Exploring the Relationship Between Cloud-Top Temperature (CTT) and Precipitation During Hurricane Fiona Over Puerto Rico

Juan L. Colón-Pérez[1], Stephanie M. Ortiz-Rosario[1], and Andrea N. Belvis-Aquino[2]

[1]Department of Physics, University of Puerto Rico, Mayagüez, P.R.
[2]Department of Industrial Engineering, University of Puerto Rico, Mayagüez, P.R.

May 13, 2024

1 Abstract

Cloud top temperature (CTT) is a useful parameter in identifying areas of heavy rainfall. In September 2022, Hurricane Fiona affected Puerto Rico with rainfall accumulations that reached more than 30 inches. This study uses remote sensing to examine the relationship between low CTTs and increased rainfall in Puerto Rico during the hurricane event. The CTT Level-2 product from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) infrared band and the National Weather Service San Juan (NWS-SJU) maximum recorded precipitation official report were crucial to exploring the variables' relationship. The ENVI Classic and 6.0 programs allowed the images' visualization of the CTTs' progression in six different regions of the island: North, South, East, West, Central, and Marueños (Ponce, PR). From September 17 to September 19, the CTTs' classifications were guided by the systems' inner core or region with the lowest CTTs, whose area shrunk as it interacted with the island's topography. The daily CTT values decreased overall as the cyclone approached Puerto Rico,

with typical values ranging from 211-198 K, which depict tall cloud tops and heavy precipitation. However, a strictly direct relationship was not found between the lowest average CTT and the highest accumulated precipitation, as observed in Marueños, where the CTT was greater than in other areas with less accumulated rainfall. Recommendations for future work include improving the comparative analysis between CTTs and precipitation by studying hourly rainfall amounts and acquiring a larger dataset to account for the external bands of the hurricane.

2 Introduction

Hurricane Fiona was a Category 1 hurricane that passed south of the island on September 18, 2022. The passage of this atmospheric disturbance left behind rainfall accumulations of over 30 inches [2]. A useful parameter for forecasting these extreme rainfall events is the cloud top temperature (CTT). As cloud top height increases, the updraft that carries warm, moist air away from the surface reaches colder temperatures. As a result, water vapor condensation is enhanced as it encounters colder air at higher altitudes, and thus more precipitation can be observed. Given this relation, colder CTTs are a useful signal of this process and may be associated with more intense precipitation. To study CTTs, remote sensing observations are key to feeding convection parameters into forecast models.

The Moderate Resolution Imaging Spectroradiometer (MODIS), a satellite-based sensor from the National Aeronautics and Space Administration (NASA), was selected to perform this research. Specifically, the cloud products from this sensor were used. The MODIS cloud products combine infrared and visible wavelengths to determine clouds' physical and radiative properties. The infrared band methods produce relevant information such as cloud top temperature,

phase, emissivity, height, and cloud fraction for both day and night [1]. Platnick et al. (2003) provide [3] extensive details on the types of cloud information that can be extracted from the sensor, including cloud top temperature.

3 Objectives

This study aims firstly to develop satellite imagery processing skills using the MODIS sensor. These skills are crucial to analyzing the variating CTTs as Hurricane Fiona strikes Puerto Rico. Moreover, this research pursues to associate the areas of different CTTs with the rainfall amounts measured between different island regions. In sum, the following questions will be addressed: 1) Can the MODIS sensor identify different low CTT areas associated with deep convection in Hurricane Fiona? and 2) Can we relate this information with the measured rainfall in different island regions due to the cyclone's landfall? Examining how CTT values are related to precipitation amounts will provide insight into how remote sensing can provide accurate information about the intensity of cyclones.

4 Methodology

Images for September 18 and September 19, 2022 over the Caribbean region were obtained from NASA Level-1 and Atmosphere Archive and Distribution System Distributed Active Archive Center (LAADS DAAC). The area of interest over the Caribbean was delimited by 78.8° W, 28.4° N, 53.6° W, 6.9° N. The studied images were taken by the MODIS sensor onboard the Terra Earth Observing Satellite (EOS). Particularly, the product used was the MODIS Level-2 Cloud Product (MOD06L2), which contains cloud top temperature. This cloud product algorithm uses infrared band-29, with wavelength between 8.400 µm

and 8.700 µm, to calculate cloud top properties. MODIS Cloud Product [1] provides daily global data with a 1 km spatial resolution.

