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An Evaluation of the WES3 and WES4 Analytic Wind Generation Methods

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14. ABSTRACT

Two methods for generating analytic wind fields for tropical cyclones are evaluated. The two methods utilize the same algorithm for generating the initial wind field. The WES3 method uses a function of the forward speed and the angle between the track direction and surface wind direction to parameterize the wind field asymmetry. The WES4 method applies asymmetry to the analytic wind field using the radius of 35 knot winds provided by a forecast bulletin. Wind fields generated by the two methods are compared and used to force a surge model of Hurricane Ida. Model wind magnitude and direction and water levels are compared for each of the two models and to data.

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Introduction

A number of Navy installations as well as areas of interest to the Navy lie in areas that are vulnerable to tropical cyclones. In order to protect lives, assets and critical infrastructure, the Navy values robust storm surge predictions provided by numerical models. Robust storm surge predictions depend heavily on the quality of a model's atmospheric forcing which includes wind magnitudes and directions and atmospheric pressure. In the absence of a specialized, numerical tropical cyclone forecast, acquiring atmospheric forcing involves building an analytical wind field based on the best available meteorological forecast bulletin.

The software WES (Wind Enhancement Scheme; [1]), was developed to address the generation of the analytical winds. The method was based on [2] to compute surface winds and pressure around the center of the storm given maximum wind speed, central pressure drop, radius of maximum winds and the storm track. The wind field is then calculated on a polar coordinate grid or "spiderweb" type grid with the origin at the center of the storm. The Holland formulation produces a symmetric wind field around the center of the storm. Asymmetry is then introduced by adding the effect of storm translation using various published formulations.

Two methods for building the analytic wind fields, referred to as WES3 and WES4 are evaluated. Both methods use [3] to generate the initial wind field. The difference between WES3 and WES4 is in the formulation used to apply asymmetry to the wind fields. WES3 introduces asymmetry as a function of the forward speed and the angle between the track direction and the surface wind direction. WES4 uses the radius of 35 knot winds provided by a forecast bulletin to apply asymmetry to the analytic wind fields.

A more detailed description of the WES3 and WES4 methods is provided in section 1.1, and a qualitative comparison of the analytic wind fields for Hurricane Ida is given in section 1.4. Both analytical wind fields are applied to a Delft3D-Flexible Mesh [4] model of Hurricane Ida. The model configuration is described in section 1.2. Qualitative model-model-data comparisons of wind magnitude and direction are provided, and qualitative and quantitative model-model-data comparisons of resulting water levels are given.

Approach

The general approach is to generate analytic wind fields for a chosen tropical cyclone using the WES3 and WES4 methods and to apply the analytic wind magnitudes and directions blended with COAMPS (Coupled Ocean and Atmospheric Mesoscale Prediction System) wind magnitudes and directions as meteorological forcing to a Delft3D-Flexible Mesh model giving two model cases—WES3 and WES4. The analytic wind magnitudes are examined and compared to identify the resulting differences from the WES3 and WES4 methods. Then, the blended winds and modeled water levels are compared to data from NOAA [5] observation locations. Finally, modeled water levels are compared to USGS observation locations [6]. The tropical cyclone of choice is Hurricane Ida.

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Hurricane Ida (Figure 1) started as a tropical wave off the west coast of Africa [7] on August 14, 2021 and emerged over the southeastern Gulf of Mexico on August 28, 2021. Favorable shear and sea surface temperatures led to intensification for the next 24 hours with winds increasing from a peak of 70 knots (30 m/s) to 130 knots (~67 m/s) along with a fall in central pressure from 986 to 929 mb (hPa). By this time, the storm was also close to the mouth of the Mississippi River making landfall at Port Fourchon, LA at 1655 UTC August 29. The maximum winds at landfall were 130 knots (67 m/s) and the central pressure was approximately 931 hPa, making it a category 4 on the Saffir-Simpson Hurricane Wind Scale, and tying the record for the strongest storms to make landfall in Louisiana west of the Mouth of the Mississippi River. Shortly after landfall, Ida turned north-northwestward moving between Houma, LA and Baton Rouge, LA early on August 30. It weakened to a tropical storm before moving into southwestern Mississippi.

1.1 Analytic Wind Field Generation

In this report, we focus on the winds generated using WES3 and WES4 schemes. WES3 was the scheme that was used in the CSIPS Toolbox [8] whereas WES4 is used in the recently transitioned PSIPS [9] toolbox. In contrast to the original formulation, WES3 uses the formulation in [3] to generate the initial wind field. Asymmetry in the wind field is then introduced via the parameterization developed by [10] as a function of the forward speed and the angle between the track direction and the surface wind direction. The function is used to enhance the winds to the right of the storm track (in the northern hemisphere) and reduce the winds to the left of the storm track. Since the parameterization is based on a statistical analysis of past storms, the individual characteristics of the storm are not represented.

WES4 is a method to introduce the variabilities encountered in the individual storms. While the base wind field is still calculated using the formulation in [3], the asymmetry is introduced via the radius of 35 knot winds (R35) that is provided for each quadrant by forecast bulletins. The size of the storm, which is a parameter in the formulation in [3], is calculated in each quadrant based on the R35 value in that quadrant. The adjustment iteratively calculated to reduce the error between the available observed/forecast values of radii of 50 kt, 64 kt, and 100 kt winds given for each quadrant by the forecast bulletin and the computed winds.

1.2 Model Setup

The chosen model is Delft3D-Flexible Mesh (DFM) [4]. The advantage of DFM is that the computational grid for ocean circulation is not restricted to rectangular elements and allows for large area simulations with high resolution elements restricted to areas of high interest. Therefore, a flexible mesh can be generated by combining multiple structured grids using triangles. The flexible mesh grid used for Hurricane Ida simulations (Figure 2) has a low resolution of 0.08° in the middle of the Gulf of Mexico, and the resolution is increased by a factor of 2, based on the water depth, until a resolution of approximately 1 kilometer is reached along the shore in the northern Gulf of Mexico.

The model is driven by tidal amplitudes and phases prescribed along the open boundaries for 13 astronomical components (M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4 and MN4) from the TPXO8.0 tidal database [11]. Both water levels and velocities normal to the boundary are prescribed. The bathymetry is derived from the National Centers for Environmental Information (NCEI) Coastal Relief Models [12], [13], [14] combined with the General Bathymetric Chart of the Oceans (GEBCO, 2019) gridded data set [15]. The bottom roughness over land was calculated using the Manning formulation, with spatially varying Manning's N coefficient, determined from National Land Cover Database (NLCD) based on the tables in [16]. For offshore areas, a constant value of 0.023 s $m^{-1/3}$ was prescribed. The atmospheric input is given by the total stress

$$\tau = C_D U_{10} \rho_a$$

with values of C_D increasing linearly from 0.001 for U_{10} = 0 m/2 to 0.003 for U_{10}=25 m/s and then decreasing linearly to 0.0015 for U_{10}=50 m/s and staying constant for larger values of U_{10}. These values closely track the essential shape and magnitudes of C_D in [17].
The wind vectors and atmospheric pressure are provided after blending the analytic wind fields with a regional COAMPS model.

1.3 Data Sources and Comparison Methods

Wind magnitudes and directions provided to the models are compared to data collected by NOAA [5] at 3 observation locations. Aside from converting between scaler and vector forms, no adjustments were made to the meteorological data.

Water levels provided by the models are compared to three NOAA [5] observation locations and four USGS [6] observation locations. The NOAA water levels are presented in metric units and referenced to mean sea level with no other adjustments. For the comparisons to USGS data, the unfiltered, storm tide data is utilized. For each USGS observation location, the water levels were adjusted to local mean sea level using VDatum [18]. The adjustment for each station is provided in Table 1.

Two statistical measures are utilized for the water level comparisons at the NOAA and USGS observation locations. Mean error is determined as

$$\frac{1}{n}\sum_{i=1}^{n}|O_i - P|,$$

Where n is the number of water levels in a time series, O is an observed water level and P is a modeled water level. Using the same nomenclature, correlation is determined as

$$\frac{n(\sum P_i O_i) - (\sum P_i)(\sum O_i)}{\sqrt{[n\sum P_i^2 - (\sum P_i)^2][n\sum O_i^2 - (\sum O_i)^2]}}.$$

Results

1.4 Analytic Wind Comparison

Comparisons of the analytic wind magnitudes are shown in Figure 3-Figure 6 for times August 27, 2021 17:00 UTC, August 28, 2021 00:00 UTC, August 29, 11:00 UTC and August 29, 2021

16:00 UTC, respectively. For each time the WES3 (left) and WES4 (middle) winds are shown in addition to the difference (WES4-WES3, right). At all times the asymmetric shape of the wind field is evident in both the WES3 and WES4 magnitudes; however, the asymmetry is more prevalent in the WES4 wind magnitudes. The WES4 wind field exhibits higher magnitudes in the northeast area and small magnitudes in the southwest area. The difference plots Figure 3-Figure 6 (right) confirm that the WES4 wind magnitudes are greater than the WES3 wind magnitudes in the northeast area and less than the WES3 wind magnitudes in the southwest area. Similar comparisons of wind magnitudes are shown in Figure 7-Figure 10 for wind magnitudes along a line dissecting the wind fields. The line is referenced in black in Figure 3-Figure 6. Figure 7shows that at lower longitudes (the southwest part of the wind field), the WES4 magnitudes are less than the WES3 magnitudes and at higher latitudes (the northeast part of the wind field), the WES4 magnitudes are only slightly greater than the WES3 magnitudes. As the wind field approaches shore, the WES4 asymmetry rotates clockwise, and the difference in wind magnitudes between WES3 and WES4 decreases along the black reference line Figure 8 andFigure 9. By landfall, there is little difference between the WES3 and WES4 wind magnitudes along the black reference line (Figure 10) with the biggest difference being just southwest of the wind field center.

