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Rapid Tidal Reconstruction for the Coastal Hazards System and StormSim

Part II: Puerto Rico and US Virgin Islands

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PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes the continuing efforts towards incorporating rapid tidal time-series reconstruction and prediction capabilities into the Coastal Hazards System (CHS) and the Stochastic Storm Simulation System (StormSim). The CHS (Nadal-Caraballo et al. 2020) is a national effort for the quantification of coastal storm hazards, including a database and web tool (<https://chs.erdcdren.mil>) for the deployment of results from the Probabilistic Coastal Hazard Analysis (PCHA) framework. These PCHA products are developed from regional studies such as the North Atlantic Coast Comprehensive Study (NACCS) (Nadal-Caraballo et al. 2015; Cialone et al. 2015) and the ongoing South Atlantic Coast Study (SACS). The PCHA framework considers hazards due to both tropical and extratropical cyclones, depending on the storm climatology of the region of interest. The CHS supports feasibility studies, probabilistic design of coastal structures, and flood risk management for coastal communities and critical infrastructure. StormSim (<https://stormsim.erdcdren.mil>) is a suite of tools used for statistical analysis and probabilistic modeling of historical and synthetic storms and for stochastic design and other engineering applications. One of these tools, the Coastal Hazards Rapid Prediction System (CHRPS) (Torres et al. 2020), can perform rapid prediction of coastal storm hazards, including real-time hurricane-induced flooding.

This CHETN discusses the quantification and validation of the Advanced Circulation (ADCIRC) tidal constituent database (Szpilka et al. 2016) and the tidal reconstruction program Unified Tidal analysis (UTide) (Codiga 2011) in the Puerto Rico and US Virgin Islands (PR/USVI) coastal regions. The new methodology discussed herein will be further developed into the Rapid Tidal Reconstruction (RTR) tool within the StormSim and CHS frameworks.

BACKGROUND: This technical note is the second in a series of documents providing guidance on the accuracy of tidal predictions using the combined ADCIRC tidal database and the UTide methodology. Each document in the series will focus on a region of interest as related to Civil Works programs and/or US Army Corps of Engineers (USACE) missions. The first technical note of the series focused on the tides in the coastal Texas and Louisiana (CTXS) region (Torres and Nadal-Caraballo 2020). In the CTXS study, the tidal reconstruction methodology was introduced, and the reconstructed time series was compared to water level predictions from the National Oceanic and Atmospheric Administration (NOAA) tidal gauges in the region. Descriptions of the ADCIRC tidal database and the UTide program are provided in Torres and Nadal-Caraballo (2020), Szpilka et al. (2016), and Codiga (2011). This study follows a similar methodology for the PR/USVI region. For more information on tidal analysis methods, please refer to Godin (1972), Parker (2007), and Foreman et al. (2009).

The SACS effort seeks to quantify coastal storm hazards for coastal communities in the southern Atlantic, western Gulf of Mexico, and Caribbean regions. Specifically, the areas of focus include

Mississippi to North Carolina as well as PR/USVI. The primary objective of the study is to determine the magnitude of existing and future coastal hazards and to compute epistemic and aleatory uncertainties for use in assessing coastal planning and engineering projects for flood-risk reduction and increased resiliency.

Coastal hazard analysis methods include a large suite of coupled hydrodynamic and wave model simulations, such as ADCIRC (Luettich et al. 1992; Westerink et al. 1993) and Steady-State Wave (STWAVE) (Massey et al. 2011), that predict the storm wave and water level response to several hundred to thousands of tropical cyclone and extratropical cyclone scenarios. Storm responses, as well as the resulting PCHA results, are saved at locations of interest (save points) within the domain. This practice is common for large regional studies such as the NACCS (Nadal-Caraballo et al. 2015) and the SACS. Establishing this ensemble of simulations and statistical results is very computationally expensive and requires several thousand processing units to compute. For regions with minimal tidal range, on the order of 0.5 m*, the hydrodynamic simulations are typically run without base tidal conditions included, and astronomical tides are instead incorporated within the probabilistic framework. This method is currently being applied in the PR/USVI region of the SACS. As a supplement to the current practice, the purpose of this CHETN is to provide computationally efficient, reliable, and accurate astronomical tidal time series at the save points within the SACS PR/USVI regional domain. As previously mentioned, the methodology discussed herein will be further developed into the RTR tool within the StormSim and CHS frameworks.

One of the primary findings of the CTXS tidal analysis was the overall reduction from 8% to 6% in root-mean-square error (RMSE) of the tidal time series when the tides were reconstructed using the most dominant constituents in the region (Torres and Nadal-Caraballo 2020). In this analysis, the number of input constituents was expanded to investigate the effect on the average RMSE.

There are four main objectives of this study: (1) assess the relationship between the number of constituents included in the reconstruction and the average error in the tidal time series; (2) determine the optimal number of constituents for the region; (3) investigate the effects of supplementing less accurate values from the ADCIRC tidal database with more trusted values from NOAA. The spatial interpolation method used for this process is briefly described, and the resulting amplitude and phase pairs are processed through the tidal reconstruction method; and (4) evaluate the computational expense required to reconstruct tides for varying time lengths (e.g., 1 year versus 5 days), as well as the resulting average error associated with series duration.

Study Area and Data. The focus areas of the SACS include (1) the South Atlantic coasts of North Carolina to South Florida, (2) the Gulf of Mexico between Mississippi and South Florida (western coast), and (3) the PR/USVI region of the Caribbean. In this study, tidal predictions from the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) network were queried for 31 stations within the PR/USVI region (19 gages in PR and 12 gages in USVI; Figure 1). Table A-1 in the Appendix provides a complete list of the NOAA stations and their

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

descriptions (<https://tidesandcurrents.noaa.gov/PageHelp.html>). For the purpose of this study, only harmonic station types were queried.

The ADCIRC Western North Atlantic, Caribbean, and Gulf of Mexico Tidal (WNAT) harmonic constituent database (Szpilka et al. 2016) is based on an unstructured mesh that contains 2,066,216 nodes overall and has a minimum spatial resolution near 150 m along the PR/USVI coastline and down to 80 m inside bays in the PR/USVI region.

