

Satellite and Surface Perspectives of Snow Extent in the Southern Appalachian Mountains

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ABSTRACT

Assessing snow cover patterns in mountain regions remains a challenge for a variety of reasons. Topography (e.g., elevation, exposure, aspect, and slope) strongly influences snowfall accumulation and subsequent ablation processes, leading to pronounced spatial variability of snow cover. In-situ observations are typically limited to open areas at lower elevations (< 1000 m). In this paper, we use several products from the Moderate Resolution Imaging Spectroradiometer (MODIS) to assess snow cover extent in the Southern Appalachian Mountains (SAM). MODIS daily snow cover maps and true color imagery are analyzed after selected snow events (e.g., Gulf/Atlantic Lows, Alberta Clippers, and Northwest Upslope Flow) from 2006 to 2012 to assess the spatial patterns of snowfall across the SAM. For each event, we calculate snow cover area across the SAM using MODIS data and compare with the Interactive Multi-sensor Snow and ice mapping system (IMS) and available in-situ observations. Results indicate that Gulf/Atlantic Lows are typically responsible for greater snow extent across the entire SAM region due to intensified cyclogenesis associated with these events. Northwest Upslope Flow events result in snow cover extent that is limited to higher elevations (> 1000 m) across the SAM but also more pronounced along NW aspects. Despite some limitations related to the presence of ephemeral snow or cloud cover immediately after each event, we conclude that MODIS products are useful for assessing the spatial variability of snow cover in heavily forested mountain regions such as the SAM.

Keywords: Snow cover, MODIS, Southern Appalachian Mountains

INTRODUCTION

Snow is a common occurrence in the SAM, and particularly in the mountainous regions of western North Carolina (Hall et al., 2010; Perry et al., 2010). MODIS snow cover products offer promising results for detection of snow cover extent. Improved snow cover maps may allow for better predictive capability of future snow accumulation and snow covered area during and after certain synoptic event types. Furthermore, detection of snow at the highest elevations is important for improving understanding of regional snow hydrology and multi-scale topographic influences on the spatial variability of snow (Perry and Konrad, 2006). Research findings will benefit state economies that spend a large portion of funding on snow removal operations throughout the winter season. Thus, coupling surface based observations and satellite snow cover mapping techniques can provide a useful opportunity for analysis and improvement of snowfall patterns across the region.

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Previous research using MODIS products has often focused on areas with little topographic variability and has failed to address issues pertaining to application of remote sensing data in mountainous terrain. Launched on the Terra and Aqua satellites in 1999 and 2002, respectively, MODIS has provided a fully-automated system for observing snow cover with near global coverage every one to two days (Hall et al., 2002; Salomonson and Appel, 2004; Riggs et al., 2006). MODIS snow cover maps are very accurate when compared to other snow mapping techniques (Hall and Riggs, 2007; Klein and Barnett, 2003). Some studies did include topographic variability in mountains as a factor when comparing MODIS performance with in-situ measurements of snow properties (Şorman et al., 2007; Tekeli et al., 2005; Tekeli et al., 2006). Others have tended to focus upon land cover type and cloud cover as a major component affecting MODIS accuracy (Ackerman et al., 1998; Klein et al., 1998; Klein and Barnett, 2003).

Since model performance is often generalized for high elevation areas, incorporation of MODIS snow cover products will provide valuable climatic information about snow cover where in-situ observations do not exist (Fuhrmann et al., 2010). Specifically in this research, we examine four case studies between 2006 and 2012, and aim to answer the following questions. How does synoptic event type affect fractional snow cover (FSC)? How do specific characteristics of the SAM affect MODIS performance? Is MODIS more/less suited to mapping a specific synoptic event type?

DATA AND METHODS

Study Area

Figure 1 is a map of the SAM showing the topography of the region. The SAM includes portions of western North Carolina (NC), Tennessee (TN), Virginia (VA), and southern West Virginia (WV) and covers 137,952 km². Land cover types in the region are mixed conifer/deciduous, with spruce fir communities existing at higher elevations. Extensive riming in the canopy is common during colder events in these communities. Cooperative Observer Stations in the region are typically located in valleys and open areas at lower elevations. Elevations generally range below 1000 m in lowland areas and above 1829 m on mountain peaks. Mt. Mitchell, the highest peak in the Appalachian Mountains at 2037 m, is located in this area of NC, while nearby Mt. LeConte in TN is 2010 m. Boone, NC, at elevation 1016 m in northwest NC, is used as a comparison for in-situ observations in valley locations. However, the most relief is located along the border of NC and TN. This area generally runs southwest to northeast in association with the topography of the mountain ranges and produces distinct windward and leeward slopes under certain event types.

Summary of Snowfall Events

Table 1 provides an analysis of snowfall events and meteorological parameters as recorded at Poga Mountain, NC (1021 m), from 2006–2012. Values are broken down by synoptic event class and are averaged for the entire period. Temperature, relative humidity, and wind speed values are derived from one hour before and after event maturation. NW Upslope snowfall accounts for the greatest percentage event type across the region and is closely followed by Gulf/Atlantic Lows. However, Gulf/Atlantic Lows and Alberta Clippers tended to produce the largest accumulations when averaged for all stations across the region. SWE followed this pattern, as well. Average temperatures for all events were relatively low and conditions were relatively humid above 85%. Values are not indicative of extreme events that occurred during the time period but do provide a general reference of measurement by synoptic class.

