CariCOOS: Improving High-Resolution Numerical Weather Prediction for the Northeast Caribbean Region

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Abstract— **The northeast Caribbean as other insular regions lack reliable high-resolution weather forecast data of 10-meter winds to serve as the engine of numerical ocean models targeting high resolution waves and currents forecasts for nearshore areas. This issue is exacerbated due to the complex orographic features of the Antilles, which govern topographic shadowing and incoming solar radiation fields responsible for the diurnally forced convection typical of tropical island weather. A solution to this problem is currently under evaluation for the CariCOOS region. This solution employs both dynamical numerical solvers of the Weather Research and Forecasting (WRF) Model, which are referred to as the ARW (Advanced Research WRF), and the NMM (Non-hydrostatic Mesoscale Model) cores. CariCOOS research and development efforts are executed in collaboration with the National Weather Service Weather Forecast Office San Juan (NWS WFO SJU). CariCOOS current operational WRF model setups are based on the NMM core at resolutions of 6-km, 2-km, and 1-km. These models target short and medium range forecast; the latest experimental WRF model setup is based on the ARW with resolutions of up to 500-m. The WRF-ARW setup is currently under evaluation to improve very-short-term weather forecast, in support of maritime operations of high-traffic ports and harbors (Bay of San Juan, PR, and Port of Yabucoa, PR). Noteworthy improvement have been achieved as evidenced by model skill assessments of forecasted wind speed, and wind direction of these WRF model setups when compared to in-situ observations of CariCOOS assets (land base weather stations and coastal buoys). The numerical weather prediction forecasting improvements realized via the implementation of both WRF dynamical cores are primarily driven by the increase in horizontal resolution. The most prominent improvements in weather forecasts is were achieved for the leeward side of Puerto Rico and U.S. Virgin Islands and harbor regions when simulated at very fine horizontal grid spacing resolution (less than 1-km). Considering forecast lead time requirements of the NWS WFO SJU, CariCOOS researchers constantly strive to optimize WRF model setups to its limit. Details of the various CariCOOS WRF model setups and implementations will be presented in this paper along with validation statistics.**

Keywords—WRF model; high-resolution; ioos; caricoos

I. INTRODUCTION

Coastal meteorology is the study of meteorological phenomena in the coastal zone that is, from 100 km inland or offshore of the coastline [1]. Caribbean countries as other insular regions depend on a reliable forecasts of coastal meteorology in support of services essential, for their societies (i.e., transportation, nourishment, and recreation). The implementation of the IOOS-CariCOOS [2], for the northeast Caribbean region, has provided the groundwork for the further implementation of high-resolution numerical models of the wind, waves, and currents. Nowadays, CariCOOS assets offer 24-7 real-time observations, which reliably operate during hurricane conditions [3], to approximately 100,000 frequent users. Data dissemination is fundamental for IOOS®[4] to contribute all relevant U.S. coastal ocean observations in near real time to the general public, to national databases and to the World Meteorological Organization Global Telecommunications System (WMO GTS). The CariCOOS Data Management and Communications (DMAC) subsystem [5] is the mechanism in place to assure said delivery. Modelers utilize these observations to assess the skills of numerical models for filling observational gaps and forecasting coastal weather in the region.

CariCOOS numerical weather prediction (NWP) utilize the Weather Research and Forecasting (WRF) model to generate the high-resolution meteorological forecasts. This effort is in support to the National Weather Service Weather

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Forecast Office San Juan, PR (NWS WFO SJU). It also seeks to fill the regional gap of reliable 10-m wind forecast to serve as the engine of current high-resolution numerical circulations models such as the CariCOOS Nearshore Wave Model (Version 4.0) [6],[7]. The implementation of high-resolution NWP model is not a trivial solution to the complex scenario of coastal meteorology. The computational resources need to be tripled to meet forecast demand promptly to meet lead operational time. High-resolution computational grids are necessary for resolving the dynamics of regional coastal meteorology resulting from complex orography and Atmospheric Boundary Layer (ABL) dynamics. As previously reported [1], the Land-Sea Breeze System (LSBS) mesoscale typifies the class of mesoscale atmospheric systems induced by spatial inhomogeneities of surface heat flux into the ABL. The LSBS has been mostly studied, observationally, analytically and numerically, over flat terrain. A constant wind direction characterizes the LSBS mechanism in diurnal periods, known as a sea breeze, which is generally perpendicular to the coastline. After a transition period, with a change in wind direction, in the nocturnal regime that flows come from land, also perpendicular to the coast, are known as land breezes [8]. Therefore, to understand LSBS effect in the ABL over complex orography typical of the coastal regions of the Caribbean islands, the implementation of high-resolution NWP models is a need.

II. METHODOLOGY

A. Model Description

The WRF model system contains two dynamical solvers, referred to as the ARW (Advanced Research WRF) [9] and the NMM (Non-hydrostatic Mesoscale Model) [10] cores. The first developed at the National Center for Atmospheric Research (NCAR) and the later at the National Centers for Environmental Prediction (NCEP). In coordination with the NWS WFO SJU, the NMM solver is engaged as the first choice to meet run-time demand on real-time weather forecasting. Current operational implementation of the WRF-NMM model covers the Caribbean region with emphasis on Puerto Rico and the US Virgin Islands at various spatial resolutions (6-km, 2-km, and 1-km). Considering forecast lead time requirements of the NWS WFO SJU, CariCOOS researchers constantly strive to optimize WRF model setups to its limit. WRF model setup configurations implemented with 45 vertical levels are provided with boundary and initials conditions by the Global Forecast System (GFS) and high-resolution sea surface temperature (SST) from NASA Short-term Prediction Research and Transition Center (SPoRT). In the following section details are specified for each WRF model configuration and its respective horizontal grid resolution.

