A Comparison of Satellite-Derived Snow Maps with a Focus on Ephemeral Snow in North Carolina

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ABSTRACT

In this paper, we focus on the attributes and limitations of four commonly-used daily snow-cover products with respect to their ability to map ephemeral snow in central and eastern North Carolina. We show that the Moderate-Resolution Imaging Spectroradiometer (MODIS) fractional snow-cover maps can delineate the snow-covered area very well through the use of a fully-automated algorithm, but suffer from the limitation that cloud cover precludes mapping some ephemeral snow. The semi-automated Interactive Multi-sensor Snow and ice mapping system (IMS) and Rutgers Global Snow Lab (GSL) snow maps are often able to capture ephemeral snow cover because ground-station data are employed to develop the snow maps. The Rutgers GSL maps are based on the IMS maps. Finally, the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) provides some good detail of snow-water equivalent especially in deeper snow, but may miss ephemeral snow cover because it is often very thin or wet; the AMSR-E maps also suffer from coarse spatial resolution. We conclude that the southeastern United States represents a good test region for validating the ability of satellite snow-cover maps to capture ephemeral snow cover.

Keywords: Snow cover, MODIS, AMSR-E, IMS, ephemeral snow

INTRODUCTION

The winter of 2009-10 was severe for the East Coast of the United States even as far south as the Carolinas (Fuhrmann et al., this volume; Perry et al., this volume). In fact it was the snowiest winter on record in Asheville, North Carolina. Large portions of the Coastal Plain, which typically have snow once every 2 to 3 years, recorded over 15 cm of snow for the season. While snow cover is quite common in the Appalachian Mountains in western North Carolina (Dobson, 2004; Perry et al., 2010), it is not a common occurrence in central and eastern North Carolina, and when it occurs it tends to be ephemeral, lasting a few hours to a few days.

Ephemeral snow and ice in North Carolina can have significant economic consequences (Fuhrmann et al., 2009) because many North Carolinians are not used to dealing with snow, and cities do not have the infrastructure and most likely have not set aside funds in their budgets for

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mitigation of the hazards that snow can create. And for remote sensing, detection of ephemeral snow can be an especially difficult problem. For one thing, validation is difficult. Two different snow maps, for example, might give different results for the same area on the same day, and they may both be correct if the snow was mapped at different times on the same day, if the snow cover only lasted for a few hours. Similarly, using meteorological stations for validation is problematic if snow is thin and/or patchy and thus the station reports do not accurately portray what satellite instruments measure. Also, most ground observations are made in the early morning, prior to satellite overpasses. In this work, we compare results from four readily-available snow products, with a focus on central and eastern North Carolina.

BACKGROUND

Study area. Figure 1 is a map showing the topography of some states in the southern United States, including North Carolina. Central North Carolina is characterized by mixed forest cover, while swamp and marshland predominate in eastern North Carolina. While mountains are found in western North Carolina, the topography is hilly in central North Carolina and relatively low and flat in eastern North Carolina.
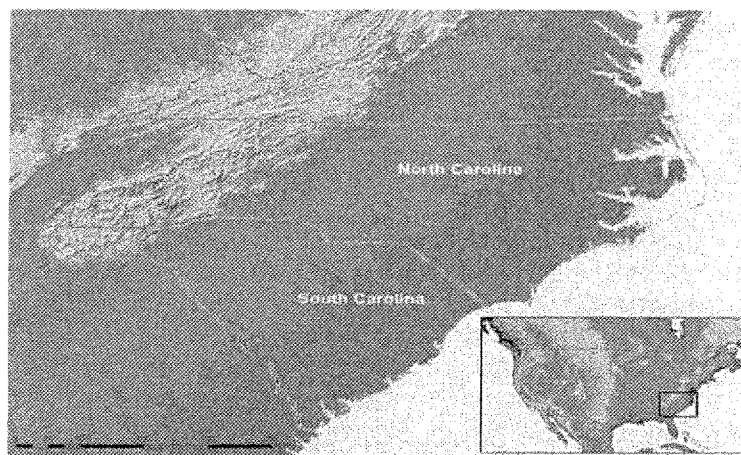

Figure 1: Location map showing North Carolina and other states in the southern United States; note the mountains in western North Carolina and the Coastal Plain in eastern North Carolina.

