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Observations of atmospheric waves that moved across northern Alabama on 4 December 2008 using the ARMOR Doppler radar and the Mobile Integrated Profiling System

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1. Introduction

This paper examines the passage of an atmospheric bore and a cold front that propagated across northern Alabama on 4 December 2008. The atmospheric bore developed in northern Mississippi as a result of a convective line that had propagated away from a cold front moving eastward across the Mississippi Valley. The bore helped to sustain convection several hundred kilometers ahead of the cold front. When the cold front moved into northern Alabama, RHI scans perpendicular to the front were conducted with the Advanced Radar for Meteorological and Operational Research (ARMOR; Petersen et al. 2005). Shallow, stratiform rainfall behind the front revealed interesting wave-like features propagating atop the cold airmass. The bore and these waves are examined in detail using radar data, surface observations and local thermodynamic profiles.

An atmospheric bore is a type of gravity wave that can be initiated when a gust front forces stable air upward (Koch and Clark 1999; Knupp 2006). Accompanying the bore, may be a wind shift in direction of its propagation, a sharp pressure rise (or hydraulic jump) and enhanced vertical motion. Temperature changes near the surface may also occur, but they can be negligible (Mahapatra et al. 1991) or there may be a quick temperature rise (Clarke et al. 1981) or there may be some cooling as the gust front arrives (Koch et al. 1991).

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2. Synoptic Overview

A 500 mb trough is draped along the Plains at 00 UTC on 4 December 2008 (Figure 1a). At the surface, a cold front extends southwest from an area of low pressure centered in southern Canada across the mid Mississippi Valley into southern

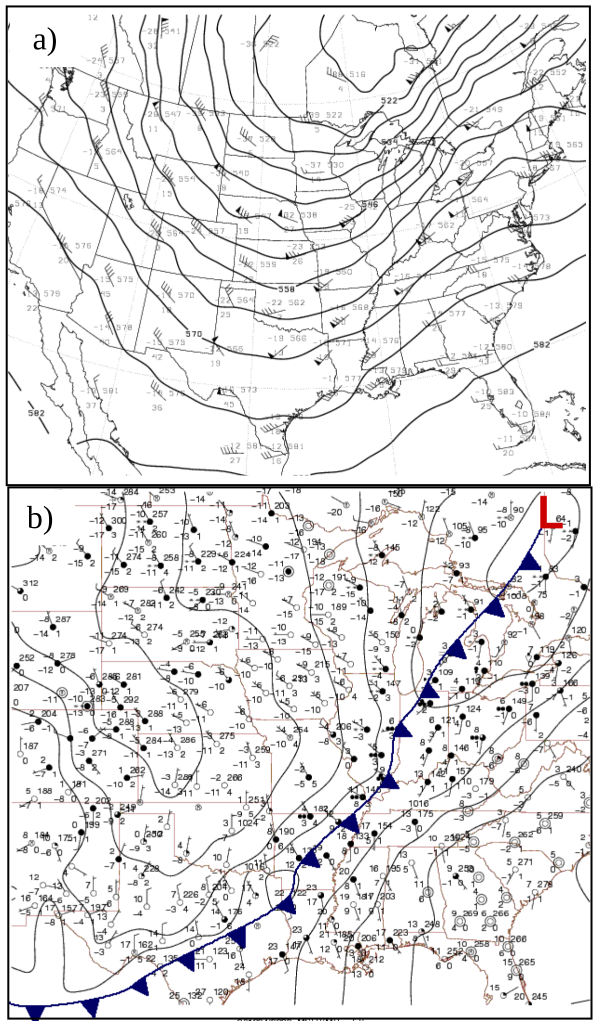

Figure 1. (a) 500 mb heights (dm) and winds (kts) and (b) surface observations at 0000 UTC on 4 December 2008.

