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Some Aspects of Marine Meteorology and Air-Sea-Wetland-River Interactions During Hurricane Ida (2021)

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Abstract

In August 2021 Hurricane Ida devastated southeast Louisiana. On the basis of numerous pertinent meteorological-oceanographic (met-ocean) information including datasets and graphics as supplied by various public agencies, several unique topics related to marine meteorology and air-sea-land interactions are investigated. It is found that a newly proposed revised relation between minimum sea-level pressure and maximum sustained wind speed is verified during Ida. Characteristics of the rapid intensification, defined as an increase in the sustained winds of a tropical cyclone (TC) of at least 30 knots in a 24-hour period, is presented. Severe wave steepness (≥1/20) was measured continuously for approximately 3 hours when the wind speed ranged between 35 to 45 m s^{-1} at 38 m and the wave direction was from the east. Estimations for the wind stress on the wind-seas and a coastal wetland are presented. Finally, hydro-meteorological phenomena related to the Mississippi River flow reversal and the storm surges along the river levees are also revealed. For operational use, estimation methods and forecast formulas related to above topics are also provided.

Keywords

Hurricane Ida (2021); coastal and marine meteorology; air-sea interaction; air-wetland interaction; Mississippi River flow reversal; storm surge along Mississippi River levees

1. Introduction

In August 2021 Hurricane Ida devastated southeast Louisiana [1, 2] (see Figure 1 for its track). Because of Ida's catastrophic destruction, there is a need to understand the causes related to operational marine meteorology and air-sea-land interactions. They include, but not limited to, verification of the most recently proposed relation between minimum sea-level pressure (P_{min}) and maximum sustained wind speed at 10-m (V_{max}), rapid intensification, severe wave steepness, wind stress on the sea surface and a coastal wetland, and because the track was located west of the Mississippi River Delta (see Figure 1), the characteristics of Mississippi River flow reversal and the storm surge propagation along the levees of the Mississippi River.

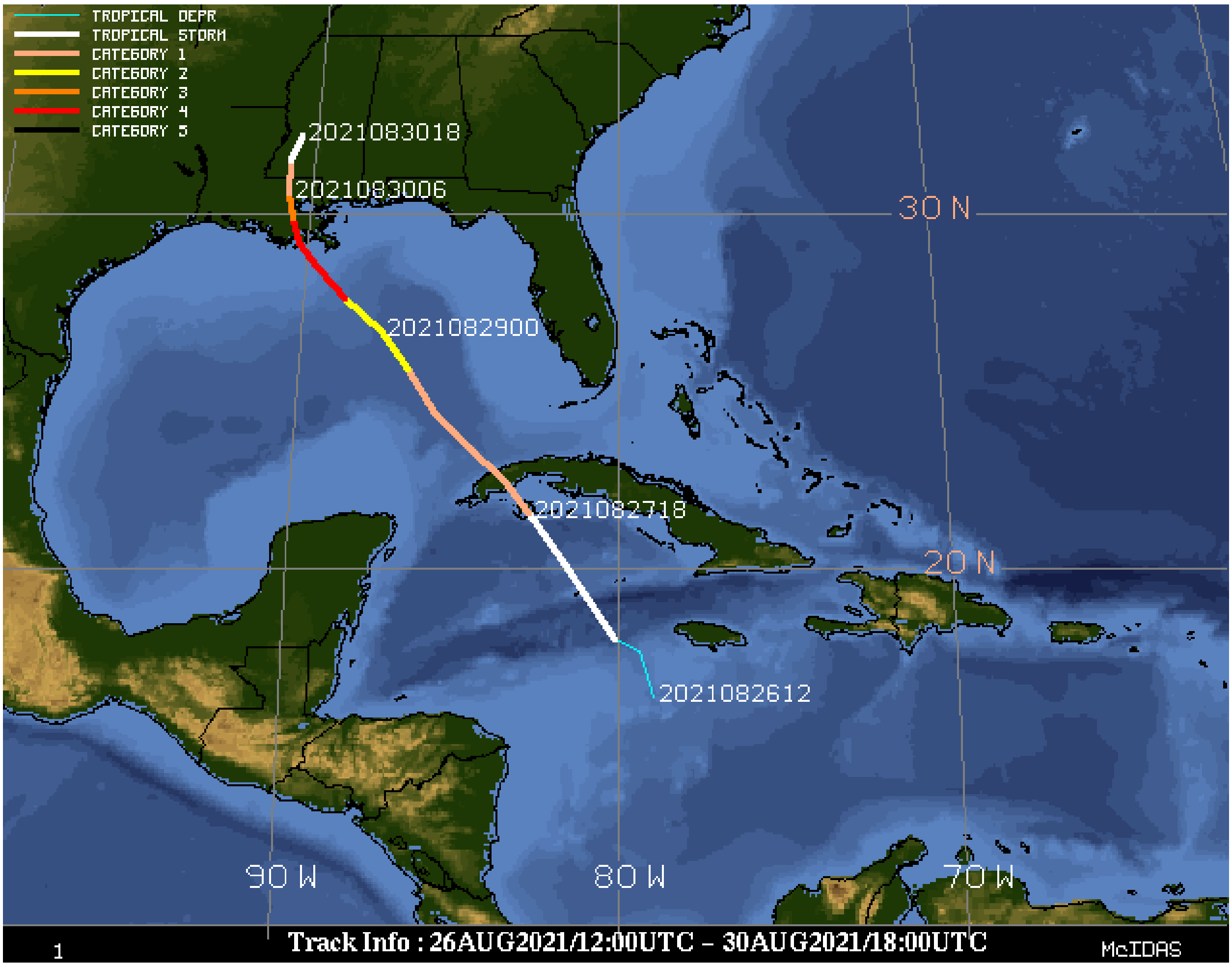

Figure 1 Hurricane Ida's track (see https://www.weather.gov/lix/hurricaneida2021) based on [2].

2. Relation Between P_{min} and V_{max}

In 2020 Klotzbach et al. [3] proposed a revised relation between P_{min} and V_{max}. Based on their datasets, this relation is illustrated graphically here in Figure 2a and Figure 2b for the metric and British systems, respectively. It is found that

$$V_{max} = -0.566P_{min} + 594 \tag{1}$$

with a coefficient of determination, $R^2 > 0.99$.

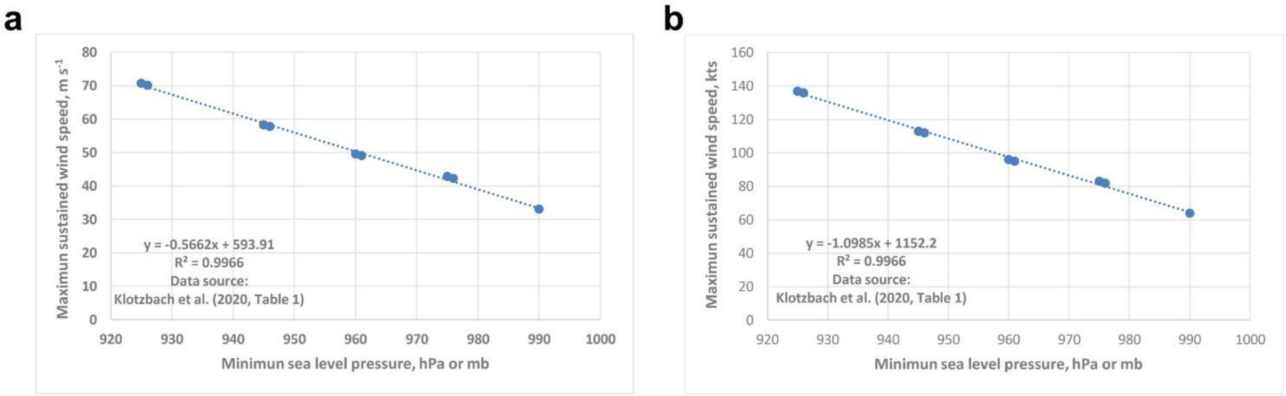

Figure 2 a: Relation between P_{min} in hPa or mb and V_{max} in m s^{-1}. b: Relation between P_{min} in hPa or mb and V_{max} in kts.