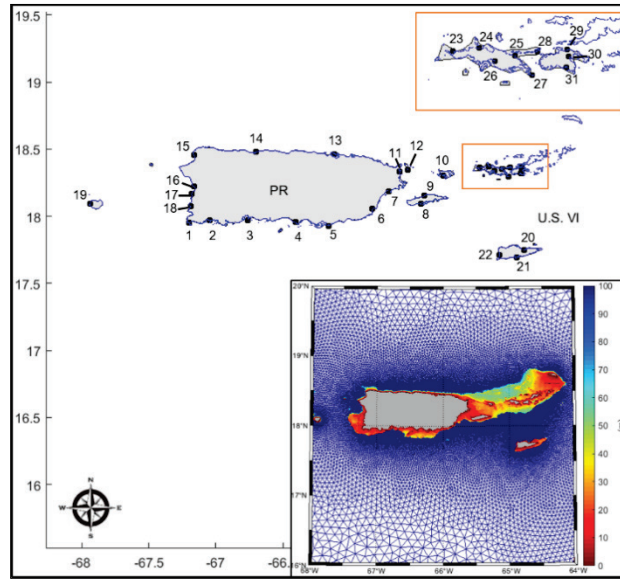


Figure 1. Geographic location of NOAA CO-OPS tidal prediction stations in PR/USVI coastal areas; (lower right) spatial resolution and bathymetry of the ADCIRC WNAT grid in the study region; (upper right) zoomed-in area of USVI station locations; see Table A-1 for full description.

METHODOLOGY: In general, the same methodology for reconstructing the tides used in the Coastal Texas and Louisiana region (Torres and Nadal-Caraballo 2020) was applied in the PR/USVI region. Tidal constituents were first sorted by amplitude at each tidal prediction station in the region, and the most common or prevalent constituents among all stations were identified for the region. The NOAA predicted time series were decomposed through the UTide solver function *ut_solv()*, in which UTide provides its best estimate of the tidal harmonic amplitude and phase pairs for either a specified list of constituents or any number of inferred constituents (if using the auto-infer feature) (Codiga 2011). In this study, the list of most prevalent constituents was specified in UTide. Tidal time series were generated over a specified period through the UTide reconstruction function *ut_reconstr()*. Multiple sets of time series were generated using harmonic amplitude and phase pairs from (1) the UTide best estimate from the solver, (2) the NOAA harmonic constituent tables, and (3) the ADCIRC tidal database. Each time series was then compared with NOAA tidal predictions to quantify accuracy and determine the best solution. The average RMSE among all stations in the region was the primary indicator of uncertainty. This process was repeated while incrementally increasing the number of constituents from 8 to 33.

The computational time required to process the 31 stations in the region for each of the added number of constituents was also assessed. The time series were reconstructed as a group of stations in sequence. Therefore, the computational time of each iteration of increasing constituents reflects the completion time of all 31 stations in the group. Assuming the total time is the sum of the individual stations, then the computational time of a single station is the total time divided by the number of stations in the group. This knowledge, in addition to the resulting total error in the time series, helped determine the final number of constituents to include in the reconstruction process moving forward.

With the final number of constituents selected, the initial conditions of the data (i.e., amplitude and phase values) from the ADCIRC database were compared with those from NOAA sources for all stations in the region. These values are the inputs to the UTide tidal analysis program. Therefore, any discrepancies in the amplitude and phase of the harmonic constituents are expected to transfer to the total error in the time series. Statistically, there was a very small sample size (31 points) with which to compare the two data sets (i.e., NOAA and ADCIRC). The amplitude and phase pairs from NOAA were assumed to be true, including zero values reported for the amplitude. The values from the ADCIRC database were considered less trustworthy for constituents outside of the eight primary constituents (M2, N2, S2, K2, O1, K1, P1, and Q1) for which the database had been validated (Szpilka et al. 2016). Relative error metrics between the two data sets were computed for the data.

Following the assessment of the amplitude and phase pairs, three sets of tidal time series were generated using UTide with input values from UTide itself, NOAA (UTide(N)) (N for NOAA), and ADCIRC (UTide(A)) (A for ADCIRC) at each tidal prediction station. The resulting reconstructed tides were then compared against NOAA predictions. Time series were generated for different time scales ranging from a full calendar year (1 January 2018 – 31 December 2018) to hurricane-level time scales on the order of 5 to 14 days. In coordination with the SACS, tidal predictions during Hurricane Maria (2017) were assessed. Each time series was reconstructed over a 6 min interval. The primary measures of error and uncertainty in the reconstructed time series were the RMSE and the Pearson correlation coefficient, providing an estimate of the differences in amplitude and time lag (i.e., phase), respectively. These variables were computed for the total time series as well as for the daily maximum (high tide) and minimum (low tide) water level. The error metrics of the reconstructed tides over the various time scales (e.g., 365 days, 14 days, and 5 days) were compared with one another. The RMSE for each case was normalized by the total length of the time series (i.e., number of time stamps). The computational time required to process the 31 stations for the final number of constituents over each time scale was also assessed.

Last, a spatial interpolation method based on kriging was employed to supplement less trustworthy data from ADCIRC with data from NOAA. The goal is to interpolate NOAA data over the ADCIRC WNAT mesh in the PR/USVI region to provide more accurate constituent data at the save points used in the SACS. Kriging is a geostatistical interpolation technique that uses a limited set of observations or response variables to estimate the value of a variable over a continuous spatial area. These response variables (e.g., harmonic amplitude) defined at their corresponding geographic locations (i.e., NOAA stations) provide a set of support points for the method to interpolate. Far away from the support points, the interpolation method defaults to a constant underlying trend. In this case, the constant trend is defined as the weighed least squares value of the respective variable, with the weights defined through the covariance function of the interpolation. The fundamentals of

kriging as a geospatial interpolation method is found in Cressie (1993). Kriging calibration and validation follows the formulation discussed in Taflanidis et al. (2017).

RESULTS AND DISCUSSION: The outline of this section follows that of the Methodology section. First, the initial assessment of tides with an increasing number of constituents and the associated computational time of each iteration is discussed. Tidal time series were generated with UTide for all 31 stations in the study region over a year-long period (1 January 2018 – 31 December 2018) in this assessment. The RMSE of the UTide, UTide(N), and UTide(A) reconstruction scenarios compared to NOAA predictions was normalized by the tidal range of the NOAA prediction, referred to as NRMSE herein. The average NRMSE among the 31 stations for each iteration of increasing harmonic constituents is shown in Figure 2. Recall that the constituents included in this analysis were sorted by amplitude and were identified in order as the most prevalent constituents over the region.

