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Some Value-Added Met-Ocean Products to the RAMMB's TC Surface Analysis for Marine Meteorological Applications

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Abstract

In the realm of air-sea interaction and marine meteorology, during a tropical cyclone (TC) worldwide since 2006, the Regional and Mesoscale Meteorological Branch (RAMMB) has issued surface wind analysis. Based on this TC's isotach (line of equal wind speed) analysis, in this paper, much more meteorological-oceanographic (met-ocean) products are developed and value-added to these isotachs. They are, for marine meteorology, overwater friction velocity, wind stress, atmospheric vorticity and the mean vertical velocity, and for oceanography, significant wave height, drift-current velocity, wind-stress tide and wave set-up. Furthermore, in order to estimate the wind-stress induced storm surges, two case studies are presented. They are the Extremely Severe Cyclonic Storm Nargis which devastated Myanmar in May 2008 from the Bay of Bengal and in August 2023 Hurricane Idalia which impacted northeastern Gulf of Mexico coastal region of Florida.

Keywords

Tropical cyclones; RAMMB's TC surface analysis; met-ocean parameters; overwater friction velocity; hurricane vorticity; wind-stress tide

1. Introduction

Since 2006, the Regional and Mesoscale Meteorological Branch (RAMMB) of NOAA/NESDIS (http://rammb.cira.colostate.edu/) has issued worldwide real-time tropical cyclone (TC) surface wind analysis similar to Figure 1. The reason to employ this figure is because that, according to Bancroft ([1] available online, at http://www.vos.noaa.gov/MWL/201604/northpacific.shtml#contents), as shown in Figure 2, around 12UTC on the 4th of August 2015, Soudelor was a super typhoon near 19N 137E with sustained winds 140 knots (72 m s^{-1}) and it is just a coincidence that we have a Jason-2 altimeter pass through the eye wall of Soudelor. Note the highest significant wave height of 27.6 m in the northwest eye wall. Since it is only fortuitous that we have both wind and wave measurements by different satellites near the same time in the same area, a question related to marine meteorology and physical oceanography (met-ocean) is raised that can one estimate the significant wave height and other variables from this routinely available RAMMB product during a TC worldwide? The purpose of this study is to provide these and other value-added met-ocean variables or products for marine meteorological applications.

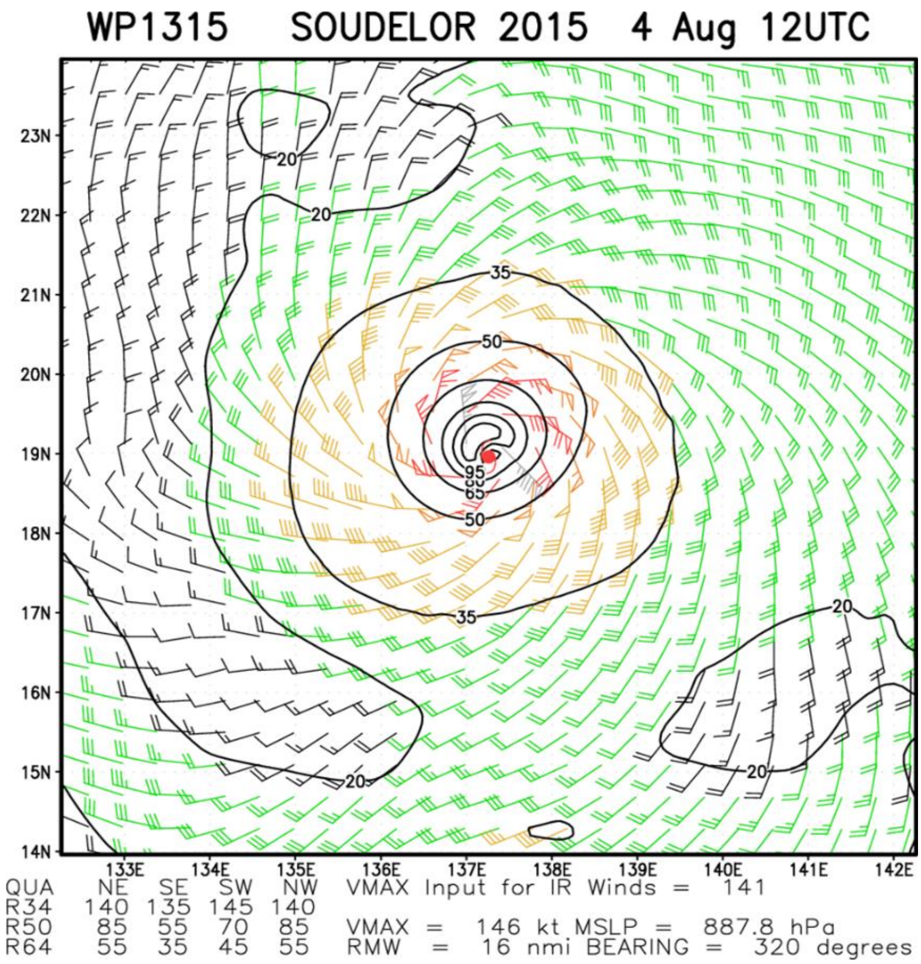

Figure 1 A real-time TC surface wind analysis issued by RAMMB. https://rammb-data.cira.colostate.edu/tc_realtime/products/storms/2015wp13/mpsatwnd/2015wp13_mpsatwnd_201508041200_swnd.gif.