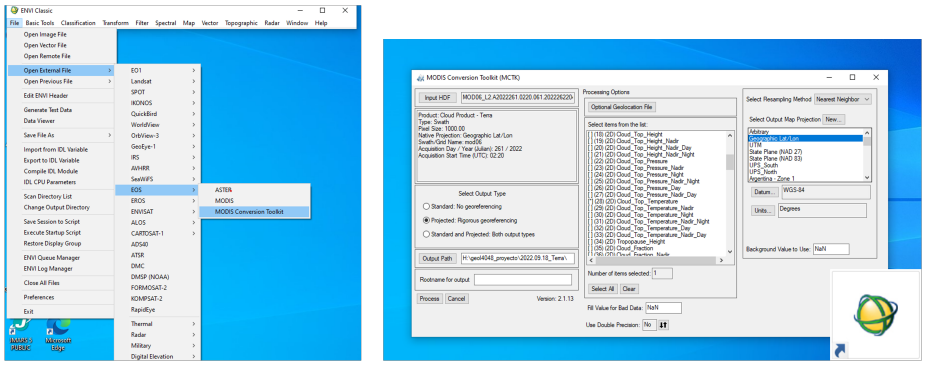

Figure 1: MODIS Conversion Toolkit created by Dr. Devin A. White from John Hopkins University

Downloaded MODIS images were opened in ENVI Classic using the MODIS Conversion Toolkit created by Dr. Devin A. White from JHU [4]. This plugin was installed in ENVI Classic to facilitate the conversion of HDF4 files to ENVI files, Figure 1. After the conversion, the images were opened in ENVI 6.0, and images over Puerto Rico were identified. Five images met the requirements and were chosen for further analysis. Table 1 shows the dates and times of the images. A Seamless Mosaic was done to images 2 and 3 to cover Puerto Rico. Next, different locations in Puerto Rico were chosen to identify CTTs, which included the neighborhood with the maximum recorded precipitation by the NWS-SJU, Marueño, Ponce. Table 2 includes the coordinates of each of the locations selected. Quick Statistics were obtained to validate the CTT values, including maximum, minimum, and mean temperatures. In addition, the Region of Interest (ROI) feature was used to estimate the area of the hurricane's inner core by measuring the organized core with lowest temperatures. This allowed to visualize the evolution of Hurricane Fiona. Moreover, a corresponding color

palette was applied to the images, as well as, a colorbar and coastlines for easier visualization. After finalizing the image processing in ENVI 6.0, precipitation data for Puerto Rico from the NWS Forecast Office in San Juan official report for Hurricane Fiona was obtained. This included accumulated rainfall data from September 18 to September 21, 2022 for 133 sites. Precipitation values for the selected locations (Table 2) were identified and compared with CTTs. The same process was applied to each of the images analyzed.

Table 1: MODIS Images of Interest.

Image Number	Filename (UTC)	Local Time (AST)	
1	MODIS-18-0220	17-Sep-22	11:20 PM
2	MODIS-18-1430	18-Sep-22	11:30 AM
3	MODIS-18-1435	18-Sep-22	11:35 AM
4	MODIS-19-0305	19-Sep-22	12:05 AM
5	MODIS-19-1515	19-Sep-22	12:15 PM

Table 2: Selected locations over Puerto Rico for analysis.

Region	**Coordinates**
North	18°25'54.87"N,66°30'41.44"W
South	18°0'55.85"N,66°33'33.00"W
East	18°11'43.15"N,65°47'47.90"W
West	18°12'17.22"N,67°2'8.70"W
Central	18°12'17.22"N,66°28'58.49"W
Marueños, Ponce, PR	18°04'55.06"N,66°40'4.98"W

5 Results

Figures 2 to 5 capture Hurricane Fiona's trajectory through Puerto Rico. The colorbar allows the observation of the hurricane structure by identifying its characteristic CTTs in shades of blue, ranging from less than 200 K to 250 K. Table 3 shows that the inner core of the system reduces in its path across Puerto Rico. The reduction can be attributed to the friction with the island's topography. Nonetheless, the core maintains a larger area than that of Puerto Rico, demonstrating the vastness of Fiona. As a note, because Hurricane Fiona entered Hispaniola, the inner core for Figure 5 was not calculated.

Table 4 depicts lowering CTTs across the different regions of the island as Hurricane Fiona approached Puerto Rico. This is observed especially between September 17 and 19, where, in general, CTTs decreased from 230-220 K to 211-198 K. Because, on September 18 and 19, Fiona's inner core was closest to Puerto Rico, the reduced CTTs represent the nature of higher and colder cloud tops, which relate to deep convection and heavy rainfall. Finally, as the hurricane exited the region on September 19, the CTTs increased in all the highlighted locations. Excluding Marueños, Ponce, the CTTs in the other areas were under the initial values, indicating that external bands of Fiona were still affecting the island, possibly with more heavy rainfall.

