Combined Atmospheric-Storm Surge Modeling of Hurricane Florence (2018)

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Abstract

Hurricane Florence (2018) was a powerful and long-lived hurricane that caused extensive damage in the Carolinas in September 2018, primarily as a result of both freshwater and saltwater flooding. Freshwater flooding resulted from extreme rainfall that totaled 25 - 30 inches over a broad portion of eastern North Carolina while storm surge caused inundation heights estimated to be 8 to 11 ft above ground level in some areas. This project focuses on the atmospheric modeling of Hurricane Florence (2018) with special attention on the wind, pressure and precipitation. These atmospheric variables are critical input to hydrodynamic/hydrologic models that seek to predict the time, location, and intensity of flooding from both freshwater and saltwater sources. For the atmospheric modeling, we adopt the Weather Research Forecasting (WRF) model, initialized by the reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), the ERA-Interim and ERA5. The binary data is preprocessed by WRF Preprocessing System (WPS) before the WRF, and the WRF output data is postprocessed by ARWpost. The simulation results are compared with the observation data from the National Oceanic and Atmospheric Administration (NOAA) and Coastal Resilience Center (CRC). The visualization tools include Grid Analysis and Display System (GrADS), NCAR Command Language (NCL), and Microsoft Excel. Our team has completed more than 60 WRF simulations with various settings and schemes. The WRF results are analyzed, visualized, and compared with the observation data for the track, wind velocity, and atmospheric pressure. Our study reveals that the WRF tracks are sensitive to the domain size with slight improvement from the frequent SST updating and high pressure-top. The detailed effect of the micro-physics schemes and starting times are also explored. There is a significant improvement of the EAR5 data over the ERA-Interim. Overall, the WRF simulation results match reasonably well with the observation data after two days simulation, the maximum wind and minimum sea level pressure move close to the observation data, although some error persists. For stations away from the track, the wind data from WRF match well with the observation data for the speed and direction. For stations near the track, there is a noticeable discrepancy between the WRF results and the observation around the landfall time on 9/14. A simple ensemble (averaging) of the WRF results improves the accuracy of the track, but not yield much improvement in the wind and pressure. The findings of this study reflect the characteristics of dynamics in the atmospheric model for the hurricane. The improved prediction of the track and intensity can be used to improve the time, location, and intensity of the associated storm surge prediction.

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1. Introduction

Florence originated from a convectively active tropical wave that moved off the west coast of Africa on August 30, 2018. The wave steadily organized and strengthened into a tropical depression on the next day [1]. Progressing along a steady west-northwest trajectory, the system gradually strengthened, acquiring tropical storm strength on September 1. Despite encountering environmental conditions that are typically not considered conducive for significant strengthening, Florence unexpectedly underwent a rapid intensification on September 4–5, becoming a Category 4 major hurricane, with estimated maximum sustained winds of 130 mph [2]. Within 12 h after becoming a category 4 hurricane, Florence underwent a period of rapid weakening (RW) due to strong southwesterly vertical wind shear of near 29 mph, and became a tropical storm by September 7. Shifting steering currents led to a westward turn into a more suitable environment; as a result, Florence re-intensified to hurricane strength on September 9 and major hurricane status by the following day. Florence reached peak intensity on September 11, with 1-minute winds of 150 mph and a minimum central pressure of 937 mb. An unexpected eyewall replacement cycle and decreasing oceanic heat content caused a steady weakening trend; however, the storm grew in size at the same time. Around 1115 UTC September 14, Florence made landfall in the United States just south of Wrightsville Beach, North Carolina as a Category 1 hurricane, and weakened further as it slowly moved inland under the influence of weak steering currents. Florence degenerated into a post-tropical cyclone over West Virginia on September 17 and was absorbed by another frontal storm two days later.

