MESOSCALE ELEMENTS OF THE 14 DECEMBER 2006 WEST PALM BEACH FLASH FLOOD

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ABSTRACT

Several substantial mesoscale features, combined with an abnormally moist atmosphere for mid-December, resulted in a record 8.22" rain event in West Palm Beach, FL, on 14 December 2006. A mesolow and several mesoscale boundaries combined with precipitable water values over two standard deviations above normal to produce widespread 4-6 inches of rain, with locally higher amounts, and flash flooding throughout the city of West Palm Beach. The mesoscale features did not initially fit any conceptual models, however, with persistent convective development leading to the formation of a mesohigh, the system evolved to closely resemble Maddox's conceptual mesohigh flash flood model. Low-level convergence was also enhanced by two mesolows.

1. Introduction

An abnormally moist atmosphere across south Florida on the morning of 14 December 2006 set the stage for heavy rainfall and flash flooding during an ENSO-warm year (CPC 2009). Cold season heavy rain events across the Florida peninsula occur more frequently during ENSO-neutral or ENSO-warm years (Paxton et al. 2006). The high moisture content was enhanced by a well-defined mid-level moisture plume extending from the central Pacific to the Florida peninsula, with low-level moisture pooling associated with a southeasterly low-level jet (LLJ) on the east side of an inverted trough. These elements, combined with several mesoscale convergence boundaries, mesolows present that morning across the area, and interactions with a mesohigh, resulted in a record 8.22 inches rainfall event at West Palm Beach International Airport.

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This paper examines the presence of different synoptic and mesoscale elements that contributed to the evolution of the heavy rainfall event. Furthermore, the analysis and review of previous conceptual models revealed that the heavy rainfall in the latter part of the event fit the conceptual mesohigh flash flood model (Maddox et al., 1979). Evaluation of forecast model guidance revealed that finer resolution models had limited success in forecasting this event.

2. Analysis of Environment, Conceptual Models, and Model Performance

a. Environment

The main synoptic-scale features identifiable on 14 December 2006 were the underlying mid and upper-level flow patterns associated with a deep ridge centered over the northern Caribbean and an upper-level trough across the south central U.S. and Mexico, with southwest flow in the mid-levels and aloft extending from the eastern Pacific across the Florida peninsula and into the western Atlantic (Fig. 1). This resulted in a plume of tropical moisture extending from the Eastern Pacific across the Gulf of Mexico and the Florida Peninsula (Fig. 2a). This pattern is further supported by the Total Precipitable Water imagery from the Advanced Microwave Scanning Radiometer aboard NASA's Aqua satellite (Fig. 2b), which shows a southwest-northeast oriented plume of higher precipitable water values across the Gulf of Mexico and some inference of moisture from the western Caribbean as well when referring to the data presented above (Remote Sensing Systems, 2009). Paxton et al. (2006) and Crow (1995) found this general upper air pattern (often observed during ENSO-warm years) to be climatologically favorable for heavy rainfall across the central Florida peninsula, and above normal rainfall across the southeastern CONUS due to an enhanced subtropical jet stream (Gershunov and Barnett, 1998). Together with a steady low-level southeasterly flow off the warm Gulf Stream waters, these features were considered to be important factors in the day's weather because they resulted in precipitable water (PWAT) values being abnormally high across the region.

The 1200 UTC Miami RAOB (Fig. 3) indicated PWAT values of 1.72 inches, which is about two standard deviations above normal (Bunkers, 2006) (Fig. 4). This abnormally large value increased throughout the day, as Global Positioning System (GPS) PWAT observations for the Fort Lauderdale area show values as high as 2.2 inches around 1500 UTC (Fig. 5). These GPS PWAT data should be used with caution since they are not entirely indicative of the vertical depth of moisture content in the atmosphere (NOAA/GSD, 2007). Similar values were obtained by the GPS sensors at Key Biscayne. Further examination of the 1200 UTC Miami RAOB (Fig. 3) revealed a low surface-based Convective Available Potential Energy (SBCAPE) environment with CAPE well distributed through the column along with weak wind shear. Three additional features were important: the calculated default storm motion of 203°\8 kt favored slow moving convection parallel to the mid-layer moisture plume; a 20 kt southeasterly LLJ just above the surface and a warm cloud layer that was nearly four kilometers deep indicating an environment capable of achieving high precipitation efficiency associated with collision/coalescence processes. These processes are more likely to occur in thunderstorms when droplets acquire electrical charges (Telford and Thorndike, 1961). The LLJ was also observed by the KAMX WSR-88D VAD wind profile around 1200 UTC (Fig. 6). This provided a persistent influx of warm, unstable air from the Gulf Stream waters which also contributed to the anomalously large PWAT observed that day.

The mesoscale environment during this event also showed some very subtle but important features. First, a north-south convergence line (inverted trough-like feature) was observed in surface observations and visible satellite imagery from south central Broward County to just west of the Miami area much of the day. More importantly, several associated west-east oriented convergence boundaries were also noted. Observations at 1500 UTC (Fig. 7) showed an inverted trough across the eastern half of south Florida. However, closer examination revealed the presence of a mesolow near the Miami-Broward county line which was more apparent around 1700 UTC (see Fig. 8). At this time, a secondary mesolow was observed in radar imagery offshore of northern Palm Beach County, as is shown by the accompanying reflectivity and velocity loops (Figs. 9 and 10). The mesolows, and associated mesoscale boundaries, moved slowly to the northeast through the early afternoon across eastern Palm Beach county and the near-shore waters. These boundaries served as foci for convective re-development, which in combination with the weak LLJ from the warm Gulf Stream waters, near-record amounts of PWAT, slow storm movement parallel to the deep layer moisture plume, and an environment of high precipitation efficiency led to the observed record rainfalls.

b. Conceptual Models

The question remains how the synoptic and mesoscale features described above combined to cause the record rainfall amounts. The configuration of the mesoscale boundaries associated with this event (Figs. 7 and 8) initially appeared somewhat similar to Maddox's (1979) frontal-type synoptic pattern but on a much smaller horizontal scale. The one very important difference, however, was there was no discernable horizontal thermal gradients across any of the mesoscale boundaries.

Maddox (1979) found that many of the frontal-type events featured an east-west oriented frontal boundary with convection forming on the immediate cool side of the boundary where warm, moist air overrode it (Fig. 11). Storms would then "train" over the same area due to their movement being parallel to the upper-level flow which allows them to remain within the mid-level moisture plume longer. The boundaries served as convergent zones and foci for renewed convective development as advection of warm, moist unstable air from the Gulf Stream overrode them. Additional convergence was enhanced across metropolitan Palm Beach County due to the presence of the low-level northerly flow associated with the mesolow offshore. Southwesterly flow aloft caused the storms to move parallel to the deep layer moisture, resulting in a training echo event. This pattern led to the development of a mesohigh, as noted by surface and mesonet observations just west of Boca Raton, FL by 1700 UTC (Fig. 8). The leading outflow boundary along the edge of the mesohigh reinforced the mesoscale boundaries already in place with a notable temperature drop to their north (also described by Maddox, 1979, see Fig. 12.) This contributed to continued regeneration of deep convection and heavy rainfall over the same area.

c. Analysis of Model Guidance

Numerical model guidance [12 km NAM (North American Mesoscale model) and locally run 4 km Weather and Research Forecast (WRF) model with the Nonhydrostatic Mesoscale Model (NMM) core referred to from here on as the 4 km wrf-nmm] indicated the presence of an inverted trough across southeast Florida during this event. The models' surface winds showed the inverted trough, with east-southeasterly winds along the Florida East Coast and northeasterly winds across western areas. However, neither the 12 km NAM or the locally run 4 km wrf-nmm mesoscale model (hot-started locally with the Local Analysis and Prediction System or LAPS initialization and using the 12 km NAM for boundary conditions, Etherton and Santos, (2008)) indicated any of the other mesoscale boundaries or the surface mesolow. Note that GFS (Global Forecast System) data was unavailable for this event.

The 12km NAM, local 4 km wrf-nmm, and the 40 km RUC all correctly indicated a southeasterly LLJ between the Bahamas and southeast Florida coast at 925 mb (Figs. 13, 14 and 15) with the RUC providing the best depiction. However, most available model guidance had a difficult time depicting accurate rainfall coverage and amount. The RUC did perhaps the best job, somewhat correctly depicting the areal coverage of precipitation (Figs. 16 and 17).

The NAM's depiction of the precipitation field was too spatially coarse for this event (Fig. 16). This is a well known characteristic of the Betts-Miller-Janjic (BMJ) convective parameterization scheme used in the model as documented in previous studies (Etherton and Santos, 2006). The BMJ scheme commonly produces broad areas of light precipitation. Although not shown in Fig. 16, the 4 km local wrf-nmm mesoscale model's precipitation forecast was the poorest. The main part of the event happened in the six to nine hour forecast period of the model run initialized at 0900 UTC. As discussed in Etherton and Santos (2008), the local model's initialization generally results in the best moisture initialization and precipitation forecasts in the very short term (generally less than six hours). However, due to balance constraints imposed in the initialization data (LAPS), the wind circulations are normally not supportive of the initialized moisture field. The result is deep convection weakens during the first few hours of integration until the model develops the mesoscale circulation on its own later in the integration. It is hypothesized this might be partly related to the poor performance during this event.

3. Summary and Conclusions

On 14 December 2006 several mesoscale and synoptic scale features combined to produce a record rain event across West Palm Beach Florida. These features included: 1) low-level mesoscale convergence boundaries along with associated mesolows and highs, 2) low-level jet off the warm southeast Florida Gulf Stream waters, and 3) abnormally high precipitable water values associated with this feature and the presence of an upper-level moisture plume streaming across the Gulf of Mexico into the Florida Peninsula from the Eastern Pacific.