B. Model configurations

The first model implementation of the WRF model is a mirror run of the official NWS WFO SJU model setup [11] based on the WRF NMM core. This configuration consist of a one-way nested domain where the parent (d01) and a child domain (d02) with horizontal grid spacing of 6 km and 2 km, respectively. Figure 1, illustrates the geographical extension of each domain. The following physical parameterization schemes are used on this configuration: (i) GFDL long and short wave radiation schemes, along with slope radiation scheme for domain d02; (ii) the Ferrier microphysics scheme; (iii) the Mellor-Yamada-Janjic (MYJ) PBL scheme; (iv) MYJ Monin-Obukhov similarity theory surface layer scheme; (v) Noah Land Surface Model scheme; (vi) and cumulus parameterization Betts-Miller-Janjic scheme for domain d01. This model configuration is run four times a date by the NWS WFO SJU and CariCOOS for cycles 00Z, 06Z, 12Z and 18Z to produce 72 hours of forecast. Also runs by CariCOOS of cycles 00Z and 12Z are extended to produce 120 hours of forecast used to provide the wind forcing to CariCOOS wave model SWAN.

The second model implementation of the WRF model employs the NMM core and consists of a single domain with a similar geographical extent as domain d02, previously described. Also, the same physical parameterization schemes are used, with the modification of the GFDL long and shortwave radiation scheme to enable slope radiation and topo-shading. This model setup has a horizontal grid spacing of 1km, with a west-east (Nx) grid dimension of 215 and south-north (Ny) grid dimension of 280 grid points. This model configuration is run two times a date by CariCOOS for cycles 00Z, and 12Z to produce 72 hours forecast.

The third and latest configuration of the WRF model employs the ARW core. This model configuration is a one-way multiple nested domain configuration that targets a finer resolution of 500-meters with a coarse parent domain of 2.5-km (d01). Finer resolution domains extend over the Bay of San Juan (d02), the Port of Yabucoa (d03) and the southwest area of Puerto Rico (d04), presented in Figure 2. The following physical parameterization schemes are used on this configuration: (i) GFDL long and short wave radiation schemes, along with slope radiation scheme for all domains and topo-shading on for domains d02, d03 and d04; (ii) the Morrison Double-Momentum 6-Class microphysics scheme; (iii) the Yonsei University PBL scheme; (iv) MYJ Monin-Obukhov similarity theory surface layer scheme; (v) Noah Land Surface Model scheme. Cumulus Parameterization is not used in this configuration since they are not needed with the high resolution adopted.

The forecast of each three WRF model configuration will be referenced as WRF_NMM_6KM, WRF_NMM_2KM, WRF_NMM_1KM, WRF_ARW_2.5KM, and WRF_ARW_500M. The nomenclature selected indicates WRF numerical core and geographical horizontal resolution.

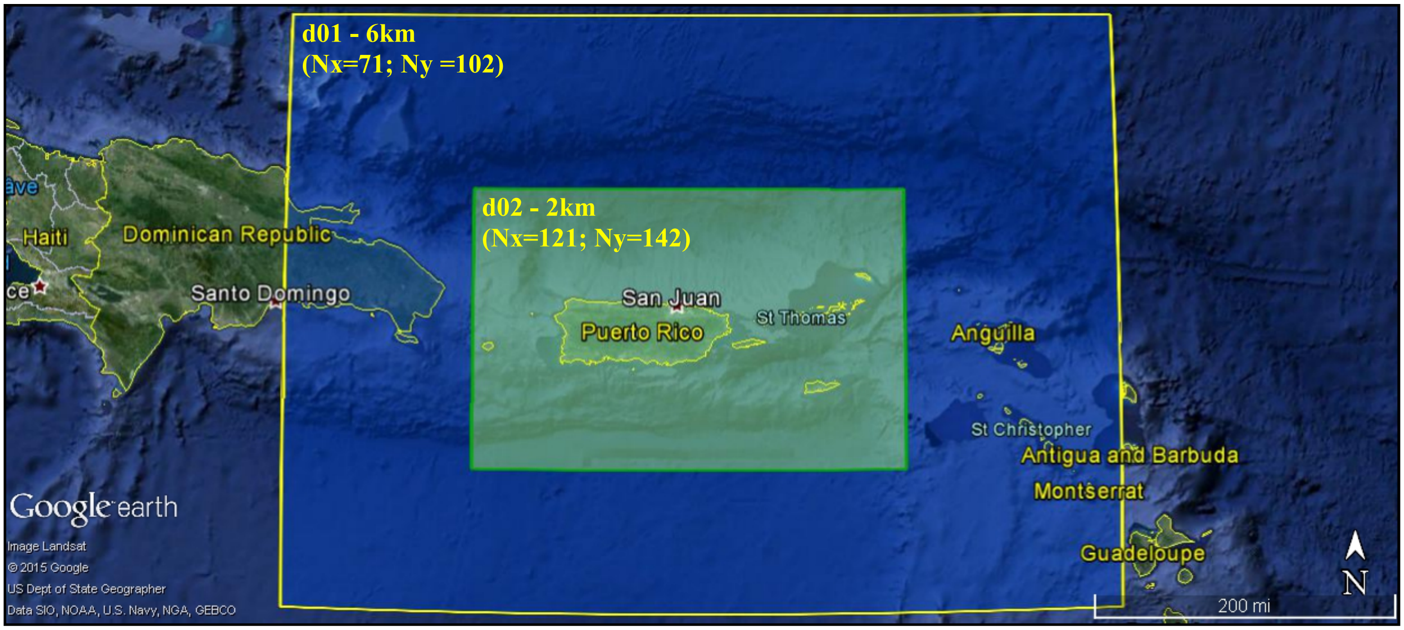

Figure 1. Computational domains of WRF-NMM model setup implemented by the NWS WFO SJU

