PICTURE OF THE MONTH

The Spectacular Undular Bore in Iowa on 2 October 2007

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A visually impressive undular bore moved across much of Iowa on 2 October 2007, and was videotaped by numerous webcams. The bore was sampled very well by Doppler radar at close range, and also by the high-density mesoscale network of surface stations in place over Iowa. Radar and surface observations are presented, along with a brief analysis of the dynamics of the bore.

1. Introduction

High-quality, ground-based photography of the cloud formations associated with atmospheric bores has not been widely available in the literature, even since these bores became well-documented (e.g., Clarke 1972; Christie et al. 1978; Clarke et al. 1981; Crook 1986; Rottman and Simpson 1989). There have been some exceptions. One example is the "Morning Glory" of the Gulf of Carpentaria in Australia, which has been well-photographed (e.g., Clarke et al. 1981; Smith et al. 1982). A photograph of the wave cloud associated with an undular bore approaching Norman, Oklahoma was published by Mahapatra et al. (1991). Also, Wakimoto and Kingsmill (1995) show photographs of an undular bore generated by the collision of a sea-breeze front and a gust front in Florida.

With the advent of nearly continuously-operating video cameras such as "towercams" and "webcams", deployed by numerous public and private interests over the past few years, photographs of many atmospheric phenomena have become more frequent. Such a case occurred on 2 October 2007, when an atmospheric undular bore propagated across much of central and eastern Iowa. This bore was apparently generated by the interaction of cool, MCS-generated density current outflow with a very stable low-level inversion. The distinctive cloud bands associated with this bore were captured on video by at least three webcams, operated by the Iowa Environmental Mesonet and KCCI-TV "Schoolnet 8" in Des Moines, Iowa (Fig. 1).

In this note, the environment in which this bore formed is examined in section 2. Meteorological measurements of the bore, including Doppler radar data and surface measurements, along with a brief analysis, are presented in section 3. Conclusions are presented in section 4.

Figure 1. Photographs of clouds associated with undular bore captured from videos taken by two Iowa Environmental Mesonet/KCCI-TV Schoolnet 8 webcams; (top) looking SSE at Saylorville Lake, Iowa at 1435 UTC (935 am CDT), and (bottom) looking NNW at Indianola, Iowa, at 1500 UTC (1000 am CDT). *(Video from these and an additional webcam at Tama, Iowa are located online at http://vortex.nsstc.uah.edu/~coleman/Iowabore)*

2. Environment

A 500-hPa trough advanced slowly eastward through the Northern Rocky Mountain states during the 12-hour period leading up to 1200 UTC on 2 October 2007. A surface cold front was also associated with the trough, and was located from North Dakota into Nebraska at 02/1200. Convective activity organized into a mesoscale convective system (MCS) during the early morning hours on 2 October, extending from western Iowa into eastern Nebraska and western Kansas at 1300 UTC (Fig. 2). With strong southwesterly flow at 850-700 hPa, the NE-SW oriented leading band of convection only slowly advanced eastward over Iowa between 1200 and 1600 UTC. As it did so, it encountered a very stable low-level inversion over eastern Iowa.

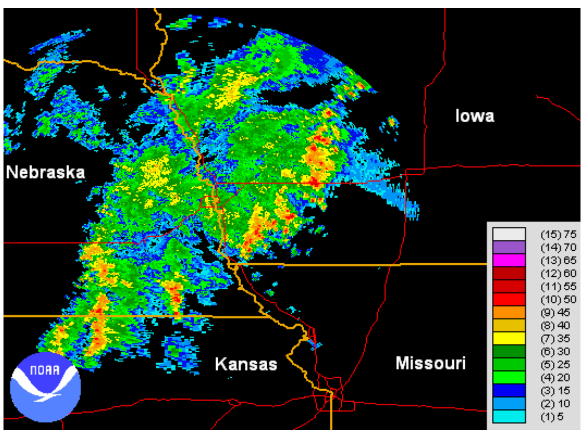

Figure 2. 0.5 degree elevation base reflectivity (dBZ) from the Omaha, Nebraska (KOAX) WSR-88D radar at 1300 UTC on 2 October 2007.

