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Numerical models for tropical cyclones prediction in Cuba

Albenis Pérez-Alarcón [1*] https://orcid.org/0000-0002-9454-2331
José Carlos Fernández-Álvarez [1] https://orcid.org/0000-0003-3409-6138
Oscar Díaz-Rodríguez [2] https://orcid.org/0000-0002-9635-1184
Alfo José Batista-Leyva [3] https://orcid.org/0000-0003-4317-0360
Ramón Pérez-Suárez [1,4] https://orcid.org/0000-0002-8024-2303
Onel Rodríguez-Navarro [1] https://orcid.org/0000-0003-4277-5384
Patricia Coll-Hidalgo [5] https://orcid.org/0000-0003-4127-4369
Arlett Díaz-Zurita [5] https://orcid.org/0000-0002-8982-7527

[1] Departamento de Meteorología, Instituto Superior de Tecnologías y Ciencias Aplicadas, Universidad de La Habana. La Habana, Cuba
[2] Instituto de Ciencias de la Atmósfera y Cambio Climático, Universidad Autónoma de México. Ciudad México, México
[3] Departamento de Física Atómica y Molecular, Instituto Superior de Tecnologías y Ciencias Aplicadas, Universidad de La Habana. La Habana, Cuba
[4] Centro del Clima, Instituto de Meteorología, Loma de Casablanca. La Habana, Cuba
[5] Oficina Principal de Vigilancia Meteorológica, Empresa Cubana de Navegación Aérea, Carretera Panamericana y Final, Boyeros. La Habana, Cuba

**Corresponding Author:* albenisp@instec.cu

Editor
Lisset González Navarro
Academia de Ciencias de Cuba.
La Habana, Cuba

Translator
Darwin A. Arduengo García
Academia de Ciencias de Cuba.
La Habana, Cuba

ABSTRACT

Introduction: The numerical forecast of tropical cyclones in Cuba is performed through the Short range Prediction System and Numeric Ocean-Atmosphere Forecasting System, but both systems allow the analysis of tropical cyclones in their computing domains. Objective: To develop and implement a model to calculate the potential intensity of tropical cyclones considering their thermoenergetic cycle as a generalized Carnot engine, and a specific numerical forecasting system for monitoring tropical cyclones from their genesis.**Methods:** We modified the classical theory of the potential intensity of tropical cyclones and configured the atmospheric component of the Hurricane Weather Research Forecast model in a new system for its operational run in Cuba. **Results:** We developed and implemented the Hurricane Maximum Potential Intensity Model and the Numerical Tools for Hurricane Forecast. **Discussion:** In the simulations performed with Hurricane Maximum Potential Intensity, it was shown that the observed values of minimum pressure and maximum winds were similar to the simulated values for the most intense hurricanes, and it was detected that the area in which they reached the maximum intensity coincided with the regions predicted by the model. The track errors of the Numerical Tools for Hurricane Forecast ranged from 41 km for the first 12 h to 356 km for the 120 h forecast. In particular, the Numerical Tools for Hurricane Forecast showed an ability to forecast the trajectory of intense hurricanes and the intensity of tropical cyclones from depression to category 3 hurricanes between 36 and 120 h. Numerical Tools for Hurricane Forecast is skillful for forecasting extreme precipitation associated with tropical cyclones in the first 24 h. **Conclusions:** The systems contribute to the operational forecast of

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tropical cyclone activity, the development of new research to improve our knowledge of the dynamic and thermodynamic factors that favor the formation and development of tropical cyclones, and its usage for academic purposes.

Keywords: tropical cyclones; numerical forecast; potential intensity; intensity and trajectory

Modelos numéricos para el pronóstico de ciclones tropicales en Cuba

RESUMEN

Introducción: El pronóstico numérico de ciclones tropicales en Cuba se realiza a través del Sistema de pronóstico inmediato y el Sistema de predicción numérico océano-atmósfera. **Objetivo:** Desarrollar e implementar un modelo para el cálculo de la intensidad potencial de los ciclones tropicales, considerando su ciclo termoenergético como un motor de Carnot generalizado y un nuevo sistema de pronóstico numérico específico para monitorear estos fenómenos desde su génesis. **Métodos:** Se modificó la teoría clásica de intensidad potencial y se configuró la componente atmosférica del modelo Hurricane Weather Research Forecast en un nuevo sistema para sus corridas operativas en Cuba. **Resultados:** Se Desarrollaron e implementaron el modelo de intensidad máxima potencial de ciclones tropicales y las herramientas numéricas para el pronóstico de huracanes. **Discusión:** En las simulaciones realizadas con el mencionado modelo se demostró que los valores observados de presión mínima y vientos máximos fueron similares a los valores simulados para los huracanes más intensos, y se detectó que la zona en la que alcanzaron la intensidad máxima coincidió con las regiones predichas por el modelo. En el caso de las herramientas numéricas para el pronóstico de huracanes, el error en el pronóstico de trayectoria varió de 41 km para las primeras 12 h a 356 km para las 120 h posteriores. En particular esta herramienta mostró la capacidad de pronosticar la trayectoria de huracanes intensos y la intensidad de los ciclones tropicales desde la depresión hasta los huracanes de categoría 3 entre las (36 y 120) h; es hábil para pronosticar precipitaciones extremas asociadas con ciclones tropicales en las primeras 24 h. **Conclusiones:** Los sistemas contribuyen al pronóstico operativo de la actividad de los ciclones tropicales, al desarrollo de nuevas investigaciones para mejorar nuestro conocimiento de los factores dinámicos y termodinámicos que favorecen la formación y desarrollo de los ciclones tropicales y su uso con fines académicos.

