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Observations and Analysis of Atmospheric Waves During the Historic April 27, 2011 Tornado Outbreak

Todd A. Murphy, Timothy A. Coleman, and Kevin R. Knupp

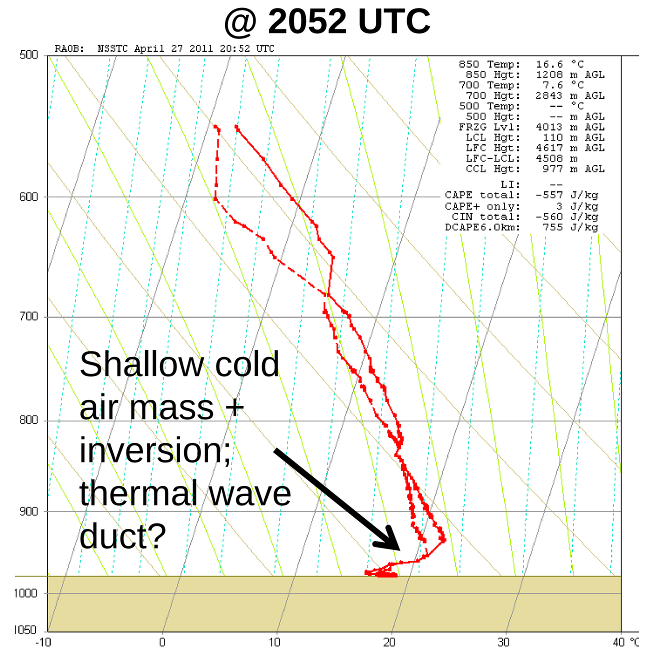
Severe Weather Institute-Radar and Lightning Laboratory, Department of Atmospheric Science, The University of Alabama in Huntsville

1. Introduction & Duct Analysis

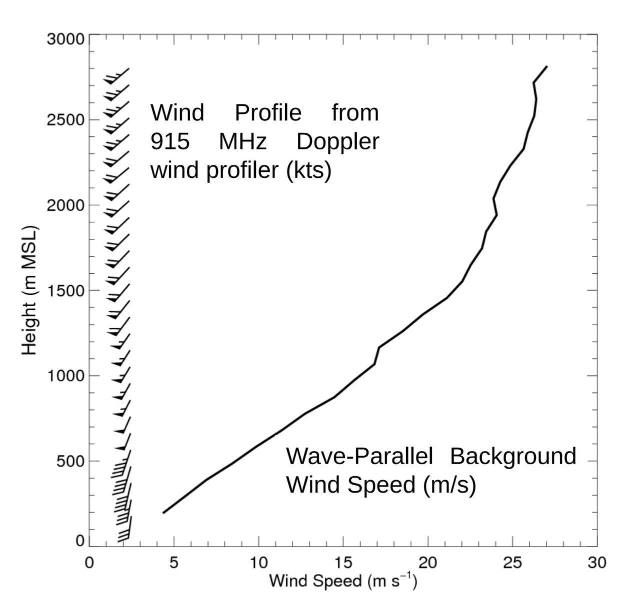
During the historic deep south tornado outbreak of 27 April 2011, early morning and mid-day convection helped establish a thermal boundary just south of the TN Valley. Surface observations around the area indicated temperatures near 60 ˚F around 1800 UTC, while locations ~160 km to the south were approaching 80 ˚F.

An atmospheric sounding launched from UAHuntsville's campus showed the TN Valley continued to be located on the cool side of the boundary as late as 2100 UTC. A shallow layer of cooler air extended from the surface (212 m MSL) to about 400-500 m.

