CariCOOS: Real-time data validation of high-resolution wind forecast

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Abstract*— CariCOOS has implemented a mirror run of the operational numerical weather prediction model employed by the National Weather Service Weather Forecast Office San Juan (NWS WFO SJU), which is based on the WRF NMM model. The model configuration consists of a one-way nesting of two domains with a horizontal resolution of 6-km and 2-km, respectively. CariCOOS developed a single domain configuration of the WRF NMM model having a finer horizontal spatial resolution of 1-km. These models, in general, are discrete approximations in space and time of a continuous geophysical medium being simulated. The solutions to these models are not an exact representation of reality. The goal is to keep track of the relative ability of a model to make accurate predictions. A real-time validation MATLAB® script, for numerical weather prediction (NWP), was developed to assist CariCOOS end-users in comparing the forecasts to actual data. The validation of these models was conducted by comparing in-situ wind observations (O_i), of CariCOOS observing network, with model forecast (M_i). Time histories plots of in-situ and modeled wind speed and direction are compared in real time; while also solving statistical algorithms with various validation parameters as outputs. The statistical parameters included in the real-time validation tool are: (i) the Pearson's moment correlation coefficient (*r*), (ii) mean bias (*MB*), (iii) mean absolute gross error (*MAGE*), (iv) root mean square error (*RMSE*), (v) Willmott index of agreement (*IOA*) and (vi) hit rate (*HR*). This useful real-time validation tool allows NWS WFO SJU forecasters and CariCOOS researchers to measure the skill of the model and quantify the error to determine future needs for modeling enhancements. The real-time validation framework developed facilitates CariCOOS researchers to set any validation date range, which can vary from days to months. The validation skill appraisal revealed noticeable improvement in the forecasting for both wind speed and direction by the WRF-1KM when compared to the WRF-2KM and the NWS National Digital Forecast Database (NDFD) operational product. Typically the most improved locations are noticed for weather stations in regions surrounded by complex topographic features,, particularly the lee side of islands. These findings suggest that the 1-km model resolves better the local orographic forcing generated by the fine-scale topography, typical of the coastal meteorology of Caribbean islands. The improvement in forecasting 10-m winds is due to a better depiction of the 1-km resolution model of complex terrain. These findings may lead to better understanding of local convection process, which dominates the diurnal and nocturnal wind cycles of sea and land breeze, respectively.

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

I. INTRODUCTION

Validation of a numerical model is an important aspect of the implementation process and operational phase. Model skill performance can be measured as how well the model results compare with reliable in-situ observations or predicted events. The Caribbean Coastal Ocean Observing System (CariCOOS) has implemented a mirror run of the operational numerical weather prediction (NWP) model employed by the National Weather Service Weather Forecast Office San Juan (NWS WFO SJU), which is based on the Weather Research and Forecast (WRF) model. The WRF model system contains two dynamical cores, referred to as the ARW (Advanced Research WRF) [1] and the NMM (Non-hydrostatic Mesoscale Model) [2]; the first developed at the National Center for Atmospheric Research (NCAR), and the second at the National Centers for Environmental Prediction (NCEP). The NWS WFO SJU currently employs WRF NMM model since it provides faster simulations run when compared to WRF ARW core, making it appropriate for operational forecasting. Also, both WRF core models are fit for use in a broad range of applications across scales ranging from meters to thousands of kilometers. The model configuration implemented by the NWS WFO SJU consists of a one-way nesting of two domains with a horizontal resolution of 6-km and 2-km, respectively, for the parent and child domains. Employing similar model setup, CariCOOS implemented a single domain WRF model configuration

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with a horizontal spatial resolution of 1 km. Both model configurations are implemented with 45 vertical levels. Boundary and initial conditions are driven by the Global Forecast System (GFS) and high-resolution sea surface temperature (SST) from NASA Short-term Prediction Research and Transition Center (SPoRT). These models, in general, are discrete approximations in space and time of a continuous geophysical medium being simulated. The solutions to these models are not an exact representation of reality. The fundamental problem lies in the numerical approximation to solve the complex Navier-Stokes equations used to simulate atmospheric flows. Our goal is to keep track of the discrepancy level in order to improve future model skill performance. The real-time validation results presented in this paper focus on current operational products by CariCOOS and NWS WFO SJU. These models are referenced as WRF_NMM_2KM, WRF_NMM_1KM and NWS NDFD operational product [3].