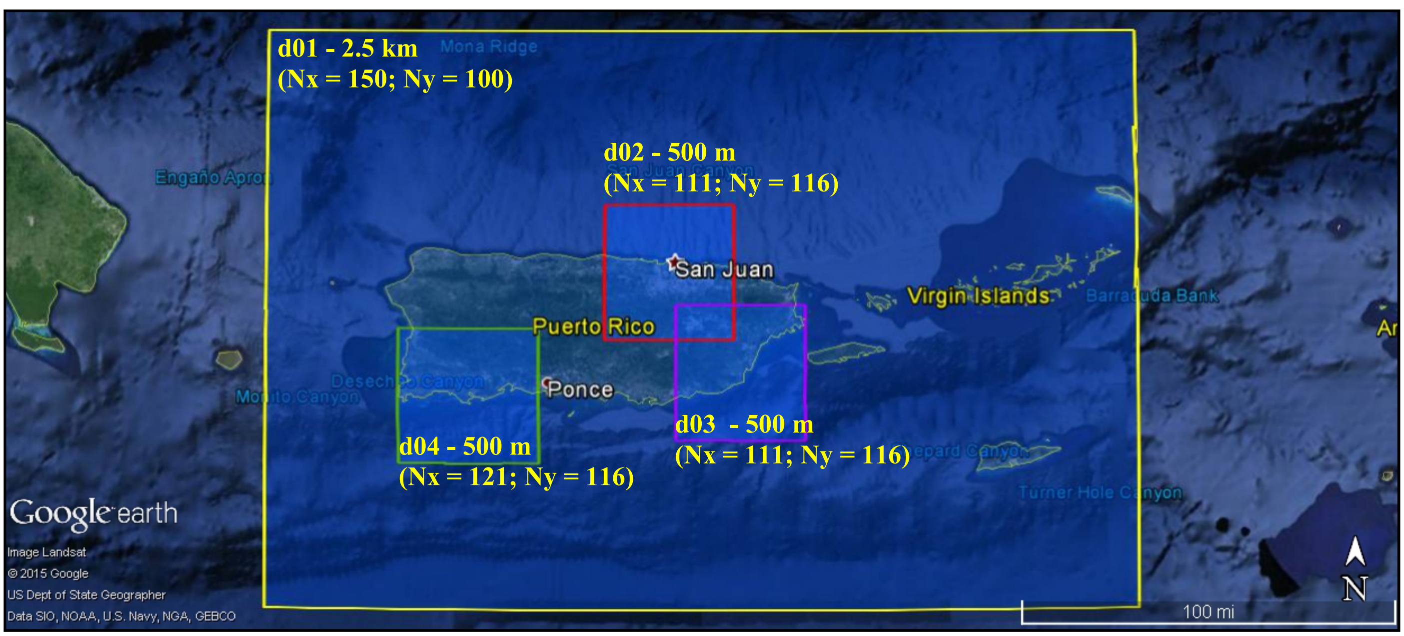

Figure 2. Computational domains of WRF-ARW model setup implemented by CariCOOS

C. Model improvements

The need for finer horizontal resolution seeks to depict better the complex topographical features and coastline geomorphology of tropical islands. This need has been addressed by adding to WRF topographic model library the digital elevation model (DEM) of NASA Shuttle Radar Topography Mission (STRM) Global 1 arc second geographical resolution (approx. 31 m) [12]. Also, WRF land-use category library data has been updated with MODIS modified

International Geosphere-Biosphere Programme (IGBP) 15 arc second geographical resolution (approx. 463 m) . These two modifications to WRF geographical database library, allow targeting the finer resolution,500 meters, defined on the third WRF model configuration and needed to obtain realistic forecasts. A comparison of terrain profiles is presented using USGS DEM of 1/3 arc second (approx. 10m) and DEM generated by WRF geoprocessing. The comparisons presented are for two of the CariCOOS/WeatherFlow Inc. weather stations located at the Bay of San Juan, PR (XJUA) and the Port of Yabucoa, PR (XYAB). Aerial imagery of each weather station is presented in Figure 3 and Figure 4, respectively. The improvement of WRF geoprocessing to better depict the complex orography as a function of horizontal resolution is illustrated in Figures 5 and Figure 6.

