An Observational and Modeling Study of an Atmospheric Internal Bore during NAME 2004

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ABSTRACT

Observations from the 2004 North American Monsoon Experiment (NAME) have been used to identify an atmospheric internal bore that occurred over the Gulf of California (GoC) on 31 July 2004. This bore disturbance was identified at Bahia Kino along the northwest coast of Mexico during the late evening of 31 July. It was hypothesized to have originated from the interaction of a gravity current from a large mesoscale convective system (MCS), which formed along the western slopes of the Sierra Madre Occidental during the afternoon, and a surface stable layer that developed from a sea-breeze circulation. It is suggested that the bore's energy was trapped at low levels by an elevated stable layer. The vertical structure and undular nature of the bore was initially identified from 915-MHz wind profiler data at Bahia Kino. Results show a series of waves along the bore's leading edge and turbulent mixing of air from above the stable layer to the surface on the downstream face of the leading undulation. The speed of the bore calculated from satellite imagery and surface observations (approximately 16.8 m s^{-1}) compared favorably with the speed of a bore from hydraulic theory when a reliable estimate of the bore depth was used.

A real-data simulation of the event was performed using the Weather Research and Forecasting model (WRF). Results show the model captured both the formation mechanism and structure of the bore, but it was produced too far south compared to observations, as the MCS also developed too far south. Model results indicated that while evidence of a trapping mechanism due to the stability of the atmosphere was present in the simulation, the conditions for trapping were modified by the passage of the bore allowing vertical propagation of wave energy. The bore led to increased moisture in the lowest levels of the atmosphere across the GoC, providing evidence of the possible importance of these features as moisture transport mechanisms in this region.

1. Introduction

Monsoon circulation systems develop over low-latitude continental regions in response to thermal contrast between continents and adjacent oceans. Monsoons are major components of warm-season precipitation regimes (Higgins et al. 2003). The North American Monsoon (NAM) develops because of heating over the elevated terrain of Mexico and the western United States beginning in early July. Although the NAM is much weaker than the more well-documented Asian monsoons, it still has prominent monsoon characteristics, such as a reversal in the mean low-level flow over the Gulf of California (Tang and Reiter 1984; Badan-

Dangon et al. 1991), areas (e.g., northwestern Mexico) receiving a major fraction (60%) of their total annual precipitation during the monsoon season (Tang and Reiter 1984; Douglas et al. 1993; Higgins et al. 1997), and a strong upper-level anticyclone (Krishnamurti 1971).

The geographical domain of the NAM includes important topographical features, such as the Sierra Madre Occidental (SMO), the Gulf of California (GoC), the Sonoran Desert, and the peninsula range of Baja California (Fig. 1). The complex topography of the NAM region makes the prediction of warm-season precipitation in this region a challenge (Xu et al. 2004).

A strong diurnal cycle of convection is present during the NAM. The combination of heating along the slopes of the SMO during the day and the afternoon sea breeze that develops off the GoC leads to lower-tropospheric convergence centered over the western slope of the SMO, collocated with strong divergence

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FIG. 1. NAME sounding network and grids used for sounding analysis: tier II array (T2A), tier I array (T1A), and enhanced budget array (EBA). Symbols indicate frequency of routine (EOP) sounding launches (left number) and frequency of increased sounding launches (right number) during IOPs.

aloft between 150 and 200 hPa (Johnson et al. 2007), and intense afternoon and evening precipitation.

One aspect of the NAM that has heretofore received little attention is the frequent occurrence of atmospheric internal bores. Observations of these phenomena have come about as a result of the 2004 North American Monsoon Experiment (NAME; Higgins et al. 2006). An internal bore in the atmosphere is a type of gravity wave disturbance that forms at an interface between two fluids and propagates on a low-level inversion ahead of a gravity current. The simplest and most general definition of a bore is a propagating disturbance characterized by a sudden, and relatively permanent change in the height of a horizontal fluid interface and in the velocity of the fluid beneath the interface.

Internal bores are classified as undular when they are

accompanied by a group of waves that radiate energy downstream (Clarke et al. 1981). Bores can arise in a variety of atmospheric situations when disturbances are generated on a preexisting inversion layer. Several theories have been proposed as to the possible external force required for the generation of bores. Cool air behind colliding gravity currents (Clarke et al. 1981; Clarke 1984; Noonan and Smith 1987; Wakimoto and Kingsmill 1995; Kingsmill and Crook 2003), thunderstorm outflows (Fulton et al. 1990; Koch et al. 1991; Mahapatra et al. 1991; Locatelli et al. 1998; Koch et al. 2005; Knupp 2006), and mesoscale fronts (Karyampudi et al. 1995; Smith et al. 1995; Koch and Clark 1999; Demoz et al. 2005) interacting with an existing stable layer may trigger bore disturbances. However, complications to these ideas arise in the real atmosphere because of complex stratification, vertical shear, elevated

inversions, and unsteady and/or multiple gravity currents.

Previous studies have shown that atmospheric bores exist in several regions of the world. Perhaps the most recognizable is the Morning Glory of the Gulf of Carpentaria in northern Australia, which was first identified as an internal undular bore initiated by the interaction of a sea breeze and a nocturnal inversion by Clarke et al. (1981). Many bores have been identified in the central United States (Doviak and Ge 1984; Haase and Smith 1984; Carbone et al. 1990; Fulton et al. 1990; Demoz et al. 2005), Florida (Wakimoto and Kingsmill 1995; Kingsmill and Crook 2003), and other regions of the world. Prior to the 2004 NAME, there has been no evidence of bores being observed in the NAM domain. However, results emerging from NAME have shown that these phenomena indeed exist in the GoC region (Rogers and Johnson 2007). In that study bores were postulated to exist based on NAME observations, although details of their structure and behavior were not fully documented.