Here V_{max} is in m s^{-1} and P_{min} is in hPa or mb. And

$$V_{max} = -1.10P_{min} + 1152 \tag{2}$$

with $R^2 > 0.99$.

Here V_{max} is in knots (kts) and P_{min} is in hPa or mb.

Now, using the pair of P_{min} and V_{max} as listed in Table 1 during Hurricane Ida, Eq. (2) is verified in Figure 3, since the slope and R^2 are near 1.0.

Table 1 Characteristics of Ida over the Gulf of Mexico and at landfall at Port Fourchon, Louisiana [1].

Date/Time, UTC	P_{min}, mb	V_{max}, kt	V_{max}, kt, Eq. (2)
28/1200	986	70	69
28/1800	976	80	80
29/0000	967	90	90
29/0600	950	115	109
29/1200	929	130	132
29/1655	931	130	129

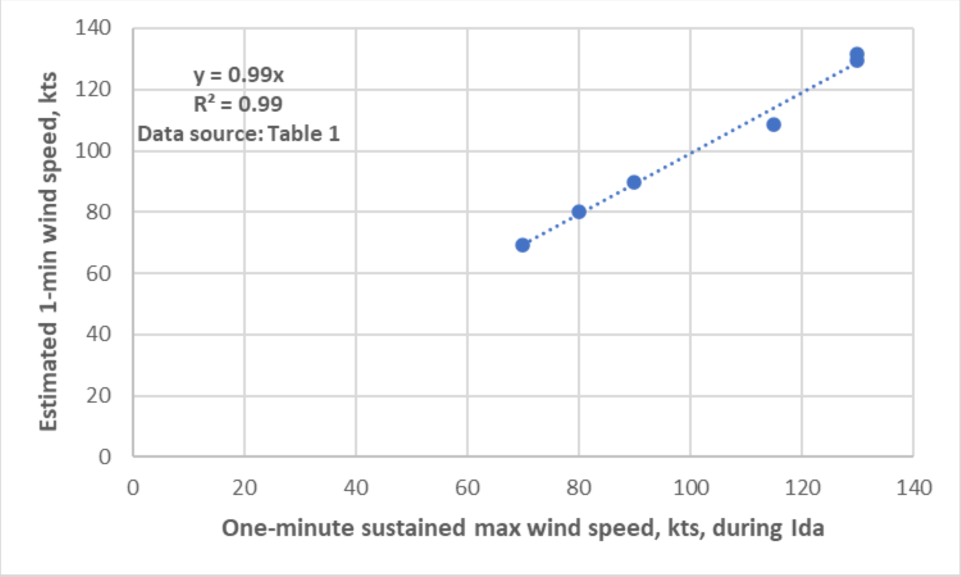

Figure 3 Verification of Eq. (2) during Ida using data as listed in Table 1.

3. Characteristics of Rapid Intensification

According to the National Hurricane Center (NHC), rapid intensification is defined as an increase in the sustained winds of a tropical cyclone (TC) of at least 30 knots in a 24-hour period. Table 1 indicates that there were 40 kts increase from 90 to 130 kts between 00UTC and 12UTC. Therefore, Ida was a rapid intensification hurricane at the time of landfall at 1655 UTC as a category 4 hurricane because the sustained winds maintained at 130 kts, see also Figure 1. The reasons may be explained as follows: According to the Regional and Mesoscale Meteorology Branch (RAMMB, see RAMMB: TC Real-Time: AL092021 - Major Hurricane IDA (colostate.edu)), at 00UTC on 29 Aug when Ida was over the central Gulf of Mexico, there was a region with ocean heat content (OHC) in excess of 100 kj cm^{-2} (see Figure 4) and low vertical shear around 10 kts (Figure 5), a value normally considered as a good indication for intensification. In addition, according to RAMMB, values of OHC greater than 50 kj cm^{-2} have been shown to promote greater rate of intensity change.

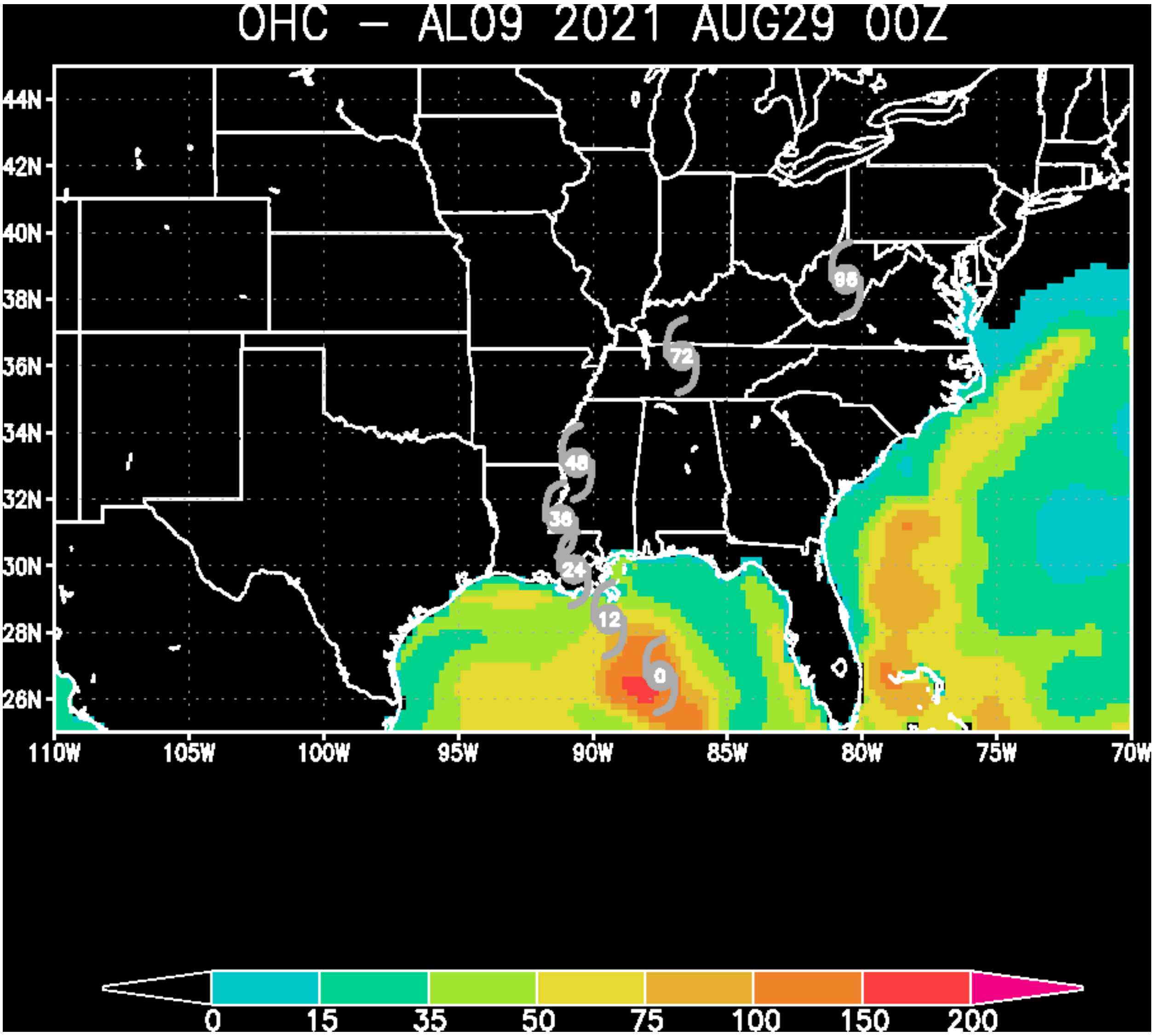

Figure 4 Ocean heat content and forecast track based on https://rammb-data.cira.colostate.edu/tc_realtime/storm.asp?storm_identifier=al092021.

