environmental sciences proceedings

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Proceeding Paper

Development and Trajectory of Hurricane Eta—Case Study Using the WRF Model with Dynamic Update of the Sea Surface Temperature (SST) †

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† Presented at the 5th International Electronic Conference on Atmospheric Sciences, 16–31 July 2022; Available online: https://ecas2022.sciforum.net/.

Abstract: This research aims to describe the synoptic and general circulation environment in which Eta developed using the ERA5 reanalysis; design experiments with the WRF model; and describe, from the numerical outputs, the meteorological conditions that influenced the two analyzed Eta life periods. When analyzing the maps of the ERA5 reanalysis system, a general underestimation of the wind speed during the analyzed periods was identified. The first moment was characterized by a system in the development phase that failed to intensify under the influence of a trough over the southeastern Gulf of Mexico that generated shear conditions that were maintained during the second moment. Through the experiments that were carried out with WRF-SST, and from the numerical outputs, it was possible to describe with greater precision the meteorological conditions that influenced the development, trajectory and intensity changes of Eta.

Keywords: tropical cyclone; Eta; re-analysis system; numerical model

Citation: Sosa-Martínez, G.; Sierra-Lorenzo, M.; Armas-Forteza, O. Development and Trajectory of Hurricane Eta—Case Study Using the WRF Model with Dynamic Update of the Sea Surface Temperature (SST). *Environ. Sci. Proc.* **2022**, *19*, 6. https://doi.org/10.3390/ecas2022-12850

Academic Editor: Anthony Lupo

Published: 25 July 2022

1. Introduction

It has been shown that the ocean–atmosphere interaction plays a fundamental role in weather and climate variability. The importance of considering this relationship is evident in studies on the forecast of storms and wind on the coasts for its use as an energy source and the forecast of atmospheric phenomena such as tropical cyclones (TC). The use of a dynamic ocean surface temperature introduces improvements in the atmospheric and oceanic representation obtained from models such as the WRF [1]. In addition, the coupling of an ocean model allows for a more realistic representation of the ocean thermal field [2,3], as well as a good representation of the ocean and atmospheric processes that occur during a TC [4].

Eta was responsible for at least 165 direct deaths and more than 100 missing persons in Central America and southern Mexico. In Cuba, the extensive and heavy cloudy areas that accompanied the tropical storm (TS) caused locally intense rains that gave rise to coastal and river flooding that caused around 25,000 evacuations [5]. In addition to its variable intensity, an outstanding aspect of Eta was its irregular trajectory and behavior, and although there are several studies on the system, they do not analyze the reasons that gave rise to its particular evolution. The need to delve into the complex mechanisms and factors that intervened in the genesis and development of this system, as well as the use of numerical weather modeling with dynamic updating of the sea surface temperature (SST) for its understanding, motivated the realization of this research, which aims to describe the synoptic and general circulation environment in which Eta was developed using the

ERA5 reanalysis, design experiments with the WRF model for the simulation of the case study with greater spatial and temporal resolution, and describe, based on the numerical outputs, the meteorological conditions that influenced the development and the change in intensity that Eta experienced between 7 and 11 November 2020, which will be divided into two moments.

2. Materials and Methods

2.1. Hurricane Eta

The study system, formed on Saturday, 31 October, and dissipating on 13 November, dates back to a tropical wave that is estimated to have moved off the west coast of Africa on 22 October 2020 [5]. It was characterized as erratic, with numerous variations in its intensity, and was reclassified several times by the National Hurricane Center and the Central Pacific Hurricane Center of the National Oceanic and Atmospheric Administration (NOAA). In this investigation, two moments of the life span of the system will be analyzed, the first from 7 to 8 November and the second from 9 to 11 November 2020.

2.2. Design of Experiments

In order to analyze and describe in greater detail the rapid intensification (RI) process of Eta, experiments were carried out using the dynamic sea temperature in the WRF model with the ARW (advanced research WRF) as the dynamic core, which consisted of a three-hour update of the SST in the atmospheric model. The SST data used in the WRF model were obtained from a daily high-resolution, real-time, analysis of the global sea surface temperature (RTG_SST_HR) that combines the data of the last 24 h derived from buoys, ships and satellites. The simulations developed were carried out on the 9 km domain, in the period from 1 to 14 November 2020, but only the days corresponding to the moments of interest described above were analyzed. Figure 1 shows the configuration of the simulation domain used in the WRF. All data were compared with the products of the ERA5 reanalysis system, which were extracted from https://www.ncei.noaa.gov/products/weather-climate-models/global-forecast (accessed on 20 October 2021).

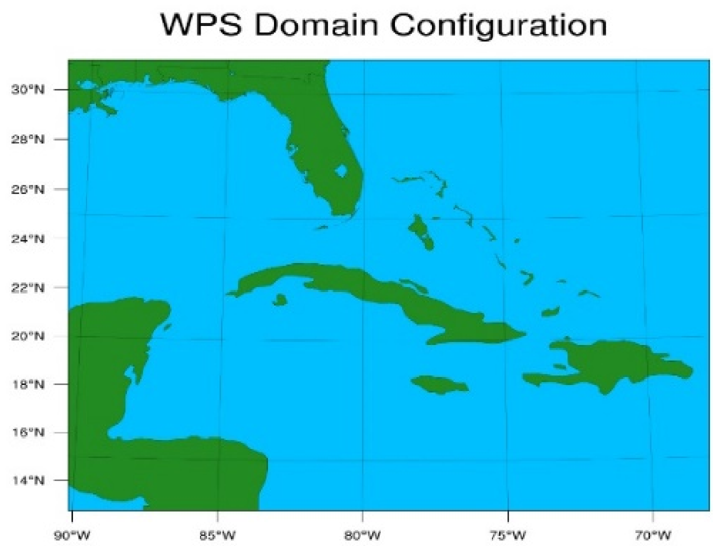
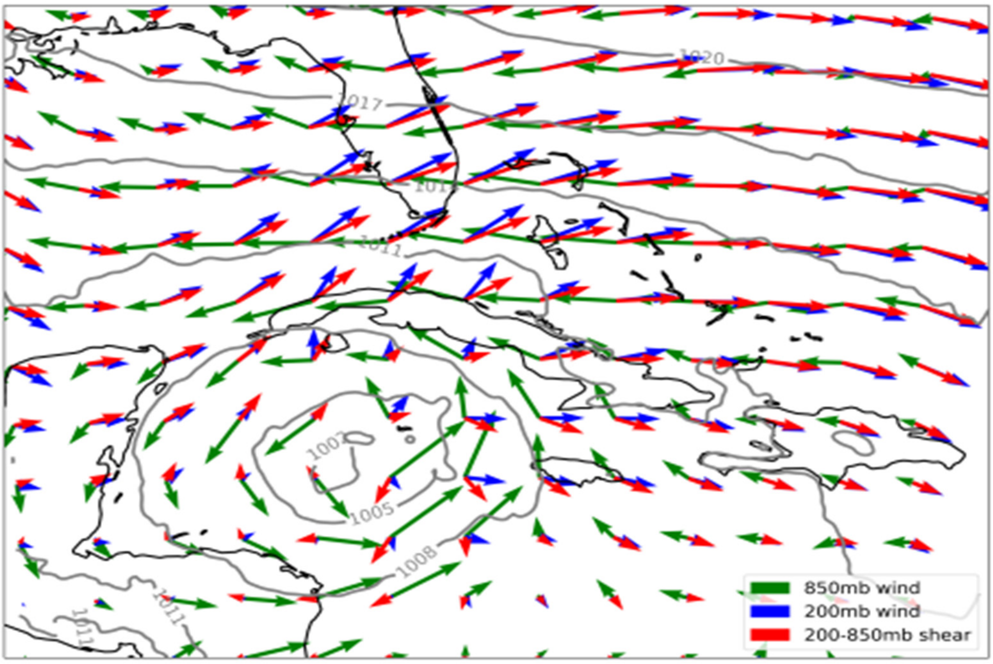


