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Rapid Estimations of Air-Sea-Land Interaction Parameters during a Tropical Cyclone

By Professor S. A. Hsu

Louisiana State University, United States

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RAPIDESTIMATIONSOFAIRSEALANDINTERACTIONPARAMETERSDURING ATROPICALCYCLONE

Rapid Estimations of Air-Sea-Land Interaction Parameters during a Tropical Cyclone

Professor S. A. Hsu

Abstract- Hurricane Ivan in 2004 and Hurricanes Katrina and Rita in 2005 devastated northern Gulf of Mexico and its coastal regions with catastrophic impacts in some regions. On the basis of applied physics of air-sea-land interaction, following formulas are derived and validated using the minimum sea-level pressure (P_o in mb) as the most important input. They are: (1) Maximum wind speed (in m/s)= 6.3 $(1013 - P_o)^{0.5}$; (2) Max significant wave height (in m) = 0.20 $(1013 – P_o)$; (3) Max wave setup (in feet)= 0.11 $(1013 – P_o)$; (4) Max surface drift velocity (in m/s) = 0.22 $(1013 – P_o)^{0.5}$; (5) Most probable shoaling depth (in m) = $(1013 – P_o)$; (6) Max storm surge (in feet) = $0.23*(1010 – P_o)*F_s*F_m$, where F_s is a shoaling factor (not the shoaling depth) and F_m is a correction factor for storm motion; And(7) Max bottom (seabed) stress (in N/m^2) = 0.016 $(1013 – P_o)$. Examples for the applications of these formulas are provided.

Keywords: hurricane winds; hurricane waves; currents during hurricane; wave setup during hurricane; shoaling depth during hurricane; storm surge during hurricane; wave setup during hurricane; shoaling depth during hurricane; seabed stress during hurricane.

I. Introduction

In 2004 Hurricane Ivan and again in 2005 Hurricane Katrina (Fig.1) devastated numerous oil and gas production facilities in the north central Gulf of Mexico (see e.g. Figs.2 and 3) as well as over 1,800 fatalities and countless destruction and damages to the near shore infrastructures including bridges (e.g. Figs 4 and 5) and buildings (costing about $81 billion in damages). In order to rapidly estimate these destructions before and after the land-falling tropical cyclones, this article provides civil and structural engineers with engineering meteorology and oceanography so that educated assessments may be made. While numerical simulations of these destructive forces can be made, the purpose of this paper is for those engineers working with emergency managers and legal professionals who may not have the access of numerical modeling of computational fluid dynamics.

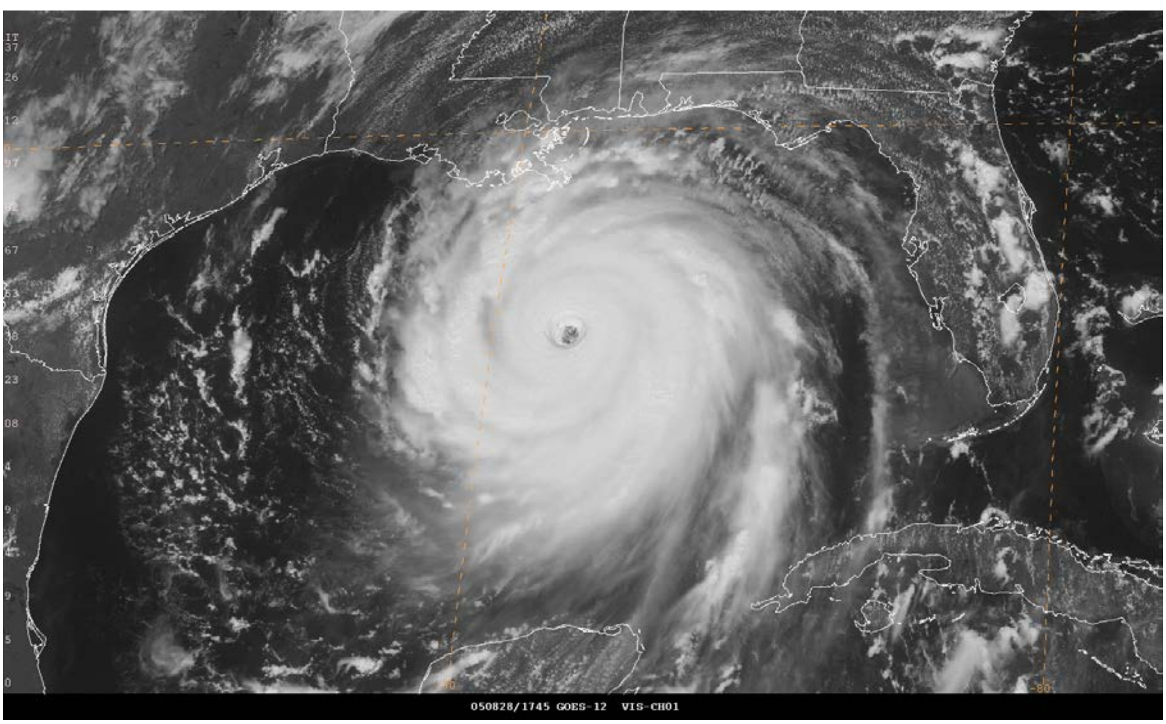

Figure 1 : GOES-12 visible image of Hurricane Katrina over the central Gulf of Mexico at 1745 UTC 28 August 2005, near the time of its peak intensity of 150kt (www.nhc.noaa.gov)

Author: Coastal Studies Institute, Louisiana State University. e-mail: sahsu@lsu.edu

Figure 2 : Mars Tension-leg platform (From http://en.wikipedia.org/wiki/Mars_(oil_platform)

Figure 3 : Mars platform showing damage from Hurricane Katrina in 2005 (From 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".

Figure 4 : 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

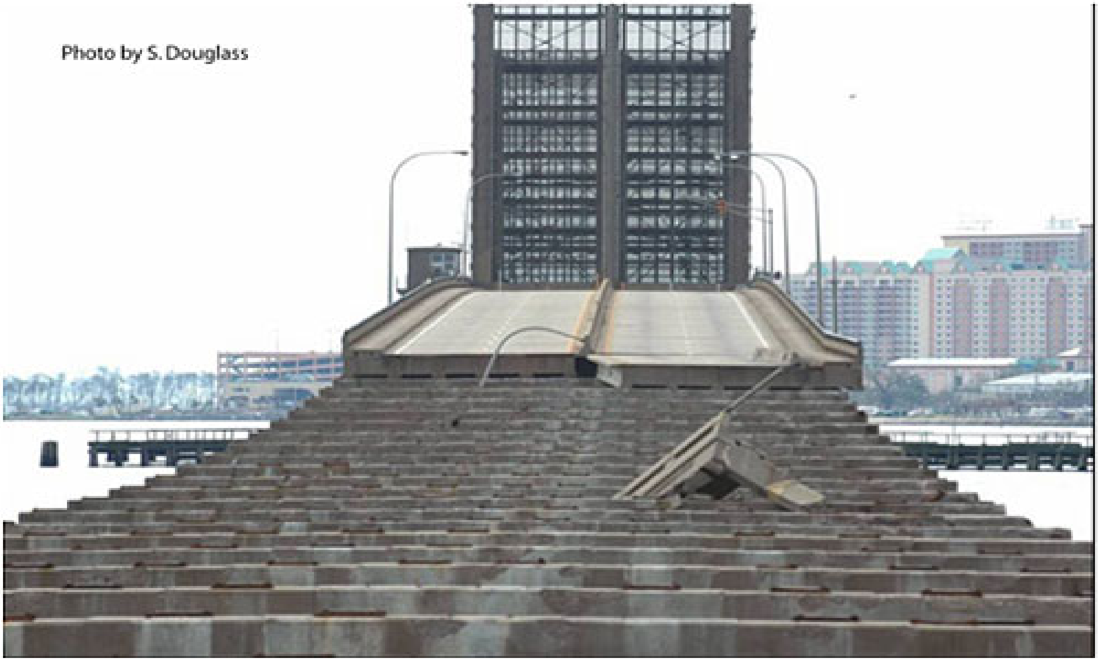

Figure 5 : US 90 bridge over Biloxi Bay, Mississippi was damaged by Katrina. Since the spans at higher elevations were not removed, the wave setup on top of the storm surge is more important than the wind loading (photo looking southwest from Ocean Springs 2/19/06, from FHWA-NHI-07-096)

