Spatial Patterns of Snow Cover in North Carolina: Surface and Satellite Perspectives

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ABSTRACT

Snow mapping is a common practice in regions that receive large amounts of snowfall annually, have seasonally-continuous snow cover, and where snowmelt contributes significantly to the hydrologic cycle. Although higher elevations in the southern Appalachian Mountains average upwards of 100 inches of snow annually, much of the remainder of the Southeast U.S. receives comparatively little snowfall (< 10 inches). Recent snowy winters in the region have provided an opportunity to assess the fine-grained spatial distribution of snow cover and the physical processes that act to limit or improve its detection across the Southeast. In the present work, both in situ and remote sensing data are utilized to assess the spatial distribution of snow cover for a sample of recent snowfall events in North Carolina. Specifically, this work seeks to determine how well ground measurements characterize the fine-grained patterns of snow cover in relation to Moderate-Resolution Imaging Spectroradiometer (MODIS) snow cover products (in this case, the MODIS Fractional Snow Cover product).

Keywords: snow cover; MODIS; soil temperature; ephemeral snow; North Carolina

INTRODUCTION

Winter storms occur less frequently across the Southeast U.S. than other parts of the country; yet, when they do, they are capable of producing large snow totals (e.g., the "Carolina Crusher" snowstorm of January 2000, which produced over 20 inches of snowfall at Raleigh-Durham International Airport in North Carolina; the "Storm of the Century" in March 1993, which produced over 60 inches of snowfall in the mountains of North Carolina). When aggregated over an entire winter season, snowfall in the higher elevations of the region (i.e., the southern Appalachian Mountains) can rival seasonal totals experienced in more northern locations, such as Portland, ME (Perry et al., 2010). Nevertheless, even minor amounts of snowfall can result in significant societal impacts across the region. Along with other parameters such as snowfall rate, temperature, and timing of snowfall, the duration and extent of snow cover are critical factors in assessing potential risk from winter storms (Fuhrmann et al., 2009). However, the ability of meteorologists and climatologists to paint a detailed and accurate picture of snow cover in the region can be a tremendous challenge due to the mesoscale nature of the precipitation, variability in topography, elevation, and land cover, and limitations with observational networks. All of

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these challenges are compounded by the often ephemeral nature of the snow cover, which calls for spatially precise and timely detection of snow accumulation to help minimize any adverse impacts. In addition, a better understanding of ephemeral snow is needed in the context of both short-term forecast models and long-term regional climate models (e.g., calculation of surface energy budgets). The objective of this research is to assess the spatial distribution of snow cover across North Carolina, particularly in relation to the underlying topography, land cover, and forest canopy. A combination of in situ and remote sensing tools and techniques are utilized for a number of recent snowfall events with the goal of identifying the best marker (or combination of markers) for detecting various types of ephemeral snow cover.

STUDY AREA

The state of North Carolina is comprised of three distinct physiographic regions (Bobyarchick and Diemer, 2000): the Appalachian Mountains, the Piedmont Plateau, and the Coastal Plain (**Fig. 1**). The Coastal Plain is a broad low-lying plain consisting of loblolly and pond pine tree species in the inner region, and hardwood swamp forests, wetlands, and upland bogs in the Tidewater region nearest the coast. The Piedmont Plateau rises above the Coastal Plain and consists of generally rolling terrain. Multiple pine species mixed with oak and hickory create a dense tree canopy throughout much of the region. The Appalachian Mountains rise abruptly from the Piedmont along the Brevard Fault, forming the eastern escarpment, or Blue Ridge. The western ridge, where the elevation and relief are greatest, is situated along the North Carolina-Tennessee border. In between is a highly dissected mountain plateau with numerous cross ridges and intermontane valleys. These include Mount Mitchell, the highest peak in the eastern United States (6,684 feet), and the French Broad River Valley, where the city of Asheville is located. Because of the pronounced topographic relief in the mountains, forest cover and tree species are highly diverse. A combination of hard maple, white pine, yellow birch, and hemlock is found in the valleys, while beech, boreal conifers, and spruce firs dominate at the higher elevations and some ridge tops (many ridge tops are devoid of tree cover and are referred to as "balds"). Forest cover in the mountains is most dense to the southwest, with more pastureland and agriculture to the northeast near the Virginia border.

Variations in elevation as well as proximity to the warm Gulf Stream have a profound impact on the snowfall climatology of North Carolina. While the highest elevations in the Appalachian Mountains can average up to 100 inches of snow each year, much of the Piedmont Plateau receives less than 10 inches. The Coastal Plain is not immune to significant snowfall events (e.g., over 12 inches fell along the Outer Banks on 23 January 2003), but can go many years without recording any measurable snowfall. The diversity of the tree canopy across the state of North Carolina and variability in annual snowfall makes it an ideal test bed for the remote sensing of ephemeral snow cover.

DATA AND METHODS

Five case studies are presented in this paper. Four of these events occurred during the winter of 2009-2010 (see Fuhrmann et al., 2010). In situ data include observations of snowfall and snow depth from stations within the Cooperative Observer (COOP) network and hourly soil temperature and soil moisture observations from stations within the North Carolina Environment and Climate Observing Network (NC ECONet: http://www.nc-climate.ncsu.edu/econet). The satellite snow product utilized in this work is the 500-meter resolution Moderate-Resolution Imaging Spectroradiometer (MODIS) daily global Fractional Snow Cover (FSC) map product (Salomonson and Appel, 2004; Hall and Riggs, 2007). Details of the MODIS snow cover mapping algorithms may be found at: http://modis-snow-ice.gsfc.nasa.gov; also see Hall et al. (2002) and Riggs et al. (2006). An overview of the MODIS FSC product and its potential suitability for studying ephemeral snow cover relative to other satellite snow products is presented in a companion paper (Hall et al., this volume).