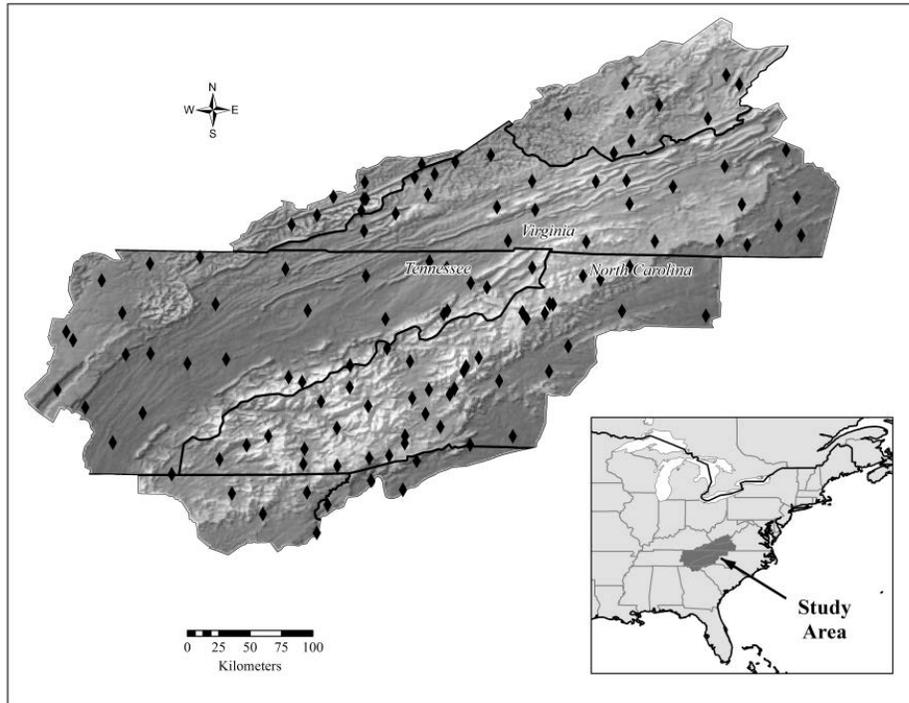


Figure 1. Location map defining the SAM study area. Areas of high elevation are shaded white. The distribution of Cooperative Observer Stations is identified.

Table 1. Summary of Snowfall Events from 2006–2012

Class	Percent of Events	Snow (cm)	SWE (mm)	SLR	Density (kg m^{-3})	Temp (C)	Relative Humidity	Wind Speed (m s^{-1})
Gulf/Atlantic Lows	25%	12.3	9.4	13	76	-4.7	90.8	4.1
Alberta Clippers	10%	12.5	6.3	20	50	-2.9	89.3	3.6
Ohio Valley Lows	18%	6.1	3.9	16	63	-2.2	91.9	3.9
NW Upslope	26%	3.9	2.3	17	59	-4.5	88.8	3.6
Other	21%	5.3	3.6	15	67	-3.6	87.7	2.9

RESULTS

26–28 February 2008, NW Upslope Flow Event

Total accumulations from this event tended to solely favor NW slopes at higher elevations along the NC/TN border. The NOAA Surface Analysis product for the event maturation hour on 2/27/2008, 1500 UTC, displays northwesterly flow behind a cold front that passed through the study area (Figure 2). Boone, NC, recorded 3.8 cm; Mt. Mitchell 7.6 cm; Poga Mt. 20.6 cm; and further west, Mt. LeConte 43.1 cm.

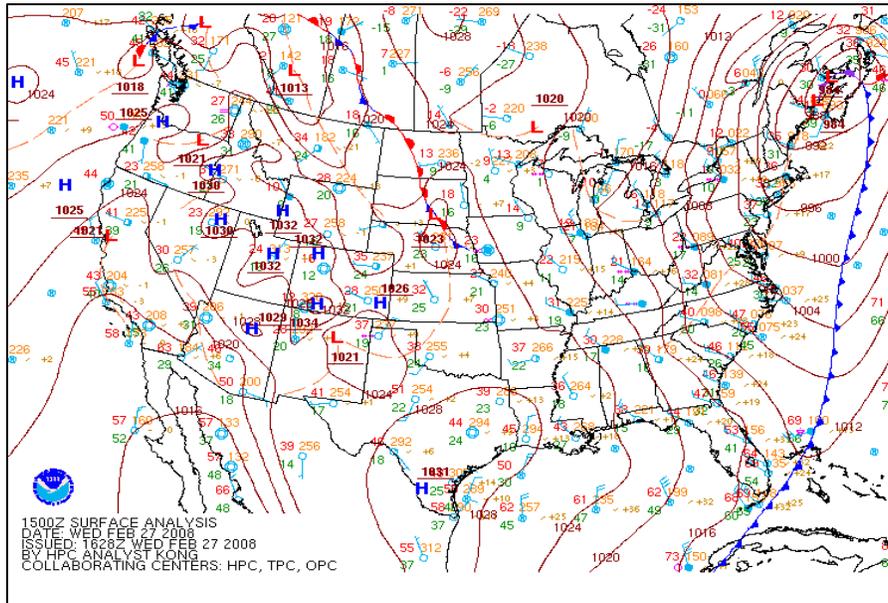


Figure 2. NOAA Surface Analysis Map from event maturation, 1500 UTC, 02/27/2008.

We acquired a Terra MODIS True Color image from 03/01/2008, one day after event end (Figure 3). The true color product from the previous day 02/28 before event end showed considerable cloud obscuration of the surface since skies had not cleared and was deemed unsuitable for detecting snow. However, on 03/01 view of the surface is mostly cloud free and a visible pattern of high elevation areas are snow covered. Boone recorded a Daily AVG Air Temperature of 4.8°C, so we expect that melting was occurring at lower elevations, whereas Mt. Mitchell Daily AVG Air Temperature was -3.6°C. Snow reflectance is still visible for much of the high elevation areas that were affected during this event.

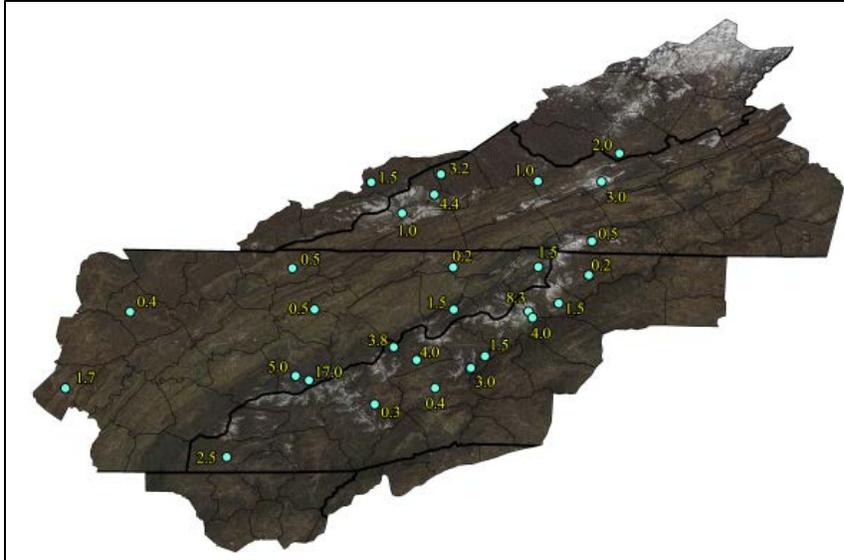


Figure 3. Terra MODIS True Color image with overlaid accumulation data, 03/01/2008.