Hurricane Florence brought a strong storm surge to NC as it approached landfall at the coast. From the report [2], the maximum storm surge inundation heights produced by Florence were estimated to be 8 to 11 ft above ground level in North Carolina along the shores of the Neuse River and its tributaries, where they emptied into Pamlico Sound. Elsewhere on the western side of Pamlico Sound, storm surge inundation levels of 5 to 7 ft occurred in parts of Pamlico, Beaufort, and Hyde Counties along the Pamlico and Pungo Rivers. On the Atlantic Ocean coastline, maximum storm surge inundation levels were estimated to be 5 to 8 ft above ground level along the North Carolina coast at Onslow Bay in parts of Carteret, Onslow, Pender, and northern New Hanover Counties.

Hurricane Florence (2018) caused extensive damage in the Carolinas, primarily as a result of both freshwater and saltwater flooding. Many places received record-breaking rainfall, with more than 30 inches (760 mm) measured in some locations. A total of 54 deaths were attributed to the storm. Property damage and economic losses in the United States reached $24.23 billion (2018 USD), with $24 billion in damages in the Carolinas alone [1].

2. Description of the Research Project

2.1 Research Problem

Predicting storm surge associated with tropical cyclones depends critically on predictions of the atmospheric pressure and wind velocity. In this project we focused on recreating the most accurate possible representation of Hurricane Florence for use in storm surge prediction. We did this by utilizing the Advanced Weather Research and Forecasting (WRF) model [3] with the objective of using WRF model output as input for the ADvanced CIRCulation (ADCIRC) storm surge prediction system [4]. It is hoped that the combined modeling prediction (in fact, hindcast) will reflect characteristics of dynamics within two different modeling systems and increase the ability of predicting the track and intensity of a landfall hurricane and the time, location, and its role in creating the associated storm surge.

2.2 Objectives

In the original proposal, I put down some quite ambitious objectives. While doing the project this summer, we decided to move some of those objectives to future study. The following is a list of our modified and realistic objectives:

- All of us learn WRF modeling for hurricanes. With some prior experience with WRF, Jackson and I still needed to learn WRF modeling for real hurricanes. Tiana had zero experience in any of these (Unix, WRF, atmosphere science).
- Study the various settings and schemes in the WRF package for the impact on the hurricane track and intensity.
- Hindcast for the atmospheric variables including the wind, atmospheric pressure and precipitation for Hurricane Florence by WRF modeling. Compare the WRF results with the observation data for the track, the maximum wind speed, the minimum atmospheric pressure at sea level, and the wind velocity for specific locations along the coast.
- Improve the WRF simulation results by various techniques.

2.3 Methodology

The WRF model is adopted for the prediction of hurricane track, intensity and other atmospheric variables. WRF is a state-of-the-art atmospheric modeling system designed for both meteorological research and numerical weather prediction (NWP) [5]. It offers a host of options for atmospheric processes and can run on a variety of computing platforms. WRF excels in a broad range of applications across scales ranging from tens of meters to thousands of kilometers, including meteorological studies, real-time NWP, idealized simulations, data assimilation, earth system model coupling, and model training and educational support.

Since the data we are dealing with is massive and usually is in a special binary format, we need to employ some special tools/techniques to process and visualize the data. Before the WRF simulation, the initial data downloaded from the website is processed by WPS (WRF Preprocessing System) [6] onto the grid points. After the WRF simulation, the results can be visualized using NCL (NCAR Command Language) [7,8], or postprocessed by ARWpost so to display in GrADS (Grid Analysis and Display System) [9,10]. The WRF output can also be written into ASCII files for some specific variables using NCL. The ASCII data can then be analyzed in Excel/Matlab or any other tools.

2.4 Data Collection

The initial data for the WRF model include the pressure level and surface analysis data. In this project, we use two data sets: the ERA-Interim [11] and ERA5 [12]. Both are from the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis. The spatial resolution of the ERA-Interim data set is approximately 80 km on 60 levels in the vertical from the surface up to 0.1 hPa. There are several quality issues with ERA-Interim data. It has been superseded by the ERA5 reanalysis. ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables. The data cover the Earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km. ERA5 includes information about uncertainties for all variables at reduced spatial and temporal resolutions.

