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Measurements of Wind-Stress Induced Positive and Negative Storm Surges During Hurricane Isaac

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MEASUREMENTSOFWIND-STRESSINDUCED POSITIVEANDNEGATIVESTORMSURGESDURINGHURRICANEISAAC

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I. Introduction

Along the coast, storm surge is often the greatest threat to life and property from a tropical cyclone (TC) (see, e.g., http://www.nhc.noaa.gov/surge/, and Rappaport, 2014). In general, positive surges are measured when the wind pushes the water from sea to land(see, e.g., Hsu, 2013, Lillibridge et al., 2013, Mas et al., 2015, Mehra et al., 2015)and negative surges occurred when the wind forces the water from land to the sea (e.g., Houston and Powell, 1994). During Hurricane Isaac in 2012 (see Figs. 1 and 2), simultaneous measurements of both positive and negative surges are available from the National Ocean Serve (NOS) stations (see www.ndbc.noaa.gov) at SHBL1 and FRWL1, respectively (see Fig. 3). The purpose of this research note is to analyze these measurements and present formulas for practical applications.

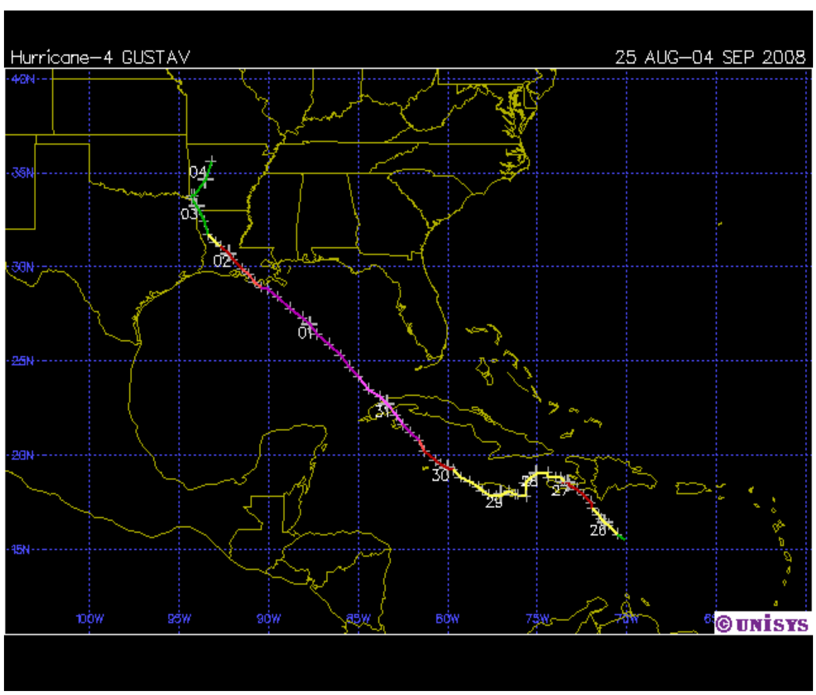

Figure 1: Track of Hurricane Isaac from 26 Aug. to 04 Sep. 2012 (Courtesy of http://weather.unisys.com/hurricane /atlantic/2012H/index.php). Note that hurricane force winds (from 18 UTC on Agu.28 thru 17UTC on Aug. 29, 2012) occurred over the Louisiana coastal regions.