The event resulted in 8.22 inches of rain at the West Palm Beach International Airport, which is a record for the day, with a reported secondary maximum of 8.04 inches reported by an observer 13 miles west of Delray Beach. The Storm Total Precipitation image from the Miami (KAMX) WSR-88D is shown in Fig. 17. Additionally, an analysis of that day's rainfall was also performed using Kriging within GIS software and shown in Fig. 18. Kriging is a geostatistical method by which unknown values are determined using known values and a semivariogram (Dorsel and La Breche, 1997). Seventeen reports from airport ASOS observations, cooperative observers, and South Florida Water Management District (SFWMD) gages were used within Palm Beach and Broward counties to produce the analysis in Fig. 18. The two highest rainfall reports have been labeled in the image. In addition to the rainfall maxima at the West Palm Beach Airport, these figures (Figs. 17 and 18) show a rainfall maximum of five to six inches in south-central Palm Beach County, with a secondary rainfall maximum offshore of Palm Beach County, nearer to the offshore mesolow. Comparison of the WSR-88D rainfall estimates to the observation-based analysis shows the radar was relatively accurate in its estimation of a widespread area of four to six inches amounts over south central Palm Beach County, although the maximum amounts were underestimated by around two inches. Notice the more northern rainfall maximum from West Palm Beach to points just south was slightly more underestimated, with the radar estimating generally two to four inches over land in this area. The radar underestimation was likely due to a combination of the radar beam overshooting much of the warm-cloud precipitation production at longer ranges.

Evaluation of surface, radar, satellite, and upper air data revealed the event fits the Maddox mesohigh type flood conceptual model (Maddox et. al, 1979). High resolution models such as the 12 km NAM, local 4 km wrf-nmm, and the coarser 40 km RUC did not properly capture the magnitude and localized natured of the event but did resolve some important mesoscale elements and features that helped create a favorable environment for heavy rainfall.

This event also highlights that proper mesoanalysis using surface, radar, satellite observations (including derived products such as PWATs), and upper air data along with the application of appropriate conceptual models can prove very useful in forecasting mesoscale heavy precipitation events. When such features are analyzed in proper context, adjustments can be made to model guidance to make up for their shortcomings which can lead to an increase in situational awareness and a better anticipation of what is likely to happen. WFO Miami issued the first of several Flash Flood Warnings at 1620 UTC for parts of Palm Beach and Broward Counties, at which point observations indicated 5.39 inches of rain had fallen in the previous three hours at West Palm Beach International Airport, and roadway flooding was beginning to occur based on reports received from law enforcement. This warning replaced an Urban Flood Advisory issued at 1556 UTC for the same general area.

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FIGURES

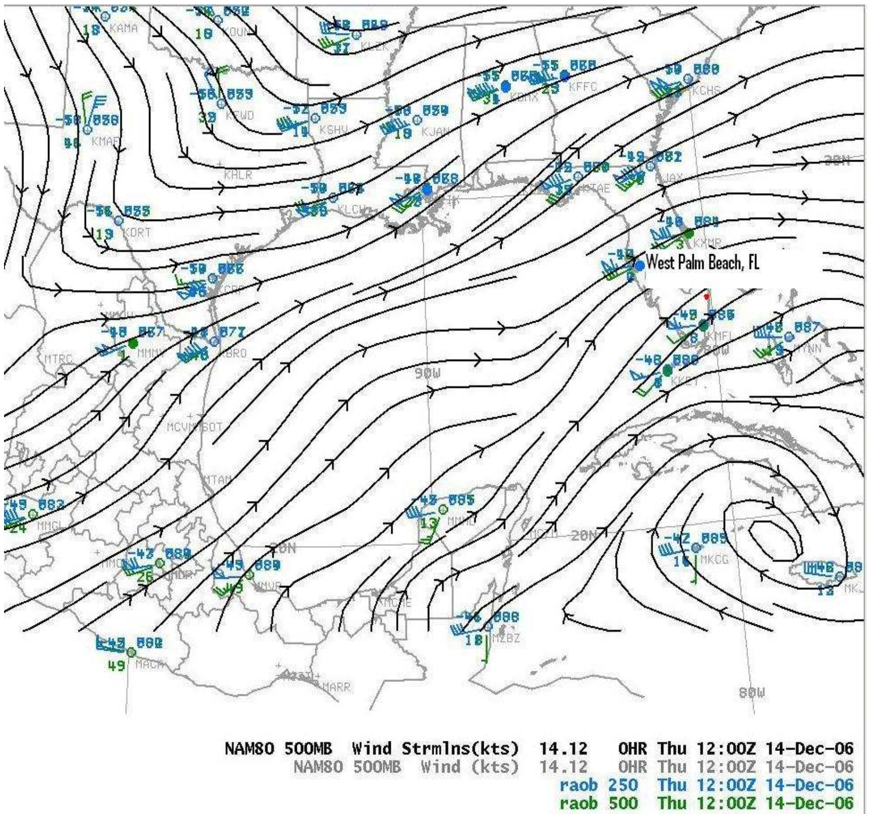

Figure 1. Plot of 500 mb (green) and 250 mb (blue) winds for 1200 UTC 14 December 2006. The 1200 UTC NAM 500 mb analysis (streamlines) is also shown. The data show the deep layer southwest flow in the mid to upper-levels across the Gulf of Mexico and Florida peninsula.

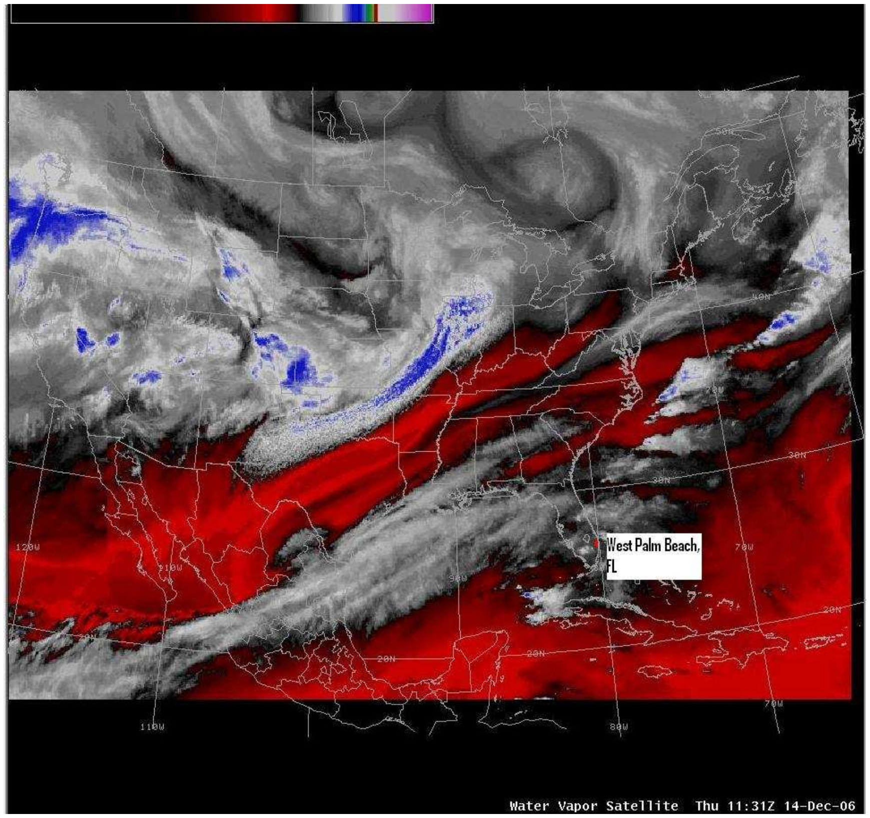

Figure 2a. Water vapor imagery from approximately 1130 UTC 14 December 2006. Note the tropical moisture plume extending northeast from the Pacific to north central Florida.

