Global Journal of Science Frontier Research: H
Environment & Earth Science
Volume 15 Issue 2 Version 1.0 Year 2015
Type : Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals Inc. (USA)
Online ISSN: 2249-4626 & Print ISSN: 0975-5896

Applied Physics of Air-Sea-Land Interaction During Hurricane Katrina

By Professor S. A. Hsu
Louisiana State University, United States

Abstract- A decade ago in August 2005 Hurricane Katrina devastated north-central Gulf of Mexico and southeastern Louisiana and Mississippi Gulf Coast. Although nearly all anemometers in the affected areas were destroyed by Katrina, few wind and wave measurement stations did survive the storm and provide some data to advance our understanding of the physics of air-sea-land interaction. Analyses of these measurements indicate that : 1. On the basis of upper-air measurements made at Key West, FL, and Slidell, LA, the power-law wind profile is verified in the atmospheric surface boundary layer (up to 300m) where the friction dominants; 2. The cyclostrophic equation, which is the balance between centrifugal force and pressure gradient force, is validated so that the wind speed at 10m over the water, U10 = 6.3(1013 - Pmin) ^ (1/2), where Pmin is the minimum sea-level pressure; 3.The significant wave height (Hs) and its dominant wave period (Tp) can be normalized by using U*, which is the friction velocity (= (τ/ρ) ^ (1/2), where τ is the wind stress and ρ is the air density).

Keywords: hurricane katrina, wind-wave interaction, friction velocity, storm surge, wave setup, cyclostrophic equation, power-law wind profile, and wind stress.

GJSFR-H Classification : FOR Code: 059999

APPLIEDPHYSICSOFAIRSEALANDINTERACTIONDURINGHURRICANEKATRINA

Strictly as per the compliance and regulations of :

Open Association of Research Society, USA
Research | Diversity | Ethics

© 2015. Professor S. A. Hsu. This is a research/review paper, distributed under the terms of the Creative Commons Attribution-Noncommercial 3.0 Unported License http://creativecommons.org/licenses/by-nc/3.0/), permitting all non commercial use, distribution, and reproduction in any medium, provided the original work is properly cited.

Applied Physics of Air-Sea-Land Interaction during Hurricane Katrina

Professor S. A. Hsu

Abstract - A decade ago in August 2005 Hurricane Katrina devastated north-central Gulf of Mexico and southeastern Louisiana and Mississippi Gulf Coast. Although nearly all anemometers in the affected areas were destroyed by Katrina, few wind and wave measurement stations did survive the storm and provide some data to advance our understanding of the physics of air-sea-land interaction. Analyses of these measurements indicate that : 1. On the basis of upper-air measurements made at Key West, FL, and Slidell, LA, the power-law wind profile is verified in the atmospheric surface boundary layer (up to 300m) where the friction dominants; 2. The cyclostrophic equation, which is the balance between centrifugal force and pressure gradient force, is validated so that the wind speed at 10m over the water, U10 = 6.3(1013 - Pmin) ^ (1/2), where Pmin is the minimum sea-level pressure; 3.The significant wave height (Hs) and its dominant wave period (Tp) can be normalized by using U*, which is the friction velocity (= (**τ**/**ρ**) ^ (1/2), where **τ** is the wind stress and **ρ** is the air density). The result shows that U* = 38 Hs^2/Tp^3; 4.Extreme Hs (=16.91m or 55.5ft) measured at NDBC Buoy 42040 can be explained by a new formula for U* using U10 and Pmin; 5.Storm surge and wave setup near Biloxi, MS, are explained physically using the measured Pmin = 927.4mb at Buoy 42007, located just south of Biloxi; and 6. Since the wind speed near the hurricane's landfall was too low to be used in the air-sea-land interaction studies, it is prudent that caution must be exercised in using the wind data when a tropical cyclone is near the coast.

Keywords: hurricane katrina, wind-wave interaction, friction velocity, storm surge, wave setup, cyclostrophic equation, power-law wind profile, and wind stress.

I. INTRODUCTION

About a decade ago in August 2005 Hurricane Katrina (see Figs.1 and 2) devastated north-central Gulf of Mexico and southeastern Louisiana and Mississippi Gulf Coast (see, e.g., Wang and Oey, 2008 and Hsu, 2014). Some examples of these destructions including one photo from Ivan in 2004 are illustrated in Figs. 3 thru 6. Although nearly all anemometers in the affected areas were destroyed by Katrina, few wind and wave measurement stations did survive the storm and provide some data for our reconstruction of the meteorological and oceanographic(met-ocean) conditions. To commemorate this infamous tropical cyclone in its 10th Anniversary this report is written to provide several applied physics of air-sea-land interaction.

Fig.1 shows that, when Katrina was in the central Gulf of Mexico, its minimum sea-level pressure (Pmin) was as low as 902hPa (or millibar, mb), which is 18mb lower than the commencement of the highest Saffir/Simspson Damage-potential Scale (i.e. category 5, for Pmin < 920mb). Also, as indicated in Table 1, even at its landfall in Louisiana, Pmin = 920mb. Furthermore, during its landfall, the radius of max wind was 65km (or 35 miles) and the tropical storm force winds (ranging from 34 to 63knots) extended out to 454km (245 miles). With this background information, we continue our analysis and discussions.

Author: Louisiana State University. e-mail: sahsu@lsu.edu.

© 2015 Global Journals Inc. (US)

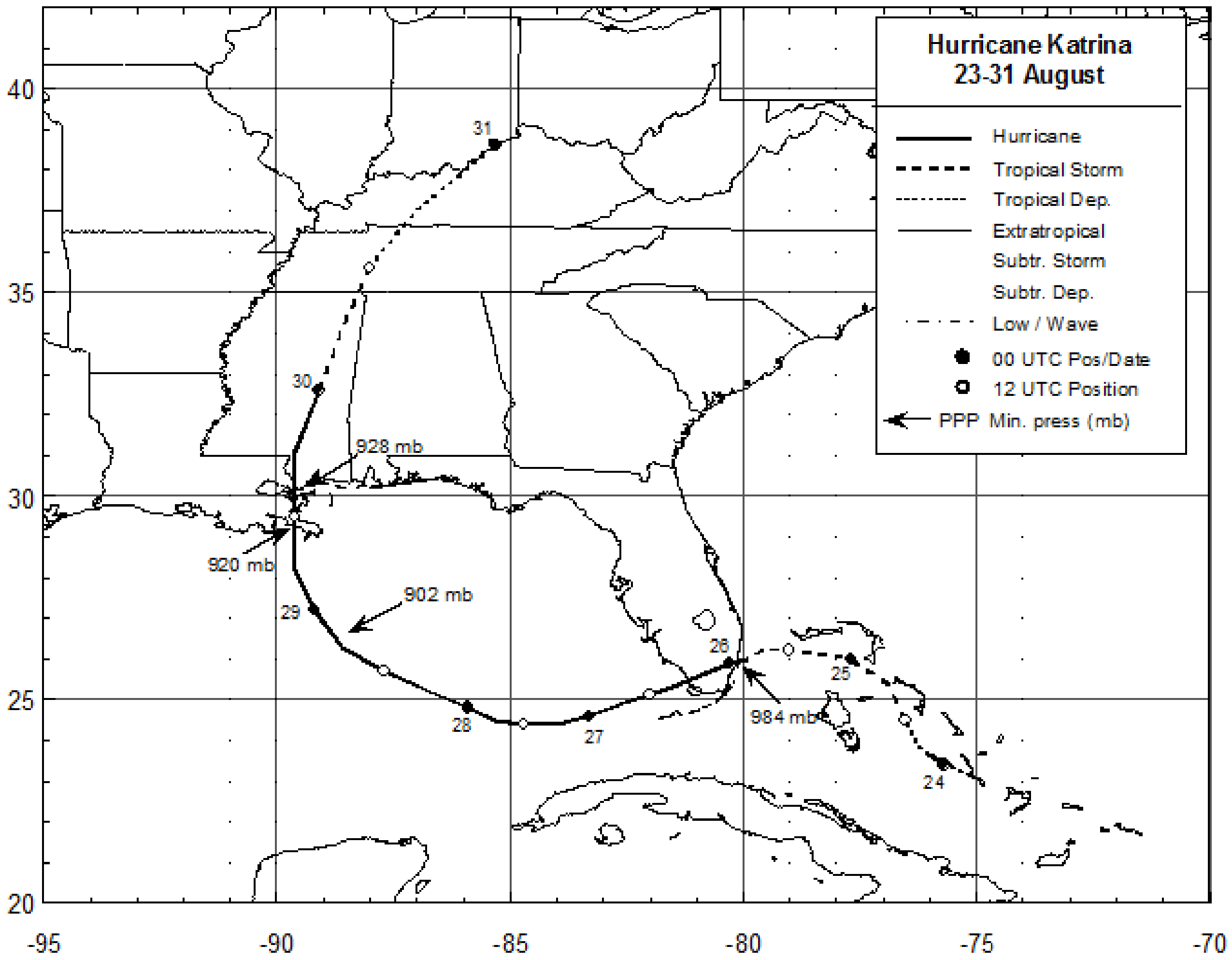

Fig. 1 : The track of Hurricane Katrina in August 2005 (see www.nhc.noaa.gov)

© 2015 Global Journals Inc. (US)

Fig. 2 : An image of Katrina over the central Gulf of Mexico near its peak wind conditions (see Table 1)

Table 1 : Radius of max wind (Rmax), minimum sea-level (central) pressure (Pmin), max wind speed at 10m (Vmax), and radius of tropical storm wind speed (R34kt) during Katrina in August 2005 (Data source: Powell and Reinhold, 2007)

Hurricane	Day	Time (UTC)	Rmax (km)	Pmin (hPa)	Vmax (m/s)	R34kt (km)
Katrina (FL)	25	2230	15	984	33	115
Katrina Peak wind	28	1200	26	909	71	349
Katrina (LA)	29	1200	65	920	52	454

© 2015 Global Journals Inc. (US)

Fig. 3 : Mars Tension-leg platform in the Gulf of Mexico (From http://en.wikipedia.org/wiki/Mars_(oil_platform))