Figure 1. Simulation domain used in the WRF model.

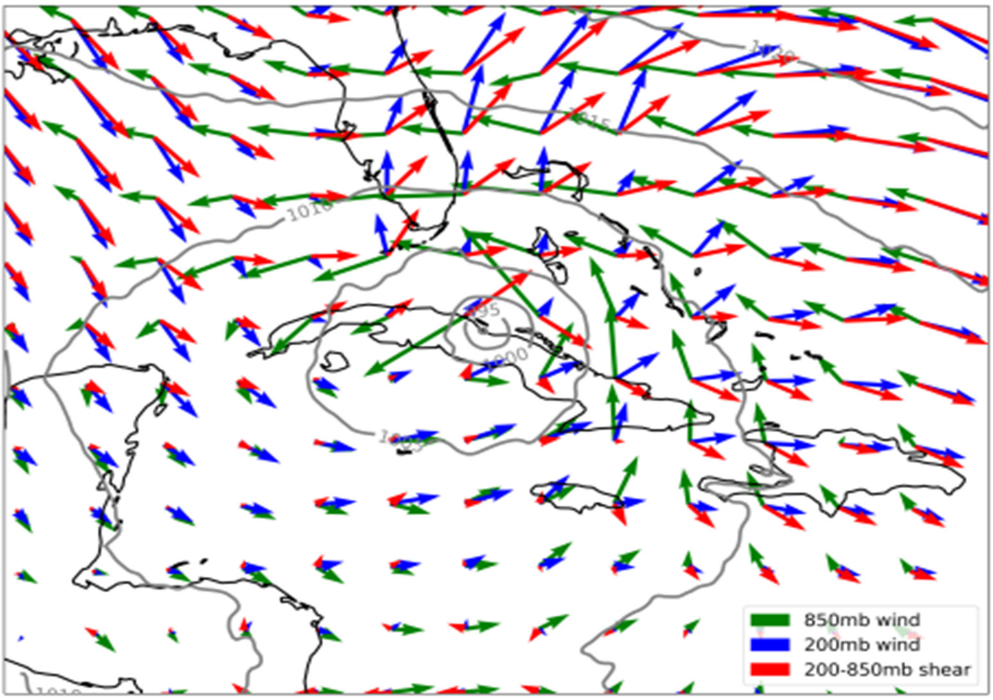
3. Results and Discussion

3.1. Moment from 7 to 8 November 2020

This moment was characterized by a sheared environment due to the presence of a trough over the western Gulf of Mexico that induced a flow from the third quadrant and influenced the displacement of the TS towards the northeast (Figure 2).



(**a**)



(**b**)

Figure 2. WRF-SST vertical wind shear map at 09:00 UTC on (**a**) 7 November 2020 and (**b**) 8 November 2020.

At 21:00 UTC on the wind maps of 7 November, from the 925 hPa level to 500 hPa, a closed circulation can be seen in the area to the south of the central region of Cuba where the system was located, so it is intuited that it was in a process of organization, although there is a shift to the right in the mid-levels, this tilt of the cyclonic center with height was a consequence of the sheared environment in which Eta was located, which is consistent with what was seen with ERA5 (Figure 3).