When comparing the average CTT values to those of the range of accumulated rainfall in Table 5, a direct relationship between the lowest CTTs and highest rainfall accumulations cannot be established. For instance, in Marueños, Ponce, where the highest rainfall accumulation was registered (32.40 in), the average CTT between September 17 and September 19 was higher than that of the East, where CTTs averaged 206.32 K Figure (5). Nonetheless, the CTTs decreased notably throughout the timeframe Fiona reached Puerto Rico in all the regions, depicting low values capable of producing torrential rainfall.

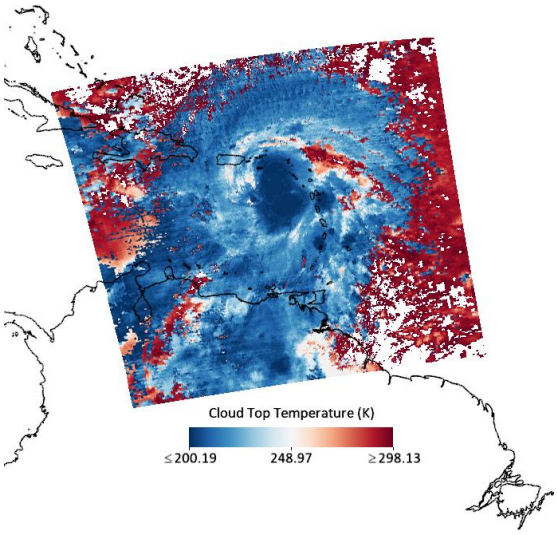

Figure 2: Cloud Top Temperature for September 17, 2024 11:20 PM

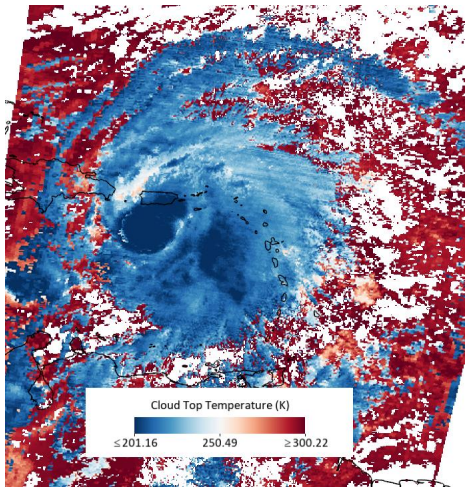

Figure 3: Cloud Top Temperature for September 18, 2024 11:30 AM

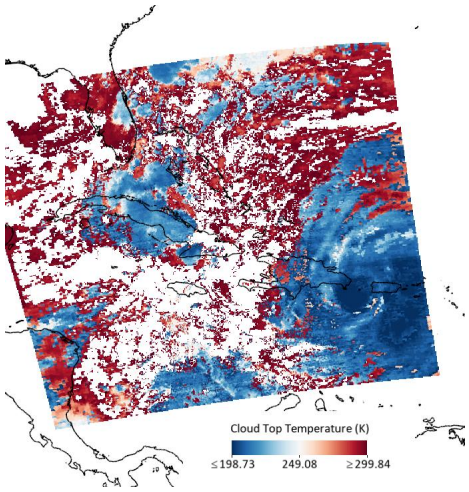

Figure 4: Cloud Top Temperature for September 19, 2024 12:05 AM

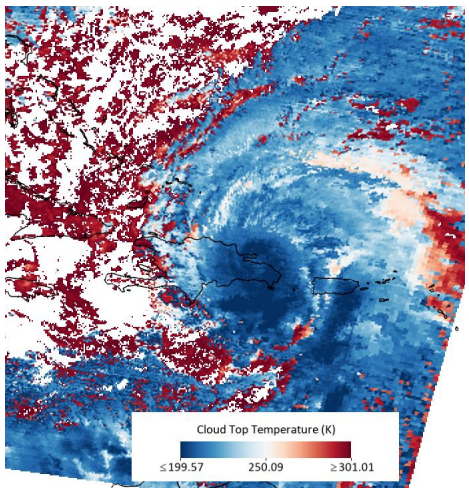

Figure 5: Cloud Top Temperature for September 19, 2024 11:30 AM

Table 3: Measured areas of Hurricane Fiona's coldest CTTs near the center of the storm (inner core)