II. Methodology

The validation of modeled forecast (M_i) from the WRF model configuration and NWS NDFD are validated using in-situ wind observations (O_i) from CariCOOS Observing Network, shown in Figure 1. CariCOOS observing network consist of 5 buoys equipped with meteorological instrumentation [4] and fifteen land-based meteorological stations. The land base mesonet stations were deployed by Weather Flow Inc. (13 sites) and CariCOOS (2 sites). Additional details of CariCOOS assests are presented in [5].

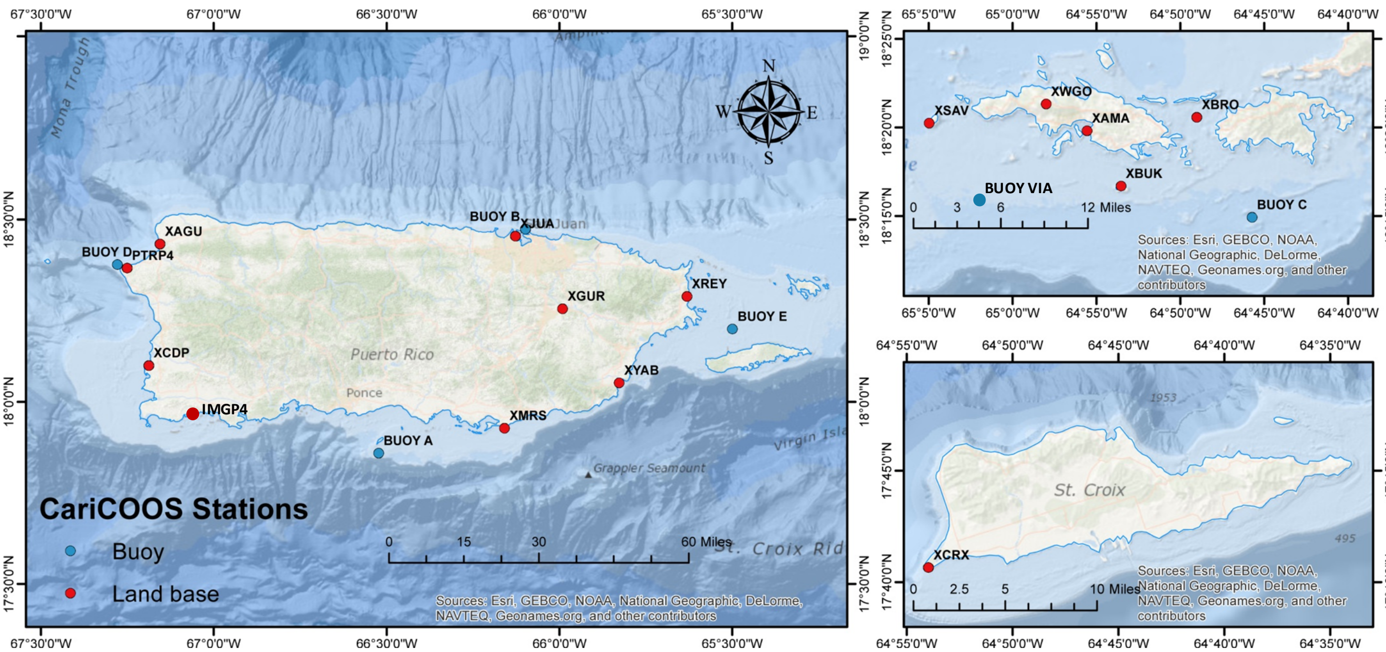


Figure 1. CariCOOS Observing Network of 5 meteorological buoys and 15 land-based weather stations.

The validation methodology employed consisted in comparing in-situ observations to 10-m wind model simulation, for this task it is necessary to adjust the observation to a 10-m elevation following the logarithmic law, where U_{10} is the adjusted wind speed, U_z is the in-situ observation at elevation 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 [6]. After all in-situ observations are adjusted by elevation, an hourly mean average is computed and compared to model outputs interpolated to each site's GPS coordinate.