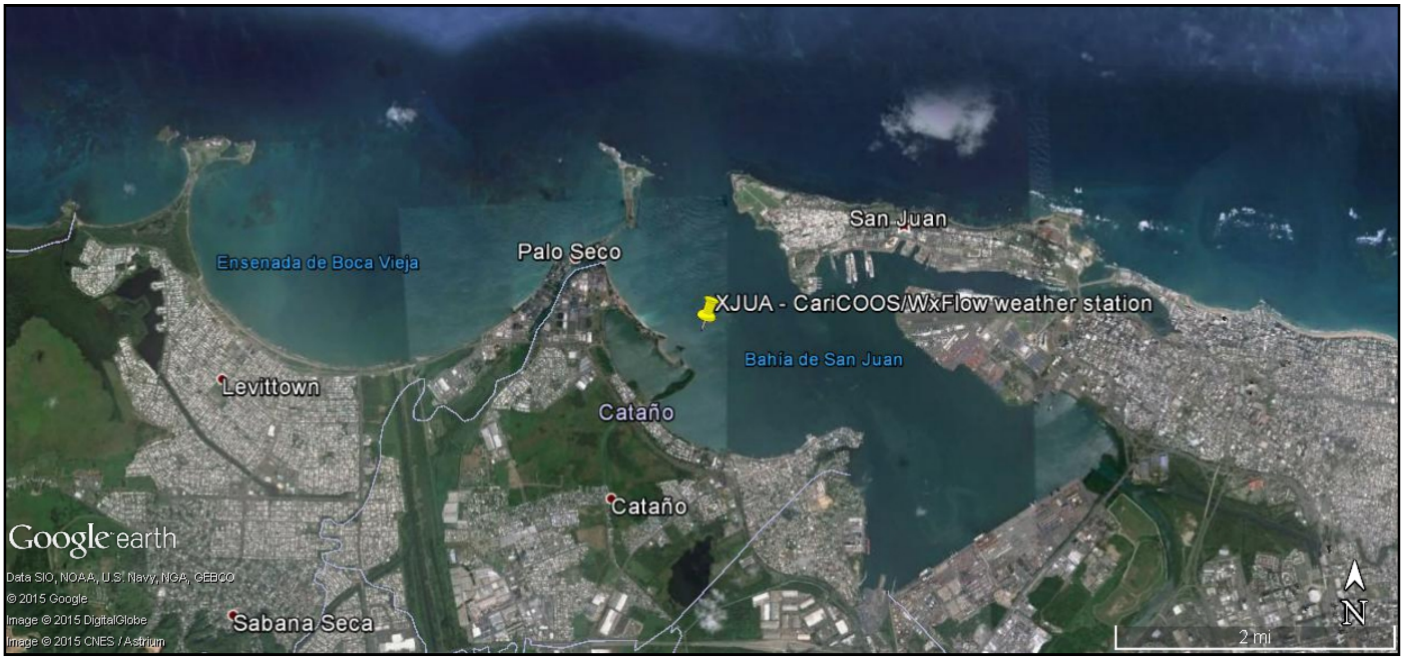

Figure 3. Aerial image of CariCOOS/WxFlow meteorological weather station located at the NavAid in the Bay of San Juan, PR

Figure 4. Aerial image of CariCOOS/WxFlow meteorological weather station located at the Port of Yabucoa, PR

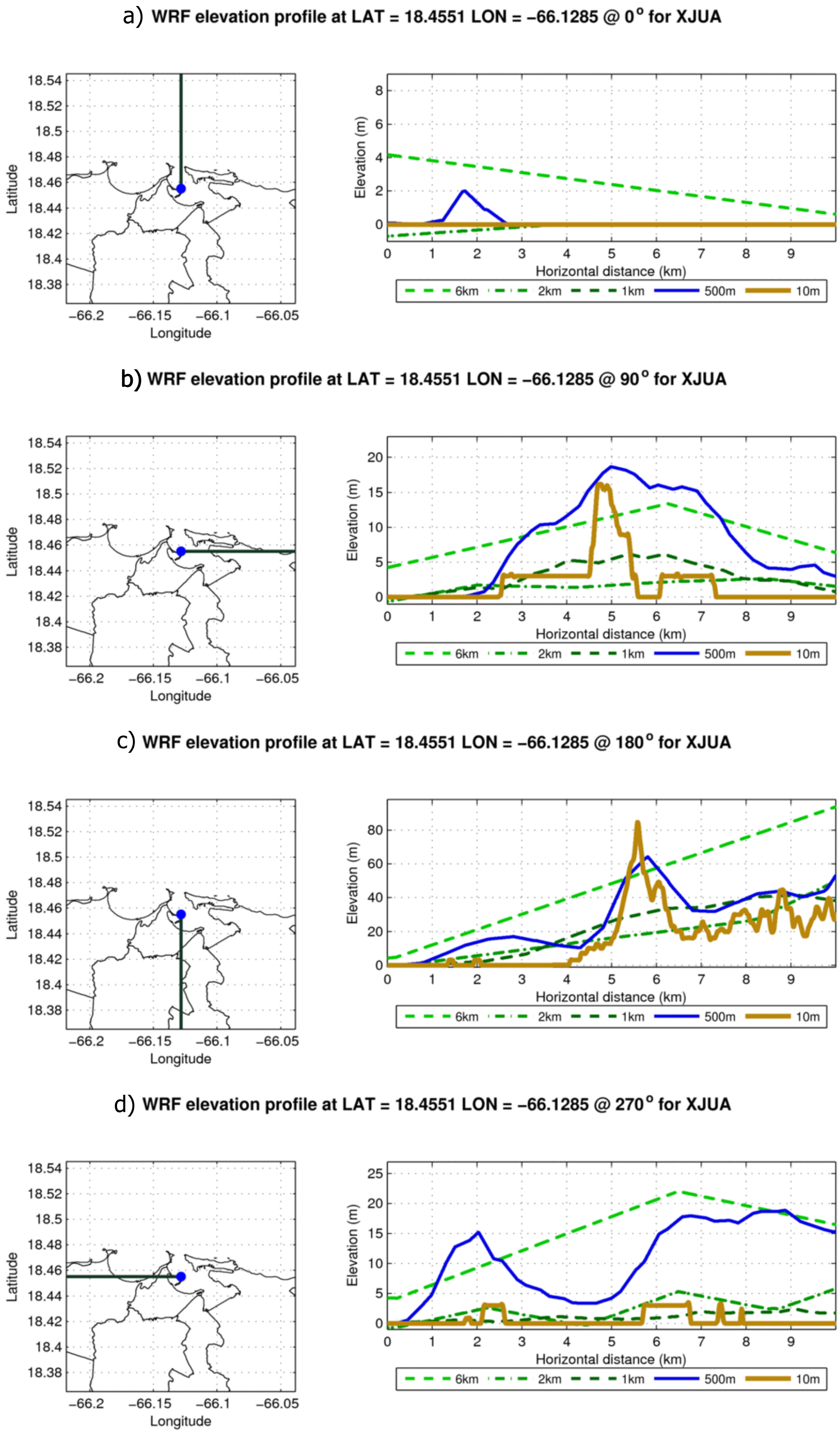

Figure 4. Terrain profiles from center of weather station XJUA due: a) north; b) east; c) south; and d) west

