The Impact of High-Resolution Terrain Data on WRF Simulations of Hurricane María (2017)

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ABSTRACT

The atmospheric processes involved in a tropical cyclone are affected by topographical factors during and after landfall. Interactions with land are capable of changing the tropical cyclone's structure, behavior, and impact on the landmass. However, one of today's forecasting problems is that computer models cannot interpret many of the factors that influence surface weather over complex terrain, and they forecast the tropical cyclone's behavior that would be expected if it was moving over a smooth landmass. This research project investigated the impact of high-resolution terrain data in Weather Research and Forecasting (WRF) model simulations of Hurricane María, focusing on its path over Puerto Rico. Two WRF simulations were compared to see the impact of the model's terrain resolution. One of the simulations used a default terrain data set that considers Puerto Rico as a smooth surface, and the other used a high-resolution terrain data set that accurately represents the island's mountainous topography. Time-series plots, horizontal maps, and swaths of atmospheric variables such as wind and rain at specific locations were used to show differences between the two simulations and demonstrate the impact of high-resolution terrain data on WRF tropical cyclone simulations. First, the high-resolution simulation showed higher rainfall. Second, the simulated wind speed was higher before the hurricane crossed the island, but it decayed after interacting with the landmass. It is concluded that high-resolution land data has the potential to lead to more accurate forecasts of wind and rain in cases when tropical cyclones interact with a landmass.

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1. Introduction

Tropical cyclones are organized thunderstorms rotating toward a center of low pressure that originate over warm tropical waters in the region between 23.5º north and 23.5º south of the equator. When these atmospheric phenomena make landfall, they bring strong winds, rainfall, and storm surge over the terrain. Tropical cyclone variables such as wind and rainfall are influenced by the topography of any landmass.

Hurricane winds produce a high amount of damage, changes in vegetation, and drive storm surge. Wind speed is subject to different forces like pressure gradient force, Coriolis force, centripetal force, and friction. Friction is drastically affected by topography. This force is usually stronger closer to the surface because of the presence of mountains and different structures. Because friction is the force that opposes air movement, higher winds would be expected where the friction is lower and weaker winds where the friction is higher. Miller et al., (2003), studying a time-stepping model for the wind field of Hurricane Fabian on Bermuda, noted that different surface conditions changed the wind speed, and concluded that the highest-elevation areas experienced a higher wind speed in contrast to the areas of lower elevation where the friction was stronger.

Besides wind, precipitation also changes with topography. Ramsay et al., (2006) studied the impact of the tropical cyclone Larry over Australia. They observed that the mountains influenced the wind field of the tropical cyclone and that the orography affected the precipitation. The precipitation in a hurricane that could produce severe flooding is enhanced by topography because when the horizontally moving air encounters an obstacle such as a mountain or hill, the air cannot go through the obstacle and instead goes over it. This additional lifting of moist air by high terrain produces more precipitation.

One of today's forecasting problems is that computer models cannot interpret many of the topographical factors that influence surface weather. Bender et al., (1987) conducted a numerical study of the effect of island terrain on tropical cyclones and noted that topography affects the flow field of a tropical cyclone and influences its structure. They concluded that topography should be included in numerical models for accurate and realistic forecasting of storm track and behavior.

To comprehend the importance of topography when a tropical cyclone interacts with landmass in models, and how the terrain resolution affects the forecast of rain and wind, this paper studies the differences between two WRF simulations of Hurricane María (2017) during its path through Puerto Rico. One of these simulations uses a default data set where Puerto Rico is represented by a smooth surface because the data is only interpolated from the low-resolution domain of the model. In contrast, the second simulation uses a high-resolution terrain data set where the data is interpolated to a high-resolution domain. This gives a more realistic representation of the island considering that Puerto Rico has a land surface composed of 40% mountains concentrated in the interior of the island and only 25% of plains [Acevedo-González (2014)]. The differences between the atmospheric parameters of the hurricane reveals the impact of high-resolution terrain data on WRF simulations of Hurricane María.

In this paper, section 2 gives background information about Hurricane María and Puerto Rico. Section 3 presents the methods to approach the scientific question. The results and discussion are given in section 4, and section 5 presents findings and conclusion.

2. Hurricane María (2017) and Puerto Rico

a. Study Area

The focal point of this study is the impact of Hurricane María on Puerto Rico. Puerto Rico is an archipelago located between the Caribbean Sea and the North Atlantic Ocean, with coordinates 18° 15' N, 66° 30' W and between Hispaniola and the British Virgin Islands. The vast majority of Puerto Rico's landscape is comprised of mountains and hills, with only 25% plains.

b. Background Information on Hurricane María

Hurricane María made landfall in Puerto Rico on September 20, 2017, and its center crossed the southeast coast of the island. The hurricane made landfall on the island 19 years after the last hurricane and became the strongest hurricane in Puerto Rico since a category 5 hurricane in 1928.

According to the National Hurricane Center, the landfall pressure of María was 920 hPa and the maximum winds were 135 kt which made it a category 4 hurricane on the Saffir-Simpson Hurricane Wind Scale. Before its landfall in Puerto Rico, the hurricane suffered an eyewall replacement where the old eyewall dissipated and a new one formed at a greater radial distance from the center. This decreased its intensity from category 5 to category 4 but increased the diameter of the wind field and the areal exposure of the island to the highest winds. After the hurricane's center crossed the island and interacted with the landmass of Puerto Rico, the maximum winds decreased. In addition to the intense winds, the hurricane produced peak rainfall totals of 38 inches causing flooding and record levels of river discharge.

The strong winds, storm surge, and heavy rainfall associated with the hurricane produced significant property damage and loss of life. The official death toll in Puerto Rico specified 65 direct deaths and an uncertain number of indirect deaths. Moreover, the property damage associated with the hurricane reached 90 billion dollars, making it the third-costliest hurricane in the history of the United States of America.

3. Methods

The basis for this research -- investigating the effects of different terrain resolutions on atmospheric process simulations -- is the Weather Research and Forecasting (WRF) model. This numerical weather prediction (NWP) model simulates the state of the atmosphere by solving mathematical equations on a three-dimensional grid. The WRF model employs three domains and a "nested grid refinement" method, where the outer domain is stationary and smaller, fine resolution domains inside the parent domain move to follow the areas of interest. The two moving nests are centered in the hurricane vortex and move with the tropical cyclone. For the research, the stationary outer domain, called domain one, has a resolution of 9 km, and the moving nests called domain two and domain three have a resolution of 3 km and 1 km, respectively. WRF gives the option to use terrain data with the same resolution as each nest, so the land data had a 9-km resolution in the parent domain, with 3-km and 1-km resolutions in the inner domains.

