Influence of precipitable water vapor in and around tropical cyclones in the Caribbean: 2007-2010

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Abstract

This study analyzes precipitable water vapor (PWV) in and around tropical cyclones (TC) over the Caribbean region. PWV is highly variable in time and space, and it is a potential energy source for tropical cyclone development. To characterize the PWV profile in and around TCs, observations of PWV are compared to PWV from an operational weather forecasting model for the years 2007-2010. PWV observations were gathered from the Suomi Network of ground-based Global Positioning System (GB-GPS) stations within a 1,000 km radius of a TC’s center and categorized by storm strength. Maximum wind speeds and coordinates of storm centers were obtained from the North Atlantic Basin Hurricane Dataset. The Global Forecast System (GFS) model initializations of PWV were then linearly interpolated to the GB-GPS at a 6-hourly time resolution for comparison. The statistical analysis of PWV from the GPS and the GFS revealed a consistent overestimation of PWV in the GFS. This overestimation ranged from 2-4 mm at distances beyond 200 km from the storms’ centers. However, at distances within 100 km from the storms’ centers, the average PWV was underestimated by the GFS in the tropical storm category. The GFS model error was greatest at approximately 200 km from storm centers. Statistics correlating PWV and storm strengths of Category 3 and higher were inconclusive due to lack of observations. This study thus provides adequate analysis of PWV for TC strengths below Category 3, and this can be useful for improving tropical cyclone forecasts.
1. Introduction

The National Hurricane Center (NHC) reported 59 tropical cyclones (TC) between the years 2007 and 2010 in the North Atlantic Basin (NAB) region that have wreaked havoc on many nations located in this region. The Caribbean region makes up large part of the NAB which includes an upward of 5,000 islands. Roughly 2% of the landmass in the Caribbean is inhabited with a census of around 42 million people. Thus, accurate and timely predictions of tropical cyclones are needed to allocate proper warnings for the millions of people scattered throughout the Caribbean region.

The NHC storm reports note that one major factor in the forecast error of the location and intensity of these storms is due to the lack of observations over the ocean and remote areas. In fact over the years TC intensity forecasts have not seen much improvement (Jack Williams, 157). One variable in TC forecasts is precipitable water vapor (PWV) which is a two-dimensional measurement of the height of the liquid amount of water vapor in a column of air, usually expressed in millimeters. PWV is related to TC because if all or some of the water vapor in a column of air were to condense the latent heat released can be a potential energy source to aggregate clouds, rain, and TCs. In fact, TCs are defined as a warm-core barotropic low which has intensified due to the widespread release of latent heat (Vasquez, 1994, 154-155). Intuitively, an accurate measurement of PWV is an essential variable to initialize forecast models in effort to improve operational weather prediction of TC.

(a) How to measure PWV?

PWV is highly variable in nature changing in a matter of seconds and in relatively short distances making it less predictable than temperature and winds. In addition to the complex nature of PWV, there are at least three ways in which PWV is obtained: satellite derived PWV, radiosondes and ground-based GPS.

Satellites detect PWV and temperature at distinct microwave lengths with a horizontal resolution between one and five kilometers (Liu et al. 2010). This method is useful over ocean surfaces where it is very difficult to set up weather stations but is also limited by the spatial and temporal availability. A second method used is radiosonde in-situ measurements.
Radiosondes PWV is the more conventional method in obtaining PWV in the atmosphere. This method launches air balloons twice daily to take in-situ pressure and temperature measurements where PWV can be calculated. This method has long been used as the “ground truth”, however the sparse spatial and temporal distribution and the high cost of equipment for long-term use renders this method insufficient. This is particularly true for third-world countries located in the Caribbean. Yet there is a third method which is more economical.

Ground-based Global Positioning System (GB-GPS) derived PWV is a relatively new technique which uses the time delay in microwave signals to transpose the liquid amount of water vapor in the air. GB-GPS receivers are relatively inexpensive and can be placed in remote areas such as the many islands in the Caribbean region. The GB-GPS network has expanded to roughly over 500 stations located throughout North America providing more spatial coverage and temporal resolution of PWV within a few hundred kilometers and shorter than a few hours, respectively (Shoji et al. 2010; Braun 1997; Businger et al. 1995). In the near future 50 GB-GPS stations are to be installed in the Caribbean region adding more spatial coverage of PWV.

