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

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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 sealevel pressure (Po in mb) as the most important input. They are: (1) Maximum wind speed (in m/s)= 6.3 (1013 - Po) 0.5; (2) Max significant wave height (in m) = 0.20 (1013 â??" Po); (3) Max wave setup (in feet)= 0.11 (1013 â??" Po); (4) Max surface drift velocity (in m/s) = 0.22 (1013 â??" Po) 0.5; (5) Most probable shoaling depth (in m) = (1013 â??" Po); (6) Max storm surge (in feet) = 0.23*(1010 â??" Po)*Fs*Fm, where Fs is a shoaling factor (not the shoaling depth) and Fm is a correction factor for storm motion; And(7) Max bottom (seabed) stress (in N/m^2) = 0.016(1013??"$Po). Examples for the applications of these formulas are provided.$

Index terms— hurricane winds; hurricane waves; currents during hurricane; wave setup during hurricane; shoaling depth during hurricane; storm surge during hurrican

1 Introduction

n 2004 Hurricane Ivan and again in 2005 Hurricane Katrina (Fig. **??**) devastated numerous oil and gas production facilities in the north central Gulf of Mexico (see e.g. Figs. **??** 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. According to Wang and Oey (2008), this billiondollar platform was designed to withstand "140-mph winds and crashing waves up to 70ft high simultaneously". (From FHWA-NHI-07-096). According to FHWA, the wave setup on top of the storm surge was the cause Figure **??** : 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.

2 Estimating Hurricane Winds

According to Hsu (1988), from the cyclostrophic equation when the centrifugal force is balanced by the pressure gradient force, we haveU a 2 / ? = (1/?) Î?"P/Î?"? = (1/?) (P n -P 0)/ (? -0)**(1)**

Where U a is the maximum sustained wind speed above the surface boundary layer, ? is the radius of the hurricane, ? is the density of air, Î?"P/Î?"? 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 ? = 1.2 kg m -3 , Î?"P = (1013 -P 0)mb, and 1 mb = 100 N m -2 = 100 kg m -1 s -2 , (1) Becomes =

[(100 kg m -1 s -2)/ (1.2 kg m -3)] 0.5 *(Î?”P) 0.5 = 9 (Î?”P) 0.5 (2) According to **??**owell (1982), U 10 = 0.7 U a ; therefore, U 10 = 6.3 (Î?”P) 0.5 = 6.3 (1013 -P 0) 0.5 (3)

Where U 10 is the wind speed at 10 m in m/s and Î?”P is in mb.

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

3 Estimating Hurricane Waves

According to the Shore Protection Manual (see **??**SACE, 1984),(g H s /U 10 ^2) = 0.0016 (g F/U 10 ^2) ^(1/2) (4) (g T m /U 10) = 0.2857 (g F/U 10 ^2) ^(1/3)**(5)**

T p = 0.95 T m (6)T p = 12.1 (H s /g) ^(1/2) (**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. Now, eliminating the fetch parameter, F, and rearraging Eqs. (**??**) and (5), we have(g H s /U 10 ^2) = 0.0113 (gTp/U 10) ^(3/2)**(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. 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 ^2) = 0.0112 (gT p /U 10) ^(3/2) (

Substituting Eq. (7) into (9), one gets Hs = 0.0050 U 10 ^2 (10)U 10 = 14.1(H s ^0.5)**(11)**

Now, from Eq. (**??**), we haveH smax = 0.20 (1013 -P o)**(12)**

Where H smax is the maximum significant wave height in meters.

Validations of Eq. (12) are provided in Fig. **??**0. Further verifications are provided in **??**su (2009) for Hurricane Ike. Furthermore, During Ivan NHC's Hurricane Report indicates that P o = 931mb near the max H s = 16m (Fig. **??**2) and during Katrina P o =927.4mb at Buoy 42007 in the vicinity of Buoy 42040 where max H s = 17m (Fig. **??**3). These maximum significant wave heights for Ivan and Katrina are nearly identical to those estimated by Eq. (12). 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. (**??**008), 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.

4 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 **??**uza and Thornton (1981), the max wave setup, W setmax , is approximately,W setmax =0.17 H smax = 0.034 (1013 -P o)**(13a)**

W setmax (in feet) = 0.11 (1013 -P o)

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. **??**) (see, e.g., McPherson (2008).For simplicity, it is illustrated as follows:

Since Force = pressure*area, we have V.

5 Estimating Hurricane-Generated Currents

According to Hsu (2003), the magnitude of surface drift velocity, U sea isU sea = 0.22 P U 10 (**14**)

Where P is the turbulence intensity which is related to the gust factor, G, as follows:G = 1 + 2P**(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 getU sea = 0.22 (1013-P o) 0.5

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.(**??**6), we have U sea = 2.0 m/s. Comparisons this value against both measurements and modeling results (Fig. 16) show that Eq.(**??**6) is consistent with both measurements and numerical modeling. Further verification for Eq. (**??**6) 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. (**??**6), U sea = 2.3 m/s. This value is in good agreement with that of modeling results by Wang and Oey (2008, Fig. 4).

