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ORIGINS OF THE CARIBBEAN RAINFALL BIMODAL BEHAVIOR

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1. INTRODUCTION

The Caribbean region is geographically located along a relative land-free tropical band, where the Tropical Atlantic and Pacific equatorial regions influence the inter-annual variability of its rainy season. Its position in a middle tropical warm pool and the ageostrophic dynamic circulation also plays an important role in that variability (Taylor et al., 2002).

Taylor et al. (2002) and Chen and Taylor (2002), ascertained that the Caribbean rainfall season has a bimodal nature, where the initial peak of this season, called the early rainfall season (ERS), begins in May and extends until June, with a brief dry period in July. The second half of the overall rainy season, or late rainfall season (LRS), spans from August to November. The rainfall's bimodal nature is observed by means of a climatological analysis of averaged precipitation data from 1979 to 2004.

In addition, the Xie-Arkin data is averaged over the Caribbean basin defined from 10ºN to 22.5ºN and from 85ºW to 60ºW. During the rainy season, the easterly waves and tropical storms begin to be frequent and the rainfall begins to increase. Intuitively, the rainfall should continue increasing, especially from the beginning of the rainy season until the end of this season. The actual data, however, shows an unexpected rainfall decrease in the month of July as shown in Figure 1. The low rainfall peak during the rainy season defines the Caribbean bimodal behavior (Chen and Taylor, 2002). The Caribbean rainfall bimodal structure has been reported in different studies over the Caribbean region. However, very little is known about this summer drought, its origins, and factors influencing it. The main objective of the work presented in this paper is to fill this knowledge gap.

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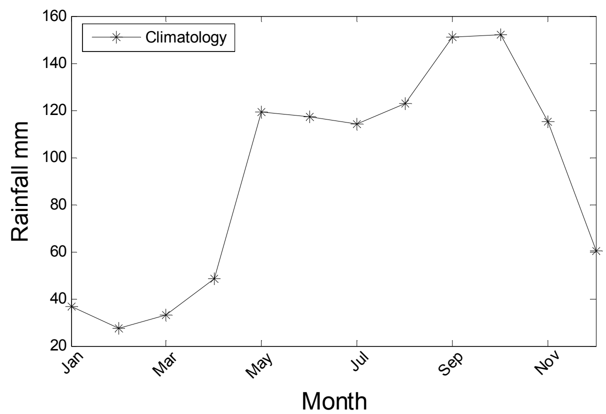

Figure 1. Climatological monthly Caribbean rainfall variability from 1983 to 2004.

2. THE CARIBBEAN RAINFALL BIMODAL TREND

To observe the temporal and spatial variability of the Caribbean rainfall, a bimodal index has been developed. The bimodal behavior is defined as the lower rainfall peak during the rainy season (Chen and Taylor, 2002) and we express it mathematically as two vectors A and B. The origin of these vectors are in July and are located in the II and I quadrant, respectively (see Figure 2). On the other hand, when vector A is placed in the III quadrant and B in the IV quadrant, the bimodal trend disappears. Vector magnitudes of A and B are the rainfall difference between June and July, and between August and July, respectively. Following these definitions, a bimodal factor (BF) is introduced,

$$BF = \begin{cases} 1, & 0^o < \theta_B < 90^o \quad and \quad 90^o < \theta_A < 180^o \\ -1, & 270^o < \theta_B < 360^o \quad and \quad 180^o < \theta_A < 270^o \\ 0, & \theta_B = 0^o \quad or \quad \theta_A = 0^o \end{cases}$$

and the bimodal index is defined as:

$$BI(\theta_A, \theta_B, y, y_{clim}) = BF \left| \frac{y}{y_{clim}} \right|$$

where y=Ay+By and $y_{clim}=Ay_{clim}+By_{clim}$. The variable y_{clim} corresponds to the Caribbean rainfall climatology, while "y" is for each grid point and year. The bimodal index shows positive and negative values indicating the existence and intensity of rainfall bimodal events (see Table 1).

The rainfall BI shows that for low latitudes and for longitudes between 80ºW and 60ºW the precipitation is not controlled by the Caribbean rainfall bimodal. For latitudes higher than 17ºN the Caribbean rainfall shows a stronger bimodal index (see Figure 3a) that begins to weaken around 30ºN. In addition, the long-term trend in the rainfall bimodal nature shows a decreasing tendency from 1983 to 2004 (see Figure 3b).

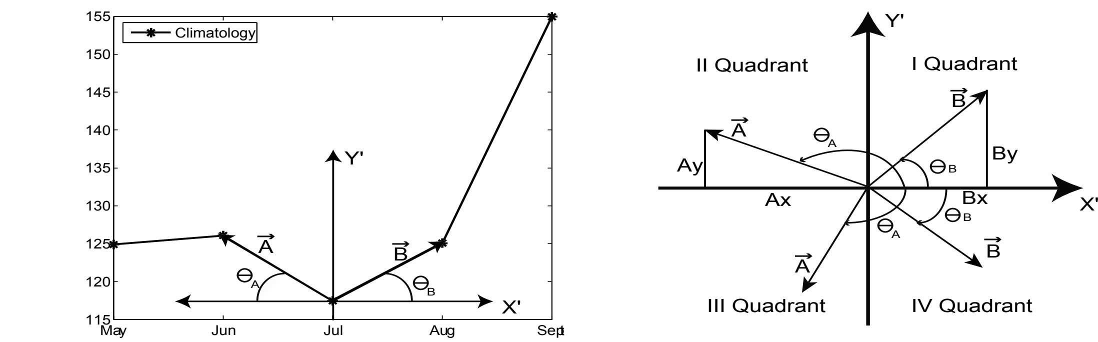

Figure 2. The bimodal event is defined using free vectors locating polar coordinates in the month of July and dividing the area in four quadrants.

