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The Birmingham, Alabama Snow "Disaster" of 28 January 2014

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ABSTRACT

A rare combination of anomalously cold air and rapidly falling snow produced a massive travel disruption in parts of the southeastern U.S. on 28 January 2014. Storm-total snowfalls were generally only 5 cm in the Birmingham, AL area, but most people were at work or school when the snow began. Due to icy roadways, thousands of people were forced to sleep in offices and schools, while many vehicles were abandoned on freeways and surface streets.

This event was a unique forecasting challenge in many aspects, especially for the southeastern U.S. In the 24 h leading up to the event, numerical model quantitative precipitation forecasting (QPF) was focused south of the main population centers where the main disruptions eventually occurred. A layer of very dry air was present up to 800 hPa, but saturation deficits were low due to the cold air. Radar data a few hours before the event provided some of the only tangible evidence that significant snow may occur. However, forecasters did not anticipate the havoc that would ensue from the relatively light snow accumulations.

In this paper, we examine the event, including the synoptic setup, vertical profiles of temperature and moisture, soil temperatures, numerical models, and radar data. On the early morning of 28 January, when school superintendents and business owners had to make decisions on whether to open, no warnings nor advisories were in effect for the majority of the Birmingham area, and the media indicated there would be no travel problems in Birmingham.

1. Introduction

On 28 January 2014, a snow event without sufficient forecasting and warning to the public caused a massive transportation gridlock in central Alabama. Only 5 cm of snow accumulated in Birmingham, yet the combination of anomalously cold air (daytime temperatures near –7°C, about 17°C below climatological normal), cold ground temperatures, rapid accumulations during the school and work day, and late advisories, led to one of the most widespread weather-related disruptions in Birmingham since the blizzard of 13 March 1993. Cars were abandoned on major roadways that quickly became impassable due to ice and snow (Fig. 1). Many school buses and even emergency vehicles were unable to travel. Thousands of people walked many miles home in bitterly cold temperatures, while additional thousands were stranded and forced to sleep in their offices, schools, makeshift shelters (including home improvement stores), and cars. Many were unable to return home until 30 January, two days later. Over 11 000 students in

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Figure 1: Photographs of snow, ice and traffic jams in Birmingham taken on 28 and 29 January 2014. a) Icy road with stranded ambulance in Alabaster, a southern suburb of Birmingham (photo by Melissa Overall); b) I-459 with snow and ice (photo by Jason Reed); c) I-459 at the US-280 exit (Moore 2014); d) I-20 at Leeds, just east of Birmingham (Moore 2014). *Click image to enlarge.*

Alabama spent the night in their schools because their parents were unable to pick them up (Leech 2014). There were at least 9 fatalities and 23 injuries in Alabama (NWS 2014; Solomon 2014) associated with the storm.

There was a combination of numerical model inaccuracy and some likely misinterpretation or neglect of atmospheric observations by forecasters. For example, a given dewpoint depression (T_{dd}) produces a smaller saturation deficit at colder temperatures than at warmer temperatures; also a closing clear area around the radar site indicated a descending virga level. A very dry layer of air at low levels was saturated rather quickly and unexpectedly by the sublimation of ice-crystal virga. The anomalous cold and favorable conditions aloft also led to a very high snow to liquid water ratio (SLR) for the southern U.S. Given the extremely cold air, conflicting model signals, and radar data in the hours leading up to the event, the weather enterprise likely could have better forecast and communicated the uncertainty of this event.

Forecasting snowstorms of any kind is difficult in the eastern U.S. (e.g., Maglaras et al. 1995; Tracton 2008). Many major snowstorms have struck with little or no warning, or were at least underforecast by meteorologists and/or computer models. These storms include the President's Day cyclone on 18–19 February 1979 (e.g., Whitaker et al. 1988), the snowstorm of 4 October 1987 in New England (Bosart and

Sanders 1991) and the "Surprise" snowstorm of 25 January 2000 along the east coast (Zhang et al. 2002). *However, forecasts are exceedingly difficult in the southern U.S., where the lack of both road treatment and snow removal equipment allows even 2–5 cm of snow to cause major travel disruptions.*

2. Data and methodology

In this paper, the synoptic setup for the storm is examined. Numerical model output, including thermodynamic profiles and model quantitative precipitation forecasts from numerous initialization times before the event occurred, are examined to discuss the difficulty that forecasters faced in the 24 h before the storm. Rapid Refresh (RAP; Benjamin et al. 2016) model sounding output is examined to illustrate how a very dry layer can be saturated quickly at extremely cold temperatures, and to examine the unusually cold air in the lower troposphere (unfortunately the BMX radiosonde data had large errors in dewpoint at low levels, so its moisture profile was not used). In addition, RAP model soundings overlaid with model vertical motion data illustrate a distinctive zone for the growth of low-density snow. SPC mesoanalyses at 300 hPa and 700 hPa for 1500 UTC 28 January (all times 28 January, unless otherwise noted), which are derived from the 1400 UTC RAP model 1-h forecast, and Plymouth State University analysis at 850 hPa enhance the synoptic and meso-α-scale analysis of the event. Archived surface observations obtained from the Iowa Environmental Mesonet are used to show the typical temperatures during snow in central Alabama. Road surface temperatures from the Vaisala RWIS (Road Weather Information Systems) program are examined. Radar data from the WSR-88D at Birmingham, AL (KBMX) are also used to show snow virga and descending snow levels over time.

3. Circumstances that led to the snow "disaster"

a. The synoptic setup

A substantial Arctic cold front moved through much of northern and central Alabama on 27 January, with temperatures at Birmingham Airport (KBHM) dropping from 11.5°C at 1500 UTC, to –1°C at 0100 UTC 28 January, then to –6°C by 1000 UTC. At 1200 UTC 28 January, the rather shallow surface cold front had pushed through all of Alabama. A deep upper-level trough was associated with the Arctic air mass, and an upper-level jet maximum was moving around the base of the trough at 1400 UTC, producing upper-level divergence over Alabama (Fig. 2). In addition, mid-level frontogenesis was occurring to the north of central Alabama, placing the area in a favorable position for banded precipitation due to frontogenetic forcing (e.g., Banacos 2003; Jurewicz and Evans 2004; Funk et al. 2004); see Fig. 3.

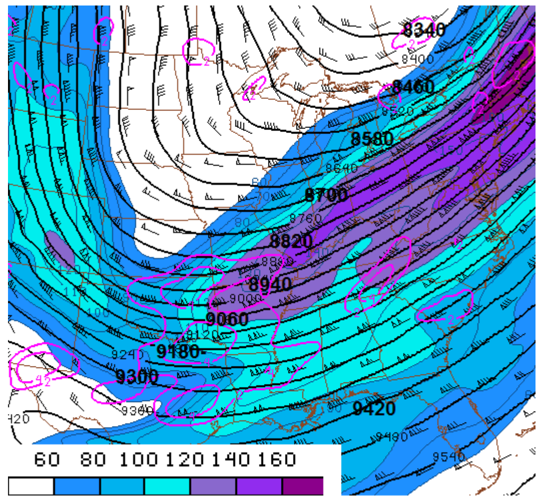

Figure 2: 300-hPa heights (black contours), isotachs (kt, shading) and divergence (purple contours) at 1500 UTC, from SPC mesoanalysis. *Click image to enlarge.*

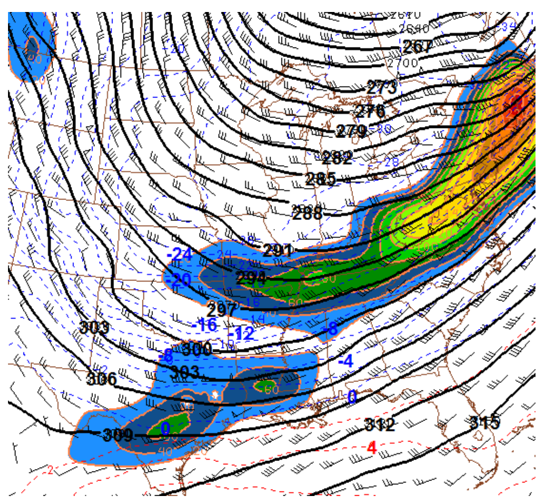

Figure 3: 700-hPa heights (dam, black contours), temperatures (dashed), wind barbs (kt), and 700-hPa Petterssen frontogenesis (shading) at 1500 UTC, from SPC mesoanalysis. *Click image to enlarge.*

The Arctic air mass was very shallow, extending up to only about 800 m MSL (600 m AGL) at Birmingham, as shown by the RAP model sounding for 1200 UTC (Fig. 4). At 850 hPa, streamline analysis at 1200 UTC indicates neutral or slightly warm advection over central Alabama (Fig. 5). Indeed, model wind profiles (not shown) indicate slight veering of the wind with height between 850 and 700 hPa, consistent with warm air advection through the thermal wind relation. In addition, due to strong cold advection over northern Alabama, the Laplacian of temperature advection was large, leading to more vertical motion through the quasigeostrophic omega equation (e.g., Holton 1992). Upward vertical motion was supported deeply, due to a combination of upper-level dynamic influences (the right-entrance region to the 300-hPa jet), midlevel frontogenetic forcing, and low-level warm air advection. At least initially, precipitation formed primarily above the elevation of the 850-hPa level.

b. Extremely cold temperatures

As shown in Fig. 4, temperatures in the main snow-formation zone (5–7 km AGL, based on radar data, RAP model relative humidity (RH), and RAP model vertical motion, see light blue box in Fig. 4) were between –10°C and –20°C according to the RAP model sounding. Temperatures near the surface were very cold, especially for snow in Alabama. The temperature at 925 hPa was –9.1°C based on the RAP model sounding, and surface temperatures at KBHM on the morning of 28 January held near –6°C until snow began at 1538 UTC, then dropped as low as –8°C after snow began. These very cold low-level temperatures likely had several impacts.

First, colder temperatures typically lead to higher snow-to-liquid-water ratios (SLR, e.g., Byun et al. 2008). Surface temperatures between –6°C and –8°C are associated with SLR between 20 and 30 (Fig. 6), well above the normal SLR of 8–10 for northern Alabama shown by Baxter et al. (2005). Surface observations at KBHM indicate that only 0.2 cm of liquid water fell on 28 January 2014, but the snow depth was 5 cm. This indicates an SLR of 25, consistent with the results of Byun et al. (2008), and much higher than weather forecasters in Alabama are accustomed to.

