OBSERVATIONS FROM THE APRIL 13 2004 WAKE LOW DAMAGING WIND EVENT IN SOUTH FLORIDA

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ABSTRACT

On Tuesday, April 13, 2004, a high wind event swept across parts of peninsular Florida in the wake of a mesoscale convective system (MCS) of thunderstorms. This is unusual because the winds, which gusted at times in excess of 70 mph in the vicinity of Lake Okeechobee, were not associated with the thunderstorms themselves, but were on the backside of the system. In fact, little or no rain was falling when the wind event was occurring. This paper presents an analysis of the data leading to and during the event revealing that it was associated with a phenomenon called a 'wake low' pressure system.

1. INTRODUCTION

Damaging winds affected portions of South Florida during the early morning of April 13, 2004. These winds occurred behind a large area of stratiform precipitation associated with a mesoscale convective system (MCS) that moved across the southeastern Gulf of Mexico during the evening of April 12, 2004 (Fig. 1). Wind speeds sustained between 30 and 50 mph with gusts reaching 76 mph were recorded on Lake Okeechobee.

These winds produced a seiche effect on Lake Okeechobee, resulting in a 5.5 ft maximum water level differential between the north and south sides of this shallow lake (Fig. 8). In addition, damages from the high winds were reported from communities situated along the lake shore.

This paper shows the event to be related to a wake low, a rare occurrence across South Florida.

2. SYNOPTIC & MESOSCALE ENVIRONMENT

At 0000 UTC on April 13, 2004, a 1002-hPa surface low was located over eastern Alabama. An associated cold front stretched across the Gulf of Mexico to the Yucatan Peninsula and a stationary front was located across central Georgia and South Carolina (Fig. 1).

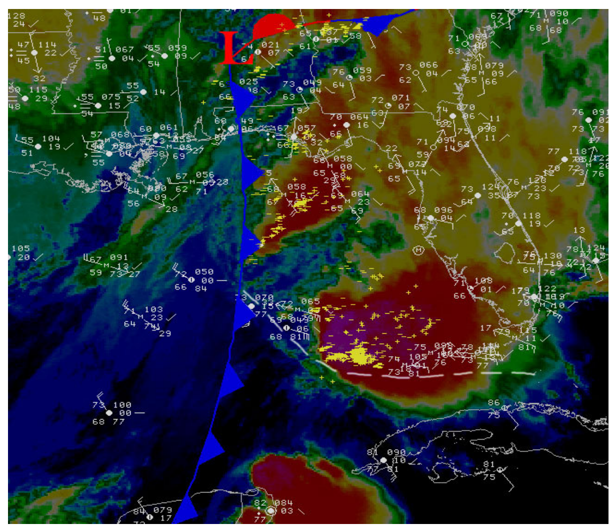

Figure 1. 0000 UTC April 13, 2004 overlay of surface observations (white), cloud-to-ground lightning strikes (yellow), and NCEP frontal analysis.

Advection of warm and moist air from the Caribbean was enhanced as an 850-hPa jet strengthened to 30-50 knots (15 to 26-m s^{-1}) by early evening. An outflow boundary from a previous MCS which tracked across South

Florida early on the morning of April 12th persisted across the Florida Straits. This boundary exhibited pseudo-warm frontal characteristics, and was lifting northward over South Florida (white dashed line in Fig. 1). To the north of the boundary, a cool and stable boundary layer was present over land.

A high amplitude longwave mid/upper tropospheric trough was located over the eastern United States. The axis of this trough extended from the Great Lakes southward to the central Gulf of Mexico while South Florida was upstream of the ridge axis located near 65°W longitude. In addition, a 130-knot (67 m s^{-1}) polar jet and 60-knot (31 m s^{-1}) subtropical jet were splitting over the eastern Gulf of Mexico producing significant upper level diffluence over South Florida. This resulted in a Mesoscale Convective System (MCS) developing and moving across the southeast Gulf of Mexico during the evening of April 12, 2004 (Fig. 1).