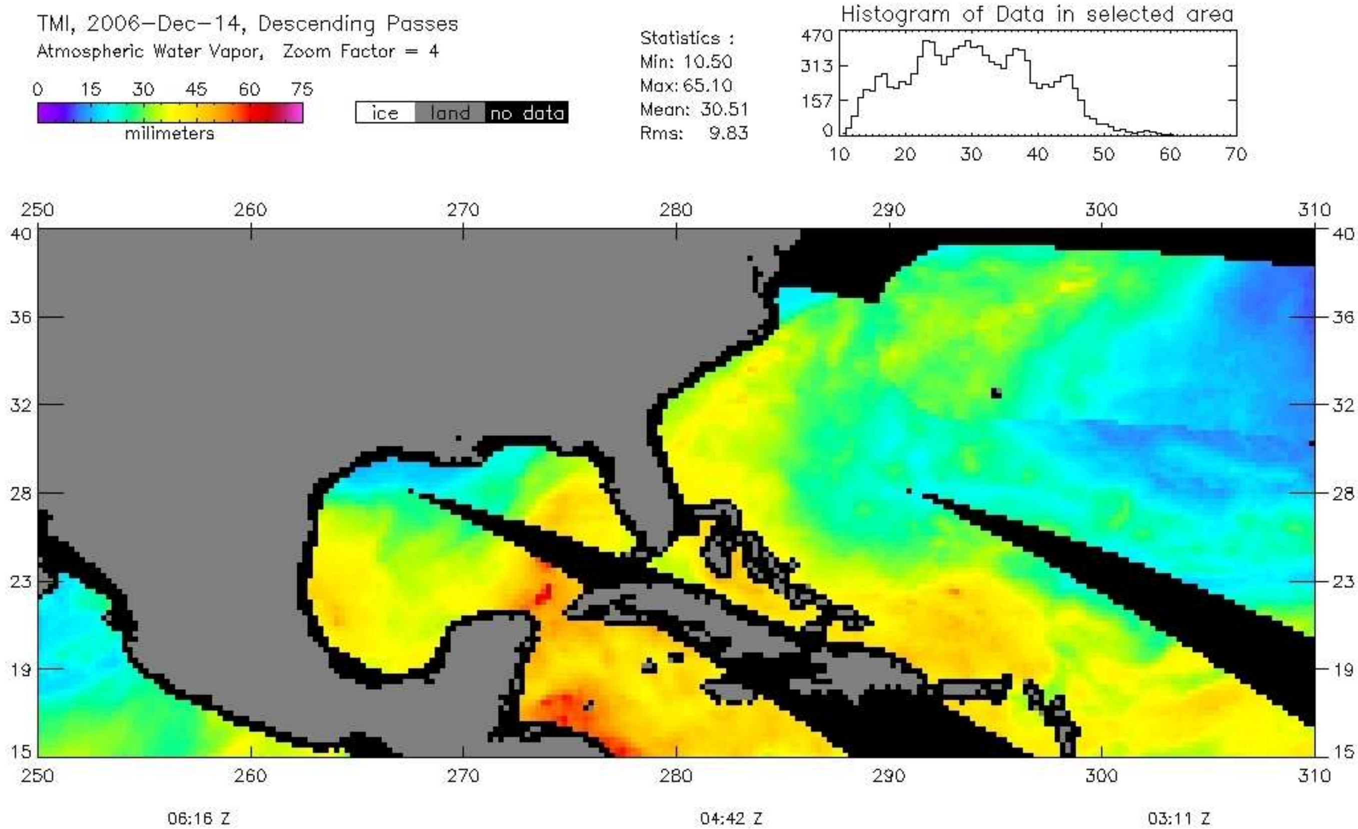

Figure 2b. Total Precipitable Water (TPW) from the AMSR-E during the morning hours on 14 December 2006. Higher precipitable water values are indicated by the graduating warm colors.

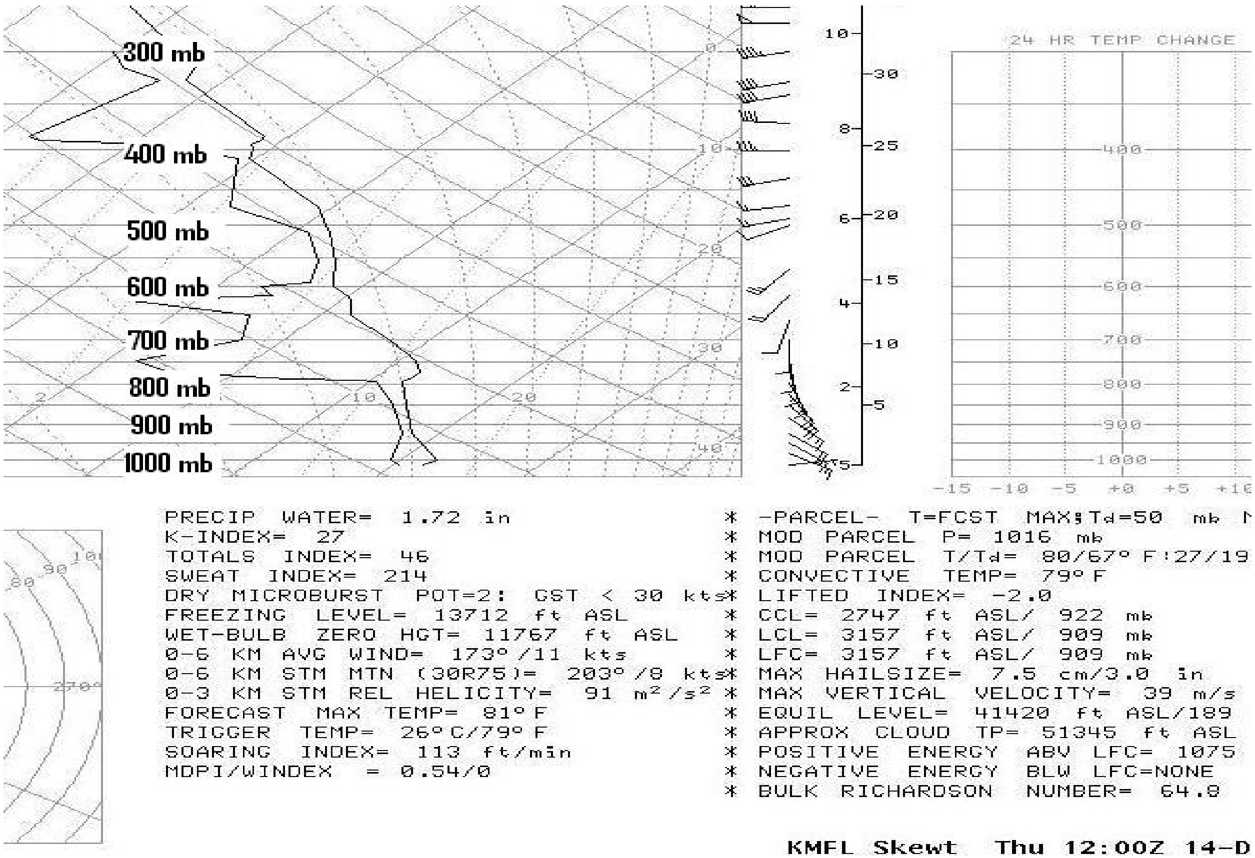

Figure 3. Miami, FL sounding from 1200 UTC 14 December 2006. Note the generally moist-adiabatic lapse rates, overall low instability and the 20kt east-southeasterly LLJ in the wind profile.

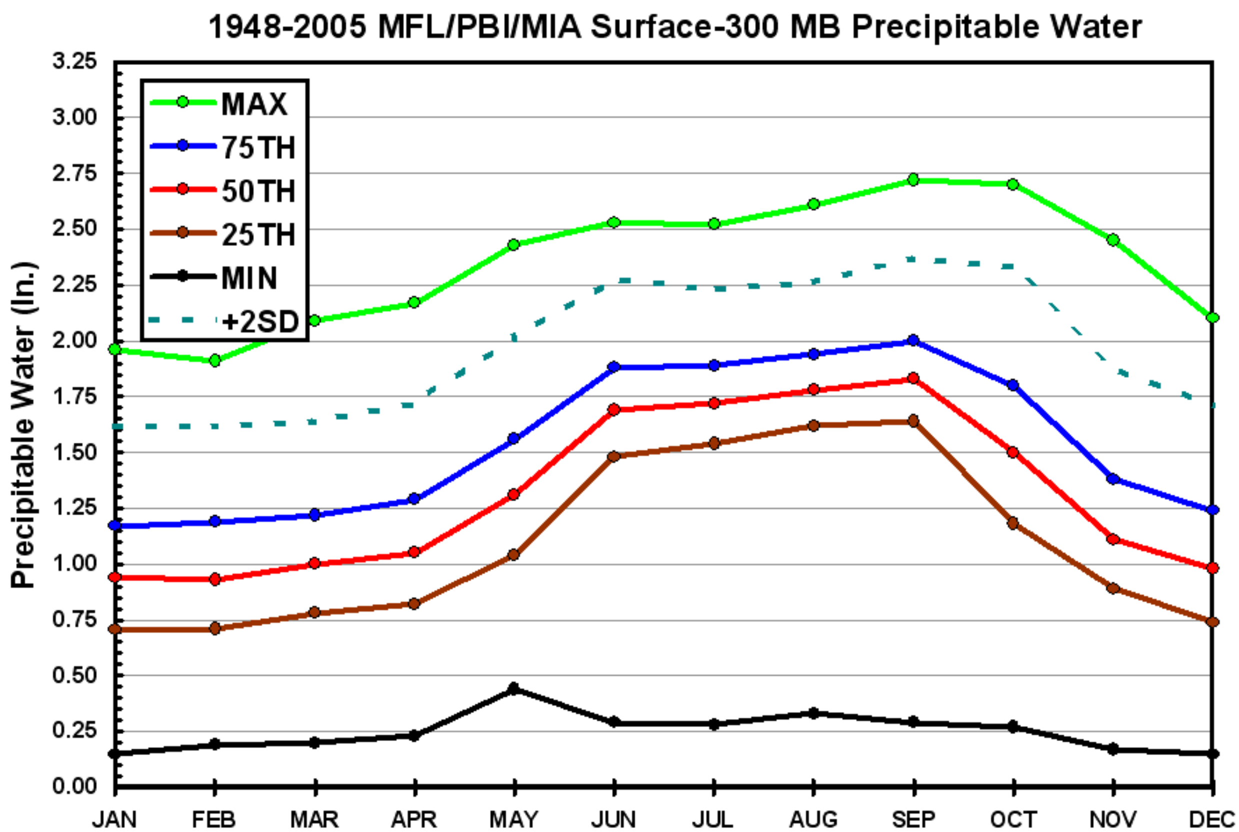

Figure 4. Annual variation in climatological precipitable water values for South Florida, 1948-2005 (Bunkers 2006). The brown, red, and blue lines indicate 25, 50, and 75 percent above normal PWAT, respectively. The black and green lines represent the minimum and maximum values observed in a given month, respectively. The dashed line represents two standard deviations above normal. Two standard deviations above normal PWAT for 12 April would be around 1.75 inches. The value for 14 December 2006 1200 UTC sounding was 1.72 inches.