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

A MATLAB® script was developed as a toolbox to enable real-time validation of NWP models. The main tasks performed were: (i) gathering of all model data, (ii) gathering of all in-situ observations and compute statistical parameters, and (iii) disseminate graphical result thru CariCOOS web portal. The first task involves accessing model data from CariCOOS DMAC Catalogue THREDDS Data Server (TDS) [7] and interpolating it to each in-situ GPS coordinate. In this task the first six hours of forecasts are discarded since the WRF model is run in "cold-start" mode. The second task involves accessing observed in-situ data from CariCOOS-TDS to generate time series plots along with best aggregated time series of the modeled wind speed and wind direction, while also solving statistical algorithms with various validation parameters as outputs. Details of each parameter used are presented in the next section. The third task involves dissemination of the plots thru a wind validation map available at CariCOOS web portal [8].

A. Mathematical definitions of statistical parameters

The use of different statistical parameters allow us to perceive more complete and broad statistical conclusions regarding our results. A total of six statistical parameters are used for the validation experiments to compare wind speed and wind direction. The first parameter presented is the, Pearson's moment correlation coefficient (r) defined as,

$$r = \frac{\sum_{i=1}^{N}[(M_i - \bar{M})(O_i - \bar{O})]}{[\sum_{i=1}^{N}(M_i - \bar{M})^2]]^{1/2} \cdot [\sum_{i=1}^{N}(O_i - \bar{O})^2]]^{1/2}}, -1 \leq r \leq 1 \tag{2}$$

where O_i and $\bar{O}$, are the adjusted in-situ observation i and the average observed variables, respectively; M_i and $\bar{M}$ are the hourly i model-predicted and the average model predicted variables, respectively; and N is the total number of cases for both observed and model-predicted variables. The second parameter presented is the bias or mean bias error (MB) defined as,

$$MB = \frac{1}{N}\sum_{i=1}^{N}(M_i - O_i), -\infty < MB < \infty \tag{3}$$

The third parameter presented is mean absolute gross error ($MAGE$) defined as,

$$MAGE = \frac{1}{N}\sum_{i=1}^{N}|M_i - O_i|, 0 \leq MAGE < \infty \tag{4}$$

The fourth parameter presented is the root mean square error ($RMSE$) defined as,

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}(M_i - O_i)^2\right]^{1/2}, 0 \leq RMSE < \infty \tag{5}$$

The fifth parameter presented is the Willmott index of agreement (IOA) [11] defined as,

$$IOA = 1 - \left[\frac{\sum_{i=1}^{N}(M_i - O_i)^2}{\sum_{i=1}^{N}(|M_i - \bar{O}| + |O_i - \bar{O}|)^2}\right], \quad 0 \leq \mathrm{IOA} \leq 1 \tag{6}$$

The sixth parameter presented is the hit rate (HR), also consider a sensitivity criteria that measures the rate of success of the prediction defined as,

$$HR = \frac{1}{N}\sum_{i=1}^{N} m_i \begin{cases} m_i = 1 \; if \; |M_i - O_i| < R \\ m_i = 0 \; otherwise \end{cases}, \quad 0 \leq \mathrm{HR} \leq 1 \tag{7}$$

where R is the hit success criteria. For the experiments presented on this paper the criteria for wind speed and wind direction used were 1.54 m/s (3kt) and 22.5°.

These statistical parameters were also applied to wind direction time series. Therefore, in the case of the mean bias positive and negative values of the calculated differences between modeled and in-situ observations, act counterclockwise and clockwise from the in-situ mean wind direction, respectively. Also, the Pearson's moment correlation coefficient is defined as,