Image Classification	**Inner Core Area (km^2)**
17-sept-2022 (Figure 2)	51,298
18-sept-2022 (Figure 3)	40,360
19-sept-2023 (Figure 4)	24,975

Table 4: Daily CTTs recorded by region

Region	CTT (K)			
	17 Sept 11:20 PM	**18 Sept 11:30 AM**	**19 Sept 12:05 AM**	**19 Sept 12:15 PM**
North	223.81	208.39	205.17	218.36
South	233.00	198.08	205.17	221.33
East	220.37	202.41	198.84	203.66
West	220.63	209.09	201.91	209.18
Central	226.72	201.19	203.85	212.05
Marueños, Ponce	220.63	205.87	211.77	221.33

Table 5: Averaged CTTs and accumulated precipitation by region

Region	**Average CTT (K)**	**Range of Accumulated Rainfall [18-21 Sept] (in)**
North	213.93	1-2.99
South	214.40	20-24.99
East	206.32	10-14.99
West	210.20	10-14.99
Central	210.95	20-24.99
Marueños, Ponce	214.90	32.40

6 Conclusion

This study utilized MODIS satellite imagery to analyze CTTs associated with Hurricane Fiona as it passed over Puerto Rico in September 2022. CTTs at different locations in Puerto Rico were identified and compared to precipi-

tation recorded during Hurricane Fiona. Most higher cloud tops were observed on September 18, 2022. On this day, the system's inner core was the closest to Puerto Rico. This is characteristic of cyclones, where the inner core has lower CTTs and higher cloud tops than the outer bands. Also, the lower CTTs on this day, compared to September 17 and 19, suggest that the system was intensifying, which was supported by the system's official intensity and track reports. Precipitation records showed the accumulated precipitation along the island varied depending on the location. However, a direct correlation between the lowest CTTs and the highest accumulated rainfall across Puerto Rico was not consistently evident. While Marueños, Ponce recorded the highest rainfall, its average CTT was higher than other areas which recorded less precipitation. This result is largely attributable to the limited availability of MODIS images, which made difficult the calculations of averages that were comparable to the recorded precipitation. This conclusion was drawn from observations of tropical cyclones, where new convective zones can develop within 12 hours, which was the approximate time between the images. However, the MODIS cloud products are highly effective for this research topic, and this project once again demonstrates their utility. One potential future application of this products could be to monitor the intensification of tropical cyclones. Overall, this study highlights remote sensing as a valuable tool for understanding cyclones, which can lead to enhanced forecasting capabilities.

7 Recommendations

To improve the comparative analysis between rainfall and CTTs, hourly precipitation data (i.e., rain gauges) can be retrieved and matched to MODIS imagery during the times it passed over Puerto Rico. This can result in a more accurate comparison than a 4-day rainfall accumulation and can also allow to

identify peak precipitation times. In addition, a larger MODIS dataset can be acquired to account for the most external rain bands from Hurricane Fiona over Puerto Rico before and after it hit the Island. A larger dataset can help quantify the evolution of CTTs as the cyclone strengthened, and characterize its structure. Finally, it could be useful to analyze other MODIS products alongside CTT (i.e., surface pressure) and compare it to the registered rainfall to understand the combination of atmospheric conditions present during Hurricane Fiona.

8 Acknowledgements

This work was possible thanks to the guidance of Dr. Fernando Gilbes Santaella. We acknowledge NASA for providing open-access satellite imagery through the LAADS DAAC platform and the National Weather Service Forecasting Office in San Juan for providing crucial data on Hurricane Fiona. Special thanks to Mr. Robert Ropiza Rivera for his technical support, which contributed to the success of this work.

References

[1] *MODIS Cloud (06_L2)*. URL: https://atmosphere-imager.gsfc.nasa.gov/products/cloud.

[2] R. Pasch, B. Reinhart, and L. Alaka. "National Hurricane Center Tropical Cyclone Report: Hurricane Fiona. National Hurricane Center (NHC)". In: (Mar. 2023).

[3] S. Platnick et al. "The Modis Cloud Products: Algorithms and examples from Terra". In: *IEEE Transactions on Geoscience and Remote Sensing* 41.2 (Feb. 2003), pp. 459–473. DOI: 10.1109/tgrs.2002.808301.

[4] D.A. White. *The modis conversion toolkit plugin for Envi*. 2023. URL: https://github.com/dawhite/MCTK.