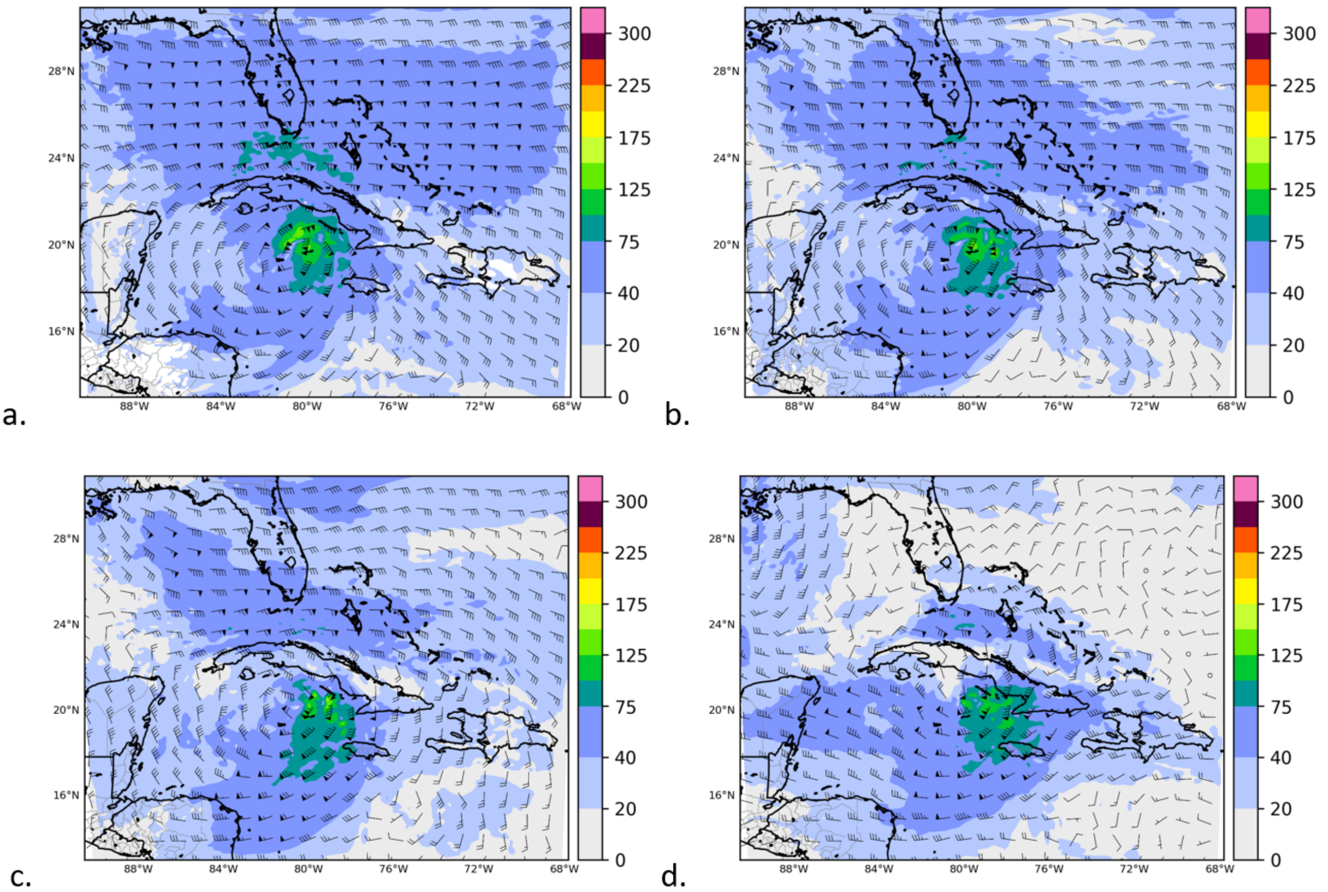


Figure 3. WRF-SST Flow Map of 7 November 2020 at 21:00 UTC at the level of: (**a**) 925 hPa, (**b**) 825 hPa, (**c**) 700 hPa y (**d**) 500 hPa.

At 00:00 UTC on 8 November 2020, the wind maps showed a center of high wind speed values, around 125 km/h, located near the southern coast of central Cuba, from 925 hPa to 500 hPa, with the previously mentioned shift to the right of the system position at height (Figure 4). This synoptic configuration is an indicator that the system re-intensified again, which could not be seen with ERA5. However, this situation would not last long since a 200 hPa trough located in the eastern Gulf of Mexico was also identified, which extended very close to the area where the system was located, in the vicinity of the central region of Cuba. This trough, (represented in Figure 5 as a brown line), interacted with the system since it appeared represented at medium levels, which would weaken it again to its TS status, a category that made landfall between the border of the Sancti Spirits and Ciego de Ávila provinces on November 8 around 09:00 UTC (Figure 5). The 500 hPa map shows the center of low geopotential value, although to a lesser extent due to the limited domain, located near the southwestern coast of the United States, over Texas and Louisiana that ERA5 was not able to represent. This synoptic configuration induced southeasterly directional currents in the deep layer, resulting in a change in the system's trajectory (Figure 5).

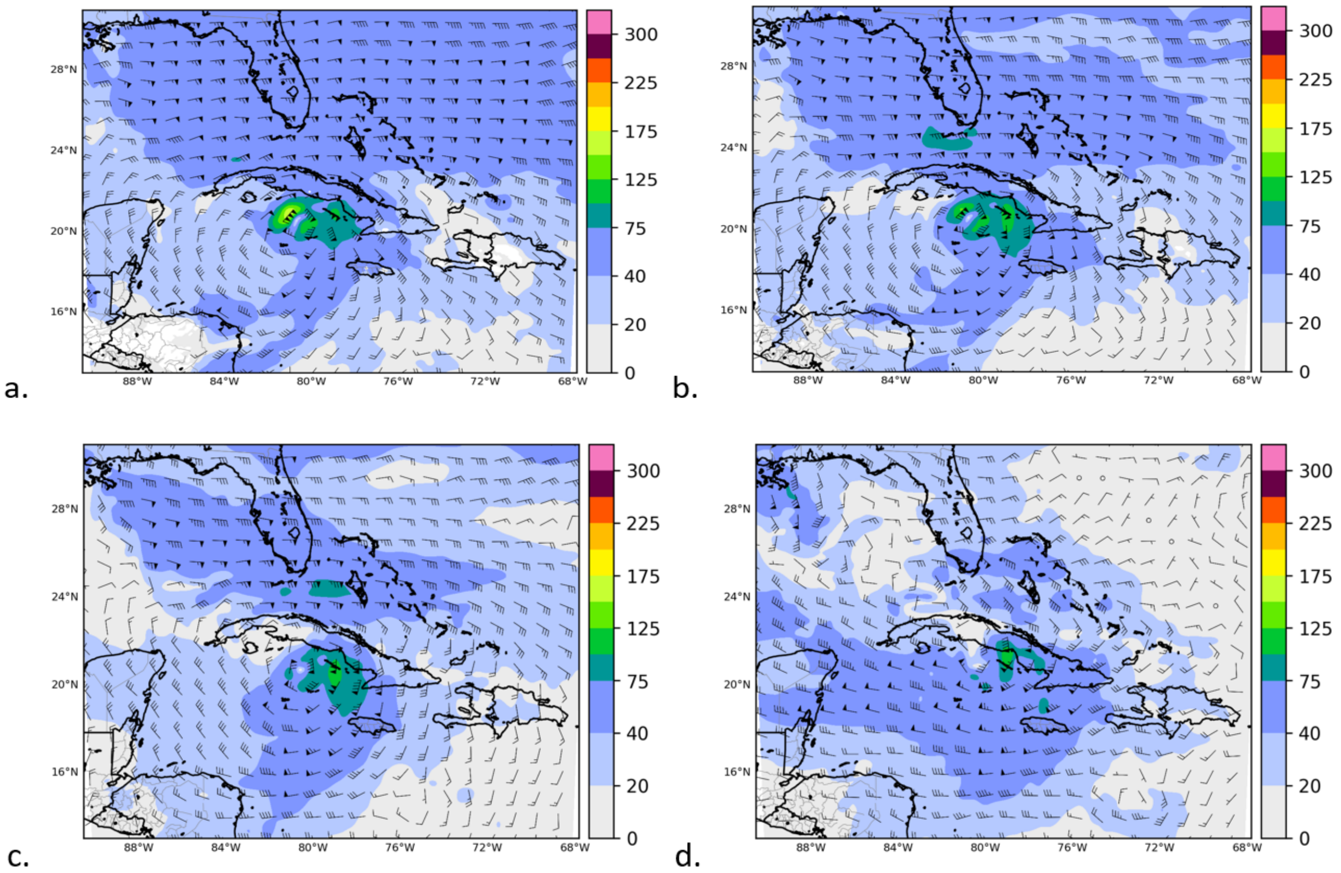


Figure 4. WRF-SST flow map of 8 November 2020 at 00:00 UTC at the level of (**a**) 925 hPa, (**b**) 825 hPa, (**c**) 700 hPa y (**d**) 500 hPa.