The research analyzes two WRF simulations of Hurricane María. The simulations start on 19 September 2017 at 6:00:00 UTC, covering the landfall of the hurricane in Puerto Rico, the hurricane crossing the island, and ended on 21 September 2017 at 23:00:00 UTC. The data sets give WRF output files of the hurricane every hour. One of the simulations uses a default land surface data set where the terrain data was only interpolated from a 9 km grid point spacing (hereafter referred to as WRF9) and this is what makes the terrain look smooth. The other simulation uses a data set with high-resolution topography at 1km grid spacing, hereafter referred to as WRF1. For the high-resolution topography data set, the terrain data is only interpolated to the high-resolution domain when the nests moved within the parent domain and encountered land, which gives a more accurate representation of the island's mountainous topography. In summary, both simulations use 1km grid spacing for the atmosphere as María crosses Puerto Rico but WRF9 uses terrain on a 9km grid and WRF1 uses terrain on a 1km grid.

The differences between the two simulations are studied using the NCAR Command Language (NCL) data analysis and visualization software. The research involves three stages of analysis using plots created by NCL. The first stage plots horizontal maps of wind speed and vertical velocity, including the pressure. The second stage plots time-series of wind speed and vertical velocity as function of time for specific locations in Puerto Rico. The third stage plots the maximum wind speed and rainfall of the hurricane using swaths.

a. Horizontal Maps

For the first stage, the WRF output files of 1 km resolution for simulations are used to study how the atmospheric variables change during the path of the Hurricane from 19 to 21 September. A contour map is created using an NCL script.

To plot the 10-m wind speed the variables that correspond to the components of the wind velocity for both data sets "U10" and "V10" from the WRF output file are used. Using the two components of the wind velocity, the magnitude of the two-dimensional variable of wind speed is calculated as:

$$Speed10 = \sqrt{(\square 10)^2 + (\square 10)^2}$$

then the units are converted to knots and plotted as a function of the latitude and longitude. In addition to the wind speed, the vertical movement of the air is plotted. Because the vertical velocity field "W" is a three-dimensional variable, its value at 40 meters above the surface is taken and treated as a two-dimensional variable to plot it in terms of latitude and longitude. The sea level pressure is represented by the variable "SLP" in the WRF output files. This variable is plotted as a contour map for each of the variables described above.

Plotting each variable for WRF9 and WRF1 for each grid of the hurricane's trajectory through the Caribbean reveals the differences in the atmospheric processes. The changing atmospheric variables as shown in the plots (shown later) reveals the differences between the simulations in terms of how the terrain has an effect on simulation of the impact of the hurricane every hour.

b. Time Series

For the second stage, the study focuses on the differences between the atmospheric processes at predetermined locations of interest in Puerto Rico using a time-series plot for each variable. These locations are included in Table 1.

Table 1: The names, latitudes, and longitudes for all locations of interest in Puerto Rico.

Location of Interest	Latitude	Longitude
Comerío	18.2180	-66.2260
Arecibo	18.4041	-66.6746
Cerro de Punta, Ponce	18.1724	-66.5918
El Yunque, Río Grande	18.2813	-65.7996
Mayaguez	18.2010	-67.1396
Yabucoa	18.0505	-65.8793
San Juan	18.3910	-66.0621
Orocovis	18.2269	-66.3910
Aguadilla	18.4660	-67.1204
Cabo Rojo	17.9813	-67.1287
Utuado	18.2655	-66.7004
Barranquitas	18.1691	-66.2916

NCL has a function to find the nearest model grid indices to a specified location, allowing researchers to extract the data for the desired parameter from that location. Time series are plotted for both simulations to study the differences between them. When plotting the time series for each variable for the desired grid, it is necessary to use all of the domains to have data of the desired variable for that point, even when the hurricane was not over that grid point location.

The atmospheric variables plotted for the second stage are wind speed and vertical velocity. The same calculations and conversions from the first stage applies to the second stage. The time series plots show the change of the atmospheric parameters as a function of time for both simulations and are useful to explore the impact of terrain resolution on the hurricane.

c. Swaths

For the final stage, the study focuses on the maximum wind speed and maximum rainfall over the lifetime of the hurricane. These atmospheric variables are studied every hour, from September 19 6:00:00 UTC to September 21 22:00:00, for every location using a contour map. An NCL script is used to find the maximum speed in the WRF output files from both simulations to reveal differences of how the terrain data affects the maximum wind speed and maximum rainfall.

To plot the wind swath, the variable "uvmet10" from the WRF output file was used to give components of wind rotated to earth coordinates. Then, the magnitude of the wind velocity vector is determined.

Two variables were used to plot the hourly precipitation: the “RAINNC” variable corresponds to the accumulated total grid scale precipitation, and “RAINC” corresponds to the accumulated total cumulus precipitation. These two variables were added to find the total precipitation.

4. Results and Discussion

To show the impact of high-resolution terrain data in WRF simulations of Hurricane María, the variation of atmospheric processes with topography were studied using different visualizations. These visualizations compared the wind speed, vertical velocity, and rainfall in cases when Puerto Rico’s representation of topography was accurate and when Puerto Rico’s surface was considered smooth.

a. Wind

The structure and behavior of the hurricane’s wind field changes with topography because of the friction present in the interaction between the tropical cyclone and the landmass. The horizontal contour map shows that the wind speed from the high-resolution topography was higher in elevated locations compared to the wind speed from the low-resolution topography. Moreover, the results show that after the tropical cyclone interacted with the landmass, its wind speed had decreased.

Figure 1 and Figure 2 show the wind speed of Hurricane María when its eye is close to Puerto Rico on 20 September 2017 at 11:00:00 UTC. For WRF9 (Figure 2), the wind speed over the islands Vieques[1] and Culebra[2] is the same wind speed expected over open ocean water. However, for the wind speed from WRF1 (Figure 1), the magnitude expected over the two islands is lower in contrast to the wind speed over the ocean and for the low-resolution terrain data. This results from the island’s topography representation because for WRF9, the islands do not have enough elevation to change the wind speed over the surface.

[1] Vieques is an island and municipality of Puerto Rico located to the east of the main island, and its coordinates are 18° 7' 29.8956" N, 65° 26' 31.6428" W.
[2] Culebra is an island and municipality of Puerto Rico and its coordinates are 18° 18' 10.8468" N, 65° 18' 3.5532" W.

