Preliminary Results of the ISS Deployment in NAME

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1. Introduction

During the Summer 2004 North American Monsoon Experiment (NAME), three Integrated Sounding Systems (ISSs) and one GPS-Loran Atmospheric Sounding System (GLASS) were deployed along the Gulf of California to measure wind and thermodynamic fields associated with the North American Summer Monsoon. A map of the sounding sites, including ISSs at Puerto Peñasco, Bahia Kino, and Los Mochis, is shown in Fig. 1.

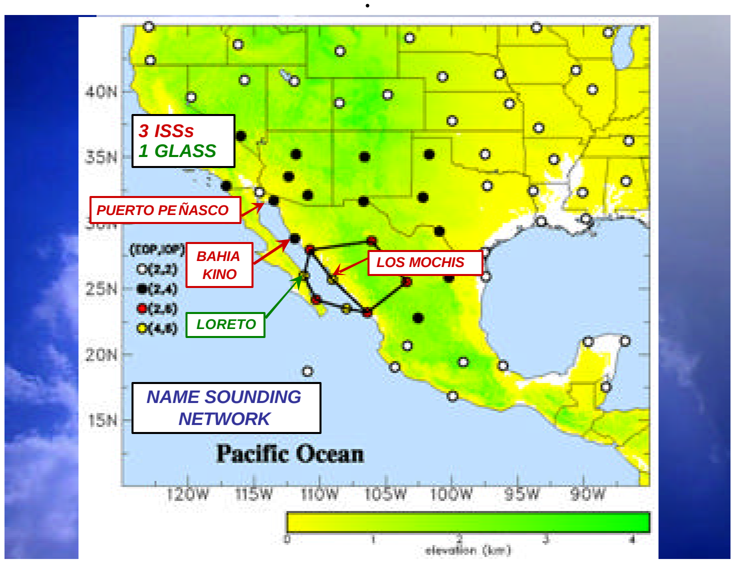

Fig. 1. ISS and GLASS sites deployed during 1 July – 15 August period of NAME.

An ISS consists of a Vaisala GPS sounding system, a 915-MHz wind profiler, a Radio Acoustic Sounding System (RASS), and a surface meteorological station. The GLASS consists only of a GPS sounding system.

These measurement systems were established to sample a number of aspects of the monsoon system: the monsoon onset, Gulf of California low-level jet and surges, the diurnal cycle of convection, land and sea breezes, the influence of easterly waves and tropical cyclones, and upper-level inverted troughs.

Prominent topographic features of the NAME Tier I region are shown in Fig. 2. The Sierra Madre Occidental (SMO) and the Baja California coastal mountains border the narrow Gulf of California, which provides an ideal configuration for the channeling of disturbances up the Gulf.

Fig. 2. Topographic features of the NAME Tier I domain.

The mean surface conditions during NAME are well represented by those shown in Fig. 3, a map of SST and QuikSCAT surface winds for 18 July. There is an extreme contrast in SST across the region, with cool water to the west of Baja (near 20°C) and very warm water within the Gulf (up to 30°C). The surface winds are from the northwest over the eastern Pacific and pass around the southern tip of Baja, with a bifurcation of the flow at the mouth of the Gulf. The summer-mean flow is southeasterly in the Gulf, although there is considerable variability and even a flow reversal at times during the monsoon.

