

## Sub-regional Snow Cover Distribution across the Southern Appalachian Mountains

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### ABSTRACT

Snowfall in the Southern Appalachian Mountain region of the eastern U.S. is characterized by a high degree of spatial and temporal variability. Annual snowfall totals can vary by up to 75 cm, and variations in snowfall intensity during individual events can lead to large differences in the local snowfall distribution. Previous research has shown that the synoptic pattern associated with the snowfall strongly influences the resulting regional-scale distribution of snow cover. However, topographic variability results in locally complex snow cover patterns that are not well understood or documented. In this study, we characterize the snow covered area and fractional snow cover associated with different synoptic patterns in 14 individual sub-regions. These sub-regions are delineated according to their established snowfall climatologies and topographic characteristics, as well as by National Weather Service local forecast area. We analyze 63 snow events using MODIS (Moderate-resolution Imaging Spectroradiometer) standard snow products to ascertain both qualitative and quantitative differences in snow cover across sub-regions. Among sub-regions, we find significant variation in the snow cover pattern from and within individual synoptic classes. Furthermore, the percent snow covered area follows the regional snowfall climatology, and sub-regions with the highest elevations and northerly latitudes exhibiting the greatest variability. Results of the sub-regional analysis provide valuable guidance to local forecasters by contributing a deeper understanding of snow cover patterns and their relationship to synoptic-scale circulation features.

Keywords: Fractional snow cover, Snow sub-regions, Synoptic-scale circulation, Southern Appalachian Mountains

### INTRODUCTION

Snow cover is an important indicator for assessing climatic variability and regulating local and global energy budgets through surface albedo feedbacks (Barry, 2008; Cohen and Rind, 1991; Frei *et al.*, 2012). It is a valuable hydrologic resource, as water is stored in snow packs and subsequently released during snowmelt (Barnett *et al.*, 2005; Fassnacht *et al.*, 2014). Snow cover is a critical component in the health of mountain ecosystems since ecological functions are highly dependent on the availability of water (Trujillo *et al.*, 2012). In addition to the environmental impacts, snowfall impacts society by generating economic revenue through recreation and tourism

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development (Elsasser and Bürki, 2002). It can also cause much devastation through avalanching (Birkeland and Mock, 1996; Fitzharris, 1976).

The diagnosis of snowfall characteristics, including the spatial pattern of snow cover, presents a major challenge for weather forecasters (Doesken and Judson, 1997). Research on the spatial distribution or pattern of snow cover informs long term snow cover climatologies and future projections (Brown and Mote, 2009; Mote *et al.*, 2005). This point is especially relevant in mountain regions where orographic effects are dominant and meteorological characteristics in the lower troposphere exert a high degree of spatial variability on the snow cover (Keighton *et al.*, 2009; Minder *et al.*, 2011; Pavelsky *et al.*, 2012).

Previous research has shown that the synoptic-scale circulation regime strongly influences the subsequent region-wide snow cover pattern. (Changnon *et al.*, 1993; Sugg *et al.*, 2014). Snowfall predictions from specific circulation patterns can also lead to better predictions in the snow cover distribution. Warning systems can be targeted to alert people who are more likely to be affected by a particular storm based on their location as opposed to blanket warnings that cover entire regions.

Snow cover detection in mountainous terrain is challenging due to the presence of cloud cover (Ackerman *et al.*, 1998), dense forest cover (Klein *et al.*, 1998), and ephemeral snow (Hall *et al.*, 2010). These factors influence the region-wide fractional snow cover (FSC) and snow covered area (SCA) values that vary according to the individual event. Another example influencing the local snowfall distribution is that for some events, snow may be present only on ridges and major peaks of the higher terrain. Derived values are then limited for sub-regions with lower elevations that are often snow free. In this study, we use sub-regions to capture local variability and improve the understanding of snow cover patterns and their relationship to synoptic-scale circulation features. We use the Moderate Resolution Imaging Spectroradiometer (MODIS) standard snow cover products capturing 63 individual snowfall events in the southern Appalachian Mountains (SAM) to determine the following: (1) how the snow cover pattern varies among sub-regions, and (2) how the most commonly occurring synoptic classes influence snow cover variability.

## BACKGROUND

In-situ measurements of snow are useful for deriving accurate snowfall observations including snow depth, density, and liquid water equivalent (Rasmussen *et al.*, 2012). However, these measurements are somewhat limited due to low spatial coverage (Bales *et al.*, 2006). Particularly in mountainous terrain, snowpack heterogeneity over short distances is problematic when sensor networks are limited (Fassnacht and Derry, 2010; Klein and Barnett, 2003). In the SAM, for example, only four National Weather Service (NWS) cooperative observer stations are located above 1200 m elevation (Perry and Konrad, 2006; Sugg *et al.*, 2014), with the majority of snowfall observations obtained in valley locations (Barry and Seimon, 2000).

Changes to snow cover can efficiently be measured using remote sensing techniques (Foster *et al.*, 1987; Hall *et al.*, 2005; Hall and Riggs, 2007). Basin-wide to continental snow cover maps from multispectral scanners increase the coverage of SCA measurements consistently through space and time, overcoming many limitations of in-situ networks (Frei *et al.*, 2012). Furthermore, snow cover is sensitive to changes in temperature (Doesken and Judson, 1997), increasing the utility of FSC measurements for assessing snow cover patterns in the context of climate variability (Richer *et al.*, 2013; Robinson and Frei, 2000). MODIS daily snow cover maps from Aqua and Terra are very useful at moderate scales (500 m) (Pu *et al.*, 2007; Tekeli *et al.*, 2005) due to their high temporal resolution, collected twice daily (Riggs *et al.*, 2006). Likewise, the temporal resolution is useful for discerning snow cover patterns in mid-latitude ranges where surface temperatures are often near freezing and melt onset between events is a common occurrence (Hall *et al.*, 2010).

