5.9 OVERVIEW OF 2 DIFFICULT FORECAST SCENARIOS FOR THE MIDATLANTIC U.S. DURING THE 2000-2001 WINTER SEASON - LESSONS FROM DATA ANALYSIS

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1. INTRODUCTION

Numerous storms with accumulating snow, sleet and freezing rain, affected the mid-Atlantic U.S during the winter of 2000-2001, providing many challenges to forecasters in the region. Defining areas where accumulating snow was expected and determining snow amounts was a very difficult task.

On 2-3 December 2000 (event 1, henceforth) and 29-30 December 2000 (event 2, henceforth), significant snow (>4 inches) was forecast for the mid-Atlantic U.S. However, the snow occurred >100 km east of where the National Weather Service Offices in Virginia and North Carolina were forecasting it.

The positions and characteristics of mid to upper-level (600-200 hPa) ridges, troughs, and jet streaks, caused an eastward shift in low-level (surface to 700 hPa) temperature advection, moisture advection, and upward vertical motion. Careful analysis of satellite data, upper air data, thermodynamic profiles, surface observations, and trends observed from these data sources, provided critical information for improving the forecast. A significant eastward adjustment (>100 km) to areas of forecasted snowfall was possible, at least 12 hours in advance of the predicted onset.

2. SATELLITE AND UPPER AIR ANALYSES OF EVENT 1

Prior to event 1, at 1200 UTC 2 December, water vapor imagery (6.7μm) depicted an upper-level low (600-200 hPa) centered in the northern plains and an upper level ridge to the north, with its axis through southern and central Canada. Based on a loop of the water vapor imagery, these two features were moving east-southeast toward the Tennessee and Ohio Valleys. The upper low was also "positively tilted", with its axis oriented southwest to northeast. Infrared satellite pictures at 1200 UTC 2 December depicted a concentrated area of cloudiness associated with the center of the upper low. The upper low was not interacting with tropical moisture seen off Florida and in the Carribean Sea, nor the Pacific moisture advecting into the southern U.S. Additionally, the northern stream portion of the upper ridge in southeastern Canada was building southeast, toward the Great lakes and Ohio Valley.

Through 2 December and into the morning hours of 3 December, the upper low continued to track southeast, while a strong upper level jet streak (seen in 0000 UTC 3 December water vapor imagery) tracked almost due east toward the Carolinas (Fig. 1). Water vapor imagery showed subsidence and a strengthening upper jet streak south of the upper low (Bader et al. 1995). This upper jet streak was confirmed in the 0000 UTC 3 December 300-hPa analysis (Fig. 2). There was limited enhanced cloud cover (infrared imagery not shown) associated with the upper low, as the northern extent of the deep cloud cover was from the Ohio Valley to southern Virginia. This implied limited moisture for widespread heavy precipitation.

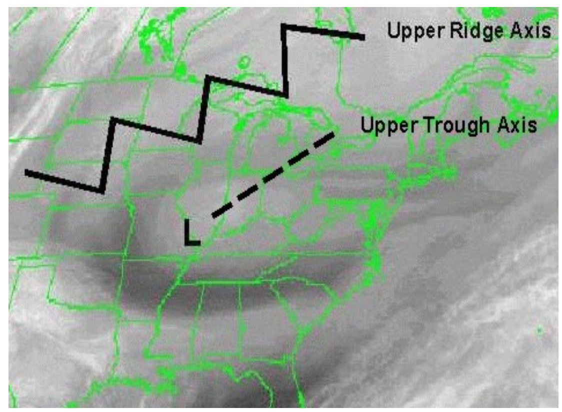

Figure 1. 0000 UTC 03 December 2000 GOES-8 Water Vapor Imagery (6.7μm).

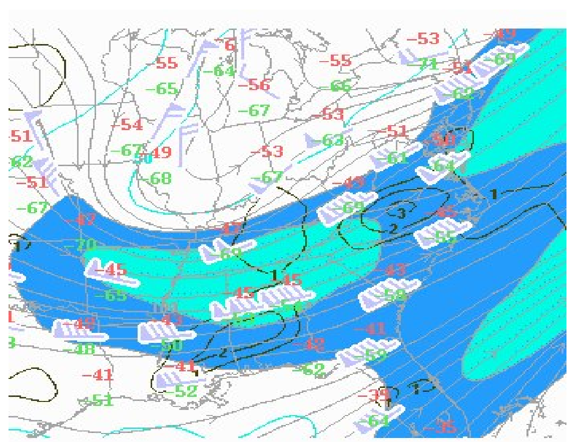

Figure 2. 0000 UTC 03 December 300-hPa upper plot with wind barbs (knots), heights (solid) and divergence (black solid).

