proceedings

MDPI

Proceedings

Performance evaluation of Numerical Tools for Hurricane Forecast (NTHF) system during 2020 North Atlantic tropical cyclones season

Albenis Pérez-Alarcón[1,3,*], **José C. Fernández-Alvarez**[1,3] **and Alfo J. Batista-Leyva**[2]

[1] Departmento de Meteorología, Instituto Superior de Tecnologías y Ciencias Aplicadas, Universidad de La Habana, 10400, La Habana, Cuba. albenisp@instec.cu (A.P.-A.); jcfernandez@instec.cu (J.C.F.-A.).
[2] Departamento de Física Atómica y Molecular, Instituto Superior de Tecnologías y Ciencias Aplicadas, Universidad de la Habana, 10400 La Habana, Cuba; abatista (A.J.B.-L.)
[2] Centro de Investigación Mariña, Universidade de Vigo, Environmental Physics Laboratory (EphysLab), Campus As Lagoas s/n, Ourense, 32004, Spain
* Correspondence: albenis.perez.alarcon@uvigo.es (A.P.-A.)

Abstract: This study evaluates the performance of the Numerical Tools for Hurricane Forecast (NTHF) system during the 2020 North Atlantic (NATL) tropical cyclones (TCs) season. The system is configured to provide 5-day forecasts with basic input from the National Hurricane Center (NHC) and the Global Forecast System. For the NTHF validation, the NHC operational best track was used. The average track errors for 2020 NATL TCs ranged from 62 km at 12 h to 368 km at 120 h. The NTHF track forecast errors displayed an improvement higher than 60% over the guidance Climatology and Persistence (CLIPER) model from 36 h to 96 h, although NTHF was better than CLIPER in all forecast period. The forecasts errors for the maximum wind speed (minimum central pressure) ranged between 20 km/h and 25 km/h (4 hPa to 8 hPa), but the NTHF model intensity forecasts showed only marginal improvement less than 20% after 78 h over the baseline Decay Statistical Hurricane Intensity Prediction Scheme (D-SHIPS) model. Nevertheless, NTHF's ability to intensity forecast of the 2020 NATL TCs was higher than the NTHF average ability in the 2016-2019 period.

Keywords: tropical cyclones; numerical model; statistical validation; intensity forecast; track forecast

Citation: Pérez-Alarcón, A.; Fernández-Alvarez, J.C.; Batista-Leyva, A.J. Performance evaluation of Numerical Tools for Hurricane Forecast (NTHF) system during 2020 North Atlantic tropical cyclones season. *Proceedings* **2021**, 65, x. https://doi.org/10.3390/xxxxx

Received: date
Accepted: date
Published: date

1. Introduction

Tropical cyclones (TCs) are low-pressure systems with a warm core that form over tropical and subtropical waters [1]. Besides, TCs are one of the most destructive natural catastrophes in the world, due to strong surface winds, tornadoes, storm surges, and heavy rainfall events [2]. The destructive effect of TCs mostly depends on changes in intensity and the trajectory followed by the TC during its lifetime [3]. Therefore, accurate forecasting of TCs trajectory and intensity plays an important role to mitigate the impact of these atmospheric phenomena [4].

The TC track forecast errors have continuously decreased in the last decades, however, the same tendency has not been observed in the intensity forecast [5]. This behavior may be related to the complex interactions that lead to the intensification of TCs. The TC intensity is not only governed by the interaction between the system and the environment that surrounds it, but also depends on other non-linear factors inherent to the dynamics of the TCs, such as those occurring within or near the eye wall [6]. Moreover, several factors that modulate TC intensity changes range from hundreds of kilometers, as the environmental shear, to tens of meters as microphysics processes and turbulent flows within the atmospheric boundary layer [7].