The primary objective of this study is to extend and expand these earlier results to better describe the structure, dynamics, and significance of atmospheric bores in the NAM region. Observational measurements collected during NAME from 1 July to 15 August 2004, allow for detailed studies of the structure and dynamical mechanisms of internal bores. Very few observations are routinely available in this region from the operational network; however, data collected during the NAME field campaign have provided an unprecedented high temporal and spatial resolution dataset (Higgins et al. 2006). Of particular importance in this study is the deployment of three National Center for Atmospheric Research (NCAR) Integrated Sounding Systems (ISS) along the east coast of the GoC to sample the lower troposphere.

It is important to identify and understand atmospheric bores in this region for several reasons. First, circulations produced by bores (and other similar phenomenon) may be capable of directly triggering convection, as maximum vertical velocities have been observed up to 15 m s^{-1} (Shreffler and Binkowski 1981; Carbone et al. 1990; Fulton et al. 1990; Karyampudi et al. 1995). The convection that is triggered by bores can range from roll clouds (Clarke et al. 1981) and light showers to squall lines with tornadic storms (Karyampudi et al. 1995), although the latter do not occur in the NAM region. Second, the accelerated and increased depth of the flow behind the leading edge of a bore may be responsible for increased moisture transport into the southwestern United States, providing the fuel for enhanced convection (Rogers and Johnson 2007).

2. Data and methods

NAME is an internationally coordinated project aimed at determining the “sources and limits of predictability of warm season precipitation over North America.” NAME seeks to improve the understanding of key physical processes that must be parameterized for more realistic simulations and accurate predictions within the NAM region with coupled numerical models. During the NAME 2004 campaign, data were gathered from more than 20 different types of instrument platforms, including surface meteorological stations, radars, aircraft, research vessels, satellites, wind profilers, rawinsondes, and rain gauge networks (Higgins et al. 2006).

NAME employs a multiscale (tiered) approach with focused monitoring, diagnostic, and modeling activities in the core monsoon region. Figure 1 shows the regions encompassed by the tier 1A (the core monsoon region) and tier 2A (covering the southwestern United States and much of Mexico) domains, along with an enhanced budget array.

During the extended observing period (EOP) three NCAR ISSs were deployed along the GoC at Puerto Peñasco, Sonora; Bahia Kino, Sonora; and Los Mochis, Sinaloa, on the eastern side of the GoC (Fig. 1). The ISSs consisted of a global positioning system (GPS) sounding system, a 915-MHz Doppler clear-air wind profiler, a Radio Acoustic Sounding System (RASS), and an enhanced surface meteorological station that measured pressure, temperature, relative humidity, wind speed and direction, radiation (solar and net), and precipitation at 1-min resolution (Higgins et al. 2006).

The atmospheric internal bore discussed in this study was identified at Bahia Kino using the signal-to-noise ratio (SNR), vertical velocities, spectral width (1-min temporal resolution) and low-mode horizontal wind data from the 915-MHz Doppler clear-air wind profiler. The NCAR Improved Moments Algorithm (NIMA) quality control program was used to correct bad or questionable profiler data. Further quality control for the wind calculation was provided by the NCAR Winds and Confidence Algorithm (NWCA). Data with a NWCA confidence value of 0.5 or greater are considered dependable. Data from the wind profiler at Bahia Kino were compared to data from the surface observations of temperature, humidity, and pressure.

In addition to the ISS surface meteorological station at Bahia Kino, additional surface observations were used from Servicio Meteorológico Nacional (SMN) sites in Mexico, which reported hourly observations of pressure, temperature, relative humidity, and wind speed and direction, and a network of automated sta-

tions maintained by SMN, which reported 10-min observations of pressure, temperature, relative humidity, wind speed and direction, and precipitation. When examining time series of surface pressure data at SMN sites, it was discovered that the overall data quality was quite poor. The surface pressure data from the SMN sites were reduced to altimeter settings and pressure values outside three standard deviations from the mean were discarded. The data from the ISS stations were of a high quality and little quality control needed to be performed.

To observe the pressure changes associated with the bore, both the diurnal and semidiurnal tides of pressure were removed from the pressure data at all stations so that the meteorological signal of the bore could be isolated. To calculate the anomalies, the mean value of pressure was calculated for each time interval (1 min, 10 min, or 1 h depending on the temporal resolution of the station) for the entire EOP. It is assumed that the diurnal and semidiurnal tidal effects don't change over the period of the study. These mean values were then removed from the pressure to produce a surface pressure anomaly.

In addition to the data described above, *Geostationary Operational Environmental Satellite-10 (GOES-10)* infrared (IR) images centered about the core monsoon region were obtained from the Cooperative Institute for Research in the Atmosphere (CIARA). Water vapor imagery was not used since this channel integrates water vapor over a depth of the atmosphere centered about the mid- to upper troposphere, whereas bore-related moisture advection is centered at low levels. The IR images were examined every 15 min during the period associated with bore formation, passage, and dissipation to determine areas of relative cloudiness associated with the bore itself and convective activity associated with bore formation. Comparison of these images with the pressure time series at all stations proved useful in relating cloud features to surface signatures of the bore. Visible satellite imagery did not prove useful because the bore event occurred at night. No NAME pilot balloon, aircraft, or radar data were used in this study, because of the location and timing of the bore in question.

3. Numerical model configuration

Despite the increased amount of data available during NAME, data were still relatively sparse in relation to the structure and dynamics of bores. To fully investigate one bore event, a numerical simulation using the Weather Research and Forecasting (WRF) Advanced Research WRF (ARW) model was performed. The

TABLE 1. Design of WRF numerical model experiment. Multiple entries indicate different configurations for domains 1, 2, and 3.