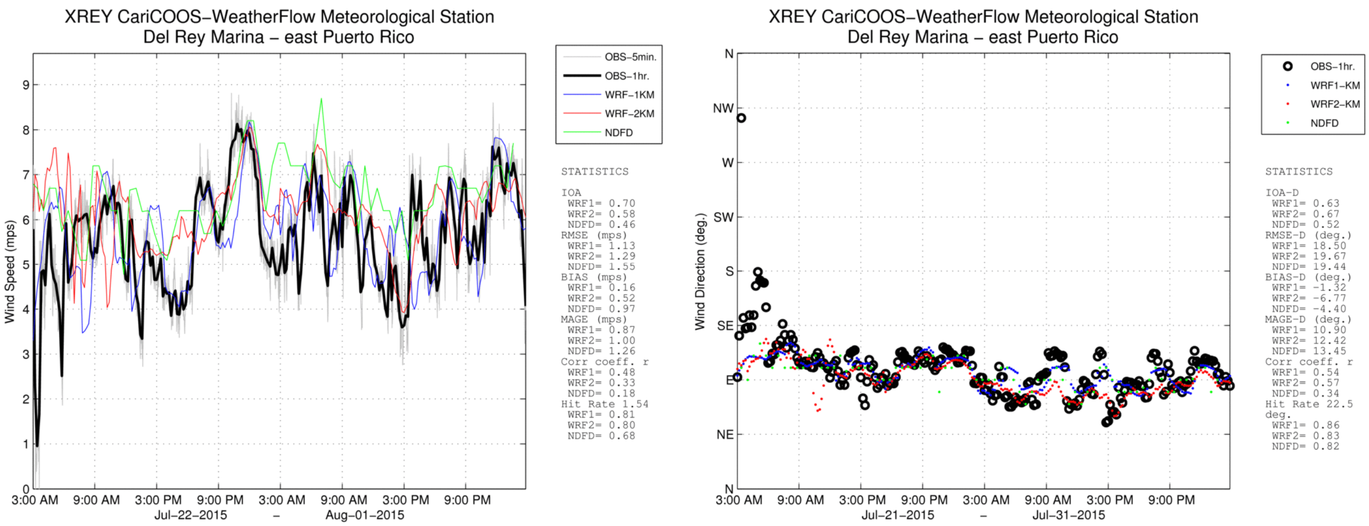
$$r_d = \sqrt{r_u^2 + r_v^2}, \quad 0 \leq r_d \leq 1 \tag{8}$$

where r_u^2 and r_v^2 are the Pearson's moment correlation coefficient of the wind direction component u and v, respectively.