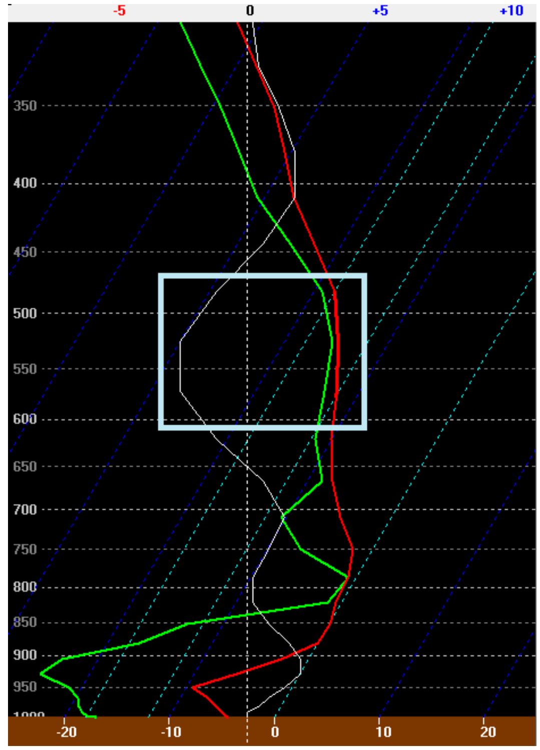

Figure 4: Skew*T*–log*p* sounding diagram for RAP 00-h sounding at KBMX for model run initialized at 1200 UTC, with vertical motion in gray (μb s^{-1}, top axis, negative is upward). Pressure (y-axis) in hPa. Temperature (x-axis) in °C. The light blue box indicates the region where low-density snow crystals likely formed (section 3d). *Click image to enlarge.*

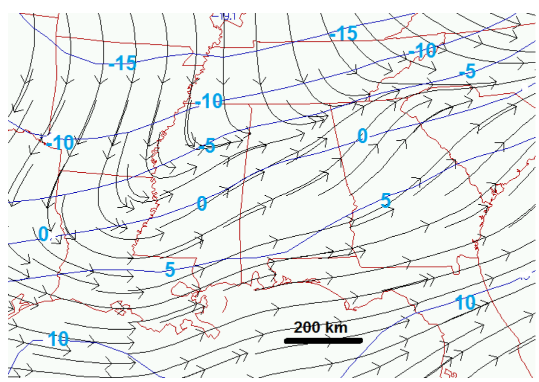

Figure 5: Plymouth State Weather Center meso-α-scale analysis of 850-hPa streamlines (dark) and temperatures (blue) at 1200 UTC 28 January 2014. *Click image to enlarge.*

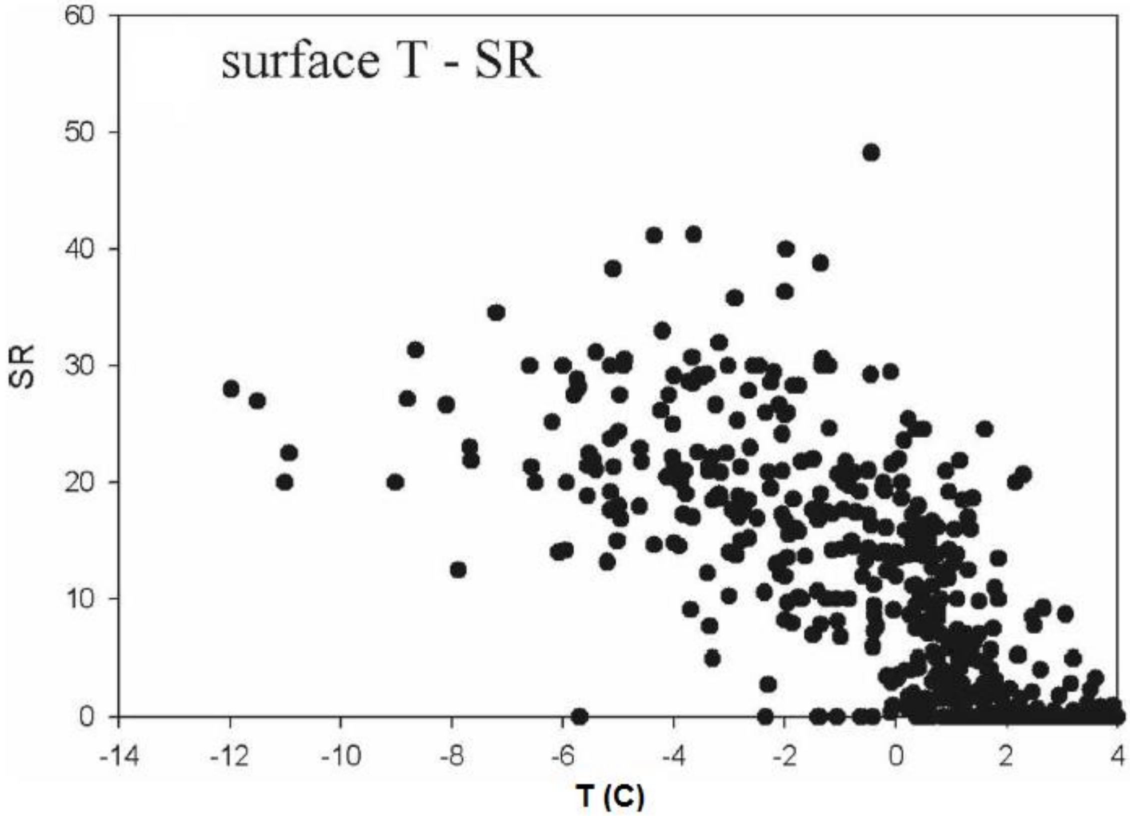

Figure 6: Snow-to-liquid-water precipitation ratio (SLR) vs. surface temperature (°C), from Byun et al. (2008).

As illustrated in Fig. 7, the median temperature at KBHM for all hourly surface observations including snow since 1948 is 1°C. Only 14% of all snow observations at KBHM occurred at a temperature of –6°C or lower. So, this event presented a fairly rare challenge to meteorologists in Alabama, with few or no *personal* analogs.

Secondly, the snowflakes were falling at very cold temperatures. The terminal fall speed of most snowflakes is 1 m s^{-1} (Geerts 2000; Bohm 1989). Given the thermal profile, the snowflakes spent about 10 min in the layer of air near the surface with an average temperature of –7°C. Therefore, there was certainly no transport of heat downward with the snowflakes to the surface, and there may have been some absorption of heat upon contact with the surface.

The cold air temperatures also led to very cold road temperatures. Temperatures at the ground and road surfaces vary much more rapidly (with air temperature, solar radiation and other factors) than 10-cm soil temperatures (e.g., Garratt 1992). The 10-cm soil temperatures at 1200 UTC were ≈6°C at Birmingham. Given the extremely cold air temperatures and cold precipitation falling on 28 January, road-surface temperatures were much colder than the soil at 10 cm. There were no road-surface temperature sensors in place in Birmingham during the event, but there was one in Guntersville, AL, 100 km northeast of KBHM. Figure 8 shows air vs. road temperatures at Guntersville as the Arctic air poured in during the morning of 28 January. All bridges and most surface streets were likely at or below freezing at the onset of the snow, and almost all surface streets likely dropped below freezing after the melting of even a small amount of snow.

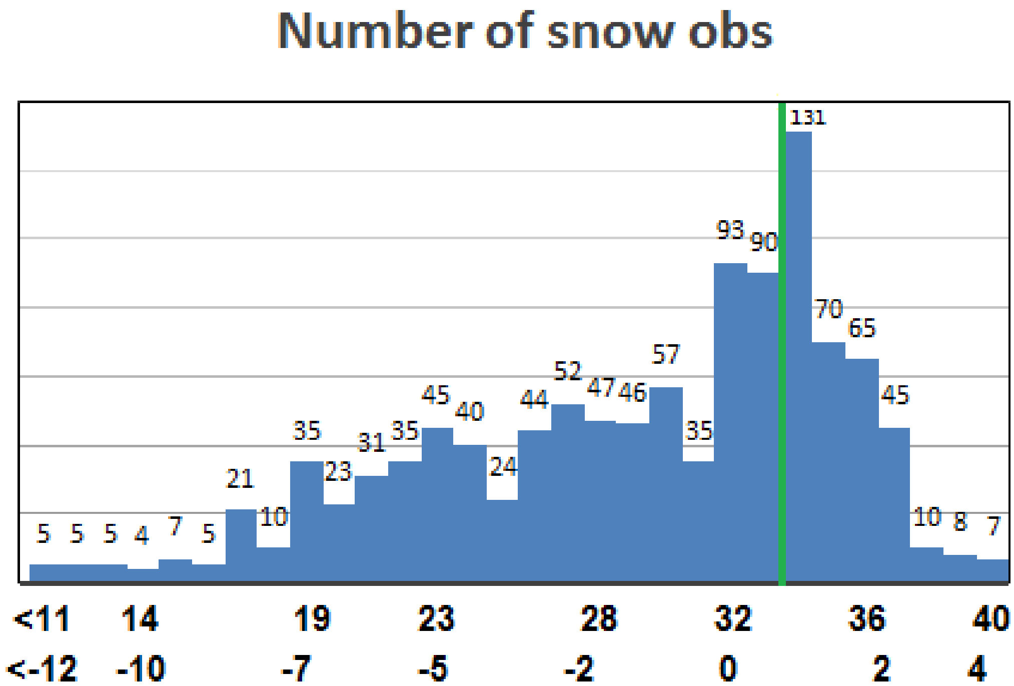

Figure 7: Distribution of the temperature (°F top x-axis labels, °C bottom x-axis labels) during all hourly observations of snow at KBHM, 1948–2014. Green vertical line indicates median temperature for all snow observations (1°C).