II. Estimating Hurricane Winds

According to Hsu (1988), from the cyclostrophic equation when the centrifugal force is balanced by the pressure gradient force, we have

$$U_a^2/\Upsilon = (1/\varrho)\,\Delta P/\Delta\Upsilon = (1/\varrho)\,(P_n - P_0)/(\Upsilon - 0) \qquad (1)$$

Where U_a is the maximum sustained wind speed above the surface boundary layer, Υ is the radius of the hurricane, ϱ is the density of air, $\Delta P/\Delta \Upsilon$ is the radial pressure gradient, P_n is the pressure outside the hurricane effect (=1013mb, the mean sea level pressure), P_0 is the hurricane's minimum central pressure. Because ϱ = 1.2 kg m^{-3},

$$\Delta P = (1013 - P_0)\text{mb, and } 1\text{ mb} = 100\text{ N m}^{-2} = 100\text{ kg m}^{-1}\text{ s}^{-2},\ (1)$$

Becomes

$$U_a = [(100\text{ kg m}^{-1}\text{ s}^{-2})/(1.2\text{ kg m}^{-3})]^{0.5} * (\Delta P)^{0.5} = 9\,(\Delta P)^{0.5} \quad (2)$$

According to Powell (1982), $U_{10} = 0.7\ U_a$; therefore,

$$U_{10} = 6.3\,(\Delta P)^{0.5} = 6.3\,(1013 - P_0)^{0.5} \qquad (3)$$

Where U_{10} is the wind speed at 10 m in m/s and ΔP is in mb.

On the basis of the datasets provided in Powell and Reinhold (2007), Eq. (3) has been verified by Hsu (2008) and is illustrated in Fig.6. In addition, according to Li et al. (2013) for 26 tropical cyclones with circle eyes over both Atlantic and north Pacific Basins, Eq.(3) is further validated in Fig.7. Since the slope of these linear regressions is almost equal to one with high correlation coefficients (for R = 0.82 and 0.89), Eq. (3) can be used operationally. Note that, although there was no derivation like aforementioned discussions, Eq. (3) has been employed by Simpson and Riehl (1981, p. 278, Fig. 127).

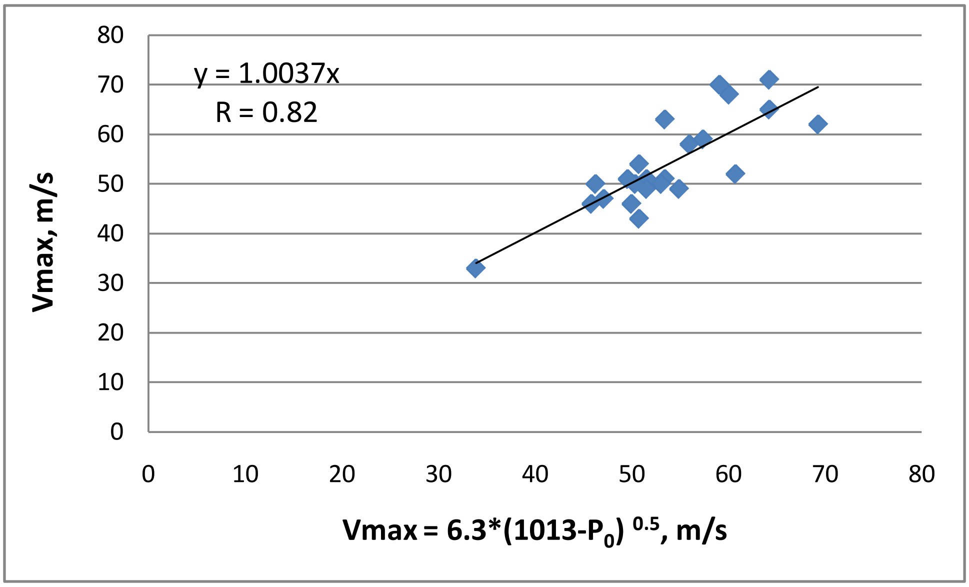

Figure 6 : Verification of Eq.(3) based on the dataset provided in Powell and Reinhold (2007)

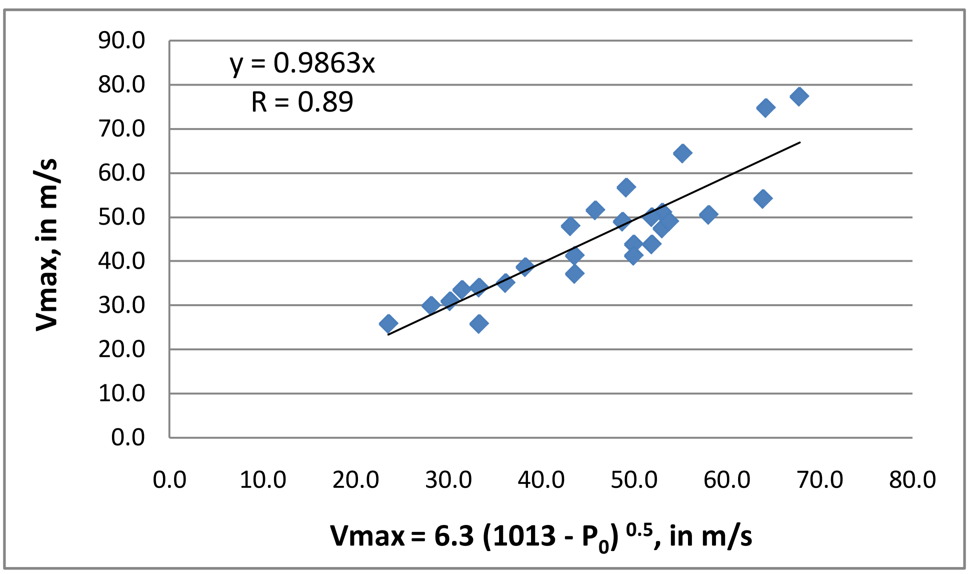

Figure 7 : Further validation of Eq. (3) based on the dataset provided in Li et al (2013)

III. Estimating Hurricane Waves

According to the Shore Protection Manual (see USACE, 1984),

$$(g\ H_s/U_{10}\text{^}2) = 0.0016\ (g\ F/U_{10}\text{^}2)\ \text{^}\ (1/2) \tag{4}$$

$$(g\ T_m/U_{10}) = 0.2857\ (g\ F/U_{10}\text{^}2)\ \text{^}\ (1/3) \tag{5}$$

$$T_p = 0.95\ T_m \tag{6}$$

$$T_p = 12.1\ (H_s/g)\ \text{^}\ (1/2) \tag{7}$$

Where g is the acceleration of gravity, H_s is the significant wave height, F is the fetch, T_m is the period of the peak of the wave spectrum, and T_p is the dominant wave period. Both T_p and H_s are measured and reported routinely by NDBC (see www.ndbc.noaa.gov).

During Hurricanes Ivan (2004) and Katrina (2005), large waves occurred. Using the data available online (see www.ndbc.noaa.gov) at Buoy 42040, Equation (7) is verified as show in Fig.8. Since the slope of this linear regression is close to one with a relatively high correlation coefficient (R = 0.85), Eq. (7) can be used operationally.