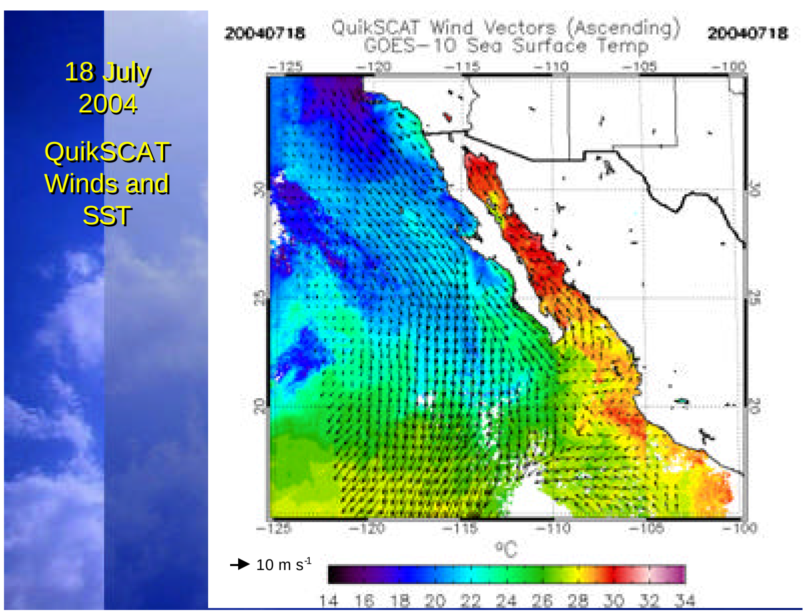

Fig. 3. Sea-surface temperature (°C) and QuikSCAT winds (m s^{-1}) on July 18, 2004. Conditions on this day were representative of the mean for the summer.

2. Monsoon onset, Gulf surge

The first major influx of moisture into the southwestern United States, leading to the onset of the monsoon at the cities of Phoenix and Tucson, AZ, occurred on 13 July. This event was associated with the passage of Tropical Storm Blas to the south of Tier I (Fig. 4).

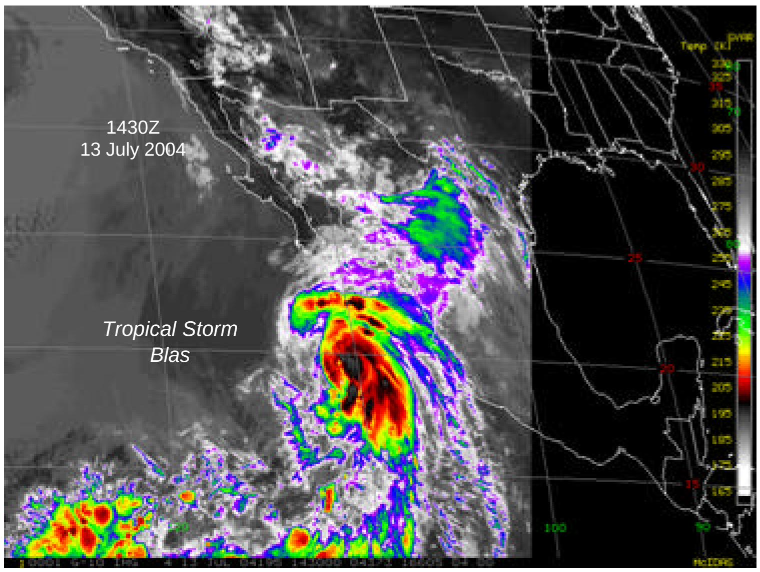

Fig. 4. Infrared satellite image of Tropical Storm Blas to the south of Tier I at 1430 UTC, 13 July, 2004.

This tropical storm produced several significant changes over Tier I. First, its passage to the south changed the midlevel flow over the Gulf of California from southeasterly to easterly, thus allowing afternoon/evening convection over the SMO to propagate westward at night over the Gulf more than in previous nights. Second, the passage southwest of the mouth of the Gulf led to an increase in surface pressure over the southern Gulf, thereby enhancing the north-south pressure gradient along the Gulf. Normally, the pressure in the southern Gulf is higher than that over the north due to a strong heat low typically centered near the Imperial Valley of California. Douglas (2004, personal communication) has shown that the passage of tropical cyclones 400-450 km south of the southern tip of Baja typically enhances this pressure gradient, often leading to Gulf surges. Indeed, this sequence of events occurred on 13 July.

A time series of the pressure difference between Mazatlan (near the mouth of the Gulf) and Yuma (near the head of the Gulf) is shown in Fig. 5 (upper panel). The lower panel of Fig. 5 is a time-latitude plot of the QuikSCAT surface wind component along the Gulf. It can be seen that Tropical Storm Blas contributed to a southerly acceleration of the winds along the entire axis of the Gulf, as well as to the south. Many of the periods of enhanced along-shore winds in the Gulf are associated with the passage of tropical cyclones to the south. The strongest pressure fluctuations actually occurred outside the NAME Enhanced Observing Period (EOP), during September in association with Hurricanes Howard and Javier. In the latter case there was a strong surge of moisture up the Gulf with significant precipitation in Arizona. This last surge led to the calling of Intensive Observing Period (IOP) 10, with special soundings taken in Tier I.

