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On the rapid estimation of wind-stress induced storm surge during tropical cyclones

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ABSTRACT Wind-stress forcing components in differential equations appropriate for tropical or extratropical storm surge problems, on the open coast and in enclosed and semi-enclosed basins, as used by the Coastal Engineering Research Center, are parameterised as a function of the significant wave height or the sea-level pressure near a tropical cyclone's landfall. Verifications of this proposed approach are successful. It is demonstrated that the extreme storm surge measurements during Hurricane Katrina are indispensable in this validation process. In addition to the five hurricane cases presented, the storm surge datasets are also incorporated from the Extremely Severe Cyclonic Storm Nargis, which was an extremely destructive and deadly tropical cyclone that caused the worst natural disaster in the recorded history of Myanmar during early May 2008.

Key words: storm surge, wind stress, tropical cyclone, significant wave height, Hurricane Katrina, Extremely Severe Cyclonic Storm Nargis.

1. Introduction

In 2005, Hurricane Katrina devastated the Gulf Coasts of Louisiana and Mississippi, USA. There are several marine meteorological and physical oceanographic (met-ocean) lessons learned; among which is applied fluid-Earth geophysics related to storm surge. Since this year marks its 20^{th} anniversary, this short note is to commemorate its contribution to the record storm surge measurement of approximately 9 m as indicated in Table 1. The purpose of this technical note is to explain this extreme value from the viewpoint of wind-stress forcing, which may be parameterised by the significant wave height, H_s or by the sea-surface pressure, P, near the landfall of a tropical cyclone (TC).

2. Methods

Based on the analysis of the datasets as listed in Abel *et al.* (1989), a relation between H_s and P along the U.S. Atlantic and Gulf of Mexico coastlines during 43 and 25 hurricanes, respectively, is analysed for coastal water environments (Fig. 1) and presented in Eq. (1) as follows:

$$H_S = -0.136P + 142 \tag{1}$$

with a correlation coefficient, R = 0.82.

The Coastal Engineering Research Center (1984) of the U. S. Army Corps of Engineers has provided the differential equations appropriate for tropical or extratropical storm surge problems on the open coast and in enclosed and semi-enclosed basin (for details, see Appendix). The component of wind stress, τ, induced storm surge can be simplified, and based on Eqs. (10) and (17) in Hsu (2025) by setting the air density, ρ_{air}=1.2 kg, m $^{-3}$, and friction velocity, $U_* = 0.17H_s$ [see also Eq. (3) in Hsu (2023)] and from Eq. (1), is:

$$\tau = \rho_{air} U *^2 = 1.2(0.17H_S)^2 = 0.035(-0.136P + 142)^2 \quad (2)$$

A graphic representation of Eq. (2) is presented in Fig. 2.

Table 1 - Validation of the storm surge (SS) induced by wind stress using Eq. (2) during TCs.

Name	Year	*P* (hPa)	SS (m) estimated	SS (m) measured	Location	Data source
Katrina	2005	928	8.7	8.5	Pass Christian, MS	NHC (n.d.) TC report, pp. 18, 28
Laura	2020	940	7.0	6.4	Calcasieu Pass and Creole, LA	NHC (n.d.) TC report, pp. 23, 27
Nargis	2008	946	6.2	5.2-7.0	Irrawaddy Delta, Myanmar	Fig.5 and in Hsu (2023), Figs.12 and 14
Helene	2024	955	5.1	5.2-5.4	NWS HWM1&2, mean TTU Net, FL	NHC (n.d.) TC report, pp. 39,40
Ian	2022	967	3.8	3.9	Ft. Myers Beach, FL	NHC (n.d.) TC report, p.50 and KFMY
Ida	2021	971	3.5	3.4	Grand Isle, LA	NHC (n.d.) TC report, pp. 27, 33