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7 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? = 4.7 Hs = 4.7 *0.2 (1013 -P o) (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. (**??**8), we get that the shoaling depth was 82 m during Ivan. Since this estimate is consistent with the measurements, Eq. (**??**8) may be useful as a first approximation.

8 VII.

9 Estimating Storm Surges

According to Hsu (2013), for estimating the storm surges caused by the wind-stress tide,gD(dS/dx)=? sx /? w (**19**)? sx = ? a C d V 2(**20**)S -S 0 = [? a C d /(? w g)](F/D) V 2(**21**)S = K 1 V 2 = K 2 (1013 -P o)(**22**)S = K 3 H s(**23**)

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. 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, ? sx is the wind stress along x, ? a and ? 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. Maximum storm surge elevation without wave setups, S, can also be estimated analytically (see Hsu, 1988, and Hsu et al., 2006) asS (in feet) = 0.23*(1010 -P o)* F s * F m**(24)**

Where P o is the minimum sea-level pressure in mb, F s is a shoaling factor (see Fig. **??**0), and F m is a correction factor for storm motion (see Fig. **??**1). An application for Eq. (24) to estimate the storm surge in the vicinity of Biloxi Bridge (Fig. **??**) 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 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.

10 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, ? cw, on the sea floor is approximately related to the wind stress, U 2 , so that from Eq. (3), we have ? cw = 0.0004 U 10 ^2 = 0.016 (1013 -P o)

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.(**??**8). 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).

11 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. g) Max bottom (seabed) stress (in N/m^2)= 0.016 (1013 -P o). Now, using Katrina as an example and application (see Fig. **??**2 and Fig. **??**), 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. **??** 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).

Median Grain Size (d50, mm) Median Grain Size (d50, Phi) Critical Stress (Pa)

2.00 -1.0 1.17 [1 2 3]

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Figure 1: Figure 1 :Figure 2 :Figure 3 :

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[3]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 © 2014 Global Journals Inc. (US) Rapid Estimations of Air-Sea-Land Interaction Parameters during a Tropical Cyclone

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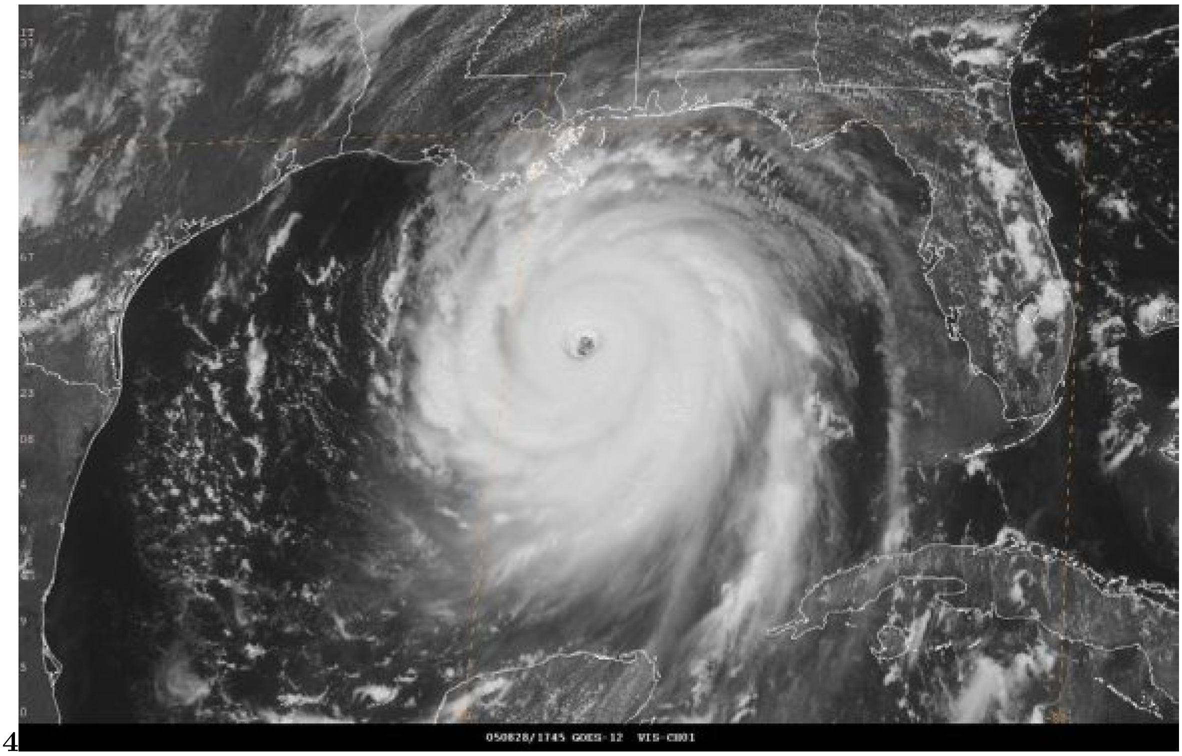