An east-west cross section analysis of 12-km NAM model data (from NOAA ARL) along latitude 41.5 North at 1500 UTC shows the low-level inversion layer over eastern Iowa very clearly. Temperatures (>20 C) occurred near 1 km MSL (Fig. 3a). A layer of very high static stability, as indicated by large values of the Brunt-Vaisala frequency *N* (Fig. 3b), extended eastward from latitude 94.5 west, below 1 km MSL. Based on this analysis, and a MAPS sounding analysis at Des Moines at 1400 UTC (Fig. 4), the height of the surface inversion

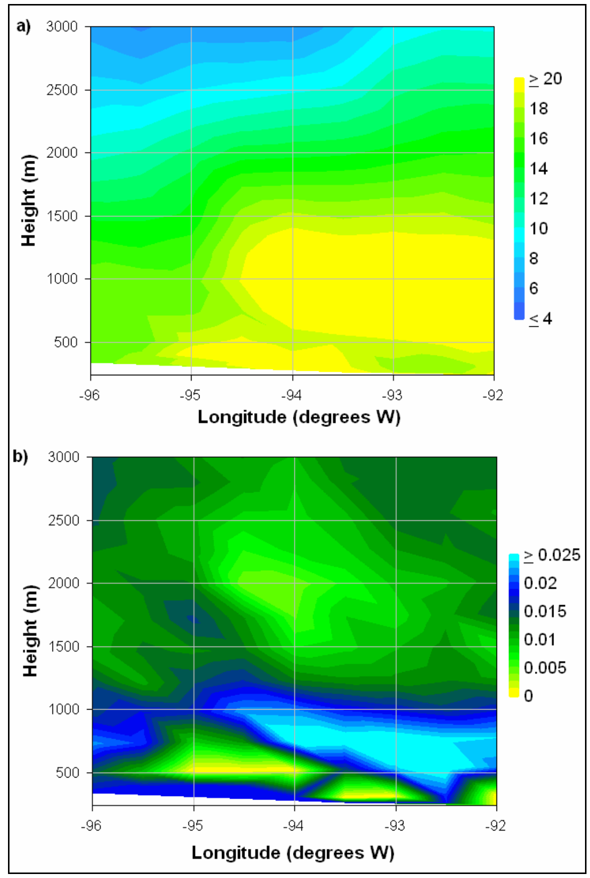

Figure 3. NAM model east-west cross-section along 41.5 degrees north latitude of a) temperature (degrees C) and b) *N* (s^{-1}) at 1500 UTC on 2 October 2007.

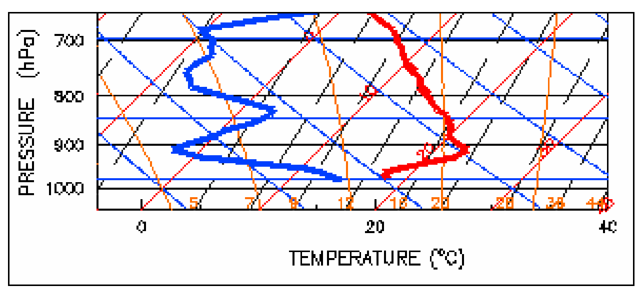

Figure 4. Skew-T ln p diagram of sounding analysis from MAPS model at Des Moines, Iowa (KDSM), at 1400 UTC 2 October 2007.

layer ahead of the MCS was near 1 km MSL, so $h_0 = 700$ m AGL.

The inversion was also topped by a much less stable layer above 1 km MSL, likely providing a duct for gravity wave energy (e.g., Lindzen and Tung 1976; Nappo 2002). *A density current impinging on a low-level stable layer is a common scenario for the initiation of atmospheric bores* (e.g., Simpson 1997). The cool outflow density current associated with the approaching MCS likely initiated the bore upon interaction with the low-level inversion over central and eastern Iowa.

3. Observations and Analysis

1) Surface observations

One characteristic phenomenon associated with the passage of an undular bore at a surface station is a sudden rise in pressure ("pressure jump", e.g., Tepper 1950). This rise is related hydrostatically to the rapid increase in the depth of the low-level cool stable layer . The initial pressure increase in an *undular* bore is typically followed by fluctuations in surface pressure, oscillating at the same period as the waves atop the deepened cool layer. However, with a bore, the overall pressure rise is not transient (as with gravity waves or solitary waves); the surface pressure remains elevated for a longer period of time, possibly more than 1 hour.

In the 2 October 2007 case, with 300 hPa divergence and low-level warm advection over Iowa, surface pressures were falling on a synoptic-scale across Iowa during the morning hours. Averaging the observations between 0800 and 1430 UTC at Des Moines (KDSM) shows a background pressure tendency about -0.91 hPa hr^{-1}, which continues into the afternoon (Fig. 5). So, in order to accurately measure the pressure perturbations associated with the bore itself, this background pressure tendency must be subtracted from the data.