Palabras clave: ciclones tropicales; pronóstico numérico; intensidad potencial; intensidad y trayectoria

INTRODUCTION

Tropical cyclones (TCs) are likely to cause natural disasters in coastal regions of tropical and subtropical latitudes, (1) including people deaths and several damages to economic infrastructure (2-4) due to the impacts of strong winds, tornadoes, heavy rainfall, flash flooding, and storm surges. (5) Cuba is located in the path of approximately 32% of TCs formed in the Main Development Region of the North Atlantic (NATL) basin, (6) while TCs formed over the Caribbean Sea and the Gulf of Mexico can also impact directly or indirectly the Cuban territory. Therefore, TCs constitute one of the most important natural hazards for the Cuban people.

Accurate and rapid TC forecast can contribute to the prevention and mitigation of human disasters. (7) While the intensity prediction has shown no consistent improvement, the track errors have steadily decreased in the past several decades. (8-12) These improvements have been mainly due to the increasing ability of the numerical weather prediction models. (8,9,12) Indeed, the regional center for predicting TC intensity and trajectory in the NATL basin is the United States National Hurricane Center (NHC), which uses as guidance the outputs of several numerical models specific for TC, such as the Hurricane Weather Research and Forecasting (HWRF) and the Hurricane Multi-scale Ocean-coupled Non-hydrostatic model (HMON). (8,12)

In Cuba, TC numerical forecast has been performed in the Instituto Cubano de Meteorología using the configurations of the Advanced Research Weather Research and Forecasting (WRF-ARW) for the mean conditions of the atmosphere in the Ocean-Atmosphere Numerical Prediction System (SPNOA, Spanish acronym) and the Short-Term Prediction System (SiSPI, Spanish acronym). ((13,14,15)

Nevertheless, due to the static computational domains, these systems only can track TCs when they move over the Inter-American seas and the coastal zone of Cuba. To avoid this, Pérez-Alarcón *et al.* (16) performed sensitivity studies using static and moving meshes, and found that the atmospheric component of the HWRF was skillful for predicting TCs trajectories and intensities. Based on these results, Pérez-Alarcón *et al.* (17) developed the Numerical Tools for Hurricane Forecast (NTHF) in the Departamento de Meteorología, Instituto Superior de Tecnologías y Ciencias Aplicadas, Universidad de La Habana, which allows the tracking of TCs since their genesis. NTHF has been operational during the TC season in the NATL basin since 2019.

The response of TCs to global warming is still an active area of inquiry. (18,19) It is well-known that the sea surface temperature (SST) is the principal source of energy for TCs. Therefore, it is expected that the rising of SST leds to TCs to be more intense. (19) The maximum potential intensity (MPI) of TCs is generally taken as the upper TC intensity limit, which plays a role in understanding the relationship between TCs intensity climatology and global changes due to global warming. (20-23) The widely accepted theory of MPI of TC (24) was proposed by Emanuel, (20) assuming a TC as a classic Carnot heat engine. A limitation of Emanuel's MPI theory is the assumption of gradient wind balance in the atmospheric boundary layer, (25) causing super-intense TCs, defined as those that exceed the MPI, (26) Ojeda modified the MPI theory by including a TC boundary layer model. (27,28) Pérez-Alarcón (29) considered a TC as a generalized Carnot heat engine and used the radial wind profile developed by Willoughby *et al.* (30) at the top of the boundary layer, while Fernández-Alvarez *et al.* (31) obtained a radial pressure profile of a TC based on the radial wind profile developed by Willoughby *et al.* (29) Recently, Pérez-Alarcón *et al.* (32) combined these previous updates and developed the Hurricane Maximum Potential Intensity (HuMPI) model, which is currently operational for daily MPI estimations in the Departamento de Meteorología, Instituto Superior de Tecnologías y Ciencias Aplicadas, Universidad de La Habana.

Given the linkages between intensity, trajectory and TC impacts, it is worthwhile to develop and improve modelling tools for diagnosing and predicting tropical cyclone path and strength and improving our knowledge about these severe storms. This study aims to summarize the development and implementation of the HuMPI model and the NTHF system for estimating the MPI and predicting the intensity and trajectory of TCs in the NATL basin. Likewise, we discuss the performance of both tools during the major hurricane Iota that formed in the Caribbean Sea in the 2020 TC season in the NATL basin.