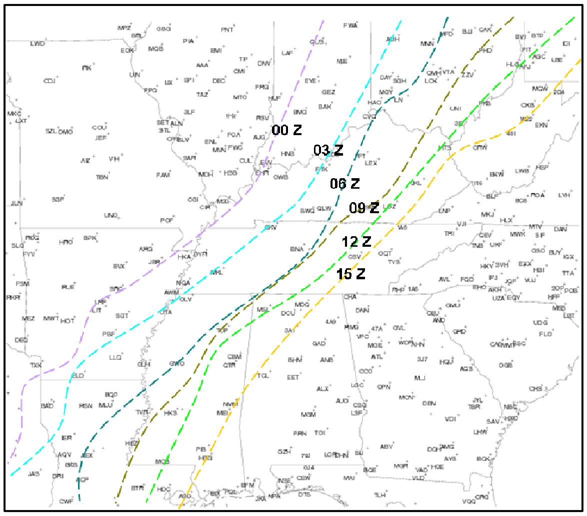

Figure 2. Isochrone analysis of the cold front position between 0000-1500 UTC on 4 December 2008.

Texas (Figure 1b). The wind field at 500 mb is parallel to the surface front over the southern states, which hinders the eastward progression of the front after 0000 UTC. The present weather symbols in Figure 1b indicate an area of rainfall across Arkansas, Missouri and Illinois, along and behind the front. The NEXRAD mosaic at 0000 UTC (not shown) reveals scattered convective precipitation along the front in Arkansas. By 0300 UTC, stratiform precipitation had increased in aerial extent behind the front, and the convection became focused in a narrow line along the front. Between 0300-0900 UTC the line of convection and trailing stratiform precipitation moved eastward across northern Mississippi, ahead of the front.

Figure 2 shows the progression of the cold front across the southeastern states between 0000-1500 UTC. Surface observations (not shown in Figure 2) indicate a region of trailing stratiform precipitation behind the front at 0600 UTC and a line of robust convection in northeastern Mississippi. Three hours later, the front made little eastward progression across northern Mississippi, but the line of convection continued eastward into northern Alabama ahead of the front. The near-surface winds across northern Alabama between 0600-0900 UTC shifted from southerly to the northwest as the line of convection moved across the state. This change in wind direction between 0600-0900 UTC is coincident with the passage of an atmospheric bore.

By 0900 UTC, the cold front had just entered the far northwestern part of Alabama and near-surface winds ahead of the front backed to the south. The cold front had moved across northwest Alabama by 1200 UTC and was catching up with the decaying convection that had outrun it earlier. However, much of the trailing stratiform precipitation behind the front had now dissipated across northern Mississippi. Between 1200-1500 UTC, the front moved across northern Alabama and winds shifted to the northwest as a result. Also, during this time precipitation had redeveloped behind the cold front as it moved across eastern Mississippi and the northwestern quarter of Alabama. This provided the opportunity for a detailed look using the ARMOR radar at the vertical structure of the cold front as it moved across northern Alabama.

3. Atmospheric bore

Figure 3 shows surface observations between 0600-1600 UTC from NWS/FAA ASOS sites in Northeast Mississippi and northern Alabama. At Tupelo, MS (TUP) between 0610-0620 UTC, a hydraulic jump of 2 mb was recorded along with a brief increase in wind speed to 7.5 m s^{-1} and a wind shift (Figure 3a). The wind shift and hydraulic jump were also accompanied by a decrease in temperature and increase in dewpoint temperature, which was caused by rainfall from the line of convection that had moved across the region in advance of the cold front. Between 0640-0650 UTC, the wind direction became northerly at TUP. This wind shift to the north around 0645 UTC was not accompanied by an increase in pressure as observed 20 min prior. Outflow from nearby convection is likely what caused the northwest wind shift

