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MULTISENSOR STUDY OF A DUAL BORE EVENT OBSERVED DURING IHOP

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1. Introduction

The International H2O Project (IHOP-2002) field experiments took place in the Southern Great Plains (SGP) of the U.S. from 13 May to 25 June 2002. The principle goal of IHOP is to obtain an improved characterization of the time-varying three-dimensional water vapor field and evaluate its utility in improving the understanding and prediction of convective processes. With this purpose in mind, IHOP-2002 brought together many of the existing operational and new state-of-the-art research water vapor sensors and numerical models. A concentration of instruments at the Homestead Profiling Site in the Oklahoma Panhandle enabled very detailed study of the structure and dynamics of mesoscale phenomena responsible for triggering convection. The NCAR Integrated Sounding System and Multiple Antenna Profiler (ISS/MAPR, Cohn et al. 2001), an Atmospheric Emitted Radiance Interferometer (AERI, Feltz et al. 2003), and FM-CW radar (Ince et al. 1998) were located at the Homestead site. In addition, low-level fields of refractivity were derived from measurements made by the NCAR S-POL 10-cm radar (Fabry et al. 1997; Lutz et al. 1995), and a surface mesonetwork provided useful data. Also, a Scanning Raman Lidar (SRL, Demoz et al. 2003), a Doppler lidar (GLOW, Gentry et al. 2000), and an aerosol backscatter lidar (HARLIE, Schwemmer et al. 1998) – all from NASA – were collocated to respectively provide information on water vapor, aerosols, and winds.

Although not one of the primary objectives of IHOP, numerous bores were observed by these ground-based remote sensing systems, as well as research aircraft, during the six-week field experiment. These observing systems were well-suited for giving probably the most extensive set of remotely-sensed and airborne observations ever collected of the evolving structure and dynamics of bores, solitons, and solitary waves. This paper describes two particularly well-observed bore events that occurred on 4 June 2002. Although not shown here, bore A was generated by an advancing outflow boundary acting as a gravity current, whereas bore B (which occurred ~4 h later) was generated along a southward-advancing cold front (the parent gravity current likely having been enhanced by postfrontal convection).

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2. Background on Bores

The presence of low-level stratification favors the ordered evolution of gravity currents into turbulent bores, undular bores, solitons, and finally solitary waves (Christie et al. 1979; Simpson 1987). A characteristic of gravity currents is a “feeder flow” of air directed from behind the head of the gravity current toward its leading edge in a current-relative framework. Passage of gravity currents at a ground site is usually identifiable by an abrupt pressure jump hydrostatically related to the mean cooling throughout the depth of the current, a sharp wind shift caused by the horizontal gradient of the pressure perturbation, and increased gustiness due to strong vertical mixing in the head of the current.

An internal bore in the atmosphere is a type of gravity wave disturbance that propagates on a low-level inversion ahead of a gravity current. Bores typically are generated as a gravity current intrudes into a stably stratified atmosphere of sufficient depth near the ground, resulting in a sustained elevation of the inversion layer. Amplitude-ordered solitary waves (a train of which is referred to as a soliton) can evolve from bores in some instances. Because the speed of a solitary wave is proportional to the wave amplitude, a dispersive family of waves evolves from the initial bore with amplitudes inversely related to their widths. The number of waves increases continuously with time to a finite value, though the number of waves is highly dependent upon the turbulent dissipation. The presence of the density current is no longer critical to the evolution of the undular bore and solitary waves once the bore has been generated (Christie 1989).

In the simplest case, the bore is generated on top of a surface-based, prefrontal stable layer of sufficient depth as the gravity current intrudes into the stable boundary layer (SBL). In the real atmosphere, complex stratification, vertical shear, elevated inversions, and unsteady and/or multiple gravity currents may complicate matters. In addition, the SBL must be sufficiently deep and intense to support a bore of a given strength (Rottman and Simpson 1989), and a mechanism must be present to trap the vertical propagation of wave energy, for otherwise the bore will quickly diminish (Crook 1988; Koch et al. 1991; Koch and Clark 1999).

Gravity currents may generate other kinds of gravity waves besides bores and solitary waves. Model simulations show that a broad spectrum of gravity waves may be produced by a gravity current, including trapped lee-type waves created by strong flow over the head of the gravity current (Jin et al. 1996). Trapped lee waves display no vertical tilt and are motionless relative to the gravity current head. Lee-wave trapping occurs only under a very special condition in which the Scorer parameter decreases rapidly with height. Kelvin-Helmholtz (K-H) waves may also be produced in a thin region of strong vertical wind shear between the body of cold air in the gravity current and the air above it. K-H waves propagate rearward relative to the gravity current head.

