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Short Communication

Spatial variability of the Caribbean mid-summer drought and relation to north Atlantic high circulation

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ABSTRACT: Annual rainfall in the Caribbean exhibits a bimodal structure with two rainfall maxima (May–June and September–October) separated by what has been termed a mid-summer drought (MSD) (July–August). Despite general acceptance of the intensification and expansion of the North Atlantic High Pressure (NAHP) as the cause of the Caribbean MSD, it has been noted in several studies that the influence of the NAHP may not be consistent across the region. The purpose of this research is to better understand the Caribbean MSD by mapping the spatial co-variability of the Caribbean MSD and then determining the association between these spatial patterns and NAHP circulation. The spatial variability of the Caribbean MSD is identified through mapping of Principal Component Analysis (PCA) loadings of Caribbean MSD season rainfall time series. A correlation analysis was completed between monthly MSD region rainfall time series and measures of the NAHP to assess the degree of association between the spatial variability in the Caribbean MSD and NAHP circulation. The PCA identified six MSD regions, the northwestern Caribbean, the interior Caribbean, the eastern rim Caribbean, Coro Venezuela, Grantley Barbados, and a transition zone. The spatial pattern of the MSD regions suggests that the NAHP impacts the eastern Caribbean first and then progresses westward as the summer develops. In regard to the association between NAHP circulation and MSD region precipitation time series, correlation analysis indicates that overall, a modified Bermuda High Index (BHI) is a more effective tool in evaluating the association between the NAHP and Caribbean MSD as compared to the traditional indices, NAO EOF and BHI. Lagged correlations support previous findings that the winter preceding a particularly dry summer in the Caribbean is characterized by a strong pressure gradient on the southeastern flank of the NAHP; implying stronger Trade Winds, cooler sea surface temperatures, and reduced convective rainfall. Copyright © 2007 Royal Meteorological Society

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1. Introduction

Annual rainfall in the Caribbean exhibits a bimodal structure with two rainfall maxima (May–June and September–October) separated by what has been termed a 'mid-summer' drought (MSD) (July–August) (Magaña *et al*., 1999; Chen and Taylor, 2002; Ashby *et al*., 2005). The most widely accepted theory as to the cause of the Caribbean MSD is the intensification and expansion of the North Atlantic Subtropical High Pressure Cell (NAHP) into the region in July (Hastenrath, 1976, 1978, 1984; Granger, 1985; Knaff, 1997; Giannini *et al*., 2000). According to this theory, the intensification and expansion of the NAHP translates into stronger trade winds, cooler sea surface temperatures (SST), increased susbsidence and diminished Caribbean rainfall. Hastenrath (1976) also notes that the winter preceding a particularly dry summer in the Caribbean is characterized by an early southward displacement of the NAHP, stronger Trade Winds and an equatorward shift of the east Pacific intertropical convergence zone (ITCZ).

Despite general acceptance of this theory, it has been noted in several studies that the influence of the NAHP on the Caribbean MSD may not be consistent across the region (Granger, 1985; Magaña *et al*., 1999; Curtis, 2002; Ashby *et al*., 2005). For example, Giannini *et al.* (2000) found that the bi-modal pattern of annual rainfall centred around a MSD accounts for 66% of the total variance of the annual cycle of Caribbean rainfall and is most pronounced in the western Caribbean. Thus, it is obvious that despite the general acceptance of the NAHP as one of the dominant controls of Caribbean MSD occurrence, spatial variability exists in the occurrence of the phenomena and the cause(s) of this variability is not completely understood.

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Accordingly, the purpose of this research is to better understand the causes and occurrence of the Caribbean MSD through mapping the spatial co-variability of the Caribbean MSD and then determining the association between these spatial patterns and NAHP circulation. This study differs from previous research of Caribbean rainfall in that the analysis focuses upon the MSD season alone as opposed to examination of early or late rainfall season totals or extreme precipitation values (Hastenrath, 1976; Chen and Taylor, 2002; Taylor *et al*., 2002; Spence *et al*., 2004; Ashby *et al*., 2005).