In recent years, numerical prediction models have been widely implemented to provide high-resolution spatial and temporal TCs forecasts [4]. Since 1999 the trajectory forecasts have improved substantially not only in the Global Forecast System (GFS) model, but also in the Geophysical Fluid Dynamics Laboratory (GFDL) model [8]. Combining the advancements of the GFDL and GFS models, the US National Centers for Environmental Prediction (NCEP)/Environmental Modeling Center (EMC) developed the Hurricane Weather Research and Forecast (HWRF) model to address the nation's next-generation hurricane forecasting problems. HWRF became operational in 2007 in the NCEP and has been constantly improved since then using annual updates to increase the forecast skill for all global basins [9]. As part of the National Oceanic and Atmospheric Administration (NOAA) Hurricane Forecast Improvement Project (HFIP) [10], the HWRF has advanced and evolved as one of the best models for tropical cyclone forecasting [9]. Furthermore, since 2017 the Hurricanes in a Multi-scale Ocean-coupled Non-hydrostatic (HMON) model has been operational at the NCEP, which is an important step towards implementing a long-term strategy for multiple static and moving nest [9].

However, both the HWRF and HMON models require high computing resources for their operational runs, which limit their use and implementation in research centers in low-income countries. In Cuba, for example, Pérez-Alarcón et al. [11] developed the Numerical Tools for Hurricane Forecast (NTHF) system, which is based on the atmospheric component of the HWRF model and can be implemented using low computational power. NTHF has been operating during the North Atlantic basin TC season since 2019 in the Department of Meteorology of the Higher Institute of Technologies and Applied Sciences, University of Havana.

The main goal of this work is to assess the NTHF skill to forecast the intensity and trajectory of TCs during the 2020 North Atlantic season. In the next section, we provide a brief description of the NTHF system, especially the physics and computing domains configuration. The results are discussed in Section 3 and conclusions are drawn in Section 4.

2. Material and Methods

2.1 Brief description of the NTHF system

The NTHF system is based on the atmospheric component of the HWRF model as dynamic core, following the recommendations of Pérez-Alarcón et al. [11]. Furthermore, it is composed by computational algorithms that guarantee the initialization of the model during the operational runs with the position of the storm provided by the NHC and the forecast outputs of the GFS model. Moreover, NTHF system contains some post-processing python scripts. Figure 1 shows the block diagram of NTHF system.

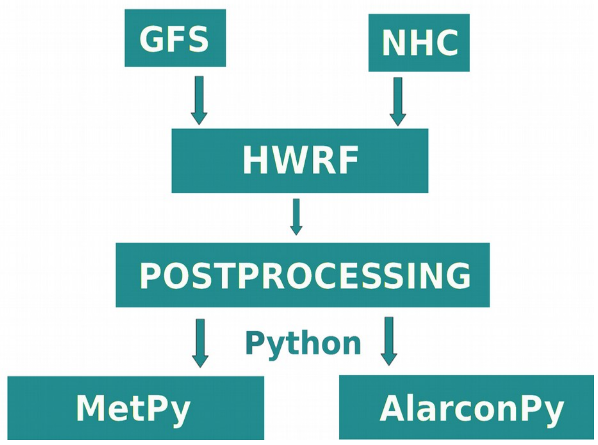

Figure 1. NTHF block diagram. Metpy [12] and Alarconpy [13] are Python packages for the treatment and handling of meteorological data. NTHF only use the atmospheric component of HWRF model.

Furthermore, NTHF uses two bidirectional interactive nested domains with 27 and 9 km of horizontal resolution and 32 vertical levels. The parent grid covers approximately a 72°x72° area with 0.18 horizontal grid spacing while the nested domain covered an 11°x10° area with 0.06 grid spacing. It also uses a rotated latitude/longitude staggered Arakawa E-grid and has the possibility of moving meshes for vortex tracking [11]. NTHF is also skillful to forecast the precipitation associated to TCs [13]. The NTHF operational runs cover a 120 hour forecast and are initialized at 0000 and 1200 UTC with the GFS outputs at 0.25 degrees of spatial resolution (update for 2020 NATL TC season forecast), while the boundary conditions were updated every 6 hours. Table 1 shows the most important aspects of the physical configuration of NTHF.

Table 1. Configuration used in the NTHF system.