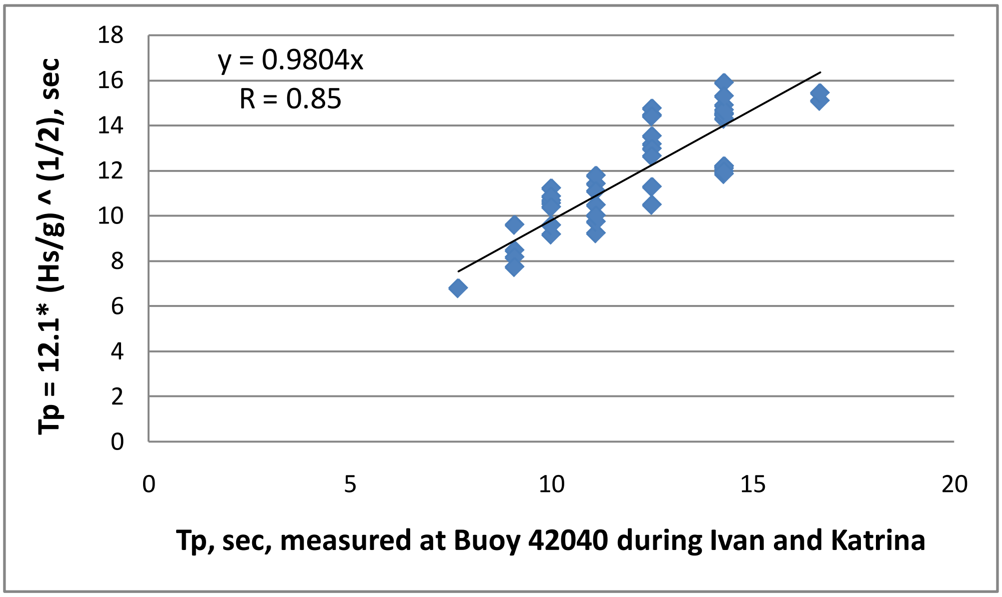

Figure 8 : Verification of Eq. (7) during Hurricanes Ivan and Katrina

Now, eliminating the fetch parameter, F, and rearraging Eqs. (4) and (5), we have

$$(g\,H_s/U_{10}\text{^}2) = 0.0113\,(gTp/U_{10})\ \text{^}\ (3/2) \qquad (8)$$

Equation (8) is validated in Fig.9 based on datasets not only in Hsu (2003) but also extending all measurements with the pressure less than 1013mb.

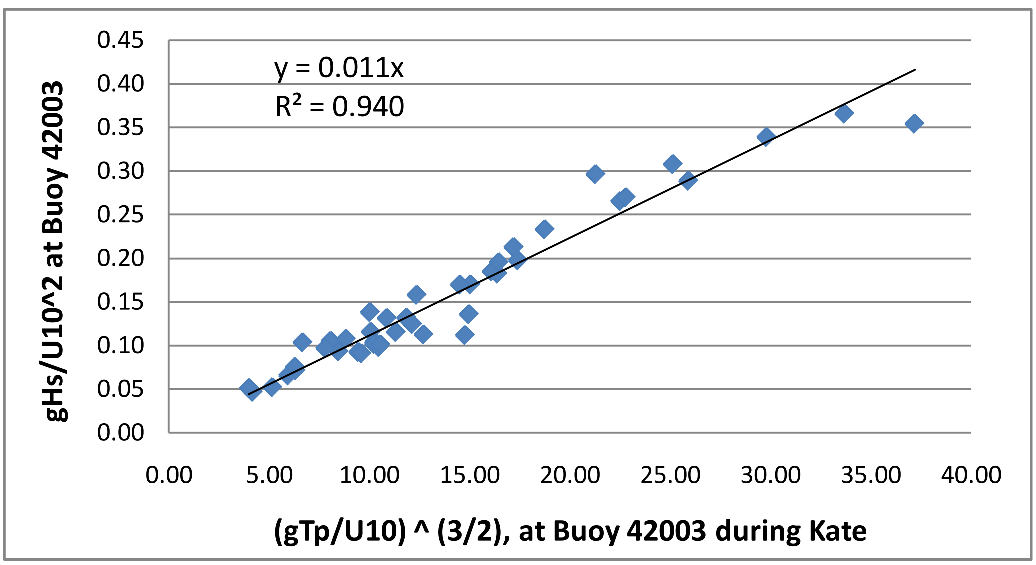

Figure 9 : Validation of Eq. (8) during Hurricane Kate (data source: www.ndbc.noaa.gov) for all measurements with pressure < 1013mb

For operational applications, the coefficient needs to be changed from 0.0113 to 0.0112 so that

$$(g\,H_s/U_{10}\text{^}2) = 0.0112\,(gT_p/U_{10})\ \text{^}\ (3/2) \qquad (9)$$

Substituting Eq. (7) into (9), one gets

$$Hs = 0.0050\,U_{10}\text{^}2 \qquad (10)$$

$$U_{10} = 14.1(H_s\text{^}0.5) \qquad (11)$$

Now, from Eq. (3), we have

$$H_{smax} = 0.20\,(1013 - P_o) \qquad (12)$$

Where H_{smax} is the maximum significant wave height in meters.

Validations of Eq. (12) are provided in Fig. 10. Further verifications are provided in Hsu (2009) for Hurricane Ike. Furthermore, During Ivan NHC's Hurricane Report indicates that P_o = 931mb near the max H_s= 16m (Fig.12) and during Katrina P_o =927.4mb at Buoy 42007 in the vicinity of Buoy 42040 where max H_s = 17m (Fig.13). These maximum significant wave heights for Ivan and Katrina are nearly identical to those estimated by Eq. (12).

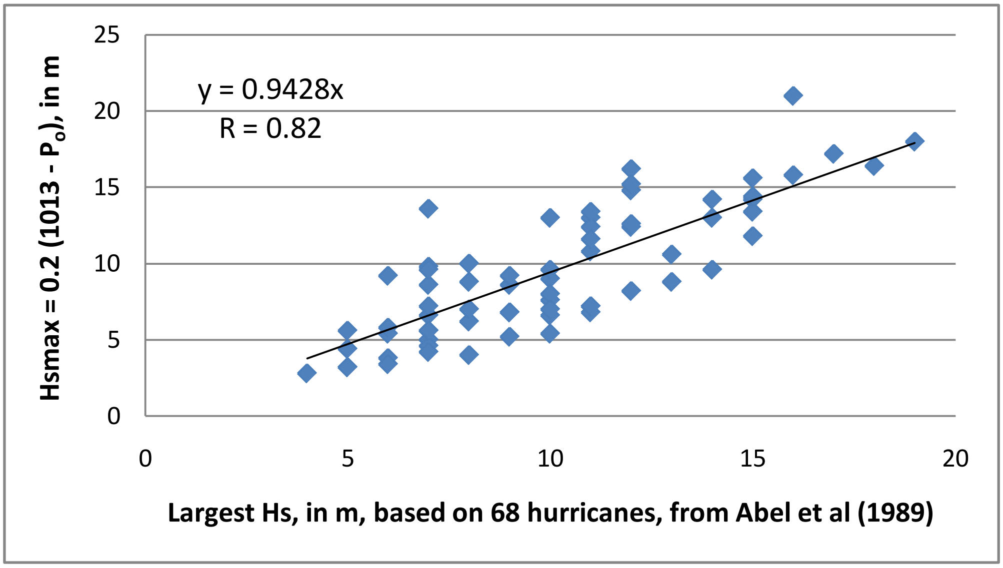

Figure 10 : Validation of Eq. (12) based on the datasets provided in Abel et al (1989)

Verification of Eq. (12) for a typhoon is presented as follows:

According to the Joint Typhoon Warning Center (see Fig. 11), on 6 October 2007, Super Typhoon Krosa was near northeastern Taiwan. The minimum sea-level pressure, P_o = 929mb. Substituting this value into Eq. (12), we get the maximum significant wave height to be approximately 17m. Now, according to Liu et al. (2008), the maximum trough-to-crest wave height was measured to be 32.3m by a data buoy near northeast Taiwan in the western Pacific that was operating during the passage of Krosa.

According to the World Meteorological Organization (1998), the maximum trough-to-crest wave height may be statistically approximated by 1.9 times the significant wave height. Therefore, the maximum significant wave height is 32.3/1.9 = 17m during Typhoon Krosa near NE Taiwan. This value is identical to the result using Eq. (12). In addition, Eq. (12) is found to be consistent with Wave watch III modeling in the South China Sea during Typhoon Muifa in 2004 (see Chu and Cheng, 2008).We can say that Eq. (12) is applicable during a typhoon.