1.5 Model-Data Comparisons

1.5.1 Wind Magnitudes and Directions

Model wind fields and water levels are compared to in situ data for three NOAA stations, Bay Waveland Yacht Club (BWYC), Pilot Station East, and Grand Isle. Station locations are labeled in red on the map shown in Figure 11. Figure 12 and Figure 13 show that at locations near landfall, the WES3 and WES4 wind magnitudes and directions are mostly similar. At Pilots Station East (Figure 12), the WES3 and WES4 wind magnitudes and directions agree with in situ measurements up until gauge failure.

At the NDBC Grand Isle location, however, WES3 and WES4 overpredict the wind magnitudes and shift the wind directions during the peak of the event (Figure 13, top and bottom). Around midnight on August 31, 2021, there is a discrepancy in the WES3 and WES4 wind magnitudes and directions, and generally, WES3 and WES4 underpredict wind direction leading up to the peak in wind magnitude and after the peak. At the peak of the wind magnitude and for a short time after, WES3 and WES4 overpredict the wind direction.

The largest differences in the WES3 and WES4 magnitudes and directions occur at the BWYC location (Figure 14). At the BWYC location, the WES4 wind magnitudes are in better agreement with in situ measurements around the location's peak of the event than the WES3 wind magnitudes (Figure 14, top). The wind directions, however, are overpredicted by the WES4 magnitudes during this time (Figure 14, middle).

1.5.2 Water Levels

In addition to wind magnitudes and directions, modeled water levels are compared to in situ observations at the NOAA observation locations (Figure 11).

At Pilots Station East, where WES3 and WES4 wind magnitudes and directions agree with observations, the resulting modeled water levels mostly agree with observations (Figure 15).

Slight discrepancies are found in the maximum water level and the time of the maximum water level. Still error statistics reveal a mean error of only 0.08 and a good correlation of 0.90 (Table 2).

At the Grand Isle observation location, where WES3 and WES4 overestimate the wind magnitudes and directions around the peak of the event, the modeled water levels, too, overestimate the maximum water level (Figure 16). Leading up to the peak in wind magnitude and water level, the modeled and measured wind magnitudes closely agree with a slight over estimation by the analytic winds (Figure 13, top), but the modeled water levels under estimate the measured water levels (Figure 16). After the peak in wind magnitude and water level, the wind magnitudes overestimate the measured wind magnitudes (Figure 13, top); however, the modeled water levels underestimate the measured water levels (Figure 16). During this period, we see the biggest difference in water levels resulting from the WES3 and WES4 analytic winds, and the WES4 winds produce water levels that agree with measurements better than the WES3 winds. The WES4 mean error (0.10) is less than the WES3 mean error (0.22). WES4's correlation acceptable correlation of 0.81 is an improvement over the WES3 correlation (0.68). In both cases (before and after the event peak), the analytic wind directions underestimate the measured wind directions (Figure 13, middle).

At the BWYC observation location, the water levels resulting from the WES3 and WES4 wind fields are similar and compare to the data similarly with exception around the peak of the water level and wind magnitude (Figure 17). Around the peak of the event, the water levels resulting from the WES3 analytic winds underestimate but more closely agree with the measured water levels than the water levels resulting from the WES4 analytic winds. The comparison is quantified in mean errors of 0.13 and 0.15 and strong correlation coefficients of 0.94 and 0.92 for the water levels resulting from the WES3 and WES4 wind fields, respectively. The slightly lower correlation and higher mean error for WES4 is unexpected because the WES4 wind magnitudes appear to agree with measured wind magnitudes more than the WES3 wind magnitudes (Figure 14, top). Perhaps it is the error in wind direction that inhibits WES4 improvement in water level prediction over the WES3 prediction. A more thorough examination is required.

Water levels were compared to model results at four USGS observation locations. Two of the observation locations were located on the Grand Isle State Park pier near the NOAA Grand Isle observation location (Figure 11).

At both USGS Grand Isle observation locations, water levels were recorded in excess of 3 meters. Like we observed at the NOAA Grand Isle location (Figure 16), the water levels resulting from the WES3 and WES4 wind fields are similar through the peak of the event (Figure 18 and Figure 19); however, at the USGS Grand Isle comparison locations, the modeled water levels slightly underestimate (Figure 18) and agree (Figure 19) with water level measurements. For the comparison in Figure 19, the mean error of 0.15 indicates that the WES3 and WES4 models capture the peak water level well. The WES3 model provides a slightly stronger correlation (0.66) than the WES4 model (0.63) (Table 2). As seen at the NOAA Grand Isle observation location (Figure 16), the WES4 model results predict water levels greater than those predicted by the WES3 model following the event peak (Figure 18 and Figure 19).

The remaining two USGS observation locations are at Buras (Figure 20) and Bridgeside Marina (Figure 21). At both of these locations, there are small, if any, differences in water levels resulting from the WES3 and WES4 wind fields. The models do not compare well to the observations at these locations. Mean errors are high (0.87), and correlations are low (0.12 and -0.02) at Bridgeside Marina (Table 2). At Buras (Figure 20), the modeled water levels agree with water level measurements leading up to the peak water level, but the modeled water levels underestimate the peak and overestimate water levels following the peak. The mean errors (0.19) and correlation coefficients (0.49, WES3 and 0.34, WES4) at Buras are improved over those at Bridgeside Marina (Table 2); however, these values are not desirable.

Discussion

To evaluate an update to the method of generating analytic winds for storm sure prediction, we generated analytic winds using the CSIPS method (WES3) and the PSIPS method (WES4). Then, we blended the analytic wind fields with a COAMPS regional model wind field and used the blended wind fields to force Delft3D-FM storm surge models of Hurricane Ida. We qualitatively compared the WES3 and WES4 analytic wind magnitudes, and we qualitatively compared wind magnitudes and directions of the models' wind fields to NOAA in situ measurements. Finally, we compared modeled water levels resulting from the two blended wind fields to in situ water level observations from NOAA and USGS.

The qualitative comparison of the WES3 and WES4 wind fields show that the WES4 wind field is more asymmetric than the WES3 wind field with increased magnitudes in the north east area of the field extending further from the storm center and decreased magnitudes in the south west area.

The water levels generated from the WES4 analytic winds strongly correlate with data at the NOAA Pilots Station East, Grand Isle, and BWYC observation locations. At the Grand Isle location, the WES4 water level predictions show an improvement over the WES3 predictions. Correlations at the USGS Grand Isle observation locations are lower than at the NOAA location despite a stronger qualitative comparison. The cause is likely the shorter data record giving fewer observations for the statistical measures. Both WES3 and WES4 predicted water levels correlate strongly to observations at the BWYC location, but the WES3 correlation is slightly stronger. The location is furthest from Hurricane Ida's landfall, and the model wind field may be more blended than analytic here. Further examination is required. Overall, WES4 provides a more realistic, asymmetric analytic wind field based on individual storm properties and results in water levels as or more robust than water levels resulting from WES3.