3. WAKE LOW DYNAMICS

An early model of the structure and life cycle of mesoscale systems producing intense wake lows was proposed by Fujita (1955). This model has been examined and expanded upon by several researchers since. In general, researchers have found wake low events to be associated with significant low level warming and surface pressure falls of up to 5 hPa within an hour at times. Quantitative evidence that subsidence warming can account for the reduced pressures in wake lows were demonstrated in a numerical modeling study by Johnson (2001). Johnson and Hamilton (1988) and Gallus (1996) proposed that a wake low is formed by a descending rear inflow jet and that the warming due to descent was maximized at the back edge of the precipitation area where evaporative cooling was insufficient to offset adiabatic warming (Fig. 2).

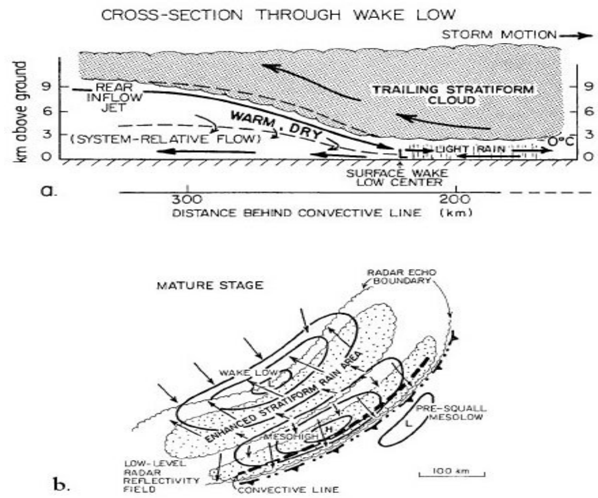

Figure 2. Schematic cross section through wake low, from Johnson and Hamilton (1988).

This suggestion was furthered by Stumpf (1991) who contended that stratiform precipitation regions can be dynamically significant phenomena, generating rapidly descending inflow jets at their back edges, capable of producing lower-tropospheric warming, intense low level pressure gradients, and strong low level winds.

4. WAKE LOW OBSERVATIONS

4.1 Vertical Wind/Temperature Profiles

Upper atmospheric wind and temperature profiles were similar to other well documented cases where the environment supported mesoscale convective systems (Maddox 1983), as well as case studies from events in the Mississippi Valley (Gaffin, 1999) and Oklahoma (Hunter, 1989). The wind above 850-hPa was unidirectional from the southwest and speeds increased with height. Near the surface, light easterly winds were found to the north of the quasi-warm frontal boundary with southeast to south winds in the warm sector. Rawinsonde observations from Key West and Miami revealed precipitable water values of 1.84 and 1.76 inches respectively. Observed values of precipitable water prior to MCS development are typically in excess of 1.4 inches (Maddox 1980).

Soundings derived from Local Analysis and Prediction System (LAPS) objective analyses across Lake Okeechobee indicated warming by as much as 2 to 3°C in the layer between 700 and 800-hPa from 0700 to 0800 UTC (Fig. 3). A similar degree of cooling was depicted between 450 and 650-hPa in the same time period. Additionally, between 0800 and 0900 UTC, the LAPS soundings show descent of the anomalously warm air to the 850-hPa to surface layer, especially near the lake where the atmosphere lacked an elsewhere substantial temperature inversion in the boundary layer.

Note that over mainland South Florida, LAPS analyses are typically quite reliable due to the increased number of mesonet, aircraft, and NWS observations that are readily available, particularly within the last few years (Etherton et al., 2004; Etherton and Santos, 2004). Although aircraft data are far less frequent late at night, between 0600 and 0900 UTC some flights (approaching or departing any of the three international airports in close proximity to each other on the southeast Florida coast) report upper air data and they are processed by the LAPS program. Most of the flights departing to or coming in from the west fly between the Fort Myers to Lake Okeechobee area at an altitude of around 15-25 kft. So even though LAPS had limited aircraft data some were still available, enough to detect the warming at the transition between the low to mid levels. LAPS ingests high resolution satellite data which may have helped the analysis detect the low to mid level warming/cooling signatures also. In short, LAPS sounding analysis supports the observation of subsidence induced low level adiabatic warming as will be further shown in sections 4.2 through 4.4.