The Terra MODIS FSC product (MOD10A1) from 03/01/2008 is used to compare performance with the true color image (Figure 4). The majority of pixels mapped as snow by MODIS fell between 1 and 20% FSC and covered roughly 4000 km² of the study area. MODIS detected very few pixels with 80–100% FSC. These areas are located at high elevation peaks across the region and relative scarcity of these cells may also result from a combination of melting in the 1-day time lag of MODIS products from the event end and dominant forest cover type at high elevations.

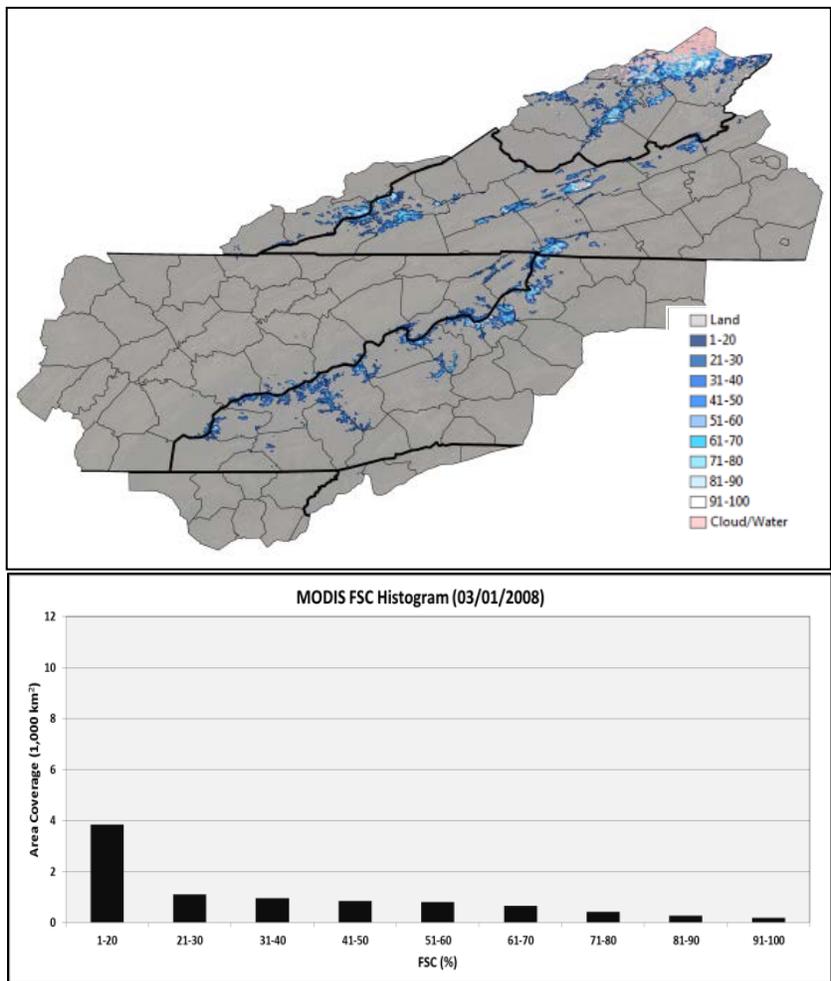


Figure 4. Terra MODIS FSC product, MOD10A1, 03/01/2008 (upper); MODIS FSC histogram, 03/01/2008 (lower).

The NOAA IMS product from 03/01/2008 reveals snow cover in expected high elevations areas, but resolution is too coarse to provide comparative detail with the MODIS products in isolated areas (Figure 5).



Figure 5. NOAA IMS map from 03/01/2008. Green is snow free and white indicates snow cover.

18–21 December 2009, Gulf/Atlantic Low Event

Total accumulations from this event are widespread across the study area, more pronounced at higher elevations, and also extend snow coverage across many valley locations. The NOAA Surface Analysis product for the event maturation hour on 12/19/2009, 0000 UTC, displays a low pressure system off the coast of NC, which supplied available moisture for snowfall to be widespread when combined with low temperatures across the study area (Figure 6). Boone, NC, recorded 37.6 cm; Poga Mt. 38.9 cm; Mt. Mitchell 71.1 cm; and further west, Mt. LeConte 72.4 cm, accumulation totals much higher across all locations when compared with other event types.

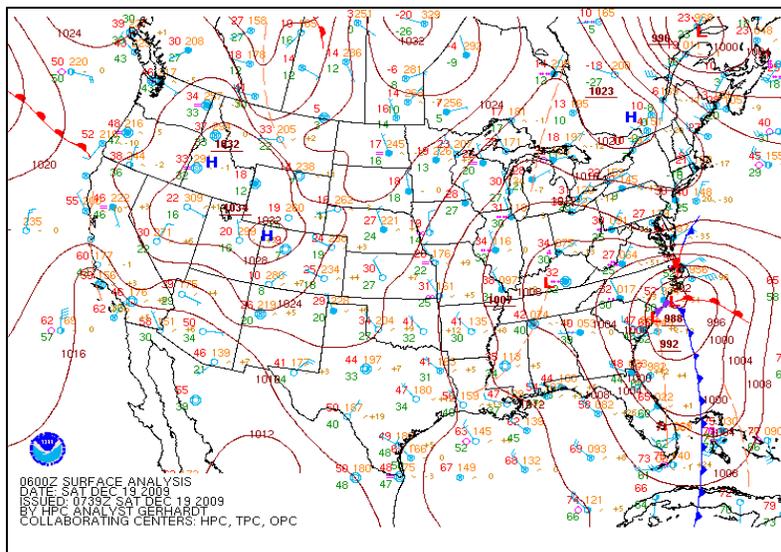


Figure 6. NOAA Surface Analysis Map from event maturation, 0000 UTC, 12/19/2009.