Parameterization of Longwave Radiation	Rapid Radiative Transfer Model for General Circulation Models (RRTMG)
Parameterization of Shortwave Radiation	Rapid Radiative Transfer Model for General Circulation Models (RRTMG)
Cumulus Parameterization	Scale-Aware Simplified Arakawa-Schubert
Microphysics Parameterization	Ferrier-Aligo Scheme
Parameterization of the Planetary Boundary Layer	HWRF Planetary Boundary Layer
Surface Layer Parameterization	HWRF surface-layer Scheme
Land model	Noah Land Surface Model
Vortex Tracker	GFDL vortex tracker
Vortex Relocation	no
Coupling with the ocean model	no

2.1 Data

The 2020 North Atlantic TCs season was the most active on record since 1851, with 30 named storms, of which 7 reached the hurricane category and 6 the major hurricane (category 3+ on the Saffir–Simpson hurricane wind scale).

During 2020 NATL TC season there were 247 NTHF forecasts, which is notably higher than the 82 long-term average (2016 - 2019) number of NTHF forecasts. Table 2 summarizes the number of NTHF predictions analyzed in each forecast hour.

Table 2. Number of NTHF predictions for each forecast hour

	12 h	**24 h**	**36 h**	**48 h**	**60 h**	**72 h**	**84 h**	**96 h**	**108 h**	**120 h**
NTHF 2020	247	216	185	161	151	119	94	76	54	44
NTHF 2016-2019	330	303	277	244	212	184	157	123	103	85

For verification, the operational NHC best track available on https://ftp.nhc.noaa.gov/atcf/btk/,(Accessed on 8 April 2021) was used. From this, the position, the maximum wind speed and the minimum central pressure of each system was extracted. The Atlantic hurricane database (HURDAT2)[15] with 2020 NATL TCs is not available yet. Furthermore, the official NHC forecast, HWRF and HMON prediction were extracted from the Automated Tropical Cyclone Forecasting System (ATCF) files on https://ftp.nhc.noaa.gov/atcf/aid_public/ (Accessed on 8 April 2021)

2.2 Methodology

The NTHF provide as an output the tropical cyclones position, minimum central pressure and maximum simulated wind speed. To gain a more complete overview of NTHF performance, the NTHF forecast was statistically compared with the NHC official forecast and the prediction of HWRF, HMON, Climatology and Persistence (CLIPER) and Decay Statistical Hurricane Intensity Prediction Scheme (D-SHIPS) models for the same forecast hours and cases.

To evaluate the performance of NTHF system in predicting the 2020 NATL TCs trajectory and intensity, a set of statigraphs was used: mean absolute error, bias and forecasting skill. The latest statigraphs is widely applied by NHC for the official forecast verification and is define as follow:

$$S_f = \frac{e_b - e_f}{e_b} \tag{1}$$

where e_b is the baseline error and e_f the forecast error. The CLIPER and D-SHIPS errors were used as reference to quantify the skill in the track and intensity forecast, respectively

3. Results and Discussion

3.1 Track forecast errors

Track forecast errors, which are defined as the distance between the forecast storm center and the storm best track center, were conducted for all NTHF runs. During the 2020 NATL TC season, the NTHF track forecast errors ranged from 62 km at 12 h to 368 km at 120 h, as shown in Figure 2a. For all forecasts hours, the NTHF track forecast are comparable at most lead times with the HWRF, HMON and the official NHC forecasts, however, between 48 hand 96 h it exhibits the highest error of all.

