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Overwater Turbulence Intensity during Hurricane Katrina and Typhoon Russ

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Abstract- When Hurricane Katrina was over the Gulf of Mexico in 2005 an unprecedented significant wave height ($\boldsymbol{H_s}$) of 17 m was measured at the National Data Buoy Center (NDBC) station 42040. Using this extreme $\boldsymbol{H_s}$ value and those from NDBC Buoy 42003 in the Gulf of Mexico during Katrina and Buoy 52009 during Typhoon Russ near Guam in the Pacific in 1990, it is found that approximately 85% of the variation in turbulence intensity (TI) over the wind seas can be explained by the variation in $\boldsymbol{H_s}$. Application of this relation between TI and $\boldsymbol{H_s}$ shows that the estimated drift velocity is in excellent(over 95%) agreement with that measured during Hurricane Ivan.

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Overwater Turbulence Intensity during Hurricane Katrina and Typhoon Russ

Professor S. A. Hsu

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I. Introduction

According to Glickman (2000), turbulence intensity (TI) is the ratio of the root-mean-square of the eddy velocity to the mean wind speed. Following Panofsky and Dutton (1984), for strong winds, the power-law wind profile may be applied that,

$$\frac{U_2}{U_1} = \left(\frac{Z_2}{Z_1}\right)^p, \qquad (1)$$

Where U_1 and U_2 are the wind speeds at height Z_1 and Z_2, respectively, and "*p*" is the exponent of the power law.

In addition, according to Hsu (1988, pp.199-200, and 2003), this exponent, *p*, is also related to the logarithmic wind profile law so that

$$p = 1/\ln\left(\frac{10}{Z_0}\right) = \left(\frac{U_*}{kU_{10}}\right), \qquad (2)$$

Where *p* is named here as the turbulence intensity, Z_0 is the aerodynamic roughness length, U_* is the friction velocity, k (=0.4) is the von Karman constant, and U_{10} is the wind speed at 10 *m*.

Now, according to Taylor and Yelland (2001),

$$\frac{Z_0}{H_s} = 1200\left(\frac{H_s}{L_p}\right)^{4.5}, \qquad (3)$$

And, for deep water waves,

$$L_p = \left(\frac{gT_p^2}{2\pi}\right), \qquad (4)$$

Where H_s and L_p are significant wave height and peak wavelength for the combined sea and swell spectrum, respectively, and T_p is its corresponding wave period. Note that the parameter $\left(\frac{H_s}{L_p}\right)$ is called wave steepness.

In order to minimize the swell effects, the criterion for the wave steepness as set forth by Drennan et al. (2005) is used such that, for the wind seas,

$$\frac{H_s}{L_p} \geq 0.020, \qquad (5)$$

From Equations (2) and (3), it is clear that TI is related to the wave characteristics. Since H_s can be measured by remote sensing systems such as satellite altimetry (see, e.g., Wang and Oey, 2008), the purpose of this research note is to find a relation between TI and H_s, so that TI may be estimated from H_s, particularly during tropical cyclones.

II. Datasets and Analysis

Three datasets are employed in this study. They are based upon the measurements made by the National Data Buoy Center (see www.ndbc.noaa.gov) and all analyses are according to Equations (1) thru (5):

a) Typhoon Russ

According to the Joint Typhoon Warning Center (see http://www.usno.navy.mil/NOOC/nmfc-ph/ RSS/ jtwc/atcr/1990atcr.pdf). TyphoonRuss, the last western North Pacific tropical cyclone of 1990, was the most severe to strike Guam in 14 years. During the passage of Typhoon Russ in 1990, the U. S. National Data Buoy Center (NDBC) (see, www.ndbc.noaa.gov) owned and maintained a station near Guam, Buoy 52009, which measured Hs and Tp. The data are presented in Table 1, which will be incorporated into a much larger datasets during Hurricane Katrina over the Gulf of Mexico as provided in the next section.

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Table 1 : Measurements of significant wave height (Hs) and dominant wave period (Tp) at Buoy 52009 in December 1990 during Typhoon Russ (Data source: www.ndbc.noaa.gov).