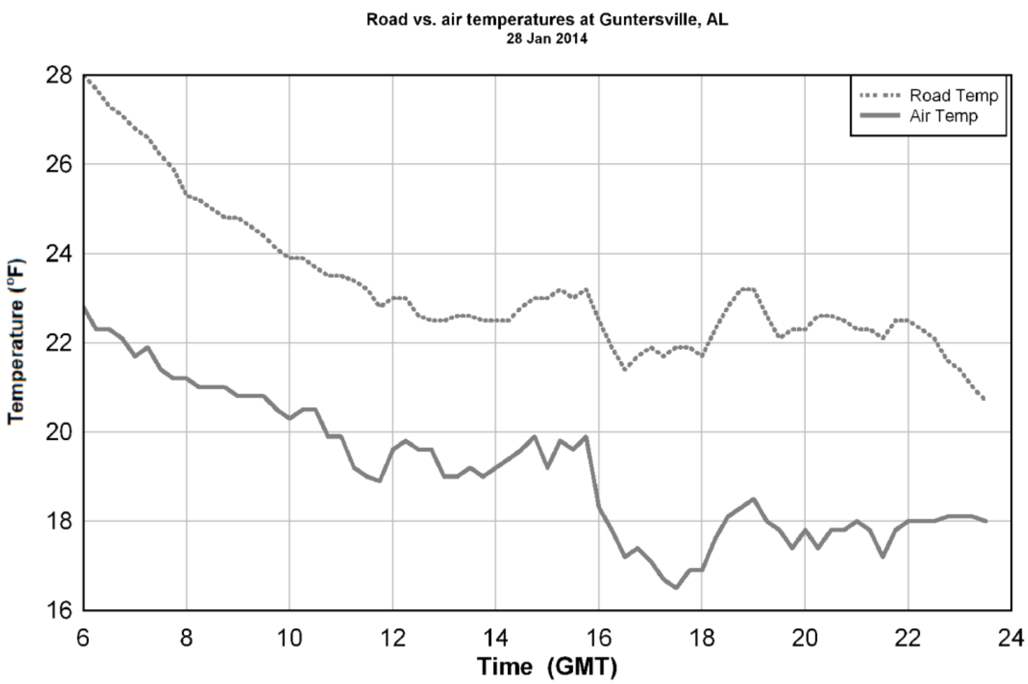

Figure 8: Air temperatures (bottom) and road temperatures (°F) vs. time at Guntersville, AL on 28 January 2014.

The drop in road-surface temperature was well-correlated with that in air temperature, with the road generally about 2°C warmer than the air. Assuming a similar result in Birmingham, given the air temperature of –6°C at the time of snow onset, road-surface temperatures were likely between –5°C and –3°C. It had been below freezing for 12 h at KBHM prior to snow onset. While extremely cold soil temperatures associated with the prior cold month likely limited the upward transfer of heat from the soil to the surface, the extremely cold air temperatures, and associated cold road temperatures, seemingly were the primary factors that allowed the small amount of snow to accumulate on surface roads so quickly.

Perhaps most importantly, some melting and refreezing of the snowflakes occurred at some point, since streets became very icy, as opposed to simply snowy (see Figs. 1a, 1b). This is likely explained by vehicle compaction (pressure melting), or by vehicle tires spinning and creating friction melting. Under some pressure or due to friction, ice can develop a thin layer of liquid near its surface (e.g., Rosenburg 2005). The fusion line, or freezing line (between liquid water and solid ice), has a negative slope (dT/dp <0) below 0°C, as shown in Fig. 9. So, at temperatures just below 0°C, a large increase in pressure [such as the pressure exerted by a vehicle tire, approximated in static conditions to be around 200 kPa (e.g., VDI 2014)], can lower the freezing temperature and melt ice. However, at the extremely cold air temperatures, this water would refreeze very quickly, creating the glaze of ice on many roadways.

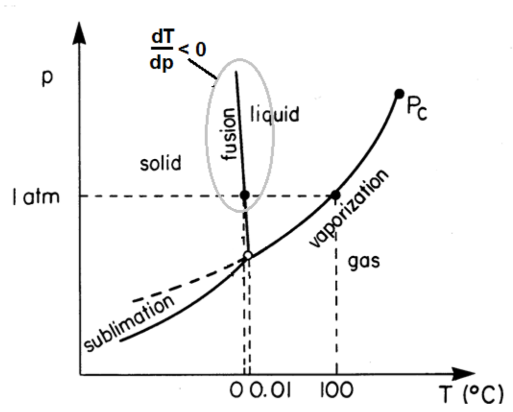

Figure 9: Phase diagram of water (pressure vs. temperature). Adapted from Iribarne and Godson (1973).

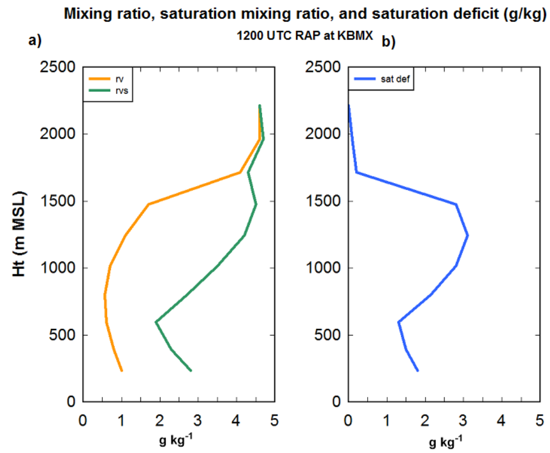

Figure 10: Profiles based on RAP 00-h initialized model sounding at KBMX. 1200 UTC 28 January 2014: a) mixing ratio (g kg^{-1}, green) and saturated mixing ratio (g kg^{-1}, blue), and b) saturation deficit (g kg^{-1}). Panel (b) represents the difference in the two profiles in (a).

c. Moisture profile

The early morning area forecast discussion (AFD) from the National Weather Service in Birmingham (NWS BMX) on 28 January referred to the layer of very dry air near the surface, including surface dewpoints near –17°C (these are 3σ below normal in central Alabama even for December–January–February). However, through the Clausius-Clapeyron relation, the change in mixing ratio r_v (saturation mixing ratio r_{vs}) is much smaller relative to a change in dew point (temperature) at cold temperatures than it is at warmer temperatures. Therefore, the saturation of a dry air mass by precipitation occurs with much less evaporation or sublimation in very cold air than it does in warmer air. The 1200 UTC RAP sounding at KBMX shows very dry air in the lowest 2 km AGL. Figure 10a shows vertical profiles of r_v and r_{vs}. Figure 10b shows the saturation deficit (amount of water vapor, in g kg^{-1}, that must be added to saturate the air at each level, not considering the effects of diabatic cooling). The profile in Fig. 10b is the difference between the two curves in Fig. 10a. Note that at 1000 m AGL, despite a temperature of –1°C, a dewpoint of –19°C, and a relative humidity of only 24%, the saturation deficit was only 3.1 g kg^{-1}. Given the same relative humidity (24%), but at a warmer temperature of 20°C and a resulting dewpoint of –1°C, the saturation deficit would be four times as large, 12.6 g kg^{-1}. So, the amount of precipitation required to saturate a layer with very low relative humidity is much less at cold temperatures than it is at warmer temperatures. Many forecasters in the South are not accustomed to precipitation falling through layers that cold.

d. Rapid snowfall

As discussed above, the storm total snowfall at KBHM was only 5 cm. However, once the surface layer of the atmosphere became saturated, the snow was heavy and accumulated quickly. The horizontal visibility at KBHM in the snow dropped from 8 km at 1553 UTC to 0.8 km at 1627 UTC. This increasing snow resulted in rapidly deteriorating travel conditions. Roads became snow and ice covered very quickly during this time, and by 1648 UTC (10:48 am CST), police departments had reported numerous car accidents in Tuscaloosa and Birmingham. The official observation at KBHM included a "snow increasing rapidly" remark at 1853 UTC (SNINCR 1/1), indicating that 1 in. (2.5 cm) of snow accumulated in that hour.

The unexpectedly high snowfall rate was partially related to the large SLR (e.g., Cobb and Waldstreicher 2005, herein CW05). As pointed out in section 3b, this high SLR has been associated with cold low-level temperatures. In addition, this ratio is inversely proportional to snow-crystal density. Low-density ice-crystal formation is favored at temperatures near –15°C and at high relative humidities (e.g., CW05; Fukuta and Tashahaki 1999). In addition, significant vertical motion in the snow formation zone reduces ice crystal density (e.g., CW05). Figure 4 shows the RAP model profile of vertical motion at KBMX at 1200 UTC overlaid on the model sounding. In the layer roughly between 600 and 475 mb (light blue box in Fig. 11), the largest upward vertical motions in the atmosphere are observed, and they are collocated with temperatures between –11°C and –19°C, and nearly saturated conditions. Therefore, this layer was very favorable for the formation of low-density, high-SLR ice crystals.

Dual-polarization radar variables indicated the pristine, low-density ice crystals aloft, with slightly more aggregated snow at low levels (after the snow fell through the layer between –5°C and –1°C centered near 800 mb, just below 2 km AGL). As discussed by several authors (e.g., Ryzhkov et al. 2011), pristine ice crystals typically have low reflectivity, and much higher differential reflectivity (Z_{DR}) than snow aggregates do. Figure 11 shows reflectivity >0 d*BZ* extending up to about 7 km AGL, consistent with snow formation aloft in the layer outlined in Fig. 4. However, reflectivity between 1.5 and 2.5 km AGL peaks near 20 dB*Z* to the north of the radar, with Z_{DR} near 0 dB, indicating at least some aggregates; above 3 km AGL, reflectivity was generally lower (7 to 15 dB*Z*) with higher Z_{DR} (mainly between 0 and 0.5 dB). The low reflectivity and high Z_{DR} are consistent with low density ice crystals and a high SLR aloft. So, the rapid snow fall and high SLR was consistent with past observations of cold surface temperatures (Fig. 6), and with the layer near –15°C aloft containing high relative humidity and upward vertical motion.

4. Forecasting and warning challenges

Many school systems in Alabama have initiated early releases, late starts, or closings due to tornado watches and winter weather advisories since 2011. Given these past decisions by school superintendents and businesses, many of the thousands of people who were stuck at work, on the roads, or at schools likely would have stayed home on 28 January 2014 if a winter storm warning or even a winter weather advisory had been in effect during the early morning hours, or if forecasts from NWS and local TV meteorologists had indicated anything close to the scope of the impending event. Below, we present a chronology of the computer model output, observations, forecasts and warnings for 28 January.

a. Afternoon on 27 January

Starting with the late-afternoon forecasts on 27 January, forecasters focused on south Alabama as the region of primary concern, for very good reason. The North American Mesoscale (NAM; Janjić 2003, 2004) computer model QPF was much higher there than in north and central Alabama (Fig. 12), and precipitation type was also a major concern, with ice accumulations appearing possible. However, farther to the north over the Birmingham area, models were inconsistent both between each other, and from run to run.

