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Relation between Overwater Friction Velocity and Wind Speed at 10m During Hurricane Rita

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RELATIONBETWEENOVERWATERFRICTIONVELOCITYANDWINDSPEEDAT10MDURINGHURRICANERITA

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I. INTRODUCTION

Overwater friction velocity, U_*, is a fundamental parameter in the air-sea interaction, because it is related to the wind stress such that (see, e.g., Hsu, 1988).

$$\tau = \rho\, U_*^2 = \rho\, C_d U_{10}^2 \qquad (1)$$

Here τ is the wind stress, ρ is the air density, C_d is the drag coefficient, and U_{10} is the wind speed at 10m.

According to Anthes (1982, pp. 70-71), the wind stress is also related to the absolute vorticity (ʂ_a) and the height of the atmospheric boundary layer (h) such that

$$\tau = \rho U_{10} \text{ʂ}_a\, h \qquad (2)$$

From Equations (1) and (2), one can estimate the friction velocity if U_{10}, ʂ_a, and h are known. This is called vorticity or momentum balance method. An example to use this method is provided in Anthes (1982) based on the analysis of Hawkins and Imbembo (1976) during Hurricane Inez, which was a very small, but intense tropical cyclone with its U_{10} reached to 67 m/s. This dataset will be incorporated into our analysis. For more detail about hurricane boundary-layer theory, see Smith and Montgomery (2010), for hurricane boundary-layer height, see Zhang et al. (2011), for momentum flux in the hurricane boundary layer, see French et al. (2007), and for most recent parameterization of momentum flux across the air-sea interface, see Edson et al. (2013).

Now, according To the Geophysical Fluid Dynamics Laboratory (GFDL), U. S. National Oceanic and Atmospheric Administration (NOAA), (see http://www.gfdl.noaa.gov/wave-atmosphere-coupled system), C_d varies greatly with U_{10}, particularly for $U_{10} \geq$ 30m/s (see Fig. 1). Therefore, our scientific purpose and motivation of this paper are as follows:

(1) To find the most pertinent relation (i.e., with the highest coefficient of determination, R^2) between U_* and U_{10} based on direct measurements by eddy-correlation method for strongest U_{10} possible from a fixed platform during storms so that a baseline can be established;

(2) To see whether the formula obtained from (1) can be extended into hurricane conditions by incorporating the dataset presented in Anthes (1982) for Hurricane Inez;

(3) To analyze the complete dataset of wind and wave measurements by the National Data Buoy Center (NDBC) (www.ndbc.noaa.gov) during Hurricane Rita in 2005, which was one of the strongest tropical cyclones (with a 5-second gust reached 61 m/s) encountered by a data buoywith the anemometer height located at the standard 10 m; and most importantly,

(4) To evaluate whether one can "bypass" the use of C_d as it is traditionally done but to relate U_* directly to U_{10}, specifically under hurricane conditions.

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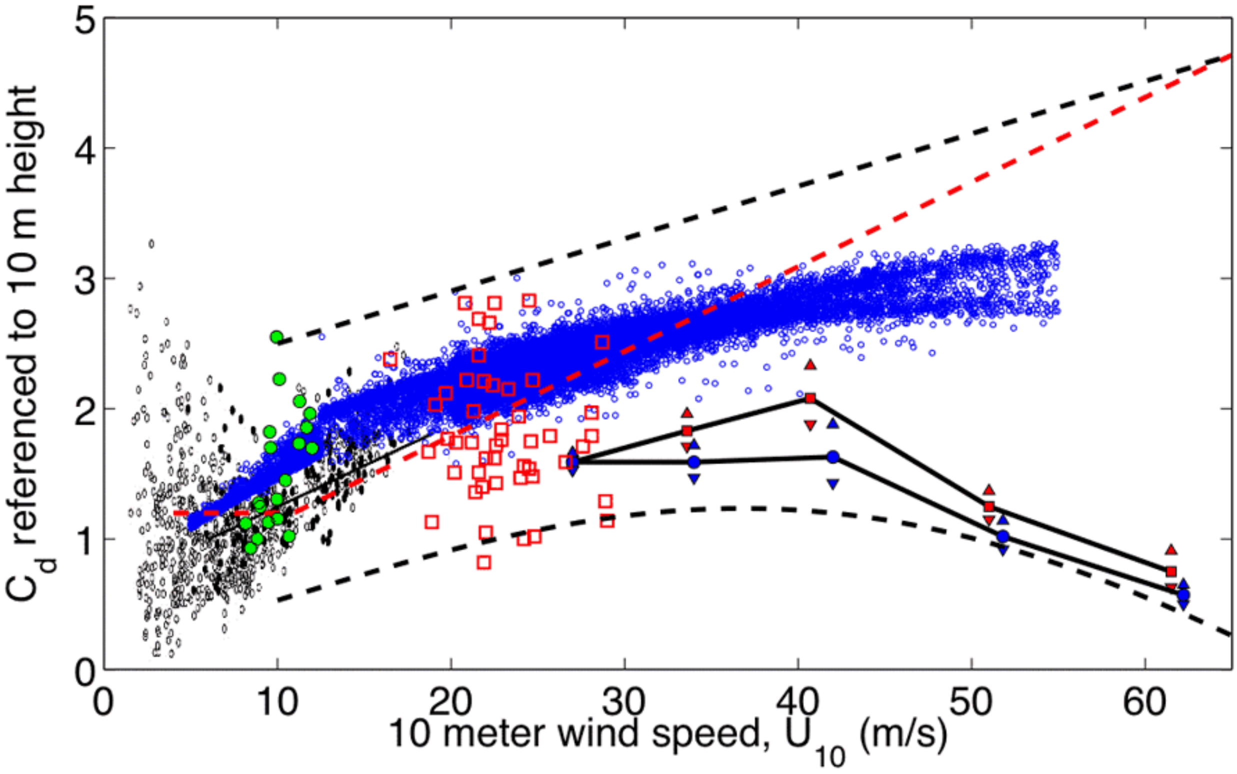