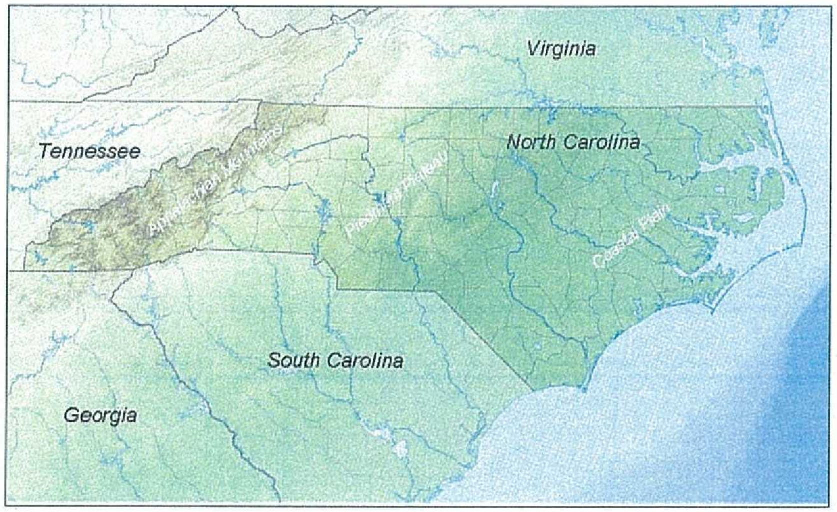

Figure 1: Study area with shaded topography.

RESULTS OF CASE STUDIES

26-27 February 2004

A Miller-A cyclone (Miller, 1946) tracked along the East Coast of the U.S. in late February 2004, resulting in a significant winter storm across much of central North Carolina from 26 to 27 February. Using COOP station data, the Raleigh National Weather Service (NWS) produced a snow accumulation map for the event which indicated that the greatest snowfall (> 12 inches) occurred through the central Piedmont and within a narrow corridor along the Blue Ridge (**Fig. 2**).

Clear-sky conditions on 28 February allowed for a vivid depiction of the resulting snow cover in both the MODIS visible and FSC imagery (**Fig. 2**). In general, the pixels with the highest FSC correspond with the area of greatest accumulation in the central Piedmont (Hall et al., this volume). However, some important differences in the NWS map and the FSC map are discernable. First, an apparent "snow shadow" is identified by the FSC map in the western Piedmont, while the NWS analysis indicates as much as 12 inches in this region. Snow (and rain) shadows in the lee of the mountains can occur when the low-level flow is out of the north-northwest, typically in the wake of a departing coastal cyclone, causing downsloping winds and less clouds and precipitation in the western Piedmont. Second, a narrow corridor of generally low FSC (< 50%) is found along the boundary between the Piedmont and Coastal Plain with 0% FSC in parts of Person, Granville, and Durham Counties to the north where the NWS indicates accumulation of up to 6 inches (red circle in **Fig. 2**).

Examination of soil properties before, during, and after the snowfall, as well as photographs taken of the snow cover shortly after the event ended provide some insight into these apparent discrepancies. Photographs taken in Chapel Hill (**Fig. 3**) reveal that the low to zero FSC in this area was due to very thin, patchy snow cover that either melted quickly or was obscured by the forest canopy. Hourly soil temperature observations from 0.1 meters below ground at Siler City (FSC < 50% and accumulation of 8-10 inches) reveal the timing and duration of the snow cover (**Fig. 4**). In the days prior to the event, soil temperatures reached the low 50's (degF) and decreased to the low 40's (degF) following the event. The diurnal warming-cooling signal, which is diminished beneath the snow pack, returned on 28 February, suggesting that solar radiation was reaching the upper-most soil layer. Further evidence for this is revealed in the plot of hourly soil moisture (0.2 meters below ground), which indicates a corresponding spike in soil moisture, likely due to melt water from the snow pack. Similar plots of soil conditions at Lindale Farm (FSC 80-

100% and accumulation of 16-18 inches) reveal a more delayed diurnal signal due to the deeper snow pack, although the soil moisture plot reveals that some melting was likely taking place by 28 February (**Fig. 5**).

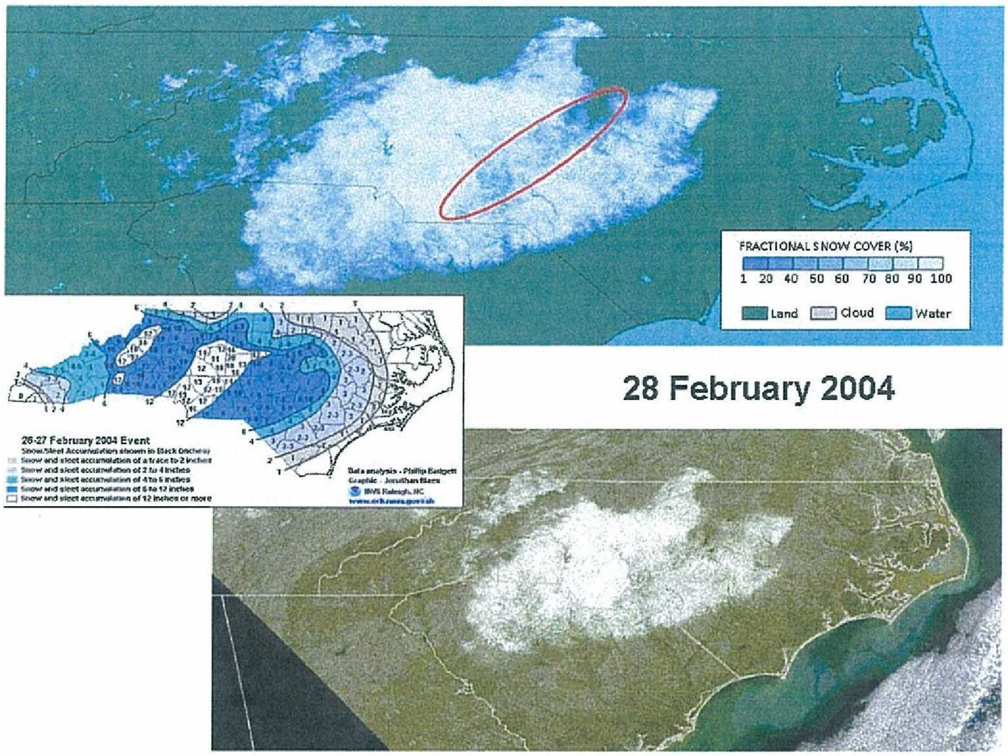

Figure 2: MODIS Fractional Snow Cover (FSC) map from 28 February 2004 (top); National Weather Service (NWS)-Raleigh Forecast Office snow accumulation map for 26-27 February 2005 (left); MODIS true-color image from 28 February 2004

