Radiometer and Profiler Analysis of the Effects of a Bore and a Solitary Wave on the Stability of the Nocturnal Boundary Layer

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Abstract

This study uses data from a microwave profiling radiometer (MPR), along with 915-MHz wind profiler, Doppler radar, and surface data to quantify the kinematic and thermodynamic effects of two wave features, an undular bore and a soliton, on the nocturnal boundary layer (NBL) at high temporal resolution. Both wave features passed directly over the MPR and the wind profiler, allowing for detailed analyses. The effects of the wave features on the convective environment are examined, and convective initiation (CI) associated with the wave features is discussed.

The undular bore was illustrated well in Doppler velocity data, and profiler measurements indicated that it produced four wavelengths of upward and downward motion. MPR-derived time–height sections of potential temperature and mixing ratio showed an increase in the depth of the stable boundary layer, along with a decrease in stability, partially associated with mixing of the NBL. The soliton produced a temporary decrease in the depth of the NBL, and also produced destabilization. Trajectory analyses were performed assuming the wave features were two-dimensional, allowing a time-to-space conversion of profiler data. Trajectory analyses, in addition to propagation speed, confirm that the wave features were indeed a bore and a soliton, and that there was vertical divergence in the NBL, likely associated with the decrease in static stability.

MPR data were also used to produce time series of convective parameters, including CAPE, convective inhibition (CIN), and the level of free convection (LFC). The CIN was initially too large for free convection despite sufficient CAPE, but MPR data showed that the CIN decreased by more than 50% upon passage of the bore, and again with the soliton. The waves also decreased the LFC due to cooling above the NBL and slight warming near the surface in the bore. Both the reduction in CIN and the lowering of the LFC made convection more likely. Convective initiation occurred behind both wave features, and the vertical motion provided by the waves may have also aided in this CI.

1. Introduction

Atmospheric bores may form when a density current, often produced by convection, or a cold front, impinges on a stable layer such as the nocturnal boundary layer (NBL; e.g., Crook 1988; Rottman and Simpson 1989; Hartung et al. 2010). It has been shown that atmospheric bores may destabilize the boundary layer through mixing or permanent upward displacements (e.g., Koch et al. 2008a; Koch et al. 1991), and the lifting may also aid in convective initiation (e.g., Koch et al. 2008a; Locatelli et al. 2002; Koch and Clark 1999; Karyampudi et al. 1995).

Solitary waves or solitons (e.g., Doviak and Ge 1984; Peters and Stoker 1960) may also destabilize the NBL (e.g., Rottman and Einaudi 1993) and may, similarly, be formed when density currents interact with a stable NBL (e.g., Christie et al. 1978). In this study, multiple bores and solitary waves, initiated by density currents from various convective systems and arriving from different directions, were observed over northern Alabama during the evening hours of 26 June 2008. The wave features passed within 50 km of the University of Alabama in Huntsville (UAH) Advanced Radar for Meteorological and Operational Research (ARMOR) dual-polarimetric radar, and were also sampled by the UAH Mobile Integrated Profiling System (MIPS), including a 915-MHz wind profiler and a 12-channel microwave profiling radiometer (MPR), located only 14 km ENE of ARMOR. The purposes of this study are to identify and document...
the bores and solitary waves, and to quantify the vertical displacements of air parcels by the wave features. We also quantify the thermodynamic changes resulting from the destabilizing effects of these features as they pertain to convective initiation. One of the wave features being examined was associated with prolific convective initiation (CI).

Doppler radar reflectivity and velocity data show the bores and waves propagating horizontally in the NBL, while the 915-MHz wind profiler detected the vertical and horizontal motion perturbations associated with the passing wave features. A time-to-space conversion was performed on the wind profiler data for the two most vigorous wave features, assuming that the features were two-dimensional. This allowed for flow trajectories through the wave feature to be calculated. These showed significant vertical displacements of air parcels associated with wave passage (some near 1 km), and vertical flux divergence of air parcels within the lowest 2 km AGL. MPR potential temperature calculations showed the vertical spreading of isentropes in the wave features, indicating a decrease in static stability (in some cases, \(N\) decreased by more than 50%). Convective parameters including convective available potential energy (CAPE; Moncrieff and Miller 1976), convective inhibition (CIN; Colby 1984), lifted condensation level (LCL), and the level of free convection (LFC) were also calculated using MPR temperature and humidity measurements at 1-min resolution. [This is similar to the process used by Koch et al. (2008a), where the University of Wisconsin—Madison’s Atmospheric Emitted Radiance Interferometer (AERI) was combined with Rapid Update Cycle (RUC) model output to determine CAPE, CIN, and LCL at 2-h intervals around the time of passage of atmospheric wave features.] The MPR measurements clearly showed a decrease in CIN and a lowering of the LFC behind the main wave features. The decrease in stability and convective inhibition, in addition to the vertical motion associated with the wave, apparently resulted in CI behind the main wave feature.