III. Results and Discussion

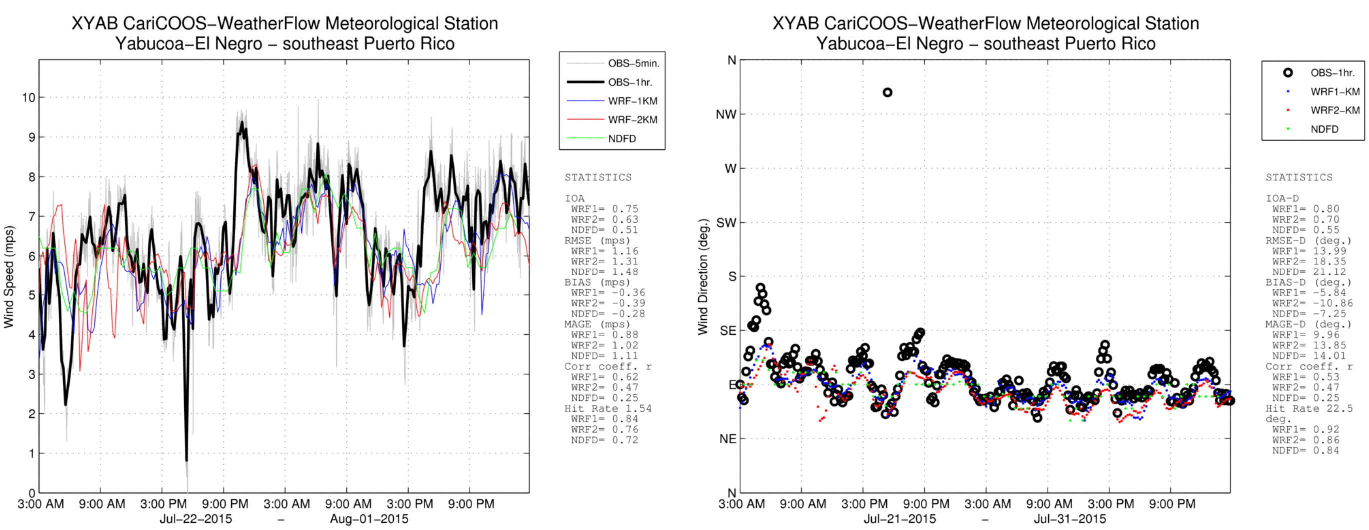
A. *Graphical validation plots*

The validation experiment results presented in Figures 2, 3, and 4 consist of 10-day simulations from July 22, 2015, to July 31, 2015. Each figure illustrates the comparison of wind speed and wind direction real-time data with each model. These figures represent the graphical product of the real-time validation toolbox for stations: XREY, XYAB and BUOY B, respectively. Each plot has a list, in the right corner, with the statistical results for all three models validated along with its respective legend on the upper right corner side. The gray line represents the real-time data collected adjusted to 10-m height. The real-time data averaged to the same time-step of the model data (1-hour) is represented by the black line and circles in the case of wind speed and direction, respectively. The blue, red and green lines and dots represent the WRF_NMM_1KM, WRF_NMM_2KM and NDFD models, respectively.



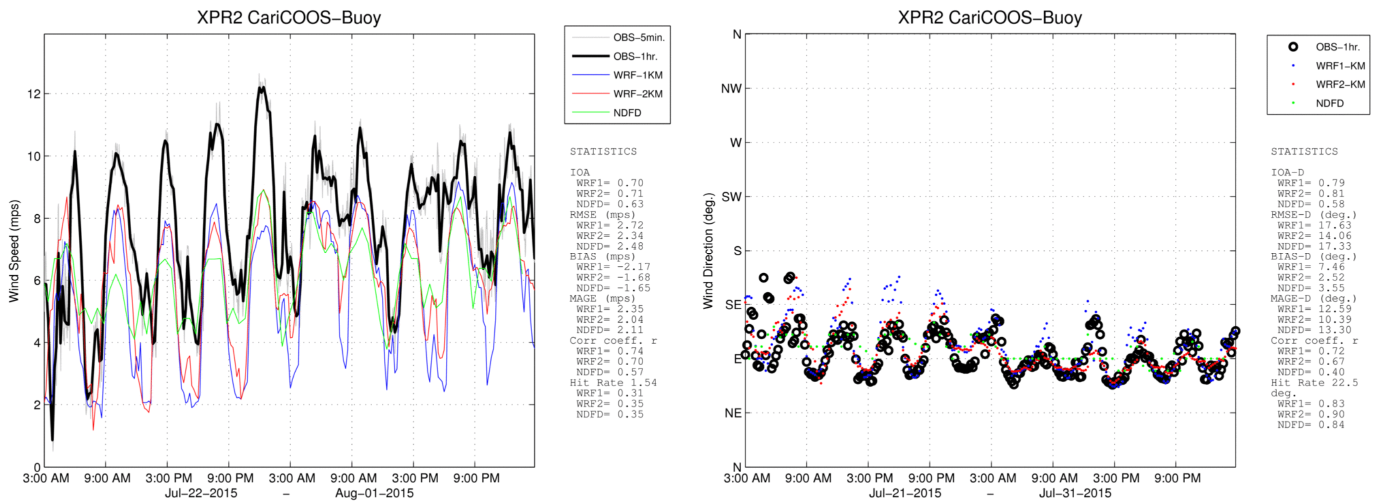
(a) (b)

Figure 2. Ten-day validation plots for CariCOOS/WxFlow station XREY located at Marina Puerto Del Rey Fajardo, PR: (a) wind speed (b) wind direction.



(a) (b)

Figure 3. Ten-day validation plots for CariCOOS/WxFlow station XYAB located at the Port of Yabucoa, PR: (a) wind speed (b) wind direction.



(a) (b)

Figure 4. Ten-day validation plots for CariCOOS Buoy B (XPR2) located north the Bay of San Juan, PR: (a) wind speed (b) wind direction.