Table 1 Bimodal index values

BF RANGE	DESCRIPTION	BF RANGE	DESCRIPTION
BI>1	Bimodal intensifies in a value BI-1	BI<-1	Zero Bimodal, the deviation intensifies in |1+BI|
0<BI<1	Bimodal is weakened in a value 1-BI	-1<BI<0	Zero Bimodal, the deviation is weakened in |1+BI|
BI=1	Bimodal = Climatology	BI=-1	Zero Bimodal, the deviation = climatology in magnitude
BI=0, Zero bimodal, rainfall is constant from June to July or from August to July			

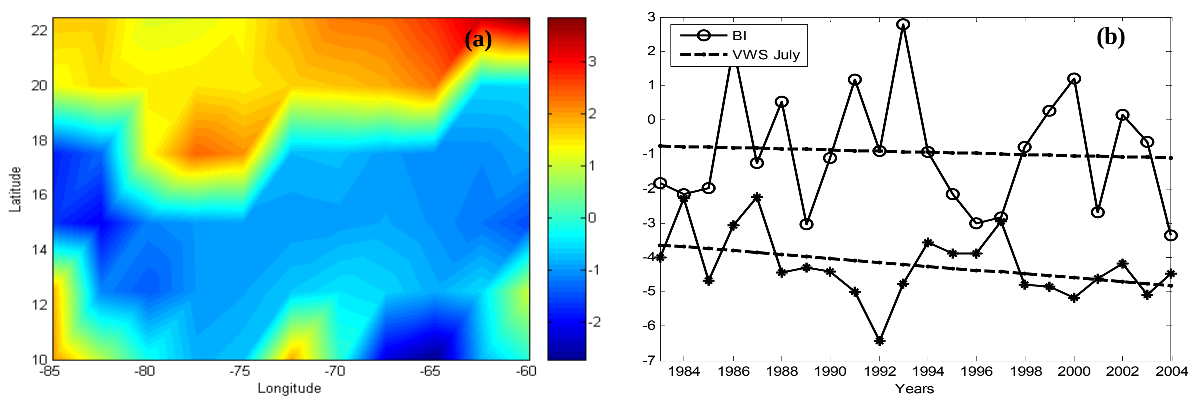

Figure 3. Caribbean rainfall bimodal index showing (a) the climatological spatial distribution and (b) the temporal variability from 1983 to 2004.

3. ATMOSPHERIC VARIABLES CONTROLLING THE CARIBBEAN RAINFALL BIMODAL

Taylor (1999) and Giannini et al. (2000) showed that a strong relationship exists between the early rainfall season and El Niño events. Chen and Taylor (2002) established that the ERS anomalies are influenced implicitly by the wintertime Pacific anomalies by means of the influence that it has on the sea surface temperature anomalies (SSTAs) over the North Tropical Atlantic (NTA) and the Main Development Region (MDR) during the spring months. In addition, Chiang and Kushnir (2000) showed that the El Niño3 event is correlated with the Tropical Atlantic Intertropical Convergence Zone (ITCZ). According to Liu and Xie (2002), the ITCZ is defined as a narrow belt, zonally oriented, where the surface winds convergence, and is located north of the Atlantic and Eastern Pacific oceans Equator. The ITCZ stimulates thunderstorm activity parallel to the Equator, and its seasonal variability (Figure 4) generates rainfall seasonal variations in certain regions of the tropics (Moran, 2002). Furthermore, there are theories that point out that the

ITCZ is determined or modulated by the latitudinal position of the westward propagating synoptic-scale disturbances. These disturbances contribute to the mean rainfall and cloudiness in the ITCZ and could develop tropical cyclones (Gu and Zhang, 2000). Consequently, a variation in the latitudinal position of the ITCZ causes a variation in the deep convection process and tropical cyclone development location and could affect the Caribbean rainfall (Gu and Zhang, 2000). In addition, a shift of the ITCZ toward the north implies warmer SSTs over the tropical region.

It is well documented that the tropical rainfall is insensitive to SSTs when SSTs are below 26.5°C, increasing rapidly for SSTs between 26.50C and 29.50C and decreasing again for SST>29.50C (Folkins and Braun, 2003). In addition, SSTs are coupled with the wind by means of the atmospheric stability change. Increments on SST cause more air buoyancy and mixing, reducing the wind shear and increasing surface winds (Liu et al., 2000). According to Arkin (1998), Bell et al. (1998), and Gerald et al. (1999), the weakening of VWS below 8 m/s causes an increment on rainfall amount over the Caribbean basin, especially when the NTA and the MDR have SSTs> 26.5°C.

The vertical wind shear (VWS) is defined as the wind variation with height (Gray, 1967). A global climatological analysis developed by Gray (1968) has shown that a very large VWS is present when strong upper level wind controls the sheared atmosphere. In addition, he has pointed out that the regional variation of VWS is a consequence of upper tropospheric wind instead of low level winds. Gray (1968), Giannini et al. (2001), Chen and Taylor (2002), and Kingtse et al. (2001) defined the VWS as the difference between the wind speed in the upper troposphere at 200 mb and in the lower troposphere at 850 mb. Independently of its definition, the VWS is in direct relation with the horizontal air temperature gradient (Gray, 1967; Corbosiero and Molinari, 2002); thus, changes in thermal fields that produce a baroclinicity increase generate increases of the VWS, while changes of inertial parameters of the atmosphere results in new thermal wind balances. In contrast, the VWS is weakened into cumulus penetration by means of vertical momentum transport (Gray, 1968).

Malmgren et al. (1998) claims that the Caribbean mean air temperature is influenced by the El Niño event while the rainfall is correlated with the North Atlantic Oscillation (NAO). The NAO is a dipole pattern of the north-south sea level pressure. A pole is located over Iceland, while the other is positioned approximately over the Azores Islands. According to Pozo-Vázquez et al (2001), positive phases appear below normal pressure across Iceland (high latitudes of the North Atlantic), and above normal pressure over the Azores Islands (Central North Atlantic). A positive NAO affects the North Tropical Atlantic (NTA) basin by mean of anomaly strong trade winds, anomalous ocean-atmosphere heat fluxes and cooling of SSTs in the NTA, while negative NAO causes opposite effects. In addition, positive phases of NAO events during the wintertime generate a drier NTA summer, while negative phases of the NAO causes a wetter NTA spring (Giannini et al., 2001).