By 1200 UTC 3 December, the upper low was centered in eastern Tennessee and Kentucky, with

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another upper level jet streak denoted by an area of subsidence, tracking into the Tennessee Valley in the southwestern quadrant of the upper low. This second upper impulse was evident in the wind field of the 1200 UTC 3 December 500-hPa analysis (Fig. 3). Low-level cyclogenesis had begun along the Carolina coast (cold air cyclogenesis), denoted by the wedge-shaped cloud feature in southwestern Virginia (Fig. 4), between the upper low and the leaf cloud structure along the Carolina coast (Bader et al. 1995).

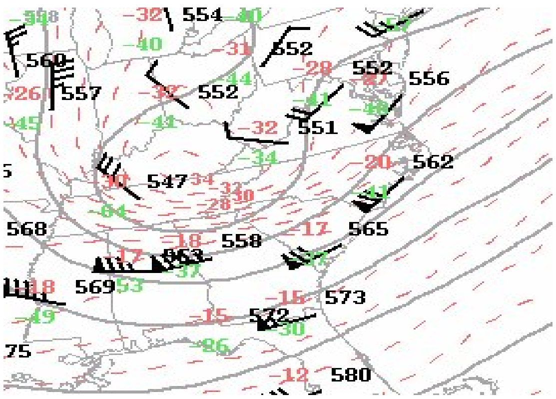

Figure 3. 1200 UTC 03 December 500-hPa upper plot with wind barbs (knots), heights (solid) and temperature (dashed).

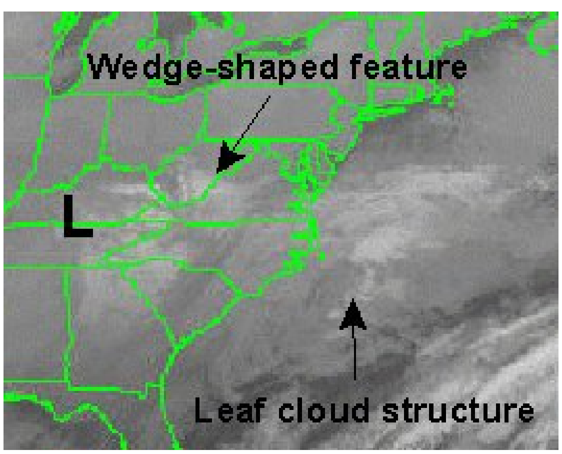

Figure 4. 1200 UTC 03 December 2000 GOES-8 Infrared Imagery.

Through 0000 UTC 4 December, the upper low tracked southeast through the Carolinas, and the northern extent of the deep cloudiness was through the Carolinas into southeastern Virginia. The wind flow in the southern semicircle of the upper low was west to east from 2 December through 3 December. The due west winds in the upper jet streak limited the northward thermal and low-level moisture advection associated with the indirect thermal circulation (Uccellini and Kocin 1987), as no moisture from the Gulf of Mexico was entrained into the system. The sharp northern edge of the thermal and moisture advection through northeast North Carolina was evident in the 1200 UTC 3 December 850-hPa analysis (Fig. 5), as Wallops Island, Virginia (WAL) observed a northeast wind and Morehead City, North Carolina (MHX) observed a southeast wind. Hence, the moisture at and above the boundary layer, represented by cloud cover in infrared imagery, extended no farther north than extreme southeast Virginia.

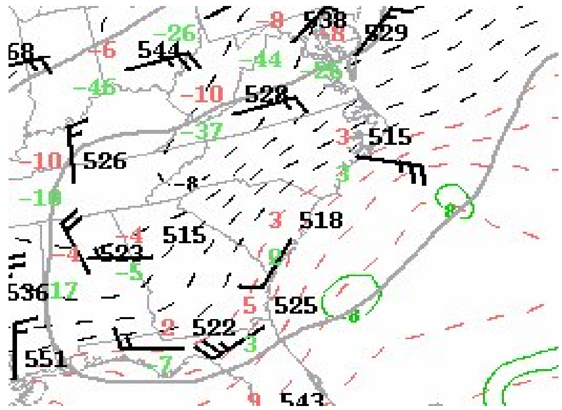

Figure 5. 1200 UTC 03 December 850-hPa upper plot with wind barbs (knots), heights (solid) and temperature (dashed).