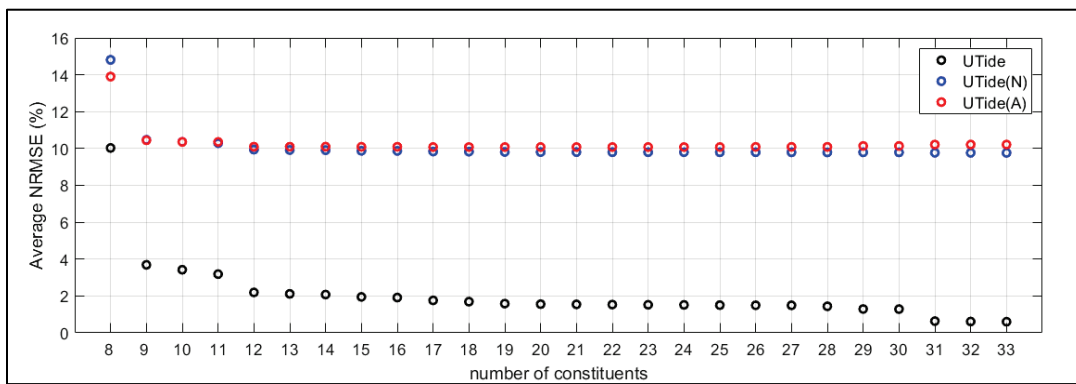


Figure 2. Trend of average normalized RMSE (NRMSE; %) of the reconstructed time series for UTide, UTide(N), and UTide(A) scenarios, shown as black, blue, and red circles, respectively, with an increasing number of harmonic constituents included in the reconstruction process.

There is a significant difference between UTide (black) and the UTide(N) and UTide(A) series, shown in blue and red, respectively (Figure 2). The average error in the UTide(N) series is on par with the error in the UTide(A) series, approximately 5 to 10 times higher than UTide for the same number of constituents. These discrepancies are primarily a result of differences between the amplitude and phase pairs from each data source, which is investigated in more detail later in this document. In general, the addition of a ninth constituent reduced the total error by 4% for UTide(N) and UTide(A), and up to 6% for UTide. With the addition of more constituents, the UTide(N) and UTide(A) scenarios held constant near an average 10% NRMSE. For UTide(A), these results are a testament to the inaccuracies of lesser supported tidal constituents in the ADCIRC database. For UTide, the average NRMSE improved incrementally with the addition of constituents, reducing to approximately 0.6% with 33 constituents included in the reconstruction process. Between 12 and 30 constituents, the error in UTide was near 2%, reflecting approximation errors within the UTide program itself.

The computational time needed to reconstruct the year-long time series at a single location for each iteration was also investigated. UTide was executed on a Dell Precision T3620 (16 GB ram, Intel® Xeon® processor E3-1270 v6 3.8 GHz) operating Windows 10 with Matlab 2019a. Recall that this completion time reflects the total time to reconstruct the group of stations, divided by the number of

stations in the group. The total time to reconstruct the group of stations was found to be between 93 sec and 124 sec for each iteration, which breaks down to 3 to 4 sec per station. Generally, it was expected that the computational time would linearly increase with an increasing number of constituents. However, this trend was not the case as the total time remained between 3 sec and 4 sec per station in each iteration. This initial analysis provided a baseline on which to test the computational efficiency of UTide. Considering the minimal changes in NRMSE beyond 12 constituents (Figure 2) and in computational time, it was decided to proceed with 12 constituents in the remaining analysis.

Initial Conditions. The top 12 most prevalent tidal constituents were identified as SA, SSA, Q1, O1, P1, S1, K1, N2, M2, T2, S2, and R2. A complete list of these constituents and their formal descriptions are provided in Table 1. Out of this list, seven of the eight most common constituents are included (Q1, O1, P1, K1, N2, M2, and S2). Of these seven, it was expected that the ADCIRC database would provide sufficient amplitude and phase data in comparison to NOAA sources. The eighth constituent (K2) was observed as the seventeenth constituent in the list of 33 constituents sampled.

Table 1. Top 12 most prevalent tidal harmonic constituents in PR/USVI with physical description from NOAA Harmonic Constituent webpage; mean bias error (MBE) among NOAA, ADCIRC, and UTide amplitude and phase pairs included.					
Top 12	Description of Constituent	MBE in amplitude (cm)		MBE in phase (deg)	
		NOAA – ADCIRC	NOAA – UTide	NOAA – ADCIRC	NOAA - UTide
SA	Solar annual	5.38	0.047	-108.8	-81.8
SSA	Solar Semiannual	1.05	-0.021	-134.2	-92.9
Q1	Larger lunar elliptic diurnal	-0.114	0.034	10.5	2.39
O1	Lunar diurnal	-0.314	0.007	4.84	0.058
P1	Solar diurnal	-0.381	-0.002	7.54	1.00
S1	Solar diurnal	0.619	-0.211	12.4	56.3
K1	Lunar diurnal	-0.559	-0.045	6.03	0.105
N2	Larger lunar elliptic semidiurnal	0.309	0.024	7.70	-19.5
M2	Principal lunar semidiurnal	1.22	-0.027	-35.7	-11.3
T2	Larger solar elliptic	0.274	0	-140.9	-37.7
S2	Principle solar semidiurnal	-0.045	0.012	4.6	-0.037
R2	Smaller solar elliptic	0.508	0.090	52.2	-17.3

Figure 3 provides a general comparison of ADCIRC (top) and UTide (bottom) to the NOAA constituent data in the PR/USVI region. The amplitude (left) and phase (right) data generally tended to overlap between NOAA and ADCIRC for the seven common constituents. There was increased uncertainty in the ADCIRC data set for the other five constituents in the list (SA, SSA, S1, T2, and R2), as these constituents are less commonly included in hydrodynamic modeling simulations. The amplitudes and phases of these five constituents were considered for replacement with NOAA data using the spatial interpolation method.

