpolated to the 5-minute NYSM forcing data (Letcher, 2022).

Preliminary results revealed that the point simulations were predicting a higher maximum snow depth and a longer period of snow cover when compared to the NYSM observations (Letcher, 2021). This motivated further research into how the accumulation and melting periods could be improved in the model. Sensitivity runs on the point simulations revealed that simulated snow depth during the accumulation period was sensitive to precipitation phase partitioning which is how the model determines if precipitation is rain or snow. The default precipitation phase partitioning method is called Jordan which decides all snow below 0°C, all rain above 2°C, and a mixture of the two in between (Jordan, 1991). Other precipitation partitioning methods were tested in altered model runs including switching precipitation phase at a surface temperature of 0°C or 2°C, switching at a surface wet bulb temperature of 0°C, and using precipitation phase predicted by the HRRR mesoscale atmospheric model (Dowell et al. 2022). Analysis showed that the snow accumulation period improved because the peak snow depth and
SWE was reduced in the model when using the HRRR partitioning scheme bringing the simulations closer to the observations. This research project will specifically focus on biases during the ablation period and the role of snow albedo parameterization choices in influencing these biases. The precipitation phase partitioning methods chosen for analysis were HRRR for the point simulations and T=0°C for the distributed runs.

Next, the sensitivity experiments revealed that the ablation period is very sensitive to the value of $\tau_0$ which is a variable that impacts albedo decay (Letcher, 2022). BATS simulates the snow aging process using a non-dimensional snow age ($\tau_{\text{snow}}$) that increases over time according to:

$$\Delta \tau_{\text{snow}} = \tau_0^{-1} (r_1 + r_2 + r_3) \Delta t$$

where $\tau_0$ is a tuning parameter that controls the rate of aging. Other variables in the equation are $r_1$, $r_2$, and $r_3$ which represent dry-snow metamorphosis, wet-snow metamorphosis, and metamorphosis from snow impurities, respectively, and $\Delta t$ is the model timestep (Letcher, 2021). The default value for $\tau_0$ in Noah-MP is $10^6$ seconds, so the values $10^4$ s, $10^5$ s, $1.5 \times 10^5$ s, $10^7$ s, and $10^8$ s were tested in altered model runs. Lowering the $\tau_0$ value should cause the snow to age faster, become less reflective faster, and absorb more shortwave radiation over time which causes the snow to melt faster.

2.1.3 Distributed Runs

Initially, point simulations were used to analyze Noah-MP to avoid uncertainties in distributed runs associated with biases in forcing data and land-cover mismatches. However, there can be more information gained by including them in this analysis of the NWM. This type
of model run is more operationally relevant than point simulations because the whole state of New York is modeled rather than just the mesonet sites. Distributed simulations of Noah-MP were run across the entirety of New York State by project collaborator Arezoo Rafieei Nasab at National Center for Atmospheric Research. These simulations had 1-kilometer grid spacing, used mostly forested land surface type, used WRF-hydro v5.2.0, and were forced by gridded meteorological analysis data.

Since the distributed runs were executed after the point simulations, results from analysis of the altered point simulations were taken into account when altering the distributed runs so the two could be compared. Both the Jordan and T=0°C precipitation partitioning methods were used with only $\tau_0$ values at and below the default value, but only T=0°C will be used for this analysis. The T=0°C method was used instead of HRRR because the two behave similarly in the model and using T=0°C is easier.

2.2 Methods

The simulated snow depth analysis is accompanied by SWE data. To summarize how well the models predict snow depth, an average between most of the NYSM stations is taken and for SWE, an average of the snow sites is used. Roof-top New York City sites and sites with more than 20% missing data are excluded from these averages.

In order to further understand the biases in the modeled snow depth in the ablation period, the albedo values are compared between the model runs and observations. Since $\tau_0$
adjusts how the albedo decays over time, an albedo decay rate (ADR) was calculated. Only the NYSM flux sites have a measurement of albedo, so 15 sites were usable after excluding the NYC flux sites (indicated within the dashed circle in Figure 1). The daily ADR was analyzed at these 15 sites by taking daily observed and modeled albedo values. The daily albedo value was at approximately solar noon each day (1700 UTC) because the sun is highest in the sky at this time which minimizes potential shading on the site by nearby vegetation. The unfiltered albedo data is shown in Figure 2 at the Claryville NYSM site (circles in Figure 1) plotted along with the snow depth data. Figure 2 shows that during the main ablation period (after 28 February), the default point and distributed model runs have albedo values higher than the observations and altered model runs. Snow depth is included in this figure to show that albedo values are reported when there is no observed snow.