METHODS

Hurricane Maximum Potential Intensity Model

The HuMPI model estimates the maximum potential wind speed (VmaxT) at the top of the boundary layer (BL) based on the thermodynamic disequilibrium given by the difference in temperature at the top of the BL (Tb) and the outflow temperature (T00) as:

$$V_{maxT} = \frac{T_b - T_{00}}{T_b}\frac{C_k}{C_d}\left(h_s^x - h\right) \qquad (1)$$

where Cd is the drag coefficient, Ck is the coefficient of heat exchange h_s^x is the wet static energy of saturation at the sea surface and h is the humidity static energy of the air at the top of the BL. By applying the principle of quasi-equilibrium in the atmospheric BL to Equation (1) and solving the equations for a TC in the BL, we obtained the maximum potential wind speed (Vmax) and the central pressure (Pmin) on the surface. HuMPI model requires for running the SST. Further details of the formulation of the HuMPI model can be found in Pérez-Alarcón *et al.* (32) In addition, the source code of HuMPI can be retrieved from the GitHub repository, (33) and can be installed using the Anaconda environment in Python.

Radial wind profiles

The BL model included in the HuMPI model requires a radial wind profile (RWP) of TC to describe the wind structure of TCs during the integration time. Pérez-Alarcón *et al.* (34) performed a comparative climatology of RWPs of TC. Their study evaluated the ability of five RWPs (Holland, DeMaria, Willoughby et al., Emanuel and Rotunno and Frisius T, Scgönemann) (35,36,30,37,38) to reproduce the radial distribution of azimuthal wind in TC. Therefore, the RWP that better fitted the radial wind structure of TC was used in the BL model.

Numerical tools for hurricane forecast system

The NTHF system is based on the atmospheric component of the National Oceanic and Atmospheric Administration (NOAA) HWRF system. The simulations of NTHF have been performed in two bidirectional interactive nested domains in the rotated latitude-longitude staggered Arakawa E-grid with 216 × 432 grid points in the (x, y) direction for the parent domain of 27 km (approximately 0.18º) grid spacing and 106 × 204 grid points for the nested grid of 9 km (approximately 0.06º) of resolution. The model also contains 32 vertical pressure-sigma hybrid levels. (39,40) An important feature of NTHF is the vortex tracking module for following the TC during the model runs.

The physics suite package of NTHF follows the recommendation of Biswas *et al.* (41) for the operational runs of the NOAA's HWRF system. Overall, NTHF includes the Ferrier-Aligo scheme (42) for microphysics, the Scale-Aware Simplified Arakawa–Schubert scheme (43) for cumulus, HWRF surface-layer scheme, the Noah Land Surface Model, the HWRF Planetary Boundary Layer scheme and the Rapid Radiative Transfer Model for General Circulation Models applications scheme for shortwave and longwave radiation. Pérez-Alarcón *et al.* (17) provides a complete description of the NTHF system.

The operational runs of NTHF start at synoptic times (00, 06, 12, 18 UTC) fed by the forecast outputs of the NOAA's Global Forecast System at a grid scale of 0.25º horizontal grid spacing and 6-hourly temporal resolution for updating the boundary conditions. Overall, the time window for NTHF covers 120 h of forecasting. In addition, the NTHF is launched when the NHC classified an atmospheric disturbance as a low pressure with a probability of TC development.

Data

The previous evaluations of the ability of NTHF for predicting the intensity, (17,44,45) trajectory and precipitation associated with TCs, used the system simulations from the 2016 to 2020 TC seasons, while the HuMPI model was evaluated by estimating the MPI of intense TCs formed in the NATL basin, such as Gilbert (1988), Mitch (1988), Wilma (2005), Matthews (2016), Irma (2017), Maria (2017), Lorenzo (2018), Michael (2018) and Dorian (2019).

In this work, for assessing the performance of HuMPI and NTHF, we investigated the Hurricane Iota (46) that formed over the eastern Caribbean Sea in the 2020 TC season in the NATL basin. Iota reached major hurricane strength (Category 3+ on the Saffir-Simpson wind scale) before landfalling on the coast of Nicaragua as Category 4 Hurricane. (41) The best track of Iota was extracted from the revised Atlantic hurricane database (HURDAT2), (47) provided by the NHC. The lifetime of Iota extended from November 12th 2020 to November 18th 2020 at 1200 UTC.

The SST for feeding the HuMPI model was extracted from the Daily Optimum Interpolation Sea Surface Temperature (OISST) dataset, (48-50) supported by the NOAA's National Centers for Environmental Prediction. The OISST database has a daily temporal resolution and 0.25º horizontal grid spacing in latitude and longitude. OISST includes bias adjustment of satellite and ship observations to compensate for platform differences and sensor biases. (48)

RESULTS

Assessment of the radial wind profiles

Pérez-Alarcón *et al.* (34) revealed that the RWP developed by Willoughby *et al.* (30) fitted very well with the radial structure of TCs by comparing it with observations from the HURDAT2 database. This result confirmed the previous finding by Pérez-Alarcón *et al.*, (29) who noted the ability of Willoughby *et al.* (30) RWP to reproduce the wind structure of TCs. These authors used the aircraft reconnaissance observations for Hurricane Ivan, which formed in the NATL basin in 2004. The ability of Willoughby *et al.* (30) RWP was also demonstrated by Kepert (51) in a case study of Hurricane Mitch (1998) and Schwendike and Kepert (52) for study cases with hurricanes Danielle (1998) and Isabel (2003). Therefore, the RWP developed by Willoughby *et al.* (30) was used in the BL model included in the HuMPI model.