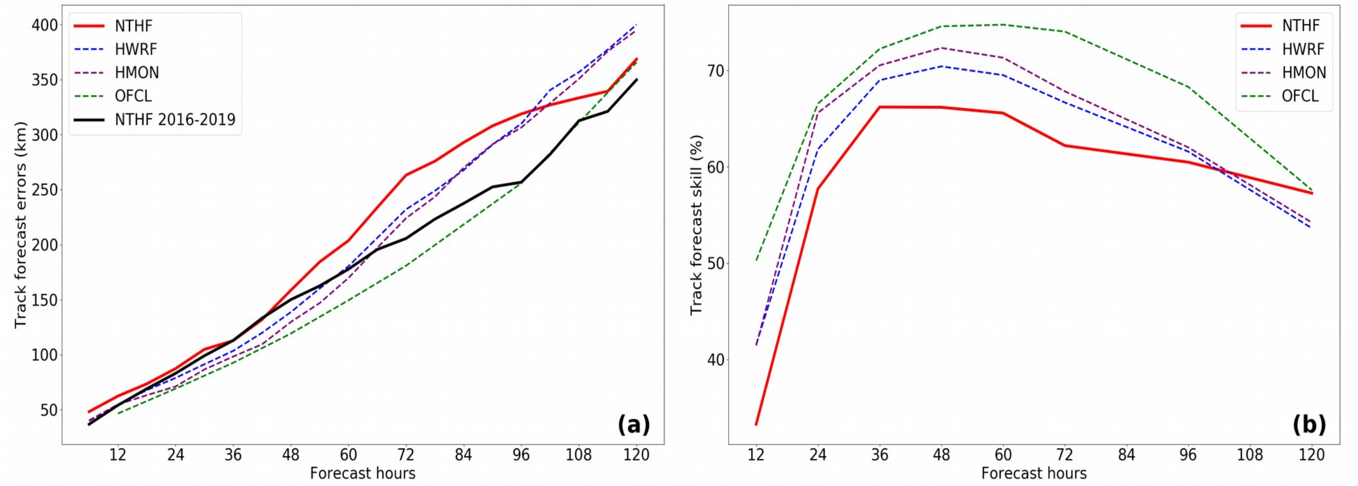

Figure 2. NTHF **(a)** track forecast errors and **(b)** track forecast improvement (vs CLIPER) are shown for the 2020 North Atlantic TC season. The track forecast errors and track forecast skill over CLIPER for HWRF, HMON and the official NHC are also plotted. The black line represent the 2016-2019 NTHF average and OFCL (dashed green line) represent the official NHC forecast.

Moreover, the mean track forecast error of NTHF is close to or higher than the NTHF average errors from 2016 to 2019 for almost all of the lead times throughout 120 h. On average, NTHF errors in the 2020 NATL TC season were 13% higher than the NTHF average in the previous four years (2016-2019). Furthermore, Figure 2b reveals that NTHF skill to track forecast was 40-60% over CLIPPER ability during all forecast hours, but NTHF exhibited the worst performance of all models used as guidance.

This slight increase in the mean track forecast errors may be linked to the 190 (76%) initializations of NTHF when TCs were tropical depression or tropical storm. Previously, Pérez-Alarcón et al. [11] pointed out that the largest track errors of NTHF are observed in the trajectory forecast of tropical depressions and tropical storms. At these stages, the vortex is generally weak, thus the vortex tracking algorithm (GFDL vortex tracker) can track secondary vortices, which are not directly related to the TC center.

The NTHF track errors were also examined for every Atlantic basin TC individually for 2020 TC season (not shown). It is remarkable that track errors and the NTHF ability vary considerably from one TC to another. The highest track errors were found during the operational runs of the Tropical Storm Cristobal and the Hurricane Eta. Both TCs described complex trajectories, as shown in Figure 3, that affected the NTHF skill.