Filters were applied to the data to remove accumulation, no snow, and missing data days. Some observations of albedo at 1700 UTC were missing, giving no control value, so days were filtered out of all model runs if observation values were missing. The distributed runs report specifically snow albedo, but observations and point simulations report surface albedo. To ensure only snow albedo values, days were filtered out if the snow depth was less than 0.01 meters in any of the data sets being compared. Although only periods of ablation periods are in question here, the whole time frame from 1 January to 1 April was analyzed because each of the sites has snow melting at different times. In order to only include albedo values during ablation periods, only days where all data sets had a decreasing albedo were used. Filtered data at one of the NYSM sites is shown in Figure 3. This analysis method was used on the dates 1 January to 1
April for 2020 and 2021. For 2020 and 2021, the sum of filtered ADR values at all 15 stations was 134 and 189 values respectively.

**Figure 2:** Data shown for one NYSM station located in Claryville, NY. Albedo data at approximately solar noon from point and distributed simulations compared to NYSM observations indicated in the lines with dots and stars. Snow depth from point and distributed simulations compared to NYSM observations indicated in the colored lines towards the bottom of the plot. For both variables, the observation values are in the bold lines.

**Figure 3:** Data shown for one NYSM station located in Claryville, NY. Depiction of the albedo data after being filtered shown in the colors. Gray lines show where data has been filtered out of the models and black line shows where data was filtered out of the observations.
3 Results

3.1 Snow Depth and SWE Analysis

The goal of this research is to improve the way snow depth is predicted in the NWM, so it is essential to start by looking at how the snow depth predictions compare to observations. Figure 2 shows the observed and point simulation snow depth (average of most NYSM sites) and SWE (average of NYSM snow sites). The figures show how the snow depth decreases after a fresh snow event while the SWE remains consistent because the snow is compacting, not melting. In the 2020-21 snow season, there is generally one long accumulation and one long ablation period other than the event in late December (Figure 5). Conversely, the 2019-20 snow season has a few intermediate melting periods (Figure 4). For the most part, the accumulation period is accurate compared to the observations especially in Figure 5 when there are less ablation periods in the early snow season. The accumulation periods are not affected by the changed $\tau_0$ values and a spread in the models occurs only when there is a melting period. In the 2019-20 snow season, there is more of a spread at the maximum snow depth than the 2020-21 season because of the intermediate melting events. Focus will be drawn to the ablation periods since this is where the differences in predicted snow depth and SWE are occurring.

When it comes to the $\tau_0$ values, the default value of $10^6$ s as well as $10^5$ s were used in the point simulations. Figure 2 illustrates how decreasing the $\tau_0$ value improves snow depth predictions because the observed snow depth and SWE are closer to the observations and the melt-out date becomes more accurate. When the $\tau_0$ value is increased, snow depth and SWE predictions are too high throughout the ablation period. Evaluating just one smaller $\tau_0$ value
should be enough to see how albedo is affected. Altering $\tau_0$ is the main focus of this research since $\tau_0$ determines how the albedo of the snow decreases over time. Although it is observed that decreasing the $\tau_0$ value improves snow depth predictions, it is important to determine the extent that the modeled albedo values are consistent with the actual behavior of the observed snow albedo. The result that decreasing $\tau_0$ improves the snow depth and SWE motivates the decision to only further test $\tau_0$ equal to $10^6$ s and $10^5$ s in this study. Although the value of $10^4$ seems to have results most similar to observations, it is excluded from further analysis for now for simplicity in this study.

![Figure 4: Point simulation for 2019-20 snow season with varied $\tau_0$ values snow depth and SWE averaged across most NYSM stations on the top axis in the colored lines. Observed NYSM snow depth and SWE averaged across all NYSM stations plotted in the black line.](image-url)
Figure 5: Point simulation for 2020-21 snow season with varied $\tau_o$ values snow depth and SWE averaged across most NYSM stations on the top axis in the colored lines. Observed NYSM snow depth and SWE averaged across all NYSM stations plotted in the black line.

3.2 Albedo Decay Rate Histograms for 2020 and 2021

When analyzing the effects of changing a variable that adjusts the rate of albedo decay, it is important to see how the ADR is actually changing. In the top panel of Figures 6 and 7, a histogram of the observed albedo decay values are plotted which reveals a spread of values between 0 and 0.14 albedo value decrease per day and no clear mode for either year. The median in the observations is lower in 2020 (0.051) than 2021 (0.032) which indicates more rapid daily albedo decay.

