15A.6 EPISODES OF THERMODYNAMIC SUPEREFFICIENCY IN RAPIDLY INTENSIFYING ATLANTIC BASIN HURRICANES

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1. INTRODUCTION

A relationship between unusually high equivalent potential temperature (theta e or Θ_e) measurements collected by reconnaissance aircraft in the core of tropical cyclones, and subsequent episodes of rapid intensification (R.I.), was proposed by Dunnavan (1981) and Sikora (1976) years ago using data gathered in a large sample of Western Pacific typhoons. Since 1987, all such operational reconnaissance missions have been flown in either the Atlantic Basin or the Central and Eastern Pacific (with only a limited number of flights off the western Mexican coast or in what have been remarkably quiet waters near Hawaii (where there has been no reconnaissance data gathered within an intense hurricane since 1994)).

Dunnavan looked at 700 millibar Θ_e values measured by WestPac reconnaissance aircraft. In the Atlantic Basin, there is also some data gathered at 850 mb prior to episodes of R.I. in addition to the 700 mb level. This study attempts to determine whether such a relationship exists in the Atlantic data, and perhaps more importantly, whether a prognostic tool can be developed to help develop some skill in predicting R.I., one of the most difficult challenges in the field of TC intensity forecasting.

In this study, data was examined for several intense Atlantic Basin hurricanes that all achieved Category Four or Five status through episodes of rapid intensification. The storms examined include: Bret and Floyd (1999), Charley (2004), Katrina and Rita (2005) and Dean and Felix (2007).

The final intensification episode of Hurricane Dean, just prior to its landfall along the Yucatan Coast, was particularly interesting. A US Air Force Reserve (AFRES) reconnaissance mission was flown using an SFMR equipped WC-130J (Mission# AF306 1504A directed by Lt Colonel Richard M. Harter and Captain Tina Young Smith). During the predawn hours of 21 August 2007, Dean exhibited many of the characteristics of Superintensity described by Persing and Montgomery (2003). This is a condition where winds in the inner edge of the eyewall are especially fierce, where the most extreme winds derive their energy from not only the ocean surface below the eyewall but also by gathering enriched, very high Θ_e air from inside the eye. This was later explored in papers by Montgomery, Bell, Aberson and M. Black (2006) that discussed possible causes for the extreme dropsonde winds seen in Hurricane Isabel (2003) above what would be expected by Maximum Potential Intensity (MPI) calculation proposed by Emmanuel (1986 and 1988).

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2. EYE AND EYEWALL Θ_e MEASUREMENT VIA DROPSONDE

Taking temperature and dew point values obtained from aircraft reconnaissance data for a given pressure level (from which mixing ratio can then be inferred), theta e was calculated using standard methodology (published by Kean University using their web based atmospheric calculation scheme at the following URL: http://hurri.kean.edu/~yoh/calculations/diagnostic/) as follows: (using the specific gas constant for dry air R = 287.04 J kg^{-1} K^{-1} and specific heat capacity at constant pressure for dry air c_p = 1005.7 J kg^{-1} K^{-1}) first potential temperature (theta or Θ) is calculated:

$$\theta = T\left(\frac{1000mb}{p}\right)^{\frac{R}{c_p}}$$

Then moist potential temperature (theta m or Θ_m) using dew point expressed equivalently as mixing ratio (w):

$$\theta_m = T\left(\frac{1000mb}{p}\right)^{\frac{R*(1-0.28*w)}{c_p}}$$

Followed by Lifting Condensation Level Temperature or T_{LCL}:

$$T_{LCL} = 56 + \frac{1}{\frac{1}{T_d - 56} + \frac{\ln\frac{T}{T_d}}{800}}$$

Then finally Equivalent Potential Temperature (theta e or Θ_e):

$$\theta_e = \theta_m * exp\left[\left(\frac{3376}{T_{LCL}} - 2.54\right)*w*(1. + 0.81w)\right]$$

Some extremely high surface Θ_e values measured in the planetary boundary layer of the eye by dropsondes were recorded during AFRES and NOAA W-P3 missions into Katrina, Rita and Dean. NOAA 43 Katrina Mission 1312A with Rob Rogers acting as the LPS, was flown on Saturday 27 August (prior to Katrina's most extreme episode of R.I. from a Category 3 to a Category 5 system). At 2012 UTC an eye sonde measured a temperatures and dew point of 28.2C at the surface with a SLP of 945 millibars (yielding a Θ_e of 386.2K). This compares with the August 2007 surface Θ_e mean for Key West, San Juan and Barbados of around 355K. Fifteen hours later, AFRES Katrina Mission AF302 1712A, with the author of this paper acting as Mission Director, measured almost exactly the same value (386.3K) at 1107 UTC with a SLP down to 910 mb, even though the surface winds in the latter drop were 26 knots (versus only 12 knots for NOAA's 2012 UTC sonde).