Performance of the Hurricane Maximum Potential Intensity Model: the case of Hurricane Iota

The 2020 TC season in the NATL basin was extremely active on records since 1850, with 30 named storms, (53) of which six reached hurricane categories 1 and 2, and seven reach the major hurricane strength. The recent paper by Reed *et al.* (53) revealed that the mean SST during the 2020 TC season was approximately 0.4-0.9°C higher than the average SST in the NATL basin in 1850 due to the increasing amount of greenhouse gases in the atmosphere. Hurricane Iota was storm number 31 that formed in NATL in 2020. (46) Figure 1A displays that Iota originated in the eastern Caribbean Sea south of Hispaniola over SSTs higher than 28.5ºC from a tropical wave that moved off the coast of Africa. (46) Firstly, it moved southwestward, influenced by a subtropical ridge situated north of the storm over the southwestern Atlantic. (46) By November 15th, Iota began to move westward, reaching its maximum intensity. Figure 1A also shows that Iota found SSTs ranging from 28.5ºC to 29.5ºC along its trajectory, which with favorable environmental conditions, promoted the rapid strengthening of Iota until it reached the category 4 hurricane on the Saffir-Simpson wind scale.

The potential maximum wind speed and the minimum central pressure for Hurricane Iota from HuMPI estimations are displayed in figures 1B and 1C, respectively. Note that HuMPI simulated along the Iota pathway a potential wind speed ranging from 270 km/h to 290 km/h and a minimum central pressure varying from 890hpA to 900hPa. From the HURDAT2 dataset, the intensity of Iota was 249.7 km/h for the maximum wind speed and

917hPa for the minimum central pressure, which was reached on November 16th at 1200 UTC when it was about 37 km northwestern of the Colombian island of Providencia. (46)

The evolution of the intensity of Iota from the HURDAT2 database and the HuMPI outputs depicted in figures 1D and 1E reveals that its strength was closer to its MPI as it intensified. Overall, the MPI calculated for Iota was 292 km/h for the maximum wind speed and 901 hPa for the minimum central pressure. Therefore, Iota reached approximately 85.3% of its MPI.

Performance of the NTHF system: the case of Hurricane Iota

The simulations for Hurricane Iota were performed using NTHF for the initialization of November 14th and 15th at 0000 and 1200 UTC. Figure 2 displays the NTHF outputs for the 120 forecast hours of the trajectory and strength of Hurricane Iota. We discuss below the intensity and track errors for Iota predictions by comparing the NTHF simulations with the best track archive from the HURDAT2 database.

From figure 2A, in all runs of NTHF, the predicted pathway of Iota was north of the best track. The position errors ranged from 70 km to 220 km in the first 96 forecast hours but notably increased to 385 km for the 120 h. Overall, the errors increased as the forecast hours moved away from the initialization time, although the significant increase from (108 to 120) h was mainly because NTHF simulated a higher Iota translation speed than the one archived

