Revista Cubana de Meteorología, Vol. 27, No. 1, January-March 2021, ISSN: 2664-0880

Artículo Original

System for numerical forecast of intensity and trajectory of tropical cyclones in the North Atlantic basin

https://eqrcode.co/a/43uSoj

Sistema para el pronóstico numérico de la intensidad y trayectoria de los ciclones tropicales en la cuenca del Atlántico Norte

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RESUMEN: Se implementó un sistema para el pronóstico numérico de ciclones tropicales (CTs) llamado Numerical Tools for Hurricane Forecast (NTHF), en el cual se emplean mallas de cómputo móviles. Las simulaciones se extendieron hasta 5 días y fueron inicializadas con las salidas de pronóstico del Global Forecast System (GFS) a las 0000 UTC y la posición de tormenta dada por el National Hurricane Center (NHC. Para la evaluación del sistema, se utilizaron los ciclones tropicales formados en la cuenca del Atlántico Norte en las temporadas del 2016 al 2018. El error medio en el pronóstico de trayectoria de NTHF varió entre 56 km para las primeras 12 horas y 356 km para las 120 horas de pronóstico. Sin embargo, la habilidad de NTHF para la predicción de trayectoria no es tan buena como la del NHC, aunque el sistema mostró ser muy hábil para predecir la trayectoria de huracanes intensos. Además, NTHF es útil para el pronóstico de la intensidad de los ciclones tropicales desde depresión hasta huracanes categoría 3 en la escala Saffir-Simpson entre las 36 y 120 horas, mientras que para los huracanes intensos (categorías 4 y 5) los menores errores se encuentran entre 72 y 108 horas de pronóstico, con un error en la velocidad máxima del viento cercano a los 25 kmh^{-1}. Además NTHF es adaptable a bajos recursos computacionales y permitirá el desarrollo de estudios para profundizar en el conocimiento de los mecanismos físicos y dinámicos que controlan los procesos de intensificación y debilitamiento de los CTs.

Keywords: intensity forecast, track forecast, tropical cyclone, numerical modeling, statistical validation.

ABSTRACT: A system for the numerical forecast of tropical cyclones (TCs) named Numerical Tools for Hurricane Forecast (NTHF), that uses movable computing meshes, was implemented in a small computing cluster. The simulations are initialized with the forecast outputs of the Global Forecast System at 0000 UTC and the storm position provided by the National Hurricane Center (NHC) and are extended up to a period of 5 days. For the evaluation of the system, tropical cyclones formed in the North Atlantic basin in the seasons from 2016 to 2018 were used. The mean error in the NTHF trajectory forecast ranged between 56 km for 12 hours and 356 km for 120 hours; however, NTHF does not perform as well as NHC official forecast. Nevertheless, the system showed good ability to predict the track of intense hurricanes. Besides, it is useful for the forecast of the intensity of tropical cyclones from depression to category 3 hurricanes on the Saffir-Simpson scale between 36 and 120 hours, while for intense hurricanes (category 4 and 5) the lowest errors are between 72 and 108 forecast hours, with an error in the maximum wind speed close to 25 kmh^{-1}. Moreover, NTHF is adaptable to low computational resources and will allow the development of studies to deepen the knowledge of the physical and dynamic mechanisms that control the intensification or weakening of TCs.

Palabras claves: pronóstico de intensidad, pronóstico de trayectoria, ciclón tropical, modelo numérico, validación estadística.

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Received: 19/07/2020

Accepted: 20/11/2020

INTRODUCTION

A tropical cyclone (TC) could be defined as a non-frontal low-pressure system, which is formed on tropical or subtropical waters at a synoptic scale, with a warm core, organized deep convection and a cyclonic circulation of wind defined on the surface.

The track followed by a TC and the evolution of its intensity depends on processes that occur at different scales. While the track mostly depends on large-scale processes and therefore can be simulated with a good approximation by global models (Goerss, 2006), the intensity changes depend on the internal structure of the storm, the features of the core and its relationship with large-scale atmospheric processes. For that reason, high-resolution models are needed to simulate core structure, but they demand of high computational power and nowadays exist some computer restraints, so regional and mesoscale models are used for TCs intensity forecast (Marks and Shay, 1998).

In the North Atlantic basin (NATL), the regional center for TC forecasting is the National Hurricane Center (NHC), which uses, among other tools, information from several hurricane prediction operational models to make its official forecasts. Insufficient advances in the ability of the models in the forecast of TC's intensity led to the National Oceanic and Atmospheric Administration (NOAA) launching the Hurricane Forecast Improvement Project (HFIP) in 2007 (Gall *et al*., 2013). One of the numerical models developed as part of HFIP is the Hurricane Weather Research and Forecasting model (HWRF), which presents modifications in the physical parameterizations it employs for its specific use in the numerical hurricane forecasts.

The influence of terrain features in HWRF on hurricane structure after landfall has been studied (Bozeman, 2011). It was concluded that the model is sensitive to three factors: the type of parameterization used for the land surface, the initial conditions and the boundary layer scheme used. Numerous studies (Gopalakrishnan *et al*., 2011; Bao *et al*., 2012; Gopalakrishnan *et al*., 2012; Gopalakrishnan *et al*., 2013; Chen and Gopalakrishnan, 2015; Zhang and Marks, 2015) have used the HWRF to examine the impact of many parameterizations on the hurricane intensity forecasts.

Currently, in the Cuban Meteorological Institute (INSMET, Spanish acronym), the numerical forecast of TCs is made through two configurations derived from Advanced Research Weather Research and Forecasting model (WRF-ARW) termed SisPI (Sierra *et al*., 2015) and SPNOA (Pérez, Díaz and Mitrani, 2013; Pérez-Bello *et al*., 2019). The atmospheric component of the SPNOA system has a skill for a TC track forecast in the first 48 hours (Mitrani *et al*., 2017; Mitrani *et al*., 2019).

On the other hand, a sensitivity study was made by Alarcón *et al*. (2020) using the Non-hydrostatic Mesoscale Weather Research and Forecasting Model (WRF-NMM) vortex tracking option as well as the atmospheric component of the HWRF system for TCs forecast. As a result, the atmospheric component of the HWRF system was included in a system for the numerical forecast of TCs named Numerical Tools for Hurricane Forecast (NTHF), implemented in a small computing cluster at the Higher Institute of Technologies and Applied Sciences (InSTEC, Spanish acronym).

