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6.4 Northwest Flow Snow Aspects of Sandy. Part IV: Radar and Satellite Observations

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ABSTRACT

Cold air and moisture circulating around the western periphery of Hurricane and Post-tropical Storm Sandy contributed to a period of primarily northwest flow snow (NWFS) in the southern Appalachians during the last few days of October 2012. The NWFS phase of the event began on 29 October 2012 as a gradual increase in the coverage and intensity of radar echoes and an increase in the coverage of cloud top temperatures favorable for dendritic ice crystal growth were observed. The generally shallow nature of the precipitating clouds was revealed by vertically pointing radar at Poga Mountain, North Carolina. During the early stage of the NWFS phase, Morristown, Tennessee (KMRX), WSR-88D radar echoes with reflectivity greater than 20 dBZ showed a pronounced northeast to southwest movement atypical of NWFS events. Strong terrain-induced upward vertical motion and deep moisture were evident in a mountain wave signature in the reflectivity detected by the KMRX radar. As the NWFS phase matured, numerous wave-like features moving northeast to southwest also were noted in the reflectivity field. The widespread light precipitation on the windward side of the Appalachians provided for an interesting comparison of reflectivity values between the dual-polarized KMRX radar and the single-polarized WSR-88D radar at Jackson, Kentucky (KJKL). The slight reflectivity difference between the two radars possibly was caused by atmospheric propagation variability, frequency and calibration differences, or minor signal loss in the dual-polarized radar compared to the single polarized radar. Latter stages of the NWFS phase were dominated by a deep northwest flow after the middle part of the day on 30 October. Infrared satellite imagery showed a plume of clouds extending in an arc from Lake Michigan to the northern mountains of North Carolina coincident with a channel of weak surface-based buoyancy. However, the reflectivity pattern did not display a cellular structure often evident in more typical NWFS events with weak buoyancy during the daytime, which might have contributed to higher snowfall totals over a larger area.

1. Introduction

The following is part four of a four-part series in which aspects of the remnants of hurricane and post-tropical storm Sandy are investigated for a domain in the Southern Appalachian Mountains (SAMs), following Keighton et al. (2013), Miller et al. (2013), and Hotz et al. (2013). The purpose of the study is to highlight unusual aspects of the

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event as observed in radar and satellite imagery, during the time when a prolonged period of northwesterly flow in the lower troposphere combined with a deep layer of moisture to cause a significant accumulation of snow at elevations above approximately 900 meters above mean sea level (MSL) near the Tennessee – North Carolina border (Miller et al., 2013). The Northwest Flow Snow (NWFS) phase of the event began with an atypical radar echo movement, and as the event matured, radar detected the presence of a mountain wave to the lee of the SAMs. There also was evidence to suggest the passage of gravity waves on the west side of the SAMs. Vertically pointing research radar revealed the shallow nature of precipitation echoes. Adjacent WSR-88Ds afforded a comparison of reflectivity features detected by a dual- and single-polarized beam. Finally, a connection with the Great Lakes was observed toward the end of the event.

2. Data collection

Most of the radar data were obtained from the National Weather Service (NWS) WSR-88D radars located at Morristown, Tennessee (KMRX), and Jackson, Kentucky (KJKL) (Fig. 1). Data from other WSR-88Ds at Charleston, West Virginia (KRLX), Roanoke, Virginia (KFCX), and Greer, South Carolina (KGSP), as well as the Terminal Doppler Weather Radar near Charlotte, North Carolina (TCLT) were incorporated in mosaics. A vertically-pointing Micro-Rain radar (MRR) was located at Poga Mountain, North Carolina, at an elevation of 1140 meters MSL. An overview of terrain features in the SAMs region was given by Perry et al. (2013).

3. Analysis and discussion

The coverage and intensity of radar echoes on the KMRX radar increased steadily after approximately 1600 UTC on 29 October 2012, which heralded the start of the main NWFS production phase of the event. By this time, the center of Sandy had changed course and was moving west-northwestward toward New Jersey (Blake et al. 2012). The course change and the expansion of the circulation as the storm approached land allowed more moisture to advect southwestward at mid-levels (approximately 600 hPa to 400 hPa) during the afternoon of 29 October, providing more moisture for precipitation production.