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Figures

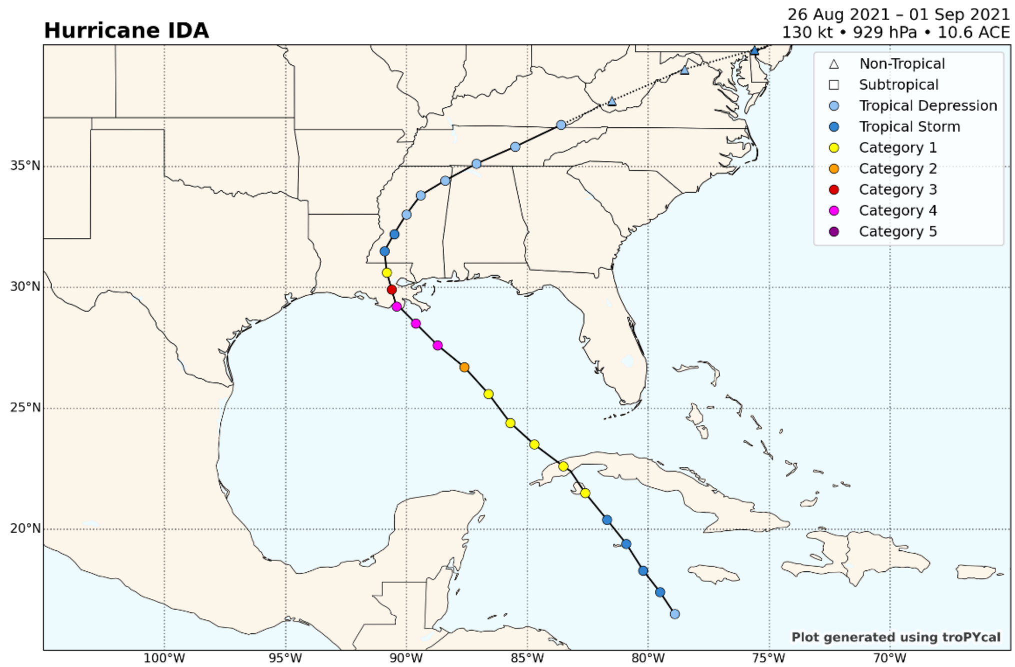

Figure 1. Hurricane Ida track and Intensity

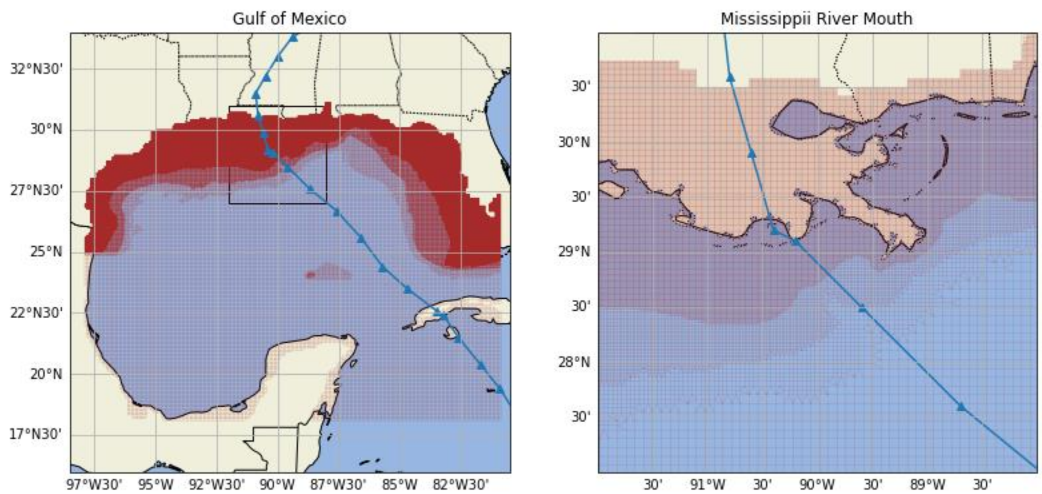

Figure 2. Flexible mesh grids used for Hurricane Ida simulations. The zoomed in areas around the mouth of the Mississippi River shows the grid refinement near the coast. The blue line is the Ida track.

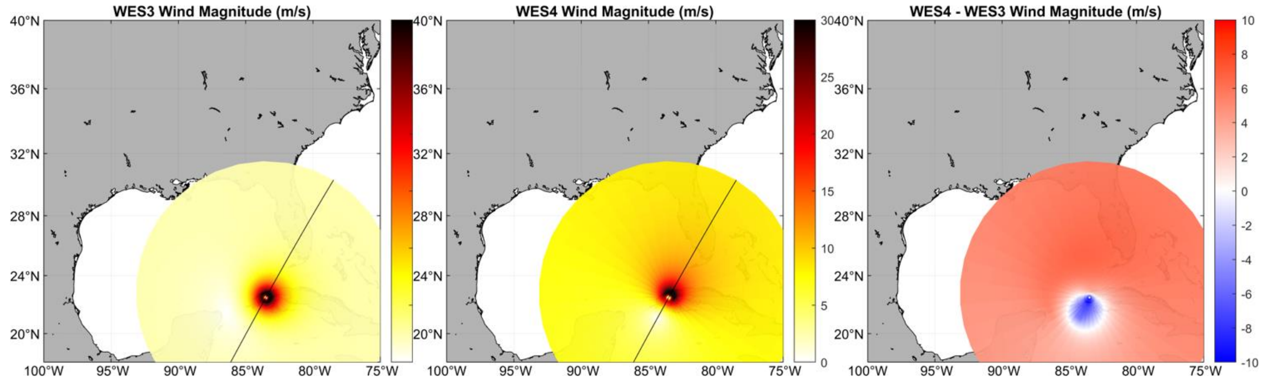

Figure 3. Comparison of WES3 (left) and WES4 (middle) analytic wind magnitudes for August 27, 2021 at 17:00 UTC. The right plot is the WES4-WES3 difference. The black lines in the left and middle plots indicate the cross-section where magnitudes are compared in Figure 7.

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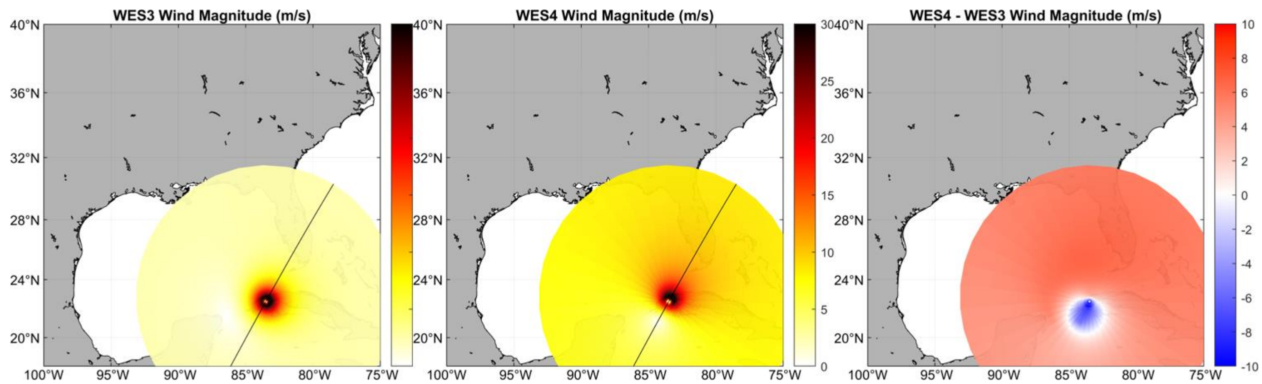

Figure 4. Comparison of WES3 (left) and WES4 (middle) analytic wind magnitudes for August 28, 2021 at 00:00 UTC. The right plot is the WES4-WES3 difference. The black lines in the left and middle plots indicate the cross-section where magnitudes are compared in Figure 8.

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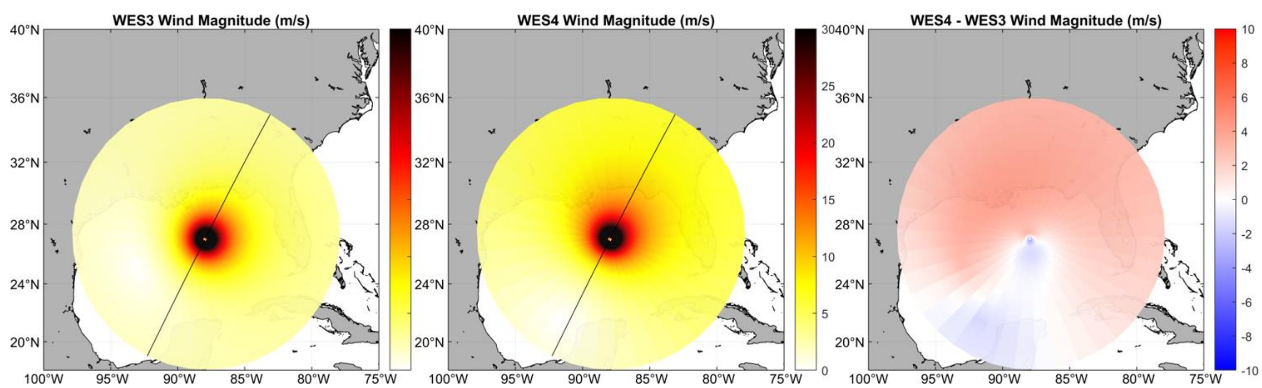

Figure 5. Comparison of WES3 (left) and WES4 (middle) analytic wind magnitudes for August 29, 2021 at 11:00 UTC. The right plot is the WES4-WES3 difference. The black lines in the left and middle plots indicate the cross-section where magnitudes are compared in Figure 9.