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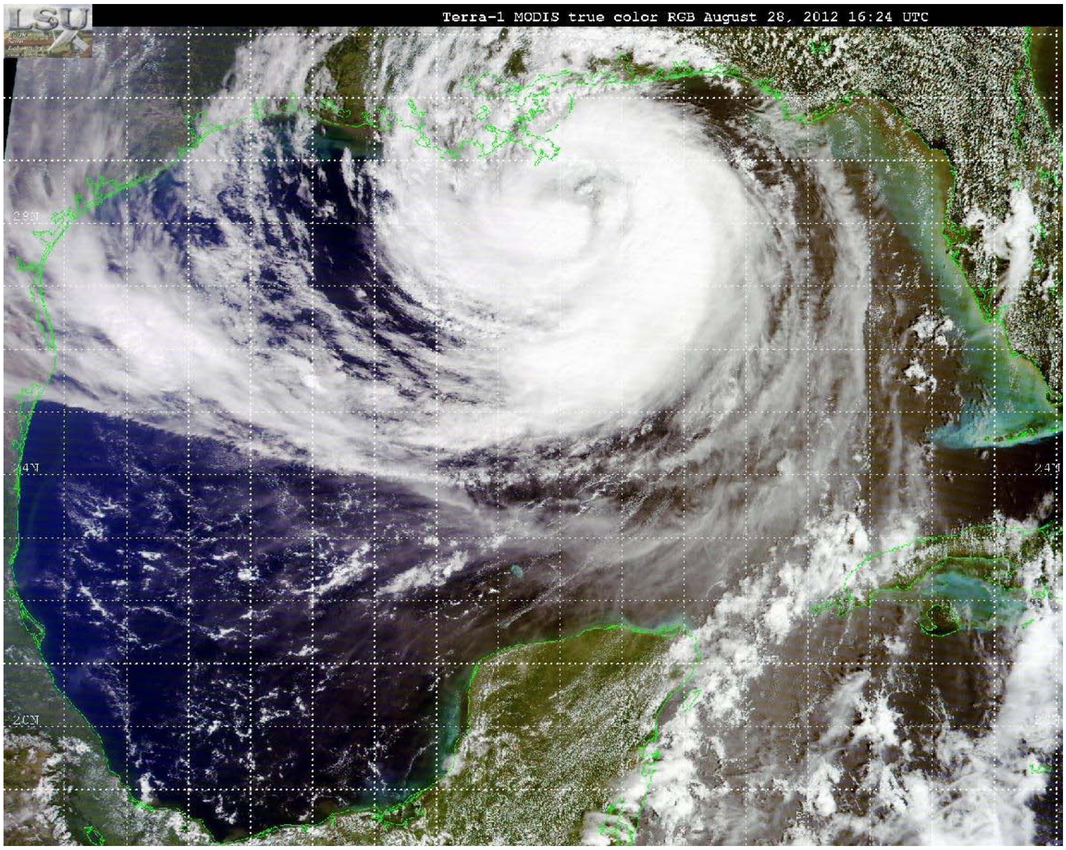

Figure 2: Satellite image of Isaac at 1624 UTC on Aug. 28, 2012 (Courtesy of the Earth Scan Lab, Louisiana State University, see www.esl.lsu.edu).