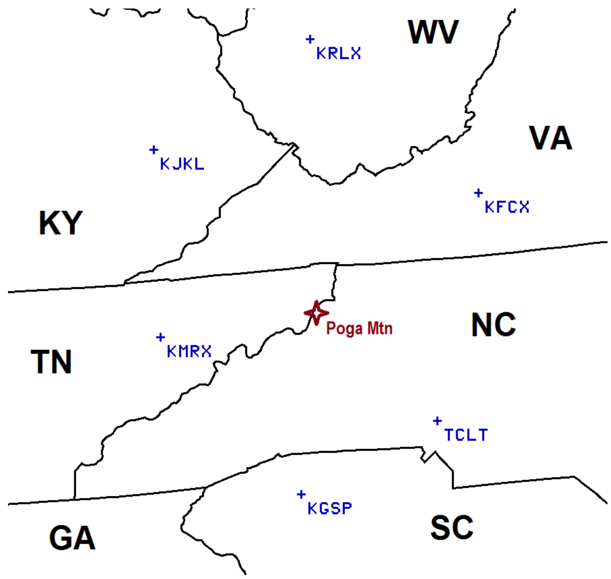

Figure 1. Locations of NWS WSR-88D radars pertinent to the Southern Appalachian Mountain region. The location of the vertically-pointing radar at Poga Mountain, North Carolina, is shown by the dark red star.

a. Unusual echo movement

The label "northwest flow snow" was somewhat of a misnomer for this event, at least at the beginning. Between 1600 UTC on 29 October and 0000 UTC on 30 October, the radar echoes with a reflectivity of greater than 20 dBZ as detected by the KMRX radar showed a pronounced north-northeast to south-southwest movement (Fig. 2). The unusual direction of motion might have been a result of the expansion of the precipitation shield as the center of Sandy moved northwest toward the coast of New Jersey. Another possible explanation was the mean wind in the cloud-bearing layer that contained a significant northerly to northeasterly component as the result of a shear axis on the outer edge of the circulation associated with Hurricane Sandy off the East Coast. The unusual motion could also be a manifestation of the "Atlantic connection" suggested by Hotz et al. (2013).

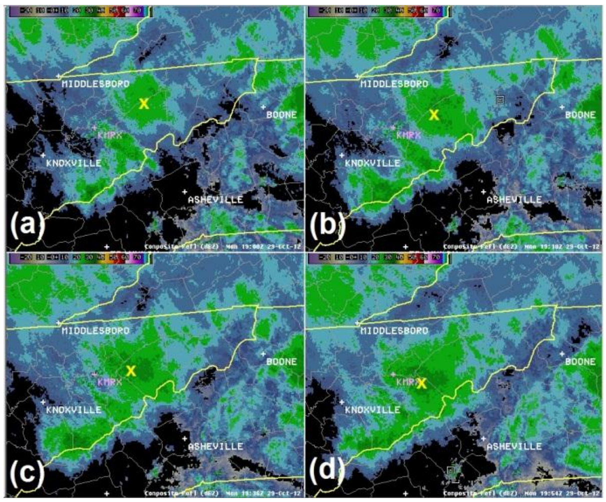

Figure 2. Composite radar reflectivity mosaic at (a) 1900 UTC, (b) 1918 UTC, (c) 1936 UTC, and (d) 1954 UTC on 29 October 2012. An area of higher reflectivity moving south southwest over northeastern Tennessee is marked with an 'x' for clarity.

b. Radar evidence of a mountain wave

Typical of most NWFS events, a mountain wave developed to the lee of the Appalachians by the early evening of 29 October. At 2300 UTC, the Rapid Refresh model (RAP) analysis at 850 hPa showed the northwest wind and an area of upward motion on the east side of the Blue Ridge (Fig. 3). A cross-section along a line A – A', from London, Kentucky (LOZ), to Columbia, South Carolina (CAE) showed the mountain wave in the lines of saturated equivalent potential temperature, and the upward motion (solid blue contours in Fig. 3b) on the lee side of the mountains slanted with height in the upwind direction. Of note was the relatively high humidity through 5 km in the region of upward motion in the mountain wave. Also note points B and C in the cross-section, which corresponded to linear features seen in the base reflectivity on the lowest two elevation scans from the KMRX radar at 2304 UTC (Fig. 4).