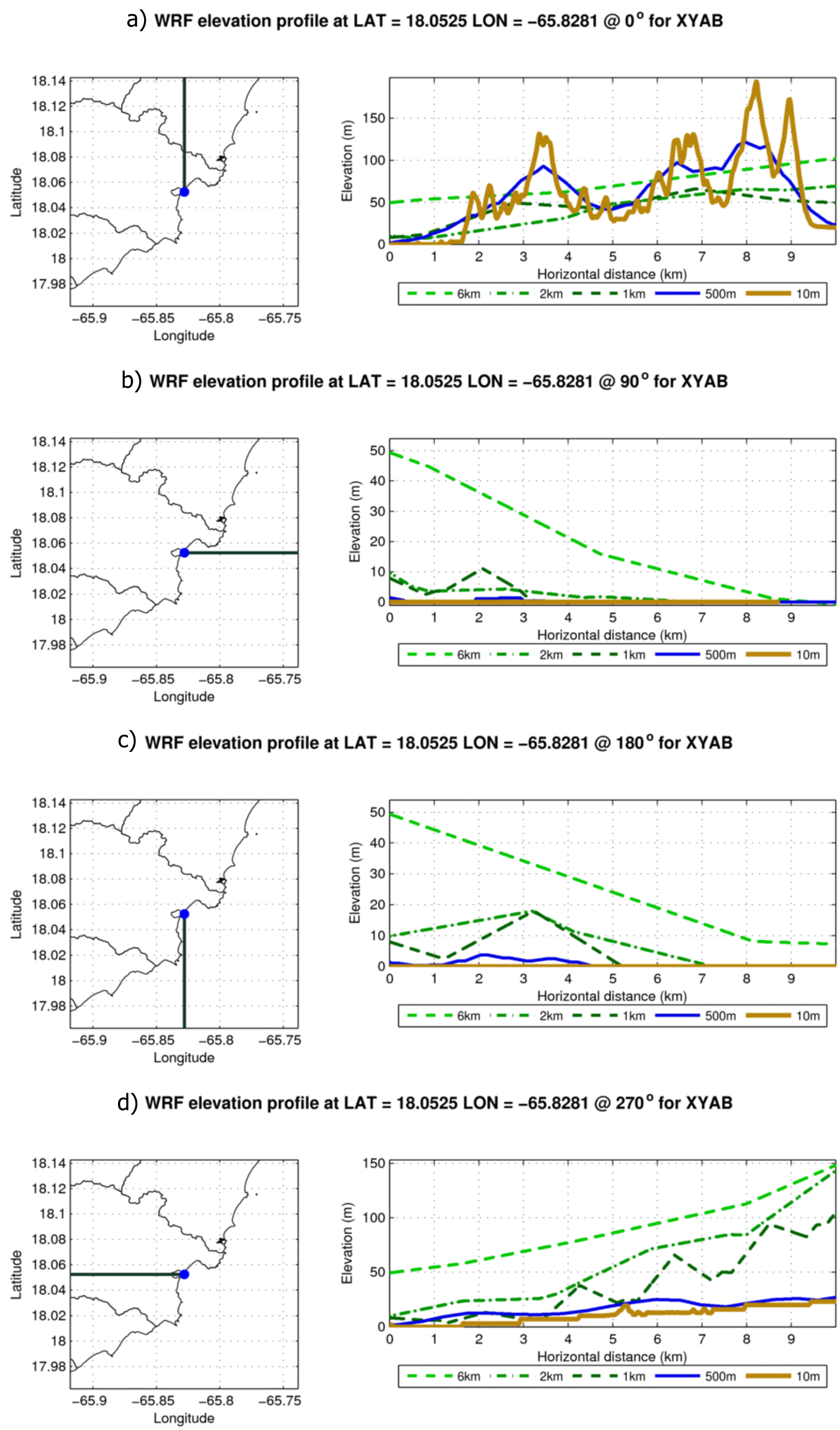

Figure 5. Terrain profiles from center of weather station XYAB due: a) north; b) east; c) south; and d) west

III. RESULTS AND DISCUSSION

WRF simulations are validated against CariCOOS Observing Network in-situ observations. The network consist of six oceanographic buoys (five equipped with meteorological instrumentation) and fifteen land-based weather stations distributed throughout Puerto Rico and U.S. Virgin Island, as shown in Figure 6. All in-situ observations are adjusted to 10-m height following the logarithmic law, where U_{10} is the adjusted wind speed, U_z is the in-situ observation at heigth z (in m/s) from ground level or mean-sea-level at buoys, and z_0 is the terrain roughness (in m). Terrain roughness values were assigned to each site following recommended published values [13]. After all in-situ observation are adjusted by height an hourly mean average is computed and compared to model simulation output interpolated to each site GPS coordinate.

$$U_{10} = U_z \frac{\ln\left(\frac{10}{z_0}\right)}{\ln\left(\frac{z}{z_0}\right)} \tag{1}$$

Two validation experiments were conducted to determine model skill performance for medium range (up to 120 hours) and short range forecast (up to 24 hours). Statistical parameters used for quantifying model skill performance include standard parameters such as the root mean square error (RMSE), and the Willmot index of agreement (IOA) [14].