We acquired an Aqua MODIS True Color image from 12/22/2009, one day after event end (Figure 7). The true color product from the previous two days 12/20–12/21 before event end showed complete cloud obscuration of the surface since skies had not cleared and was deemed unsuitable for detecting snow. However, on 12/22, view of the surface is visible through gaps in heavy patches of cloud cover. This image offered the best view of the surface since the following days were marked by another incoming event and thus, more cloud cover. Boone recorded a Daily AVG Air Temperature of 1.9°C, so we expect that conditions warmed enough by this time to produce some melting at lower elevations, whereas Mt. Mitchell Daily AVG Air Temperature was -7.2°C. Snow reflectance is visibly widespread across the entire study area, although the southwestern portion of the region appears snow free. A snow shadow is present on the leeward (eastern) side of the escarpment over a smaller area of the foothills where accumulation totals were not as high compared to other areas.

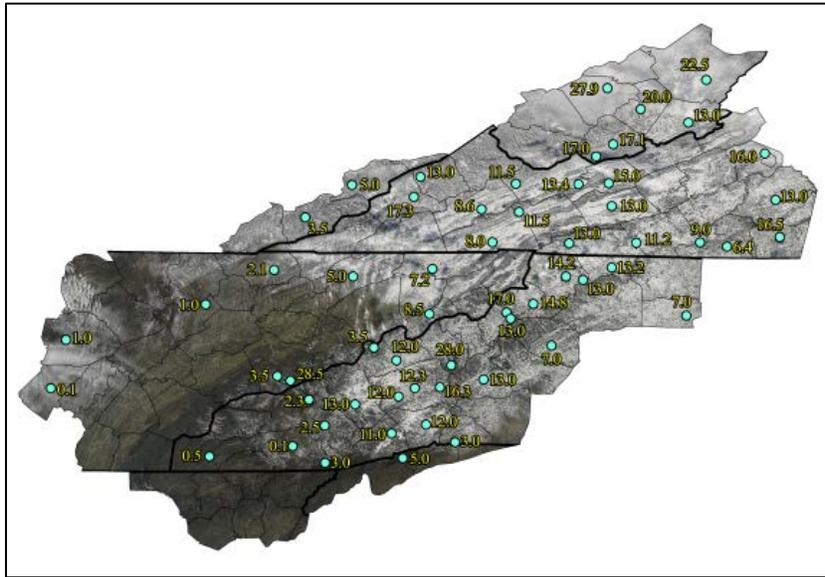


Figure 7. Aqua MODIS True Color image with overlaid accumulation data, 12/22/2009.

The Aqua MODIS FSC product (MYD10A1) from 12/22/2009 is used to compare performance with the true color image (Figure 8). The majority of pixels mapped as snow by MODIS fell between 91 and 100% FSC and covered roughly 12,000 km² of the study area. In the 81–90% FSC bin, MODIS detected pixels covering almost 8000 km² of the study area. MODIS detected the same amount of coverage in the 1–20% FSC bin along coverage margins and in lower valley locations. Between 21 and 80% FSC, MODIS detected much lower values, near 4000 km² of the study area, in each bin, that are a result of thick, patchy cloud cover obscuring much of the snow covered area that may have fallen within this middle range of values. The snow shadow is also visible with lower FSC values. In this case, persistent low temperatures for days following event end preserved a widespread amount of snow covered area across the region.

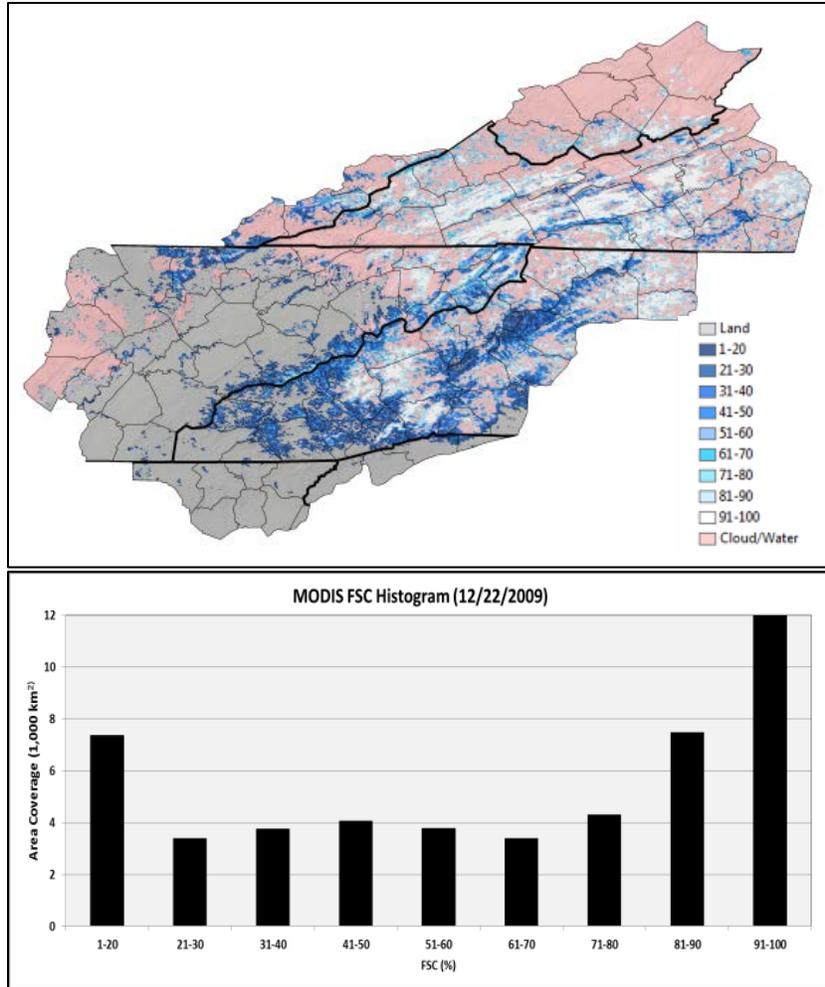


Figure 8. Aqua MODIS FSC product, MYD10A1, 12/22/2009 (upper); MODIS FSC histogram, 12/22/2009 (lower).