2. Data and methods

In order to determine the spatial variability in the onset and duration of the Caribbean MSD, a mapping analysis of loadings from a Principal Component Analysis (PCA) of monthly Caribbean rainfall data was completed. The technique of applying PCA to mean monthly rainfall climatologies has long been noted as an efficient summary of the salient features of the annual cycle of precipitation (Stidd, 1967; Comrie and Glenn, 1998; Jayawardene *et al*., 2005). Data included in this analysis were chosen from a total of 28 Caribbean weather stations in the Global Historical Climate Network Version 2 (as available from the NOAA National Climate Data Centre (NCDC) website) (Table I). These 28 stations each have at least 85% monthly precipitation records from 1960–1995 and are located in an expanded definition of the Caribbean basin (5°–25 °N, 50°–90 °W). The annual mean monthly precipitation for each station was first reviewed in order to determine if the bimodal distribution in annual rainfall existed at the given location. For the purpose of this initial review, a bimodal distribution was defined as two maxima separated by a minimum sometime between April and October. Non-MSD locations were excluded from the analysis in order to ensure identification of distinct regions of MSD development. Upon review for the bimodal distribution, eight locations were removed from the data set.

Before the PCA was completed with the remaining 20 stations, data was manipulated to focus on the MSD season and standardized in regard to magnitude. Specifically, for each station, only monthly rainfall from March through October was retained for the PCA. The traditional definition of the MSD season was extended two months earlier because our initial examination of the bimodal distributions found that the first maximum in rainfall sometimes occurred in April, and March is required to calculate monthly differences in rainfall for April.

Table I. List of Caribbean weather stations with 85% of monthly precipitation records 1960–1995 that were included in analysis and the appropriate bimodal annual precipitation regime classification.

Station Name	Latitude (north)	Longitude (west)	Bimodal distribution
Barcelona, Venezuela	10.10	−64.70	No
Basse Terre, Guadeloupe	16.00	−61.43	Yes
Belize Int. Airport, Belize	17.50	−88.30	Yes
Cabo San Antonio, Cuba	21.87	−84.95	Yes
Camaguey, Cuba	21.57	−77.85	Yes
Casablanca, Cuba	23.17	−82.35	Yes
Cayenne/Rochambea, French Guiana	4.80	−52.40	No
Coro, Venezuela	11.40	−69.70	Yes
Grantley/Seawell, Barabados	13.10	−59.50	Yes
Guantanamo Bay, Cuba	19.90	−75.15	Yes
Guiria, Venezuela	10.60	−62.30	No
Hato Airport/Curacao, Dutch Antilles	12.20	−68.97	No
Juliana Aero, Dutch Antilles	18.05	−63.12	Yes
Key West WSO AP, USA	24.55	−81.75	Yes
Kingston/Manley I, Jamaica	17.90	−76.80	Yes
Maracaibo-LA Chin, Venezuela	10.70	−71.60	Yes
Maracay-B.A.Sucre, Venezuela	10.30	−67.70	No
Miami Fl, USA	25.80	−80.30	Yes
Nassau Int. Airport, Bahamas	25.10	−77.40	Yes
Piarco Int. Airport, Trinidad and Tobago	10.60	−61.40	No
Puerto Limon, Costa Rica	10.00	−83.05	No
Punta Maisi, Cuba	20.30	−74.20	Yes
Roosevelt Roads, Puerto Rico	18.25	−65.63	Yes
San Juan Int. Airport, Puerto Rico	18.50	−66.00	Yes
Santo Domingo, Dominican Republic	18.40	−69.90	Yes
Sesquicentena, Colombia	12.40	−81.40	Yes
Simon Bolivar, Colombia	11.10	−74.10	Yes
Zanderij, Suriname	5.47	−55.20	No

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To standardize for magnitude across the region, rainfall was expressed as a proportional difference. This proportional difference was calculated by subtracting the current month (m) from current month plus one ($m + 1$) and dividing the difference by the current month (m). The monthly proportional differences in precipitation for the 20 stations were then used as a raw data matrix in an S-mode PCA (multiple stations over time). The resultant PCA factor pattern was rotated orthogonally through a varimax rotation. The loading of each weather station on the rotated components was mapped to determine regions of the Caribbean MSD. Regions of similar MSD were defined as an area that encompasses all weather stations with a 0.5, or greater loading on a specific component (Henderson and Vega, 1996; Jayawardene *et al*., 2005).