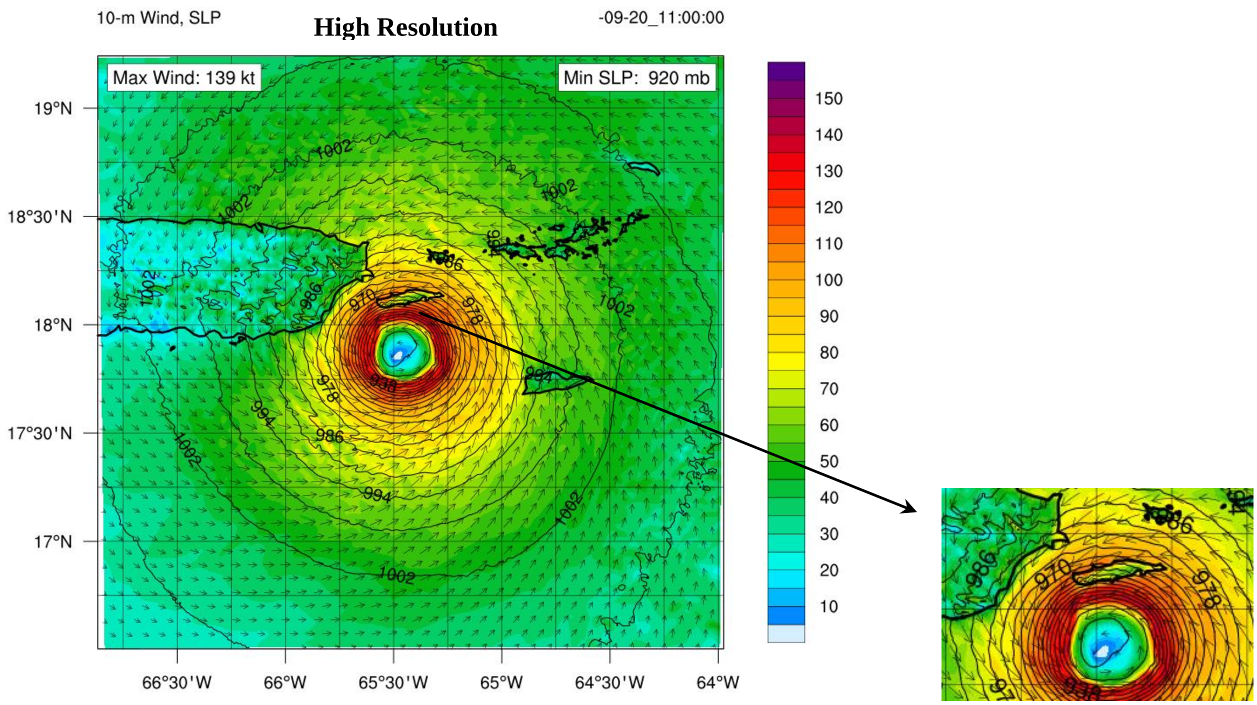

__Figure 1__: Wind speed of Hurricane María (knots) for WRF1 on 20 September 2017 at 11:00:00. The arrows show wind direction and velocity.

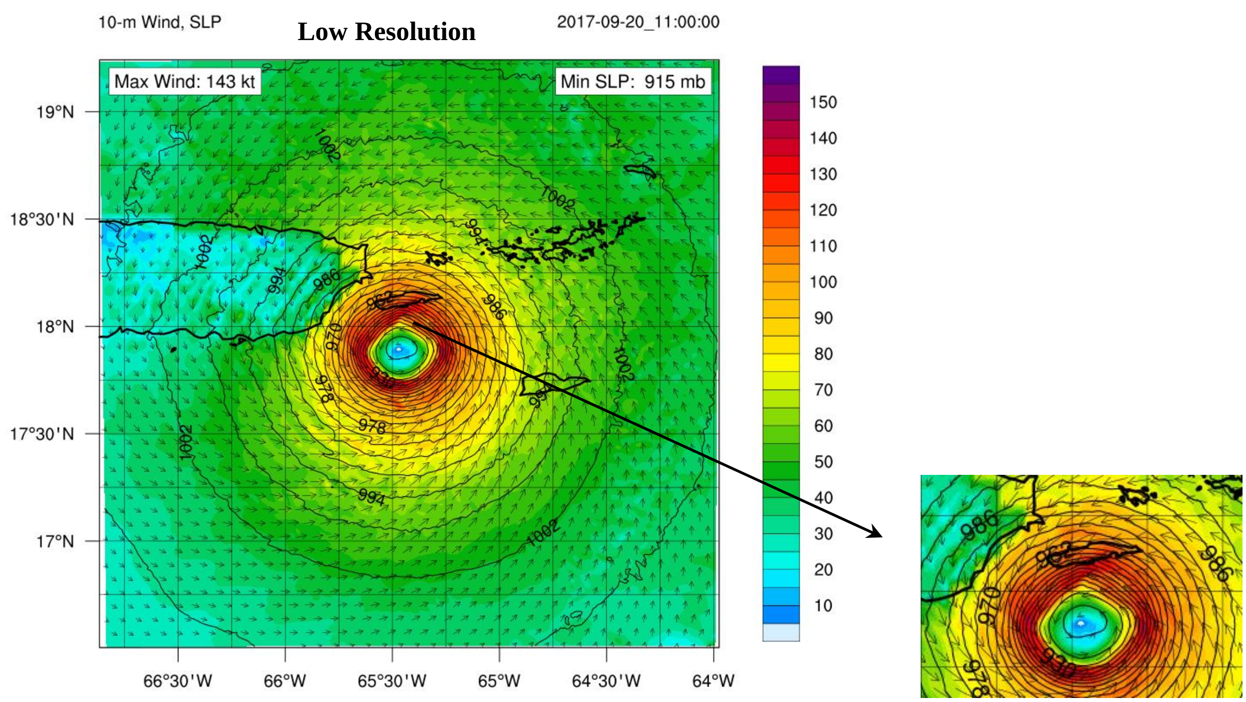

__Figure 2__: As in Fig. 1 but for WRF9.

Figure 3 and Figure 4 show the wind speed of Hurricane María when it made landfall in Puerto Rico. At this time, the figures show the behavior of the hurricane's wind field when it interacts with the landmass. For WRF9, the wind speed over the northeast coast of Puerto Rico is higher in contrast to the wind speed in this location in WRF1. However, over points in the southeast interior of the island, WRF1 produces higher wind speeds than WRF9 at the same points. The points where WRF1 presents the highest wind speeds coincide with the points where the main chain of mountains in Puerto Rico “Cordillera Central” begins. This chain of mountains has an average elevation of 900m, starts on the eastern interior of the island, ends on the western interior of the island, and it separates northern coastal plains from the southern coastal plains.