Tracking changes to snow cover at moderate scales is often used to drive model assessments of future snow cover patterns (Mote *et al.*, 2005; Stewart *et al.*, 2004). Sub-regional perspectives are employed to capture local variability that exists where topography (e.g. slope, aspect, elevation) and land cover influence the spatial heterogeneity of the snow (Perry and Konrad, 2006; Raleigh *et al.*, 2013). Sub-regions developed using a self-organizing map technique proved useful in defining snowpack characteristics in local areas including accumulation, persistence, and ablation patterns

(Fassnacht and Derry, 2010). Snow zones that were created using a geospatial approach integrated the MODIS snow cover maps to develop a snow cover index and define regions of persistent, transitional, intermittent, and seasonal snow (Moore *et al.*, 2014; Richer *et al.*, 2013). Sub-regions also facilitated intraregional comparisons of meteorological snowfall characteristics when boundaries were delineated according to a combination of zone grouping in the NWS forecast products, snowfall climatology, and elevation (Perry *et al.*, 2007).

Classifying the atmospheric circulation is an important step in understanding the regional snowfall pattern. Synoptic flow patterns in the middle troposphere were analyzed in conjunction with annual and multi-decadal snowpack patterns to develop a method for monitoring regional hydroclimatology (Changnon *et al.*, 1993). Primary precipitation regions were delineated to identify wet-dry north-south gradients that describe the snowfall climatology across the Rocky Mountains in the western U.S (Changnon *et al.*, 1993). The major atmospheric circulation regimes in the SAM also play an important role in the timing, development, and delivery of snowfall (Perry *et al.*, 2010; Perry *et al.*, 2013). Among these flow patterns, synoptic classes including Miller cyclones and southeastward tracking clipper systems produce the greatest SCA, while non-upslope events, northeastward tracking lows, and Upslope Flow in absence of surface or frontal features produce the least SCA (Sugg *et al.*, 2014).

## DATA AND METHODS

### Study Area and Sub-regions

In this study, we define the SAM region the same as in previous research, capturing the elevation range (183 - 2037 m) and topographic distribution (roughly SW to NE) of the higher terrain and low valleys in context with the annual snowfall climatology (25 - >250 cm) (Fuhrmann *et al.*, 2010; Perry and Konrad, 2006; Perry *et al.*, 2010). We employ the 14 snow sub-regions that were previously developed to facilitate intraregional comparisons of antecedent upstream air trajectories associated with Northwest Flow snowfall (Perry *et al.*, 2007). In Figure 1, sub-regional boundaries are delineated according to a combination of NWS forecast zone, snowfall patterns, elevation, and topographic distribution, yet considerable variability of snowfall still occurs within individual sub-regions (Perry *et al.*, 2007).

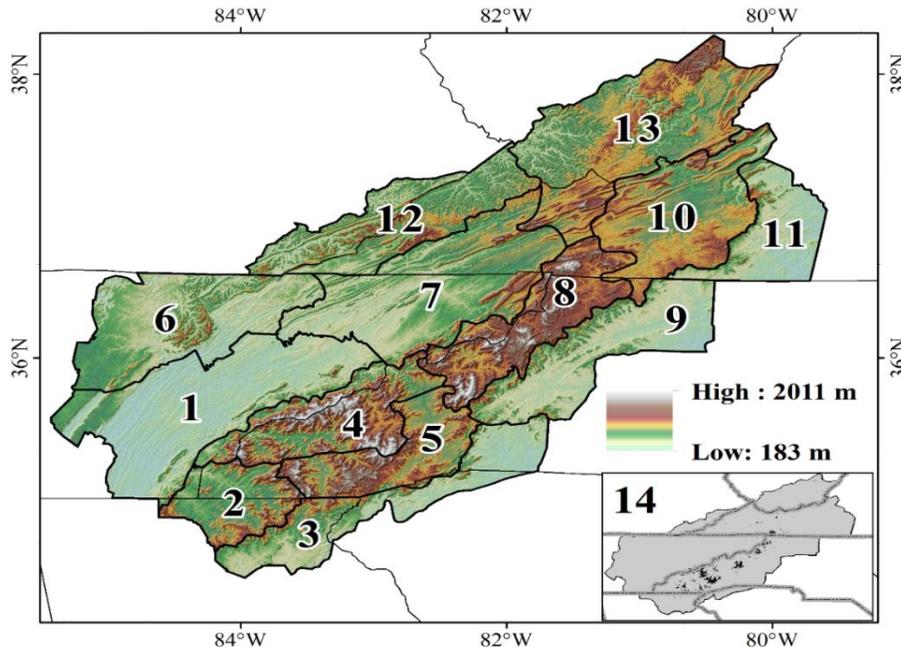


Figure 1: SAM study area with sub-regional boundaries 1-14 and elevation. In sub-region 14, terrain >1200m is shaded black.