In order to assess the degree of association between the spatial variability in the Caribbean MSD and the NAHP circulation, a Spearman rank correlation analysis was completed between MSD season monthly rainfall and measures of the NAHP circulation. Specifically, the rainfall data included in the correlation analysis was a single de-trended, standardized monthly rainfall data (1963–1992) for each identified MSD region. The regional time series was calculated as an arithmetic mean of the de-trended, standardized monthly rainfall for each station within a MSD region. The de-trending of the data is necessary since Caribbean rainfall has exhibited a marked negative trend since the 1960s (Peterson *et al*., 2002; Taylor *et al*., 2002). This study used the same technique as Ashby *et al*. (2005) to de-trend the data, subtraction of a 7-year moving average from each observation. The use of the moving average to de-trend the data reduced the period of record used in correlation analysis from 1960–1995 to 1963–1992. After the trend was removed, the monthly rainfall data for each location was standardized by the mean and standard deviation of the 1963–1992 time series.

NAHP circulation was represented in the correlation analysis by the North Atlantic Oscillation (NAO) and the pressure gradient of the southwest flank of the Bermuda High as measured by the Bermuda High Index (BHI). The NAO represents an oscillation in the sea level pressure between the Iceland Low (about 65°N) and the Azores High (approximately 40°N) (Hurrell, 1995). A multitude of studies have found the NAO to be linked to climatic and oceanographic variables in the North Atlantic, Europe and North America (Rogers, 1990; Wallace *et al*., 1995; Hurrell, 1996; Reverdin *et al*., 1997; Molinari *et al*., 1997; Ulbrich *et al*., 1999). More recently, studies have found the NAO to influence subtropical and tropical locations such as the Canary Islands (Herrera *et al*., 2001), Barbados (Charlery *et al*., 2006), and the Caribbean (Ashby *et al*., 2005). In this study, the NAO is represented by an empirical orthogonal factor (EOF) index of hemispheric mean sea level pressure anomalies available on NOAA's Climate Prediction Center web site (http://www.cpc.noaa.gov/products/precip/CWlink/pna/nao.shtml). The EOF derived NAO was chosen for use in this study because it represents variation across the entire north Atlantic basin and has greater potential to represent the influence of the NAHP on the Caribbean as opposed to a traditional two-station index.

The BHI is defined as the difference in standardized monthly sea-level pressure at New Orleans and Bermuda and is purported to provide a more appropriate assessment of the southwestern flank of the NAHP. Researchers have used the BHI in the past to assess the interaction between the NAHP, moisture advection, and spring rainfall in the southeastern United States (Stahle and Cleaveland, 1992; Henderson and Vega, 1996). The BHI used in this study is calculated with monthly mean sea-level pressure for the New Orleans International Airport as reported in Monthly Meteorological Reports on NOAA's NCDC website and monthly mean sea-level pressure for the 32°N, 65 °W grid point from the COADS data set.

Beyond these two traditional measures of the NAHP, modified BHIs were also used in correlation analysis. The modified BHI represents the difference in standardized sea level pressure between the centre of the NAHP (30°N, 40 °W) and the centroid of weather stations in each MSD region. The centre of the NAHP was identified through a review of the National Centers for Environmental prediction (NCEP) reanalysis plots of long-term surface pressure data (1960–1995) and represents a location enclosed by the 1020 mb contour during all months of the MSD season. The sea level pressure data used in the calculation of the modified BHI were 1° box mean values from the NOAA COADS data-set (Woodruff *et al*., 2002), as available on EarthInfo Co. CD-ROMS. The data was standardized with the mean and standard deviation of the 1960–1995 time series.

The correlation analysis was completed with precipitation time series representing the MSD season May through July for each region, and times series of each NAHP measure. The months of May, June and July are used to represent the MSD, because these are the months in which the MSD occurs for all multiple station MSD regions and the majority of the study area. A lagged correlation analysis was also completed with the modified BHIs and the MSD season precipitation time series. Correlations were calculated at lags with the modified BHI time series lagged behind the regional precipitation time series from 1 to 8 months. These lags represent the September–April preceding the MSD season and will be used to further assess Hastenrath (1976) findings that the winter preceding a particularly dry summer in the Caribbean is characterized by an early southward displacement of the NAHP, stronger Trade Winds, and an equator-ward shift of the east Pacific ITCZ.