Figure 1 : Variations of C_d with U_{10}(see http://www.gfdl.noaa.gov/wave-atmosphere-coupled-system).

II. HURRICANE RITA

According to Knabb et al.(2005), Hurricane Rita in 2005 was a Category 5 hurricanefor the Atlantic Basin, which is equivalent to a super typhoonfor the Pacific Basin sincethe maximum sustained 1-minute $U_{10}\geq$65m/s(see http://www.aoml.noaa.gov/hrd/tcfaq/A3.html). A satellite image of Rita is provided in Fig. 2 and its track in Fig.3. Note that the National Data Buoy Center (NDBC) Buoy 42001 (see Fig.4) was located along its track. This gives us an opportunity to investigate the air-sea interaction under hurricane conditions, because both U_{10} and waveswere measured. Some data are plotted in Figs.5 and 6. For references, several extreme values shown in Figs.5 and 6 are also listed in Table1. Detailed hourly measurements are provided in Table 2. These information indicate that if a relation between U_* and U_{10} can be found, the result should be very useful to other tropical cyclones such as super typhoons, since U_{10} may be estimated using remote sensing systems, so that in turn U_*or τ may be computed.

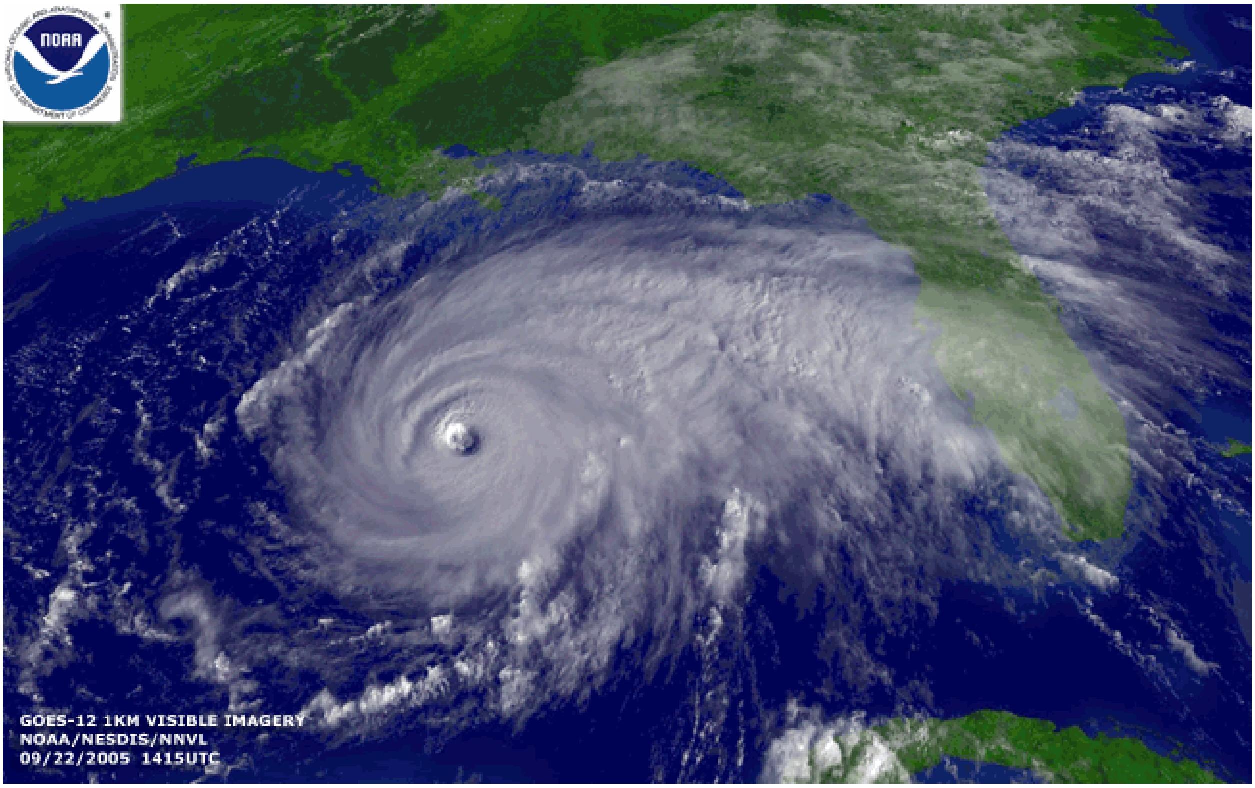

Figure 2 : Satellite image of Rita near its peak intensity over the Gulf of Mexico (see http://www.ncdc.noaa.gov/extremeevents/specialreports/Hurricane-Rita2005.pdf)

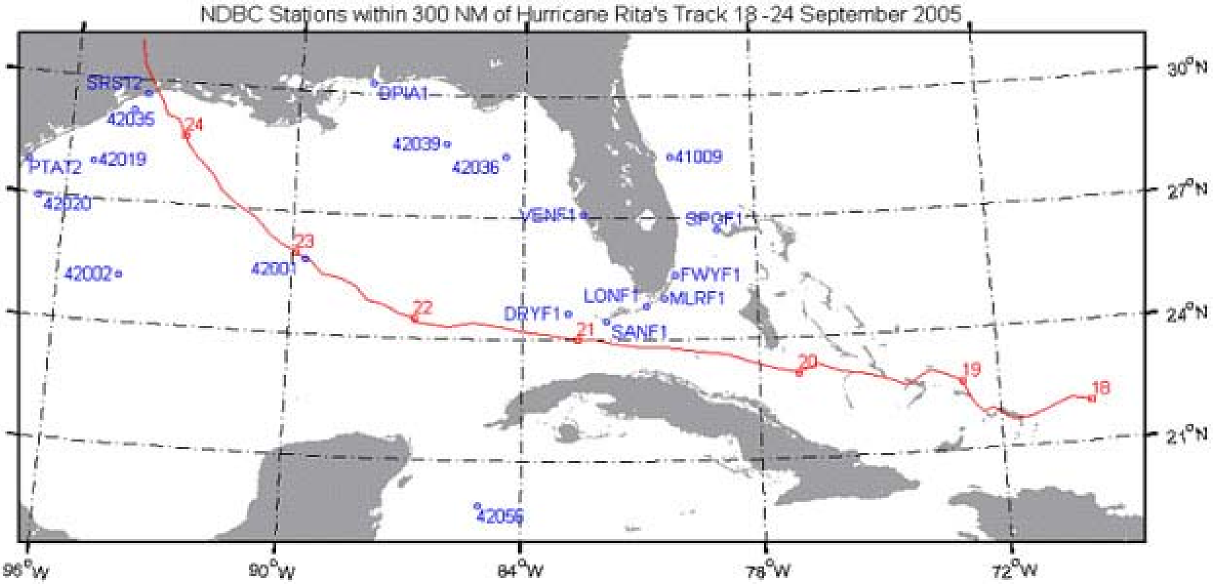

Figure 3 : Location of NDBC Buoy 42001 with respect to Hurricane Rita's track near the central Gulf of Mexico(see http://www.ndbc.noaa.gov/hurricanes/2005/rita/)

Figure 4 : Wind and wave measurements at NDBC Buoy 42001 during Rita and the Buoy was identical to the one shown at Buoy 42040 (see http://www.ndbc.noaa.gov/station_page.php?station=42040)