The one-minute time-series of pressure perturbations (p') at KDSM from 1415 to 1515 UTC (Fig. 6a) clearly show the pressure jump associated with bore passage. After a small

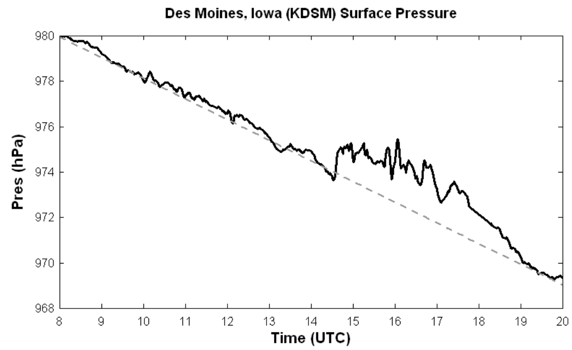

Figure 5. Surface pressure (hPa, solid) at Des Moines, 0800-2000 UTC on 2 October 2007, and background pressure tendency of -0.91 hPa hr^{-1} (dashed).

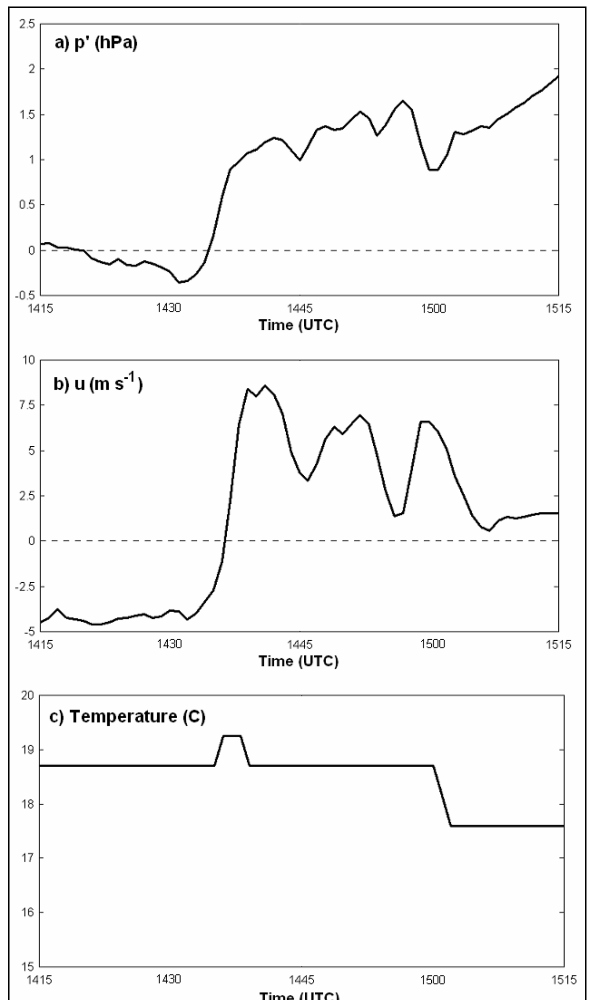

Figure 6. One-minute observations at Des Moines, 1415-1515 UTC 2 October 2007, of a) pressure perturbation p' (hPa); b) wind perturbation u (m s^{-1}, in direction of bore motion) and c) temperature (degrees C)

drop in *p*' just ahead of the bore, there was a rapid rise in pressure of about 1.5 hPa in 9 minutes (1432-1441 UTC). Two more pressure oscillations followed the initial pressure jump, both with periods about 8 minutes and amplitudes of 0.20 to 0.25 hPa.

Surface winds also rapidly fluctuated with bore passage. The component of the 2-minute averaged surface wind in the direction of observed bore motion (from 300 degrees/12.8 m s^{-1}) is plotted in Fig. 6b. As is typical for bores, the wind shifted to the direction of bore motion as it passed, increasing to 8.4 m s^{-1}. Oscillations in bore-normal wind also occurred behind the initial wind shift, with periods around 9 minutes and amplitudes 2 to 3 m s^{-1}.

One-minute surface temperature observations are shown in Fig. 6c. Note that surface temperatures remained basically constant throughout the passage of the bore, with the exception of a slight (0.5 C) temperature rise at the same time as the initial pressure jump. This could be attributed to measurement noise, or it may be associated with the downward mixing of slightly warmer air in the stable boundary layer as the bore and associated gusty winds pass by. *The lack of any temperature drop associated with the pressure rise rules out the possibility that this feature is a density current.* The 1 C temperature drop just after 1500 UTC was coincident with the onset of heavy rain at the observation site.