Figure 2: Figure 4 :

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Figure 3: Figure 6 :Figure 7 :

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Figure 4: Figure 8 :

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Figure 5: Figure 9 :

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Figure 6: 2014 Figure 10 :

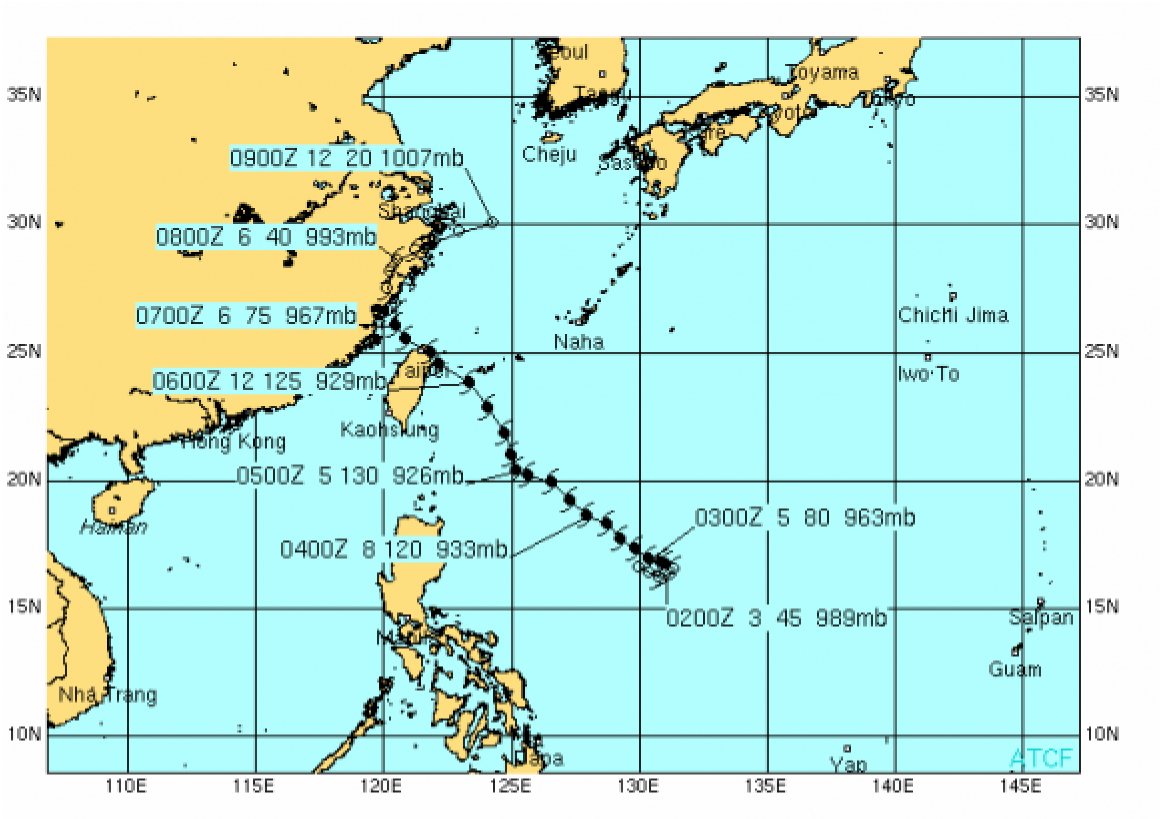

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Figure 7: Figure 11 :