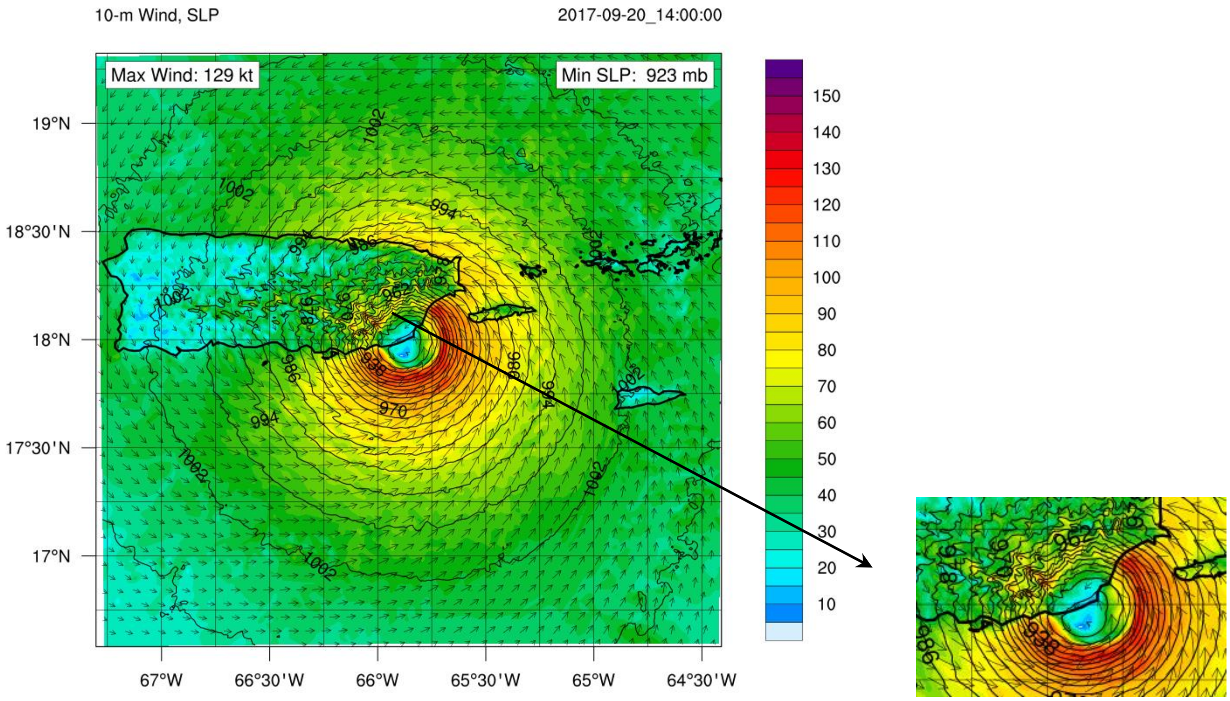

***Figure 3**: Wind speed of Hurricane María (knots) for WRF1 on 20 September 2017 at 14:00:00 UTC.*

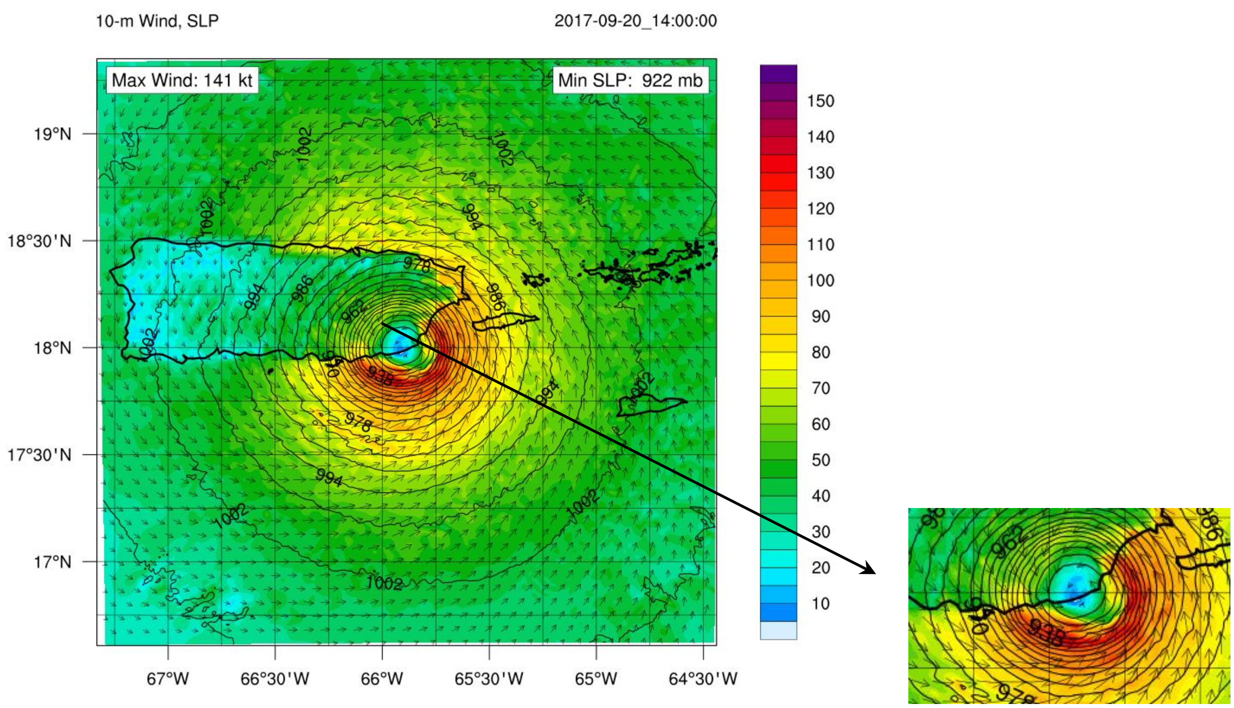

***Figure 4**: As in Fig. 3 but for WRF9.*

Figure 5 and Figure 6 show the wind speed of Hurricane María when the eye is over the mountainous interior of Puerto Rico. At this time, the wind speeds for the points in the mountainous interior of the island are higher for WRF1 than WRF9. However, for the rest of Puerto Rico's land area, WRF1 shows lower wind speeds than WRF9. With its accurate representation of topography, WRF1 shows higher wind speed in the interior of the island because that is where the highest land elevations are located. WRF9, however, shows higher wind speeds outside the mountainous interior of the island because it does not consider the decay in wind speed caused by the high mountains' interaction with the tropical cyclone.

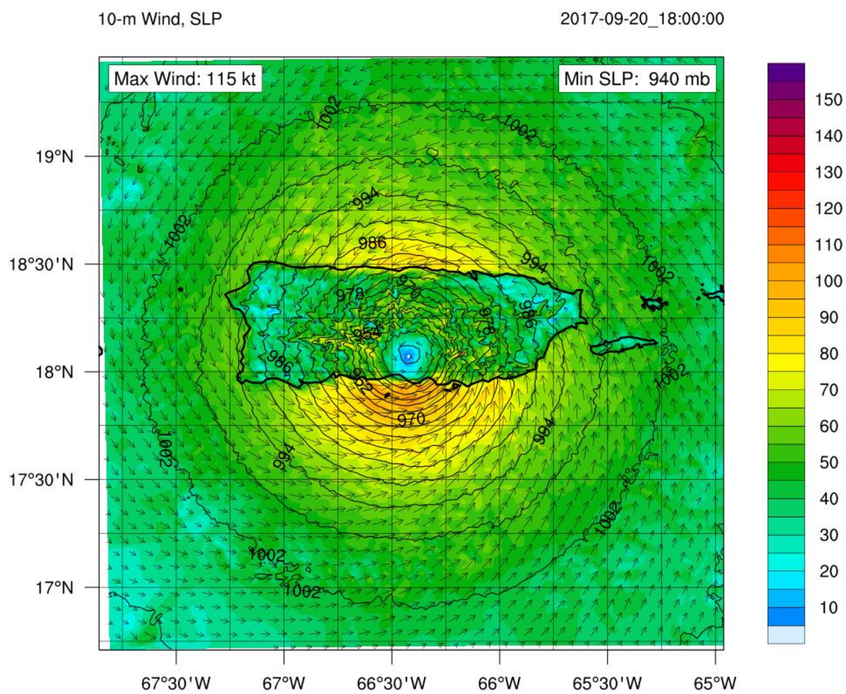

Figure 5*: Wind speed of Hurricane María (knots) for WRF1 on 20 September 2017 at 18:00:00 UTC*