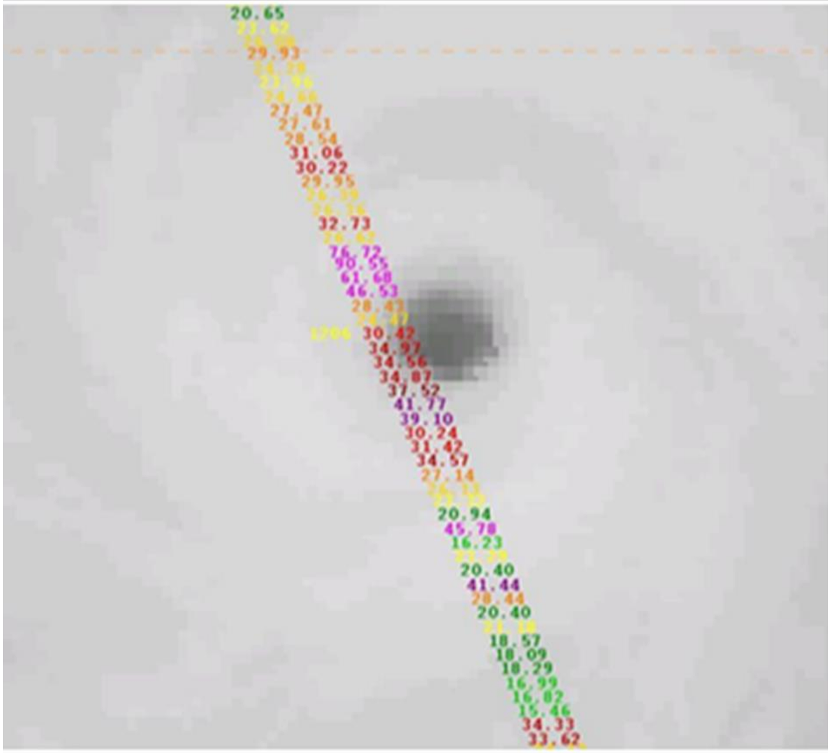

Figure 2 A zoomed-in infrared satellite Image of Super-Typhoon Soudelor valid 1232 UTC August 4, 2015. A Jason -2 altimeter pass appears as a swath of significant wave heights given in feet to two decimal places cutting across the central core of Soudelor [After Bancroft GP [1], for more detail, see: http://www.vos.noaa.gov/MWL/201604/northpacific.shtml#contents)]. Based on: http://www.vos.noaa.gov/MWL/201604/northpacific.shtml%23contents.

2. Methodology

2.1 Relation between Wind Speed and Significant Wave Height

During wind seas, from the literature [1] (Equation 12 and Figure 12) and [2] (Equation 2 and Figure 3 and Figure 4), an operational formula relating the wind speed at 10 meter, U_{10}, in m s^{-1}, to the significant wave height, H_s, in m, is

$$H_s = 0.4U_{10} - 1 \tag{1}$$

Further verification of Equation (1) during an extreme wind-wave conditions is to employ Figure 1 and Figure 2. Note that as stated in the introduction, for U_{10} = 72 m s^{-1}, H_s = 27.8 m, which is in excellent agreement with the 27.6 m as measured by Jason-2 altimeter. Since this formula is also valid during Hurricane Maria (2017) [1] in the Atlantic, Hurricane Lane (2018) [2] in the Central Pacific near Hawaii, and Typhoon Russ (1990) [2] near Guam in the Western Pacific, it is employed in this study as the first value-added parameter which is to convert the iostach of U_{10} as shown in Figure 1 to the values of H_s for practical marine meteorological use.

2.2 Relation between Wind Speed and Wind-Induced Drift Current

According to Wu ([3], Equation 2), the wind-induced surface drift current, U_{sea}, is related linearly to the friction velocity, U_*, that

$$U_{\mathrm{sea}} = 0.53U_* \tag{2}$$

Using the datasets of 4 slow-moving super typhoons as provided in [4] (Table 4), a relation between U_* and H_s is found based on Figure 3 that

$$U_* = 0.17H_{\mathrm{s}} \tag{3}$$

With a very high coefficient of determination, R^2 = 0.97, indicating that this equation is a very useful value-added formula for marine meteorology.

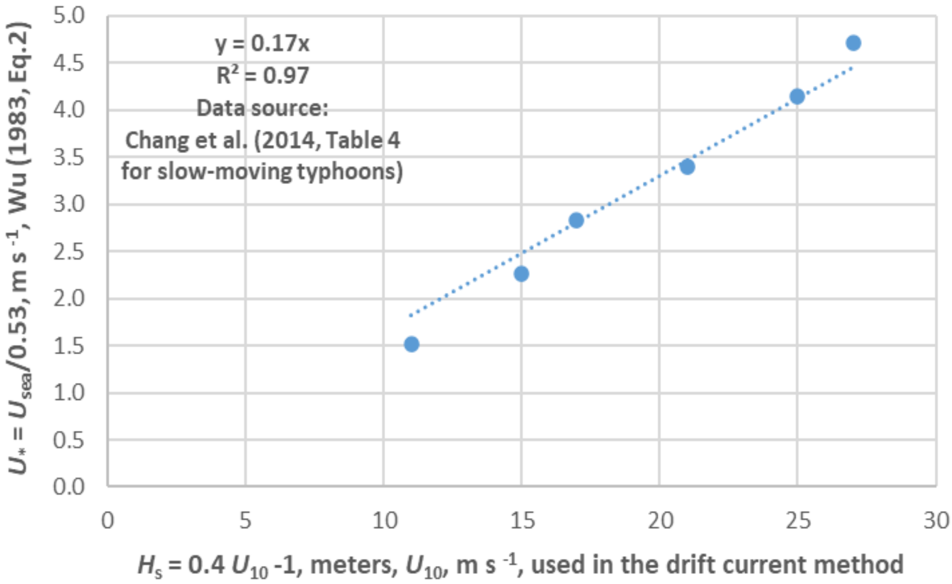

Figure 3 A relation between H_s and U_* based on the drift current method.