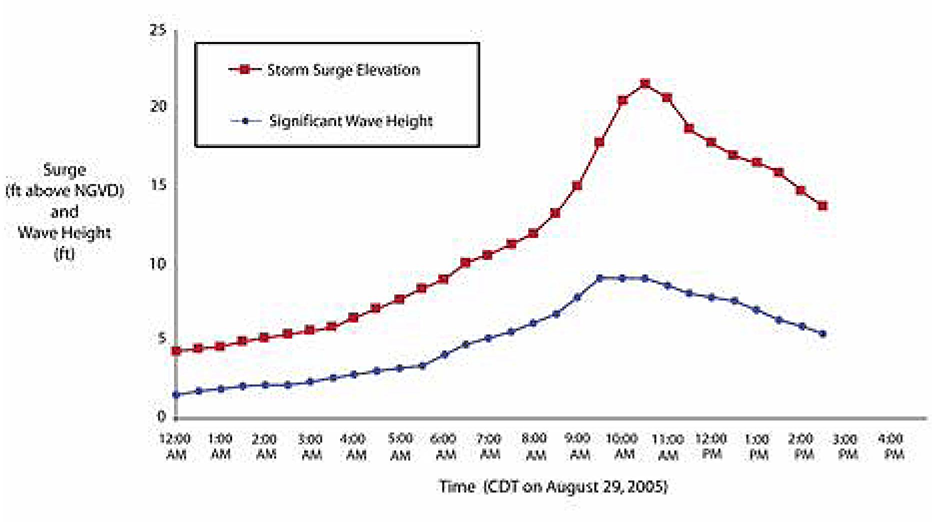

Figure 8: Force

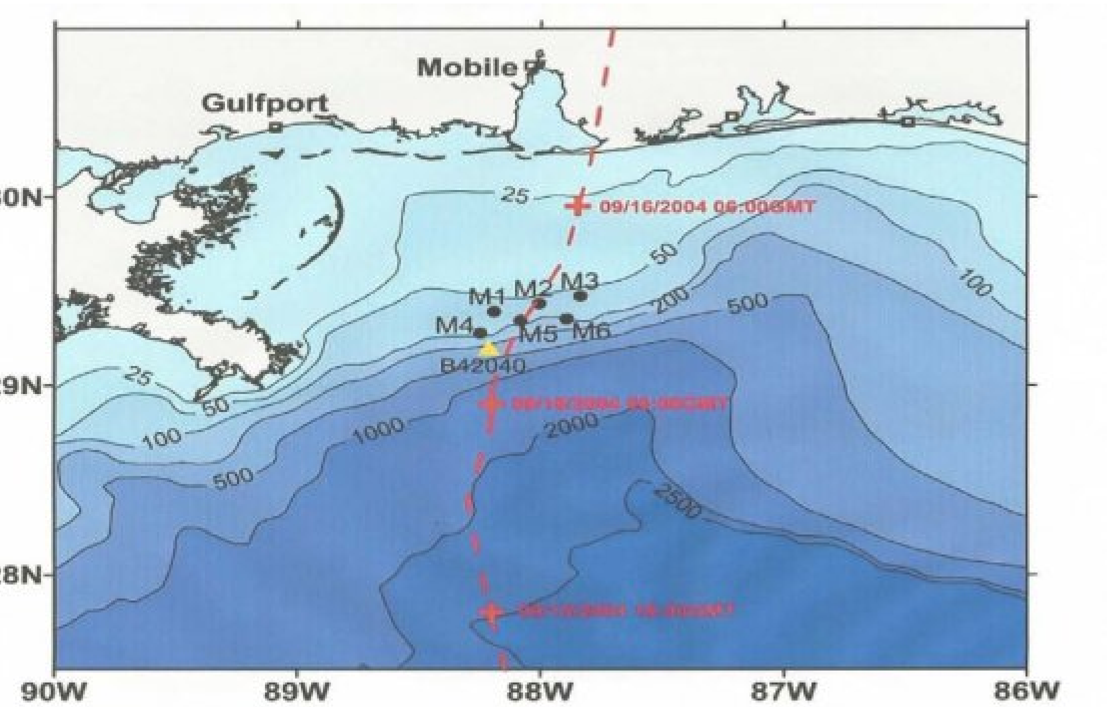

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Figure 9: Figure 12 :Hours after 8 / 27 /

