12.2 **ANALYSIS OF THE 13 JULY GULF SURGE EVENT DURING THE 2004 NORTH AMERICAN MONSOON EXPERIMENT**

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1. INTRODUCTION

Gulf surges are disturbances that move northward along the Gulf of California (GoC) frequently advecting cool, moist air from the GoC or eastern tropical Pacific Ocean into the deserts of the southwest United States and northwest Mexico during the North American Monsoon (NAM) (Hales 1972; Brenner 1974). Little attention has been given to the dynamics of these disturbances due to the lack of reliable high-resolution data across the NAM region. High temporal and spatial observations collected during the 2004 North American Monsoon Experiment (NAME) are used to investigate the structure and dynamical mechanisms of a significant gulf surge event. Integrated Sounding Systems (ISSs) deployed along the east coast of the GoC and an enhanced network of rawinsonde sites across the NAM domain are used in this study.

2. DATA AND METHODS

The extended observing period (EOP) associated with the NAME field campaign was conducted from 1 June to 30 September 2004. From 1 July to 15 August there were nine intensive observing periods (IOPs) involving twenty IOP days. IOPs were generally accompanied by an increased frequency of rawinsonde launches from the sounding network (Fig. 1). The gulf surge investigated in this study occurred on 13 July during IOP 2. Several other surges were observed from 1 July to 15 August, but the 13 July case was one of only two major events during NAME, the other occurring on 22-24 July (Higgins et al. 2006).

Maintained by the National Center for Atmospheric Research (NCAR), three ISSs (located at Puerto Peñasco and Bahia Kino in Sonora, and Los Mochis in Sinaloa) were deployed during the NAME EOP from 1 July to 15 August (Fig. 1). The ISS consisted of 1) a GPS balloon-borne atmospheric rawinsonde system, 2) a 915 MHz Doppler clear-air wind profiling radar, 3) an enhanced surface observing station, and 4) a Radio Acoustic Sounding System (RASS).

In addition to the ISS sites, an extensive rawinsonde network (Fig. 1) was deployed during the NAME EOP. All NAME sounding data were objectively analyzed using a multiquadric interpolation (Nuss and Titley 1994) onto a 1°x1° grid over 15°-40°N and 90°-120°W (Tier 2 Array - T2A) two times per day (0000 and 12000 UTC), and over 22°-35°N and 100°-115°W (Tier 1 Array - T1A) four times per day (0000, 0600, 1200, and 1800 UTC) with 25 hPa vertical resolution (surface, 1000 hPa – 50 hPa) (Johnson et al. 2006) (Fig. 1). Profiler data from the ISS sites were included in the gridded analyses at those times where rawinsonde winds were unavailable. NCEP reanalyses data (Kalnay et al. 1996) were used over data-sparse regions of the east Pacific Ocean and Caribbean Sea to assist the analysis.

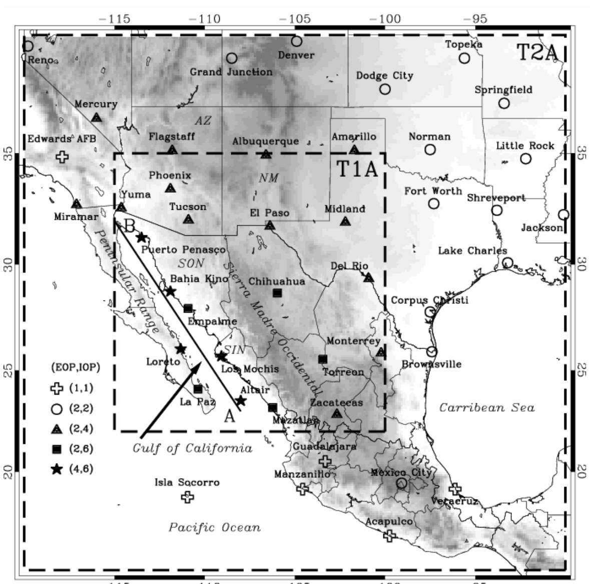

Figure 1: 2004 NAME EOP rawinsonde network and EOP/IOP launches per day.