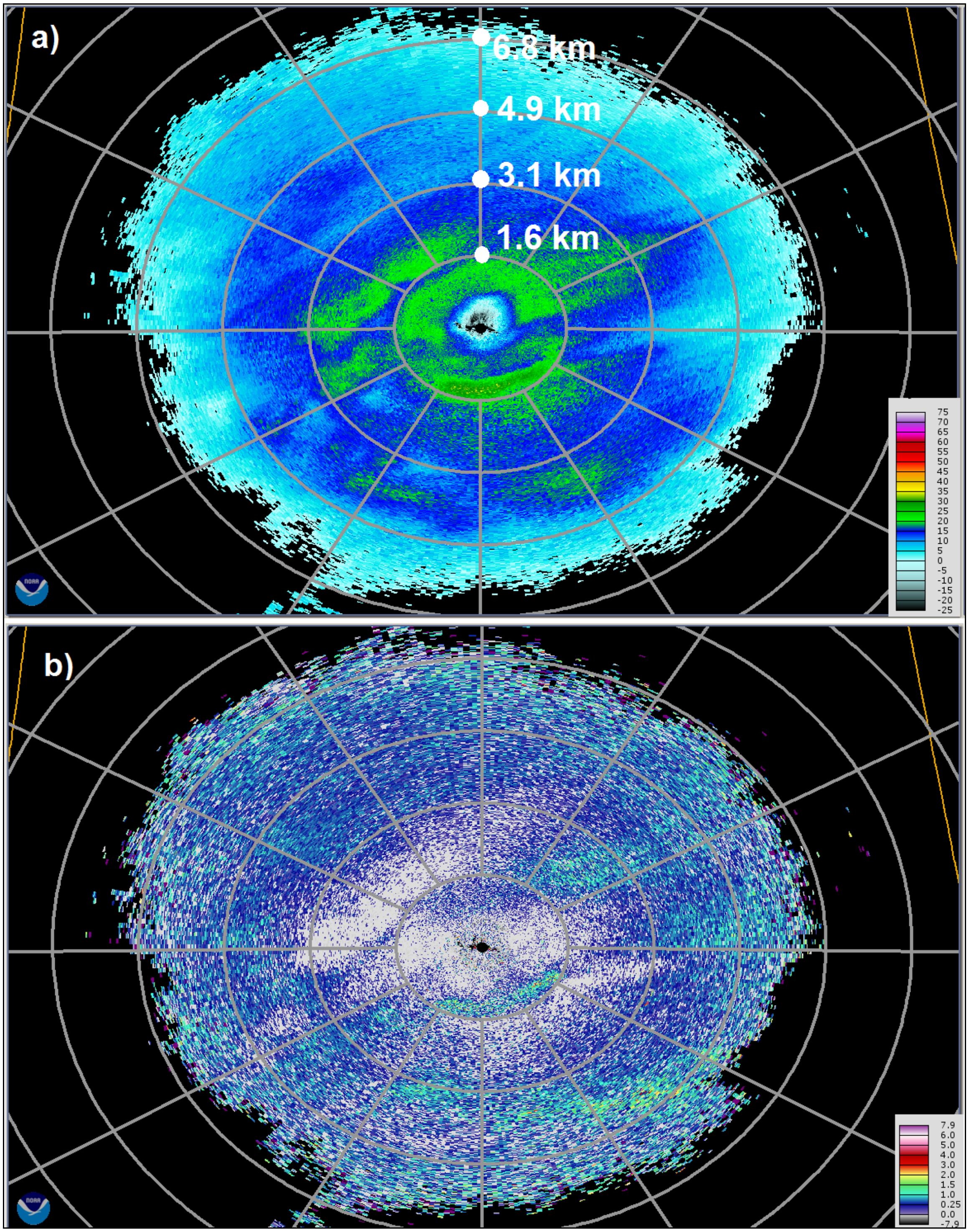

Figure 11: PPI scans of: a) base reflectivity (dB*Z*) and b) differential reflectivity (dB) at 3.4° beam elevation at 1504 UTC, from KBMX. Range rings are every 25 km. Labeled white dots on the range rings in (a) show the approximate height of the radar beam AGL, assuming standard propagation. *Click image to enlarge.*

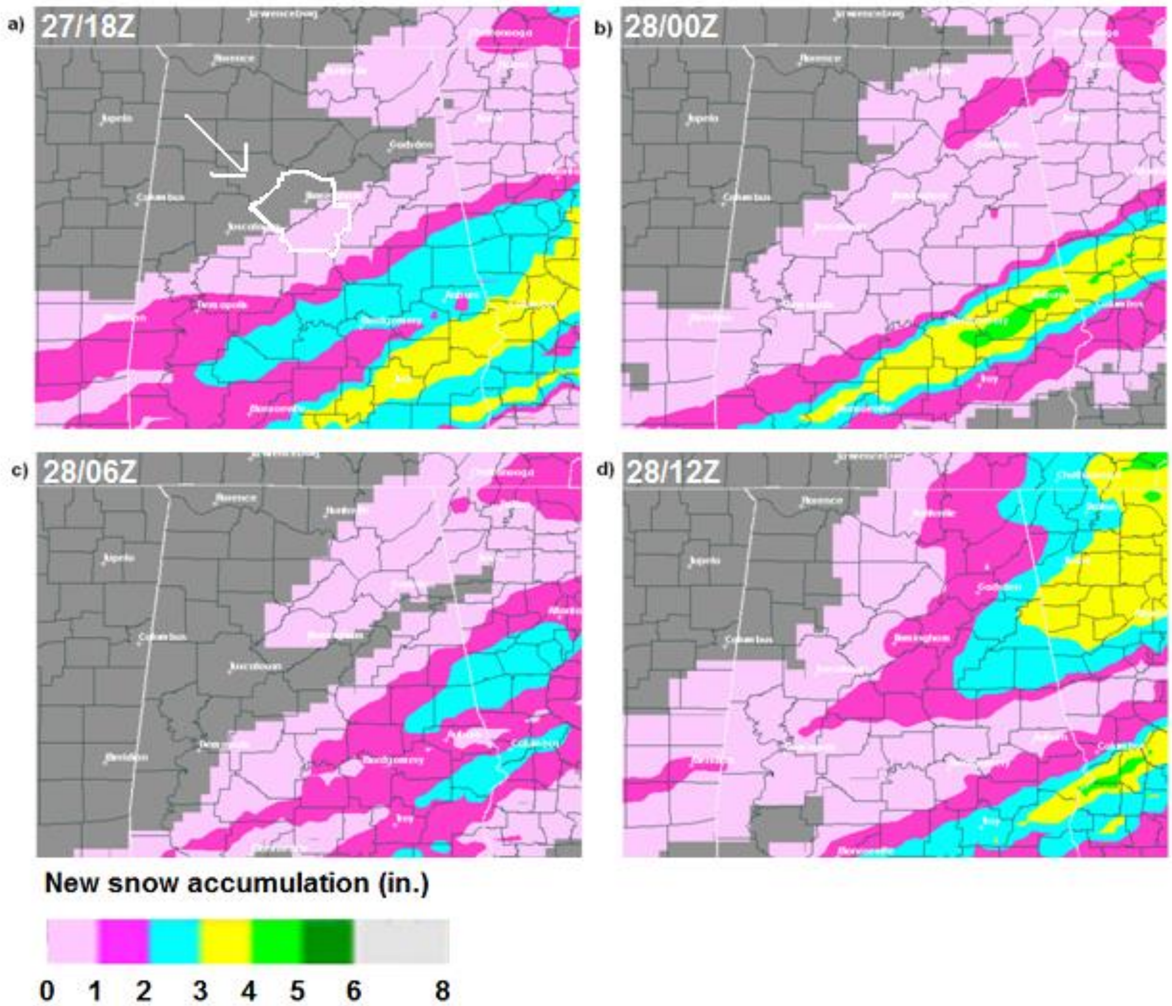

Figure 12: NAM model total snowfall accumulations (in) for north and central Alabama from: a) 1800 UTC 27 January 2014; b) 0000 UTC 28 January; c) 0600 UTC 28 January; d) 1200 UTC 28 January. The main counties of the Birmingham area (Jefferson north, Shelby south) are highlighted in panel (a).

As for the Birmingham area, as shown in Fig. 11, the NAM model run initialized at 1800 UTC (the last one available for the afternoon forecast package) was showing 0 to 1 inches (0 to 2.5 cm) of storm-total snow for Shelby County, and none for most of Jefferson County (the two main counties in the Birmingham metropolitan area, Fig. 12). The storm-total liquid quantitative precipitation forecast (QPF) was extremely light (0.01 in, 0.025 cm) for Birmingham on the operational NAM. The 1200 UTC 4-km NAM indicated no precipitation, and the Global Forecast System (GFS; Kanamitsu 1989) indicated 0.09 in, 0.23 cm of liquid precipitation at BMX. Notably, the RAP model only went out to 18 h in January 2014, and did not fully capture the event temporally until around the 0000 UTC run. Air temperatures were forecast by NWS to remain below –1°C all day on 28 January. The NOAA Weather Prediction Center (WPC) graphics showing areas with a greater than 10% chance of receiving >4 in (10 cm) of snow did not include any of Alabama at 0000 UTC on 28 January, and only included about two counties in extreme east Alabama, far southeast of Birmingham, on the 1200 UTC graphics.

The NWS afternoon forecast package indicated the following for 28 January in Jefferson County: "CLOUDY. SLIGHT CHANCE OF SNOW IN THE MORNING...THEN CHANCE OF SNOW IN THE AFTERNOON. HIGHS IN THE UPPER 20S. NORTH WINDS 10 TO 15 MPH. CHANCE OF SNOW 40 PERCENT." One of the TV meteorologists in Birmingham stated that residents of Birmingham would see snowfall, but the accumulating snow would be south of the Birmingham area. Another TV meteorologist wrote that he expected snow in Birmingham, but it should be very light and scattered, no significant accumulation was expected, and no travel issues were expected.

A winter storm warning was issued at 1511 UTC on 27 January, for much of south-central Alabama, effective at 10:00 a.m. CST (1600 UTC) 28 January. A winter weather advisory, based on "light snow" with "potential accumulations near 1 inch" was issued at the same time for a band of counties farther north. However, the closest county to Birmingham in the warning was Autauga, centered about 100 km south of the center of the Birmingham metropolitan area. The closest county in the advisory was Chilton, centered about 60 km south of the center of Birmingham metro. No warnings or advisories were issued by NWS on 27 January for Jefferson or Shelby Counties of the Birmingham Metropolitan Area, which are outlined in Fig. 12a.