3. THERMODYNAMIC PROFILES AND SURFACE OBSERVATION TRENDS

At 0000 UTC 3 December, directional cold temperature advection (backing with height) was occurring below 700-hPa at the Dulles Airport, Virginia (IAD) and Wallops Island, Virginia (WAL) upper air stations. However, warm advection was occurring at Morehead City, North Carolina (MHX). Surface temperatures and dew points in northern and central Virginia fell steadily between 0000 UTC and 1200 UTC 3 December.

Surface high pressure, centered in the midwestern U.S., built east of the Appalachian Mountains, then built south into the mid-Atlantic U.S. (Fig. 6). This evolution of the surface high pressure was in response to a combination of the direct thermal circulation associated with an exiting 500 to 300-hPa jet streak off New England (Uccellini and Kocin, 1987), and the increasing 500 to 300-hPa confluence in southeastern Canada (Bluestein, 1993), due to the east and southeast movement of the northern stream portion of the 500 to 300-hPa upper ridge.

At 1200 UTC, the IAD and WAL thermodynamic profiles indicated continued deep drying, with low-level winds from the northeast, and dew point depressions >15°C through most of the atmosphere between the surface and 300-hPa. The 1200 UTC Roanoke, Virginia (RNK) thermodynamic profile depicted a near-saturated atmosphere below 500-hPa, except for a dry layer at 850-hPa (Fig.7).

However, the wind flow between 500 and 700-hPa was negligible, and from the east below 700-hPa, indicating negligible eastward moisture advection between 500 and 700-hPa, and low-level drying below 700-hPa, based on the WAL and IAD thermodynamic profiles.

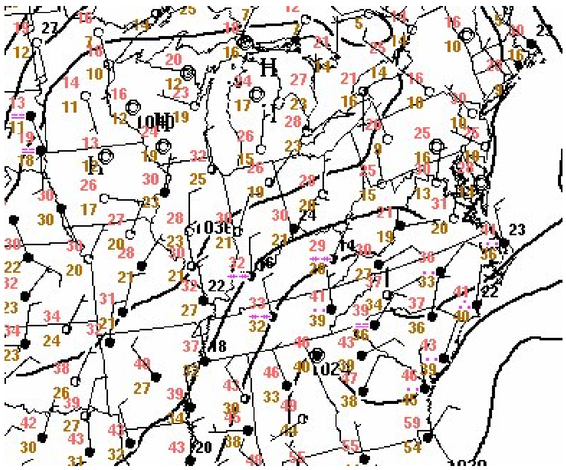

Figure 6. 0000 UTC 03 December plot of mean sea level pressure with isobars (solid), temperatures and dewpoints.

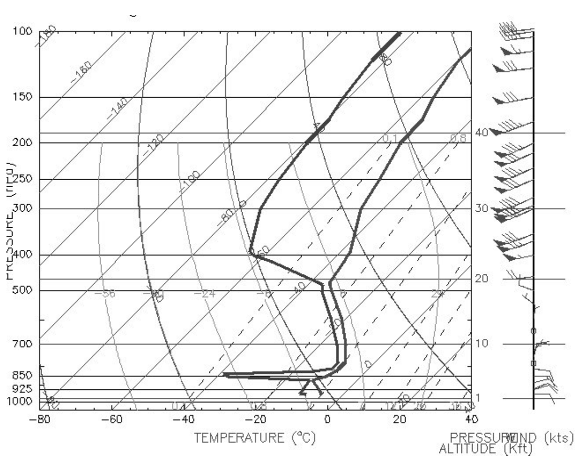

Figure 7. 1200 UTC 03 December 2000 thermodynamic profile from Roanoke, Virginia (ROA).