29-30 January 2010

A hybrid Miller A/B cyclone in late January 2010 produced a large swath of winter precipitation from the Great Plains through the Tennessee Valley and into the Carolinas and mid-Atlantic (Fuhrmann et al., 2010). Much of the precipitation that fell across North Carolina occurred over the period 29-30 January. With the exception of the southeast corner of the state, most COOP stations reported at least a trace of snow accumulation with the highest amounts (> 12 inches) along the North Carolina-Virginia border and in the French Broad River Valley (**Fig. 6**). Generally clear skies allowed for the generation of the FSC map on 31 January, which revealed good agreement with the snow accumulation depicted by the NWS map (**Fig. 6**).

Outside of the mountains, the lowest FSC (< 50%) identified on 31 January is found in the region of the Uwharrie National Forest (red circle in **Fig. 6**). The dense forest canopy in this region likely obscured the snow pack that had accumulated beneath the canopy (2-4 inches). Soil temperature and soil moisture plots from the Sandhills Research Station (~30 km to the east; **Fig. 7**) indicate that some snow remained on the ground for at least another two days, but melting was likely occurring and therefore similarly low FSC was observed there. Interestingly, a narrow ribbon of high FSC (90-100%) is observed along the eastern-most region of snow cover. Within this region, there is a transition in the percent coverage of open canopy forest and therefore more continuous snow cover is perceived by the satellite.

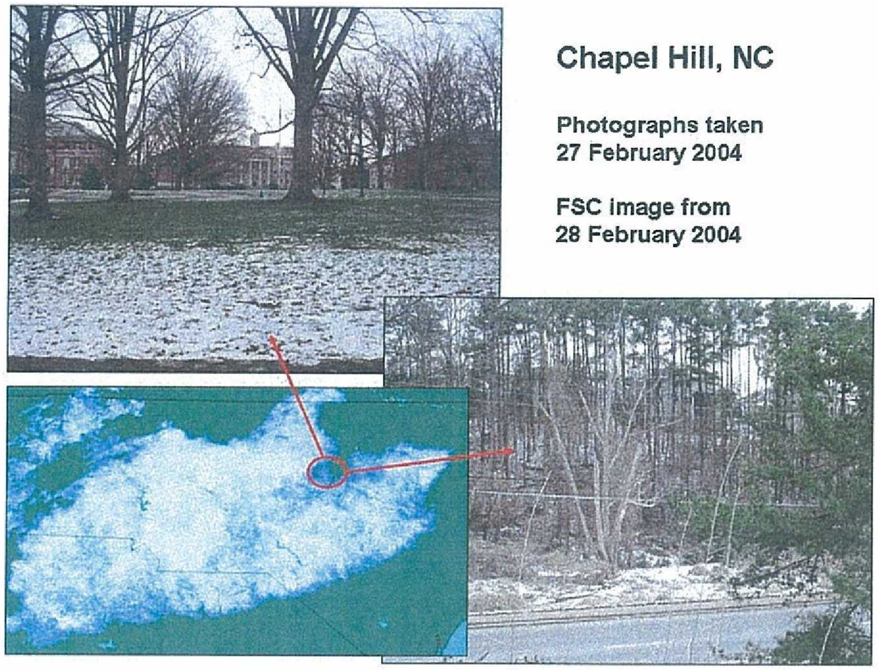

Figure 3: Photographs of snow cover in Chapel Hill, NC taken in the late afternoon of 27 February 2004.

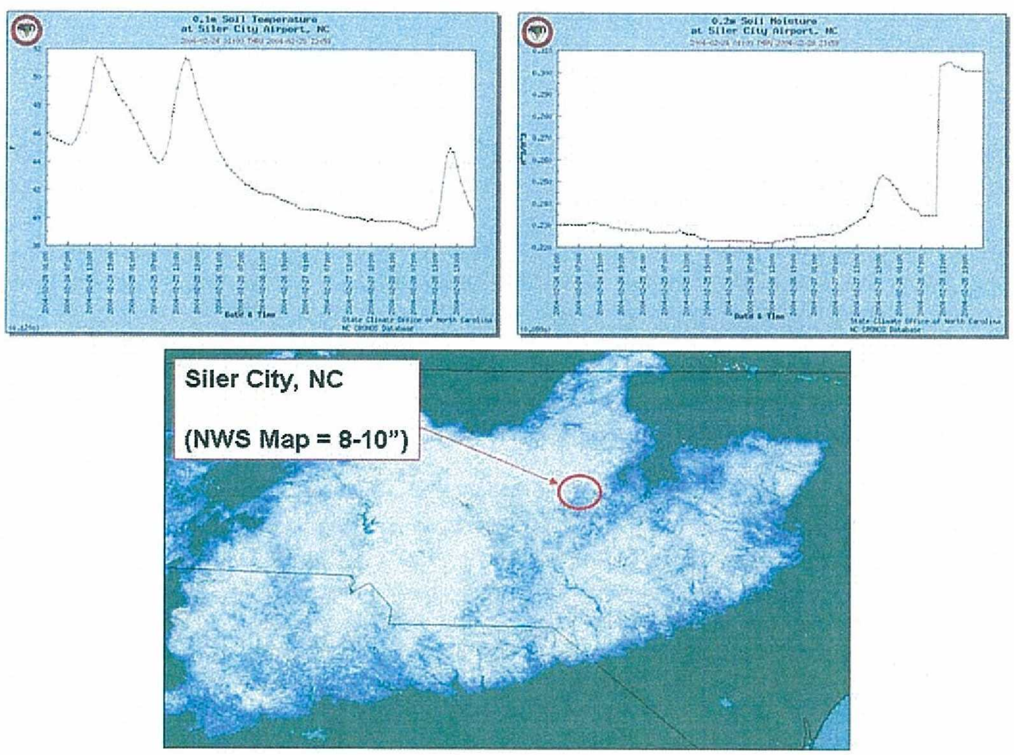

Figure 4: Plots of hourly soil temperature (top left) and soil moisture (top right) at the Siler City Airport ECONet station from 24 February to 28 February 2004.