In this paper, a brief review of the dynamics of bores and solitary waves is presented in section 2. The UAH instrumentation that gathered the high-resolution kinematic and thermodynamic data on the wave features, and the methods used to make further calculations based on the data, are discussed in section 3. The environment of the features is reviewed in section 4, and an analysis of the measurements of the wave features, and comparison to theory, are presented in section 5. In section 6, the rapid effects of the wave features on convective parameters such as CAPE, CIN, and LFC are examined, along with an examination of deep convection likely related to the wave features. Conclusions are presented in section 7.

2. Brief review of bores and solitary waves

a. Atmospheric bores

Atmospheric bores have been examined by many authors (e.g., Tepper 1950; Clarke 1972; Clarke et al. 1981; Crook 1986; Rottman and Simpson 1989; Koch et al. 1991). Bores are accompanied by a rapid and sustained increase in surface pressure associated with the upward displacement and increase in boundary layer depth, often followed by wavelike undulations in the surface pressure; a wind shift into the direction of bore motion; and sometimes an increase in surface temperature, caused by mixing in the inversion layer (Koch et al. 1991; Simpson 1997). The increase in depth of the stable layer is "relatively permanent" (e.g., Locatelli et al. 1998; Knupp 2006). A wave-reflecting or trapping mechanism is also favorable to allow a bore to propagate over a significant distance (e.g., Crook 1986).

The theoretical intrinsic bore speed (relative to the background wind) may be determined based on the bore strength and the theoretical speed for an internal gravity wave in the surface-based layer (\(C_{gw}\)). Here, \(C_{gw}\) is given by (Simpson 1997)

\[
C_{gw} = \left[ g \left( \frac{\Delta \theta_v}{\theta_v} \right) \frac{h_0}{h_1} \right]^{1/2},
\]

where \(\Delta \theta_v\) is the difference in average \(\theta_v\) between the lower stable layer and the upper layer, and \(h_0\) is the depth of the stable layer. The intrinsic bore speed (\(C_{bore}\)) is then (Rottman and Simpson 1989)

\[
C_{bore} = C_{gw} \left[ \frac{1}{2} \frac{h_1}{h_0} \left( 1 + \frac{h_1}{h_0} \right) \right]^{1/2}.
\]

The vertical displacements of air as a bore passes may be significant. Koch et al. (1991) combined Raman lidar and radiosonde data to produce an estimate of the change in the vertical structure of potential temperature associated with the passage of a bore (Fig. 1). Note the large vertical displacement of some isentropes, which roughly represent air parcel displacements in the absence of evaporation or condensation. For example, the 306-K isentrope is displaced upward by about 1400 m in about 45 min.

b. Solitary waves

A solitary wave is typically a single wave of elevation, propagating at uniform velocity (e.g., Lamb 1932; Christie et al. 1978; Simpson 1997). Solitary waves may exist at the interface of two fluids with slightly different densities (Simpson 1997) and, typically, produce a temporary increase in surface pressure (Simpson 1997). They
may be generated when density currents, such as thunderstorm outflows, interact with a stable layer (e.g., Christie et al. 1978; Doviak and Ge 1984). The equations governing solitary waves were developed over a long period (e.g., Boussinesq 1871; Rayleigh 1876; Abdullah 1956; Benjamin 1967; Davis and Acrivos (1967); Christie et al. 1978). The intrinsic speed of a solitary wave is given by (e.g., Christie et al. 1978)

$$C = \sqrt{\frac{gh}{\rho_1}} \left(1 + \frac{3}{4}\alpha\right)^{1/2}.$$

The relative amplitude is $$\alpha = a/h$$, where $$a$$ is the maximum amplitude of the wave, $$h$$ is the depth of the undisturbed stable layer, $$\rho_1$$ is the density of the stable layer, and $$\rho_2$$ is the density of the layer above. A recent paper by Koch et al. (2008b) utilized lidar data to illustrate the vertical circulations within a train of solitary waves, known as a soliton.