Regions 2 and 3 fall along the far southwestern perimeter of the SAM, making up the Southwest Mountains and Southern Foothills. Region 4 contains the Great Smoky Mountains with the highest elevation (> 2000 m) windward (leeward) slopes oriented to the northwest (southeast). Further southeast, region 5 encompasses the Southern Blue Ridge escarpment. The interior high elevation locations fall within the High Country region number 8, directly contrasted with the lower Central Foothills of region 9, located down the southeast escarpment. Upstream of the northwestern escarpment, regions 1 and 7 occupy the southern and northern Tennessee River Valley, an area of low lying valleys located in the interior of the SAM. The most extreme western regions 6, 12, and 13 are characterized by slightly higher elevations along the southern, central, and northern plateau. The most northern regions include Virginia's New River Valley (10) and the lower Northern Foothills (11), located eastward. Finally, region 14 is not contiguous, spanning all the high elevations >1200 m across the entire SAM region.

### **Snowfall Event Data and Synoptic Classification**

Snowfall data utilized in this study were obtained from Flat Springs 1.2E, an official NWS cooperative observer station and Community Collaborative Rain, Hail, and Snow (CoCoRaHS) station (Cifelli *et al.*, 2005) located at Poga Mountain (1021 m) in the central portion of the SAM High Country, sub-region 8. Snowfall data were collected from October 2006 – April 2012. Individual events were defined relative to periods of snow accumulation; as long as snowfall remained active over the course of a six hour period, meteorological data collected at the observation site were attributed to the same event. In total, there were 122 snowfall events over the course of the study period. Assignment of event beginning, maturation, and ending hours is described in full detail in a previous study (Sugg *et al.*, 2014).

A synoptic-event-database was previously created using a manual classification scheme, resulting in eight synoptic classes (Perry *et al.*, 2013). Synoptic characteristics were defined for each class and the events with clear sky conditions in the MODIS snow maps (n= 63) were distributed according to meteorological characteristics falling within each description. We used these classes to derive SCA values on a region-wide basis in previous research, where specific circulation characteristics of each are discussed in detail (Sugg *et al.*, 2014). For this study, we use the same classifications, though instead focus on the most commonly occurring events in the SAM.

The M\*-U (combination of Miller cyclones or Gulf/Atlantic lows undergoing cyclogenesis across the area) class includes both Miller Type A and Type B cyclones, with 18 total events that were suitable for analysis with the MODIS snow maps. During the Upslope events (U, NW flow in the absence of surface features) favoring the high elevation windward slopes, 16 events produced clear sky conditions for a suitable analysis with the MODIS snow maps. In the SE-U (south-eastward tracking clipper that passes north or across the area) class, also known as the Alberta Clippers, 10 events were particularly fast moving, leading to favorable conditions for analysis with the MODIS snow maps. The U postscript is often appended to other synoptic classes in cases where periods of NW Flow occur at the event maturation hour. Combined, these synoptic classes comprised 69% (n = 44) of the suitable event sample in the MODIS data. We chose to eliminate the remainder of events from other synoptic classes since the sub-regional variability of snow cover is difficult to detect with the limited number of snow pixel values, and potential for heavy cloud cover in isolated portions of the SAM.

### **MODIS Data and Sub-regional analysis**

We use the MODIS standard snow cover products from both the Terra and Aqua platforms (Hall and Riggs, 2013) corresponding to event maturation hour for the 63 events deemed suitable for analysis in our previous study (Sugg *et al.*, 2014). The MODIS data in this study are a collection of FSC maps from MOD10A1 (Terra) and MYD10A1 (Aqua), version 5, from tile h11v05 (Hall and Riggs, 2013). The snow maps were previously screened for cloud cover to reduce obscuration of the surface. Thus, our analysis refers to clear sky conditions. FSC values are parsed according to bins where values represent percentage snow cover in each pixel (500 m), from 0 to 100 percent. Histograms display the distribution of FSC bins according to each event. SCA values are derived according to total pixel counts of snow cover vs. non-snow as a percentage of the sub-regional area.

The snow maps were processed in a GIS environment where an automated iterative routine was used to extract pixel values according to each sub-region among the 63 events. Data were analyzed using the R software environment for statistical computing and graphics (R Core Team, 2014). Percent SCA was initially calculated for all 63 events over each sub-region irrespective of synoptic class. This analysis provided a broad sub-regional comparison of SCA since all combined events from multiple synoptic classes are expected to follow the regional snowfall climatology. Percent SCA values were analyzed using box-and-whisker plots and descriptive statistics to determine the performance of the snow maps compared with previous research (Perry *et al.*, 2007) using the same sub-regions.

We identified sub-regions with a combination of the greatest interquartile range, median, and maximum outlier values to examine variability in the snow cover distribution. Box and whisker plots and descriptive statistics were also used to incorporate analyses of the three most commonly occurring synoptic classes (M\*-U, U, SE-U). Percent SCA was analyzed as a function of synoptic class for these specific sub-regions. We assessed percent SCA by comparing descriptive statistics between sub-regions within the same synoptic class, as well as between the same sub-regions by different synoptic class. This procedure allowed for a comparison of snow cover variability among the same events but across different sub-regions, and among different events occurring within a single sub-region. We assessed variation between FSC classes for the three most commonly occurring synoptic classes as well as between the selected sub-regions with the greatest variability. For each FSC bin 0-100% according to synoptic class, we calculated the number of snow covered pixels as a percentage of the total sub-region.