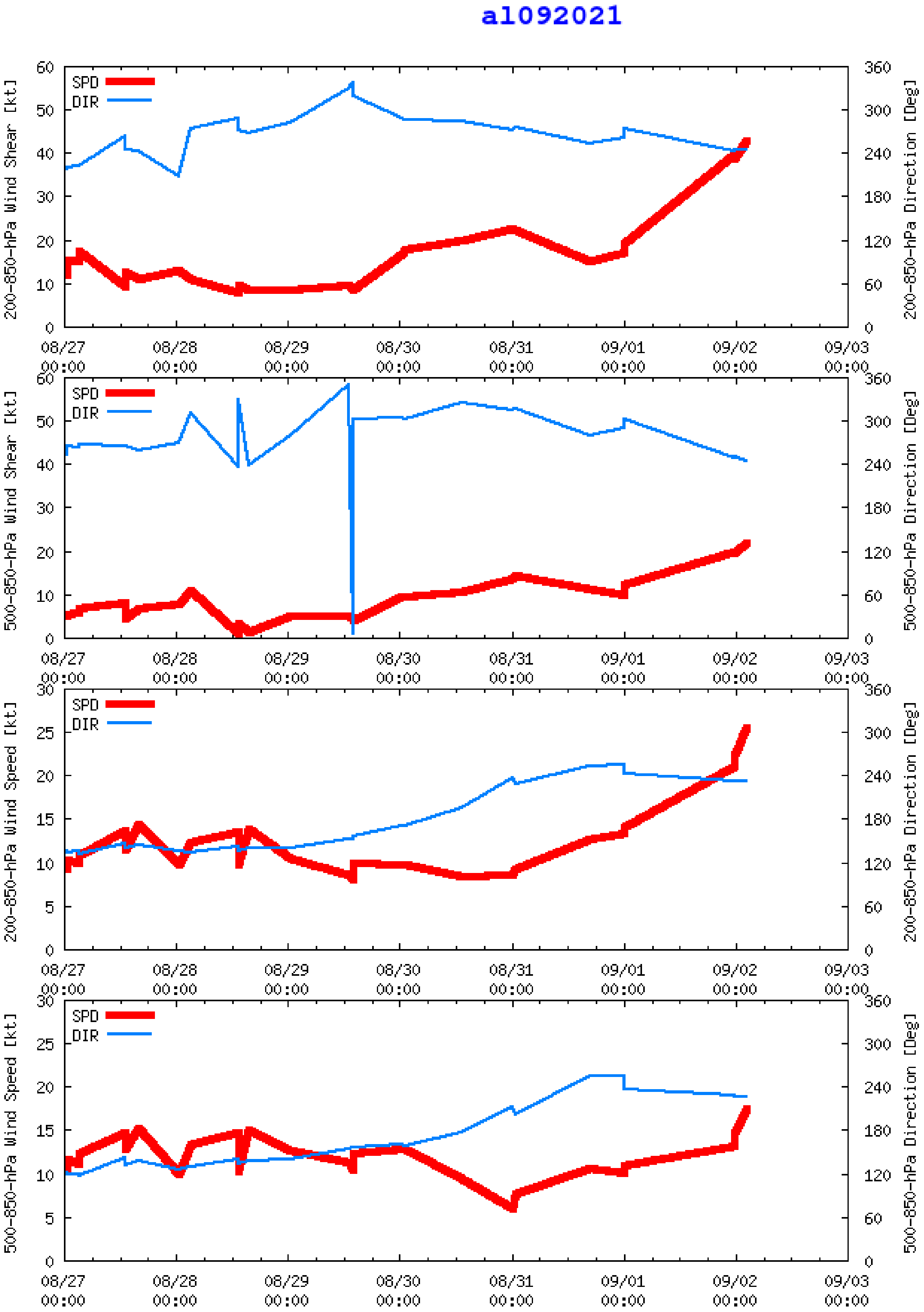

Figure 5 Characteristics of vertical wind shear during Ida, based on https://rammb-data.cira.colostate.edu/tc_realtime/storm_experimental.asp?storm_identifier=al092021.

4. Characteristics of Severe Wave Steepness

According to the Oil and Gas Drilling Glossary by the IADCLexicon.org, severe wave steepness is defined when a wave steepness = $H_s/L_p \geq 1/20$ or 0.050 where H_s is the significant wave height in meters and $L_p = 1.56T_p^2$, here L_p is the dominant wave length in meters and T_p is the peak wave period in seconds. For more detail, see [4].

Meteorological and oceanographic (met-ocean) stations used in this study are provided in Figure 6. Note that Buoy 42084 is located at the water depth of 44.8m and operated by the Coastal Data Information Program (see website at cdip.ucsd.edu/m/products/?stn=256p1) and is posted on the website of National Buoy Data Center at www.ndbc.noaa.gov. Based on the simultaneous measurements of H_s and T_p at Buoy 42084 during Ida as presented in Figure 7, characteristics of wave steepness is shown in Figure 8. From the wave direction measurements as depicted in Figure 9, it is found that severe wave steepness occurred when the wave direction was from the east and lasted about 3 hours. Certainly, more data are needed to further investigate the physical reasons.