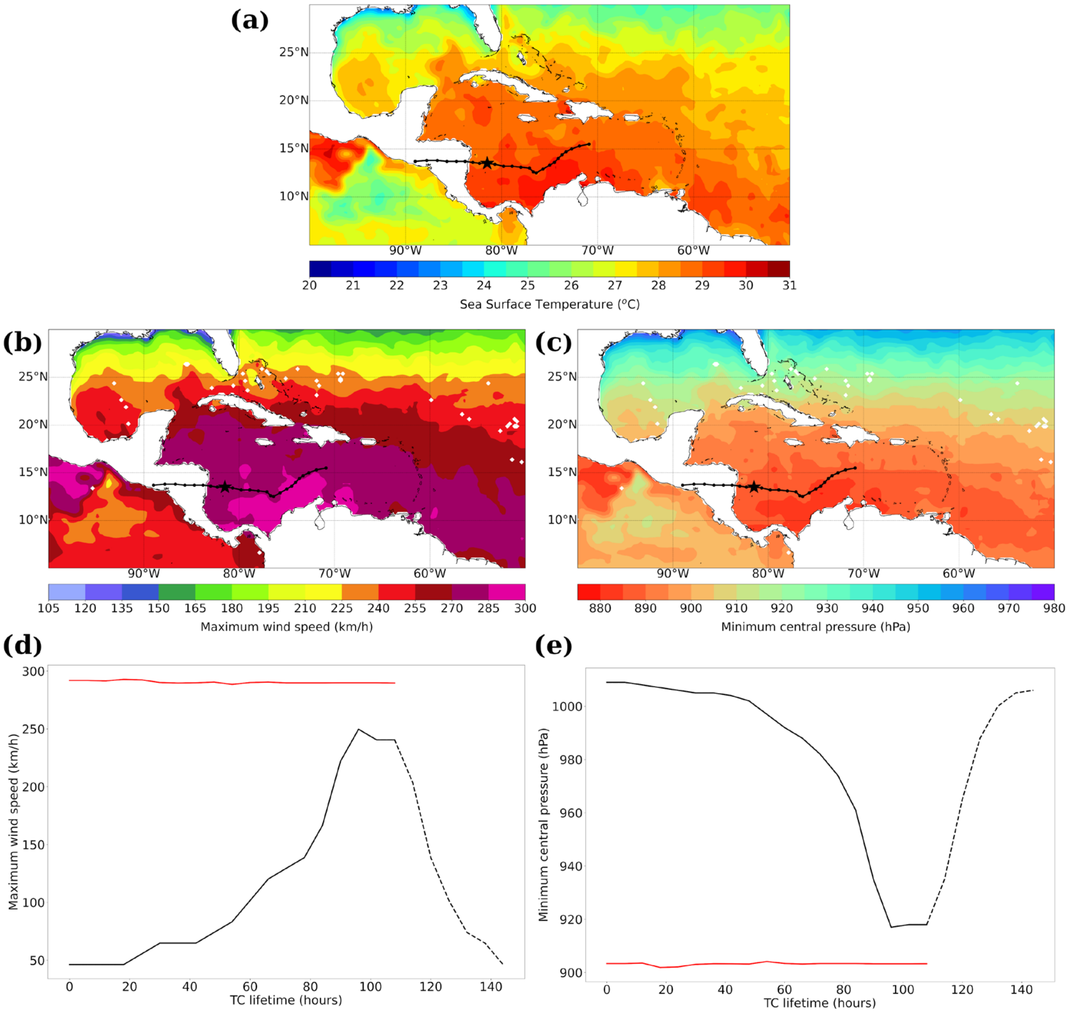

Fig. 1. A) Sea surface temperature when Hurricane Iota reached the tropical storm category on November 13th 2020, B) Outputs of HuMPI for the maximum wind speed, C) Outputs of HuMPI for the minimum central pressure, D, E) Evolution of the maximum wind speed and the minimum central pressure from the HURDAT2 database (black line) and HuMPI outputs (red line) along the Iota trajectory. In (A), (B) and (C) the trajectory of Iota is depicted with the solid black line and the dots represents the 6-hourly positions of the storm. The black star denotes the location of Iota when achieved the maximum intensity. In (D) and (E), the dashed line represents the movement of Iota over land

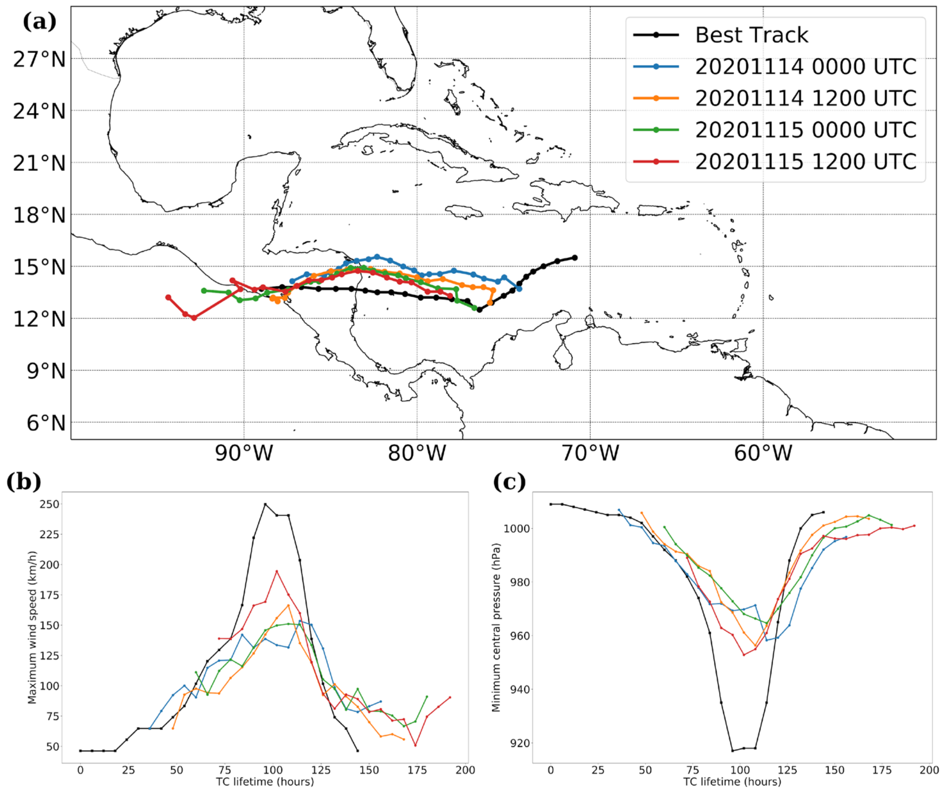

Fig. 2. Numerical predictions of NTHF for Hurricane Iota, A) Trajectory, B) maximum wind speed, C) minimum central pressure. The black line denotes the trajectory and the intensity of Iota according to the best track archive