© 2015 Global Journals Inc. (US)

Fig .4 : Mars platform showing damage from Hurricane Katrina in2005(http://en.wikipedia.org/wiki/Mars_(oil_platform)). According to Wang and Oey (2008), this billion-dollar platform was designed to withstand “140-mph winds and crashing waves up to 70ft high simultaneously”

© 2015 Global Journals Inc. (US)

Fig. 5 : Interstate I-10 over Mobile Bay damaged by Hurricane Ivan in 2004(From FHWA-NHI-07-096).According to FHWA, the wave setup on top of the storm surge was the cause

© 2015 Global Journals Inc. (US)

Fig. 6 : US 90 bridge over Biloxi Bay, Mississippi, was damaged by Katrina. Since the spans at higher elevations were not removed, the wave setup on top of the storm surge is more important than the wind loading (photo looking southwest from Ocean Springs 2/19/06, from FHWA-NHI-07-096)

II. A VERIFICATION OF THE POWER-LAW WIND PROFILE

During a tropical cyclone the atmosphere is well mixed or homogenized. This is represented by a skew T-log P thermodynamic diagram (see, e.g., Hsu, 1988) as shown in Fig. 7 at Key West, Florida, near the track of Katrina (Fig. 1). Since the dew-point measurements on the left is fairly close to that of dry-bulb temperature and since both curves also follow the saturation-adiabatic lapse rate, clouds could have been extended into the lower stratosphere. Therefore, deep convections ensue. However, because of the frictional effects near the ground or sea surface, mechanical turbulence over-powers the thermal convection so that the wind must decrease from cloud base to the surface. This is illustrated in Fig. 8. It is found that the height of the surface boundary layer extends to only 305m or approximately 1000 ft. This means that, based on the wind profile, we have a simple two-layer flow, i.e., above 300m the wind speed is nearly constant or changing slower than that in the sub-cloud layer, whereas blow this height, frictional effects prevail. Similar conditions over Slidell, Louisiana, during Katrina are demonstrated in Figs.9 and 10. The usefulness of this finding is further substantiated as follow:

According to Hsu (2003), under hurricane conditions, the power-law wind profile is valid so that

$$U2/U1 = (Z2/Z1)\ \hat{}\ p \qquad (1)$$

$$p = (G - 1)/2 \qquad (2)$$

$$G = Ugust / U1 \qquad (3)$$

Where U2 and U1 are the wind speed at height Z2 and Z1, respectively, p is the exponent of the power-law for the wind profile, G is the gust factor, and Ugust is the gust measured at Z1. Note that both U1 and Ugust are measured routinely at Z1 by the National Data Buoy Center (NDBC) (see www.ndbc.noaa.gov).

At 12Z 26 Aug 2005 at NDBC station DRYF1 (see Fig. 11), which was located offshore but near the upper-air measurement station in Key West, U1 =14.7m/s, Ugust = 16.8m/s, and Z1 = 5.7m. Now, by substituting these values into above equations and setting Z2 = 305m, we get U2 = 19.5m/s at 305m. This result is in excellent agreement with the measured value of 20.1m/s or 39kts as shown in Fig.8, since the difference is only 3%. Therefore, the power-law wind profile is verified using the known surface boundary-layer height. This means that we can use routine measurements of U1and Ugust at Z1 to estimate U2 at given Z2.

© 2015 Global Journals Inc. (US)

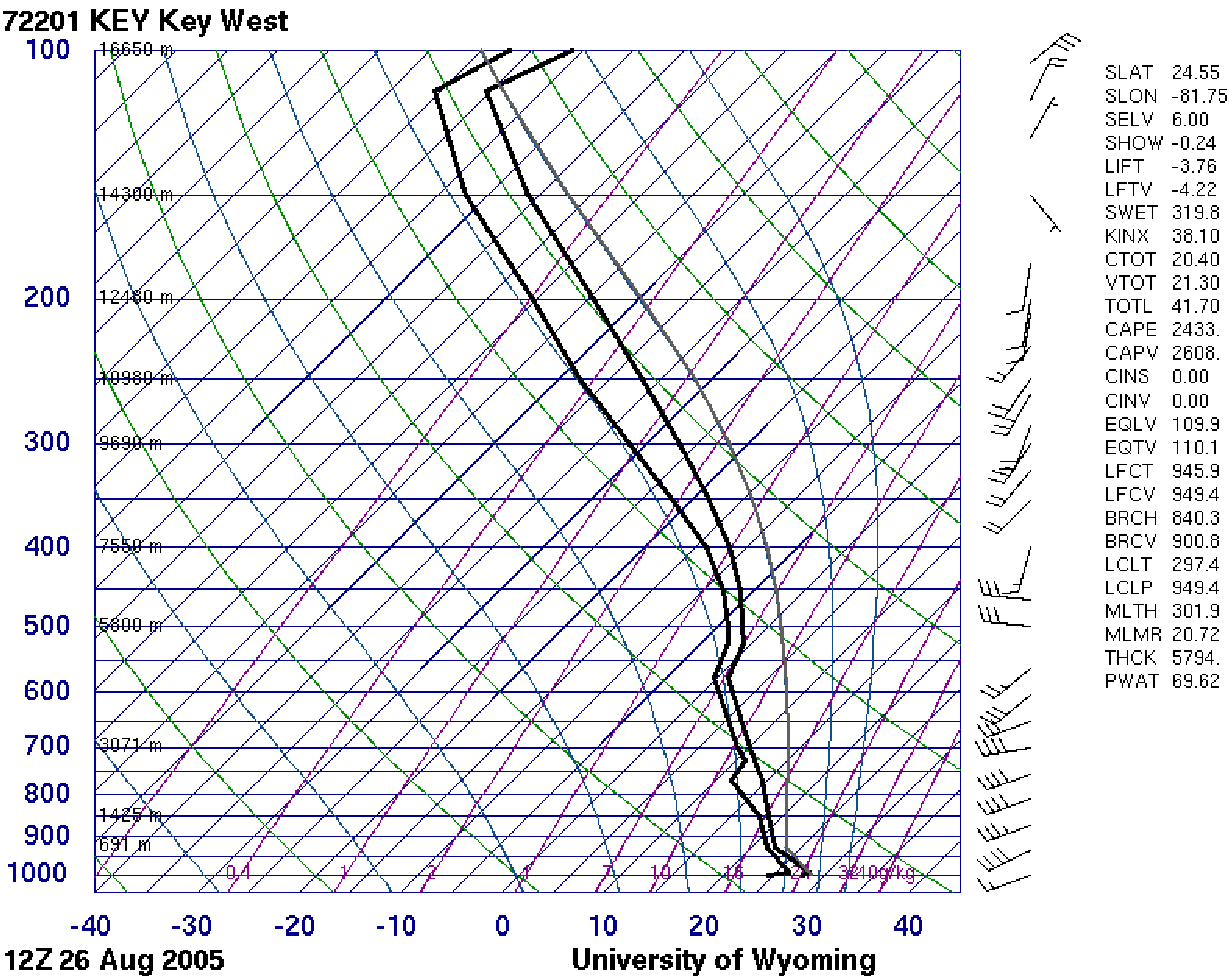

Fig. 7 : Upper-air sounding at Key West, FL, at 12Z 26 Aug 2005 (courtesy of the Department of Atmospheric Science, University of Wyoming, see http://weather.uwyo.edu/upperair/sounding.html)

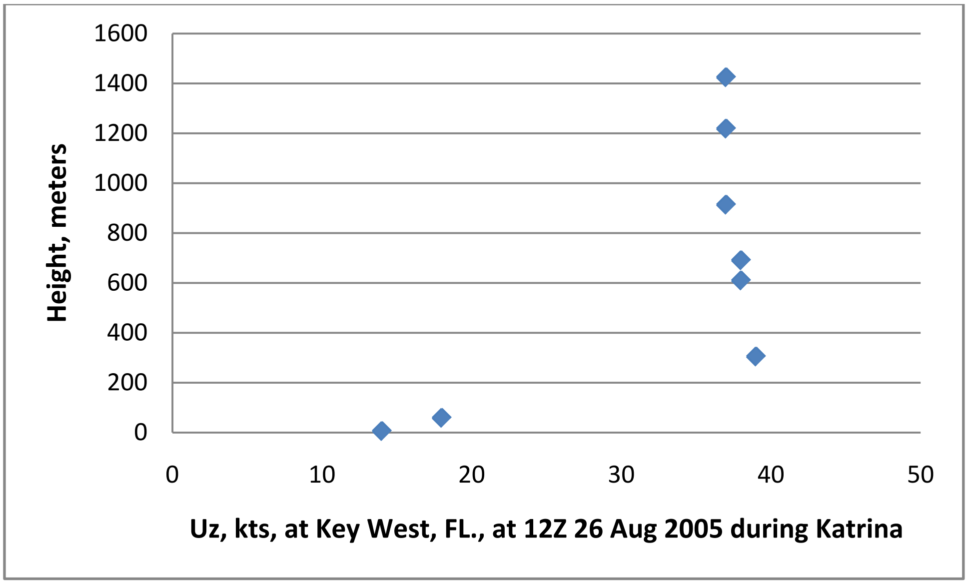

Fig. 8 : Wind profile at 12Z 26 Aug 2005 at Key West, FL, during Katrina

© 2015 Global Journals Inc. (US)