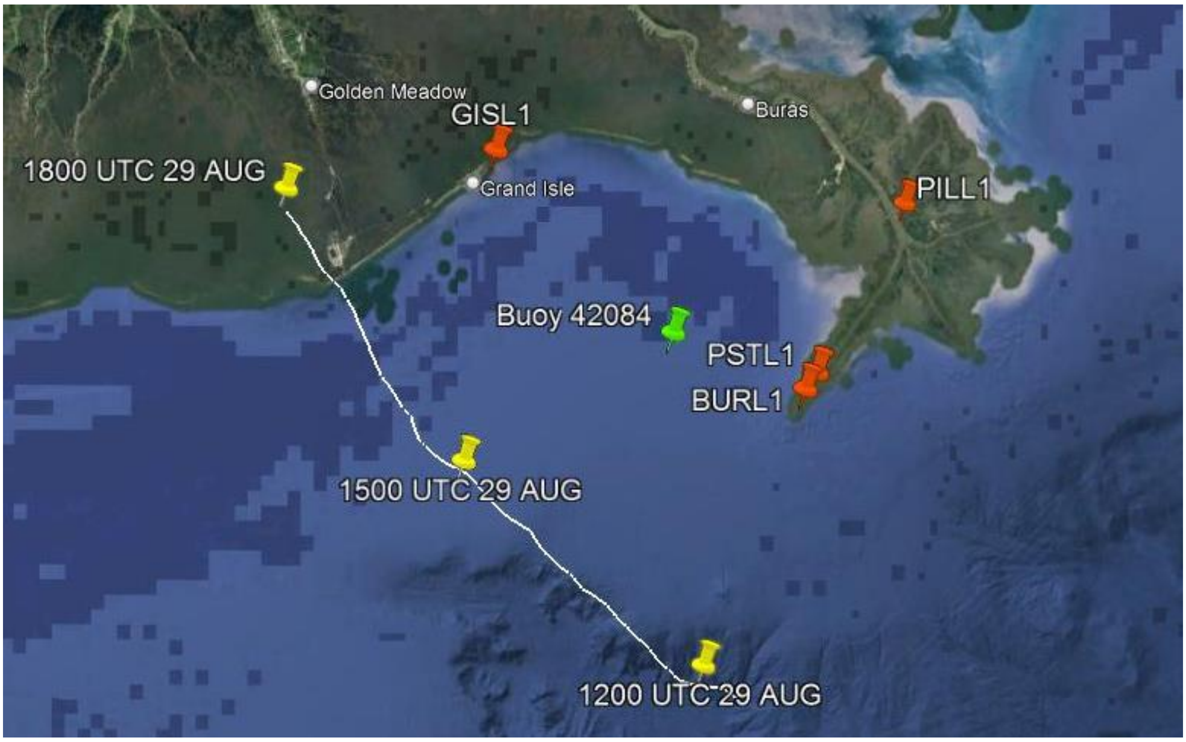

Figure 6 Met-ocean stations located on the right-hand side of Ida's track used in this study, base map courtesy of Google Earth Pro.

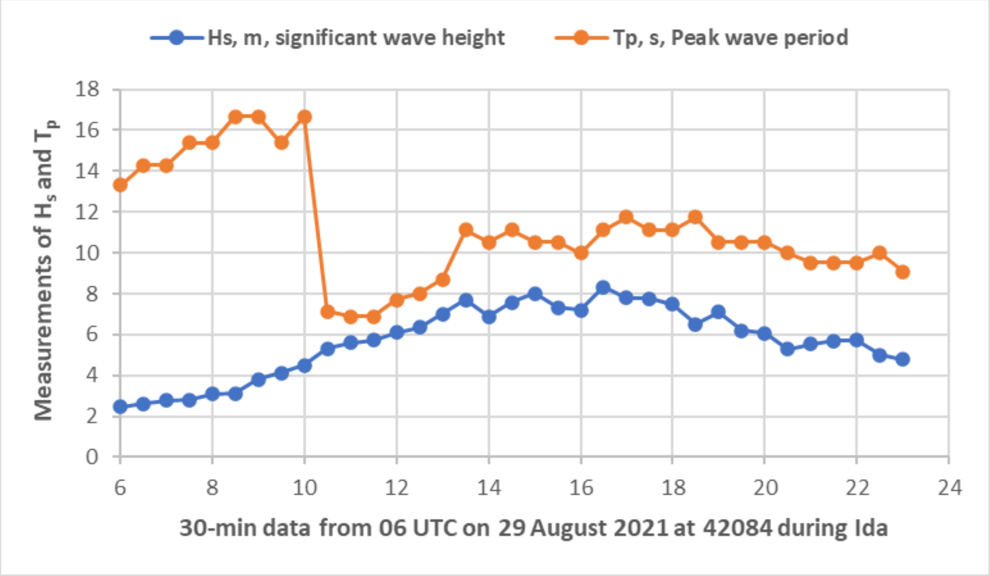

Figure 7 Measurements of H_s and T_p at Buoy 42084 during Ida.

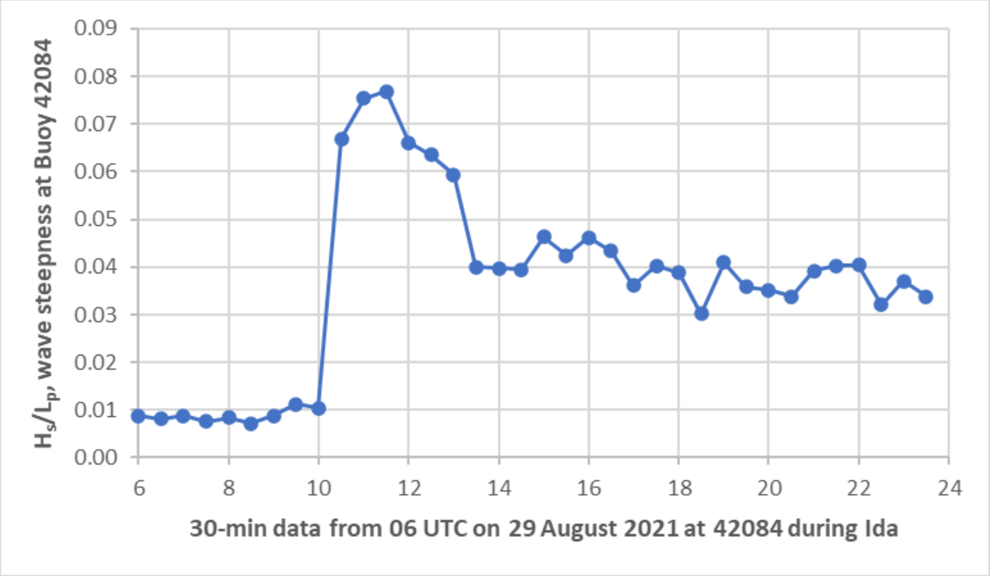

Figure 8 Measurements of wave steepness at Buoy 42084 during Ida.

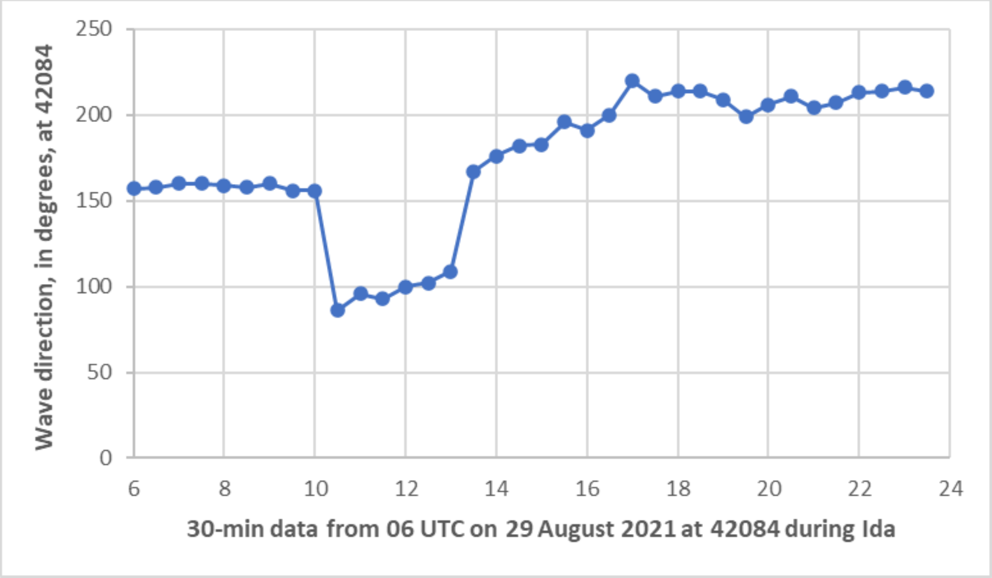

Figure 9 Measurements of wave direction at Buoy 42084 during Ida.