3. Results

Upon examination of the PCA scree plot and map of component loadings, a total of five MSD regions were identified in the Caribbean that explained 96% of the total variance in proportional difference of monthly MSD season precipitation for the 20 weather stations (Table II).

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All weather station locations had component loadings over 0.5 and were, therefore, placed within a MSD region (Table II). The five factors identified three MSD regions with multiple stations, the northwestern Caribbean, the interior Caribbean, the eastern rim Caribbean and two regions with single stations, Coro, Venezuela and Grantley, Barbados (Table II, Figure 1). The PCA also identified one transition zone between MSD regions. The transition zone has stations with loadings of greater than 0.5 on multiple factors, and thus cannot be assigned to an individual region. The transition zone is located in the central portion of the study area and has stations with high loadings on the northwest, interior and eastern rim region components (Table II).

Review of the mean proportional differences in monthly precipitation for the MSD season indicates that each of the regions has a different month of MSD occurrence or a different MSD duration (Figure 2). For the northwestern Caribbean region, the MSD separating the two precipitation maxima occurs during June–July. For the Transition zone, the MSD occurs during June–July but has a greater magnitude than the northwest region MSD. The interior region MSD occurs during May–June, has the greatest magnitude of all regions, and extends into June–July. The eastern rim region MSD also occurs during May–June and has the smallest magnitude of all the regions. For the two single station MSD regions, the MSD occurs much later in the year, during July–August for Venezuela and August–September for Barbados. The magnitude of the MSD in these two single station regions is of moderate magnitude as compared to the multiple station regions.

Based upon the results of the PCA analysis, three modified BHI were constructed and used in the correlation analysis: eastern rim BHI (ERBHI) (30°N, 40 °W) – (15°N, 68 °W), interior Caribbean BHI (IBHI) (30°N, 40 °W) – (19°N, 70 °W), and northwestern Caribbean BHI (NWBHI) (30°N, 40W) – (23°N, 83 °W). Concurrent correlation analysis indicates that overall, modified BHIs are more effective tools in evaluating the association between NAHP circulation and Caribbean precipitation as compared to the more traditional indices, NAO EOF and BHI (Table III). Correlation coefficients for the NAO and BHI ranged between −0.050 and 0.305, while modified BHI correlation coefficients ranged between 0.080 and 0.430.

Patterns in the lagged correlations indicate that the correlation between the modified BHI and regional precipitation series change from positive at 0–1-month lag

Table III. Correlation coefficients of MSD region May–July monthly precipitation and north Atlantic high pressure indices 1963–1992.

	NAO EOF	BHI	ERBHI	IBHI	NWBHI
Eastern Rim	*0.305*	−0.005	0.190	***0.367***	0.080
Interior	*0.278*	*−0.203*	*0.217*	***0.430***	*0.260*
Transition	*0.242*	−0.134	0.137	0.184	***0.252***
Northwest	*0.228*	***0.244***	0.121	0.114	*0.224*

Bold text indicates greatest degree of association for each MSD region. Italic text represents correlation coefficients significantly different from zero at 95% confidence interval.

Table II. Factor loadings for each of the 20 weather stations included in the principle component analysis of proportional difference in monthly precipitation. The percent variance explained by each factor is listed in the last row. Shaded cells represent multi-station regions, numbers in bold represent loadings over 0.5, and numbers with asterisk represent transition stations.