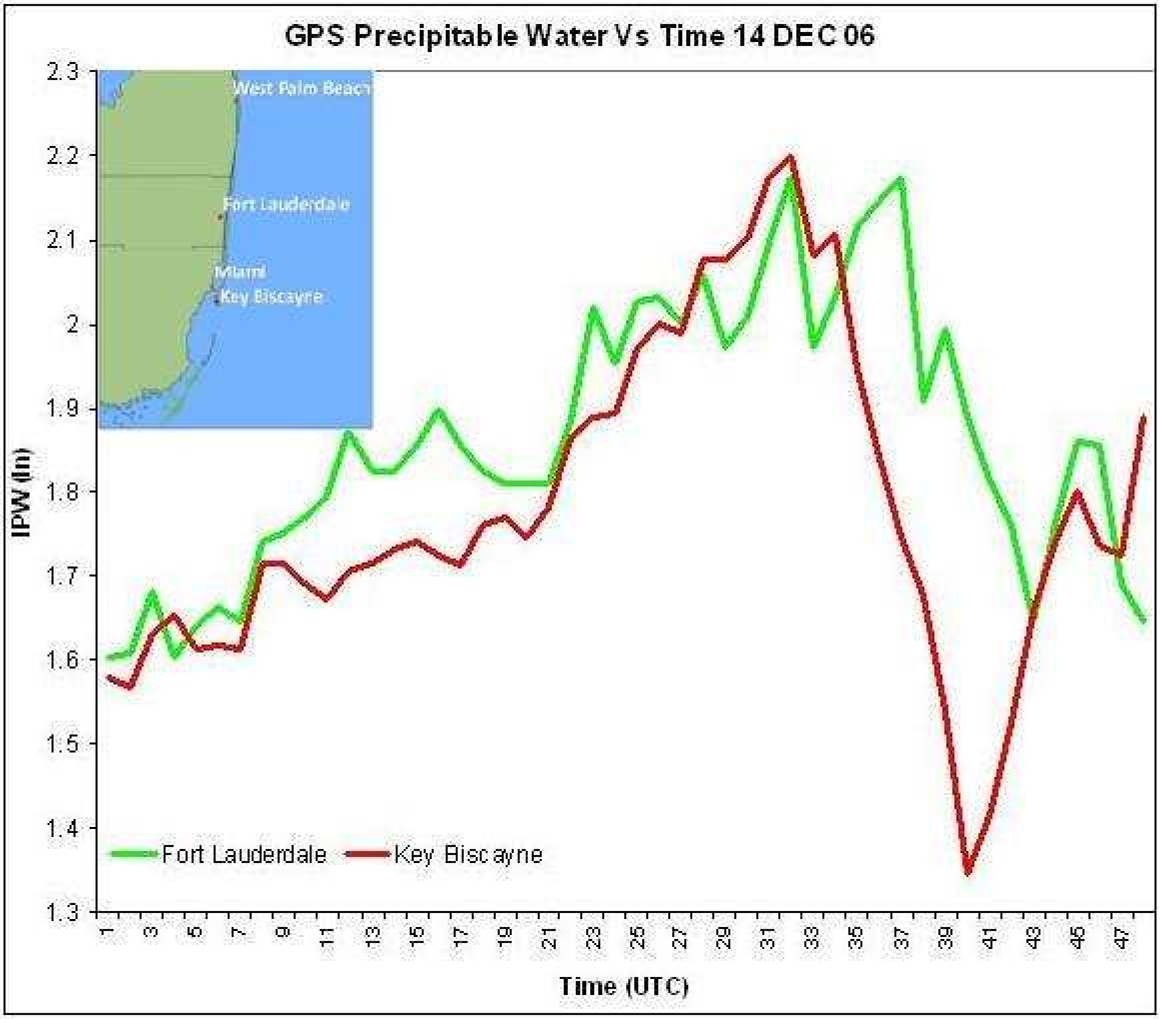

Figure 5. Time series of GPS-based precipitable water observations for Fort Lauderdale and Key Biscayne, in south Florida on 14 December 2006. Miami and West Palm Beach are also shown for reference. Note the peak of heaviest rainfall near two inches around the time of occurrence (1300-1700 UTC).

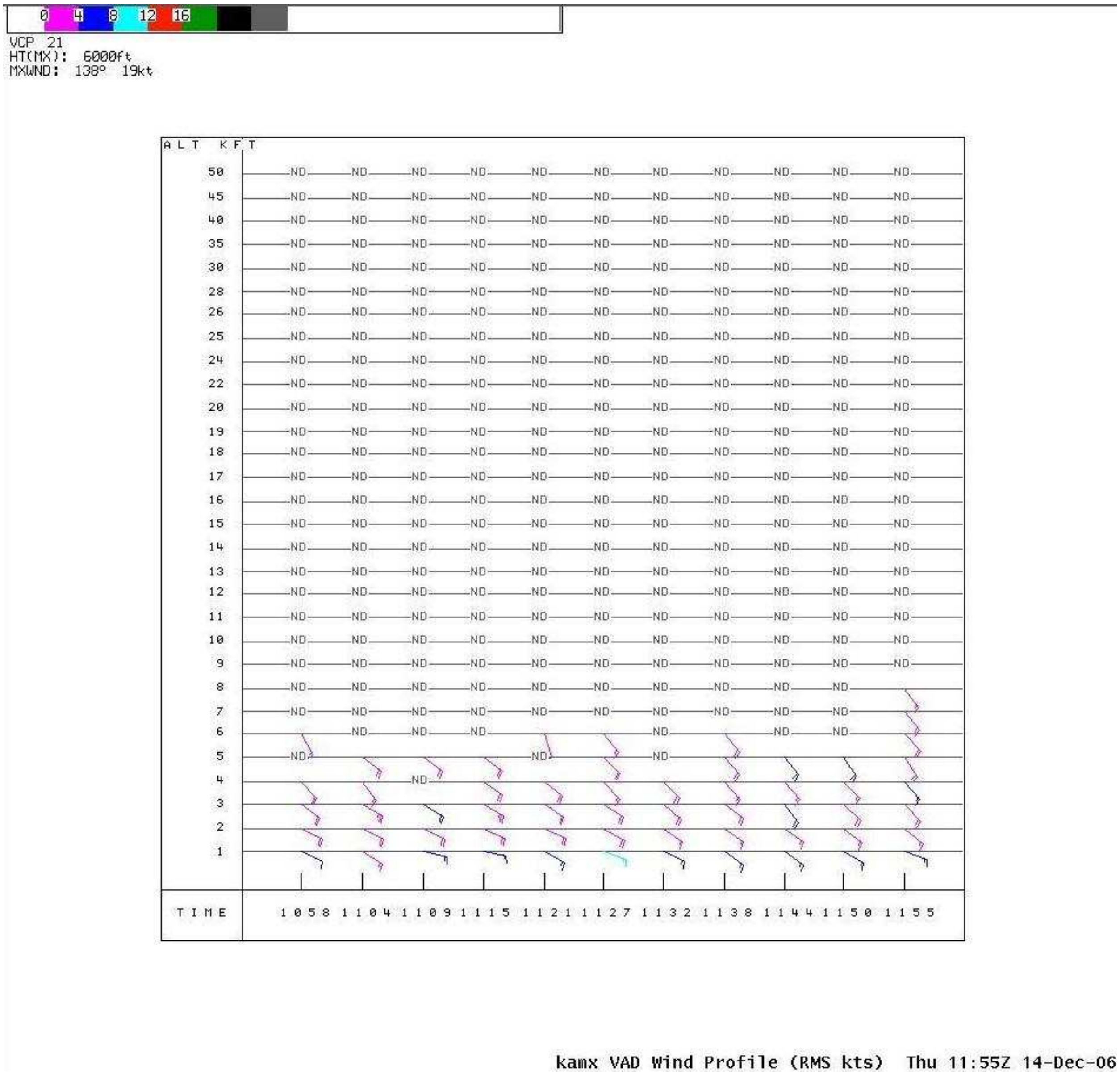

Figure 6. KAMX WSR-88D VAD wind profile around 1200 UTC 14 December 2006. The data support the weak east-southeasterly LLJ observed in Fig. 3.

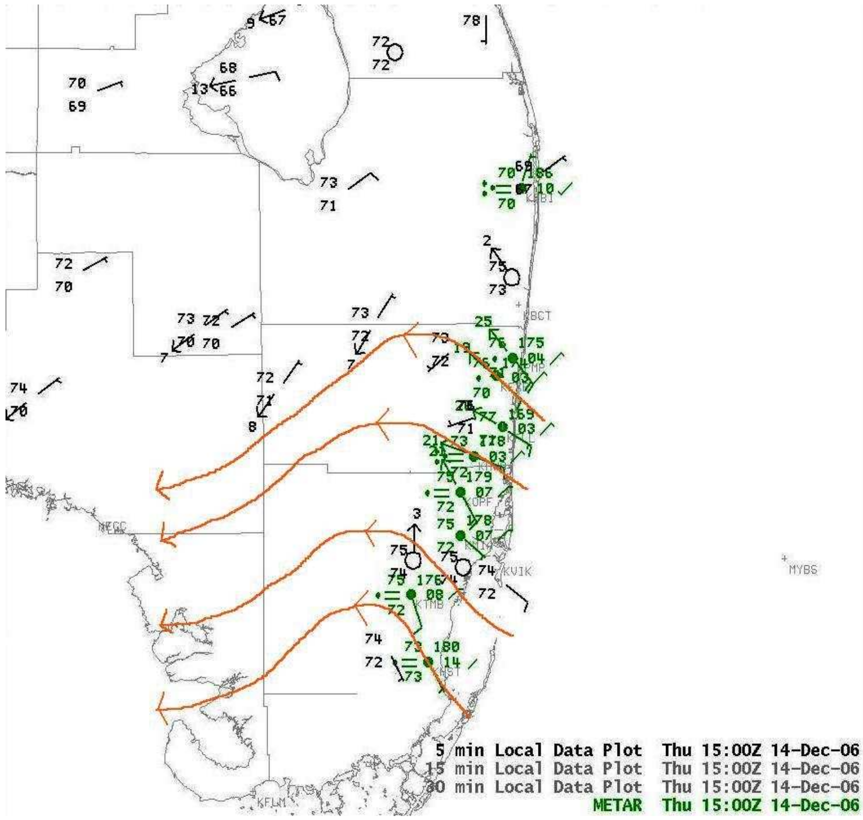

Figure 7. Manual surface streamline analysis for 1500 UTC 14 December 2006 depicting a broad inverted surface trough over eastern portions of South Florida.