Day	Hour, UTC	Hs, m	Tp, sec	Hs/Lp	Zo, m	1/Ln(10/Zo)
16	1	2.1	8.3	0.020	5.1E-05	0.08
16	3	2.2	7.7	0.024	1.3E-04	0.09
17	14	2.2	7.1	0.028	2.7E-04	0.10
17	15	2.2	7.1	0.028	2.7E-04	0.10
17	20	2.1	7.1	0.027	2.1E-04	0.09
17	21	2.3	7.7	0.025	1.7E-04	0.09
17	23	1.9	7.7	0.021	5.8E-05	0.08
18	0	2.1	7.1	0.027	2.1E-04	0.09
19	18	5.4	12.5	0.022	2.3E-04	0.09
19	21	5.5	10	0.035	1.9E-03	0.12
19	22	4.9	9.1	0.038	2.4E-03	0.12
19	23	5.3	10	0.034	1.6E-03	0.11
20	1	5.3	11.1	0.028	6.1E-04	0.10
20	3	5.6	12.5	0.023	2.8E-04	0.10
20	4	6.5	12.5	0.027	6.4E-04	0.10
20	5	6.3	12.5	0.026	5.4E-04	0.10
20	6	6.1	12.5	0.025	4.5E-04	0.10
20	8	6.3	14.3	0.020	1.6E-04	0.09
20	10	8.1	14.3	0.025	6.4E-04	0.10
20	13	7.8	14.3	0.024	5.2E-04	0.10
20	14	9.8	14.3	0.031	1.8E-03	0.12

b) *Hurricane Katrina*

Hurricane Katrina devastated north-central Gulf of Mexico and south-eastern coastal regions of Louisiana and Mississippi Gulf coast (see, e.g., Wang and Oey, 2008). For wind-wave interaction and other characteristics of Katrina, see Hsu (2015). Since the maximum $H_s$measured at the National Data Buoy Center (NDBC) station 42003 was approximately 11*m*before that buoy was capsized (see Table 2) and at Buoy 42040 was 17m (see Table 3)that is considered as an extreme significant wave height (www.ndbc.noaa.gov), these datasetsprovide us unique opportunity to investigate the relation betweenTI and H_s.

Table 2 : Measurements of significant wave height (Hs) and dominant wave period (Tp) at Buoy 42003 in August 2005 during Hurricane Katrina (Data source: www.ndbc.noaa.gov).

Day	Hour,UTC	Hs, m	Tp, sec	Hs/Lp	Zo, m	1/Ln(10/Zo)
26	4	0.69	4.55	0.021	2.5E-05	0.08
26	5	0.79	5	0.020	2.3E-05	0.08
26	6	0.89	5	0.023	4.4E-05	0.08
26	7	0.94	5.26	0.022	3.7E-05	0.08
26	8	1.04	5	0.027	1.0E-04	0.09
26	9	1.15	5.56	0.024	6.9E-05	0.08
26	10	1.15	5.56	0.024	6.9E-05	0.08
26	12	1.26	6.25	0.021	4.0E-05	0.08
26	13	1.25	5.88	0.023	6.6E-05	0.08
26	14	1.44	6.67	0.021	4.6E-05	0.08
26	15	1.5	6.67	0.022	5.8E-05	0.08
26	16	1.6	7.14	0.020	4.5E-05	0.08

26	17	1.73	7.14	0.022	6.9E-05	0.08
26	18	1.82	7.14	0.023	9.1E-05	0.09
26	19	1.91	7.69	0.021	6.1E-05	0.08
26	20	2.12	7.69	0.023	1.1E-04	0.09
26	21	2.11	7.14	0.027	2.0E-04	0.09
26	22	2.44	7.69	0.026	2.3E-04	0.09
26	23	2.61	8.33	0.024	1.6E-04	0.09
27	0	2.94	7.69	0.032	6.5E-04	0.10
27	1	2.94	7.69	0.032	6.5E-04	0.10
27	2	2.68	8.33	0.025	1.9E-04	0.09
27	3	3.44	10.81	0.019	7.2E-05	0.08
27	4	3.98	10.81	0.022	1.6E-04	0.09
27	5	4.45	10	0.029	6.0E-04	0.10
27	6	5.09	11.43	0.025	3.8E-04	0.10
27	7	5.2	11.43	0.026	4.2E-04	0.10
27	8	5.37	10.81	0.029	8.3E-04	0.11
27	9	5.68	12.12	0.025	4.1E-04	0.10
27	10	6.29	12.12	0.027	7.1E-04	0.10
27	11	5.67	12.12	0.025	4.0E-04	0.10
27	12	6.12	12.12	0.027	6.1E-04	0.10
27	13	6.32	12.12	0.028	7.3E-04	0.10
27	14	6.72	12.9	0.026	5.8E-04	0.10
27	15	7.35	12.12	0.032	1.7E-03	0.11
27	16	7.64	12.9	0.029	1.2E-03	0.11
27	17	7.15	12.9	0.028	8.2E-04	0.11
27	18	7.06	12.12	0.031	1.3E-03	0.11
27	19	7.81	12.9	0.030	1.3E-03	0.11
27	20	7.68	12.12	0.034	2.1E-03	0.12
27	21	6.85	12.9	0.026	6.5E-04	0.10
27	22	7.41	12.12	0.032	1.7E-03	0.12
27	23	7.48	12.9	0.029	1.1E-03	0.11
28	0	8.27	12.12	0.036	3.2E-03	0.12
28	1	9.26	12.9	0.036	3.4E-03	0.13
28	2	9.9	12.9	0.038	4.9E-03	0.13
28	3	10.28	13.79	0.035	3.3E-03	0.12
28	4	9.44	13.79	0.032	2.1E-03	0.12
28	5	10.57	12.9	0.041	7.0E-03	0.14