3. Synoptic-Scale and Convective Environment

Two transient synoptic-scale features were evident over the monsoon region during gulf surge initiation and propagation. At 700 hPa, Tropical

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Storm (TS) Blas followed a northwest trajectory from the eastern Pacific Ocean to the west of Baja California, and at 200 hPa, an upper-tropospheric inverted trough propagated across north central Mexico south of the subtropical high centered near the Four Corners (not shown). The location, movement, and timing of TS Blas is consistent with the interpretations of Fuller and Stensrud (2000) and Douglas and Leal (2003), who have related gulf surge initiation with tropical cyclone passage south of the GoC. In addition, the inverted trough may have played a key role in the convective development on 13 July.

Figure 2 details the complex convective environment every six hours on 13 July. At 2346 UTC 12 July (~1800 LST) (Fig. 2a), the northernmost extent of TS Blas was just south of the mouth of the GoC. A large thunderstorm complex was positioned over northern Sonora and southeast Arizona. Numerous convective cells were also developing along the Sierra Madre Occidental (SMO).

Six hours later (Fig. 2b) TS Blas moved farther north and its outer rain bands penetrated the southern GoC and Baja Peninsula. The convective cells over the SMO merged with the thunderstorm complex over northern Sonora and formed an impressive mesoscale convective system (MCS) over the GoC coastal plain. Gulf surge initiation and propagation was most likely tied with the evolution of these systems. By 1200 UTC (~0600 LST) 13 July (Fig. 2c), the MCS dissipated over the central GoC and at 1800 UTC 13 July, (Fig. 2d) convection was suppressed over the northern and central gulf with TS Blas' center of circulation visible southwest of Baja California.

4. Gulf Surge Structure

Heretofore, Douglas and Leal (2003) have conducted the most comprehensive analysis of gulf surge vertical structure and evolution using 12-h rawinsonde data at Empalme over nine years. However, the ISS profilers provided a much higher spatial and temporal resolution of this phenomenon (~100 m, half-hour). In this section wind profiler data and surface winds are presented at the ISS sites up to 2 km AGL for the period 1800 UTC 12 July to 0000 UTC 14 July (Fig. 3). Also shown are half-hour linearly interpolated rawinsonde potential temperature anomalies from 5 July to 15 August means, and surface pressure and temperature anomalies from 7 July to 14 August means. The method used to calculate the anomalies removed diurnal signals, so only meteorological signals remained.