The NOAA IMS product from 12/22/2009 displays continuous snow cover extending well into portions of southwestern NC, which may indicate more melting had taken place in this area before MODIS passed over the region (Figure 9). The snow covered area is consistent with the expected extent from passage of a low pressure system moving through the region.



Figure 9. NOAA IMS map from 12/22/2009. Green is snow free and white indicates snow cover.

15–18 February 2010, Gulf/Atlantic Low Event

Total accumulations from this event are widespread across multiple elevations of northwest NC, southern VA, and WV. The southwestern portions of NC picked up snowfall accumulation only along the highest elevation peaks and ridges. The NOAA Surface Analysis product for the event maturation hour on 12/16/2010, 900 UTC, displays the tracking of a low pressure system off the mid-Atlantic coast which supplied available moisture for snowfall to be widespread with the passage of a cold front across the study area (Figure 10). During this event, Boone, NC, recorded 12.7 cm; Poga Mt. 30.5 cm; Mt. Mitchell 38.1 cm; and further west, Mt. LeConte 15.2 cm; and most accumulation totals tended to favor areas further north.

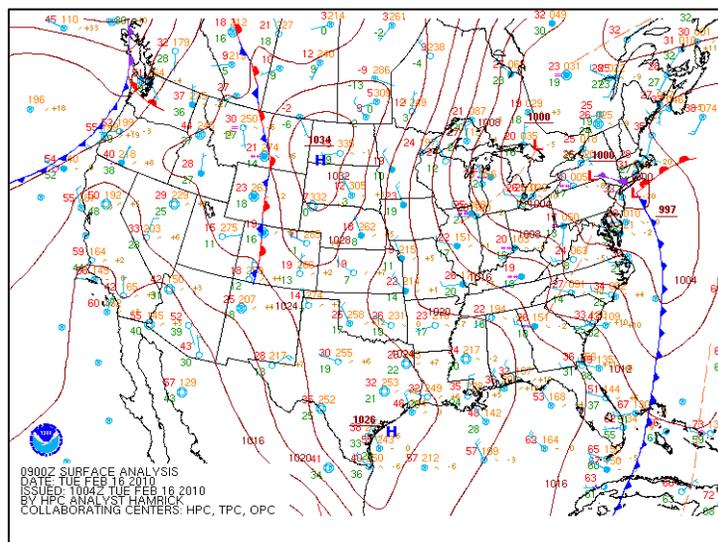


Figure 10. NOAA Surface Analysis Map from event maturation, 900 UTC, 02/16/2010.

We acquired a Terra MODIS True Color image from 02/19/2010, one day after event end (Figure 11). The true color product from the previous day, 02/18, showed cloud obscuration of the surface since skies had not cleared and was deemed unsuitable for detecting snow. However, on 02/19, the surface is visible over the majority of the study area excepting a small portion of WV. This image offered the best view of the surface since the following days were marked by snow melt. Boone recorded a Daily AVG Air Temperature of 1.2°C, so we expect that conditions warmed slightly to produce some melting at lower elevations, whereas Mt. Mitchell Daily AVG Air Temperature was -8.3°C . Snow reflectance is visibly widespread across the northern study area, although the southwestern portion of NC only shows snow covered area along ridges and high elevation peaks.

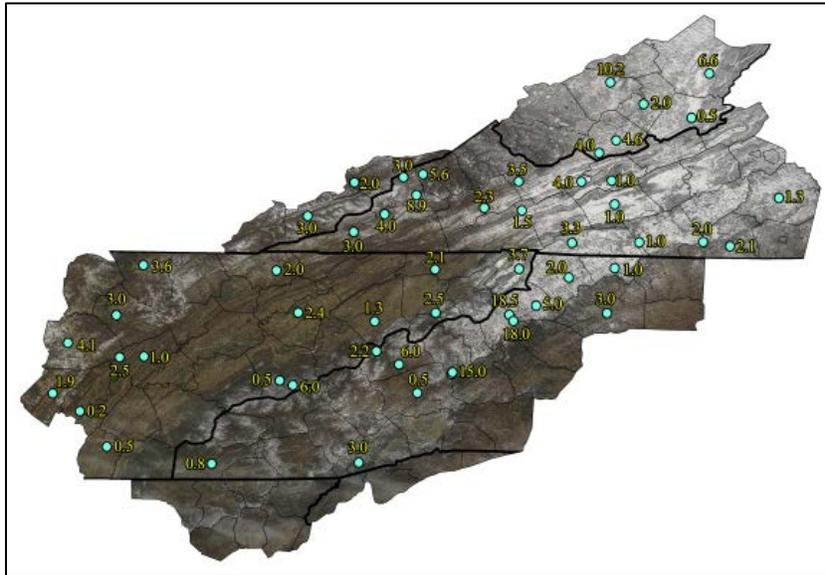


Figure 11. Terra MODIS True Color image with overlaid accumulation data, 02/19/2010.

The Terra MODIS FSC product (MOD10A1) from 12/19/2009 is used to compare performance with the true color image (Figure 12). The majority of pixels mapped as snow by MODIS fell within 1 to 20% FSC and covered over 13,000 km² of the study area. This event may have favored regions further north, resulting in predominately low FSC for the study area. For each subsequent bin between 21 and 100% FSC, MODIS detected a moderate amount of snow from 4000–6000 km² of the study area; so greater accumulations did occur in a few areas. MODIS detected minimal cloud cover, though some obscuration of the surface is present where snow is assumed to cover the ground. In this case, melting the day after event end may have reduced some reflectance values of fractional snow cover; but snow cover extent is still maintained based on synoptic flow characteristics.

