29th AMS Conference on Hurricanes and Tropical Meteorology, Tucson, AZ
13B.2 Thursday May 13, 2010

Analysis of data gathered during a NOAA WP-3D penetration of Hurricane Felix (2007) during an episode of extreme intensity

Corresponding author: Richard G. Henning, Flight Director, NOAA Aircraft Operations Center MacDill AFB, FL
Email: richard.henning@noaa.gov

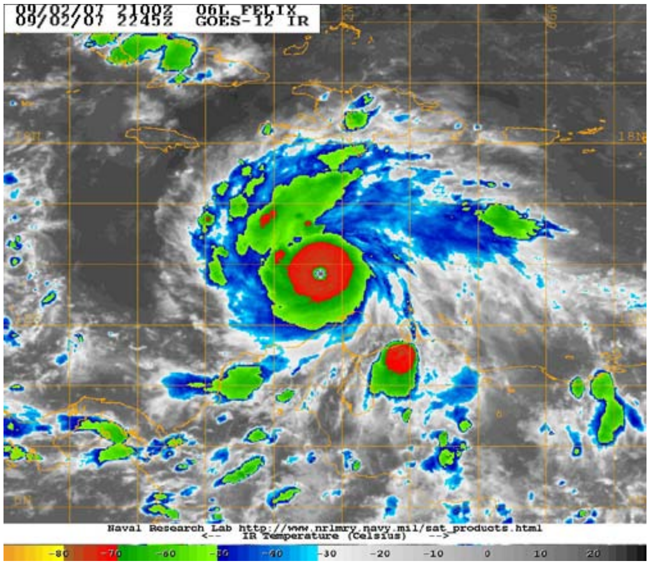
Co-Authors: Jessica Williams (presenting), Paul Flaherty, Jack Parrish, A. Barry Damiano, Ian Sears, LT Jackie Almeida, LCDR Nancy Ash, Dr Jim McFadden and Tom Shepherd (Retired)– NOAA Aircraft Operations Center

1. Introduction

On the afternoon of 2 September, 2007, the NOAA Aircraft Operations Center (AOC) WP-3D crew of N42RF along with embarked scientists from the AOML HRD (Atlantic Oceanographic and Meteorological Laboratory Hurricane Research Division), NESDIS (National Environmental Satellite Data and Information Service) and the University of Massachusetts, prepared for takeoff from their forward deployed operating location in St Croix, USVI for a research mission into Hurricane Felix. The process of rapid intensification (RI) was already underway in Felix with a 37 millibar (mb) drop in MSLP (minimum sea level pressure) in the preceding 24 hours ending at 1800z accompanying an increase in best track maximum sustained winds from 31 m/s to 59 m/s (60 to 115 knots). A USAF Reserve WC-130J had left the storm having seen a 24 mb drop during their flight with 67.9 meters per second (m/s) (132 knot) flight level winds measured at 700 mb in the eyewall and 65.9 m/s (128 knots) seen at the surface with a dropsonde. NHC Forecasters warned in their Forecaster Discussion issued prior to takeoff of the NOAA aircraft that the intensity forecast might be too conservative and continued RI to Category 5 status was a definite possibility.

During their first eyewall penetration, the crew and scientists onboard N42RF, encountered extreme turbulence (including an updraft of +26.9 m/s vertical velocity and a downdraft of -14.3 m/s that overstressed the aircraft with 4 negative Gs) and heavy graupel. This necessitated early termination of the mission and a return to St Croix. Peak one second averaged flight level (FL) winds of 82.8 m/s (161 knots), a peak near-surface quality controlled dropsonde wind reading of 95.6 m/s (186 knots), and peak SFMR surface winds of 163 knots prompted NHC to immediately upgrade Felix to 145 knot maximum sustained wind Category 5 status. Further analysis of data from this mission by NHC in the following weeks lead to the Best Track maximum intensity of Felix being bumped up to 150 knots.

While infrared imagery (see **Figure 1a**, at the top of Page 2 on the left) shows a solid ring of -70C temperatures surrounding a perfect eye (the classic Dvorak Cat 4 appearance) there was no evidence of overshooting tops (which would have appeared as darker red or yellow cloud top temperatures of -80C or colder). Visible imagery (see **Figure 1b** on the right) shows the classic pattern of gravity waves emanating outward from the core along the top of the CDO, suggesting vigorous outflow of mass at the top of the storm, a classic symptom of Pacific typhoons undergoing RI into supertyphoons or Atlantic storms intensifying into Category 5 systems, but still no overshooting towers in the eyewall.



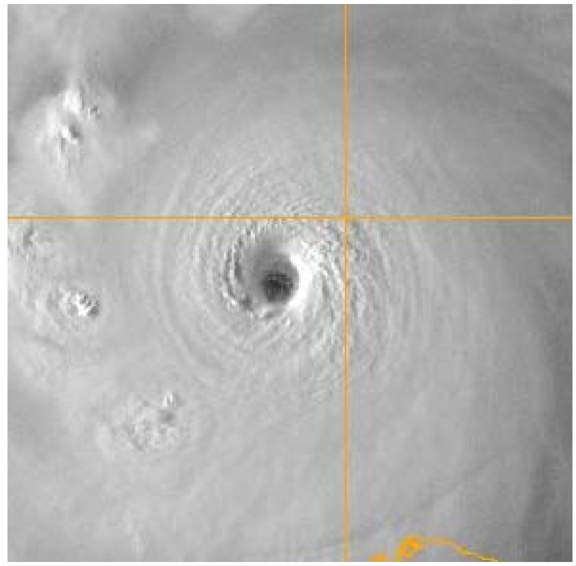


Figure 1a (left) NRL GOES IR imagery of Felix from 2245z 2 September 2007 and **Figure 1b** (right) from 2145z, the last good visible image prior to sunset.

There was no clear indication in either satellite image to suggest the presence of abnormally intense convection, supercells, or mesocyclones embedded in the eyewall. Penetration into a Category 4 hurricane in the process of RI would warrant expectations of a rough ride inbound and a great visual stadium effect once in the eye but not necessarily the extreme turbulence, frequent lightning, and heavy graupel experienced by N42RF in Felix at its 700 mb flight level or the extraordinarily high wind vales measured at or near the surface measured by dropsondes and the Stepped Frequency Microwave Radiometer (SFMR).