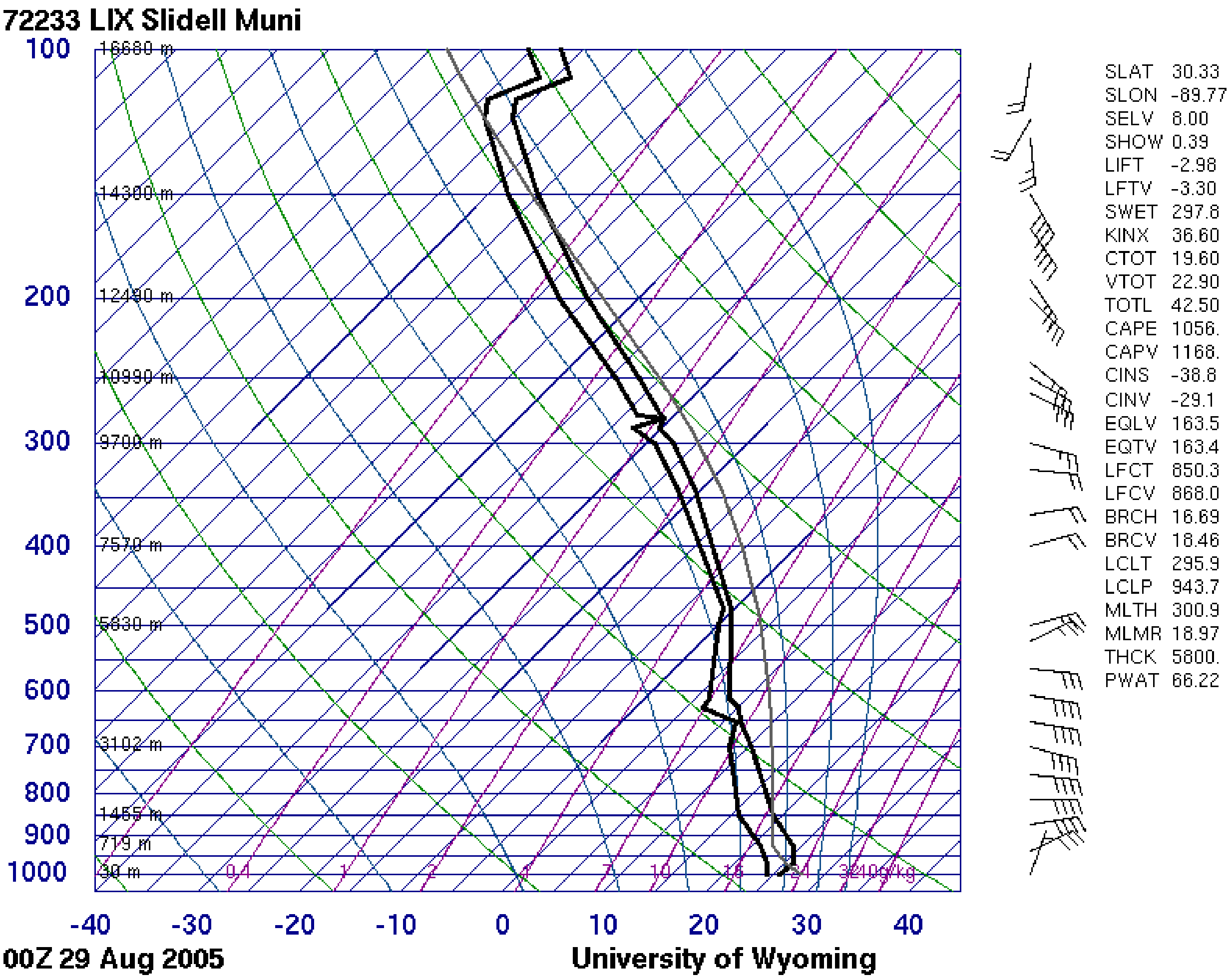

Fig. 9 : Upper-air sounding at 00Z 29 Aug 2005 at Slidell, LA, during Katrina (courtesy of the Department of Atmospheric Science, University of Wyoming, see http://weather.uwyo.edu/upperair/sounding.html)

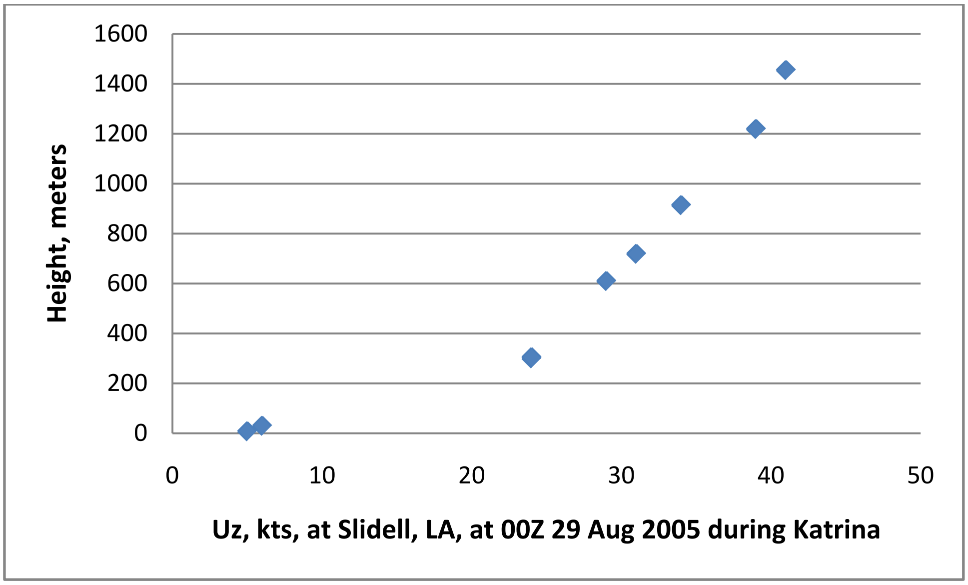

Fig. 10 : Wind profile at 00Z 29 Aug 2005 ay Slidell, FL, during Katrina

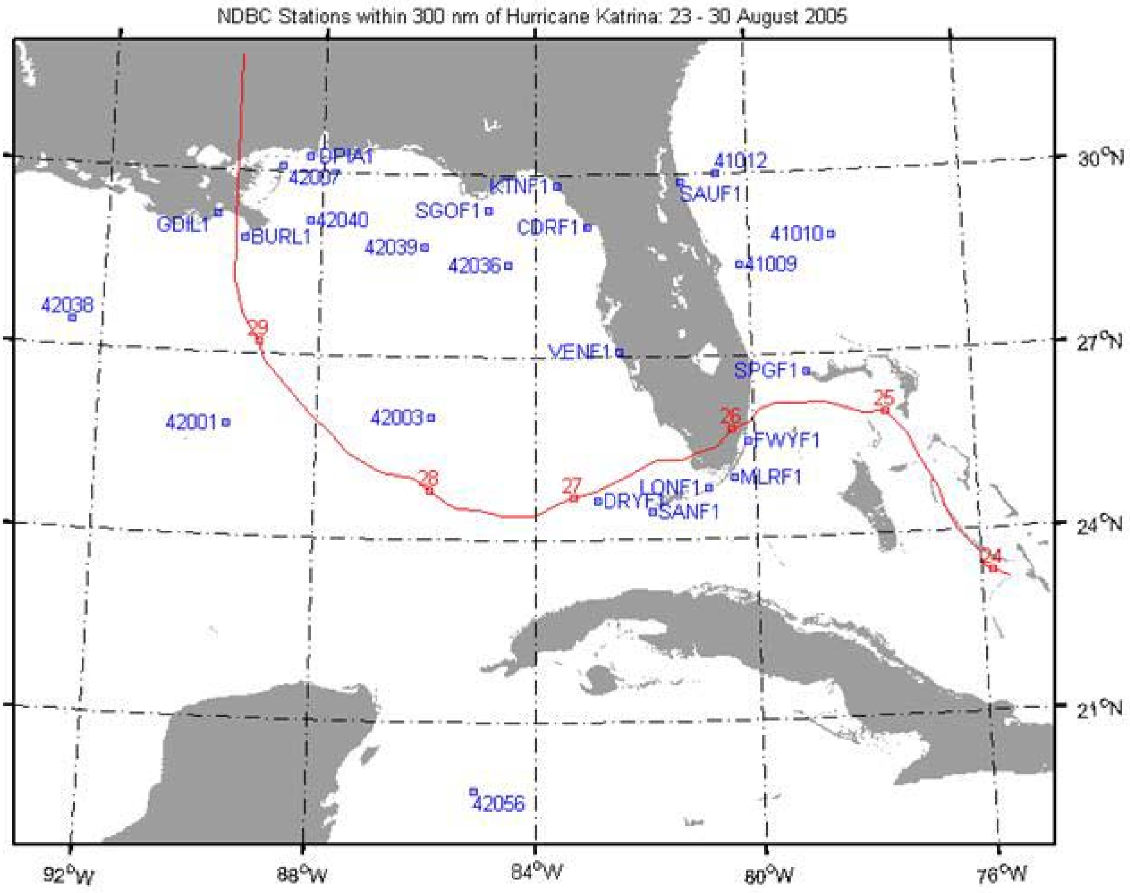

Fig. 11 : Hurricane Katrina's Track and NDBC Stations. Katrina's track (in red with the start of each day numbered) is from the current positions of the National Hurricane Center's Forecasts/Advisories (see http://www.ndbc.noaa.gov/hurricanes/2005/katrina/)

III. Relation Between Minimum Sea-Level Pressure and Wind Speed at 10m

On the basis of the balance between centrifugal force and pressure gradient force Hsu (2005) has formulated an operational cyclostrophic equation such that,

$$U10 = 6.3\ (1013 - Pmin)\ ^\wedge\ (1/2) \qquad (4)$$

Where U10 (in m/s) is the wind speed at 10m and Pmin is the minimum sea-level pressure (hPa or mb).

Further validations of Eq. (4) are presented in Fig.12 based on estimations from the National Hurricane Center (NHC) as listed in Table 2 during Katrina. Since Hurricane Lili had much higher U10 measurements than Katrina, we employ Lili data as measured at NDBC Buoy 42001 (see Fig.11) in 2002over the Gulf of Mexico (see Fig.13). These results indicate that Eq. (4) is very useful operationally.