Station Name	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
BASSE Terre, Guadeloupe	−0.054	**0.937**	0.125	−0.050	0.262
Belize Int. Airport, Belize	**0.834**	−0.347	−0.058	0.053	0.097
Cabo San Antonio, Cuba	**0.834**	0.312	−0.035	0.048	0.385
Camaguey, Cuba*	**0.655**	0.262	0.086	0.008	**0.701**
Casablanca, Cuba	**0.919**	−0.212	0.217	0.236	0.056
Coro, Venezuela	−0.123	0.173	0.077	**0.962**	0.150
Grantley/Seawell, Barabados	0.032	−0.230	**−0.940**	0.016	−0.244
Guantanamo Bay, Cuba	0.157	−0.051	0.290	0.092	**0.933**
Juliana Aero, Dutch Antilles	−0.134	**0.935**	0.246	−0.209	0.052
Key West WSO AP, USA	**0.946**	0.178	0.056	−0.229	0.106
Kingston/Manley I, Jamaica*	**0.536**	0.316	0.249	−0.280	**0.577**
Maracaibo-La Chin, Venezuela	0.032	**0.804**	−0.092	0.373	−0.239
Miami Fl, USA	**0.931**	0.161	0.024	−0.145	0.220
Nassau Int. Airport, Bahamas	**0.882**	−0.031	−0.216	−0.097	0.392
Punta Maisi, Cuba*	0.056	−0.126	**0.630**	0.322	**0.614**
Roosevelt Roads, Puerto Rico	0.356	0.295	0.253	−0.039	**0.847**
San Juan Int. Airport, Puerto Rico	0.181	**0.850**	0.024	0.266	0.416
Santo Domingo, Dominican Republic	0.397	0.259	−0.045	0.157	**0.843**
Sesquicentena, Colombia*	**0.768**	−0.006	−0.164	0.287	**0.541**
Simon Bolivar, Colombia	0.370	**0.761**	−0.113	0.484	0.063
Percentage Variance Explained By Component	33.0	22.2	8.7	9.3	22.8

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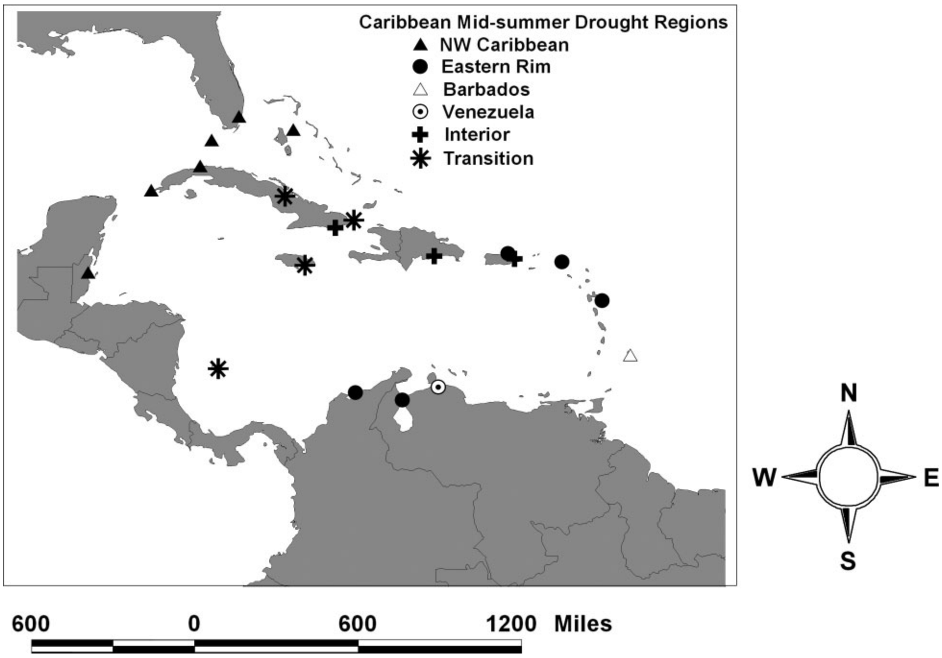

Figure 1. Map of Caribbean mid-summer drought regions as determined by principal component analysis.