While eye dropsondes are released at the flight level wind minimum / wind shift they may fall into significant winds by the time they reach the surface depending on the tilt of the vortex. This is especially true for tightly would cores where each ten knots of wind seen on the surface is estimated by NHC forecasters to approximate each millibar of "miss" from the exact center. Therefore, even the eye sondes can be subjected to some significant evaporative cooling in the planetary boundary layer just prior to splashing into the sea. In spite of this, both the Katrina drops discussed above and Dean Mission 1504A, mentioned in the Introduction, saw similarly extreme surface Θ_e values in wind fields displaced a kilometer or more from the exact center. Such was the case for the 21 August 0605 UTC eye release into Dean (with a surface temperature of 27.7C, a dew point 26.8C, SLP of 909 mb again yielding an Θ_e of 386K) in spite of 27 knots of surface winds.

Even higher values of Θ_e were observed underneath the eyewall of Hurricane Rita on Mission AF307 1618A directed by Lt Colonel Warren Madden in the early morning of 22 September 2005. On the first eyewall penetration of the flight, inbound through the northwest quadrant of the Category 5 storm, the crew recorded some extraordinary data (see **Figure 1**) on a sonde released along the inner edge of that eyewall. As the sonde fell through the layer 236 meters above the surface, winds reached 205 knots (105.5 meters per second or 236 MPH). The final readings for temperature and dew point at the surface (with a SLP of 925 mb) were 29.6C and 29.0C respectively, yielding a Θ_e of an amazing 397K. The 397 degree theta e is made even more extraordinary by the fact that the free air temperature was measured in an emulsive layer of sea spray characterized by winds near 100 m sec^{-1} amidst the commensurate amount of evaporative cooling that would be expected with such extreme winds blowing across the ocean surface. Dean Mission 1504A measured 178 knots within 33 meters of the surface (see **Figure 2**, the TEMP DROP message from an eyewall sonde released into the northern quadrant of Dean at 0728 UTC and **Figure 3**, an IR satellite image of Dean near this time) and a surface theta e of 375K. During Katrina Mission 1712A, an 1108 UTC sonde release into the southeastern eyewall measured a surface Θ_e of 381K.

3. FLIGHT LEVEL Θ_e MEASUREMENT IN THE EYE AND EYEWALL

During the Rita and Dean missions discussed earlier, 700 millibar flight level (FL) temperatures in the innermost edge of the eyewall exhibited evidence of hot towers containing high theta e air. Temperature measurements are somewhat hindered by the well-known problem with wetting of the WC-130J temperature probe in bands of very heavy precipitation resulting in readings often at least 3 to 4 degrees C too low. In Dean, inbound to the 0816 UTC eye center fix through the southern eyewall, sensor wetting dropped FL temperatures reported on HDOBS down to as low as 7C. Outbound, through the northeast eyewall, 700 mb winds surged up to as high as 164 knots (10 second average at 0818 + 30 seconds UTC) as SFMR rain estimates (path mean rain rates) were as much as 41 mm $hour^{-1}$. In spite of this, the FL temperature was 15.6 degrees at 0818 UTC with 149 knot 10 second average winds and no dew point depression (100 percent humidity is common in the eyewall). Ninety seconds later, the temperature increased to 17.0 degrees with a 6.5 degree dew point depression. It is presumed that the 15.6 C 100 percent humidity regime was inside a buoyant updraft along the innermost edge of the eyewall (as was discussed by Eastin, Gray and P. Black 2005) and the subsequent drying was within a downdraft just slightly further outboard. Another warm event in the eyewall occurred earlier in the same mission after the 0648 UTC center fix while the aircraft was outbound through the northern eyewall (at 0652 + 30 seconds UTC). After temperatures initially dropped several degrees transitioning from the eye into the eyewall, they spiked back up to 16.9C as 10 second average winds surged up to 163 knots.