5. Wind Stress on the Wind-Seas

The wind stress on the sea surface, which can be estimated from overwater friction velocity (U^*), affects nearly all air-sea interaction processes [5]. According to [5], for the wind-seas, $H_s/L_p \geq 0.020$, and

For deep water environment,

$$U^* = 28H_s/T_p + 0.12 \tag{3}$$

For shoaling wave environment,

$$U^* = 30H_s/T_p + 0.26 \tag{4}$$

And, for transitional water-depth environment,

$$U^* = 31H_s/T_p + 0.14 \tag{5}$$

Furthermore, according to [5],

$$U_z = 2.5U^* \mathrm{Ln}(Z/Z_o) \tag{6}$$

Where Z = 38 m at BURL1,

$$Z_o = 1200H_s(H_s/L_p)^{4.5} \tag{7}$$

Here Z_o is the roughness length,

And finally, from [5],

$$\text{The shoaling depth} = 0.39{T_p}^2 \tag{8}$$

Now, using the datasets of H_s and T_p from Buoy 42084 and the wind speed measurements at 38 m, U_{38m}, from BURL1 as shown in Figure 10, Eqs. (3) through (5) are verified in Figure 11. Since the slope is unity and $R^2 = 0.93$, U^* can be computed for air-sea interaction applications.

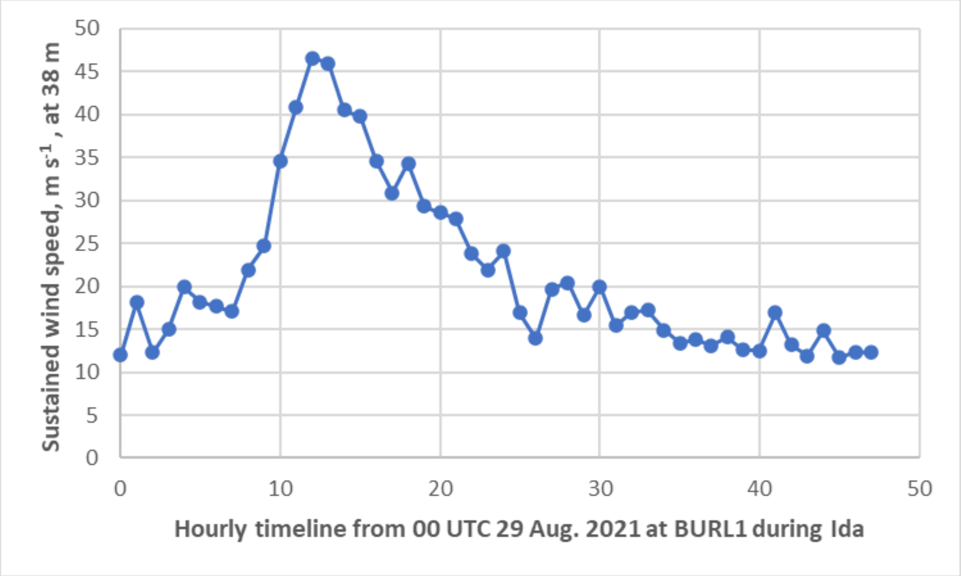

Figure 10 Continuous hourly measurements of the sustained wind speed at BURL1 during Ida.

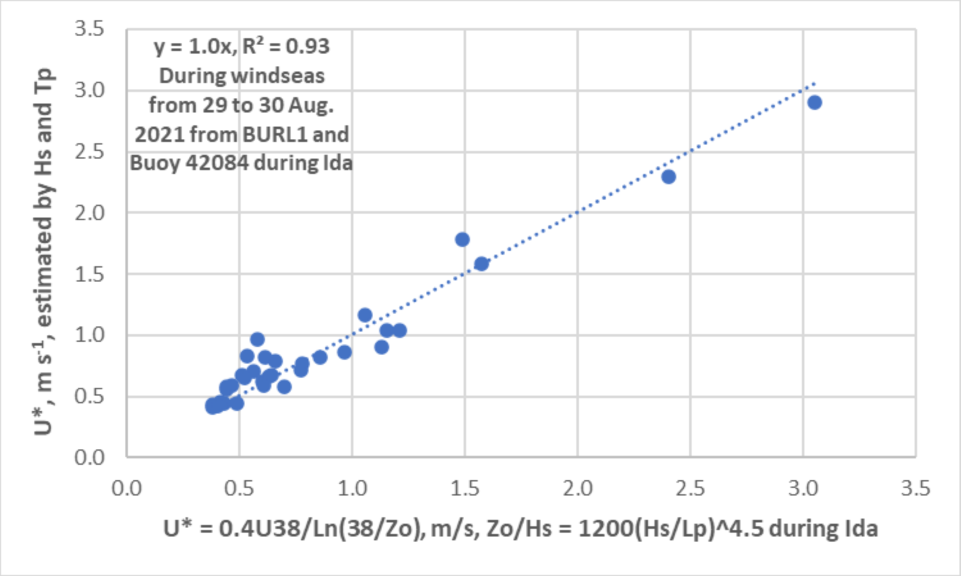

Figure 11 Verification of Eqs. (3) through (5).

6. Wind Stress on a Wetland

According to [6], numerous wetland erosion, deformation, and deposition in south Louisiana were caused by many hurricanes. The wind stress on a wetland may be estimated as follows [5, 7]:

$$\text{Wind stress} = \rho U^{*2} = 1.25 \times \left[0.2\left(U_{\text{gust}} - U_{10}\right)\right]^2 \tag{9}$$

Here ρ is the air density ≈1.25 kg m^{-3}, U_{gust} is the wind gust and U_{10} is the sustained wind speed at 10 m, both in m s^{-1}. Note that the unit of the wind stress is in N m^{-2} or Pascal (Pa).

During Ida simultaneous U_{gust} and $U_{9.3m}$ were measured at GISL1 (see Figure 6 for its location). In addition, sea-level pressure was recorded. Using these datasets and Eq. (9), wind stress on GISL1 may be estimated as shown in Figure 12 based on a polynomial analysis and Figure 13 on linear regression approach. However, because values of R^2 in Figure 12 and Figure 13 are the same, the simplified relation between the wind stress and sea-level pressure as presented in Figure 13 is found for practical use that,

$$\text{Wind stress} = -0.201 \times \text{sea} - \text{level pressure} + 203 \tag{10}$$

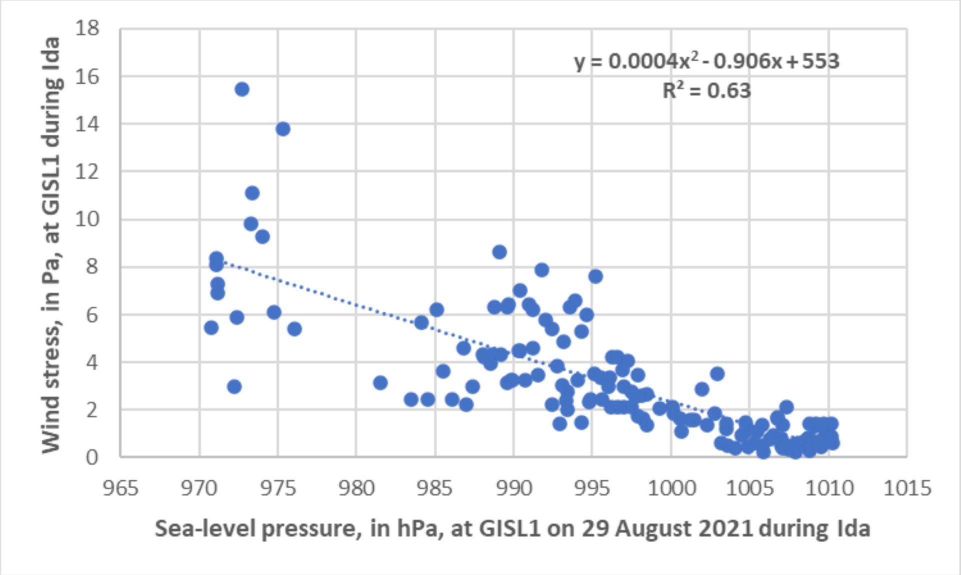

Figure 12 Relation between estimated wind stress and sea-level pressure at GISL1 during Ida.