(b) Influence of Precipitable Water Vapor and Storm Strength

Shoji et al. (2010) conducted a case study of tropical cyclone Nargis to study the factors which led to the rapid intensification of this storm. In the course of 24 hours Nargis went from a Category 1 to a Category 4 (Saffir-Simpson 1974) and claimed more than 130,000 lives. Shoji et al. (2010) claimed the fact TC intensity forecast was challenging during the early stages of TC development was due to insufficient National Weather Prediction (NWP) model resolution and physical processes to simulate the evolution of TC accurately. Their solution to this challenge was to obtain more accurate initial conditions for subsequent model forecasts by assimilating GB-GPS PWV. Having accurate, and widely available data to input into the model proved very important because a 1mm PWV difference can change the convective parameters enough inhibit or produce rain producing clouds (Braun, 2010). It is hypothesized since the models have a larger horizontal resolution than the GB-GPS PWV there would be a significant underestimation of PWV. In addition model initializations are gathered from multiple instruments with a variety of temporal and spatial resolution which can smooth out localized effects on TC genesis. Thus,
timely and spatially abundant PWV observations are necessary to obtain a better overall PWV average.

This study proposed that the network of GB-GPS receivers in the Caribbean would provide necessary observations to correlate PWV with tropical cyclone (TC) strength based on the Saffir-Simpson scale. This study also compared GB- PWV to the Global Forecast System (GFS) model PWV (GFS-PWV) fields. In addition, PWV was evaluated with respect to the center of TCs between the years of 2007-2010 over the Caribbean region. This paper is organized in the following manner (1) Introduction, (2) Methods, (3) Results, (4) Discussion and (5) Summary.

2. Methods

Our study examined TC which propagated through the Caribbean region and whose storm center did not extend north of 26° N latitude. This boundary was set to strictly analyze low latitude TCs in the Caribbean. Our research period begins in the year 2007 because the ground-base network became more extensive during this time in the Caribbean region and 2010 concludes the most recent and complete storm record to date.

2a. Datasets

Data for this study was obtained from three online databases, North Atlantic Hurricane Data (HURDAT), Global Forecast System model analysis (GFS) (National Operational Model Analysis and Distribution System) and ground-base GPS (Suomi Network) for three reasons. One reason was to ensure the data quality. Two of the three online resources are monitored by National Oceanic and Atmospheric Administration (NOAA) and the third is monitored by National Center for Atmospheric Research (NCAR) and its affiliate the University Corporation of Atmospheric Research (UCAR), respectively. The second was to ensure the data was regularly updated with new and future analysis of TCs for future research. These three online datasets are also readily available online and free to users who wish to repeat this experiment which was our the third reason why we decided to use these products.
2 b. Data Selection

Storm data was obtained from HURDAT and can be found on the National Hurricane Center (NHC) website. HURDAT is maintained by the NHC to document the best available post-analysis of all TC which occurred in the NAB region. More information on the analysis process and definitions is provided by Jarvinen et al. (1988). This data set provided 10–maximum wind speeds in knots, date, time and location of a TC’s center at a 6 hourly time resolution. For our study and purposes we created a database to included these TC characteristics for further data selection. In fact, storms’ center coordinates obtained from the HURDAT file were used to create a 31,741,592.7 square kilometer research area relative to the storms’ center to locate GB-GPS.

2.c. Ground-base Global Positioning System

Ground-based GPS derived precipitable water vapor data set were obtained from the SuomiNet data download website (Suomi Network, 2011). More details on SuomiNet operations and network can be found Ware, R.H. D. W. et al. (2000). This experiment used the Combined North American Network-Daily NetCDF files at a 30 minute resolution. A 3600 time-offset to obtain PWV measurements at 0000Z, 0600Z, 1200Z and 1800Z, the same date and time as in the HURDAT file. Ground-base GPS with a latitude and longitude within this research area were also utilized to obtain PWV derivations in the model analysis.

2.d. Global Positioning System PWV model analysis

00 Z initializations of the Global Forecasting System (GFS) model analysis were obtained from the same location, date and time as the GPS observations. The GFS-PWV fields were linearly-interpolated to the same latitude and longitude of the GB- GPS and then converted from kg/m² to mm then. GFS-PWV analysis has a 6 hourly time resolution and a 1.0 degree spatial resolution. These records are maintained by the National Operational Model Archiving and Distribution System (NOMADS).