As the aircraft approached the NE eyewall after takeoff and a short ferry from St Croix, red colors (39-41 dBz) can be seen on the Lower Fuselage (LF) Radar (see **Figure 2** below) in a solid ring around the eye but no colors associated with more extreme convection are evident as the crew began the eyewall penetration:

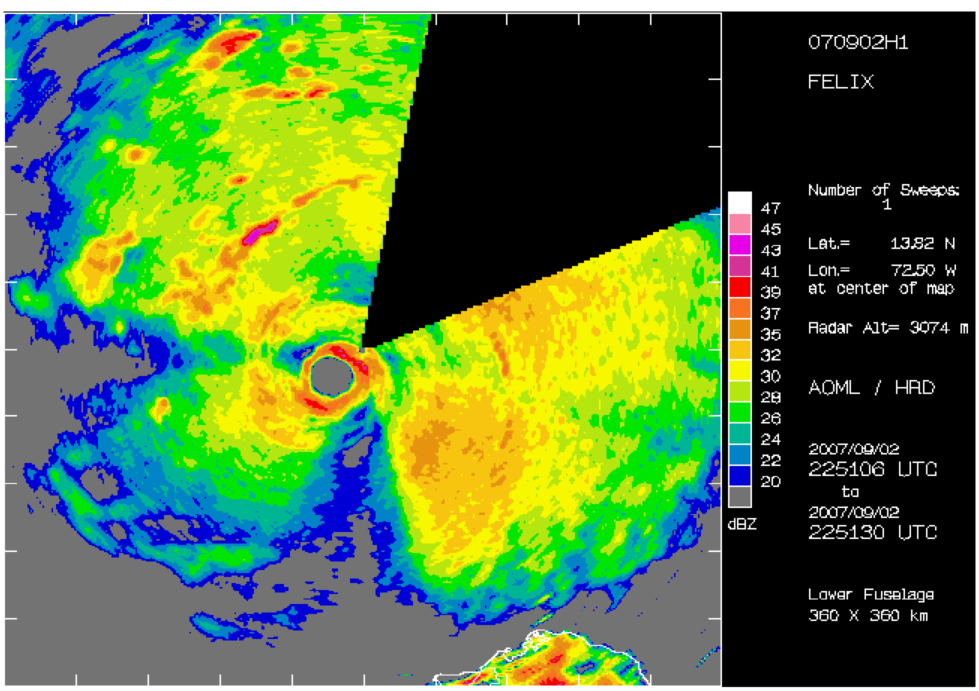


Figure 2: LF reflectivity gathered in a 24 second sweep at 2251z during eyewall penetration near 700 mb

2. N42RF Penetration through the Northeast Eyewall of Felix

Upon eyewall penetration, events started to happen very quickly. By 22:50:32z FL winds had reached 50 m/s (97.2 knots). At 22:51:18z they reached 60 m/s (116.7 knots). FL winds appeared to peak at 22:51:58z at 69.7 m/s (135.5 knots). It is possible this is about what would have been the maximum winds if not for the embedded convective structure lying just ahead (see the time series of FL winds: **Figures 3 and 4** on Page 4).

Two seconds later, at 22:52:00z the aircraft encountered what is suspected to have been an intense convective scale feature embedded in the mesoscale eyewall. The first indication was a -13.9 m/s vertical wind downdraft (see **Figure 5** on Page 5) accompanied by the onset of extreme turbulence, abnormally frequent lightning and extremely heavy precipitation that eventually included large amounts of graupel. After decreasing for several seconds from that earlier maximum, winds sharply increased again passing through 70 m/s (136.1 knots) seven seconds later (at 22:52:07z). Fourteen seconds later (at 22:52:21z) FL winds reached 80 m/s (155.5 knots). Three seconds later, at 22:52:24z, the aircraft encountered the +26.9 m/s vertical wind velocity updraft that put 4 positive Gs on the aircraft.

Three seconds further into penetration of this feature, at 22:52:27z, FL winds peaked at a one second average of 82.8 m/s (161 knots) then rapidly diminished back down through 70 m/s two seconds later and down below 60 m/s after one more second. Two more seconds later (at 22:52:32z) the highest value of FL equivalent potential temperature (theta e or Θ_e) during the mission (370.2 Kelvin) was measured (see **Figure 6** on Page 5). At 22:52:37z, the strongest downdraft (with -14.3 m/s vertical winds) was encountered causing 4 negative Gs to be recorded on the cockpit accelerometer.

While passing through this convective feature, the extrapolated surface pressure fell 26.4 millibars in 32 seconds (across a distance of about 2.9 kilometers (1.8 miles) travelled over the ocean). By 22:52:43z extrapolated surface pressure had plunged down to 947.2 mb and would continue to fall through the remainder of the eyewall but not at such an extreme rate.

After the plane broke out of the embedded convective feature and winds dropped sharply, winds briefly surged back up to 60.6 m/s (118 knots) near the innermost edge of the eyewall but then began a rapid decline as the plane reached the eye (with FL winds dropping to below 25 m/s). With the slope of the eyewall now below the plane, maximum surface winds were measured by the SFMR as an average of 83.9 m/s (163 knots) for the 30 second interval ending at 22:53:00z.

At 22:54:30z N42RF reached the center of the eye for the first time where the extrapolated surface pressure was down to 935.4 mb, 21 millibars lower than what the USAF plane had measured on their last fix a few hours earlier. The crew orbited in the eye seven times trying to assess the situation and the condition of their aircraft. On their last pass through the flight level center, they released the eye sonde which found 936 mb at the surface but with 24 knots of wind at splashdown. Using NHC's rule of thumb that for each 10 knots of wind on the eye sonde at splashdown, you can generally subtract a millibar from what it records as an estimate for the true minimum pressure, this suggests the sonde missed the true surface center by about 2.5 millibars. In the eye the maximum flight level temperature at 700 mb was 26C with a dew point as low as 4C (a 22 degree dew point depression indicating extreme subsidence was taking place).

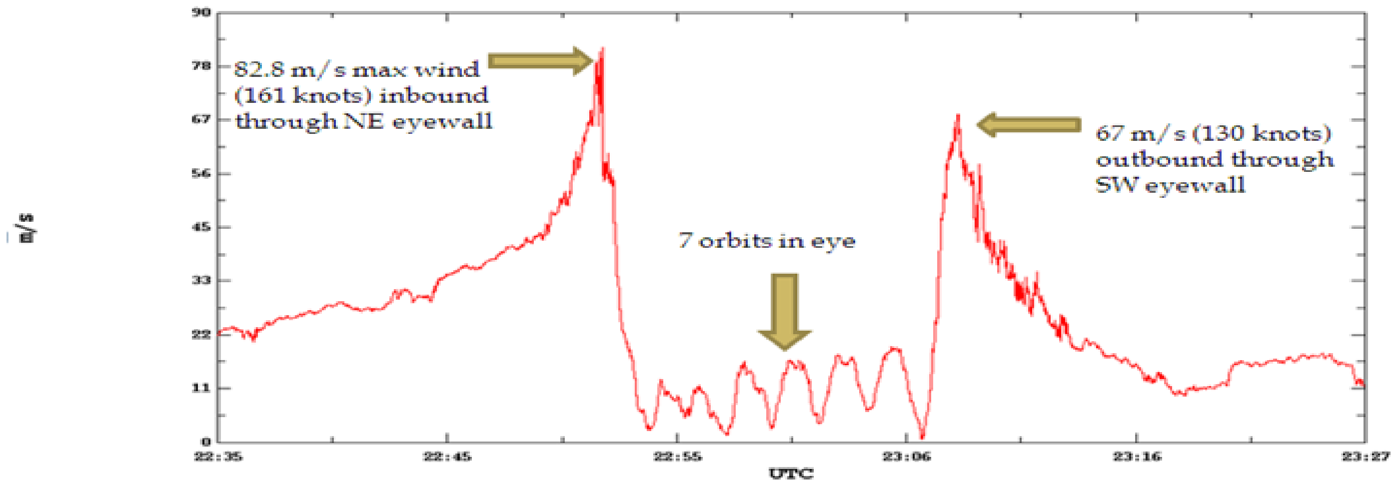


Figure 3: Profile of 700 mb FL winds from 22:35z to 23:37z as N42RF passed through the northeast eyewall, then orbited seven times in the eye, before exiting the storm out the southwest eyewall of Hurricane Felix on 2 September 2007. Note how the wind profile looks very symmetrical comparing the two eyewall penetrations except for the exaggerated spike in the NE eyewall which added 25 extra knots within the embedded convective feature. Examining Figures 3 and Figure 4 below (a blown up view of the NE eyewall) the slope of the wind increase up to the first peak of 69.7 m/s at 22:51:58z, and then down through the rest of the eyewall and into the eye, is typical of what is seen in an intense hurricane (and matches very closely with the SW eyewall). The abnormal pattern of rapidly fluctuating wind speeds, containing the 82.8 m/s absolute peak value, represents the convective feature superimposed onto the more gently sloping mesoscale wind field.