For FSC and SCA relationships, we used a series of non-parametric statistical tests to determine statistical significance between snow cover distributions among sub-regions. Among all sub-regions 1-14, we assessed differences in percent SCA using all synoptic classes with a Kruskal Wallis one-way analysis of variance by ranks test. This method provided a means of comparison for snow cover between sub-regions as a whole. We also used the Kruskal Wallis test to determine any significant differences in the sub-regional percent SCA for the same synoptic classes, and differences among synoptic classes within the same sub-regions, further confirming the variability on a local basis. We used the same test as a means of confirming significant differences in FSC bins in each synoptic class and sub-region. P-values from each test are provided to assess significant differences across the entire study area.

To further quantify the range of variability in the SCA values, we calculated coefficients of variation (CV) for each sub-region and in the three synoptic classes as:

$$Cv = \frac{\sigma}{\mu}$$

where  $Cv$  is the CV value of relative dispersion,  $\sigma$  is the standard deviation of the selected snow cover values, and  $\mu$  is the mean snow cover value. The CV values provided a normalized and dimensionless characterization of the dispersion occurring within each comparison of the snow cover values. Collectively, these analyses provide quantitative conclusions based on the observations in the snow cover maps and lead to further hypotheses regarding the distribution of snow cover from individual events among the sub-regions.

## RESULTS

### Sub-regional Percent SCA

For each sub-region, we used descriptive statistics to examine the trends in percent SCA for all the snowfall events in the sample (Figure 2). Many individual events produced outliers with 75 – 100% SCA among all the sub-regions, with the exception of the southern (6) and central (12) Plateaus. For these two sub-regions, percent SCA maxed out near 50 and 70%, respectively. Among all the sub-regions, percent SCA tended to follow the regional snowfall climatology since predominately lower areas were marked by less snow cover when compared to the highest sub-regions for all the events.

In the southern TN Valley (1), southwest Mountains (2), southern Foothills (3), and central Foothills (9), median SCA values were only slightly above 0%, highlighting the minimal snow cover patterns occurring in these areas. In the southern Blue Ridge (5), southern Plateau (6), and northern Foothills (11), median SCA was still near 0% with respect to all the events, though the maximum values of the interquartile range were much greater with SCA near 10%, 15%, and 10%, respectively. In the Great Smoky Mountains (4), the northern TN Valley (7), and the central Plateau (12), the interquartile range was also slightly higher with max SCA near 25% and median values near 15%.

For the remaining four sub-regions, median SCA tended to be the greatest among all sub-regions, with the exception of the New River Valley (10) where the maximum outlier snow events produced near 100% SCA. In the High Country (8) and northern Plateau (13), the maximum in the interquartile range was near 30% SCA. For the High Elevations (14), the interquartile range extended to maximums near 50% SCA. Results from the Kruskal Wallis one way analysis of variance by ranks test indicate a significant difference in the median SCA between all the sub-regions ( $\alpha = 0.05$ ) (Table 1). In this case, we reject the null hypothesis, since there is a significant difference in SCA between sub-regions.

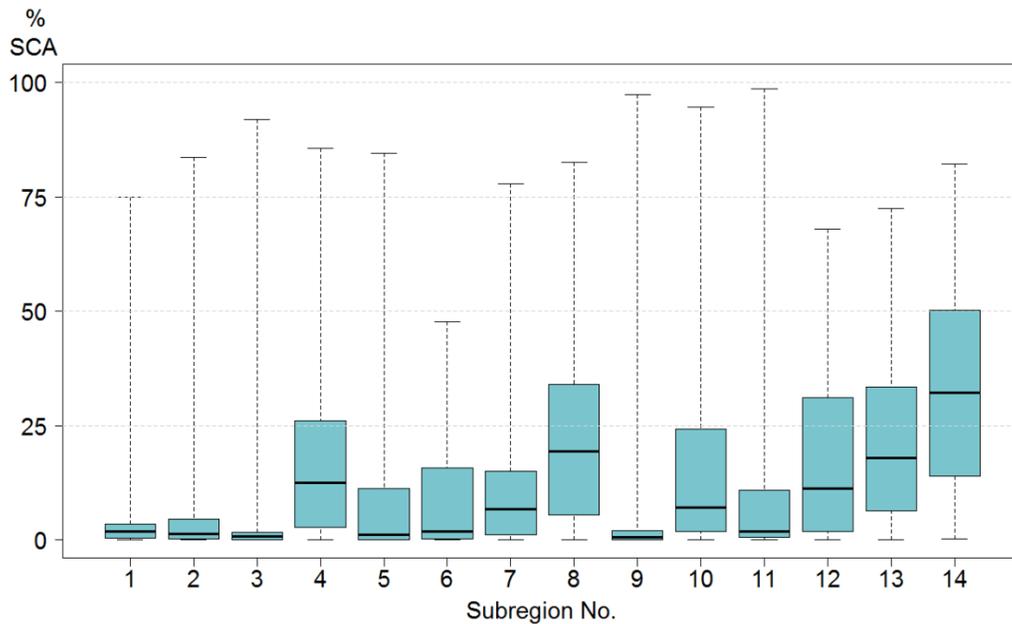


Figure 2: Box and whisker plots displaying the minimum, 1<sup>st</sup> quartile, median, 3<sup>rd</sup> quartile, and maximum SCA according to sub-region. Each sub-region includes 63 snowfall events.

Table 1: P-values from the Kruskal Wallis one way analysis of variance rank sums test. Comparisons use percent SCA for all subregions 1-14, sub-regions 8-14 as a group, and sub-regions 8-14 individually. Significant relationships are starred.