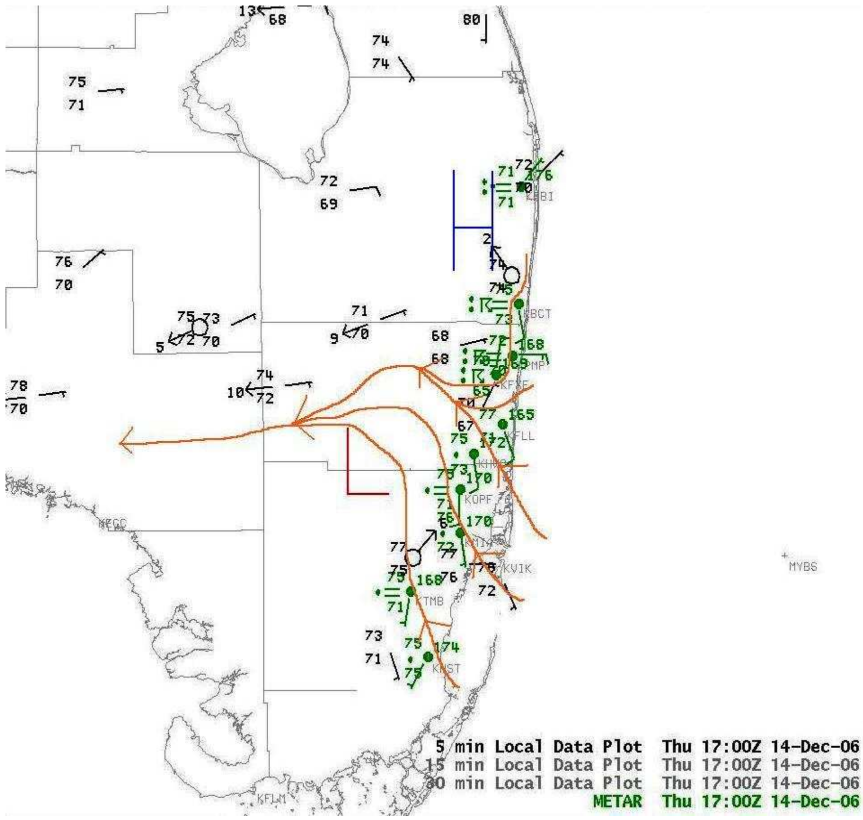

Figure 8. Same as Fig. 7, except for 1700 UTC 14 December 2006**.** Note now the formation of the mesolow at the apex of the inverted trough as well as mesohigh formation beneath the large, stationary convective cluster (see also Figs. 9 and 10).

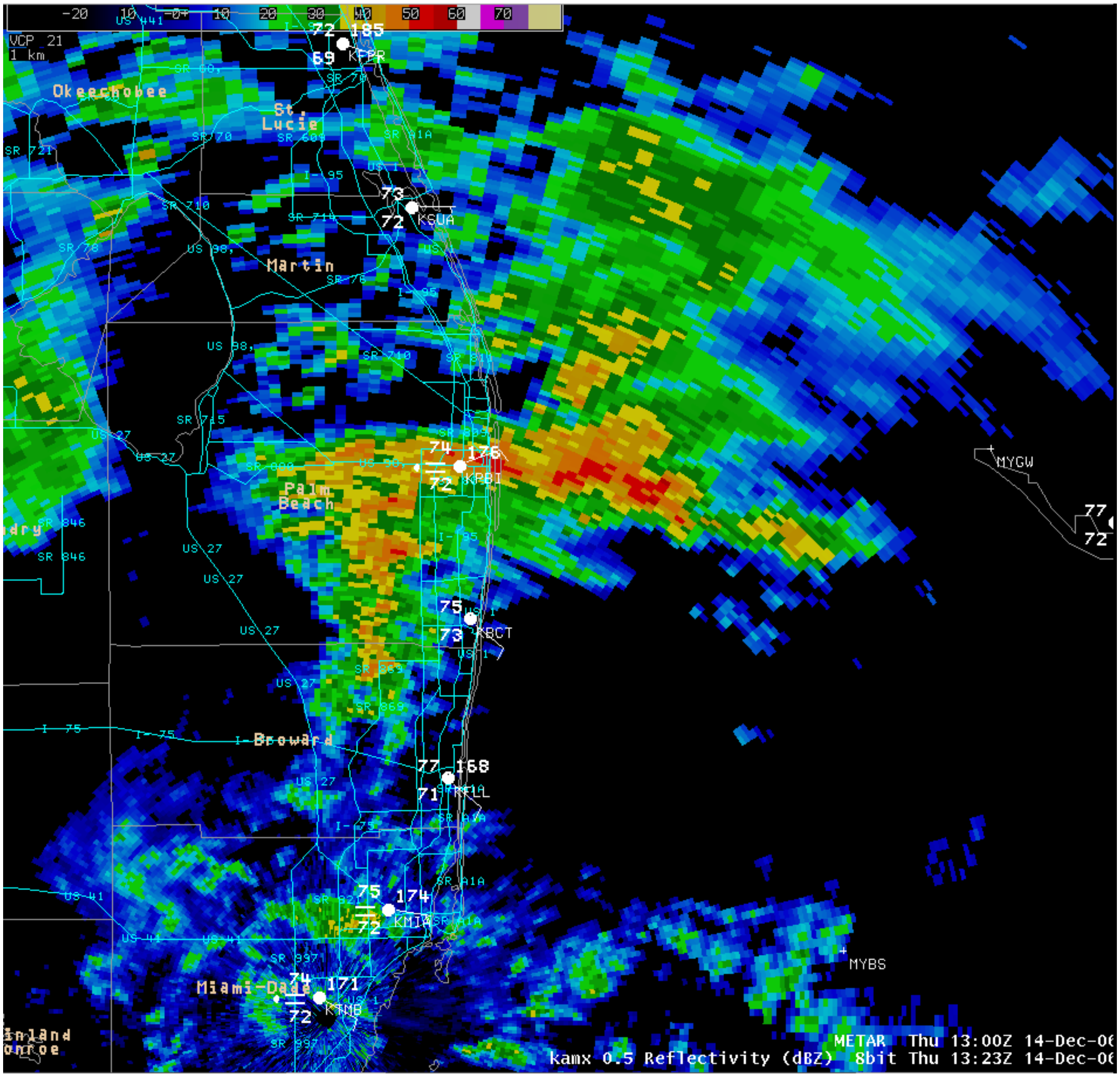

Figure 9. KAMX 88D base reflectivity loop from 1323 UTC-1758 UTC, showing training convection over Palm Beach County. The location of West Palm Beach is denoted by the surface observation KPBI in the top center. **Note – This is an animation. Press control and click on the image to open a browser window containing the loops.**