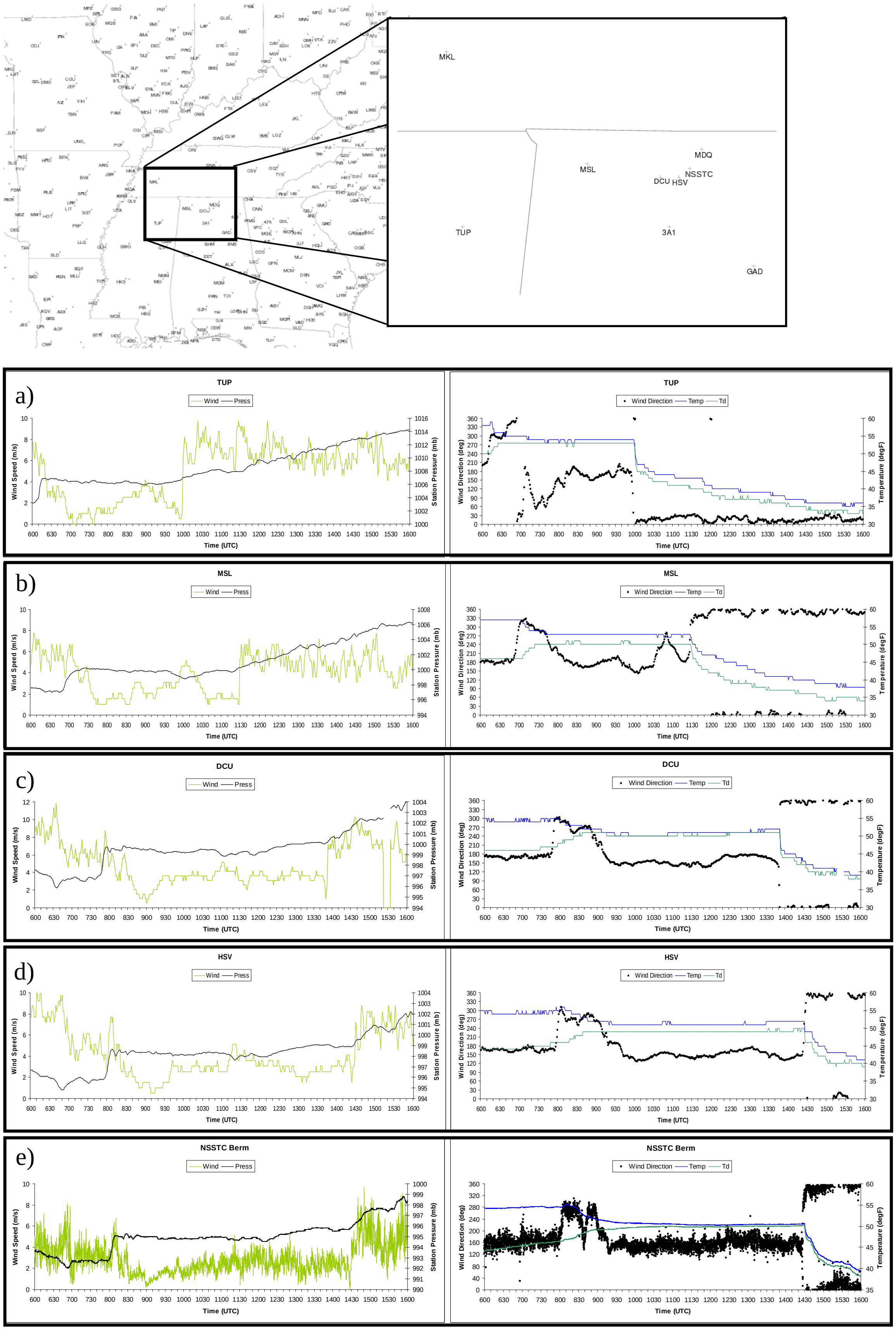

Figure 3. Time-series of surface data from (a) TUP, (b) MSL, (c) DCU, (d) HSV and (e) NSSTC Berm. Plots (a-d) are 1-min resolution and (e) is 5-sec resolution. The map above shows these locations.

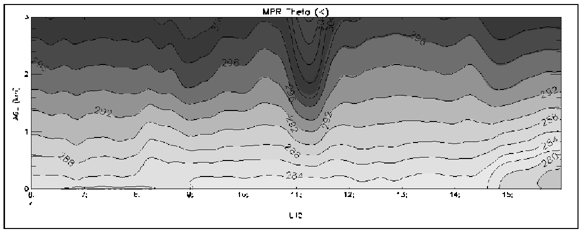

Figure 4. Time series of potential temperature (K) retrieved from the Mobile Profiling Radiometer located at the NSSTC berm (see map in Figure 4).