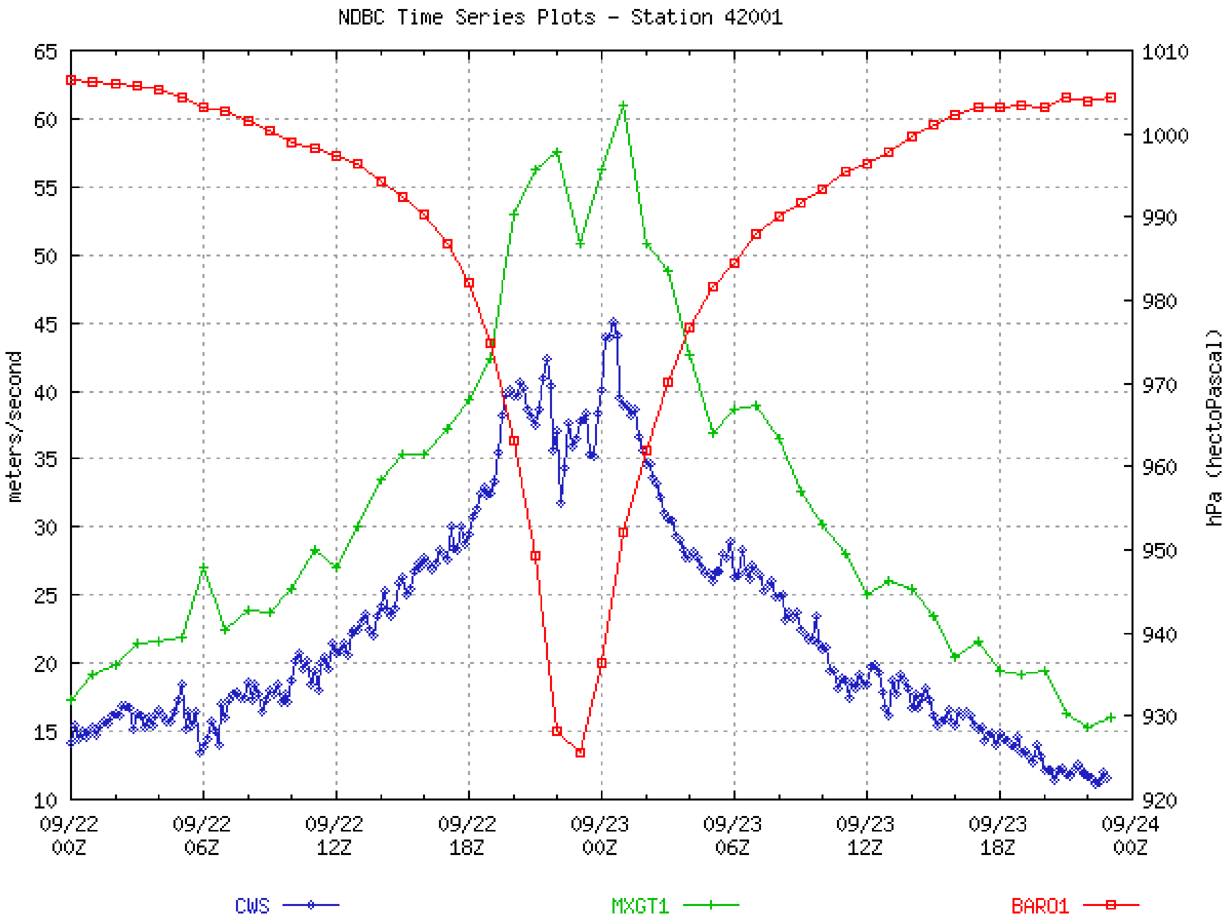

Figure 5 : Time series of wind speeds at 10min m/s (units are shown on the left axis) and sea-level pressure in hPa (right axis) at Buoy 42001 during Rita (see http://www.ndbc.noaa.gov/hurricanes/2005/rita/).

Note that here CWS is the average wind speed over a 10-minute period at the anemometer height. In this figure, data are plotted at the time of the end of the valid 10-minute period, MXGT1isthe peak 5-second gust during the past hour at the anemometer height(the time of MXGT1 is reported to the nearest minute, however, in this figure data are plotted at the valid time of the hourly report), and Baro1 is the sea-level pressure.