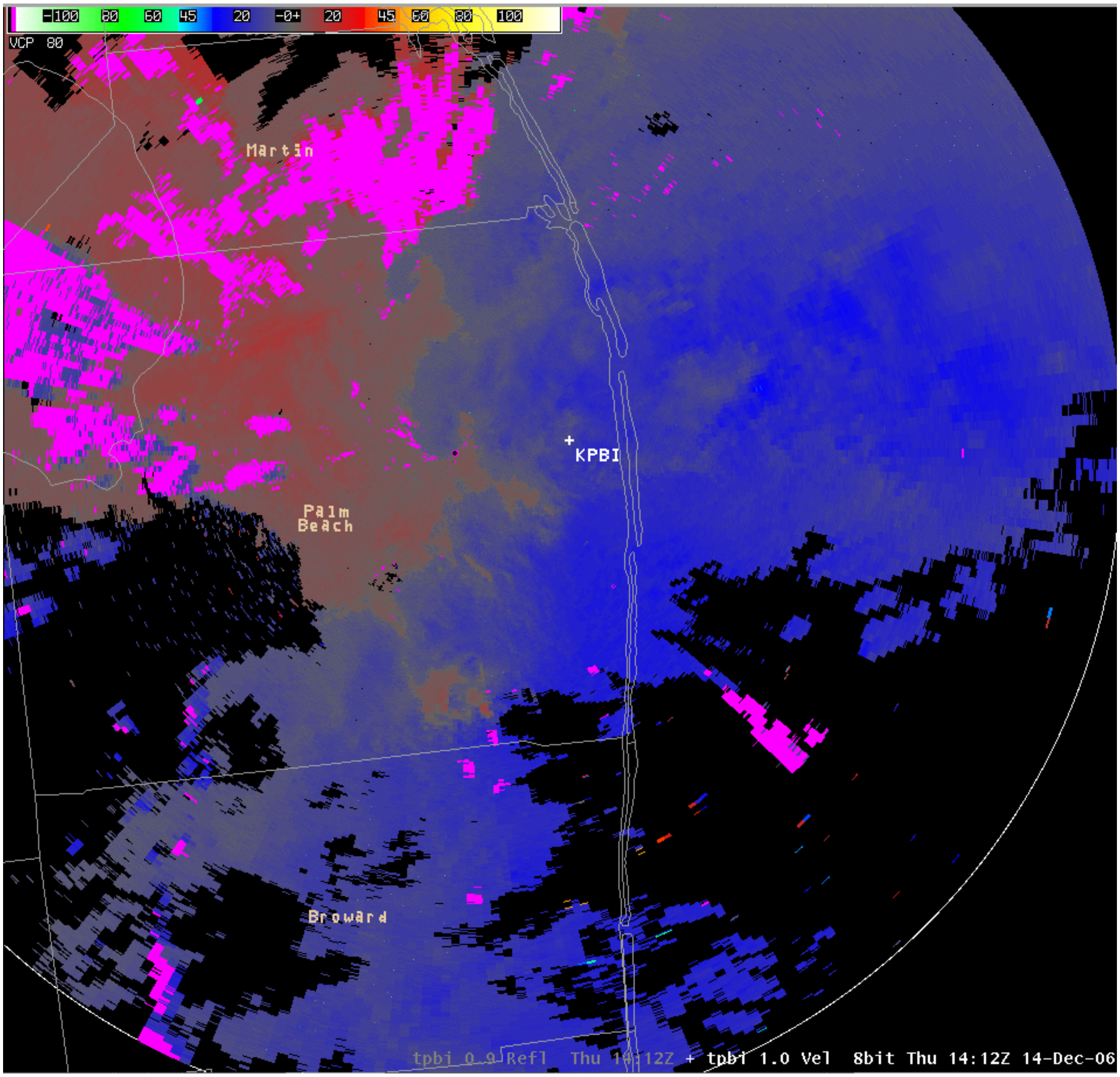

Figure 10. TPBI Terminal Doppler Weather Radar (TDWR) 1.0 degree velocity loop from roughly 1424 UTC-1700 UTC, showing convergence associated with the mesolow offshore of Palm Beach County. The location of West Palm Beach is denoted by the surface observation KPBI in the top center. **Note – This is an animation. Press control and click on the image to open a browser window containing the loops.**

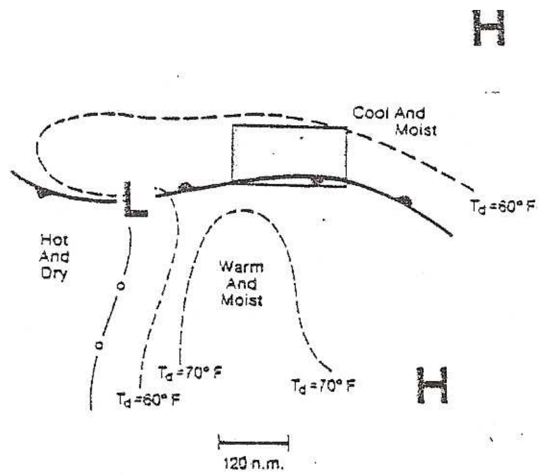

Figure 11. Depiction of a typical frontal type flood event as shown in Maddox (1979).

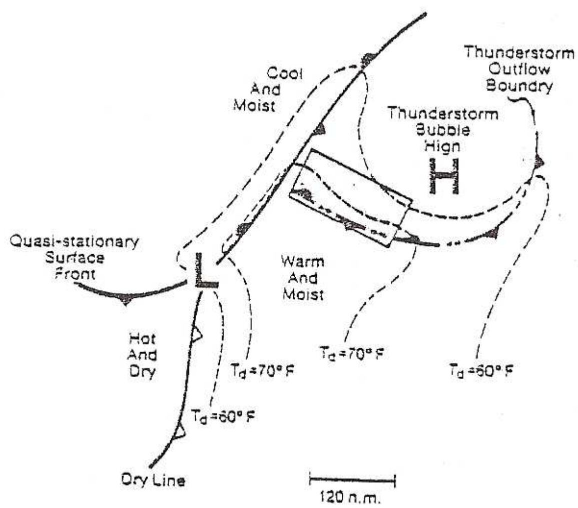

Figure 12. Depiction of a typical mesohigh type flood event from Maddox (1979).

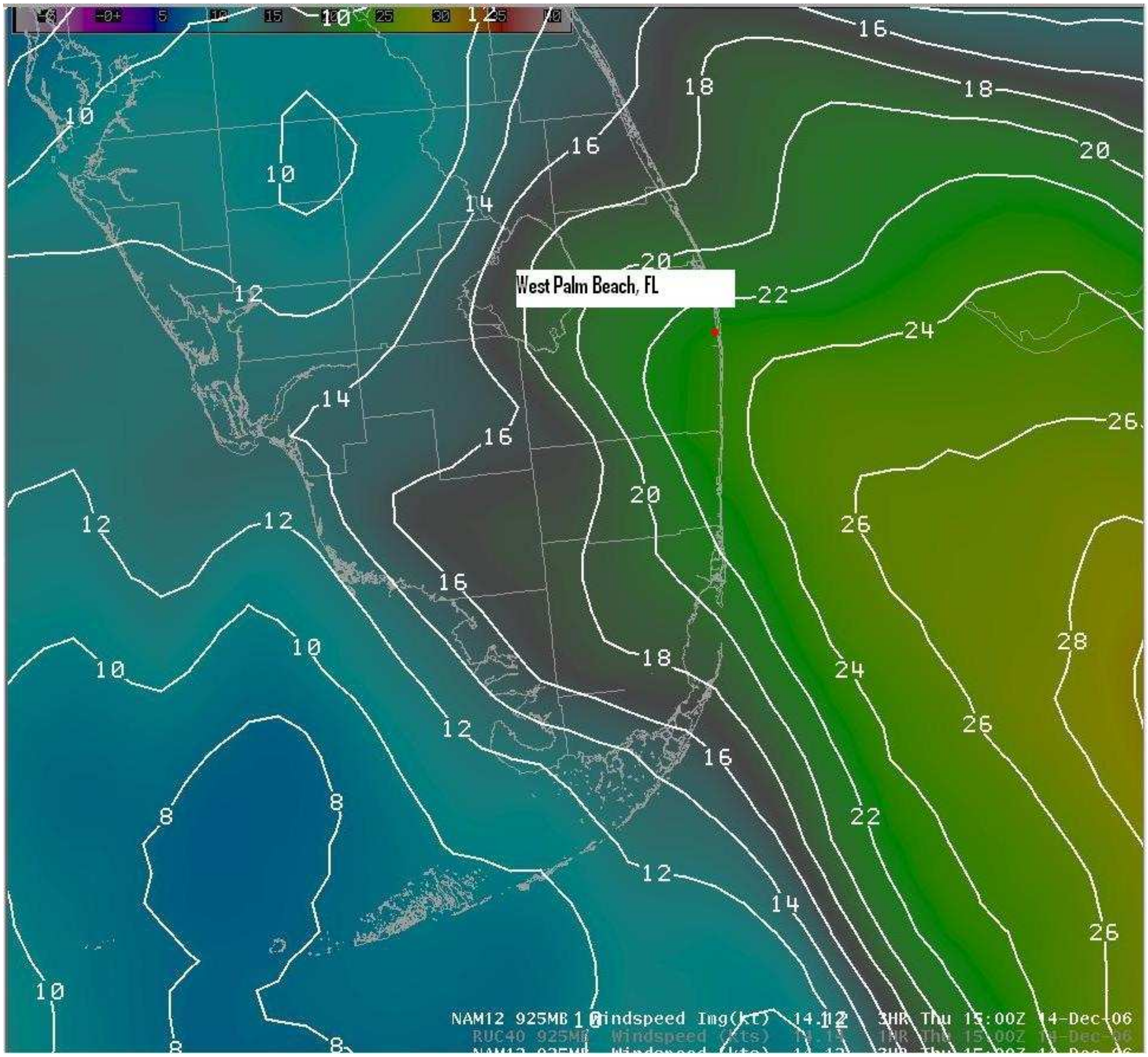

Figure 13. 12 km NAM depiction of the 925mb LLJ at 1500 UTC on 14 December 2006. Note the 20+ knot maximum from the SE Florida coast to the central Bahamas.