On the other hand, easterly waves are responsible for the 10%-20% of dust concentration transport into the North Atlantic from North Africa (Jones et al., 2003). The dust particles are coming from northern Africa toward the NTA covering a wide latitudinal region from 5ºN to 30ºN. According to Rosenfeld et al. (2000), the dust by itself produces a rainfall reduction when the cloud is forming within desert dust layers. Saharan dust with large concentration of small size Cloud Condensation Nuclei (CCN) generates cloud formation with small droplets. Commonly, it has been believed the giant CCN (GCCN) causes a rainfall increase in convective clouds, enhancing the coalescence and collision, regardless of the distribution of small CCN. But we found that the coalescence-suppressing effect of very large concentration of small dust particles inhibits precipitation, event when GCCNs are present. Over the NTA, from June to August, an increase of aerosol optical thickness (AOT) causes a shallow cloud cover increase, a cloud droplet size decrease and the reduction/delay of the rainfall formation (Kaufman et al., 2005). Satellite images were used by Blanco et al. (2003) to analyze the African dust transport over the Mediterranean basin; those results demonstrated the existent of an annual Saharan dust cycle. It begins in spring, reaching its maximum concentration during the summer and decreasing appreciably during autumn and winter. We recently observed an apparent correlation of variations of AOT with precipitation while conducting routine measurements at the Arecibo Observatory. This in part motivated this research.

All the variables reviewed above could have a significant influence on the Caribbean rainfall bimodal nature. The main objective of this research consists in determining the level of influence of these variables on the Caribbean rainfall bimodal nature.

4. DESCRIPTION OF THE DATA

The Reynolds-Smith data set from the National Oceanographic and Atmospheric Administration-National Center for Environmental Prediction (NOAA-NCEP) at 1 degree resolution, the NCEP 2.5 degree reanalysis data, and the NOAA-NCEP CPC merged analysis (Xie-Arkin) dataset are used to perform a climatological and statistical analysis for the SST-ITCZ, VWS and rainfall, respectively. All these data sets were analyzed from 1983 to 2004.

The ITCZ could be calculated by means of the surface wind convergence, but the coarse resolution of the wind field information from the NCEP-reanalysis data do not allow us to calculate the ITCZ. Liu and Xie, 2002, used radar scatterometer – QuikSCAT wind data (from 1999 to 2002) at 25 km resolution to calculate the ITCZ. They found the ITCZ location corresponds to the maximum SST latitudinal position. Hence, the SST from the Reynolds-Smith data set allows computing the ITCZ using relative coarse data. The SSTs were averaged from 34.5ºW to 14.5ºW and the maximum SST position between 10ºS and 10ºN corresponds to the ITCZ.

The VWS is calculated over the Caribbean basin by mean of the NCEP-reanalysis data computed as the wind speed difference between the upper (200 mb) and lower atmosphere (850 mb). A bimodal index (BI) is determined to obtain a spatial and temporal variability around the Caribbean region. The Xie-Arkin data is employed to observe the BI variability. Additionally, the NAO normalized index dataset from 1983 to 2003 was obtained from the Climate Prediction Center-National Weather Service.

The aerosol optical thickness (AOT) and aerosol volume distribution (AVD) data were obtained from AERONET, while the Aerosol size distribution (ASD) was collected from the Arecibo Observatory. AOT and AVD were selected for the following stations: Dry Tortugas (24ºN, 82ºW), La Parguera (17ºN, 67ºW), Barbados (13ºN, 59ºW) and Guadeloupe (16ºN, 61ºW), these stations were selected because they provide a good coverage of the Caribbean basin and have more extensive records. The AOT data is available for 9, 5, 4, and 5 years, respectively for each station, while the AVD is available for 3, 2, 1, and 2 years, respectively.

5. METHODOLOGY

The proposed methodology for studying the bimodal events in the Caribbean essentially consists of three major steps: a) develop the atmospheric variables that are likely to be related with the Caribbean bimodal behavior, b) apply regression techniques to identify the variables that exhibit the highest coefficient of multiple determination, and c) use a regional numerical model to test whether or not some the parameters proposed have an impact on the bimodal pattern.

A linear correlation was explored between the ITCZ, VWS, NAO, AOT and the Caribbean rainfall to statistically determine which of these variables, or combination of them, potentially controls the lower rainfall peak during the rainy season. A variable will have an important correlation with the rainfall when its correlation coefficient is higher than an absolute value of 0.6. In addition, periodogram, autocorrelation, and multiple regression analysis complement the study.

Numerical simulations were conducted to uncouple the effects of the variables found to be the most relevant. The numerical simulations performed used the Regional Atmospheric Modeling System (RAMS) coupled with a microphysics parameterization that incorporates CCN and/or GCCN activation.

6. ATMOSPHERIC VARIABLES RELATED TO CARIBBEAN BIMODAL BEHAVIOR

The monthly variability of the ITCZ and the Caribbean rainfall variability (see Figures 1 and 4a) show similar patterns. Although a discrepancy emerges in the month of July, while the rainfall follows a bimodal distribution, the ITCZ shows an increment and a displacement towards the north. The higher position corresponds to 6ºN for 28ºC. At the same time, the SST around the Caribbean basin is below 28.25ºC, and consequently the rainfall should increase according to Folkins and Braun (2003). To corroborate this discrepancy, a linear correlation between the ITCZ and rainfall is performed for the month of July. A weak linear correlation is obtained in this month (see Figure 4b), which could imply the ITCZ is not an important variable to generate the lower rainfall peak in July. A possible lag of the ITCZ effect over the Caribbean rainfall is analyzed where we performed a linear correlation between the rainfalls in July with the ITCZ for each month. The R-square is accumulated for each grid point of the Caribbean region. This R-square fluctuates around 10 along the different months, thus we conclude the ITCZ does not have a lagged effect over the rainfall.