3. Instrumentation and methodology

Both wave features were very well sampled by the ARMOR radar and the MIPS, which included the 915-MHz wind profiler and the 12-channel MPR. Surface observations of temperature, pressure, water vapor, and wind were also collected at the MIPS site at 5-s intervals. The ARMOR radar allowed for examination of the evolution and propagation characteristics of the disturbances over a long time scale (hours), and also allowed the speed and wavelength of the wave features to be measured.

The MIPS wind profiler explicitly showed the high-frequency oscillations in vertical motion associated with the bore and the solitary wave. In addition, time–height sections of the component of the wind in the direction of propagation ($$u$$) of each wave feature were produced using MIPS profiler data. Then, assuming that the bore and the solitary wave were both two-dimensional, steady-state features, a valid approximation based on ARMOR radar data, the following is true:

$$\frac{dJ}{dx} = -\frac{1}{c} \frac{dJ}{dt}, \quad (4)$$

where $$J$$ is some variable and $$c$$ is the propagation speed of the feature. This allowed a time-to-space conversion to be performed on the time–height sections of $$u$$ and $$w$$, producing approximations of the two-dimensional flow field in the vertical plane oriented parallel to the wave propagation. Trajectories were then calculated, using these data, for parcels originating at various altitudes just ahead of each wave feature.

The MPR collected vertical profiles of temperature and water vapor at 1-min intervals. The vertical resolution of the MPR measurements was 100 m below 1 km AGL, and 250 m from 1 to 10 km AGL. Time–height sections of potential temperature $$\theta$$ and water vapor mixing ratio $$r_v$$ were calculated using the MPR dataset. Those shown in the figures are smoothed temporally to remove noise. In addition, convective parameters such as CAPE, CIN, LCL, and LFC were calculated for parcels originating at multiple vertical levels, at 1-min resolution, using the MPR data. The convective parameters were smoothed using 15-min moving averages. However, the UAH instrument suite, at a fixed nonfield experiment location as the wave features passed by, provided evaluation of the changes in the thermodynamic environment associated with a bore and a solitary wave at very high temporal and spatial resolutions.

4. Synoptic–mesoscale environment

On 26 June 2008, northern and central Alabama were located in a surface ridge, and under light winds aloft ($$5–10$$ m s$$^{-1}$$ at 500 and 300 hPa). Conditions were seasonably favorable for pulse-type convection on 25–26 June 2008. The vertical wind shear was very low ($$0–10$$ km AGL bulk shear around $$10$$ m s$$^{-1}$$), but surface-based CAPE values at 0000 UTC ranged from $$1000$$ J kg$$^{-1}$$ over northern Alabama to near $$2000$$ J kg$$^{-1}$$ over central Alabama, and atmospheric precipitable water values were near 3 cm.

Scattered deep convection developed over much of Alabama between 1800 UTC 25 June and 0000 UTC 26 June, and persisted well after sunset. An 0200 UTC
plan-position indicator (PPI) reflectivity scan at 0.7° elevation from the UAH ARMOR radar (Fig. 2) indicates two primary areas of convection: one extended from southern Tennessee into northwest Alabama, west and northwest of the radar at 75–100-km range, and the other was located in north-central Alabama, SSE of the radar at 85–125-km range. Both areas of convection were weakening around 0200 UTC, as they moved slowly north-to-northeastward about 5 m s⁻¹.

A pronounced low-level stable layer was present at 0200 UTC at the National Space Science and Technology Center (NSSTC) in Huntsville, as evidenced by MPR data (Fig. 3). The stable layer extended from the surface to about 400 m AGL, with Brunt–Väisälä frequencies in this layer of between 0.015 and 0.030 s⁻¹. The inversion was topped by a much less stable layer above 500 m AGL, with a fairly constant N near 0.010 s⁻¹ through most of the layer between 1 and 5 km AGL. This profile of stability allowed at least some vertically propagating wave energy to be reflected and trapped at low levels (e.g., Nappo 2002).