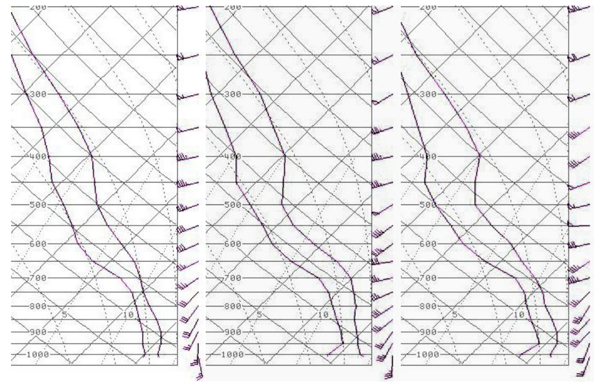

Figure 3. LAPS analysis skew-t log-p diagrams over Lake Okeechobee from 0700, 0800, and 0900 UTC April 13.

4.2 Satellite Imagery

Subtle hints of subsiding air could be found both in the GOES-12 infrared and water vapor satellite imagery. Infrared satellite showed cloud tops warming 10°C in the 30 minutes between 0845 UTC and 0915 UTC (top panels Fig. 4) when the strongest surge of low level winds (sections 4.3 and 4.4) was observed, and the corresponding water vapor imagery suggests mid-tropospheric drying was taking place from Lake Okeechobee southwest to the Gulf of Mexico (bottom panels Fig. 4).

4.3 High-Resolution Radar Data

From a radar perspective, a series of distinctive events can be identified, two of which are presented in Fig. 5. These events were accompanied by significant pressure falls, strong winds, low level warming, and/or a combination of these, all signatures accompanying wake low events (see Fig. 3 and Fig. 6).

Between 0400 and 1000 UTC, a large area of stratiform rain covered much of South Florida with its trailing edge remaining from Marco Island to Lake Okeechobee. The initial wind surge event happened shortly before 0500 UTC (Fig. 6a). Figure 5 (top panels) shows the 0.5 degree base reflectivity and velocity images. Notice a west southwest rear inflow jet with maximum radial velocities in excess of 40 knots (20 m s^{-1}) (white circles) while a rear inflow notch signature is present just southwest of Lake Okeechobee on the trailing edge of the stratiform precipitation shield.

About 4 hours later, the most significant peak wind associated with the event occurred (Fig. 6a). A band of high velocities was observed along the trailing edge of the stratiform precipitation shield around 0918 UTC. Radial velocities from the Miami radar exceeded 50 knots (26 m s^{-1}) and are shaded yellow and light blue in Fig. 5 (white circles in bottom panels). Maximum radial velocities of up to 106 knots (55 m s^{-1}) were also detected. The radar beam height of the 0.5° tilt was around 6,000 feet at the distance of the sharp reflectivity gradient. Looking at the orientation of the wind maximum and the zero isodop, these features represent a rear inflow jet from the southwest which is supported by Fig. 3, the LAPS sounding analysis.

An interesting feature with this final event is the magnitude of the observed velocities by Doppler radar. It appears the radar is seeing contribution to the along radial component from a descending and slanting rear inflow jet that is turning out of the southeast at lower levels as it descends due to the lower pressures to the northwest and higher pressures to the southeast (next section). This is evidenced by the superimposed surface observations in Fig. 7 where a 6.1 hPa pressure gradient is noticed between Naples and Miami.

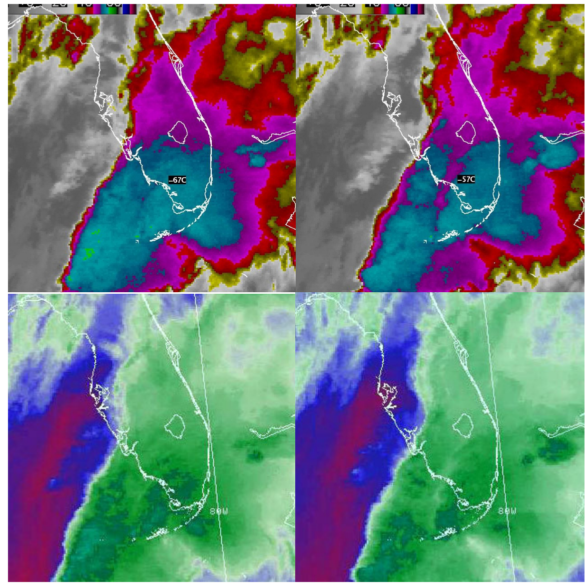

Figure 4. GOES-12 IR brightness temperature (C) (top) and Water Vapor (bottom) Images from 0845 UTC (left) and 0915 UTC (right). Red indicates mid level dry air while green indicates moist air in bottom Water Vapor images.