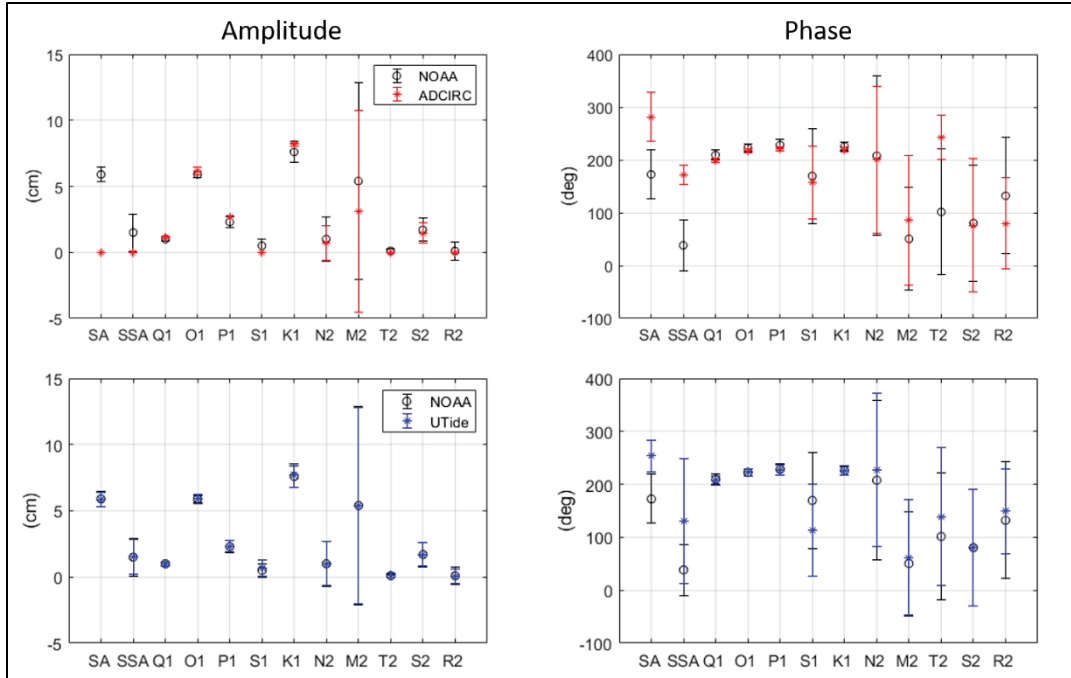


Figure 3. Comparison of median amplitude in centimeters (left) and mean phase in degrees (right) of top 12 harmonic constituents for the 31 stations within the PR/USVI region, as reported by (top) NOAA (black) and ADCIRC (red), and (bottom) NOAA and UTide (blue); the error bars represent the population standard deviation (IQR/1.34) for the amplitude, and one standard deviation from the mean for the phase.

The MBE between NOAA and ADCIRC, and NOAA and UTide data is shown in Table 1. The primary difference between NOAA and the UTide estimations is observed in the phase ranges of the SA, SSA, S1, and T2 constituents. The mean phase shift between NOAA and UTide for each of these constituents is between 70° and 90° , which can significantly affect the phasing of the tidal time series. For these same constituents, the ADCIRC database reported average phase shifts as low as 14° and as large as 140° in the same direction as the UTide estimates.

Considering the differences among the harmonic constituent sources from Figures 2 and 3, it is believed that UTide might provide a better estimate of the tidal time series for this period of record, as opposed to the published NOAA harmonic amplitude and phase pairs. The understanding is that the published harmonic data are founded on the present national tidal datum epoch (1983–2001) and as such may not reflect more recent sea level trends in the Caribbean. Since the reference time of the tides considered in this analysis is of a much shorter scale (≤ 365 days versus 19 years), the static published values may not accurately reflect the phase of long period harmonics (e.g., SA and SSA) over these time scales. The advantage of UTide is the flexibility to estimate harmonics over relevant time frames and durations. The NOAA tidal predictions remain the trusted and reliable source of still water levels (SWLs) for the country and are the standard by which UTide is compared. Moving forward in this document, the differences between UTide and NOAA tidal time series generated over hurricane-scale durations are investigated to determine the optimal dataset for this application.

Time Scales. The expected application of the RTR tool is to estimate the SWL over the lifespan of an approaching (real time) or historical tropical cyclone (TC). These time scales can range from ± 2 days from when a TC makes landfall to ± 5 or more days if considering the effects of enduring inundation due to rainfall. As such, the tides were reconstructed over these expected time scales. The UTide, UTide(N), and UTide(A) time series were reconstructed over the 14-day (16 September 2017 – 2 October 2017) and 5-day (18 September 2017 – 23 September 2017) periods relating to the SWL during Hurricane Maria (2017). The amplitude and phase pairs from the year-long UTide estimate were applied to the shorter time scales. Each series was compared to the NOAA tidal predictions over the same periods, and the total RMSE was computed. The average RMSE of each scenario was first normalized by the tidal range to compare across the stations and normalized again by the 5-day time series duration (i.e., length of 5-day time series in minutes) to compare across the varying time scales.

It was observed that the total error in the UTide(N) and UTide(A) reconstructed time series was 4.6 to 19 times higher than the total error in the UTide estimate, as compared to NOAA tidal predictions in each of the 365-, 14-, and 5-day scenarios. These results show that the static amplitude and phase pairs queried from both the NOAA webpages and the ADCIRC database do not provide the most accurate tidal reconstruction across varying time scales, especially over a TC lifespan. Even the best estimate from the UTide 365-day time series produced a more accurate result for the 14- and 5-day series. A sample 5-day time series is shown in Figure 4 comparing the three reconstructed time series to the NOAA predictions in San Juan and Mayaguez, Puerto Rico. Again, considering the differences in NRMSE in the reconstructed time series from this discussion and Figures 3 and 4, the UTide estimates of amplitude and phase pairs were used to supplement the ADCIRC data in the spatial interpolation method in the PR/USVI region, as opposed to using the NOAA amplitude and phase pairs.