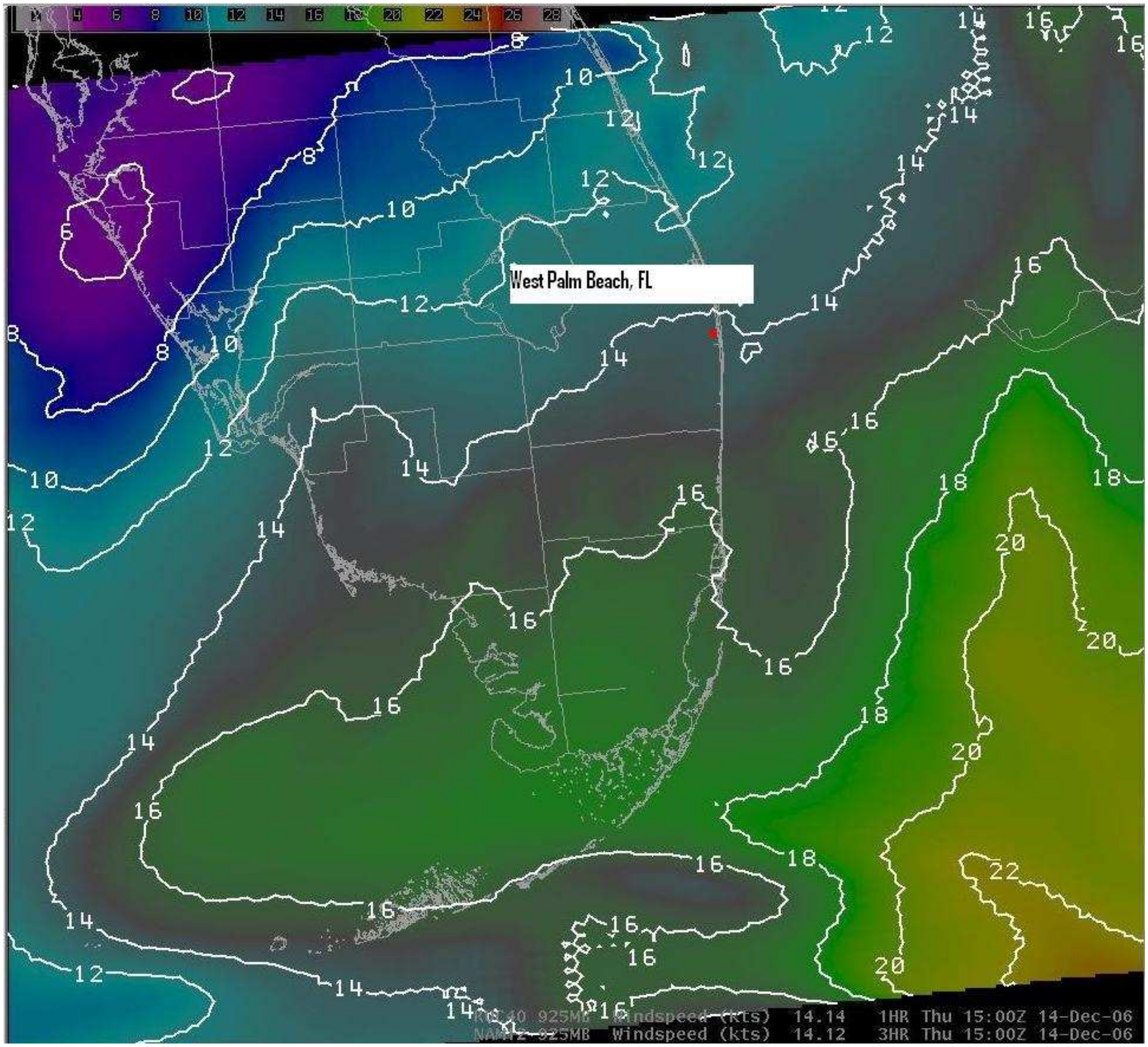

Figure 14. Same as Fig. 11, except for the locally run 4 km wrf-nmm. Note the weaker LLJ.

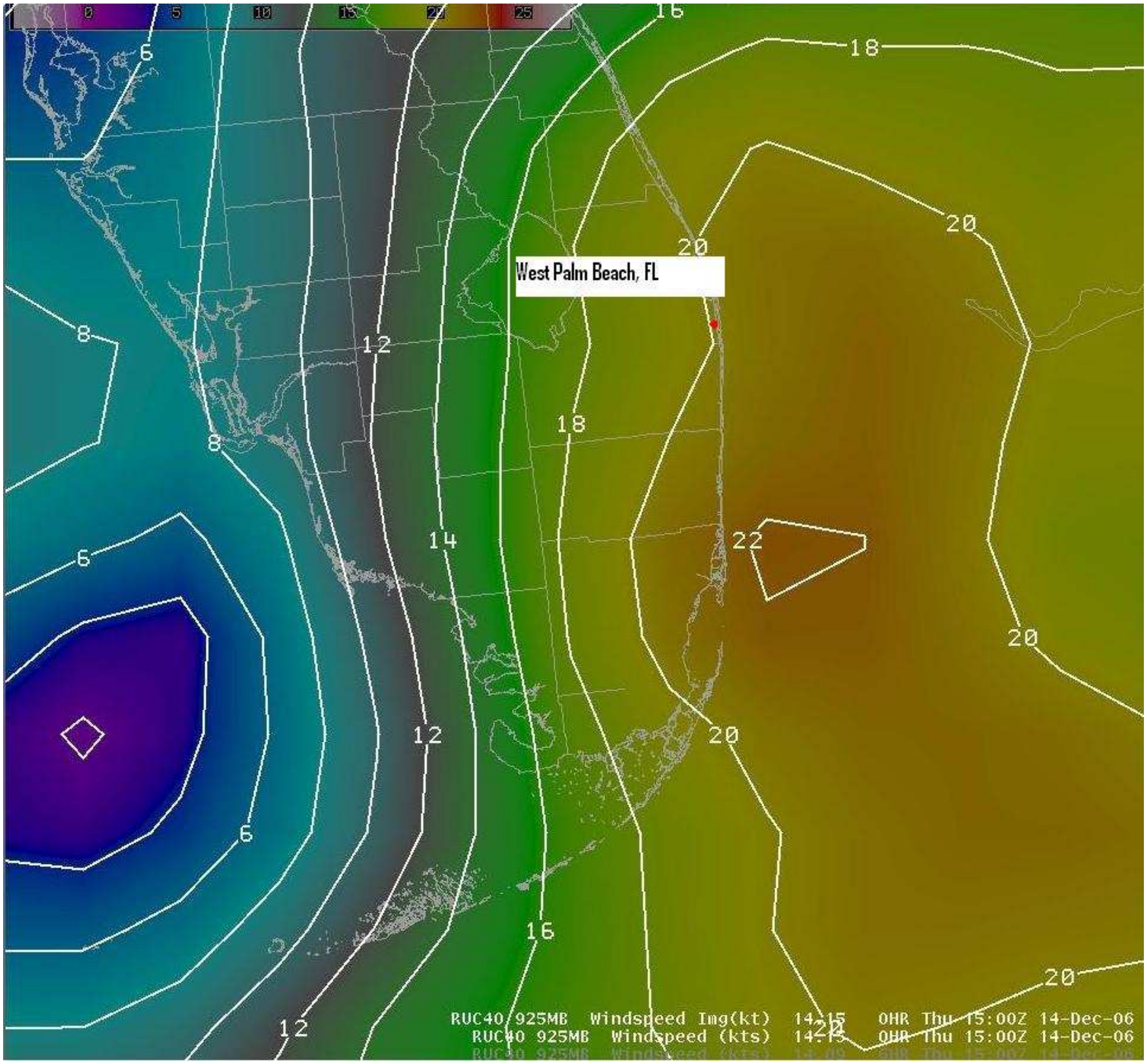

Figure 15. Same as Figs. 11 and 12, except for the 40 km RUC.

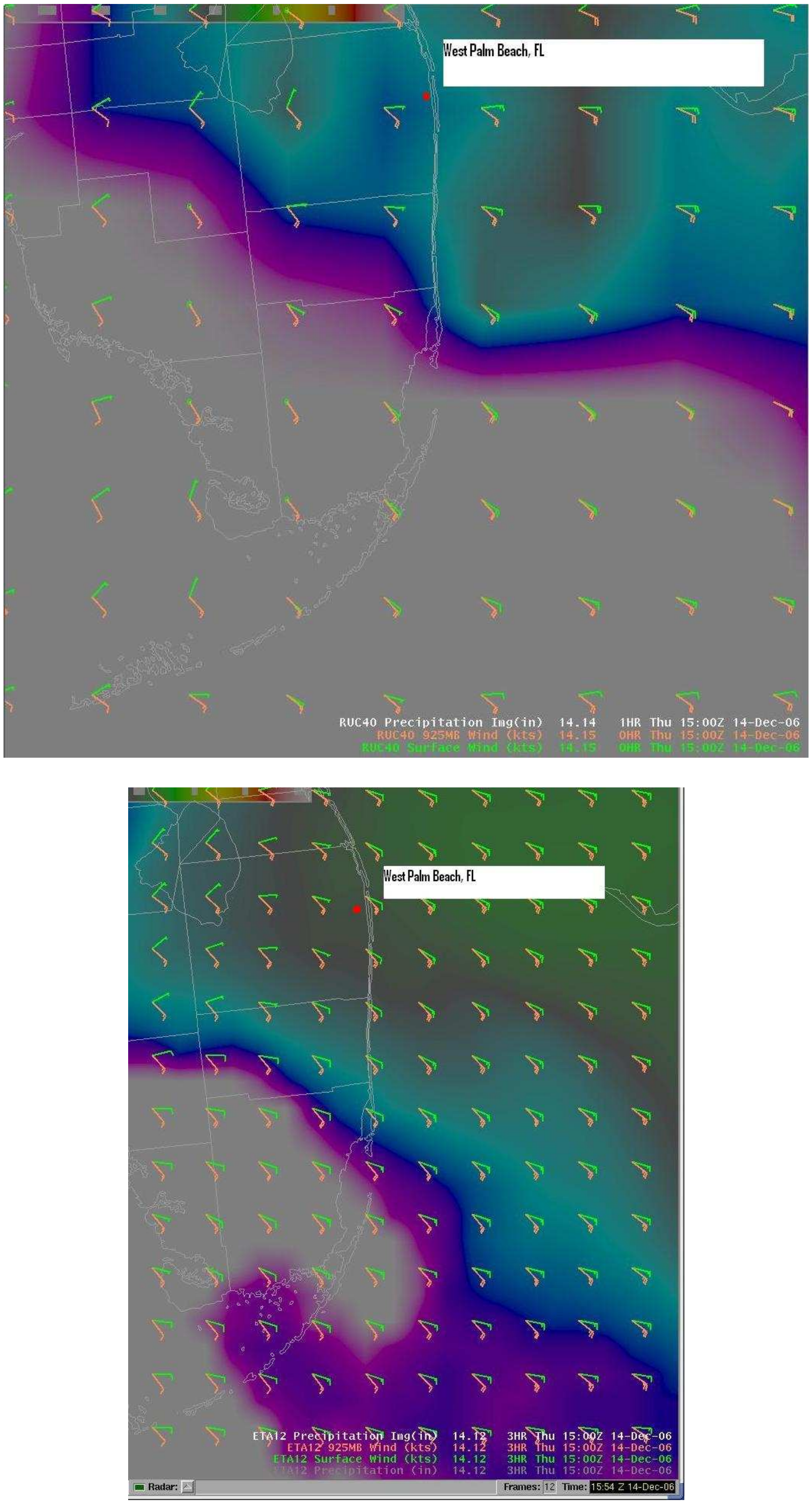

Figure 16. RUC (top) and NAM (bottom) three hourly rainfall forecasts (images) valid 1500 UTC 14 December 2006 with surface (green barbs) and 925 mb (orange barbs) wind forecasts. RUC precipitation amounts range from 0.1 inches across the area of maximum rainfall to up to 0.25 inches offshore in the green colors. The NAM rainfall amounts range from 0.35 inches across the area of maximum rainfall to 0.4 inches offshore.