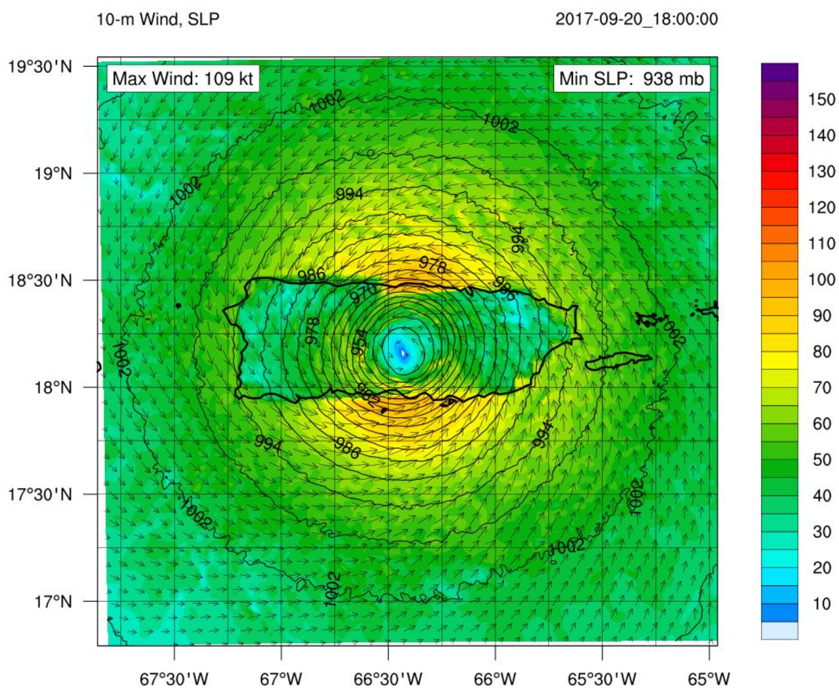

Figure 6*: As in Fig. 5 but for WRF9.*

The time-series plots used to study the wind speed related to Hurricane María over specific points of Puerto Rico showed the expected behaviors in every location of interest. These behaviors included an increase in the wind speed until reaching a maximum value, a decrease in the wind speed as the hurricane's center approached the location of interest, then an increase until reaching a maximum value. The time-series plots across all the locations had differences in the magnitude of the wind speed depending on the distance to the hurricane's center, a result of the spatially varying pressure gradient force.

Figure 7 shows the time-series plot of wind speed for Cerro de Punta[3] in Ponce, Puerto Rico. Located in the mountainous interior of the island, this point is the highest location in Puerto Rico. The graph compares the wind speed for WRF1 (black) and WRF9 (blue). The graph shows that for the first half of the hurricane, WRF1 produced higher wind speeds than WRF9. For the second half of the hurricane, however, WRF9 produced higher wind speeds than WRF1. The difference in the wind speed for the first half of the hurricane showed that for higher terrain, the magnitude of the winds increased. The difference in the wind speed for the second half of the hurricane demonstrated that when the tropical cyclone interacted with the landmass of Puerto Rico, the magnitude of the winds decreased.

[3] Cerro de Punta has an elevation of 1338 m.

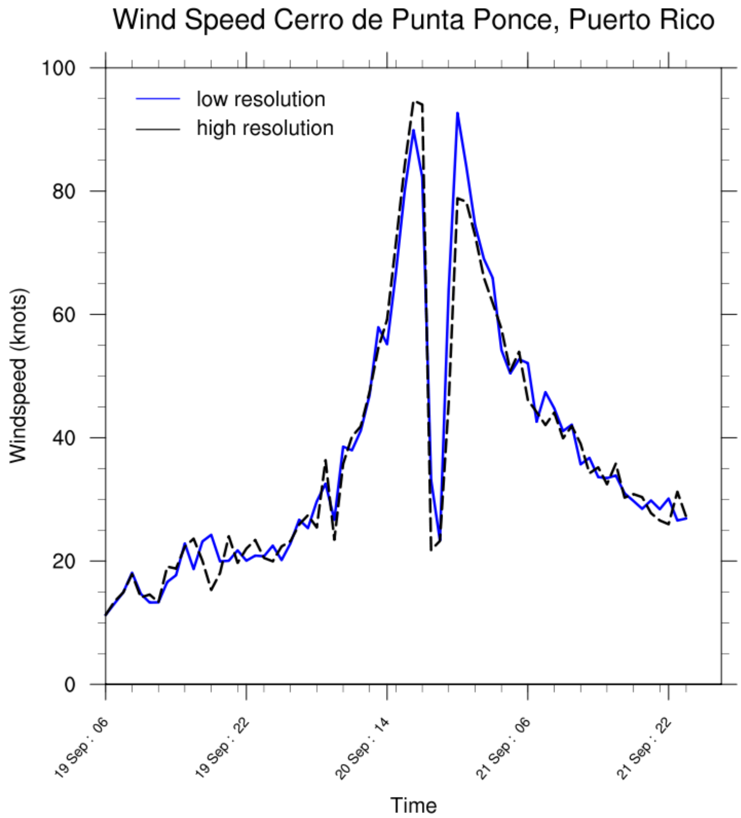

Figure 7*: Time series of Hurricane María wind speed (knots) over Ponce, Puerto Rico from 19 September 2017 at 6:00:00 UTC to 22 September 2017 at 00:00:00 UTC. The graph compares the WRF1 wind speed (dashed) with the WRF9 wind speed (solid).*

The maximum wind speed of Hurricane María over Puerto Rico from 19 September 2017 6:00:00 UTC to 22 September 2017 0:00:00 UTC was studied using swaths for WRF1 (Figure 8) and WRF9 (Figure 9).

Comparing the swaths of wind speed, it was noted that over the islands of Vieques and Culebra, the maximum wind speed expected over land and over the ocean was the same in WRF9. For WRF1, however, the maximum wind speed expected over the same islands was lower than that expected over the ocean, and also lower than WRF9. Moreover, for the mountainous interior of the island, WRF1 showed higher wind speeds than WRF9 Considering that the highest mountains are located in the interior of Puerto Rico, this showed that the high-resolution terrain produced higher wind speeds at higher elevations. Because the low-resolution terrain does not accurately represent the elevations of the mountainous interior of the island, it produces lower wind speeds.