It is shown from the wind speed validation plot of XREY station in Figure 2(a) that all three models are overestimating the in-situ observations. This can be reassured by looking at the bias statistical value. All three mean bias values are positive, meaning an overestimation on the prediction. The behavior of the model improving statistical measurements with increased resolution is consistent across the three models. For example, considering the wind speed index of agreement, an improvement of 26% and 52% is noted for WRF_NMM_2KM and WRF_NMM_1KM, respectively, when compared to the NWS NDFD. On the other hand, the wind direction validation plot of XREY, shown in Figure 2(b), presents nearly similar measurements on both WRF models when compared to NWS NDFD, resulting in similar statistical measurements. These similar results can be explained by the location of this particular station (XREY) on the east side of the Puerto Rico, which is dominated by easterly trade winds.

The wind speed validation plot of station XYAB is presented in Figure 3(a). An improvement of 24% and 47% in IOA is noted for WRF_NMM 2km and 1km, respectively, in relation to NWS NDFD. Also, an overall improvement is observed by the 1-km WRF model on XYAB when compared to all statistical parameters for both wind speed and direction forecasts. The statistical values in Figure 3(b) reveal an improvement in WRF to forecast wind direction.

The wind speed validation plot of Buoy B (XPR2) is presented in Figure 4(a). By looking at the IOA, it can be noted an improvement of 13% and 11% of this statistical measure in the WRF_NMM models of 2-km and 1-km when compared to NWS NDFD, respectively. In a similar manner, an overall improvement is observed in wind direction on this buoy (XPR2) as shown in Figure 4(b).

B. Tabulated validation experiment results

The real-time validation toolbox was used to evaluate model skill at all sites for an experiment length of 21-day. The validation period selected for this experiment ranges from July 11, 2015, to July 31, 2015. Tables 1 and 2 summarize the statistical parameters results for all available CariCOOS observing assets concerning wind speed and direction. A color gradient code format is selected to compare the three models for each particular statistical parameter, where the intense color indicates the "best" and the light colors indicating the "worst" model prediction statistic value.

The results presented in Table 1 indicate that the WRF_NMM_1KM model, in general, performs better in most cases compared to the WRF_NMM_2KM and NWS NDFD operational model. In summary all buoy sites and land-based stations in Puerto Rico show better statistical parameters. The exceptions are stations XBRO, located between St. Thomas and St. Croix, and XWGO, located at the highest peak in St. Thomas. On the other hand, Table 2 reveals that wind direction forecasts were improved at all sites. These findings may be indicative that finer resolution models should be employed in the U.S. Virgin Islands to properly solve topographic effects.