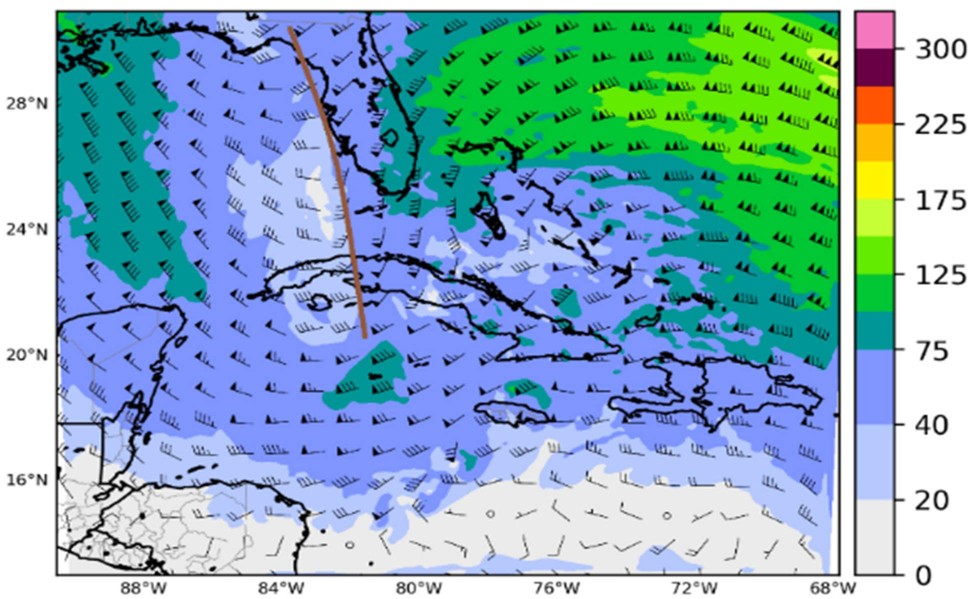


Figure 5. WRF-SST Flow Map of November 8 at 09:00 UTC at the level of 200 hPa.

The relative humidity maps showed an intrusion of dry air from 700 hPa to 200 hPa that progressed with the hours (Figure 6) until it surrounded the area where the system was located in the upper levels of the atmosphere when it was departing from the north coast of Ciego de Ávila province at 21:00 UTC on the same day. The lowest reflectivity values were concentrated in the center of the system and the highest values in its outer bands (Figure 7).

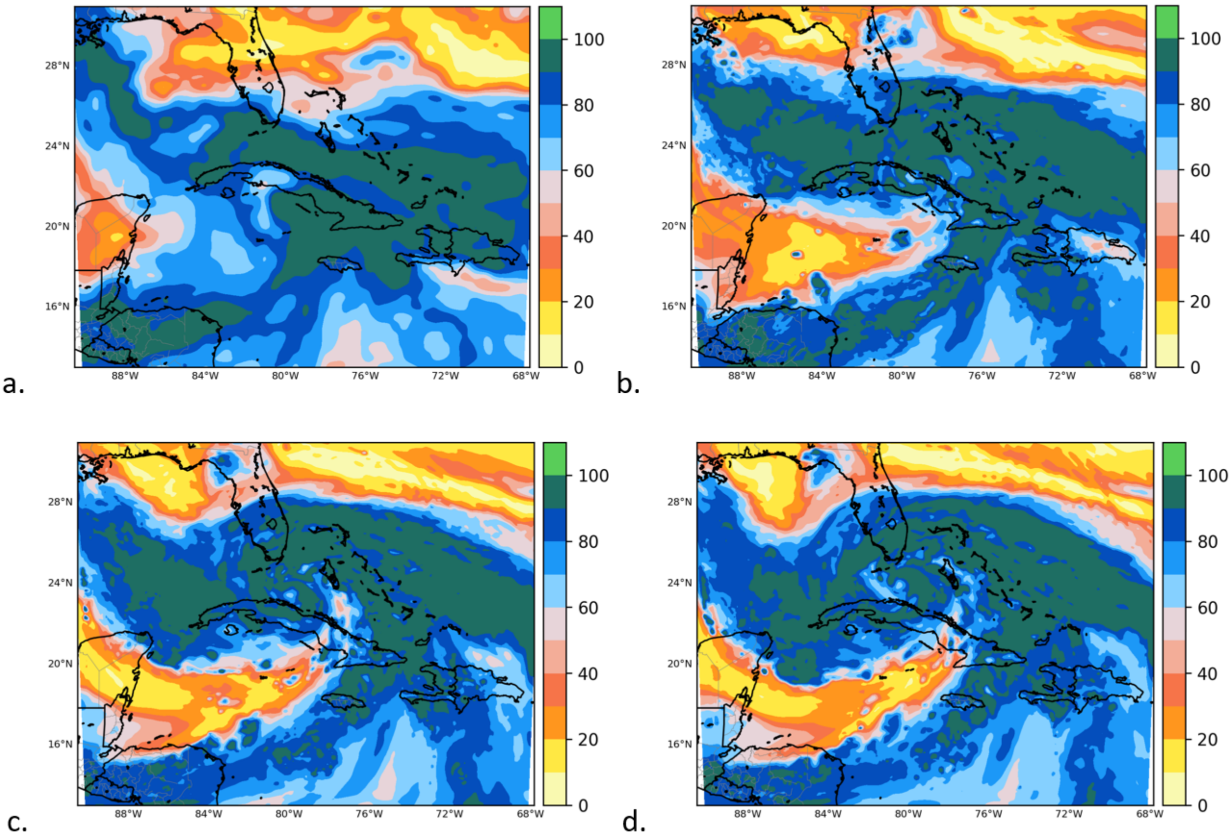


Figure 6. WRF-SST Relative Humidity Map of November 8 at the level of 700 hPa at (**a**) 00:00 UTC, (**b**) 12:00 UTC, (**c**) 18:00 UTC, (**d**) 21:00 UTC.

3.2. Moment from 9 to 11 November 2020

At 00:00 UTC, on 9 November, a center of minimum geopotential value from the level of 925 hPa to 500 hPa, near the coast, could be identified on the geopotential height maps of Florida right where Eta was at that time. At 300 hPa and 200 hPa, the presence of a trough was observed that extends over the eastern United States and interacts with the system in its lower sector. In addition, a low is seen at 300 hPa which, unlike the one that represents Eta at lower levels, is immersed in the same axis of the trough (Figure 8).

The relative humidity maps show the persistence of the intrusion of dry air, which would last for the next few days. Dry air entrainment caused some weakening, and the storm's winds decreased later, on November 9, as the system turned to the west-southwest and southwest (Figure 9).

The cyclone made a cyclonic loop north of far western Cuba, with little change in intensity, on 10 November.

In the geopotential height maps at the level of 500 hPa of November 11 at 00:00 UTC, an area of high gradient value is evidenced in the west of the north Atlantic, and at 06:00 UTC what is presented in that position is the dorsal of the aforementioned system, which has its ascending sector to the west, the one that favored the shear found in the synoptic environment. It breaks into the Caribbean area as it passes from the hours to Jamaica at 21:00 UTC on the same day. This disruption may have been one of the factors influencing the system's northward trajectory (Figure 10).

With the WRF-SST maps it was possible to identify systems that the ERA5 was not able to show, the wind speed values offered by the flow maps were much closer to those estimated than those of the re-analysis system.