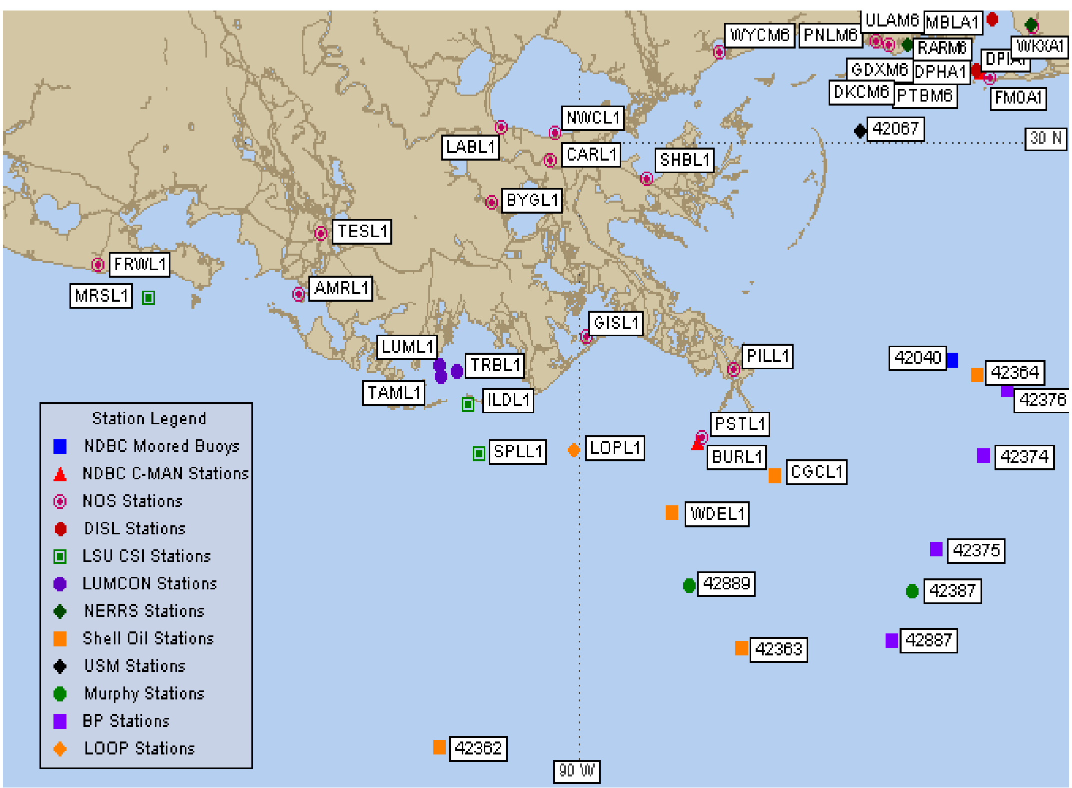

Figure 3: Locations of NOS stations at SHBL1 on the right hand side of the Isaac track east of New Orleans, Louisiana and FRWL1 on the left at the westernmost locale in the figure, see www.ndbc.noaa.gov).

II. Methods

Before our methods are discussed, basic hydrodynamic equations related to the storm surge are quoted from the Shore Protection Manual (1984, see pages 3-119 thru 3-121 for detailed explanation) as follows:

The differential equations appropriate for tropical or extratropical storm surge problems on the open coast and in enclosed and semienclosed basins are as follows:

$$\frac{\partial U}{\partial t} + \underbrace{\frac{\partial M_{xx}}{\partial x} + \frac{\partial M_{xy}}{\partial y}}_{\text{Advection of Momentum}} = \underbrace{fV}_{\text{Coriolis}} - \underbrace{gD\frac{\partial S}{\partial x}}_{\text{Surface Slope}} + \underbrace{gD\frac{\partial \xi}{\partial x}}_{\text{Inverse Barometer}} + \underbrace{gD\frac{\partial \zeta}{\partial x}}_{\text{Astro. Tide Potential}} + \underbrace{\frac{\tau_{sx}}{\rho}}_{\text{Wind Stress}} - \underbrace{\frac{\tau_{bx}}{\rho}}_{\text{Bottom Stress}} + \underbrace{W_x P}_{\text{Rainfall Rate}} \qquad (3\text{-}77)$$

$$\frac{\partial V}{\partial t} + \overbrace{\frac{\partial M_{yy}}{\partial y} + \frac{\partial M_{xy}}{\partial x}} = \overbrace{-fU} - \overbrace{gD\frac{\partial S}{\partial y}} + \overbrace{gD\frac{\partial \xi}{\partial y}} + \overbrace{gD\frac{\partial \zeta}{\partial y}} + \overbrace{\frac{\tau_{sy}}{\rho}} - \overbrace{\frac{\tau_{by}}{\rho}} + \overbrace{W_y P} \qquad (3\text{-}78)$$

An evaluation of the relative magnitude for the above terms is provided in USACE (1977) for Hurricane Camille, which also affected our study area. The most important finding of that evaluation is that approximately 80% of the total surge was caused by the wind stress in the x-component (used here for onshore component). Therefore, we postulate that, in order to investigate the contribution of wind stress to the total surge, the term of surface slope needs to be balanced by that of wind stress such that,

$$g\,D\,(dS/dX) = \tau_{sx} / \rho_{sea}, \qquad (1)$$

$$dS = [dX/(gD\rho_{sea})]\, \tau_{sx} \qquad (2)$$

$$S - S_0 = [X/(gD\rho_{sea})]\, \tau_{sx}, \qquad (3)$$

$$S - S_0 = K\tau_{sx}, \qquad (4)$$

$$\tau_{sx} = \rho_{air} U_*^{\,2}, \qquad (5)$$

According to Andreas et al. (2012),

$$U_* = 0.0583\, U_{10} - 0.243, \qquad (6)$$

Following Carter (1982),

$$H_s = 0.0163\, X^{0.5} U_{10}, \qquad (7)$$

According to Hsu (2016), under hurricane conditions in the Gulf of Mexico,

$$H_s = 0.47\, U_{10} - 3, \qquad (8)$$

The symbols for above equations are: g = gravitational acceleration, D = water depth, S = total surge, S_0 = predicted astronomical tide, X = fetch, ρ_{air} and ρ_{sea} = air and sea-water densities, respectively, τ_{sx} = the wind stress, U_* = friction velocity, U_{10} = wind speed at 10m, and H_s = significant wave height. All units are in SI except that the fetch is in km. Note that coefficient K in Eq. (4) can vary with X as shown in Eq. (3) (see, e.g., Irish et al., 2008). However, for a given wind speed, X may be considered as a constant based on Equations (7) and (8).