MODIS snow maps. The Moderate-Resolution Imaging Spectroradiometer (MODIS) was first launched on the Terra satellite in December 1999, and a second MODIS was launched on the Aqua satellite in May of 2002. The MODIS fractional snow-cover (FSC) product (Salomonson and Appel, 2004; Riggs et al., 2006; Hall and Riggs, 2007) represents one of many standard products, and is available to download from the National Snow and Ice Data Center (NSIDC). The daily, global FSC maps are available at a spatial resolution of up to 500 m, and the fully-automated snow-mapping algorithm continues to be improved (see, for example, Riggs et al., this volume). Details about the MODIS snow-cover products may be found at: http://modis-snow-ice.gsfc.nasa.gov/. The accuracy of the maps is ~93% (under cloud-free conditions) according to many studies that are summarized in Hall and Riggs (2007). The MODIS snow-cover products are used widely by modelers and others; examples of community use of the MODIS snow-cover products may be found at: http://modis-snow-ice.gsfc.nasa.gov/MODIS%20snow-ice%20papers.pdf.

The main limitation of the MODIS snow-cover products is the presence of cloud cover which obscures the view of the surface. To address this issue, we have developed a cloud gap-filled (CGF) product that is described in Hall et al. (2010). The CGF MODIS snow-cover product provides a cloud-free snow map each day. If the current day is cloudy, then the snow result from

the previous day is used; if that day was also cloudy then the snow result from two days prior to the current day is used, and so on. While this CGF product is useful during times of the year and at latitudes when the snowpack is not changing much, it is not a good choice for studying ephemeral snow.

AMSR-E snow maps. The Advanced Microwave Scanning Radiometer for EOS (AMSR-E) was launched on the Aqua satellite in May of 2002. One of the standard products developed from AMSR-E data, with heritage from the Scanning Mulitchannel Microwave / Imager (SSM/I), is snow-water equivalent (SWE) (Kelly et al., 2003; Chang et al., 2005; Foster et al., 2005; Kelly, 2009). The AMSR-E SWE product can provide an estimate of SWE and also maps snow cover, at a spatial resolution of 25 km.

IMS snow maps. The Interactive Multi-sensor Snow and ice mapping system (IMS) (Ramsay, 1998; Romanov et al., 2000; Helfrich et al., 2007) is an outgrowth of the original NOAA snow-cover product that began its production in 1966 (cf. Rutgers maps below). In June 1999, the IMS became operational (Ramsay, 1998). The IMS snow-cover product http://www.natice.noaa.gov/ims/ is currently produced operationally by analysts using data from several satellites, station data and other data sources at the National Ice Center (NIC) in Suitland, Maryland. The pre-IMS product was produced with a nominal spatial resolution of 190 km and a temporal resolution of seven days. NSIDC archives and distributes the 24-km and the 4-km IMS product from February 1997 to present and February 2004 to present, respectively http://nsidc.org/data/docs/noaa/g02156_ims_snow_ice_analysis/index.html.

Rutgers University Global Snow Lab snow maps. Since 1966, data from geostationary operational environmental satellites and data from the Very High Resolution Radiometer and its successor, the Advanced Very High Resolution Radiometer on polar orbiting environmental satellites have been used extensively by NOAA to produce operational snow products. Trained meteorologists map snow-cover extent from visual analyses of visible satellite imagery. Snow-cover identification is made by manual inspection of hardcopy imagery and graphics products, online imagery loops, and the previous day's and/or week's analysis. Map quality is predicated on the availability of clear-sky visible imagery and the meteorologist's experience.

The weekly NOAA snow-cover product, produced since 1966, has been continued in the IMS era by reducing the spatial resolution to that of the pre-IMS NOAA weekly map product (Robinson, 1993). Daily IMS maps are degraded to this resolution for use in a climate-data record (CDR) of Northern Hemisphere snow cover. The Rutgers Global Snow Lab (GSL) has recently generated a quality-controlled CDR from the NOAA operational maps, which include establishing consistency of base grid cells and treatment of mountainous areas throughout the satellite era [see http://climate.rutgers.edu/snowcover]. Though the IMS and Rutgers maps used in this study are from the same original IMS maps, there are differences between them in spatial resolution and with some of the base cells that were found to have been mapped inconsistently over time.

The Rutgers product is the IMS product with reduced resolution to match that of the pre-IMS weekly map product. Though they are not two distinctly different products, we show some Rutgers product results to demonstrate the detection of ephemeral snow cover in the Northern Hemisphere snow-cover CDR.