UAHuntsville Sounding @ 2052 UTC



Wind Profiler Data



The atmospheric temperature profile above provides a potential thermal duct for the generation and propagation of ducted gravity waves (Lindzen and Tung 1976; Koch and O'Handley 1997). Internal gravity waves are reflected by the ground and layers with vertical gradients of m^2 (vertical wavenumber), thereby trapping the wave within a "duct" (Gill 1982; Nappo 2002). The vertical wavenumber is associated with gradients in the Scorer parameter l^2 (Scorer 1949) through $m^2 = l^2 - k^2$, where k is horizontal wavenumber, l^2 is

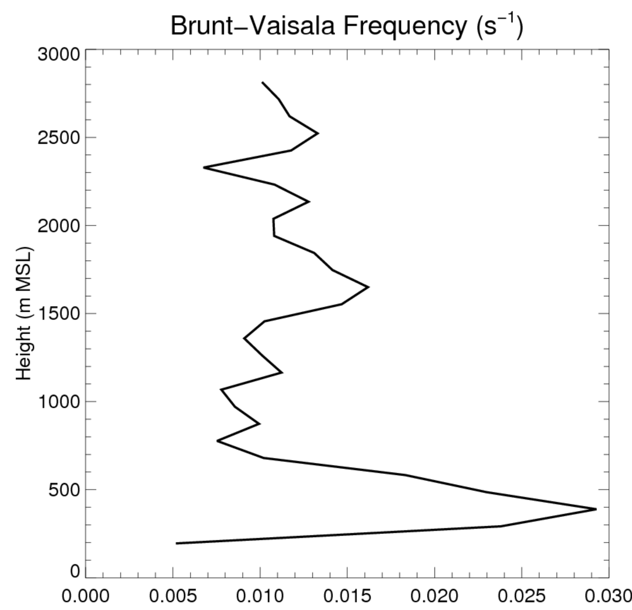
$$l^2 = \frac{N^2}{(c-U)^2} + \frac{\frac{\partial^2 U}{\partial z^2}}{(c-U)}$$

and c is the ground-relative wave phase speed, U is the mean wave-normal background wind (see above wind profile), and N is the Brunt-Vaisala frequency.

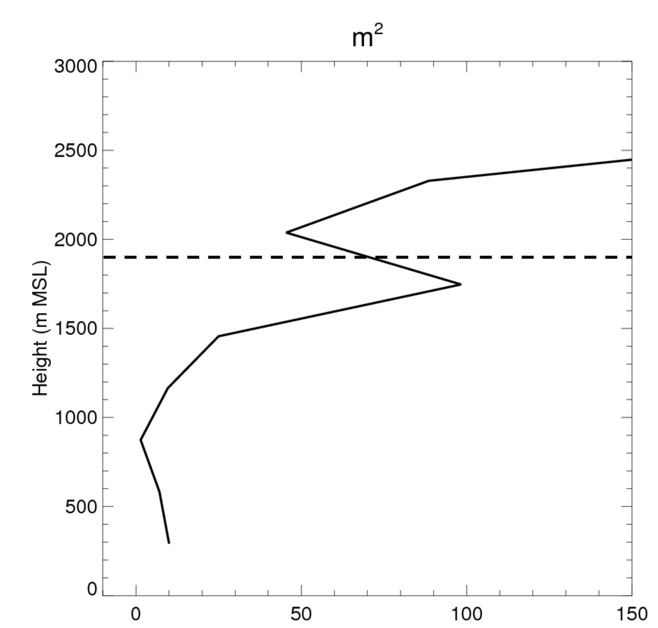
The wave duct analysis (below) shows a potential reflecting level near 1900 m, which indicates an environment supportive of ducted gravity waves. This has important implications, since gravity waves have been shown to initiate or enhance convection (e.g., Uccellini 1975; Stobie et al. 1983; Koch et al. 1988) and also increase the potential for tornadogenesis if they were to interact with a mesocyclone (Coleman and Knupp 2008). Additionally, the theoretical ducted wave speed is given by (Lindzen and Tung 1976):

$$c - U = \frac{2ND}{\pi}$$

where D is the duct depth. The potential wave duct below supports ducted waves with c = 26 m s^{-1}.