by the TC. Despite the poor performance of NTHF in the last forecast hours, the track errors were relatively lower than the position errors previously found by Pérez-Alarcón *et al.* (17) for the period 2016-2018. The report of the NHC for Iota noted that the official forecast errors were better than average, and so were the climatology track errors, which is an indication that Iota was not a particularly difficult hurricane to forecast for the track. (46)

The intensity forecast exhibited the highest differences when Iota reached the maximum intensity (see figure 2A, B); underestimating (overestimating) Vmax (Pmin) at 80 km/h (31hPa), although the evolution of the maximum wind speed (see figure 2B) and minimum central pressure (see figure 2C) described a similar tendency that intensity recorded by the TC. Iota underwent a 42 h rapid intensification process from November 14th at 1800 UTC to November 16th at 1200 UTC, (46) and NTHF detected the rapid intensification and weakening times, but the predicted intensification and weakening rates were lower than those achieved by the storm. Overall, NTHF performed notably well during the first h of forecasting. Likewise, (24-30) the performance of NTHF for Iota intensity prediction agrees with previously evaluations. (17)

DISCUSSION

The ability of the HuMPI model to estimate the MPI of Hurricane Iota was in line with previous evaluations. Pérez-Alarcón et al. (32,54) addressed that HuMPI performed very well for hurricanes Irma (2017), Lorenzo (2018) and Dorian (2019). Note that these TCs reached the major hurricane status, for which the MPI is more relevant. Likewise, a recent proceeding by Pérez-Alarcón and Fernández-Álvarez applied the HuMPI model for investigating the changes in the intensity of TC formed in the NATL basin based on their MPI. (55) These authors found that climatological potential maximum wind speed from 2002 to 2021 has increased by 3.20% compared with the climatological MPI in the period 1982-2001. The MPI rising can be explained by the increasing trend (0.20°C/decade) in the SST in the NATL basin. (55,56) As discussed above, hurricane Iota moved over the noticeable warm waters of the Caribbean Sea (see figure 1A).

The MPI is highly sensitive to the surface relative humidity under the eyewall and changes in ocean surface temperature. (22) Several authors (57-59) have projected an increase in moisture availability in the atmosphere due to the SST rising in a warmer climate. Therefore, one of the advantages of HuMPI is its usage for evaluating the changes in the TCs intensity due to the global warming in order to design plans to reduce vulnerabilities during the impact of intense TCs. Precisely, Pérez-Alarcón et al. (54) applied the HuMPI model for quantifying the potential intensity of TC in the middle and the end of the century using the SST from the outputs of the Geophysical Fluid Dynamics Laboratory-Climatic Model (60) version 4.0 under the shared socio-economic pathways 8.5 scenario. They found that by the end of the century, the peak of the MPI will be observed in June, and the Caribbean Sea and Intra-American Seas will achieve the highest MPI. Therefore, future TCs with a trajectory similar to Iota will be more intense than today.

Regarding NTHF, as noted in Section 3.2, the system performance during the simulations for hurricane Iota matches with previous works. (17) Indeed, during the 2020 TC season, NTHF produced 247 predictions, notably higher than the 82 long-term average (2016-2019) number of NTHF forecasts. (44) The evaluation of NTHF skill in the 2020 TC season revealed that the position errors ranged from 62 km at 12 h to 368 km at 120 h, (44) while NTHF underestimated the maximum wind speed from 10 km/h to 20 km/h. Recently, Pérez-Alarcón et al. (45) updated the long-term ability of NTHF previously addressed by Pérez-Alarcón et al. (17) by considering the period 2016-2020. In this period, 577 forecasts were considered, which is lower than the total official forecast of the NHC. The differences can be explained by flaws (e.g., loss of internet connection, loss of energy power) in the Benjamin cluster at the Departamento de Meteorología, Instituto Superior de Tecnologías y Ciencias Aplicadas. (45)

Overall, in the 2016-2020 period, NTHF track forecast errors increased linearly with forecast hours, ranging from 41 km in the first 6 h to 356 km in the 120 h of forecasting (figure 3). Pérez-Alarcón et al. (45) noted that the NTHF system exhibits a track forecast error ~10% higher than the NHC forecast errors for a lead time of up to 60 h. The trajectory error was 30% higher than the NHC from (60 to 72) h. The trajectory prediction for depressions and tropical storms exhibited high position errors, while NTHF is skillful for predicting the pathway of intense category 4 and 5 hurricane strength, with track errors less than 295 km at 120 h, as shown in figure 3

The long-term errors of NTHF in the intensity forecast were also assessed by Pérez-Alarcón et al. (45) The NTHF errors in the maximum wind speed varied from 26.5 km/h at 12 h to 33.7 km/h at the end of the forecast period (figure 4), being higher than the average forecast errors of the official forecast by the NHC. From figure 4, NTHF also shows the ability to predict the intensity of TC from depression to category 3 hurricanes from 36 to 120 h of forecasting and between (72 and 108) h for intense hurricanes (category 4 and 5). The higher errors of NTHF than the NHC reveal deficiencies in the initialization of NTHF and low resolution of the inner domain to represent the complex dynamic processes involved in the intensification or weakening of TC.