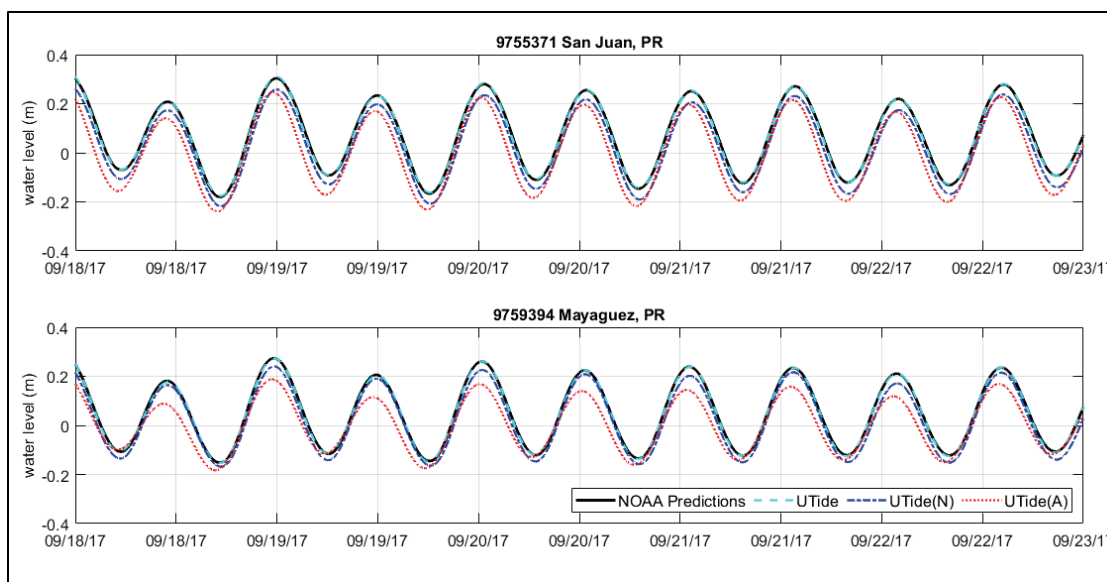


Figure 4. Reconstructed 5-day time series for the UTide best estimate (dashed cyan), UTide(N) (dot-dashed blue), and UTide(A) (dotted red) compared to NOAA tide predictions (solid black) in San Juan (top) and Mayaguez (bottom), Puerto Rico.

In addition, the computational times needed to reconstruct the 14-day and 5-day series were computed and compared with the 365-day series. The program completion time reflects the total time required to reconstruct the tides for the group of stations, divided by the number of stations in the group. The computational expense over the 365-day record (3-4 sec) is significantly reduced to a fraction of second per station to reconstruct a 5- to 14-day time series (0–0.1 sec and 0.1–0.2 sec, respectively). This speed is essential for the application of the RTR tool over several thousand save points in the SACS and CHS domains.

Spatial Interpolation. The average NRMSE of the reconstructed time series using the UTide best estimate was 2.1%, versus using NOAA (9.9%) and ADCIRC (10.1%) data (Figure 2). The original goal was to interpolate NOAA data over the ADCIRC WNAT mesh in the PR/USVI region to provide more accurate constituent data at the save points used in the SACS. Given the results in this analysis, the amplitude and phase pairs from the UTide best estimate were used as the response variables in the spatial interpolation method instead. The five less common constituents (SA, SSA, S1, T2, and R2) were considered for replacement. At the support point locations, the interpolated values were defined as the response variables themselves. Therefore, in this analysis, the error response in the reconstructed time series reflects the direct replacement of ADCIRC data with UTide estimates at the station locations.

The spatially interpolated constituent amplitude and phase pairs replaced the ADCIRC values in the UTide(A) reconstruction in an iterative process. The first constituent to be replaced was SA, followed by SSA, S1, T2, and R2. In each iteration, the previously replaced constituents remained in the reconstruction as another constituent was replaced, producing a compounding effect until all five constituents were replaced. The average NRMSE across the stations were computed upon each iteration. With no constituents replaced in the UTide(A) reconstructed time series, the NRMSE was 10%, 22%, and 27% for the 365-, 14-, and 5-day scenarios, respectively. The overall reduction in error in the UTide(A) time series with the replacement of the five constituents was 5.7%, 8.3%, and 10.1% for the 365-, 14-, and 5-day scenarios, respectively. These results are 1.7 to 2.7 times lower than the original average NRMSE with no amplitude and phase pairs replaced from the ADCIRC database. The resulting heat maps of the spatially interpolated amplitude and phase for each of the five constituents can be found in the Appendix (Figures A-1, A-2, and A-3).

IMPLEMENTATION: Accurately predicting the astronomical tides over a very short period of time (e.g., 5 days) is challenging for most applications since a full tidal cycle is not realized. The trend of average NRMSE is shown to decrease with an increase in the length of time considered in the reconstruction. This effect is due in part to the importance of the annual and semi-annual constituents (SA and SSA) in the tidal signal. Therefore, considering a longer tidal record may be beneficial in terms of accuracy for CHS and CHRPS applications. The primary drawback is the computational time required to reconstruct tides over a longer time period for thousands of stations or save points (e.g., >5 hr over 700K+ tide nodes for a 30-day time series).

In a real-time application, such as the CHRPS, reconstructing a longer period for thousands of stations is not feasible, as the computational expense would not produce results in a timely manner. However, a longer record of tides can be precomputed for all tide nodes in a region and stored in the pre-established database structure. The tides can be queried at the specific location of interest selected by the user, and by the specified period of record of a selected TC event. This method can be utilized by both the CHRPS and CHS/SACS applications.

For the SACS, tidal time series are reconstructed over a 5 yr period (1 January 2015 – 31 December 2020) at each of the save points in the PR/USVI region (Figure 5). This record encompasses all historical tropical and extra tropical cyclones that were simulated in the hydrodynamic and wave modeling portion of the study. Random sampling of tides from this 5 yr record is also applied to synthetic storm events as appropriate. The reconstructed tidal time series are a product of the amplitude and phase pairs from the ADCIRC tidal database for the seven common constituents (M2, N2, S2, O1, K1, P1, and Q1) and the spatially interpolated pairs from the UTide estimate for the five less common constituents (SA, SSA, S1, T2, and R2).