Within Rita, an examination of 1 second data sets from Mission 1618A reveals that sensor wetting hid what was probably an even more impressive temperature anomaly. Raw analog dew point readings, outbound from the 0714 UTC center fix just prior to the maximum wind band, of as high as 18.5C suggest that unless conditions of supersaturation were present (something that is possible but not likely to have accounted for true air temperatures more than a few tenths of a degree below the dew point) that the 0716 + 49 second UTC 700 mb Θ_e was at least 386K. Earlier in that same mission, outbound from the first fix through the southeastern eyewall, a raw analog 700 mb dew point of 19.96 degrees at 0540 + 11 seconds UTC would yield an even more remarkable Θ_e of 394K (see this one second data depicted in **Figure 4** and **Figure 5**).

In all of the storms examined, there was a trend toward increasing flight level Θ_e , prior to R.I., in the eye at either 850 or 700 mb. Katrina 700 mb Θ_e rose to 373.7K at 0326 UTC with a 936 mb SLP during the evening of 27 August prior to the rapid deepening on the morning of 28 August down to 902 mb. The extreme subsidence event in the eye leads to a very sudden spike in 700 mb temperatures that often accompanies R.I. (helping to hydrostatically drive the SLP down to its absolute minimum). The extreme drying that takes place helps to clear out the eye and give Category 4 and 5 hurricanes their distinctively dark "bulls eye" satellite appearance when still surrounded by bright, deep convection. However, this drying acts to significantly decrease Θ_e in the eye at flight level during maximum intensity. Even though the 700 mb temperature in the eye would increase from 19C at 0326 UTC, to 26C at 1417 UTC (and continue to rise to 29C by 1755 UTC), the accompanying drop in dew point down to only 6C yielded a Θ_e decrease from 373.3 down to 359.6K.

The same occurred in Dean prior to the intensification episode described earlier. For several 700 mb fixes throughout a six hour interval late on 20 August, the SLP hovered around 925 mb with FL Θ_e around 380K (with a maximum of 387K measured during the 2302 UTC center fix). The MSLP then dropped to 906 mb just prior to landfall on the Yucatan Coast.

4. OUTFLOW Θ_e NEAR THE TROPOPAUSE

There were NOAA Air Operations Center (AOC) Gulfstream-IV high altitude surveillance missions flown around the periphery of Hurricane Katrina, including NOAA 49 Mission 1412A (see flight path shown as **Figure 6**) flown by dropsonde scientists Krystal Valde and Chris Landsea and Mission 1612A (see flight path shown as **Figure 7**) flown by Stan Goldenberg. The sondes released during these missions are highly valuable in the process of initializing global models in an effort that has dramatically helped to increase TC track forecast accuracy. An extra benefit of this data is the ability to examine the high altitude outflow around a storm.

Examination of the outflow of Katrina, from late in the day on 27 August to early in the morning of 28 August, supports several assertions published elsewhere regarding the "exhaust" layers of intensifying hurricanes. First, while there is a somewhat uniform expanding mass envelope around the periphery of the storm (with common thermodynamic characteristics across most azimuths outward), there also do appear to be discrete outflow jets or channels where a large portion of the heat energy was transported toward sinks located far from the storm environment by bands of much stronger winds. Development of a classic equatorial outflow channel certainly seems to have aided Katrina's intensification to a 902 millibar Category Five system (see **Figure 8**, an NRL water vapor image of Katrina from 2245 UTC Saturday 27 August (showing the storm in a preparatory mode in advance of R.I. establishing the equatorial outflow channel).

Also, dropsonde data from the two G-IV missions shows a vertical protrusion of Katrina upward to the tropopause accompanied intensification, with the level of non divergence (LND)…basically where flow transitioned from spiraling cyclonically inward to spiraling anticyclonically outward…being displaced upward. This LND was highest at points closest to the center of Katrina and sloped downward to below 300 millibars at locations furthest displaced from the core. In many places, the transition from inflow to outflow regimes was marked vertically by a nearly 180 degree shift in wind direction across a small number of millibars change in height.