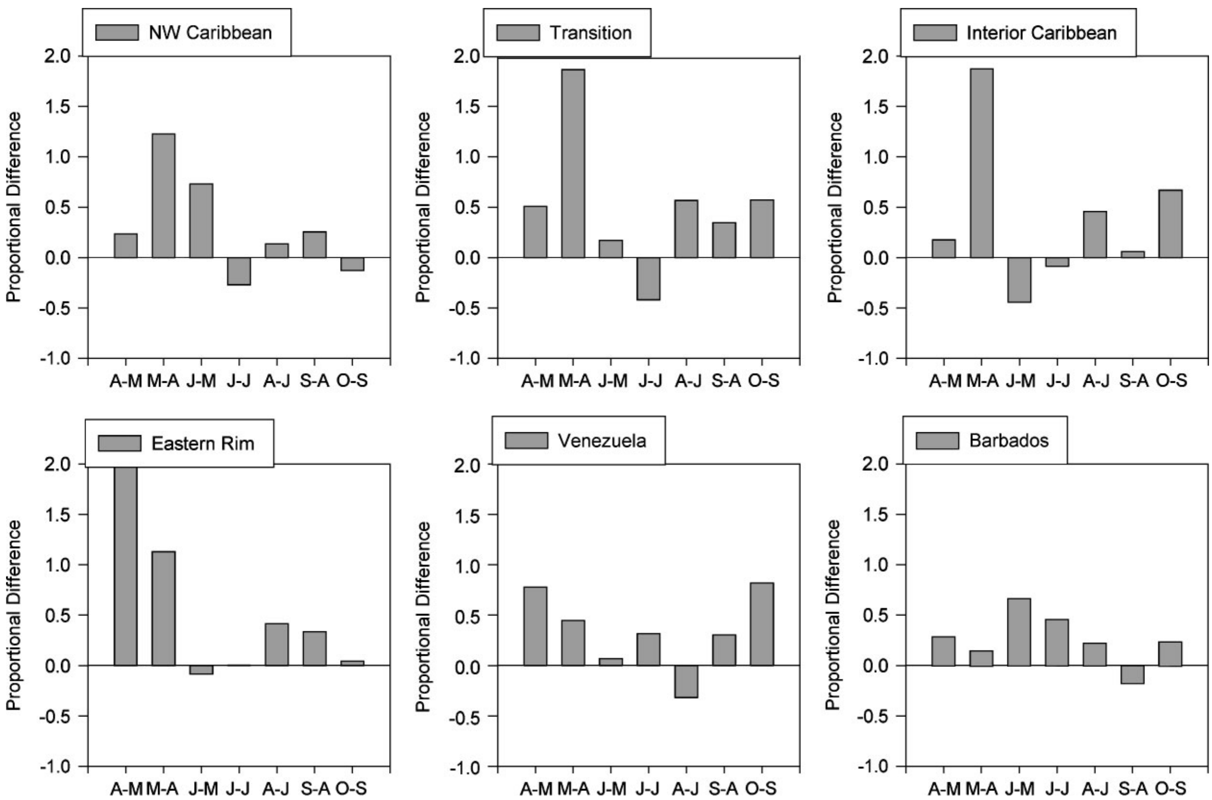

Figure 2. Mean proportional difference in monthly rainfall (1960–1995) for Caribbean mid-summer drought regions.

to negative at the 2–6-month lag and then back towards positive at the 7–8-month lag (Figure 3). The greatest negative correlation usually occurs at the 3–4-month lag, except for the Northwest region for which the greatest negative correlation occurs at a 6-month lag. The 3–6-month lag corresponds to the December–April, or winter-spring, preceding the MSD. The greatest lag correlation for each region occurs during the negative phase of the pattern, and is equal to or greater than the degree of association found in concurrent correlation analysis.

4. Discussion

The overall patterns in spatial variability appear to support the hypothesis that the NAHP is the major