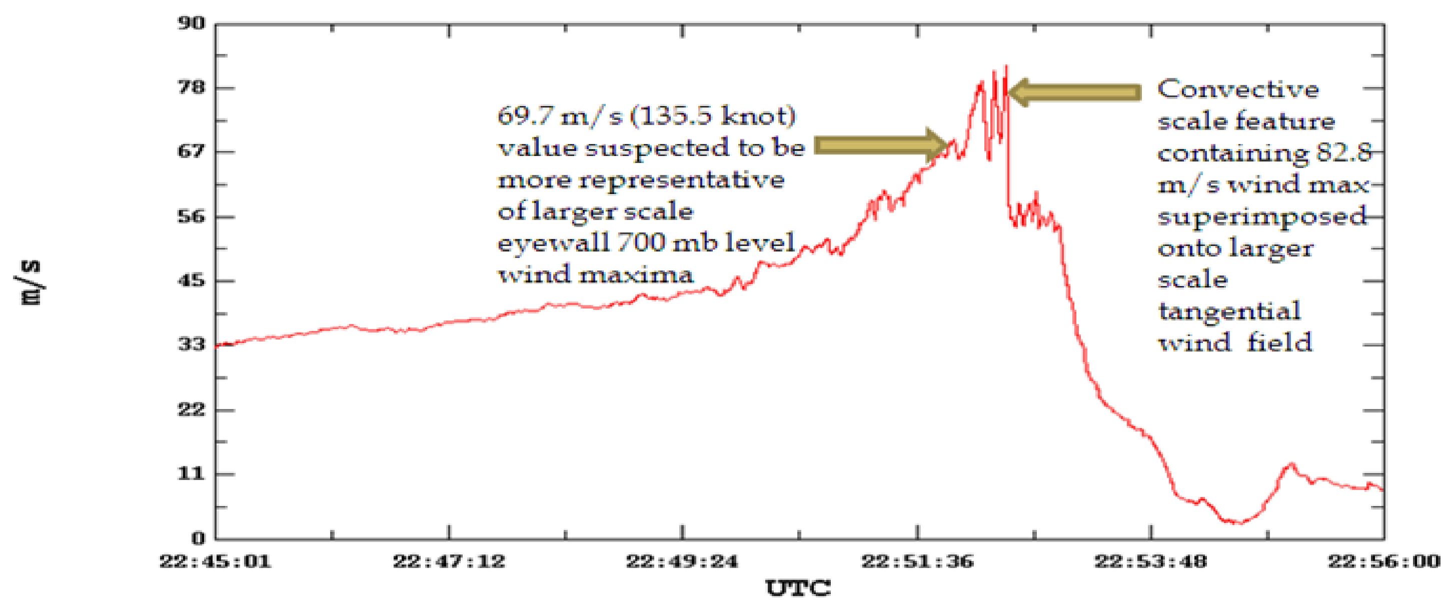


Figure 4: A higher resolution plot of FL winds in the northeast eyewall from 22:45z to 22:56z.

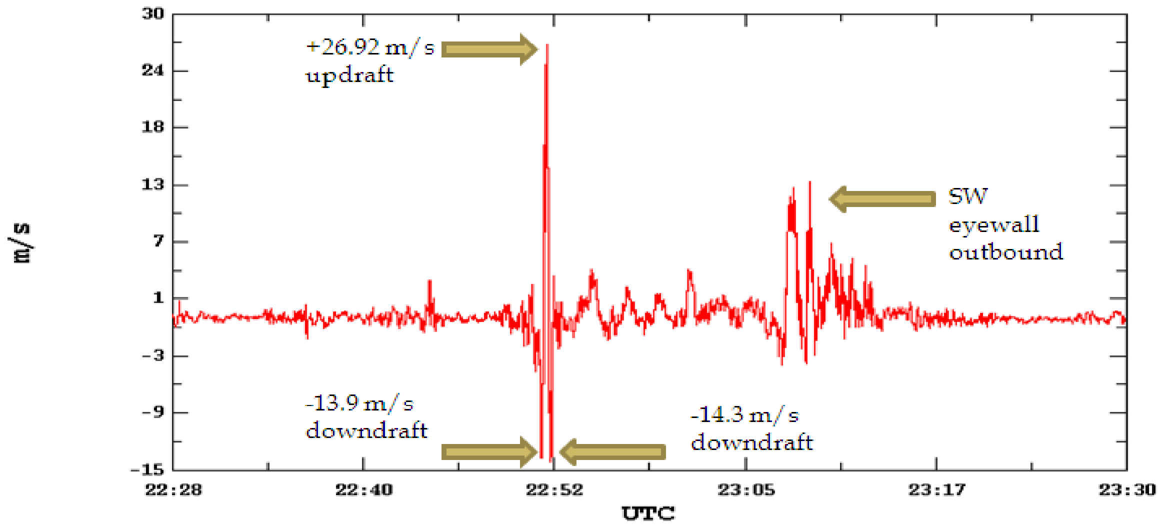


Figure 5: Vertical velocities encountered by N42RF during the penetrations of the NE and SW eyewalls as depicted earlier in Figure 3.

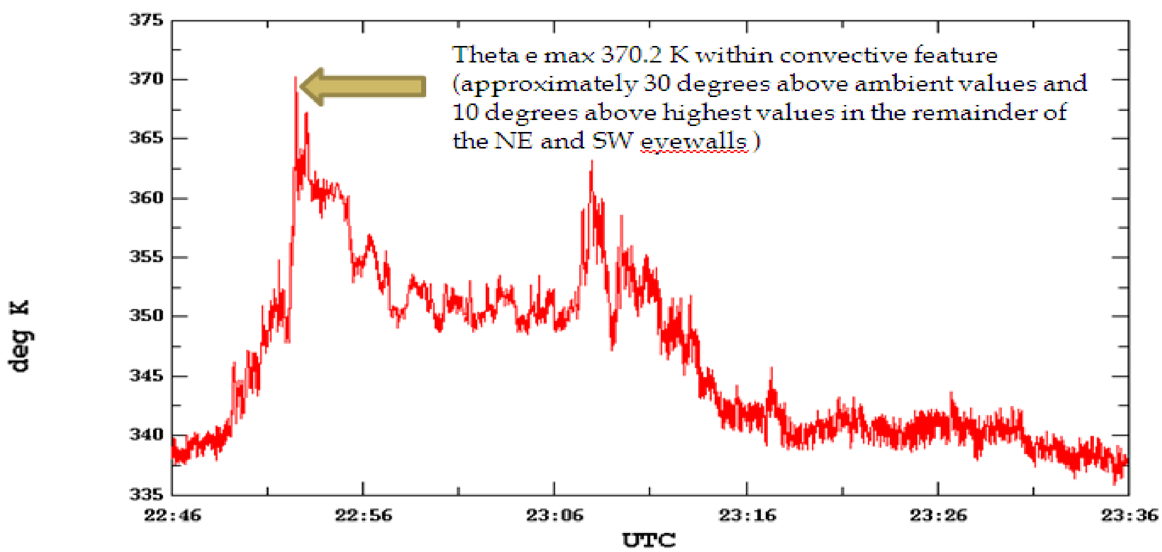


Figure 6: Profile of flight level equivalent potential temperature (theta e or Θ_e) across Hurricane Felix from the northeast eyewall to the southwest eyewall during the eye penetration shown in Figure 3.