From Equation (1) and Equation (2) by eliminating H_s, we have

$$U_* = 0.068U_{10} - 0.17 \tag{4}$$

And from Equation (2) and Equation (3), one gets

$$U_{\mathrm{sea}} = 0.090H_{\mathrm{s}} \tag{5}$$

Furthermore, from Equation (2) and Equation (4), we have

$$U_{\mathrm{sea}} = 0.036U_{10} - 0.090 \tag{6}$$

A comparison between Equation (6) and the measurements by [4] (for the error bars) is presented in Figure 4. Since the slope is near unity and R^2 = 0.97, Equation (6) can be employed to estimate U_{sea} based on the isotach as shown in Figure 1.

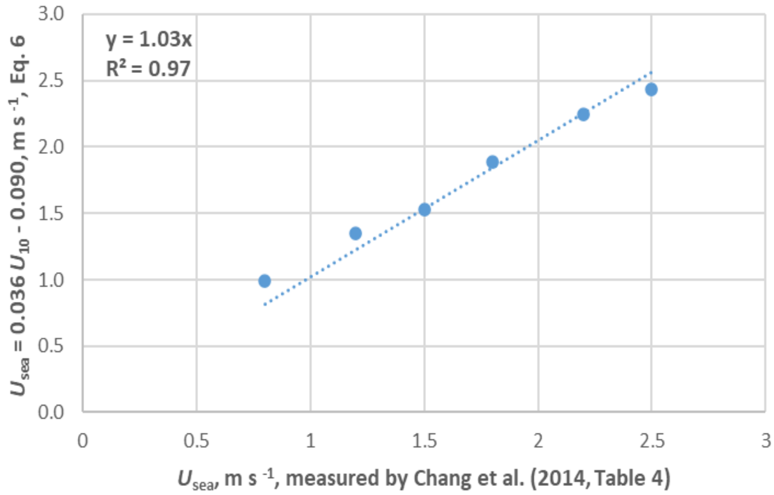

Figure 4 Comparison between Equation (6) and observations.

2.3 Relation between Friction Velocity and Wind Speed

Similar to Equation (6), the linear relation between U_{10} and U_* has been parameterized extensively (for a review, see [5]). Since most direct measurements of U_* were within U_{10} < 25 m s^{-1}, we employ the datasets based on the atmospheric vorticity method [6] (Table 3.3) as shown in Figure 5. It can be seen that, if one accepts the high R^2 = 0.94, the linear relation between U_* and U_{10} can be extend from gale force wind to a hurricane. If fact, if we include the wind-current measurements by [4] (Table 4) as depicted in Figure 6, R^2 increased from 0.94 to 0.97. A comparison between the formula obtained in Figure 6 and the equation derived in [5] (Equation 22) is depicted in Figure 7, indicating that, for U_{10} > 45 m/s, the formula available in the literature [5] (Equation 22) underestimates the value of U_* for a given wind speed. Since the datasets used in Figure 6 are not routinely available, we need to compare the formula shown in Figure 6 to Equation 4 using the U_{10} values as provided in Figure 6. Our result is presented in Figure 8. Since the difference between the slope of 1.06 versus 1.0 is 6% and R^2 = 0.89, Equation (6) is recommended as an approximation for the relation between U_* and U_{10} from gale to hurricane force winds.

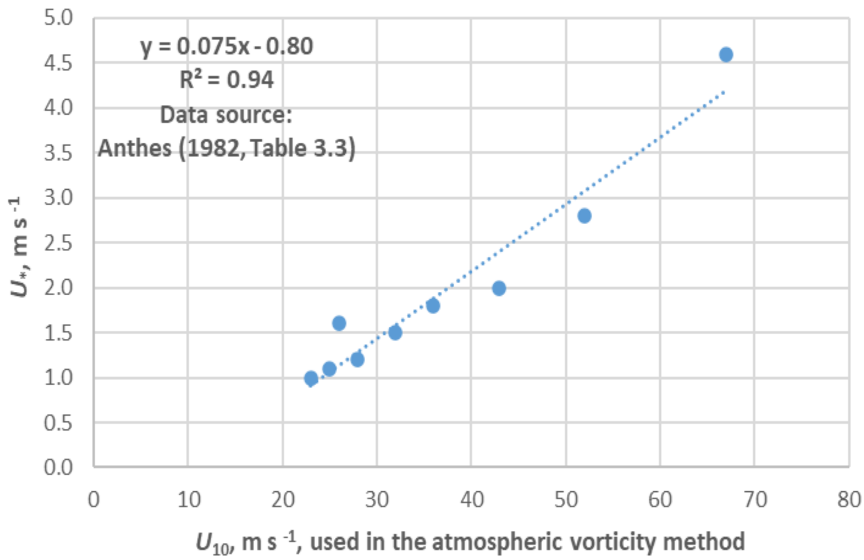

Figure 5 Linear relation between U_* and U_{10} based on the atmospheric vorticity method.