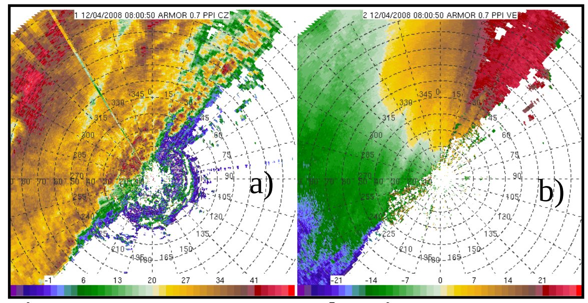

Figure 5. ARMOR 0.7° elevation scan at 0800 UTC showing (a) reflectivity (dBZ) and (b) radial velocity (m s^{-1}) of precipitation behind the bore.

at 0645 UTC. This also explains the further cooling and moistening observed at 0645 UTC.

A similar pressure trend was observed further east at the Northwest Alabama Regional Airport in Muscle Shoals, AL (MSL). At MSL, a 2 mb pressure increase occurred between 0650-0710 UTC and it also was accompanied by an increase in wind speed to 7 m s^{-1}, wind shift, cooling and moistening (Figure 3b). Similar 2 mb increases in pressure were recorded at Pryor Field in Decatur, AL (DCU; Figure 3c) and the Huntsville International Airport in Huntsville, AL (HSV; Figure 3d). However, the pressure trend at DCU and HSV exhibited more variation immediately after the hydraulic jump than did the TUP and MSL observations. Furthermore, the wind speeds at DCU and HSV during the hydraulic jump increased by 4-6 m s^{-1}, whereas the wind speed increases at TUP and MSL were only around 1-1.5 m s^{-1} during the hydraulic jump.

A comparison of the hydraulic jumps in Figure 3 was conducted to determine the speed of the bore, which was moving southeast across the region. The bore speed was 12 m s^{-1} between TUP and MSL between 0615-0650 UTC. Its speed increased between MSL and DCU to 14m s^{-1} and further accelerated between DCU and HSV to 22 m s^{-1}. However, after 0800 UTC, the bore speed decreased to 11 m s^{-1} as it moved between HSV and the NSSTC. Interestingly, the first relatively significant pressure variation after the hydraulic jump occurred within 5-min of the jump at DCU and HSV, whereas at the NSSTC the first relatively significant pressure variation occurred between 0815-0840 UTC, 10 min after the hydraulic jump (Figure 3e). This discrepancy between pressure trace responses after the bore passage is perhaps attributed to the deceleration of the bore between HSV and NSSTC. Similarly, the lack of any significant pressure variation immediately after bore passage at MSL and observed pressure variation between 0755-0820 UTC at DCU is perhaps a result of the increased bore speed between MSL and DCU.

An isentropic profile from a mobile profiling radiometer located at the NSSTC is shown in Figure 4. A vertical increase in the height of the isentropes occurred just after 0800 UTC. The vertical growth of the isentropes is indicative of the boundary layer depth increasing and decreasing static stability after the bore passage. This destabilization helped to sustain convection, which was detected by the ARMOR radar in northern Alabama at 0800 UTC (Figure 5), well ahead of the cold front.

4. Gravity waves atop the cold front

By 1340 UTC, the cold front was within 20 km of ARMOR. Figure 6 shows the reflectivity and radial velocity relative to ARMOR at 1345 UTC. The convergence along the front at this time was 60 x 10^{-2} s^{-1} and there was a line of growing cumulus along the front, but reflectivity associated with these cumulus clouds was only 20-

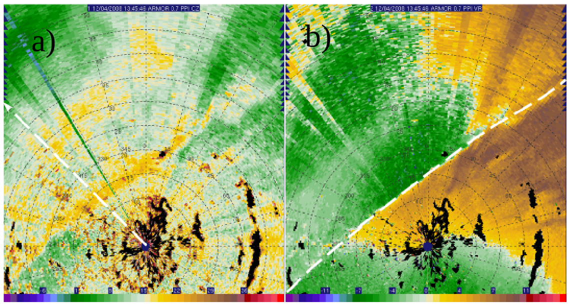

Figure 6. ARMOR 0.7° elevation scan at 1345 UTC of (a) reflectivity (dBZ) and (b) radial velocity (m s^{-1}). The dashed line in (a) is the azimuth of the RHI scans and the dashed line in (b) represents the convergence zone associated with the cold front.