2.e. Procedures

The experimental data acquired was stored in two separate databases. One database contains HURDAT data on the storm name, year, day of year, hour, latitude and longitude of the storm center, and maximum wind speeds in knots. A second database was used
to organize GB-PS station name, year, day of year, hour, latitude and longitude of the station and the corresponding interpolated GFS-PWV. The purpose of this database was to make a series of useful Standard Query Language (SQL) commands which compares and analyzes the two datatables without modifying the contents.

To study the PWV distribution as a function of storm strength the following criteria were used when making GPS and GFS comparisons of PWV. GPS-PWV were obtained within in a 1,000 km radius relative to the storm’s center. GFS-PWV were linearly interpolated to the same latitude and longitude as the GPS-PWV. The PWV points obtained were then put into one of the five hurricane categories defined by the Saffir-Simpson scale and Jarvinen et al. (1988), tropical storms were defined as Category 0 for this study, as the maximum wind speed which occurred during the moment of observation; details are provided in Table 1.

<table>
<thead>
<tr>
<th>Wind Speed (knots)</th>
<th>Tropical Storm</th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
<th>Category 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>34-63</td>
<td>64 – 82</td>
<td>83 – 95</td>
<td>96 – 113</td>
<td>114 - 135</td>
<td>136+</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. This table shows the six storm strength categories as described by Jarvinen et al. (1988) and the Saffir Simpson Scale.

GPS PWV data point were then used to determine the overall coverage of PWV in TC at the six TC stages. To determine the overall accuracy of the operational model initialization the linear regression of the GFS and GPS PWV measurements were taken with the GPS as the control. A second statistical analysis of GFS and GPS PWV determined the precision and accuracy of average error of PWV as a function of distance from the storm center. This statistical analysis also included the standard deviation in PWV. A third statistical analysis incorporated the percent error of PWV with GPS data as the control.

3. Results
From the data collection and SQL criteria as explained above, the total number of storms in the HURDAT file reduced to 45 from 59 TCs. Figure 1a. shows the location of the all the GB-stations that were used for this study. Stations above 26° N latitude were selected based on the 1000 km radial vicinity of a TC center. Figure 1b. shows the full storm track of each TC used for this study by year. The point location at the ends of the storm tracks indicate the point of origin.
Although this image shows the storm track extending beyond 26° N latitude data was not collected if the TC’s center extended northward beyond this boundary.

Figure 1. Shows the study region with the storm’s center northern boundary limited to 26°N. (a) shows the point location (red) of the ground-based stations within a 1,000 km periphery of the storm’s center. (b) Is a four-panel plot of the storm track by for each TC that occurred between the years 2007-2010.