Cumulus convection	KF, KF, explicit
Boundary layer	Mellor–Yamada–Janic (Eta) TKE
Surface layer	Monin–Obukhov (Janic Eta)
Microphysics	Purdue Lin
Land surface	Noah
Turbulence	2D Smagorinsky
Shortwave radiation	Dudhia
Longwave radiation	Rapid Radiative Transfer

ability of the WRF model, initialized with real data, to simulate bore phenomenon has not previously been investigated. The WRF modeling system is a multiagency effort intended to provide a next-generation mesoscale forecast model and data assimilation system that will advance the understanding and prediction of mesoscale weather.

Version 2.1.2 of the Advanced Research WRF was set up in a triple, one-way nested grid configuration with 18-, 6-, and 2-km horizontal grids. The coarsest grid was initialized with 40 km Eta Model data at 0000 UTC 31 July 2004 and run for 12 h with model output every 15 min. All three nests contained 53 vertical levels, with the greatest resolution in the boundary layer. Cumulus convection was parameterized using the Kain–Fritsch scheme on domains 1 and 2, while convection was explicitly resolved in domain 3. (Further details of the model configuration are shown in Table 1 and details of the parameterization schemes are available at www.mmm.ucar.edu/wrf/users/.)

4. Observational analyses

This section presents the observational evidence of an atmospheric internal bore that was observed during the evening (local time) at the Bahia Kino ISS site on 31 July 2004 during NAME. A variety of data from different instruments will be presented.

a. Satellite data

Figure 2 shows *GOES-10* IR images of the core monsoon region from 0130 to 0430 UTC 31 July. At 0130 UTC (Fig. 2a), a series of mesoscale convective systems (MCSs) had developed along the SMO due to westerly upslope flow at low levels and strong solar heating and moisture availability along the SMO, consistent with the diurnal cycle of convection in this region. The northernmost MCS, located east of the Bahia Kino ISS site had already developed, with a large cloud anvil and cloud-top temperatures below -60°C .

One hour later, at 0230 UTC (Fig. 2b) the convective

FIG. 2. Infrared *GOES-10* satellite imagery over the core NAM domain at (a) 0130 UTC 31 Jul, (b) 0230 UTC 31 Jul, (c) 0330 UTC 31 Jul, and (d) 0430 UTC 31 Jul 2004. Coldest cloud-top temperatures are shaded. The BK in (a) shows the location of the ISS site at Bahia Kino and HE the surface station at Hermosillo.

system to the east of the Bahia Kino ISS site had developed a low-level cloud feature (cloud-top temperatures between 276 and 279 K) to its southwest. Intermediate satellite imagery (not shown) suggests that this cloud feature was generated by the convective system and began moving westward and away from its parent system by 0200 UTC. This low-level cloud feature continued to propagate westward, at a speed of 16.5 m s^{-1} , and by 0330 UTC (Fig. 2c), had a distinctive arc-shaped structure as it moved into the GoC. While we cannot explicitly determine the nature of this cloud feature from the satellite imagery alone, the fast propagation speed suggests an atmospheric bore. During this time, the MCS that produced the bore moved northward and weakened.

Through 0430 UTC (Fig. 2d) the northernmost portion of the low-level cloud feature was in the region of the Bahia Kino ISS site. The approximate length of the cloud feature at this time was 220 km. The MCS continued to dissipate as a second larger MCS developed to the southeast.

The linear structure of the cloud feature began to break down and become disorganized as it progressed across the GoC between 0500 and 0600 UTC (not shown). After 0600 UTC the satellite imagery (not shown) shows that while the southern part of the cloud feature had dissipated, the northern section stalled over the eastern slopes of the Baja California Peninsula until 0800 UTC when it dissipated completely.

b. 915-MHz Doppler clear-air wind profiler

The 915-MHz wind profiler located at the Bahia Kino ISS site was ideally situated to investigate the vertical structure of the lower atmosphere in conjunction with the cloud feature seen in the satellite imagery (Fig. 2). A 2-h section of the profiler data, at the time of the cloud passage is shown in Fig. 3. Four different data products are shown from top to bottom: the SNR, vertical velocity, spectral width, and horizontal winds every 30 min. Data are only displayed when the SNR is greater than -15 dB .

The large values of SNR at low levels (Fig. 3a) were

FIG. 3. 915-MHz wind profiler data from the Bahia Kino ISS, 0400–0600 UTC 31 Jul 2004; (a) SNR, (b) Doppler vertical velocity (negative vertical velocities indicate motion away from the profiler), (c) spectral width, and (d) horizontal winds derived from NIMA processing.

due to changes in the refractive index. At the beginning of the time series a shallow layer (200–400 m) of enhanced SNR close to the surface, due to a surface stable layer is evident. At 0435 UTC (2135 LT) this surface-based region of enhanced SNR rapidly evolved, increasing in depth to approximately 1 km and increasing in magnitude. This evolution coincided with the low-level cloud passage in the satellite imagery and the updraft seen in Fig. 3b. The depth of the surface-based

SNR region remained large through 0600 UTC, supporting evidence that the disturbance is an atmospheric bore. However, the most convincing evidence that the disturbance is an atmospheric bore is the series of undulations in the SNR in the lowest 3 km, much like the undular bore documented during the International H₂O Project (IHOP) by Koch et al. (2005).

At least two undulations are evident in the SNR around 1 km, indicating the bore was undular at this

period in its life cycle. The time between the first undulations is 14 min and between the second is 11 min. Assuming the bore is propagating at 16.5 m s^{-1} , as determined from the speed of the low-level cloud in the satellite, this corresponds to wavelengths of 14 and 11 km. The wavelength fits within the range of observations from previous studies. The greater distance between the first undulations compared to the succeeding undulations has also been observed in studies of bores and solitary waves (Fulton et al. 1990) and is attributed to the larger amplitude of the initial undulation (or wave), hence, a greater propagation speed of the first undulation and increased separation between the first two wave crests.