Recent intense hurricanes that have affected the Caribbean islands and the United States (e.g. Irma (2017), María (2017), Harvey (2017), and Michael (2018)) demonstrate the constant need to improve our understanding of rapid changes in TC track, intensity and structure of the TCs during its life cycle, with special emphasis before landfall. In this purpose, the numerical prediction models play an important role. This contribution aims to evaluate the ability of the NTHF system in the numerical forecast of trajectory and intensity of TCs in the NATL.

MATERIALS AND METHODS

2.1 NTHF description

The TC forecast system to be tested in this research (NTHF), operating during the cyclonic season of the NATL, has been implemented following the recommendations made by Alarcón *et al*. (2020). It is composed of computational algorithms that guarantee the initialization of the model during the operational runs with the storm position given by the NHC and the Global Forecast System (GFS) forecast outputs, as well as the subsequent post-processing of the outputs obtained by the system. Figure 1 shows the NTHF block diagram.

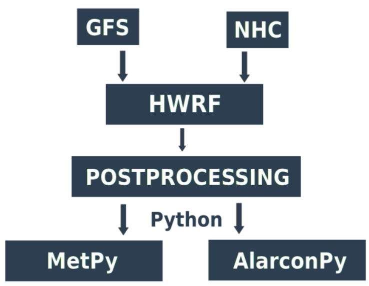

Figure 1. NTHF block diagram. Metpy (May *et al*., 2020) and Alarconpy (Pérez-Alarcón and Fernádez-Alvarez, 2020) are Python packages for the treatment and handling of meteorological data.

Due to computing power limitations, the NTHF system is based only on the atmospheric component of the NOAA's HWRF system. It employs two bidirectional interactive nested domains with 27 and 9 km of horizontal resolution as shown in figure 2. The parent grid covered 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.

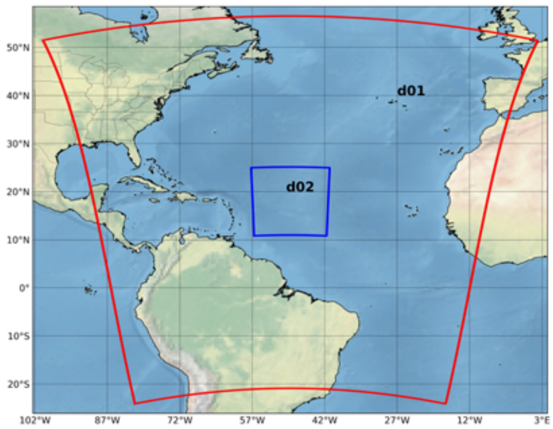

Figure 2. Nested domains used in the implementation.

NTHF contains the possibility of selecting the number of vertical levels for the simulations. Time integration is performed with finite difference forward-backward schemes (Mesinger, 1977) for fast waves, implicit schemes (Tamsir and Kumar, 2011) for vertically propagating sound waves, Adams-Bashforth Scheme (Misirli and Gurefe, 2011) for horizontal advection and the Coriolis force, and Crank-Nicholson scheme for vertical advection (Biswas *et al*., 2017). The same time step is used for all terms. In the vertical, the sigma-pressure hybrid coordinates are used. Horizontal diffusion is based on a second-order Smagorinsky scheme (Smagorinsky, 1963).

The runs covered a time horizon of 120 hours of forecast and were initialized in all cases at 0000 UTC with initial and boundary conditions taken from GFS outputs at 0.5° horizontal grid spacing, obtained from https://nomads.ncdc.noaa.gov/data/gfs4/. Boundary conditions were updated every 6 hours and the time step of integration for the external domain (27 km of resolution) was 69 seconds, while for the internal domain (9 km of resolution) was 23 seconds. An algorithm from HWRF code was modified to detect the position (*i*, *j*) of the internal domain in the outer one, measured from the center of the storm.

2.1.1 NTHF physics description

Table I shows the fundamental aspects of the configuration of NTHF. The parameterizations coincide with the configuration of NOAA's HWRF system described by Biswas *et al*. (2017) for its operational runs at the National Center for Environmental Prediction (NCEP), during the 2017 cyclonic season.

Below is a simple explanation of the used parameterizations. There were proposed by Biswas *et al*. (2017) and specially developed for the tropics. They are separated by categories: microphysics, cumulus, surface layer, planetary boundary layer, land and radiation.

The microphysics parameterization is the FerrierAligo scheme (Aligo *et al*., 2017). This is a modified version of the Ferrier tropical microphysics scheme, based on the Eta Grid-scale Cloud and Precipitation scheme (Rogers *et al*., 2001; Ferrier *et al*., 2002). This predicts changes in water vapor and condensation state forms as droplets clouds, rain, ice crystals and precipitation as graupel, snow and sleet. The individual fields of each species of hydrometeors are combined in the form of total condensation and water vapor.

The used cumulus parameterization is the Scale-Aware Simplified Arakawa-Schubert scheme (Han *et al*., 2017). It is an extension of the Simplified Arakawa-Schubert (SAS) method (Tallapragada, 2014), that is scale dependent and does not separate between resolved convection and sub-grid. This parameterization is an improvement of Arakawa-Schubert, being less computationally expensive. It uses the depth of the convective cloud as a parameter to differentiate deep or shallow convection. When the extent of the convective cloud is larger than 150 hPa it is considered deep, otherwise, it is treated as shallow. It also incorporates mechanisms of evaporation of precipitation in the

Table 1. Configuration used in the NTHF system.

Vertical resolution	32 vertical levels
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
Time step	69 s

downdrafts, the entry of dry air in the updrafts and the exit in the downdrafts in the sub-cloud layers. Also, the downdraft strength is based on vertical wind shear within the cloud.

The used surface layer parameterization is known as the HWRF surface-layer scheme. This calculates the friction speeds and the exchange coefficients that make it possible to obtain the momentum, heat and humidity fluxes exchange with the surface of land or water. Air-sea flux calculations use bulk parameterization based on the Monin-Obukhov similarity theory (Kurihara and Tuleya, 1974; Sirutis and Miyakoda, 1990). This scheme is influenced by the type of stability.

It was used the Noah Land Surface Model, that has been developed by the National Center for Atmospheric Research (NCAR) and NCEP. It is a 4-layer soil temperature and moisture model with canopy moisture and snow-cover prediction. The layer thicknesses of 10, 30, 60, and 100 cm from the top down are chosen to simulate the evolution of soil moisture (Chen and Dudhia, 2001). It has been incorporated into the HWRF system since 2015 implementation (Biswas *et al*., 2017).