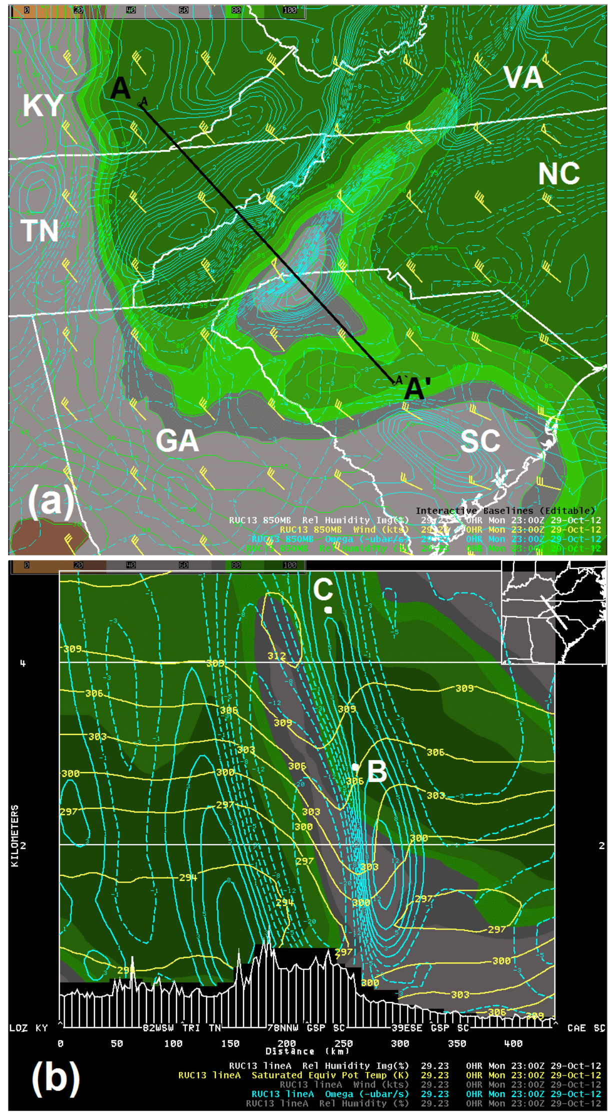

Figure 3. RAP initial hour analysis of (a) 850 hPa relative humidity (percent; green contours and color fill), vertical motion [blue contours, dashed (downward motion) and solid (upward motion)], and wind (yellow barbs), and (b) vertical cross-section of saturated equivalent potential temperature (Kelvins; yellow contours), vertical motion, and relative humidity at 2300 UTC on 29 October 2012. The line A-A' denotes the location of the vertical cross-section in (b).

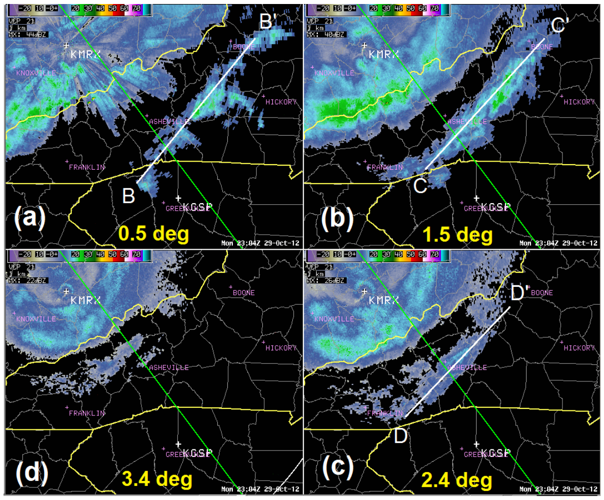

Figure 4. Base reflectivity from the KMRX radar at 2304 UTC on 29 October 2013 on the (a) 0.5 degree, (b) 1.5 degree, (c) 2.4 degree, and (d) 3.4 degree scans. The green line denotes the location of the vertical cross-section in Fig. 2. The lines B-B', C-C', and D-D' correspond to the mountain wave signature at that elevation. The intersections of lines B-B' and C-C' with the vertical cross-section are shown as points 'B' and 'C' in Fig. 2.