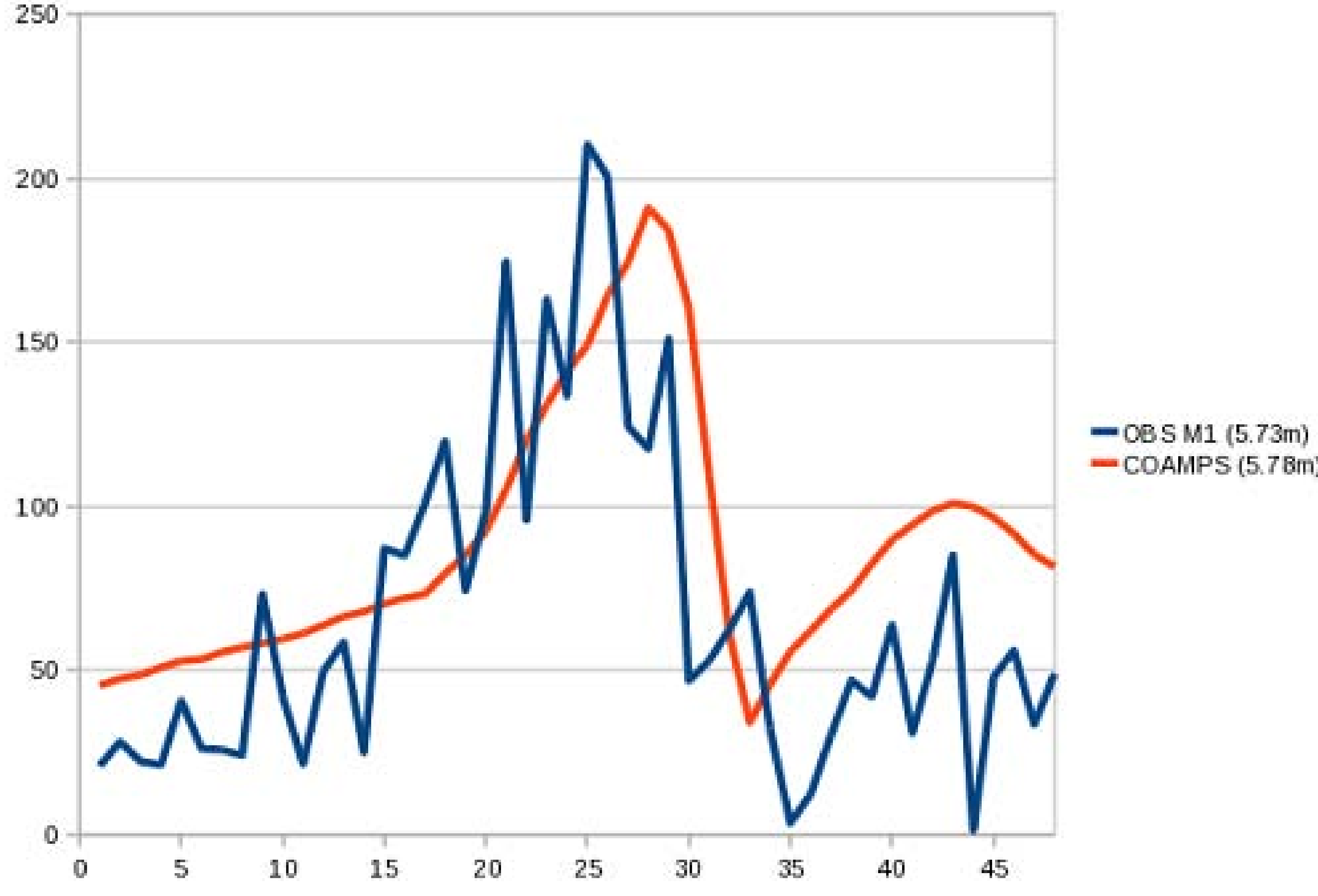

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Figure 10: Figure 14 :

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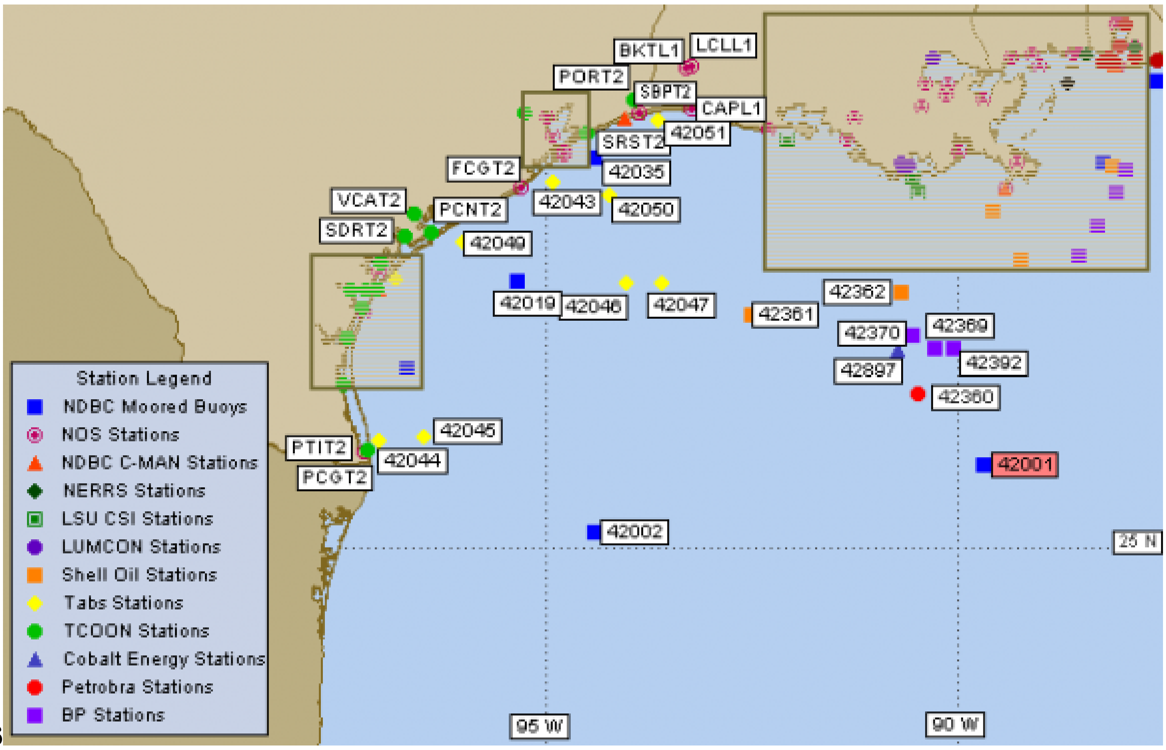

Figure 11: (Figure 16 :