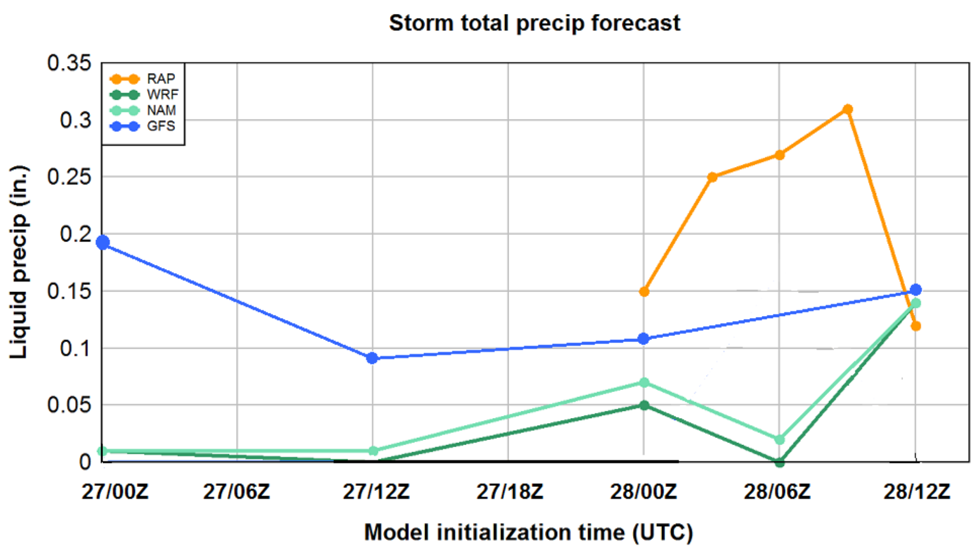

Figure 13: Computer model forecast storm total liquid precipitation at KBMX for each run of the NAM (light green), WRF (dark green), GFS (blue), and RAP (orange). The horizontal axis indicates initialization time, but for each model run, the time period for precipitation is between 0600 UTC 28 January and 0000 UTC 29 January.

b. Early morning on 28 January

By early morning on 28 January, the numerical models were a bit more aggressive with snowfall in Birmingham. The 0000 UTC NAM (available for early morning forecasts) showed light accumulations over the entire Birmingham area, and the 0000 UTC GFS continued to indicate liquid-water totals near 0.1 inch. In addition, the RAP model, which then only went out 18 h, began to depict a more substantial event in the Birmingham area, with storm-total liquid precipitation amounts between 0.15 and 0.30 inches on the 0000, 0300, 0600, and 0900 UTC runs. Clearly, if the RAP model had been examined more thoroughly and trusted, the forecast could have been modified for the morning forecast package. (See Fig. 13 for trends in QPF from all 4 models.) In addition, and perhaps more importantly, observed surface temperatures at KBHM by 1100 UTC (5:00 am CST) had dropped to –6°C.

Moreover, as early as 1000 UTC 28 January, snow virga was observed over much of central Alabama, based on KBMX WSR-88D data. Figure 14 shows base reflectivity from KBMX at 1000 UTC, at elevation angles of 0.5°, 1.5°, 2.5°, and 4.5°. The widespread nature of the snow virga is apparent, and all four images indicate a 2–2.5 km AGL sublimation level.

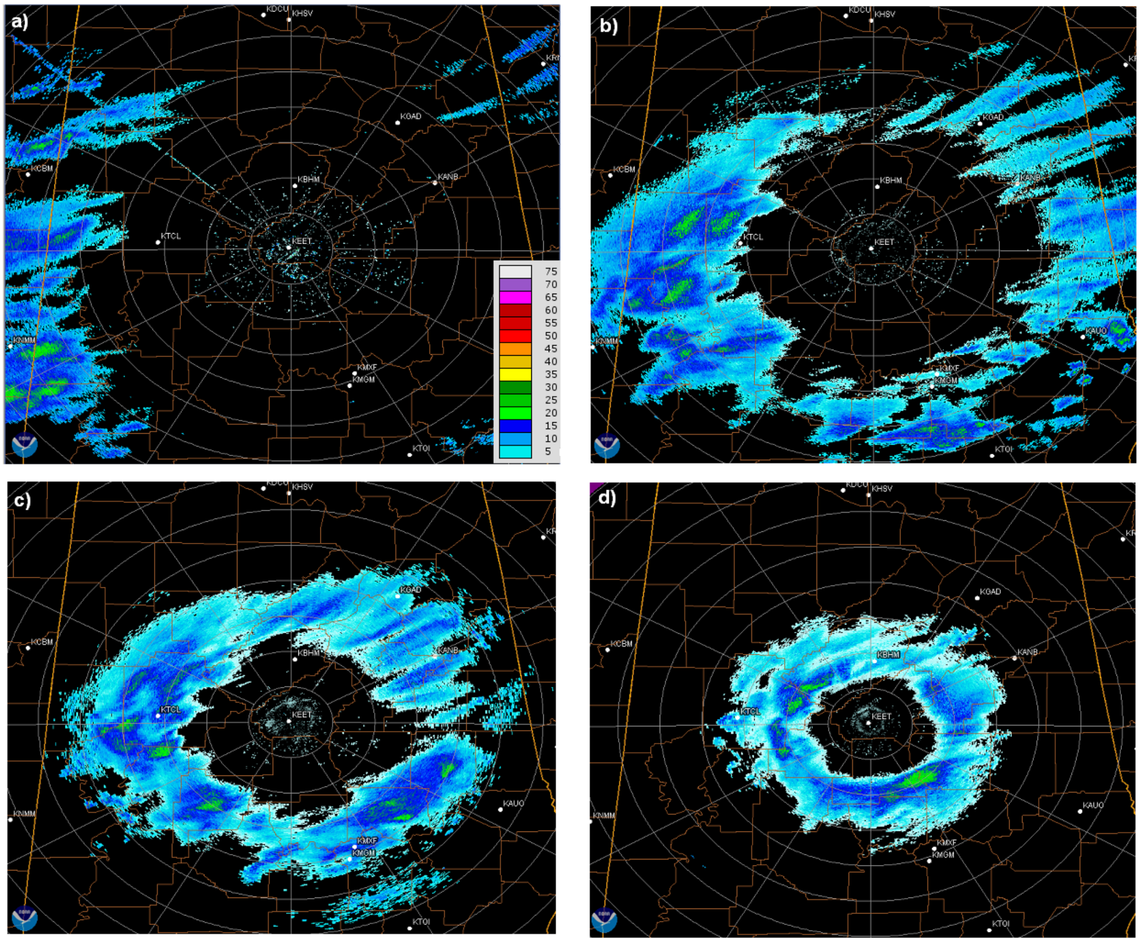

Figure 14: Radar reflectivity (dB*Z*) from KBMX at 1000 UTC at a) 0.5° b) 1.5°, c) 2.5°, and d) 4.5° beam elevation. Range rings are at 25-km intervals. *Click image to enlarge*.

However, the sublimation level was descending with time, due to top-down saturation of the air by sublimating snow (e.g., Market et al. 2006), as shown by the 0.5° elevation radar reflectivity loop in Fig. 15. Note that the reflectivity-free area near the center of the radar became smaller with time, as the air became saturated at, and snow reached, lower levels. This closing "doughnut hole" with time in radar reflectivity is a classic pattern indicating the descent of the precipitation-drying layer. The hole disappeared by 1600 UTC, and snow began at KBHM at 1538 UTC.

The main forecast package for Jefferson County, issued at 1024 UTC, read "TODAY...CHANCE OF FLURRIES IN THE MORNING...THEN SNOW LIKELY IN THE AFTERNOON. LITTLE OR NO SNOW ACCUMULATION. HIGHS IN THE UPPER 20S. NORTH WINDS 10 TO 15 MPH. CHANCE OF SNOW 70 PERCENT." In Shelby County, the forecast read ".TODAY...CHANCE OF FLURRIES IN THE MORNING...THEN SNOW IN THE AFTERNOON. SNOW ACCUMULATION UP TO 1 INCH. HIGHS IN THE UPPER 20S. NORTH WINDS 10 TO 15 MPH. CHANCE OF SNOW NEAR 100 PERCENT." The winter storm warning was not moved any closer to Birmingham with this forecast package, but Shelby County was added to the winter weather Advisory. So, the probabilities of snow were raised significantly for the Birmingham area, but the forecast indicated little or no snow accumulation over the most populous county, and only up to 1 in (2.5 cm) in Shelby County.

For NWS BMX, the criterion for a winter weather advisory is any accumulating snow of 5 cm or less, and the criterion for a winter storm warning is snow accumulation greater than 5 cm.

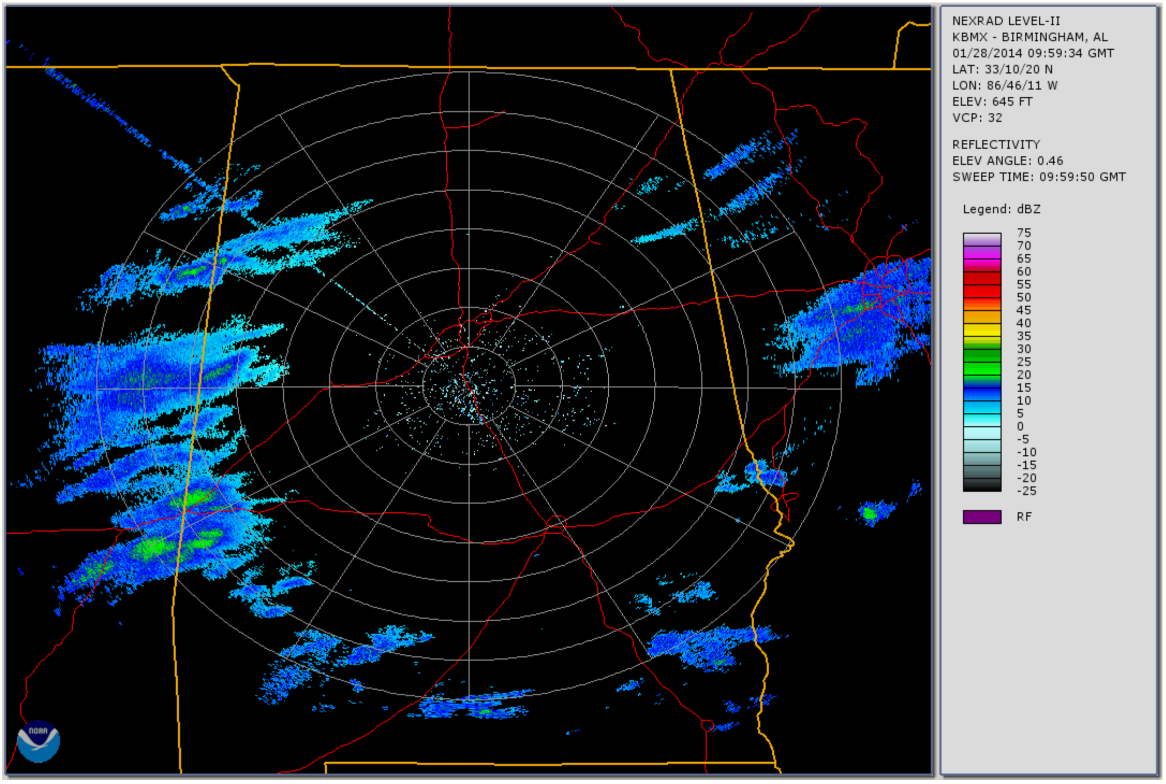

Figure 15: Loop of radar reflectivity (dB*Z*) from KBMX at 0.5° beam elevation from 1000 through 2200 UTC. Range rings are at 25-km intervals. *Click image for animation.*

However, NWS Instruction 10-513 allows forecasters to issue warnings at lower thresholds based on local conditions such as timing and threats to life. The text of the winter weather advisory for Shelby County included "A WINTER WEATHER ADVISORY MEANS THAT PERIODS OF SNOW WILL CAUSE TRAVEL DIFFICULTIES. BE PREPARED FOR SLIPPERY ROADS AND LIMITED VISIBILITIES...AND USE CAUTION WHILE DRIVING."