5. Overview of the wave features

a. Wave feature 1: Undular bore

The first significant wave feature, an undular bore, passed over the UAH instrument suite at around 0225 UTC. The bore was approaching from the NW and is shown fairly well in Fig. 4 as an alternating inbound–outbound velocity signature from the ARMOR Doppler radar as early as 0144 UTC. The radial velocity image at 0144 UTC shows the bore front and 1.5 wavelengths of undulations behind it, with wavelengths around 5 km. The undular bore arrived at UAH at around 0225 UTC, causing an abrupt but small 0.25-hPa pressure jump in only 3 min, followed by slowly oscillating and rising pressure (see Fig. 5). It is notable that, after bore passage, the surface temperature rose slightly (about 1°C) and the surface dewpoint dropped slightly (about 1°C). These are consistent with the passage of a bore, as opposed to an outflow boundary; outflow would cause a drop in temperature and typically a rise in dewpoint.
The bore developed additional undulations by the time it reached the UAH MIPS site at around 0225 UTC. A time–height section of vertical motion from the MIPS 915-MHz Doppler wind profiler (Fig. 6) shows four full-wavelength oscillations in vertical motion between 0225 and 0241 UTC. The first vertical motion couplet was the strongest and deepest vertically, extending above 1500 m AGL, with a maximum upward motion of 1.5 m s$^{-1}$ and a maximum downward motion of 2.2 m s$^{-1}$. A plot of vertical motion at 400 m AGL versus time is also included in Fig. 6 and, clearly, shows four wavelengths in vertical motion.

The vertical motion associated with the bore, and its effects on the vertical temperature and moisture profile in the atmosphere, are indicated by potential temperature $\theta$ and water vapor mixing ratio $r_v$ data derived from

![Fig. 3. MPR-derived vertical profiles at 0200 UTC of (a) potential temperature (K) and (b) Brunt–Väisälä frequency (s$^{-1}$).](image)

![Fig. 4. (a) ARMOR Doppler velocity image (NW quadrant only) showing an undular bore NNW of the radar site at 0144 UTC. (b) A zoomed-in and color-enhanced image of the velocity at the same time in the box shown in (a).](image)
the MPR dataset. Time–height sections of $\theta$ and $r_v$ are shown in Fig. 7 for 0200–0300 UTC. Since ceilometer data (not shown) and the relatively high lifted condensation levels (LCLs) indicate that no evaporation nor condensation were occurring during this time frame (i.e., no clouds were detected during the bore passage), $\theta$ and $r_v$ were conserved during vertical motion and, therefore, serve as good indicators of parcel displacements.

The sudden increase in the depth of the NBL associated with the passage of the bore is apparent in Fig. 7. The 303-K isentrope, near the top of the nocturnal inversion, jumped from around 400 m AGL at 0215 UTC to 1300 m AGL by 0245 UTC. The 10.5 g kg$^{-1}$ mixing ratio contour, also at 400 m AGL before bore passage, jumped to about 1150 m AGL very quickly after the bore passed the site at around 0225 UTC. Basically, the isentropes spread vertically upon passage of the bore, indicating a decrease in static stability. Also, the 0–3-km AGL adiabatic precipitable water increased from 27.7 to 32 mm in only 5 min (e.g., Koch et al. 2008a).

These observations indicate that the height of the NBL before the passage of the bore, $h_0$, was about 400 m AGL, and the NBL height after the bore, $h_1$, was near 1200 m AGL, indicating a bore strength of $h_1/h_0 = 3$. Using Eqs. (1) and (2), along with the mean potential temperature in and above the prebore NBL, the theoretical intrinsic bore speed would be $C_{bore} = 14$ m s$^{-1}$. The mean of the component of the background wind in the direction of bore motion (from the surface to 1200 m AGL), indicated by profiler measurements, was 1.5 m s$^{-1}$ just ahead of the bore, so the ground-relative speed should be 15.5 m s$^{-1}$. ARMOR radar data indicate the actual motion of the disturbance was from the NW (300°) at 12.2 m s$^{-1}$, fairly close to the theoretical bore speed.