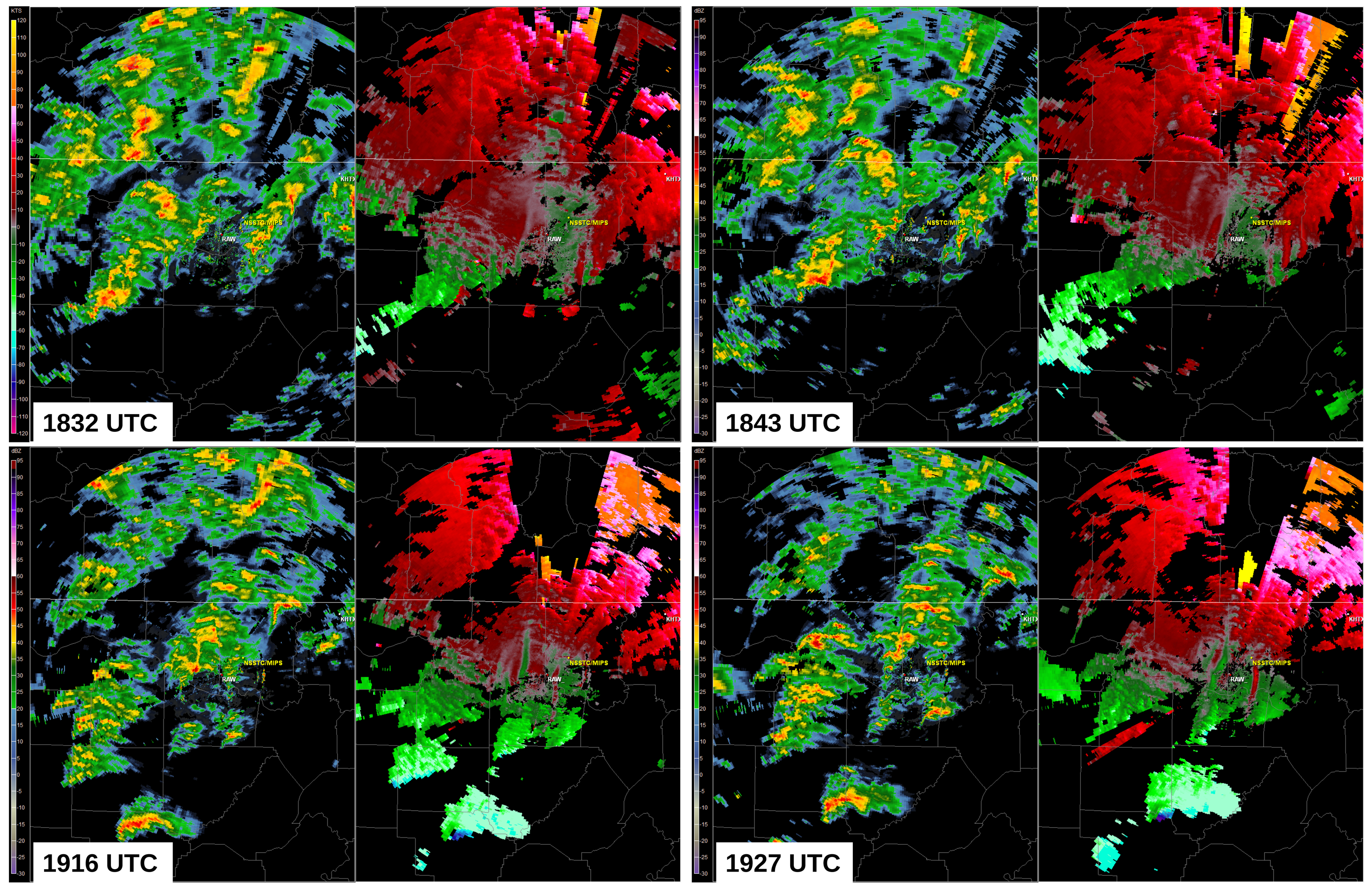


Profile of N with height for the above sounding



Profile of m^2 with height for the above sounding + 915 MHz wind profile. Wave reflection would occur near the area indicated by the dashed-line and the ground.