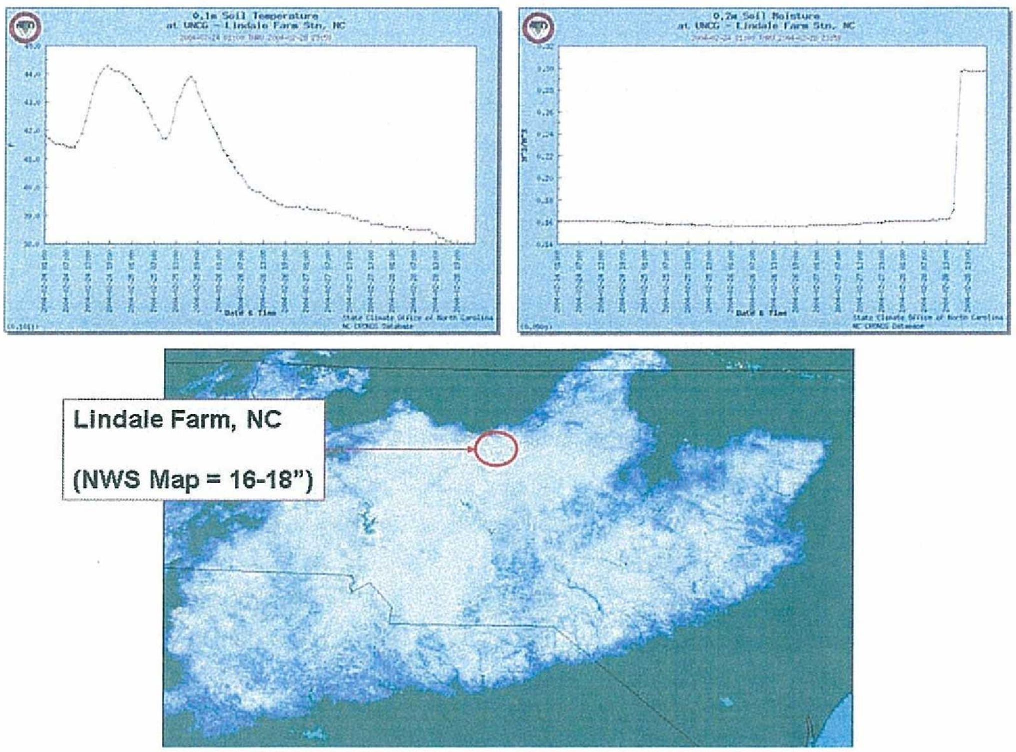

Figure 5: Same as Figure 4, but for the Lindale Farm ECONet Research Station.

12-13 February 2010

A winter storm (Miller-A) in mid-February 2010 severely impacted a large portion of the southern United States, with measurable snow as far south as the Gulf Coast (Fuhrmann et al., 2010). In North Carolina, much of the precipitation fell over the period of 12-13 February and covered nearly the entire state (**Fig. 8**). The greatest accumulation (> 6 inches) was recorded in parts of the Coastal Plain (8.5 inches at Harker's Island along the Outer Banks). In the Piedmont, between two and five inches was recorded with < 4 inches recorded in the mountains (**Fig. 8**).

The FSC map produced for 14 February indicates that nearly all of the snow that accumulated in the Piedmont, with the exception of the narrow ribbon of > 4 inches in the southwest Piedmont, had melted by the time of the satellite overpass (**Fig. 8**). Indeed, hourly soil temperature plots from the Sandhills Research Station revealed that, while soil temperatures overall were quite cold (low 40's to mid 30's degF), the diurnal warming-cooling signal had returned by 14 February (**Fig. 9**). Much of the snow cover observed by the FSC map in the mountains was the result of a significant northwest flow snow event that produced up to 20 inches of snow on 10 and 11 February. Along the Coastal Plain, the snow cover observed in the FSC map on 14 February is validated by examining the soil temperature plot from the Cunningham Research Station, which reveals that the diurnal warming-cooling signal did not return until one day later (15 February; **Fig. 9**). Within the Coastal Plain there is much variability in the FSC on 14 February on a pixel-by-pixel basis (Hall et al., this volume). This is likely due to variations in the canopy as well as land cover, which is dominated by swamp forests, wetlands, and bogs. Variations in percent open canopy and land type can result in "patchy" snow cover and decreased snow covered area (SCA; Hall et al., 2002).