CASE STUDIES

Case Study: 12 – 14 February 2010. A weak area of low pressure tracked from the Gulf of Mexico to the Carolina coastline on 12-13 February 2010, producing accumulating snowfall

across nearly the entire state of North Carolina. Low-level northwest flow behind the storm system continued to produce orographic snowfall along the immediate Tennessee border through 14 February. The National Weather Service (NWS) snow analysis from 12-13 February, developed from Co-operative Observer station data, shows that snow cover was present across nearly the entire state of North Carolina by 13 February (Fig. 2), with the highest totals near the track of the surface low (>15 cm) in eastern North Carolina.
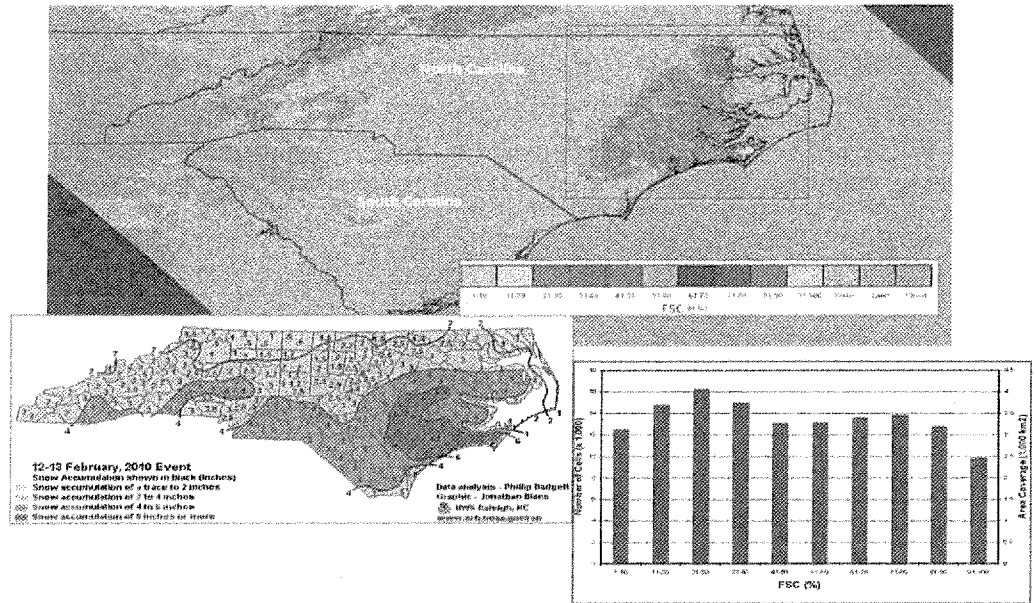
Figure 2: Moderate-Resolution Imaging Spectroradiometer (MODIS) fractional snow-cover (FSC) map, 14 February 2010 (top); National Weather Service (NWS) snow analysis for 12-13 February 2010 (left); histogram of snow cover within boxed area (see red box on FSC map) (right).
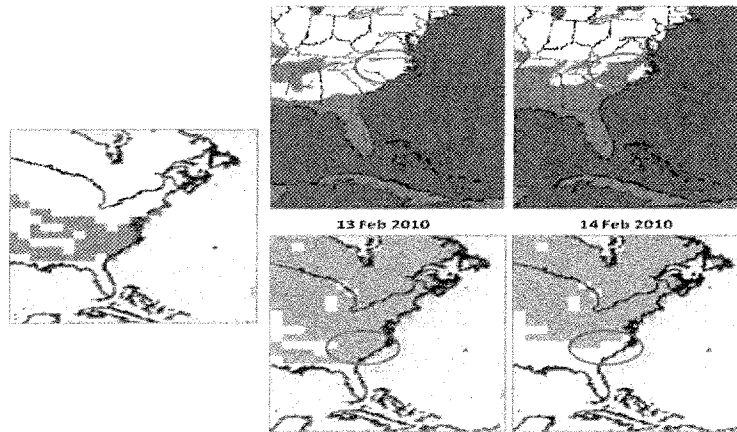

Figure 3: Interactive Multi-sensor Snow and ice mapping system (IMS) snow maps on 13 and 14 February 2010 (top); Rutgers Global Snow Lab (GSL) snow maps on 13 and 14 February 2010 (bottom); GSL daily departures map is generated based on 30-year means generated from the earlier weekly maps (blue signifies above average snow cover for 13 February) (left).

