JP1.1 REDUCTION OF BOUNDARY LAYER DROPSONDE WINDS TO ESTIMATE SURFACE WINDS AND THEIR COMPARISON WITH SFMR DATA IN LANDFALLING HURRICANE KATRINA

Richard G. Henning*
Consulting Meteorologist, Niceville, FL

1. INTRODUCTION

More than 60 dropsondes were released by three reconnaissance aircraft during the hours around landfall of Hurricane Katrina on the morning of 29 August 2005. These measurements, along with Stepped Frequency Microwave Radiometer (SFMR) readings sampled over the Mississippi, Breton and Chandeleur Sounds, and far northern Gulf of Mexico waters, were all considered by NHC and HRD personnel arriving at Katrina landfall maximum sustained wind (MSW) intensity estimates of 110 knots (for the Louisiana landfall near Buras around 1100 UTC) and 105 knots for the final landfall near the Pearl River in westernmost Hancock County MS around 1500 UTC. These values can be found in the NHC Katrina Tropical Cyclone Report published a few months later. This paper will briefly examine:

First, every sonde released into regions of eyewall or feeder band flight level wind maxima that morning showed a marked drop-off in wind values closest to the surface (with no surface winds higher than 101 knots seen in any of the 43 NOAA/AFRES sondes released after sunrise that morning). These measurements were, at least in part, corroborated by examining SFMR readings that all showed 100 knots or less. The first question is whether there is a reasonable probability that higher surface winds may have existed over the Mississippi Sound that morning that were simply missed by the drops. This is unlikely based on examination of the SFMR data, continuously sampling surface winds below the aircraft, that show nothing to suggest higher surface wind streaks or swaths existed between the spots where the sondes fell.

Secondly, If the SFMR is used to help “ground truth” the surface sonde measurements, then uncovering any reason to suspect a low bias in the SFMR data that morning would suggest there may have been areas of surface winds stronger than 100 knots.

2. SFMR DISCUSSION

The SFMR uses radiative emissions expressed in terms of brightness temperature at six frequencies from 4.55 to 7.22 GHz. An increase in the amount of foam on the ocean surface, associated with higher wind speeds, creates greater amounts of microwave energy. Many years of prototype tests flown by HRD yielded thousands of data points that were used to establish empirically determined curves that were then used to assign surface wind speeds to corresponding brightness temperature in all types of intervening weather conditions. The SFMR works in clear weather or in areas of extremely high precipitation rates (even in eyewall reflectivity of 50 dBz or higher) as the attenuation of the surface brightness signal was been accounted for after exhaustive calibration and further testing. Indeed, the calibration that has been accomplished in the past few years since the SFMR has been flown regularly onboard NOAA W-P3 aircraft (into nine tropical cyclones in 2005) has significantly refined the wind retrieval algorithms, greatly reducing what had been a noted low bias in major hurricane force wind fields. This improvement in SFMR accuracy has been enhanced even more by introduction of the instrument into routine TC reconnaissance since it was fitted one by one onto all the WC-130J aircraft flown by the USAF Reserve 53rd Weather Reconnaissance Squadron during the 2006 and 2007 Atlantic Hurricane Season. SFMR data is now collected on every AFRES operational storm mission and overwater weather training flight and this volume of data is then made available to Pro Sensing contractors and HRD scientists to continue fine tuning this ongoing calibration effort.

There are two ocean variables that must be assessed by the onboard meteorologist to ensure maximum SFMR performance. These are sea surface temperature and salinity. The software which collects the brightness temperature data and processes it into surface wind speed readings uses default values of 28 degrees C for SST and 36 parts per thousand (ppt) for salinity. As the calibration effort continues to make the SFMR more and more accurate, the error induced by flying over ocean surfaces with SST and salinity qualities different from the default values is becoming less problematic. For example, even if the SST is 3 degrees C different than the default value, less than a 10 percent error in SFMR surface wind speeds can be expected. In order to make this error as small as possible, the flight meteorologist has the ability to select a more appropriate SST and salinity based upon local conditions expected to be overflown.

Variance in ocean salinity in most areas flown by Atlantic Basin reconnaissance aircraft is relatively small. The SFMR default value of 36 ppt is actually quite representative of what can be expected in most areas of the Caribbean and tropical /subtropical Atlantic. Obviously, there can be significant difference in SST from the 28C default value depending on the location and time of year.