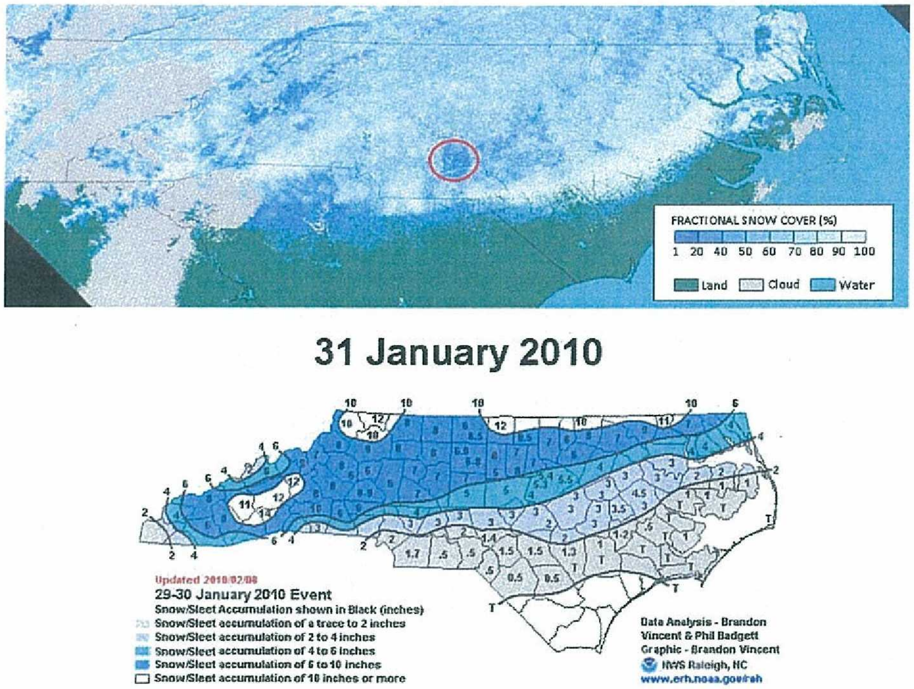

Figure 6: MODIS FSC map from 31 January 2010 and location of the Uwharrie National Forest (top); NWS-Raleigh Forecast Office snow accumulation map for 29-30 January 2010 (bottom).

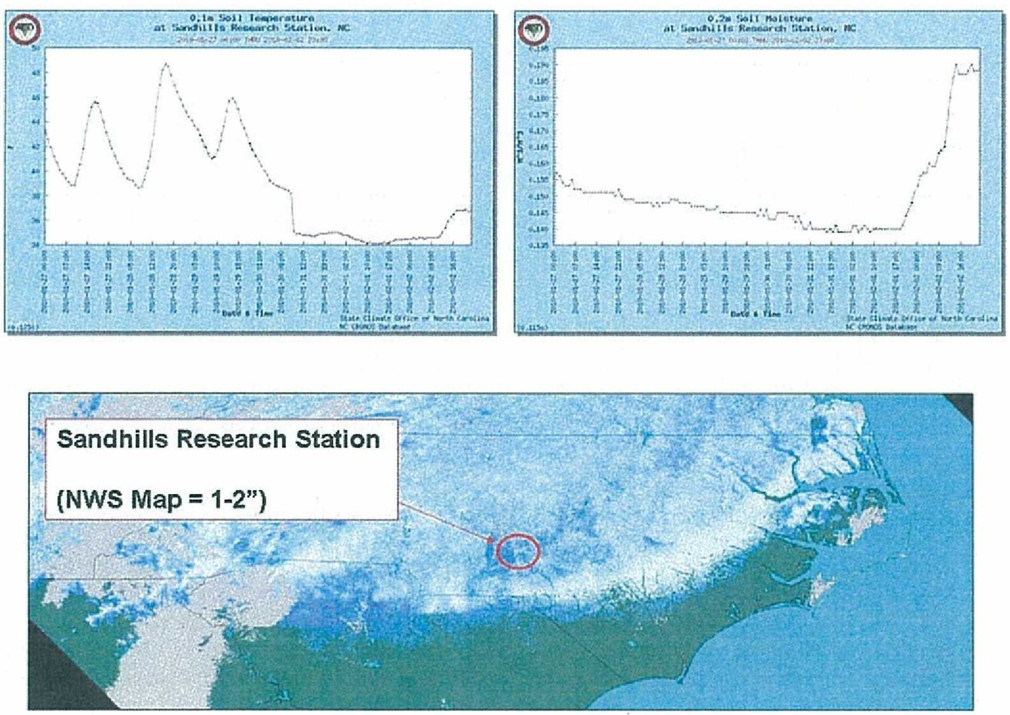

Figure 7: Plots of hourly soil temperature (top left) and soil moisture (top right) at the Sandhills ECONet Research Station from 27 January to 2 February 2010.

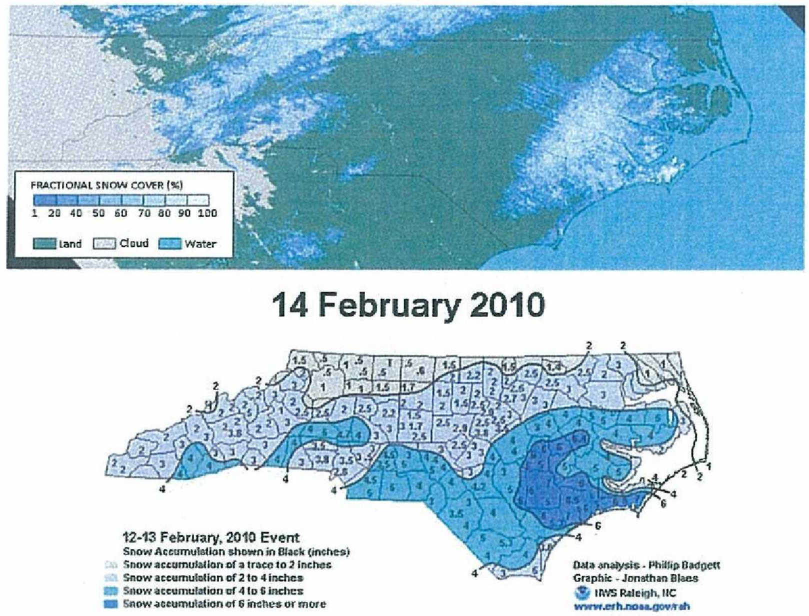

Figure 8: MODIS FSC map from 14 February 2010 (top); NWS-Raleigh Forecast Office snow accumulation map for 12-13 February 2010 (bottom).