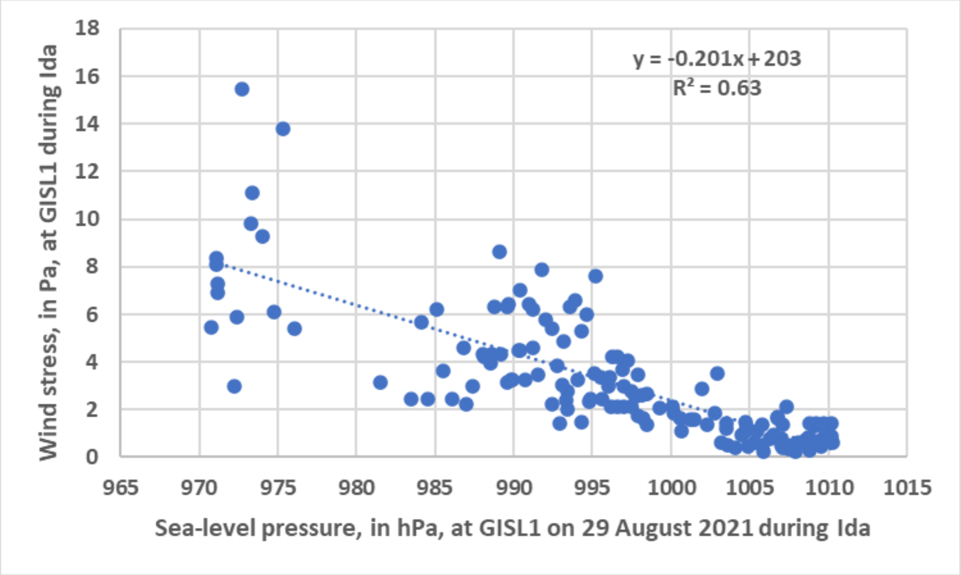

Figure 13 Simplified relation between estimated wind stress and sea-level pressure at GISL1 during Ida.

Figure 13 indicates that when the sea-level pressure is 990 hPa or the starting value for Category 1 hurricane [3], the wind stress is about 4 Pa. Therefore, for wetland scientists, using the barometric pressure measurements many be more feasible than the wind speed records because the anemometers are more vulnerable to be damaged than a barometer during a hurricane [3].

7. Mississippi River Flow Reversal

When a hurricane is near the coast, storm surges ensure [8]. According to [8], during a hurricane's landfall, the area inside of 65 kts (34 m s^{-1}) isotach (a line of equal wind speed) can produce up to 18 ft (5.5 m) inundation and the area inside of 50 kts (26 m s^{-1}) up to 11 ft (3.3 m) high water level above the ground. As recommended in [8], the TC surface wind analyses near landfall by RAMMB are provided in Appendix A1, A3, and A5. In addition, pertinent surface analyses by the National Center for Atmospheric Research (NCAR, see Image Archive (ucar.edu)) are shown in A2 and A4. Based on these analyses, strong winds (over 65 kts) from southeast to south prevailed from 12 to 18 UTC on 29 Aug 2021 over the Mississippi River Delta region. Therefore, the storm surge from the mouth of Mississippi River and wave flow can propagate along the river levee further inland. Evidence of the Mississippi River flow reversal is shown in Figure 14 and river velocity in Figure 15, respectively. In order to investigate just how far upstream these storm surges along the Mississippi River levee could have been propagated, series of river gage datasets are presented in Appendix B1 thru B5. These datasets are based on the webpage at New Orleans District > Missions > Engineering > Stage and Hydrologic Data > Mississippi River Basin Stages (army.mil). On the basis of the figures presented in Appendix B, the water level, which is the difference between maximum and minimum recordings in each of the figures, along the Mississippi River during Ida is presented in Figure 16 so that

$$Y = -0.0149X + 5.78 \tag{11}$$

With $R^2 = 0.91$, here Y is the storm surge along the Mississippi River levees in feet and X is in river miles from the Gulf of Mexico. Now, if one sets Y = 0, X = 388, indicating that the storm surge and wave flow could have been impacted upstream to 388 river miles or 625 km. Therefore, this phenomenon is important for the operational marine meteorologists who are responsible for river forecasts. Because there are many rivers in the TC prone regions around the world, formulas similar to Eq. (11) may be developed to add in the river stage forecast so that various marine vessels can be safely moored.

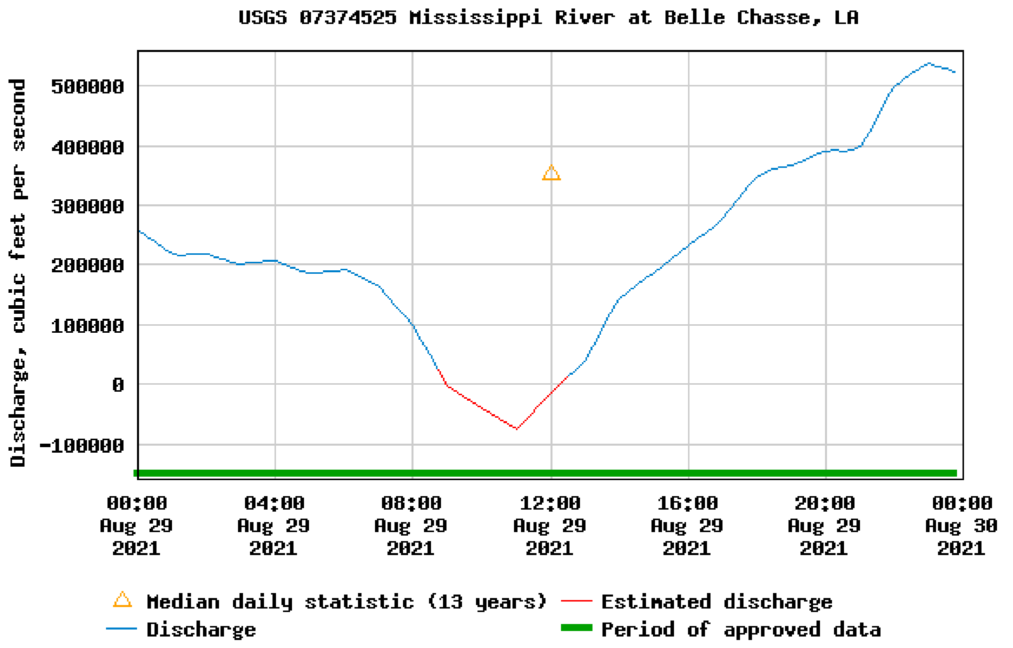

Figure 14 Measurements of Mississippi River flow reversal in red by the U. S. Geological Survey station at Belle Chasse, LA during Ida based on https://nadww01.er.usgs.gov/nwisweb/data/img/USGS.07374525.167809.00060..20210829.20210829.log.0.p50.gif.