The WRF simulated results are compared with the observation data. For the storm center locations, the maximum wind and minimum sea level pressure (SLP), we use the best track data from HURDAT2 [13,14]. The observation data for the wind speed and direction from 61 stations along the coast of NC is provided by Dr. Rick Luettich from CRC.

2.5 Results and Discussion

With various settings in WRF, Tiana completed 27 cases and Jackson 36 cases. The settings include the domain, map projection, SST updating, pressure top, micro-physics scheme and starting time. All Tiana's cases are with ERA-Interim data, while Jackson has 20 cases with ERA-Interim and 16 cases with ERA5.

2.5.1 Parameters and schemes sensitivities

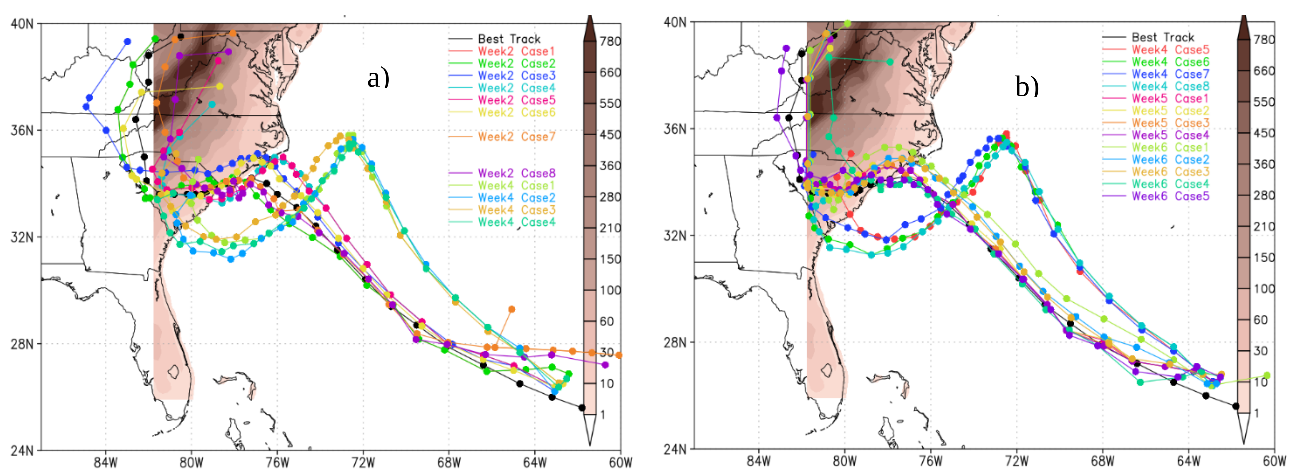

Fig. 1 Comparison of tracks from WRF simulations and the best track from NHC. The Week 4 cases are with large domain

Different settings in WRF lead to different simulation results. For this particular hurricane, the WRF results appear to be sensitive to the domain choice. It is consistent from Tiana's and Jackson's cases that with the large domain (e.g. 11.3N-41.6N, 91.4W-36.2W) when the storm approaches the coast, it swings to north then turns to south-west moving along the coast and makes landfall far south of the real landfall location. This can be seen in Fig. 1 where the Week 4 cases utilize the large domain. When the southern boundary of the domain is moved north, the track moves south coming closer to the best track. Also, when the western boundary of the domain is moved east, the track moves along the coast moving farther from the best track. The best cases (closest match with the best track) from Tiana and Jackson are with the small domain (26.5N-42.6N, 85.6W-53.7W).

The map projection (Lambert conformal and Mercator) does not affect the results much. In general, both the SST updating and high pressure-top improve the results, but not significantly. The performance of different micro-physics schemes varies slightly. These differences and improvements are mainly near the coast and the landfall locations. Over the sea away from the coast, the WRF results match well with the best track (except those from the large domain). The starting time affects the track. However, there is not much room to wiggle around: the starting time cannot be later than 9/11_00Z since we need to have reliable data for 9/13—9/16 when the storm impacted land; the starting time cannot be too early either as it requires a large domain to include the storm.