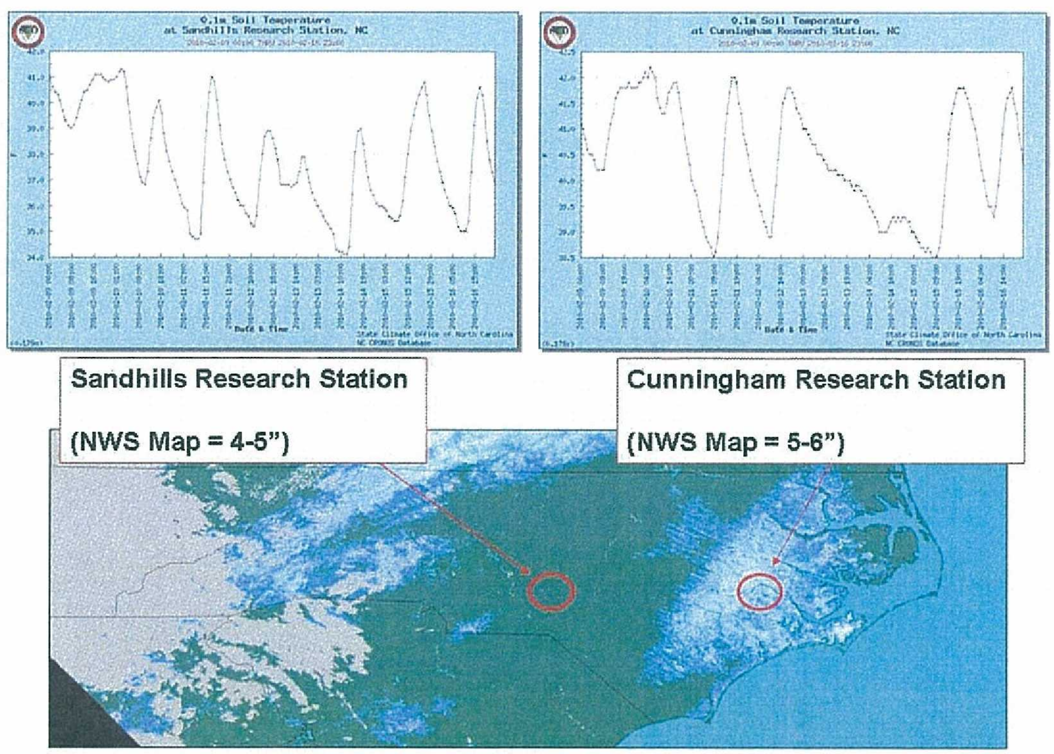

Figure 9: Plots of hourly soil temperature at the Sandhills ECONet Research Station (top left) and at the Cunningham ECONet Research Station (top right) from 9 February to 16 February 2010.

15-18 February 2010

A cyclone moving northeast through the Ohio River Valley on 15 February 2010 produced up to seven inches of snow in the mountains of northwest North Carolina (not shown). Low-level northwest flow in the wake of the departing storm persisted across the mountains for the next four days and contributed to an additional 12-14 inches of snow across the region (not shown).

The FSC map produced for 19 February 2010 indicates nearly continuous snow cover in northwest North Carolina with generally high FSC (> 80%; **Fig. 10**). In contrast, much of southwest North Carolina is devoid of snow cover according to the FSC map, with the exception of the higher elevations and ridge tops where generally low FSC is observed (< 50%). A small number of pixels near the ridge tops did record high FSC (> 80%). One of these locations was Mount Mitchell. A photograph taken on 20 February looking west towards the summit (**Fig. 10**) reveals generally continuous snow cover from 3,000 feet up to the summit at 6,684 feet with the spruce and fir trees covered by rime ice and snow above approximately 6,000 feet. Rime ice and snow on the spruce and fir may also be responsible for the high FSC observed along the North Carolina-Tennessee border in the Great Smoky Mountains. The photograph of Mount Mitchell was taken in the valley approximately 3,000 feet below the base of the summit and clearly shows that snow was on the ground in the valley (**Fig. 10**). However, the FSC map from the day before (19 February) only resolves the snow/rime ice at the summit with 0% FSC in the valley to the east. It is believed that the tree canopy in the valley is obscuring the significant snow cover on the ground. In fact, field observations on 20 February indicated snow depth (snow water equivalent) ranging from 8.5 inches (2.5 inches) at 3,000 feet in the valley to 43 inches (9.9 inches) near the summit. This may also explain the lack of snow cover as observed by the MODIS FSC algorithm throughout the lower elevations of the interior southwest mountains as forest cover is more dense there than in the northwest mountains.

2-3 March 2010

The last winter storm of the 2009-2010 winter season in North Carolina occurred over 2-3 March as a Miller A cyclone tracked across the southern United States and then along the east coast. A trace to two inches of snow covered much of North Carolina with heavier amounts (> 4 inches) in the mountains and in a narrow corridor extending through the northern and central part of the state (**Fig. 11**). The FSC map produced for 4 March indicates that all of the snow east of the mountains had melted while the snow cover in the mountains that began in mid-December was still present into early March (see Perry et al., this volume). The snow melt in the Piedmont following this event was rather dramatic, particularly in Chatham and Randolph Counties where 6-8 inches of snow accumulation was recorded. A soil temperature profile from Siler City (**Fig. 12**) reveals a diminished diurnal signal during the period of snow on 2-3 March with temperatures falling from the low 40's to the upper 30's (degF). This was immediately followed by a pronounced diurnal signal on 4 March, indicating that solar insolation was reaching the upper soil layer.

The FSC map from 4 March indicated significant snow cover across the North Carolina mountains (**Fig. 13**), particularly at higher elevations along the Tennessee border. Fieldwork on Roan Mountain (NC/TN) on 8 March indicated average snow depth (snow water equivalent) of 13 inches (3.6 inches) at 4,000 feet, 23 inches (5.5 inches) at 5,500 feet, and 36 inches (10.3 inches) at 6,286 feet. Photographs from the dense spruce-fir forest above 6,000 feet (**Fig. 13**) highlight the significant snow cover as well as snow and rime ice loading on the trees. It is likely that the snow and rime ice on spruce and fir trees above 6,000 feet on Roan Mountain and elsewhere (particularly in the Great Smoky Mountains) contributed to the very high observed FSC (> 80%) in these areas.