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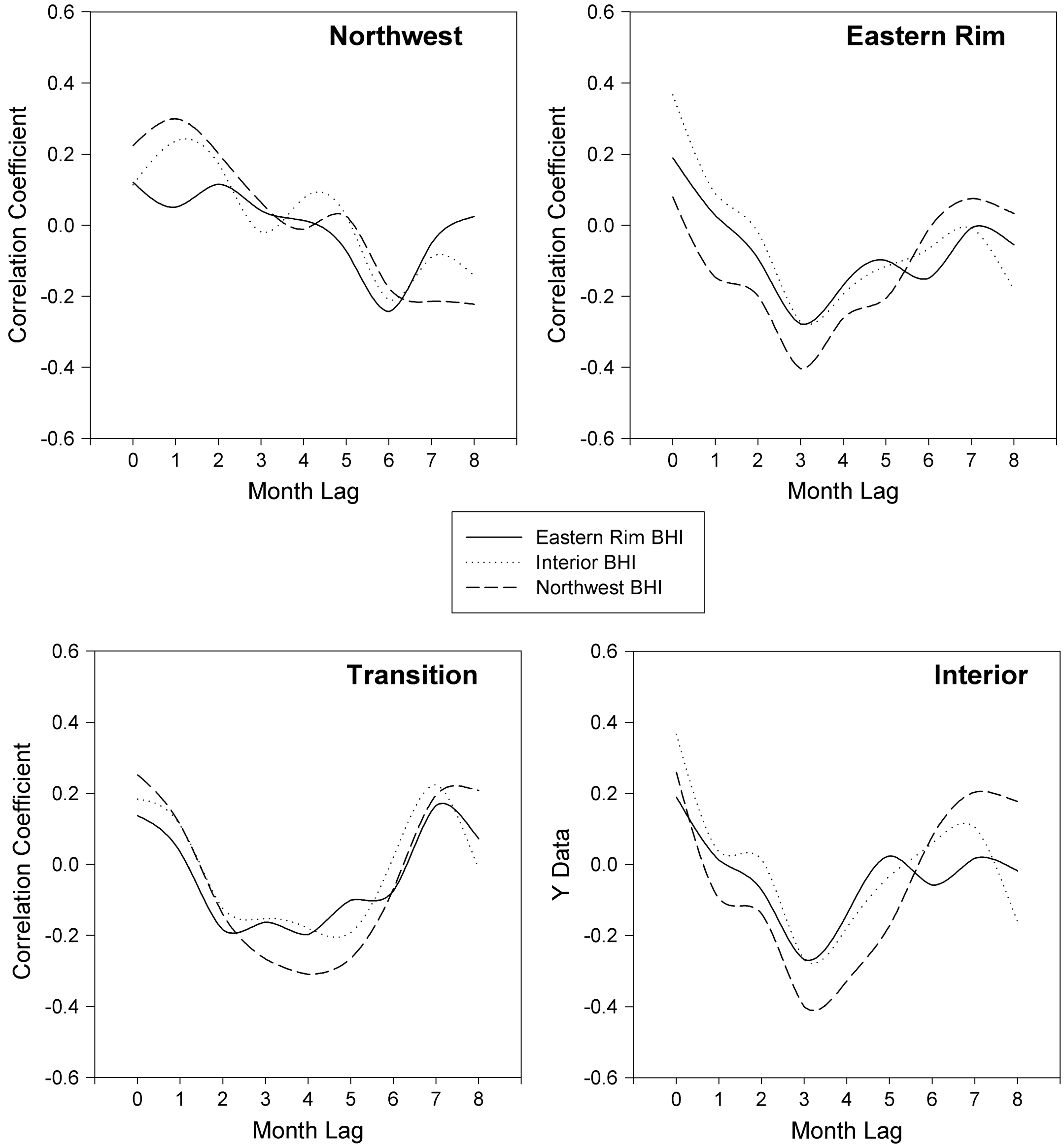

Figure 3. Lagged Spearman ranked correlations between MSD region May–July precipitation and modified BHIs (1963–1992).

control on the timing and development of the Caribbean MSD. This interpretation is primarily based upon the temporal progression of the Caribbean MSD from east to west across the region. A review of the months in which the decrease in precipitation, signifying the start of the MSD, occurs for the eastern most regions, eastern rim and interior, indicates that the MSD develops in May–June. For the western-most regions, northwest and transition, the MSD develops in June–July. Such a spatial pattern agrees with the concept of the late spring early summer expansion of the NAHP into the region, causing a decrease in rainfall through stronger trade winds, cooler SSTs, and general subsidence in the eastern and interior portions of the Caribbean first. Then in June–July the expansion of the high-pressure cell begins to influence the west and northwestern portions of the Caribbean. Potentially adding to the influence of the NAHP upon the transition and northwest regions may be increased subsidence that is created by a regional teleconnection initiated by intense convection over the western part of the northeast Pacific warm pool (Magaña and Caetano, 2005).

The occurrence of the MSD in July–September for the two single station regions, Venezuela and Barbados, suggest that these two locations are influenced by unique local processes that separate them from the overall circulation impacting the rest of the Caribbean MSD. For Barbados, the Seawell/Grantley station is located on the southeastern side of the island which is located in a rain shadow, receiving less than 1150 mm/year as compared to greater than 1750 mm/year on the windward side of the island (Sealey, 1992). Such local topographic features may have caused the location to not be included in basin-wide spatial patterns as identified by the PCA.