Intermediate structures between a pure gravity current and an undular bore may occur as the gravity current begins to intrude into a stably stratified air mass, and the prefrontal air envelops the head of the gravity current (Fulton et al. 1990). The incipient bore initially carries a remnant of the cold air originally contained in the gravity current within a closed circulation at the leading edge of the bore in the form of a solitary wave. Numerical simulations reveal that, as the gravity current slows down with time in association with a decrease of the current depth, the current head becomes separated from the body of the current and resembles a large amplitude wavelike disturbance, with cold air contained within the closed circulations.

3. The 4 June 2002 IHOP bores

Two of the more spectacular bores sampled during IHOP occurred early in the morning of 4 June. Bore A developed from an outflow boundary that emanated from eastern New Mexico across the Oklahoma Panhandle, reaching the Homestead network at ~0630 UTC. Bore B developed in association with a southward-advancing cold front, likely enhanced by postfrontal convection in northwestern Kansas, reaching the Homestead network at ~1030 UTC.

The bores were well-sampled by the ground-based systems at Homestead. Bore A is very impressive in the FM-CW and MAPR (Fig. 1) displays. At this stage, the bore displayed the character of a soliton composed of waves with horizontal wavelengths of ~10 km, consistent with the S-POL radar reflectivity imagery (not shown). The influence of the bore is felt as high as the top of the MAPR data (to at least 3 km). Bore B was characterized by at least 6 waves with a similar period of 15-20 min (not shown).

HARLIE shows more clearly the stratified nature of the atmosphere perturbed by the solitary wave disturbances (Fig. 2). The original SBL at 0.7 km is incrementally elevated to a height of 1.2 km following the second wave in the soliton. A 3-layer atmospheric structure is seen by all three observing systems, but the HARLIE most clearly reveals the lifting by the bore of the less strongly defined layer from 1.0 to ~2.1 km and lifting of the third layer from 2 to ~4 km.

MAPR data were used to examine the influence of the bore lifting on the atmospheric stability and its ability to generate deep convection. Maximum updrafts below 2 km exceed 2 m s^{-1}, but average ~1 m s^{-1} over the 10-min bore lifting periods, resulting in 600 m of lifting, which is consistent with the observed increase of the SBL depth. Although much of the MAPR data is lost above 2 km, it is reasonable to expect similar agreements between vertical motions and layer displacements. The MAPR data do suggest that most of the lifting is contained below 2 km, indicating that wave energy is not propagating upward, and that waves dampen in the near-neutral layer above the SBL, as can be seen in the Harlie data (Fig 2). Application of these layer displacement profiles to the special CLASS soundings taken in the Homestead vicinity did not result in air parcels attaining their Level of Free Convection (LFC) because the lower troposphere was very dry. In fact, deep convection was not initiated by bore A.

AERI measurements taken during the passage of the two bores are shown in Fig. 3. These data have a temporal resolution of 10 min and vertical resolution of 50, 200, and 250 m in the 0–1, 1–2, and 2–3 km layers. Although coarser in resolution than the other remote sensing observations discussed above, AERI reveals in the case of both bores a sudden cooling and moistening aloft with no attendant near-surface cooling, which is a characteristic of bores. The Wyoming King Air in-flight measurements of bore B (not shown) detected similar moistening and cooling as it passed through the upper parts of the wave crests. In addition, the aircraft data showed a quadrature phase relation between fluctuations in potential temperature and vertical motions, with updrafts leading cooling periods, and vice versa, as expected for gravity waves (or solitary waves). The magnitude of the vertical motions was 1 or 2 m s^{-1}, similar to that seen in the MAPR data.

The near-surface refractivity fields computed from the S-POL measurements (Fabry et al. 1997) show the propagation of a pronounced band of reduced refractivity associated with the leading edge of bore A (Fig. 4). Refractivity may be reduced by warming and/or drying. The S-POL derived changes in refractivity are