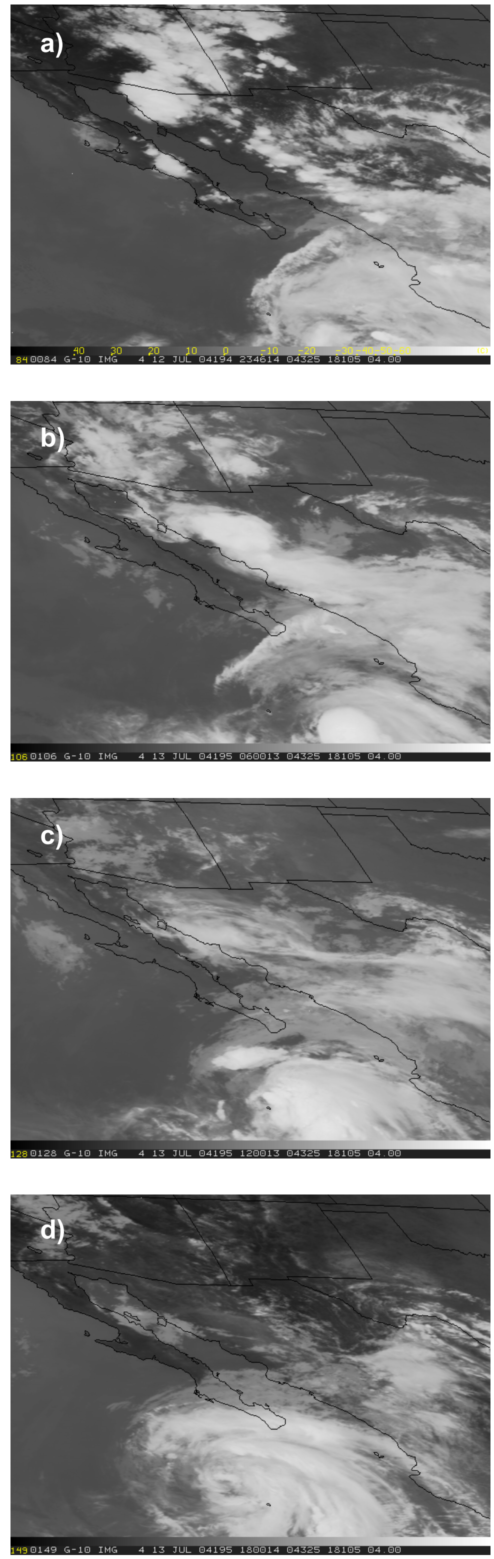

Figure 2: Infrared GOES-10 satellite imagery at a) 2346 UTC 12 July, b) 0600 UTC 13 July, c) 1200 UTC 13 July, and d) 1800 UTC 13 July 2004. Shaded contours represent cloud top temperatures (°C).