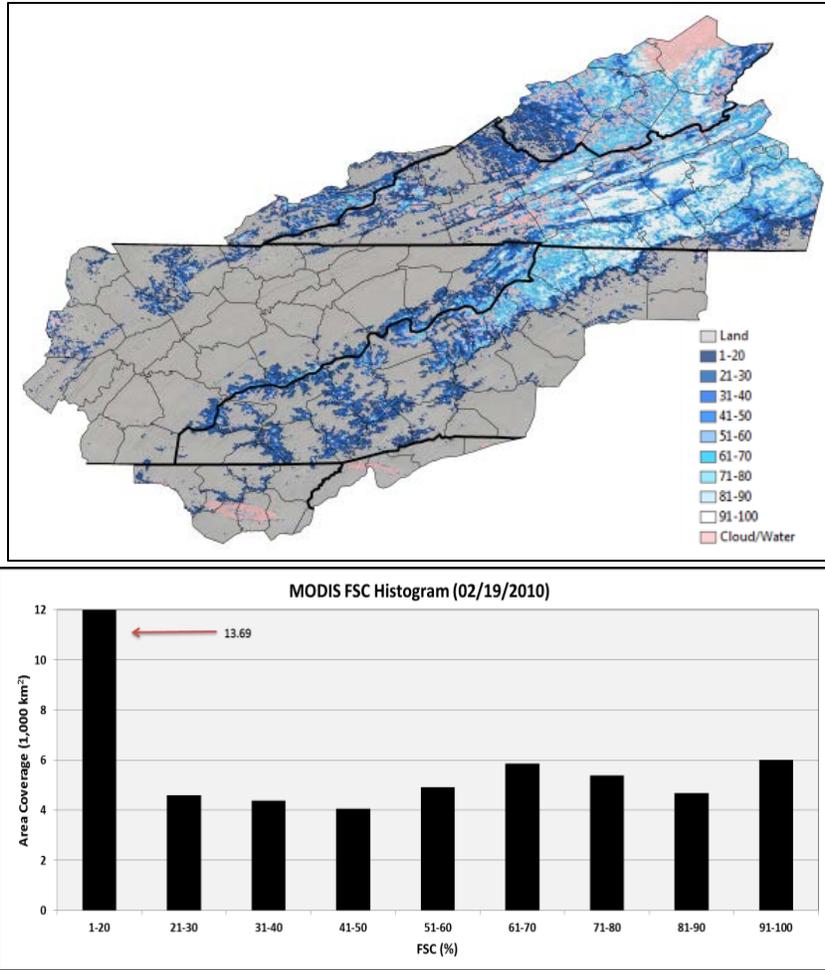


Figure 12. Terra MODIS FSC product, MOD10A1, 02/19/2010 (upper); MODIS FSC histogram, 02/19/2010 (lower).

The NOAA IMS product from 02/19/2010 displays continuous snow cover extending into southern VA and more patchy extent in portions of western NC and TN (Figure 13). In this case, snow covered area is consistent with characteristics of a Gulf/Atlantic Low that are enhanced in more northerly areas.

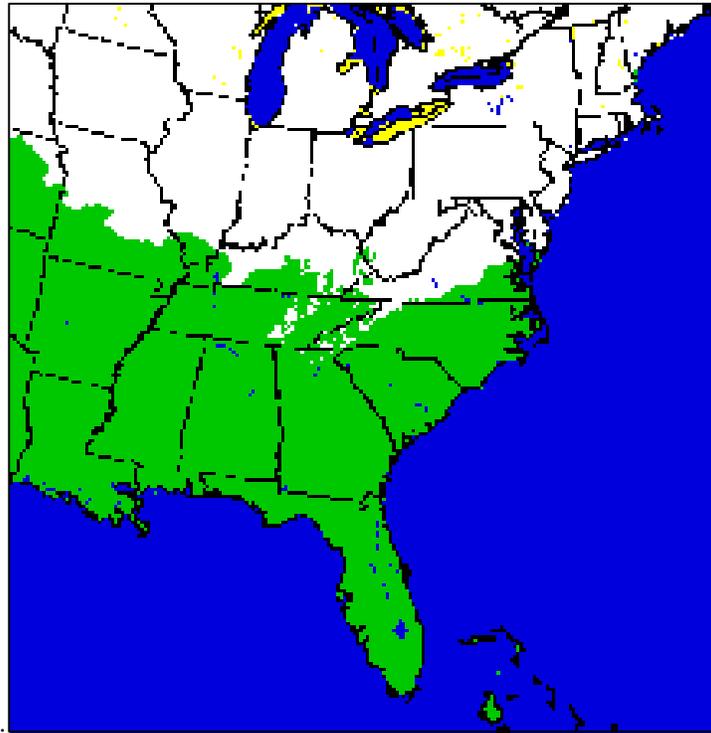


Figure 13. NOAA IMS map from 02/19/2010. Green is snow free and white indicates snow cover.

Case Study: 05 March, 2012, Alberta Clipper Event

Total accumulations from this clipper event are isolated to a few high elevation areas of northwestern NC and are mostly located in southern WV. The NOAA Surface Analysis product for the event maturation hour on 03/05/2012, 1400 UTC, displays northwesterly flow into the region that is enhanced by elevation or temperature, depending on local conditions at the surface (Figure 14). During this event, Boone, NC, recorded 7.6 cm; Poga Mt. 9.1 cm; Mt. Mitchell 25.4 cm; and most other accumulation totals tended to favor areas further north. Western NC and TN experienced trace amounts of accumulation.