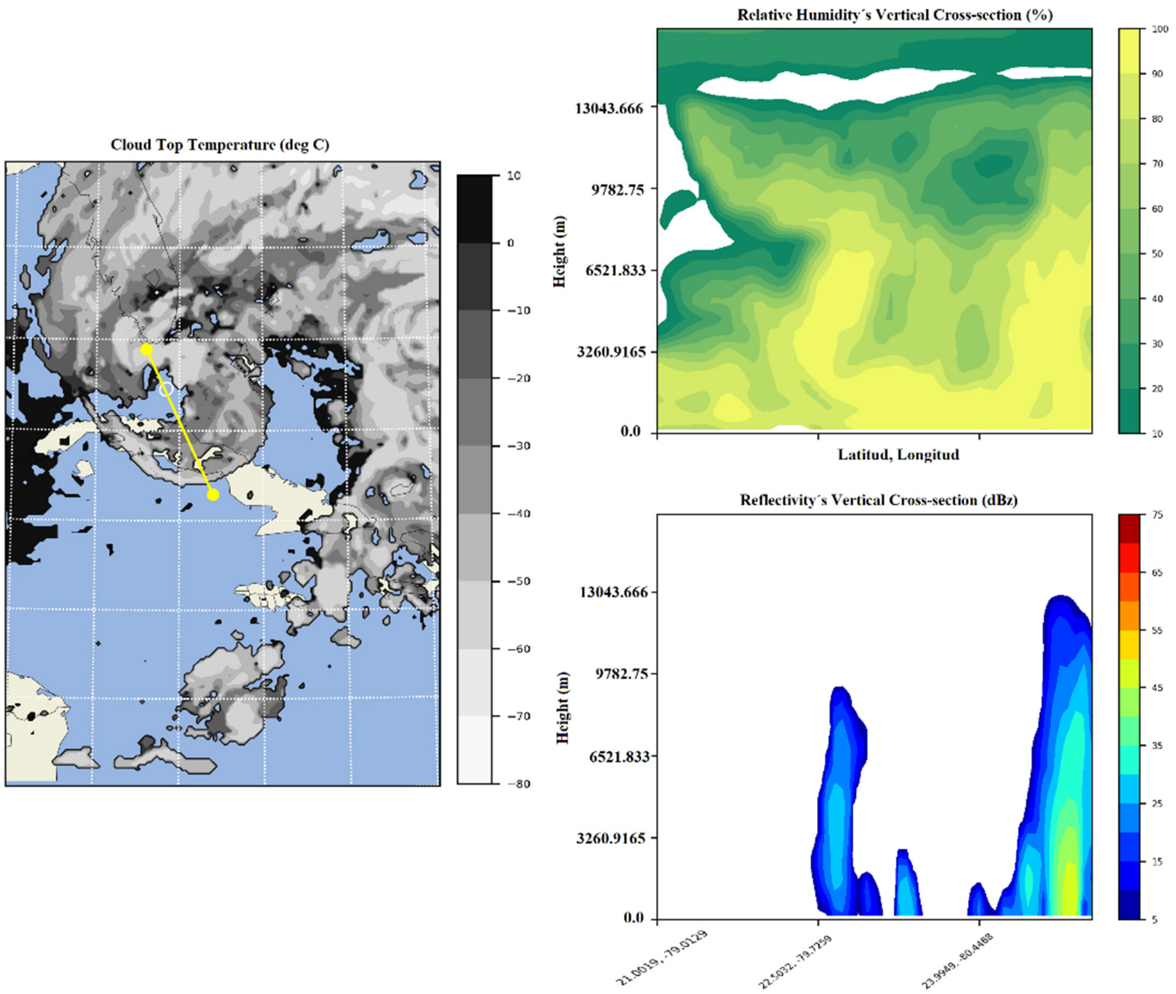


Figure 7. WRF-SST relative humidity's vertical cross-section and reflectivity on November 8 at 21:00 UTC.