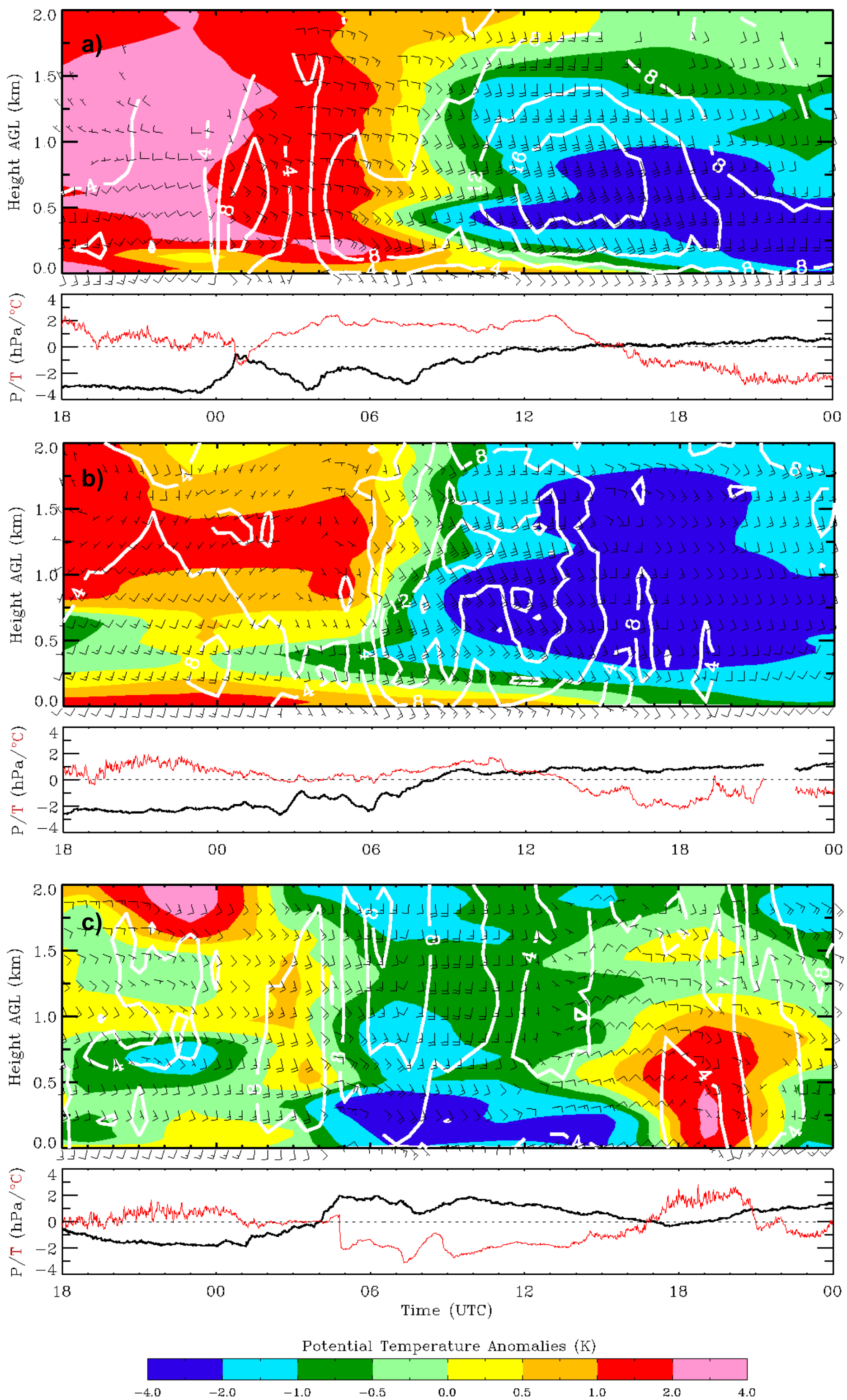

Figure 3: Top panels depict half-hour linearly interpolated rawinsonde potential temperature anomalies (K) (colored) at a) Puerto Peñasco, b) Bahia Kino, and c) Los Mochis from 1800 UTC 12 July to 0000 UTC 14 July. Also shown are profiler and surface wind data every half-hour. One full barb equals 5 m s^{-1} and the white contours highlight wind speed (m s^{-1}). Bottom panels depict surface pressure (hPa) (black) and temperature (°C) (red) anomalies every minute. See text for further details.

At Puerto Peñasco (Fig. 3a) and Bahia Kino (Fig. 3b) gulf surge passage most likely occurred between 0600 and 1200 UTC 13 July as evident in strong south-southeasterly flow (up to 20 m s^{-1}) from the surface up to 2.0 km combined with strong cooling aloft (-2.0 to -4.0 K), which preceded cooling at the surface by 6 h or more. This cooling pattern throughout the column resulted in dramatic pressure increases at the surface that continued throughout the day on 13 July. Surge passage was also preceded by substantial warming (+1.0 to +4.0 K), which was strongest at Puerto Peñasco.

The character of the gulf surge at Los Mochis (Fig. 3c) is somewhat different from its appearance at Puerto Peñasco and Bahia Kino. Relatively strong south-southeasterly flow aloft (up to 10 m s^{-1}) occurred between 0000 and 0600 UTC 13 July. This signal was not accompanied by strong cooling, but instead a slight warming. The strong cooling within 500 m of the surface beginning near 0400 UTC was related to an intense convective outflow marked by a turning of the winds from southerly to easterly and the coincident surface pressure (temperature) rise (fall). However, the cooling and 5.0 to 10.0 m s^{-1} southerly winds above this signal were most likely related to surge passage. These characteristics did not last long and were interrupted near 1800 UTC 13 July by a strong warming feature, perhaps due to local effects and a greater easterly component of the winds aloft.

The differences between surge behavior at the northern ISS sites and Los Mochis may be related to two factors. First, the Puerto Peñasco and Bahia Kino sites were located very near the GoC coast, whereas the Los Mochis site was several kilometers inland, possibly limiting the extent to which the gulf surge was observed. Second, the timing of the surge along the northern gulf is coincident with the GoC nocturnal low-level jet (LLJ) (Douglas 1995), which may have led to amplification of the flow.

Given the difficulty of accurately defining gulf surge vertical structure along the southern GoC from the above figure, an along-gulf cross section (23°N,108°W to 32°N,115°W) (Fig. 1) showing along gulf component winds, mixing ratios, and potential temperatures has been generated from the T1A gridded dataset every six hours on 13 July (Fig. 4). Although the cross section contains interpolated rawinsonde data using onshore observations (except at the R/V *Altair*), areas along the southern GoC are better represented than those to the north given the five rawinsonde sites nearby (Fig. 1).

At 0000 UTC, the strongest winds are along the southern gulf above 900 hPa. The greatest moisture (> 12 g kg^{-1}) is confined to the lowest 100 hPa of the atmosphere and extends north to approximately 30°N. A significant dome of cold air resides below 800 hPa along the southern gulf, as evident in the sloping isentropes. A cold-air dome is also evident over the southern GoC and intersecting the SMO at this time when examining east-west cross sections (not shown). This cold-air intrusion along the SMO barrier is most likely due to strong evaporational cooling associated with TS Blas precipitation bands and developing convection along the SMO (Fig. 2).