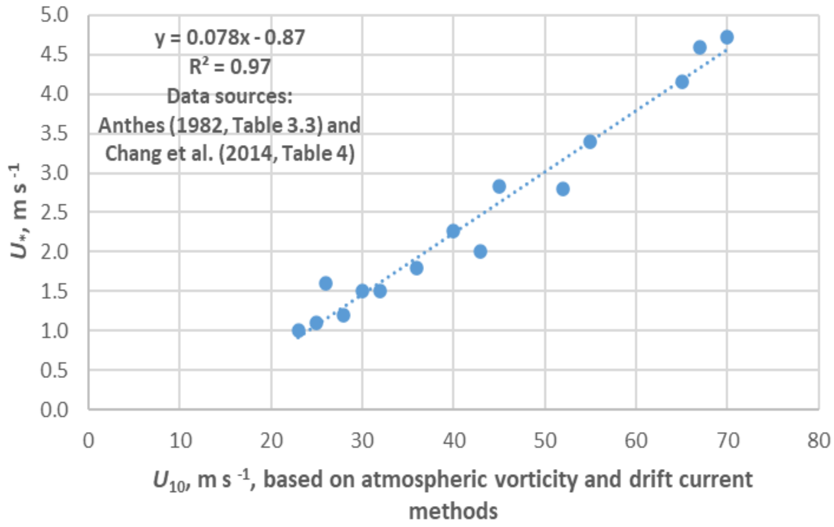

Figure 6 Linear relation between U_* and U_{10} based on both atmospheric vorticity and wind-induced drift current methods.

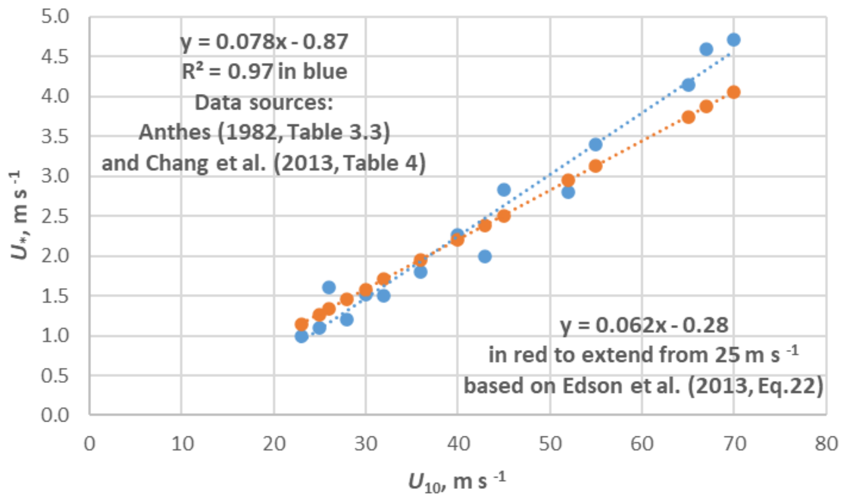

Figure 7 Comparison of the formula presented in Figure 6 and that of [5] (Equation 22).

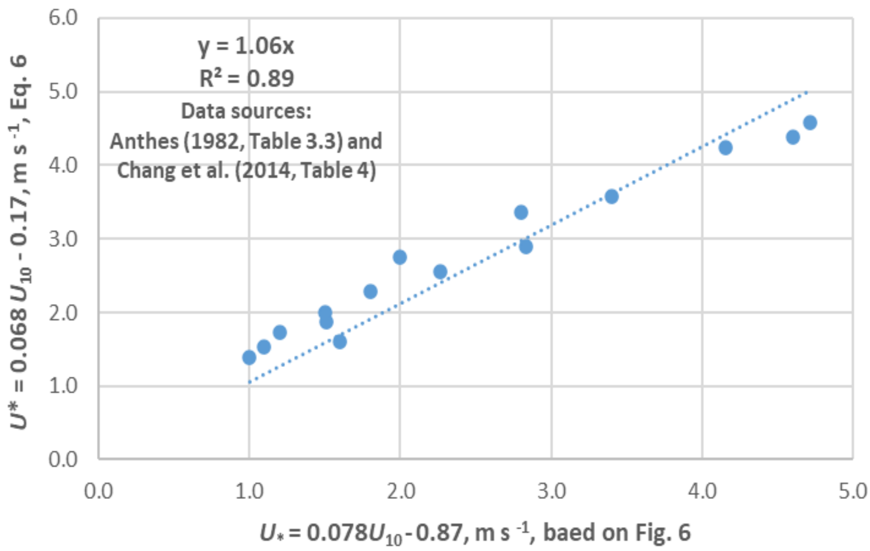

Figure 8 Comparison between Equation 4 and the formula presented in Figure 6.

2.4 Relation between the Wind Stress and Significant Wave Height

According to [5], for $U_{10} > 8.5$ m s^{-1}, the seas are considered fully rough and the surface waves support most of the surface stress via form drag (normal stress). Since we need to find an explicit relation between the wind stress and H_s, Figure 9 is presented as an attempt to provide such a relation that

$$\text{The wind stress} = 0.0314{H_s}^2 \tag{7}$$

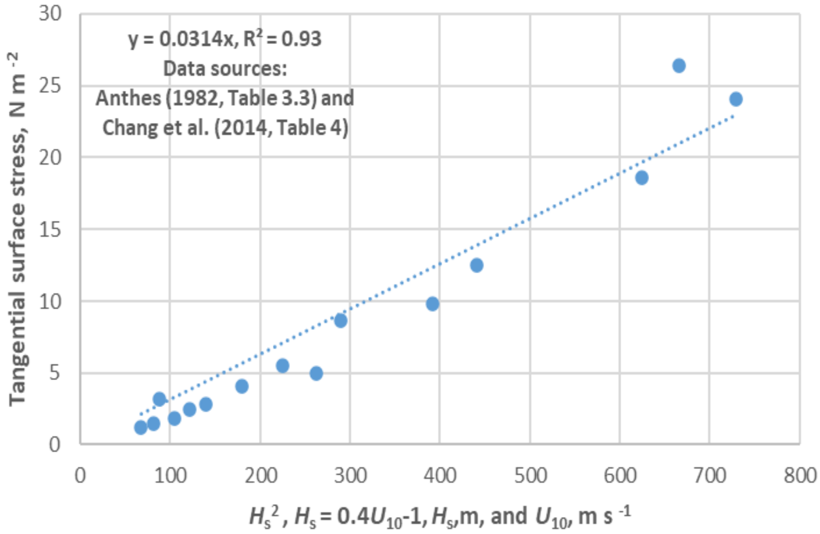

Figure 9 An explicit Relation between the wind stress and significant wave height.