Making the valid approximation that the bore was a fairly steady-state, two-dimensional phenomenon, a time-to-space conversion (TSC) of 915-MHz profiler winds and vertical motion from 0219 through 0258 UTC was used to produce a 2D vertical ($x$, $z$) cross section of the vertical motion and winds in the bore. Air parcel trajectories within a plane in the direction of bore motion (toward 120° azimuth) were produced, assuming the bore (and its associated cross section of air motion) was steady state. Simulated parcels, all starting at the same horizontal position, but at heights of 200, 400, 600, and 800 m AGL at 0219 UTC (see Fig. 8), were allowed to flow through the bore, and the positive horizontal direction was the same as the direction of the bore motion. The TSC-simulated trajectories also show vertical divergence of air parcels that is consistent with the MPR-derived isentropes (shown in Fig. 7), assuming the motion is adiabatic. The parcel that entered the bore at a height of 200 m AGL at 0219 UTC only rose to about 450 m AGL by 0258 UTC (see Fig. 8). However, the parcels that entered the bore at heights of 400 and 600 m AGL rose to 900 and 1200 m AGL, respectively, by 0258 UTC, indicating significant vertical divergence. This makes sense physically since the more stable parcels near the surface
would resist a vertical displacement more than the parcels higher up. Also, vertical mixing behind the bore should redistribute potential temperature more evenly (in the vertical). This vertical divergence associated with vertical spreading of the isentropes (mentioned above) indicates that the bore destabilized the NBL. This destabilization will be discussed in more detail in section 6.

It should also be noted that, during the 39-min time period of the trajectory analysis, the bore itself would have propagated horizontally over 28 km. However, Fig. 8 shows that air parcels originating above 200 m AGL only traveled 8–17 km horizontally during this time period. This is typical of wave propagation in an environment with light background winds, since individual fluid parcels affected by a wave phenomenon often experience only small net horizontal displacements due to wave passage.

b. Wave feature 2: Solitary wave—soliton

Intense convection was on going at 0130 UTC 75–125 km SSE of the ARMOR radar location, near and northeast of Birmingham, Alabama (see Fig. 2). Cold outflow from these storms, in the form of a density current, moved northward and initiated a wave feature to the SSE of the radar between 0200 and 0300 UTC (see Fig. 9). This feature moved generally northward (at a direction of motion from 170°) at an average speed of 8 m s$^{-1}$ through 0300 UTC, then its speed increased significantly to almost 20 m s$^{-1}$ between 0300 and 0400 UTC. This acceleration is characteristic of a density current to bore to soliton transition (e.g., Knupp 2006). In general, upon examination of Eqs. (2) and (3), and the speed of a density current (e.g., Seitter 1986), given the same density difference between the stable NBL and the layer above, amplitude of the feature, and other relevant parameters, the speed of a bore is greater than that of a density current, and the speed of a solitary wave is faster than that of a bore. The density of the stable boundary layer $\rho_1 = 1.13$ kg m$^{-3}$ and the density of the free atmosphere above was $\rho_2 = 1.07$ kg m$^{-3}$, the depth of the stable layer was 400 m, and the amplitude of the wave was about 500 m. These parameters and Eq. (3) indicate an intrinsic solitary wave speed of 20.1 m s$^{-1}$. Wind profiler data indicate the background wind in the wave layer (from the surface to 900 m AGL) was very light (only 0.3 m s$^{-1}$), so the theoretical ground-relative speed of the wave was 20.4 m s$^{-1}$, very close to the observed speed of the disturbance after acceleration.
The wave evolved into a soliton, or a train of two solitary waves, with the first having a higher amplitude and more significant vertical motion. The data shown in Fig. 10 indicate that the period of the vertical motion oscillations was significantly longer for the second wave feature than for the bore at around 0225 UTC. There was a sustained period of upward vertical velocities at the UAH MIPS 915-MHz profiler site from about 0338 to about 0350 UTC, followed by brief downward motion then more upward motion. At the surface (Fig. 11), the waves were associated with temporary increases in pressure, and only a 1°C drop in temperature, typical of solitary waves as opposed to bores (sustained pressure increase) and density currents (sustained pressure increase and usually a large temperature decrease). Time–height sections of MPR $\theta$ and $r_v$ (see Fig. 12) also show the two temporary increases in the depth of the boundary layer. Again, since the vertical displacement at the profiler site was not sufficient to bring parcels to their LCL’s, $\theta$ and $r_v$ were conserved during vertical motion and serve as excellent indicators of parcel displacements. One can clearly see the temporary upward vertical displacement. In the case of the solitary wave, just like in the case of the bore, there was a vertical spreading of the isentropes, indicating destabilization of the atmosphere in the wave, consistent with the findings of Rottman and Einaudi (1993). The solitary wave also increased the 0–3-km AGL precipitable water rather quickly, from 29.3 to 31.5 mm in only 4 min.