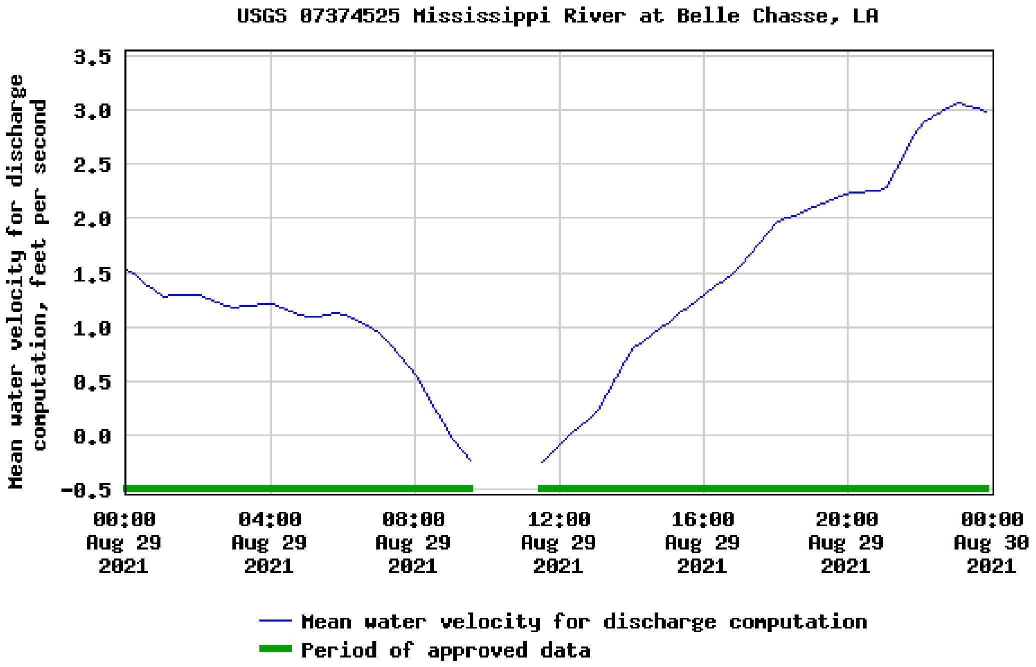

Figure 15 Measurements of Mississippi River velocity at Belle Chasse, LA during Ida, based on https://nadww02.cr.usgs.gov/nwisweb/data/img/USGS.07374525.62538.72255..20210829.20210829..0..gif.

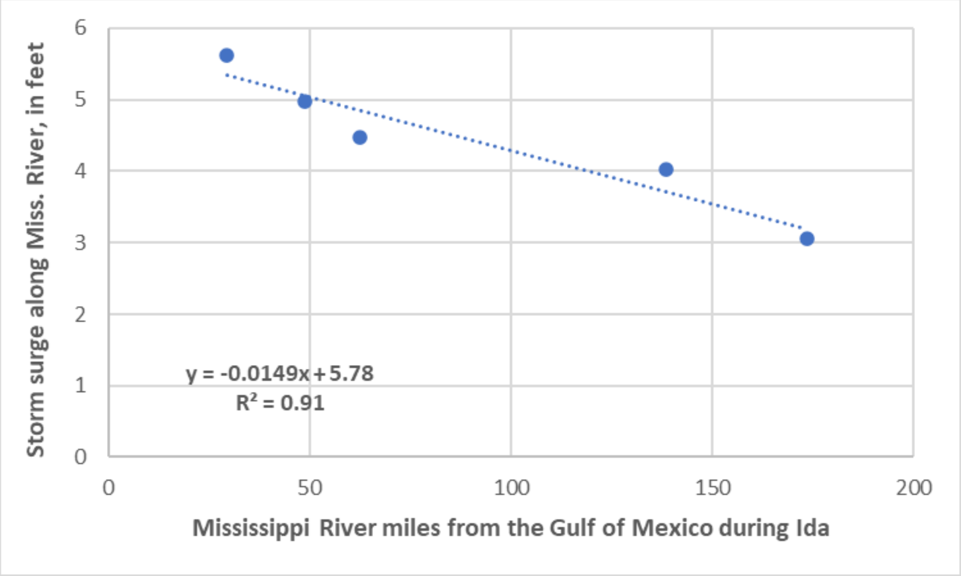

Figure 16 Storm surge along the Mississippi River levees during Ida.

During the review process of this manuscript a question was raised as to the relative contribution of inverted barometric effect versus the wind stress effect for the increase in water level along the Lower Mississippi River System. This question is answered as follows using the continuous meteorological measurements at PILL1 (for location, see Figure 6) presented in Figure 17 thru Figure 20. According to the Glossary of Meteorology (Second Edition, 2000, p. 414) by the American Meteorological Society, the inverted barometric effect is an adjustment of sea level to changes in barometric pressure. The change occurs when the pressure falls 1 mb the sea level increases 0.01 m. Figure 17 shows that during Ida at PILL1, the barometric pressure decreased from 1012.2 to 995.2 mb. Therefore, this 17 mb drop can produce only 0.17 m or 0.56 feet increase in sea level, indicating that about 10 % of the total water level increase of 5.6 ft is due to the inverted barometric effect and that 90 % owing to the wind-stress forcing and other factors as depicted in Figure 16 near the mouth of the Mississippi River. Based on simultaneous measurements of sustained wind speed and correspondent wind gust at PILL1, Eq. (9) can be used to estimate the magnitude of the wind stress. Our result is presented in Figure 20, indicating that the wind stress could have been reached to 10 Pa. Therefore, from the view point of operational marine meteorology for the Mississippi River water-level forecasting, consideration must be taken into account that when persistent strong wind speeds (>20 m s^{-1}) (see Figure 18) blowing southerly from the Gulf of Mexico (Figure 6 and Figure 19), the water level along the river levees will increase.

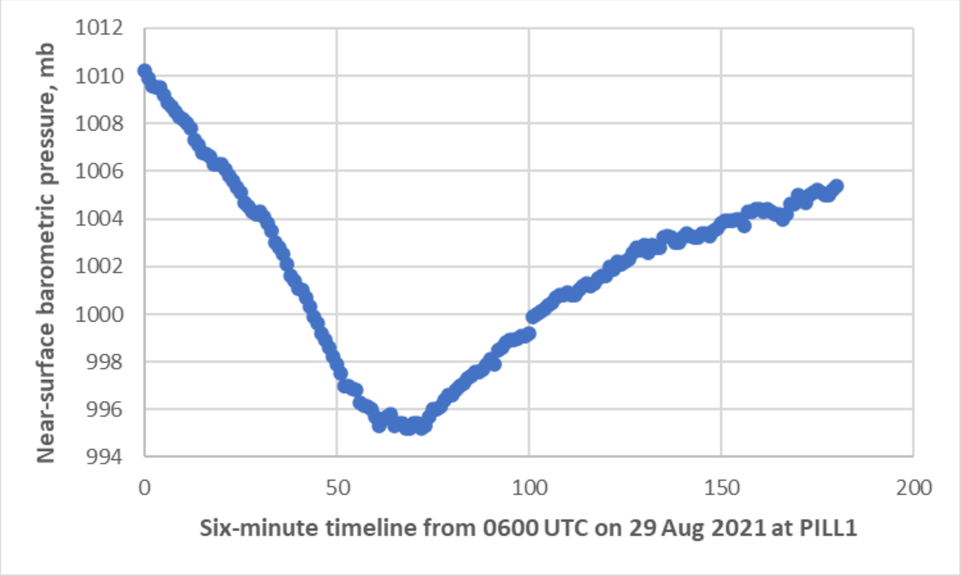

Figure 17 Measurements of near-surface barometric pressure, hPa or mb, on 29 Aug 2021 at PILL1 within the Mississippi River Delta (see Figure 6) during Ida.