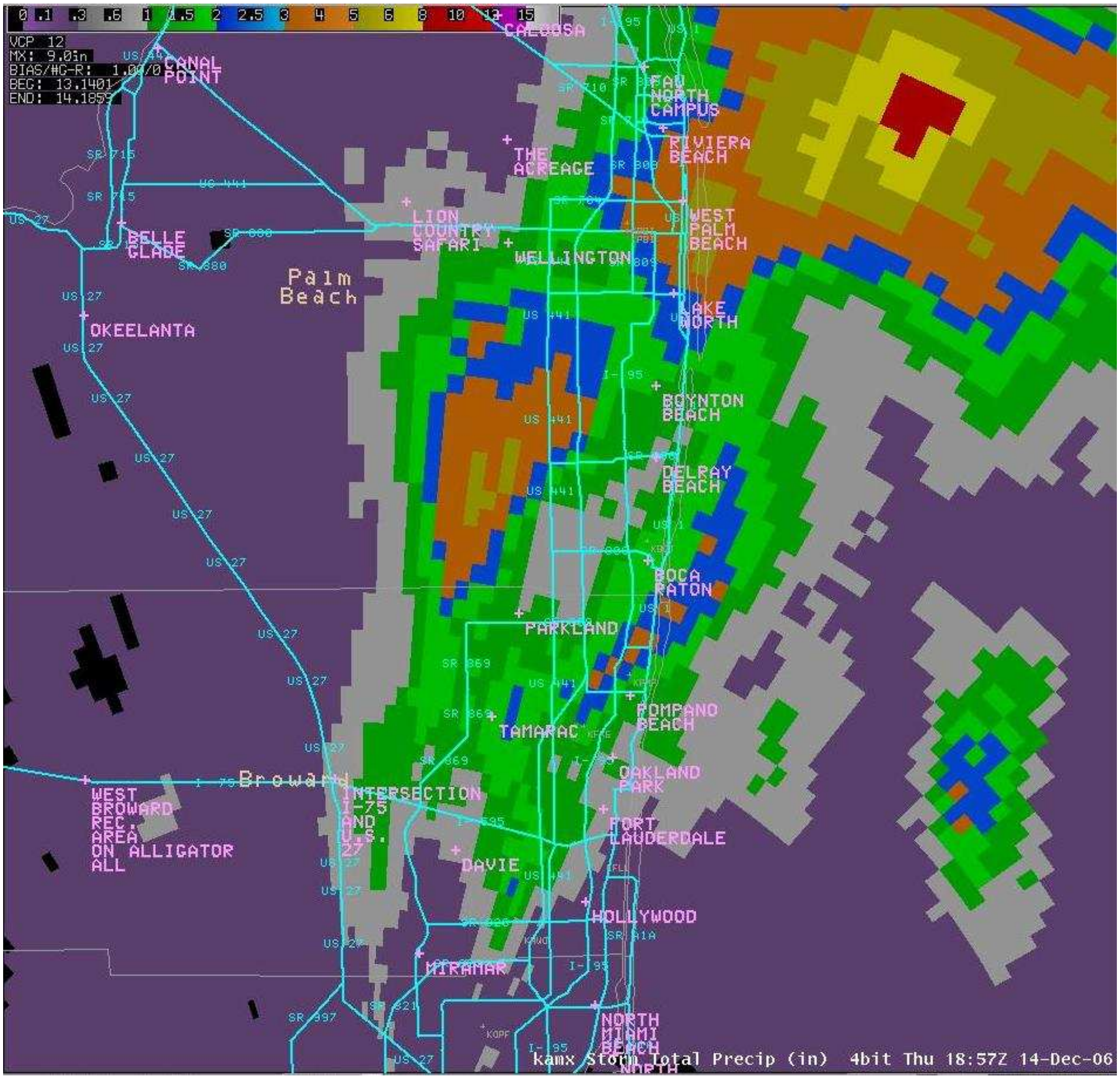

Figure 17. Storm total precipitation ending 1700 UTC 14 December 2006 from KAMX WSR-88D. Main roads and highways are shown in blue, with cities in purple, for reference purposes. Note the maximum radar-estimated rainfall over a populated land area is over West Palm Beach. Also, note the overall maximum radar-estimated rainfall offshore of northeast Palm Beach county, where the second mesolow was noted.

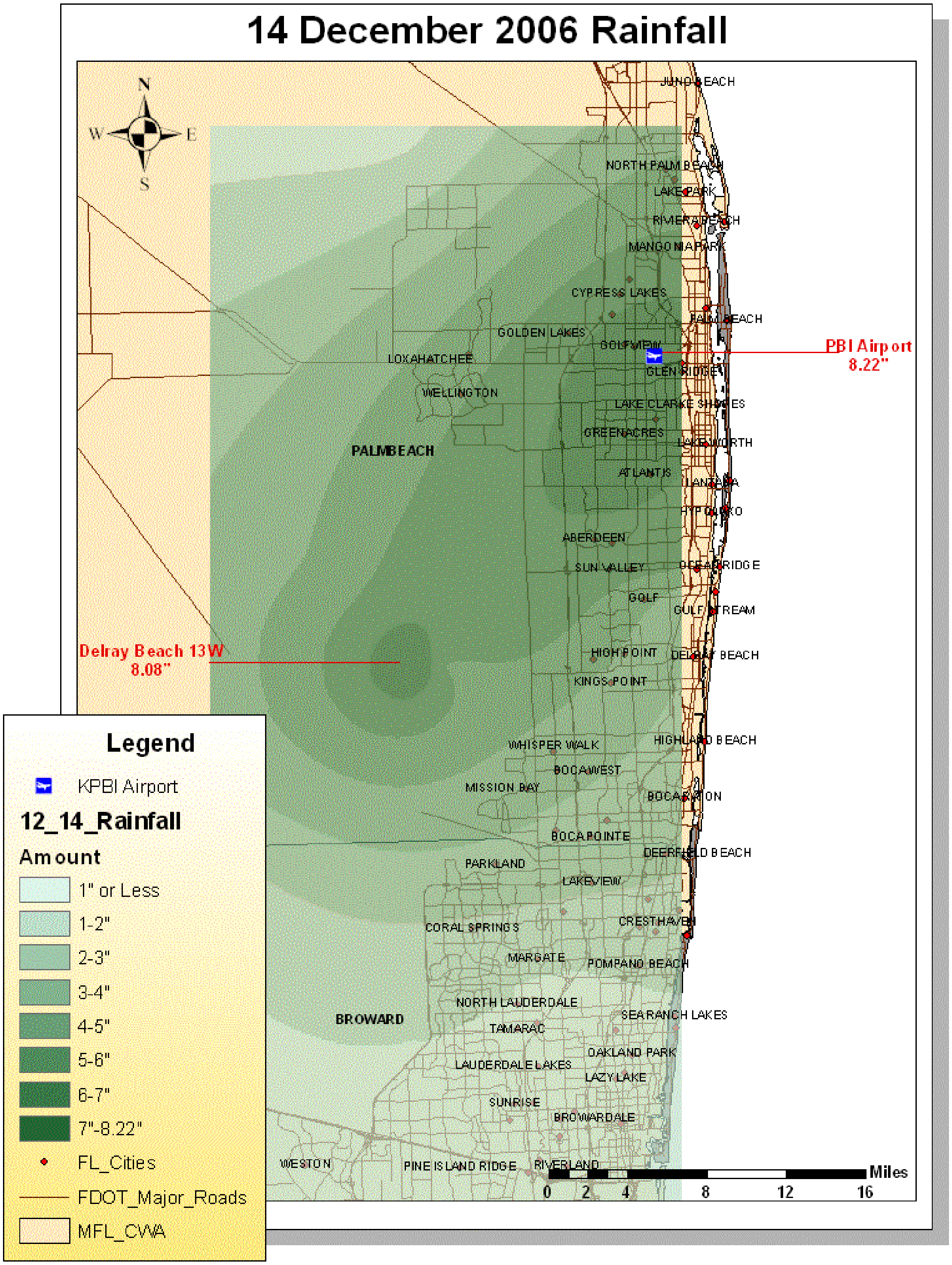

Figure 18. Rainfall analysis from ASOS, COOP, and SFWMD reports for 14 December 2006. Roadways are indicated by the thin maroon lines, with point locations denoting cities (see labels). The Storm Total Precipitation from KAMX (Fig. 17) generally agrees with the "ground-truth" analysis presented above.