Note that since both U_* and the wind stress values are available in [6] (Table 3.3), H_s are computed from Equation (1) for a given U_{10}. For the data sets based on [4] (Table 4), H_s and U_* are computed from Equation (1) for a given U_{10} and Equation (2) for a given U_{sea}, respectively, and the wind stress = density for moist air * (friction velocity)^2 = 1.2 U_*^2. Since $R^2 = 0.93$, Equation (7) may be used to estimate the wind stress.

2.5 Estimating Hurricane Vorticity and Mean Vertical Velocity in the Air-Sea Boundary Layer

For diagnostic and prognostic analysis of a TC such as a rapid intensification, characteristics of atmospheric vorticity and the mean vertical velocity may be useful. According to [6] (p. 70, Equation (3.7)), the hurricane vorticity may be estimated that

$$\text{Vorticity} = \text{windstress}/(\text{air density} * \text{wind speed} * \text{boundary} - \text{layer height}) \tag{8}$$

By setting air density = 1.2 kg m^{-2}, boundary-layer height = 500 m [6], the wind speed from a given isotach as shown in Figure 1, and the wind stress as computed from Equation (7), the vorticity may be estimated. as a value-added met-ocean parameter for marine meteorological applications.

In addition, following [6] (p.72, Equation (3.15)), the mean vertical velocity, in m s^{-1}, may be calculated from Equation (8) that

$$\text{The mean vertical velocity} = 134 * \text{vorticity} \tag{9}$$

Since both vorticity and the mean vertical velocity are useful, they are included in this study as value-added met-ocean parameters for marine meteorological applications.

2.6 Estimating Wind-Stress Tide and Wave Set-Up

Finally, in order to save life and protect property along the relatively flat coastal zones in a TC-prone region, the magnitude of storm surge induced by the TC needs to be estimated. According to [7, 8], the wind-induced water level, S_{wind} in meters, constitutes more than 80% of total storm surge and following [9, 10] it may be estimated as

$$S_{\mathrm{wind}} = 0.005{U_{10}}^2 \tag{10}$$

This formula has been applied by [11] that, during Hurricane Delta (2020), the areas inside of 50 knots (25.8 m s^{-1}) isotach can produce up to 11 ft (3.3 m) high water level above the ground, whereas during Laura's landfall in 2020, the area inside of 65 knots (33.5 m s^{-1}) isotach up to 18 ft (5.6 m) inundation.

In addition, because of its destructive wave-force impact on structures, the magnitude of wave set-up, $S_{\text{set-up}}$, on the top of the storm surge, needs to be estimated that [10],

$$S_{\mathrm{set-up}} = 0.15H_{\mathrm{s}} \tag{11}$$

3. Results

Based on aforementioned methods, our results are presented in Table 1 using the known isoch as provided in Figure 1. Note that the last horizontal row is based on the max wind speed, Vmax, at the radius of max wind, RMW, as provided in Figure 1. Table 2 shows the estimation of potential wind-stress tide and wave set-up for a given isotach. These value-added met-ocean parameters may be useful for marine meteorological applications.

Table 1 Some value-added met-ocean parameters for Figure 1.

Isotach U_{10}	Isotach U_{10}	H_s, m	U_*, m s^{-1}	U_{sea}, m s^{-1}	Wind stress, N m^{-2}	Vorticity, s^{-1} in 10^{-4}	Vertical velocity, cm s^{-1}
kts	m s^{-1}	Equation (1)	Equation (4)	Equation (5)	Equation (7)	Equation (8)	Equation (9)
35	18.0	6.2	1.1	0.6	1.2	1.1	1.5
50	25.8	9.3	1.6	0.8	2.7	1.7	2.3
65	33.5	12.4	2.1	1.1	4.8	2.4	3.2
80	41.2	15.5	2.6	1.4	7.5	3.0	4.0
95	49.0	18.6	3.2	1.7	10.9	3.7	5.0
146	75.3	29.1	5.0	2.6	26.6	5.9	7.9

Table 2 Estimating potential wind-stress tide and wave set-up for the isotach near landfall.