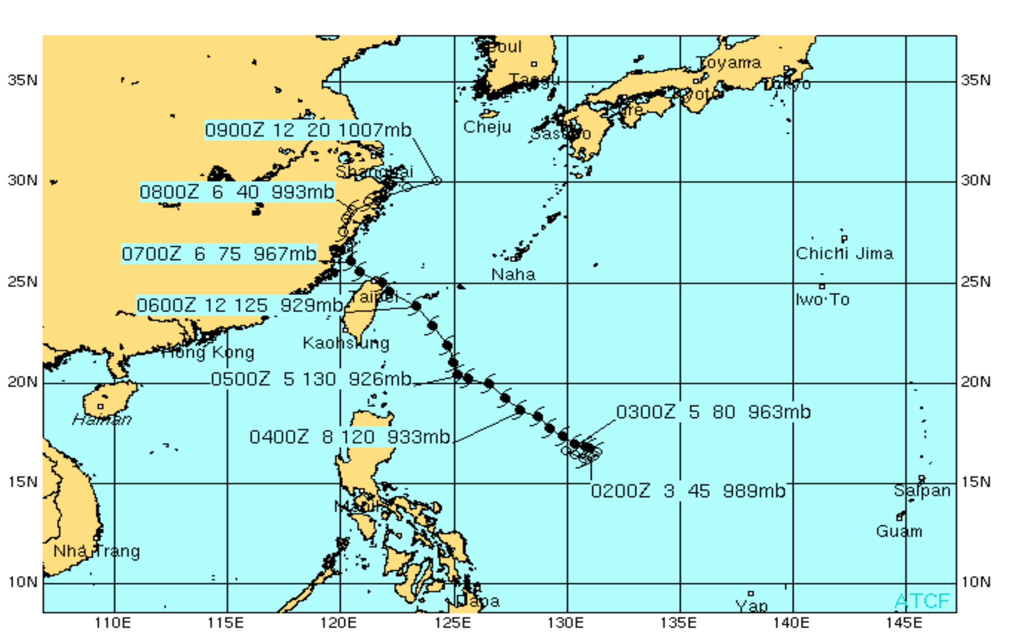

Figure 11 : Best Track of Super Typhoon Krosa in October 2007 (http://www.usno.navy.mil/NOOC/nmfc-ph/RSS/jtwc/atcr/2007atcr.pdf)

IV. Estimating Maximum Wave Setup

According to Dean and Dalrymple (2002, page 84),the wave setup is a phenomenon that occurs primarily within the wave breaking zone and results a super elevation of the water level. According to Guza and Thornton (1981), the max wave setup, W_{setmax}, is approximately,

$$W_{setmax} = 0.17\ H_{smax} = 0.034\ (1013 - P_o) \qquad (13a)$$

$$W_{setmax}\ (\text{in feet}) = 0.11\ (1013 - P_o) \qquad (13b)$$

Where H_{smax} is the maximum significant wave height in deep-water before shoaling and P_o in mb.

During Ivan in 2004 and Katrina in 2005, values of H_{smax} are available from NDBC as shown in Figs. (12) and (13), respectively. Substituting the average value of 16m into Eq. (13a), the maximum wave setup was about 2.72m or 8.9ft. This value is in good agreement with ADCIRC modeling (see Douglass, 2006) (see Fig.14). Note that the value of 8ft for the wave setup has been used in wave force estimation for the failure of the Biloxi Bridge during Katrina (Fig.5) (see, e.g., McPherson (2008).For simplicity, it is illustrated as follows:

Since Force = pressure*area, we have

Force per unit area = pressure = density*gravitational acceleration*height

= unit (or specific) weight of water*height

$= 62.4(\text{lb/ft}^3)*W_{setmax} = 62.4*8 = 499\text{lb/ft}^2.$

Therefore, this 8ft wave setup can exert approximately 500 pound wave force per square foot impacted on the Biloxi Bridge during Katrina.

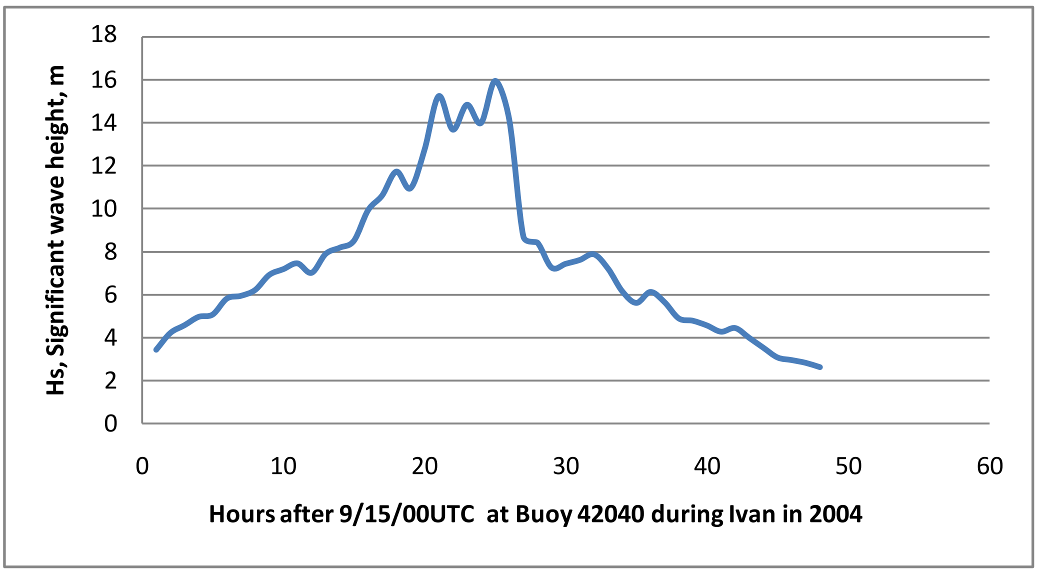

Figure 12 : Measurements of significant wave height at NDBC Buoy 42040 during Ivan

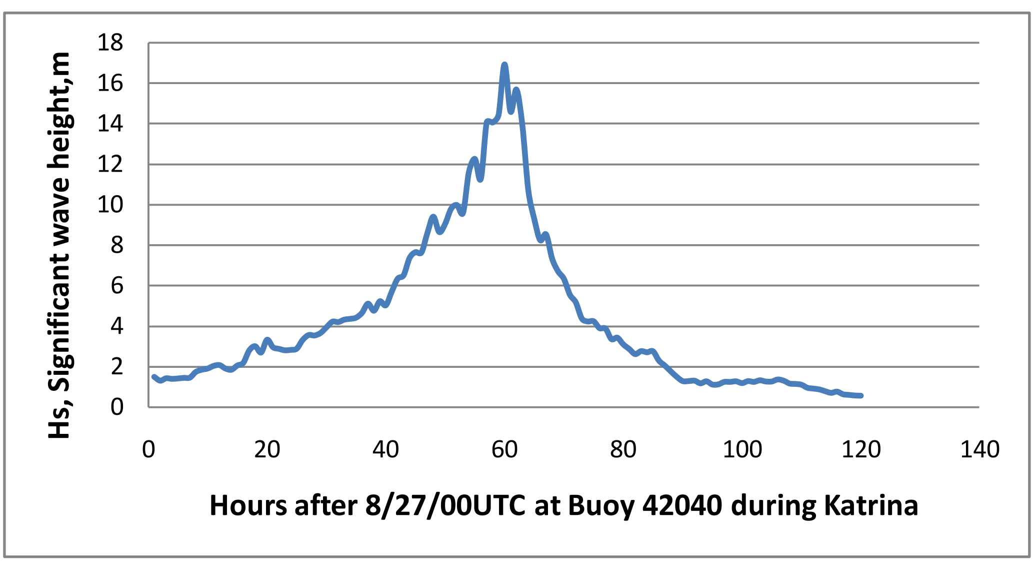

Figure 13 : Measurements of the significant wave height at Buoy 42040 during Katrina