A second layer of enhanced SNR observed at 1 km at 0400 UTC was elevated approximately 800 m by the passage of the bore at 0435 UTC. The undulations seen in the surface based layer of enhanced SNR were also observed in this elevated layer. The lack of tilt between the undulations in these layers suggests that wave energy is being trapped (Koch et al. 2005), which will be explored further in section 3f.

The maximum vertical motion associated with the bore was $4\text{--}5 \text{ m s}^{-1}$ (Fig. 3b). Three distinct couplets of ascent and descent are seen in the profiler data in phase with the undulations in the SNR, supporting the hypothesis that this is an atmospheric internal undular bore. The first couplet contains the largest magnitudes of vertical motion (both ascent and descent). One of the important features of the vertical velocity profile is that the vertical velocities extend considerably higher than the region of enhanced SNR, indicating that the bore's energy was not trapped close to the surface (below approximately 3 km).

Spectral width from the profiler is shown in Fig. 3c. There are four processes that contribute to spectral width: turbulence, wind shear within the pulse volume, differential fall velocities, and antenna movement. In the boundary layer, the largest contribution to the spectral width is likely to be from turbulence, with wind shear as the secondary contributor. A region of enhanced spectral width at and below 1 km was observed beginning at 0440 UTC and lasting for 10 min. This maximum is collocated with the downstream face of the first undulation in SNR and the downward motion in the first vertical velocity couplet. It is hypothesized that this maximum in spectral width was due to enhanced turbulence on the downstream face of the first undulation that mixed turbulent air from above the stable layer toward the surface. This downward mixing has been observed in laboratory studies (Rottman and Simpson 1989) and atmospheric bores (Knupp 2006).

FIG. 4. The 0–10-km vertical profile of potential temperature ($^{\circ}\text{C}$) (solid line, lower axis) and mixing ratio (g kg^{-1}) (dashed line, upper axis) from the 0000 UTC 31 Jul 2004 sounding from Bahia Kino.

The vertical profile of the horizontal winds, processed using NIMA (section 2), is displayed in Fig. 3d. Unfortunately, the NIMA processing algorithm only produced winds at 30-min intervals to ensure high-quality data. However, the change in wind direction from southwesterly before the bore to southeasterly (in the direction of the bore motion) after the bore passage is clearly evident. The southwesterly winds prior to the bore passage are consistent with upslope flow along the SMO that generated the convection seen in the satellite imagery (Fig. 2).

The RASS at Bahia Kino was switched off at 0400 UTC, when the surface stable layer was 400 m in depth, just prior to bore passage, so no observations of the vertical profile of virtual potential temperature of the bore are available.

c. Soundings

The potential temperature from the sounding released from Bahia Kino at 0000 UTC 31 July (1700 LT 30 July) is shown in Fig. 4. Unfortunately, this bore did not occur during an intensive observation period (IOP), so a sounding was not released at 0600 UTC. While the sounding at 0000 UTC was over 4 h prior to the passage of the bore, it is still useful in determining the prebore environment and understanding why the bore was able to propagate.

The 0000 UTC sounding shows a strong stable layer extending to approximately 250 m above the surface. This stable layer is not due to nocturnal cooling as the sounding was taken at 1700 LT. It is suggested that this

FIG. 5. One-minute resolution observations from the surface meteorological station at Bahia Kino, 31 Jul 2004: (a) pressure anomaly (green) (hPa), temperature (red) (°C), and dewpoint temperature (blue) (°C) and (b) wind speed (dotted) (m s^{-1}) and wind direction (solid).

low-level stable layer is due to the sea breeze that developed along the eastern coast of the GoC during the afternoon, and that the bore propagated along this stable layer. Above the stable layer, between 0.5 and 3 km, the temperature profile is close to neutral, hence the ideal conditions for wave trapping are present; a stable layer capped by a layer of neutral stability (Crook 1986). An elevated stable layer between 5.5 and 6 km is a prominent feature above the low-level stable layer.

As discussed in section 4a, the cloud-top temperature of the low-level cloud feature associated with the bore, was between 276 and 279 K, which would place the cloud top at or close to 600 hPa (4 km AGL) from the 0000 UTC sounding (assuming the cloud is optically thick), noting that this sounding was several hours prior to bore passage. This is consistent with the vertical velocities within the bore (Fig. 3b) being large, and extending up to at least 3 km for the first undulation, where the mixing ratio is largest and the environment is close to saturation (not shown). It is suggested that the low-level cloud feature identified in the satellite imagery is generated by the ascent associated with the leading edge of the bore.

d. Surface observations

The pressure anomaly, temperature, dewpoint temperature, wind direction, and wind speed associated with the bore passage at Bahia Kino are shown in Fig. 5 for the 3 h surrounding the passage of the bore (0330–0630 UTC). A 1.5-hPa rise in the pressure anomaly in

8 min was associated with the arrival of the bore at 0432 UTC. The pressure was at its maximum value at 0440 UTC, followed by an oscillation of magnitude 0.5 hPa. The timing of the pressure oscillations is consistent with the undulations in the profiler SNR and the satellite imagery of the low-level cloud feature.

We see little change in the surface temperature before and after the bore passage. However, the dewpoint temperature increased 2°–3°C as the bore passed the measurement site. The dewpoint temperature remained elevated, indicating a moistening at the surface, while the pressure was elevated. This moistening is consistent with some previous studies (Koch et al. 1991; Mahapatra et al. 1991); however, other studies show a drying accompanying bores (Fulton et al. 1990; Koch and Clark 1999).