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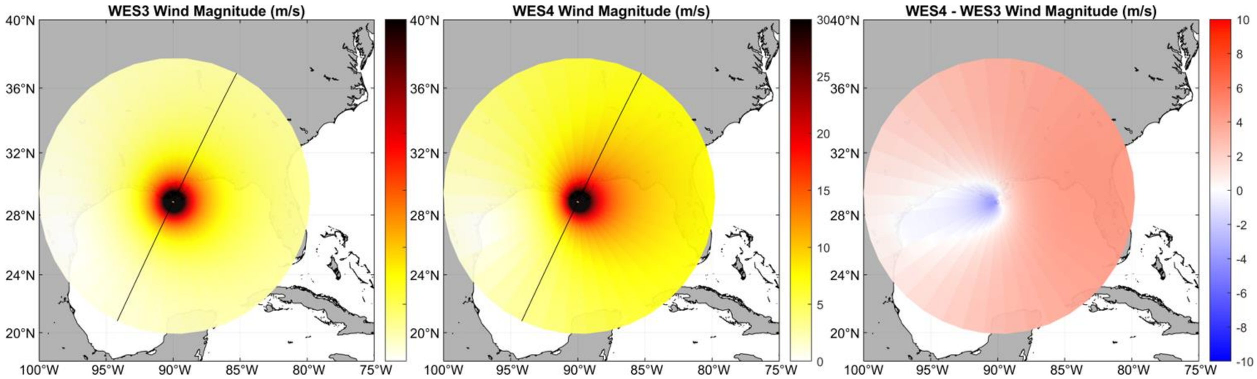

Figure 6. Comparison of WES3 (left) and WES4 (middle) analytic wind magnitudes for August 29, 2021 at 16:00 UTC. The right plot is the WES4-WES3 difference. The black lines in the left and middle plots indicate the cross-section where magnitudes are compared in Figure 10.

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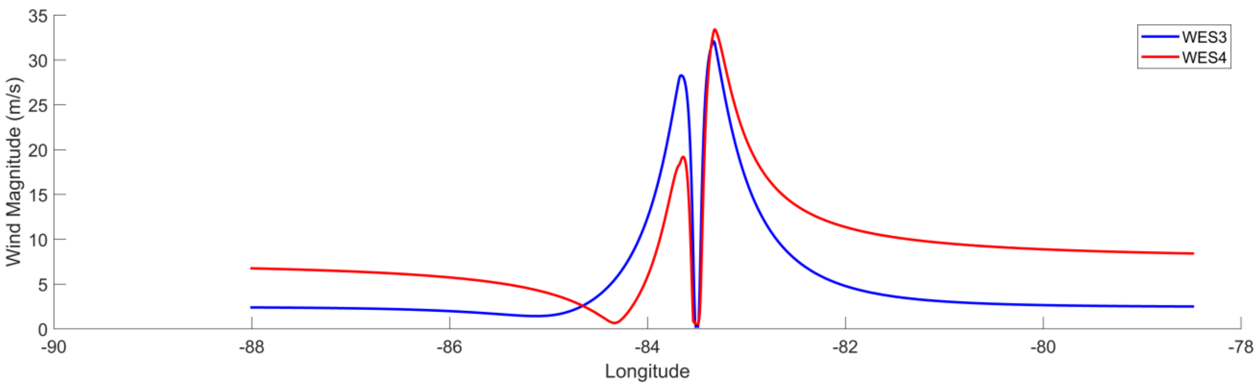

Figure 7. Comparison of WES 3 (blue) and WES4 (red) wind magnitude along the cross-section (black line) in Figure 3. The UTC time is August 27, 2021 17:00.

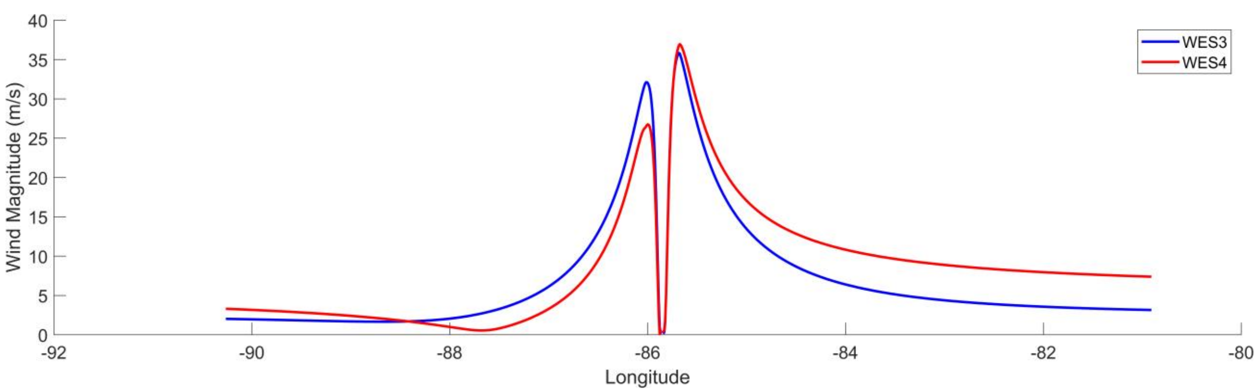

Figure 8. Comparison of WES 3 (blue) and WES4 (red) wind magnitude along the cross-section (black line) in Figure 4. The UTC time is August 28, 2021 00:00.

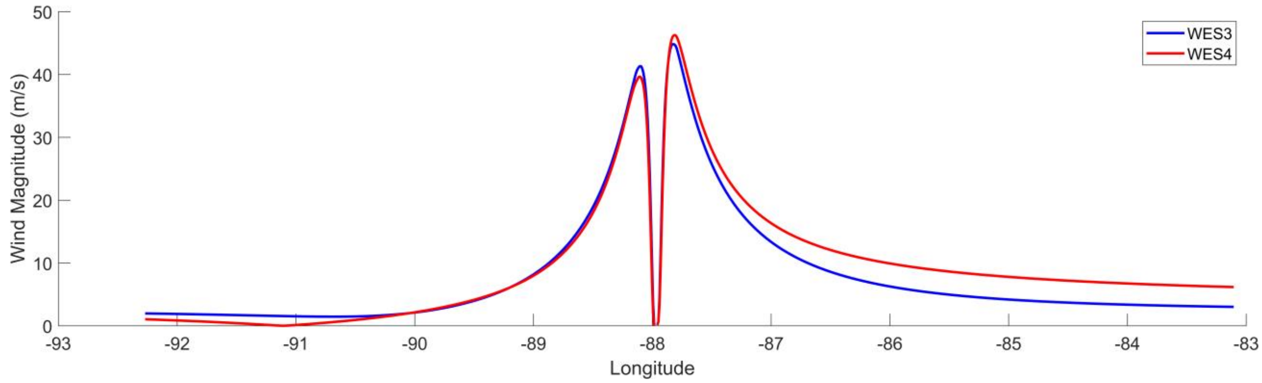

Figure 9. Comparison of WES 3 (blue) and WES4 (red) wind magnitude along the cross-section (black line) in Figure 5. The UTC time is August 29, 2021 11:00.

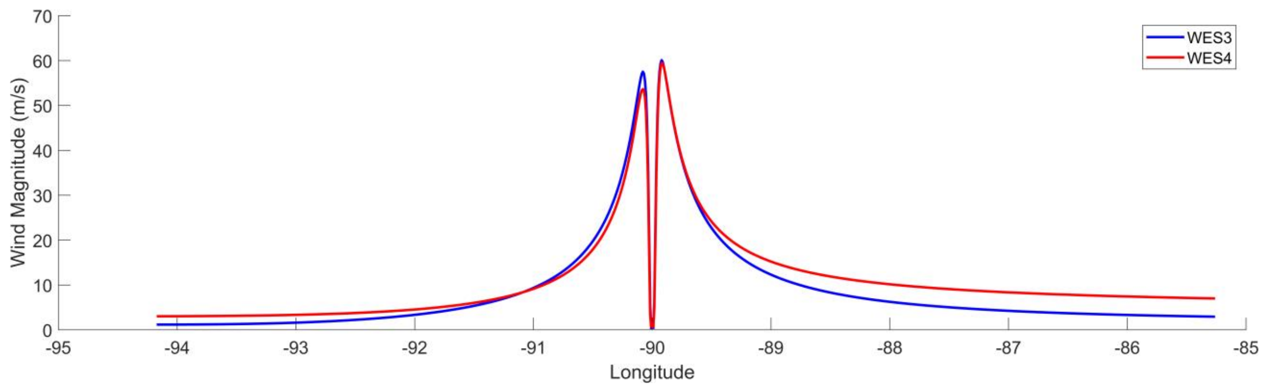

Figure 10. Comparison of WES 3 (blue) and WES4 (red) wind magnitude along the cross-section (black line) in Figure 6. The UTC time is August 29, 2021 16:00.