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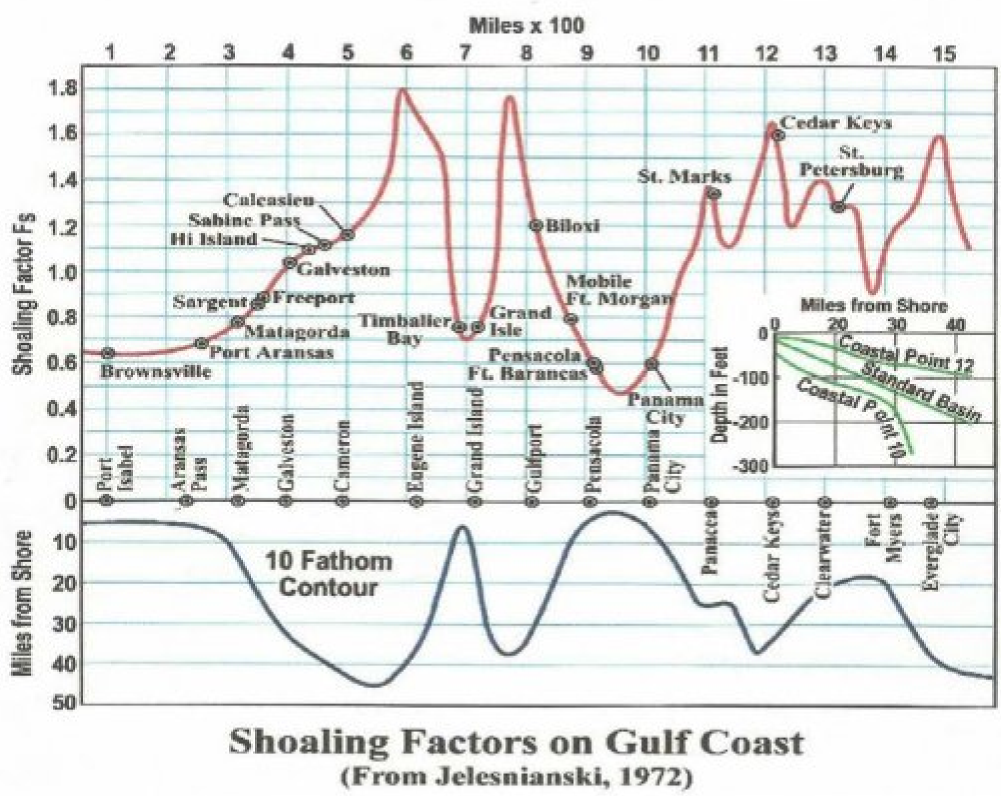

Figure 12: Figure 15 :

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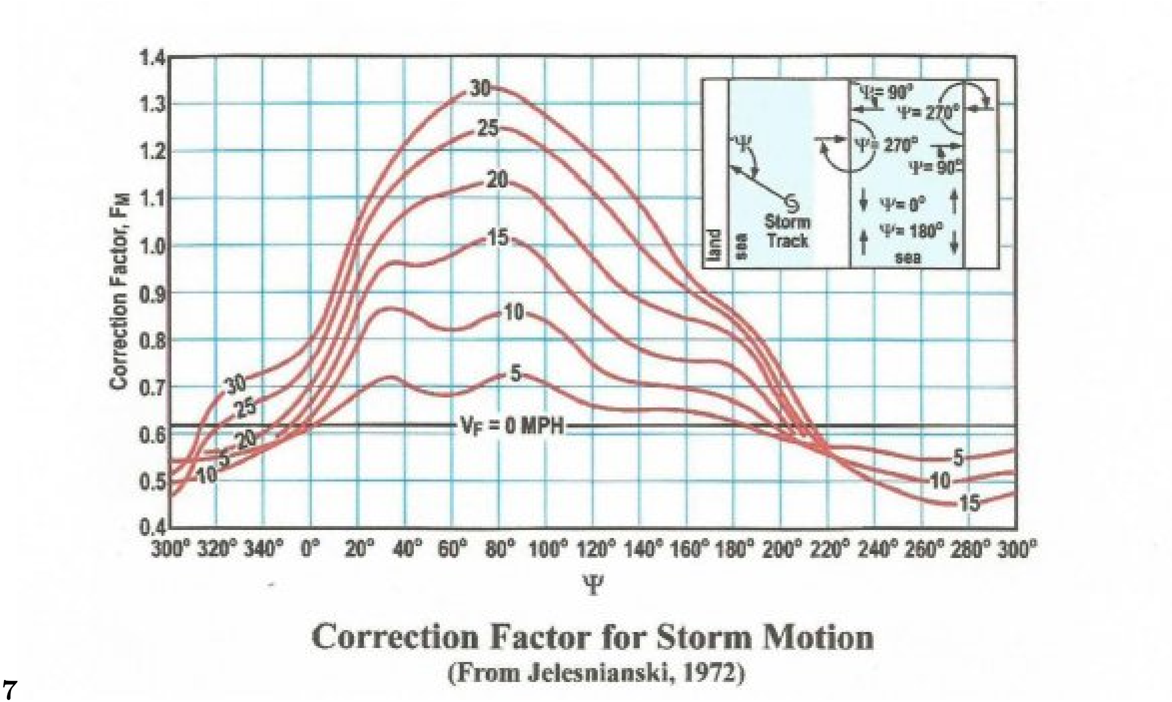