NWS BMX produced a graphic for their website around the time of the issuance of this forecast showing only a "dusting" of snow over most of the Birmingham area (Fig. 16). One of the TV meteorologists stated at 1130 UTC that a dusting of snow was possible around Birmingham, but no significant accumulation nor travel issues were expected. Another stated that only a dusting to 1 in (2.5 cm) of snow was possible in central Alabama, and the greatest risk for accumulating snowfall would be along the I-85 corridor; he stated that the dry air would result in much of the precipitation evaporating before reaching the ground in central Alabama. Most forecasters seemingly were anticipating some snow in the Birmingham area by the time of the early morning forecast, but no one was discussing road problems in Jefferson County, and, to the authors' knowledge, the NWS was discussing only minor road problems for Shelby County. Even there, the focus of the time period for the snow accumulations was stated in the text of the winter weather advisory for Shelby County, "THE BEST CHANCE FOR ACCUMULATIONS WILL BE BETWEEN NOON AND 9 PM." So, operators of schools and businesses in the Birmingham metropolitan area may have thought they had until midday to make decisions about early closures.

A few light snow reports began around the Birmingham metropolitan area (Jefferson and Shelby counties) just before 1500 UTC, and light snow began to fall at KBHM at 1538 UTC (9:38 am CST), after most workers and students were at work or school. NWS expanded the winter weather advisory northward at 1501 UTC to include Jefferson county, but the closest winter storm warning was still 100 km to the south.

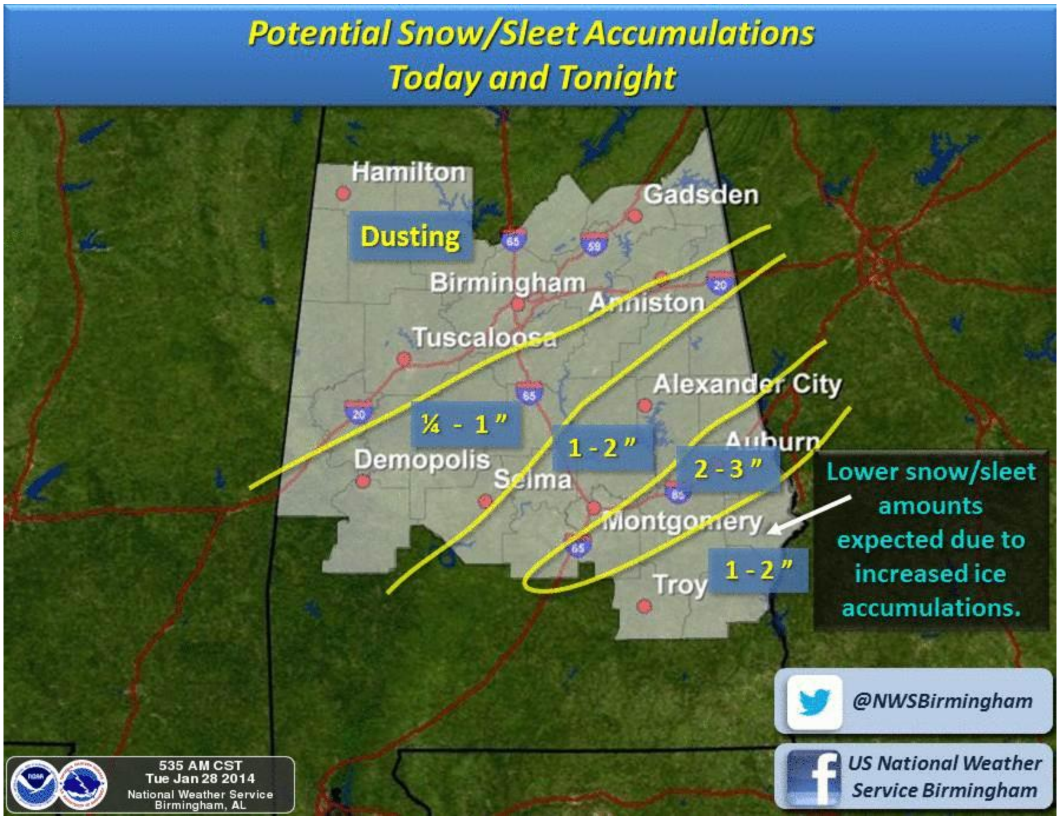

Figure 16: NWS map showing forecast snow accumulations within BMX county warning area, issued at 1135 UTC (5:35 am CST) on 28 January 2014.

c. Rapid snow accumulation, issuance of warning

Snow became heavier and more widespread very rapidly over the Birmingham area between 1530 and 1700 UTC, as the dry layer near the surface became saturated by the falling snow. Meanwhile, the horizontal visibility at KBHM dropped quickly from 8 km to 0.8 km, and numerous car accidents began to occur. Major U.S. highways and interstates, as well as secondary roadways, were becoming snow-covered and icy (e.g., Coleman 2014; Stinnett 2014). Rapid snow accumulation likely contributed to the sudden deterioration of roadways. Unusually high SLRs also contributed to the larger snow accumulations than expected. Schools closed due to the unexpectedly icy road conditions, forcing the parents of students onto the icy roadways from work and home. Businesses also closed, placing thousands of workers on the roads very quickly.

The NWS issued a greatly expanded winter storm warning at 1706 UTC (arguably a new warning in response to events unfolding in north-central Alabama). Jefferson and Shelby Counties were included in this expanded winter storm warning. The text of this warning included, "ACCUMULATIONS...2 TO 3 INCHES." This warning was clearly too late for many people.

One of the authors of this paper left home in Shelby County at 1600 UTC, with only light snow occurring. The author noticed only light accumulations in the grassy areas. But, an accumulation of ice was occurring on primary and secondary roads. This is the reverse of what normally happens in a light snow event in Alabama, where grassy areas receive the greatest accumulations, and roadways remain wet. This was likely due to the anomalously cold temperatures and vehicle pressure, as discussed in section 3b. The roads quickly became impassable and traffic came to a standstill from a combination of locally steep terrain and ice on the road. Given the slow speeds and heavy traffic, vehicle pressure possibly was greater than normal, and the drafts due to quickly passing vehicles that would normally blow light snow off the road were not present. According to Murray (2014a,b), by 1732 UTC several pieces of Birmingham Fire Department equipment were stuck on icy roads, and one of the main hospitals in Birmingham had become inaccessible. By 1841 UTC, there were so many car wrecks that only those with injuries were being handled by the authorities. Cell phone networks were jammed, and tens of thousands of people were stuck on area roadways, with some moving only 1 mph (0.4 m s^{-1}).

Large numbers of people abandoned their cars and walked many miles in the very cold temperatures to get home or to their children in schools, while thousands more slept in their cars, at work, in schools, and in temporary shelters including churches and home improvement stores (e.g., NWS 2014; WBRC 2014; Murray 2014b; Carlton 2015). In one case, a neurosurgeon had to abandon his car on the icy roads and walk 6 mi (9.7 km) to a hospital to perform surgery (Carlton 2015). The travel situation became so severe that a civil emergency message was issued by the Alabama Emergency Management Agency (and relayed to the public by the National Weather Service) at 1727 UTC, stating that "*numerous roadways…both major through fares [sic] and lesser traveled roadways…are becoming extremely hazardous and in most cases impassible…county emergency management agencies request that travel be limited to emergencies only for your safety and the safety of first responders*."

5. Discussion and conclusions

The combination of very cold air temperatures, cold road temperatures, and brief heavy snowfall rates (despite a light storm total accumulation of 5 cm) combined to cause almost all roadways in the Birmingham metropolitan area to become icy and impassable on 28 January 2014. This occurred over a short time period, primarily between 1600–1900 UTC, in the middle of the work and school day. Incidentally, slightly greater snowfall occurred south of Birmingham.

In the southern United States, especially in the Deep South (including Mississippi, Alabama, Georgia, and South Carolina), very little money is spent on the infrastructure necessary for road pre-treatment or treatment with ice-reducing materials. Little, if any, equipment for snow removal from roads exists in the state departments of transportation, counties, or cities. If this event had occurred in the northern U.S., road treatment and snow removal may have mitigated the impact of this event, allowing people to drive home after the snow had accumulated and been removed from the roads. But, given the lack of snow removal and road treatment, in addition to the pressure melting by vehicles and extremely cold air temperatures, *the effects were similar to that of an ice storm.*

The authors emphasize that they were involved in the forecasting process. The 0000 UTC model runs on 28 January, more than 12 h prior to the event, became more aggressive with snowfall in the Birmingham area, but still only a winter weather advisory was issued, and then only for the southern part of the metropolitan area, with no advisory for Jefferson County, which contains downtown Birmingham. This was a very low-QPF, yet high-impact event. Several factors were working against forecasters in this event during the 12–24 h prior:

1) A major ice and snow storm was being output by most computer models across southern Alabama, and attention was focused there;
2) Extremely cold air temperatures and resulting high SLR's and rapid accumulation, rare in a Birmingham snow event, may not have been taken into account in areas where light snow was possible;
3) The RAP model was not fully used at that time, and it showed the ideal conditions aloft for low-density, high SLR snow;
4) The extremely cold air temperatures also led to rapid refreezing of the snow when it melted due to vehicle pressure, an uncommon process in Alabama;
5) Rapid cold advection was occurring during the prior 12 h;
6) Few personal analogs for major snow events in north Alabama during cold advection existed;
7) Winter weather impacts and snow amounts are sensitive to only small errors in model QPF, especially when SLRs are very high; and
8) The low RH and large dewpoint depressions, during normal temperatures in Alabama, would preclude surface precipitation, but with the extremely low temperatures, saturation deficits were unusually small.