For the coastal cities in Puerto Rico, the high-resolution terrain produced lower wind speeds than the low-resolution terrain. Excepting the mountainous interior, the high-resolution terrain produced lower wind speeds than the low-resolution terrain, especially on the west side of the island. This results from the interaction between the hurricane and land after the hurricane encountered the friction added by the chain of mountains that crosses the island from east to west. Also, over the ocean beyond the west coast of Puerto Rico, WRF1 produced lower wind speeds than WRF9. Both simulations showed that the hurricane's intensity decreased after interacting with land, but the wind swaths showed that there was a larger decay in WRF1

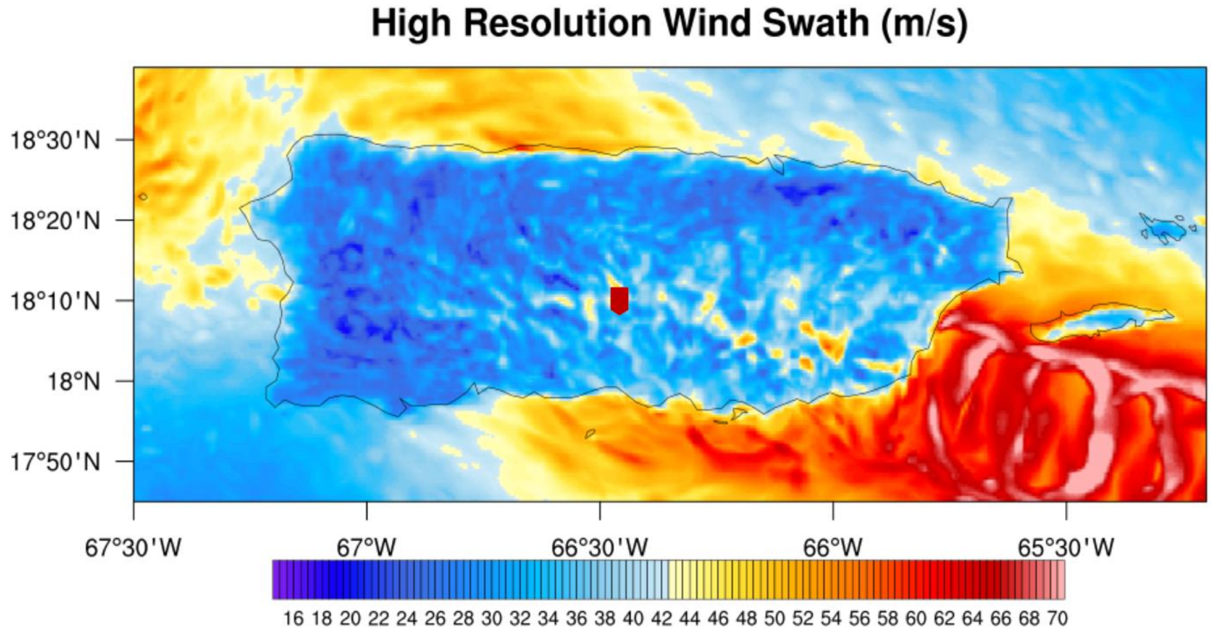

Figure 8*: Wind swath for WRF1. The figure shows the maximum wind speed (m/s) over Puerto Rico from 19 September 2017 at 6:00:00 UTC to 22 September 2017 at 0:00:00 UTC. The red square presents the location of Cerro Punta in Ponce Puerto Rico from figure 7.*

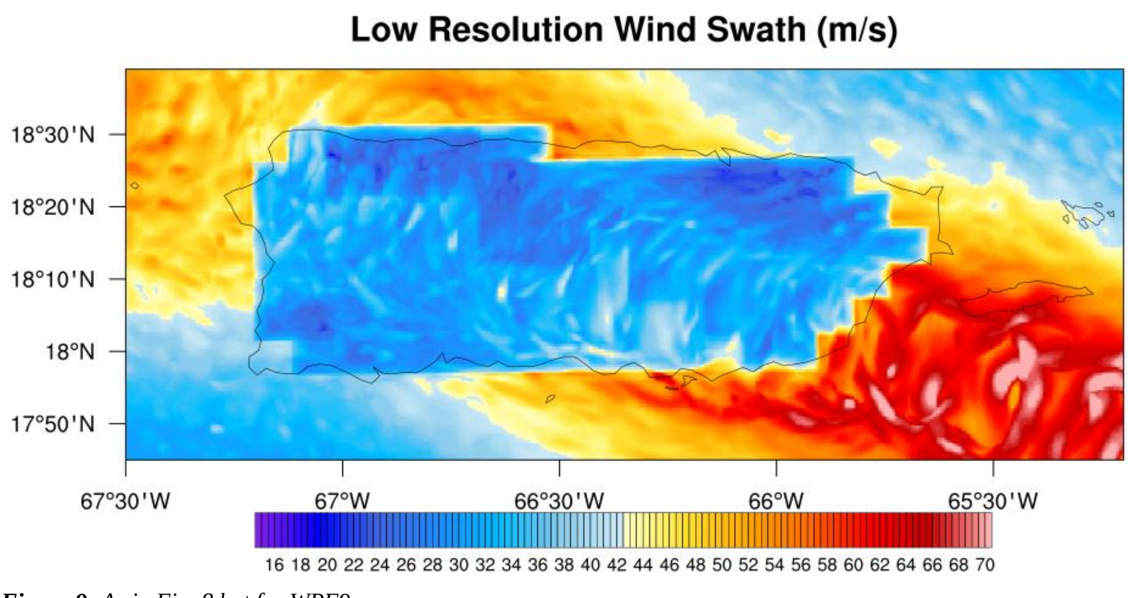

Figure 9*: As in Fig. 8 but for WRF9.*

b. Vertical Velocity and Rainfall

The amount of precipitation over land during a tropical cyclone is also influenced by topography. The additional lifting of air caused by higher land elevations increases the precipitation. Because the vertical movement of the air is important in the process of precipitation, the vertical velocity of Hurricane María was studied to show how the terrain resolution affected the WRF simulation of rainfall.

Figure 10 and Figure 11 show the vertical velocity of Hurricane María when its eye is located over central Puerto Rico. This variable gives information about the vertical movement of the air at 40 m above the surface. In contrast to the vertical velocity in WRF9, the vertical velocity in WRF1 shows stronger updrafts and downdrafts concentrated in the interior of the island where the highest points of the island are located. This happens because WRF9 considers Puerto Rico as a smooth surface and it simulated a horizontally smooth movement of the air over that surface.