2. Ducted Wave Radar & Surface Observations

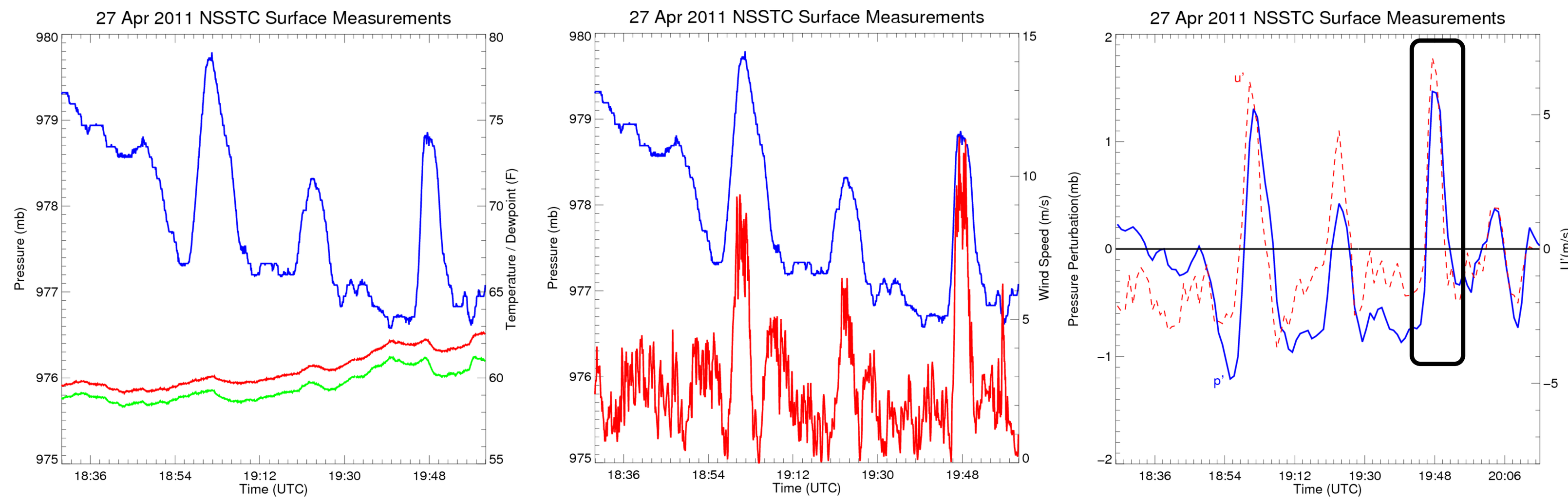


The mid-day QLCS exited the TN Valley near 1800 UTC and was followed by convective showers that formed along NNE-SSW oriented lines. The convective lines moved easterly at near 25 m s^{-1}, close to the theoretical ducted wave speed. Based on the speed and the wave duct in place, it is believed these showers formed along wave ridges (w > 0) of a packet of ducted gravity waves.

Of particular interest is the observation that the supercell which produced an EF-4 tornado in Cullman, AL appears to link up and propagate with a gravity wave ridge.

Photograph taken near 1910 UTC from the NSSTC on UAH's campus; view is toward the east. A low-level roll cloud is visible, extending from N to S.

This particular cloud lines up with a radar observed convective lines.



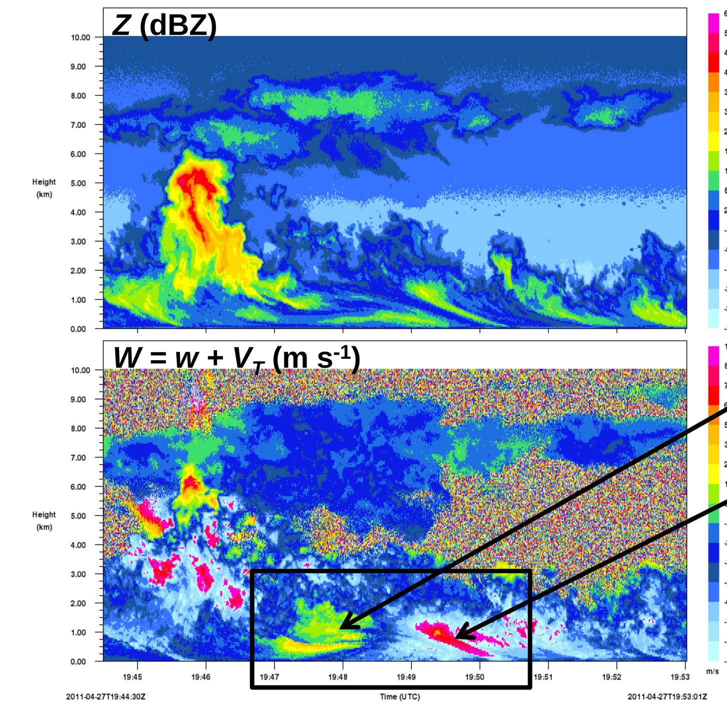
Left: *5-s surface observations of pressure (blue), temperature (red), and dew point (green) at the NSSTC/MIPS location*
Middle: *Same as left but for surface pressure (blue) and wind speed (red)*
Right: *Same as middle but for surface pressure perturbation (blue) and wind speed perturbation (red dashed). Oscillation near 1948 UTC is examined in greater detail in the next section (XPR measurements).*