G-IV Mission 1412A Dropsonde #19 was released just west of Naples, FL at 2247 UTC 27 August from an altitude of 13.5 kilometers or approximately 45,000 feet. At the time, Katrina was centered about 300 miles to the WSW over the Gulf of Mexico's Loop Current with an intensity of 945 millibars (Category Three) but in the process of gathering organization preparing for a 43 millibar deepening event late that night and into the morning hours of 28 August. The sonde shows strong cyclonic circulation from the surface (with 22 knot southerly winds and a SLP of 1006 mb) up through a very deep layer of the troposphere with backing of the winds with height from southerly to SE to ESE to easterly. Suddenly, at 206 millibars, northerly winds of 17 knots indicate a transition to the outflow layer. Evidence of a full fledged outflow jet or channel was clear at 150 mb with winds of 355 degrees at 54 knots just below the release altitude of the flight. The theta e of this outflow jet was slightly higher (358.6K) than other samples from up at the 150 millibar level.

Several sondes were released in the central and western Gulf of Mexico well west of Katrina on both G-IV missions (1412A on the 27^{th} and 1612A on the 28^{th}). They show a somewhat uniform pattern of a gently expanding outflow mass envelope with nearly uniform thermodynamic properties. Nearly all soundings west of Katrina showed a Θ_e of 355K in the outflow layer between 173 and 162 millibars.

Sonde releases #03 and #04, from NOAA 49 on Mission 1612A, were made close enough to the center to clearly paint the eyewall and eye on the Gulfstream aircraft's nose radar (see **Figure 9**). Both sondes show a strongly cyclonic circulation up through the entire depth of the soundings to 181 millibars where a Θ_e of 357.7K was measured.

5. DISCUSSION

What is proposed is that at times of hurricane "superefficiency" a functional continuum exists between very high values of Θ_e (as high as 386K) measured in the boundary layer by eye dropsondes and buoyant warm ribbons that spiral upward along the inner edge of the eyewall up through and beyond the nominal 700 mb reconnaissance flight level (where most intense hurricanes are flown). This air acts to feed mesovortices embedded within the innermost edge of the eyewall.

Theta e values as high as 397K were recorded by dropsonde in Rita at the surface underneath such an eyewall structure. If the raw analog dew point of 19.96C found in Rita one second resolution 700 millibar flight level data (during an eyewall penetration) is valid (assuming only a small amount of supersaturation, if any) this would imply a FL Θ_e of 394K.

While toroidal vorticity is distributed throughout all azimuths around the eyewall (an idealized model of a torus is shown as **Figure 10**), the presence of discrete ribbons of this high theta e air feeding mesovortices along the inner surface of the eyewall gives an extra boost to the winds through vertical buoyancy (a significant portion of which is then translated into horizontal tangential wind enhancement as small scale, convectively generated vortices are tilted laterally into the primary vortex circulation). This helps to account for the extreme winds seen in dropsondes and flight level data being correlated to temperature spikes. The turbulent nature of this phenomenon also helps explain sudden, jarring *lateral* g forces experienced by the AFRES crew of Dean Mission 1504A (personal communication with the Mission Director, Lt Colonel Richard Harter) who reported violent acceleration in the horizontal plane passing through the convective structures described earlier.

In this state of heightened efficiency, wind speeds can continue to increase and MSLP can continue to drop without necessarily needing to have the very large subsidence response in the eye. That event is characterized by very rapid warming (and a more sudden hydrostatic drop in MSLP) but is also accompanied by very pronounced drying of all levels except the boundary layer. This drying causes a net reduction in theta e in the eye and what is ultimately the beginning of a decidedly negative feedback process which begins to erode the adjacent eyewall convection as parcels with lower Θ_e air are advected into eyewall mesovortices, first weakening them, then as this dryer air spreads through the eyewall as a whole, weakening the convective forcing driving the primary vortex circulation. Such was the case in Rita, which began to weaken immediately after the record-setting 34 degree eye dew point depression was observed.

Regarding the discussion of high altitude dropsonde measurements using the G-IV, the assumption was made that air flowing cyclonically near the core of Katrina was part of the inflow (even up as high as 181 millibars). This is based on the further assumption that the G-IV flight path, even though at times it was close enough to paint the eye clearly on radar, still wasn't quite close enough to the eyewall to be part of what is postulated to have been vigorous cyclonic outflow for a small radius outward from the center near the tropopause during Katrina's period of most rapid intensification.