To solve the initialization problems, Rodríguez-Navarro (61) evaluated the feasibility of applying a vortex relocation scheme based on a synthetic vortex in NTHF. The results revealed that the relocation scheme represented a more structured vortex but the dynamic instability caused by the introduction

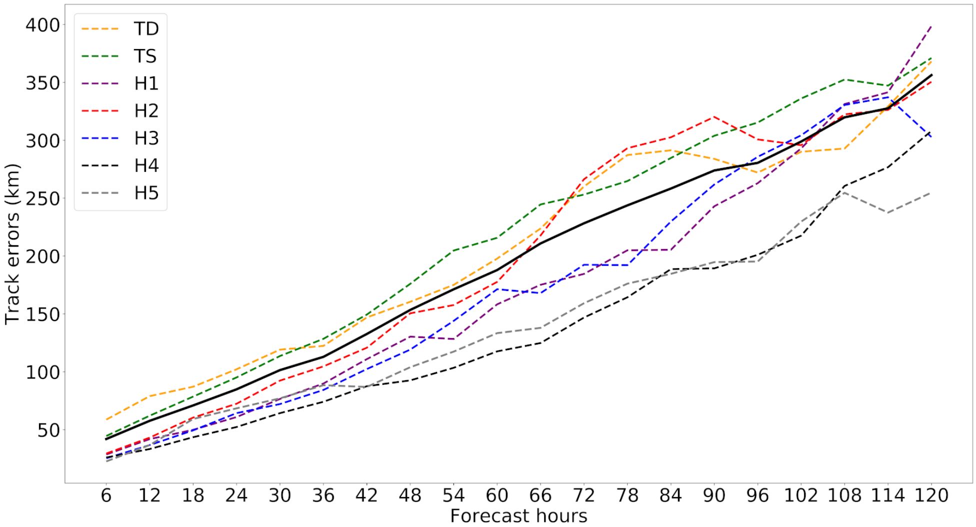

Fig. 3. Track errors (dashed colored lines) for each TC intensity category. TD: Tropical depression, TS: Tropical storm, HN (N = 1, 2, 3, 4, 5): Hurricane category according to the Saffir–Simpson wind scale. The solid dark line represents the mean track error of NTHF including all TC stages. Period 2016-2020

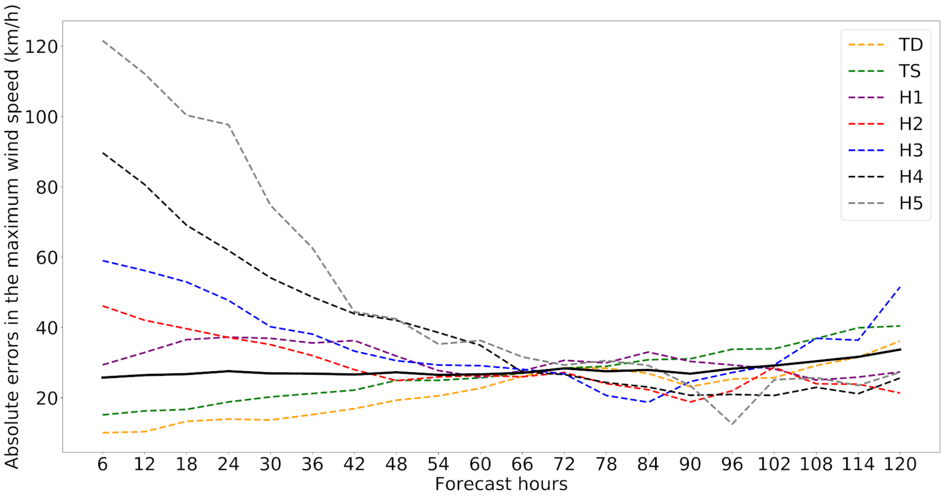

Fig. 4. Absolute errors (dashed colored lines) in the maximum wind speed forecast for each TC intensity category. TD: Tropical depression, TS: Tropical storm, HN (N = 1, 2, 3, 4, 5): Hurricane category according to the Saffir–Simpson wind scale. The solid dark line represents the mean track error of NTHF including all TC stages. Period 2016-2020

of the synthetic vortex in the background field conditioned that the center of the TC developed in a drier environment, and the center of the system was colder, causing an increase of the forecast errors. Likewise, Fernández-Alvarez *et al.* (62) addressed the ability of NTHF to predict the rainfall totals and amounts over land, but its prediction of extreme rain is only applicable for the first 24 h of the forecast.