3. Eyewall Dropsonde Data

At 22:53:07z, the Flight Director Tom Shepherd called for the release of the dropsonde (to capture the maximum winds below as close as possible to the surface given the slope of the eyewall). The sonde had an extremely wild ride down to the water. It recorded peak QC'd winds (from Editsonde) of 95.6 m/s (186 knots) at the 929 mb level (just over 90 meters above the surface). The highest raw winds in the D file were 102 m/s (198 knots) measured 11 seconds later (see **Figure 7** on Page 6). This value didn't make it through the QC algorithm in spite of the fact that it was based off of 10 GPS satellites. Just before splashdown the sonde was blown radially into the eye and the last QC'd wind (at 66 meters) dropped to only 19.5 m/s (38 knots).

The first eyewall sonde was released in the northeast quadrant and spiralled counterclockwise with the tangential wind field into the northwest quadrant (splashing almost 11 kilometers from where it was released). The outbound sonde, released at 23:08:05z into the southwest eyewall spiraled all the way from the SW to S to SE to E quadrants (staying in the eyewall the whole time and splashing almost 14 kilometers from its release point).

By the time the second eyewall sonde was close to the surface it had been blown around to the eastern side of Felix and recorded QC'd 36 meters winds that were southerly at 95.7 m/s (186 knots). Winds in the lowest 150 meters sampled (from 186 meters to 36 meters above the surface) averaged 185 degrees at 88.0 m/s (171 knots).

Figure 8 (on Page 7) shows the fall rate (vertical velocity) of the sondes. The canopy which deploys after launch is not a true parachute, but rather simply a means to stabilize the cylindrical instrument (to keep it from tumbling as it falls) and retard its descent rate to better sample each layer it passes though. Significant deviations from the normal fall rate in calm air (typically about -12.5 m/s at 700 mb slowing to around -10 m/s near the denser air at the surface) mark passage through updrafts and downdrafts. **Figure 9** (on Page 8) is a plot of temperatures for both eyewall sondes. The graph shows that while the SW eyewall sonde followed a very typical eyewall temperature and humidity profile (steady lapse rate and saturated), the NE eyewall sonde displayed extreme fluctuations in both temperature and humidity (see the humidity plot **Figure 10** on Page 8).

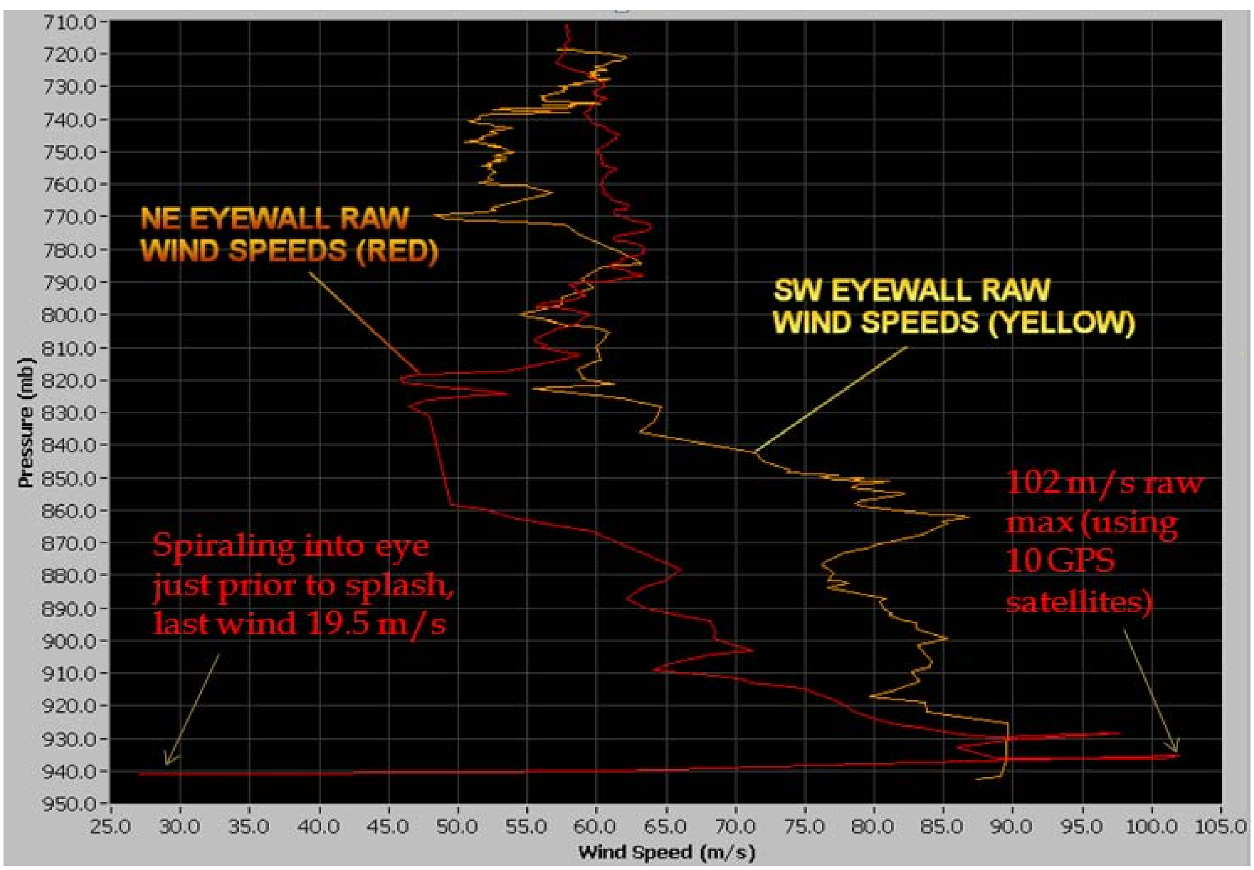


Figure 7: Trace of the raw wind speeds measured by the inbound dropsonde released into the NE eyewall (shown in red which spiraled approximately 90 in azimuth and splashed down in the NW eyewall) and the outbound dropsonde released into the SW eyewall (shown in yellow which spiraled well over 90 degrees and splashed due east of the center).