Table 2 : Timeline and characteristics of Hurricane Katrina over the Gulf of Mexico in August 2005 (for data source, see www.nhc.noaa.gov)

Advisory number	Latitude degrees	Longitude degrees	Time UTC	Wind Speed, Kts	Minimum sea-level pressure mb	Saffir/Smpson Category
11	25.3	-81.5	08/26/09Z	65	987	HURRICANE-1
11A	25.3	-81.8	08/26/11Z	65	987	HURRICANE-1
11B	25.2	-82	08/26/13Z	65	987	HURRICANE-1
12	25.1	-82.2	08/26/15Z	70	981	HURRICANE-1
13	25.1	-82.2	08/26/15Z	85	971	HURRICANE-2
13A	24.9	-82.6	08/26/18Z	85	969	HURRICANE-2
14	24.8	-82.9	08/26/21Z	85	965	HURRICANE-2
14A	24.7	-83.3	08/27/00Z	85	965	HURRICANE-2
15	24.6	-83.6	08/27/03Z	90	965	HURRICANE-2
15A	24.4	-84	08/27/06Z	95	963	HURRICANE-2
16	24.4	-84.4	08/27/09Z	100	945	HURRICANE-3
16A	24.4	-84.6	08/27/12Z	100	940	HURRICANE-3
17	24.5	-85	08/27/15Z	100	940	HURRICANE-3
17A	24.5	-85.4	08/27/18Z	100	949	HURRICANE-3
18	24.6	-85.6	08/27/21Z	100	945	HURRICANE-3
18A	24.8	-85.9	08/28/00Z	100	944	HURRICANE-3
19	25	-86.2	08/28/03Z	100	939	HURRICANE-3
20	25.1	-86.8	08/28/06Z	125	935	HURRICANE-4
21	25.4	-87.4	08/28/09Z	125	935	HURRICANE-4
22	25.7	-87.7	08/28/12Z	140	908	HURRICANE-5
23	26	-88.1	08/28/15Z	150	907	HURRICANE-5
23A	26.5	-88.6	08/28/18Z	150	906	HURRICANE-5
24	26.9	-89	08/28/21Z	145	902	HURRICANE-5
24A	27.2	-89.1	08/29/00Z	140	904	HURRICANE-5
25	27.6	-89.4	08/29/03Z	140	904	HURRICANE-5
25A	27.9	-89.5	08/29/03Z	140	908	HURRICANE-5
25B	28.2	-89.6	08/29/07Z	135	910	HURRICANE-5
26	28.8	-89.6	08/29/09Z	130	915	HURRICANE-5
26A	29.1	-89.6	08/29/11Z	125	918	HURRICANE-5
26B	29.7	-89.6	08/29/13Z	115	923	HURRICANE-4

© 2015 Global Journals Inc. (US)

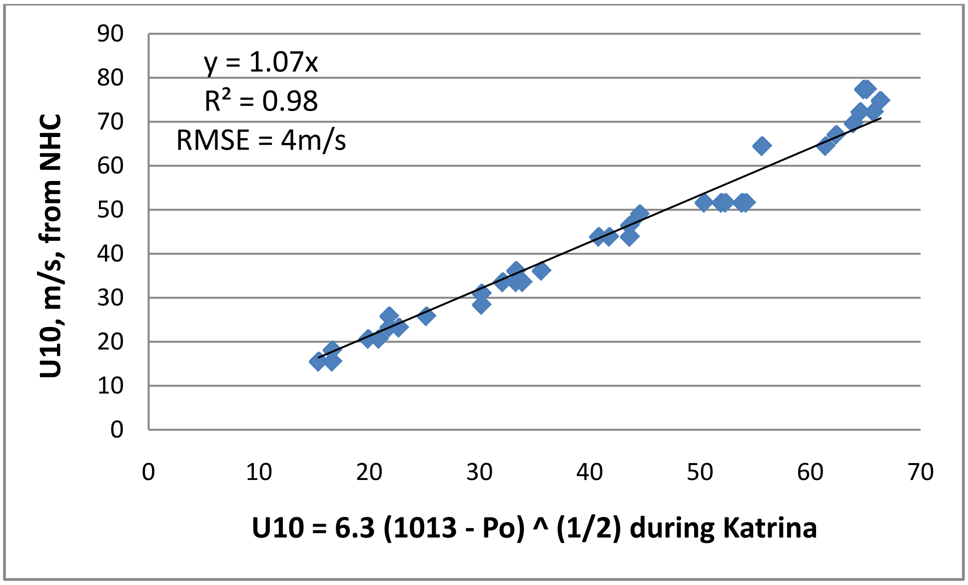

Fig. 12 : A verification of Eq. (4) based on data as listed in Table 2

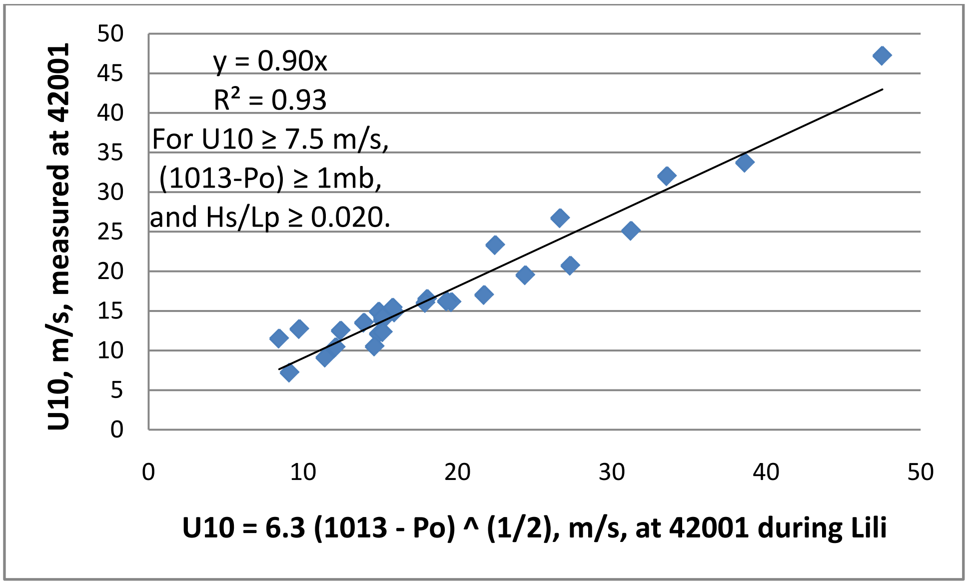

Fig. 13 : Further verification of Eq.(4) using the measurements made at Buoy 42001 during Lili in 2002

IV. Wind-Wave Interaction at NDBC Buoy 42003

As shown in Fig.11, NDBC Buoy 42003similar to that shown in Fig.14 was located on the right-hand side of the Katrina tack. Therefore, the wind and wave interaction should be intense. Unfortunately, the buoy was capsized during the storm (see, http://www.ndbc.noaa.gov/hurricanes/2005/katrina/). The data before its capsizing are listed in Table 3.

In order to investigate the wind-wave interaction, the effects of swell need to be minimized. According to Drennan et al (2005), the criterion to do so is to set that

$$Hs/Lp \geq 0.020 \qquad (5)$$

$$Lp = (g/2\pi)\ Tp\ \hat{}\ 2 = 1.56\ Tp\ \hat{}\ 2 \qquad (6)$$

Where Hs is the significant wave height, Lp is the dominant wave length, g (=9.8 m/s^2) is the gravitational acceleration, and Tp is the dominant wave period, and the parameter, Hs/Lp, is called wave steepness.

For wind-wave interaction, according to Csanady (2001, p.68),

$$g\ Hs/U^*\ \hat{}\ 2 = A\ (g\ Tp\ /U^*)\ \hat{}\ (3/2) \qquad (8)$$

$$U^* = (\tau/\rho)\ \hat{}\ (1/2) \qquad (9)$$

Where U* is the friction velocity, τ is the wind stress, ρ is the air density, and coefficient, A, needs to be determined from the field measurements.

The problem now is to estimate U* independently from the wave parameters. This is accomplished by employing the sonic anemometer measurements made over the North Sea during storms (for details, see Geernaert et al.1987). The results are presented in Fig.14, so that

$$U^*=0.0195U10^{1.285} \qquad (10)$$

In order to extend Eq. (10) into hurricane conditions, Fig. 15 is presented. Because the vorticity method is based on atmospheric physics (Anthes, 1982), it is used here. Since the slope between this method and Eq. (10) is near one and that the R ^2 value reaches to 94%, we are confident that Eq. (10) can be extended into hurricane conditions.

Now, with the data provided in Table 3, we can compute U* from U10 based on Eq. (10). Our results are shown in Fig.16. The coefficient "A" is determined to be 0.052 with R ^2 = 0.84 so that Eq. (8) becomes

$$g\,Hs/U^{*2} = 0.052\,(g\,Tp/U^*)^{(3/2)} \qquad (11)$$

Or,

$$U^* = 38\,Hs^{2}/Tp^{3} \qquad (12)$$

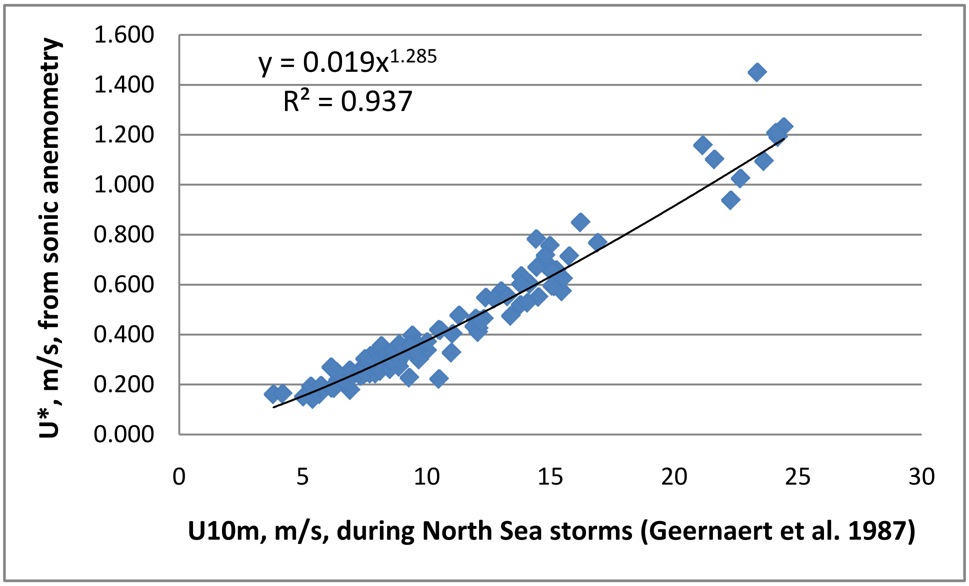

Fig. 14 : Relation between direct measurements of U* and U10m using sonic anemometers based on data provided in Geernaert et al. (1987)