The reflectivity images clearly show the band of enhanced reflectivity oriented parallel to the mountain chain denoting the upward moving current in the lee side mountain wave, tilted in the upstream direction with height. The detection of the wave feature by radar was significant because it was indicative of the mechanical forcing provided by the strong northwesterly upslope flow at low- to mid-levels and the relatively deep moisture that could fuel the production of light snow over the western slopes of the mountains. The radar signature of the mountain wave on the KMRX radar persisted until the late afternoon of 30 October, but could be seen once again as it redeveloped during the early morning hours on 31 October.

c. Radar evidence of gravity waves

During the overnight hours of 29-30 October, some interesting wave-like features were seen on the KMRX and KJKL radar imagery, but were not detected in radar imagery east of the Appalachians. The wave forms propagated from the northeast toward the southwest and were evident on the 2.4 degree scans from KMRX at an elevation between 1 km and 4 km above MSL from approximately 0400 UTC to 0500 UTC on 30 October (Fig. 5). The cessation of these wave-like features corresponded roughly to the rapid backing of the flow from northeast to northwest in the layer from 500 hPa to 300 hPa in the 1400 UTC to 1700 UTC time frame seen on RAP initial hour soundings on 30 October (not shown).

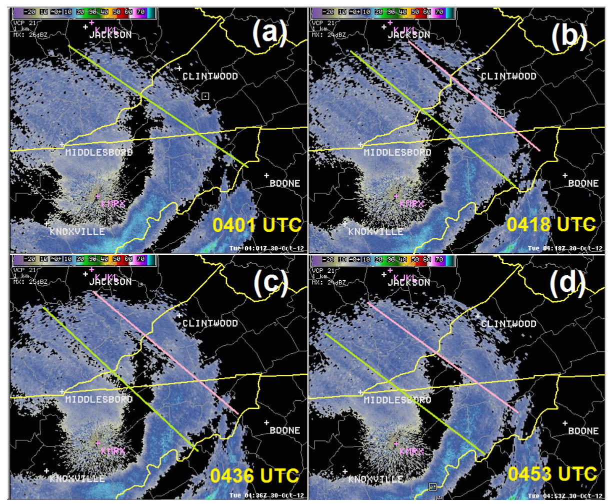

Figure 5. KMRX base reflectivity on the 2.4 degree elevation scan at (a) 0401 UTC, (b) 0418 UTC, (c) 0436 UTC, and (d) 0453 UTC on 30 October 2012. The first wave-like feature is shown by the green line and the second wave is shown by the pink line. The approximate height of the radar beam in the vicinity of the wave features is between 3 km and 4 km MSL.

One possible explanation for the wave-like features might be inertial gravity waves from Sandy. The RAP initial hour temperature and dewpoint profile at Jackson, Kentucky, at 0400 UTC on 30 October (Fig. 6) showed a stable layer through which waves could be ducted between roughly 850 hPa and 725 hPa. However, there does not appear to be a well-defined and deep conditionally unstable layer above the stable layer that would be needed to trap the waves. There might be a small layer between 500 hPa and 400 hPa that is conditionally unstable. Surface observations were not studied to see if there was evidence of inertial gravity waves in the sea level pressure. The nature of these waves remains a topic for further investigation.

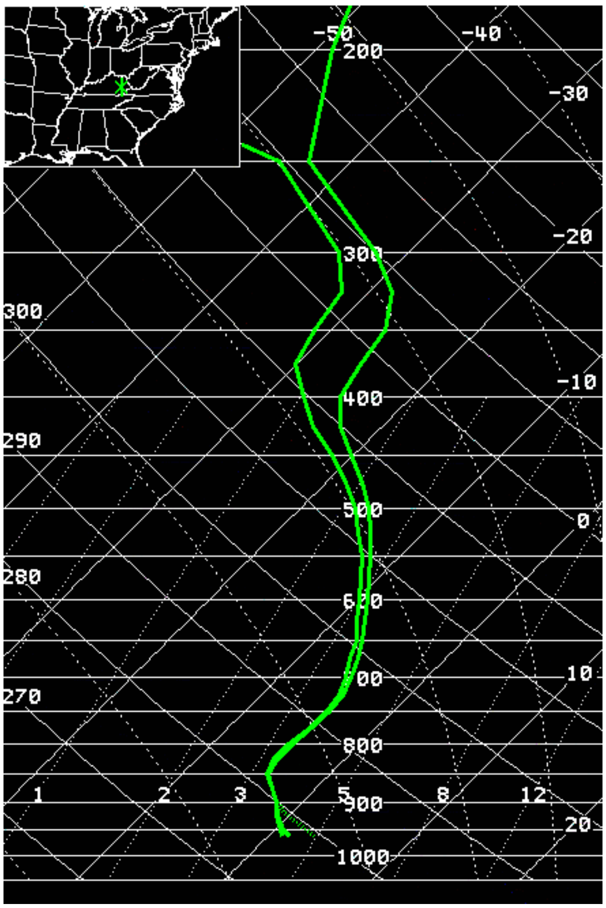

Figure 6. Skew-T log P diagram for RAP initial hour profile of temperature and dew point at 0400 UTC at Jackson, Kentucky.