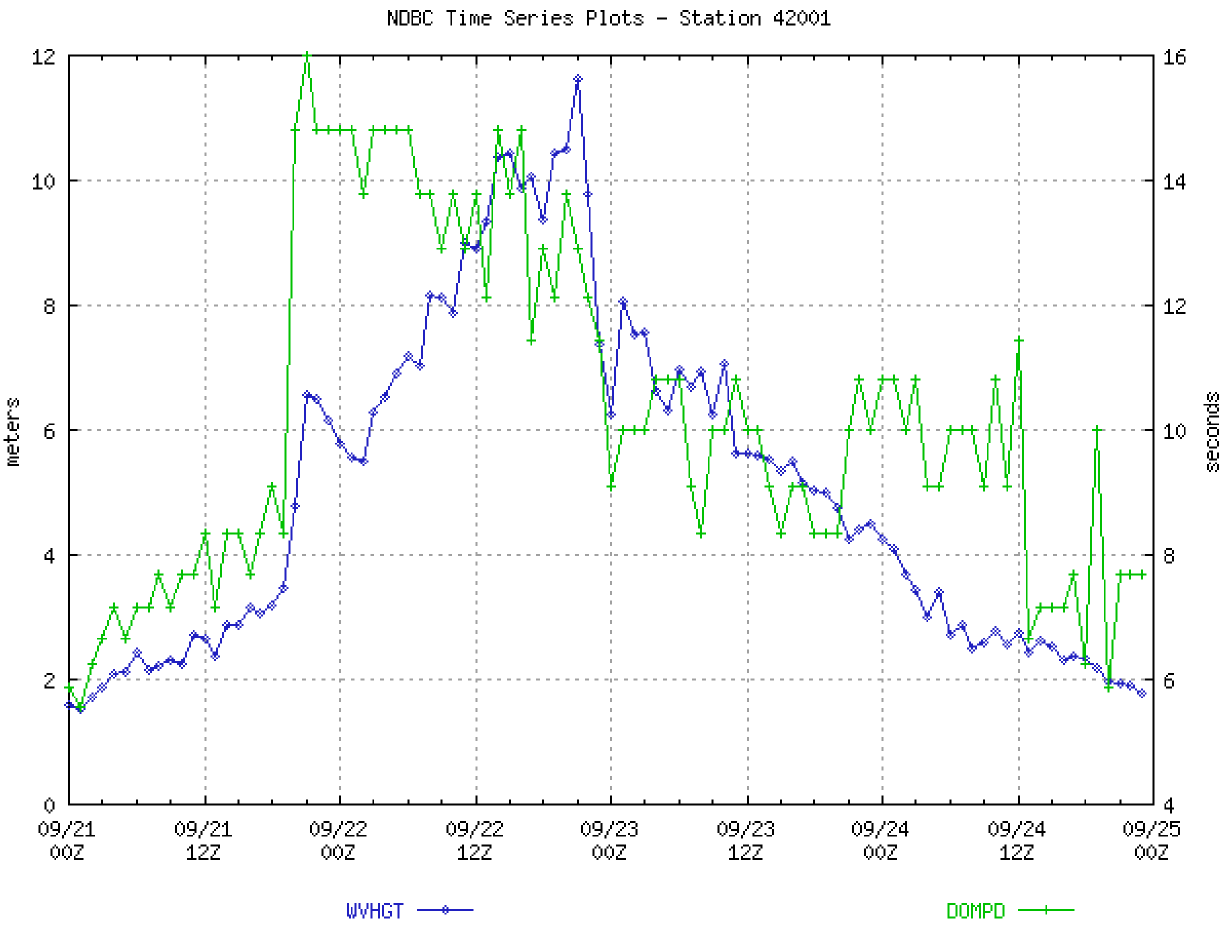

Figure 6 : Measurements of significant wave height (WVHT) (units are shown on the left axis) and dominant wave period (DOMPD) (right axis) at NDBC Buoy 42001 during Rita (see http://www.ndbc.noaa.gov/hurricanes/ 2005/rita/)

Table1 : Some statistics related to Rita as measured at NDBC Buoy 42001 (Data source: http://www.ndbc.noaa.gov/hurricanes/2005/rita/) (see also Figs.5 and 6).

Event	Reported Value	Date/Time of Event
Lowest Sea-Level Pressure (BARO1)	925.7 hPa	09/22 2300Z
Maximum 10-minute Wind Speed (CWS)	45.1 m/s	09/23 0030Z
Maximum 5-s Gust (MXGT1)	61.0 m/s	09/23 0021Z
Maximum Significant Wave Height (WVHGT)	11.63 m	09/22 2100Z
CPA Bearing and Distance To Hurricane*	042°/2 nm	09/22 2200Z

**Closest Point of Approach (CPA): Time, bearing (degrees True), and distance (Nautical Miles) from the station to Hurricane Rita at CPA are computed using the positions from the National Hurricane Center's advisories that have been interpolated to hourly values for positions, wind speed (intensity), and central pressure.*

III. METHODS

In the atmospheric surface boundary layer during storms at sea, the logarithmic wind profile has been verified by Hsu (2003) so that

$$U_{10} = \frac{U_*}{k} \mathrm{Ln}\left(\frac{10}{Z_0}\right) \qquad (3)$$

Where k (=0.4) is the von Karman constant and Z_0 is the roughness length.