A cloud-free MODIS FSC map was acquired on 14 February 2010 (Fig. 2), but not on 12 and 13 February due to cloud cover. The histogram in Figure 2 shows that, though most of the MODIS snow-covered pixels (in the snow deposited on the Coastal Plain as seen within the red box in Fig. 2), show FSC of 40% or less, there are also a considerable number of pixels that show >40% FSC. The MODIS FSC maps are not able to capture the ephemeral snow in eastern North Carolina on 12 and 13 February due to cloud cover.

IMS maps from 13 and 14 February (Fig. 3 – top images) capture ephemeral snow cover even though it was cloudy on 13 February. The IMS uses station data and the stations reported snow on 13 February so the map captures that snow cover. Coarse-resolution CDR-quality Rutgers GSL maps (Fig. 3 bottom images), based on IMS maps, also capture the ephemeral nature of this snow event on 12 and 13 February. We also see the result of the Rutgers project wherein a daily departures map is generated based on 30-year means generated from the earlier weekly maps (blue signifies above average snow cover for 13 February) (Fig. 3, left image).
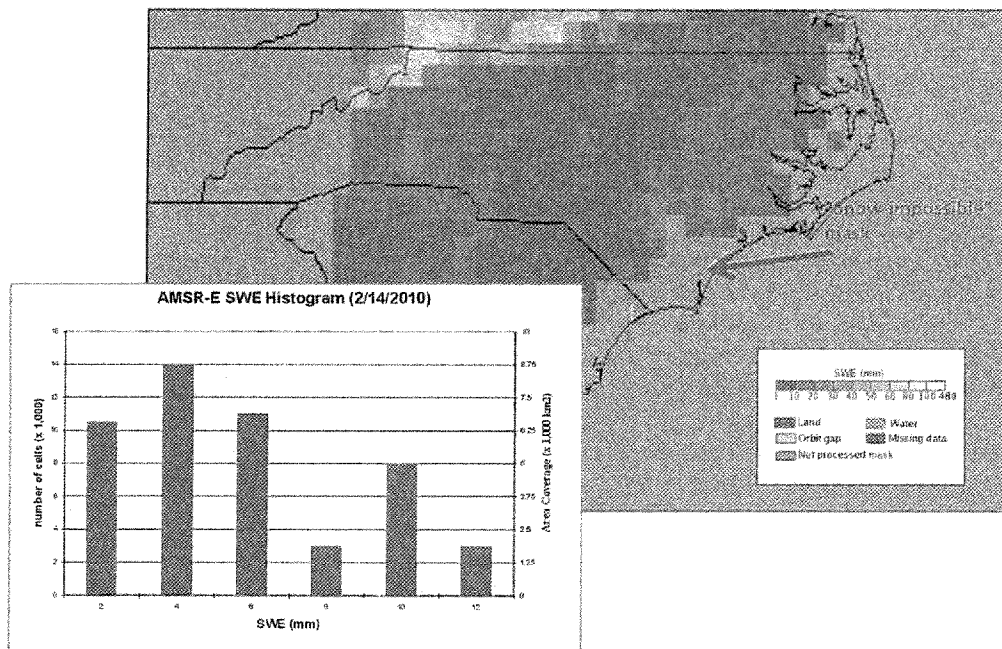

Figure 4: Advanced Microwave Scanning Radiometer for EOS (AMSR-E) snow-water equivalent (SWE) map for 14 February 2010 along with histogram developed from SWE data within same area as shown in the boxed area in Figure 2.