In conjunction with these mean changes in temperature and dewpoint temperature, we see a distinct signature in both variables coinciding with the downstream face of the first undulation of the bore. At this time there is a slight increase in temperature of 1°C, a sharp decrease in the dewpoint of 7°C, and a minor dip in pressure, which lag the pressure maximum by 7–8 min. This lag is consistent with results from Fulton et al. (1990) and Koch and Clark (1999). The timing of this warming and drying corresponds to the region of high spectral width (increased turbulence) seen in Fig. 3c. The warming and drying at the surface, and increased turbulence below 1 km together indicate turbulent motion (due to shear instability) in the lee of the first undulation of the bore, which mixed potentially

FIG. 6. One-hour resolution observations from the surface meteorological station at Hermosillo, 31 Jul 2004: (a) pressure anomaly (green) (hPa), temperature (red) (°C), and dewpoint temperature (blue) (°C) and (b) wind speed (dotted) (m s^{-1}) and wind direction (solid).

warmer, drier air from above the surface stable layer downward to the surface.

Coincident with the two oscillations in pressure are two maxima in wind speed (Fig. 5b), with wind speeds more than doubling as each undulation passed over the observing station. This in-phase relationship between pressure and wind speed undulations has been well documented in observations of both solitary waves and undular bores (Haase and Smith 1984; Fulton et al. 1990; Mahapatra et al. 1991; Koch et al. 1991; Karyampudi et al. 1995; Knupp 2006). The wind direction at the surface is consistent with the profiler-measured wind direction close to the surface.

To investigate the mechanism involved in generating the bore, hourly surface observations from Hermosillo (see Fig. 2a for location) are presented in Fig. 6. This station is situated to the west of the MCS that generated the outflow boundary that led to the generation of the bore observed at Bahia Kino. Despite only having hourly observations from Hermosillo, Fig. 6 shows surface observations consistent with a gravity current. The pressure increases by 4.9 hPa between 0300 and 0500 UTC and rapidly decreases after this time, in agreement with previous observations of gravity currents (Wakimoto 1982). The large pressure change is accompanied by a temperature drop of 7°C, between 0400 and 0500 UTC. This drop in temperature, accompanied by pressure and wind speed increase, indicates that the disturbance was a strong gravity current at this time.

It is suggested that the gravity current arrived at Hermosillo after 0400 UTC, when the large temperature

drop is measured. The timing of the gravity current passage at Hermosillo (at most 35 min prior to the bore's arrival at Bahia Kino) suggests that the bore had already been generated before the gravity current passed Hermosillo, and was not observed at Hermosillo because of the hourly resolution of the data. It is likely that it is the propagation of this gravity current into the stable layer present at Bahia Kino (which is likely to also be present in the surrounding regions) that generated an atmospheric internal undular bore. This mechanism, rather than the collision between the sea breeze itself and the gravity current is plausible for bore formation as the structure of the sea-breeze front would have been significantly weaker during late evening local time.

No observations are available between the MCS and Hermosillo or between Hermosillo and Bahia Kino so we cannot ascertain the exact formation time of the bore or observe the processes involved in generating the bore from the gravity current. The low-level cloud feature is initially evident in the satellite at 0230 UTC, but the bore may have formed sooner and not developed clouds until this time, or the cloud feature may initially have been associated with the edge of the gravity current.

e. Theoretical aspects

Satellite and surface observations were used to determine the speed of the bore to be $16.8 \pm 1 \text{ m s}^{-1}$, which adjusted for the headwind into which the bore is

propagating becomes an actual bore speed $C_b = 21.8 \pm 1 \text{ m s}^{-1}$. For a bore advancing into a fluid that is at rest, the theoretical speed of a bore in this frame of reference is found using hydraulic theory and conservation of mass and momentum (Rottman and Simpson 1989), yielding

$$\frac{C_b^2}{C_{\text{gw}}^2} = \frac{1}{2} \frac{h_1}{h_0} \left(1 + \frac{h_1}{h_0} \right),$$

where h_1 is the depth of the bore, h_0 is the depth of the prebore stable layer, and $C_{\text{gw}}^2 = g'h_0$ is the speed of a long gravity wave (with $g' = g\Delta\theta/\theta$ the reduced gravity). The theoretical speed of a bore is faster than that of linear waves on fluid of depth h_0 , because the fluid following the bore is moving in the same direction (in this reference frame).

The depth of the prebore stable layer at Bahia Kino (h_0) was determined to be 400 m at 0400 UTC from the RASS profiler virtual temperature data (not shown) just prior to it being switched off. As the wind profiler was the only instrument to measure the vertical structure of the bore itself, the depth of the bore (h_1) proved difficult to evaluate. A combination of the average depth of the two enhanced SNR layers (Fig. 3a) and the depth of the enhanced spectral width region (Fig. 3c) were used to estimate h_1 as approximately 1500 m. Using the classification system of Rottman and Simpson (1989), who determine the strength of a bore, S , to be the ratio between the bore depth and the prebore stable layer depth (h_1/h_0) we find for the bore at Bahia Kino, $S = 3.8$. This classifies the bore as type B, a smooth undular bore but with some mixing, due to shear instability, on the downstream face of the first undulation. This classification fits well with the surface observations at Bahia Kino (Fig. 5), where we see warmer drier air mixed down to the surface from above the bore on the downstream face of the first undulation. This mixing also coincides with the enhanced spectral width in Fig. 3c.