d. Vertically pointing research radar

The MRR at Poga Mountain showed the main NWFS production ongoing at 2100 UTC on 29 October (data was missing between 1500 UTC and 2100 UTC), then continuing unabated through about 1200 UTC on 30 October (Fig. 7). Although the reflectivity during this event extended higher than that seen during the 27 February 2008 event (see Miller et al. 2013), it was still generally below 3 km MSL. Note the "burst" of precipitation on the reflectivity time series centered around 1000 UTC on 30 October. The fall velocity associated with this reflectivity showed a transition between values less than 2 m s^{-1} above 2 km MSL to values between 2 m s^{-1} and 4 m s^{-1} below this level. This might be due to falling ice crystals growing through riming and accretion as they fall through the very moist and cold layer closer to the ground.

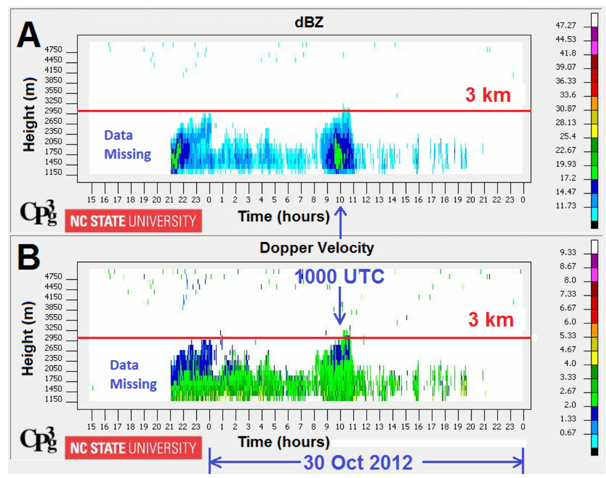

Figure 7. Time series of (A) reflectivity (dBZ) and (B) Doppler velocity (m s^{-1}) from the MRR at Poga Mountain, North Carolina. Time advances from left to right (1500 UTC, 29 October 2012 to 0000 UTC, 31 October 2012). Data are missing between 1800 and 2100 UTC on 29 October.

As for the issue of dry v. wet snow, the dual-polarization products from the 0.5 degree scans from the KMRX radar at 1001 UTC on 30 October were inconclusive around the Poga Mountain site. The differential reflectivity (ZDR) showed values ranging from 0.25 to 1 dB and was noisy, indicating that some wet snow might be present, as opposed to the uniform values closer to zero around Hot Springs, North Carolina, which indicated a dry snow (Fig. 8). However, the Correlation Coefficient values suggested a weak returned signal (not shown), probably because the radar was not effectively sampling the precipitation over that part of northwest North Carolina. The center of the radar beam from KMRX on the 0.5 degree elevation scan was approximately 2700 meters above MSL when it reached Poga Mountain and the precipitation could not be seen on the 1.5 degree scans. The radar beam was probably overshooting the shallow precipitation elsewhere across northwestern North Carolina, as it often does in NWFS events.

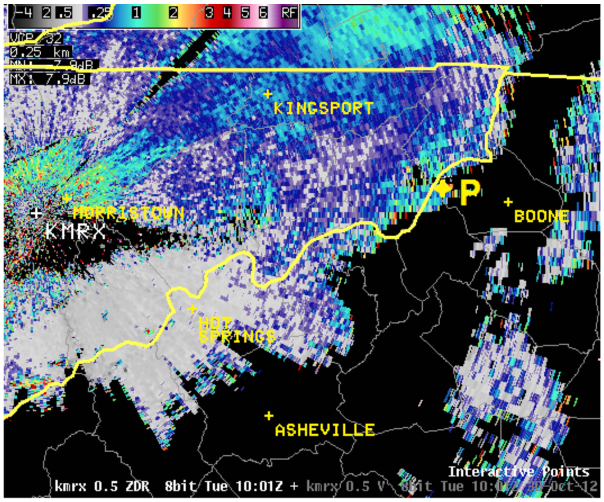

Figure 8. KMRX 0.5 degree scan of differential reflectivity (dB) at 1001 UTC on 30 October. The location labeled 'P' corresponds to the location of the Poga Mountain site.