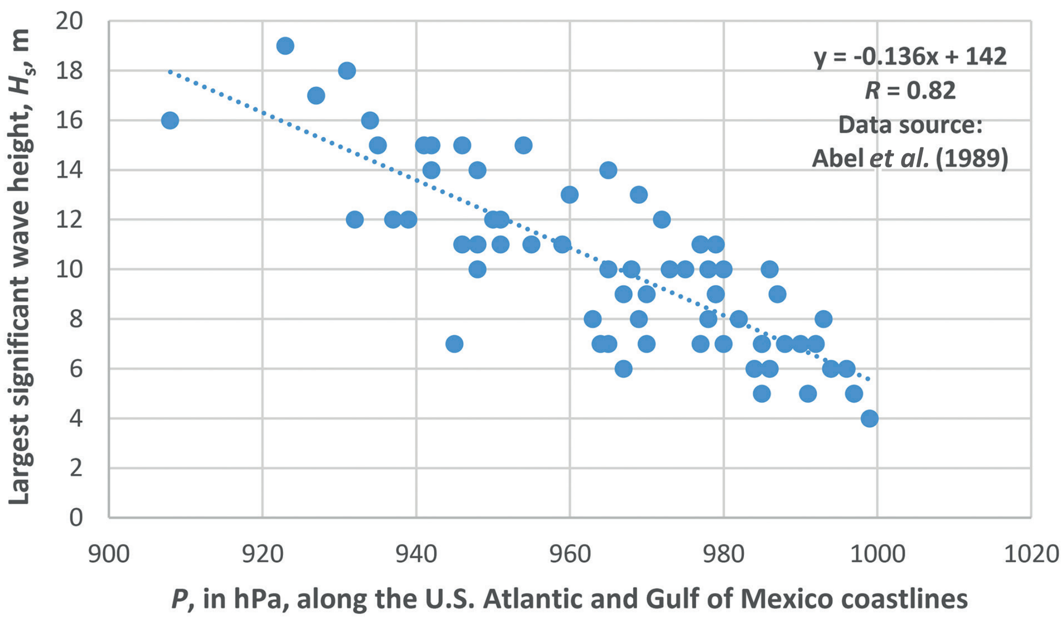

Fig. 1 - Relation between H_s and *P* along the Atlantic and Gulf coastlines during 68 hurricanes based on the datasets provided in Abel *et al.* (1989).

3. Results

Our results are presented in Table 1, which is mainly based on the TC reports issued annually by the National Hurricane Center (NHC). Note that the data for Cyclone Nargis are reported in Figs. 12 and 14 of Hsu (2023) and Figs. 3 and 4. This is because in Myanmar there were no met-ocean measurements. The isotach or equal wind speed analysis by the Regional and Mesoscale Meteorology Branch is employed as shown in Fig. 3. The sea-level pressure, *P*, is not available but the max U_{10} of 105 knots (54 m s^{-1}) is provided. If we use the measured relation between *P* and U_{10} as shown in Fig. 4, *P* = 946 hPa so that the storm surge is estimated at 6.2 m as provided in Table 1, which is consistent with the measurements. Therefore, Table 1 indicates that the analytical formula as proposed in Eq. (2) is useful for a rapid estimation of the storm surge component induced by wind stress alone. For operational met-ocean applications, a graphic representation of Eq. (2) is presented in Fig. 2.

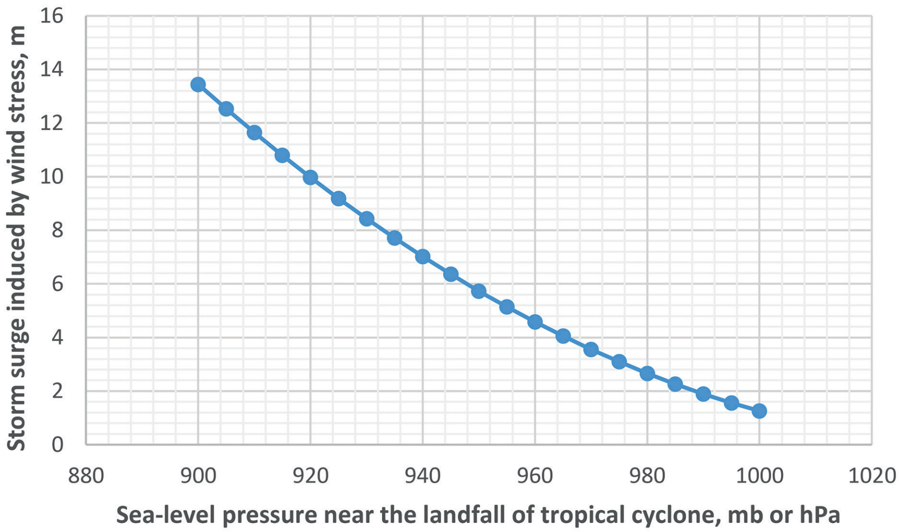

Fig. 2 - Graphic representation of Eq. (2).