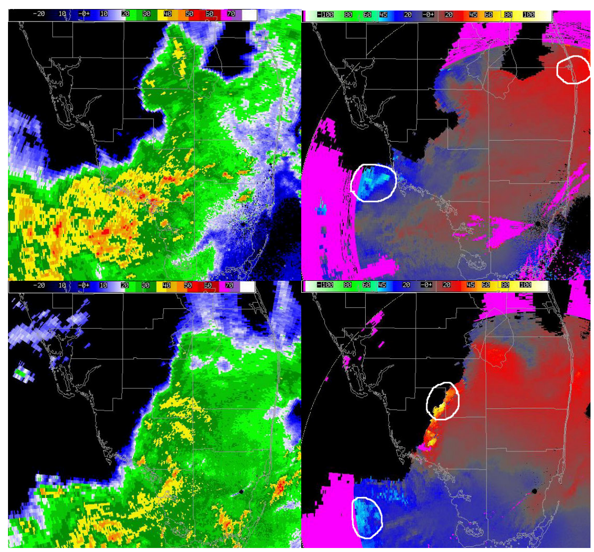

Figure 5. Upper images are from the Miami WSR-88D radar at 0410 UTC prior to initial 22 m s^{-1} wind gust (Fig 6a). Lower images at 0918 UTC, time of peak 34 m s^{-1} gust. 0.5° reflectivity (left) and 0.5° velocity (right). Outbound velocities in red, inbound blue.

4.4 Surface Observations

Three distinct pressure falls and wind speed maxima occurred as the back edge of the precipitation shield passed over Lake Okeechobee. The first observed wind gust of 22 m s^{-1} was preceded by a pressure fall of around 5 hPa in one hour (Fig. 6a). The second and third events were close together and consisted of a wind gust of 25 m s^{-1} around 0745 UTC and a more intense gust reaching 34 m s^{-1} near 0915 UTC (Fig. 6a). Pressure falls of up to 5 hPa were observed in the hour preceding the observed peak gusts.

The well mixed marine layer near Lake Okeechobee and the southwest Florida coast (similar temperature and wind behaviors to those in Fig. 6a were observed in Naples on the southwest Florida coast) allowed the high wind speeds to be registered in those areas. The effect on inland locations was primarily a rise in temperature, since the presence of a strong surface-based inversion prevented the strongest winds from reaching the surface. The temperature at Palmdale (Fig. 7) climbed from 69°F (21°C) at 0600 UTC to 76°F (24°C) at 0900 UTC, with nearly 50% of that rise occurring between 0800 and 0900 UTC (Fig. 6b). Although not of the same magnitude, a similar temperature trend was observed in Moore Haven. Notice that this warming was not only at the surface but throughout the low levels as illustrated earlier in section 4.1, Fig. 3. Additionally, this degree of warming was not observed prior to the first peak wind around 0500 UTC across Lake Okeechobee although Fig 6b suggests a warming trend had begun to take place.

This suggests adiabatic warming with the descending rear inflow jet had been taking place throughout the early morning hours on the trailing edge of the light precipitation shield that over the course of several hours led to the formation of the wake low west of the Lake Okeechobee region and the formation of an intense low level pressure gradient (see Figs. 7 and 10). All these factors together combined to result in stronger wind surges near 0800 UTC and 0900 UTC.