2.5.2 ERA data analysis

It is interesting to check out the track, the wind and SLP values directly from the ERA-Interim and ERA5 data. A simple analysis is conducted on these GRIB data by comparing the track, the maximum wind and minimum SLP with the corresponding best track data, shown in Fig. 2. From Fig. 2a) for the track comparison, both tracks match well with the best track. Figure 2b) shows the big discrepancy from the ERA-Interim data whereas the ERA5 matches reasonably well with the best track data for the maximum wind after 9/12_12Z. From Fig. 2c) for the minimum SLP, the ERA-Interim remains 995 mb all the time, while the ERA5 drops down to 970 mb.

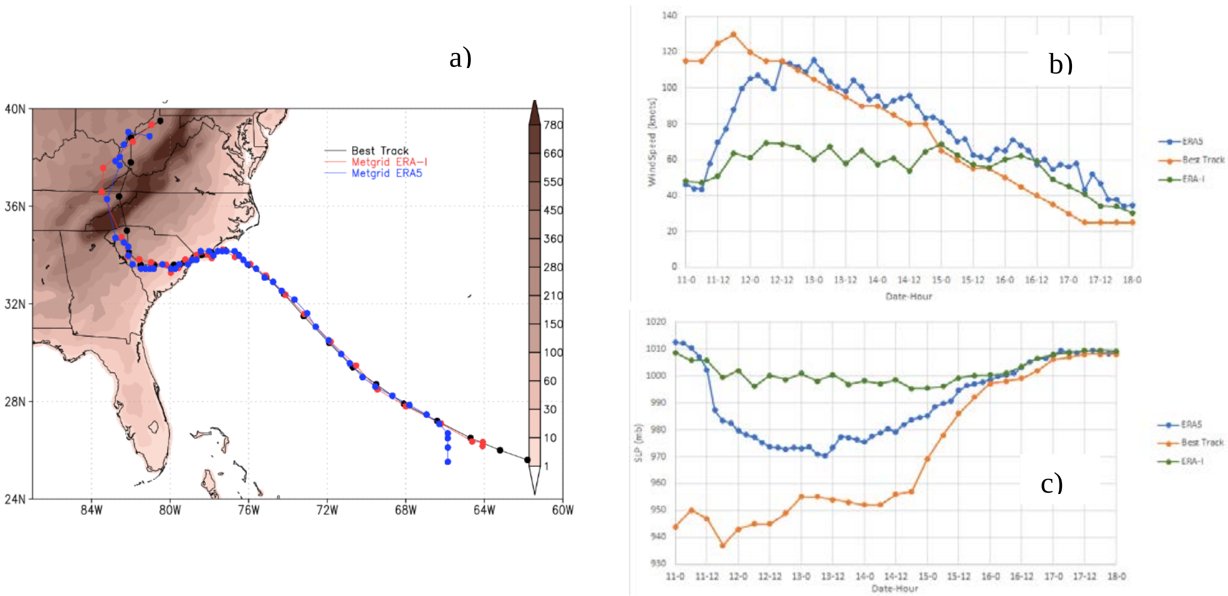

Fig. 2 Comparison of the ERA data with the best track data for: a) track; b) maximum wind; c) minimum SLP.

2.5.3 Comparison for the max wind and min SLP

Some details may vary case by case for the maximum wind and minimum SLP values. In general, most cases in the small domain with ERA-Interim data show similar profile as in Fig. 3. For the maximum wind in Fig. 3a), the WRF maximum wind starts with a low value, increases and passes over the best track value at 9/13_00Z, 18 hours later the WRF value starts to decrease following the trend of best track but remains higher than the best track value. For the minimum SLP in Fig. 3b), the WRF SLP starts with a high value, decreases yet remains above the best track value until 9/15_12Z, after which the pressure returns back to normal when the storm dissipates. The WRF results from ERA5 present a better agreement with the best track data than that from ERA-Interim, with the lowest SLP as 965mb.