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Figure 1 TEMP DROP message of dropsonde released by Mission AF3071618A at 0534 UTC 22 September 2005 into the northeastern eyewall of Hurricane Rita near maximum intensity. The sonde splashed down in the northwestern eyewall recording winds of 060 degrees at 205 knots at 236 meters above the surface. A few seconds later, the sonde reached the surface where it measured a Θ_e of 397K (a surface temperature of 29.6C and a dew point of 29.0C at a SLP of 925 millibars)

UZNT13 KNHC 220548
XXAA 72068 99248 70874 08147 99925 29606 ///// 00/// ///// /////
92/// ///// ///// 85738 21403 09686 70415 13800 88999 77999
31313 09608 80534
61616 AF307 1618A RITA OB 05
62626 EYEWALL 045 SPL 2490N08755W 0538 LST WND 236 DLM WND 10665 900735 =

XXBB 72068 99248 70874 08147 00925 29606 11923 26202 22916 24002
33850 21403 44711 16403 55703 16400 66697 11000

21212 00925 ///// 11900 06705 22888 07192 33860 08683 44858 08685
55849 09687 66697 14653

Figure 2 TEMP DROP message of dropsonde released by Mission AF3061504A at 0728 UTC 21 August 2007 into the northern eyewall of Hurricane Dean near maximum intensity. The sonde splashed down in the northwestern eyewall a few miles off the Yucatan Coast. The final winds recorded prior to reaching the surface were 030 degrees at 178 knots only 33 meters above the surface (effectively within the emulsive layer of spray and foam at the air-sea interface). In spite of the immense potential for evaporative cooling within this layer, a Θ_e of 375K was recorded (a surface temperature and dew point of 26.0C at a SLP of 931 millibars).

UZNT13 KNHC 210748
XXAA 71077 99188 70873 04587 99931 26000 ///// 00/// ///// /////
92059 26004 03673 85804 22200 08648 70492 14800 11157 88999 77999
31313 09608 80728
61616 AF306 1504A DEAN OB 22
62626 EYEWALL 360 SPL1882N08739W 0731 LST WND 033 DLM WND 09153 928702 WL150 03178 105 =

XXBB 71078 99188 70873 04587 00931 26000 11850 22200 22814 21001
33796 23641 44750 20834 55722 17000 66702 16000 77696 11400

21212 00931 ///// 11928 03178 22908 05664 33895 06663 44884 07153
55865 07664 66859 08159 77853 08648 88850 08648 99842 08663 11822
08653 22742 10667 33724 11150 44696 11152

Figure 3 0715 UTC 21 August 2007 Naval Research Lab IR image of Dean about to make landfall as a 906 millibar Category 5 Hurricane on the Yucatan Coast. Location of the 0728 UTC eyewall release and 0731 UTC splashdown point are shown (which measured 178 knots of wind at 33 meters and a surface Θ_e of 375K).