Using these observational values along with the reduced gravity determined from the 0000 UTC sounding, we obtain a theoretical bore speed of $C_b = 21.5 \text{ m s}^{-1}$, which compares well with the observed bore speed, taking into account the adjustment for the headwind. We must, however, note the limitations to the simple hydraulic theory of Rottman and Simpson (1989) for determining the speed of a bore. This theory assumes that fluid mixing and interfacial stress between the two layers are negligible, which is likely not the case in the event studied here where the profiler data indicate turbulence and intermittent mixing.

f. Trapping mechanisms

To produce a wavelike disturbance with a large amplitude near the ground, such as a bore, it is necessary to restrict the radiation of energy upward, which considerably reduces the amplitude of the disturbance. Figure 4 showed that the environment at Bahia Kino at 0000 UTC consisted of a low-level stable layer capped by a near-neutral layer, which is known to inhibit the vertical propagation of energy (Crook 1986) by creating a wave duct. To investigate the possibility that a wave-ducting mechanism was involved in maintaining the bore's longevity, the Scorer parameter was determined from the 0000 UTC sounding at Bahia Kino. Bores can be trapped and maintained in regions where the Scorer parameter l^2 decreases with height, where

$$l^2 = \frac{N^2}{(U - C_b)^2} - \frac{\partial^2 U / \partial z^2}{U - C_b}.$$

The first term measures the effects of static stability, where N^2 is the Brunt–Väisälä frequency, U is the wind speed in the direction of motion of the bore, and C_b is the speed of the bore. The second term measures the effects of wind profile curvature.

The components of the Scorer parameter [(Fig. 7a) bore relative wind and (Fig. 7b) Brunt–Väisälä frequency], the Scorer parameter itself (Fig. 7c), and the stability and curvature terms of the Scorer parameter (Fig. 7d) are shown. The bore relative wind was smoothed in order to filter small-scale variations in the wind speed profile that lead to rapid fluctuations in the Scorer parameter.

It is seen in Fig. 7c that there are two layers where the Scorer parameter decreases rapidly with height. The first layer, below 0.5 km, is associated with the small-scale fluctuations in the curvature of the wind profile (Fig. 7a) close to the surface. It is unlikely that wave energy is being trapped at this level, as this is the depth of the stable layer that the bore is propagating along. The second layer is at 6 km and is associated with the increase in stability at this level because of the elevated stable layer evident in the 0000 UTC sounding (Fig. 7b). In most previous studies of atmospheric bores that have analyzed the Scorer parameter with respect to wave trapping, it has been the curvature term that has been the dominant contributor to the decrease in height of the Scorer parameter due to the presence of a low-level jet in the region. In this case, there is no low-level jet (Fig. 7a) and it appears to be the stability of the atmosphere that is trapping the wave energy below 6 km. There is a small region of decreasing Scorer parameter with height at 3 km, due to slight curvature of

FIG. 7. Vertical profiles derived from the 0000 UTC sounding at Bahia Kino: (a) smoothed bore relative wind ($U - C_b$), (b) Brunt-Väisälä frequency, (c) Scorer parameter, and (d) the curvature and stability terms of the Scorer parameter.

the wind profile that may also be contributing to wave trapping.

Evidence from the wind profiler (Fig. 3), indicates that the strongest vertical velocities are trapped at low levels (approximately at 1.5 km). However, as the maximum height of reliable profiler measurements on this day is close to 3 km, it cannot be determined whether the elevated stable layer at 6 km, which is causing the Scorer parameter to decrease with height, is trapping the wave energy associated with the bore below this level, or whether the vertical motion associated with the bore extends above 6 km. The full vertical extent of atmospheric bores has not been presented in previous studies of bores, and it is unknown whether vertical motion associated with a bore's undular nature extends above the depth of the stable layer increase (h_1).

5. Numerical model results

While the observations from NAME 2004 provided an unprecedented look at the structure and mechanisms involved in the atmospheric bore on 31 July 2004,

the observations were still relatively sparse and certain physical characteristics of the bore could not be determined. Also, the effect of the bore on its environment could not be determined due to the temporal resolution of the observations. The model simulation configured as discussed in section 3 produced an atmospheric internal bore with many similar characteristics to the observed bore.

a. Formation and evolution

The generation of a convective system, and more importantly an associated gravity current, was essential in the generation of an atmospheric bore in this case. Due to the initial conditions that forced the model, an upper-level anticyclone developed as expected, leading to easterly winds aloft across much of northwest Mexico and afternoon low-level convergence along the western slope of the SMO.

Convection developed along the SMO in the region with strongest onshore winds and largest virtual potential temperature advected inland from the GoC. Convection that began to develop around 0100 UTC, was

most intense at 0200 UTC (50–55-dBZ reflectivity maxima; Fig. 8a, left panel), and by 0400 UTC (Fig. 8c, left panel) the reflectivity associated with the convective system had maintained a similar size but had reduced in strength. The convective system propagated southward and developed an arc-shaped line of weak reflectivity along its southern edge. This arc-shaped reflectivity feature propagated southward and away from the dissipating convection and remained a prominent feature even when the convection almost completely dissipated at 0600 UTC (Fig. 8d, left panel).

From the reflectivity alone it cannot be determined if this feature is an atmospheric bore, but the horizontal divergence at the first model level (Fig. 8, right panels) clearly indicates a large arc-shaped feature consisting of regions of alternating convergence and divergence consistent with an undular atmospheric bore. The convergence/divergence couplets associated with the undular nature of the bore were captured at the highest model resolution (2 km) in domain 3 but not in domain 2 (6 km), where only the convergent leading edge of the feature was captured.

It is evident from Figs. 8a,b that the atmospheric bore that developed was generated by a gravity current that developed from the convective system, and is distinguished by an intense, narrow region of convergence surrounding the western side of the surface divergence from the convective system. By 0400 UTC (Fig. 8c) the gravity current formed an atmospheric bore, which is evident in the large increase in propagation speed of the boundary from 14 to 22 m s⁻¹. The intense region of convergence that initially marked the edge of the gravity current and now marks the leading edge of the bore, propagated westward, and expanded in radius. By 0500 UTC (Fig. 8d) the bore further expanded in radius and propagated westward over the GoC. The convergence marking the leading edge of the bore corresponds with the enhanced reflectivity from the model, indicating light precipitation associated with the southern part of the bore's leading edge. For purposes of brevity, the central part of the bore will be the primary focus of further results.