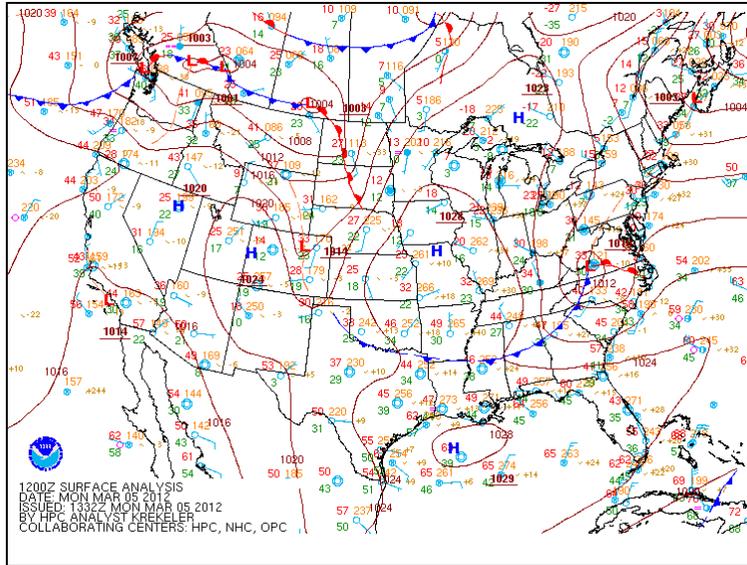


Figure 14. NOAA Surface Analysis Map from event maturation, 1400 UTC, 03/05/2012.

We acquired a Terra MODIS True Color image from 03/06/2012, one day after event end (Figure 15). The true color product from the previous day, 03/06, showed cloud obscuration of the surface since skies had not cleared and was deemed unsuitable for detecting snow. However, on 02/19, the surface is visible over the majority of the study area. Snow cover was practically non-existent on the following day. Boone recorded a Daily AVG Air Temperature of 1.7°C, so we expect that conditions warmed to produce melting at lower elevations, whereas Mt. Mitchell Daily AVG Air Temperature was -5.0°C.

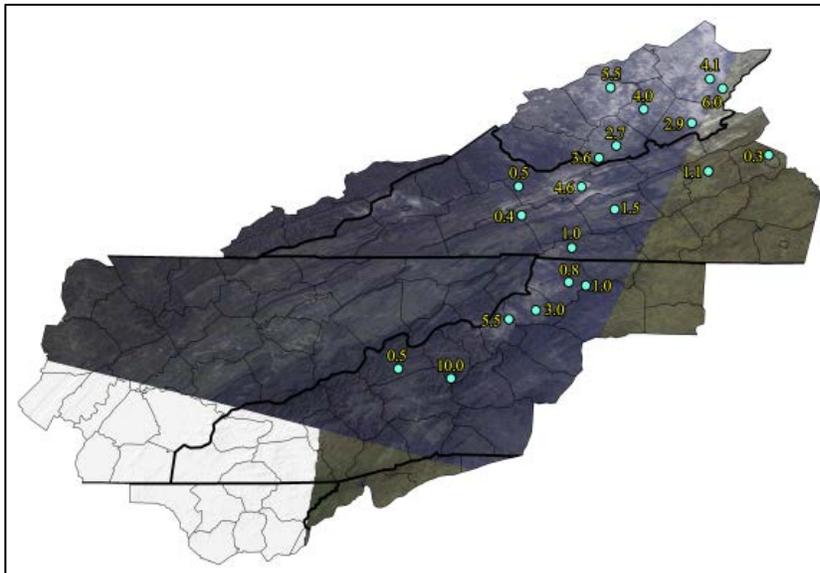


Figure 15. Terra MODIS True Color image with overlaid accumulation data, 03/06/2012.

The Terra MODIS FSC product (MOD10A1) from 03/06/2012 is used to compare performance with the true color image (Figure 16). The majority of pixels mapped as snow by MODIS fell within 1 to 20% FSC and covered less than 6000 km² of the study area. This event favored isolated areas where conditions were ideal for snowfall. Most of the FSC is noticeable in southern WV, though some isolated snow cover exists at higher elevations of northwestern NC. This event

produced virtually no FSC higher than 50%. MODIS identified cloud cover in the northern reaches of the study area which is difficult to distinguish in the true color product. In this case, trace amounts of snow were undetectable when melt onset occurred after event end.

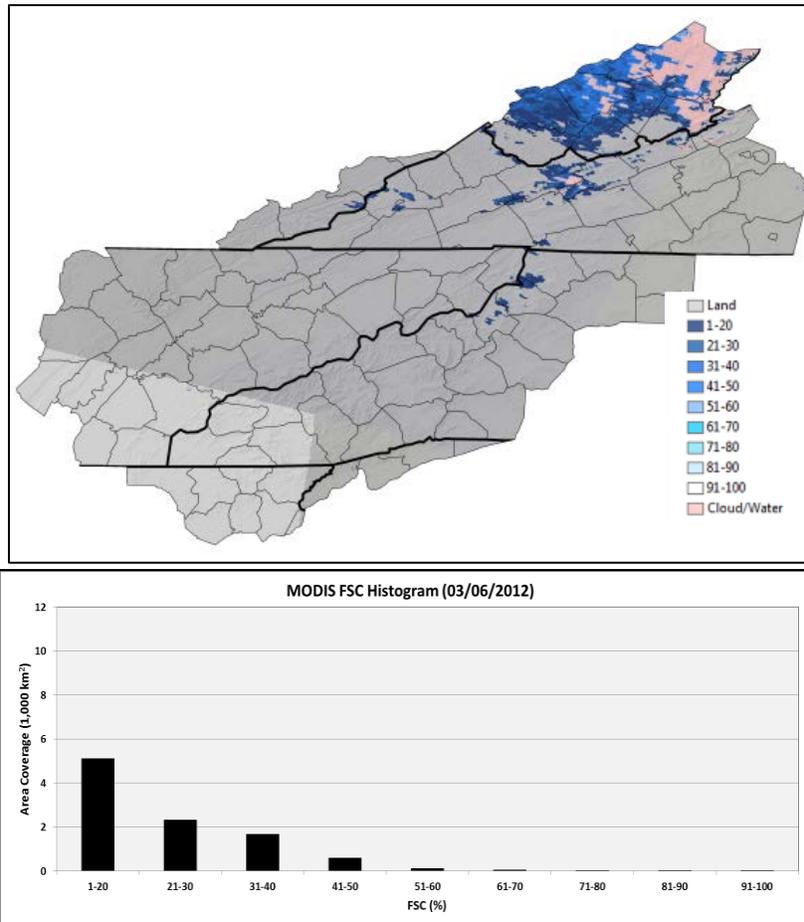


Figure 16. Terra MODIS FSC product, MOD10A1, 03/06/2012 (upper); MODIS FSC histogram, 03/06/2012 (lower).