Significant oscillations in surface pressure and wind speed occurred as these features moved over the NSSTC/MIPS surface instrumentation.

A nonlinear impedance relation between pressure and wind apply in gravity waves, such that the positive/negative pressure and wind perturbations will correlate (Gossard and Hooke 1975; Coleman and Knupp 2010).

This pressure/wind correlation is observed as the N-S oriented lines moved over the NSSTC/MIPS site, providing further validation they may be gravity waves.

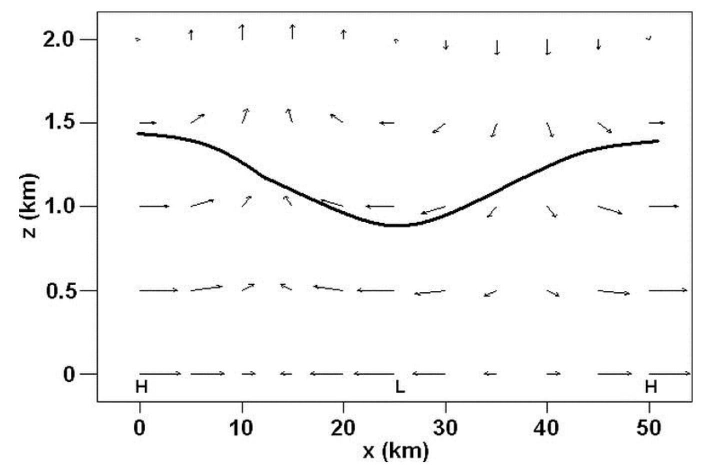
3. Profiling and Dual-Doppler Observations

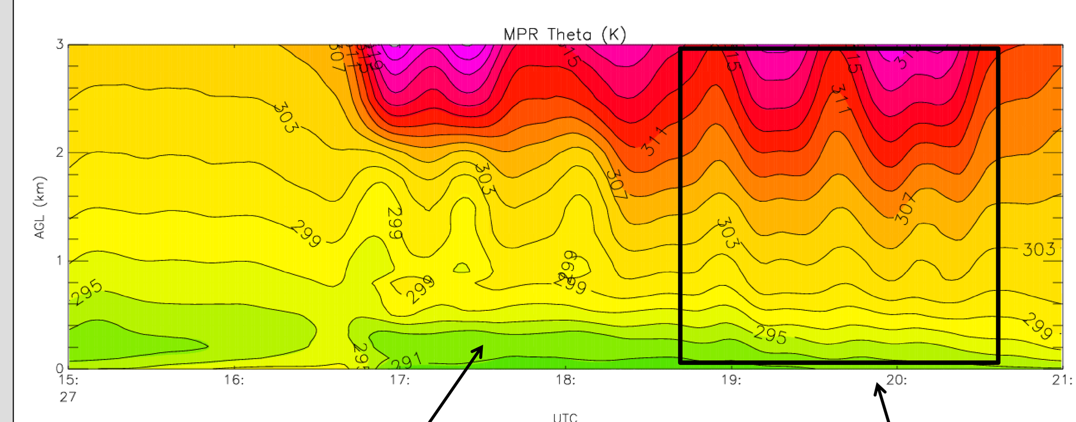


The convective cell in the top panel was likely influenced by this gravity wave.