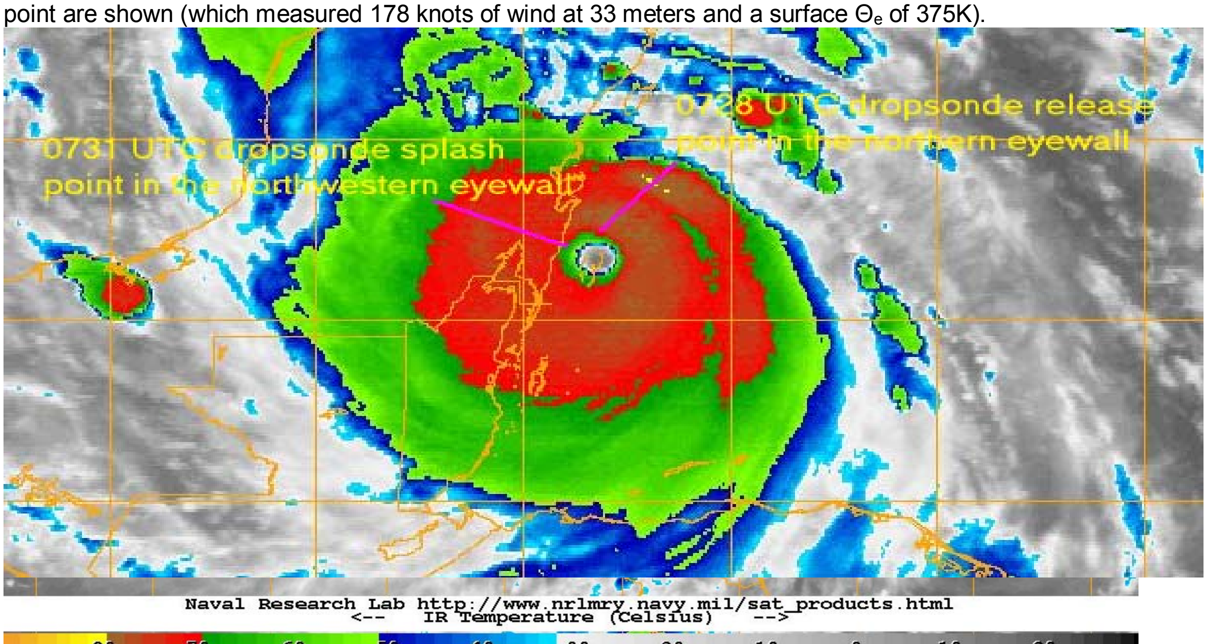


Figure 4 Plot of one second resolution raw analog dew point data measured at flight level (700 millibars) during Rita mission 1618A. The spike up to 19.96C in the southeastern eyewall outbound after the first center fix mentioned in section 3 is shown. Also shown are some of the extremely low dew points seen in each eye penetration (as low as

-3.51C during the second pass through the center).

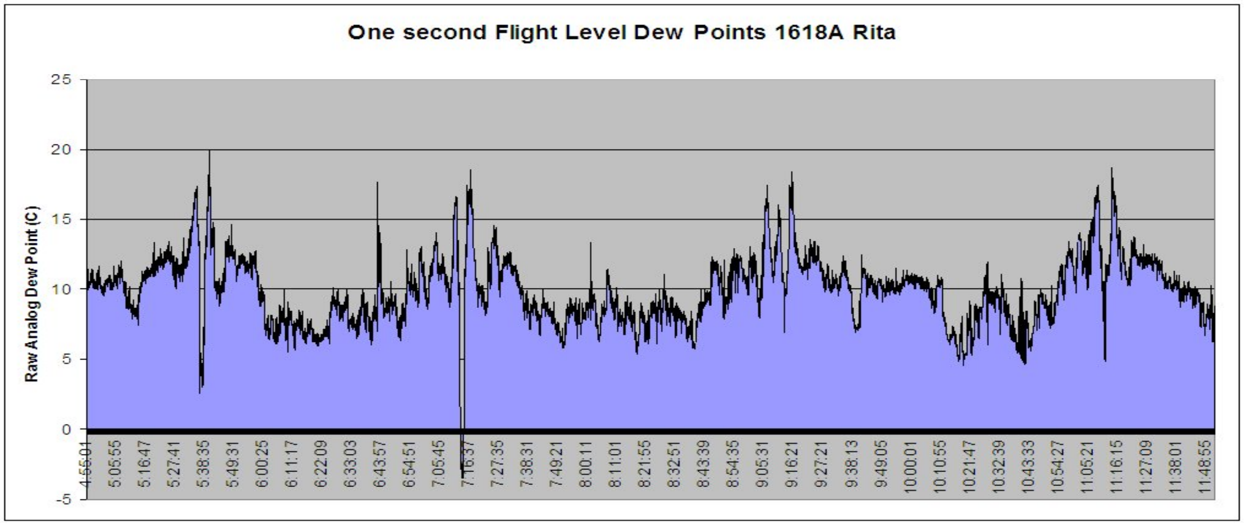
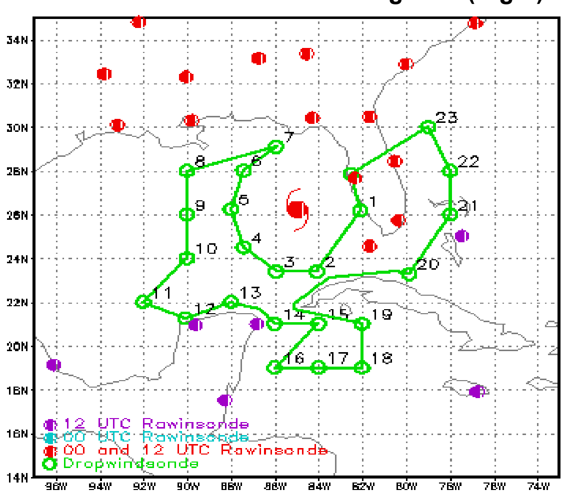