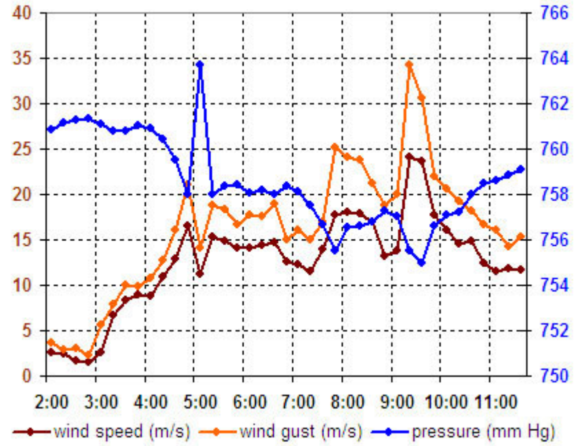

Figure 6a. 15 minute wind speed, wind gust, and pressure from the South Florida Water Management Division (SFWMD) weather station L005 on the north end of Lake Okeechobee from April 13, 2004. All times are in UTC. *Data courtesy of SFWMD.*

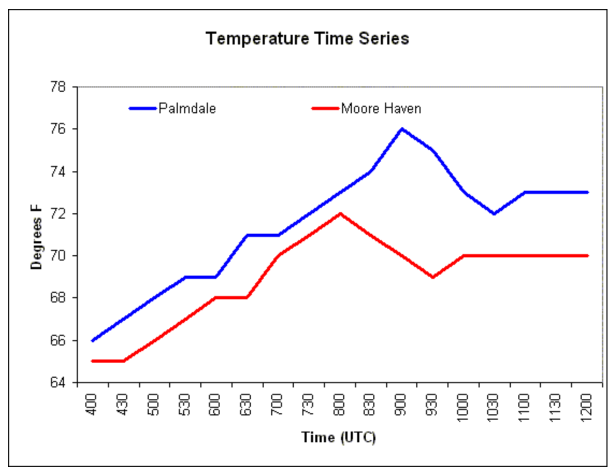

Figure 6b. 30 minute temperature data for Palmdale and Moore Haven (red circles in Fig. 7). *Data courtesy of the Florida Agricultural Weather Network (FAWN) and AWS Convergence Technologies, Inc.*

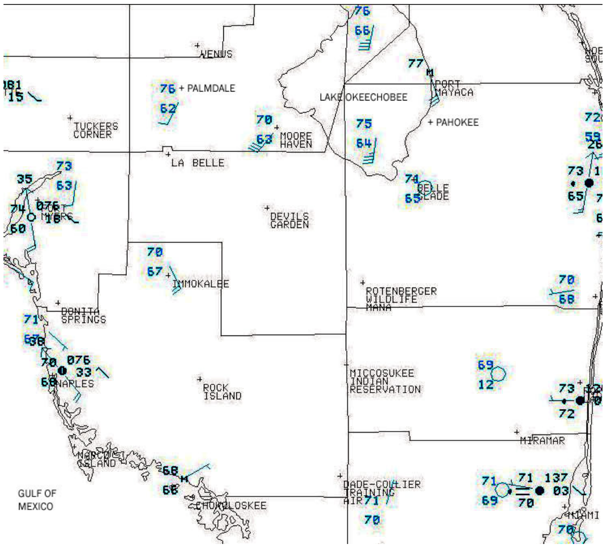

Figure 7. Plot of surface observations at 0900 UTC. Note the 6.1 hPa pressure gradient between Naples and Miami.

4.5 Wind Damage Reports

The strong winds inflicted damage to communities near Lake Okeechobee as well as along the Gulf of Mexico. The winds severely damaged several mobile homes along the south shore of the lake, and blew out a store window in Belle Glade (Fig. 7). A 50-knot wind gust at the Fort Myers Southwest Florida International Airport pushed a Boeing 737 aircraft into a jetway bridge. Roofs, carports, and other structures were damaged in Fort Myers, Moore Haven, Belle Glade, and Pahokee (Fig. 7).

4.6 Lake Okeechobee Water Level

Water level rises and falls were recorded by the U.S. Army Corps of Engineers gages on Lake Okeechobee in response to the high winds, and corresponded closely with the time of greatest wind speeds. Figure 8 shows that the lake level was fairly uniform near 14.5 feet until rapidly rising between 0400 and 0500 UTC (23:00 to 00:00 EST) when the average north end gages initially peaked at 15.9 feet. A second peak of 17.6 feet occurred around 0900 UTC (04:00 EST). A lake level minimum was measured at the south end gages around 1100 UTC (06:00 EST) when the average level fell to 12.1 feet. These lake responses correlate well with the observed maximum wind surges discussed in the previous sections. The multiple peaks noticed beyond these times in the north end gage are related to the seiche oscillating effect of the water level which lasted for several hours after the wind surges as it gradually damped out. The south end gage stopped reporting shortly after 1200 UTC.