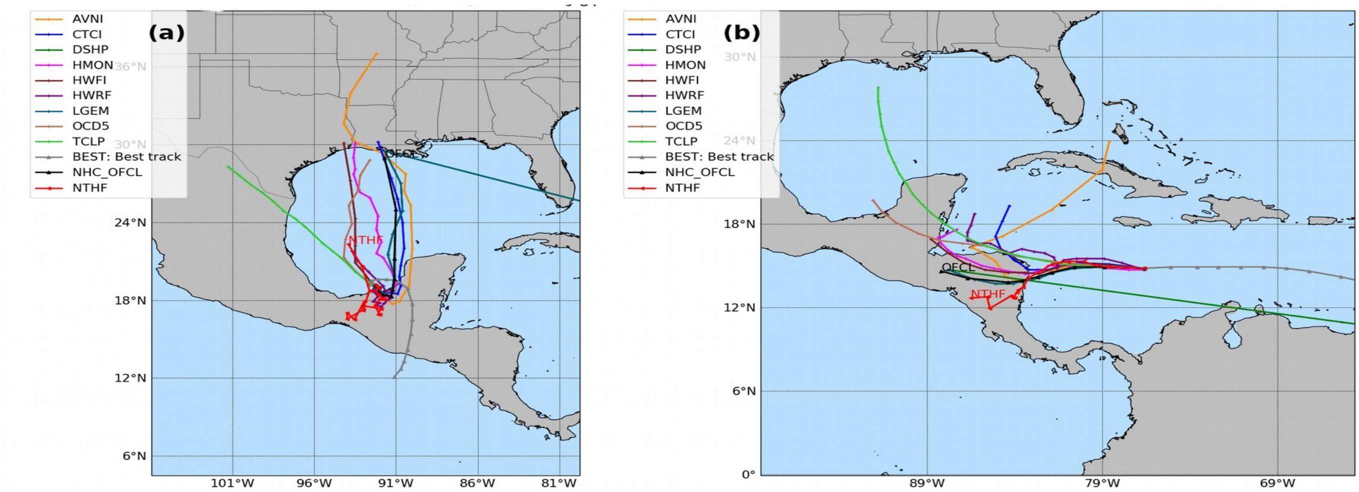

Figure 3. Operational NTHF track forecast (red) for **(a)** tropical storm Cristobal initialized at 20200603 0000 UTC and **(b)**Hurricane Eta initialized at 20201101 1200 UTC. The official NHC forecast is represented by the black line. The track forecasts of other models available in the ATCF are also plotted.

Furthermore, the operational NTHF track guidance has generally remained inferior to global model track guidance [11]. TC tracks are primarily determined by the large-scale environment, especially the large-scale wind fields [16,17]. Regarding the previous issue, the operational NTHF has two important limitations: it is storm centric and has a small outermost domain.

3.2 Intensity forecast errors

The TCs intensity forecasts were verified against the operational NHC best-track data, as mentioned earlier. Figure 4 shows a comparison of the performance of NTHF, HWRF, HMON, average NTHF from 2016-2019 and the official NHC forecast errors. From Figure 3a, NTHF underestimated between 10 km/h and 20 km/h the maximum wind speed of the 2020 NATL TCs, however, its performance was notably higher than the NTHF average from 2016 to 2019. Nevertheless, the NTHF exhibits the worst performance of all. The wind velocity bias (Figure 4a) suggests that the model predicts weaker storms. In agreement with Pérez-Alarcon et al [11], the largest errors were observed in the first 12 h - 36 h, probably as consequence of the non vortex relocation during model initialization and the time needed by the model to derive a physical valid state.

Overall, the average improvement is less than 20% over D-SHIPS from 78 h to 120 h, as reflected in the intensity forecast skill comparison in Figure 4b. Although, after the 48 forecast hours the NTHF ability was similar to that of the HMON model, while it was better than HWRF model after 72 hours.