The AMSR-E SWE map provides good delineation of the snow on the ground on 14 February 2010 in central and eastern North Carolina. A histogram, developed from the same area that is found within the red box in Fig. 2, shows that all of the snow cover contains 12 mm or less of SWE. However some caveats are needed. Because of the coarse resolution of the AMSR-E product (25 X 25 km), there are often mixed-pixel effects near the coastline and near large lakes (Figure 5; see yellow oval near the coast). Also, the erroneous masking of snow cover along the coast by the "impossible snow" mask (see red arrow in Fig. 4) creates a problem in the southern part of coastal North Carolina. Snow is definitely possible along the southeast coast of North Carolina, and therefore the snow impossible mask should be adjusted in this region.
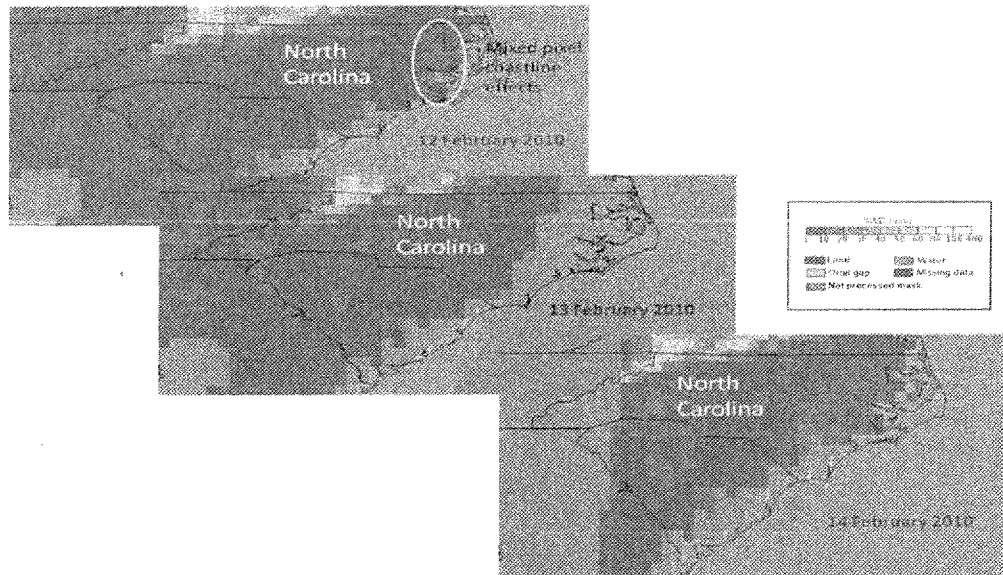
Figure 5: Advanced Microwave Scanning Radiometer for EOS (AMSR-E) snow-water equivalent (SWE) maps for 12, 13 and 14 February 2010.

AMSR-E SWE maps do not map snow in central and eastern North Carolina during the period of snowfall on 12 February 2010 (Fig. 5). An orbit gap occurred on 13 February, therefore no decision was made by the SWE algorithm on that day for areas within the orbit gap. The AMSR-E failed to map the thin snow cover in the central part of the state on 13 February and the snow in central North Carolina was gone by the next day, 14 February (Fig. 5). AMSR-E often fails to map thin snow because the thin snow is transparent to the microwave radiation emanating from the ground. In particular, the AMSR-E has difficulty mapping thin snow that lacks structure such as ice lenses and layers that attenuate the microwave signal.
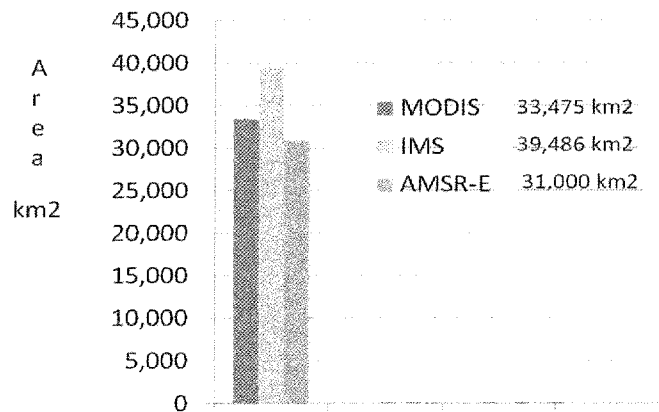

Figure 6: Graph showing snow-covered area measurement from within the boxed area of the MODIS, IMS and AMSR-E snow maps (see boxed area in Fig. 2), from different snow maps acquired on 14 February 2010.

Figure 6 is a graph showing the amount of snow mapped within the boxed area (see red box in Fig. 2) on each of the snow products, covering the snow on the ground on the coastal plain of North Carolina on 14 February 2010. MODIS FSC maps provide the most accurate snow-covered

area of the four maps mainly due to their high resolution (500 m) and also because fractions of pixels can be mapped rather than the entire pixel which is useful when the entire pixel is not snow covered. The IMS snow map appears to map too much snow, perhaps because of the somewhat higher (4 km) resolution as compared to MODIS (both the FSC map and the visible MODIS data (not shown), and because it is developed from a binary algorithm. The AMSR-E underestimates snow cover on 14 February 2010 because it does not detect thin snow, whether dry or wet, and there is no SWE decision being made by the AMSR-E algorithm within the area masked as "impossible snow."