2) Radar observations

The initial band of vertical motion associated with the bore produced a "fine line", with maximum reflectivities > 25 dBZ, in PPI reflectivity scans from the Des Moines, Iowa (KDMX) WSR-88D Doppler radar (Fig. 7a). This indicates that the bore may have produced some light precipitation. The bore, including three wavelengths of the waves generated behind it, is clearly visible in PPI base velocity scans from KDMX (Fig. 7b).

1450 UTC Doppler velocity cross-sections at 140 degrees azimuth from the KDMX radar offer a more detailed analysis of the kinematics of the bore (Fig. 7c). Doppler velocities were gridded (resolution 1 km horizontal, 200 m vertical). The main wind shift at the leading edge of the bore is apparent, with radial velocities shifting from inbound near 29 km range to outbound, at speeds > 10 m s^{-1}, near 26 km range. The waves behind the leading edge of the bore are also apparent, with at least two more regions of outbound radial velocities centered at ranges of 19 km and 12 km, flanked by inbound velocities.

Using the 1450 UTC Doppler velocity data, 2-D convergence was calculated, and upward integration of the continuity equation allowed for estimates of vertical motion, assuming that convergence occurred only parallel to bore motion. The radar cross-section values of horizontal wind and analyzed vertical motion at 1450 UTC, along with bore speed, were utilized to estimate a time series of vertical displacement of the top of the stable inversion layer through the bore, making the assumption that the bore was steady state (Fig. 7d). This analysis indicates that the top of the boundary layer was displaced upward about 400 m in 300 seconds, then oscillated about an average height of 958 m after the leading edge of the bore passed.

3) Analysis

The one-minute ASOS data available from Des Moines, along with the high-resolution Doppler radar imagery of the bore, which passed directly over the KDMX WSR-88D radar, allow for excellent analysis of the characteristics of the bore. These may be compared with theory.

As stated in section 2, the height of the pre-bore stable boundary layer on 2 October 2007 was h_0 = 700 m AGL. The height of the boundary layer after bore passage, h_1, may be estimated using the vertical displacement calculations described in section 3.2. These calculations indicate that the average height of the boundary layer behind the leading edge of the bore was 958 m AGL. PPI scans of velocity indicate that oscillations in velocity associated with the bore occurred as high as 900-1100 m AGL. So, using an average from the two methods, h_1 is estimated at 1000 m AGL. This implies a bore strength (h_1/h_0) of 1.43. According to Simpson (1997), when bore strength is between 1 and 2, the bore is undular, as is the case here.