Again assuming that the wave feature was two-dimensional, a time-to-space conversion of 915-MHz profiler winds and the vertical motion from 0330 to 0515 UTC were used to produce trajectories, within a plane perpendicular to wave motion (the positive $x$ direction is $350^\circ$), of parcels released from 200, 400, 600, 800, and 1000 m AGL (Fig. 13). Note that all five trajectories follow at least one pattern similar to that for a solitary wave, and the four trajectories at highest altitudes also

![Figure 9](image_url1)

**Fig. 9.** (a) ARMOR Doppler velocity image showing a wave feature SSE of the radar site at 0228 UTC. (b) A zoomed-in and color-enhanced image of the velocity at the same time in the box shown in (a).

![Figure 10](image_url2)

**Fig. 10.** As in Fig. 6, but (b) at 1000 m AGL.
show some evidence of the second wave in the soliton. It is also interesting that there is some vertical spreading of the parcels in the solitary wave. The maximum vertical displacement achieved by a parcel entering the wave at 200 m AGL was 600 m, while the maximum vertical displacement for a parcel entering the wave at 600 m AGL was 1100 m, indicating vertical divergence.

6. Thermodynamics and CI

As mentioned in section 5, both wave features are associated with upward vertical displacement, even if temporary, and destabilization. The destabilization appears to be the result of a combination of vertical mixing of the stable boundary layer, and also the vertical divergence associated with upward motion near the surface, where \( w = 0 \). A simple examination of dry static stability using the Brunt–Väisälä frequency from 0100 through 0500 UTC (Fig. 14) shows two important findings. First of all, a low-level stable layer lies beneath a less stable layer above, providing a low-level trapping mechanism for gravity wave energy (see section 2). Second, it should be noted that the low-level static stability (primarily below 500 m AGL) is decreased dramatically by the first wave feature around 0230 UTC, with \( N \) at 125 m AGL decreasing from 0.027 to 0.013 s\(^{-1}\) by 0300 UTC. Then after a brief increase in \( N \), to 0.020 s\(^{-1}\) at 0341 UTC, the soliton is associated with another decrease in stability, with \( N \) decreasing to 0.014 s\(^{-1}\) after 0400 UTC.