The used planetary boundary layer parameterization is the HWRF Planetary Boundary Layer scheme. This is responsible for sub-scale fluxes due to turbulent transport throughout the atmospheric column. Therefore, when this scheme is activated, no explicit vertical diffusion is active. It also determines the flux profiles, the well-mixed boundary layer and the stable layer and thus provides atmospheric tendencies of temperature, moisture (including clouds), and horizontal momentum in the entire atmospheric column (Biswas *et al*., 2017).

Finally, the parameterization of shortwave and longwave radiation is the RRTMG scheme. It provides atmospheric heating due to divergent radiative fluxes and the information of longwave and shortwave radiation. Longwave radiation includes infrared or thermal radiation absorbed and emitted by gases and surfaces. Upward longwave radiative flux from the ground is determined by the surface emissivity, which in turn depends on land-use type, as well as the ground (skin) temperature. The processes included are absorption, reflection and dispersion in the atmosphere and surface. This is a modified version of RRTM (Iacono *et al*., 2008), with greater computational efficiency and variability in cloud treatment at the sub-grid scale. It considers absorption of water vapor, carbon dioxide, ozone, methane, nitrogen, oxygen and halocarbons for longwave and shortwave radiation and divides the longwave spectrum into 16 bands while the shortwave spectrum is divided into 14 bands. The optical properties of cloud water are calculated for each spectral band according to Hu and Stamnes (1993).

2.2 NTHF system vs NOAA’s HWRF system

The NOAA’s HWRF system is a model for operational hurricane prediction in the NCEP. It was jointly developed by the NCEP Environmental Modeling Center (EMC), the Geophysical Fluid Dynamics Laboratory (GFDL) of NOAA and the Atlantic Oceanographic and Meteorological Laboratory (AOML). It includes the WRF infrastructure and is based on the NMM dynamic core. It is a model of non-hydrostatic primitive equations with ocean-atmosphere coupling. It uses a set of physical parameterizations developed for TC forecast. The initialization of the model consists of both a procedure of vortex relocation and data assimilation. Unlike other models that remain operational in the NCEP throughout the year, the HWRF is used operationally when the NHC or the Joint Typhoon Warning Center (JTWC) consider that an atmospheric disturbance has conditions to develop and become a TC (Holt *et al*., 2014; Biswas *et al*., 2017). The physics of the model has been taken mainly from the GFDL hurricane model (Bender *et al*., 2007). HWRF system requires high computational resources.

Unlike the HWRF system, the NTHF configuration has certain limitations, being the first associated with the non-coupling with the ocean model (MPIPOM-TC) available in this version. Therefore, there is not an ocean-atmosphere feedback during the integration of solutions, making it impossible to take into account changes in the Sea Surface Temperature (SST), contributing to errors in intensity forecast (Bender and Ginis, 2000). Cione and Uhlhorn (2003) showed that changes in SST are directly related to changes in hurricane intensity because the ocean provides the necessary energy to establish and maintain deep convection, so more favorable conditions are expected for intensification of a TC in areas with higher SST.

Moreover, the non-vortex relocation may imply errors in the initial deadlines, because the storm position and intensity reported by NHC are not incorporated in the model initial conditions, although the centers of the parent and nested domains coincide with the center of the storm. The vortex relocation scheme consists primarily of the decomposition of the atmospheric flow in that associated with the circulation of the TC and in the environmental flow. Then, the circulation of the TC is relocated in the environmental flow in such a way that its position coincides with the observed position of TC. The vortex relocation scheme also has impacts on the representation of the TCs vertical structure. All of the above has direct implications on the TCs intensity and track forecast.

It must be noticed that the ability of the parameterizations to represent small-scale physical processes are directly influenced by the resolution of the model. The use of low resolution in NTHF affects the performance of the parameterizations, specifically those related to the representation of turbulent flows and the clouds physics, which implies errors in the intensity forecast.

2.3 Study area and study cases

For the evaluation of the NTHF system for the numerical forecast of the intensity and track of TCs, all cyclonic systems formed in the NATL during 2016, 2017 and 2018 seasons were selected. Their tracks, according to the reports of the NHC, are shown in figure 3. A total of 24 hurricanes were used, 12 of them reached category 3 or higher in the Saffir-Simpson scale, 21 were tropical storms and 3 tropical depressions. It is worth noting that their spatial distribution covers all the NATL. For further information about these tropical cyclones, consult the web site at https://www.nhc.noaa.gov/data/tcr/.

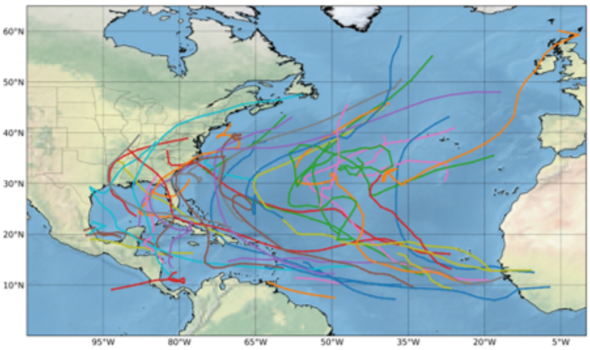

Figure 3. Study area and study cases. The lines represent the official track of NHC of the 24 TCs used in the evaluation. Note that their tracks cover the NATL.

2.4. Methodology

The NTHF, using the vortex tracker option, provide as an output the tropical cyclones position, minimum central pressure and maximum simulated wind speed. To verify their performance, the HURDAT2 database was assumed as reference. This data set has a text format with contain information every six hours about the location, maximum winds, minimum central pressure and size of all known tropical and subtropical cyclones (Landsea and Franklin, 2013). It is available at https://www.nhc.noaa.gov/data/. To compare NTHF skill was used the official forecast of the NHC. Also, to have a better vision of the performance of NTHF, the forecast errors of the HWRF system and GFS model for the same time and same TCs simulated by NTHF are plotted.

To evaluate NTHF forecasts, the simulations were divided according to the category of the TC on the Saffir-Simpson scale at the time of initialization, as shown in Table II. In this way, the class D_TS includes tropical depressions and tropical storms, H1_3 is formed with hurricanes between categories 1 and 3 on the Saffir- Simpson scale, while class H4_5 includes the most intense hurricanes (category 4 and 5).

From the simulated and observed variables, different statigraphs were applied to calculate the ability of the used configurations. Their definitions are presented below.

2.4.1. Mean Absolute Error

It is a measure of how far simulated values are from those observed. It is defined as:

$$\text{MAE}=\frac{\sum|x_i - y_i|}{n} \quad (1)$$

The closer the MAE values are to zero, the more accurate is the simulation. Here and in what follows x_i and y_i are simulated and observed values respectively and n is the number of points.