27 dBZ (Figure 6a). At 1340 UTC, RHI scans across the cold front were conducted with the ARMOR radar. A sequence of reflectivity scans between 1350-1408 UTC is shown in Figure 7. The reflectivity field shows two distinct air masses. A shallow, denser airmass extends roughly 0.7 km above the radar level (ARL) and the other airmass exists in a layer extending from 0.5-2.0 km ARL. The reflectivity layer extending from 0.5-2.0 km ARL is the trailing part of a precipitating cloud that had caused very light rainfall to be reported at HSV between 1300-1345 UTC. The radar is also detecting non-precipitating clouds above 2.0 km ARL. At 1350 UTC, the 0.5 km lower airmass extends 10 km horizontally from the radar and deepens to a depth of 1.5 km about 15 km away from the radar. However, the opposing flow in the radial velocity field (see Figure 8) verifies this is in fact two separate air masses. The streamlines annotated at 1350 UTC show airflow within the very shallow air mass closer to the radar extends 10.5 km from the radar and then it rises vertically up and over a denser airmass collocated with the leading edge of the cold front. Between 18-20 km away from the radar and around 1500 m height, atop the denser air associated with the cold front, a wave-like feature is present.

The next RHI scan shown in Figure 7 (1355 UTC), shows the front has moved roughly 2 km in the previous 5 min thus giving it a speed near 16 m s^{-1}. The wave atop the cold front is much more