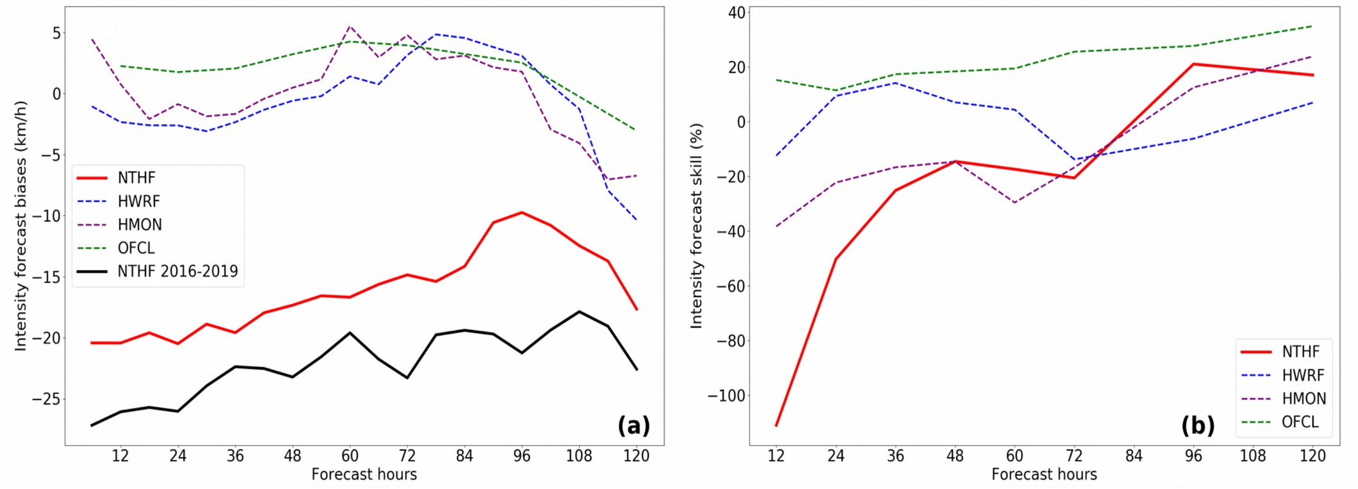

Figure 4. NTHF **(a)** maximum wind speed forecast biases and **(b)** intensity forecast skill (vs D-SHIPS) are shown for the 2020 North Atlantic TC season. The maximum wind speed forecast biases and intensity improvement over D-SHIPS for HWRF, HMON and the official NHC are also plotted. The black line represent the 2016-2019 NTHF average and OFCL (dashed green line) represent the official NHC forecast.

Results illustrated in Figure 5 show that NTHF overestimated the minimum central pressure during the 2020 NATL TC season, and, as for maximum wind speed, NTHF predicted TCs weaker than those real occurring. The mean absolute error range from 4 hPa to 8 hPa along the 120 forecast hours. Furthermore, NTHF was 36.7% higher than average NTHF skill in 2016-2019 period. Nevertheless, it is clear that NTHF did not perform as well as HWRF and HMON predicting the TCs minimum central pressure.

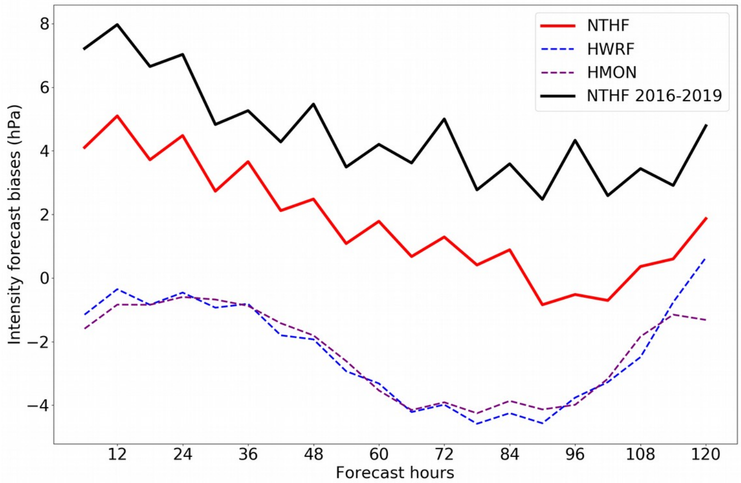

Figure 5. NTHF minimum central pressure forecast biases. The central pressure forecast biases for HWRF, HMON and the official NHC are also plotted. The black line represent the 2016-2019 NTHF average.

The NTHF improvements in the intensity forecast during the 2020 NATL TC season compared to the 2016-2019 average may be related to the increase in the spatial resolution of the input data (from 0.5ºx 0.5º to 0.25º x 0.25º in latitude and longitude). The accuracy of the initial and boundary conditions plays an important role in the model skill to represent the TC trajectory and intensity changes [17].

4. Conclusions

Accurate forecasting of the trajectory and intensity of tropical cyclones (TCs) plays an important role to mitigate the impact of these atmospheric phenomena. Recently, numerical prediction models have been widely implemented to provide special forecasts. Numerical Tools for Hurricane Forecast system, based on the atmospheric component of the Hurricane Weather Research and Forecast, is one of the numerical TCs forecasting models. In this study, the NTHF system was evaluated for the 2020 North Atlantic tropical cyclones season.