Additionally, as part of the development and implementation of HuMPI and NTHF, it was developed a Python library named Alarconpy, (63) which includes functions for post-processing the outputs of both systems and for processing meteorological data. Alarconpy is available for installation in the Anaconda3 Python environment.

Conclusions

In this study, we summarized the assessment of the Hurricane Maximum Potential Intensity (HuMPI) model and the Numerical Tools for Hurricane Forecast (NTHF) for numerical predictions of tropical cyclones (TC) in Cuba. HuMPI is a modified version of the potential intensity theory proposed by Emanuel (20) that included the representation of a TC as a generalized Carnot heat engine, a TC boundary layer model and the radial wind profile by Willoughby *et al.* (29) at the top of the boundary layer. Additionally, it includes the radial pressure profile proposed by Fernández-Alvarez *et al.*, (31) based on the combination of the gradient wind balance equation and the Willoughby *et al.* (29) profile. The development of HuMPI started in 2015. It has also been previously applied for investigating the climatological changes in the maximum potential intensity in the last two decades and for projecting the impact of global warming on the intensity of TC. HuMPI has been coded in Python and can be freely installed using the Anaconda tool, and its GitHub repository provides a detailed guide for its usage.

NTHF is based on the atmospheric component of the Hurricane Weather Research and Forecasting model. It includes parameterizations specific developed for TC numerical forecast. Additionally, NTHF uses the vortex tracking scheme, which allows to follow the TC during the simulations. The operational runs of NTHF for 120 h of forecasting are launched when the National Hurricane Center state that an atmospheric disturbance could become a TC. The evaluation of NTHF (period 2016-2020) revealed that positions forecast errors increased from 41 km at 12 h to 356 km at 120 h of the forecast. Likewise, NTHF underestimates the observed intensity by 26.5 km/h in the first 12 h to 33.7 km/h at the end of the forecast period. It can predict the intensity of TCs from depression to category 3 hurricanes between 36 h and 120 h and for intense hurricanes (category 4 and 5) from 72 h to 108 h. The evaluations of the rainfall pattern showed that NTHF has a skill for forecasting extreme precipitation associated with TCs in the first 24 h.

The development of the HuMPI model contributes to the development of techniques for estimating in Cuba the intensity reached by TCs and is a powerful tool in the study of changes in the strength of TCs due to global warming. Meanwhile, NTHF allows the monitoring of the evolution of TCs since their genesis due to the use of mobile computing grids and provides compact information to the Cuban meteorological system, including the official forecast of the National Hurricane Center and the outputs of other numerical weather prediction models, which facilitates the preparation of TC forecasts and warnings. These tools also can be used for academic and research purposes.

The outputs of both systems are freely available on the web site of the Instituto Superior de Tecnologías y Ciencias Aplicadas. Finally, as part of the development of both, HuMPI and NTHF, it was developed the Alarconpy Python library, which includes functions for processing HuMPI and NTHF outputs and for processing meteorological data. Future works will examine the inclusion of a novel vortex relocation scheme in the initialization of NTHF to improve the NTHF forecast. Additionally, we will work with researchers from the Centro de Física de la Atmósfera del Instituto de Meteorología to implement an ensemble forecast using NTHF, SisPI and SPONA predictions.

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Conflicts of Interest

The authors declare that there are not conflicts of interest among them or with the research presented.

Authors Contributions

Conceptualization: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Oscar Díaz-Rodríguez; Alfo José Batista-Leyva; Ramón Pérez-Suárez
Data curation: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez
Formal analysis: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Onel Rodríguez-Navarro; Patricia Coll-Hidalgo; Arlett Díaz-Zurita
Research: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Oscar Díaz-Rodríguez; Alfo José Batista-Leyva; Ramón Pérez-Suárez; Onel Rodríguez-Navarro
Methodology: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Oscar Díaz-Rodríguez; Alfo José Batista-Leyva; Ramón Pérez-Suárez; Onel Rodríguez-Navarro
Project administration: Albenis Pérez-Alarcón
Resources: Albenis Pérez-Alarcón
Software: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Oscar Díaz-Rodríguez; Onel Rodríguez-Navarro
Supervision: Albenis Pérez-Alarcón; Oscar Díaz-Rodríguez; Alfo José Batista-Leyva; Ramón Pérez-Suárez
Validation: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Onel Rodríguez-Navarro; Patricia Coll-Hidalgo; Arlett Díaz-Zurita
Visualization: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Onel Rodríguez-Navarro
Draft writing: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Onel Rodríguez-Navarro; Patricia Coll-Hidalgo; Arlett Díaz-Zurita
Writing, review and editing: Albenis Pérez-Alarcón; José Carlos Fernández-Alvarez; Oscar Díaz-Rodríguez; Alfo José Batista-Leyva; Ramón Pérez-Suárez; Onel Rodríguez-Navarro; Patricia Coll-Hidalgo; Arlett Díaz-Zurita

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