In short, only the IMS (and GSL) snow maps were able to map the ephemeral snow that covered most of the state of North Carolina on 13 February 2010. The MODIS FSC maps do not capture the ephemeral snow on 12 and 13 February due to clouds, and the thin snow was not mapped by AMSR-E on 13 February. However the MODIS maps generally provide the most accurate snow-covered area measurement once the clouds have cleared.
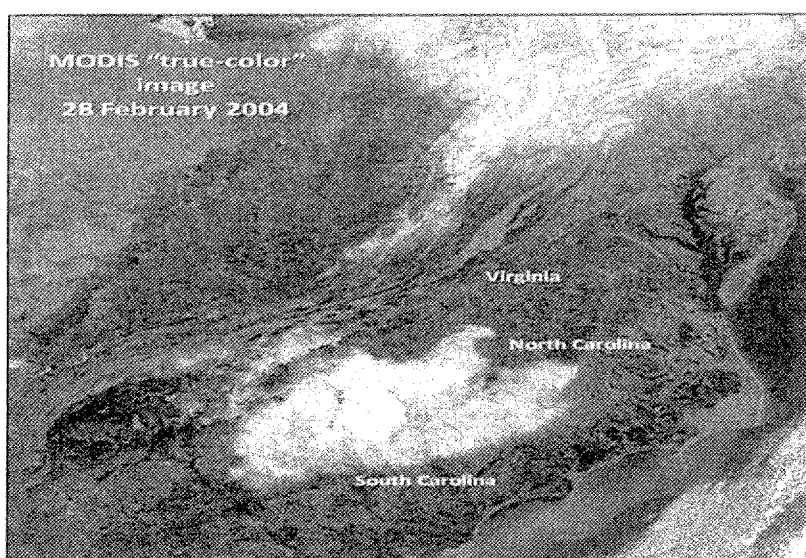

Figure 7: Moderate-Resolution Imaging Spectroradiometer (MODIS) true-color image showing snow on the ground in central North Carolina on 28 February 2004.
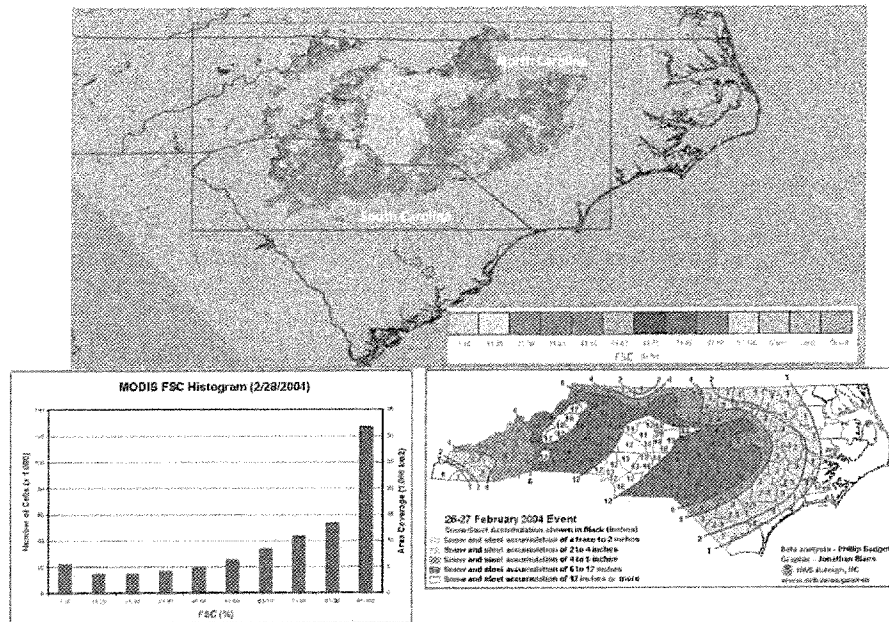
Figure 8: Moderate-Resolution Imaging Spectroradiometer (MODIS) fractional snow-cover (FSC) map, 28 February 2004 (top); National Weather Service (NWS) snow analysis for 12-13 February 2010 (right); histogram of snow cover within boxed area (left) (see red box on FSC map).