Using these aforementioned formulas or methods, we can now continue our analysis.

III. Analysis and Results

a) *Positive surges*

Simultaneous measurements of wind speed and direction and water level were made by the NOS during Isaac. Pertinent datasets and analysis for the wind characteristics are presented in Figures 4 and 5, respectively. It can be seen that, from 0000UTC on 28 August to approximately 0400UTC on 29 August, onshore winds produced positive surge for more than 3 meters. Using the 6-minute datasets from NDBC (see www.ndbc.noaa.gov) for SHBL1during this period, relation between the positive surge and wind stress is found and presented in Figure 6. Since the coefficient of determination, R^2 = 0.93, meaning that 93% of the variation between positive surge and wind stress can be explained by

$$S - S_0 = 1.5\, \tau_{sx} + 0.13 \qquad (9)$$

Since the correlation coefficient, R = 0.96, is very high, Eq. (9) may be useful operationally. Note that the wind stress can be estimated routinely from Equations (5) and (6) since ρ_{air} = 1.22 kg m^{-3} for the moist air (Zedler, 2009) and the wind speed is measured.

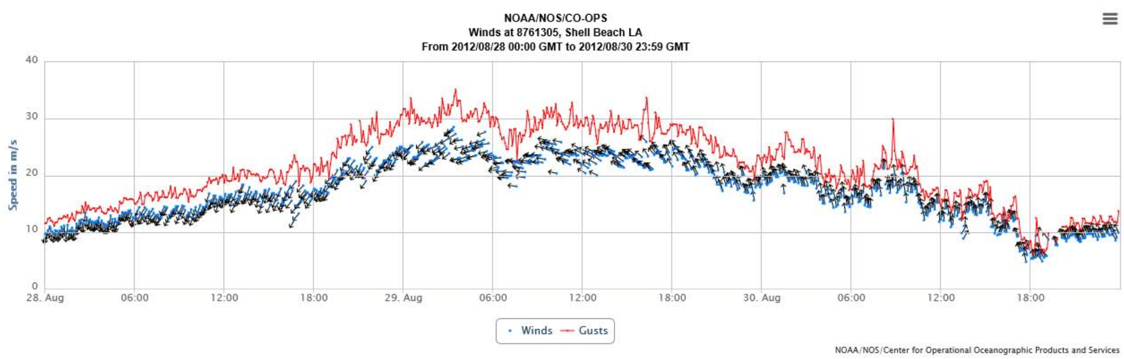

Figure 4: Measurements of wind speed, direction, and gust from 28 thru 30 August 2012 at NOS station SHBL1 during Hurricane Isaac (see www.ndbc.noaa.gov)

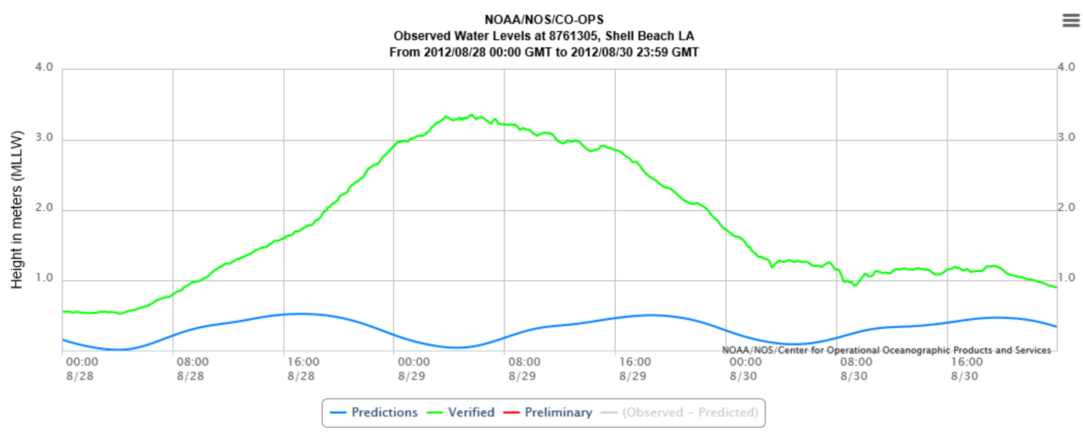

Figure 5: Measurements of total water level (in green) and predicated astronomical tide (in blue) during the period shown in Figure 4 (see www.ndbc.noaa.gov).