Despite the extremely cold surface temperatures and radar observations the morning of the event, no advisories nor warnings were issued by NWS for Jefferson County in the main forecast package (issued around 1000 UTC). This package would be used by most TV meteorologists in morning newscasts. The possibility of greater accumulation was not mentioned either. Radar indicated widespread virga, extending at least 125 km northwest of KBMX at 1130 UTC, and the virga base was descending rapidly between 1000 and 1400 UTC. The air was very dry, but the amount of sublimation required to saturate the air at such cold temperatures was very low. With air temperatures of –6°C and descending virga, in retrospect, the confidence displayed by forecasters that no snow would accumulate, and there would be no travel problems, was misplaced. As shown in Fig. 15, radar observations easily could have prompted advisories by 1300 UTC (7:00 am CST), likely allowing time for most people to get safely home from school and work. Snow began to reach the ground in the Birmingham area between 1500 and 1600 UTC.

In addition, the question of whether or not air temperatures and, more importantly, road surface temperatures, should become a part of winter weather advisory and warning criteria, is valid. With the spread of RWIS road surface temperature sensors across the southeastern U.S., and especially given what happened on 28 January 2014 with only 5 cm of snow accumulation (that, by the book, would not have verified a winter storm warning anyway), perhaps they should be. Ultimately, it is the impact on the public, in this case mainly their ability to drive, which is the reason for warnings and advisories. NWS Instruction 10-513, "WFO Winter Weather Products Specification," states: "*Protection of life and property takes precedence in decision making processes. As such, criteria for winter storm watches, warnings and advisories are considered as guidance only, not strict thresholds.*" Given that Southern States are unlikely to invest in the infrastructure needed to mitigate an event like this, our opinion is that air and road temperatures should be part of the warning and advisory criteria, or at least considered by forecasters in every event, anywhere in the United States.

One of the reviewers asked if we would be in the same "pickle" if this type of event happened again in January 2020. Hopefully, this paper will make that less likely for operational forecasters, wherever this type of event occurs. First of all, the relatively high-resolution models (RAP, High Resolution Rapid Refresh, etc.) performed better in this event than the operational models of that era did, and those models are mainstream in operational forecasting now. Also, to their detriment, forecasters seemingly focused more on model output than on real-time radar and surface data, and continued to focus on southern Alabama as the main location for a winter storm, likely due to persistence. In a sense, forecasters had become myopic, placing undue trust in previous forecasts and computer model output. On 28 January 2014, we did not "look out the window." Instead, we remained confident in the forecast and reacted only once serious travel issues began. This was one of the largest forecast "busts" in many meteorologists' careers, considering the impact of the forecasting and warning. In such difficult situations where a county warning area or designated market area is large and a weather system is complex, operational meteorologists must frequently step back and note real-time observations and react accordingly, even if they go against the numerical models and that person's experience.

ACKNOWLEDGMENTS

The authors wish to thank Rodger Getz of Agricultural Weather Information Service, Inc. for soil temperature data, Jerry Waldman of Vaisala, Inc. for road surface temperature data, and the Iowa Environmental Mesonet for archived surface data. We also wish to thank Jill Gilardi of WBRC for thoughtful discussions regarding the event. Finally, most of the authors have experience as operational meteorologists (Coleman, 9 y in NWS and 3 y in TV; Dice, 22 y in TV; Darden 24 y in NWS; Laws 17 y in NWS), and wish to acknowledge the dedication and hard work of operational meteorologists everywhere, especially since operational people conduct themselves in a professional manner in the face of difficult public scrutiny. We also wish to thank the reviewers, Dan Nietfeld, Joey Picca, and John Knox, whose insight and additions made this paper so much better. This research was funded by the National Science Foundation under grant AGS-1247412.

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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Daniel D. Nietfeld):

Initial Review:

Recommendation: Accept with major revisions.

Overall Summary: This submission describes a rare, extreme, winter precipitation event in Alabama with a significant impact to society and associated forecasting and communication challenges. The authors are commended for taking a close examination at an event that proved to be challenging for them to operationally forecast. Their pursuit to understand the characteristics of the event is a very worthwhile endeavor, for them and for readers to learn from. The manuscript captures many key aspects, but needs major revisions before it is ready for publication. This is a case review, and some important details of the data, chronology, events, and actions are missing and leave the reader trying to fill in the gaps, or needing to make assumptions. Furthermore, there are some general concerns with the data and methodology of the case review, as described below.

Thank you for your thorough review of our paper. We have made some fairly significant changes and additions based on the concerns you raised. The paper is now much better and more thorough! Please note that some figure numbers have changed, and even some section numbers since the former section on road temperatures was integrated into the section on cold temperatures.

Major Concerns: A primary concern is the general use of model data in the study. The following points must be addressed, with significant reasoning or additional data provided, if the manuscript is to achieve publication quality.

1. The authors rely heavily on the North American Model (NAM), especially to examine the temperature and moisture profile of the atmosphere, however they also point out significant errors in the NAM's prediction of the event. The authors do note the unfortunate problem with the BMX radiosonde having large errors in dewpoint at low levels, so some model data is understandably needed. However, a) there is no reference to the model run or lead time of the NAM sounding used, and b) there is no reason given as to why the NAM was chosen. This second point is important, and expanded on below in item #2.

   You're correct. The NAM performed poorly in this event until the 12 UTC runs on 28 January, which came in too late to help with the forecast. However, given that the NAM was the primary model examined (especially on the day before the event) and its output was very similar to the WRF (see new figure), the QPF maps from the NAM are still shown. Model initialization times are added in several places in text and figure captions. See further changes below.

2. Other (often more appropriate) model data was available such as the RAP and HRRR models which assimilate observations, and initialize, much more frequently (every hour). The RAP and/or HRRR are never mentioned in the manuscript, which is a major shortcoming. The RAP was operational at the time of the event and available in the WFO on AWIPS, and the early morning AFD from Jan. 28, 2014 specifically mentions the RAP (referred to as "RUC" in the AFD), the HRRR, and 4KM WRF. If the point of the use of the model is to provide the closest estimation to the observed atmosphere, there are references available showing the advantages of the use of the RAP (previously known as the RUC) such as: Thompson, R.L. and R. Edwards, 2000: A Comparison of Rapid Update Cycle 2 (RUC-2) Model Soundings with Observed Soundings in Supercell Environments.

   The model sounding used for BMX (Figure 4) was replaced with a RAP sounding, as you suggested. The other figure that used this sounding data (vertical profiles of rv, rvs, and saturation deficit, old Fig. 9) has been redone using the RAP sounding data. According to NOAA, the HRRR was not implemented until 30 September 2014.

3. The GFS is mentioned later in the manuscript, but not until section 4. This is fine to include other models such as the GFS, but there is no logic given as to what is included or why.

   The GFS graphic (old Fig. 12) has been removed. We have added a new figure showing the performance of each run of 4 models (WRF, RAP, NAM, and GFS) in predicting the liquid water equivalent precipitation at BMX. Clearly, the RAP indicated a lot more precipitation than the other 3 models once it got in range of the event, and should have been taken more seriously during the overnight hours. Ironically, the GFS also handled the liquid QPF better. This is all discussed in a partially overhauled section 4a and beginning of 4b (and shown clearly in the graph).

4. With all model data, providing the initialization time and forecast hour are important temporal reference components (as mentioned in item #1A above). This applies to the text as well as figures (e.g., Fig. 2 of 300-hPa heights).

   Done. For SPC mesoanalyses in Fig. 2 and Fig. 3, pointed out that times are 1-h forecasts from RAP.

5. The model data presented is deterministic, with no mention of ensemble solutions or probabilistic information. For such a high-impact event, even low probabilities from sources such as the SREF, or WPC's probabilistic winter precipitation guidance could have been useful and provided insight into the predictability of this event and would certainly be relevant to the NWS's current focus of providing decision-support services through the communication of various scenarios. I realize the authors chose to only include a limited set of deterministic model data, but in an era when ensemble-based probabilistic solutions are becoming the norm, this leaves the readers with a narrow perspective on the predictability of this event. Providing the reasoning of the choices of data to include seems important here, especially if additional model data cannot be included.

   We have included a lot of new model data (specifically from RAP and WRF), but have been unable to locate SREF data for the event 5 years ago. NOAA webpage said that event was not available. Regarding WPC probabilities of snow amounts, we did locate those, but the lowest amount archived from that time is the map showing probability of 4" or more of snow. The 28/0000 UTC showed no such probability anywhere in Alabama, and the 28/1200 UTC only showed a 10–40% probability contour barely covering part of extreme east Alabama, well south and east of Birmingham. The charts were not shown, but a discussion of them was added to the text.

The second significant concern is the proclamation that the atmosphere was "extremely dry" as mentioned in the Introduction and again in section 2c. Although there isn't an accepted definition for "extremely" dry, the sounding from the NAM in Figure 4 doesn't seem extremely dry. It does indeed look dry, but as mentioned in item #1 above, it's not clear that the NAM was accurate, nor does the dew point depression appear to be especially large (approximately around 10˚C). This point might seem minor, but the dry atmosphere is mentioned as a key component to the challenging aspect of the event. Perhaps using other observed data, such as dew point depressions from surface METARs could help substantiate this claim.

I suppose the definition of "extremely dry" is subjective. To us, a T_{dd} of 10°C is not necessarily extremely dry, but surface dewpoints (from an ASOS) of −17 °C in Alabama are 3 sigma even for DJF (I have data back to 1948 at BHM). We changed the wording to "very dry" in the abstract, introduction, and in Section 3c, and we do include the above mentioned surface dewpoint. We also added a note about the 3-sigma dewpoint. The dry air was a problem with the forecasting, however, as many of us thought the dry air would prevent much precipitation from reaching the ground. Hopefully this is satisfactory.

A third significant concern is how the authors address snow/liquid ratios and snow fall rates. There is a lack of addressing the factors that lead to the high snow fall rate, which appears to be a critical aspect of the event and associated forecast challenges. This is touched on in section 3e, but this should also include an investigation of the observed or anticipated snow flake/crystal type. It is also related to the snow-liquid water ratios as discussed in section 2e, but is less a function of air temperature and more of a function of snow growth factors such as distributions of vertical motion, temperature, and humidity. There are numerous references for this, including:

Cobb, D. K. and J. S. Waldstreicher, 2005: A simple physically based snowfall algorithm. Preprints, *21st Conf. on Weather Analysis and Forecasting/17th Conf. on Numerical Weather Prediction*, Washington, DC, Amer. Meteor. Soc., 2A.2. [Available online at http://ams.confex.com/ams/pdfpapers/94815.pdf].

Furthermore, section 2e, is problematic in that the authors state, "Surface temperatures between −6°C and −8°C are associated with SR between 20 and 30" but the referenced Fig. 6 shows SR values ranging more broadly than that—from around 12 to 35.