Table 2. show the full list of TC selected which is correspondent to Figure 1b. This table also lists the year in which the storm occurred, the peak maximum winds observed, and the corresponding category based on the Saffir-Simpson scale. This table, however, does not indicate peak intensity of TC observed and used for this study. Meaning throughout a TC lifecycle PWV observations were obtained, if available, no matter what the final peak intensity of that storm was.
<table>
<thead>
<tr>
<th>Storm Name</th>
<th>Storm Year</th>
<th>Max Wind</th>
<th>Storm Category</th>
<th>Storm Name</th>
<th>Storm Year</th>
<th>Max Wind</th>
<th>Storm Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karen</td>
<td>2007</td>
<td>65</td>
<td>Category 1</td>
<td>Dean</td>
<td>2007</td>
<td>150</td>
<td>Category 5</td>
</tr>
<tr>
<td>Lorenzo</td>
<td>2007</td>
<td>70</td>
<td>Category 1</td>
<td>Felix</td>
<td>2007</td>
<td>150</td>
<td>Category 5</td>
</tr>
<tr>
<td>Noel</td>
<td>2007</td>
<td>75</td>
<td>Category 1</td>
<td>Ingrid</td>
<td>2007</td>
<td>40</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Kyle</td>
<td>2008</td>
<td>75</td>
<td>Category 1</td>
<td>Barry</td>
<td>2007</td>
<td>50</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Hanna</td>
<td>2008</td>
<td>75</td>
<td>Category 1</td>
<td>Erin</td>
<td>2007</td>
<td>50</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Shary</td>
<td>2010</td>
<td>65</td>
<td>Category 1</td>
<td>Olga</td>
<td>2007</td>
<td>50</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Otto</td>
<td>2010</td>
<td>75</td>
<td>Category 1</td>
<td>Arthur</td>
<td>2008</td>
<td>40</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Dolly</td>
<td>2008</td>
<td>85</td>
<td>Category 2</td>
<td>Edouard</td>
<td>2008</td>
<td>55</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Ida</td>
<td>2009</td>
<td>90</td>
<td>Category 2</td>
<td>Josephine</td>
<td>2008</td>
<td>55</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Richard</td>
<td>2010</td>
<td>85</td>
<td>Category 2</td>
<td>Marco</td>
<td>2008</td>
<td>55</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Tomas</td>
<td>2010</td>
<td>85</td>
<td>Category 2</td>
<td>Fay</td>
<td>2008</td>
<td>60</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Alex</td>
<td>2010</td>
<td>90</td>
<td>Category 2</td>
<td>Ana</td>
<td>2009</td>
<td>35</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Paula</td>
<td>2010</td>
<td>90</td>
<td>Category 2</td>
<td>Erika</td>
<td>2009</td>
<td>45</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Bertha</td>
<td>2008</td>
<td>105</td>
<td>Category 3</td>
<td>Henri</td>
<td>2009</td>
<td>45</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Fred</td>
<td>2009</td>
<td>105</td>
<td>Category 3</td>
<td>Danny</td>
<td>2009</td>
<td>50</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Karl</td>
<td>2010</td>
<td>110</td>
<td>Category 3</td>
<td>Gaston</td>
<td>2010</td>
<td>35</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Omar</td>
<td>2008</td>
<td>115</td>
<td>Category 4</td>
<td>Bonnie</td>
<td>2010</td>
<td>40</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Gustav</td>
<td>2008</td>
<td>125</td>
<td>Category 4</td>
<td>Nicole</td>
<td>2010</td>
<td>40</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Ike</td>
<td>2008</td>
<td>125</td>
<td>Category 4</td>
<td>Colin</td>
<td>2010</td>
<td>50</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Paloma</td>
<td>2008</td>
<td>125</td>
<td>Category 4</td>
<td>Matthew</td>
<td>2010</td>
<td>50</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Billi</td>
<td>2009</td>
<td>115</td>
<td>Category 4</td>
<td>Fiona</td>
<td>2010</td>
<td>55</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Earl</td>
<td>2010</td>
<td>125</td>
<td>Category 4</td>
<td>Hermine</td>
<td>2010</td>
<td>55</td>
<td>Tropical Storm</td>
</tr>
<tr>
<td>Igor</td>
<td>2010</td>
<td>135</td>
<td>Category 4</td>
<td>Total # of storms 45</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2. List of selected storms names, year and the peak max wind speed and intensity.

Table 3. Shows the total number of GPS observations for each storm category from each TC which occurred between the years 2007 and 2010.

<table>
<thead>
<tr>
<th>Category 0</th>
<th>Category 1</th>
<th>Category 2</th>
<th>Category 3</th>
<th>Category 4</th>
<th>Category 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Observations</td>
<td>2757</td>
<td>926</td>
<td>588</td>
<td>234</td>
<td>347</td>
</tr>
<tr>
<td>Number of Storms Observed</td>
<td>35</td>
<td>18</td>
<td>15</td>
<td>7</td>
<td>9</td>
</tr>
</tbody>
</table>

Table 3. Shows the total number of GPS-PWV observations for each category and the number of storms which data is collected from.
From Table 3, we can conclude there were not enough observations for a fair statistical analysis for each TC category. Instead, we combined the categories to make two comparisons. One comparison combined Category 0 through Category 2 TCs which was compared with Category 3 through Category 5 TCs. The second comparison compares Category 0 TCs to Category 1 through 5 TCs. The first comparison was made to compare good statistical observation numbers with categories with not so good number of observations. The second comparison was made to compare close to equal number of observations with another.