The model sounding at 0300 UTC (Fig. 9), just prior to bore passage, shows ideal conditions for wave ducting and the propagation of an atmospheric bore, with a strong stable layer extending close to 900 hPa, and a near-neutral layer above capped by a region of higher stability. The near-surface structure is very similar to the 0000 UTC sounding at Bahia Kino (Fig. 4), but the stable layer is 50 hPa deeper in the model by 0300 UTC. The structure of the winds (westerly within the stable layer and easterly above) and the dry layer just above

the surface are seen in both the model sounding and observations.

Results from the simulation (not shown) provide evidence that a deep sea breeze developed along the GoC by 0030 UTC and moved 30 km inland by 0130 UTC, supporting the hypothesis from the observations that the low-level stable layer at Bahia Kino developed due to the sea breeze that formed along the GoC and moved onshore.

At 0230 UTC the westward (downslope) moving gravity current produced by the convective system and seen in Fig. 8, and the eastward-moving sea breeze began to interact and this led to an increase in stable layer depth (not shown). At this point the gravity current evolved into a modified gravity current (Locatelli et al. 1998), which had features of both bores and gravity currents, with evidence of undulations atop the gravity current in the potential temperature field. These undulations did not propagate away from the gravity current to become a bore or sequence of solitary waves at this time possibly due to the strength of the sea-breeze-induced stable layer being too weak to sustain propagation along it. However, this feature developed into an atmospheric bore by 0315 UTC.

b. Structure and features

A vertical cross section of potential temperature and relative humidity at 0400 UTC is shown in Fig. 10. At this time the bore exhibited a sharp gradient in θ at its leading edge as the prebore stable layer was rapidly elevated. Three significant undulations and a suggestion of two weaker undulations are seen, consistent with the profiler observations of the bore at Bahia Kino (Fig. 3). The stable layer remained elevated due to the bore for 70 km behind its leading edge.

Within each undulation (at approximately 1 km) we see regions of high relative humidity, with values close to 100% in the first undulation and 80% in subsequent undulations. This humidity enhancement over background values (40%–50% at this level) is due to moister air close to the surface of the GoC being elevated by the vertical motions associated with the bore. The moisture is lifted successively higher with each undulation.

The high humidity values associated with the first undulation of the bore corresponded to the lower of two regions where the model produced cloud. While the cloud mixing ratios are small (0.5–1.5 g kg⁻¹) in both layers, the cloud-top heights (4.2 and 2.0 km), depths (1.2 and 0.8 km) for each layer, respectively, and cloud-top temperatures in the model are consistent with the observations from the satellite imagery.

The vertical motion associated with the bore at 0400 UTC is shown in Fig. 11. Four vertical velocity (w)

FIG. 8. (left) The simulated reflectivity (dBZ) for domain 2 and (right) horizontal divergence at the first model level (97 m) for domain 3 for (a) 0200, (b) 0300, (c) 0400, and (d) 0500 UTC. The black line in (d) indicates location of cross sections, and the red X the location of the model sounding. The box in (a) (left) shows the location of domain 3. The Mexican coastline is shown for reference in (a)–(d).

FIG. 9. Model sounding and hodograph at location X (see Fig. 8d) at 0300 UTC.

couplets with widths similar to those observed are present below 5 km, associated with the undulations in potential temperature seen in Fig. 10. The first w couplet is the strongest with magnitudes between 4 and 5 m s^{-1} , equal to those seen in the profiler data (Fig. 3b). The maximum w in the first couplet is 1.5 km higher than seen in the wind profiler data; possibly due to the location and time of the cross section (the bore has a nonuniform structure along its length as seen in Fig. 8). The succeeding w couplets have decreasing magnitude and depth with each subsequent undulation, as seen in the profiler data. The good agreement between the simulation and observations of the vertical structure of w gives us confidence in analyzing the bore's vertical structure in the simulation.

Several features of the observed bore were well represented in the simulation, including the wavelength of the bore's undulations and several features not shown: the rapid increase in surface pressure associated with the leading edge of the bore, the elevation of the pressure for several hours after the bore's passage, and little change in the surface temperature associated with the bore passage.

The speed of the simulated bore was found to be very close to that calculated from the observations. When not accounting for the headwind (which was also similar in the observations and simulation) the average simulated bore speed throughout the bore's lifetime was 15.6 m s^{-1} . We can determine from the model output that the bore propagated faster in its initial stages, and slowed as it propagated across the GoC and began to dissipate.

c. Maintenance

Observations suggest that wave trapping by the elevated stable layer at 6 km (and possible wave trapping at lower levels) prevented the upward propagation of wave energy associated with the bore, leading to a large-amplitude wavelike disturbance at low levels. The model sounding, however, did not fully capture the strength and intensity of this elevated stable layer (Fig. 9), likely due to the vertical resolution within the model. Despite this, the model still produced a bore with a large amplitude at low levels (as seen in Fig. 11), suggesting that even with a weaker elevated stable layer

FIG. 10. Model cross section at 0400 UTC of potential temperature (K) (solid contours) and relative humidity (shaded above 70%) from 0 to 5 km.

at 6 km than seen in the observations, wave trapping can occur.

In Fig. 11 we see that while w (and hence the bore) is strongest close to the surface (between 1 and 3 km),

vertical motions associated with the bore are evident up to 12 km where a secondary maximum is present. The secondary maximum consists of a region of downward motion (3 m s^{-1} maximum) followed by a region of

FIG. 11. Model cross section at 0400 UTC of vertical velocity (cm s^{-1}) from 0 to 20 km. Dashed lines indicate enhanced domain on right.