Six hours later (0600 UTC), the cold-air dome moves north ~2° latitude. Concurrently, a stable layer develops below 900 hPa along the northern GoC, as evident in the tightly packed isentropes, likely aided by nocturnal cooling aliased from coastal sites out over the water. The strongest winds are still along the southern gulf, although there is a slight intensification of the low-level flow throughout most of the gulf.

Dramatic changes occur by 1200 UTC. The cold-air dome has advanced northward and appears to have reached the low deserts of northwest Mexico as the 302 K isentrope now extends along the entire length of the GoC. The low-level stable layer appears to have been lifted somewhat over the northern half of the gulf, although this feature is not well resolved by the analysis. Strong winds (> 10 m s^{-1}) and abundant moisture (> 9 g kg^{-1}) below 800 hPa are now over the northern gulf. These patterns qualitatively hold through 1800 UTC, although moisture maxima decrease slightly. From this analysis, it appears that the gulf surge did traverse the entire length of the GoC.

5. Propagation Characteristics and Dynamical Mechanism

Theories for gulf surges suggest they are either advective (gravity current, isallobaric flow) or propagating (Kelvin or Rossby wave) phenomena (Zehnder 2004). The complexity of flows associated with the 13 July surge as well as limitations in the NAME observational network precludes a thorough analysis of surge dynamics. However, the bulk of evidence does suggest that this particular surge event was a propagating phenomenon. In particular, if we first examine the wind-speed maxima at the three sites (Fig. 3), their centroids may be tracked to give a propagation speed for this feature.