	P-values ( $\alpha = 0.05$ )					
	All Sub-regions	8-14	8	10	13	14
All Events	2.2e-16*	-	0.001034*	0.001202*	0.2061	0.005309*
M*-U	1.91e-07*	0.1081	-	-	-	-
SE-U	1.029e-07*	0.2556	-	-	-	-
U	3.003e-07*	0.0797	-	-	-	-

### Sub-regional Percent SCA by Synoptic Class

Based on the descriptive statistics of SCA between sub-regions, we identified the High Country (8), New River Valley (10), northern Plateau (13), and High Elevation (14) sub-regions having a combination of the greatest interquartile range, median, and maximum outlier values. While these regions do not characterize the entire variability of the SAM, particularly areas with the lowest snow cover, they do allow for an assessment of snow cover variability by synoptic class in areas where SCA is typically greater. These sub-regions were further categorized according to the three most commonly occurring synoptic classes (M\*-U, SE-U, and U) to assess differences in SCA.

Descriptive statistics were used to assess SCA between sub-regions within the same synoptic class (Figure 3). In the Miller Cyclones, the most commonly occurring synoptic class (n = 18), median SCA values were generally  $\geq 25\%$ , the highest among all synoptic classes. The lowest median SCA occurred in the northern Plateau (13) at 24%, followed by a 25% median SCA in the New River Valley (10). The highest median SCA values occurred in the High Country (8) and the High Elevations (14) with 34% and 46%, respectively. For each sub-region, minimum SCA occurred near 0% among the Miller Cyclones, yet the highest SCA (94%) was observed in sub-region 10. Statistical tests indicated a significant difference in the Miller Cyclone SCA between sub-regions, providing evidence of the variability between sub-regions (Table 1).

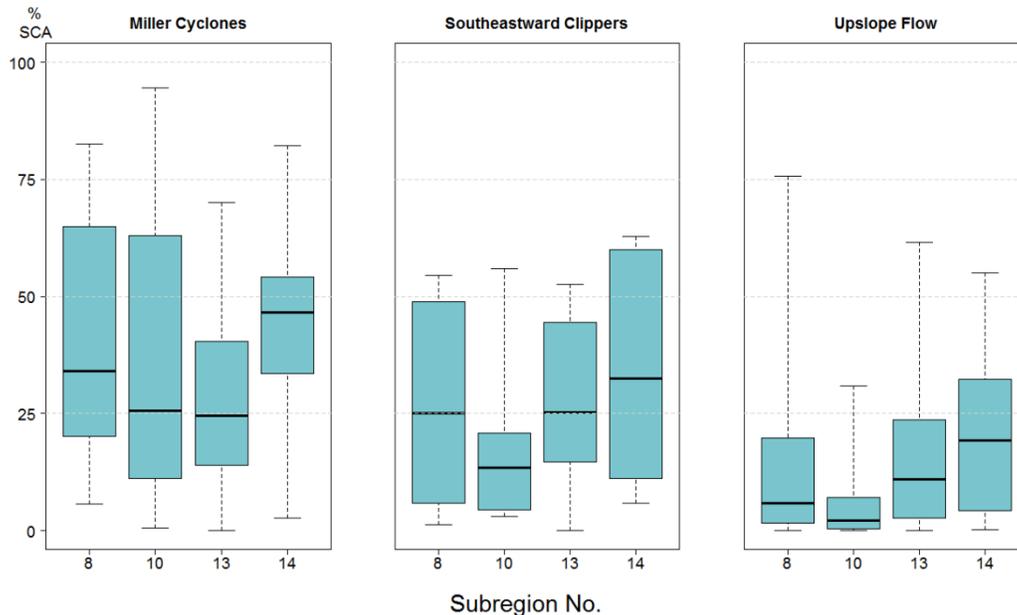


Figure 3: Box and whisker plots displaying the minimum, 1st quartile, median, 3rd quartile, and maximum SCA according to sub-region. Each sub-region is split according to the most commonly occurring synoptic classes, Miller cyclones (n=18), Southeastward tracking Clippers (n = 16), and Upslope Flow (n = 10).

For the southeastward tracking clipper systems (n = 16), there was no significant difference in the variance by ranks of SCA between sub-regions (Table 1). Minimum SCA was less than 10% among the individual events across the sub-regions. Likewise, maximum SCA was quite similar across the sub-regions, with 52% SCA occurring in the northern Plateau (13) at the low end, and 62% SCA occurring from the SE-U class in the High Elevations (14) as the absolute maximum. Median SCA was similar among the High Country (8) and northern Plateau (13), near 25%, while sub-region 10 experienced the minimum median SCA at 13%. Across the High Elevations (14), median SCA topped out covering 32% of the sub-regional area.

During Upslope Flow in absence synoptic support (n = 10), the lightest events tended to produce minimal snow cover patterns near 0% among all sub-regions. SCA is generally limited to the highest terrain or within a few windward pixels in these cases. All median SCA values were less than 25% for each sub-region, the lowest among each of the synoptic classes. The highest maximum SCA occurred in the High Country (8) covering slightly greater than 75% of the area.

One major difference occurred in the New River Valley (10), where maximum SCA was limited to just 30% of the region among all of the events. There were no significant differences in SCA between sub-regions for the Upslope Flow events.

Differences in SCA were also compared between the same sub-regions for different synoptic classes to provide an analysis of the sub-regional variability between classes. In the High Country sub-region 8 and New River Valley sub-region 10, we found a significant difference in the variance by ranks of the SCA between the M\*-U, SE-U, and U synoptic classes. This result is contrasted with the northern Plateau sub-region 13 where there was no significant difference in SCA between the synoptic classes. Across the High Elevations sub-region 14, we found a significant difference in the SCA between the synoptic classes. Tests provide conclusions that lend to the discussion on sub-regional variability, as many climatological and geographic characteristics tend to vary from region-to-region. For example, sub-region 13 benefits from the most northerly latitude of the SAM, potentially increasing the SCA among all classes and thereby reducing variability.