According to Giannini et al. (2000), the positives/negatives phases of the NAO in the wintertime affects the summertime NTA. To determine the possible NAO effect lag over the Caribbean region, the sum of the R-squared for each grid-point of the Caribbean basin is calculated. The R-squared is calculated correlating the Caribbean rainfall in July with NAO index for each month from January to December. Although the largest correlation was observed for the month of September, it is weak. In addition, the NAO periodigram, from 1982 to 2003 shows that it does not have any periodicity.

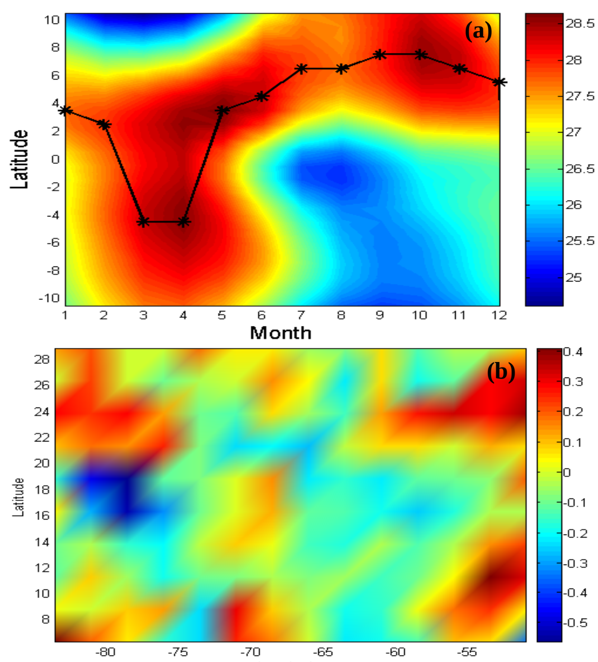

Figure 4 (a) Climatological Monthly variability of the ITCZ in the Atlantic Ocean. The maximum SST position in each month is considered as the monthly evolution of the ITCZ. The shadow color depicts the SST values, (b) Linear correlation coefficient between the ITCZ and the Caribbean rainfall for July.

A non-linear relation of the VWS with respect to the rainfall is clearly observed when their monthly climatological variability is compared. During summertime, when the SST increases above the threshold for convection and greater baroclinicity is present, the VWS obtains lower and negative values to allow the atmosphere to adjust to a new thermal wind balance. In the month of June, the VWS is in direct relation with the Caribbean rainfall, reaching -5 m/s in the month of July when the bimodal appears. This direct relation continues from August to September (see Figure 5) and implies that the upper level easterly wind is weakening in the summer when the lower level wind increases. Although an important positive linear correlation, around 0.6, is observed from June to August, in the month of July the linear correlation is weakened to +/-0.4 (see Figure 6). This fact entails the idea that the VWS is an important variable to lead the rainfall variability, but in the month of July maybe other variables also contribute to the rainfall variability. On the other hand, a direct relationship between the BI and the VWS from 1983 to 2004 is clearly observed when the VWS in the month of July is decreasing approximately from -2 to -5 m/s and the BI follows this variability, decreasing between -0.7 and -1 (see Figure 3b).

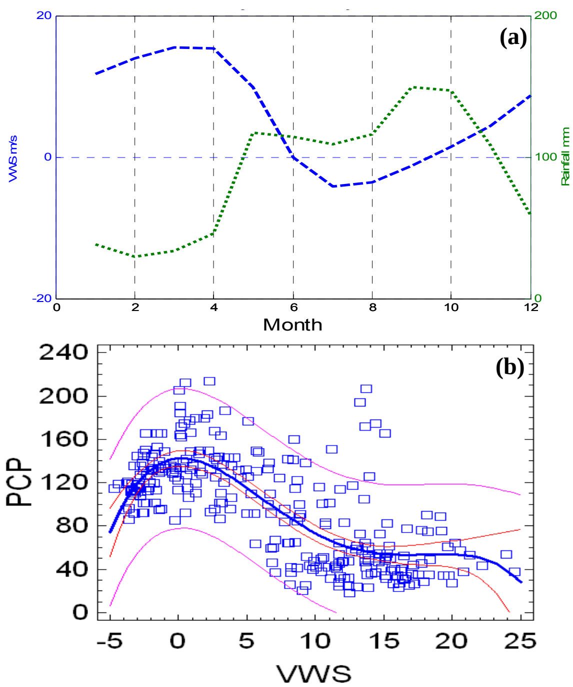

Figure 5 (a) Climatological monthly variability of the VWS calculated from NCEP-reanalysis data over the Caribbean basin. (b) Polynomial regression analysis fitting a fourth order polynomial model. The model explains 54 % of the variability in PCP. Since the P-value is less than 0.05, there is an indication of possible serial correlation with a 99% confidence level.

AOT at 440 ηm for the four Caribbean stations were linearly correlated with the Caribbean rainfall. Negative correlation predominates in the Caribbean region with exception of the La Parguera Station, maybe because the dataset is very short. A more intense correlation is observed in the month of July with respect to the correlation for the period of June-August (Figure 7) and consequently the aerosol participation in the rainfall generation for that month should be more intense. The 440 ηm AOT increases could be an indication of the smaller particle concentrations overlaying the larger particles. Less collision and coalescence processes might be occurring and as consequence, a lower rainfall is generated. According with Kaufman et al. (2005) an AOT increase will increase the shallow cloud cover and decrease the cloud droplet size over the Caribbean region, where the convective clouds are most affected by aerosols. When the AOT increases, shallow and cumulus clouds could increase their lifetime and the VWS is weakened through the horizontal momentum transport carried by vertical updraft to the upper atmosphere. The Dry Tortugas station is located in the region where the rainfall bimodal nature is very intense. In years where the 440 ηm AOT show maximum values in July, a probable smaller cloud droplet concentration increase could cause a rainfall decrease (but this is not the case here). In the other stations the rainfall bimodal behavior is very weak or there is no bimodal.