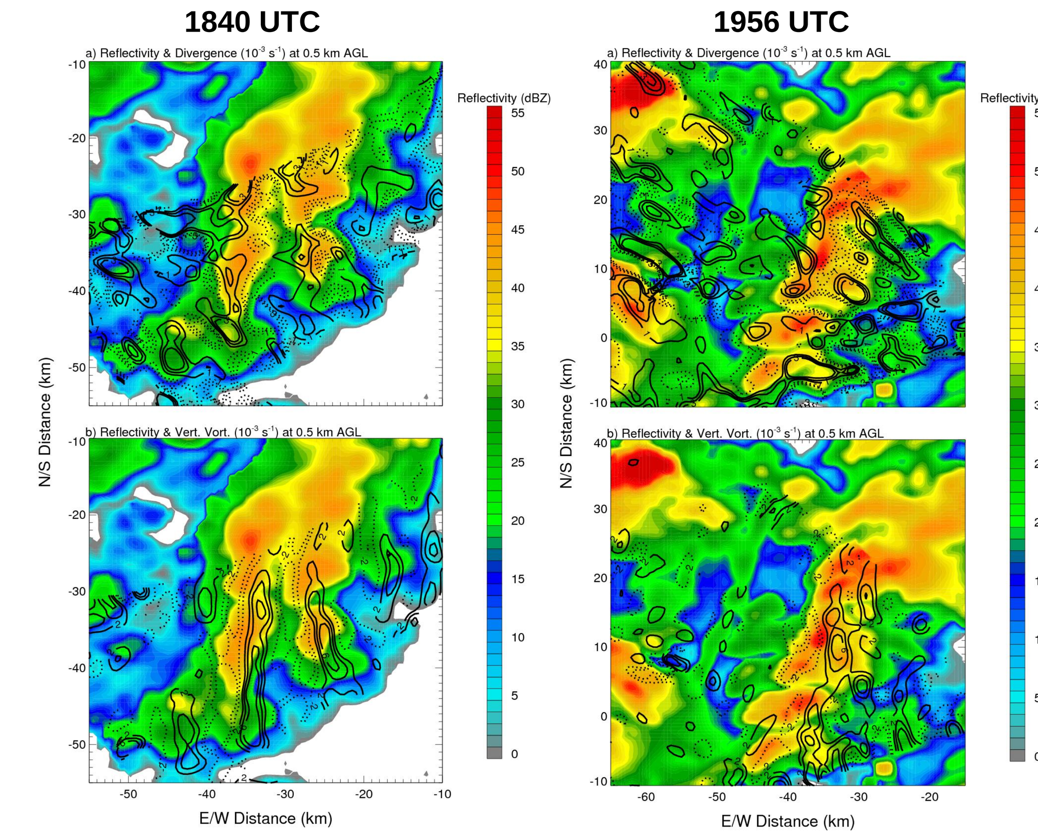
- Measurements from the MIPS vertically pointing X-band radar (XPR; 6 Hz sampling) centered around the pressure/wind oscillation near 1948 UTC
- Wave model (see below) tells us to expect +/- vertical velocity couplet before +/- p'
- rising air just prior to $+p'$ (adiabatic cooling; wave ridge)
- sinking air just prior $-p'$ (subsidence warming; wave trough)
- Max updraft (downdraft) (w = W - V_T) estimated at 6-8 (10-11) m s^{-1}, near 1 km.

- Theoretical model of air flow and surface pressure perturbations in a ducted gravity wave
- From Coleman and Knupp (2008)





- Potential temperature (θ) derived from the MIPS MPR
- "Jumps" in θ surfaces are often observed during the passage of atmospheric waves (Koch et al. 1991; Knupp 2006; Coleman and Knupp 2011)
- Deeper "cool" layer near the surface
- Time of suspected wave passages
- Wave like oscillatory signature in θ



- Divergence (top) and vertical vorticity (bottom) at 0.5 km AGL
- Low-level convergence (dotted contours) generally located ahead of Z_{max} and divergence (solid contours) behind Z_{max}
  - Matches wave theory
- +/- ζ couplet associated with the N/S oriented lines
  - +ζ along wave ridge
  - -ζ along wave trough

This ζ configuration may have important considerations since the Cullman tornadic supercell was observed propagating along the gravity wave ridge shown in the 1956 UTC analysis.

It is speculated the ducted gravity waves helped initiate the Cullman supercell, while also supplying a source of ambient vorticity.

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