Interestingly though, one area where there is a significant deviation in salinity from the default value is the extreme north central Gulf of Mexico near the

* *Corresponding Author Address:* 822 Sparkleberry Cove, Niceville, FL 32578 Email: richard.henning@cox.net

mouth of the Mississippi River. The large volume of fresh water discharged by the Mississippi River (and to a lesser but still significant extent, also by other nearby rivers flowing south into the Gulf (such as the Pearl River, Alabama River and Biloxi River)) reduces salinity in the Mississippi Sound to around 22 ppt most of the year. The effect on the SFMR of overestimating the salinity (using the default value of 36 ppt rather than this 22 ppt value) creates a net result of somewhat lower surface wind speed readings. The same net effect happens to be true for underestimating the SST. Using the default value of 28C, rather than the warmer SST value of 30 to 31 C that existed in the Mississippi Sound on the morning of 29 August 2005, results in a small under representation of the surface wind speeds. A combination of underestimated SST and overestimated salinity might produce what should still be a small low bias in SFMR winds but one that is worth investigating. This is especially true since all the raw SFMR brightness temperature measurement data from NOAA 43's flight into Katrina that morning is archived and can be re-run against any SST and salinity settings, taking advantage of all the additional calibration work done in the past two years since Katrina, to remove any potential low bias if it exists.

3. ANALYSIS OF NOAA W-P3 / AFRES WC-130J DROPSONDES

One advantage of the NOAA W-P3 configuration is that the dropsonde operator can swivel their seat and reach the sonde release tube without unstrapping and getting out of their seat (a handy feature in the sometimes very turbulent environment of eyewalls and feeder bands). This means the operator can make multiple releases in a short interval (especially if the sonde fails after leaving the aircraft, another can be launched in very nearly the same location). In contrast, the WC-130J operator must get out of their seat to load another sonde in the launch tube. As a result, the W-P3 missions tend to drop many more sondes and can make measurements of each important convective feature. Even if they encounter multiple sonde failures, an eyewall max wind measurement will typically not be missed by the NOAA mission whereas the AFRES WC-130J crews typically often only have one shot at sampling the max wind during an eyewall penetration, and if the sonde fails on its way down, the opportunity to collect boundary layer and near-surface data on that pass is lost.

NOAA 43 released 36 sondes during its landfalling TC experiment (see Figure 1 for the flight path). Only one was released into the eye and only three others failed or could not be processed (an excellent sonde performance rate) so there were 32 available to examine surface winds. The first seven dropped into eyewall regions, as well as the first three dropped into rainbands, all successfully coded surface winds. Of those that did not receive sufficient satellite signals all the way down to the surface, most did code winds very close to the water (with "LAST WIND" remarks averaging around 15 meters on eight drops and only one losing GPS wind signals as high as 242 meters above the surface). The strongest surface winds measured were 101 knots over the Mississippi Delta, south of Pilottown, at 1034 UTC. That sonde recorded mean boundary layer (MBL) winds of 124 knots with maximum winds of 138 knots approximately 350 meters above the surface within an area of strong convection in the eastern eyewall (see Figure 2 from 1033 UTC). It is difficult to determine using reflectivity imagery, at this large a distance from the radar site at Slidell, whether the sonde may have emerged slightly into the eye just before reaching the surface

About 2.5 hours later, at 1306 UTC, NOAA sonde #053116061 measured winds just south of Pascagoula of 63 m/sec (123 knots or 142 MPH) approximately 300 meters above the surface. That sonde failed to transmit any more winds below 241 meters (at which time winds were 112 knots or 129 MPH). This release was made just inside of a very strong convective band associated with the outer eyewall that was sweeping across Jackson County MS. However, it apparently fell into the stratiform rain found in the moat between this and another intense rain band just to the west as seen in Figure 3 from the Mobile radar site at 1305 UTC.

Only a few of the NOAA and AFRES sondes, while they may have been released into the strongest band of winds and highest reflectivity at flight level (or just inboard of these features as a technique to take advantage of the slope of the eyewall to sample the strongest near-surface winds) appear to have fell through the strongest areas of convection closer to the surface. This can be seen by examining the vertical velocity (fall rate). Being retarded by a parachute, sondes normally fall at a rate of 12-13 m/sec between 700 mb and the surface when encountering neutral buoyancy.