Track forecast results from the NTHF exhibited the mean track errors increasing linearly with time from 62 km at 12 h to 368 km at 120 h forecast time. Although the NTHF track forecast errors showed an improvement higher than 60% over the reference Climatology and Persistence model (CLIPER) from 36 h to 96 h, the NTHF skill was 13% lower than the NTHF 2016 - 2019 average.

Furthermore, NTHF predicted on average a weaker TC than the one occurring, but showed an improvement of 26.5% and 36.7% compared to the 2016 - 2019 average in the maximum wind speed and minimum central pressure forecasts, respectively. This improvement in the intensity forecast can be attributed to the increase in the spatial resolution of the input data. Nevertheless, the NTHF model intensity forecasts showed only marginal improvement (less than 20%) after 78 h over the baseline Decay Statistical Hurricane Intensity Prediction Scheme (D-SHIPS) model. The maximum wind speed (minimum central pressure) ranged between 20 km/h and 25 km/h (4 hPa to 8 hPa).

In future works, we will perform a more in-depth evaluation of NTHF ability to forecast the trajectory and intensity of TCs classified by different categories the Saffir-Simpson scale, as well as the rapid intensification changes. We are also expecting to conduct an evaluation of the NTHF skill for determining rainfall pattern, average rainfall, rainfall volume, and extreme amounts of rain observed during the 2020 NATL landfalling TCs or moved very close to coastline

Author Contributions: A.P-A. conceived the idea of the study. A.P-A., and J.C.F-A. processed the data and made the figures. A.P-A. And A.J.B-L analyzed the results and wrote the manuscript. All authors analyzed the results and revised the final version of the manuscript.

Funding: This research received no external funding

Institutional Review Board Statement: Not applicable

Informed Consent Statement: Not applicable

Data Availability Statement: The 6-hourly tropical cyclone track data supporting this article are based on publicly available operational best track from the National Hurricane Center at https://ftp.nhc.noaa.gov/atcf/btk. The Automated Tropical Cyclone Forecasting System (ATCF) files were obtained from https://ftp.nhc.noaa.gov/atcf/aid_public. The Global Forecast System (GFS) model outputs from NTHF operational runs were downloaded from https://nomads.ncep.noaa.gov/pub/data/nccf/com/gfs/prod/. The NTHF outputs to reproduce our results are obtained upon request from the corresponding author.

Acknowledgments: The authors acknowledge the availability of public datasets from the National Hurricane Center and the Global Forecasting System.

Conflicts of Interest: The authors declare no conflict of interest

References

1. Roy, C.; Kovordányi, R.. Tropical cyclone track forecasting techniques – A review. *Atmos. Res.* **2012**, 104-105, 40–69. doi:10.1016/j.atmosres.2011.09.012
2. Ankur, K.; Busireddy, N.K.R.; Osuri, K.K.; Niyogi, D. On the relationship between intensity changes and rainfall distribution in tropical cyclones over the North Indian Ocean. *Int. J. Climatol.* **2020**, 40, 2015–2025. doi: 10.1002/joc.6315
3. Ye, M.; Wu, J.; Liu, W.; He, X.; Wang, C. Dependence of tropical cyclone damage on maximum wind speed and socioeconomic factors. *Environ. Res. Lett*. **2020**, 15, 094061. doi: 10.1088/1748-9326/ab9be2
4. Al-Yahyai, S.; Thani, A.A.; Al-kaabi, N.; Al-Sudairi, K.; Al-Mawali, B.; Amri, I. A. Performance evaluation of HWRF model during post monsoon tropical cyclone Nilofar. *Arab. J. Geosci. **2017***, 10, 76. doi: 10.1007/s12517-017-2866-7
5. Otkin, J. A.; Lewis, W. E.; Lenzen, A. J.; McNoldy, B. D.; Majumdar, S. J. Assessing the Accuracy of the Cloud and Water Vapor Fields in the Hurricane WRF (HWRF) Model Using Satellite Infrared Brightness Temperatures, *Mon. Wea. Rev.* **2017**, 145(5), 2027-2046, doi: 10.1175/MWR-D-16-0354.1