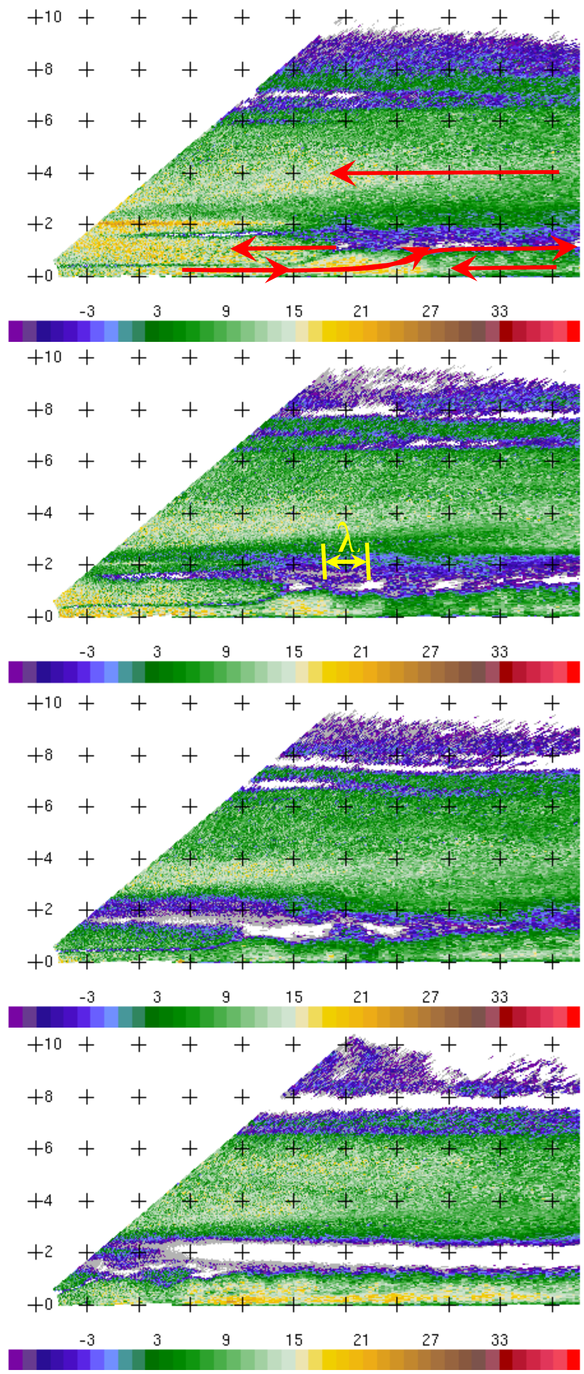

Figure 7. A sequence of RHI scans showing reflectivity (dBZ) perpendicular to the cold front. Times shown (a) 1350, (b) 1355, (c) 1401 and (d) 1422 UTC. Vertical and horizontal distances (in km) from the radar are annotated on the abscissa and ordinate axes, respectively. The arrows in the (a) RHI denote the airflow relative to the radar. Note the reflectivity scale is only from -10 dBZ to 40 dBZ. The λ indicates wavelength.

pronounced and several wave crests exists between 10 to 20 km away from the radar. The wavelength of this wave is about 1.2 km