Table 1. Summary of wind speed validation for all CariCOOS observations

Station	*r*			*MB (m/s)*			*MAGE (m/s)*			*RMSE (m/s)*			*IOA*			*HR*		
	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD
XJUA - San Juan NavAid, PR	0.74	0.73	0.52	-1.31	-0.92	-0.64	1.82	1.65	1.89	2.20	1.98	2.30	0.79	0.80	0.64	0.44	0.51	0.48
XREY - Puerto Del Rey Fajardo, PR	0.48	0.44	0.25	0.18	0.44	0.99	0.92	0.93	1.25	1.19	1.18	1.57	0.69	0.65	0.48	0.83	0.83	0.67
XMRS - Las Marea Guayama, PR	0.70	0.65	0.24	0.30	0.29	-0.16	1.69	1.84	2.25	2.06	2.18	2.74	0.74	0.68	0.47	0.52	0.43	0.38
XAGU - Aguadilla, PR	0.52	0.53	0.25	2.20	2.93	2.21	2.44	3.03	2.53	2.89	3.43	3.02	0.60	0.54	0.47	0.31	0.19	0.31
XCDP - Club Deportivo Cabo Rojo, PR	0.49	0.55	0.39	1.99	1.87	2.16	2.32	2.09	2.29	2.82	2.59	2.77	0.54	0.57	0.49	0.39	0.46	0.39
XYAB - Yabucoa, PR	0.64	0.56	0.25	-0.01	-0.10	-0.04	1.00	1.12	1.34	1.38	1.49	1.80	0.75	0.67	0.44	0.81	0.75	0.67
XGUR - Gurabo, PR	0.84	0.83	0.50	1.99	2.44	2.55	2.01	2.45	2.72	2.33	2.72	3.11	0.76	0.70	0.56	0.37	0.21	0.26
XPTRP4 - Rincon, PR	0.36	0.37	0.20	1.01	2.19	1.77	1.36	2.30	1.98	1.72	2.76	2.37	0.53	0.41	0.38	0.63	0.31	0.43
Buoy A - Ponce, PR	0.60	0.56	0.23	-0.72	-0.68	-0.97	1.34	1.35	1.77	1.64	1.71	2.19	0.71	0.69	0.50	0.65	0.65	0.55
Buoy B - San Juan, PR	0.67	0.68	0.44	-1.82	-1.47	-1.46	2.22	2.00	2.18	2.61	2.29	2.57	0.70	0.72	0.58	0.35	0.35	0.35
Buoy C - South of St. John, US VI	0.67	0.52	0.44	-0.23	-0.43	-0.06	0.79	0.99	0.89	0.99	1.22	1.14	0.79	0.69	0.63	0.89	0.81	0.85
Buoy E - Vieques, PR	0.78	0.63	0.59	-0.55	-0.94	-0.81	0.81	1.18	1.14	1.01	1.41	1.36	0.81	0.68	0.68	0.88	0.71	0.74
Buoy XVIA - South of St. Thomas , US VI	0.71	0.61	0.61	-0.72	-1.06	-0.80	0.98	1.28	1.16	1.20	1.52	1.37	0.76	0.67	0.68	0.81	0.64	0.73
XBUK - Buck Island, US VI	0.69	0.59	0.55	-1.55	-1.97	-1.76	1.69	2.11	1.92	1.96	2.39	2.23	0.64	0.56	0.57	0.47	0.32	0.39
XBRO - Two Brothes, US VI	0.64	0.57	0.42	-1.71	-1.18	-0.05	1.79	1.41	1.18	2.08	1.73	1.48	0.59	0.62	0.63	0.42	0.62	0.73
XCRX - St. Croix, US VI	0.68	0.57	0.27	2.07	1.72	2.07	2.10	1.82	2.26	2.45	2.27	2.77	0.63	0.60	0.49	0.40	0.49	0.46
XWGO - Crown Mountain, US VI	-0.21	0.23	0.27	1.80	2.42	3.03	2.04	2.45	3.03	2.76	2.86	3.37	0.34	0.43	0.40	0.54	0.31	0.14
XSAV - Savana Island, US VI	0.72	0.23	0.18	1.13	1.62	2.21	1.39	2.11	2.42	1.70	2.48	2.91	0.77	0.51	0.48	0.63	0.39	0.37