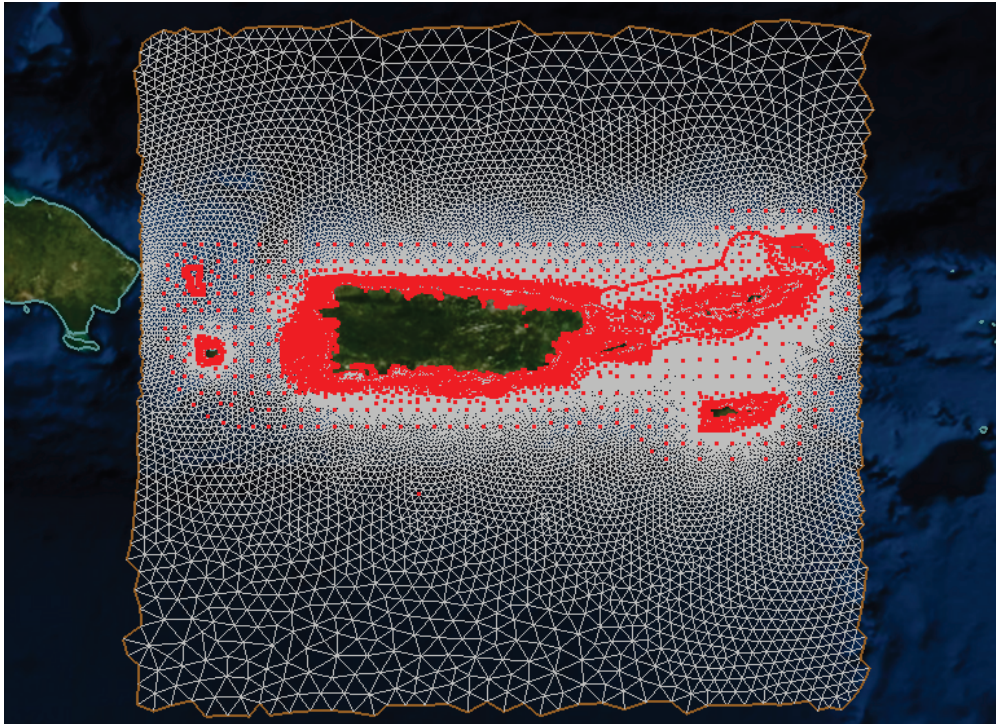


Figure 5. Visualization of the extent of coverage and spatial resolution of a sub-grid extracted from the ADCIRC WNAT mesh in the PR/USVI region (white), with the coverage and density of SACS PR/USVI save points shown in red.

Further, the reconstructed tides will contribute to the PCHA framework. The SWL will be added to the probabilistic storm surge time series through linear superposition. Various inundation levels will be determined by randomly selecting sections of the 5 yr record to simulate random phasing of the tides. These results will contribute to the final hazard curves for the region.

SUMMARY AND FUTURE DEVELOPMENT: The purpose of this document was to evaluate and quantify the accuracy of the ADCIRC tidal database and the UTide tidal reconstruction program compared to NOAA tidal predictions in coastal PR/USVI. Three sets of tidal time series were reconstructed over three periods, and the average RMSE was assessed across 31 NOAA CO-OPS tidal prediction harmonic stations in the region.

There were three primary conclusions from this study. First, the computational time of the UTide program is dictated by the length of the time series to be reconstructed and the total number of computation stations. The computational time per station was 4 sec for a 365-day record and a

fraction of a second (0.1–0.2 sec) for the 14- and 5-day records. Second, it was determined that 12 constituents were sufficient in producing accurate tidal time series with minimal error (2%) (nearly the same error as using all 30 constituents) and less complexity. Third, and most notably, was that the UTide estimate of the harmonic amplitude and phase pairs produced a more accurate time series when compared to the NOAA tidal predictions than when reconstructed with published NOAA values from the harmonic constituent station webpages. This difference is believed to be a result of the published values by NOAA being based on the present national tidal data epoch (1983–2001) whereas the UTide estimates more closely represented the shorter records (i.e., 365-, 14-, and 5-days) considered in this analysis.

The results of this work culminate to a better understanding of regional tide characteristics in PR/USVI. Advances in accurate reconstruction and projection of astronomical tides is vital for reducing uncertainty in coastal hazard analysis, especially for coastal communities vulnerable to severe environmental and economic damage from landfalling tropical cyclones. Local and regional emergency management officials can leverage the probabilistic hazards analysis provided in the CHRPS web tool for decision-making under uncertainty in real time.

ADDITIONAL INFORMATION: The work reported in this CHETN was conducted as part of the “StormSim: Metamodeling of Coastal Storm Hazards for Probabilistic Applications” effort funded by USACE Flood and Coastal Systems R&D Program. This work was undertaken in response to the following Flood and Coastal Risk Management Statements of Need: 2017-F-17 Stochastic Coastal Forcing Data Used for Coastal Structure Design, 2017-F-33 Uncertainty in Design Flood Estimates, 2017-F-34 Model Uncertainty, 2017-F-43 Future Conditions, and 2014-F-29 Frequency Estimates for Extreme Flood Events. This CHETN was prepared as part of the USACE Flood & Coastal Systems program by Marissa J. Torres, US Army Engineer Research and Development Center (ERDC), Cold Regions Research and Engineering Laboratory, and Dr. Norberto C. Nadal-Caraballo, ERDC, Coastal and Hydraulics Laboratory, with support from Alexandros A. Taflanidis, College of Engineering at the University of Notre Dame. Questions pertaining to this CHETN may be directed to Ms. Torres (Marissa.J.Torres@erdc.dren.mil) or to Dr. Norberto C. Nadal-Caraballo (Norberto.C.Nadal-Caraballo@erdc.dren.mil).

This ERDC/CHL CHETN-I-101 should be cited as follows:

Torres, M. J., N. C. Nadal-Caraballo, and A. A. Taflanidis. 2021. *Rapid Tidal Reconstruction for the Coastal Hazards System and StormSim Part II: Puerto Rico and US Virgin Islands*. ERDC/CHL CHETN-I-101. Vicksburg, MS: US Army Engineer Research and Development Center.
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APPENDIX