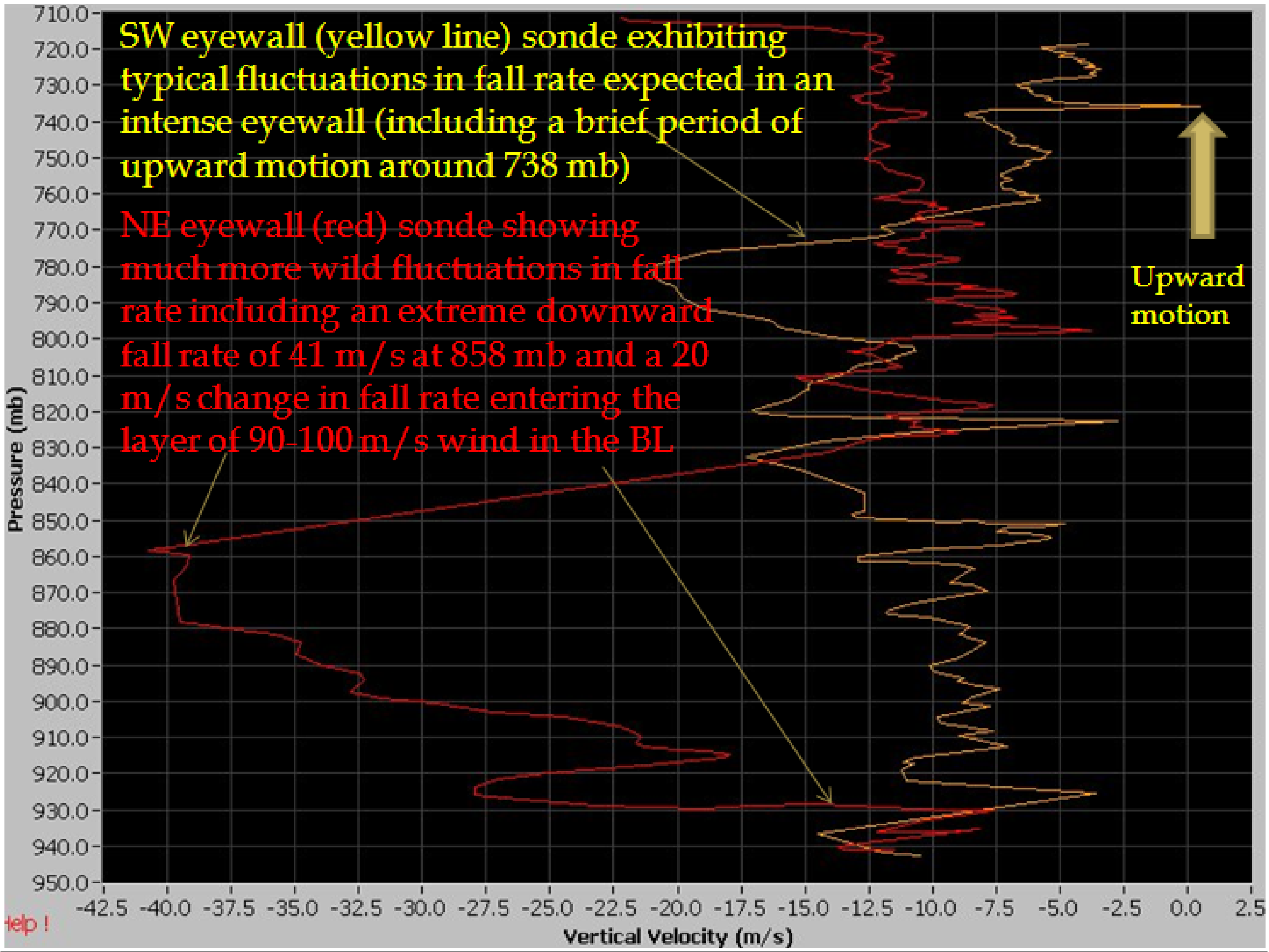


Figure 8: Trace of vertical velocity (fall rate) of the two sondes. The SW eyewall sonde shows what would be expected when dropping into a very intense eyewall with fluctuations in fall rate (including a brief moment of "upsonde" at 738 mb). The NE eyewall sonde fall rate was relatively normal until a huge departure to the left on the graph showing extreme downdrafts as it reached a point just beyond due north of the center falling through 820 mb where very unusual wind direction deviations begin (shown later in Figure 9). The fall rate of -41 m/s at 858 mb is extreme as is the 20 m/s change in fall rate in the boundary layer at around 925 mb as it encountered 90-102 m/s winds.

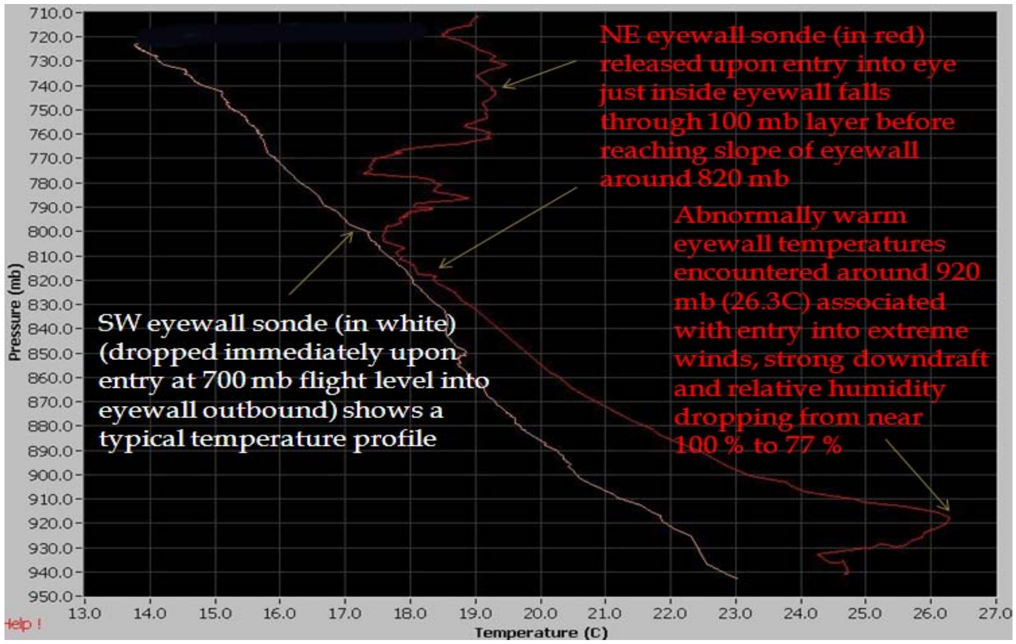


Figure 9: The SW eyewall sonde was released immediately upon the plane entering the SW eyewall at flight level. It also was not radially carried into the eye, as was the NE eyewall sonde, so it remained in the eyewall (or just underneath it in the boundary layer at the end) during its entire descent. The NE eyewall sonde was released after breaking into the eye, taking about 100 mb of fall before intersecting the slope of the eyewall below at 820 mb. It was much warmer the rest of the way down (compared to the second sonde) and peaked in temperature at around 920 mb at 26C (abnormally warm for an eyewall sonde and about 1.5C warmer than when it splashed in the outermost edge of the eye).