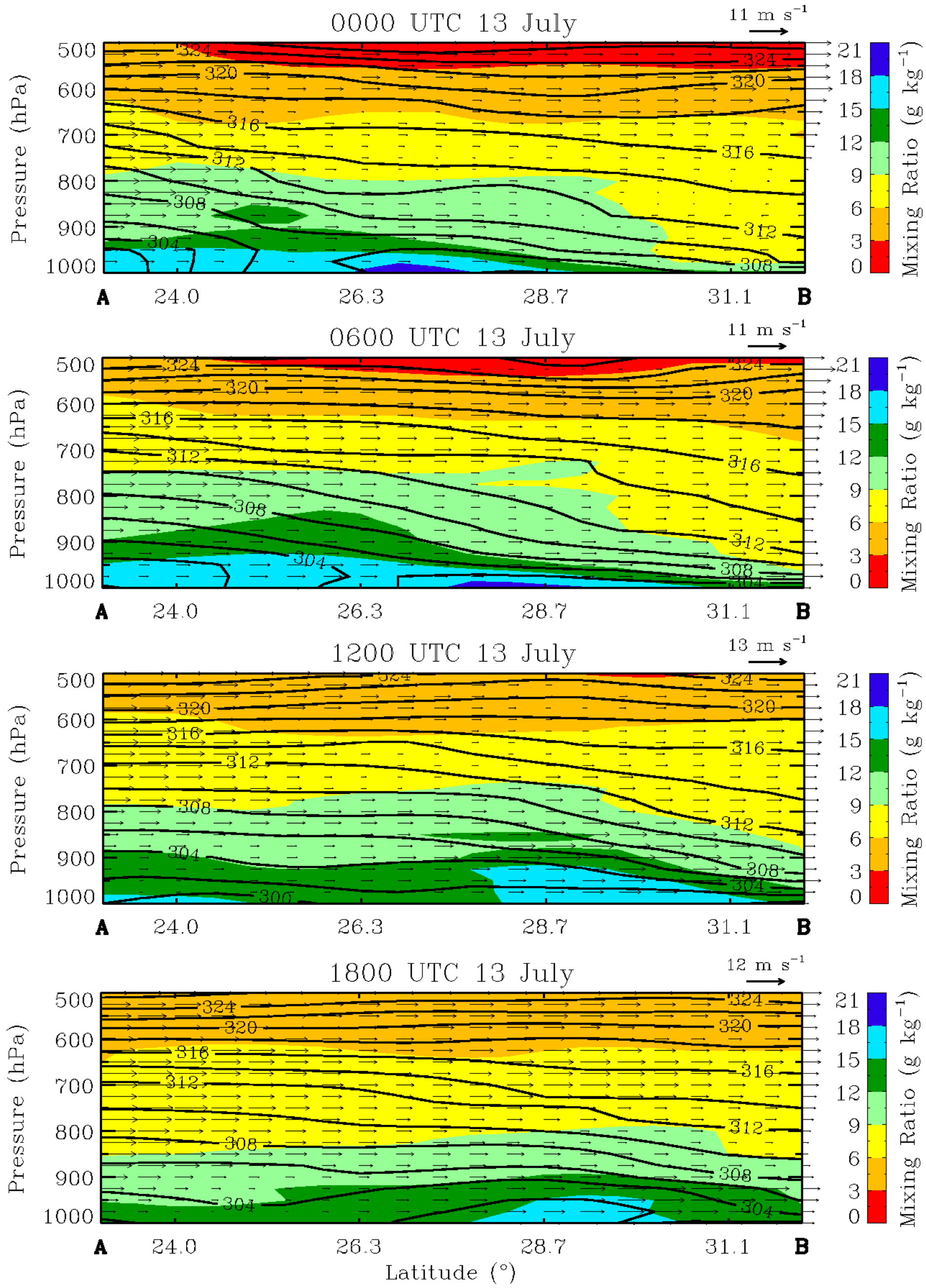

Figure 4: T1A potential temperatures (2 K intervals), mixing ratios (g kg^{-1}) (colored), and along gulf wind component (m s^{-1}) from 0000 UTC 13 July to 1800 UTC 13 July every six hours along a cross section through the GoC (see Fig. 1) from 23°N,108°W to 32°N,115°W.

The centroids are centered at 0300 UTC at Los Mochis, 1000 UTC at Bahia Kino, and at 1400 UTC at Puerto Peñasco, which yield (assuming the disturbance is channeled along the axis of the gulf) speeds of 17 m s^{-1} between Los Mochis and Bahia Kino and 22 m s^{-1} between Bahia Kino and Puerto Peñasco. These speeds exceed most of the flow speeds in the lower troposphere throughout the period, suggesting the surge is indeed a propagating phenomenon.

The cold-air intrusion likely due to strong evaporational cooling along the southern GoC depicted in Fig. 4 suggests that the gulf surge may have first initiated as a barrier-induced linear Kelvin wave-like disturbance (Skamarock et al. 1999; Zehnder 2004). However, the calculated gulf surge propagation speed (~17-22 m s^{-1}) is

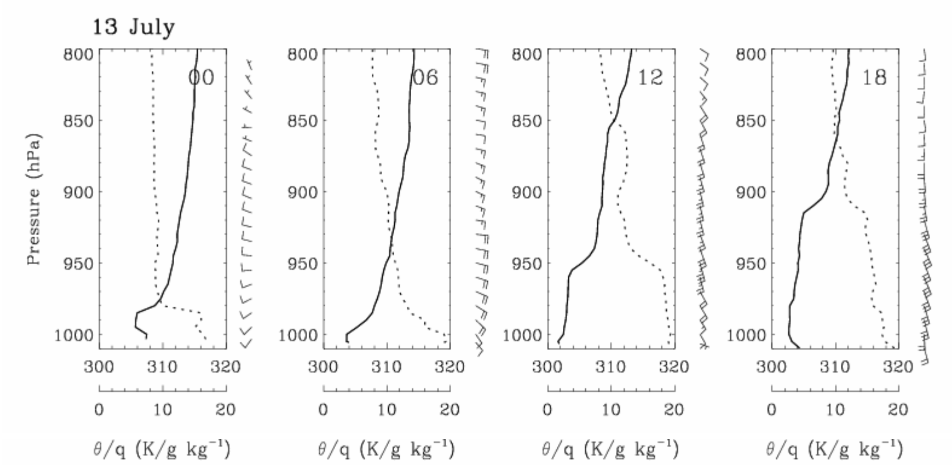

Figure 5: Puerto Peñasco rawinsonde potential temperature (K) (solid), specific humidity (g kg^{-1}) (dotted), and wind (1 full barb = 5 m s^{-1}) profiles at 0000, 0600, 1200, and 1800 UTC 13 July.