According to Taylor and Yelland (2001),

$$\frac{Z_0}{H_s} = 1200\left(\frac{H_s}{L_p}\right)^{4.5} \qquad (4)$$

And, for deep water waves,

$$L_p = \left(\frac{gT_p^2}{2\pi}\right) \qquad (5)$$

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 (H_s/L_p) is called wave steepness.

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

$$\frac{H_s}{L_p} \geq 0.020 \quad (6)$$

Before the measurements of Rita are analyzed, literature research was conducted relating U_* to U_{10}. It is found that the datasets provided in Geerneart et al. (1987) can be employed. On the basis of their direct measurements of U_* by sonic anemometers and U_{10} over the North Sea during storms, our analysis and results show that (see Fig. 7),

$$U_* = 0.0195\ U_{10}^{1.285} \quad (7)$$

With a very high coefficient of determination (see, e.g., Panofsky and Brier, 1968), $R^2 = 0.94$, meaning that, using Eq. (7), 94 per cent of the variability of U_* can be explained by U_{10}.

In order for Eq.(7) to be applicable under hurricane conditions, the datasets provided in Anthes (1982) are analyzed. Our results are presented in Fig. (8). Note that, since the slope is nearly one and R^2 = 0.94, we can say that Eq.(7) is also valid under hurricane conditions.

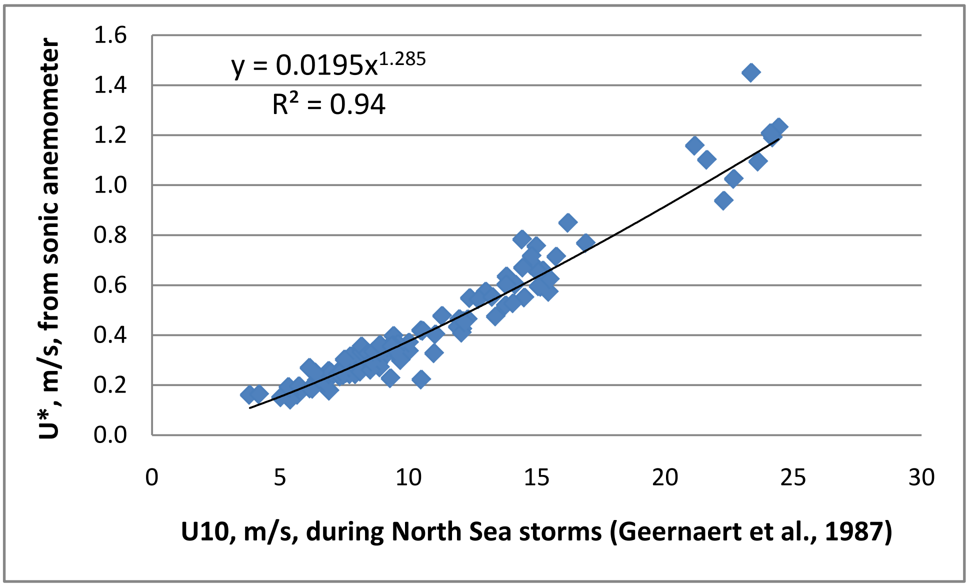

Figure 7 : The power law relation between U_* and U_{10} over the North Sea during Storms (Data source: Geerneart et al., 1987)

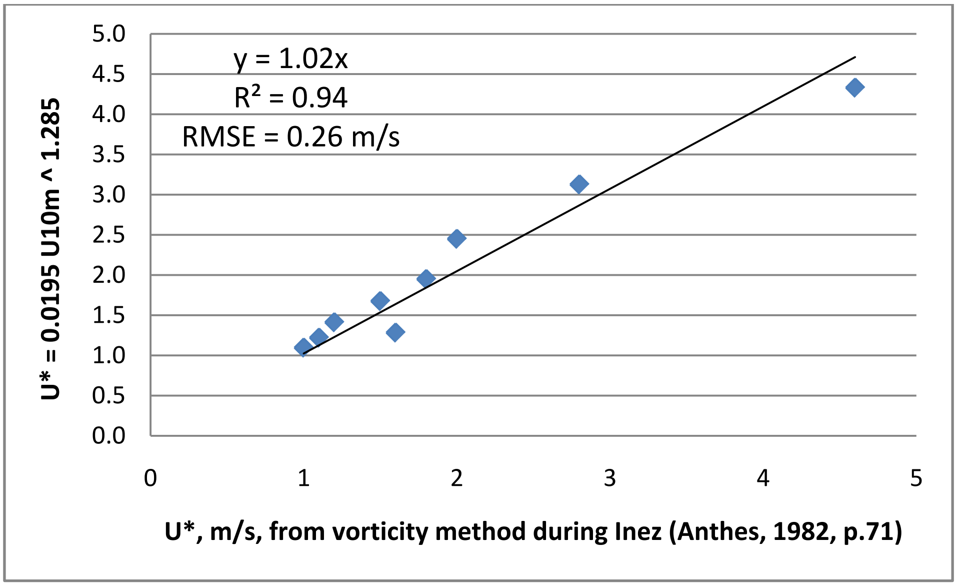

Figure 8 : Further verification of Eq.(7) against vorticity method during Hurricane Inez (Data source: Anthes,1982)