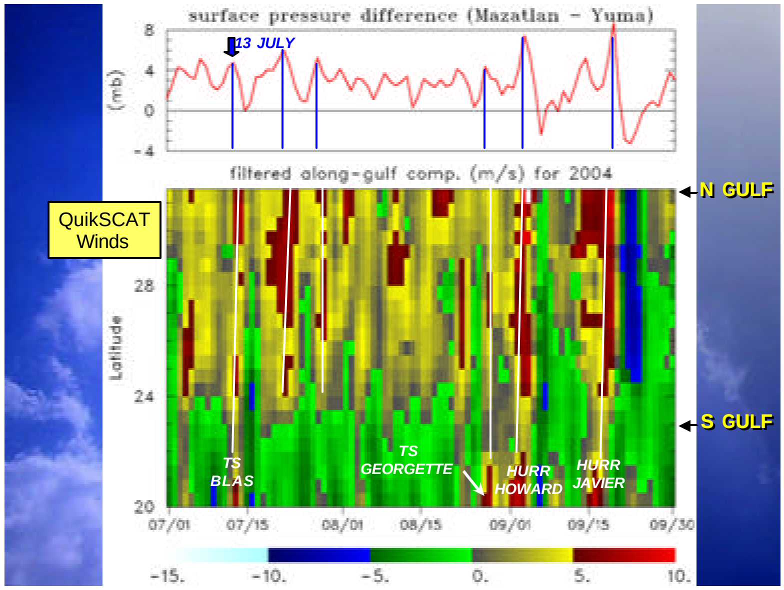

Fig. 5. Mazatlan minus Yuma surface pressure (hPa; upper panel) and along-Gulf wind component (m s^{-1}) from QuikSCAT data. Many Gulf surges are associated with tropical cyclone passages to the south.

Late on the evening of July 12, thunderstorms developed over the SMO and moved westward toward the coastal plain, with associated convective outflows passing over the three ISS sites (Fig. 6). All sites recorded sharp wind shifts associated with the gust front passages.

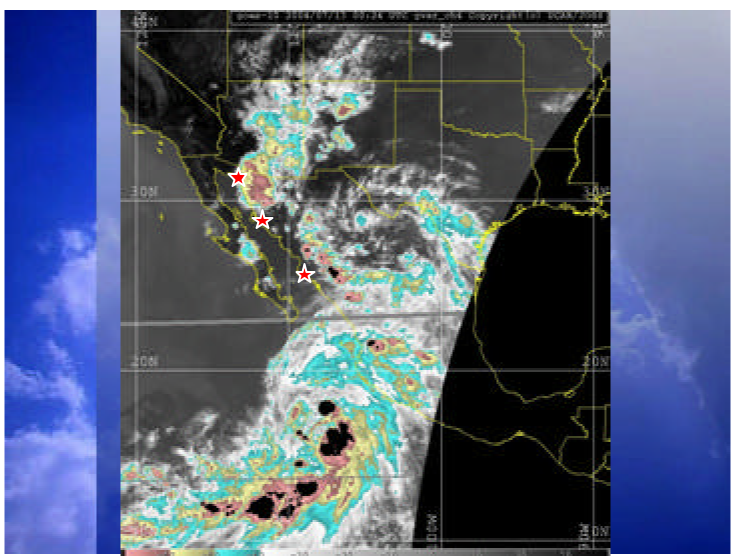

Fig. 6. Satellite infrared image at 0024 UTC 13 July 2004. Stars are the three ISS sites.

At Los Mochis, the southernmost ISS site, the gust front can be seen in a time series plot of the profiler winds (Fig. 7). The gust front is confined to a layer from the surface to 500 m. Above this layer, there is another increase in the wind speeds over a longer period of time, from about 0200 to 1100 UTC in a layer from 800 m to 2 km. This feature is referred to here as a surge. The gust front passage was accompanied by a 3°C surface temperature drop (not shown). The wind surge was accompanied by a steady pressure rise of 6.5 hPa (also not shown) over a period of nine hours, which is considerably greater than the amplitudes of the semidiurnal and diurnal tides.