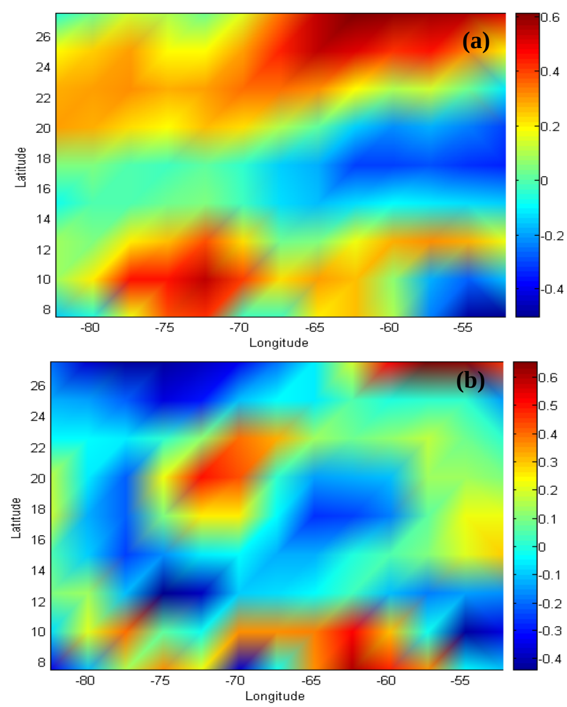

Figure 6 Linear correlation coefficient between the precipitation and the VWS for the months between (a) June and August and (b) July.

Although a small number of AVD data are available, they are related with the rainfall for Dry Tortugas and La Parguera stations. We took these stations into account because they are located at the boundaries of an area where the rainfall bimodal nature is present. According to King et al. (1978), the aerosol size classification consists of smaller Aitken-type particles with radii<0.1µm, a large type with radii between 0.1 and 1.0 µm and Giant particles (r>1.0 µm). The La Parguera station has data from AERONET for the years 2002 and 2004. In both years, the Giant atmospheric particles (AP) seem to be the more important factor to lead the rainfall generation from June to July, even over the VWS. In the year 2004, although the small AP concentration increases, the Giant AP concentration increase predominates (see Figure 8a), maybe causing a wetter month of July with respect to June. Giant AP concentration increases by 124.2%, while the small AP increases by 102.8%. On the other hand, the Dry Tortugas station shows a more important impact of the VWS over the local rainfall, especially when the VWS intensifies. AERONET data is available for 1997, 1999 and 2001. During the year 1999, from June to July, the large AP concentration increases from 0.015 to 0.019 $\mu m^3/\mu m^2$ (equivalent to 27.25%), while the Giant AP increases by 17.48% (see Figure 8b). Although the large and Giant AP should enhance the rainfall, the VWS intensification predominates over the AP effects and the rainfall production decreases. According to Kaufman et al. (2005), small particles have greater impact over the cloud formation and rain generation, even if giant particles are present. Subsequently, the small increase in AP could be affecting the rainfall in July. Thus, the large and giant AP in the Caribbean region seems to be an important variable to influence the rainfall bimodal nature.

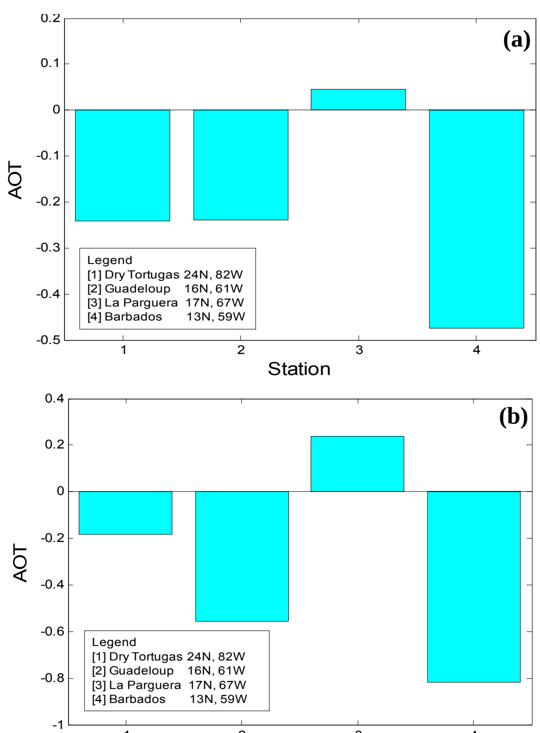

Figure 7 Linear correlation coefficient between the AOT and the precipitation for the months between (a) June and August and (b) July.

7. MULTIPLE REGRESSION ANALYSIS

A multiple linear regression model was identified to describe the relationship between the rainfall in July and the variables ITCZ, VWS, both in the month of July and the NAO in November. The AOT and/or the aerosol size distribution are not taken into account to be compared with these variables due to the very small number of data available. It will be considered later in the numerical simulations. A forward and backward method is applied. Both methods eliminate the ITCZ as a significant variable to impact the rainfall generation in July. The VWS shows to be very relevant and it would be the principal variable to explain the rainfall bimodal nature (Table 2). Since the P-value is less than 0.01, the highest order term is statistically significant at the 99% confidence level.