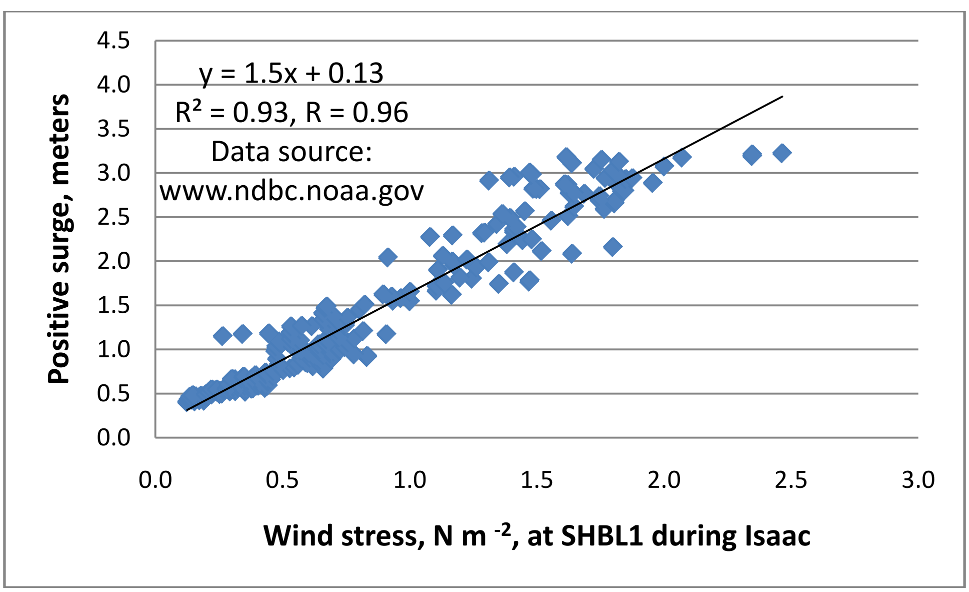

Figure 6: Relation between positive surge and the wind stress at SHBL1 during Isaac

b) Negative surges

Similar analysis for the negative surge is performed during the same period for FRWL1. Results are presented in Figures 7 thru 9. Therefore, for negative surge, we have

$$S - S_0 = -1.4\ \tau_{sx} - 0.19 \qquad (10)$$

Note that, since R = 0.86, the wind stress also plays a dominant role in the boundary-layer physics of negative surge.

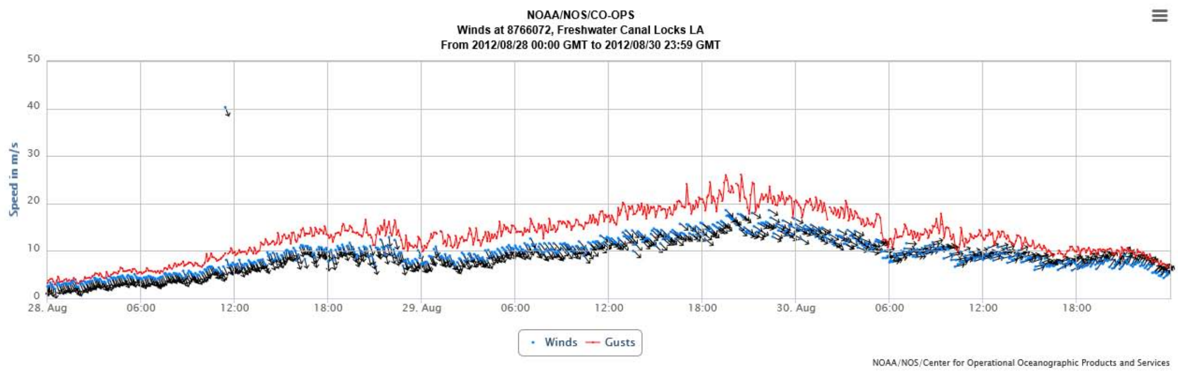

Figure 7: Measurements of wind speed, direction, and gust from 28 thru 30 August 2012 at NOS station FRWL1 during Hurricane Isaac (see www.ndbc.noaa.gov)