Table 3 : Measurements of significant wave height (Hs) and dominant wave period (Tp) at Buoy 42040 in August 2005 during Hurricane Katrina (Data source: www.ndbc.noaa.gov).

Day	Hour, UTC	Hs, m	Tp, sec	Hs/Lp	Zo, m	1/Ln(10/Zo)
27	2	1.43	6.67	0.021	4.4E-05	0.08
27	4	1.42	6.67	0.020	4.3E-05	0.08
27	6	1.46	6.67	0.021	5.0E-05	0.08
27	7	1.74	5.88	0.032	4.1E-04	0.10
27	8	1.85	6.67	0.027	1.8E-04	0.09

27	9	1.91	6.67	0.028	2.2E-04	0.09
27	10	2.04	7.14	0.026	1.7E-04	0.09
27	11	2.08	7.14	0.026	1.9E-04	0.09
27	12	1.91	6.67	0.028	2.2E-04	0.09
27	13	1.85	6.67	0.027	1.8E-04	0.09
27	14	2.06	7.69	0.022	9.2E-05	0.09
28	7	4.2	11.11	0.022	1.7E-04	0.09
28	11	4.66	11.11	0.024	3.0E-04	0.10
28	12	5.11	12.5	0.021	1.7E-04	0.09
28	13	4.76	11.11	0.025	3.4E-04	0.10
28	14	5.23	12.5	0.021	1.9E-04	0.09
28	15	5.03	11.11	0.026	4.5E-04	0.10
28	16	5.7	11.11	0.030	9.0E-04	0.11
28	17	6.34	11.11	0.033	1.6E-03	0.11
28	18	6.51	12.5	0.027	6.5E-04	0.10
28	19	7.36	12.5	0.030	1.3E-03	0.11
28	20	7.65	14.29	0.024	4.7E-04	0.10
28	21	7.63	14.29	0.024	4.7E-04	0.10
28	22	8.59	14.29	0.027	8.9E-04	0.11
28	23	9.4	14.29	0.030	1.5E-03	0.11
29	0	8.64	14.29	0.027	9.2E-04	0.11
29	1	9.05	14.29	0.028	1.2E-03	0.11
29	2	9.79	14.29	0.031	1.8E-03	0.12
29	3	9.97	14.29	0.031	2.0E-03	0.12
29	4	9.58	14.29	0.030	1.6E-03	0.11
29	5	11.61	12.5	0.048	1.6E-02	0.15
29	6	12.25	12.5	0.050	2.1E-02	0.16
29	7	11.26	12.5	0.046	1.3E-02	0.15
29	8	14.06	14.29	0.044	1.3E-02	0.15
29	9	14.04	14.29	0.044	1.3E-02	0.15
29	10	14.43	14.29	0.045	1.6E-02	0.15
29	11	16.91	14.29	0.053	3.7E-02	0.18
29	12	14.58	12.5	0.060	5.5E-02	0.19
29	13	15.67	14.29	0.049	2.4E-02	0.17
29	14	13.9	12.5	0.057	4.2E-02	0.18
29	15	10.7	12.5	0.044	1.0E-02	0.14
29	16	9.29	11.11	0.048	1.3E-02	0.15
29	17	8.24	11.11	0.043	6.9E-03	0.14
29	18	8.52	12.5	0.035	2.9E-03	0.12
29	19	7.34	11.11	0.038	3.6E-03	0.13
29	20	6.71	11.11	0.035	2.2E-03	0.12
29	21	6.33	12.5	0.026	5.6E-04	0.10
29	22	5.55	12.5	0.023	2.7E-04	0.10
29	23	5.17	11.11	0.027	5.3E-04	0.10
30	0	4.38	11.11	0.023	2.1E-04	0.09