4. Discussion

During the review process, questions were raised in relation to the dimension of the approach applied in this study. Answers to these questions can be found in this Section and in the Appendix where a set of differential equations for tropical and extratropical storm surge problems is listed.

If the surface slope is balanced by the wind stress, the following equations are obtained:

$$gD\, \partial S/\partial X = \tau/\rho_W = (\rho_{air}/\rho_W)U*^2, \quad (3)$$

$$\Delta S = (\rho_{air}\Delta X/\rho_W\, gD)U*^2, \quad (4)$$

$$S - S_0 = (\rho_{air}F/\rho_W\, gD)U*^2. \quad (5)$$

According to the Joint North Sea Wave Project wave spectra (see Carter, 1982), the relation shown in Fig. 4 is obtained with Eq. (6), i.e.:

$$H_S = 0.0163F^{0.5}U_{10}\,. \tag{6}$$

In Eqs. (3), (4), (5), and (6) *S* is the storm surge, S_o is the known background water level (e.g. the astronomical tides), *F* is the overwater fetch length which generates *S*. For all other symbols used in these equations, reference should be made to the Appendix.

Based on the SI units, the dimensions on both sides of Eq. (5) are in metres.

The units for Eq. (1) can also be explained by the fact that, since air pressure is proportional to air density × gravitational acceleration × height, then *P* is proportional to H_s.

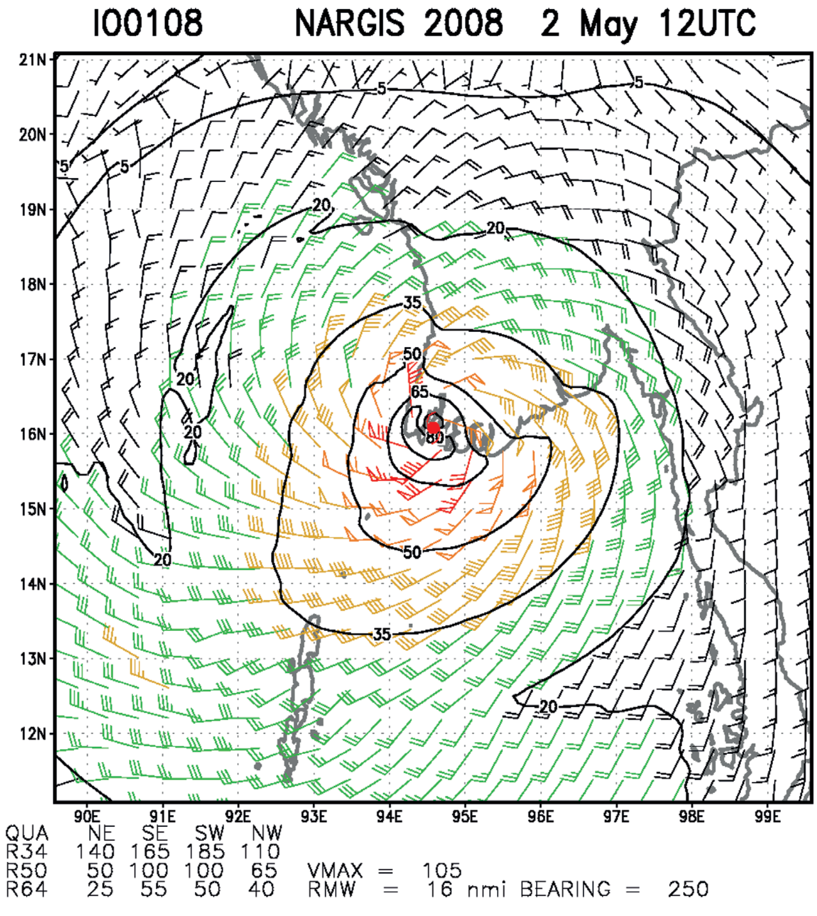

Fig. 3 - Isotach or equal wind speed analysis by the Regional and Mesoscale Meteorology Branch during the landfall of Nargis.