e. Comparison of dual- and single-polarization radar data

The NWFS event on 30 October afforded a comparison between the reflectivity observed by a radar with a dual-polarized beam (KMRX) and one that had not yet been upgraded (KJKL, which at the time had a single-polarized beam). Pre-deployment testing of the dual polarization radars revealed a signal loss of approximately 3-4 dB compared to the single polarized radar in weak signal areas (Saxion et al. 2011). Scans from KMRX and KJKL at 1159 UTC on 30 October demonstrated a lower reflectivity detected by the dual-polarized KMRX radar. The center point of the radar beam on the 1.5 degree elevation scans from both radars passed through approximately the same location around 2850 m MSL in northwest Harlan County, Kentucky (Fig. 9). The dual-polarized KMRX radar detected a reflectivity of 19 dBZ while the single-polarized KJKL radar showed a reflectivity of 22 dBZ at the same approximate location. Other nearby range gates showed a similar reflectivity loss from KMRX. A definitive reason for the unequal values is not known. Contributions to the dBZ difference in this case possibly were due to atmospheric propagation variability or to frequency and calibration differences between the two radars (Ice et al. 2011).

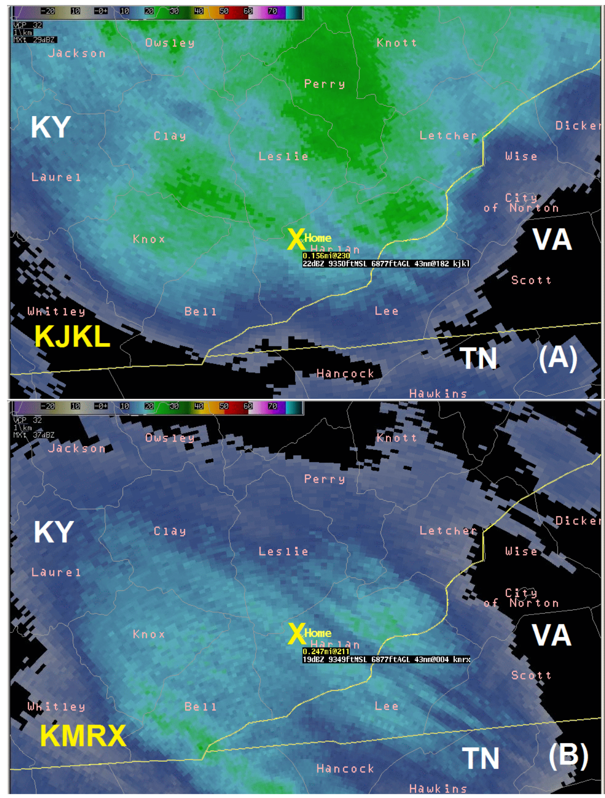

Figure 9. Base reflectivity on the 1.5 degree elevation scans from (A) the KJKL radar and (B) the KMRX radar at 1159 UTC on 30 October 2012. The location marked "X" corresponds to a point equidistant from both radars where the beam passes through, at approximately 2850 m MSL.

f. Great Lakes connection

The expanding shield of high cloudiness around the remnant circulation of Sandy made it difficult to discern the path of moisture moving toward the North Carolina Mountains at low and mid-levels. It was not until the remnant circulation turned northward on the morning of 30 October and the high clouds thinned that a plume of cloudiness and moisture was revealed in the infrared imagery curving northwest and north from northwest North Carolina to the vicinity of Lake Michigan (Fig. 10). The visible imagery continued to be masked by mid-level clouds. The RAP initial hour analysis at 1700 UTC on 30 October showed a channel of surface-based convective available potential energy (CAPE, on the order of 25 J kg^{-1} to 50 J kg^{-1}) that stretched from Lake Michigan to the northern mountains of North Carolina. This band of CAPE persisted from 1500 UTC to about 2300 UTC on 30 October. Wind streamlines in the 0-1 km layer also showed the flow moving down the long axis of Lake Michigan and curving southeasterly to northwest North Carolina. After 0000 UTC on 31 October, the RAP indicated that any connection to the Great Lakes would be directed toward West Virginia and southwest Virginia. Backward air parcel trajectories calculated from the NOAA HYSPLIT model (Draxler and Rolph 2013; Rolph 2013) for the 48 hour period leading up to 1800 UTC on 30 October also showed the flow at 100 m, 500 m, and 1000 m AGL could be traced to the area around Lake Michigan (Fig. 11).