Figure 13: Figure 17 :

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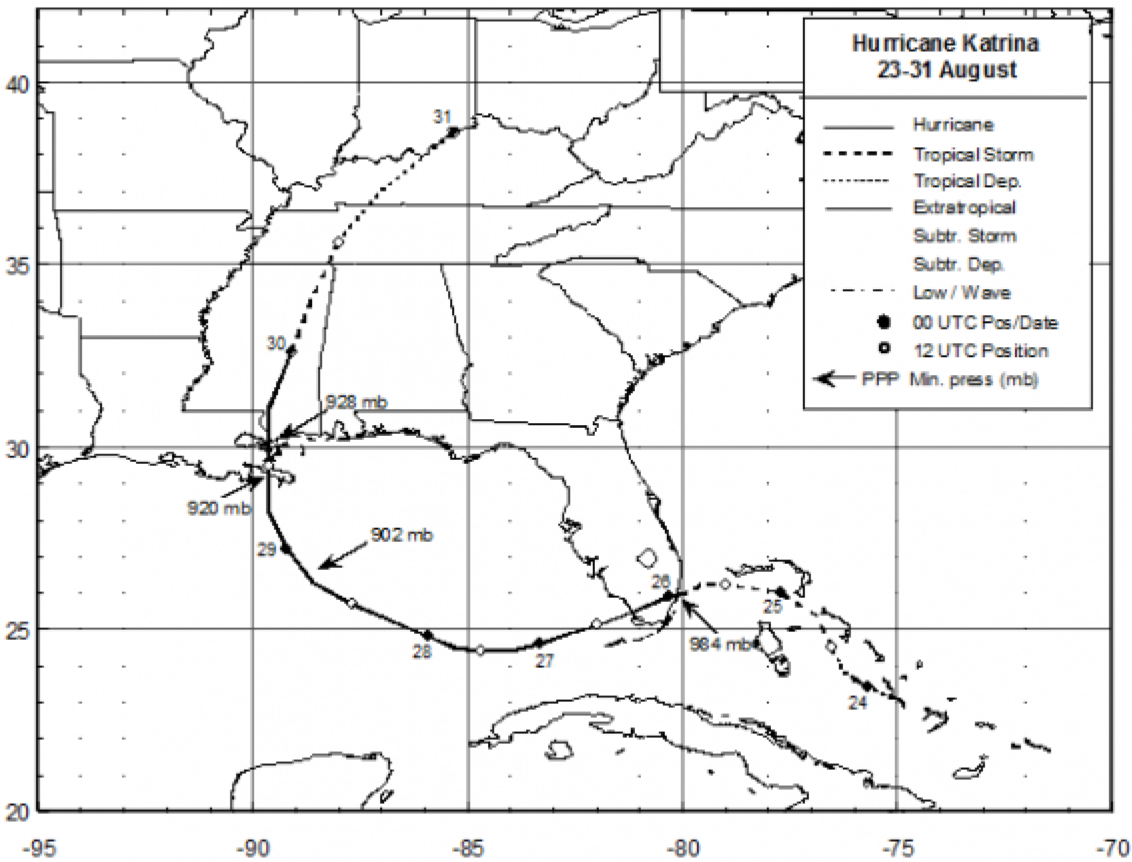

Figure 14: Figure 18 :

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IX.

Figure 15: Table 1 :

[Stewart ()] , S R Stewart . www.nhc.noaa.gov *Tropical Cyclone Report* 2004.

[Knabb et al. ()] , R D Knabb , J R Rhome , D P Brown . www.nhc.noaa.gov 2005. Hurricane Katrina, National Hurricane Center. (Tropical Cyclone Report)

[Powell] '1982, the transition of the Hurricane Frederic boundary-layer wind field from the open Gulf of Mexico to landfall'. M D Powell . *Monthly Weather Review* 110 p. .

[Hsu ()] 'A wind-wave interaction explanation for Jelesnianski's open-ocean storm surge estimation using Hurricane Georges' (1988) measurements'. S A Hsu . http://www.nwas.org/digest/papers/2004/Vol28/Pg25-Hsu.pdf *National Weather Digest* 2004. 28 p. .

[Teague et al. ()] 'Bottom scour observed under Hurricane Ivan'. W J Teague , E Jarosz , T R Keen , D W Wang , M S Hulbert . *Geophysical Research Letters* 2006. 33 p. L07607.

[Hsu ()] *Coastal Meteorology*, S A Hsu . 1988. Academic Press.