30	1	4.23	11.11	0.022	1.8E-04	0.09
30	2	4.24	11.11	0.022	1.8E-04	0.09
30	3	3.9	10	0.025	2.9E-04	0.10
30	4	3.88	10	0.025	2.8E-04	0.10
30	5	3.36	9.09	0.026	3.0E-04	0.10
30	6	3.43	9.09	0.027	3.4E-04	0.10
30	7	3.1	8.33	0.029	4.2E-04	0.10
30	8	2.87	7.69	0.031	5.7E-04	0.10
30	9	2.62	8.33	0.024	1.7E-04	0.09
30	10	2.77	7.69	0.030	4.7E-04	0.10
30	11	2.71	7.14	0.034	8.1E-04	0.11
30	12	2.76	7.69	0.030	4.6E-04	0.10
30	13	2.3	6.67	0.033	6.1E-04	0.10
30	14	2.05	6.25	0.034	5.8E-04	0.10

III. Results

Our results are presented in Fig.1. Since the coefficient of determination, $R^2 = 0.85$ or the correlation coefficient $R = 0.92$, relation between TI and H_s does exist, so that,

$$p = 0.0003H_s^2 + 0.0018H_s + 0.0842, \qquad (6)$$

In order to validate this relation further, we employ the near-surface current measurements during Hurricane Ivan (Teague et al., 2007)in 2004. Since H_s=16 m(see www.ndbc.noaa.gov) and by substituting this value into Eq. (6), we get $p = 0.19$. Also, since $U_{10} =$ 48 ms^{-1} (seehttp://www.hwind.co/legacy_data/Products/PostAnalysis/2004/AL092004/AL092004_swath_max1minWind_ms.pdf), we have, from Eq. (2),

$$U_* = 0.4 \times 0.19 \times 48 = 3.65\ m\ s^{-1}.$$

According to Wu (1975) and Hsu (2003), the surface drift velocity, U_{sea} , is

$$U_{sea} = 0.55U_* = 2.0\ m\ s^{-1}.$$

This value is in excellent agreement (over 95 per cent) with the measured maximum near surface current of 2.1 $m\ s^{-1}$ (see Teague et al., 2007).

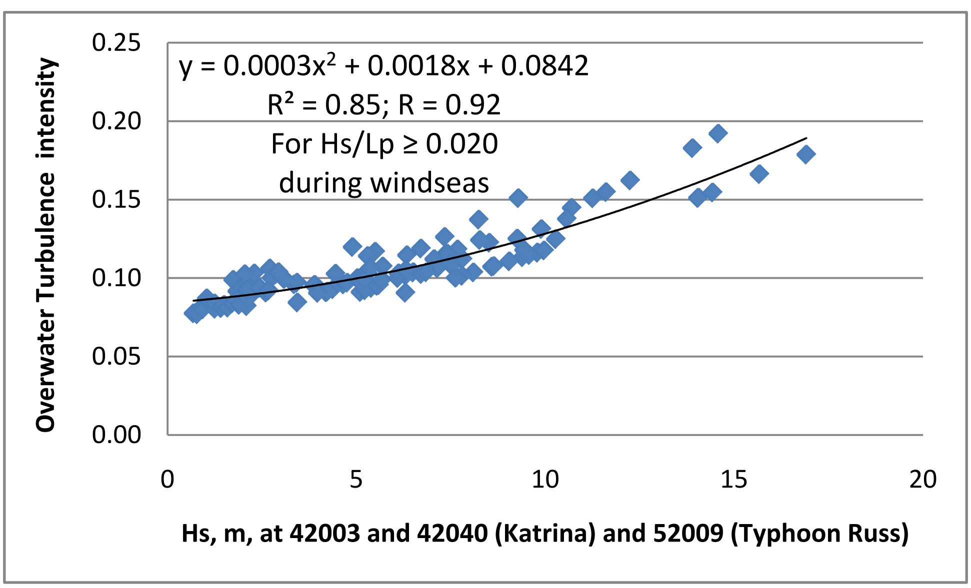

Figure 1 : Relation between overwater turbulence intensity and significant wave height during Typhoon Russ in 1990 near Guam and Hurricane Katrina in 2005 in the Gulf of Mexico

IV. Conclusions

On the basis of wave measurements during Typhoon Russ in 1990 and Hurricane Katrina in 2005, it is found that, during wind seas, overwater turbulence intensity and significant wave height are related through Equation (6)with a correlation coefficient as high as92 per cent. Application of this relation between TI and H_s shows that the estimated drift velocity is in excellent (over 95%) agreement with that measured during Hurricane Ivan.

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