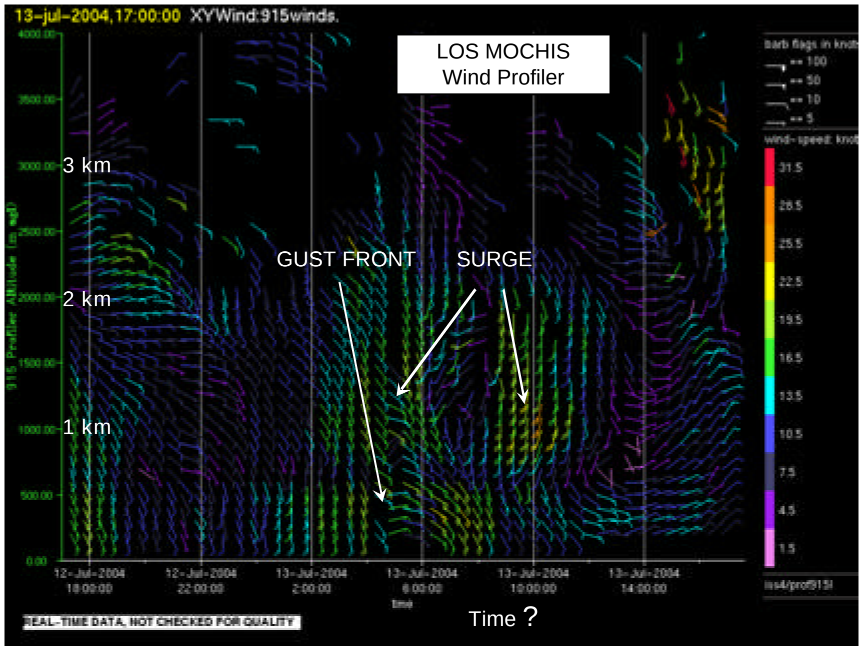

Fig. 7. Wind profiler time series at ISS site at Los Mochis from 1800 UTC 12 July to 1800 UTC 13 July. Gust front and surge are labeled. Wind speeds are in kt.

The wind accelerations at Los Mochis were also associated with changes in virtual temperature, as shown in the RASS time series in Fig. 8. Sharp cooling occurred near the surface and below 500 m at 0430 UTC with the passage of the gust front.

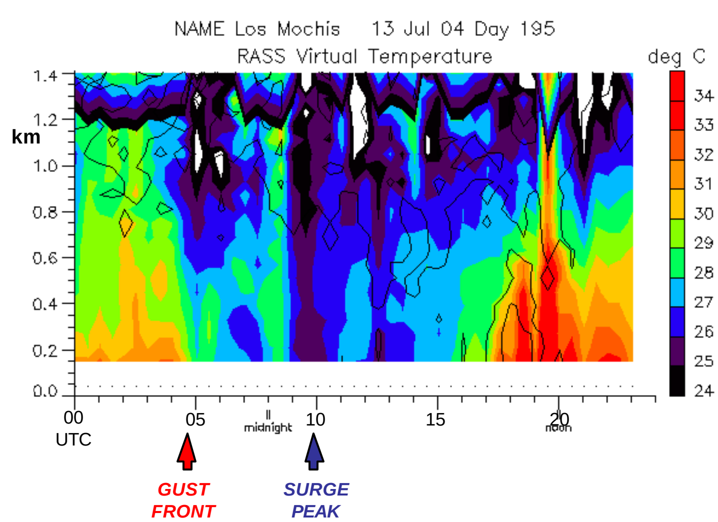

Fig. 8. Time-height series of virtual temperature (°C) at Los Mochis ISS site.

However, in a layer above the surface, from 600 m up, there is a longer period of cooling, roughly corresponding to the time of the wind surge, but extending somewhat beyond. Soundings taken at Los Mochis (not shown) show that the cooling aloft from 0000 to 0400 UTC extends to about 550 hPa, followed by strong low-level cooling below 850 hPa from 0400 to 0800 UTC. This period of lower-tropospheric cooling approximately corresponds to the period of 6.5 hPa pressure rise at the surface.

The passage of a gust front and wind surge also occurred at Bahia Kino (not shown). Once again, the gust front wind shift occurred in the lowest 500 m and the wind surge in a layer extending to 2 km above. In addition, the surface pressure at Bahia Kino rose 6.5 hPa during the time period of the wind surge.

Finally, the Puerto Peñasco ISS also recorded gust front passages (two) and an associated wind surge (Fig. 9). The surface pressure rose 5 hPa. The wind surge was strongest at Puerto Peñasco, with winds exceeding 20 m s^{-1} near 1 km. These strong winds were supported by a P-3 aircraft mission over the northern Gulf at the same time.