In spite of the low level connection to Lake Michigan and the trajectory of air parcels across a region with weak surface-based buoyancy, the precipitation failed to organize into cells and lines as observed in other NWFS events in the presence of weak CAPE during daylight hours (Fig. 12). At 1700 UTC on 30 October, a large mass of light precipitation was observed over northeast Tennessee and eastern Kentucky with a stratiform appearance. In contrast, the precipitation elements in the 27 February 2008 NWFS case became loosely organized into cells and lines during the time of peak heating (Fig. 13), while satellite imagery (not shown) gave the appearance of open cell convection over northeast Tennessee.

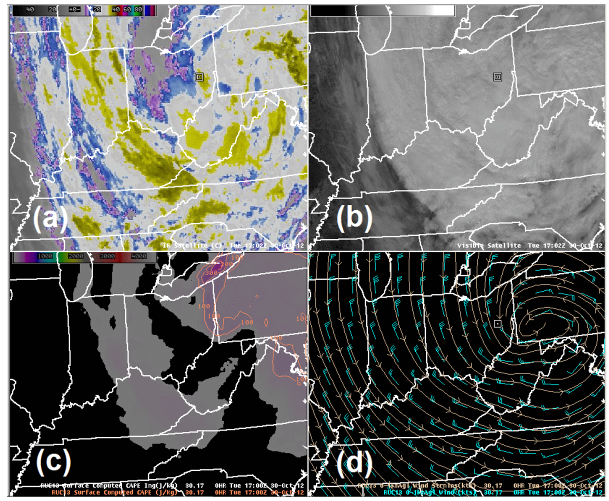

Figure 10. GOES-13 satellite imagery in the (a) IR window and (b) visible window, along with RAP initial analysis of (c) surface based CAPE (J kg^{-1}; orange contours and color fill) and (d) wind (kt; barbs and streamlines) in the 0-1 km layer at 1700 UTC on 30 October 2012.

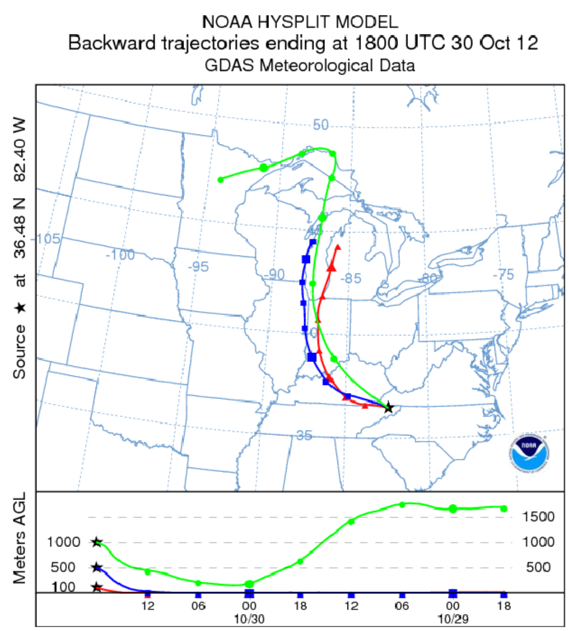

Figure 11. Backward air parcel trajectories at the Tri-Cities airport, Tennessee, from the NOAA HYSPLIT model at 100 m (red line), 500 m (blue line), and 1000 m (green line) for the 48 hour period ending at 1800 UTC on 30 October 2012.