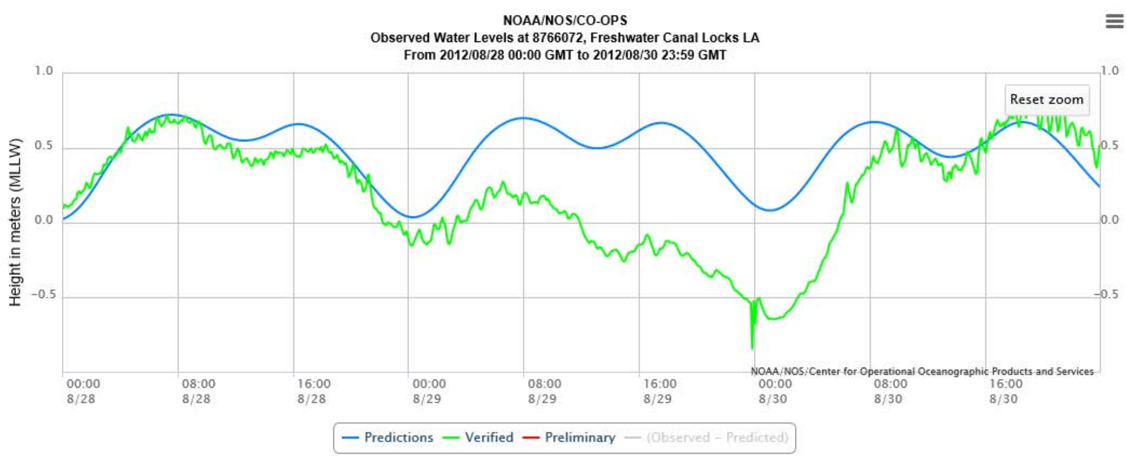

Figure 8: Measurements of total water level (in green) and predicated astronomical tide (in blue) during the period shown in Figure 7 see www.ndbc.noaa.gov).

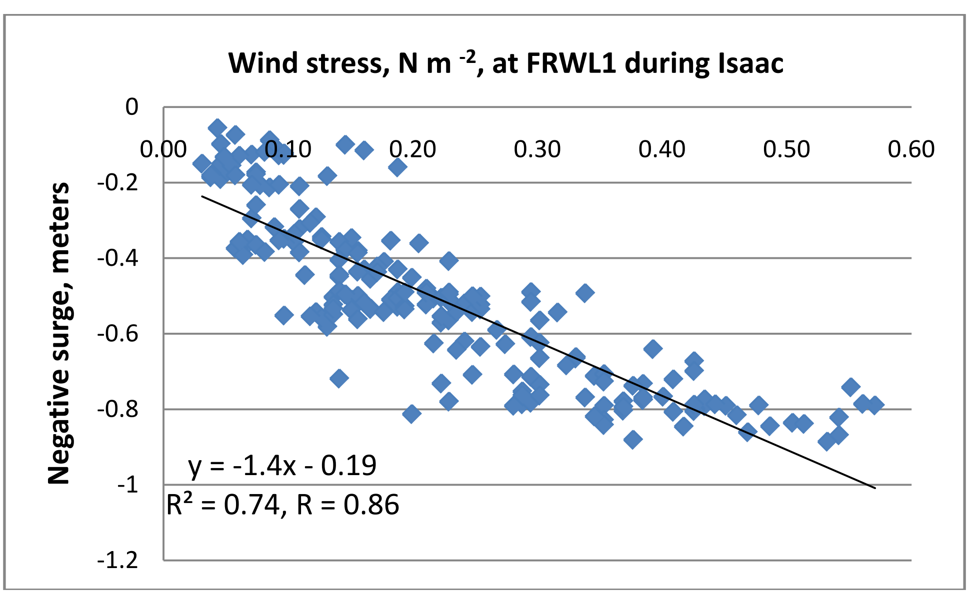

Figure 9: Relation between negative surge and the wind stress at FRWL1 during Isaac

IV Conclusions

On the basis of aforementioned analysis and discussion, it is concluded that

(1) When the winds blow from sea to land during a TC, positive storm surges prevail. Its relation with the wind stress is presented in Eq. (9);

(2) When the winds blow from land to the sea, negative surges occur. Its relation with the wind stress is shown in Eq. (10), and most importantly;

(3) It is found that the ratio of wind stress to either positive or negative surge is approximately 1:1.5, meaning that one Pa (pascal = 1 N m $^{-2}$) wind stress can produce 1.5 meters of water-level increase or decrease. Using this ratio, it is possible to reconstruct or estimate the maximum wind stress or TC intensity from the maximum water level recorded in an area affected by a TC in the past, or to forecast future water level change caused by a TC.

V. Acknowledgements

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