2.4.2. Bias

The bias provides the difference between the observed and estimated values:

$$\text{BIAS}=\frac{\sum(x_i - y_i)}{n} \quad (2)$$

The simulation is more precise when bias values are closer to zero. Differently from MAE, that by definition is always positive, bias indicates when the forecast underestimates (BIAS < 0) or overestimates (BI AS > 0) the observed values.

2.4.3. Forecasting Skill

The forecasting skill could be measured as the relative forecast error with respect to a standard value. Naming e_f the forecast error and e_r the reference one, the definition is:

$$S_f = \frac{e_r - e_f}{e_r} \cdot 100 \quad (3)$$

To quantify the skill in the track forecast, Climatology and Persistence Model (CLIPER5) is used as a reference. For intensity prediction Decay - Statistical Hurricane Intensity Forecast model (DSHIFOR5) is

Table 2. Number of cases analyzed at each forecast hour based on the clustering of tropical TCs accordingly with their intensity at the time of initialization of NTHF. The value corresponds to the number of NTHF outputs for each forecast hour.

Classes	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h	108 h	120 h
D_TS	164	148	133	110	91	79	63	45	34	29
H1_3	81	77	74	68	60	49	41	34	28	22
H4_5	22	21	20	19	19	18	17	12	12	8
Total	**267**	**246**	**227**	**197**	**170**	**146**	**121**	**91**	**74**	**59**

used as a standard value. The forecast of DSHIFOR5 is obtained from the output of Statistical Hurricane Intensity Forecast model (SHIFOR5), which is adjusted to represent the interaction of the system with land, following the methodology described by DeMaria, Knaff and Kaplan (2006). In average, the errors of DSHIFOR5 are 5 - 15% lower than SHIFOR5 for the first 72 hours forecast, while from 96 to 120 hours the errors are similar (Cangialosi, 2019).

RESULTS AND DISCUSSION

3.1. NTHF track forecast

Figure 4 a shows the mean errors in the track forecast in the 2016 - 2018 cyclonic seasons in the NATL for all systems. It can be appreciated how the position errors were lower at all forecast hours than the mean errors of CLIPER5 but not as good as to the NHC official forecast. Also, in the first 84 forecast hours, the track error is higher than the mean error of the HWRF and GFS models.

The NTHF skill for TC track forecasting, in the categories of depression and tropical storm, is not as good (in the first 60 forecast hours) as the track forecast for systems with hurricane category, although for longer terms, the greatest errors were observed in the hurricane track forecast with categories from 1 to 3 on the Saffir-Simpson scale with ~ 400 km for the 120 hours of forecast (Fig 5 b-d).

For systems in the early stages of development of a TC (tropical depression and tropical storm) position errors ranged from ~ 65 km for the 12-hour forecast to ~ 350 km at 120 hours. These errors are consistent with the characteristics of the vortex, if it is weak, it can lead to the vortex tracking algorithm (GFDL vortex tracker) to follow secondary vortexes, which are not directly related with the system. It is noteworthy that from the 84 forecast hours the NTHF average error is less than the mean errors of both the official NHC forecast as well as the GFS and HWRF models (Fig. 4 b).

For hurricanes up to category 3, the NTHF is as good as the HWRF for the track forecast in the first 24 forecast hours, however, from this time on trajectory error increases considerably (Fig. 4 c). This behavior may be associated with the fact that in a large number of initializations made with these categories, the tropical systems did not evolve towards higher intensities, but rather underwent dissipation processes until they became tropical storms or tropical depressions.

The trajectories of hurricanes category 4 and 5 were the best predicted by NTHF, with an error that ranged between ~ 35 km for the 12-hour forecast to ~ 270 km at 120 hours, which is attributed to the fact that, for these intensities, the vortex is well structured and facilitates its tracking in run time. The NTHF average error is similar to the mean error of the GFS model for the first 54 forecast hours, however from this time to 120 forecast hour the NTHF ability is

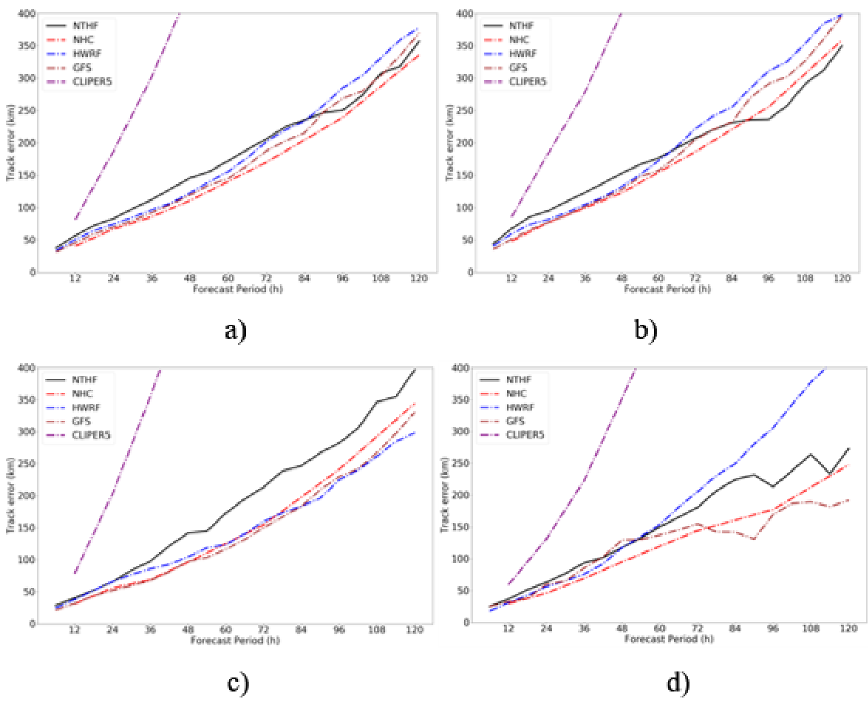

Figure 4. Error in the NTHF track forecast in the 2016 - 2018 period. The mean errors of the NHC official forecast, CLIPER5, GFS and HWRF models have been represented. The mean error of CLIPER5 (purple line) increase continually until reaches values close to 1000 km at 120 forecast hours. a) for all categories b) for depressions and tropical storms, c) for hurricanes up to category 3, d) for category 4 and 5 hurricanes.

inferior than the official NHC forecast and the GFS, but it is much better than the one of HWRF (Fig. 4 d).