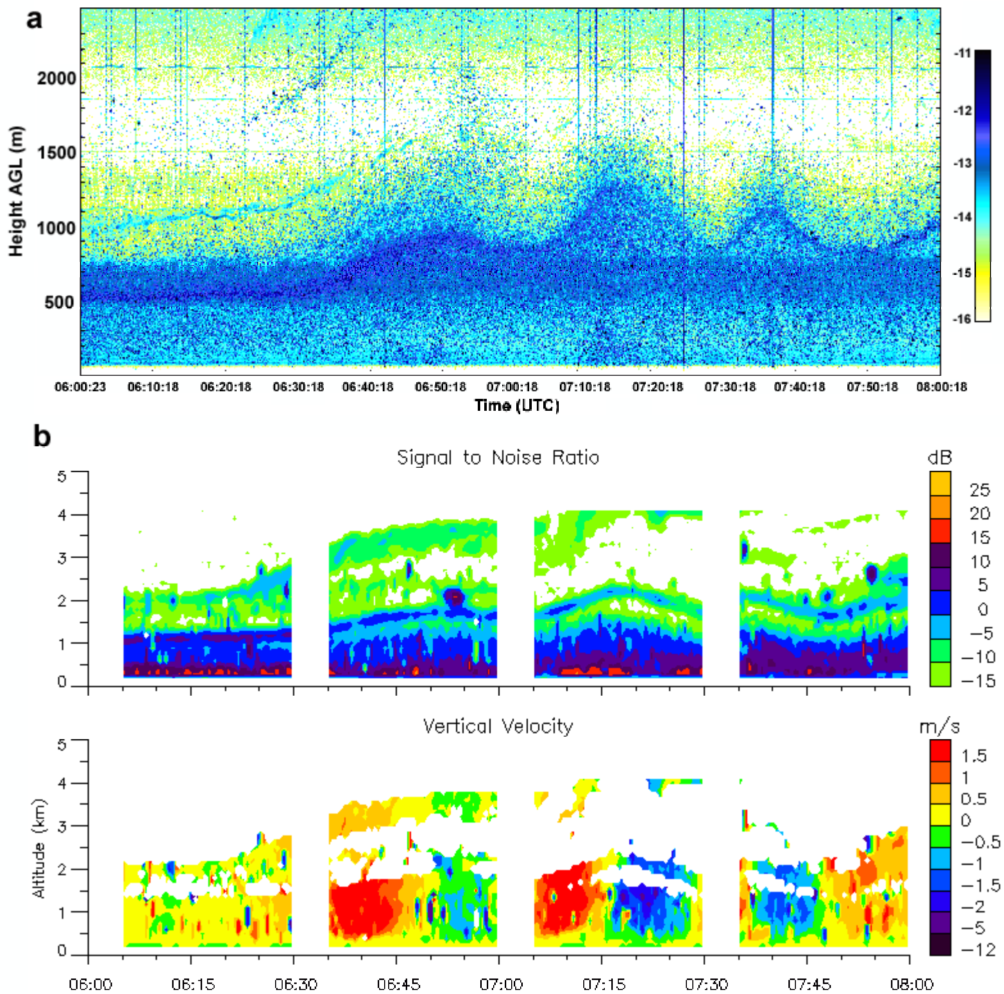

Fig. 1. Bore A as observed by a) FM-CW (reflectivity, units of dBZ) and b) MAPR. Middle panel shows MAPR SNR (dB), bottom panel shows measured vertical motions (m s^{-1}), with updrafts in red and downdrafts in blue. FM-CW and MAPR data have been remapped to the same temporal scales. Bore front passes at 0630 UTC 4 June 2002, and results in a sustained SBL deepening followed by 2 or 3 solitary waves.

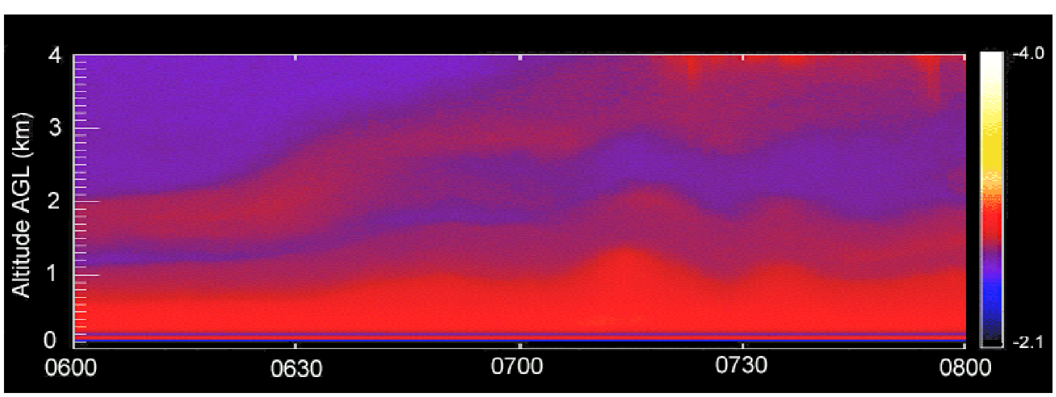

Fig. 2. Bore A as observed by HARLIE (0600–0800 UTC). Note the stratified structures in aerosols.