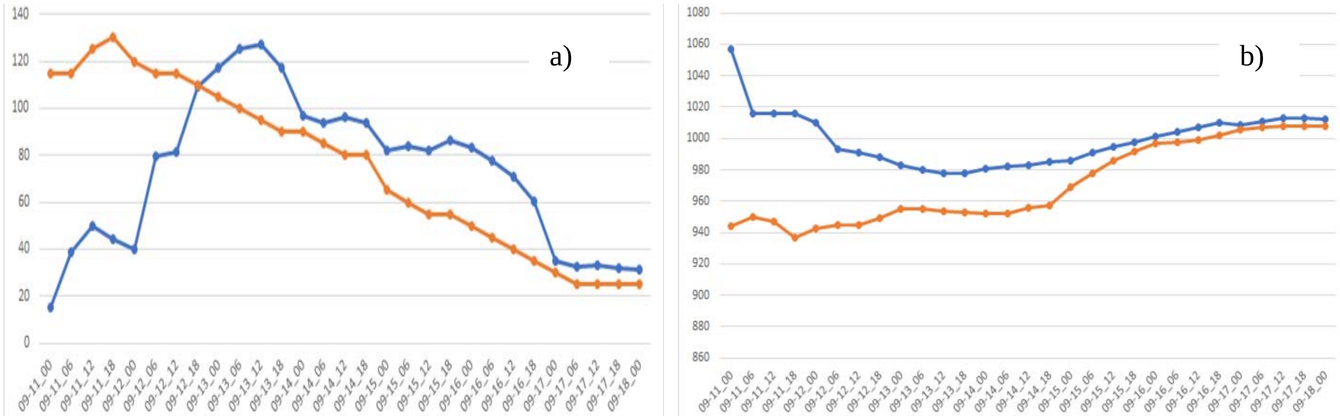

Fig. 3 The maximum wind and minimum SLP from Week 6 Case 7 in comparison with best track data, a) maximum wind; b) minimum SLP

2.5.4 Comparison with stations data

Out of the 61 stations, we choose 7 around the landfall location to study with the wind data. The wind direction from WRF matches well with the stations' data in general with very few exceptions. The wind speed from WRF matches well with the stations' data except for some stations for the day 9/14. The Fort Macon and Cape Lookout stations are away from the best track and the WRF tracks. Therefore, the WRF results match well with these stations' data (Fig. 4a)). The North Myrtle Beach and Sunset Beach Buoy are not too close to the landfalling location, but there are close to the Best Track. Since they are along the coast, they both experience strong wind when the storm passing over the coast. The WRF results match well for these stations except for a very short time when the actual storm passes by closely while the WRF storm passes by not so closely (Fig. 4b)). The other three stations (Wilmington, Wilmington Buoy, and Wrightsville Buoy) are close to the landfall location. In particular, the best track storm passes through Wrightsville Buoy directly. None of the WRF simulated storm passes through Wrightsville Buoy directly. If the station is on or very close to the track of the WRF storm, the wind speed tends to drop down for quite some hours, thus the big dip, which is reasonable as we imagine it takes a while for the storm comes and goes. It is somewhat puzzling to me that we do not see the big dip in the station data (Fig. 4c)) even for the Wrightsville Buoy staying on the track of the storm. From the map, it takes about 8 or 10 hours for the storm to come by and leave.