### FSC and SCA Variability

Individual tests were conducted to assess the differences between FSC classes for all combinations of specific synoptic classes and sub-regions (Table 2). For each synoptic class in the High Country sub-region 8, we found a significant difference in the variance by ranks between each FSC bin, indicating variability in the distribution of the snow cover pattern from 0 – 100% area coverage. In sub-region 10, the New River Valley, we found significant differences in FSC during southeastward tracking clipper systems and the Upslope Flow events. Differences in FSC were not significant succeeding the Miller Cyclones, which tend to provide the highest accumulation event total snowfall. Further into the northern Plateau, sub-region 13, the same result is present, where differences in FSC are significant in the SE-U and U classes. Likewise, there is no significant difference in FSC from the Miller Cyclones. At the High Elevations spanning the entire SAM (14), all synoptic classes present significant differences in the FSC pattern.

**Table 2: P-values from the Kruskal Wallis one way analysis of variance rank sums test. Comparisons use FSC among select sub-regions with the most commonly occurring synoptic classes. For each test, we examine any significant difference among FSC classes. Significant relationships are starred.**

	P-values ( $\alpha = 0.05$ )			
	Sub-region 8	Sub-region 10	Sub-region 13	Sub-region 14
Miller Cyclones	7.704e-06*	0.285	0.3475	2.2e-16*
Southeastward Clippers	2.37e-07*	1.508e-06*	0.003435*	8.98e-08*
Upslope Flow	5.093e-12*	3.177e-12*	4.511e-13*	2.489e-14*

To further characterize the variability of the snow cover pattern between synoptic classes and sub-regions, we calculated the CV to provide a normalized and dimensionless classification of the dispersion in SCA. Variability in SCA decreased sequentially among U, SE-U, and M\*-U classes (Table 3). The most highly dispersed SCA occurred following the upslope events, where snow cover was either isolated to individual pixels corresponding with high elevation peaks, or spanned large portions of windward and leeward slopes during extended periods of NW flow. Southeastward tracking clippers were less variable compared to the Upslope events. With the exception occurring in the northern Plateau (sub-region 13), the Miller Cyclones displayed the least variable SCA compared to the other events, as the heaviest events (M\*-U) also tend to produce the greatest SCA.

We found that the variability also fluctuated according to sub-region, with the New River Valley (10) exhibiting the highest CV among each synoptic class. For the Upslope Flow events, and following the southeastward tracking clippers, CV tended to decrease from sub-regions 8, 13, and 14. The trend in dispersion of SCA was reversed, however, following the Miller Cyclones where CV decreased from sub-regions 13 and 8 to 14.

**Table 3: CV values provide a normalized characterization of dispersion for each synoptic class according to specific sub-region.**

	Coefficients of Variation			
	Sub-region 8	Sub-region 10	Sub-region 13	Sub-region 14
Miller Cyclones	0.62	0.86	0.80	0.48
Southeastward Clippers	0.73	0.95	0.68	0.64
Upslope Flow	1.38	1.48	1.06	0.82

## DISCUSSION

Assessing the sub-regional variability of mountain snow cover is a challenging yet important step to further understand snowfall patterns and their relationships to synoptic scale circulation features. While previous research has emphasized the region-wide snow cover pattern in mountain regions (Rittger *et al.*, 2013; Tekeli *et al.*, 2005), fewer have used remote sensing techniques in ephemeral snow environments where snow is often more difficult to detect in local areas (Fuhrmann *et al.*, 2010; Hall *et al.*, 2010). There is no strictly objective method for defining sub-regional snow zones, as areas of homogeneity must be upscaled using intermittent and local observations (Fassnacht and Derry, 2010). In this study, predefined sub-regions were employed to define common characteristics of the snow cover associated with the synoptic scale circulation.

When examining the distribution of SCA events ( $n = 63$ ) in all 14 sub-regions in the SAM, we found that snow cover followed the regional snowfall climatology, with significant differences between sub-regions. Areas with predominately high elevations and a greater percentage of steep slopes favored higher SCA. For example, median SCA in the High Country (sub-region 8) is near 25%, meaning that for at least half the events, snow covers approximately a quarter of the entire region. This sub-region is contrasted with median SCA in broad and low-lying river valleys of the southern Blue Ridge (sub-region 5), where median values are closer to 0%. Half of the events displayed little to no snow coverage, a result complemented by the composite mean snowfall totals per sub-region (Perry *et al.*, 2007).

It is important to note that while SCA relationships in sub-regions were significantly different, events with nearly total area coverage occurred in all sub-regions. Likewise, it was quite common for some sub-regions to experience little to no snow cover associated with a snowfall event, as the minimum SCA for all areas was near 0%. These results imply that at the sub-regional scale, further examination of the meteorological and topographic characteristics is necessary to characterize the variability in snow cover. For example, one question is what degree do lower tropospheric available moisture, lifting, and system movement lead to a big event in some areas, and a bust for other sub-regions? Topographic characteristics including distance from windward slopes and dominant slope aspect were found to influence the annual percentage of snowfall occurring from NW Flow in the SAM (Perry and Konrad, 2006), so the question remains if the same relationships can be translated for the snow cover pattern. Our results confirm the snowfall climatology between sub-regions, but revealed new findings about the sub-regional variability of snow cover.