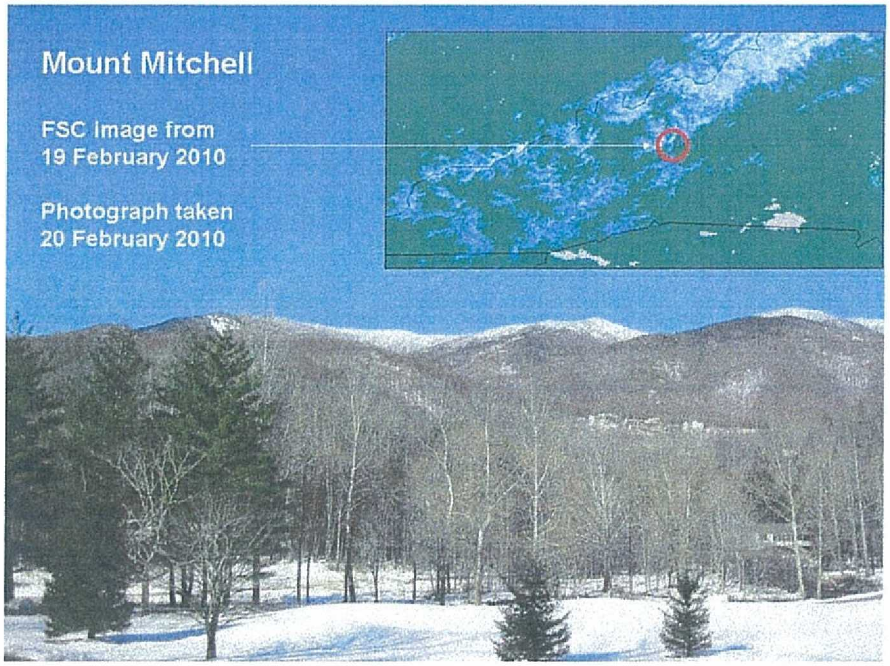

Figure 10: Photograph of snow cover at the summit of Mount Mitchell taken on 20 February 2010.

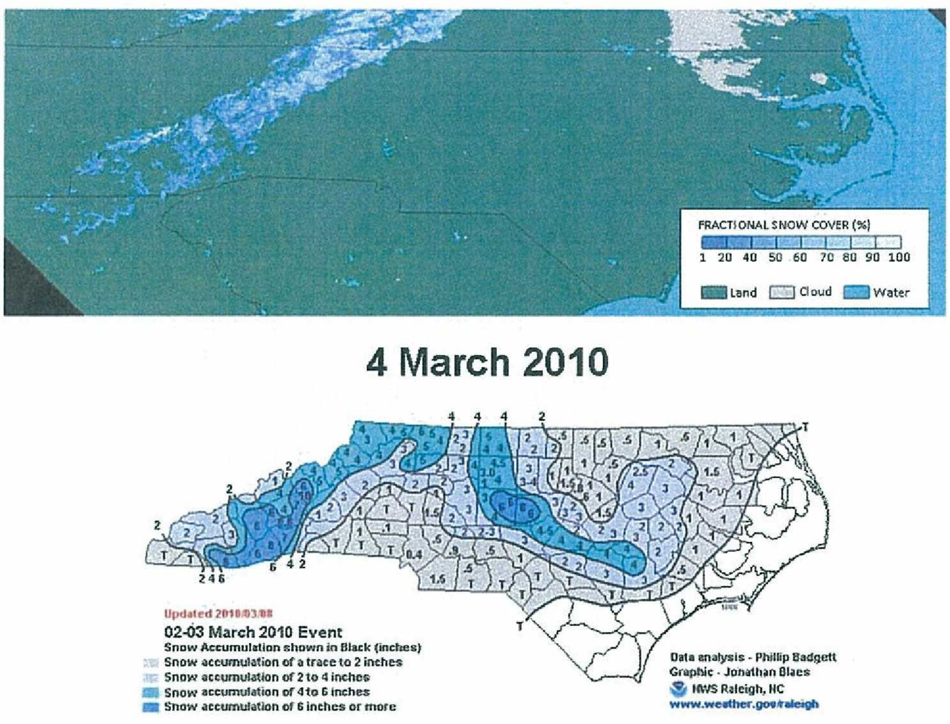

Figure 11: MODIS FSC map from 4 March 2010 (top); NWS-Raleigh Forecast Office snow accumulation map for 2-3 March 2010 (bottom).

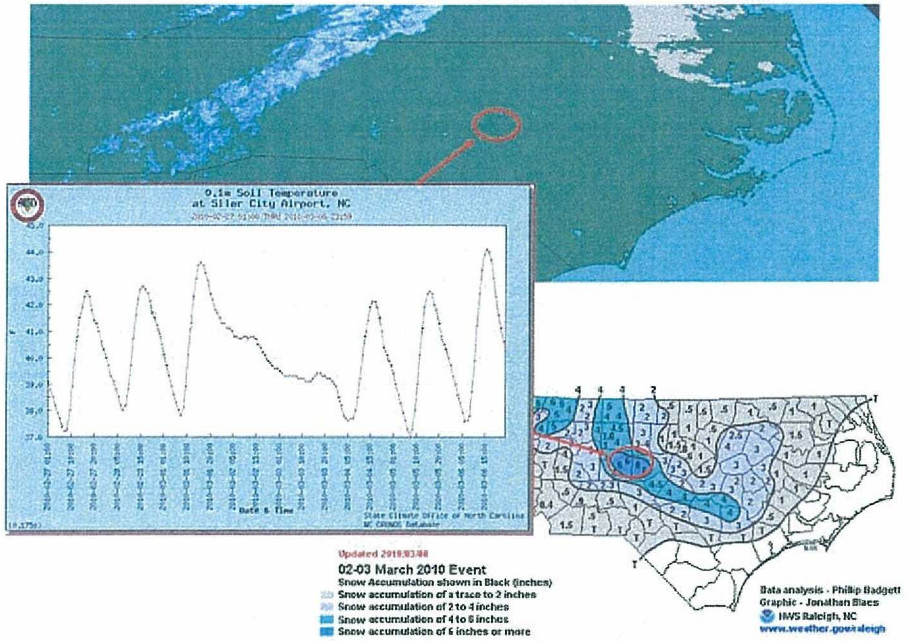

Figure 12: Plot of hourly soil temperature at the Siler City Airport ECONet station from 27 February to 6 March 2010.