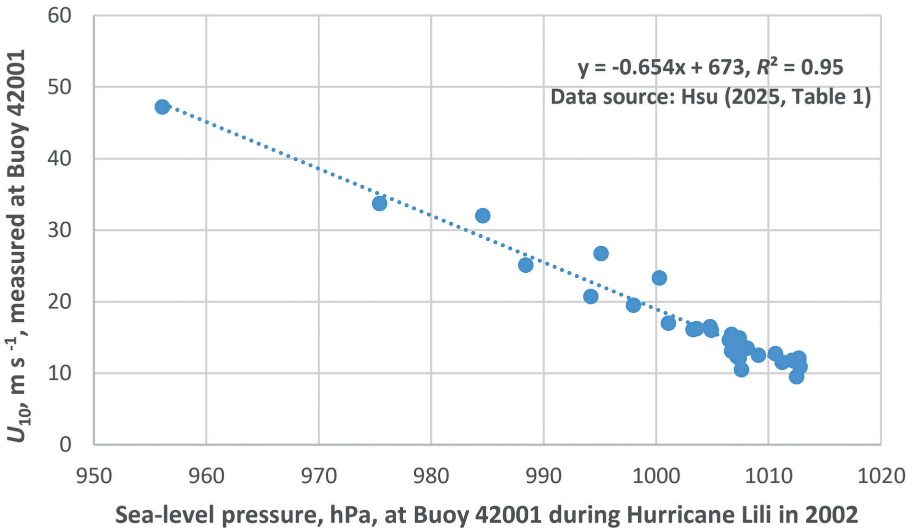

Fig. 4 - Relation between P and U_{10} at buoy 42001 during Hurricane Lili in 2002.

5. Conclusions

On the basis of the aforementioned analysis and discussion, it is concluded that the wind-stress forcing component in the differential equations appropriate for tropical or extratropical storm surge problems on the open coast and in enclosed and semi-enclosed basins, as used by the Coastal Engineering Research Center, can be parameterised as shown in Eq. (2) using the significant wave height or the sea-level pressure near a tropical cyclone's landfall. In addition, the measurement of storm surge during Katrina, as shown in Table 1, is indispensable to further extend the validity of Eq. (2), which may be useful for those regions prone to TCs, if numerical models of storm surge are not available or a rapid estimation of the storm surge is needed. Although there are six TCs employed to verify Eq. (2), more datasets are needed to quantify the approach as proposed in this research note.

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NHC; n.d.: *National Hurricane Center and Central Pacific Hurricane Center.* www.nhc.noaa.gov.

Appendix

The differential equations appropriate for tropical or extratropical storm surge problems on the open coast and in enclosed and semienclosed basins are as follows (see Coastal Engineering Research Center, 1984):

$$\partial U/\partial t + \partial M_{xx}/\partial x + \partial M_{xy}/\partial y = fV - gD\,\partial S/\partial x + gD\,\partial \xi/\partial x + gD\,\partial \zeta/\partial x + \tau_{sx}/\rho w - \tau_{bx}/\rho w + W_x P \quad \text{(A1)}$$

$$\partial V/\partial t + \partial M_{yy}/\partial y + \partial M_{xy}/\partial x = -fU - gD\,\partial S/\partial y + gD\,\partial \xi/\partial y + gD\,\partial \zeta/\partial y + \tau_{sy}/\rho w - \tau_{by}/\rho w + W_y P \quad \text{(A2)}$$

$$\partial S/\partial t + \partial U/\partial x + \partial V/\partial y = P \quad \text{(A3)}$$

$$D = d + S \quad \text{(A4)}$$

where

$$M_{xx} = \int_{-d}^{S} u^2\,dz; \quad M_{yy} = \int_{-d}^{S} v^2\,dz; \quad M_{xy} = \int_{-d}^{S} uv\,dz; \quad U = \int_{-d}^{S} u\,dz; \quad V = \int_{-d}^{S} v\,dz.$$

The symbols are defined as:

- U, V = x and y components, respectively, of the volume transport per unit width
- t = time
- M_{xx}, M_{yy}, M_{xy} = momentum transport quantities
- $f = 2\omega \sin \varphi$ = Coriolis parameter
- ω = angular velocity of earth (7.29×10^{-5} radians per second)
- φ = geographical latitude
- g = gravitational acceleration
- ξ = atmospheric pressure deficit in head of water
- ζ = astronomical tide potential in head of water
- τ_{sx}, τ_{sy} = x and y components of surface wind stress
- τ_{bx}, τ_{by} = x and y components of bottom stress
- ρw = mass density of water
- W_x, W_y = x and y components of wind speed
- u, v = x and y components, respectively, of current velocity
- P = precipitation rate (depth/time)
- D = the total water depth at time t
- d = the undisturbed water depth
- S = the height of the free surface above or below the undisturbed water depth due to surge

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