AF306 and AF300 released a total of 11 sondes into eyewalls and max wind bands that were useful in surface wind estimation. Most lost their GPS wind signal at much higher altitudes above the surface than the newer NOAA UBLOX sondes that the Air Force now also uses. For example, the release by AF306 at 1346 UTC reported no winds below 405 meters. A few did manage to sample winds deeper into the boundary layer. The 0857 UTC release into the northern inner eyewall (see Figure 4 from the Slidell radar at 0859 UTC) that splashed down at 0901 UTC about 25 miles south of Buras, LA (near where the center of the eye crossed the coast about two hours later) showed MBL winds of 129 knots with easterly winds of 127 knots as its final wind reading at 85 meters. A plot (see Figure 5) of vertical velocity (fall rate in meters per second) can provide a crude proxy for the intensity of the convection as updrafts and downdrafts disrupt what is normally a fall rate of around 13 m/sec at 700 mb that slowly decreases with the increasing air density to around 12 m/sec by the time the sonde reaches the surface (see Figure 6 as an example of a drop into the smooth air of the eye at 1055 UTC). Figure 5 clearly shows that the 0857 UTC sonde was dropped into an area of significant turbulence, with the fall rate swinging from almost 19 m/sec at 855 mb to only 6.63 m/sec at 895 mb. However, below 900 mb the fall rate settled down generally to remain between 11 and 14 m/sec. This suggests the last 300 meter layer was relatively smooth. Also, when compared to the eye drop, it was certainly a rough three minute ride, however, the magnitude and number of updrafts and downdrafts pale in comparison to the extreme fluctuations that were seen in many of the sonde releases done the previous morning that clearly "nailed" the strongest near-surface convective band on the innermost edge of what was, at that time, a unitary eyewall structure (see Figure 7 from 1421 UTC on Sunday 28 August). Figure 7 shows that when Katrina was a Category Five hurricane 18 hours earlier, with 166 knot MBL winds and 158 knot mean winds in the layer from 63 to 213 meters, that there were extraordinary fluctuations in fall rate with a half-dozen instances of the sonde suspended to a fall rate near zero with one extreme updraft occurring only 33 meters above the surface. Finally, it should be noted that the SLP of this 0857 UTC Monday morning eyewall sonde south of Buras was 923 mb, or only six millibars different from the eye center drop done five minutes earlier that measured a 917 mb SLP and four knot winds. This suggests the 0857 UTC sonde was probably released from 700 mb a few moments too early and just inside the radius of maximum surface winds below.

At 1205 UTC a sonde was released by AF300 just east of St Bernard Parish that was carried from the northeast into the northern eyewall (see Figure 8 from the 1206 UTC Slidell radar showing the impact location at 1209 UTC just east of Delacroix, LA) recorded an MBL of 122 knots, a max of 134 knots at 892 mb (385 meters aloft), and a final wind value of 106 knots at 34 meters. Examination of the fall rates of this sonde (see Figure 9) suggest it was released embedded within convection but slightly outboard of the maximum surface wind band. Only one significant updraft was encountered at 788 millibars with a relatively smooth ride below 850 mb.

Another drop by AF306 into that same northern eyewall, 34 minutes later at 1239 UTC, that splashed just north of St Bernard Parish at 1242 UTC (see Figure 10 from the 1238 UTC Slidell radar), showed as much as 133 knots at 900 mb and still maintained 129 knots down at the 923 mb level (about 250 meters) but only 92 knots at 17 meters as the most intense convection near the surface associated with the innermost eyewall was still just a little further to the south and southeast of this splash point.