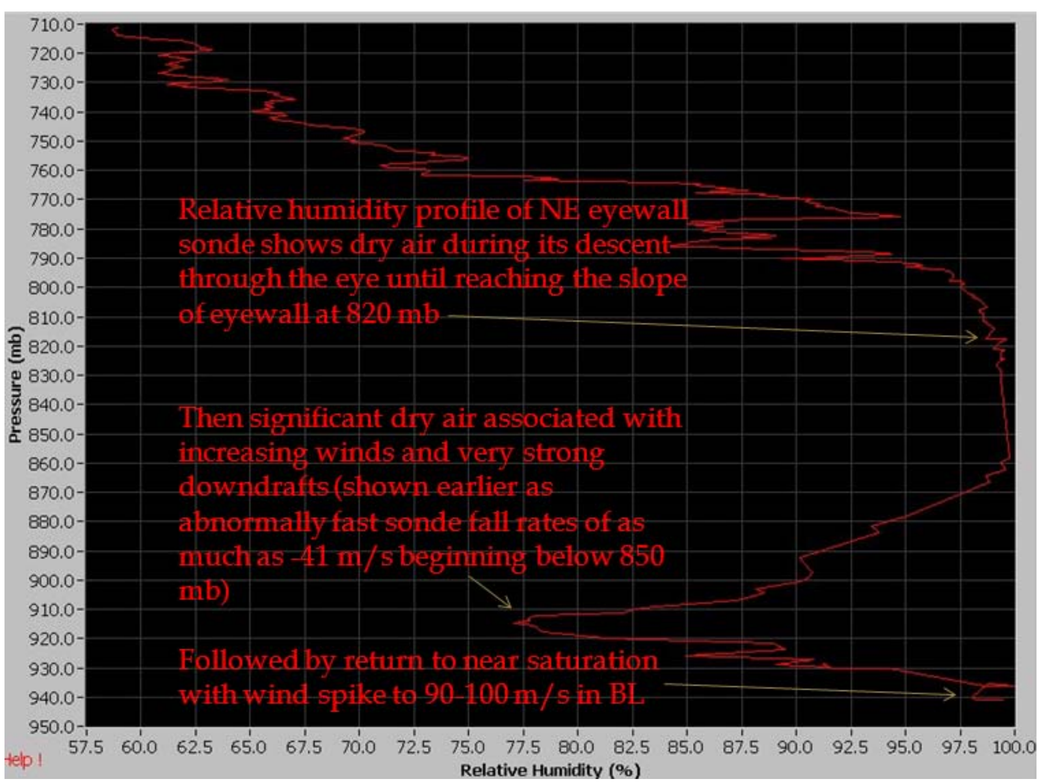


Figure 10 shows the warming seen in Figure 9 was associated with some significant drying where the RH dropped from near saturation at 870 mb to 77 % at 915 mb (in the lowest downdraft layer shown in Figure 8)

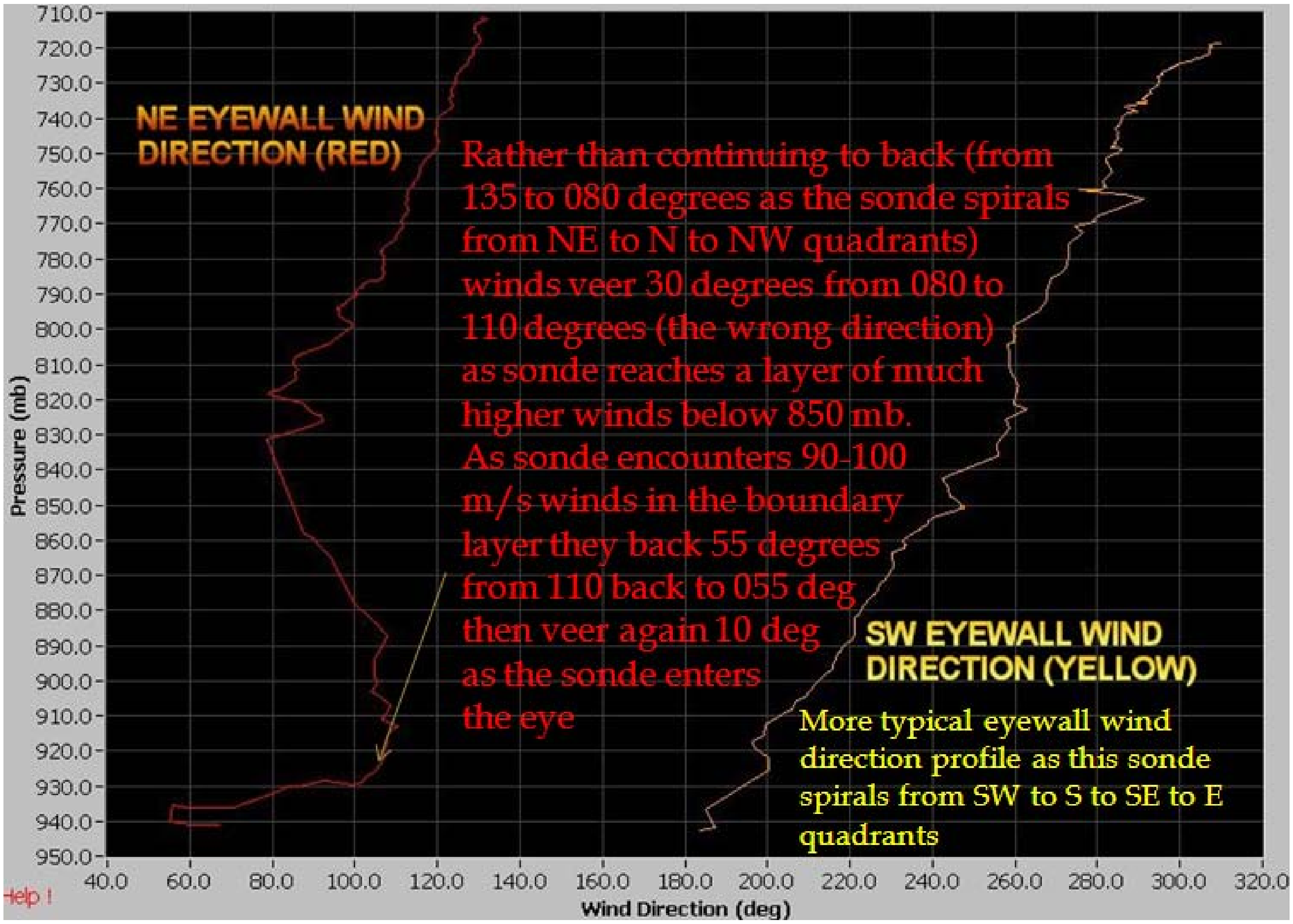


Figure 11 points again to the difference between the NE and SW eyewall dropsondes. This slide shows the plot of wind direction as each sonde fell. Note the SW eyewall sonde (in yellow) shows the expected, steady change in wind direction as it spirals from the SW to S to SE to E quads (staring with NW winds and ending with southerly winds). By contrast, when the NE eyewall sonde spiraled counterclockwise with the tangential winds to a point just past due north of the center (with winds of 080 deg at 820 mb) the wind direction veers briefly between 820 and 825 mb, then upon reaching 830 mb it displays a very deep layer of veering winds (rather than backing) with the wind direction changing the wrong way, veering all the way from 080 to 110 degrees as it fell down to 920 mb. Then as it encountered the extreme winds in the boundary layer, it suddenly backed 55 degrees from 110 to 055 degrees before veering again 10 degrees after it was blown into the eye.