Isotach U_{10}	Isotach U_{10}	Wind-stress tide, Equation (10)	Wind-stress tide, Equation (10)	H_s, Equation (1)	Wave set-up, Equation (11)	Wave set-up, Equation (11)
kts	m s^{-1}	m	feet	m	m	feet
35	18.0	1.6	5	6.2	0.9	3
50	25.8	3.3	11	9.3	1.4	5
65	33.5	5.6	18	12.4	1.9	6
80	41.2	8.5	28	15.5	2.3	8

In addition, as stated in the last section, the phenomenon of storm surge is also important. In this regard, the storm surge in Myanmar induced by Severe Tropical Cyclone Nargis in 2008 is discussed as follows because its impact was a catastrophic event for Myanmar:

According to the World Meteorological Organization [12], Extremely Severe Cyclonic Storm Nargis was an extremely destructive and deadly tropical cyclone that caused the worst natural disaster in the recorded history of Myanmar during early May 2008. The cyclone made landfall in Myanmar on Friday, 2 May 2008, sending a storm surge 40 kilometers up the densely populated Irrawaddy delta, causing catastrophic destruction and over 138,000 fatalities. Figure 10 depicts Nargis track and intensity. An example of satellite image before its landfall is presented in Figure 11. For more details about Nargis track and intensity, see Joint Typhoon Warning Center (Joint Typhoon Warning Center (JTWC) (navy.mil)) at 2008atcr.pdf (navy.mil). According to [12], Figure 12 provides the widespread storm surges as high as 23 ft (≈7 m) as measured along the southwestern coasts of Myanmar impacted by Nargis.

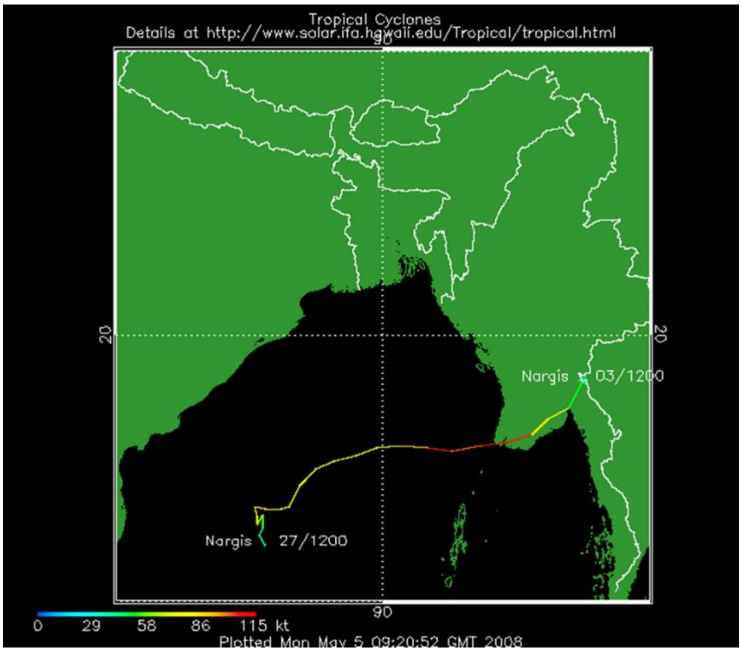

Figure 10 Nargis track and intensity over the Bay of Bengal based on May 2008 Global Hazards | National Centers for Environmental Information (NCEI) (noaa.gov) nargis-08. gif (640 × 580) (noaa.gov).

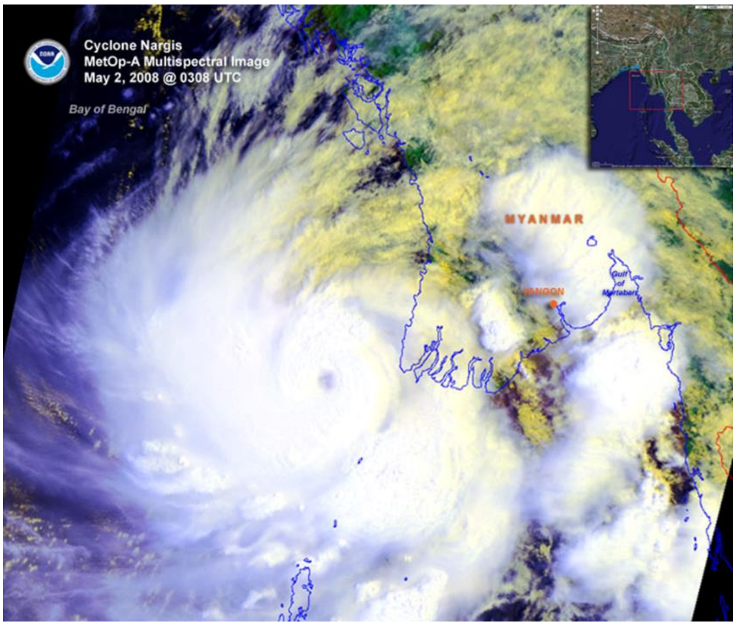

Figure 11 A satellite image for Nargis before its landfall in Myanmar based on May 2008 Global Hazards | National Centers for Environmental Information (NCEI) (noaa.gov).

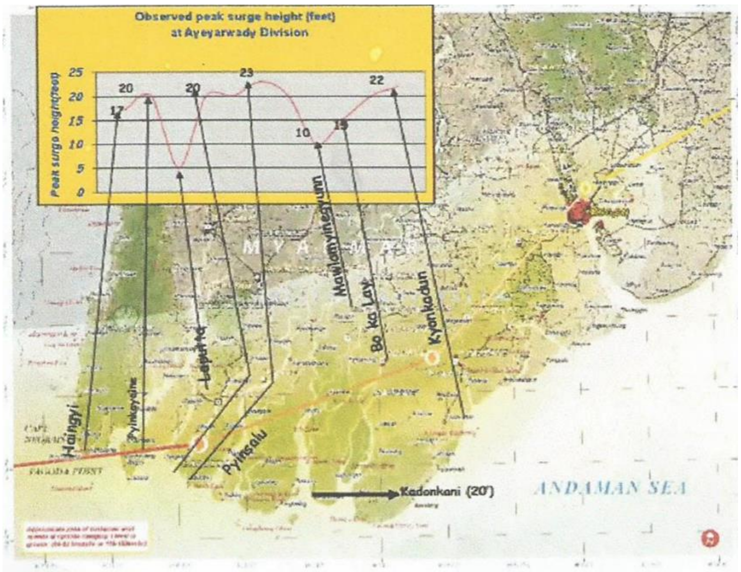

Figure 12 Measurements of storm surge in Myanmar during Nargis in 2008 based on World Meteorological Organization [12].