too fast to propose pure linear Kelvin wave theory (~10 m s^{-1} or less). Speeds of ~20 m s^{-1} seem to fall more in line with nonlinear wave phenomena, such as atmospheric bores (Simpson 1997), which have been found to propagate at speeds greater than 15.0 m s^{-1} across portions of the United States (Fulton et al. 1990; Koch et al. 1991). However, there is also the possibility that the surge behaves like a mixed-Kelvin wave bore, as has been found for coastally trapped disturbances along the California coast (Ralph et al. 2000).

Bores are generally thunderstorm-induced shallow-water phenomena that propagate along the tops of low-level stable layers and resemble a hydraulic jump, in which fluid depth significantly increases after passage (Simpson 1997). The fact that the surge arrived during the nighttime hours (particularly over the northern gulf) following the development of a nocturnal inversion raises the possibility that at least the initial surge impulse was a bore-like disturbance. Boundary layer observations at Puerto Peñasco (Fig. 5) indicate low-level inversions at 0000 and 0600 UTC 13 July. Downdraft outflows from convection (Fig. 2) impinging on this stable layer would be capable of lifting this low-level stable layer and creating a bore. In fact, the multiple mesoscale convective systems in the region (Fig. 2) may have contributed to multiple bores over the area, much as has been observed at night during the recent International H_2O Project (IHOP) (Weckwerth et al. 2004). The shelf-like layer of cooling just below 500 m at Bahia Kino and Puerto Peñasco in Fig. 3 may be evidence of this bore-related cooling. Further evidence of bore-like behavior is the rapid rise of the surface pressure to a new level (Fig. 3), which is a characteristic feature of bores (Simpson 1997). Following this initial impulse there is a deeper layer of cooling which may be related to a Kelvin wave. The potential temperature and specific humidity profiles at 1200 and 1800 UTC indicate a deepening mixed layer accompanying this feature as the strong winds and turbulence extend the boundary layer upward.

The sequence of events occurring on 13 July is complex and subject to several possible interpretations. However, the weight of the evidence presented here suggests that the initial surge over the northern gulf may be due to bore-like disturbances (possibly containing a series of waves) that owed their existence to convective downdrafts impinging on the nocturnal inversion over the region. Strong pressure rises to a new level accompanied the passage of these disturbances at Bahia Kino and Puerto Peñasco. Then following these initial pulses, a deeper layer of sharp cooling and strong winds ensued, which likely represents a Kelvin wave that appeared to travel along the entire gulf. Pressures continued to rise as this feature passed. Another possibility is that the leading edge of this Kelvin wave steepened nonlinearly into a bore-like disturbance (Skamarock et al. 1999). The data are not adequate to delineate between these possible mechanisms.

6. Conclusions

This study reports on high-resolution wind profiler and sounding observations of a prominent gulf surge on 13 July during the 2004 NAME. The surge structure and properties have been defined in a detail heretofore not possible. The overall surge propagates rapidly up the Gulf of California

(~17-22 m s^{-1}) and is characterized by sharp cooling and strengthening of the wind in the lowest 2 km. Inferences regarding the dynamics of the surge are inclusive, but it appears to originate from cooling by convective downdrafts, advances initially as a series of bores (particularly in the north), is amplified by the nocturnal low-level jet in the north, and is followed by a Kelvin wave disturbance. These features are accompanied by strong surface pressure rises to a new level.

Future work should focus on further integrating other observational platforms from the 2004 NAME field campaign (i.e. aircraft, pilot balloon, radar, precipitation) into the gridded analyses as a means to more accurately compare against mesoscale model simulations. Only then can a more complete picture emerge concerning gulf surge structure and probable dynamical mechanisms.

7. Acknowledgments

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