4. Radar Data (all courtesy of John Gamache AOML/HRD)

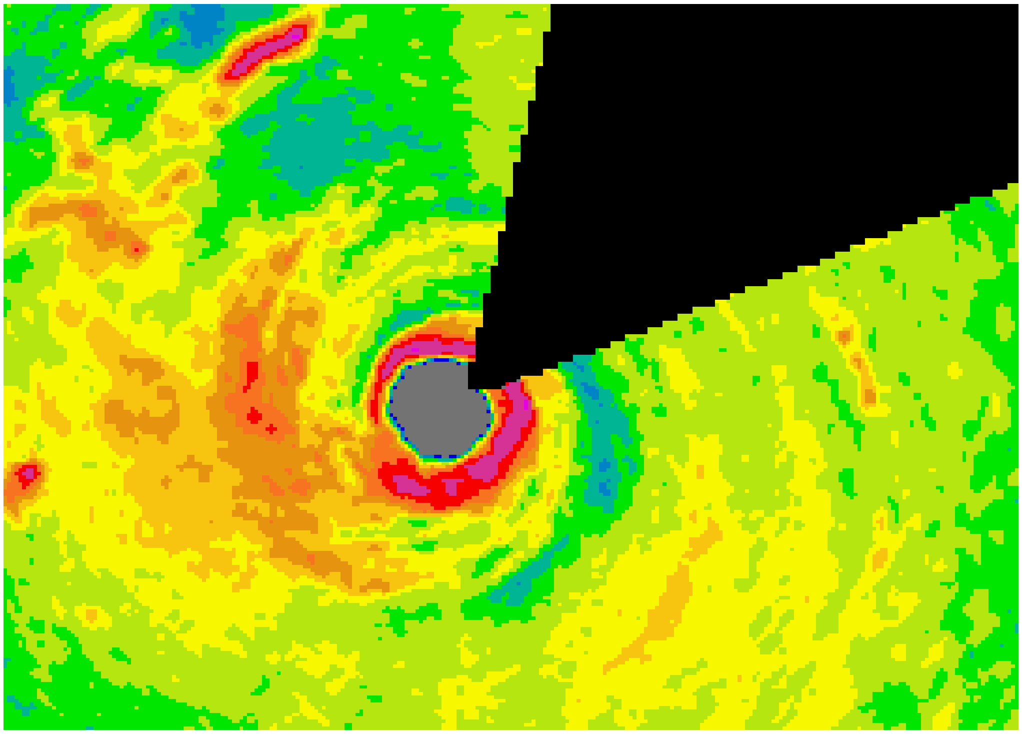


Figure 12: Lower Fuselage radar reflectivity at 2253z just after eyewall penetration. None of the first level of magenta (41-43 dBz shown throughout much of the eyewall) was evident until the plane broke into the eye. The small pixels of second and even third levels of magenta seen in the NE eyewall suggest reflectivity of up to 47 dBz there.

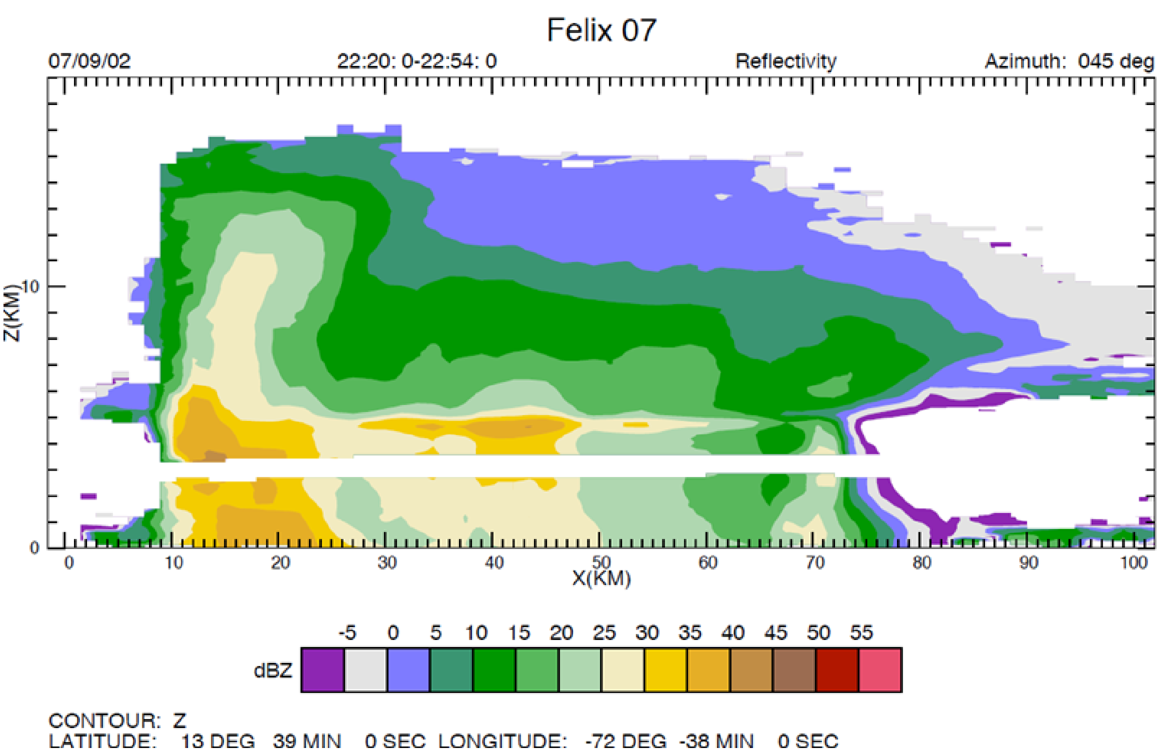


Figure 13: Tail Doppler Radar (TDR) reflectivity imagery showing the 40-45 dBz that N42RF flew through in the northeast eyewall (and up to 15 dBz all the way up at 16.5 kilometers (over 55,000 feet))