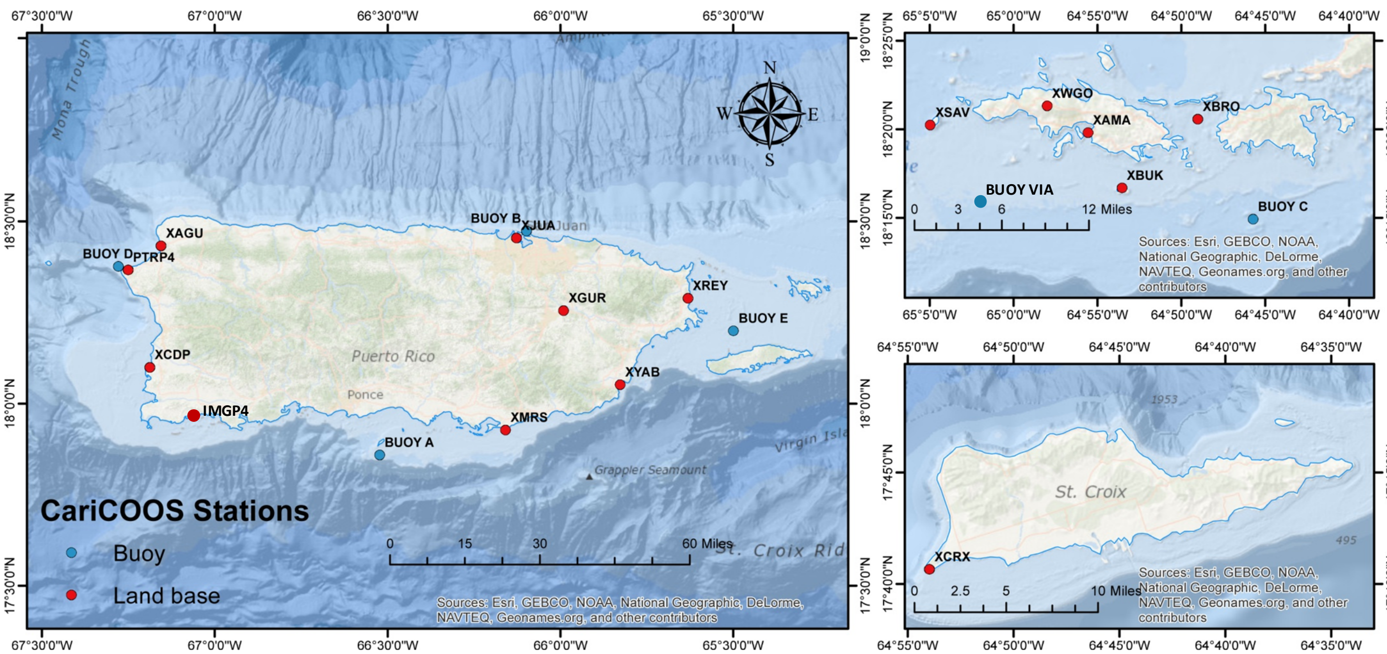

Figure 6. CariCOOS Observing Network of 5 meteorological buoys and 15 land base weather stations

A. *Validation experiments for medium range forecast*

The first experiment aimed at evaluating WRF model skill forecasting of 10-m winds by comparing the output from simulations of WRF_NMM_6KM, WRF_NMM_2KM, WRF_NMM_1KM, and NWS National Digital Database Forecast (NDFD) [15]. The validation experiment conducted from April 7-27, 2015, compares the model output of the 00Z cycle simulation to mean hourly-adjusted in-situ wind observations to 10-m height. For each forecast day, RMSE was computed and averaged for each model during the 21-day experiment. Figure 7 summarizes the results in two CariCOOS buoy and two CariCOOS/WeatherFlow land-based meteorological locations. The in-situ most relevant buoy validations are Buoy A and Buoy B, located south of Ponce, PR and north of San Juan, PR, respectively. Also, land-base relevant validations are weather stations XJUA and XYAB, located at the Bay of San Juan, PR and the Port of Yabucoa, PR, respectively. The validation experiment reveals that the WRF_NMM_2KM model configuration is appropriate to generate 10-m winds, up to a five-day forecast, maintaining lower RMSE values when compared to the NWS NDFD. For that reason, the WRF_NMM_2KM model output is currently used as the forcing winds for the CariCOOS SWAN model. Validation of the SWAN model coupled to WRF_NMM_2KM is in progress, and preliminary results reveal an improvement in wave forecasting skill performance in the medium and range forecast.