The NOAA IMS product from 03/06/2012 displays small pixelated areas of snow in portions of northwestern NC, western VA, and is more pronounced in southern WV (Figure 17). Snow covered area is consistent with characteristics of an Alberta Clipper event but does little to distinguish smaller scale areas which produced ideal conditions for snowfall.

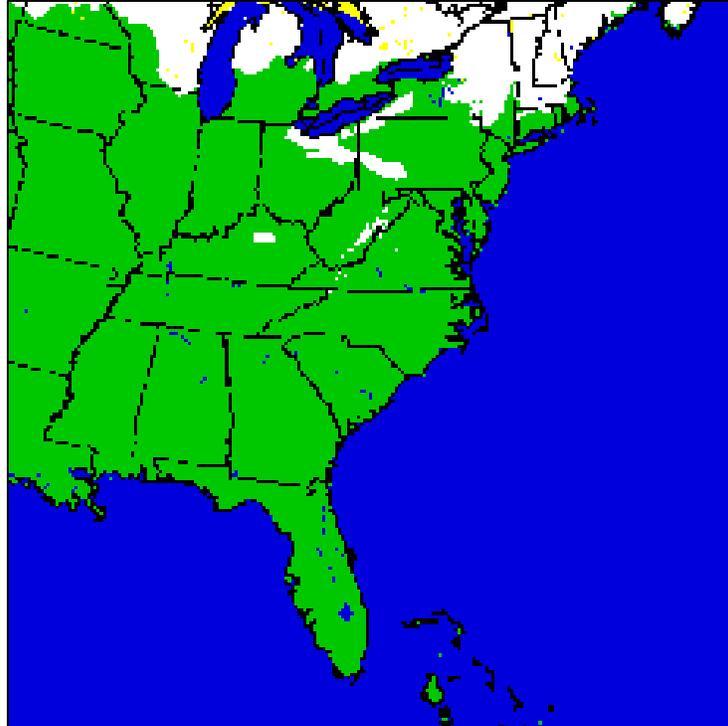


Figure 17. NOAA IMS map from 03/06/2012. Green is snow free, and white indicates snow cover.

CONCLUSION

Upon initial examination of four case studies involving multiple synoptic event types, Gulf/Atlantic Lows produced the greatest snow extent across the entire study area. This result is to be expected based upon the amount of cyclogenesis occurring during surface level low pressure systems when combined with temperatures below freezing. Typically, these events are also marked by snow cover that extends well outside of the study area into lowland piedmont regions, even though higher accumulation totals are still observed in the mountains. The Northwest Upslope event produced snow cover extent limited to high elevation areas but was consistently distributed across major mountain ridges. Snow cover and higher accumulation totals were typically more pronounced along northwest aspects which serve as windward slopes when compared to leeward eastern slopes. Finally, the Alberta Clipper event showed extremely isolated snow extent based on local conditions.

The MODIS snow mapping algorithm performs very well under ideal conditions but is limited by several circumstances that are of interest in the SAM region. Foremost, blowing or drifting of low-density snow from high winds that accompany many event types are causes for significant accumulation in some areas and trace accumulation in others. Accumulation may vary according to micro-scale topography, in this case, and have implications for measurement of FSC values within fixed resolution pixels. Also, we noticed that the problem of ephemeral snow, which has been well documented (Fuhrmann et al., 2010; Hall et al., 2010), is complicated by often persistent cloud cover in the mountains. When MODIS products were used 1–2 days after event end to minimize cloud obscuration of the surface, we noticed that it was not uncommon for melting to affect FSC or reflectance in the true color product. While not present in our case study, extended cloud cover associated with lingering Northwest/Upslope flow will often block the entire surface for days along the escarpment, while lower elevation leeward slopes are cloud free. During milder winters, rapid ablation in the snowpack can result in a snow free surface before skies have even cleared. Even when clear skies exist, the addition of mild temperatures may promote melting before MODIS makes a pass of the region.

In addition, mixed cover types, including forested mountain areas, present challenges for measuring snow extent at high elevations (Klein et al., 1998; Klein and Barnett, 2003). The dominant land cover type in the SAM is mixed conifer/deciduous forest. Dominant land cover type tended to compound the problem of lower FSC or reflectance in the true color product. We assume that values where ephemeral snow was present were generally lower as a result of snow melting from the canopy and MODIS detecting snow from the forest floor. Snow cover margins and lower elevations in the mountains are more likely to observe temperatures that rise above freezing after event end. Ephemeral snow is also problematic in dominant spruce fir forests at high elevations in the SAM since leaf off does not occur during the winter season. This effect is especially noticeable in the true color product because discriminating snow from snow free is a less obvious process. FSC values may be slightly underestimated, as well. Degree of riming in the canopy often promoted higher reflectance values of FSC (Fuhrmann et al., 2010). It is much more difficult for MODIS to sense snow beneath this cover type after melting begins, even though updates to the snow mapping algorithm have incorporated vegetation indices to better capture snow reflectance values under forest cover.

For these reasons, it is ideal to use MODIS data as soon as sky conditions permit a clear view of the surface, though for some events, a clear product may be unattainable (Hall et al., 2010). Daily observations from Cooperative Observer Stations can be used to confirm or deny the presence of clear skies and to determine whether or not temperatures will promote melting. Events where rapid snowmelt occurs are less suitable for mapping, overall. We conclude that MODIS Snow Products are most suitable for mapping heavier/lighter events in the SAM with low temperatures that persist for days. The snow maps are also useful for identifying errors in other snow mapping products that may not detect the presence of dynamic-related issues like a snow shadow due to lack of in-situ observations. These research findings should be expanded upon using quantitative analysis of pixel values to further assess FSC associated with synoptic events. MODIS may be more/less suited to accurately mapping certain event types based on the persistence of the snowpack. Thus, future questions should seek to determine if snow cover patterns are consistent from year to year. The SAM region is a good study area for testing MODIS products, improving our understanding of regional and micro-scale snow cover, and subsequently benefitting snow-removal operations and other human-related issues.

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