Coro, Venezuela is located in the west–east trending coast of northern South America where subsidence of winds initiated by the heated Llanos to the south, coastal divergence, and coastal upwelling combine to create a

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dry zone (Trewartha, 1981). Thus, any MSD occurring in this area is created by a different suite of processes as compared to the rest of the Caribbean, and consequently, is identified by the PCA as a separate region due to a different annual precipitation regime. The Simon Bolivar and Maracaibo stations, which were included in the analysis but assigned to the eastern rim region, are also located on the northern coast of South America. However, these two stations are located in areas of the coast which have a north–south orientation, negating some of the effect of divergence and upwelling that occurs at Coro, making them more likely to be influenced by climatic processes which cause the MSD in other parts of the Caribbean.

As noted, concurrent correlation results indicate that, in general, the NAO EOF and the BHI are both poorly associated with Caribbean precipitation (Table III). However, it should be noted that there appears to be a distance decay effect in these correlations. The regions closest to the centre of the NAHP (eastern rim and interior) and those regions closest to New Orleans (transition and northwest) had greater association with the NAO EOF and BHI respectively. Such a pattern in the correlation coefficients suggests that the reason for poor performance of traditional NAHP measures is that they were originally designed to measure impact of the NAHP on Europe and North America, and a 'geographic bias' exists in these measures. In order to appropriately assess the impact to the NAHP on a region outside of Europe or North America, such as the Caribbean, new region-specific measures such as the modified BHIs must be developed.

The pattern in lagged correlation coefficients, positive 0–1-month lag, negative 2–6-month lag, positive 7–8-month lag (Figure 3), is interpreted as the NAHP impacting summer Caribbean rainfall through two processes, concurrent supply of moisture and sea surface cooling previous to MSD development. The positive relationship at a 0–1-month lag from the MSD (April–May), suggests that a high-pressure gradient equates to stronger northeasterly Trade Winds, which supply more moisture to the region for rain. Conversely, when there is less moisture, or a lower pressure gradient and weak Trade Winds, less rain occurs in the region. At the 2–6-month lag period (December–March), the negative correlations suggest that a greater pressure gradient will result in a drier MSD due to strong Trade Winds that cool the sea surface and reduce the amount of energy available for convection. The change of correlation towards positive values in the 7–8-month lag indicates that this intensification of the NAHP is short-lived, but given the low, insignificant values of the correlations, this last positive phase is not deemed physically relevant. Such a pattern as presented by the lagged correlations supports Hastenrath (1976) findings of the winter preceding a particularly dry summer in the Caribbean as characterized by an early southward displacement of the NAHP, stronger Trade Winds and an equator-ward shift of the East Pacific ITCZ.

5. Conclusions

Overall, the results of this study support the hypothesis that the NAHP contributes to the development of the Caribbean MSD. However, the impact of the NAHP is not spatially consistent and is manifested as different atmospheric processes at different times relative to MSD occurrence. Each of the MSD regions identified in this study has a different month of MSD occurrence or a different MSD duration. The spatial pattern of the monthly precipitation differences for each MSD region suggests that the NAHP impacts the eastern Caribbean first and then expands westward as the summer progresses. Based upon these results, the Caribbean MSD season can be broadly defined as May through July, and more specifically, May–June for the east and interior MSD region, and June–July for the west MSD region.

In regard to the association between the NAHP circulation measures and MSD region precipitation time series, correlation analysis indicates that a modified BHI is a more effective tool in evaluating the association as compared to the traditional indices (NAO EOF and BHI). Such patterns underscore the need for use of region-specific NAHP measures. Correlations using a region-specific NAHP measure support findings that the winter preceding a particularly dry summer (3–6-month lag) in the Caribbean is characterized by a larger pressure gradient on the southeastern flank of the NAHP, which most likely equates to stronger Trade Winds and cool SSTs which reduce the probability of convective rainfall.

The authors recognize that the greatest limitation to this study is the coarse temporal resolution and exclusive use of land-based weather stations. Analysis with a finer temporal analysis and estimates of rainfall over the Caribbean waters is currently underway. This analysis is expected to allow for the capture of the timing of atmospheric processes on a daily to weekly scale across the entire Caribbean basin, creating a more accurate representation of the development of the Caribbean MSD and its link to the NAHP. Through such an analysis, a modified BHI can be combined with measures of SST and wind fields, and be more flexible in terms of identifying the timing of MSD development. Accordingly, use of a modified BHI presented in this study serves as a foundation upon which a more rigorous assessment of the Caribbean MSD–NAHP relationship can be developed.

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