However, in order to effectively quantify the effects of the passing wave features on the actual potential for convective initiation, one must use the MPR temperature and moisture profiles to examine the changes in CIN (e.g., Colby 1984) and CAPE, as well other convective parameters. The MPR retrieves vertical profiles of temperature and water vapor every minute, allowing calculations of all thermodynamic parameters at 1-min resolution. One of the primary reasons that warm-season convection often decreases dramatically after sunset is due to the radiational cooling and associated stabilization near the surface; this inhibits any surface-based or low-level convective initiation. The CIN is a measurement (typically in J kg\(^{-1}\)) of the potential energy associated with negative buoyancy that slows down a rising parcel, often preventing condensation or convection. The CAPE is a measurement of the potential energy available for producing buoyant vertical motion once a parcel reaches its LFC, where the parcel is warmer than its environment and accelerates upward without additional mechanical lifting. Therefore, sufficient CAPE, some mechanical lift, and insufficient CIN to prevent a parcel from reaching its LFC are all necessary for the initiation of deep convection.
Using MPR data, time series of CAPE, CIN, and LFC were calculated for parcels originating at the surface, as well as from 300, 500, and 800 m AGL. It should be pointed out that surface fluxes of heat and moisture were small relative to the effects of the wave features; therefore, the retrieved data from the MPR are not adjusted for these fluxes. Fifteen-minute moving averages (centered on the time indicated) were used to smooth the data. As shown in Fig. 15, surface-based CAPE was sufficient for at least some deep convection throughout the evening period, while CAPE values for parcels lifted from above the surface (that would produce "elevated convection") generally had far less CAPE, since the highest water vapor mixing ratios were below 300 m AGL (see Figs. 7b and 12b). CAPE values were gradually decreasing with time, typical of most nighttime situations, but surface-based CAPE values were still in excess of 500 J kg$^{-1}$ through 0600 UTC. Surface-based CAPE increased from 800 J kg$^{-1}$ before the passage of the bore at 0230 UTC to 1100 J kg$^{-1}$ immediately after bore passage. There were also significant increases in CAPE for elevated convection. For example, the CAPE for parcels originating at 300 m AGL quadrupled with bore passage, from 75 to over 300 J kg$^{-1}$. The increases in CAPE aloft were fairly temporary; however, after passage of the bore around 0230 UTC, the surface-based CAPE dropped significantly, reaching near 75 J kg$^{-1}$ shortly after 0300 UTC, a decrease of 64%. CIN decreased with passage of the bore for parcels lifted from 300 m AGL. Despite continued radiational cooling at the surface and a brief increase in convective inhibition between 0300 and 0330 UTC, the soliton at 0400 UTC reinforced the lower CIN values. CIN for surface-based parcels dropped as low as 60 J kg$^{-1}$ at 0406 UTC, and did not rise near the original, prebore levels of 160 J kg$^{-1}$ again until about 0530 UTC, well after the soliton had passed. There was also a second decrease in 300 m AGL CIN just ahead of the soliton, but no significant changes at higher levels. Therefore, the bore at 0230 UTC and the soliton at 0400 UTC destabilized the atmosphere enough to reduce convective inhibition, making it more likely that an air parcel could reach a given LFC and that CI could occur.

Figure 16 shows time series of the LFC for surface-based parcels. The LFC also lowered significantly with 0230 UTC also caused increases in CAPE, meaning that any deep convection that did form in its wake could contain more vigorous updrafts.

The time series of CIN in Fig. 15 further illustrate the importance of the wave features and their impacts on the thermodynamic environment. Prior to the undular bore, fairly large values of CIN had developed for parcels originating at the surface, due to the cooling and surface inversion that formed. At 0200 UTC, the surface-based CIN was around 180 J kg$^{-1}$, and the CIN for elevated parcels were generally much higher. This made it very unlikely that any parcel could reach its LFC, and this would prevent convection at the site. However, after passage of the bore around 0230 UTC, the surface-based CIN dropped significantly, reaching near 75 J kg$^{-1}$ shortly after 0300 UTC, a decrease of 64%. CIN decreased with passage of the bore for parcels lifted from 300 m AGL. Despite continued radiational cooling at the surface and a brief increase in convective inhibition between 0300 and 0330 UTC, the soliton at 0400 UTC reinforced the lower CIN values. CIN for surface-based parcels dropped as low as 60 J kg$^{-1}$ at 0406 UTC, and did not rise near the original, prebore levels of 160 J kg$^{-1}$ again until about 0530 UTC, well after the soliton had passed. There was also a second decrease in 300 m AGL CIN just ahead of the soliton, but no significant changes at higher levels. Therefore, the bore at 0230 UTC and the soliton at 0400 UTC destabilized the atmosphere enough to reduce convective inhibition, making it more likely that an air parcel could reach a given LFC and that CI could occur.

Figure 16 shows time series of the LFC for surface-based parcels. The LFC also lowered significantly with
the passage of the bore at around 0230 UTC, from about 2250 m AGL to less than 1800 m AGL. It increased temporarily between 0300 and 0330 UTC, then decreased again, to near 1700 m AGL, around the time of the passage of the soliton at 0400 UTC. This decrease in LFC height is likely associated with the fact that both the bore at 0230 UTC and the soliton at 0400 UTC produced slight cooling above 500 m AGL (see Figs. 9 and 14), and the bore passage was also associated with slight warming at the surface, probably due to mixing. In summary, the wave features also lowered the level of free convection somewhat, further increasing the possibility of convection.