6. Tang, J.; Zhang, J. A.; Kieu, C.; Marks, F. Sensitivity of hurricane intensity and structure to two types of planetary boundary layer parameterization schemes in idealized HWRF simulations. *Trop Cyclone Res Rev.* **2018**, 7, 4, 1–11. doi: 10.6057/2018TCRR04.01
7. Gopalakrishnan, S. G.; Marks Jr, F.; Zhang, X.; Bao, J.-W.; Yeh, K.-S.; Atlas, R. The experimental HWRF system: A study on the influence of horizontal resolution on the structure and intensity changes in tropical cyclones using an idealized framework. *Mon. Wea. Rev.* **2011**, 139(6):1762–1784. doi: 10.1175/2010MWR3535.1
8. Liu Q.; Lord, S.; Surgi, N., Zhu, Y.; Wobus, R.; Toth, Z.; Marchok, T. Hurricane relocation in global ensemble forecast system. In: Preprints 27th conference on hurricanes and tropical meteorology, Monterey, CA, American Meteorological. Society **2006**, P5.13
9. Mehra, A.; Tallapragada, V.; Zhang, Z.; Liu, B.; Shub, Lin.; Wang, W.; Kimb, H.-S. Advancing the State of the Art in Operational Tropical Cyclone Forecasting at Ncep. *Trop Cyclone Res Rev.* **2018**, 7(1), 51-56. doi: 10.6057/2018TCRR01.06
10. Gall, R.; Franklin, J.; Marks, F. D.; Rappaport, E. E. and Toepfer, F. The Hurricane Forecast Improvement Project. *Bull. Am. Meteorol. Soc.* **2013**, 94, 329-343. doi: 10.1175/BAMS-D-12-00071.1
11. Pérez-Alarcón, A., Fernández-Alvarez, J. C., Rodírguez-Díaz, O., Batista-Leyva, A. J., and Pérez-Suárez, R. System for numerical forecast of intensity and trajectory of tropical cyclones in the North Atlantic basin. *Rev. Cub. Met. 2021*, 27(1), online, https://eqrcode.co/a/43uSoj
12. May, R.; Arms, S.; Marsh, P.; Bruning, E. and Leeman, J. Metpy: A Python package for meteorological data. *Unidata*, **2020**, doi: 10.5065/D6WW7G29. (last accessed March 2021)
13. Pérez-Alarcón, A.; Fernández-Alvarez, J.C. Alarconpy: A Python Package for Meteorologists, *Zenodo* **2021**, doi:10.5281/zenodo.4493257. (last accessed March 2021)
14. Fernández-Alvarez ,J.C.; Pérez-Alarcon, A.; Batista-Leyva, A.J.; Díaz-Rodríguez, O. Evaluation of Precipitation Forecast of System: Numerical Tools for Hurricane Forecast, *Advances in Meteorology* **2020**, 2020, 8815949, 16. doi: 10.1155/2020/8815949
15. Landsea, C.W.; Franklin, J.L. Atlantic Hurricane Database Uncertainty and Presentation of a New Database Format. *Mon. Wea. Rev.* **2013**, 141, 3576-3592. doi: 10.1175/MWR-D-12-00254.1
16. Franklin, J. L.; Feuer, S. E.; Kaplan, J.; Aberson, S. D. Tropical cyclone motion and surrounding flow relationships: Searching for beta gyres in omega dropwindsonde datasets. *Mon. Wea. Rev.* **1996**, 124, 64–84. doi:10.1175/1520-0493(1996)124<0064:TCMASF>2.0.CO;2.
17. Singh K.S.; Mandal M. Impact of Initial and Boundary Conditions on Mesoscale Simulation of Bay of Bengal Cyclones Using WRF-ARW Model. In: Ray K., Mohapatra M., Bandyopadhyay B., Rathore L. (eds) High-Impact Weather Events over the SAARC Region. Springer, Cham, **2015**. doi: 10.1007/978-3-319-10217-7_12