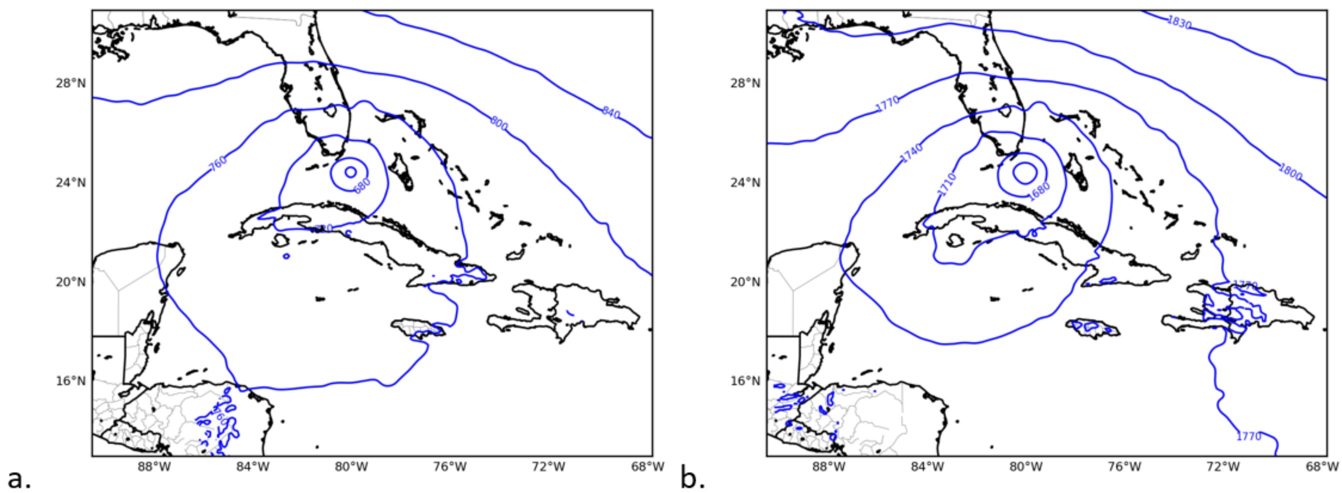


Figure 8. *Cont.*

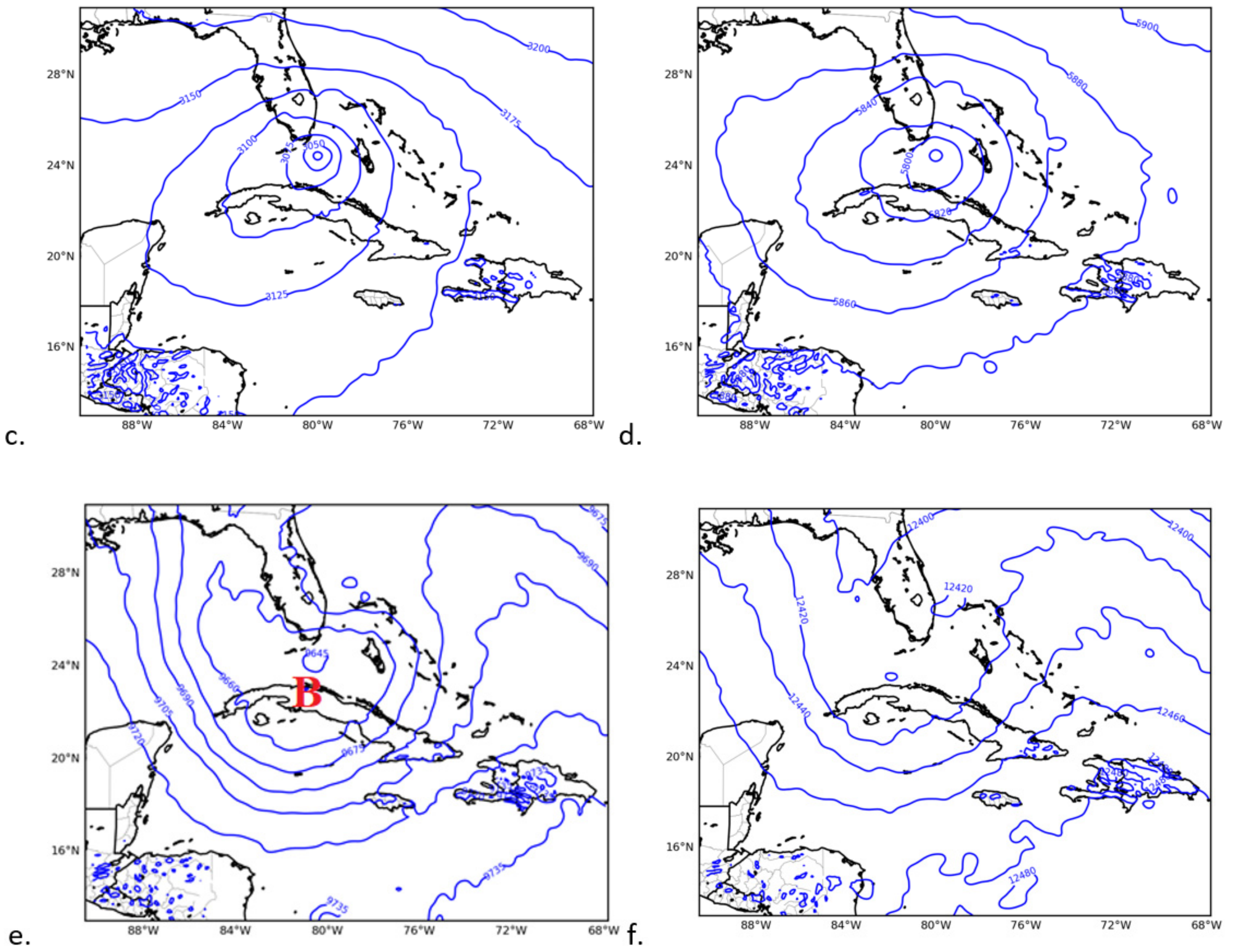


Figure 8. WRF-SST geopotential height maps of 9 November at 00:00 UTC in the levels: (**a**) 925 hPa, (**b**) 825 hPa, (**c**) 700 hPa, (**d**) 500 hPa, (**e**) 300 hPa, (**f**) 200 hPa.

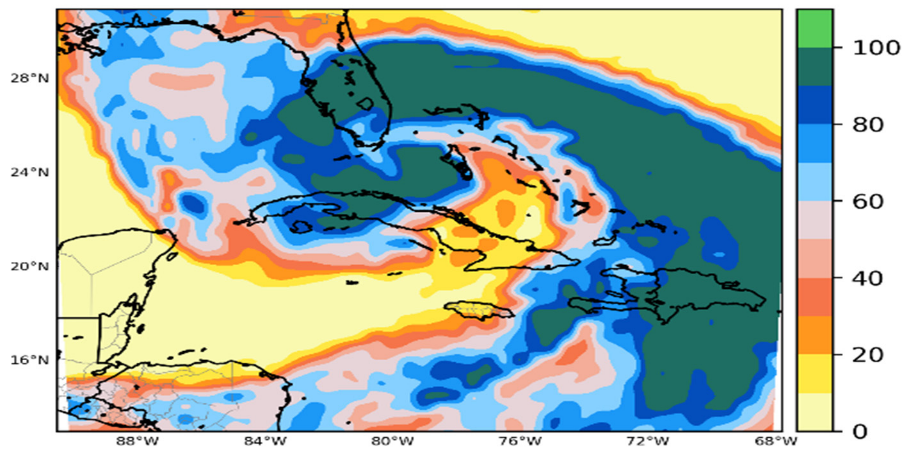


Figure 9. Relative humidity map on November 9 at 00:00 UTC in 500 hPa level.

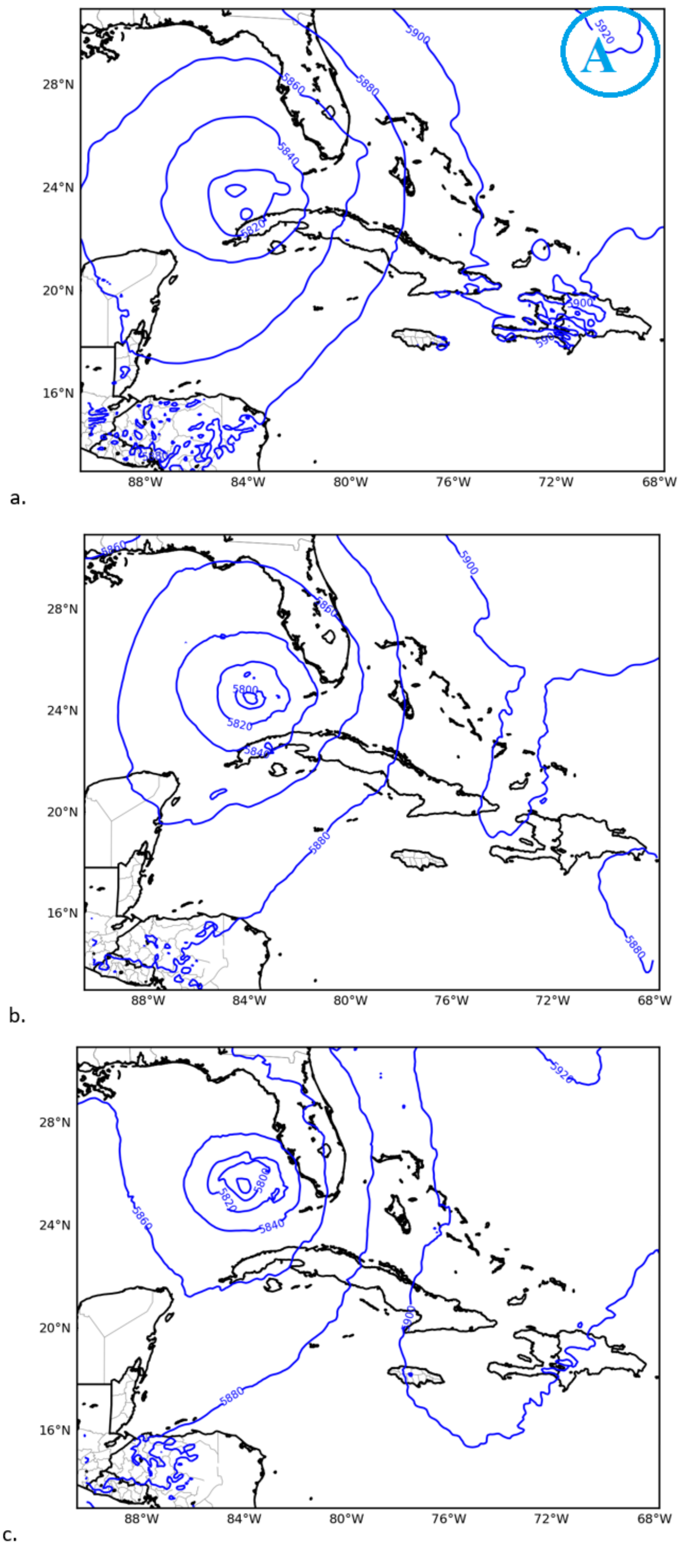
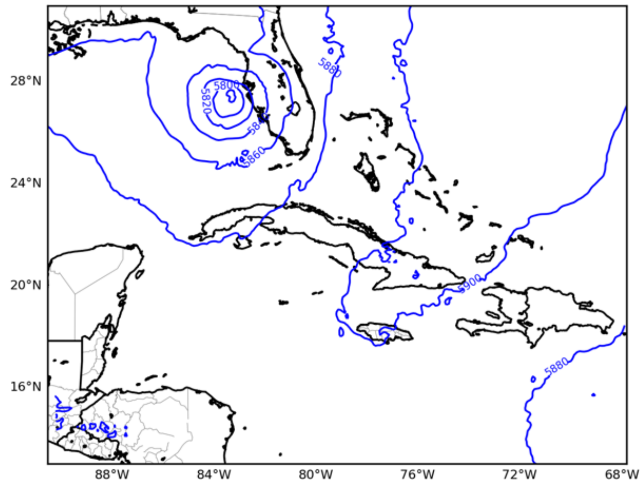