We compared the sub-regional SCA associated with most commonly occurring synoptic classes in the SAM. In line with previous research showing the greatest spatial extent of the snow cover from the heaviest events (Sugg *et al.*, 2014), Miller Cyclones produced the highest SCA, both in the median and interquartile ranges. At the highest elevations, there was generally a greater percentage of snow cover, reflecting the lower surface temperatures and less-ephemeral snow environment. Interestingly, relationships of SCA between sub-regions were not significant for the southeastward tracking clippers and Upslope Flow events, confirming differences in the event characteristics when compared to the Miller Cyclones.

While very little moisture is necessary for snow accumulations in the SE-U class, large snow-to-liquid equivalent ratios (20 to 1) coupled with strong winds substantially increase blowing and drifting snow (Perry *et al.*, 2010; Thomas and Martin, 2007). Accumulations are enhanced in sheltered areas of complex topography and dense vegetation (Musselman *et al.*, 2008), yet open areas are prone to horizontal transport of snow particles downwind from the summits into leeward

zones (Choularton and Perry, 1986; Zängl, 2005). In mountainous terrain, low density of snow particles in combination with sub-regional topography and low-level wind vectors are major components in the preferential deposition of snowfall (Mott *et al.*, 2014). Among the SE-U and U events in the SAM, we hypothesize a similar process resulting in a less variable snow cover pattern, at least where potentially large accumulations are either transported downwind to other sub-regions or shifted relative to the typical summit accumulation zones.

For each synoptic class, our results showed significant differences in the SCA among all sub-regions except the northern Plateau (13). While the atmospheric circulation does influence region-wide SCA across the contiguous SAM, the complexities of topography in addition to latitude and other geographic characteristics present a different sub-regional snow cover pattern. Furthermore, we emphasize the role of subtle variation in the 500-mb flow pattern (Bednorz, 2013), affecting steering for convection on mountain slopes that is ultimately variable across sub-regions (Perry *et al.*, 2013). We further hypothesize the location of the northern Plateau as a major factor in reducing the sub-regional variability of SCA, benefitting from a more northerly latitude and greater percentage of time interaction with the primary synoptic flow pattern. Percentage of snowfall is generally greater in this sub-region (Perry *et al.*, 2007), indicating a greater continuity in spatiotemporal SCA between events.

Relationships between FSC classes tended to vary based on the sub-region. With the exception of the Miller Cyclones in sub-regions 10 and 13, all FSC relationships were significant, confirming the actual variability in the snow cover pattern of individual events in the different sub-regions (Figures 4, 5). Low FSC associated with trace accumulations or melting snow present a significantly different pattern when compared to high FSC associated with deeper snow packs. We noticed that high FSC is usually nested within surrounding areas of lower FSC. While solar illumination angle and sensor viewing geometry can alter retrieval of FSC in mountainous terrain (Crawford, 2014), confidence is increased that lower FSC generally indicates a more sparse snow cover pattern 0-20% in areal coverage. A greater number of 80-100% pixels is equated with continuous snow cover (Hall *et al.*, 2001; Hall and Riggs, 2007). In the case of the Miller Cyclones occurring in sub-regions 10 and 13, FSC relationships were generally very similar, with consistent coverage among FSC classes as a potential function of the northern latitude in both regions. One avenue of future research is exploring land cover types among the New River Valley, northern Plateau, and similar sub-regions in the SAM, since the presence of a greater portion of open areas influences FSC retrieval during the individual events (Parajka *et al.*, 2012).

CV analysis showed that upslope events were the most highly dispersed in SCA, with M\*-U events the least dispersed. Among the climatological characteristics for these classes, we infer that the Miller Cyclones were the most consistent to deliver a spatially continuous snow cover pattern. This pattern was true for each sub-region. For the southeastward tracking clippers, snow cover tended to vary in size and shape more than with the Miller Cyclones, but less so than occurred from Upslope Flow in absence of synoptic support. Following the upslope events, snow cover remained highly variable. Depending on local and meteorological characteristics during the event, snow cover was relegated to a few isolated summit zones. During other events, Upslope Flow produced a snow cover pattern spanning nearly 75% of the sub-region and leading to the pronounced difference in the CV for the U class.

CV in the SCA values also varied among sub-regions, with the New River Valley (10) displaying the highest dispersion for all synoptic classes. In the High Elevations, CV were much lower for each synoptic class, indicating that sub-region 14 is generally a favored region for consistent snow cover patterns, regardless of the event. We expect that trends in CV would likely translate to other sub-regions exhibiting similar topographically-mediated climate characteristics. These findings are in line with other research where Miller Cyclones contributed the heaviest snowfall in the Great Smoky Mountains National Park (Perry *et al.*, 2010), and also produced the subsequent greatest spatial snow cover (Sugg *et al.*, 2014). Furthermore, we hypothesize the strong wind component and variable moisture content found in the southeastward tracking clippers as factors increasing SCA variability (Perry *et al.*, 2013; Thomas and Martin 2007). Overall, the sub-regional approach using the MODIS snow maps confirmed the regional snowfall climatology (Changnon *et al.*, 1993; Perry *et al.*, 2013), though highlighted the range of variability of the snow cover pattern in context with the atmospheric circulation.