Case Study: 26 – 28 February 2004.   An area of low pressure that developed over the Gulf of Mexico and tracked along the Carolina coast also produced significant snowfall (nearly 50 cm) in portions of North Carolina on 26 – 27 February 2004.   A MODIS true-color image from 28 February 2004 depicts the result of this snowfall event very nicely (Fig. 7) -- note the significant snow cover present in central North Carolina.   The MODIS FSC map (Fig. 8) also captures the resulting snow cover very well (see snow cover within red boxed area in Fig. 8).   Note that the highest fractions of snow cover correspond to the areas of deepest snow according to the NWS snow analysis.   The histogram of FSC shown in Figure 8 reveals that most of the pixels have FSC in the range of 80 – 100% which is consistent with the area of deepest snow cover (up to ~48 cm).
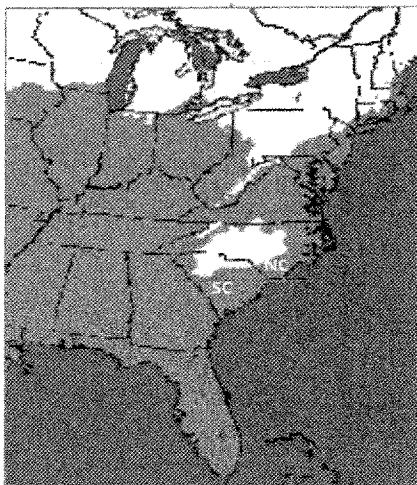

Figure 9: Interactive Multi-sensor Snow and ice mapping system (IMS) map showing snow cover in central North Carolina on 28 February 2004.

The IMS and AMSR-E also capture this event well (Figs. 9 and 10), but tend to overestimate the snow-covered area (SCA). IMS, with its 4-km pixel, may be overestimating SCA because each day's map is modified from the previous day and therefore sometimes "retains" too much snow from 27 February 2004. Also, if snow was mapped for the IMS product early in the day, it may differ, especially around the edges, from maps developed later in the day. AMSR-E, with its 25 km pixel, that registers either "snow" or "no snow," tends to map too much snow in this case because of its large pixel size.
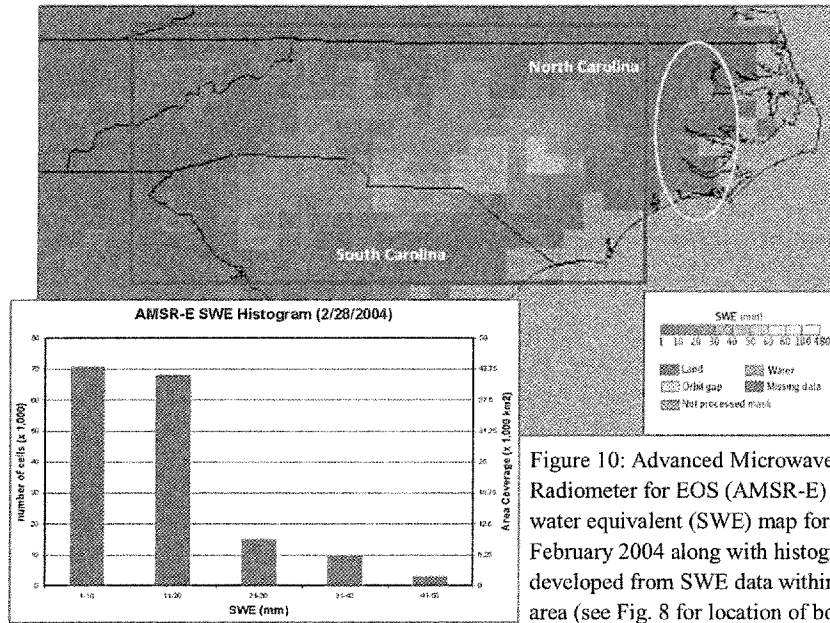

Figure 10: Advanced Microwave Scanning Radiometer for EOS (AMSR-E) snow-water equivalent (SWE) map for 28 February 2004 along with histogram developed from SWE data within boxed area (see Fig. 8 for location of boxed area).