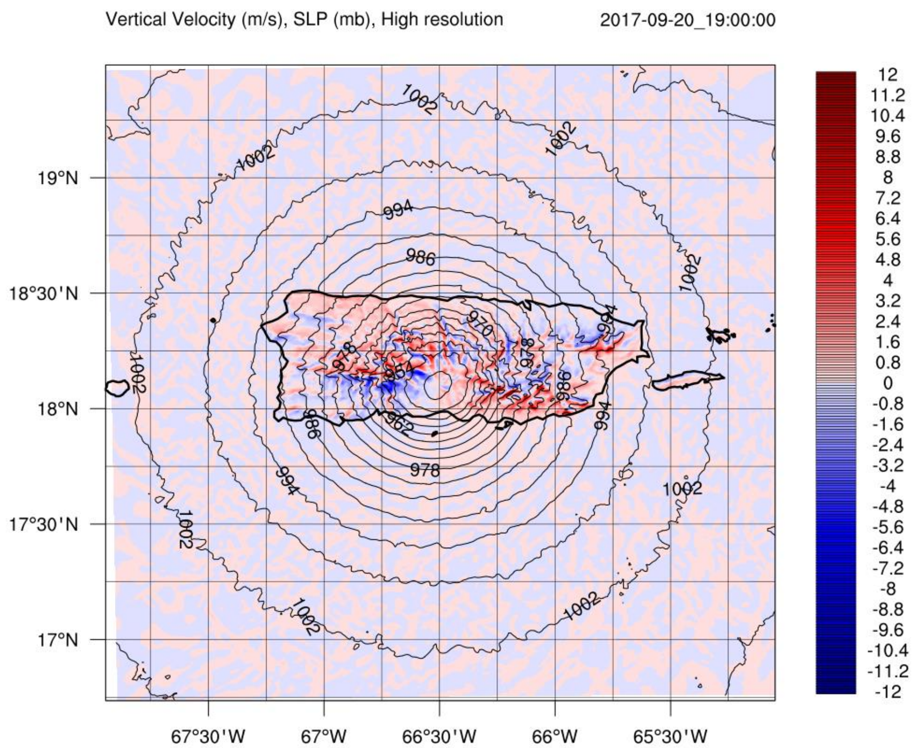

Figure 10*: Vertical velocity from WRF1 output file of 19 September 2017 at 19:00:00 UTC when the hurricane's eye is located near the center of Puerto Rico.*

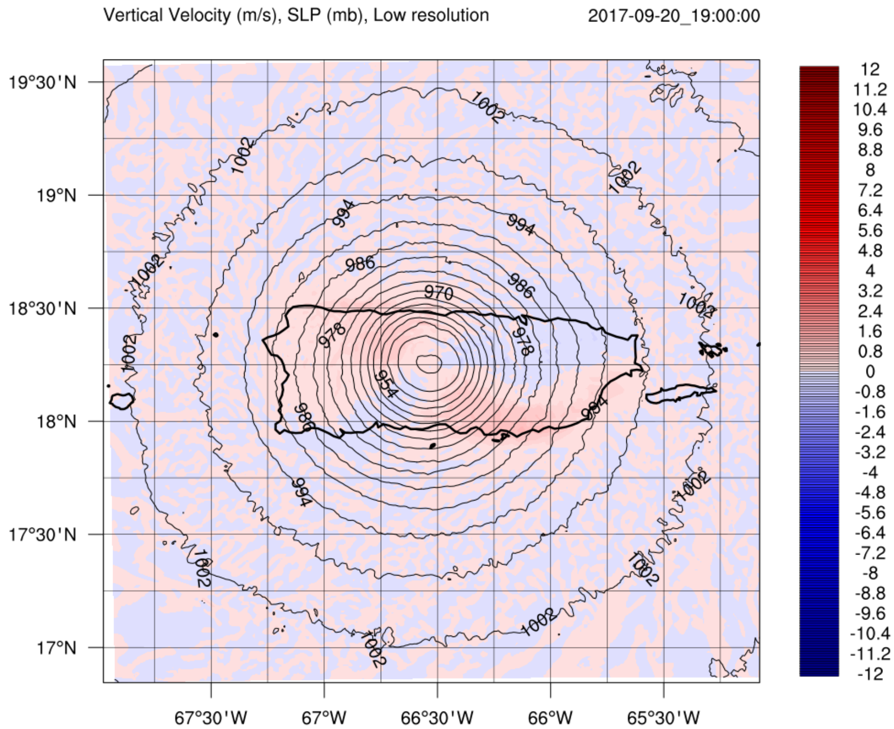

***Figure 11**: As in Fig. 10 but for WRF9.*

Using a time-series plot to study the vertical velocity for specific points of Puerto Rico, it was found that the vertical velocity between WRF1 and WRF9 were most different for the most elevated locations. WRF1 produced strong updrafts and downdrafts, while WRF9 produced a stable magnitude for this variable, with only small variances.

Figure 12 shows the vertical velocity for San Cristobal Canyon in Barranquitas, Puerto Rico, which is located at 500m elevation in the mountainous interior of the island known as Cordillera Central. The graphic shows a strong updraft of up to 4 m/s for WRF1, whereas the vertical velocity stayed less than 1 m/s for WRF9.

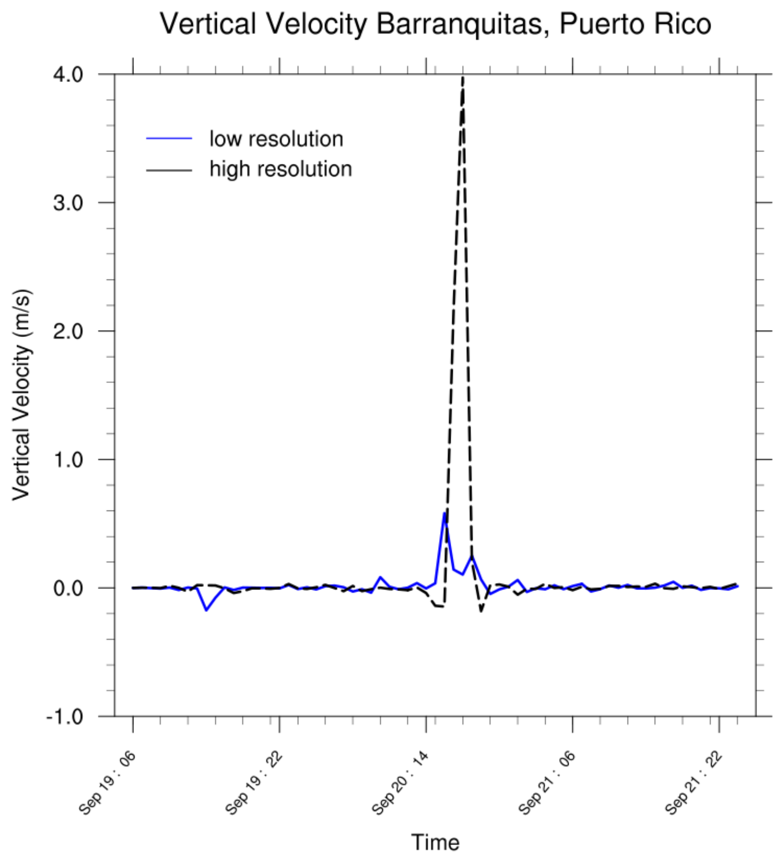

Figure 12*: Time series of Hurricane María vertical velocity (m/s) over Barranquitas, Puerto Rico from 19 September 2017 at 6:00:00 UTC to 22 September 2017 at 00:00:00 UTC. The graph compares the vertical velocity from WRF1 (dashed) with that of WRF9 (solid).*

For the low-elevation locations of interest, there was no significant difference in the vertical velocities between the simulations. In contrast, the elevated locations studied showed clear vertical movement differences caused by the interaction of the hurricane with topographical obstacles. This vertical movement of air is caused by the high-resolution terrain data's more accurate representation of topography in places with high elevation and mountains. Knowing that orographic lifting of air could enhance the precipitation during the hurricane, an increase of precipitation is expected in WRF1.