IV. Results

Following our previous discussions, we can now analyze the wind and wave data as listed in Table 2. Our results are presented in Fig. 9 using the analyzed datasets as provided in the last two columns in Table 2. It is very surprising that the agreement between Equations (3) and (7) is excellent, since the slope is almost one and $R^2 = 0.97$. In addition, the root-mean-square-error (RMSE) (see, e.g., Panofsky and Brier (1968) is only 0.10 m/s, meaning that Eq. (7) is indeed a very useful relation between $U_*$and U_{10} under hurricane conditions.

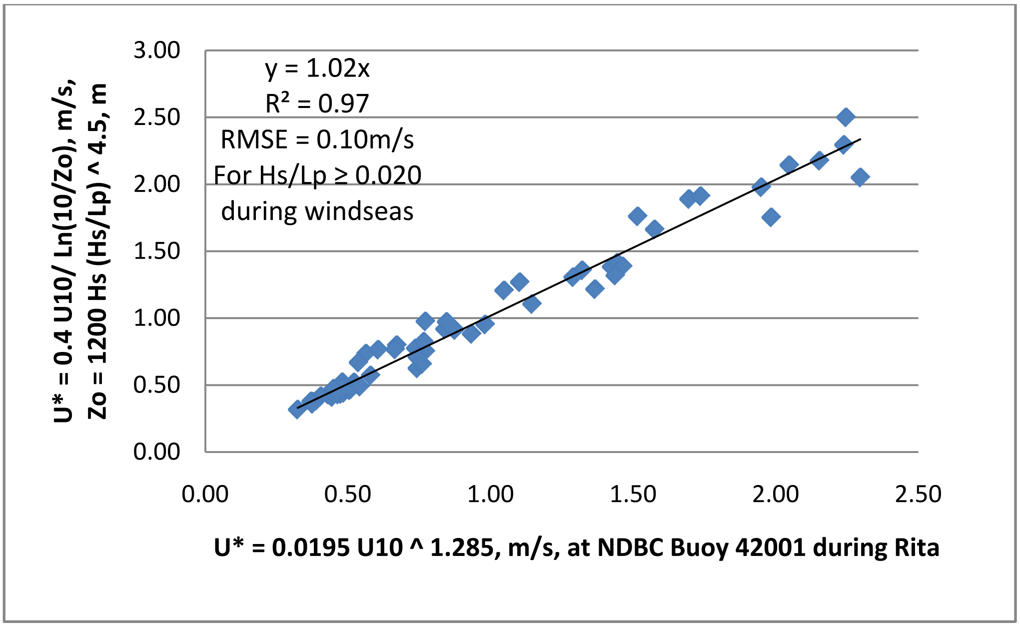

Figure 9 : A verification of Eq. (7) against measurements (as listed in Table 2) at NDBC Buoy 42001 during Rita.

V. Conclusions

On the basis of aforementioned discussions and analyses, it is concluded that Eq. (7), which is originally developed using the direct measurements of $U_*$and U_{10} duringextra-tropical cyclones over the North Sea, is also applicable under the condition of tropical cyclones over the Gulf of Mexico. It is recommended that more measurements of air-sea interaction are needed, e.g., during typhoon conditions using both in situ and remote sensing systems.

Table 2 : Measurements of wind and wave parameters at NDBC Buoy 42001 in September 2005 during Hurricane Rita (Data source: www.ndbc.noaa.gov). For other parameters, see text

Day	Hour	U_{10}	H_s	T_p	H_s/L_p	Z_0	U_*,Eq.7	U_*,Eq.3
	UTC	m/s	m	sec		m	m/s	m/s
21	0	10.3	1.57	5.88	0.029	0.00023	0.39	0.39
21	1	11.2	1.49	5.56	0.031	0.00029	0.43	0.43
21	2	11.4	1.61	6.25	0.026	0.00015	0.44	0.41
21	3	11.8	1.83	6.67	0.026	0.00017	0.46	0.43
21	4	12	2.01	7.14	0.025	0.00016	0.48	0.43
21	5	11.1	2.07	6.67	0.030	0.00034	0.43	0.43
21	6	10.6	2.36	7.14	0.030	0.00038	0.41	0.42
21	7	10.1	2.13	7.14	0.027	0.00022	0.38	0.38
21	8	8.9	2.21	7.69	0.024	0.00014	0.32	0.32
21	9	9.9	2.25	7.14	0.028	0.00029	0.37	0.38
21	10	10	2.25	7.69	0.024	0.00015	0.38	0.36
21	11	11.9	2.63	7.69	0.029	0.00035	0.47	0.46