4. COMPARISON OF FLIGHT LEVEL RECON DATA AND WSR-88D RADIAL VELOCITY WITH A DROPSONDE OVER PASS CHRISTIAN

AF300 (flying mission 2212A) flew at 700 mb from east to west, paralleling the MS coast just prior to the eye coming ashore in the marshes of southernmost Hancock County. At 1422 UTC the crew measured 30 second average winds of 125 knots at flight level seven miles southeast of the Long Beach/Pass Christian beaches. Flight level winds exceeding 110 knots were measured continuously for eight minutes suggesting a 25 mile wide band of high momentum air flowing above the communities around Henderson Point. A sonde was released at 1422 UTC in the Mississippi Sound at that point southeast of Pass Christian. This sonde found winds of 68 m/sec (133 knots or 153 MPH) about 350 meters above the beach as the instrument was carried onshore and landed at 1425 UTC a mile inland in the Timber Ridge neighborhood (see Figure 11 from the Mobile radar site at 1427 UTC showing the landing spot was just inside the band of intense convection into which it was released three minutes earlier (see Figure 12 from 1421 UTC to see the release point). Prior to reaching the surface, winds dropped off rapidly to 49 m/sec at 77 meters (the last wind reading). It should be noted that this was NOT inside the eye as Figure 13, from shortly thereafter at 1443 UTC, shows even more intense convection along the innermost edge of the inner eyewall moving into Pass Christian from the west. Several studies show the 60-70 m/sec winds seen in the boundary layer in these and other dropsondes were consistent with radial velocity-derived wind speeds 0.5 km above the MS coast.

5. DISCUSSION

Examination of the dropsondes released around landfall of Katrina suggest that because few of them appear to have "nailed" the exact location of the most intense convectively generated surface winds (as noted above, there were several near-misses), MSW somewhat stronger than the 100 knots seen in SFMR surface wind readings cannot be ruled out. This was acknowledged in the NHC Katrina Report as they determined MSW around the first landfall in LA at 1100 UTC to be 110 knots and the second 1500 UTC landfall in Hancock County MS at 105 knots. There is no clear and compelling evidence to support stronger surface winds in the dropsonde data set. However, examination of reflectivity and radial velocity WSR-88D data from Slidell and Mobile would suggest that while the convective appearance of Katrina's core was certainly much more chaotic and fractured than what was seen only 12 hours earlier, the intensity of the individual convective elements was sufficient to have caused localized winds in excess of the NHC Report values for brief intervals. Mechanisms suggested by Blackwell, Fitzpatrick and others where a combination of mesocyclones and collapsing thunderstorm cores may have been locally enhanced by introduction of dry mid-level air wrapping around from the southwest quadrant of the storm. While this entrainment of low Θ_e air certainly weakened the parent vortex, it may have aided in enhancing the momentum available to wet microburst downdraft and outflow events. While some of these events should have been better captured by the SFMR (recent flights into Humberto in 2007 clearly show the SFMR has the ability to identify surface winds emanating from such localized convective scale features), the calibration and/or SST/salinity setting issues discussed in Section 2 make it possible that there was some under representation of the surface wind field over the Mississippi Sound and adjacent waters. As is the case with the dropsondes, the strongest winds may also have simply been missed by not being overflown.

Figure 1 Plot of the flight path of NOAA 43 during their Landfalling TC experiment on the morning of 29 August 2005:

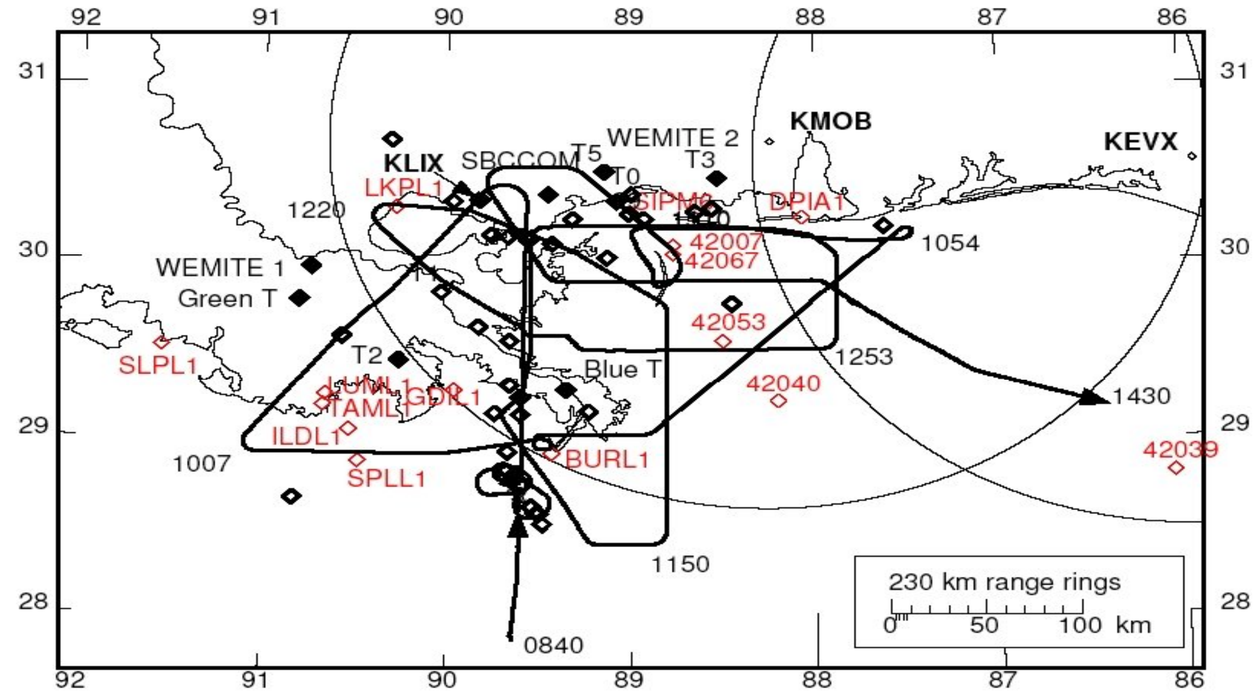
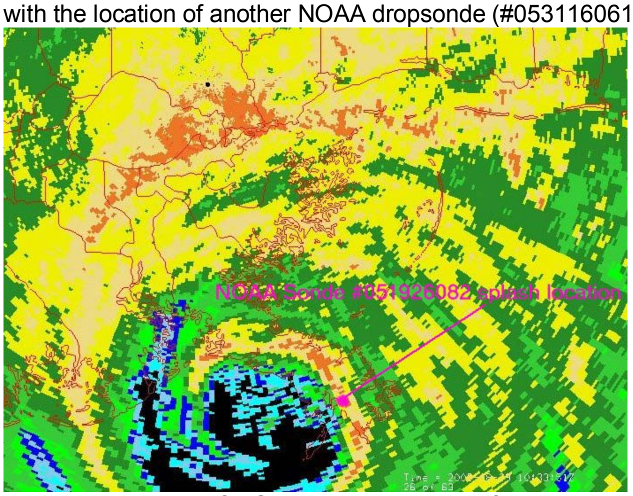


Figure 2 (below left) Slidell radar image from 1033 UTC with the location marked of a NOAA dropsonde which landed in the Mississippi River Delta south of Pilottown, LA. **Figure 3 (right)** Mobile NEXRAD image from 1305 UTC with the location of another NOAA dropsonde (#053116061) marked just south of Pascagoula, MS



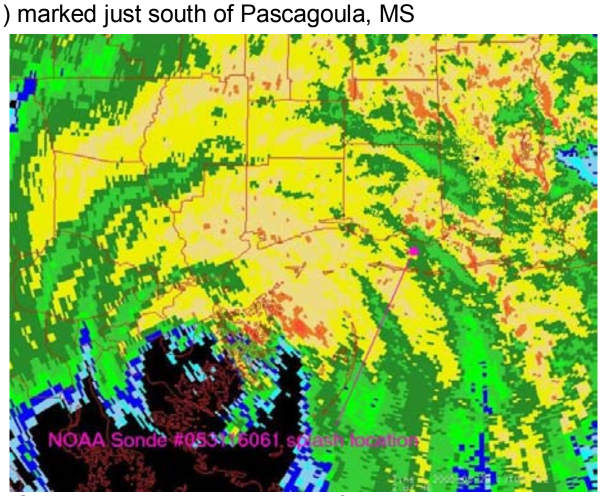
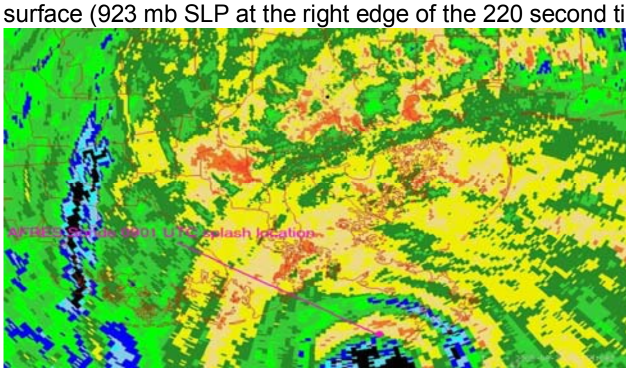


Figure 4 (below left) Slidell radar imagery from 0859 UTC with the location marked of AF306 dropsonde which splashed into the Gulf at 0901 UTC 25 miles south of Buras, LA. **Figure 5 (right)** Vertical velocity (fall rate) of that sonde in meters per second (released at 0857 UTC from 700 millibars (left edge) with fall rate traced rightward to surface (923 mb SLP at the right edge of the 220 second time series)).