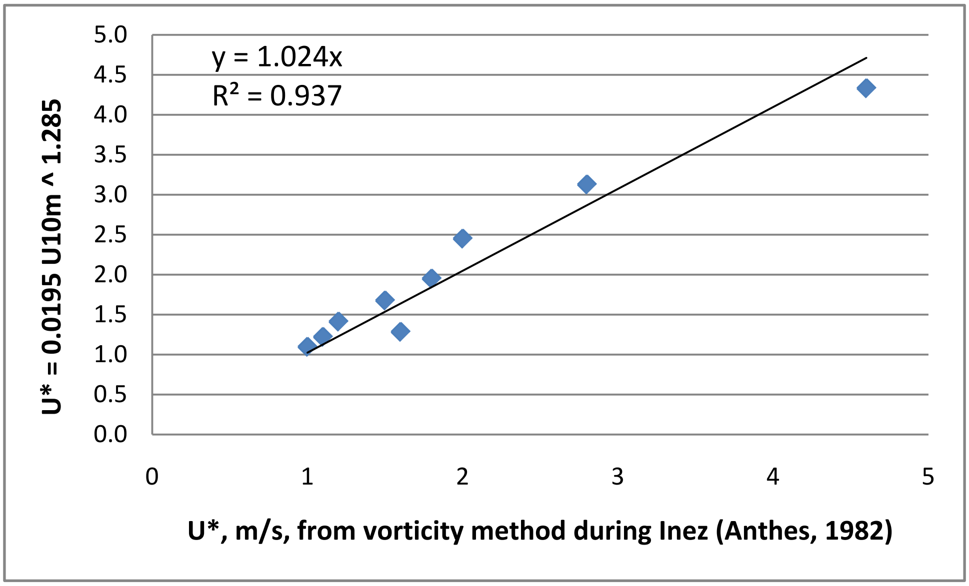

Fig. 15 : An extension of Equation (10) into hurricane conditions during Inez based on the dataset provided in Anthes (1982, p.71)

© 2015 Global Journals Inc. (US)

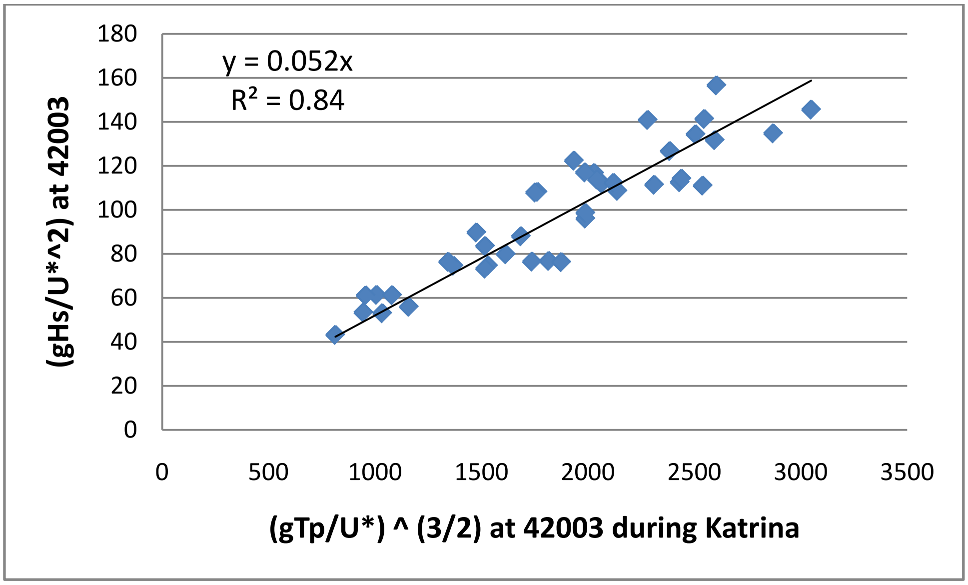

Fig. 16 : Verifying the 3/2 - power law between friction velocity, U*, and wave parameters (Hs, and Tp) at NDBC Buoy 42003 during Katrina

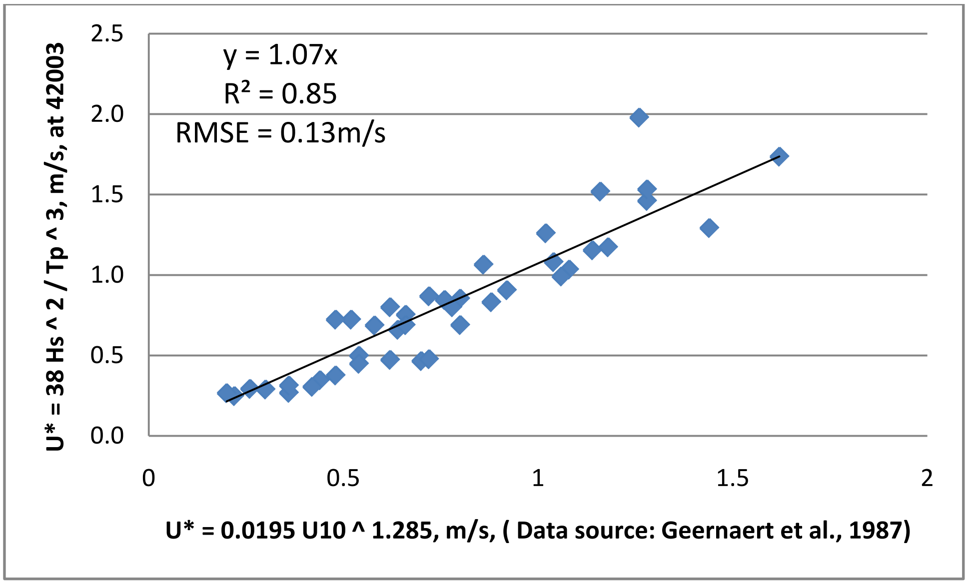

Fig. 17 : A comparison of Eqs. (10) and (12)

Table 3 : Wind and wave measurements at NDBC Buoy 42003 during Katrina in August 2005. U10 is for wind speed at 10m, Ugust for gust, Hs for significant wave height, Tp for dominant wave period, and Hs/Lp for wave steepness (for data source, see www.ndbc.noaa.gov)

Day	Hour UTC	Wind dir. degrees	U10 m/s	Ugust m/s	Hs m	Tp sec	Wave dir. degrees	Hs/Lp
26	12	12	8.2	9.3	1.26	6.25	36	0.021
26	13	15	8.5	9.8	1.25	5.88	23	0.023
26	14	19	8.9	9.9	1.44	6.67	33	0.021
26	15	12	9.7	11.2	1.5	6.67	31	0.022
26	16	9	10	11.8	1.6	7.14	28	0.020
26	17	16	11.9	13.7	1.73	7.14	28	0.022

26	18	15	10.5	12.7	1.82	7.14	29	0.023
26	19	13	12.4	14.5	1.91	7.69	30	0.021
26	20	9	12.9	15.3	2.12	7.69	25	0.023
26	21	15	13	16.5	2.11	7.14	37	0.027
26	22	26	13.4	16.1	2.44	7.69	31	0.026
26	23	36	12.8	15.5	2.61	8.33	41	0.024
27	0	50	12.8	15.4	2.94	7.69	43	0.032
27	1	42	12.2	14.6	2.94	7.69	41	0.032
27	2	41	12.8	15.9	2.68	8.33	49	0.025
27	4	44	14.1	17.7	3.98	10.81	90	0.022
27	5	44	14.6	17.9	4.45	10	91	0.029
27	6	49	14.9	18.1	5.09	11.43	96	0.025
27	7	47	14.4	17.7	5.2	11.43	100	0.026
27	8	51	14.6	18.2	5.37	10.81	92	0.029
27	9	53	15.2	19.2	5.68	12.12	100	0.025
27	10	50	14.9	18.7	6.29	12.12	97	0.027
27	11	69	16.5	19.4	5.67	12.12	99	0.025
27	12	51	16.8	19.9	6.12	12.12	99	0.027
27	13	49	16.9	20.9	6.32	12.12	100	0.028
27	14	52	17.4	21.3	6.72	12.9	104	0.026
27	15	55	18.3	24	7.35	12.12	105	0.032
27	16	63	18	23.4	7.64	12.9	106	0.029
27	17	62	19.6	24.2	7.15	12.9	111	0.028
27	18	65	20.8	25.1	7.06	12.12	104	0.031
27	19	66	20.7	25.9	7.81	12.9	113	0.030
27	20	68	20	25.1	7.68	12.12	114	0.034
27	21	64	20.7	25.1	6.85	12.9	116	0.026
27	22	64	21	26.9	7.41	12.12	111	0.032
27	23	68	23.8	29.1	7.48	12.9	116	0.029
28	0	65	25.2	31.6	8.27	12.12	120	0.036
28	1	68	28.6	34.4	9.26	12.9	116	0.036
28	2	77	25.6	33.7	9.9	12.9	119	0.038
28	3	89	26	32.4	10.28	13.79	127	0.035
28	4	96	26.6	33.8	9.44	13.79	118	0.032
28	5	105	26.3	32.6	10.57	12.9	121	0.041

V. EXTREME WAVES MEASURED AT NDBC BUOY 42040

According to NDBC (http://www.ndbc.noaa.gov/hurricanes/2005/katrina/),Station 42040, located at 29°11'03"N 88°12'48"W approximately 64 nautical miles south of Dauphin Island Alabama (Fig.11), reported a significant wave height of 16.91 meters (55.5 feet) at 1100 UTC, August 29, 2005 (see Fig.18). Station 42040 is a 3-meter diameter discus hull buoy deployed and operated by National Oceanographic and Atmospheric Administration's National Data Buoy Center (NDBC). Although 42040 does not measure maximum wave heights, the maximum wave height may be statistically approximated by 1.9 times the significant wave height (World Meteorological Organization, 1998), which would be 32.1 meters (105 feet). At the time of the report, Hurricane Katrina was approximately 73 nautical miles to the west of 42040 with maximum sustained winds of 145 miles per hour (Public Advisory 26A issued by the

© 2015 Global Journals Inc. (US)

National Hurricane Center, see Table 2). In addition to the 55-foot report, 42040 reported seas 12 feet or greater for 47 consecutive hours.