Figure 5 a shows the NTHF TCs track forecast skill for systems with all categories (see Eq. 3) using the CLIPER5 track forecast as the baseline. It is observed how the ability of NTHF has similar temporal evolution, though it is consistently worse than that of the NHC in its official forecasts while from 84 forecast hours the NTHF skill is higher than GFS and HWRF skill. In general, NTHF skill is higher than 50% relative to CLIPER5 after 24 forecast hours.

In the case of depressions and tropical storms, the ability of NTHF ranged between 20 - 50 % in the first 36 hours, while between 36 and 120 hours it was larger than 50 %. In fact, after 96 forecast hours the NTHF skill is the best of all (Fig. 5 b). For hurricanes category 1 to 3 the NTHF ability to track forecast is worse than track forecast skill for NHC official forecast, GFS and HWRF models, however, is higher than 65% after 24 hours (Fig 5 c) while for intense hurricanes, NTHF forecast skill is better than HWRF skill after 54 forecast hours with values higher than 65%, and it is worse than NHC official forecast and GFS skill for all hours (Fig. 5 d). The previous results are in correspondence with those observed in NTHF track forecast errors.

In general, NTHF has the skill to track forecast of TCs with an average error that ranges from ~ 55 km for the first 12 hours to ~ 356 km for 120 hours, presenting track skill better than CLIPER5 track forecast with values higher than 50 % after 24 forecast hours.

3.2. NTHF intensity forecast

For the intensity evaluation the methodology was similar to the one used to evaluate NTHF track forecasts.

3.2.1. Maximum wind speed

Figure 6 a shows the NTHF mean absolute error in maximum wind speed forecast. It ranges from ~ 26 kmh^{-1} for the first 6 forecast hours to ~ 34 kmh^{-1} at 120 hours. It is worse than NHC and HWRF mean error through the forecast period, while it has a similar temporal evolution that GFS mean error. From this figure, it is easy to see that on average for all the TCs analyzed the initial forecast (first 24 hours) has errors larger than DSHIFOR5 model. This behavior is a consequence of the non-adjustment of the weather fields during model initialization and the time needed by the model to derive a physical valid state, known as spin-up time.

Regarding the values of MAE in maximum wind speed forecast for depressions and tropical storms, it is significantly smaller than GFS mean errors for the first 72 forecast hours, ranging from 13 to 25 kmh^{-1} and increasing thereafter. The error reaches its maximum value of 35 kmh^{-1} at 114 forecast hours. The NTHF forecast is worse than NHC official and HWRF forecasts, however, it is slightly better than DSHIFOR5 after 36 hours of forecast (Fig. 6 b).

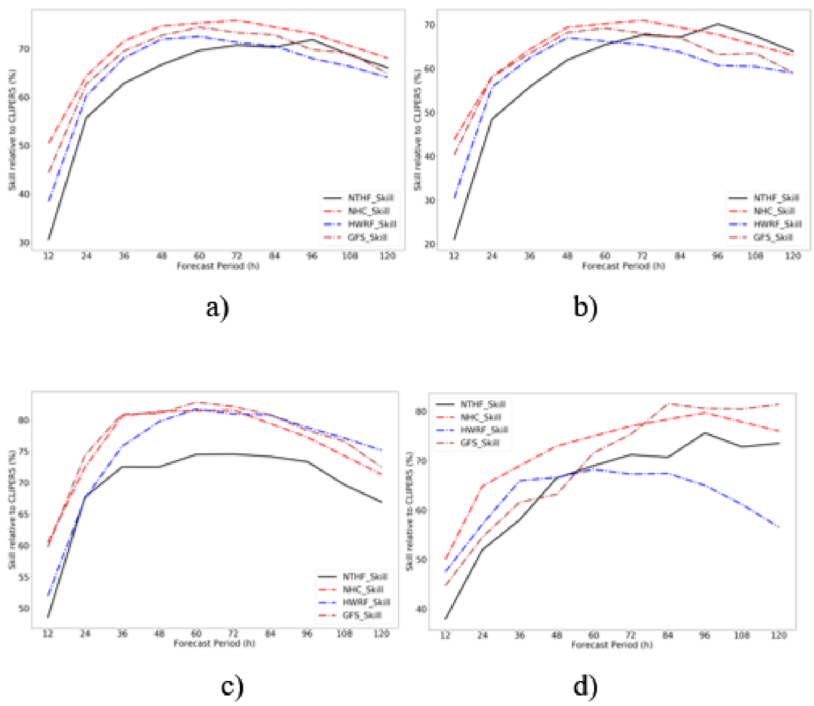

Figure 5. NTHF track forecast skill relative to CLIPER5 in the 2016 - 2018 periods. The skills of the NHC official forecast, GFS and HWRF models have been represented. a) for all categories b) for depressions and tropical storms, c) for hurricanes up to category 3, d) for category 4 and 5 hurricanes.

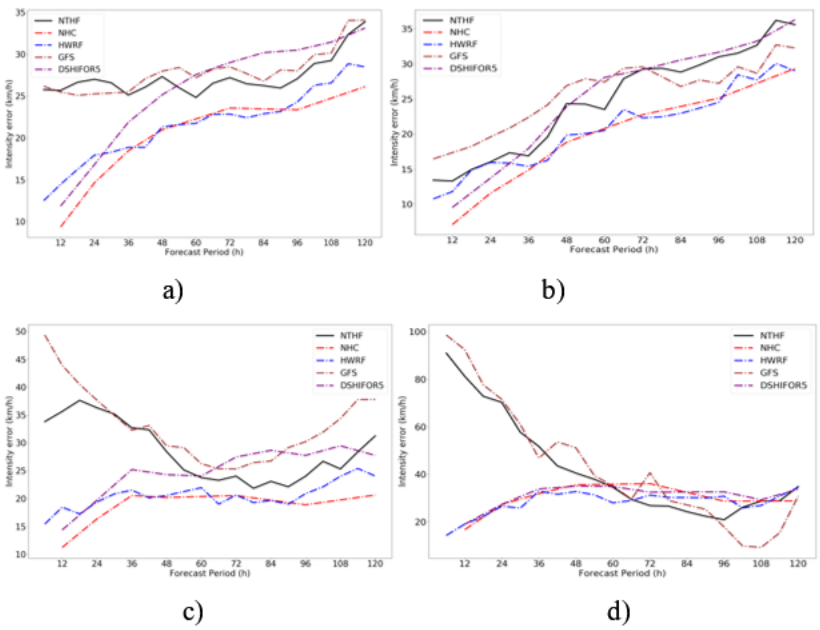

Figure 6. Mean absolute errors in the forecast of the maximum wind speed with the NTHF, during the seasons 2016 - 2018. For comparison, there are also plotted the average absolute forecast errors of NHC, HWRF, GFS and DSHIFOR5. a) for all categories b) for depressions and tropical storms, c) for hurricanes up to category 3, d) for category 4 and 5 hurricanes.