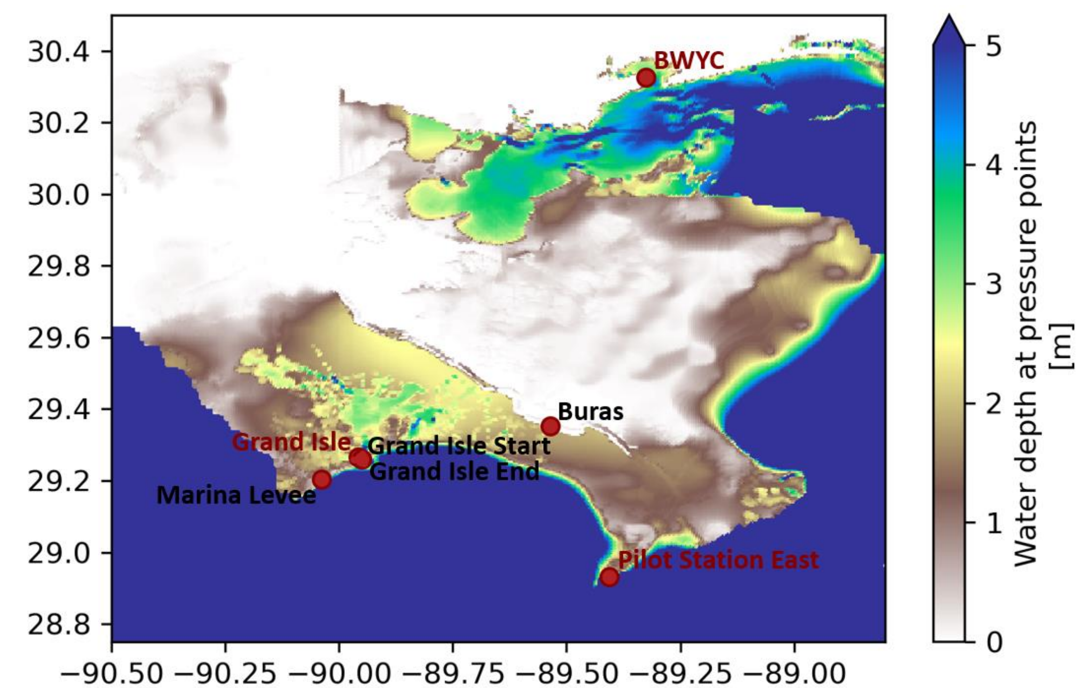

Figure 11. Map of observation station locations (red dots). The colorbar shows water depth in meters at the UTC time August 30, 2021 02:00. NOAA observation stations are labeled with red names, and USGS observation locations are labeled with black names.

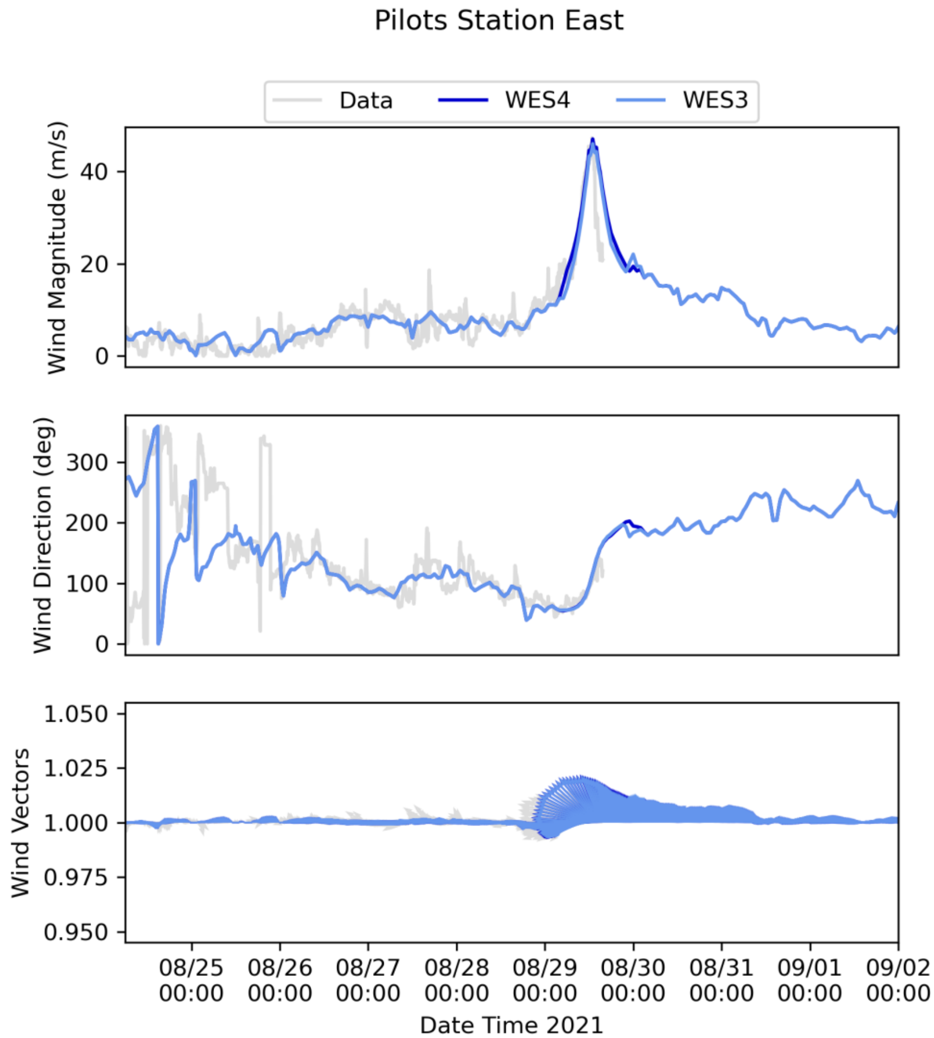

Figure 12. Model-model-data comparison of wind magnitude (top), wind direction (middle), and wind vectors (bottom) for the NOAA Pilot Station East observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

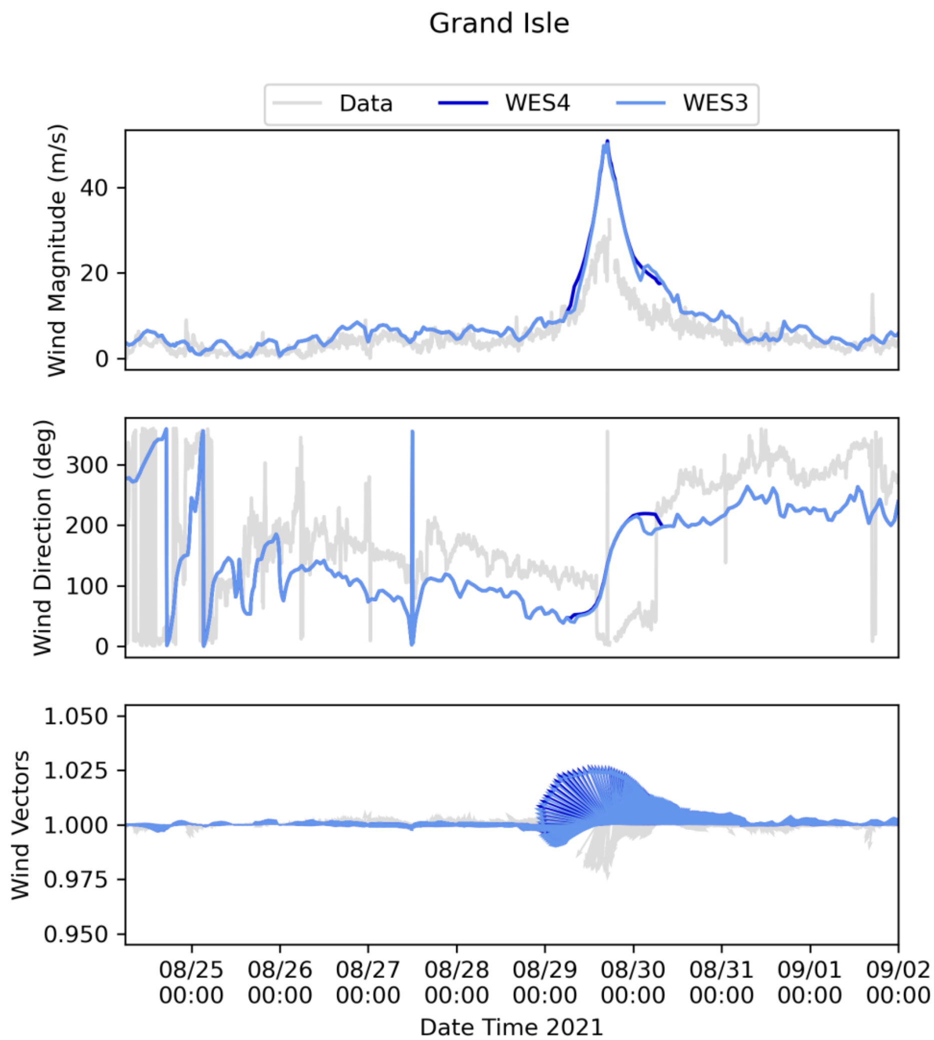

Figure 13. Model-model-data comparison of wind magnitude (top), wind direction (middle), and wind vectors (bottom) for the NOAA Grand Isle observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