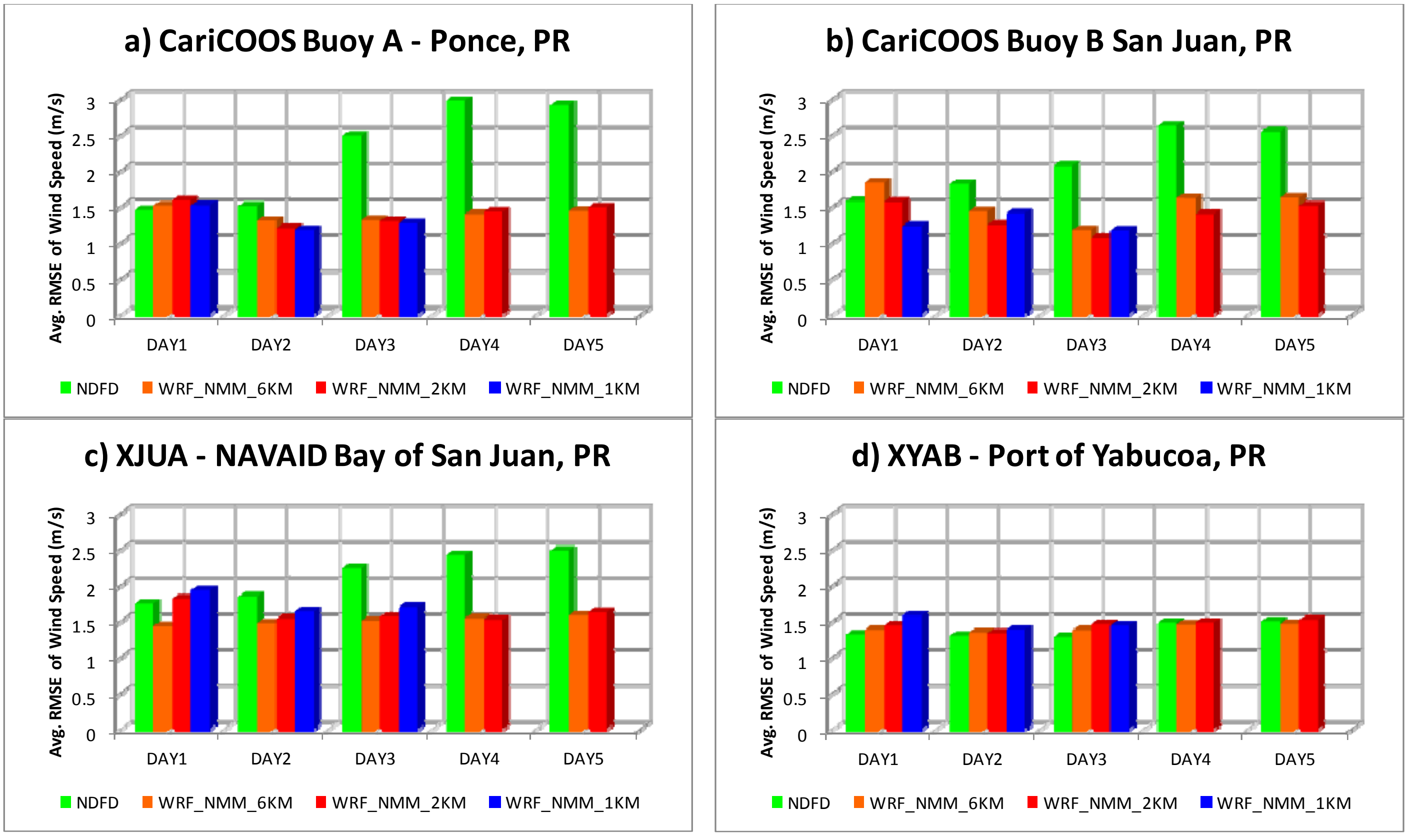

Figure 7. Validation of WRF-NMM medium range forecast to NWS NDFD, a) CariCOOS Buoy A; b) CariCOOS Buoy B; c) CariCOOS/WxFlow weather station XJUA; and d) CariCOOS/WxFlow weather station XYAB

B. *Validation experiment for short term forecast*

The second experiment seeks to evaluate WRF model skill performance for the short term forecasts by comparing the output from simulations of WRF_NMM_6KM, WRF_NMM_2KM, WRF_NMM_1KM, WRF_ARW_2.5KM, WRF_ARW_500m, and NDFD. The validation experiment, conducted from May 14-24 2015, compares the model output of the 00Z cycle simulation to mean hourly-adjusted in-situ wind observations to 10-m height. For the 11-day period, best aggregate time series are compared with the 11-day experiment. Also, it is compared the 10-m wind direction and air temperature simulated at 2-m height.

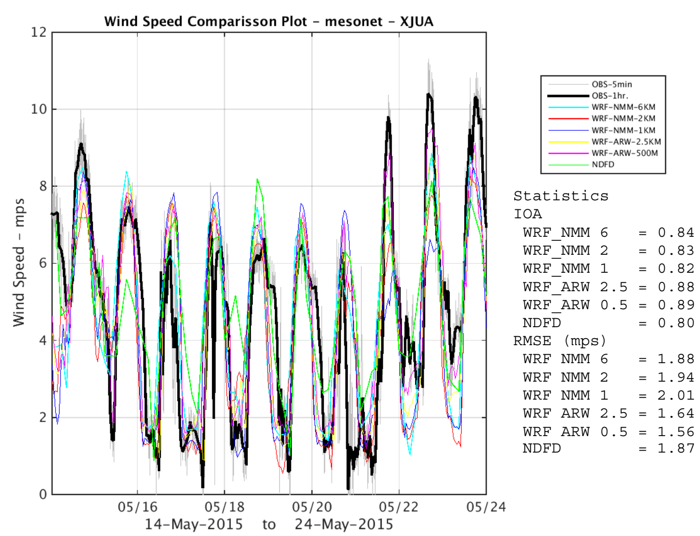

Figure 8. Wind speed comparison plot of WRF model to CariCOOS/WxFlow weather station XJUA

Wind speed and direction comparison plots, presented in Figure 8 and 9, for weather station XJUA, reveals that both dynamical cores of the WRF Model (NMM & ARW) generate better IOA statistics than NDFD. WRF_ARW_500m model configuration has the best IOA among the models forecasted wind speed and direction. Also, the lower RMSE is observed with this model configuration, suggesting that WRF-ARW improved capture of wind variations due to diurnal and nocturnal sea and land breeze cycles, respectively.

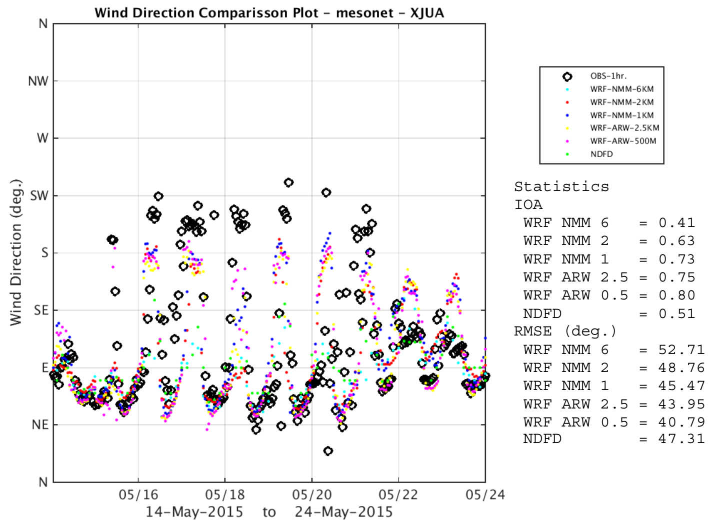

Figure 9. Wind direction comparison plot of WRF model to CariCOOS/WxFlow weather station XJUA

Air temperature simulated at 2-meter heights comparison plot, presented in Figure 10, for weather station XJUA reveals that WRF dynamical core ARW perform better that the NMM. The ARW core provides a significant improvement in the statistical parameters of IOA and RMSE. The IOA comparison of WRF_ARW_500m to WRF_NMM_1KM shows a 30% improvement. Also, RMSE statistics indicates a reduction of more than 2-°F. Furthermore, the graphical comparison plot indicates that the NMM tends to overestimate peak and lows air temperatures simulated over the diurnal and nocturnal cycles, respectively. This noteworthy validation result indicates that the ARW core might be more appropriate to target finer resolution forecast runs. The caveat of these finding strive on the computational resources needed to comply with short simulation time, less than two hours, to produce forecasts in an operational environment like the NWS WFO SJU.