The 28 February 2004 AMSR-E SWE map (Fig. 10) shows a good amount of detail in terms of SWE, both in the image and in the accompanying histogram. Though most of the SWE is <20 mm, the AMSR-E map detects the deeper, more-continuous snow with higher water content, and some SWE values are in the range of 41 – 50 mm (Fig. 10). The detail here is much greater than can be seen in the SWE map from 14 February 2010 (Fig. 4) because the 28 February 2004 snow cover was deeper and most likely had more structure within the snowpack, allowing for more microwave scattering within the snowpack.
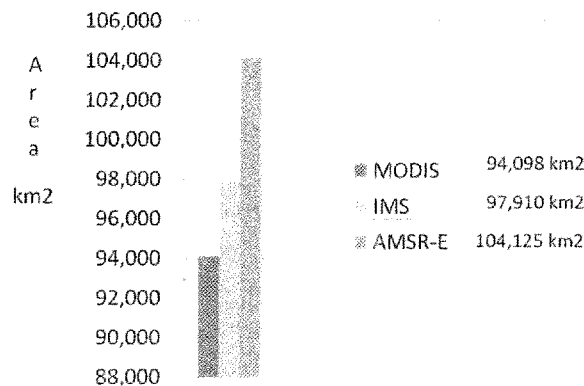

Figure 11: Graph showing snow-covered area measurement from within the boxed area of the MODIS, IMS and AMSR-E snow maps (see Fig. 8 for location of boxed area), from the snow maps of 28 February 2004.

The graph in Figure 11 shows that MODIS records the lowest amount of SCA (for the snow shown within the red boxed area seen in Fig. 8), followed by the IMS and the AMSR-E for the 28 February 2010 snow cover. In this case, since all of the maps are mapping the SCA quite well, the differences in areal extent are most likely related to resolution differences among the instruments.

Attributes and limitations of the snow maps. The AMSR-E algorithm experiences confusion due to mixed-pixel effects and can often erroneously map "snow" along the coastlines. To avoid some of this confusion along the coastal areas, an "impossible snow" mask was developed (see red arrow on Fig. 4). Thus a decision on snow cover is not made by the algorithm within this mask. AMSR-E is the only map that can provide an estimate of SWE, but it often misses shallow snow and its large footprint is not ideal for snow mapping, especially near the coast or near large lakes.

The MODIS FSC maps excel at mapping snow cover and provide good estimates of snow-cover fraction within each pixel. However, no MODIS snow maps are produced during cloudy conditions so this is the main limitation of the MODIS maps. The automated nature of the MODIS snow-cover maps has many advantages, but one disadvantage is that useful information, for example from meteorological-stations, cannot be included. This precludes MODIS from mapping ephemeral snow cover under cloudy conditions.

The IMS snow map does the best job for the 12 – 14 February 2010 event in terms of its ability to map the ephemeral snow that is present on 13 February. MODIS cannot map ephemeral snow when it is cloudy.

The Rutgers GSL maps are limited by their coarse resolution (128x128 grid size), but this is the only product that provides a long-term (44-year) record of Northern Hemisphere snow cover and is considered to be a CDR of Northern Hemisphere snow-cover extent. Because of its heritage from the IMS and predecessor NOAA snow products, it can capture widespread ephemeral snow events such as is seen in the 12 – 14 February 2010 snow event. Thus the snow-cover CDR includes ephemeral snow events.

CONCLUSION

Snowstorms that affect central and eastern North Carolina are not uncommon, with an average repeat of about one every 2 – 3 years. Typically the resulting snow cover is ephemeral but it can have significant economic consequences. Ephemeral snow also presents a number of challenges in the remote sensing of snow cover; it is difficult to validate and sometimes difficult to detect especially if it is thin. Therefore the southern United States is a good place to study the ability of various remote sensing instruments to map ephemeral snow cover.

We presented some attributes and limitations of four commonly-used snow-cover maps -- MODIS, AMSR-E, IMS and GSL - with respect to their ability to map ephemeral snow cover from winter storms in North Carolina. We found that the IMS product, because of its use of ground-station data, was able to accurately map ephemeral snow cover on 13 February 2010 while the MODIS was not (due to cloud cover). The AMSR-E SWE map had an orbit gap, so it is not known whether it would have mapped the ephemeral snow in central North Carolina on that day. The Rutgers GSL map for 13 February, based on the IMS, captured the ephemeral snow. Future work, focusing on the severe winter of 2009-10, is likely to reveal more information concerning the capability of: 1) the IMS to detect snow cover under cloudy conditions, and 2) the AMSR-E to map SWE through cloud cover in shallow or ephemeral snow.

This overview study has set the stage for future and associated work (see Fuhrmann et al., this volume and Perry et al., this volume) and we have identified some key issues to pursue. The

southern United States, and in particular North Carolina, is an excellent area for studying the ability of available snow maps to capture ephemeral snow-cover events.

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