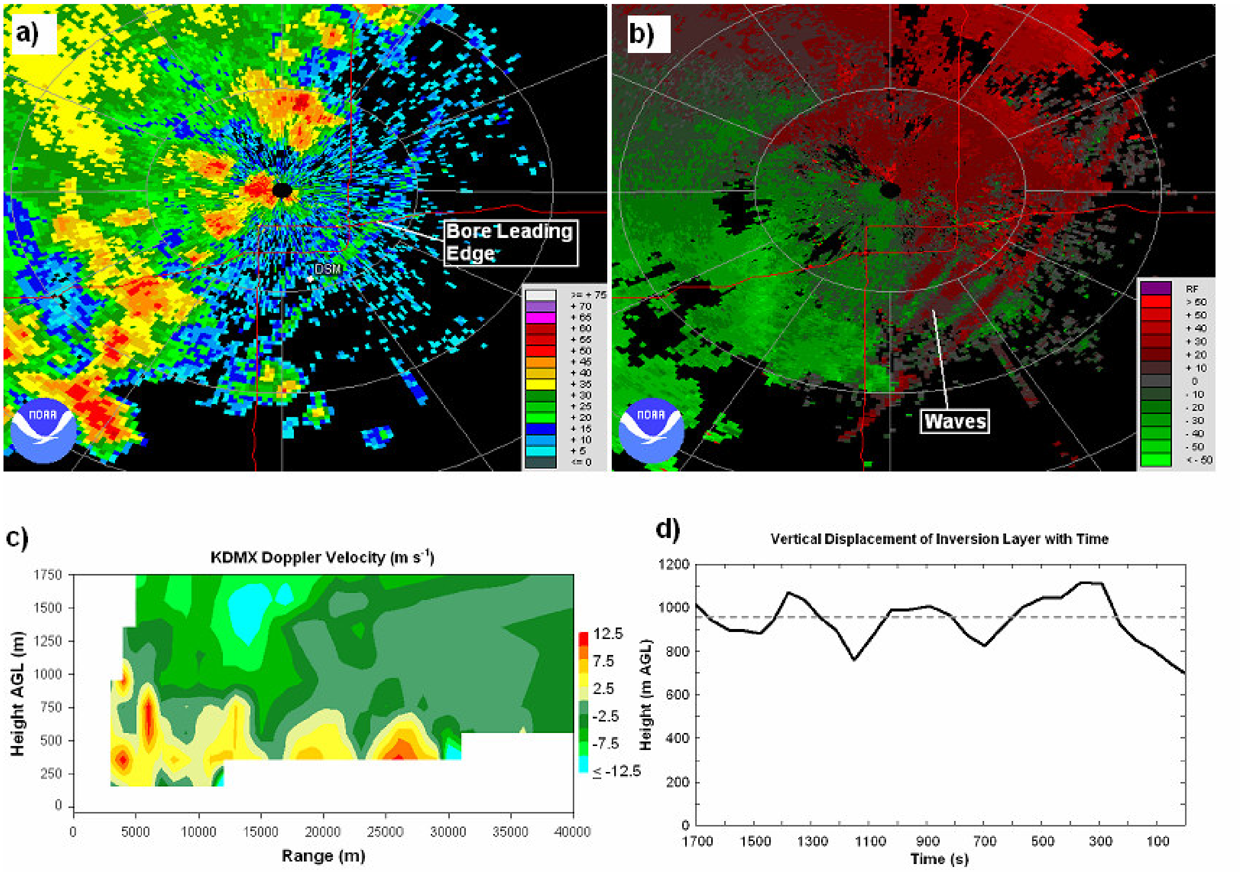

Figure 7. a) 0.5 degree elevation reflectivity scan from the KDMX WSR-88D at 1441 UTC; b) 0.4 degree elevation Doppler velocity scan from KDMX at 1458 UTC; c) Velocity cross-section at 140 degrees azimuth from KDMX at 1450 UTC; d) Analyzed vertical displacement of top of stable boundary layer with time, based on kinematics at 1450 UTC (see text).

The theoretical bore speed may be determined based on the bore strength and the theoretical speed for an internal gravity wave in the surface based layer (C_{gw}). C_{gw} is given by (Simpson 1997)

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

where $\Delta\theta_v$ is the difference in average θ_v between the lower stable layer and the upper layer, and h_0 is the depth of the stable layer. In this case, $C_{gw} = 12.24$ m s^{-1}.

The bore speed (C_{bore}) is then (Rottman and Simpson 1989)

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

where h_1 is the depth of the stable layer after bore passage. This provides $c_{bore} = 16.1$ m s^{-1} in this case. In the 2 October 2007 case, the bore was moving from 300 degrees azimuth, and NAM model soundings indicate an average bore-normal wind of -2.5 m s^{-1} in the 0-700 m AGL layer. Since C_{bore} assumes no background flow, the actual theoretical speed of the bore is 13.6 m s^{-1}, close to the observed 12.8 m s^{-1}.

Laboratory experiments done by Rottman and Simpson (1989) and atmospheric measurements by Clarke et al. (1981) indicate that, for bore strengths between 1.0 and 2.0, the horizontal wavelength of the waves behind the bore should be about 10(+/- 4) * h_1. In this case,

h_1=1000 m, so the wavelength should be around 6-14 km. The observed wavelength using radar data is about 7 km, which is in range.

4. Conclusions

An intense atmospheric undular bore was initiated over central Iowa on 2 October 2007, as an MCS interacted with a stable low-level inversion. A less stable layer was in place above the inversion, allowing for ducting of wave energy and bore maintenance.

Photographs (shown) and videos (referenced online, see Fig. 1) of the cloud features associated with the bore were dramatic. One-minute surface data were available from the ASOS at Des Moines, and the bore also moved directly over the Des Moines WSR-88D Doppler radar. These datasets allowed a simple analysis of the kinematics of the bore and comparison with theory.

Removal of the background synoptic pressure falls revealed that the bore caused a rapid rise in surface pressure, followed by pressure oscillations. Rapid changes in surface winds were also observed.

The vertical motion at the leading edge of the bore produced a "fine line" in PPI radar reflectivity scans, but the bore and its multiple wavelengths of oscillations were more apparent in Doppler velocity measurements. Analysis of Doppler velocity data allowed for estimates of the upward displacement and undulations of the top of the low-level stable layer, and assessment of bore strength, which was 1.43 in this case, consistent with the bore's undular nature.

The vertical displacement of the low-level stable layer, in conjunction with model sounding data, allowed calculation of theoretical bore speed, which was within 10% of observed bore speed. Laboratory results from the literature comparing the horizontal wavelength of the waves behind the bore, with the average height of the stable layer after bore passage, were also consistent with the wavelengths observed in this case.

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