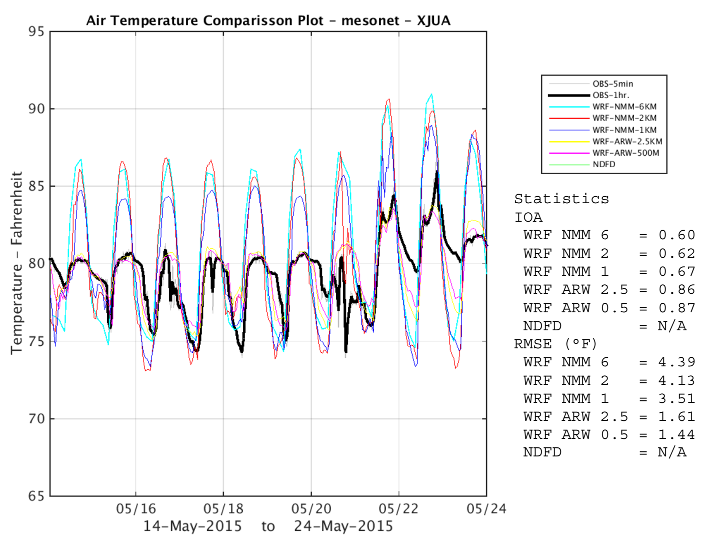

Figure 10. Air temperature at 2-m height comparison plot of WRF model to CariCOOS/WxFlow weather station XJUA

IV. CONCLUSION

We here provide concluding data from two validation experiments to determine the ability of different WRF model configurations to improve short and medium range forecast of 10-m winds. These experiments are in support of the CariCOOS operational ocean models SWAN for waves, and experimental ROMS and FVCOM hydrodynamic models.

The first validation experiment presented on this paper simulates 21-day forecast, of 120 hours and 72 hours of WRF NMM model configurations of 2-km and 1-km, respectively. Results indicate that the 2-km model configuration performs well at representing local wind conditions at a low computational cost, making it available to couple run simulations with CariCOOS SWAN model runs. Also, the second validation experiment simulates 11-day forecast and best aggregate time series compared each WRF model configuration skill to forecast wind speed, direction, and air temperature. The second validation experiment reveals that WRF ARW cores perform better that the NMM albeit at a higher computational expense, making it suitable for a short term forecasting. The improvement in model skill, shown by the ARW core, to forecast air temperature need to be further investigated along with other variables such as rain and relative humidity.

In conclusion, the implementation of high-resolution WRF model using both dynamical solvers NMM, and ARW for the CariCOOS region yields 10-m wind forecast demonstrating skills comparable or superior to the NWS NDFD operational product. Also, the results highlight the crucial role played by smaller scale needed in complex orography regions to improve NWP in support of maritime port, harbor, and marines activities.

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REFERENCES

[1] National Research Council (U.S.), Ed., Coastal meteorology: a review of the state of the science. Washington, D.C: National Academy Press, 1992.

[2] Morell, J.; Canals, M.; Capella, J.; Aponte, L.; Corredor, J.; Walington, R.; García, C., "IOOS-CariCOOS: past, present and future of a tropical coastal ocean observing system," in *Proceedings of the 2015 MTS/IEEE Oceans Meeting,* Genova, IT, May. 2015

[3] L. D. Aponte, M. F. Canals, J. E. Corredor, and J. M. Morell, "An Overview of the Caribbean Coastal Ocean Observing System and Data Measurements during Hurricane Irene," 2012, pp. 1148–1159. doi 10.1061/9780784412626.100

[4] "About Data Management and Communication, DMAC." [Online]. Available: http://www.ioos.noaa.gov/data/dmac/about_dmac.html. [Accessed: 27-Aug-2015].

[5] "CariCOOS DMAC catalog." [Online]. Available: http://dm2.caricoos.org/thredds/catalog.html. [Accessed: 27-Aug-2015].

[6] "CariCOOS Nearshore Wave Model v 4.0 | www.caricoos.org." [Online]. Available: http://caricoos.org/drupal/swan. [Accessed: 27-Aug-2015].

[7] C. M. Anselmi-Molina, M. Canals, J. Morell, J. Gonzalez, J. Capella, and A. Mercado, "Development of an Operational Nearshore Wave Forecast System for Puerto Rico and the U.S. Virgin Islands," Journal of Coastal Research, vol. 284, pp. 1049–1056, Sep. 2012.

[8] M. A. Hernández-Ceballos, J. A. Adame, J. P. Bolívar, and B. A. De la Morena, "A mesoscale simulation of coastal circulation in the Guadalquivir valley (southwestern Iberian Peninsula) using the WRF-ARW model," Atmospheric Research, vol. 124, pp. 1–20, Apr. 2013.

[9] Skamarock, W., J.B. Klemp, J. Dudhia, D.O. Gill, D. Barker, M.G. Duda, X.-Y. Huang, and W. Wang, 2008: A Description of the Advanced Research WRF Version 3. NCAR Technical Note NCAR/TN-475+STR, DOI: 10.5065/D68S4MVH.

[10] Janjic, Zavisa, Gall, Robert, and Pyle, Matthew, "Scientific Documentation for the NMM Solver," 2010.

[11] N. US Department of Commerce, "NWS San Juan - Local Models." [Online]. Available: http://www.srh.noaa.gov/sju/?n=model01. [Accessed: 27-Aug-2015].

[12] T. G. Farr, P. A. Rosen, E. Caro, R. Crippen, R. Duren, S. Hensley, M. Kobrick, M. Paller, E. Rodriguez, L. Roth, D. Seal, S. Shaffer, J. Shimada, J. Umland, M. Werner, M. Oskin, D. Burbank, and D. Alsdorf, "The Shuttle Radar Topography Mission," Reviews of Geophysics, vol. 45, no. 2, May 2007.

[13] E. Simiu and R. H. Scanlan, Eds., Wind effects on structures: fundamentals and applications to design, 3. ed. New York: Wiley, 1996.

[14] C. J. Willmott, "Some Comments on the Evaluation of Model Performance," Bulletin of the American Meteorological Society, vol. 63, no. 11, pp. 1309–1313, Nov. 1982.

[15] "NDFD Home Page." [Online]. Available: http://www.nws.noaa.gov/ndfd/. [Accessed: 29-Aug-2015].