Based on 6-hourly Multiplatform Satellite Surface Wind Analysis by RAMMB (see RAMMB: TC Real-Time: Descriptions of Products (colostate.edu)) as shown in Figures 13-15, near-surface wind speeds ranged from 50 to 80 kts (≈25 to 40 m s^{-1}), by substituting these values into Equation (10), we can estimate the wind-stress tide to be 3.1 to 8.0 m or 10 to 26 ft. Depending on the wind speed and direction at a given location, these estimates are generally consistent with the measurements as depicted in Figure 12. Note that in the Pyinsalu area near the landfall of Nargis, highest water level was measured at 23 ft (≈7.0 m). Since it is located near 73 kts (37 m s^{-1}) which is between the isotachs (equal wind speed lines) of 65 and 80 kts (see Figure 14), the storm surge is estimated from Equation (10) at 23 ft or 7.0 m, which is the same as measured. Because the estimation is in good agreement with the measurement, Equation (10) is useful for rapid estimation of the wind-stress tide induced by a tropical cyclone in the Bay of Bengal in the Indian Ocean.

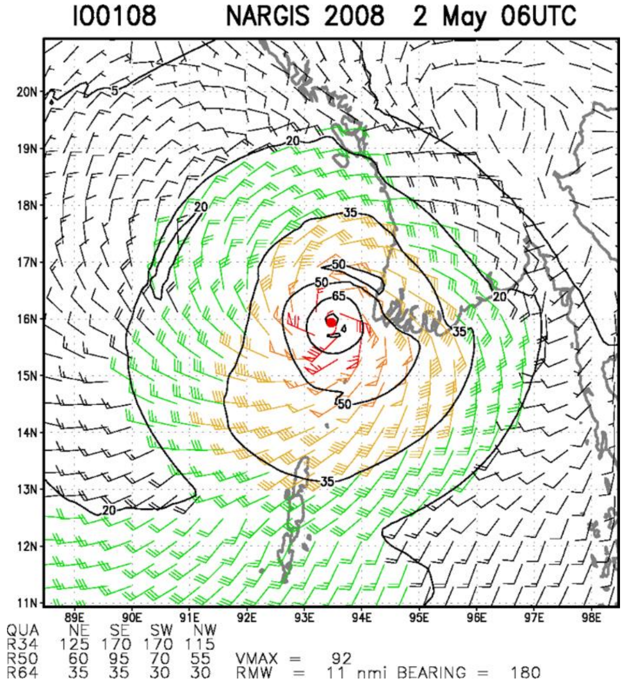

Figure 13 Wind speed (in knots) and direction at 10 m at 06 UTC on 2 May 2008 before the landfall of Nargis based on RAMMB: TC Real-Time: IO012008 - Tropical Cyclone (>=96 kt) NARGIS - Multiplatform Satellite Surface Wind Analysis (Experimental) (colostate.edu).

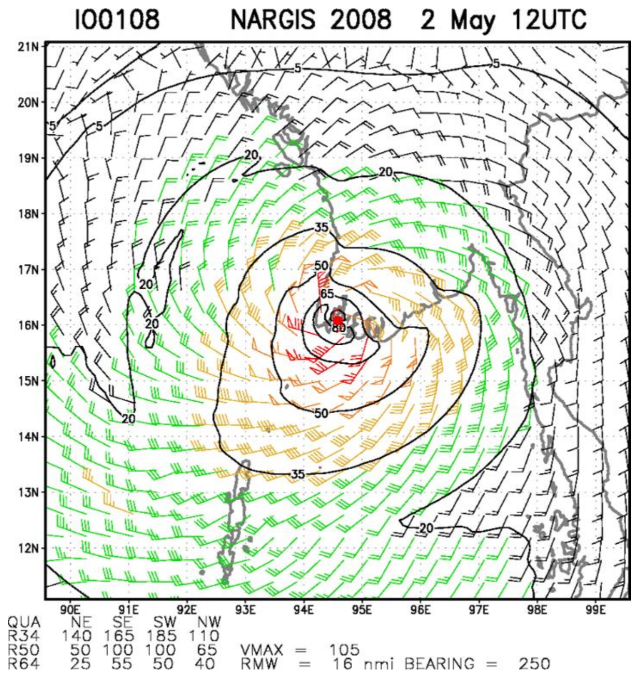

Figure 14 Wind speed (in knots) and direction at 10 m at 12 UTC on 2 May 2008 during the landfall of Nargis based on RAMMB: TC Real-Time: IO012008 - Tropical Cyclone (>=96 kt) NARGIS - Multiplatform Satellite Surface Wind Analysis (Experimental) (colostate.edu).