For hurricanes with category 3 or less, errors ranged from 30 to 40 km h^{-1} for the first time periods, while, after 60 hours the errors are less than those of DSHIFOR5. The mean errors are bigger than the mean errors of the NHC official forecast and the HWRF model for all forecast hours (Fig. 6 c).

Figure 6 d shows that the MAE in maximum wind speed forecast for the intense hurricane (category 4 and 5 in Saffir-Simpson scale) is high for the first 72 forecast hours, with a value close to 90 kmh^{-1} at the initial forecast time, however, between 72 to 114 forecast hours the NTHF forecast is better than the NHC official forecast, the HWRF and the DSHIFOR5 forecasts and similar to that of GFS.

The characteristics observed above are consistent with the NTHF skill for TC intensity forecast, relative to DSHIFOR5. Figure 8 shows the calculated skills. Values are around 20% from 60 to 114 hours for all categories (Fig. 7 a). For depressions and tropical storms, NTHF skill is about 10% after the 36 forecast hour (Fig. 7 b). For time periods of less than 60 hours, NTHF is not able to accurately predict the intensity of hurricanes category 1 to 3, while between 60 and 114 hours it is about 15% better than DSHIFOR5 (Fig. 7 c). In all the previous cases the ability of NTHF for the intensity forecast is lower than the one of the NHC and the HWRF, while for intense hurricanes NTHF skill is lower than NHC and HWRF skill in the first 60 forecast hours, with initial values below - 150 %. Nevertheless, between 72 and 108 forecast hours, the NTHF has higher skill than NHC and HWRF (Fig. 7 d). The values and temporal behavior of NTHF skill are similar to that of GFS.

Analyzing the bias shown in figure 8, it is possible to note that the model always underestimates the maximum wind speed at all forecast hours for tropical depressions, tropical storms and hurricanes category 3 or less on the Saffir-Simpson scale. For intense hurricanes, the underestimation of the maximum wind speed for the first 108 hours of forecasting has a maximum value of 90 kmh^{-1}. Nevertheless, this underestimation decreases steadily as forecast time goes on, being approximately zero at 108 hours. Then, it occurs an overestimation of 20 kmh^{-1} at 120 hours (Fig. 8 d). Again, the behavior of the NTHF and GFS are very similar.

To summarize, NTHF maximum wind speed forecast showed a good behavior for systems between tropical depression and hurricanes category 3 on Saffir-Simpson scale from 36 to 120 forecast hours, with errors less than 35 kmh^{-1} , however, for intense hurricanes, good accuracy are observed only from 72 to 108 hours. It is also appreciable as in all cases the behavior shown by NTHF is similar to the behavior of the GFS model. This behavior is due to the impact that the initial conditions, the relocation schemes and weather field adjustments have on the numerical simulations of tropical cyclones.

3.2.2. Minimum central pressure

The MAE for minimum central pressure forecast of systems with any categories (see Fig. 9 a) range between 6 and 15 hPa. Between 60 and 114 forecast hours, NTHF has a lower mean error than the GFS and a similar temporal evolution than the HWRF. For depressions and tropical storms, the NTHF mean error

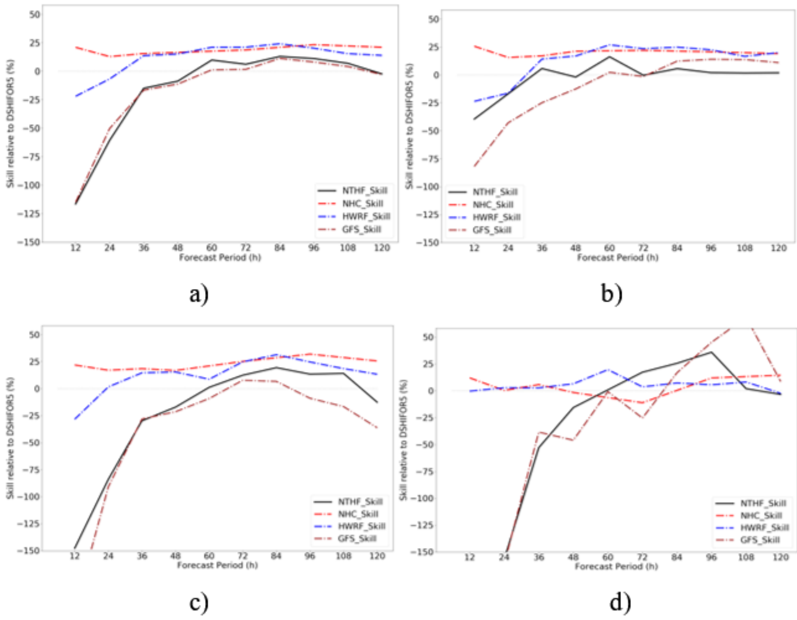

Figure 7. NTHF skill relative to DSHIFOR5 for maximum wind speed forecast in the 2016 -2018 period. For comparison, there are also plotted the skill relative to DSHIFOR5 of NHC, HWRF and GFS models. a) for all categories b) for depressions and tropical storms, c) for hurricanes up to category 3, d) for category 4 and 5 hurricanes.

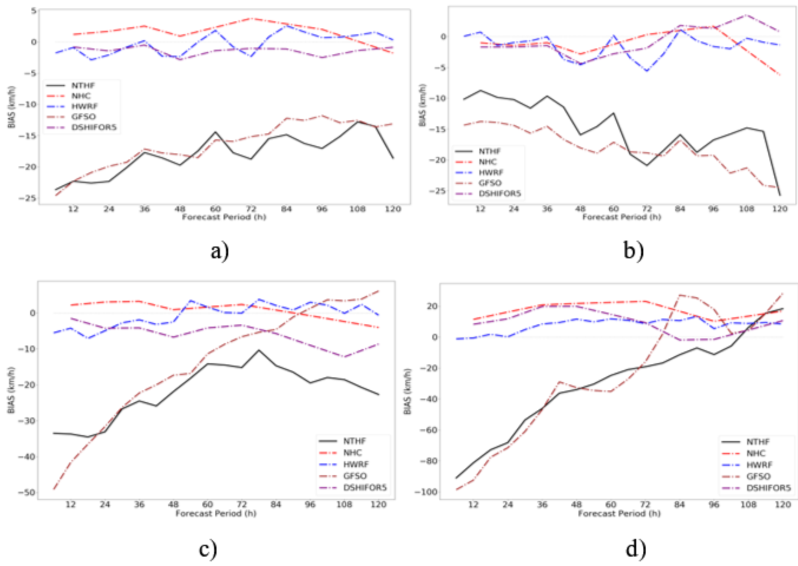

Figure 8. NTHF maximum wind speed forecast BIAS in 2016-2018 period. For comparison, there are also plotted the bias of NHC, HWRF, GFS and DSHIFOR5. a) for all categories b) for depressions and tropical storms, c) for hurricanes up to category 3, d) for category 4 and 5 hurricanes.