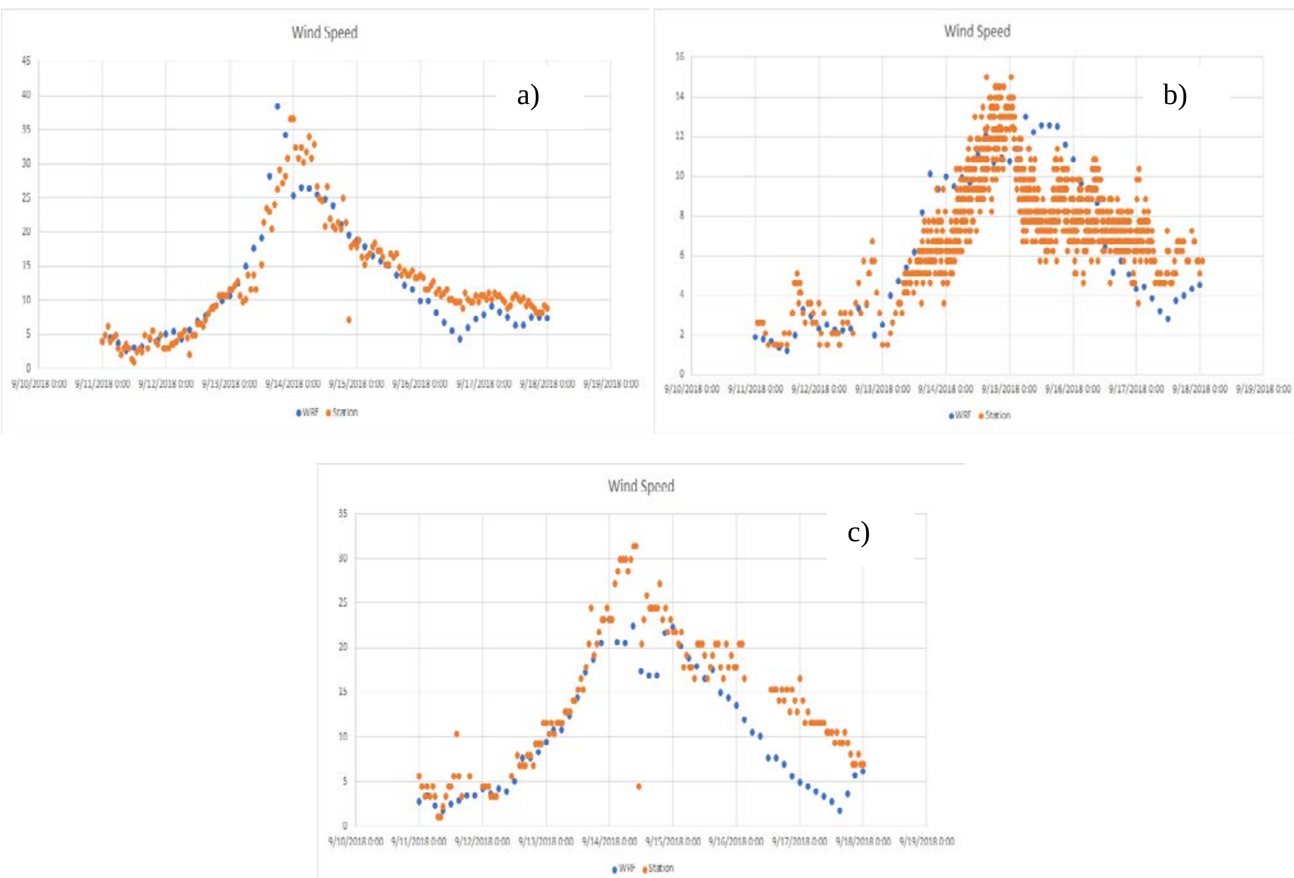

Fig. 4 The wind speed from WRF Week 6 Case 7, in comparison with the stations data, a) Cape Lookout; b) North Myrtle Beach; c) Wrightsville Beach Buoy.

2.5.5 A simple ensemble technique

None of the single WRF track matches perfectly with the best track, and the individual WRF tracks wobble, especially around the landfall location. A combination of the individual cases may arrive a better representation of the event. To start, Tiana did a simple ensemble, i.e. averaging the cases. From Fig. 1, the large domain cases deviate substantially from the best track along their entire track and therefore these Week 4 cases are excluded from the ensemble. An averaging over the other WRF cases gives us a nice clean track follow the best track steadily all the time, the blue track in Fig. 5.