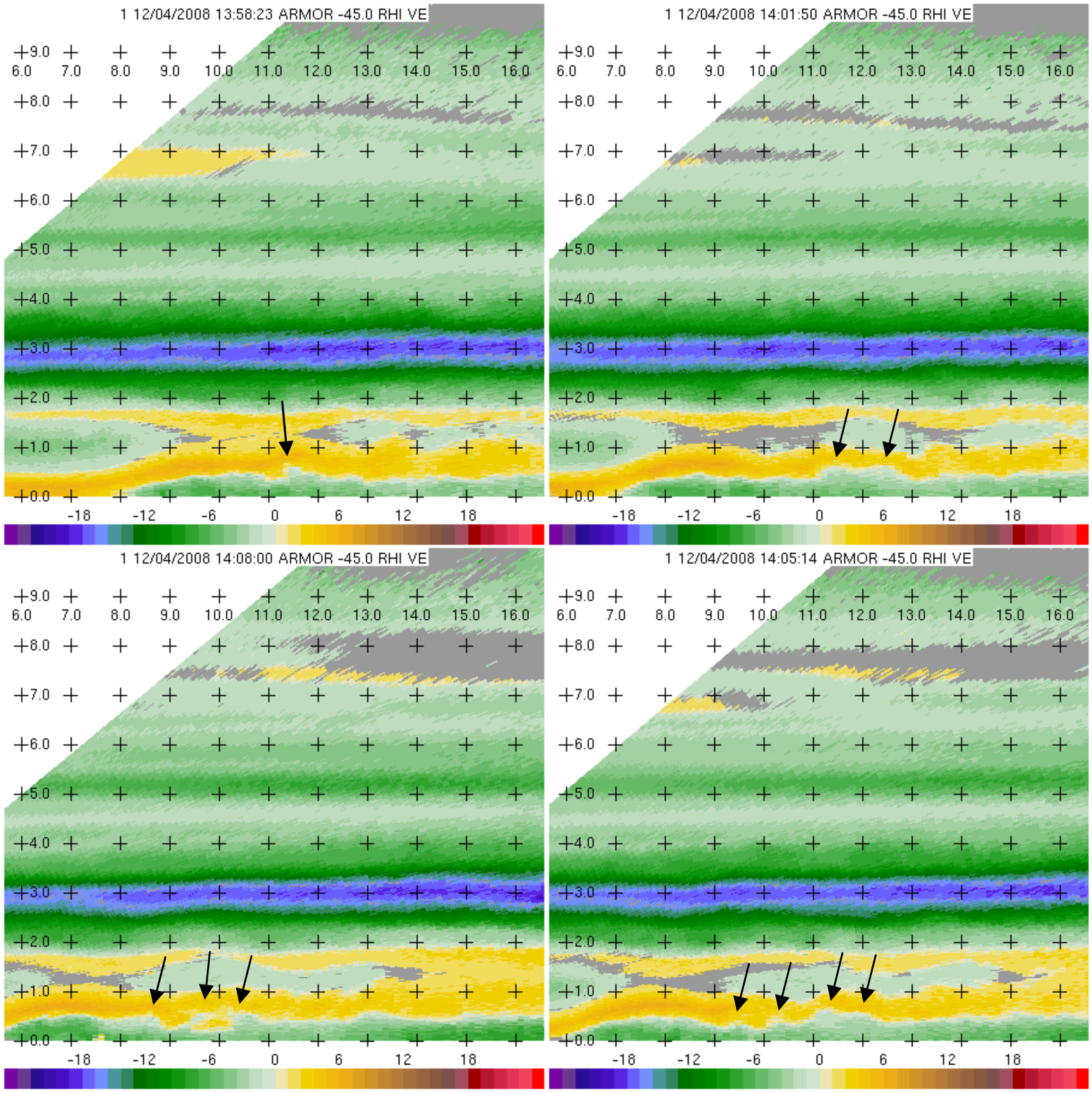

Figure 8. ARMOR RHI scans perpendicular to the cold front showing radial velocity (m s^{-1}). Times shown are clockwise from top left: 1358, 1401, 1405 and 1408 UTC.

(annotated in Figure 7b) and its amplitude is only 0.1-0.2 km. Radial velocities at the wave crests are 2 m s^{-1}, suggesting that the wave propagates 2 m s^{-1} faster than the cold front. The waves continued propagating atop the cold front through 1422 UTC, when the RHI scans were stopped. The vertical shear around 1 km ARL, between the denser airmass behind the cold front and warmer, shallower airmass being lifted over the front, could be the source of the waves. Vertical shear can lead to development of Kelvin-Helmoltz (K-H) instability in the shear zone, which can lead to gravity wave development (Fritz 1982).

In order to better visualize the nature of the waves, Figure 8 shows a zoomed-in radial velocity sequence taken from the RHI scans between 1358-1408 UTC. The strongest shear occurs around 0.5 km ARL. At 1358 UTC, the radial velocity field shows a distinct vertical perturbation about 11.5 km from the radar extending vertically from 0.5 km to 0.75 km ARL. By 1401 UTC, the vertical perturbation has become less distinct and has moved 0.25 km closer to the radar, but another vertical perturbation is developing at 12.5 km from the radar. At 1405 UTC, there are three well rounded wave crests present between 9.5 km and 12 km from the radar. These wave crests become more ragged by 1408 UTC, but there are three distinct vertical perturbations present 8.75, 9.5 and 10.5 km from the radar. The ragged wave crest at 9.5 km looks very similar to the initial stages of a K-H induced wave.

5. Summary

Two types of gravity waves were observed propagating ahead of and atop a cold front moving through northern Alabama on 4 December 2008. In the overnight hours, an undular bore was initiated from thunderstorm gust fronts, initially aligned along the cold front, which propagated hundreds of kilometers ahead of the front. This line of convection followed the bore eastward across northern Mississippi and Alabama. Pressure rises of 2 mb in a 10 min period were recorded from northeastern Mississippi and into north central Alabama with the passage of the bore. Although there was no temperature increase associated with the bore, the bore did deepen the boundary layer and as a result, convection was sustained well ahead of the cold front and immediately behind the bore. The bore accelerated as it moved across northern Alabama. Variations in the pressure trace recorded after the bore accelerated were larger than when it was moving at a slower speed. Thus these larger variations are attributed to the increased speed of the bore and the wave troughs and ridges that follow. A more detailed examination of the pressure variations immediately after a hydraulic jump may reveal better insight as to the response of the wave troughs and ridges to an acceleration of the bore.

Using the ARMOR radar, RHI scans conducted perpendicular to the cold front as it moved into north central Alabama revealed interesting waves propagating atop the dense airmass behind the front. A strong shear zone existed atop the shallow cold front and static stability was strong in the dense airmass below the shear zone. Thus these waves may be induced by Kelvin Helmholtz instability. However, further investigation of this case must be conducted to further support this hypothesis. Unfortunately, the shallow nature of this event does not allow for a dual Doppler analysis using ARMOR and the nearest NEXRAD. Thus we plan to utilize the UAH Mobile Alabama X-band radar (http://vortex.nsstc.uah.edu/mips/max/) in addition to ARMOR to collect data on other such gravity wave events and conduct dual-Doppler analysis to better resolve and understand the features and effects associated these gravity waves.

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