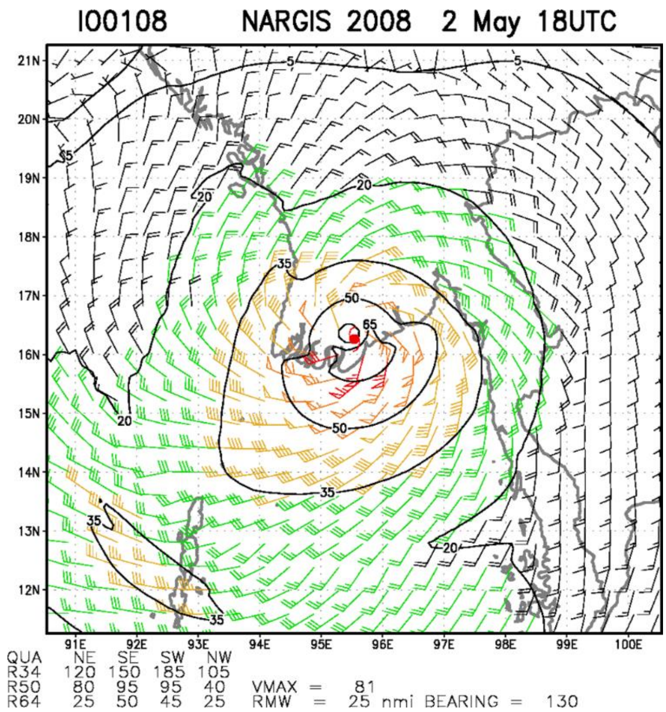

Figure15 Wind speed (in knots) and direction at 10 m at 18 UTC on 2 May 2008 after the landfall of Nargis based on RAMMB: TC Real-Time: IO012008 - Tropical Cyclone (>=96 kt) NARGIS - Multiplatform Satellite Surface Wind Analysis (Experimental) (colostate.edu).

Using the most recent case during Hurricane Idalia at 1200 UTC on 30 Aug 2023 near its landfall as depicted in Figure 16 and Figure 17, Table 2 may be employed. It shows approximately that within the isotach of 35 kts, the wind- stress tide can reach up to 5 ft, within 50 kts, up to 11 ft, and within 65 kts, up to 18 ft. These results indicate that, since they are in general agreement, our proposed value-added met-ocean parameters as presented in Table 1 and Table 2 are useful for practical marine meteorological applications.

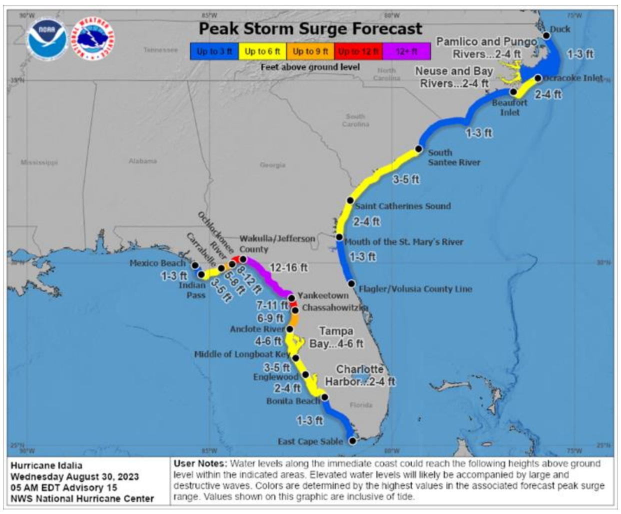

Figure 16 Peak storm surge forecast by the National Hurricane Center for Hurricane Idalia at 05 AM EDT on 3o Aug. 2023 based on https://www.nhc.noaa.gov/storm_graphics/AT10/refresh/AL102023_peak_surge+png/093940_peak_surge.png.

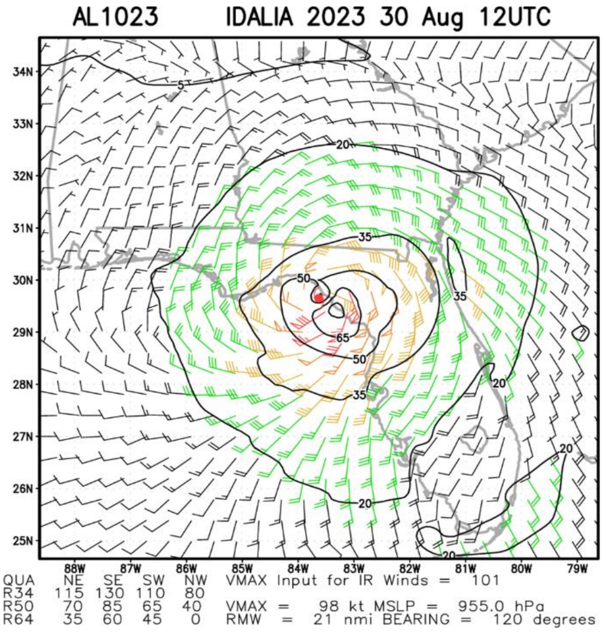

Figure 17 Isotach analysis at 1200 UTC on 30 August 2023 during Hurricane Idalia based on RAMMB: TC Real-Time: AL102023 - Major Hurricane IDALIA - Multiplatform Satellite Surface Wind Analysis (Experimental) (colostate.edu).

4. Conclusions

On the basis of aforementioned analysis and discussion, it is concluded that following met-ocean variables or products may be added to the RAMMB's TC surface wind analysis. For a given isotach: significant wave height can be estimated using Equation (1); overwater friction velocity, Equation (4); drift-current velocity, Equation (5); wind stress, Equation (7); atmospheric vorticity, Equation (8); vertical velocity, Equation (9); wind-stress tide, Equation (10); and wave set-up, Equation (11). In addition, in order to estimate the wind-stress tide, two case studies are presented. They are: during the Extremely Severe Cyclonic Storm Nargis which devastated Myanmar in May 2008 from the Bay of Bengal and during Hurricane Idalia in August 2023 which impacted on Florida Gulf Coast.

Author Contributions

The author did all the research work of this study.

Competing Interests

The author has declared that no competing interests exist.

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