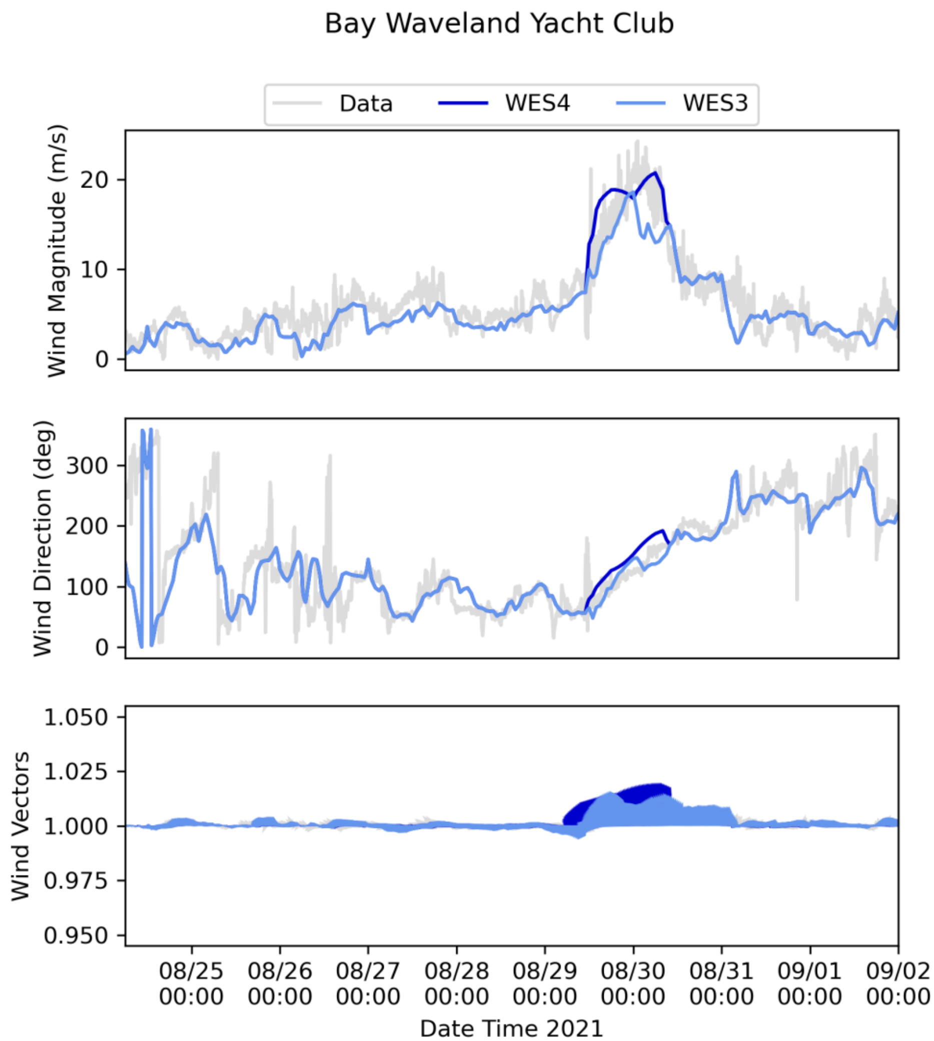

Figure 14. Model-model-data comparison of wind magnitude (top), wind direction (middle), and wind vectors (bottom) for the NOAA Bay Waveland Yacht Club observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

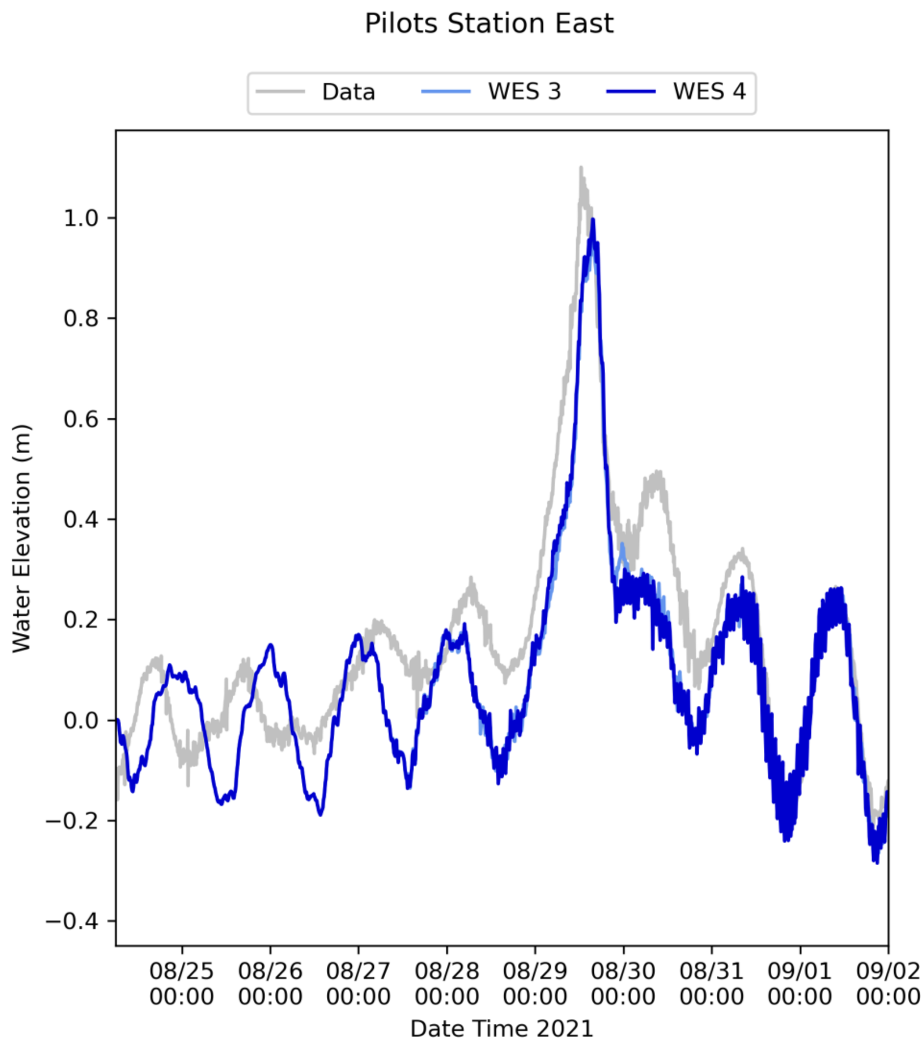

Figure 15. Model-model-data water level comparison at the NOAA Pilots Station East observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

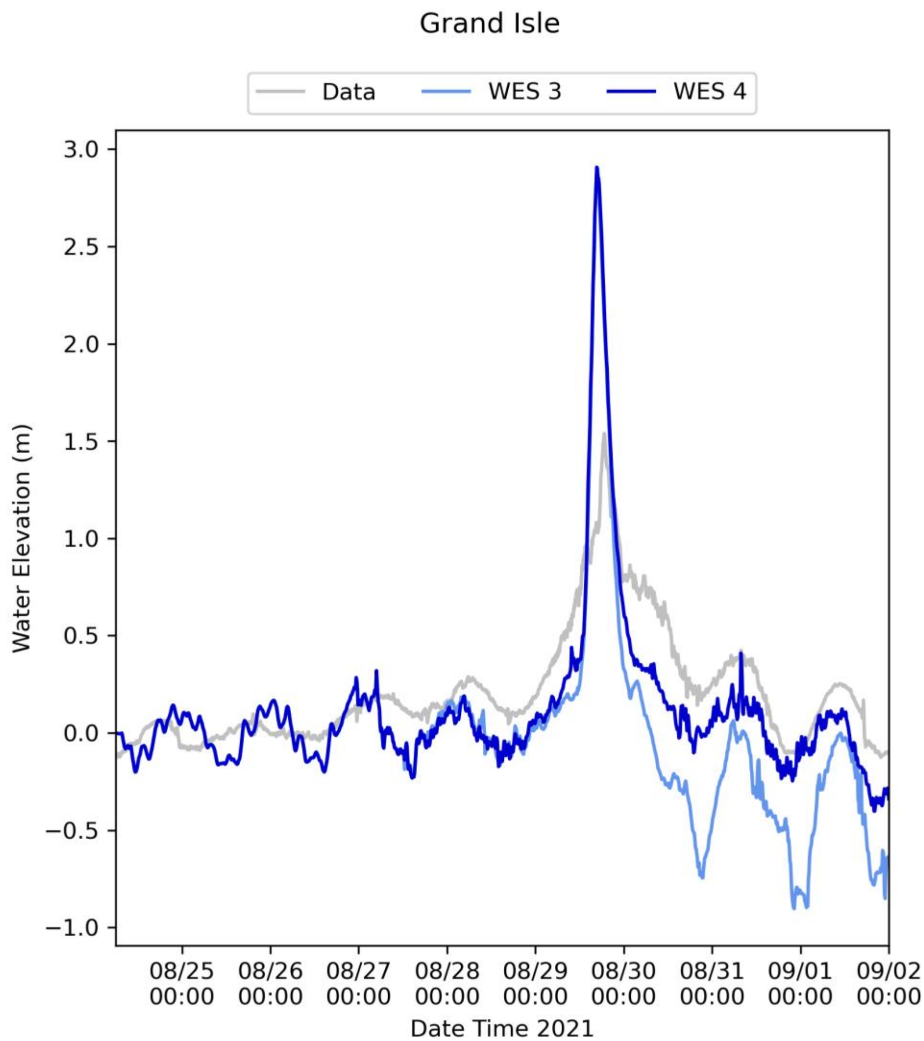

Figure 16. Model-model-data water level comparison at the NOAA Grand Isle observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