4. FORECAST SEQUENCE PRIOR TO EVENT 1

The possibility of significant snow was highlighted in the public forecasts during the afternoon of 1 December. Winter Storm Watches highlighting the potential for >4" of snow were issued for the southern half of the county warning area (CWA) for the National Weather Service Forecast Office (WFO) in Wakefield, Virginia (AKQ) during the early morning hours of 2 December. The Winter Storm Watch included the Richmond and Norfolk Metropolitan areas, southward through North Carolina into the WFO Raleigh, North Carolina (RAH) and WFO Morehead City, North Carolina (MHX) CWA. During the afternoon of 2 December, Winter Storm Warnings were issued in areas of southern Virginia around South Hill and Emporia, and for all of northeast North Carolina. A Winter Storm Watch remained in effect for central and southern Virginia, including the Tri Cities, and inland Hampton Roads.

The forecast was significantly modified during the early morning hours of 3 December, as Winter Storm Warnings in Virginia were shifted to Hampton Roads and Winter Weather Advisories (for <4" of snow) were issued for the remaining southern Virginia counties along the state border. This forecast remained unchanged through the event on 3 December.

5. FORECAST LESSONS LEARNED FROM EVENT 1

The heaviest snow fell in eastern North Carolina, where over 12" was observed. The northern edge of the accumulating snow shield was extremely sharp. Snow amounts in southeastern Virginia ranged from just a dusting to over 10" within a 30 mile distance to the state border (Fig. 8).

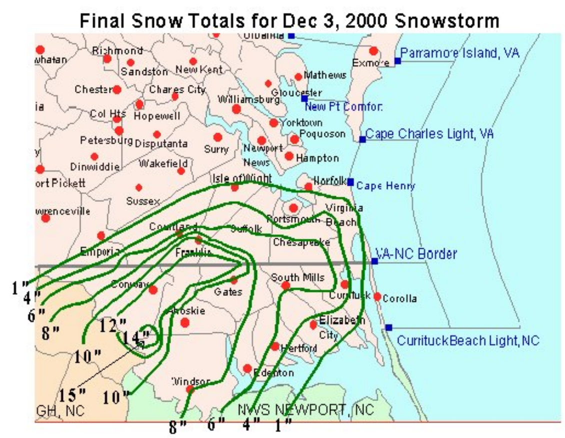

Figure 8. Final snow totals for the 3 December 2000 snowstorm.

The path of the upper low, from the Great Lakes to the mid-Atlantic U.S. limited the available moisture from the Gulf of Mexico and Atlantic Ocean. Based on climatology, upper low pressure tracking southeast out of the Great Lakes rarely produces widespread heavy snow in the Carolinas and Virginia (Albright and Cobb, 1996), unless it tracks through the Carolinas, as shown from event 1. The upper deformation zone, in combination with Atlantic moisture, produced the heavy snow in extreme eastern North Carolina.

The west/east-oriented jet streaks within the southern semicircle of the upper low limited the low-level thermal and moisture advection, as no moisture from the Gulf of Mexico was entrained into the system. Northern stream upper impulses must track south of the Tennessee Valley to interact with Gulf of Mexico moisture to increase the chances for significant precipitation in these areas, as shown from event 1.

The progressive northern stream upper ridge provided enhanced upper confluence in southeastern Canada, resulting in deeper cold advection and deep layer drying into Virginia. One final lesson from event 1 is that evolution of the upper and surface ridges are often overlooked, and must be evaluated for consideration of low-level cooling and drying, which can significantly reduce snow amounts.

6. SATELLITE AND UPPER AIR ANALYSES OF EVENT 2

Prior to event 2, at 1200 UTC 28 December, water vapor imagery depicted a strong upper low in the U.S. northern plains, tracking southeast toward the Great Lakes and Ohio Valley. A strong southern stream upper impulse tracked rapidly east, along the northern Gulf of Mexico on 28-29 December, illustrating the strong deep westward upper flow in the southern stream. There was also an upper impulse that was tracking southeast within the flow around the northern plains upper low. This impulse played a critical role in the evolution of event 2. By 1200 UTC 29 December, the southern stream upper impulse was exiting offshore, but an axis of strong subsidence associated with an extensive, strong westerly upper jet was present. Additionally, a 300-hPa jet segment was tracking southeast out of the northern plains.