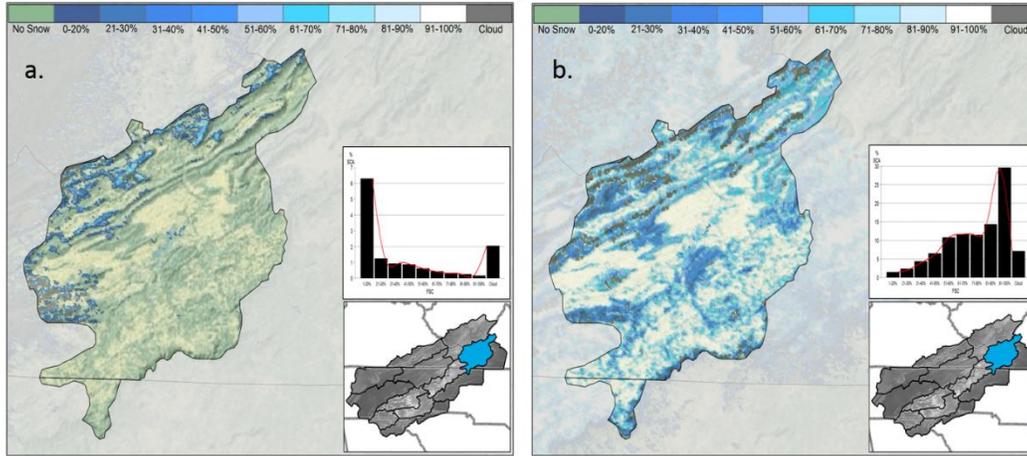


Figure 4: Example comparison of high vs. low FSC in the New River Valley sub-region 10; from a). 16 December 2007 Miller Cyclone where FSC in the 1-20% bin only covers 6% of the sub-region, and b). 19 February 2010 Miller Cyclone where FSC in the 91-100% bin covers 30% of the sub-region.

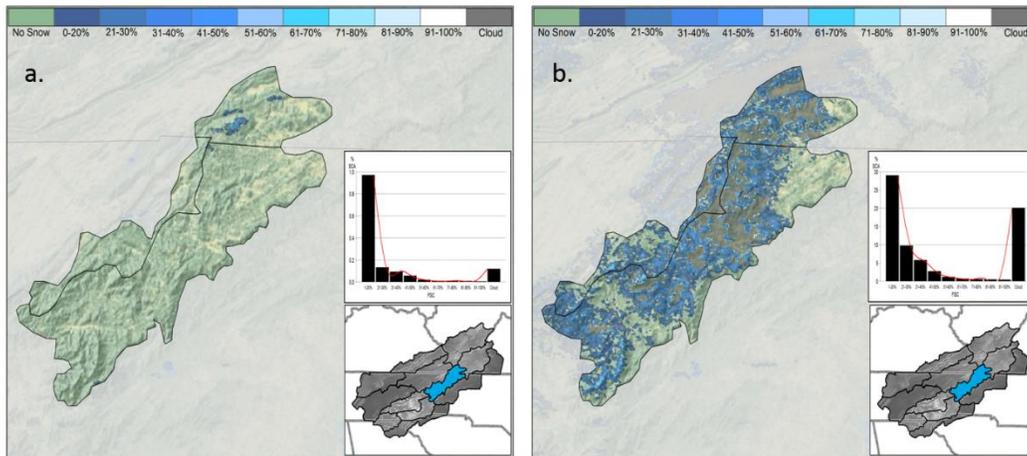


Figure 5: Example comparison of high vs. low FSC in the High Country sub-region 8; from a). 6 February 2007 southeastward tracking clipper where FSC in the 1-20% bin only covers 1% of the sub-region, and b). 9 January 2007 southeastward tracking clipper where FSC in the 1-20% bin covers nearly 30% of the sub-region. Cloud cover also extends over 20% of the sub-region.

## SUMMARY AND CONCLUSION

Sub-regional approaches to snow mapping are useful for defining snow zones with homogenous characteristics. While procedures for delineating sub-regions are generally subjective in nature, area groupings based on climatological and topographic features serve as a useful tool in determining new snowfall characteristics, including the spatial pattern of snow cover. In this study, we used the MODIS standard snow cover products from collection 5 to determine the spatial pattern of new snow cover according to 14 predefined sub-regions in the SAM. FSC data were acquired from 2006 to 2012, corresponding to the most commonly occurring synoptic classes.

Among the snowfall events, we found that SCA followed the regional climatology, with lower valley locations generally receiving the least percentage SCA, and the higher elevation sub-regions marked by the greatest percentage SCA. Miller Cyclones promoted the greatest spatial snow cover, followed by southeastward tracking clippers, and Upslope Flow which was also the most variable. These patterns were present among all sub-regions, though we identified the High

Country, New River Valley, northern Plateau, and High Elevations where SCA was generally the most variable. Differences in FSC bins highlight the local variability between individual events occurring within the same synoptic classes.

The sub-regional analysis points towards a future examination of the meteorological and topographic variables as a way forward in determining the factors that promote high vs. low performance in SCA. Though developed specifically for the SAM, these methods are transferrable to other mid-latitude mountain ranges with ephemeral snow cover and where a combination of factors exert considerable influence on the multi-scaled spatial heterogeneity of the snow. Prediction of the snow cover distribution according to synoptic characteristics can be used to generate more effective warning systems for people that are most affected by the sub-regional snowfall, thus mitigating the drawbacks of blanket warnings across entire regions. We conclude that the sub-regional analysis is ultimately of benefit to local forecasters through an improved understanding of local snow cover patterns and their relationship to synoptic-scale circulation features.

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