Figure 10. *Cont*.



d.

Figure 10. WRF-SST geopotential height maps on November 11, 2020, in 500 hPa level at: (**a**) 00:00 UTC, (**b**) 06:00 UTC, (**c**) 12:00 UTC, (**d**) 21:00 UTC.

3.3. Graphs of Minimum Central Pressure, Maximum Wind Speed and Eta Trajectory

Using the minimum central pressure graphs, it was possible to observe that the greatest overestimations of the WRF are concentrated on November 3, when the greatest values of absolute error are concentrated (between 25 hPa and 35 hPa), for the next few days, the system performs a general underestimation of pressure values. The smallest errors were found on 11 November (Figures 11 and 12).

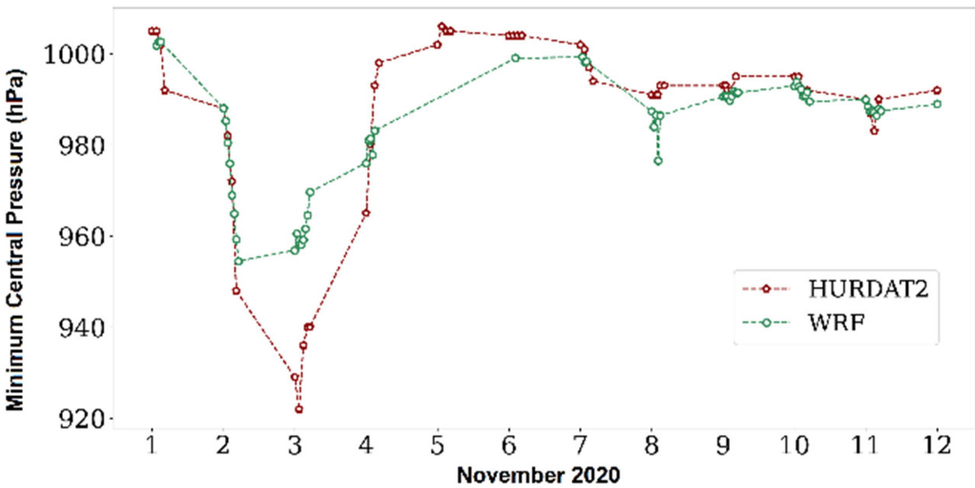


Figure 11. Minimum central pressure graph.

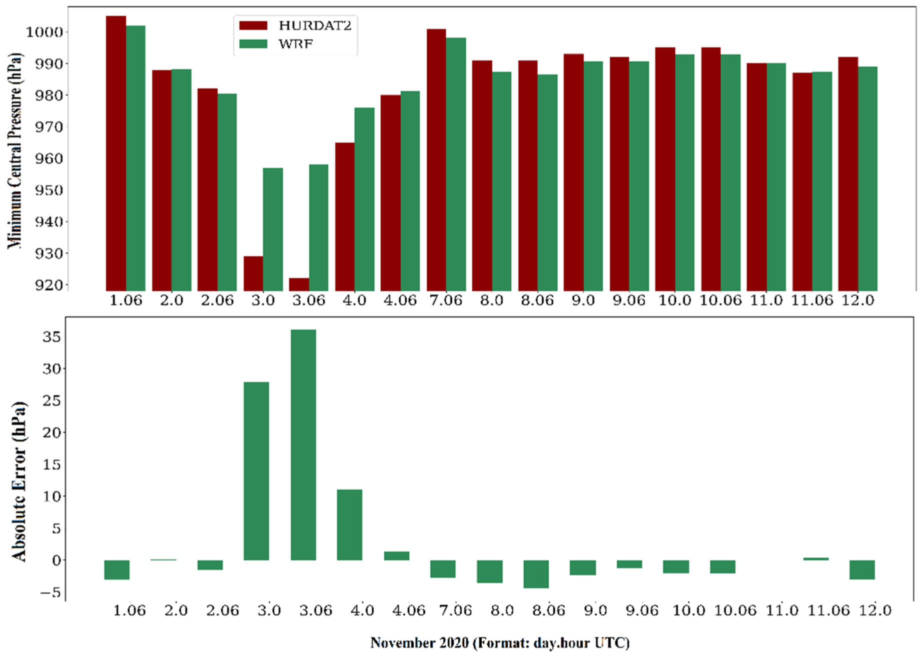


Figure 12. Bar chart of the minimum central pressure and absolute error.

The maximum wind speed graphs show the tendency of the system to underestimate these values, except on 8 November, when it was overestimated. The largest absolute errors are concentrated, like the pressure, on 3 November with values between 80 km/h and 108 km/h. The days with the fewest errors were 7 and 12 November (Figures 13 and 14).