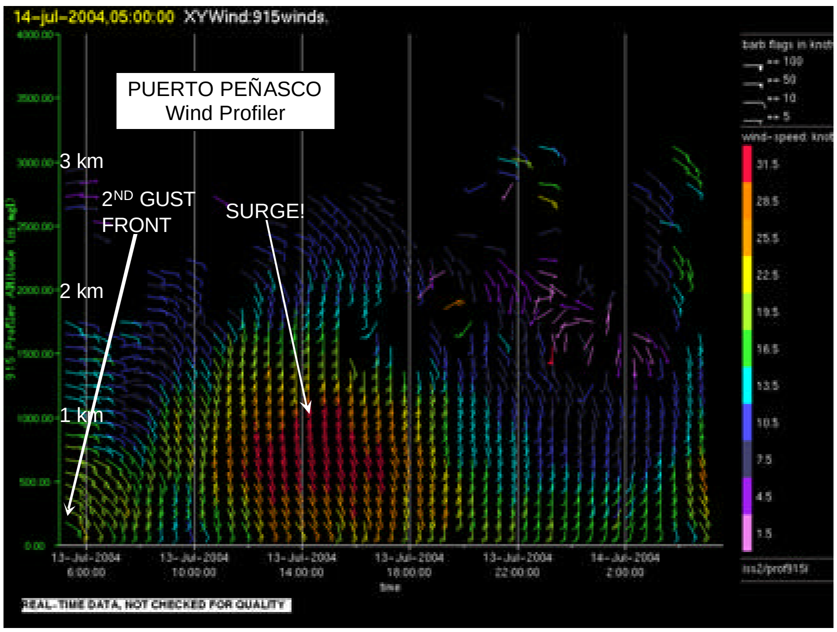

Fig. 9. Wind profiler time series at Puerto Peñasco for a 24-hour period starting at 0600 UTC on 13 July 2004. Wind speeds are in kt.

Several properties of the wind surges were evident at all three sites:

- They were accompanied by thunderstorm gust fronts
- They lasted 8-10 hours and the winds peaked near 1 km AGL at about 20 m s^{-1} in the northern Gulf
- They were accompanied by 2-4 °C cooling in the lower troposphere
- They were accompanied by 5-7 hPa surface pressure rises.

Interestingly, the surge signal from the ISS data propagated very rapidly up the Gulf of California. Considering the time of passage of this signal at the three sites and assuming the disturbance propagated *along the Gulf*, the resulting propagation speed is a remarkable 25 m s^{-1}!

The wind directions in the surges at the three sites were along the axis of the Gulf (from the southeast), which tends to support the idea of a disturbance being channeled along the Gulf. The times of surge passage are shown in Fig. 10.

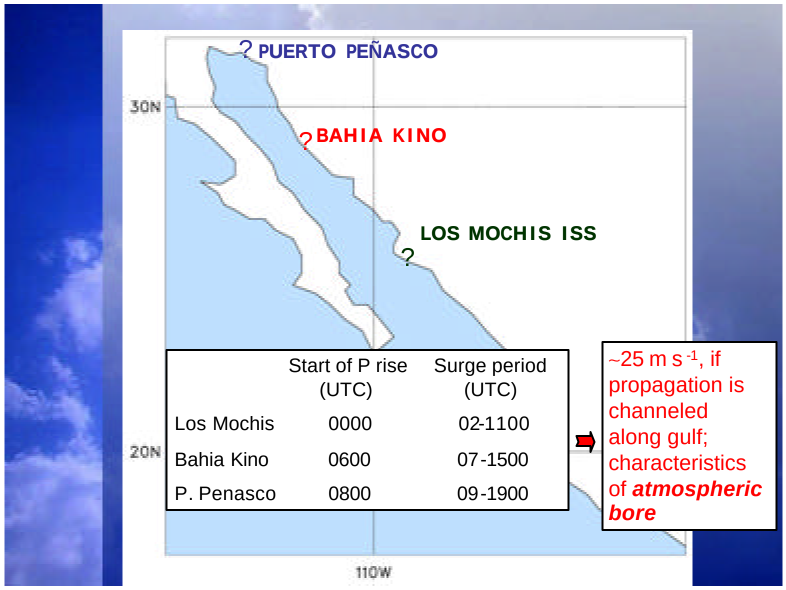

Fig. 10. Start times of surface pressure rise and durations of wind surges at three ISS sites.