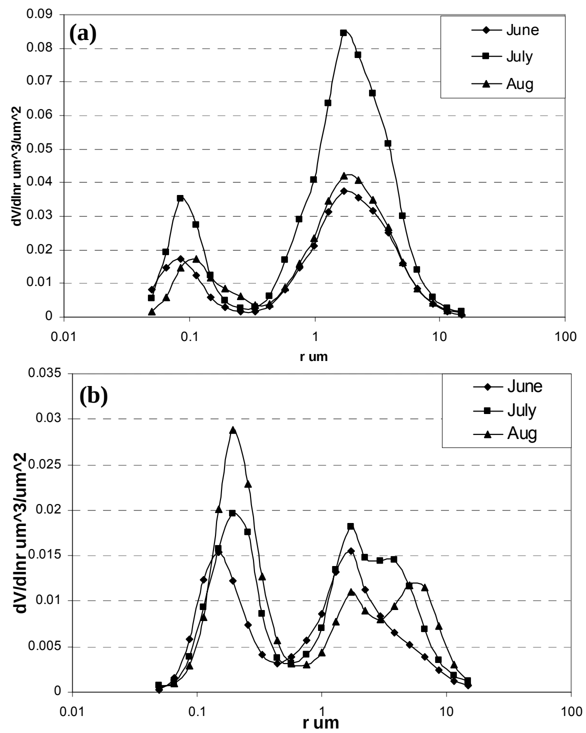

Figure 8 Aerosol size distribution for the (a) La Parguera station in the year 2004, and (b) Dry Tortugas for the year 1999.

Table 2 ANOVA table of the Multiple Regression Analysis, forward and backward selection

Stepwise regression, Dependent Variable Rainfall in July				
Parameter	Estimate	Standard Error	T Statistic	P-Value
Constant	1.44	0.34	4.22	4e-3
NAP Nov	-0.12	0.04	-2.91	8.6e-2
VWS Jul	1.1	0.33	3.37	3e-2
R-Squared = 53.9958 %				

8. NUMERICAL EXPERIMENTS

8.1 *Brief Model Description*

The Regional Atmospheric Model System (RAMS) developed at Colorado State University (CSU) was used in this research. RAMS is a numerical model able to simulate short weather events or long-term climate behavior (Pielke et al 1992, Cotton et al 2003). A new microphysics module has been included in RAMS that considers large cloud droplets with a diameter range of 40-80 μm and parameterized activation of CCN and GCCN. In the previous version, the cloud droplet varies from 2 to 40 μm and immediately passes to the next size, rain category. The existence of large cloud droplets now allows us to represent the cloud droplet's bimodal distribution. CCN and GCCN grow to small and large cloud droplets respectively by mean of vapor diffusion. The excess vapor is diffused to CCN and GCCN, where a small amount of vapor is used for GCCN. In contrast, GCCN influences the collision-coalescence with existing cloud droplets for the formation of large cloud droplets without depleting appreciably the vapor used to activate the CCN and generating a rapid transition to rain (Saleeby and Cotton, 2004). Saleeby and Cotton (2004) tested the microphysics upgrade in simulations of supercell thunderstorms; it was found that a CCN concentration increase causes a rainfall decrease, while a GCCN concentration increase generates intensification of rainfall production.

8.2 *Experimental and Model Configuration*

Three grids were selected for this study. The parent grid covers the Caribbean basin (25km grid cell size). The first fine grid is located over the island of Puerto Rico (5km), while the second fine grid is centered on the Arecibo Observatory area (1km). A control run not taking into account the aerosol particle (AP) concentration effect on precipitation is defined for July 2003. During this month, the VWS and rainfall near the island of Puerto Rico have values very close to their climatology, becoming ideal to consider as a control run. A second run is chosen for July 2002, in which the VWS and the rainfall have anomalies. To determine the influence of increased AP concentrations two additional runs are performed maintaining the near-climatological VWS of July 2003. These later numerical experiments are configured for July 2003 taking into account the CCN/GCCN size distributions measured at AO and ingested to the atmospheric model when available in the dataset. The fourth numerical experiment is performed for the same time period and atmospheric inputs, but increasing strongly the AP concentrations. The model runs are named VWS1 and VWS2 for the 2002 case, VWS3 and VWS4 for the 2003 case, and Sahara1 and Sahara2 for the case with AP variations. Under this approach the VWS and AP effects are quantified.

8.2 *Results*

The runs VSW1 and VWS2 are conducted to determine the VWS impact over the low rainfall peak during the summertime. A version of RAMS without CCN/GCCN activation was used for these runs. This microphysics approach discards the influence of small and large particles coming from the Saharan desert and only synoptic and regional atmospheric variables are allowed to generate rainfall variability. Following this approach, the regional rainfall increases during VWS2 relatively to the control run VWS2 (Figure 9). The rainfall is averaged around the area 67.15ºW-66.7ºW and 18.15ºN-18.35ºN to perform a comparison between the runs VWS1 and VWS2. The control run generates 41.28mm of rainfall while VWS2 simulated a more unstable atmosphere with a rainfall amount of 69 mm. A comparison between both runs identified the precipitation as more intense for VWS2 by approximately 27.72 mm. On the other hand, the monthly averaged VWS show a clear relationship with rainfall, increasing from VWS3 to VWS4 (see Figure 10). During VWS3, a weak VWS averaged over the same area of rainfall is present, with a value around -0.2 m/s, while in the control run the VWS is approximately -2 m/s. According to the VWS-SST relationship (see Figure 5b), the rainfall should be less intense when the VWS is around -2 m/s as confirmed by these two numerical experiments. According to Gray (1968) the upper wind drives the VWS in regional zones; consequently, a stronger upper wind should be present in VWS4, which causes the VWS to increase 90% from run VWS3 to VWS4 and the precipitation increased by 67.33%. Since the microphysics parameterization does not consider the AP coming from northern Africa in the simulations analyzed above, the VWS affects the low rainfall during the summer time at a rate of 15.44 mm/ms^{-1}.