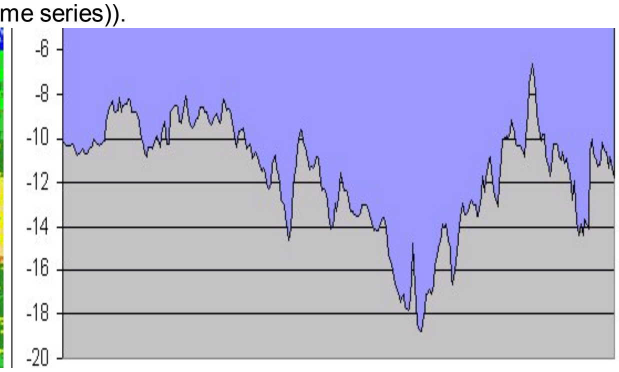
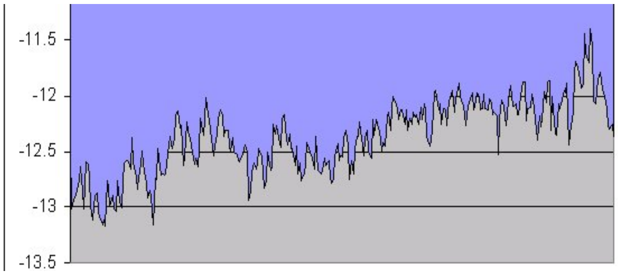


Figure 6 (below left) For comparison purposes: The fall rate of a sonde released at 1055 UTC into the center of the eye (showing smooth air and a relatively predictable fall rate that begins at around 13 m/sec at 700 mb and slows to around 12 m/sec as it reaches greater air density approaching the surface). **Figure 7 (right)**: In contrast to both Figure 5 and Figure 6, the fall rate of a sonde launched into the extreme conditions of Katrina's northern eyewall at 1421 UTC on the previous morning (29 August) showing wild fluctuations from near-zero (the sonde nearly suspended briefly by an updraft on six occasions) to almost -16 m/sec in downdrafts. This included a significant updraft, altering the fall rate by 8.7 m/sec over a 2.5 second interval, only 33 meters above the surface (far right).



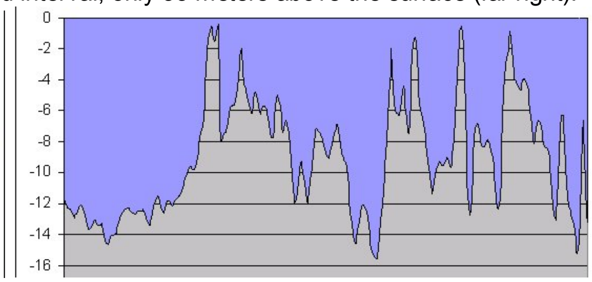
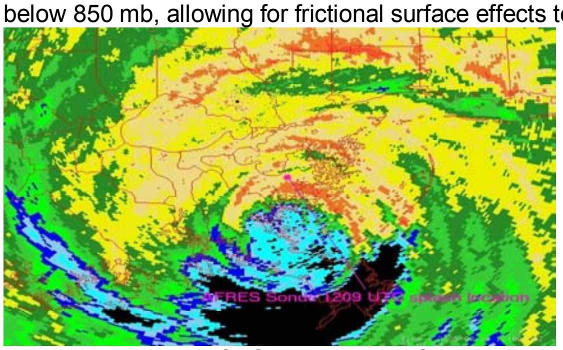


Figure 8 (below left) Slidell radar image from 1206 UTC with the impact point of the AF300 sonde released at 1205 UTC over the Chandeleur Sound that was carried ashore and landed at 1209 UTC in St Bernard Parish east of Delacroix. Wind reduction from 134 knots at 892 mb down to 106 knots at 931 mb (34 meters), along with the plot of fall rate shown in **Figure 9 (right)**, support the notion that the sonde encountered the strong inner eyewall convection seen in the corresponding reflectivity image when released at flight level, but spiraled into lighter, more stratiform rain below 850 mb, allowing for frictional surface effects to significantly reduce the near-surface wind measurements.