range between 3 and 15 hPa, being similar in all forecast hours to HWRF errors. Before the first 84 forecast hours, NTHF performance is better than the GFS (Fig. 9 b). MAE in the case of hurricanes category 1 to 3 is similar to GFS mean error during the first 36 forecast hours, and after the 66 hours it has a similar behavior as HWRF (Fig. 9 c). For intense hurricanes, the NTHF ability for minimum central pressure forecast is low during the first 48 hours, with a maximum error of 30 hPa at the 6 hours forecast, thereafter, NTHF ability is better than HWRF and GFS models (Fig. 9 d)

For systems with any categories, bias analysis (see Fig. 10 a) showed that the NTHF overestimate the minimum central pressure (BIAS ≤ 8 hPa), while the HWRF underestimates the central pressure. For tropical depressions and storms (Fig. 10 b), NTHF overestimates central pressure with BIAS<5, similarly to GFS. While for hurricanes up to category 3 (Fig. 10 c) occur an overestimation for all the forecast hours with a maximum of 10 hPa for the first forecast hours. For intense systems, NTHF overestimates the minimum central pressure during the first 78 forecast hours, with a maximum value of 30 hPa at 6 hours, while in the final terms (78 - 120 hours) the minimum central pressure is underestimated. In this case, is observed a similar evolution to the GFS model (Fig. 10 d).

A more detailed analysis of figures 10 and 11 allows verifying that the NTHF errors in the forecast of the minimum central pressure have a large systematic component. This behavior allows developing an algorithm for the correction of these errors using statistical methods.

In general, errors in minimum central pressure forecast ranged from 3 to 12 hPa for tropical depressions, tropical storms and hurricanes category 3 or less. In the case of intense hurricanes, the results are quite good between 36 and 114 forecast hours with MAE less than 15 hPa.

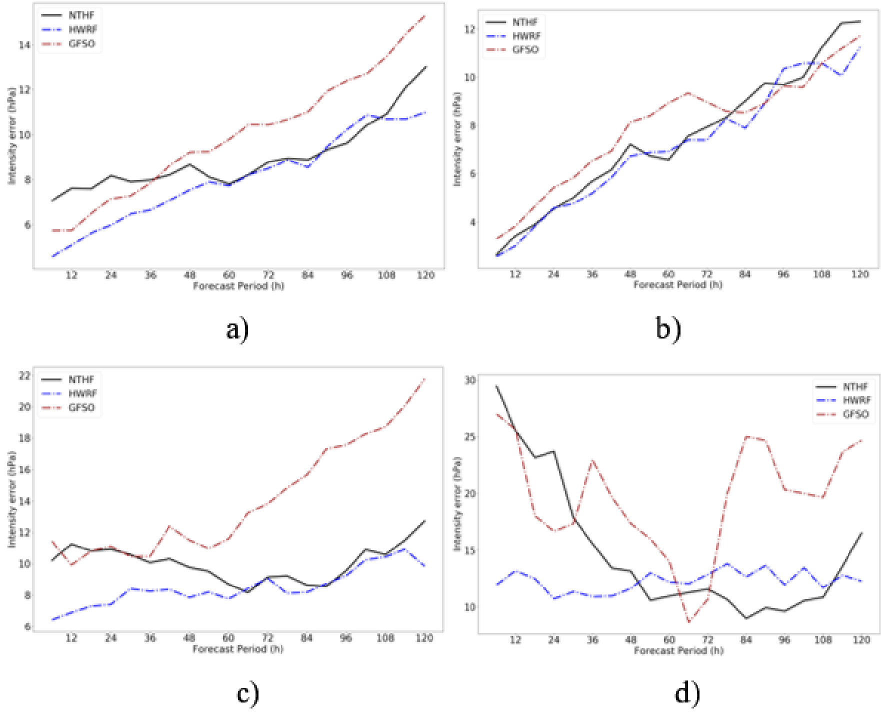

Figure 9. NTHF minimum central pressure forecast mean absolute error in 2016-2018 period. For comparison, there are also plotted mean absolute error of HWRF and GFS models. a) for all categories b) for depressions and tropical storms, c) for hurricanes up to category 3, d) for category 4 and 5 hurricanes.

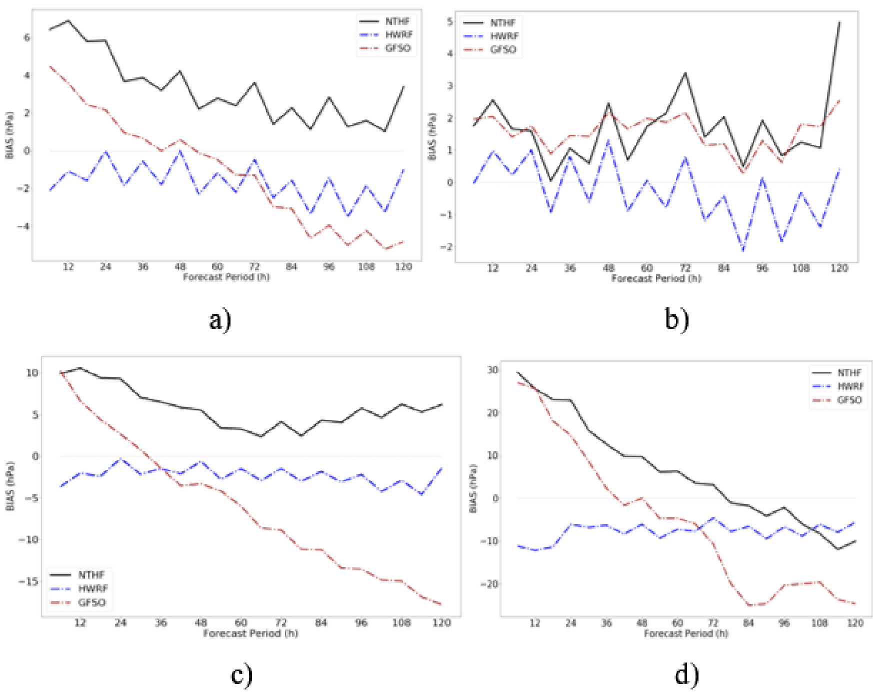

Figure 10. NTHF minimum central pressure forecast bias in 2016-2018 period. For comparison, there are also plotted the bias of HWRF and GFS models. a) for all categories b) for depressions and tropical storms, c) for hurricanes up to category 3, d) for category 4 and 5 hurricanes.