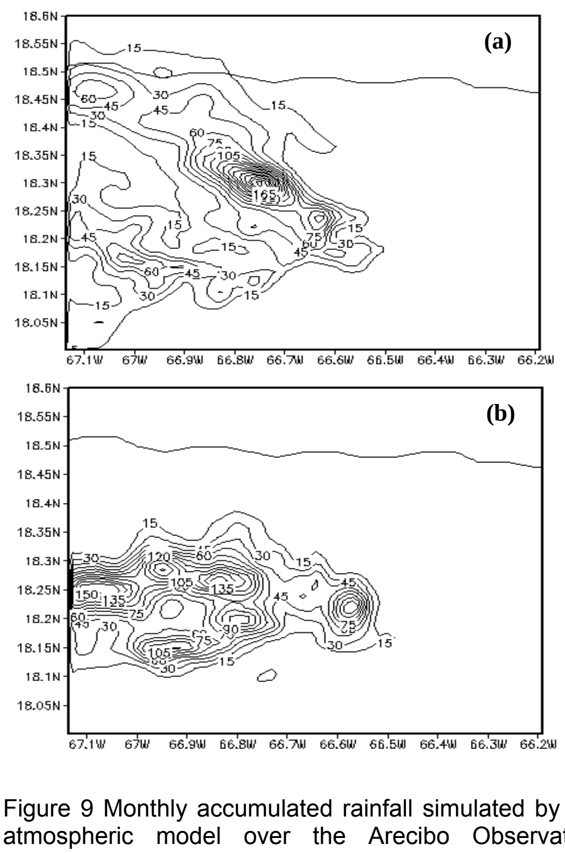

Figure 9 Monthly accumulated rainfall simulated by the atmospheric model over the Arecibo Observatory centered grid for the (a) Control run 2003 (VWS3), and (b) VWS2

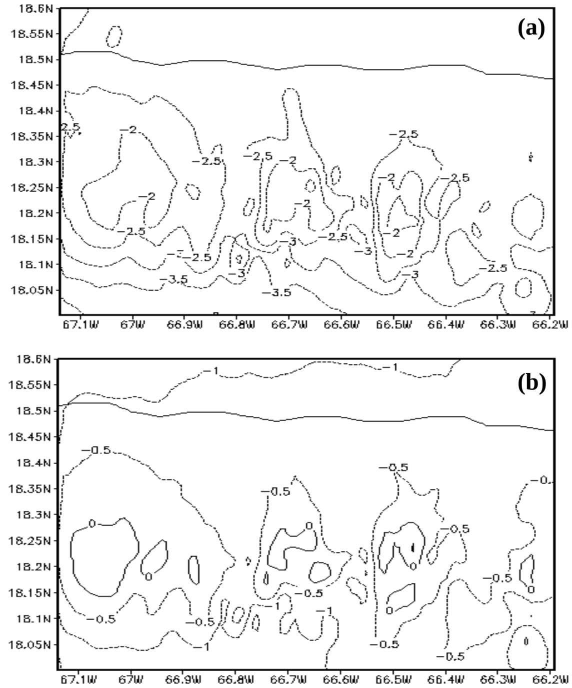

Figure 10 Monthly averaged VWS over the Arecibo Observatory centered grid for the (a) Control run 2003 (VWS3), and (b) VWS2. Weak VWS is present in the year 2002, which corresponds to intense regional rainfall.

The simulations performed with CCN/GCCNactivation, driving the model with atmospheric conditions corresponding to a near-climatology year (in our case, July 2003), and driving the cloud microphysics module with AP concentration data from the Arecibo Observatory, also yielded interesting results. As mentioned in the previous section, AP data from AO was used to drive the module and the run was called Sahara1. Then a second run, Sahara2, was configured incrementing the CCN/GCCN concentrations by a factor of 10^1. A comparison of the time series of accumulated precipitation at the location of maximum simulated rainfall is presented in Figure 11. Here we can see that the effect of enhanced AP concentration is to suppress precipitation, especially towards the end of the simulation when the rainfall appears to be heavier. Even though the concentration of particles acting as CCN and GCCN were both augmented, the effect of a higher concentration of small particles to inhibit vapor diffusion and droplet growth is expected to be more dominant than the promotion of collision/coalescence processes by larger particles

9. SUMMARY AND CONCLUSIONS

The rainfall bimodal nature predominates over the northern Caribbean boundary. In direct relationship to the annual precipitation pattern, the VWS also show a tendency to decrease during the month of July. The ITCZ, VWS, NAO and AOT/AVD (related to AP concentrations) were linearly correlated with the Caribbean rainfall in order to identify which one, or a combination of which, controls the Caribbean rainfall bimodal nature. The linear correlation showed the VWS and AP could play important roles in this matter. In addition, a multiple regression analysis defines the VWS as a very important factor for the rainfall decrease in July. The AP concentration coming from northern Africa during the summer is an important driver of the rainfall bimodal, but due to the small number of data available, numerical experiments using RAMS with a cloud microphysics module incorporating CCN/GCCN activation is used to determine the impact of different AP concentrations on the rainfall bimodal nature. First, numerical simulations are conducted to determine the VWS impact over the rainfall bimodal behavior during the summertime. Stronger upper wind can cause a VWS increase of 90%, while the precipitation increases 67.33%. The VWS simulations showed that the VWS affects the low rainfall amounts observed during the summer at a rate of 15.44 mm/ms^{-1}. Simulations with increased Saharan CCN/GCCN present reflect a suppression of precipitation during the summer time in the order of 20%. Further research is being directed to determine the relative impacts of VWS and AP in modulating the Caribbean rainfall bimodal nature.