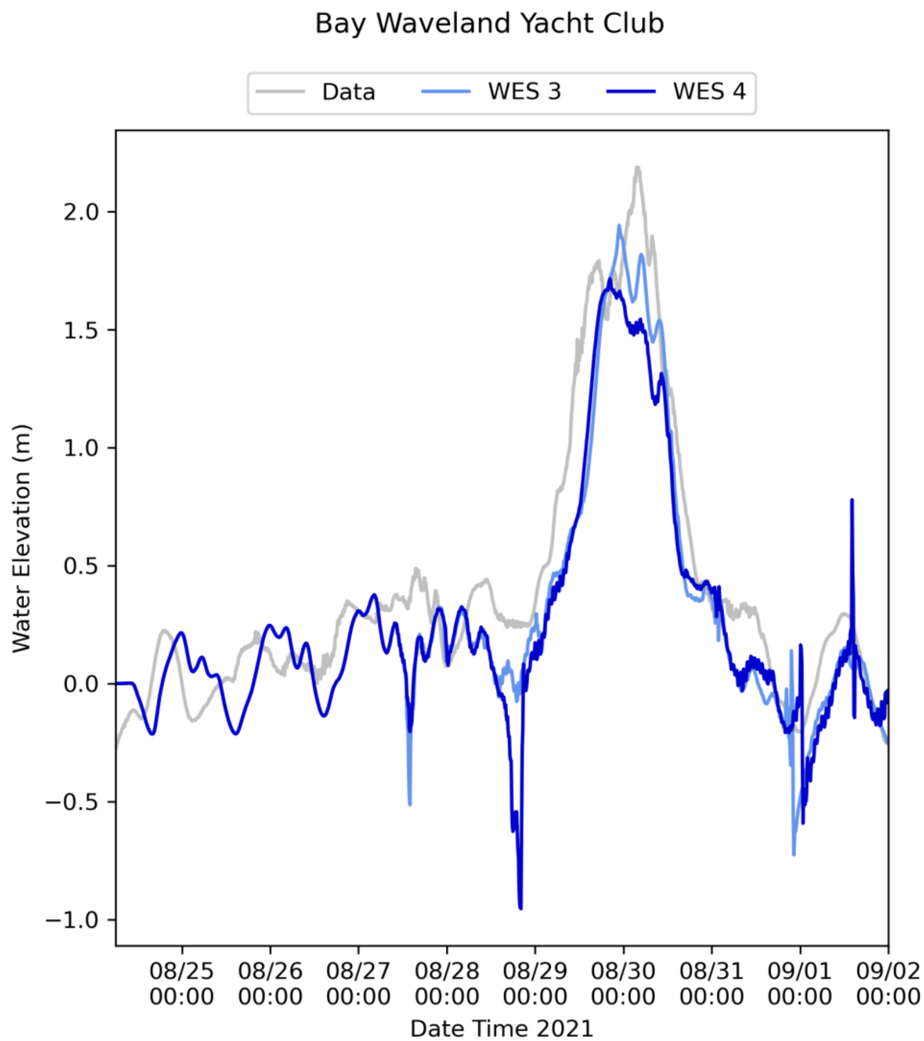

Figure 17. Model-model-data water level comparison at the NOAA Bay Waveland Yacht Club observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

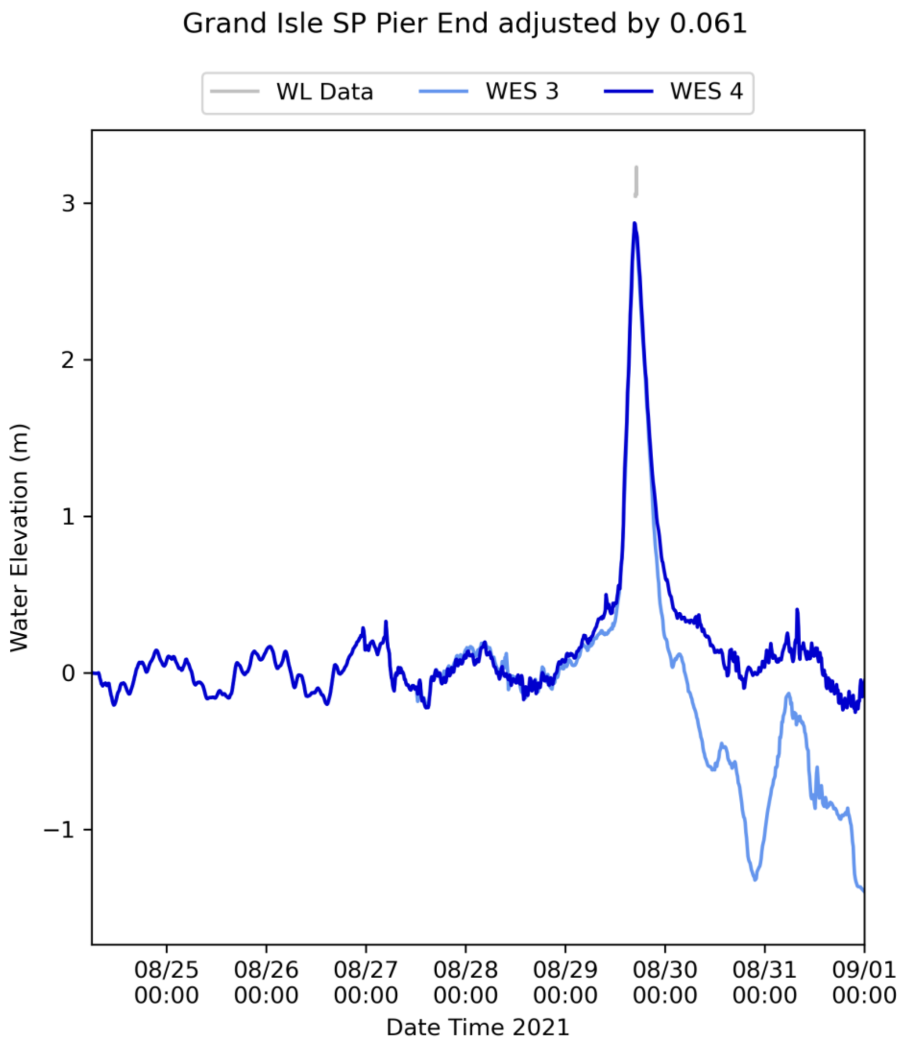

Figure 18. Model-model-data water level comparison at the USGS Grand Isle State Park Pier End observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