FIG. 12. Model cross section of relative humidity at (a) 0100 and (b) 0700 UTC.

upward motion (4 m s^{-1} maximum). The ascent in the first velocity couplet associated with the leading edge of the bore is trapped below the region of elevated stability, whereas the subsequent w maxima are not. This suggests that the bore itself modified the region of elevated stability, preventing trapping of wave energy at low levels. There is little to no tilt in w in the vertical, suggesting that the wave energy behind the leading edge of the bore is still being trapped, but not at low levels as expected from previous studies of bores.

No other studies have looked at the effect of bores at such a high level in the atmosphere. However, it cannot be said with certainty that the model simulation is a completely accurate portrayal of the observed bore. Despite the model simulating many aspects of the bore extremely well, it did not correctly reproduce the vertical structure of the environment. The lack of a strong elevated stable layer in the model soundings may have played an important role in the wave trapping mechanisms. It is suggested that if a strong elevated stable layer was present, the secondary maximum in vertical velocity at 12 km would not have been present as wave energy would have been confined to lower levels. Model simulations suggest a low-level (above the height of the bore itself) trapping mechanism is not an essential feature for the maintenance of an atmospheric bore.

d. Effects

The effect of the bore on the environment after its dissipation can be seen in Fig. 12, which shows the relative humidity of the lower atmosphere in the GoC before and after bore passage. Prior to the bore, at

0100 UTC (Fig. 12a) the environment is characterized by a shallow moist layer in the GoC, a dry layer up to 2 km and increased moisture (40%–90% relative humidity) up to 5 km. The large relative humidities over the SMO are due to the convective system, which has already developed at this time. After the bore propagated across the GoC and dissipated, a large increase in relative humidity at the lowest levels and the midlevels is seen across the domain. At midlevels (2–5 km) relative humidity increases of 20%–40% are apparent, due to the easterly steering flow at this level advecting moisture from the convective system across the GoC. At low levels in the GoC we see that moisture has increased in the lowest 1 km, particularly in the western GoC, attributed to the propagation of the bore through this region, providing evidence that the bore has acted as a moisture transport mechanism in this region.

6. Discussion and conclusions

Using wind profiler data from the NAME, which occurred in the summer of 2004, an atmospheric internal bore was identified along the northwestern coast of Mexico. The bore was found, in a broad sense, to be similar to those in two other regions of the world where bores have been associated with sea breezes: 1) over northern Australia generated by the collision of sea breezes, and 2) over southern Florida where bores have been observed to be created by collisions between sea breezes and gust fronts. Some of the features of the bore that were consistent with previous studies of atmospheric internal bores around the world are as follows:

- A rapid rise in the depth of the stable layer and surface pressure was observed and was maintained for several hours after the passage of the bore.
- The bore propagated westward, across the GoC at 21.8 m s^{-1} (accounting for an environmental headwind).
- Three undulations were identified atop the bore, associated with vertical velocities up to $4\text{--}5 \text{ m s}^{-1}$.
- Little change in surface temperature and humidity accompanied the bore, except for the slight increase in temperature and rapid decrease in dewpoint temperature associated with turbulence resulting from shear instability on the downstream face of the first bore undulation.

One important feature of the bore that differed from previous studies was the wave trapping mechanism, identified using the Scorer parameter. The Scorer parameter decreased rapidly with height at 6 km, because of the presence of an elevated stable layer, suggesting that wave ducting would occur below this height. Regions of decreasing Scorer parameter with height were observed below 6 km, with the most significant decrease at 0.5 km, at the approximate depth of the pre-bore inversion. The majority of previous studies have found the wave-trapping mechanism is due to curvature in the wind profile due to the presence of a low-level jet (Fulton et al. 1990; Karyampudi et al. 1995; Koch and Clark 1999; Koch et al. 2005). Results from this study suggest that the ability of an elevated stable layer to trap the wave energy of a bore is of importance, as it distinguishes this region from other regions where bores have been observed to form (i.e., in the Great Plains).

The bore was generated when a MCS that developed on the slopes of the SMO produced a gravity current along its western edge that propagated westward and away from its parent system. This gravity current interacted with a preexisting stable layer that had been generated from the sea breeze on the western coast of the Gulf of California.

The observations of the bore were compared with previously developed theories of atmospheric internal bores. The theoretical bore speed, developed by Rottman and Simpson (1989) was found to be in agreement with the observed bore speed, assuming a bore depth of 1500 m and a bore strength of 3.8 (a type B bore), consistent with the observations at Bahia Kino.

To further investigate the bore that was observed at Bahia Kino, and determine the ability of the Advanced Research WRF model to simulate atmospheric internal bores, a real data simulation was performed using the WRF model. The WRF model simulated both the for-

mation mechanism (including the development of an MCS and subsequent gravity current) and structure of the bore correctly, a unique aspect of this study.

One feature of the simulated bore that was not in agreement with the observations was the lack of a low-level wave-trapping mechanism behind the leading edge of the bore. The vertical velocity field extended through the entire troposphere, with little tilt in the vertical, indicative of a trapping mechanism at the upper levels. Only a weak layer of elevated stability close to 6 km was identified in the model soundings, close to the region of bore formation. This elevated stability appeared to play a role in the initial trapping of the bore's energy, but was modified by the passage of the bore, which allowed wave energy to propagate through the troposphere.

The results of the WRF simulation provided insight into mechanisms that were not seen in the observations, particularly the dissipation mechanism and the effect of the bore on the atmosphere. The bore was shown to have increased moisture in the lowest 1 km across the GoC, providing evidence that bores are an important moisture transport mechanism in this region.

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