The northern stream upper impulse and 300-hPa jet streak tracked east through the Tennessee Valley through 29 December, and the upper low did not push any further south (Figs. 9 and 10). The 500-hPa upper ridge in the western U.S. was slowly deamplifying through 0000 UTC 30 December, also suggesting less southward momentum to the northern plains upper low, as there was less of an upstream northerly component to the upper winds. An 850-hPa low pressure center began to develop by 0000 UTC 30 December over the

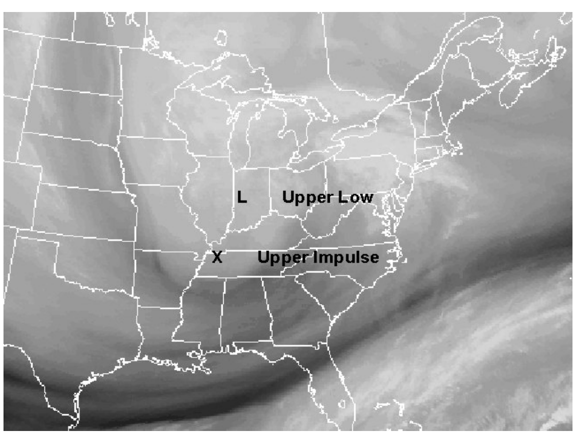

Figure 9. 0000 UTC 30 December 2000 GOES-8 Water Vapor Imagery (6.7µm).

interior southeast U.S., in response to the low level convergence and strengthening 850- hPa jet, associated with the thermally indirect circulation at the left exit region of the upper jet streak (Uccellini and Kocin 1987).

The well-defined northern stream 500 to 300-hPa impulse tracked from the Tennessee valley to the mid-Atlantic U.S. by 1200 UTC 30 December. The associated thermal and moisture advection and convergence supported rapid low-level cyclogenesis off the mid-Atlantic coast through 30 December.

7. THERMODYNAMIC PROFILES AND SURFACE OBSERVATION TRENDS

Thermodynamic profiles from northern Georgia through the Carolinas to eastern Virginia, showed a deep dry layer, and cold advection below 700-hPa, from 1200 UTC 28 December, through 1200 UTC 30 December. Some of the drying and cold advection was associated with the exiting 500-hPa impulse that tracked offshore the southeastern U.S. The thermodynamic profiles also illustrated the deep west flow above 500-hPa over the southeastern U.S., similar to event 1.

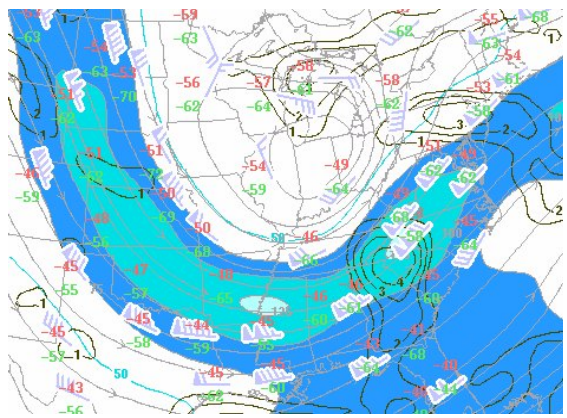

Figure 10. 0000 UTC 30 December 300-hPa upper plot with wind barbs (knots), isotachs (shaded), heights (solid) and divergence (solid black).

At 0000 UTC 30 December, a trough of low pressure was depicted in the 850-hPa analysis, seen in the wind field over the Carolinas. (Fig. 11). Development of the surface and 850-hPa low pressure did not occur until after 0000 UTC 30 December, but when it did, it occurred along the mid-Atlantic coast. Convection formed offshore North Carolina and Virginia by 0600 UTC 30 December, in response to strong low level thermal and moisture advection, convergence associated with the left exit region of the upper jet over the Carolinas and low level instability, created by relatively warm ocean temperatures (around 7°C near shore to >15°C offshore). The enhanced vertical motions in the convection aided in the development of the surface low well east of the DELMARVA between 0600-1200 UTC 30 December (Bluestein 1993).

Low level winds turned to the south and

southwest by 0000 UTC 30 December at WAL, MHX and GSO, but there was very little moisture available to advect north along the coast. Most of the deep moisture was being directed offshore, as seen in satellite and radar imagery.