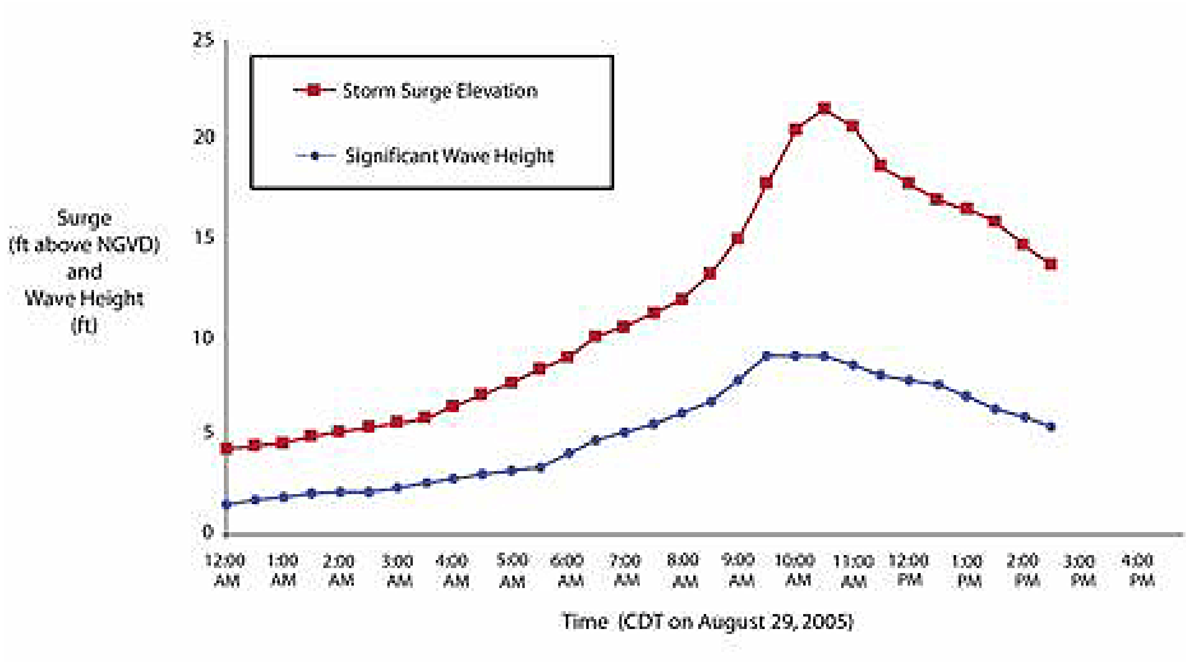

Figure 14 : Storm surge hydrograph as estimated by ADCIRC modeling for Hurricane Katrina at the US 90 Bridge across Biloxi Bay, MS (Fig.5) (from Douglass, et al., 2006)

V. Estimating Hurricane-Generated Currents

According to Hsu (2003), the magnitude of surface drift velocity, U_{sea} is

$$U_{sea} = 0.22 \; P \; U_{10} \qquad (14)$$

Where P is the turbulence intensity which is related to the gust factor, G, as follows:

$$G = 1 + 2P \qquad (15)$$

According to Stewart (2004) and Fig.15, during Ivan, G= 73kts/55kts = 1.327 at 10m at Buoy 42040 and G = 135kts/102kts = 1.324 at 122m at a nearby oil rig (NDBC station #42364, see www.ndbc.noaa.gov). Since the G values at 10 and 122m are nearly identical, we substitute either value into Eq.(15) and get P = 0.16. Substituting this P value into Eq. (14) and applying Eq. (3), we get

$$U_{sea} = 0.22 \, (1013\text{-}P_o)^{0.5} \qquad (16)$$

Now, according to the Tropical Cyclone Report for Hurricane Ivan (see p.9 in Stewart, 2004 at www.nhc.noaa.gov), P_o= 931 mb. Substituting this value into Eq.(16), we have U_{sea}= 2.0 m/s. Comparisons this value against both measurements and modeling results (Fig.16) show that Eq.(16) is consistent with both measurements and numerical modeling. Further verification for Eq. (16) during Katrina is illustrated as follows: According to Knabb et al (2005), P_o = 902 mb occurred at 18UTC28August 2005 (at 26.3N and 88.6W). Substituting this value into Eq. (16), U_{sea}= 2.3 m/s. This value is in good agreement with that of modeling results by Wang and Oey (2008, Fig.4).

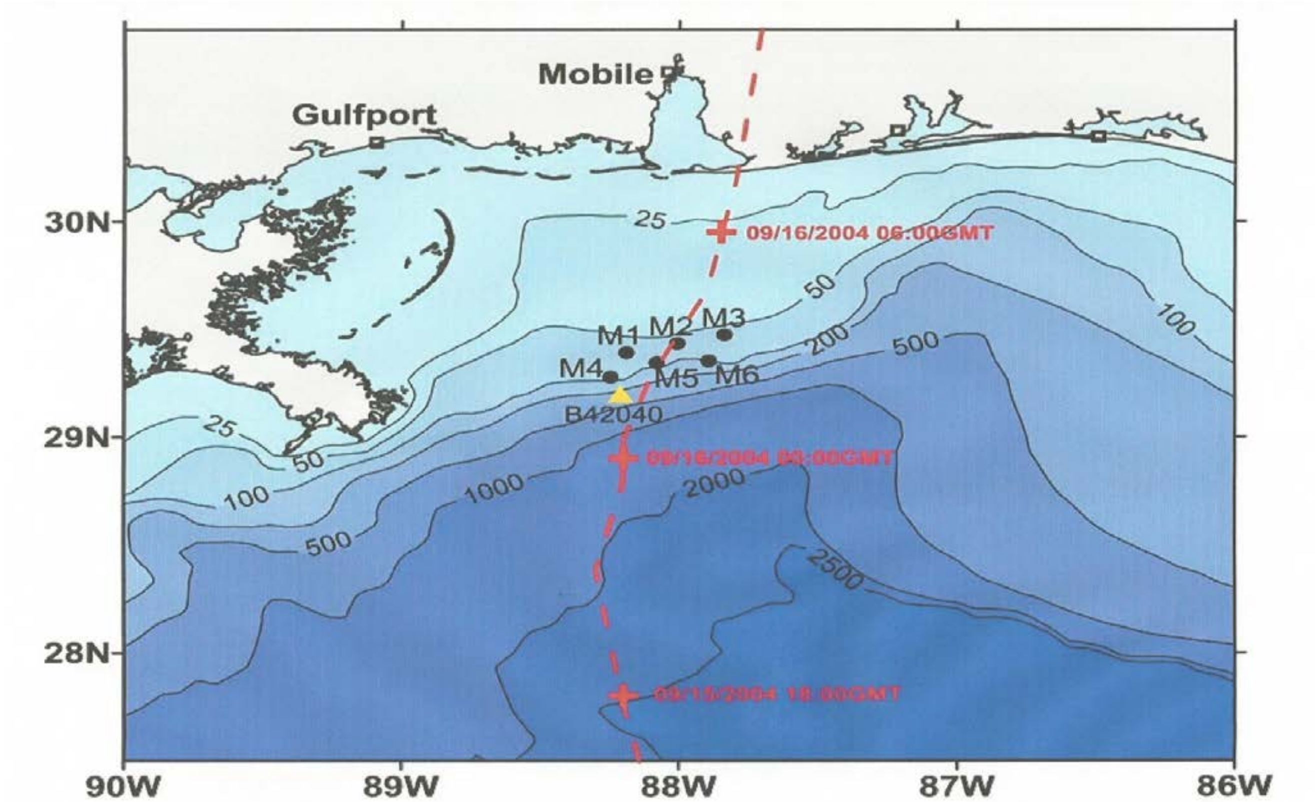

Figure 15 : Ivan Track and measurement stations (see Wijesekera et al., at http://www.motherjones.com/files/Source_177__High_Sea-Floor_ Stress_Induced_by_Extreme_Hurricane_Waves_1.pdf)

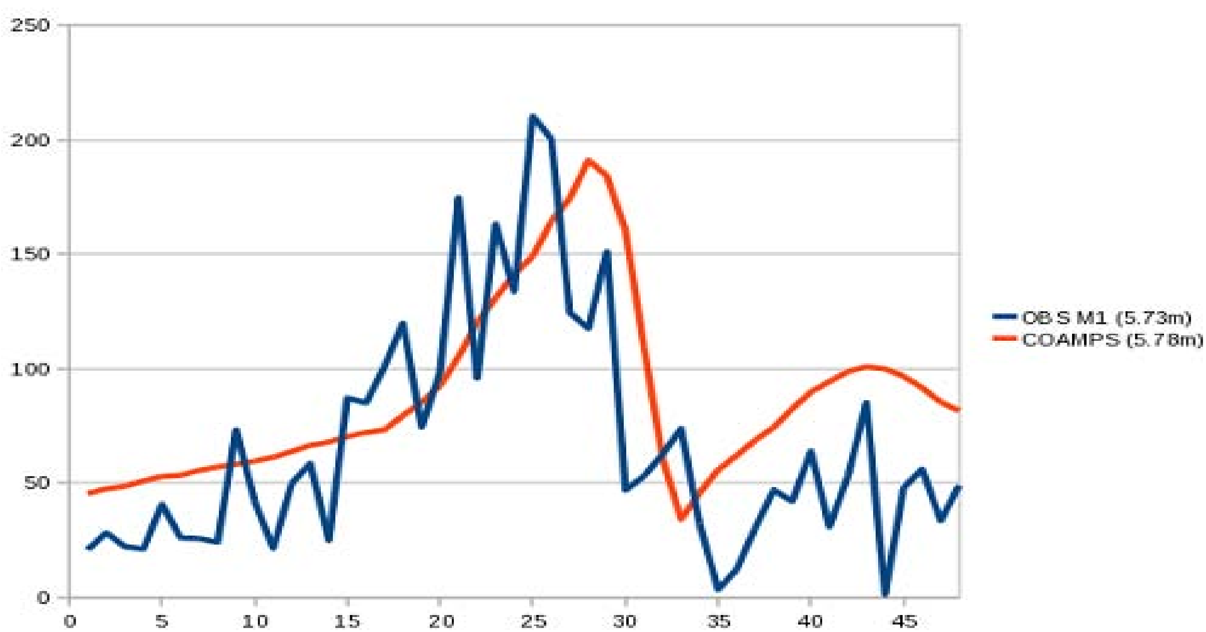

Figure 16 : ADCP measurements of the near surface current speed (cm/s) at approximately 6 m water depth (blue) and Model simulation (red) at NRL Station M1 (see Fig. 15) (see Chen et al., at www.onr.navy.mil/reports/FY10/npchen.pdf) over a 48-hour period from September 16, 2004