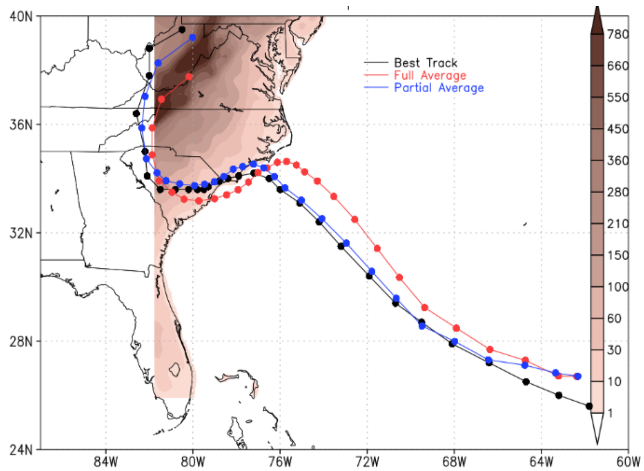

Fig. 5 Ensemble of the track for Tiana's cases.

3. Contribution to the Research Project

As a faculty mentor of the team, I designed the project, organized the team, advised students with specific steps, helped iron out technical details, and communicated with our mentor Dr. Luettich at CRC. We met on zoom every weekday with 2 hours in the morning and 2 hours in the afternoon. Every Friday we wrapped up the work and presented to Dr. Luettich. I then wrote the weekly progress report summarizing the work from the week and planning the work for the next week.

4. New Skills and Knowledge Gained

With some prior experience with WRF modeling, I gained some deeper understanding in WRF modeling for real hurricanes, including setting up the WRF on the computer, downloading the initial data from the website, and setting up the domain using Domain Wizard. Certainly, we all gained much understanding in modeling Hurricane Florence, especially on the track, the wind field and pressure. I have used GrADS before but not NCL. This time I learned NCL for plotting and writing out data for analysis. I had a better understanding on the data format when I did the analysis directly on the GRIB (GRIdded Binary) data. I gained some further understanding of the ADCIRC model and the storm surge phenomenon.

5. Impact on My Academic Planning

This project will help me to integrate research and education by advancing discovery and understanding while at the same time promoting teaching, training, and learning. Graduate student Tiana Johnson will continue working with me to extend the summer project for her graduate project. Student Jackson Wiles will continue at A&T in graduate study co-advised by me and Dr. Yuh-Lang Lin (Professor in Meteorology). As an applied mathematician, I always add my research training and findings into the course teaching and project advising. Some examples include a word problem of calculating the storm speed from the track locations in Pre Calculus, working with the wind vectors for a specific hurricane in Calculus, explaining/showing the basic conservation equations in Differential Equations, and the last but not least the various project topics related with hurricanes for our math major capstone course. Throughout the term, I normally advise a few REU (Research Experience for

Undergrads) students. The meteorology data either from the website or from the WRF simulation is perfect for students interested in data science which is currently a popular topic.

6. Relevance to the Mission of DHS

The predicted data, such as time, location, wind, pressure of hurricane (meteorological factors), and the resulting storm surge and inundation (oceanographic factors), for a landfalling hurricanes are essential to emergency management, such as evacuation of people at and near the impacted area [15]. Thus, it is crucial to continue making improvement of storm surge prediction associated with landfalling hurricanes, especially combined with hurricane prediction. The goal of this research is to improve the storm surge prediction by adopting an optimal combined WRF and ADCIRC modeling. New findings of the project will improve the representations or parameterizations of the atmospheric environmental conditions, which will improve storm weather prediction and lead to increased public safety, reduced loss of property and life, especially for people along the east coast.

7. Acknowledgements

We greatly appreciate the support from Office of University Programs at DHS S&T for this summer research team program. I would like to acknowledge Dr. Rick Luettich, our advisor from the Coastal Resilience Center and Director of University of North Carolina's Institute of Marine Science, for his tremendous help and guidance on this summer project. Dr. Luettich's advising led our team to a much better understanding of the science of hurricanes as well as the techniques for storm surge predictions. Much appreciation also goes to Dr. Yuh-Lang Lin at A&T who helped much with the meteorological understanding on the hurricane and WRF modeling.

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