3.b. GB-GPS PWV Storm Center

Figure 2. illustrates the results from the database query showing the combined point location observed GPS PWV with respect to the storm center for the two comparisons.
Figure 2. Is the combined ground-based GPS observed PWV with in a 1000 km radius of each individual tropical storm which occurred between the years 2007-2010. The x-axis is the distance in degrees longitude from the storm center. The y-axis is the distance in degrees latitude from the storm center. (a) Is the combined PWV observations for Category 0-2. (b) is the combined PWV observations for Category 3-5. (c) Is the total observations found for Category 0 and (d) is the combined point observation PWV with respect all Category 1-5 tropical storms.
Figure 1b., and 1d. show a poor distribution of GPS PWV. However, from Figure 1d. we can infer that the Category 1 and Category 2 do not contribute to the observed PWV in Figure 1a. thus Figure 1a. was also determined to be statistically insignificant for finding the statistical relationship between PWV and storm strength. It can be said that Figure 1d. the outer TC environment can be determined to be within five degrees from the TC’s center because of the sharp contrast in PWV values. The largest PWV values for Category 0-2 was 86.5 mm and the largest PWV value for Category 3-5 was 67.4 mm. The largest PWV for Category 0 was 86.5 mm and the largest PWV value for Category 1-5 was 71.1mm. The minimum values for; Category 0-2 were 6.9 mm, for Category 3-5 18.9 mm, for Category 0 6.9 mm and Category 1-5 13.7 mm. The similar max and min for Category 0-2 and Category 0 tells us that Category 0 both has the maximum PWV (86.5 mm) and the minimum amount of PWV (6.9 mm) for each of our comparisons. Category 3-5 had the highest minimum value (18.9 mm), however it had the second highest maximum value (67.4 mm). Additional statistical analysis was performed on the Category 0 and Category 1-5 comparison because there was an relatively equal distribution of PWV observations for a full profile with respect to distance away from the storm.

Figure 3. shows the absolute values obtained from linearly-interpolated GFS PWV fields to the same location as the GPS station. PWV absolute values were compared linearly with respect to the storm center in 50 km intervals to serve as a reference values in Figure 4.
Figure 3. shows the absolute GFS interpolated PWV initializations for the same location and time as the GPS observations (a) for Category 0 and (b) for Category 1 through 5.

Figure 4. shows a line plot of the average of the absolute values for every 50 km interval from the storm center, 0, to 1,000 km (a) for Category 0 and (b) for Category 1-5.

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The difference of PWV with respect to the storm center of each model initialization and corresponding GPS observations was shown in Figure 5. From this plot we saw there was a slight general pattern of where the upper right quadrant of the storm structure saw higher values of PWV error.

A linear regression plot was used to determine the overall agreement of GPS and GFS PWV measurements as shown in Figure 6. With GPS as the control the slope of this plot was above one, indicating that the GFS tended to be wetter than the observations.
Figure 6. Shows the linear regression plots with the GPS as the control for (a) Category 0 and (b) Category 1-5.

As a follow up to Figure 4, 5 and 6. The average of the differences between model initializations and the GPS PWV observations was taken with respect to the storm center. The differences were averaged between 50 km increments then plotted along with the standard deviation for each average as shown in Figure 7. The variation of the standard deviation becomes larger in the tropical cyclones greater than category 2 strength.
Figure 7. shows the average of the difference between GPS and GFS PWV. Positive values indicate the GFS PWV is wetter than observation while negative values indicate GPS is wetter than the model. The x-axis is labeled in km as distance away from the storm center, the center being zero, to 1,000 km. The standard deviation is also shown as whiskers extending from the line-point plot. (a) shows statistics for Category 0 and (b) shows statistics for Category 1-5.

Figure 8. shows the average percent difference with respect of the distance from the storm center as well as the percent difference. Equation 1. shows the general calculation.

\[
\%\text{DIFF} = \sum_{1000}^{1000} \frac{(\text{GFS} - \text{GPS})}{\text{GPS}}
\]

Equation 1.

In addition Figure 8. Also contains the number of calculations per 50 km increments with the labels on the right of the plot. For Category 0 notice how the percent difference is small near the center and increases around 200 km from the center and then stays relatively steady.
Figure 8. Shows the absolute value of the average percent difference labeled on the left y-axis with the number of calculations labeled on the right y-axis. (a) shows statistics for Category 0 and (b) shows statistics for Category 1-5.

From these figures and tables we saw the variation in GFS error with respect to PWV are generally larger the further away from the storm center (≈ 200 km). It was also apparent the model tends to be wetter outside the TC environment and inside the TC environment for Category 0 TCs. Conclusions about the behavior of model PWV within the TC environment are inconclusive for the TCs greater than Category 0.
5. Discussion

This section examines the cause of the variation in GFS-PWV error with respect to the ground-based GPS-PWV. Subsection 5.1 elaborates on the storm structure. Subsection 5.2 discusses the potential impact of such error and subsection 5.3 discusses the uncertainty in our results.