21	12	12.2	2.6	8.33	0.024	0.00016	0.49	0.44
21	13	12.3	2.35	7.14	0.030	0.00037	0.49	0.48
21	14	12.4	2.83	8.33	0.026	0.00026	0.50	0.47
21	15	11.5	2.72	7.69	0.029	0.00042	0.45	0.46
21	16	12.1	3.14	7.69	0.034	0.00093	0.48	0.52
21	17	12.1	3.04	8.33	0.028	0.00038	0.48	0.48
21	18	12.6	3.07	9.09	0.024	0.00018	0.51	0.46
21	19	12.9	3.19	8.33	0.029	0.00050	0.52	0.52
21	21	12.7	6.17	13.79	0.021	0.00020	0.51	0.47
22	0	14	5.48	11.43	0.027	0.00056	0.58	0.57
22	5	17	6.87	14.81	0.020	0.00019	0.74	0.63
22	6	13.3	6.87	14.81	0.020	0.00019	0.54	0.49
22	7	17.3	6.48	13.79	0.022	0.00026	0.76	0.66
22	8	17.5	8.12	13.79	0.027	0.00090	0.77	0.75
22	9	16.9	8.11	12.9	0.031	0.00164	0.74	0.78
22	10	17	7.73	13.79	0.026	0.00069	0.74	0.71
22	11	18.7	9.01	12.9	0.035	0.00292	0.84	0.92
22	12	21.1	8.82	13.79	0.030	0.00143	0.98	0.95
22	13	22.2	9.38	12.12	0.041	0.00639	1.05	1.21
22	14	23.8	10.37	14.81	0.030	0.00183	1.15	1.11
22	15	26.6	10.61	13.79	0.036	0.00394	1.32	1.36
22	16	27.3	9.7	14.81	0.028	0.00127	1.37	1.22
22	17	28.2	10.03	13.79	0.034	0.00289	1.42	1.38
22	18	28.5	9.13	12.9	0.035	0.00314	1.44	1.41
22	19	32.3	10.31	12.12	0.045	0.01075	1.70	1.89
22	20	40.9	10.35	13.79	0.035	0.00344	2.30	2.05
22	21	40.1	11.1	12.9	0.043	0.00921	2.24	2.29
22	22	36	9.51	12.12	0.042	0.00690	1.95	1.98
22	23	36.5	7.14	11.43	0.035	0.00242	1.98	1.75
23	0	38.9	6.08	9.09	0.047	0.00784	2.15	2.18
23	1	40.2	8.1	10	0.052	0.01610	2.25	2.50
23	2	37.4	7.33	10	0.047	0.00929	2.05	2.14
23	3	32.9	7.46	10	0.048	0.01024	1.74	1.91
23	4	28.8	6.54	10.81	0.036	0.00246	1.46	1.39
23	5	28.4	6.19	10.81	0.034	0.00182	1.44	1.32
23	6	30.5	6.87	10	0.044	0.00651	1.58	1.66
23	7	29.6	6.57	9.09	0.051	0.01201	1.52	1.76
23	9	26.1	6.1	10	0.039	0.00338	1.29	1.31
23	10	23.1	6.94	10	0.044	0.00688	1.10	1.27
23	11	20.3	5.56	10.81	0.030	0.00101	0.93	0.88
23	12	19.3	5.59	10	0.036	0.00209	0.87	0.91
23	13	17.4	5.62	10	0.036	0.00216	0.77	0.82
23	14	18.8	5.47	9.09	0.042	0.00439	0.85	0.97
23	15	17.5	5.25	8.33	0.049	0.00768	0.77	0.98
23	16	15.7	5.34	9.09	0.041	0.00384	0.67	0.80

23	17	15.6	5.08	9.09	0.039	0.00292	0.67	0.77
23	18	13.7	4.99	8.33	0.046	0.00581	0.56	0.74
23	19	14.5	4.87	8.33	0.045	0.00508	0.61	0.76
23	20	13.2	4.61	8.33	0.043	0.00376	0.54	0.67
23	21	12.1	4.26	10	0.027	0.00047	0.48	0.49
23	22	11.5	4.36	10.81	0.024	0.00026	0.45	0.44
23	23	11.5	4.46	10	0.029	0.00060	0.45	0.47

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