The 55-foot report surpasses the previous highest significant wave height reported by an NDBC buoy in the Gulf of Mexico of 15.96 meters (52 feet), also reported by 42040 during Hurricane Ivan in September 2004, and matches the previous highest significant wave height reported by an NDBC buoy of 16.91 meters reported by station 46003 (in the Northeast Pacific Ocean south of the Aleutian Islands) in January 1991.

On the basis of Table 4, the relation between Tp and Hs is plotted in Fig. 19. Since this relation is very consistent with that of other tropical cyclones including Typhoon Man-Yi in 2007(Hsu, 2015), they are combined together as presented in Fig. 20. If one accepts these statistics as indicated in the figure, according to Hsu (2015), we have

$$U10 = (21/ (12.7 – 2.2 \operatorname{Ln} (Hs))) \wedge 3.5 \qquad (13)$$

Now, substituting this max Hs (=16.91m) into Eq. (13), U10 = 61m/s. If we substitute both Hs (=16.91m) and Tp (=14.29 second) (as listed in Table 4 during 11Z on Aug 29) into Eq. (12), we get U* =3.72m/s. Then, by substituting this U* value into Eq. (10), we obtain that U10 = 60m/s. Another independent measurement of atmospheric pressure was made at NDBC Buoy 42007 located farther north from 42040 (see Fig.11). The data are shown in Fig.21. Note that the minimum pressure, Pmin=927.4mb, occurred at 15Z 29 Aug. Now, if we substitute this value into Eq. (4), we have U10 = 58m/s. Since the extreme Hs (=16.91m) occurred 6 hour earlier than the Pmin measured at 42007, the wind speed must be at least 58m/s. Since the measured max wind speed at 42040 (see Table 4) was only 28.1m/s, which occurred at 10Z 29 August, caution must be exercised in using the wind data (e.g., to estimate the significant wave height) when a hurricane is making its landfall because of the effects of landmass on air flow. Apparently, local winds near the time of a hurricane's landfall are too low to generate the waves as measured. This problem needs to be investigated further.

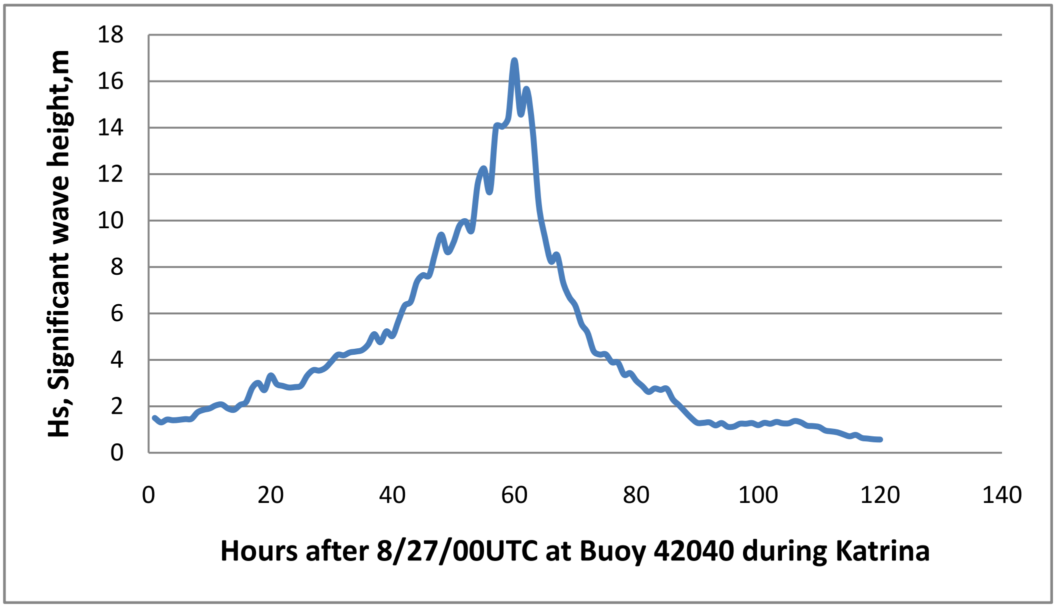

Fig. 18 : Measurements of extreme waves at NDBC Buoy 42040 during Katrina

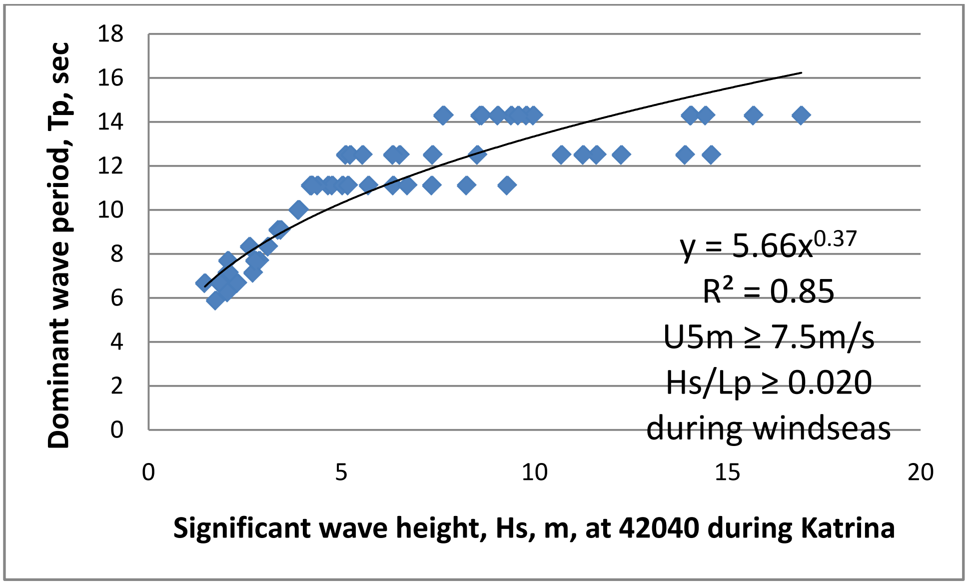

Fig. 19 : Relation between Hs and Tp at NDBC Buoy 42040 during Katrina based on Table 4 (for data source, see www.ndbc.noaa.gov)

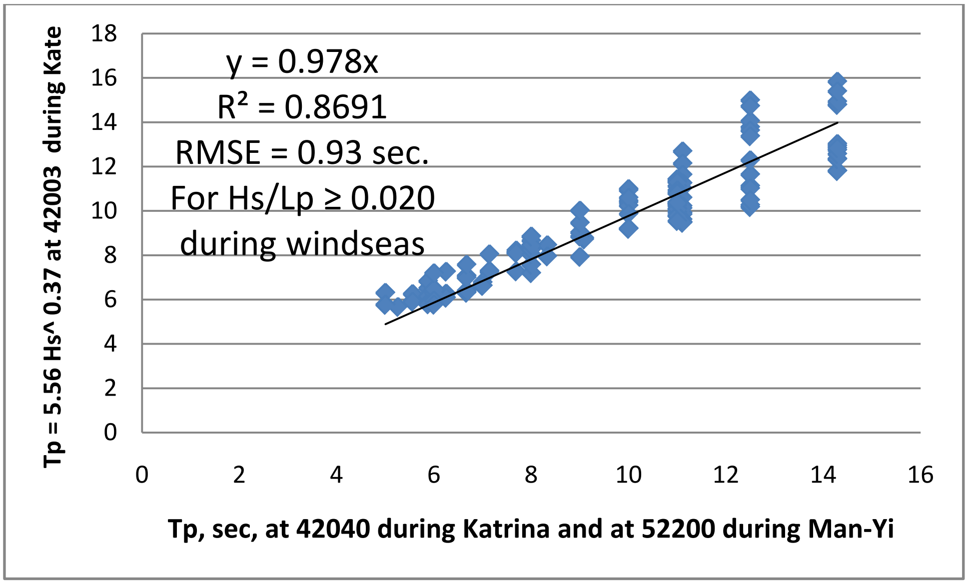

Fig. 20 : Measurements of Tp during Katrina and Typhoon Man-Yi (in 2007) and their comparison with that during hurricane Kate

© 2015 Global Journals Inc. (US)