3.3 NTHF applications

The knowledge of the physical mechanisms that control TCs intensification processes allows the development of new techniques and methods for TCs forecast. Despite the limitations and forecast errors previously discussed, NTHF is a useful tool for the study of the dynamic and thermodynamic processes that occur in a TC, allowing sensitivity studies to different microphysics, cumulus and boundary layer parameterizations. It also facilitates the numerical analysis of the role of changes in atmospheric humidity, SST variations, vertical wind shear and other environmental factors in rapid intensification processes. Additionally, the large-scale environment determines the fate of the TC in terms of intensification or weakening. As TCs are relatively long-lived structures, the flow that steers the TC evolves and could be influenced by meteorological structures. Therefore, the NTHF system will allow conduct research to know how the variations of the undisturbed environment affect the TCs, which is very important for intensity and trajectory forecasts improvements.

Moreover, the NTHF is suitable to be implemented by institutions that do not have access to the high power computational resources requires for the HWRF implementation. Therefore, the NTHF is accessible for both weather forecast centers and research groups in Central America and the Caribbean region, for forecast and low budget research. Figure 11 exhibits some graphical products developed to show the operational NTHF outputs. These are available at http://www.instec.cu/model/NTHF.php.

CONCLUSIONS

A numerical system for the TC intensity and track forecast (NTHF) was developed and implemented with accuracy. These results are related with the use of movable meshes, allowing following the center of the vortex during the period of integration of the model, that guarantees a higher spatial resolution simulation of the environment close to the TC. The system allows 120 forecast hours, showing a good skill for TCs track forecast, with errors lower than 356 km at 120 hours. The system also shows the ability for predicting the intensity of tropical cyclones from depression to category 3 hurricanes on the Saffir-Simpson scale between 36 and 120 hours of forecasting, while for intense hurricanes (category 4 and 5) the best results are obtained between 72 and 108 hours. It is important to remarks that NTHF forecast overall tropical cyclones categories is worse than NHC official forecast. This is consistent with the fact that the NHC for its official forecasts employs several numerical weather prediction models output, satellite techniques and other tools and its official forecast is directly influenced by the forecaster's expertise.

The performance of the NTHF in the intensity forecast is similar to the GFS (global model) so a more detailed analysis related to parameterizations, horizontal and vertical resolution, interaction with sea and vortex relocation scheme, is needed to explain that. However, the major errors in track forecast are always those of the NTHF and the HWRF. Therefore, some aspects of global analysis are missing in both systems.

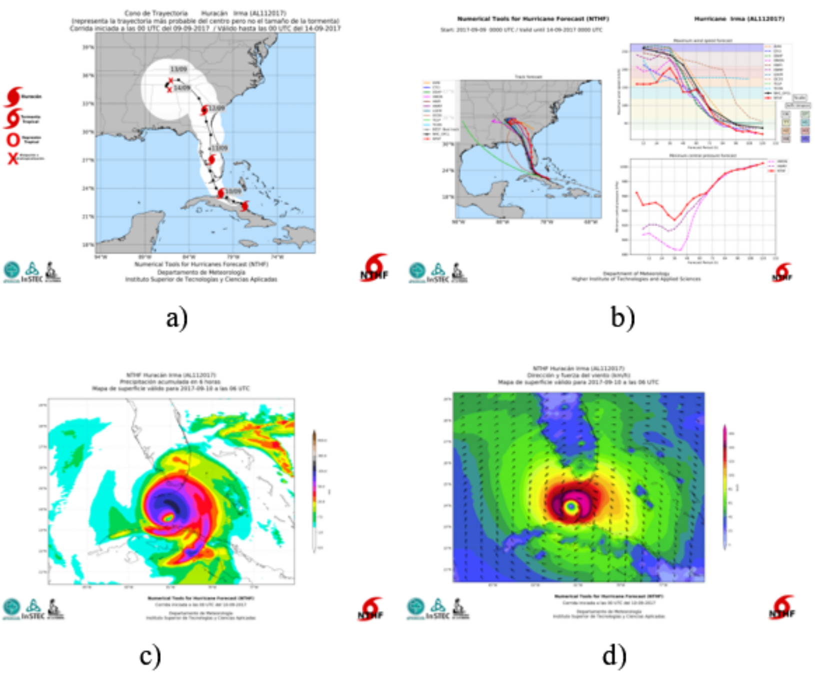

Figure 11. Examples of NTHF graphic products a) track cone, b) intensity and track forecast, c) precipitation, d) wind speed.

As an important result, it was verified that the exclusive initialization with the GFS forecast outputs has a negative impact on the performance of the numerical weather prediction models for tropical cyclones intensity and track forecasts, due to GFS forecast outputs shows a weaker hurricane as compared to NHC reports. Nevertheless, it should be noted that NTHF is a regional model that uses boundary and initial conditions from GFS. Thus, any improvements to the GFS would positively impact the NTHF system. The results indicate that the vortex initialization scheme is necessary for hurricane prediction. Moreover, NTHF is adaptable to low computational resources and will allow the development of studies to deepen the knowledge of the physical and dynamic mechanisms that control the intensification or weakening of TCs.

In the next works, we will assess the skill of spatial wind and precipitation forecasts from NTHF over the mountainous zones of Cuba and compare it with those from HWRF and GFS models. In future plans, it will be incorporated a vortex relocation scheme into the NTHF system that allows introducing into the initialization data the tropical cyclone intensity reported by the NHC, the horizontal resolution will be increased to 18 km for the parent domain and 6 km for the nested domain. Also, the developer team is working to assimilate satellite and radar data to improve the meteorological fields in NTHF initialization, and it will be implemented new graphical products that Institute of Meteorology of Cuba request to make its tropical cyclone advisories.

ACKNOWLEDGMENTS

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

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Conflicto de intereses: Los autores declaran no tener ningún conflicto de interés

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