We completely agree and have overhauled Section 3d to include a paragraph on low-density ice-crystal formation in areas with upward vertical motion, temperatures near –15°C, and high RH. We also added a figure showing RAP vertical motion and the likely layer of low density snow crystal growth. We have cited Cobb and Waldstreicher (2005) and two other sources. The paragraph on the result of the high SR was moved to Section 4c. These corrections were, perhaps, the single most important improvement to the paper. Thank you for the direction.

We disagree regarding Fig. 6. While it is true that surface temperatures between –6 and and –8°C have cases of SR ratios from 12 to 35, the core shape of the distribution is centered on 20 to 30 as was observed here, and the correlation exists. Unless the editor feels we should change this or remove it, we prefer to leave it alone.

The fourth concern is that the use of soil temperatures in section 3d is of questionable value. I understand the desire to assess how frozen the ground was that the snow was falling on, however: a) the 10-cm-deep sensors are well below the surface, and b) the statement, "Interpolation of 10-cm soil temperature readings indicated values in Birmingham near 6°C" actually does not support the point the authors are trying to make (i.e., subfreezing ground). I suggest emphasizing the road-surface temperatures, which are actually more related to the traffic problems. This would necessitate changing the title of section 3d to something such as "Road temperatures" as opposed to "Soil temperatures."

The above paragraph also raises the question of whether or not the heat from the soil (a few cm below the surface) was warm enough to melt the snow upon falling on the road and then the liquid rapidly freezing due to the sub-freezing temperature of air just above the road. This challenges the conclusion in section 2b and section 5 of the melting due to the "vehicle compaction (pressure melting), or by vehicle tires spinning."

We changed to only casually mention the 10-cm soil temperature and to accentuate how quickly road surface temperatures can change. We do not believe that heat conduction from below the surface was the cause of the melting and refreezing of the water, because in areas where no vehicle compaction occurred (for example, the lead author's back patio), powdery snow was present as opposed to ice (photograph with Beagle). Therefore, we would prefer to leave this discussion out of the paper, but can include it if the editor thinks it is relevant.

The fifth concern is that the title of section 4 is "Forecast challenges"; however, this section seems to be more about challenges related communication or "messaging". In prior sections, the authors describe challenges that are related to the prediction of the snow and slipper roads, which seem to be characterized as challenges for forecasting those elements. It appears that the authors are really trying to emphasize that, because of the lack of understanding that enough snow would fall on subfreezing roads to cause major traffic problems, actions were not taken to ***communicate*** the hazardous conditions to partners and the public. I suggest revisiting this section, providing a more accurate name, and then providing a more detailed chronology of the forecast services (e.g., products) provided and other details. This chronological format is how the section is already laid out, but additional details are needed. For example: "An update at 1241 UTC extended a winter weather advisory northward into Shelby County." This is the first mention that an advisory was issued, which seems like a significant point. Readers will likely want to know what products were issued and when, what snowfall amounts were forecasted, and how these evolved with time. Please include model initialization times, forecast hours, and lead times.

We disagree that this was entirely a "messaging" problem, as forecasters simply did not expect the amount of snow that fell, nor its impacts. However, messaging was part of the problem, and we have changed the title of the section to "Forecasting and warning challenges". We do like the chronological layout of this section and leave it this way. We provide much additional detail regarding forecasts and winter weather advisory and winter storm warning issuance times, locations, and wording. We also provide model QPF from different initialization times. A new figure was added showing model liquid QPF from 4 models (RAP, WRF, GFS, NAM) at several different initialization times before the event. These were significant improvements to Section 4.

[Minor comments omitted…]

Second Review:

Recommendation: Accept.

REVIEWER B (Joseph C. Picca):

Initial Review:

Recommendation: Accept with major revisions.

General Comments: This paper examines a high-impact, poorly forecast winter-weather event in the Birmingham metropolitan area. Analyses such as these are of critical importance for the operational community, as they can draw attention to critical aspects of both the forecast process and societal impacts. This analysis performs reasonably well at highlighting the importance of observational data and drawing conclusions about future best practices. With that said, there are several concerns I have with the organization, questionable analyses, speculative arguments, and several of the figures. They are summarized below. Major comments are annotated.

Thank you for your thorough review of our paper. We have made some fairly significant changes and additions based on the concerns you and Dr. Nietfeld raised, especially in the area of snow physics and dual polarization radar detection. I have organized this response as you did your comments. Please note that some figure numbers have changed, and even some section numbers since the former section on road temperatures was integrated into the section on cold temperatures. The paper is much better now and we're more proud of it.

Major Comments: I think more detailed information could be provided on the expected presence of crystals aloft. Dual-polarization signatures at colder temps can reveal the presence of crystals (higher Z_{DR} associated with light Z). That would be much better than a simple reference to a probability of ice crystals based on a past study. Use the data from this event instead!

Additionally, the sounding in Fig. 4 suggests potential for crystals at colder temperatures than −12°C (i.e., it still looks saturated at higher altitudes). What did radar say? Based on Fig. 13, I can see echoes all the way to at least 75 km from radar on the 4.5° scan. That's a lot higher than 4 km AGL. Your crystal generation zone extended to much colder temps than -12 C, and this would be consistent with higher SLRs (which was a function of more than just cold ground temps). This part of the analysis needs to be revised because I do not think it is accurate based on the information provided.

On the topic of SLRs, you should mention that much more goes into them than simply the surface temperature. Yes, this is important, but the preferred crystal generation zone is critical to SLRs. In other words, what is the temp, RH, omega at the level where we're generating crystals? I think you have some answers in your data (i.e., it was saturated/quite cold 5–6+ km AGL where crystals were initially forming), but you fail to highlight that. That is just as critical, if not more, than the cold surface temps.

On the second point about the efficient accumulation of the snowflakes, I have a question: How is this any different than the discussion on high SLRs? I could make an argument that high SLRs and quick road accumulations are worth two separate points, but these are closely related. Would focus this discussion more on the cold road temps, vs the air temps. That is a little more distinctive.

Based on a combination of your and Nietfeld's comments, section 3e now connects the rapid fall of snow to the high SR ratios. It contains information from the RAP sounding (new Fig. 4), including the temperatures near -15°C collocated with high RH and significant vertical motion. This produced a snow formation zone with low ice crystal density (high SR). References to Cobb and Waldstreicher (2005), Fukuta and Tashahaki (1999), and Libbrecht (1999) were added.

A brand new Fig. 11 has been added, showing a 3.4° PPI scan of Z and Z_{DR}. This shows the pristine crystals aloft (low Z and high Z_{DR}), and more aggregates below 3 km AGL (higher Z and lower Z_{DR}), below a layer of air above –5°C. A new paragraph was also added to section 3e discussing this dual-polarization radar data.

The relation of the SR to surface temperatures was kept, since there is a correlation shown by Byun et al. (2008), and it occurred in this case. It was also climatologically abnormal for the Southeast (as shown in Fig. 7). If the editor wants us to we remove this, we can, but we would prefer not.

We agree regarding the importance of road temperatures, and have combined the section on cold road temperatures into this section. We also shortened some of the paragraphs to avoid redundancy and put a focus on cold air and road temperatures.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revisions.

General Comments: I am quite satisfied with the changes incorporated by the authors. The scientific background has been bolstered considerably and now illustrates many important “take home” points that readers can apply in their own operational work. Most of my comments are fairly minor, but there remain some details that I think should be addressed.

Thank you for another detailed review of our paper. Your first review was very thorough and made the paper much better scientifically, and we appreciate your comments to that effect! This review helped us correct some glaring errors from a stylistic point of view, and made the figures better.

[Minor comments omitted…]

REVIEWER C (John A. Knox):

Initial Review:

Recommendation: Accept with minor revisions.

Summary: This is a valuable study of a high-impact, low-water-equivalent snowstorm that eluded the forecasting abilities of experienced public-sector and private-sector meteorologists. The authors, who were among those who took the brunt of the blame for the forecast bust, do an admirable job of assessing the scientific reasons for the bust while also holding themselves accountable for the bust. The scientific explanations are very plausible and reflect deep after-the-fact thought and analysis.

In terms of any additions in this regard, my only question is the typical one I have for case studies of busts: would we be in the same pickle today, or more accurately next winter, if it happened again? Have there been any improvements in NWP that would make it an easier forecast, or would we have the same exact challenge, in January 2020?

I have embedded minor corrections and comments in the attached manuscript.

Well done!

Thanks for the kind words. It was a wild event for us. As far as whether or not we would be in this same pickle again, I don't think so if we actually: a) utilize the high-resolution models that are more mainstream now, (like the RAP and the HRRR), and b) get out of the models and look at radar and surface observations when the event is only 6 h away. That is one of the key takeaways of this paper, and we do further accentuate that fact in the conclusions, and make a point about the question you asked.

[Minor comments omitted…]

Second Review:

Recommendation: Accept with minor revisions.

General Comment: An already interesting and valuable manuscript has been improved in revision. I have minor comments and one somewhat more substantive scientific point.

The reference to warm air advection and vertical motion is presumably an allusion to QG theory, in particular the omega equation. However, in that equation, omega (that is, negative omega, i.e. $+w$, the vertical motion) is proportional to the negative of the *Laplacian* of temperature advection, not warm advection itself. This actually could strengthen your case a bit. While the temperature advection over north-central Alabama was small, the cold temperature advection to the north, over southern Tennessee, was large. This large change over a small spatial distance suggests that the *Laplacian* of temperature advection might be big. If my back-of-the-envelope calculations re: second derivatives are correct, this configuration would have resulted in a not-small negative value for the Laplacian of temperature advection over north-central Alabama. And that would give a positive contribution to vertical motion via the omega equation. You can check my math and/or directly calculate the QG forcing term to see if I'm right; if so, this would reinforce your point in this section a little better than the present discussion does.

Wow. OK. Never quite thought of it that way. Obviously the first derivative with respect to y of thermal advection is negative, but the derivative becomes larger with y from the weak warm advection over south AL to the strong cold advection over north Alabama. Per Holton (1992) QG omega equation, since the gradient in cold advection is increasing as you go north, that would mean a very negative Laplacian, so a larger vertical motion. I am going to ease this in so as to not scare too many readers off with QG omega, much less a Laplacian. Added a reference to Holton.

[Minor comments omitted…]

Thanks to the editor for the opportunity to review this manuscript. It reminds me of the very best contributions in the old "Forecasters' File" at the Birmingham WSFO back in the 1980s, and will be widely appreciated by forecasters throughout the South (at least) for its thoroughness and candor.

Thanks for the kind words at the bottom of your review! You obviously hung around my old stomping grounds (lead author) at BHM WSFO when Bill Herrmann, Felipe Tobias, Joe Wheeler, J. B. Elliott, and Bob Deitlein were there. I started working there in 1991, at age 16. Hopefully this will help forecasters, especially in the Southeast.