Figure 5 A tabular sample of one second data from Rita Mission 1618A showing the dew point spike in the eyewall at 0540 + 11 seconds UTC shown plotted above in Figure 4.

GMT Time	DVAL	HSS	LAT	LON	PA	RA	SLP	TA	TDA	WD	WS
5:40:00	-637.74	2374.72	24.661	-87.662	3007.92	2416.75	922.81	10.68	17.38	328.62	114.02
5:40:01	-628.74	2383.97	24.659	-87.662	3003.87	2421.7	924.07	10.52	18.09	325.93	110.9
5:40:02	-624.45	2388.72	24.658	-87.663	2996.56	2418.67	924.67	10.5	18.09	323.02	113.49
5:40:03	-615.32	2398.4	24.657	-87.663	2987.44	2418.69	925.89	10.5	18.09	321.65	120.94
5:40:04	-618.11	2395.63	24.656	-87.663	2987.84	2416.29	925.11	10.9	17.25	319.52	133.51
5:40:05	-611.38	2402.84	24.654	-87.664	2980.68	2415.85	925.71	11.05	17.59	323.24	119.24
5:40:06	-611.1	2403.47	24.653	-87.664	2976.44	2411.89	925.32	11.57	18.22	323.7	121.42
5:40:07	-615.26	2399.41	24.652	-87.665	2975.37	2406.65	924.64	11.57	17.48	327.34	124.71
5:40:08	-610.64	2404.48	24.651	-87.665	2968.64	2404.53	925.26	11.6	18.03	329.62	121.23
5:40:09	-609.46	2405.83	24.65	-87.666	2964.95	2402.02	925.8	11.5	18.92	330.73	112.83
5:40:10	-604.23	2411.05	24.648	-87.666	2965.5	2407.81	926.22	11.55	19.8	327.1	112.97
5:40:11	-602.84	2412.22	24.647	-87.667	2967.66	2411.37	926.73	11	19.96	329.2	113.01
5:40:12	-597.31	2417.45	24.646	-87.668	2971.93	2421.18	927.43	10.73	18.93	324.97	119.01
5:40:13	-588.95	2425.74	24.645	-87.668	2972.54	2430.18	928.49	10.73	18.12	323.87	122.85
5:40:14	-585.31	2429.33	24.644	-87.669	2973.79	2435.07	928.65	11	17.97	323.99	128.88
5:40:15	-581.15	2433.36	24.643	-87.669	2976.68	2442.14	928.73	11.15	17.4	326.87	138.91
5:40:16	-577.37	2437.09	24.641	-87.67	2975.81	2445.05	929.84	10.52	17.87	329.18	136.78
5:40:17	-567.7	2446.98	24.64	-87.67	2973.35	2452.27	930.45	11.16	18.2	322.21	126.62
5:40:18	-559.16	2455.24	24.639	-87.671	2977.57	2465.08	931.4	10.75	18.95	324.46	128.58
5:40:19	-555.39	2458.52	24.638	-87.671	2983.97	2475.25	932.42	10.1	18.41	323	130.6
5:40:20	-550.53	2463.28	24.637	-87.672	2985.74	2481.9	932.88	10.31	17.3	319.42	143.59
5:40:21	-544.41	2469.5	24.635	-87.672	2985	2487.29	932.99	10.85	17.25	320.95	142.43
5:40:22	-546.3	2467.28	24.634	-87.672	2989.55	2489.94	933.27	10.3	17.1	325.11	143.83

Figure 6 (Left) Flight path and dropsonde release locations for afternoon and evening 27 August NOAA 49 AOC Gulfstream IV Mission 1412A and **Figure 7 (Right)** Mission 1612A from the early morning of 28 August 2005.