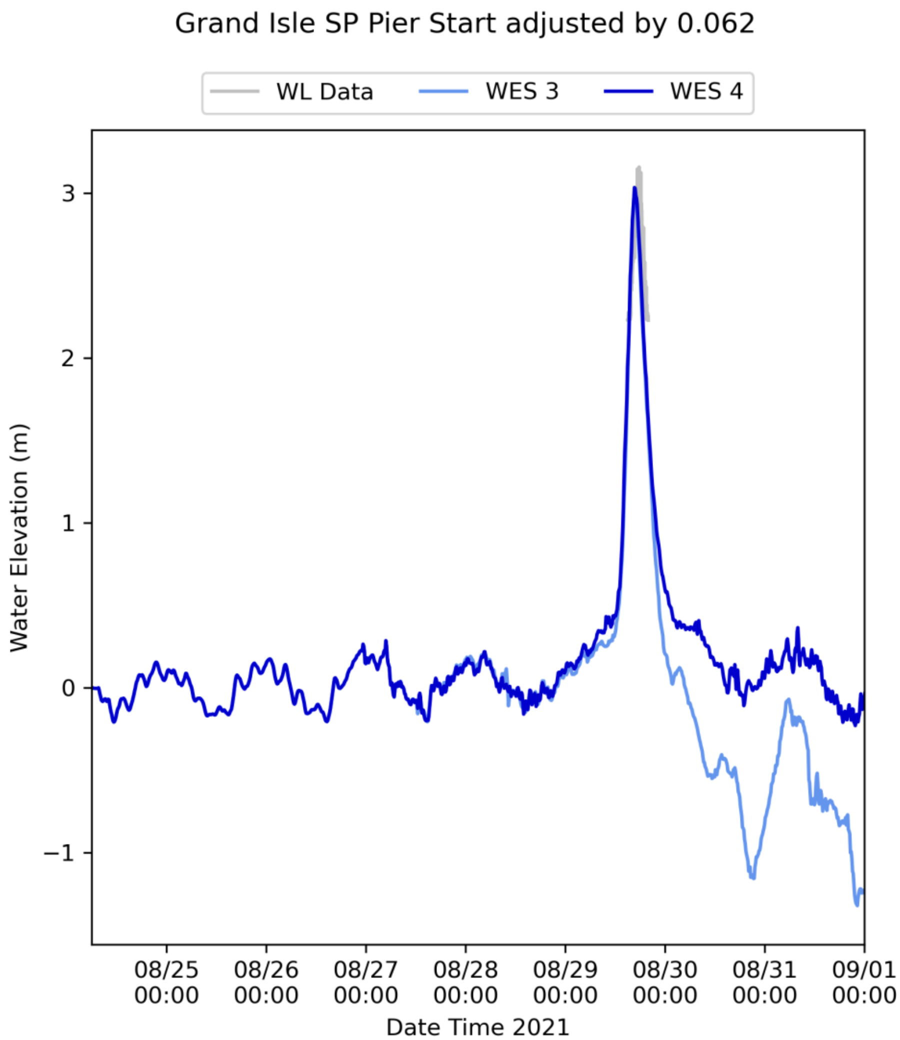

Figure 19. Model-model-data water level comparison at the USGS Grand Isle State Park Pier Start observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

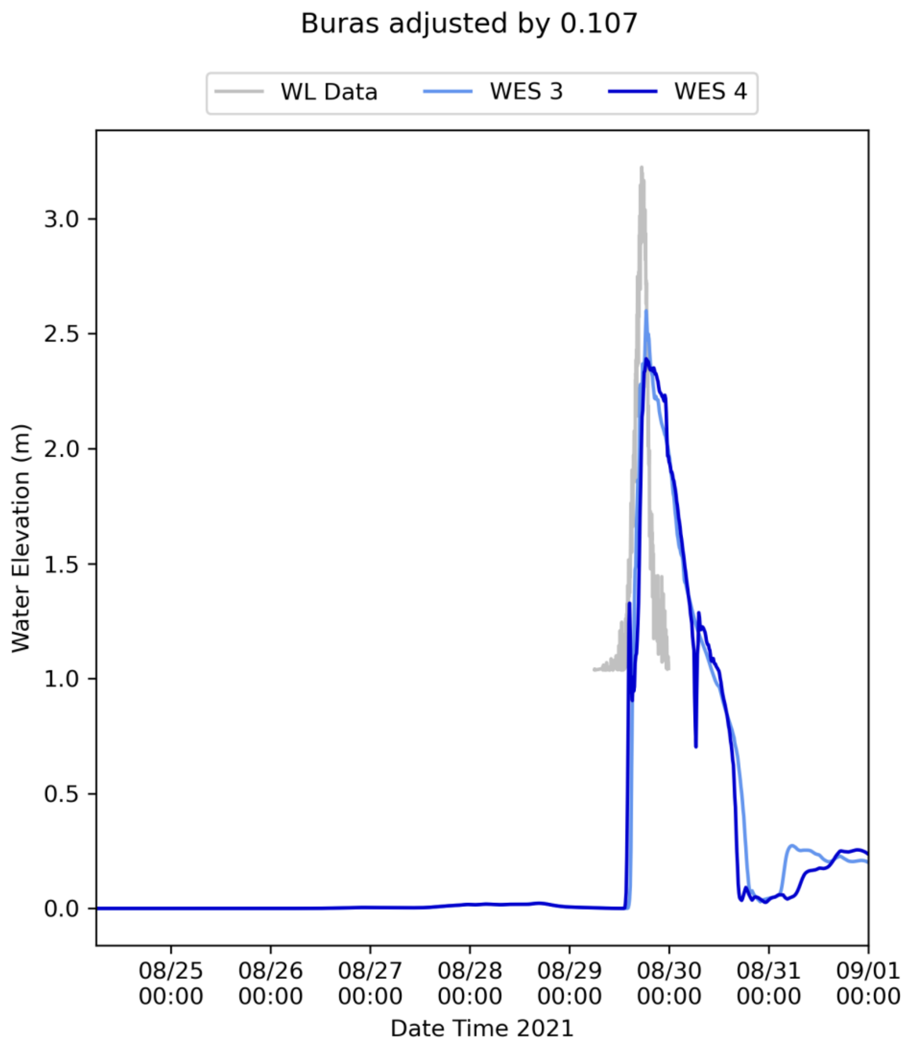

Figure 20. Model-model-data water level comparison at the USGS Buras observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

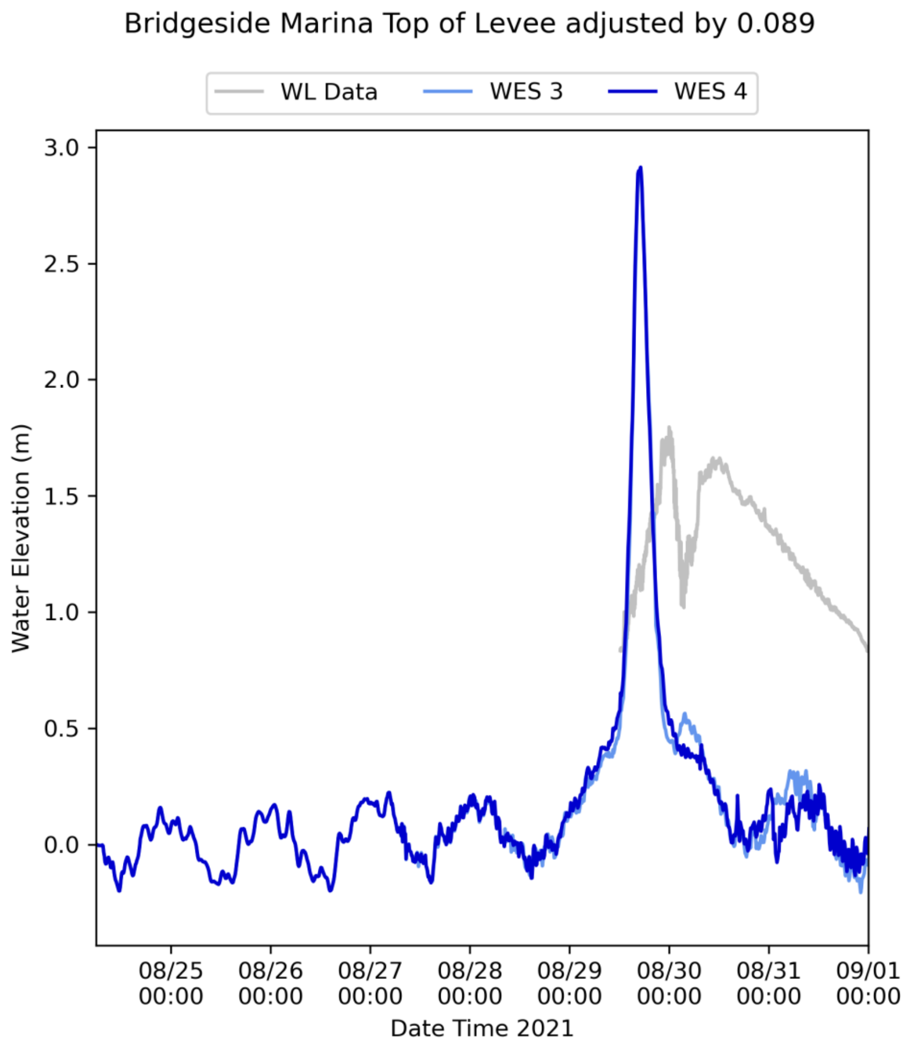

Figure 21. Model-model-data water level comparison at the USGS Bridgeside Marina observation location. Data are shown in gray; WES4 winds are shown in royal blue, and WES3 winds are shown in light blue.

Tables

STATION	ADJUSTMENT VALUE (M)
BURAS	0.107
GRAND ISLE STATE PARK PIER END	0.061
GRAND ISLE STATE PARK PIER START	0.062
BRIDGESIDE MARINA	0.089

Table 1. List of adjustments made to USGS water level data to correct to local mean sea level.

	WES3	WES4
Pilots Station East		
Mean Error	0.08	0.08
Correlation	0.90	0.90
Grand Isle		
Mean Error	0.22	0.10
Correlation	0.68	0.81
Bay Waveland Yacht Club		
Mean Error	0.13	0.15
Correlation	0.94	0.92
Grand Isle SP Pier Start		
Mean Error	0.15	0.15
Correlation	0.66	0.63
Grand Isle SP Pier End		
Mean Error	0.31	0.31
Correlation	-0.65	-0.60
Bridgeside Marina		
Mean Error	0.87	0.87
Correlation	0.11	-0.02
Buras		
Mean Error	0.19	0.19
Correlation	0.49	0.34

Table 2. Error statistics for the WES3-data and WES4-data comparisons.