Both the point and distributed simulations with the default $\tau_o = 10^6$ have albedo decay rates that are slower than the observations. There is also a clear mode around 0.01 for both years
in both simulations. There is a greater spread of values in the point simulations with some ADR values as high as 0.13 while the distributed run ADRs stay below 0.03. Similar to the observations median between the two years, the median is slightly higher in 2020 than in 2021 for the default point and distributed model runs.

The point and distributed simulations with altered $\tau_0 = 10^5$ have more of a spread toward higher values than the default runs. The point simulations reach ADR values as high as 0.14 and the distributed runs reach ADR values of 0.10. The median increases by about 0.01 in both simulations during both years. In 2020, the mode shifts higher to around 0.02, but in 2021, the mode remains around 0.01 in both simulations. Although the median has increased with the lower $\tau_0$ value, the median daily albedo decay is not as low as the observed daily albedo decay median.
Figure 6: Histograms of daily albedo decay rate for observations, point simulations, and distributed simulations during melt periods from 1 January to 1 April 2020. The median is indicated by the dotted line with the value of the median displayed. n=134 signifies that there are 134 station days included in each histogram.
Figure 7: Histograms of daily albedo decay rate for observations, point simulations, and distributed simulations during melt periods from 1 January to 1 April 2021. The median is indicated by the dotted line with the value of the median displayed. n=189 signifies that there are 134 station days included in each histogram.

3.3 Scatter Plots of Albedo Decay Rates

The purpose of these plots is to illustrate how well the ADR is predicted in the models compared to the observations on the same day. If a point lies on the 1:1 ratio line, then the model had the same ADR as the observations at one of the stations that day. Figures 8 and 9 show the results in 2020 and 2021 respectively. The top two plots in both figures represent the point simulation results while the bottom two show the distributed run results. Other than some of the values close to zero, few points on any of the plots lie on the 1:1 ratio line. Points above the 1:1 ratio line indicate that the model ADR was too low that day and a point below the line indicates that the model ADR was faster than observations.
In all the subplots, the points are concentrated below the 1:1 ratio line which re-confirms that the model ADRs are closer to zero than the observed ADRs. This pattern also leads to a best fit line with a gentle slope which is labeled on each plot. In the point simulations for both years, the intercept of the best fit line shifts down by 0.01 when the $\tau_o$ value decreases to $10^5$, but the slope of the line decreased. In the distributed runs for both years, the intercept of the best fit line shifted down by 0.01 when the $\tau_o$ value was decreased to $10^5$, and the slope of the line increased. The lowered intercept and slight slope change reveals that the model ADR values decrease across the range of observed ADR values. This means that points with high observed ADR and low modeled ADR become closer to the 1:1 ratio line, but points with low observed and modeled ADR drop above the line. Additionally, points that were already below the line drop further below.

To more easily see how the ADR is changing in both model types when $\tau_o$ is altered, the difference is plotted in Figure 10. Previous figures suggested that all ADR values stayed the same or decreased with a smaller $\tau_o$ value which is true for most of the days, but some point simulation ADR values increased. This is likely because the point simulations measure ground albedo and a snow fraction is considered rather than just snow albedo which is measured in the distributed runs. In the future, the ground snow-cover fraction could be considered along with the snow depth while filtering the data. There are also a few point simulation differences that are greater in magnitude than any of the distributed run differences. The difference between altered model runs does not seem to be related to what the observed ADR is.
Figure 8: Scatter plots comparing the observed albedo decay rates in 2020 to each of the simulation runs. The 1:1 ratio is indicated by the dotted line and the best fit line is indicated by the solid black line with the formula displayed.
Figure 9: Scatter plots comparing the observed albedo decay rates in 2021 to each of the simulation runs. The 1:1 ratio is indicated by the dotted line and the best fit line is indicated by the solid black line with the formula displayed.
Figure 10: Difference in ADR between altered $\tau_o = 10^5$ model run and default $\tau_o = 10^6$ model run plotted based on the observed albedo decay for 2020 and 2021. Point simulations (blue triangles) and distributed simulations (orange plus) are shown with both x- and y-axes remaining the same between the two years. No difference is indicated by the black dashed line.