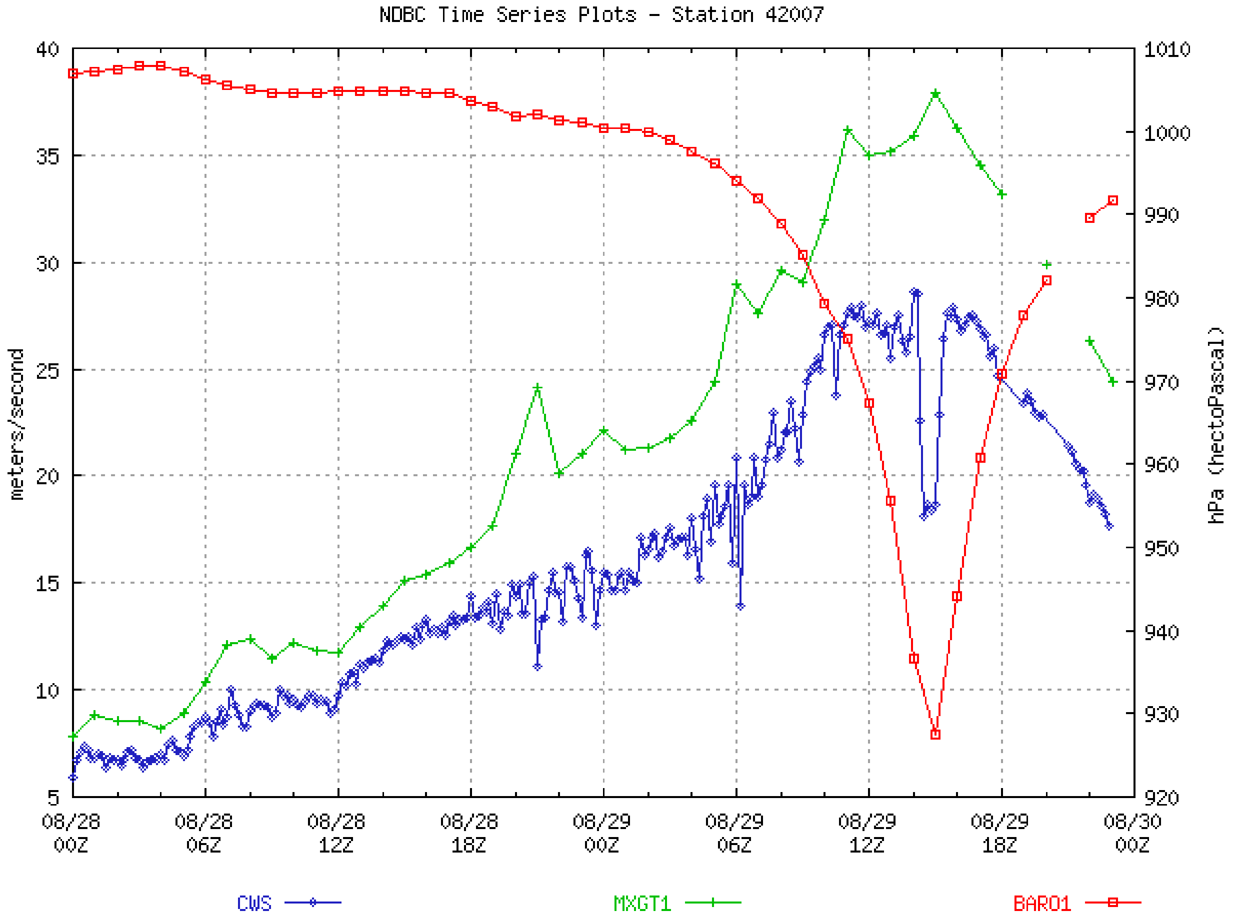

Fig. 21 : Station 42007: Winds (Anemometer Height 5m) and Sea-level Pressure (see http://www.ndbc.noaa.gov/hurricanes/2005/katrina/)

Table 4 : Wind and wave measurements at NDBC Buoy 42040 during Katrina in August 2005. U5 is for wind speed at 5m, Ugust for gust, Hs for significant wave height, Tp for dominant wave period, and Hs/Lp for wave steepness (for data source, see www.ndbc.noaa.gov).

Day	Hour UTC	Wind dir. degrees	U5m m/s	Ugust m/s	Hs m	Tp sec	Wave dir. degrees	Hs/Lp
27	6	57	9.2	10.9	1.46	6.67	101	0.021
27	7	65	9.5	10.9	1.74	5.88	105	0.032
27	8	74	9.2	10.8	1.85	6.67	100	0.027
27	9	80	9.2	10.6	1.91	6.67	103	0.028
27	10	67	8.1	9.8	2.04	7.14	101	0.026
27	11	62	8.2	9.6	2.08	7.14	104	0.026
27	12	61	7.7	9.3	1.91	6.67	97	0.028
27	13	61	7.5	9	1.85	6.67	89	0.027
27	14	60	7.6	9.1	2.06	7.69	103	0.022
28	7	66	11.8	14.8	4.2	11.11	126	0.022
28	11	73	12.5	15.4	4.66	11.11	124	0.024
28	12	70	13.1	15.9	5.11	12.5	120	0.021
28	13	70	13.7	16.2	4.76	11.11	122	0.025

28	14	70	13.8	17.6	5.23	12.5	117	0.021
28	15	73	13.3	17.3	5.03	11.11	124	0.026
28	16	72	16	19.2	5.7	11.11	127	0.030
28	17	76	15.8	20.5	6.34	11.11	123	0.033
28	18	69	16.1	20	6.51	12.5	112	0.027
28	19	61	14	17.5	7.36	12.5	113	0.030
28	20	77	15.4	19.4	7.65	14.29	108	0.024
28	21	84	17	21.4	7.63	14.29	108	0.024
28	22	95	15.8	19.3	8.59	14.29	123	0.027
28	23	86	18.5	23.8	9.4	14.29	106	0.030
29	0	78	18	21.4	8.64	14.29	101	0.027
29	1	82	18.6	24.6	9.05	14.29	102	0.028
29	2	82	19.1	24.4	9.79	14.29	101	0.031
29	3	84	15.5	19.8	9.97	14.29	105	0.031
29	4	85	21	27.1	9.58	14.29	94	0.030
29	5	108	18.4	29.3	11.61	12.5	100	0.048
29	6	104	23.8	30.1	12.25	12.5	94	0.050
29	7	108	24	32.3	11.26	12.5	96	0.046
29	8	111	25.5	32.1	14.06	14.29	256	0.044
29	9	128	25.1	32.3	14.04	14.29	250	0.044
29	10	127	28.1	35	14.43	14.29	242	0.045
29	11	139	27.3	33.9	16.91	14.29	0	0.053
29	12	147	27.1	34.6	14.58	12.5	213	0.060
29	13	159	28	35.8	15.67	14.29	161	0.049
29	14	166	25.2	31.2	13.9	12.5	198	0.057
29	15	174	22.9	29.2	10.7	12.5	157	0.044
29	16	190	22.3	28.1	9.29	11.11	219	0.048
29	17	196	19.9	24.5	8.24	11.11	217	0.043
29	18	203	19	24.1	8.52	12.5	219	0.035
29	19	204	17.4	21	7.34	11.11	225	0.038
29	20	211	17.2	21.9	6.71	11.11	230	0.035
29	21	215	15.1	18	6.33	12.5	238	0.026
29	22	217	13.8	17.2	5.55	12.5	237	0.023
29	23	212	12.6	15.5	5.17	11.11	220	0.027
30	0	206	11.8	14.6	4.38	11.11	212	0.023
30	1	203	11.5	13.9	4.23	11.11	210	0.022
30	2	200	10.6	13.2	4.24	11.11	196	0.022
30	3	186	11.9	15.6	3.9	10	191	0.025
30	4	195	11.1	13.8	3.88	10	192	0.025
30	5	202	10	11.8	3.36	9.09	184	0.026
30	6	209	8.8	10.6	3.43	9.09	188	0.027
30	7	209	9.1	10.7	3.1	8.33	182	0.029
30	8	199	9.2	11	2.87	7.69	188	0.031
30	9	201	10.1	12.1	2.62	8.33	193	0.024
30	10	204	10.2	12.4	2.77	7.69	196	0.030

© 2015 Global Journals Inc. (US)

30	11	205	8.9	10.6	2.71	7.14	197	0.034
30	12	210	8.3	9.8	2.76	7.69	208	0.030
30	13	215	8.3	9.7	2.3	6.67	201	0.033
30	14	212	7.9	8.9	2.05	6.25	199	0.034

VI. Storm Surge and Wave Setup Near Biloxi, MS, during Katrina

In August 2005Hurricane Katrina induced widespread coastal flooding in southeastern Louisiana and Mississippi Gulf coast including the City of New Orleans. The most important cause for these extensive damages is the storm surge, which is the water-level rise above normal astronomical tide. According to the S*hore Protection Manual* (USACE,1977), the total water level rise at the coast is due to the wind-stress tide, the Coriolis tide, the barometric tide, wave set-up, and local conditions including water depth and fresh water run-off from land into rivers and bays. Further analyses of the relative contribution of these various factors indicate that during Hurricane Camille in 1969, approximately 80% of the total surge was due to the wind-stress tide (Hsu, 2004). In addition, as demonstrated in Hsu (2012), during Hurricane Irene in 2011, approximately 92% of the total storm surge affecting the New York Harbor could be explained by a wind-stress tide relation proposed by Hsu et al. (1997). Some physics of the wind stress tide during Hurricane Sandy in 2013 are given in Hsu (2013).

According to Dean and Dalrymple (2002), the wave setup is a phenomenon that occurs primarily within the wave breaking zone and results a super elevation of the water level. Some characteristics of wave setup during Hurricane Katrina and Tropical Cyclone Mahina have been presented in Hsu(2014). An illustration of storm surge and wave setup with reference to the normal water level is shown in Fig.22 (see FEMA, 2006). High water mark surveys of both storm surge and wave setup near Biloxi, MS, located just north of Buoy 42007, are presented in Fig.23, which indicates that the storm surge was 25ft and wave setup 8ft, a 33ft (10m) in total water level rise.They are explained as follows:

According to Hsu (2004),

$$\text{Storm surge} = 0.07*(1010 - P_{min})*F_s*F_m \qquad (14)$$

Where Fs is a shoaling factor and Fm is a correction factor for storm motion. According to Hsu (2004), in the Biloxi area, Fs =1.2, and Fm = 1.0 (based on Advisory #26A and #26B, the forward motion speed of the storm was near 15 miles per hour) (http://www.nhc.noaa.gov/archive/2005/pub/al122005.public_a.026.shtml?).

Now, substituting these values and Pmin = 927.4mb from Fig.21 as measured at Buoy 42007, the storm surge from Eq. (14) is 24ft, which is in excellent agreement with the 25ft as measured (see Fig.23).

According to Guza and Thornton (1981), the max wave setup is linearly related to the max Hs, H_{smax} , so that

$$\text{Wave setup} = 0.17\, H_{smax} \qquad (15)$$

Now, substituting Hsmax (=55ft, from Fig.18), wave setup is 9ft. Again, this is in good agreement with the 8ft wave setup as measured (see Fig.23).