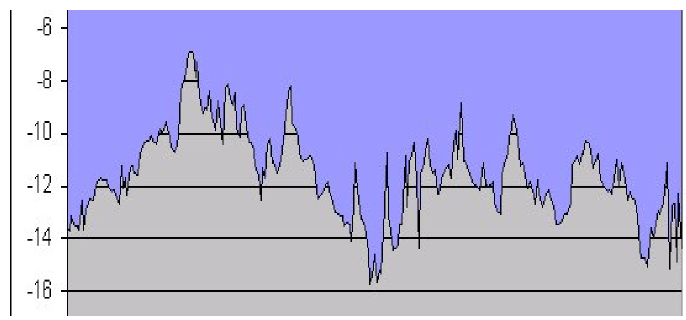
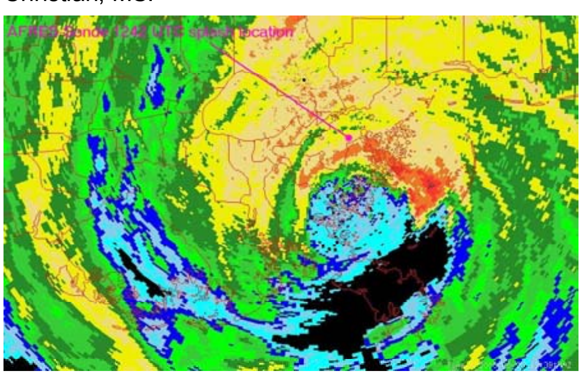


Figure 10 (below left) Slidell 1238 UTC imagery showing the location of the AF306 sonde released at 1239 UTC that landed in Lake Borgne at 1242 UTC, again falling just shy of the most intense surface convection a few miles to the south and southeast**. Figure 11 (right)** from the Mobile WSR-88D site at 1427 UTC with the 1425 UTC impact point of the AF300 sonde released at 1422 UTC shown in the Timber Ridge neighborhood about a mile inland over Pass Christian, MS.



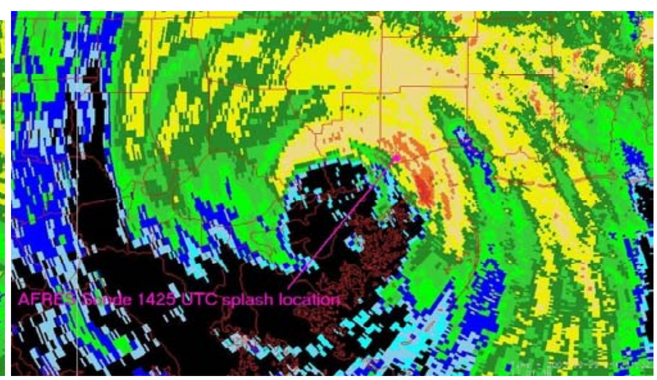
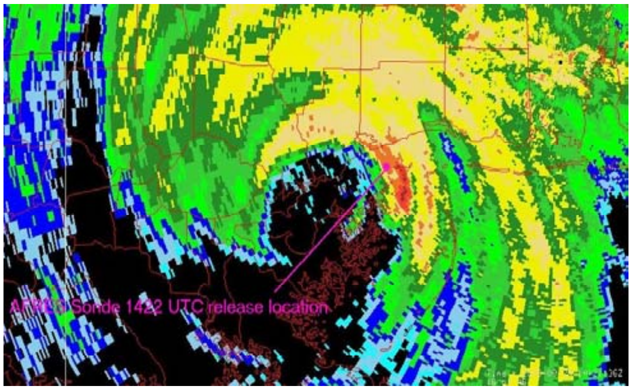


Figure 12 (below left) Mobile radar imagery from 1421 UTC showing the location of the 1422 UTC release amidst an intense convective band associated with the middle portion of the inner eyewall about seven miles southeast of Pass Christian **Figure 13 (right)** Mobile radar imagery from 22 minutes later showing the explosion of a convective ring along the inner edge of that eyewall (seen in Figure 12 as a narrow line developing about 15 miles west of the release point) that pushed into Pass Christian 18 minutes after the sonde landed.


Sonde 1422 UTC release location