4 Discussion and Conclusion

The goals of this research are to: 1) reveal how accurately or inaccurately Noah-MP can predict snow in New York State by comparing retrospective runs of the model to observational data and 2) examine where the inaccuracies in snow depth ablation period are coming from in the model by testing and adjusting the snow albedo decay parameterization.

In the point simulations of Noah-MP, retrospective analysis of the 2019-20 and 2020-21 snow seasons shows that simulated snow depth and SWE was accurate at the maximum snow depth with a later melt out date than observed. While snow accumulation is close to accurate using the HRRR precipitation partitioning method, the modeled snow depth grows more distant from the NYSM observations as the snow melts. This growing error during the ablation period suggests that the snow in the model is melting too slowly. Sensitivity experiments reveal that
biases in the rate of snow aging and therefore albedo decay in the model could be causing this slow rate of snow melt.

Within Noah-MP parameterizations, $\tau_o$ is a tuning parameter in a formula calculating how snow ages and specifically how albedo decreases with time. The analysis shows that changing $\tau_o$ indeed changes how the albedo decays which confirms that snow depth in the model is indeed sensitive to this variable. To improve the albedo decay process, decreasing $\tau_o$ increases how quickly snow ages and therefore decays the albedo and melts faster. This is found to be the case because the altered model runs with smaller $\tau_o$ values melt out faster and sooner than the default runs. Conversely, increasing $\tau_o$ values causes the snow depth in the ablation period to melt out even slower and later than the default runs. Since the point simulations were run before the distributed simulations, this result informed the decision to only decrease the $\tau_o$ value in the distributed runs.

The snow depth plots show that decreasing $\tau_o$ to $10^5$ creates a snow depth closer to observations, but still melts too slowly especially in the 2020 season. This is also supported by the histogram plots where the median observed ADR value is higher than the models in 2020 than in 2021. This could be due to the difference in number or types of melting events during these two years. The histogram plots also seem to suggest that lowering the $\tau_o$ value even more will help improve the modeled ADR become more like the observed ADR. The scatter plots, however, show that while some of the modeled ADRs are improving because they were originally too low, the modeled ADRs that were already accurate to observations are also increasing and becoming further from the observed ADR. It would be easy to draw conclusions
about how well decreasing $\tau_0$ improves snow depth and SWE prediction without making sure that the albedo is also becoming more like the observed albedo. Further research is necessary to determine which $\tau_0$ value is best for improving the ADR, but this research suggests that lowering the $\tau_0$ value is a good start.

4.1 Disclaimers

This albedo analysis using only 15 NYSM sites may not be representative of the entire state of New York. The flux NYSM sites are mostly located in low elevation or coastal areas that may not get as much snow as other sites such as those in the Adirondack Park region. Additionally, most of the NYSM sites are located in clearings while most of the land in New York State is forested, so snow depth analyzed at the sites may not be representative of snow across the state as a whole. In forested areas, the canopy may decrease the sensitivity of snow depth and SWE to $\tau_0$ because there is shading of the surface snowpack from solar radiation by the vegetation.

There is a limit on the sample size of days because there are only two snow seasons analyzed here with a lot of days filtered out. There is also a fair amount of missing albedo data when possibly there was precipitation or decreased albedo on cloudy days. These are both factors that impact how albedo observations are recorded because the albedo depends on the amount of direct versus diffuse radiation which is different on sunny versus cloudy days. Scattered clouds can cause albedo observations to spike up and down throughout the day.
4.2 Further Research

While it is established that in general, decreasing the $\tau_0$ value improves snow depth predictions, it is not yet determined what exact value of $\tau_0$ is ideal for the model. Analysis of the albedo values is essential for determining an ideal $\tau_0$ value rather than just the snow depth to ensure that we are fixing a difference made by $\tau_0$ and not over compensating for some other difference in the model. Additionally, although the point and distributed simulations have similar responses to changing $\tau_0$, there are clearly differences between them when it comes to predicting snow depth. Further research is needed to determine what is causing these differences. One cause that could be explored is the land surface type since this is classified as grasslands in the point simulations and forested in the distributed runs. The canopy of a forest could have impacts on how sensitive the snow depth and SWE are to the albedo.
References:


Dickinson, E., Henderson-Sellers, A., & Kennedy, J. (1970, January 1). *Biosphere-Atmosphere Transfer Scheme (BATS) version 1E as coupled to the NCAR Community Climate Model*. Name-to-Thing (N2T) Identifier Resolver. http://n2t.net/ark:/85065/d7ns0t8g