If the surge event did indeed propagate up the Gulf at 25 m s^{-1}, one likely explanation for its behavior is that it is an atmospheric bore. Bores have the characteristic of a significant surface pressure rise and rapid propagation, such as has been observed for undular bores (called "Morning Glories") over northern Australia in the Gulf of Carpenteria (e.g., Clarke et al. 1981). Zehnder (2004) has considered possible dynamical mechanisms for Gulf of California surges and concludes that they could be explained by gravity current, Kelvin wave, or Rossby wave dynamics. However, the linear analyses presented therein seem to exhibit propagation speeds in the 10 m s^{-1} range, much less than that observed here. He suggests that the steepening of gravity waves may result in nonlinear, bore-like disturbances. The atmospheric soundings at Los Mochis, Kino Bay, and Puerto Peñasco showed a stable layer in the lower troposphere prior to the surge surmounted by a dry, nearly neutral layer above, an ideal configuration for the development of a bore (by a disturbance impinging on the stable layer) and the trapping of wave energy in the lower troposphere. Thus, the mean state may have been conducive to a bore-like disturbance.

However, the above line of reasoning has an important caveat. In addition to the cooling at low levels (which would be reasonable to expect accompanying a bore) cooling also occurred in a layer extending to the mid-troposphere. This cooling appeared to accompany the westward movement of convection off the SMO (Fig. 6). The convection was aligned in a band (northwest-southeast) parallel to the SMO. If the surface pressure changes are alternatively ascribed to this westward-moving feature, one may not have to resort to a bore disturbance moving rapidly up the Gulf to explain the changes. However, this explanation would have to account for the strong acceleration of the low-level flow, along with cooling at low levels, which is not obvious. It is possible that some combination of a bore-like disturbance and cooling aloft may account for the changes observed for this surge event. Further work is needed to clarify the dynamics of Gulf surges, but the NAME ISS data have provided unique observations to test various theories.

Accompanying this Gulf surge was a northward transport of water vapor and a spread of precipitation into the Southwest. These changes are shown in Fig. 11. By 14 July, significant precipitation moved into southern and central Arizona.

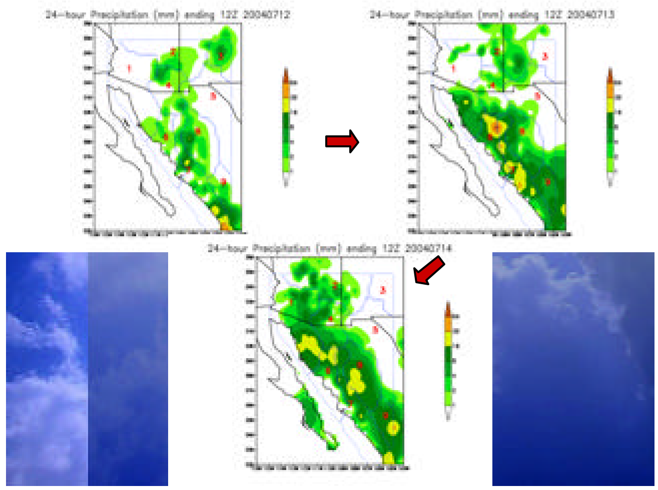

Fig. 11. Twenty-four hour precipitation totals from 12 to 14 July 2004.

3. Summary and conclusions

During NAME, three NCAR Integrated Sounding Systems (ISSs) were deployed along the Gulf of California from about 1 July to 15 August 2004. Among other phenomena, these systems documented a strong Gulf surge around the onset of the summer monsoon. The surge was associated with the passage of Tropical Storm Blas to the south of the Gulf and accompanied by strong convective outflows from mesoscale convective systems that originated and propagated westward from the Sierra Madre Occidental.

Around the time of arrival at the ISS sites of the gust fronts associated with convective outflows, a strong wind surge appeared to move rapidly up the Gulf. It was characterized by an increase in the low-level flow, peaking near 1 km AGL and up to 20 m s^{-1}, over a period of 8-10 hours accompanied by lower tropospheric cooling of 2-4°C and a surface pressure rise of 5-7 hPa. This disturbance had the characteristics of an atmospheric bore being channeled up the Gulf. However, cooling and moistening also occurred above the surge, complicating the dynamical interpretation of the phenomenon. Further work is underway to understand the mechanisms for this and other Gulf surges using the unprecedented NAME ISS dataset.

4. Acknowledgments

This research has been supported by Grant ATM-0340602 of the National Science Foundation for the ISS deployment (Steve Nelson, Program Director) and NOAA Grant NA17RJ1228 of the NOAA Office of Global Programs (Mike Patterson, Program Director).

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