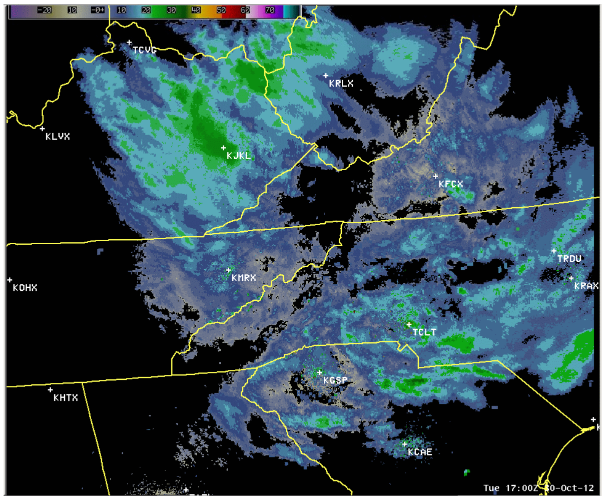

Figure 12. Composite reflectivity mosaic at 1700 UTC on 30 October 2012.

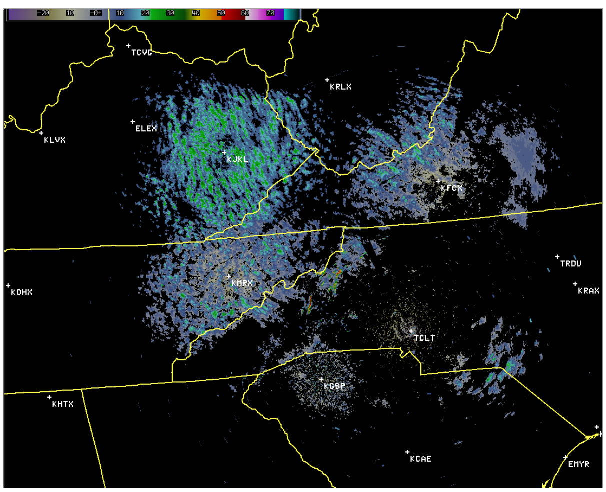

Figure 13. Composite reflectivity mosaic at 1700 UTC on 27 February 2008.

4. Conclusions

An image from the Moderate Resolution Imaging Spectroradiometer (MODIS) on the Aqua satellite, taken about 24 hours after the end of snow production, revealed the dependence of the snow cover on elevation (Fig. 14). Snow accumulation was limited to elevations above at least 900 meters (about 3000 feet) above MSL mainly along the Tennessee border and over the Black Mountains of North Carolina.

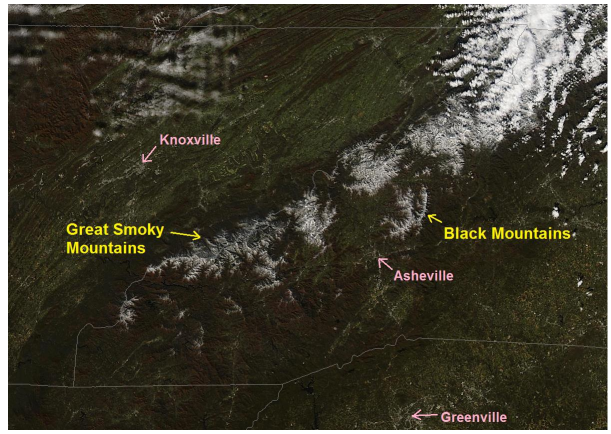

Figure 14. NASA Aqua MODIS image at 1850 UTC on 1 November 2012.

Some of the more unusual aspects of the Sandy event, compared to the typical NWFS event, were manifest in radar observations. The anomalous northeast to southwest motion of radar echoes above 20 dBZ early in the event was evidence of an "Atlantic connection" (Hotz et al. 2013). The deep moisture allowed a mountain wave to the lee of the Appalachians to be revealed in the KMRX radar imagery as hydrometeors grew to a detectable size in the upward-directed part of the wave. A train of wave-like features was observed moving through the radar imagery at KMRX and KJKL during the main NWFS production phase. The nature of the waves and their cause remains an area for further study. Vertically-pointing radar at Poga Mountain, North Carolina, demonstrated the shallow nature of radar echoes during the event and suggested ice crystal growth through riming and accretion. A comparison of reflectivity detected by dual- and single-polarized beams from adjacent radars resulted in a 3 dBZ difference. The difference can be attributed to some combination of atmospheric propagation variability, frequency and calibration differences, and possibly a slight signal loss in the dual-polarized radar. A connection to the Great Lakes suggested by backward air parcel trajectories was inferred by satellite imagery late in the event. Finally, although weak surface-based buoyancy was expected, the radar echoes did not reorganize into cells and lines during the time of peak heating, as is often the case in NWFS events.

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