VI. Estimating Shoaling Depth

From Taylor and Yelland (2001) and Equations (7) and (12), the shoaling depth is

$$D_{shoaling} = 0.2\ L_p = 0.2\ gT_p^2/2\pi = 4.7\ Hs = 4.7 * 0.2\ (1013 - P_o) \quad (17)$$

Where L_p is the wave length.

Therefore, Shoaling depth ≈ (1013 – P_o), in meters (18)

According to Wijesekera et al (2010, see www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA523020), during the passage of Ivan (see Fig. 15), the bottom stress was dominated by the wind-induced stresses, and exceeded critical levels at depths as large as 90 meters. Now, substituting P_o = 931mb into Eq. (18), we get that the shoaling depth was 82 m during Ivan. Since this estimate is consistent with the measurements, Eq. (18) may be useful as a first approximation.

VII. Estimating Storm Surges

According to Hsu (2013), for estimating the storm surges caused by the wind-stress tide,

$$gD(dS/dx)=\tau_{sx}/\rho_w \quad (19)$$

$$\tau_{sx} = \rho_a\ C_d\ V^2 \quad (20)$$

$$S - S_0 = [\rho_a\ C_d/(\rho_w\ g)](F/D)\ V^2 \quad (21)$$

$$S = K_1\ V^2 = K_2\ (1013 - P_o) \quad (22)$$

$$S = K_3\ H_s \quad (23)$$

Where g is the acceleration due to gravity, D is the water depth, S represents the wind-stress tide along the prevailing wind direction, x, τ_{sx} is the wind stress along x, ρ_a and ρ_w are the density of air and water, respectively, C_d is the drag coefficient, V is the wind speed, S_o is the astronomical tide, F is the fetch along x, and K_1, K_2, and K_3 are constants to be determined by high water marks and P_o is the minimum sea-level pressure in mb.

Eq. (22) has been verified by Hsu (2013) during Hurricane Sandy in 2012 and by Hsu (2012) during Hurricane Irene in 2011, both hurricanes affected the New York area.

Eq. (23) is evaluated as follows:

During Hurricane Ike in 2008, extensive damages and coastal flooding were inflicted along the coasts of upper Texas and southwestern Louisiana. According to the data available thru NDBC, three stations are employed for our analysis: they were NDBC Buoy 42035 located about 22 NM east of Galveston, TX and two NOS water level stations (Figs.17 thru 19). Since these R^2 (coefficient of determination) values are very high, we can say that Eq. (23) can be used operationally.

In addition, on the basis of wind-wave interaction during Hurricane Georges in 1998, K_3=0.285 (see Hsu, 2004). From Fig.18, K_3=0.276. Because the difference between these K_3 values is only 3%, we can again say that Eq. (23) is useful.

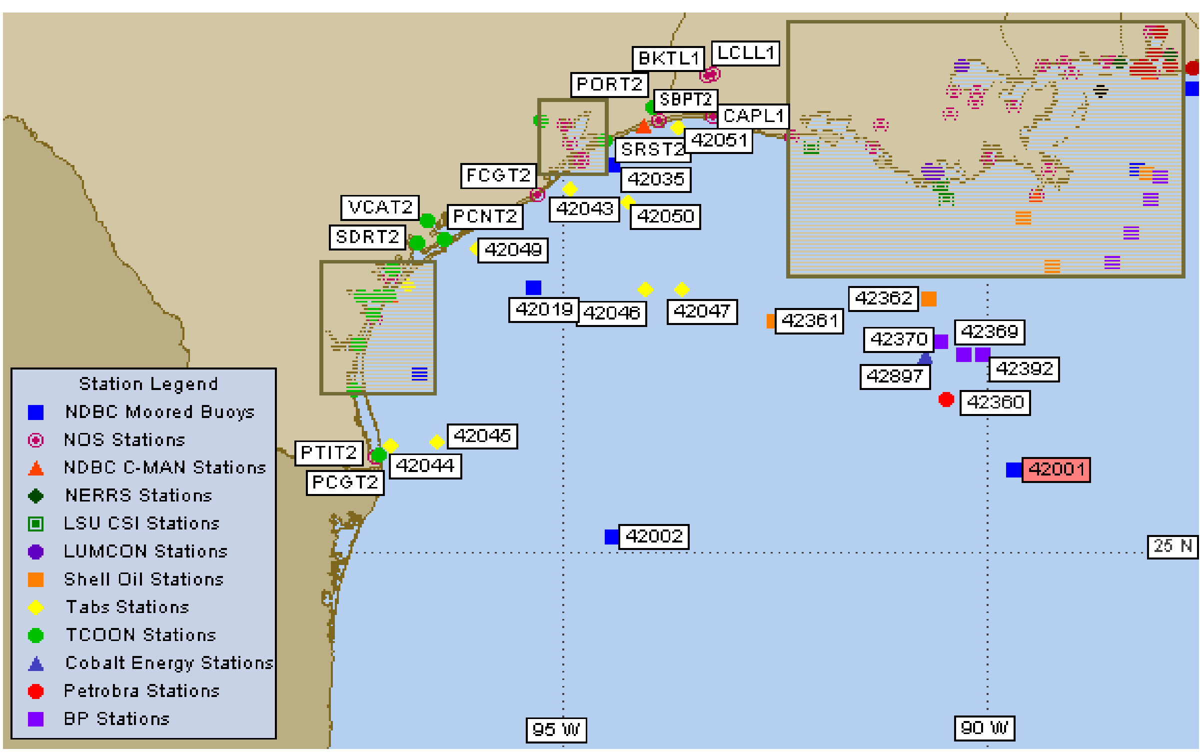

Figure 17 : Location map for NDBC Buoy 42035 and NOS Stations CAPL1 and GSPT2 (inside the box for Galveston, TX) (see www.ndbc.noaa.gov)