Table 2 Summary of wind direction validation for all CariCOOS observations

Station	*r*			*MB (deg)*			*MAGE (deg)*			*RMSE (deg)*			*IOA*			*HR*		
	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD	WRF 1KM	WRF 2KM	NDFD
XJUA - San Juan NavAid, PR	0.50	0.51	0.28	5.90	-0.42	0.00	18.16	16.04	20.02	29.09	27.37	30.26	0.68	0.64	0.42	0.76	0.83	0.71
XREY - Puerto Del Rey Fajardo, PR	0.60	0.61	0.37	-0.80	-6.20	-2.30	10.08	11.89	13.25	15.66	16.88	18.09	0.70	0.71	0.56	0.89	0.88	0.83
XMRS - Las Marea Guayama, PR	0.72	0.72	0.39	3.05	2.29	3.58	8.44	9.34	13.68	12.45	12.52	17.10	0.81	0.78	0.60	0.94	0.95	0.79
XAGU - Aguadilla, PR	0.26	0.28	0.16	1.46	-2.95	-1.96	32.00	31.73	33.33	48.77	49.21	50.60	0.55	0.52	0.30	0.60	0.60	0.57
XCDP - Club Deportivo Cabo Rojo, PR	0.46	0.34	0.19	1.38	6.14	22.72	46.53	50.69	55.38	69.81	76.08	80.86	0.56	0.35	0.25	0.47	0.48	0.42
XYAB - Yabucoa, PR	0.07	0.14	0.02	0.75	-3.91	0.61	14.44	17.68	18.60	27.91	29.79	30.97	0.59	0.51	0.40	0.88	0.83	0.75
XGUR - Gurabo, PR	0.01	-0.04	-0.06	2.71	-4.24	-3.29	42.46	43.52	40.68	64.36	65.25	61.70	0.43	0.23	0.28	0.55	0.53	0.56
XPTRP4 - Rincon, PR	0.34	0.16	0.00	4.66	1.97	9.66	32.49	35.78	45.23	52.90	56.33	65.92	0.74	0.60	0.45	0.63	0.60	0.49
Buoy A - Ponce, PR	0.55	0.54	0.29	2.61	1.69	3.46	8.89	8.70	13.62	15.32	14.59	18.84	0.78	0.79	0.57	0.95	0.94	0.83
Buoy B - San Juan, PR	0.51	0.52	0.26	3.55	-1.93	-0.54	14.12	12.35	15.69	23.92	21.79	25.37	0.69	0.64	0.39	0.84	0.89	0.85
Buoy C - South of St. John, US VI	0.71	0.62	0.41	0.44	-4.34	-2.04	7.04	9.61	10.36	10.19	12.13	13.98	0.81	0.74	0.61	0.96	0.94	0.91
Buoy E - Vieques, PR	0.78	0.69	0.39	3.55	-3.14	-0.22	6.24	6.68	9.41	7.89	8.95	11.87	0.84	0.80	0.61	0.99	0.97	0.94
Buoy XVIA - South of St. Thomas , US VI	0.80	0.70	0.43	-9.94	-13.52	-12.28	10.55	14.04	13.80	12.02	15.75	16.66	0.73	0.61	0.55	0.96	0.90	0.83
XBUK - Buck Island, US VI	0.79	0.71	0.42	10.63	7.09	8.83	11.28	8.69	10.02	12.68	10.74	14.46	0.71	0.76	0.56	0.96	0.96	0.89
XBRO - Two Brothes, US VI	0.65	0.62	0.40	-25.45	-32.28	-31.45	26.45	32.53	31.74	29.58	35.83	36.21	0.52	0.46	0.44	0.36	0.24	0.32
XCRX - St. Croix, US VI	0.80	0.67	0.46	1.55	-2.37	-1.05	8.71	10.65	12.80	11.18	3.18	15.38	0.82	0.74	0.60	0.95	0.92	0.85
XWGO - Crown Mountain, US VI	0.73	0.67	0.43	7.24	-1.01	2.35	18.93	17.33	20.57	23.55	23.16	26.34	0.69	0.66	0.49	0.63	0.75	0.61
XSAV - Savana Island, US VI	0.73	0.57	0.37	6.77	0.29	1.03	13.26	16.48	18.86	19.34	20.49	23.26	0.72	0.66	0.51	0.84	0.76	0.68

IV. CONCLUSION

We have presented a real-time validation toolbox and provided data from validation experiments of 10-days and 21-days. On these experiments, the WRF NMM model implemented by the NWS WFO SJU at 2-km and the CariCOOS 1-km version were evaluated along with the NWS NDFD operational product. The validation experiments compared best aggregate forecast to the CariCOOS in-situ observations of wind speed and direction.

The first validation results presented correspond to a 10-day period, which is the period length used in the real-time product available at CariCOOS web portal (http://www.caricoos.org/drupal/wind_validation_map). In a second experiment of 21-day, complete statistical validation results of wind speed and direction were provided in a simple summary statistics color-coded table format to emphasize the model with the best skill.

In conclusion, the validation toolbox facilitates the validation of both WRF NMM model configuration implemented by NWS WFO SJU and CariCOOS and NWS NDFD operational product. Also, the results feature an improvement in NWP for the region. The improvement is mainly attributed to an increase in horizontal resolution when comparing CariCOOS-WRF_NMM_1KM model to the WRF_NMM_2KM along coastal weather stations and buoys. Finally, the validation reveals an overall improved forecast skill of both WRF model configurations compared to the NWS NDFD for most of the sites evaluated; the exceptions are for weather stations XBRO and XWGO. These findings reveal that a WRF model configuration domain with lower resolution than 1-km might be necessary to the U.S. Virgin Islands.

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