Finally, the vertical motion associated with the bores and solitary waves likely provided at least some of the mechanical lifting in the lower atmosphere required to force parcels to their LFCs and cause convective initiation. Figures 6, 8, 10, and 13 confirm this vertical motion. Widespread convective initiation occurred along and just behind the soliton as it moved through northeast Alabama (see Figs. 17a–c). The soliton is also visible in the form of fine lines of enhanced reflectivity, likely associated with the lifting of insects. It is possible that the density current (outflow) that initiated the solitary wave was following closely behind it at around 0230 UTC, and may have provided additional lift for convective initiation. In this case, the wave could reduce the stability, and the following density current could lift parcels to their LFCs. The convection may have been enhanced by topography, and perhaps in the area of collision of the soliton with the undular bore southeast of NSSTC (the location of MIPS). However, the widespread nature of the convection and its proximity to the soliton indicate that the destabilization associated with the wave feature played a significant role in the CI southeast of NSSTC, and the mechanical lift associated with the wave was at least partially responsible for some of the CI. While no convection occurred immediately over the MIPS site associated with the undular bore, a thunderstorm (see Fig. 17d) developed at 0300 UTC about 50 km WSW of MIPS, behind the undular bore. Once again, other boundary layer (BL) processes may have been involved in this CI, but the bore was likely instrumental in destabilizing the atmosphere, making the CI possible.

7. Conclusions

This study quantifies the kinematic and thermodynamic effects of two wave features, an undular bore and a soliton, on the NBL, using measurements from the ARMOR Doppler radar, a microwave profiling radiometer (MPR), and a 915-MHz profiler that are part of the UAH MIPS system, as well as surface data. The effects of the wave features on the convective environment are examined in detail, and convective initiation associated with the wave features is discussed.

The first wave feature, an undular bore apparently initiated by cold outflow from thunderstorms interacting with a shallow stable layer, was shown very well by the ARMOR radar, and passed the MIPS at around 0230 UTC. MIPS 915-MHz profiler measurements of
vertical motion show four wavelengths of short-period upward and downward motion as the bore passed by, and MPR-derived time–height sections of potential temperature and mixing ratio show an increase in the depth of the stable boundary layer, along with a decrease in stability and a rapid increase in low-level precipitable water. Trajectory analyses, using a time-to-space conversion of 915-MHz profiler winds and vertical motion, assuming the waves were two-dimensional, showed vertical oscillations and also vertical divergence, consistent with a decrease in stability.

The second wave feature, a soliton or train of two solitary waves, passed the MIPS around 0400 UTC. These features were associated with variations in vertical motion having longer periods, and trajectory analyses show distinct, temporary upward displacements of air parcels, consistent with solitary waves. This feature also decreased the stability and caused a rapid increase in precipitable water.

Basically, convective initiation (CI) requires three ingredients: (a) sufficient instability (high enough CAPE and a low enough LFC), (b) a triggering mechanism, and (c) a relative lack of CIN that could suppress the vertical motion of a parcel, preventing it from reaching its LFC. It was shown using MPR data that fairly sufficient CAPE was present in the nocturnal environment prior to the passage of the wave features, but CIN associated with a nocturnal inversion prevented convection. The wave features greatly reduced the CIN, primarily through the destabilization of the atmosphere due to mixing. The waves also decreased the LFC, since slight cooling was associated with the waves just above the NBL, and slight warming even occurred at the surface in the bore. Both the reduction in CIN and the lowering of the LFC made convection more likely. In other words, the waves lowered the LFC, and also made it easier for a parcel to reach it. Widespread convection developed near and just behind the soliton.

This study uses 1-min-resolution measurements of temperature and water vapor in the nocturnal boundary layer to illustrate the rapid changes that may occur due to the passage of wave features such as bores and solitons. These wave features are quite common in the NBL. A recent preliminary analysis of UAH MIPS MPR and 915-MHz profiler data along with ceilometer and surface data for 237 warm season nights (May–September) showed that bores or solitary waves were detected on 64 occasions, or on 27% of warm-season nights. Further study of these features in the nocturnal boundary layer is required, as they may be responsible for a large percentage of nocturnal convective initiation events away from well-defined synoptic-scale features or low-level jets.
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