Table A-1. List of NOAA tidal gages within PR/USVI region.				
Station #	Lat (deg)	Lon (deg)	Station ID	Station Name
1	17.9514	-67.1966	9759197	Bahia Salinas, PR
2	17.9701	-67.0464	9759110	Magueyes Island, PR
3	17.9725	-66.7618	9758053	Peñuelas (Punta Guayanilla), PR
4	17.9550	-66.4067	9756639	Santa Isabel, PR
5	17.9283	-66.1583	9755679	Las Mareas, PR
6	18.0551	-65.8330	9754228	Yabucoa Harbor, PR
7	18.1871	-65.7114	9753641	Naguabo, PR
8	18.0939	-65.4714	9752695	Esperanza, Vieques Island, PR
9	18.1525	-65.4438	9752619	Isabel Segunda, Vieques Island, PR
10	18.3009	-65.3025	9752235	Culebra, PR
11	18.3352	-65.6311	9753216	Fajardo, PR
12	18.3450	-65.5695	9752962	Isla Palominos, PR
13	18.4592	-66.1164	9755371	San Juan, PR
14	18.4805	-66.7024	9757809	Arecibo, PR
15	18.4566	-67.1646	9759412	Aguadilla, PR
16	18.2189	-67.1625	9759394	Mayagüez, PR
17	18.1650	-67.1817	9759421	Punta Guanajibo, Mayagüez, PR
18	18.0748	-67.1888	9759189	Puerto Real, PR
19	18.0844	-67.9342	9759938	Mona Island, PR
20	17.7477	-64.6984	9751364	Christiansted Harbor, St. Croix, USVI
21	17.6947	-64.7538	9751401	Lime Tree Bay, St. Croix Island, USVI
22	17.7133	-64.8833	9751584	Fredericksted, St. Croix, USVI
23	18.3633	-65.0350	9751774	Botany Bay, St. Thomas Island, USVI
24	18.3712	-64.9635	9751768	Dorothea Bay, St. Thomas Island, USVI
25	18.3489	-64.8642	9751583	Water Bay, St. Thomas Island, USVI
26	18.3358	-64.9200	9751639	Charlotte Amalie, St. Thomas Island, USVI
27	18.2971	-64.8178	9751494	Dog Island, St. Thomas Island, USVI
28	18.3607	-64.8035	9751467	Lovango Cay, St. Johns Island, USVI
29	18.3676	-64.7207	9751309	Leinster Point, Leinster Bay, St. Johns Island, USVI
30	18.3482	-64.7167	9751373	Coral Harbor, St. Johns Island, USVI
31	18.3182	-64.7242	9751381	Lameshur Bay, St. Johns Island, USVI

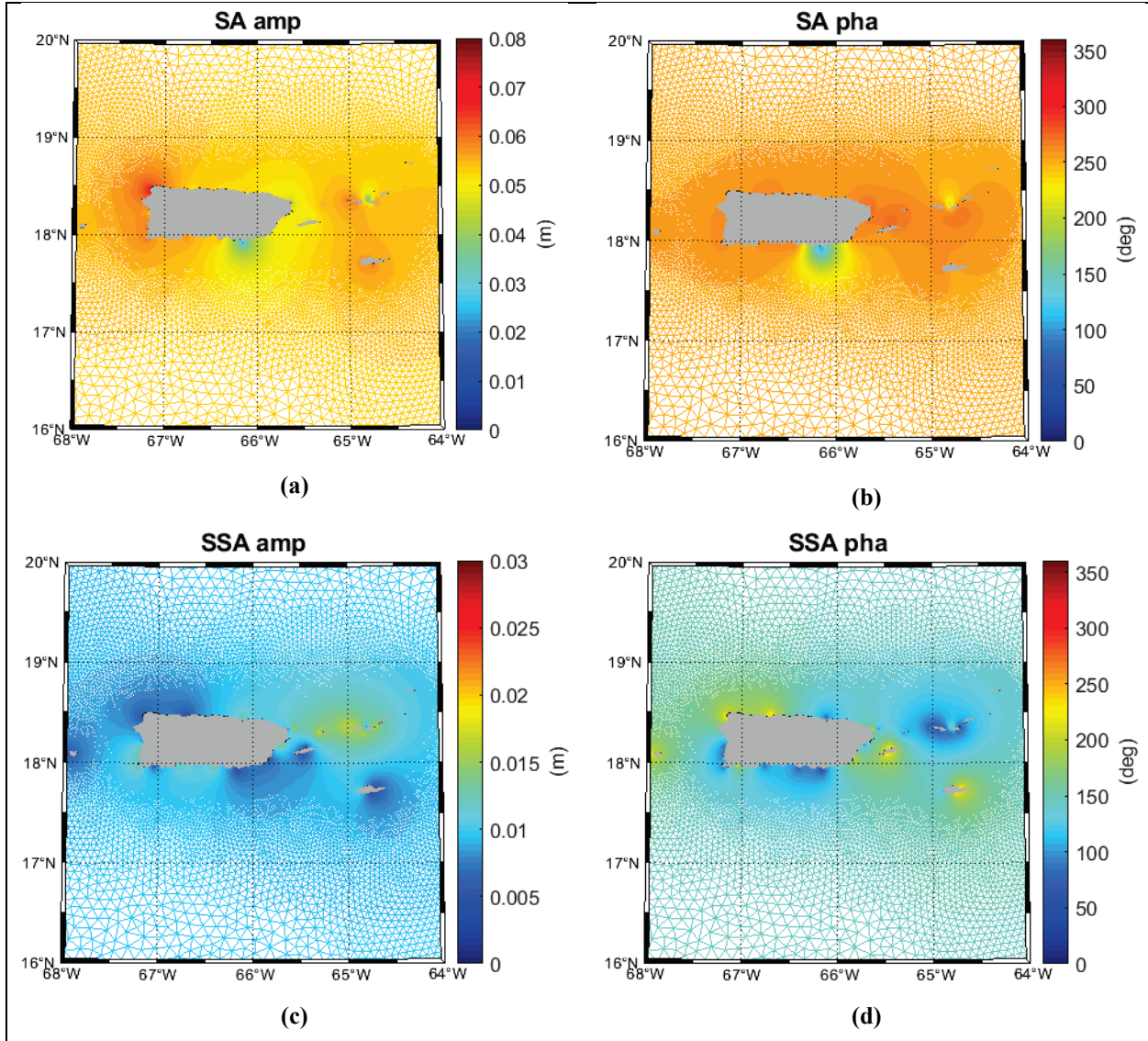


Figure A-1. Spatially interpolated values for SA and SSA amplitude (a, c) and phase (b, d) over the PR/USVI region of the ADCIRC WNAT mesh.