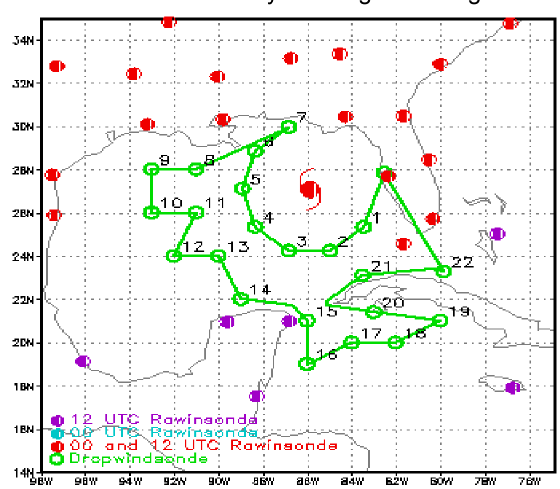


Figure 8 2245 UTC 27 August NRL water vapor image of Katrina clearly showing some of the equatorial outflow channels streaming across the Yucatan and the NW Caribbean that were sampled by the G-IV.

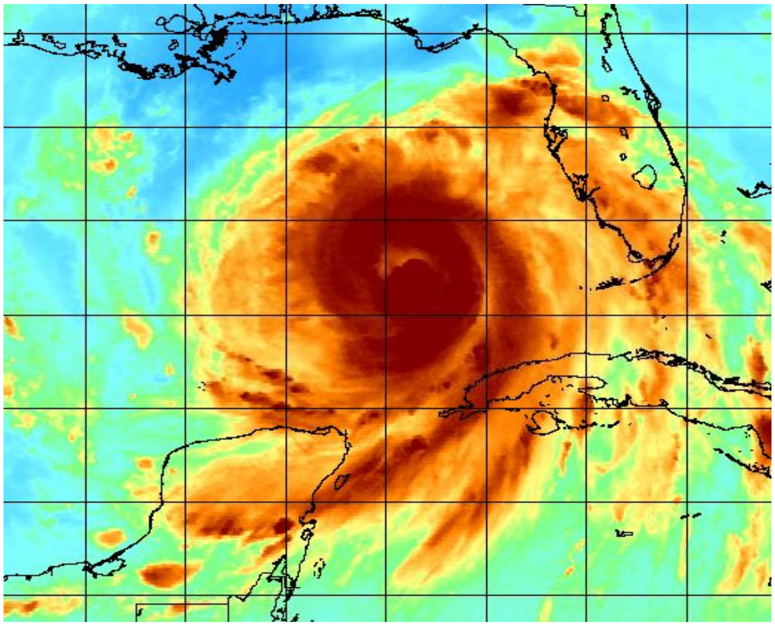


Figure 9 The eyewall and eye of Katrina as seen on radar from the NOAA Gulfstream IV high altitude surveillance aircraft during the early morning of Sunday 28 August as the storm was approaching maximum intensity

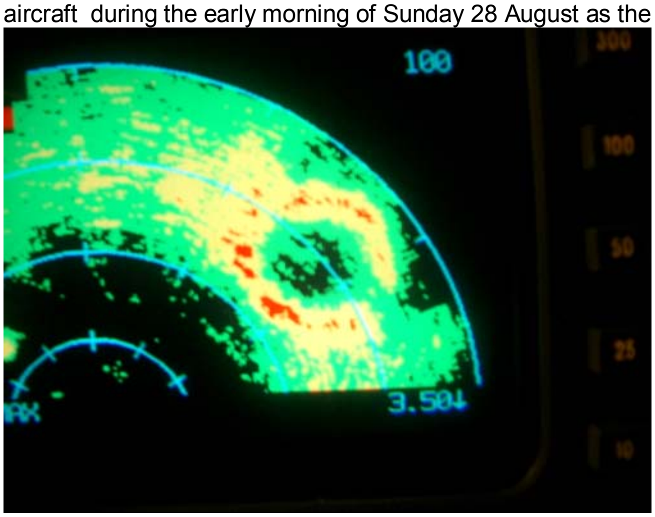


Figure 10 An idealized torus depicting the mean state of eyewall vorticity in the vertical plane. Asymetric distribution of hot, buoyant towers feeding ribbons of extreme wind speeds are superimposed onto this mean structure and are marked by pronounced warm theta e anomalies