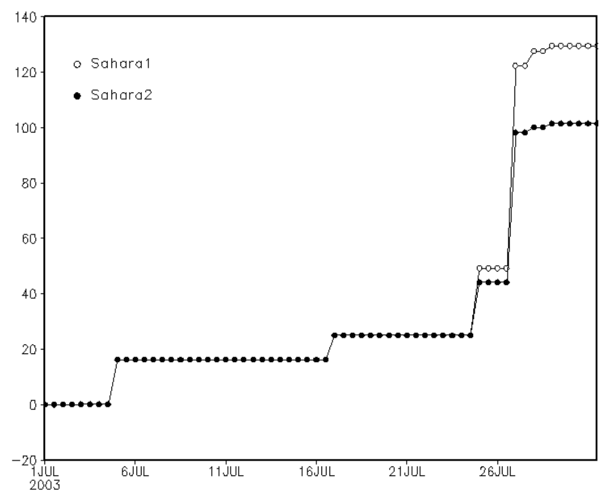

Figure 11 Time series of total accumulated precipitation, at the location of maximum rainfall, for the runs Sahara1 (open circles) and Sahara2 (closed circles)

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11. REFERENCES

P. A. Arkin. (1998). The relationship between the interannual variability in the 200 mb tropical wind field and the Southern Oscillation. Monthly Weather Review 110: 1393.

D. Bell Gerald, S. Halpert Michael. (1998). Climate Assessment for 1997. Bulletin of the American Meteorological Society 79(5): 1.

A. Blanco, F. De Tomasi, E. Filippo, D. Manno, M. R. Perrone, et al. (2003). Characterization of African Dust Over Southern Italy. Atmospheric Chemistry and Physics 3: 2147.

A. Chen, Taylor Michael. (2002). Investigating the Link between Early Season Caribbean Rainfall and the El Niño+1 Year. International Journal of Climatology 22: 87.

Chiang John, Kushnir Yochanan. (2000). Interdecadal changes in eastern Pacific ITCZ variability and its influence on the Atlantic ITCZ. Geophysical Research letters 27 (22): 3687.

L. Corbosiero Kristen, Molinari John. (2002). The Effects of Vertical Wind Shear on the Distribution of Convective in Tropical Cyclones. Monthly Weather Review 130: 2110.

W. R. Cotton, R. A. Pielke, R. L. Walko, G. E. Liston, C. J. Tremback, et al. (2003). RAMS 2001: Current status and future directions. Meteorology and Atmospheric Physics 82: 5.

Folkins Ian, Braun Christopher. (2003). Tropical Rainfall and Boundary Layer Moist Entropy. American Meteorological Society 16: 1807.

D. Gerald, M. S. Halpert, C. F. Ropelewski, E. Kousky Vernon, A. V. Douglas, et al. (1999). Climate Assessment for 1998. Bulletin of the American Meteorological Society 80 (5): 1.

A. Giannini, Y. Kushnir, M. A. Cane. (2000). Interannual Variability of Caribbean Rainfall, ENSO and the Atlantic Ocean. Journal of Climate 13: 297.

Giannini Alessandra, M. A. Cane, Y. Kushnir. (2001). Interdecadal changes in the ENSO Teleconnection to the Caribbean Region and the North Atlantic Oscillation. Journal of Climate 1: 1.

M. Gray William. (1967). The Mutual Variation of Wind, Shear, and Baroclinicity in the Cumulus Convective Atmosphere of the Hurricane. Monthly Weather Review 95 (2): 55.

M. Gray William. (1968). Global View of the Origin of Tropical Disturbances and Storms. Monthly Weather Review, 96 (10): 669.

Gu Guojun, Zhang Chidong. (2000). A Spectrum Analysis of Synoptic-Scale Disturbances in the ITCZ. American Meteorological Society 14: 2725.

Jones Charles, Mahowald Natalie, Luo Chao. (2003). The Role of Easterly Waves on African Desert Dust Transport. American Meteorological Society 16: 3617.

J. Kaufman Yoram, Koren Ilan, A. Remer Lorraine, Rosenfeld Daniel, Rudich Yinon. (2005). The Effect of Smoke, Dust, and Pollution Aerosol on Shallow Cloud Development Over the Atlantic Ocean. PNAS 102 (32): 11207.

M. D. King, D. M. Byrne, B. M. Herman, J. A. Reagan. (1978). Aerosol Size Distributions Obtained by Inversion of Spectral Optical Depth Measurements. J. Atmos. Sci. 35: 2153.

M. Kingtse, G. D. Bell, W. M. Thiaw. (2001). Impact of the sea surface temperature anomalies on the Atlantic tropical storm activity and West African rainfall. American Meteorological Society 58: 3477.

W. Liu Timothy, Xie Xiaosu, S. Polito Paulo. (2000). Atmospheric Manifestation of Tropical Instability Wave Observed by QuikSCAT and Tropical Rain Measuring Mission. Geophysical Research Letters 27 (16): 2545.

Liu Timothy, Xie Xiaosu. (2002). Double Intertropical Convergence Zones—a New Look Using Scatterometer. Geophysical Research Letters 29 (22): 1.

A. Malmgren,Björn, Winter Amos, Chen Deliang. (1998). El Niño-southern Oscilllation and North Atlantic Oscillation Control of Climate in Puerto Rico. Journal of Climate 11: 2713.

M. Moran Joseph. (2002). Online Weather Studies. American Meteorological Society, second edition, 1-416.

R. A. Pielke, W. R. Cotton, R. L. Walko, C. J. Tremback, W. A. Lyons, et al. (1992). A Comprehensive Meteorological Modeling System RAMS. Meteorology and Atmospheric Physics 49: 69.

D. Pozo-Vázquez, M. J. Esteban-Parra, F. S. Rodrigo, Y. Castro-Díez. (2001). A Study of NAO Variability and its Possible non-linear Influences on European Surface Temperature. Climate Dynamics 17: 701.

Rosenfeld Daniel, Rudich Yinon, Lahav Ronen. (2000). Desert Supressing Precipitation: A Posible Desertification Feedback Loop. PNAS 98 (11): 5975.

M. Taylor. (1999). The effect of warm tropical Atlantic SSTs on Early Season Caribbean rainfall. Ph.D. thesis, University of Maryland, College Park.

M. Taylor, D. B. Enfield, A. A. Chen. (2002). Influence of the tropical Atlantic Versus the Tropical Pacific on Caribbean Rainfall. Journal of Geophysical Research 107 (C9): 1.