[Cruz and Krausmann ()] 'Damages to offshore oil and gas facilities following hurricanes Katrina and Rita: an overview'. A M Cruz , E Krausmann . *Journal of Loss Prevention in the Process Industries*, 2008. 21 p. .

[Dean and Dalrymple ()] R G Dean , R A Dalrymple . *Coastal Processes with Engineering Applications*, 2002. Cambridge University Press.

[Souls By ()] *Dynamics of marine sands-a manual for practical applications: London*, R Souls By . 1997. Thomas Telford Publications.

[Hsu ()] 'Estimating overwater friction velocity and exponent of power-law wind profile from gust factor during storms'. S A Hsu . *Journal of Waterway, Port, Coastal, and Ocean Engineering* 2003. 129 (4) p. .

[Final Coastal and Riverine High Water Mark Collection for Hurricane Katrina in MS, FEMA-1604-DR-MS, Task Orders FEMA 'Final Coastal and Riverine High Water Mark Collection for Hurricane Katrina in MS, FEMA-1604-DR-MS, Task Orders'. *FEMA* 2006. 413 (420) .

[Wang and Oey ()] 'Hind cast of waves and currents in Hurricane Katrina'. D.-P Wang , L.-Y Oey . *Bulletin* 2008. American Meteorological Society. 89 (4) p. .

[Abel et al. ()] 'Hurricane hind cast methodology and wave statistics for Atlantic and Gulf hurricanes from'. C E Abel , B A Tracy , C L Vincent , R E Jensen . *WIS Report* 1989. 1956-1975. 19 p. .

[Mcpherson ()] *Hurricane Induced Wave and Surge Forces on Bridge Decks*, R L Mcpherson . 2008. Texas A&M University (A Thesis)

[Liu et al. ()] 'Monstrous ocean waves during Typhoon Krosa'. P C Liu , H S Chen , D.-J Doong , C C Kao , Y.-G Hsu . *Annales Geophysicae* 2008. 26 p. .

[Hsu et al. ()] *Rapid estimation of maximum storm surges induced by Hurricanes Katrina and Rita in 2005, National Weather Association Electronic Journal file 2006-EJ9.pdf*, S A Hsu , Dewitt Braud , Brian Blanchard . http://www.nwas.org/ej/2006/2006.html 2006.

[Shore Protection Manual ()] *Shore Protection Manual*, 1984. Vicksburg, MS 39180. USACE ; Coastal Engineering Research Center, U. S. Army Corps of Engineers

[Chu and Cheng ()] 'South China Sea wave characteristics during Typhoon Muifa passage in Winter'. P C Chu , K.-F Cheng . *Journal of Oceanography* 2008. 2004. 64 p. .

[Jelesnianski ()] 'SPLASH (Special Program to List Amplitudes of Surges for Hurricanes): 1. Landfall storms'. C P Jelesnianski . NTISCOM-72-10807. NOAA Tech. Memo. NWS TDL- 1972. 46.

[Hsu ()] 'Storm surges in New York during Hurricane Sandy in 2012: A verification of the windstress tide relation'. S A Hsu . *Boundary-Layer Meteorology* 2013. 148 (3) p. .

[Hsu (2012)] 'Storm surges in New York Harbor during Hurricane Irene'. S A Hsu . //www.vos.noaa.gov/MWL/201208/MWL_0912.pdf *Mariners Weather Log* 2012. August 2012. 56 (2) p. .

[Taylor and Yelland ()] 'the dependence of sea surface roughness on the height and steepness of the waves'. P K Taylor , M J Yelland . *Journal of Physical Oceanography* 2001. 31 p. .

[Simpson and Riehl ()] *The Hurricane and Its Impact*, R H Simpson , H Riehl . 1981. Baton Rouge, LA. Louisiana State University

[Powell ()] 'Tropical cyclone destructive potential by integrated kinetic energy'. M D Powell , Reinhold , TA . *Bulletin of American Meteorological Society* 2007. 84 (4) p. .

[Li et al. ()] 'Tropical cyclone morphology from space borne synthetic aperture radar'. X Li , J A Zhang , X Yang , W G Pichel , M Demaria , D Long , Z Li . *Bulletin* 2013. American Meteorological Society. 94 (2) p. .

[Douglass et al. ()] *Wave Forces on Bridge Decks*, S L Douglass , Q Chen , J M Olsen , B L Edge , D Brown . 2006. 74 p. pp. report by the Coastal Transportation Engineering Research and Education Center of the University of South Alabama to FHWA. Washington D.C.

[Guza and Thorton ()] 'Wave set-up on a natural beach'. R T Guza , E B Thorton . *Journal of Geophysical Research* 1981. 96 p. .

[World Meteorological Organization Guide to Wave Analysis and Forecasting ()] 'World Meteorological Organization'. *Guide to Wave Analysis and Forecasting*, (Geneva) 1998. 28 p. 10. (nd Edition)