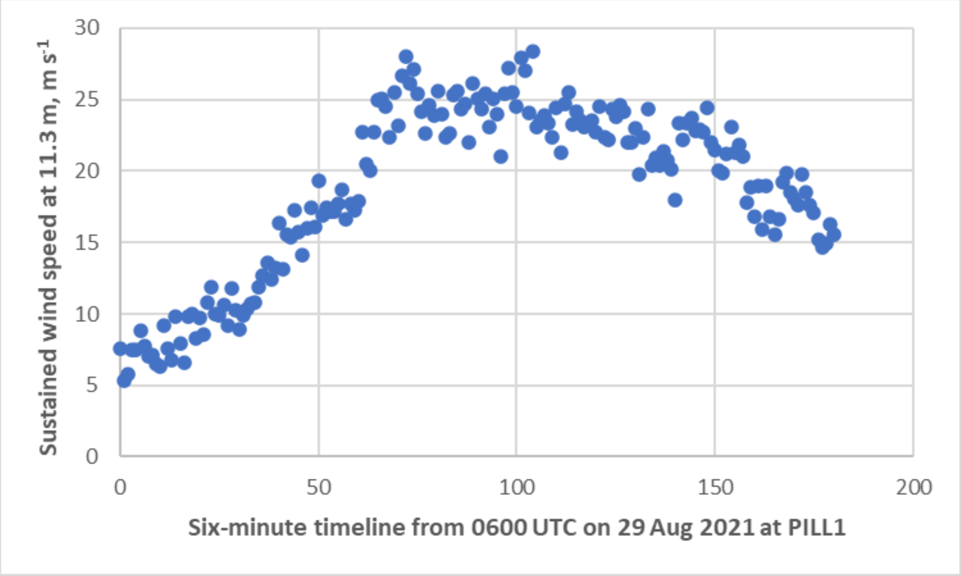

Figure 18 Same as Figure 17 but for the sustained wind speed, m s^{-1}.

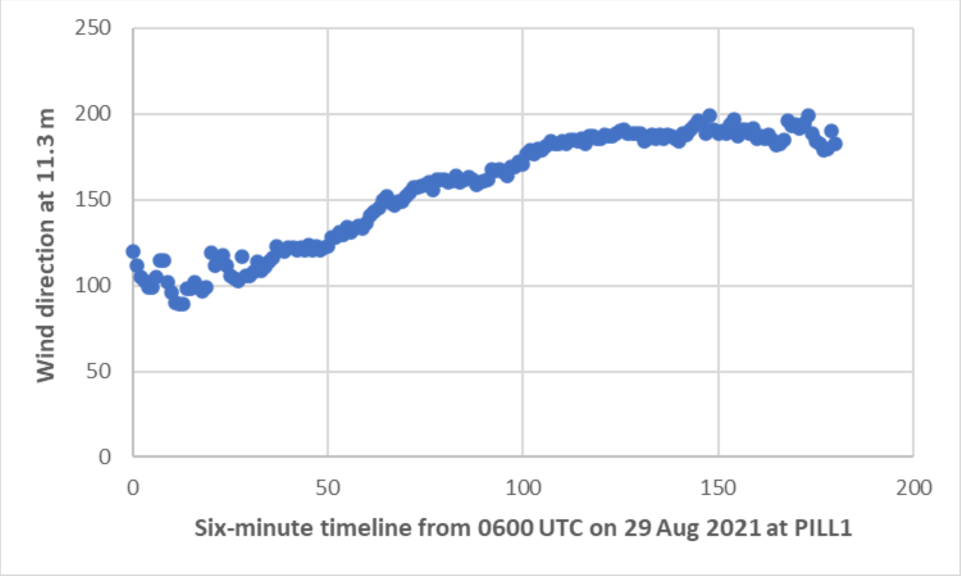

Figure 19 Same as Figure 17 but for the wind direction.

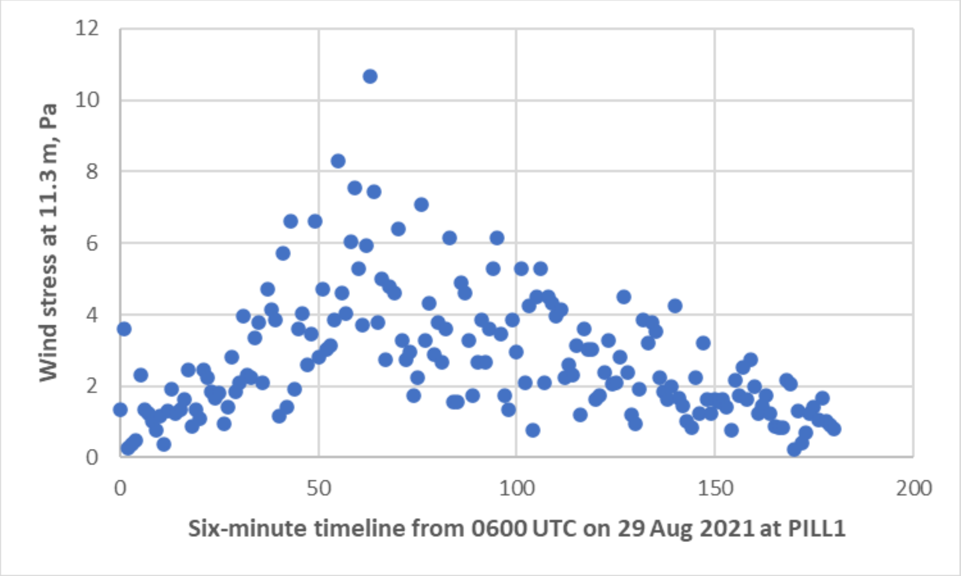

Figure 20 Same as Figure 17 but for wind stress.

8. Conclusions

On the basis of aforementioned analyses, it is concluded that

(1) During Ida the newly proposed revision of the relation between the minimum sea-level pressure and the maximum sustained wind speed [1] is verified. For operational marine meteorologists, this relation is presented in Eqs. (1) and (2) for metric and British units, respectively.

(2) When Ida was over a region of high ocean heat content (>100 kj cm^{-2}) and low vertical wind shear (≈10 kts), rapid intensification ensured from 90 to 130 kts within 12 hours. These 130 kts sustained winds continued till landfall.

(3) Severe wave steepness (≥1/20) based on Oil and Gas Drilling Glossary was measured continuously for about 3 hours when the wave direction was from the east and sustained wind speeds between 35 to 45 m s^{-1} at the anemometer height of 38 m.

(4) Formulas to estimate overwater variations of friction velocity from deep to shoaling water (including the transitional water depth) [5] are verified.

(5) Estimation of the wind stress over a coastal wetland is made by the wind-gust method [7]. It is found when the minimum sea-level pressure is 990 hPa, the wind stress is approximately 4 N m^{-2} or Pa. A relation between the wind stress and minimum sea-level pressure is presented in Eq. (10).

(6) Finally, during Ida, Mississippi River flow reversal was measured. It is revealed that the storm surge and wave flow could have been propagated to 390 river miles or ≈630 km upstream along the Mississippi River levees. In this regard, a formula (11) is developed for operational marine meteorologist to use to improve river stage forecasts. Characteristics of the inverted barometric effect and the wind stress forcing are also presented.

Acknowledgments

Information employed in this study as provided by various public agencies including NHC, NWS-LIX, RAMMB, CDIP, NDBC, NOS, USACE, NCAR and USGS are greatly appreciated.

Author Contributions

The author did all the research work of this study.

Competing Interests

The authors have declared that no competing interests exist.

Additional Materials

The following additional materials are uploaded at the page of this paper.

1. Appendix A.
2. Appendix B.

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