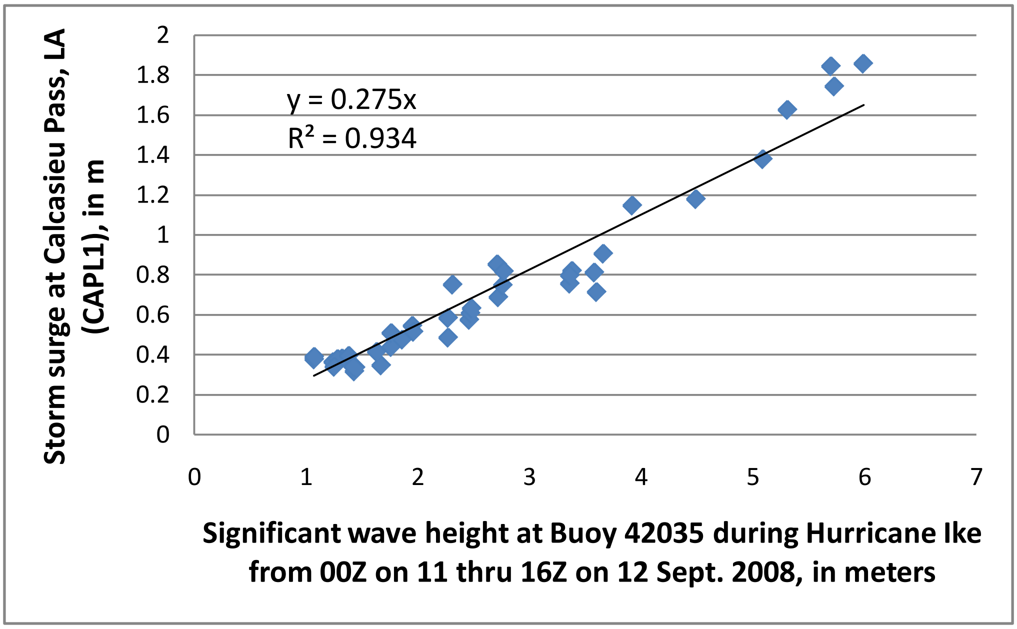

Figure 18 : Validation of Eq. (23) during the passage of Hurricane Ike

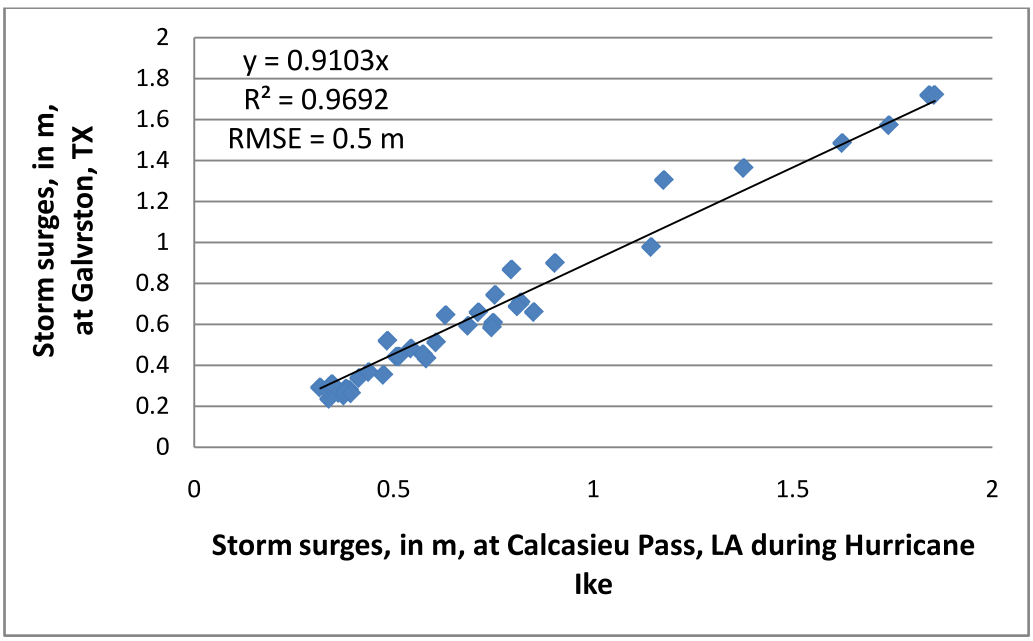

Figure 19 : Storm surges on the right-hand side of Ike track

Maximum storm surge elevation without wave setups, S, can also be estimated analytically (see Hsu, 1988 and 2004, and Hsu et al., 2006) as

$$S \text{ (in feet)} = 0.23*(1010 - P_o)* F_s* F_m \qquad (24)$$

Where P_o is the minimum sea-level pressure in mb, F_s is a shoaling factor (see Fig. 20), and F_m is a correction factor for storm motion (see Fig. 21).

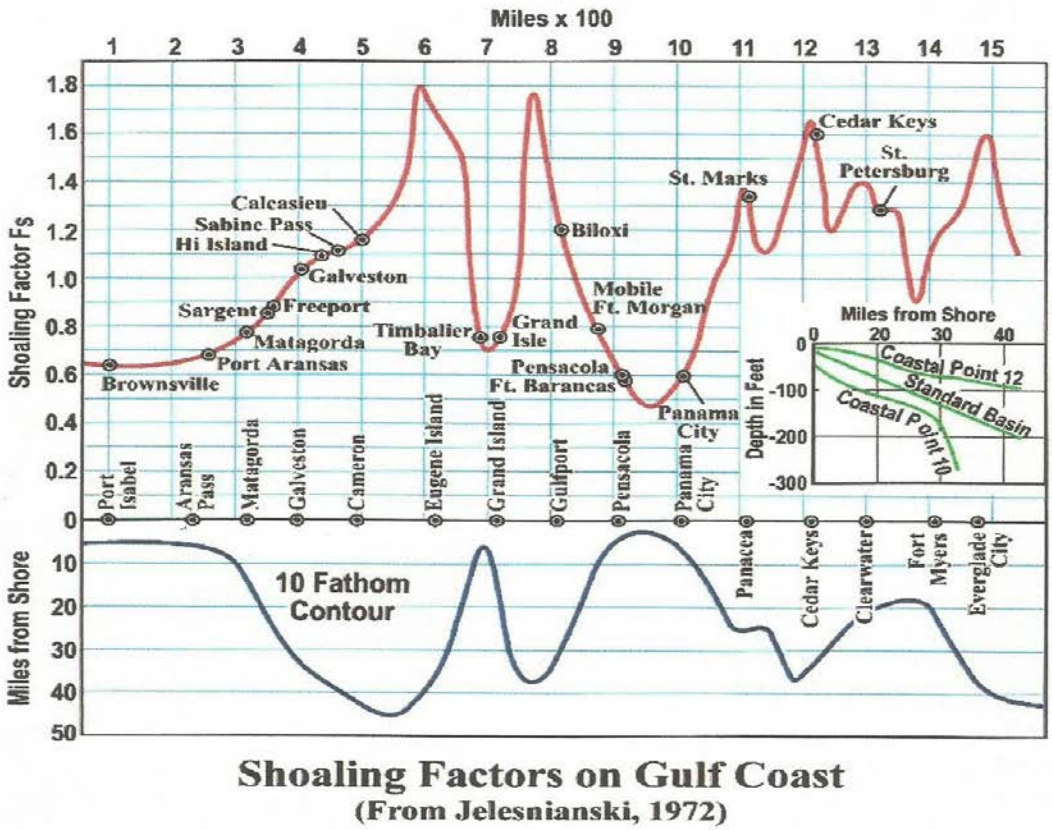

Figure 20 : The Shoaling factor, F_s, for Eq. (24) (from Jelesnianski, 1972)

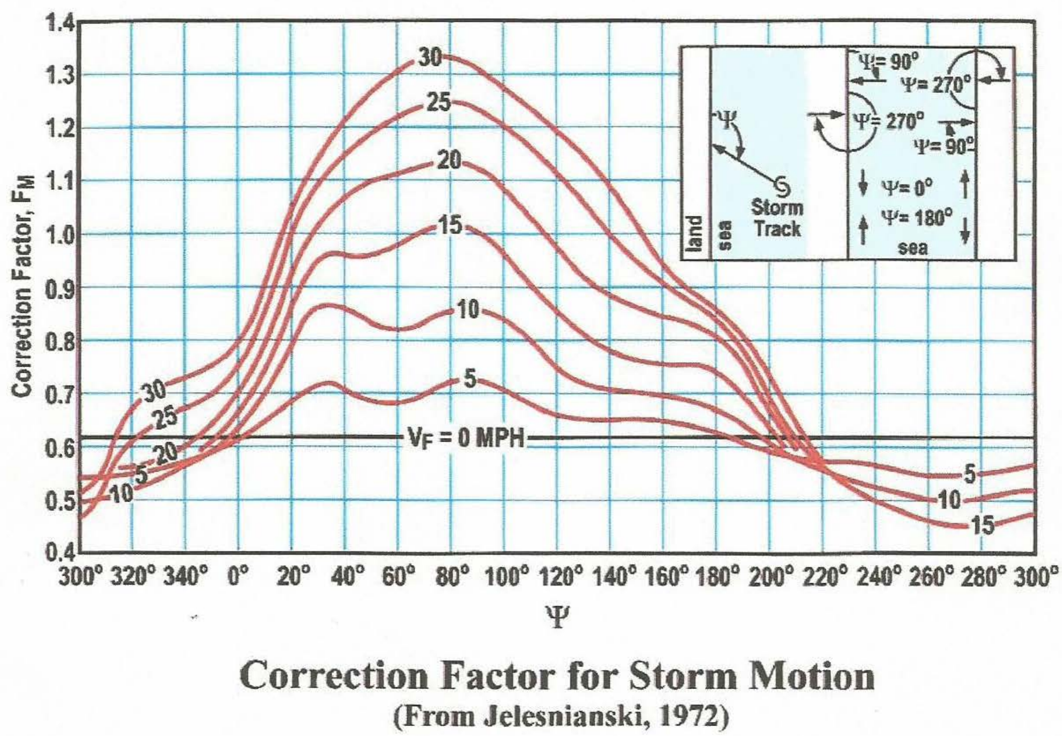

Figure 21 : Correction factor for storm movement, F_m, used in Eq. (24) (from Jelesnianski, 1972)

An application for Eq. (24) to estimate the storm surge in the vicinity of Biloxi Bridge (Fig.5) is presented as follows:

According to the Tropical Cyclone Report for Hurricane Katrina issued by the National Hurricane Center (NHC) (see http://www.nhc.noaa.gov/pdf/TCR-AL1220 05_Kat rina.pdf). The lowest pressure was 927.4mb (see NHC, Page 32) recorded at Buoy 42007, which was located about 25 miles due south of Biloxi.