8. FORECAST SEQUENCE PRIOR TO EVENT 2

Winter Storm Watches, highlighting the potential for >4" of snow were issued late on 28 December for areas of Virginia, east of Interstate 95, including the Richmond metro area, Hampton Roads, and all the DELMARVA except the southern tip. The Winter Storm Watches extended north into the WFO Sterling, VA (LWX) and WFO Mount Holly, NJ (PHI)

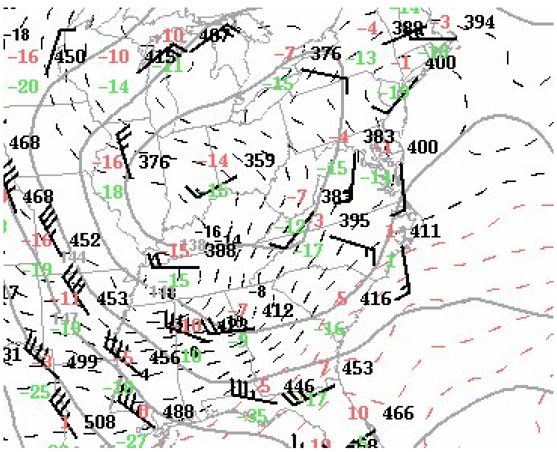

Figure 11. 0000 UTC 30 December 850-hPa upper plot with wind barbs (knots), heights (solid) and temperature (dashed).

CWAs. Special Weather Statements were issued, highlighting the potential for accumulating snow into the Richmond metropolitan area. Winter Storm Warnings were issued for the DELMARVA and northern neck areas of Virginia during the afternoon of 29 December, while Winter Weather Advisories were issued for areas as far west as the Richmond metropolitan area and as far south as Hampton Roads.

During the early morning hours of 30 December, all Winter Storm Warnings were cancelled, and Winter Weather Advisories were shifted to areas of Maryland from Ocean City (OXB) to Salisbury (SBY), where 1 inch of snow fell.

9. LESSONS LEARNED FROM EVENT 2

Areas from Norfolk to the DELMARVA from WAL to OXB and SBY received freezing rain at the onset of the precipitation just after 0000 UTC 30 December. The thermal and moisture advection warmed boundary layer temperatures just above freezing along the Virginia and Maryland coast, resulting in the freezing rain. OXB and SBY received up to 1 inch of snow later in the morning and the precipitation ended before noon.

Evolution of upstream and downstream upper features can have a significant impact on the amplification and deamplification of the primary system being diagnosed. One important lesson from event 2 is that the deamplification of the upper ridge in the western U.S., evident as early as the morning of 29 December, resulted in less amplification of the eastern U.S. upper trough and associated northern stream upper low. Similar to event 1, the upper low tracked southeast into the Ohio Valley, but the center of the upper low in event 2 did not track as far south. If movement of the upper low in satellite imagery suggests the center will not pass south of the forecast area, the chances of precipitation associated with the upper deformation zone (Bader et al. 1995) can be greatly reduced, as learned from event 2.

The upper impulse, associated with the upper jet streak, tracked quickly east through the Tennessee Valley and Carolinas. This limited the low-level thermal and moisture advection and convergence in the southeast and mid-Atlantic U.S.

The upper impulse that rotated around the southern semicircle of the upper low initiated the cyclogenesis over the interior southeastern U.S. Identification of upper impulses in satellite imagery is crucial, based on lessons from event 2.

10. CONCLUSION

Upper impulses and jet streaks within strong west to east upper flow, can produce significant snow (>4") in northeast North Carolina (Albright and Cobb, 1995) after interacting primarily with Atlantic moisture, but these types of systems do not typically produce significant snow in Virginia. In the past 7 years, most heavy snow events in the AKQ CWA were associated with upper level impulses that entrain moisture from the Gulf of Mexico, and whose upper level deformation zone tracked through Virginia. Events 1 and 2 featured northern stream systems that tracked southeast, out of Canada, and interacted with Atlantic moisture.

Identifying upper and low level features in satellite imagery and upper air analyses, can provide valuable information on movement and evolution of weather systems. Recognizing the upper level pattern along with knowledge of upper jet dynamics, and their relationship to thermal/moisture advection and upward vertical motion, can aid a forecaster in pinpointing the areas of greatest threat for significant snow. Detailed data analysis is just one element of effectively diagnosing the state of the atmosphere prior to forecast model evaluation. Please refer to the following website for more images and analysis: http://www.nws.noaa.gov/er/akq/winterfcst.html

11. REFERENCES

References are available upon request.