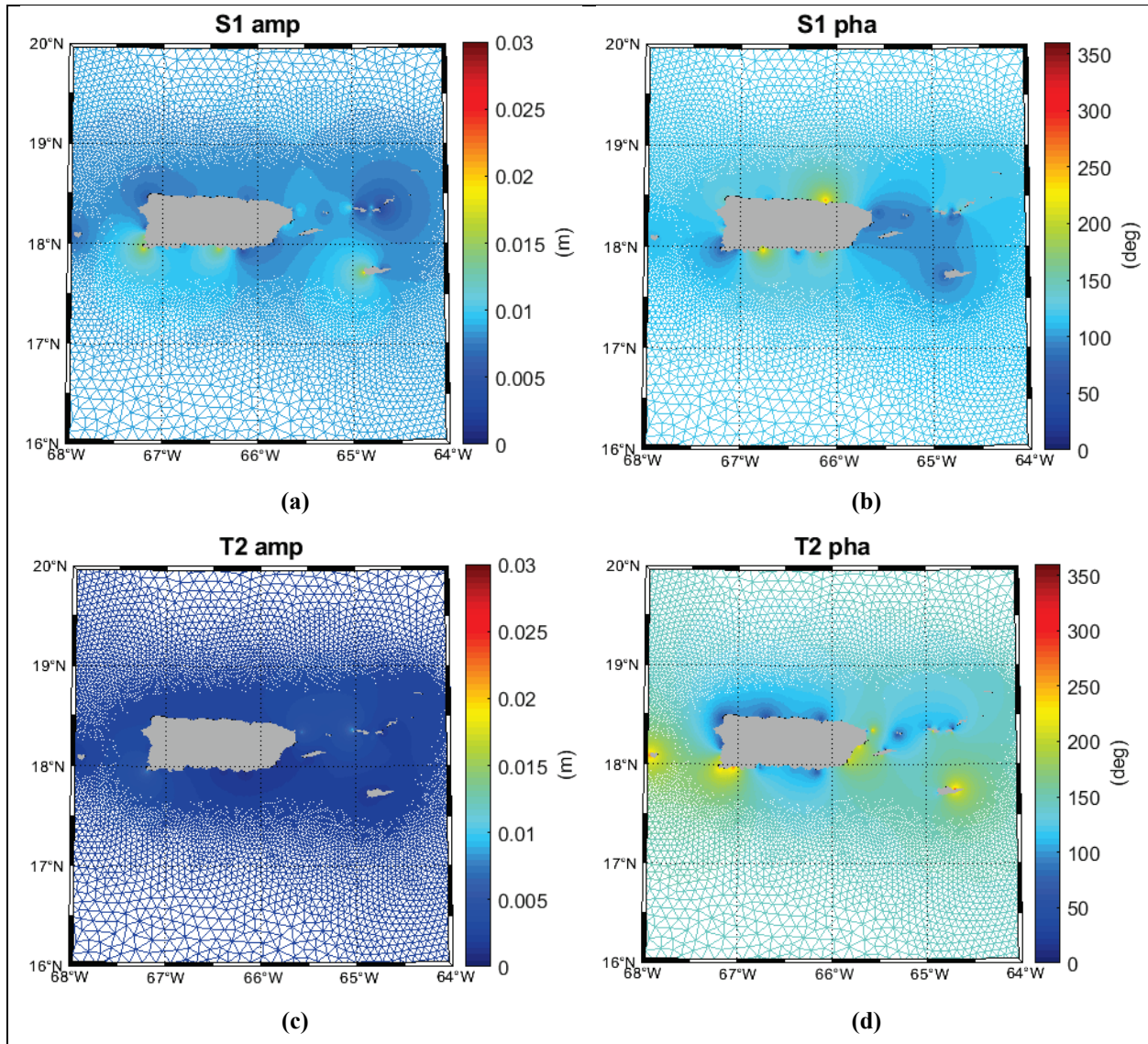


Figure A-2. Spatially interpolated values for S1 and T2 amplitude (a, c) and phase (b, d) over the PR/USVI region of the ADCIRC WNAT mesh.

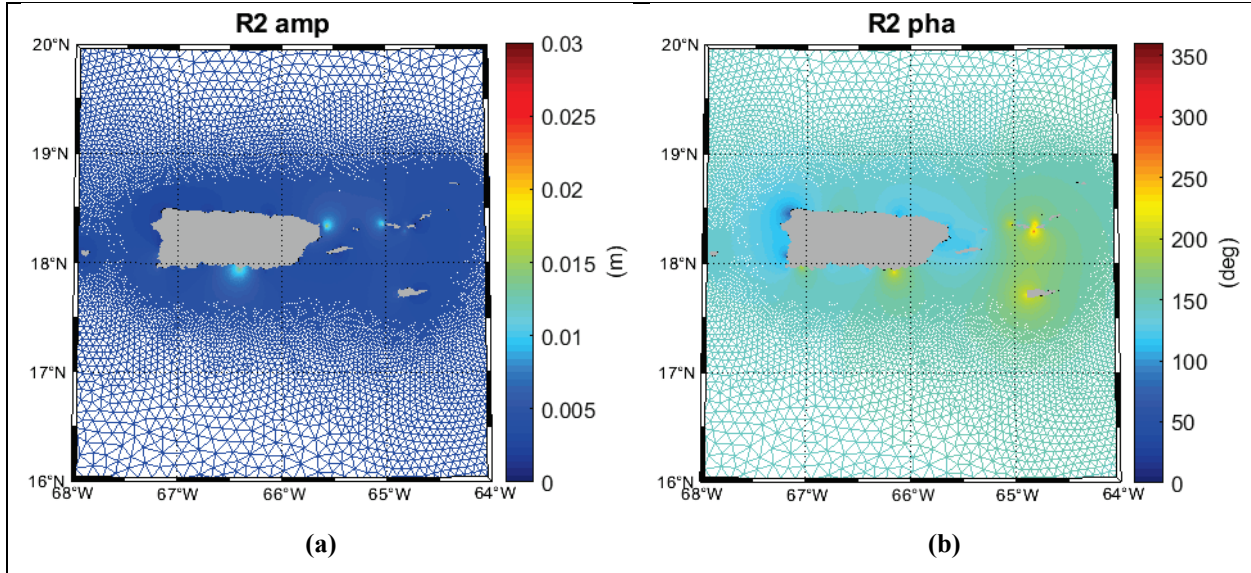


Figure A-3. Spatially interpolated values for R2 amplitude (a) and phase (b) over the PR/USVI region of the ADCIRC WNAT mesh.

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