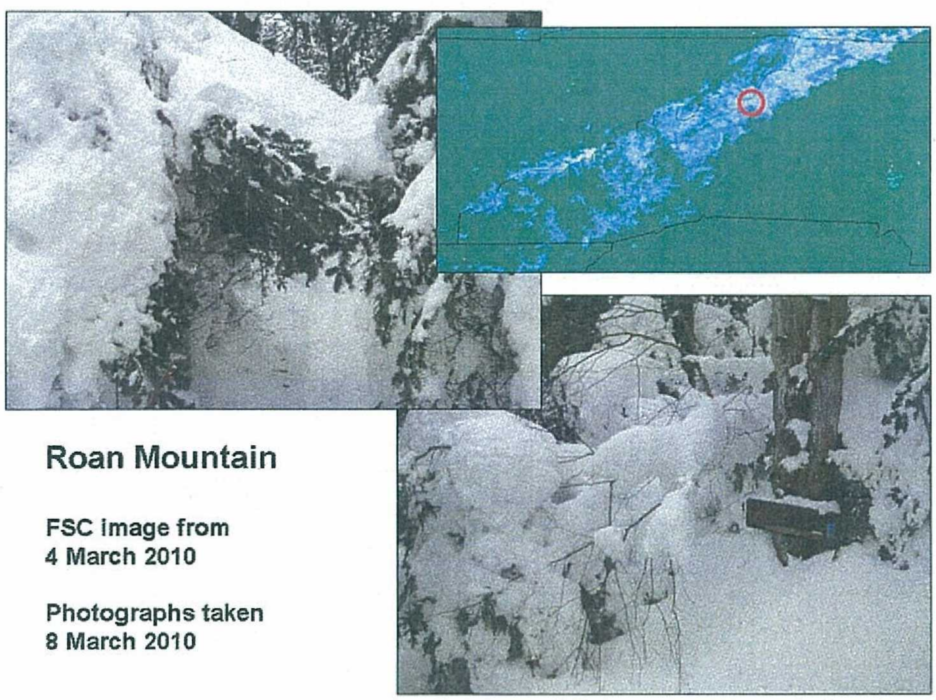

Figure 13: Photographs of snow cover on Roan Mountain taken on 8 March 2010.

DISCUSSION AND CONCLUSIONS

This paper assessed the spatial distribution of snow cover in North Carolina using both in situ data and the MODIS FSC product. Snow cover in North Carolina, particularly east of the mountains, is generally ephemeral in nature and this poses challenges in determining its spatial and temporal extent. This is compounded by the fact that snow depth measurements taken at COOP stations across the state are sparse, sometimes non-existent, and in the mountains are confined to lower elevations. Snow accumulation maps produced by the Raleigh NWS are useful in painting a broad picture of where the heaviest snow fell across the state during individual events. However, when these maps are analyzed in tandem with satellite snow cover imagery, a more complete picture of snow cover is revealed. For example, the MODIS FSC product revealed the presence of a snow shadow east of the Blue Ridge escarpment. This feature was not present in the corresponding NWS snow accumulation map. Snow shadows are not well-documented in the snowfall literature of the southern Appalachian Mountains and this may be due to the sparseness of observing stations on the ground. In some of the cases analyzed in this work, the FSC product revealed a significant reduction or lack of snow cover in these snow shadow regions. This has major implications in the forecasting of snowfall and snow accumulation in the lee of the mountains, particularly when the low-level flow turns north-northwesterly.

The snowfall climatology of the southern Appalachians is hindered by the lack of observations at the highest elevations. Statistical techniques and digital elevation models have been utilized to estimate snow accumulation at these points (Perry and Konrad, 2006), but the pattern and longevity of resulting snow cover at the higher elevations following an event remains unclear. This work reveals that the FSC product can possibly delineate snow cover along the ridge tops, but there may be confounding variables such as the presence of rime ice (which increases the surface brightness perceived by the satellite) and cloud cover (which obscures ground information). Surface vegetation and forest canopy are also important considerations when determining the extent of snow cover from the FSC product. In some cases, a low FSC may be perceived by the satellite due to the protrusion of the forest canopy when in fact nearly continuous snow cover is observed beneath the canopy (either through field work, visual observation, or analysis of soil conditions). In other cases, a high FSC may be perceived when the canopy is particularly dense (e.g., Roan Mountain) and a combination of snow and rime ice settles mostly on top of the canopy and not below.

The deployment of the North Carolina ECONet provides another potential proxy for snow cover across the state. Snow acts as an insulator and prevents the upper-most layer of soil from warming or cooling. Plots of hourly soil temperature at ECONet sites that receive measurable snow can therefore reveal when the snow cover has fully ablated and may be useful in validating various satellite snow cover products when snow depth information is unavailable or questionable. Soil moisture is also a useful parameter in determining the melt characteristics of a snow pack, though the relationship between FSC and soil moisture in the cases examined in this work are not entirely clear. In situations where the snow pack is rather deep (> 10 inches), increases in soil moisture may give forecasters and hydrologists a sense of how effectively the snow pack is ablating.

Numerous avenues for future work exist and they include a quantitative validation of the FSC product using all available and suitable ground observations, including COOP stations, soil parameters, and snow depth observations from the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) as well as an assessment of FSC in relation to land cover using the MODIS land cover products.

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