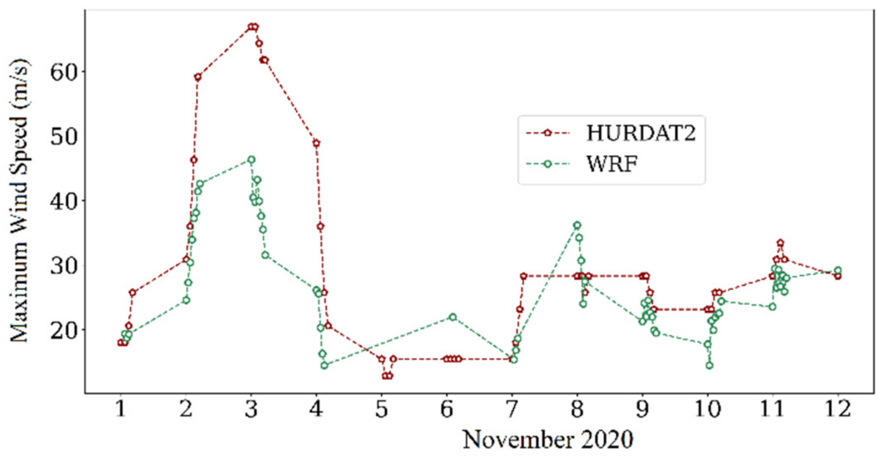


Figure 13. Maximum wind speed graph.

Regarding the trajectory, it can be concluded that the system made a very good estimation in general (Figure 15).

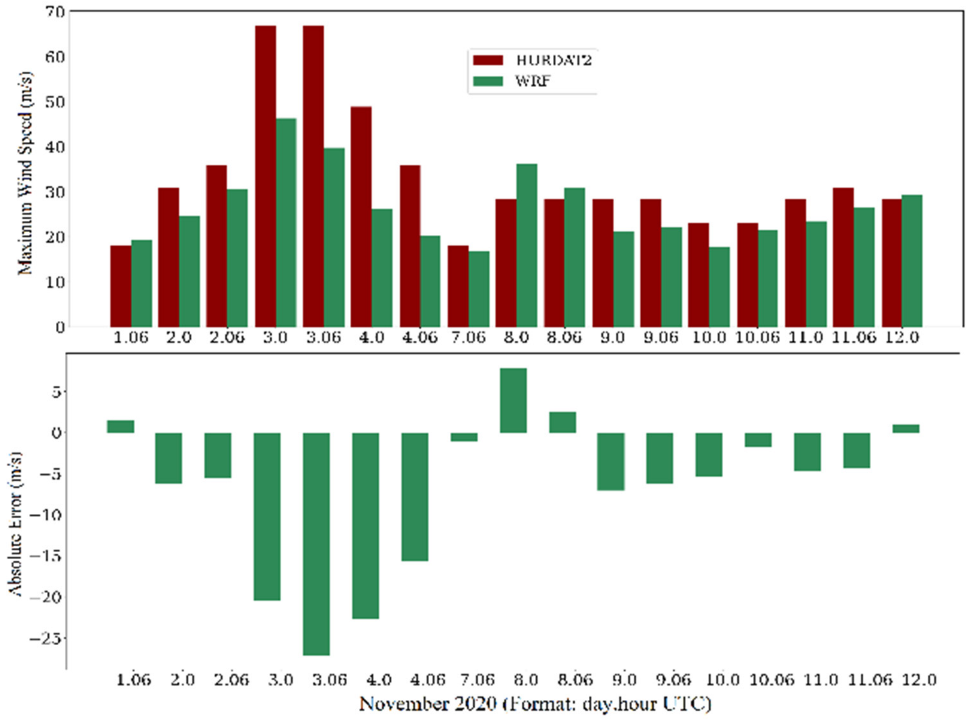


Figure 14. Bar chart of the maximum wind speed and absolute error.

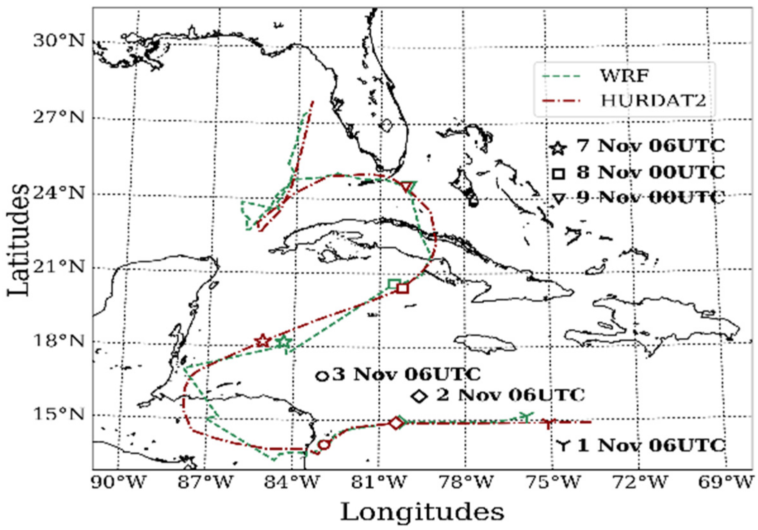


Figure 15. Trajectory map.

4. Conclusions

After completing the study of the case proposed in this investigation, the objectives proposed at the beginning were met, which allowed the following conclusions to be reached:

1. When analyzing the maps of the ERA5 reanalysis system, a general underestimation of wind speed during the analyzed periods. The first moment was characterized by a system in the development phase that failed to intensify under the influence of a trough over the southeastern Gulf of Mexico that generated a sheared environment. These conditions were maintained during the second moment when the organism described an erratic trajectory due to the fact that it was under the influence of weak directing currents until it entered the flow of a ridge that led it to redirect its trajectory towards the north.

2. Through the experiments that were carried out with the WRF-SST and from the numerical outputs, it was possible to describe with greater precision the meteorological conditions that influenced the development, trajectory and intensity changes of Eta.
3. With the WRF-SST flow maps, an improvement was observed in terms of the estimation of wind speed and geopotential found in the ERA5 maps during the study periods. It was possible to specify, through the vertical cross sections, the behavior of the vertical wind speed, the reflectivity and the relative humidity in the vertical which allowed one to have a more realistic vision of the evolution of Eta.

Author Contributions: Conceptualization, G.S.-M. and M.S.-L.; methodology, G.S.-M. and M.S.-L.; software, M.S.-L.; validation G.S.-M. and M.S.-L.; formal analysis, G.S.-M. and O.A.-F.; investigation, G.S.-M.; resources, M.S.-L.; data curation, M.S.-L.; writing—original draft preparation, G.S.-M.; writing—review and editing, G.S.-M.; visualization, G.S.-M.; supervision, M.S.-L.; project administration, G.S.-M.; funding acquisition, M.S.-L. All authors have read and agreed to the published 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: http://modelos.insmet.cu (accessed on 25 July 2022).

Acknowledgments: The authors thank Lic. Liset Vázquez Proveyer from the Center for Physics of the Atmosphere, Institute of Meteorology, Casablanca, 10900 Havana, Cuba; for her contribution to the simulation domains used in conducting this research.

Conflicts of Interest: The authors declare no conflict of interest.

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