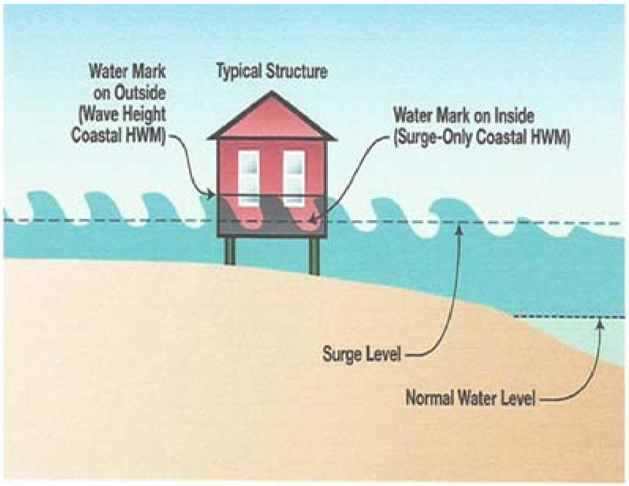

Figure 13 – Coastal HWM Resulting from Wave Height

Fig. 22 : An illustration of wave setup = (high water mark outside – high water mark inside the structure) (See FEMA, 2006). Note that HWM stands for High Water Mark

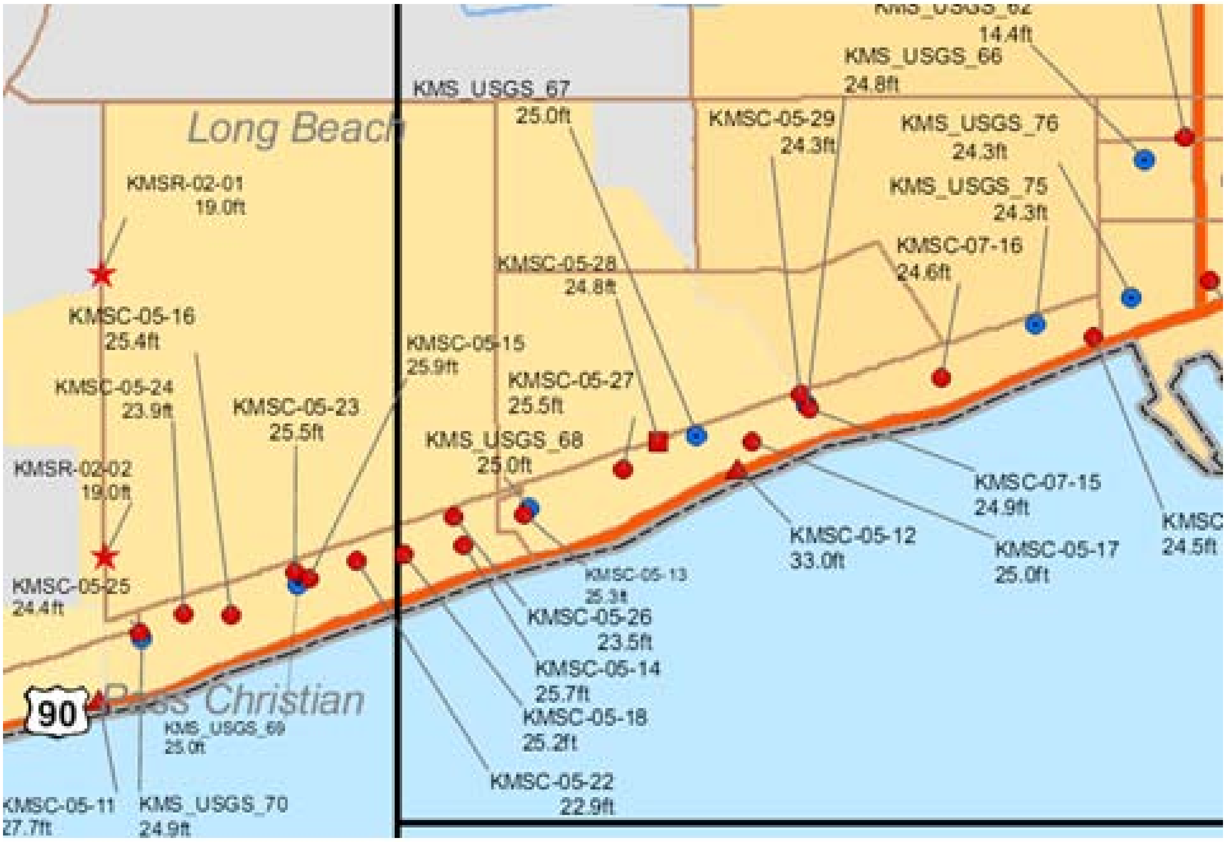

Fig. 23 : A section of HWM surveys along MS after Katrina (see FEMA, 2006). Note that an 8ft wave setup existed as a result of the difference between total inundation of 33ft at station KMSC-05-12 and the 25ft surge-only at nearby KMSC-05-17 (see FEMA, 2006)

VII. CONCLUSIONS

On the basis of aforementioned analyses and discussions, several conclusions can be drawn:

1) The power-law wind profile can be extended from the sea surface to 300m, which is approximately the top of the frictional boundary layer, see Equations (1) thru (3). This law is useful to estimate the wind loading on offshore structures during storms whether it is for design or forensic purpose;
2) The cyclostrophic equation, which is the balance between centrifugal force and pressure-gradient force, is valid so that the overwater wind speed at 10m, U10, can be estimated from the minimum sea-level pressure, Pmin, see Eq. (4);
3) Wind-wave interaction in the open sea as represented by NDBC Buoy 42003 indicates that the significant wave height, Hs, and its dominant wave period, Tp, can be normalized by the friction velocity, U*, resulting that U* can be estimated directly from Hs and Tp and that one can bypass the use of U10 and the drag coefficient; Extreme Hs (=17m or 55ft) measurement at Buoy 42040 could not be explained by the in-situ U10 data, but by Pmin (= 927mb) at 42007 in the vicinity as well as by the new U* and U10 formulations (see Equations (12) and (13), respectively);
4) Storm surge and wave setup near Biloxi, MS, can be explained physically by Equations (14) and (15), respectively; and
5) Because the wind data near Katrina's landfall is insufficient to explain the extreme wave, high storm surge and wave setup, caution must be exercised to use these wind data for the investigation of air-sea-land interaction when a tropical cyclone is near the coast.

REFERENCES RÉFÉRENCES REFERENCIAS

1. Anthes, R A (1982) Tropical Cyclones: Their Evolution, Structure and Effects. Meteorological Monographs, Volume 19, Number 41, American Meteorological Society, Boston, MA, 208pp.
2. Csanady, GT (2001) Air-Sea Interaction, Laws and Mechanisms. Cambridge University Press, 239pp.

3. Dean, R. G., and R. A. Dalrymple, 2002, Coastal Processes with Engineering Applications, Cambridge University Press.
4. Drennan, W. M., P. K. Taylor and M. J. Yelland, 2005: Parameterizing the sea surface roughness, Journal of Physical Oceanography, 35, 835-848.
5. FEMA, 2006, Final Coastal and Riverine High Water Mark Collection for Hurricane Katrina in MS, FEMA-1604-DR-MS, Task Orders 413 and 420.
6. Geernaert, G. L., S. E. Larsen, and F. Hansen, 1987: Measurements of the wind stress, heat flux, and turbulence intensity during storm conditions over the North Sea, Journal of Geophysical Research, 92, C12, 13,127-13,139.
7. Guza, R. T., and E. B. Thorton, 1981: Wave set-up on a natural beach, *J. Geophys. Res.*, 96, 4133-4137.
8. Hsu, S. A., 1988: Coastal Meteorology, Academic Press, 260pp.
9. Hsu, S. A., 2003: Estimating overwater friction velocity and exponent of power-law wind profile from gust factor during storms, Journal of Waterway, Port, Coastal, and Ocean Engineering, Vol. 129 (4), 174-177.
10. Hsu, S. A., 2004, A wind-wave interaction explanation for Jelesnianski's open-ocean storm surge estimation using Hurricane Georges' (1988) measurements. National Weather Digest, Vol. 28, 25-31, available online at http://www.nwas.org/digest/papers/2004/Vol28/Pg25-Hsu.pdf.
11. Hsu, S. A., 2005. "Air-Sea Interaction". In Water Encyclopedia, Vol. 4, pp. 1 - 4, Wiley – Interscience.
12. Hsu, S. A., 2012, Storm surges in New York Harbor during Hurricane Irene. Mariners Weather Log, 56(2), pp.7-11, August 2012, available online at http://www.vos.noaa.gov/MWL/201208/MWL_0912.pdf.
13. Hsu, S. A., 2013: Storm surges in New York during Hurricane Sandy in 2012: A verification of the wind-stress tide relation, Boundary-Layer Meteorology, 148(3), 593-598.
14. Hsu, S. A., 2014: Rapid estimations of air-sea-land interaction parameters during a tropical cyclone. Global Journal of Researches in Engineering: E, Civil and structural Engineering, 14(2), 1-16.
15. Hsu, S. A., 2015, Relation between sea surface roughness, wind speed at 10m, and wave parameters during a tropical cyclone, Global Journal of Science Frontier Research (H), Vol. 15, Issue 1, Version 1, pp.45-55.
16. Hsu, S. A., J. M. Grymes, III, and Z. Yan, 1997, A simplified hydrodynamic formula for estimating the wind-driven flooding in the Lake Pontchartrain – Amite River Basin, National Weather Digest, 21(4), 18 – 22.
17. Powell, M. D., and Reinhold, T. A., 2007, Tropical cyclone destructive potential by integrated kinetic energy, Bulletin of American Meteorological Society, 84(4), 513-526.
18. U.S. Army Corps of Engineers (USACE), 1977: Shore Protection Manual. 3rd. ed., US Government Printing Office, 3-101-3-145.
19. Wang, D.-P., and L.-Y. Oey (2008), Hindcast of waves and currents in Hurricane Katrina, Bulletin of American Meteorological Society, 89(4), 487-495.

© 2015 Global Journals Inc. (US)