Now, substituting P_o=927.4mb, F_s=1.2 for Biloxi, MS, and F_m=1.0, according to the NHC Advisories at the time of Katrina landfall near LA/MS border, which was approximately 15 mph, into Eq. (24), we have

$$S = 0.23^* (1010 - 927.4)^*1.2^*1.0 = 23 \text{ feet.}$$

Since this value is in excellent agreement with the results of ADCIRC modeling (Fig. 14) and high-water mark survey by FEMA (2006), we can say that Eq. (24) is useful for practical use.

VIII. Estimating the Stress on Seabed

According to Wijesekera et al (2010, see www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA523020), strong surface waves and currents generated by major hurricanes can produce extreme forces at the seabed that scour the sea floor and cause massive underwater mudslides. The combined current-wave stress, $\tau_{cw,}$ on the sea floor is approximately related to the wind stress, U^2, so that from Eq. (3), we have

$$\tau_{cw} = 0.0004\ U_{10}\text{^}2 = 0.016\ (1013 - P_o) \qquad (25)$$

Note that the units of bottom stress are N/m^2 or Pa and P_o is in mb.

The critical bottom stress to initiate the sediment movement is provided in Table 1. It can be seen that for the median grain sand of 0.06 mm and finer ones, a tropical storm force (P_o=1005mb, approximately) wind can start these sands in motion at water depth shallower than 8 m according to Eq.(18). Now, on the basis of Eq. (25) and Fig.15, the bottom stresses caused by Ivan (when P_o=931mb) and Katrina (P_o=927mb) could have exceeded 1.31 and 1.38 Pa, respectively, more than 10 times of the critical bottom stress needed to set the sediment in motion. These estimates may be used to explain massive sediment transport near the seabed shallower than 80-90m that in turn caused numerous structural failure and pipeline displacements due to strong near-bottom orbital wave velocity (>2m/s) and near-bottom currents ranged from 0.40 to 1.20 m/s at all moorings (see Fig.15) during Ivan's passage (Teague et al., 2006).

Table 1 : Critical stress thresholds for sand mixtures of select median grain sizes following Souls by (1997)

Median Grain Size (d50, mm)	Median Grain Size (d50, Phi)	Critical Stress (Pa)
2.00	-1.0	1.17
1.00	0.0	0.48
0.50	1.0	0.26
0.25	2.0	0.19
0.13	3.0	0.15
0.06	4.0	0.12

IX. Conclusions

On the basis of aforementioned analyses, during a tropical cyclone, several air-sea-land interaction parameters can be estimated rapidly using the minimum sea-level pressure (P_o, in mb) as the most important input.

They are:

a) Maximum wind speed (in m/s)= 6.3 $(1013 - P_o)^{0.5}$.
b) Max significant wave height (in m) = 0.20 $(1013 - P_o)$.
c) Max wave setup (in feet)= 0.11 $(1013 - P_o)$.
d) Max surface drift velocity (in m/s) = 0.22 $(1013 - P_o)^{0.5}$.
e) Most probable shoaling depth (in m) = $(1013 - P_o)$.
f) Max storm surge (in feet)= $0.23^*(1010 - P_o)^*F_s{}^*F_m$, where F_s is a shoaling factor (not the shoaling depth) and F_m is a correction factor for storm motion. And,
g) Max bottom (seabed) stress (in N/m^2)= 0.016 $(1013 - P_o)$.

Now, using Katrina as an example and application (see Fig.22 and Fig.1), by setting P_o= 902mb, we have, from (1) above, max wind speed = 66 m/s= 148 mph, and (2), max significant wave height = 22.2m= 73ft. Referring back to Fig.2 and 3, since both wind speed and wave height as estimated exceeded the designed limits (140 mph winds and 70ft wave height), the designed criteria for the Gulf of Mexico need to be re-examined as suggested by many engineers (see, e.g. Cruz and Krausmann, 2008).

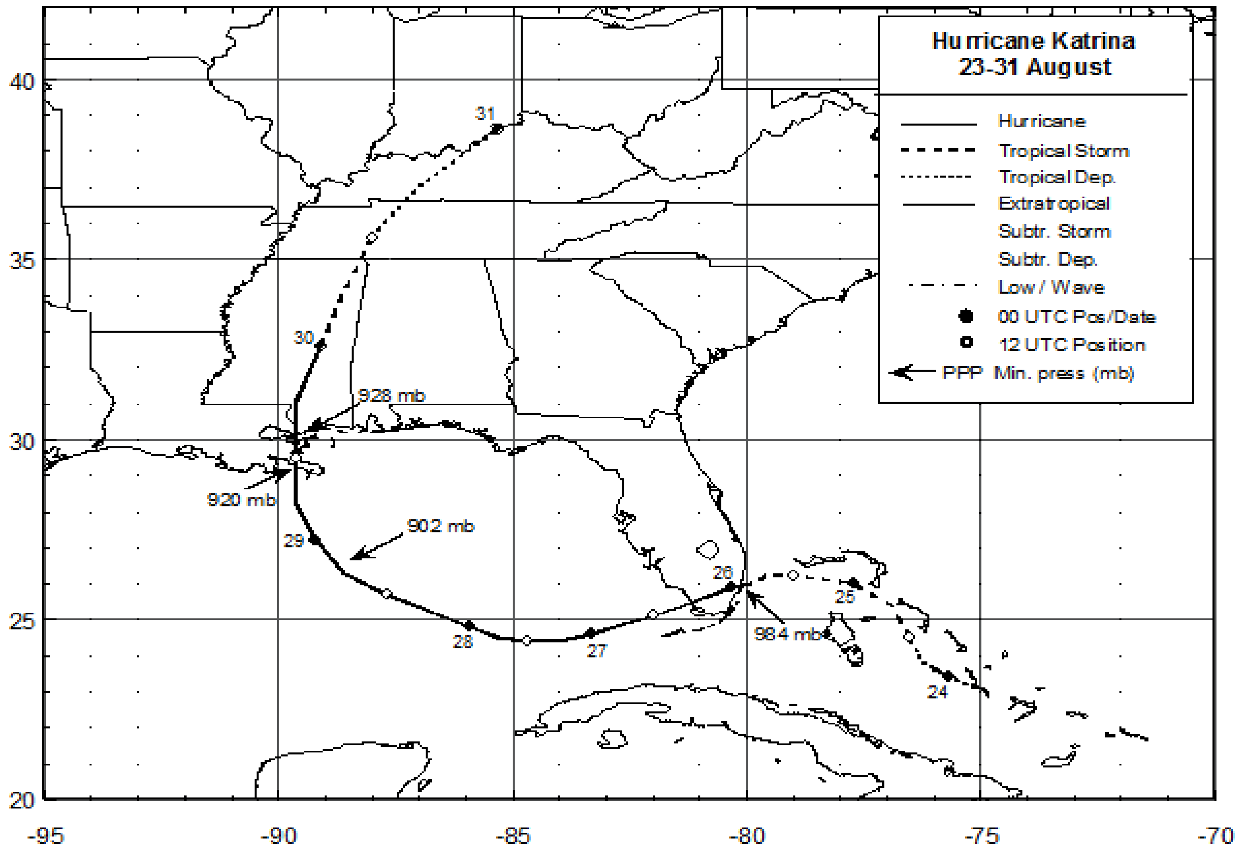

Figure 22 : Best track of Katrina (www.nhc.noaa.gov)

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