5.1 Importance of Storm Structure

One of the main mechanisms for PWV transport in TCs are winds. Maximum wind strengths in a tropical cyclone can be highly asymmetrical and are usually located in the right front of the storm relative to its directional path (Djuric, 1994, 227). Along the path of converging wind speeds, PWV will be transported typically from the equator into concentrated areas initiating convection. First indications of this is in Figures 2a and Figure 2c. In the right two quadrants of each figure we can saw higher values of PWV indicated with cool colors (dark green, blues and purples) while warm colors (red, orange, yellow, light green) tend to be located in the left 2 quadrants. The significance of this asymmetric PWV distribution could cause great variation in GFS-PWV error analysis because each quadrant of the storm has a different PWV profile. Averaging the left quadrant with the right quadrant would result in a large standard deviation as shown in Figure 7. (+/- 8 mm). To make this argument more idealized the next step in this research process would be to incorporate the location of the max wind with respect to each individual storm and do a statistical analysis of each quadrant including GFS-PWV error.

5.2 Impact of PWV forecast error

It is known that PWV is a suitable quantity to complement the stability indicators, which is a factor in tropical cyclone intensity forecasts (Djuric, 1994, 86). The model initialization error observed between the GFS-PWV and the GPS-PWV ranges from -8 mm to 6 mm while the percent difference ranges from -16 % to 10%. An error as much as 1 mm per km$^2$ means that as much as $2.26 \times 10^{12}$ J of potential energy from latent heat would be factored in/out of the model simulations. This could ultimately
limit or enhance the convection parameters in the model to produce clouds, rain and tropical cyclone intensification (John Braun, 2006; Andrew Crook, 1996).

As an example Tropical Storm Arthur caused 5 deaths and a total of $72 million in damage along the coastal shores and rivers of Belize. Figure 9. Shows the storm track for Arthur and Figure 10. shows the average PWV error for Arthur as a function of distance away from the storm. Arthur had a negative 6 mm PWV error near the center indicating the model forecast was not initialized with adequate amount of PWV. Subsequently, the National Hurricane Storm Report reported that the intensity and storm track error of Arthur was above average and the rainfall associated with Arthur was not well forecast (Eric S. Blake, 2008). On the other hand, the TC with the least PWV error, Fay(2008), was reported to have a good forecast of the genesis (Stacy R. Stewart and John L. Beven II, National Hurricane Center). Figure 11 show the storm track and Figure 12. shows the PWV error and percent difference of Tropical Storm Fay.
Figure 9. (a) shows the storm track and (b) the average difference (blue) and percent difference (green) for Tropical Storm Arthur (2008). Notice the percent error is above 10% near the storm’s center and ~49% in the outer TC environment.

Figure 10. (a) shows the storm track and (b) the average difference (blue) and percent difference for Tropical Storm Arthur (2008). Notice the percent error does not exceed 10%.

5.3 Uncertainty

Statistical comparison of Category 0 with that of Category 1-5 tropical storms leaves uncertainty in the first 200 km of the storm system due to the lack of observations near the storm center for the latter. Figure 2c. illustrated a decent coverage of ground-based observations for
Category 0 storms near the storm center which Figure 2d. and Figure 2b. lack. This lack of ground-based stations near the storm center could be due to equipment damage as the TC approaches and crosses over the ground-based station. Another cause for lack of ground-based observations in higher category tropical storms would be the de-intensification of the TC as the storm center propagates over the GPS station, which can be housed further inland.

Summary

Our study indicated the GFS-PWV tended to have a 2-4 mm wet bias beyond 200km of the TC center. The over-estimation of PWV in the initialization of the forecast model could have lead to the under-estimations of the rainfall and intensity of Tropical Storm Arthur. The uncertainty for Category 1-5 TC within the 200 km of the storm center was due to the lack of observations contributed to the destruction of the ground-based GPS station and or the overall lack of stronger category tropical cyclones within the Caribbean region. A longer research period which includes more observations of TCs and more ground-based stations located throughout the Caribbean and over the ocean (ie. Ships, oil rigs, buoys .etc) would help increase the number of observations over land and ocean. It is apparent model initialization error greater than 1mm of PWV per square kilometer could result in the over/under prediction of TC. Thus the ground-based GPS derived PWV has proved to be useful in model verification and the network should be expanded to obtain a better 2-dimensional field analysis PWV because it is a highly spatial, temporal variable in TC forecasts.

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