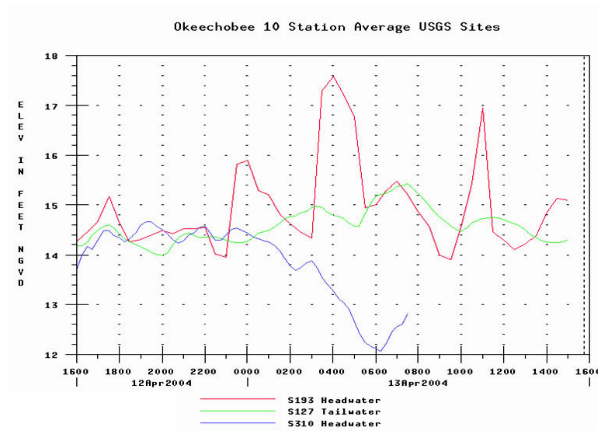

Figure 8. Mean lake level from Lake Okeechobee gauges near the north end of the lake (red) and the south end (blue). *Image courtesy of the U.S. Army Corps of Engineers. All times in are in EST.*

4.7 Numerical Modeling and Objective Analysis Data

The 0000 UTC run of the workstation ETA, run locally at the National Weather Service Miami office, depicted an area of deep layer subsidence along the trailing edge of a cluster of rain and thunderstorms. The forecast of 700 hPa vertical motion valid at 0800 UTC showed maximum downward motion of 7 to 9 $\mu b\ s^{-1}$ (Fig. 9).

Additionally, the development of the wake low led to the creation of an intense low level pressure gradient analyzed by LAPS. The analysis showed the coupling of lower

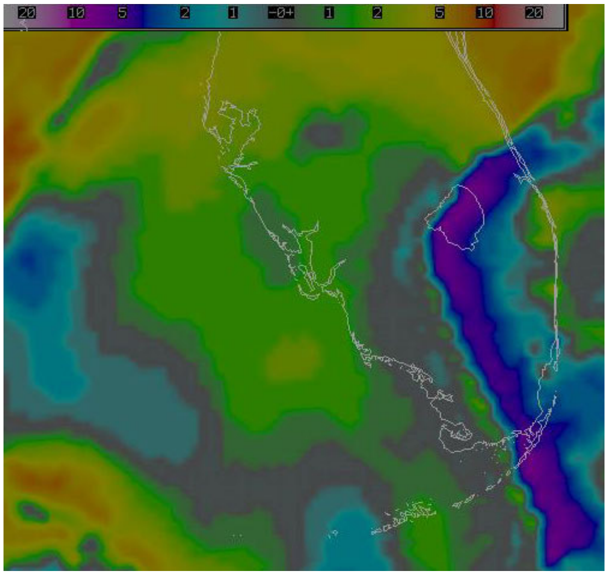

Figure 9. Hydrostatic Workstation ETA 700-hPa vertical motion field 8-hour forecast valid 0800 UTC April 13, 2004. Vertical Motion field depicted in units of -μb s^{-1}. Therefore, a -10 is equivalent to 10 μb s^{-1} which means subsidence.

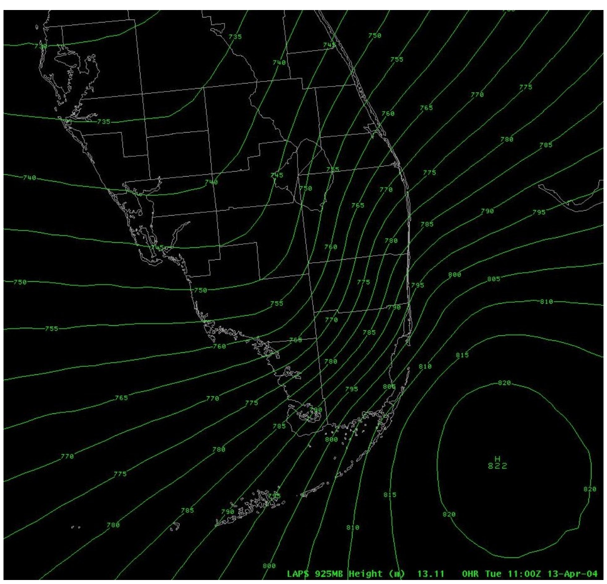

Figure 10. 1100 UTC April 13, 2004 925 mb LAPS Height Analysis.