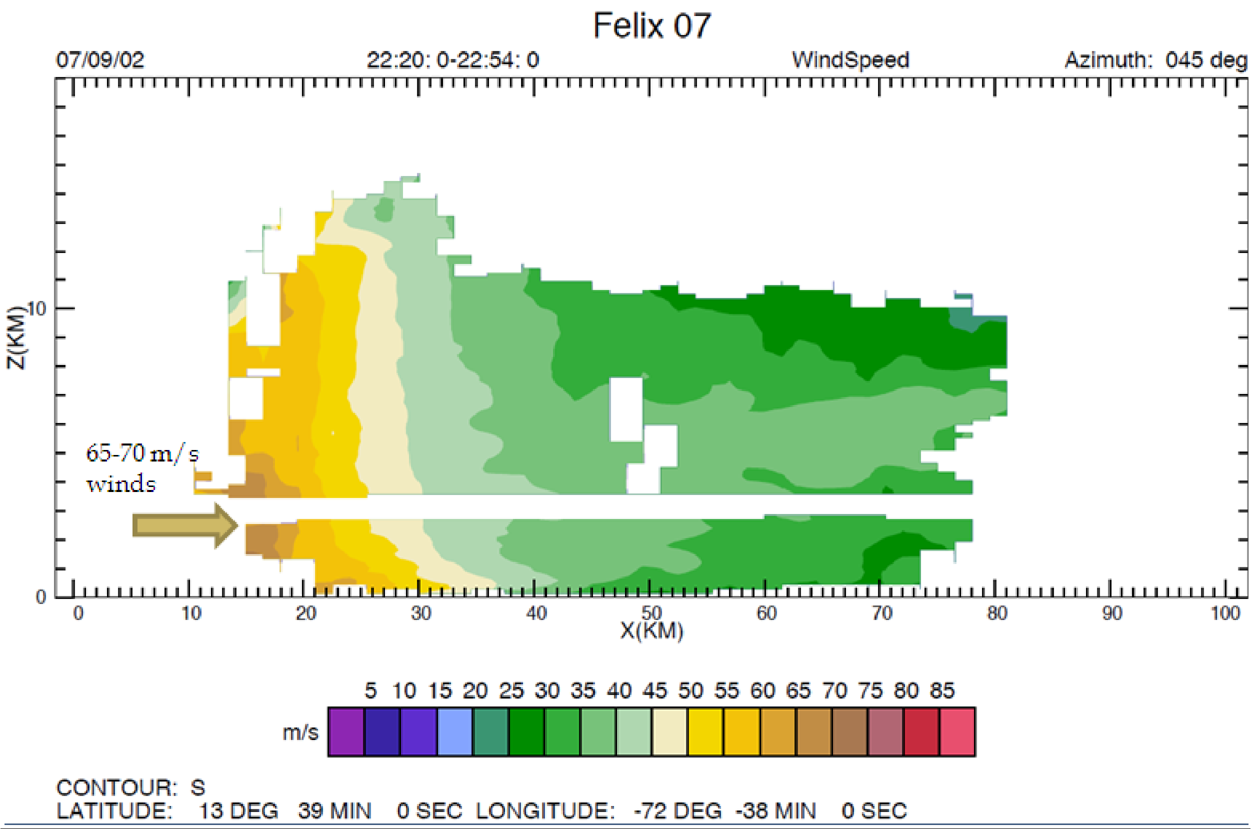


Figure 14: TDR velocities in the NE eyewall showing 70 m/s values at the 3 kilometer flight level and up to 55 m/s extending as high as 13 kilometers (42,650 feet or the 180 mb level)

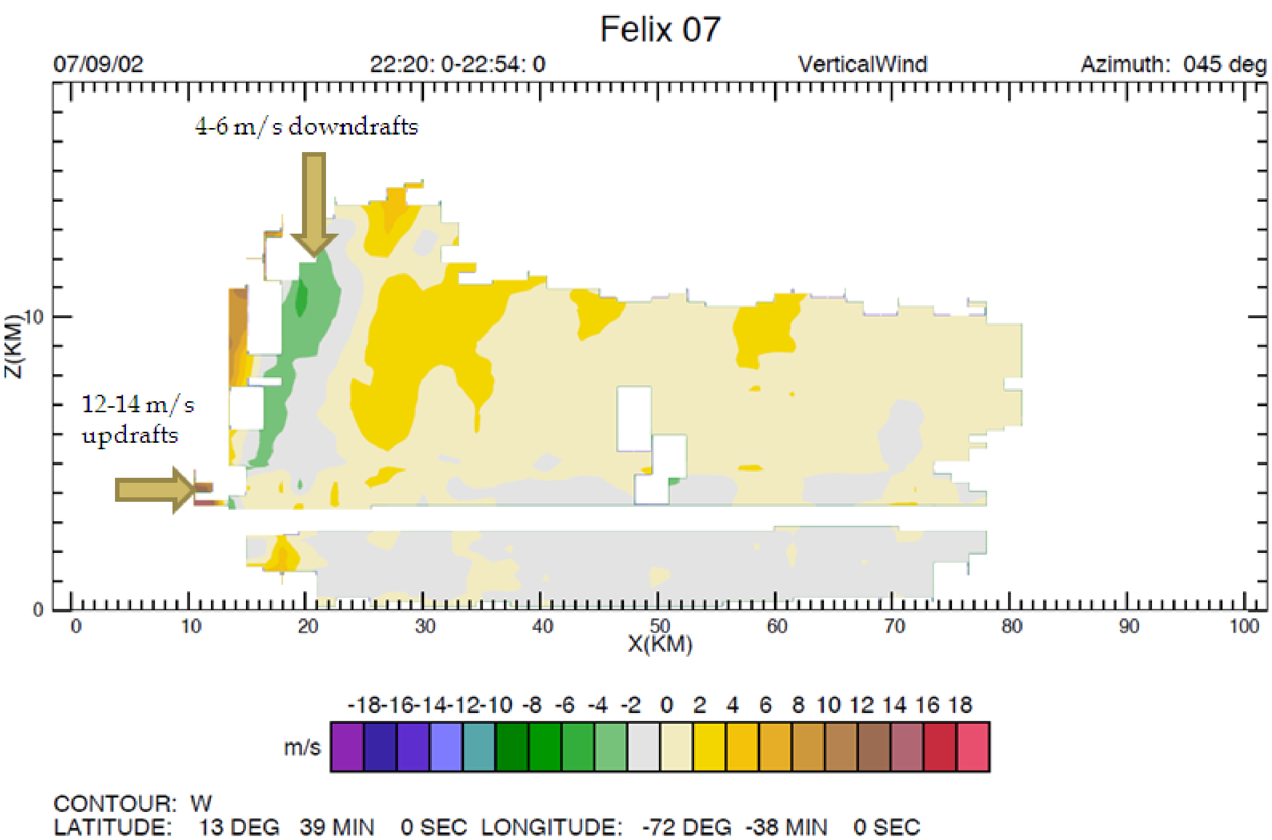


Figure 15: TDR Vertical Velocities. This product's spatial resolution is best suited to show mesoscale patterns (not the highly localized extreme values of +26.9 to -14.3 m/s in the embedded convective scale feature)

5. Summary

Initially the NHC forecasters on duty in Miami on the evening of 2 September 2007 were skeptical of the 163 knot SFMR surface wind value (thinking it was contaminated by the graupel). However, further examination of the SFMR data (and the existence of extreme near-surface winds measured by both eyewall dropsondes) suggests that 163 knot surface reading was likely to have been an accurate measurement.

A larger issue for discussion is how representative are the extreme wind values that were encountered at flight level in the NE eyewall (as the plane flew through a convective scale feature embedded within the mesoscale core) and by the first sonde near the surface as it spiraled into what appeared to be another extremely intense cell (or set of cells) in the N-NW quads. The eyewall second sonde on the outbound leg also found extremely high winds in the boundary layer (186 knots only 36 meters above the surface) due east of the center as it spiraled there from its release into the SW quad. This sonde did not exhibit any strange behavior characteristic of being drawn into mesocyclones as did the first. This suggests the very high wind values it recorded were perhaps more representative of the mesoscale tangential wind field in the eyewall.

So what wind value best represents the maximum intensity of Felix? Felix may have briefly been a 160+ knot hurricane at around 00z on 3 Sept 2007. That depends on how much one chooses to factor in data gathered in the convective scale features penetrated at flight level in the NE quadrant, and near the surface in the NW quadrant as seen in the first dropsonde, to characterize its overall maximum intensity. Another question would be to ask how representative were the 186 knot winds seen just above the surface east of the center (that were arguably a better representation of the larger scale wind field than the convective scale phenomena captured elsewhere).

One could argue that much of the answer lies with how long these convective scale features persist. If they are transient features that dissipate before the next reconnaissance mission, they are less likely to translate their energy into intensification of the larger scale parent vortex.