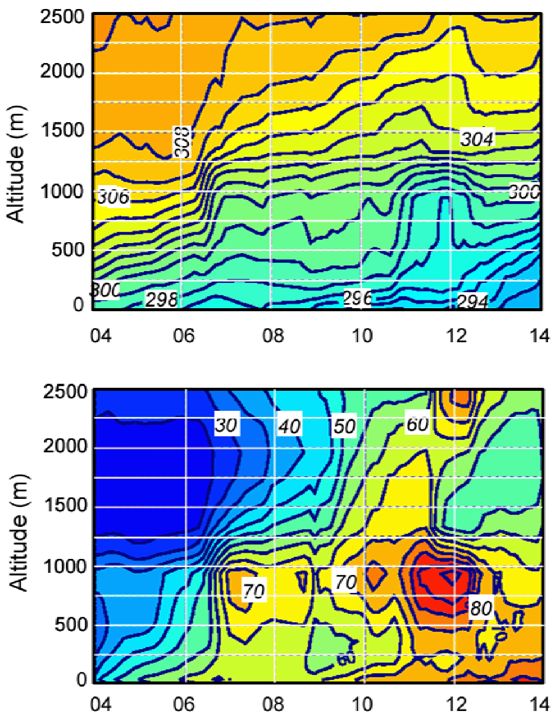

Fig. 3. AERI time-height displays showing (top) potential temperature and (bottom) relative humidity changes caused by passage of bore A (0630 UTC) and bore B (1030 UTC). The most pronounced changes are evident above 500 m AGL.

consistent with computed changes from the NCAR mesonet station time series data for bore A (Fig. 5), though comparisons are only valid for short distances from the radar (near the ground).

4. Conclusions and Plans

The picture that emerges from the synthesis of the mesonet, S-POL, AERI, and King Air data is one of drying near the surface (the warming was rather insignificant) and cooling and moistening at the tops of wave crests associated with the passage of bore A. This would seem to be the natural consequence of adiabatic lifting processes aloft, and entrainment processes within the turbulent bore head near the surface. However, the refractivity changes with bore B were not nearly as evident. These differences are the subject of continuing investigation, which will involve the use of very high-resolution model simulations.

The origin of the bores has not been fully determined from these data. Differences in wave characteristics (wavelength, number, etc.) and inversion layer details existing between the observing systems require explanation. It is unknown why the number of waves within the soliton varied with the life cycle of the bore. The actual cause(s) for the observed changes in the refractivity fields seen from S-POL and the mesonet data are also unclear at this time. Future plans include the need to compare these synthesized data analyses with theory and with the results of large-eddy simulation modeling. Of particular interest are the nature of the entrainment process, the height dependency of the wavenumbers, and the cause for the waves behind the bore head. The latter waves are suggestive of lee-wave activity, as opposed to theoretical predictions of dispersive waves related to the intrinsic nonlinear dynamics of bores.

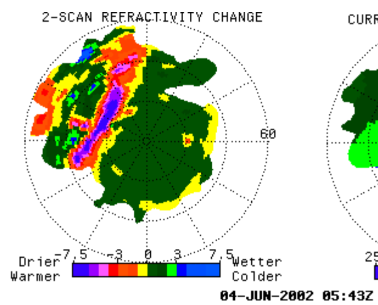

Fig. 4. Refractivity fields and 12-min changes in the computed refractivity from S-POL measurements at 0543 UTC 4 June.

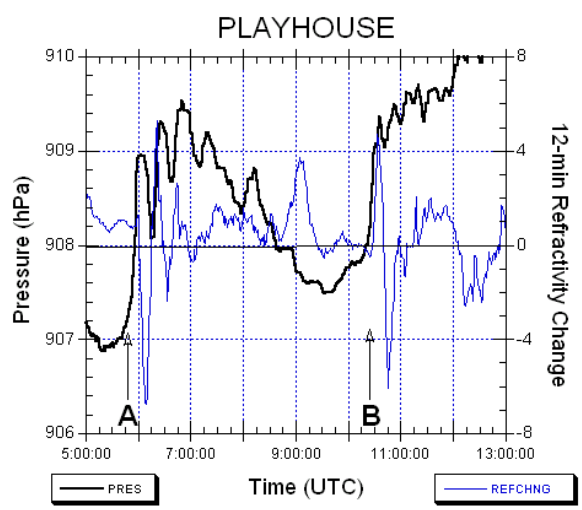

Fig. 5. Time series of pressure and computed refractivity changes from one of the NCAR mesonet stations (Playhouse) in the path of bores A and B.

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