pressure west of the lake and a meso high to the south where debris from the MCS that moved across the southeast Gulf of Mexico the evening of the 12th was producing light to moderate rainfall and more dominant evaporational cooling at the low levels. Figure 10 shows the 925 hPa height analysis from the 1100 UTC LAPS analysis depicting this well. We believe this contributed to windy conditions remaining for a few hours after the occurrence of the high wind events around 0500, 0800, and 0900 UTC (Fig. 6a).

5. OPERATIONAL CONSIDERATIONS

Challenges remain in our quest to better observe and predict the strength of wake low wind events in an operational environment. Most critically, many of the observational datasets were not available to the forecaster rapidly enough to provide insight to the degree found in this examination. LAPS analysis latencies were typically around 1 hour, while many of the mesonet surface observations were made available every 30 minutes. With the advent of the Advanced Weather Interactive Processing System (AWIPS) Operational Build 4.2, LAPS latency is now less than 30 minutes. The authors believe this will help monitor potential events as the one described here in a more timely manner. The mesonet sites on Lake Okeechobee record peak wind gust data, but only sustained winds were available to forecasters at the time. This has also changed since the event occurred and real time gust data is now available to the forecasters from those sites. Official NWS sites interrogated to acquire instantaneous data during the event didn't capture the magnitude of the situation due to the fact that a significant inversion prevented the strongest winds from reaching the surface at most of these land based locations. Information available to meteorologists in assessing potential for wake low damaging wind events has been greatly enhanced over the last few years, and will no doubt continue to improve dramatically. Monitoring and timely assimilation of these observational and forecast datasets can help us recognize and provide accurate and timely warnings for damaging wake low events.

Cross sectional analysis of the velocity data at the time could have also helped reveal the unfolding event and descending jet. This could help gain some lead time on the event assuming it is properly attributed to the conceptual model of a wake low. This is perhaps the most important lesson learned from this event together with a reminder of the importance of monitoring closely all available data.

6. DISCUSSION AND CONCLUSIONS

The passage of the trailing edges of the stratiform precipitation shield and associated band of high wind velocities, as depicted by the lowest elevation angle radar scan (Fig. 5), coincided with the times of peak wind gust, short-duration pressure minima, and low level warming (Figs. 3 and 6). These were observed in official NWS and mesonet surface data from Lake Okeechobee and surrounding areas.

Both direct and indirect evidence of subsidence was found in the observational and numerical model datasets. Infrared satellite data showed a narrow band of significant cloud top warming while the water vapor imagery indicated mid-tropospheric drying around the time of the second and third wind surges around 0800 and 0900 UTC. LAPS soundings revealed a descending warm layer during the two hours preceding the 76 mph (34 m s^{-1}) wind gust observed on Lake Okeechobee. The 0000 UTC NWS Miami workstation ETA model predicted a band of strong downward vertical motion which closely matched the observed event.

The LAPS analyses (Figs. 3 and 10) depicted mid-tropospheric cooling, lower tropospheric warming, and strong low level pressure gradients occurring while radar detected no precipitation size hydrometeors around 6,000 feet on the trailing edge of the precipitation shield. This lends credibility to the idea that evaporative cooling was the dominant dynamic mechanism in the mid-levels, while adiabatic warming was occurring in the low-levels. Surface observations showed temperature increases of 3 to 4°C around the time of the highest observed peak wind and even up to 10°C during the 5 to 6 hours period preceding the highest observed peak wind. This suggests that the evaporative cooling was indeed insufficient to offset adiabatic warming, as was found in Johnson and Hamilton (1988).

These data support the contention that this high wind event was the result of a wake low, a rare event across South Florida. While the presence of wake lows may be apparent in real-time, the magnitude of such events can be difficult to assess until later.

7. REFERENCES

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