Figure 13 and Figure 14 show the maximum hourly precipitation over Puerto Rico. In contrast to the rainfall swath in WRF9 (Figure 6), the rainfall swath from WRF1 (Figure 5) showes that there is more precipitation in the mountainous interior of the island. Note that the apparent arcs of precipitation are a result of using hourly model output. A smoother precipitation field would be expected had higher temporal resolution model output been available.

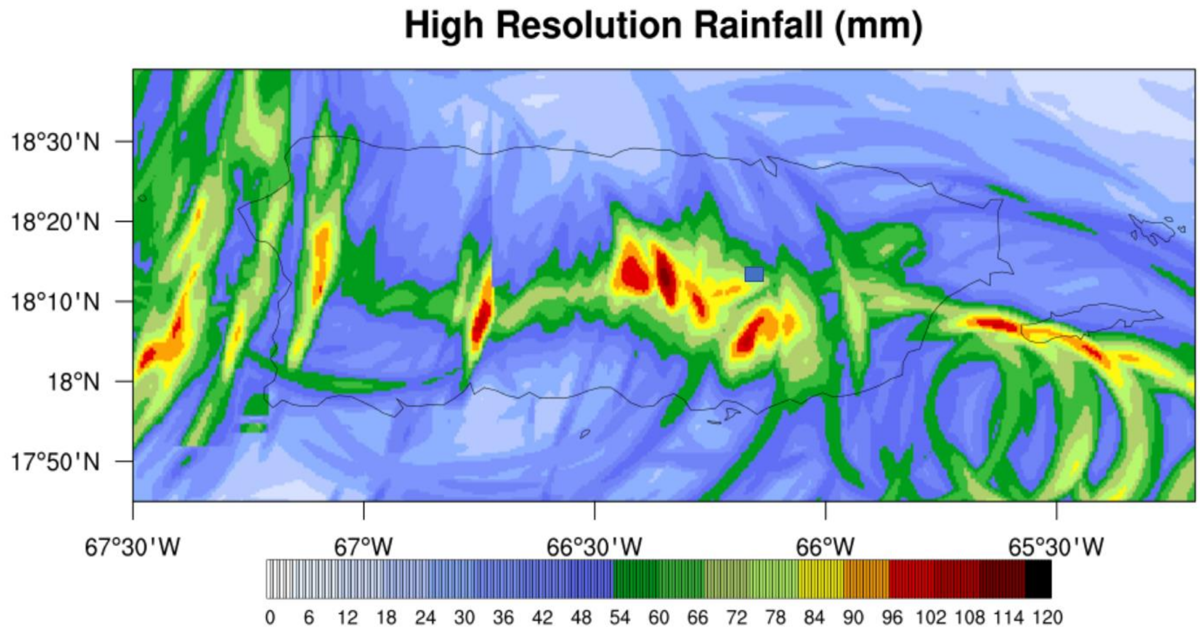

Figure 13*: Rainfall swath from WRF1. The figure shows the maximum hourly precipitation (mm) over Puerto Rico from 19 September 2017 at 6:00:00 UTC to 22 September 2017 at 0:00:00 UTC. The blue square presents the location of Barranquitas, Puerto Rico from figure 12.*

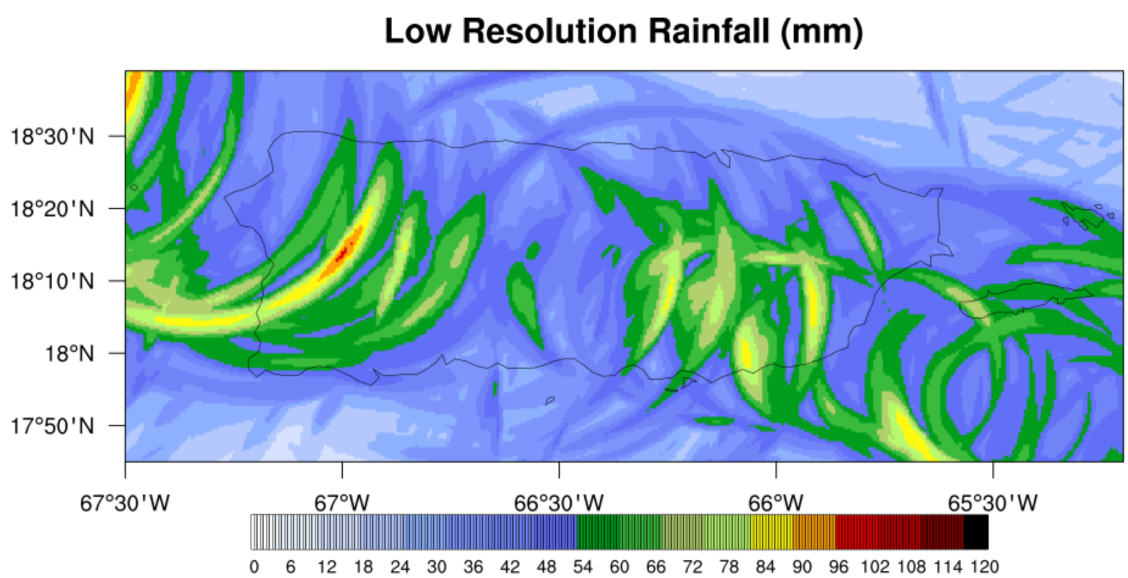

Figure 14*: As in Fig. 13 but for WRF9.*

5. Conclusions

While previous work studied the impact of topography on the behavior of a tropical cyclone, this study focused on the effect of terrain resolution in a model that uses the same high-resolution atmosphere, with emphasis on the simulated winds and rainfall. Variations in topography in the more accurate high-resolution terrain produced changes in the hurricane's structure and behavior. The research showed that high-resolution terrain resulted in higher wind speeds in the most elevated locations of Puerto Rico and a decrease in the hurricane's intensity after traversing Puerto Rico. It was found that the high-resolution terrain data led to the simulation of strong updrafts and downdrafts caused by the interaction between the hurricane and high mountains. A result of this vertical movement of air in the simulation with high-resolution terrain data is higher precipitation in the mountainous interior of the island relative to the simulation using low-resolution terrain data. It is anticipated that the impacts of the higher resolution terrain shown here for Hurricane María extend to other cases of tropical cyclones making landfall in complex terrain. In conclusion, higher-resolution land data has the potential to lead to more accurate forecasts of wind and rain when hurricanes interact with landmass.

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